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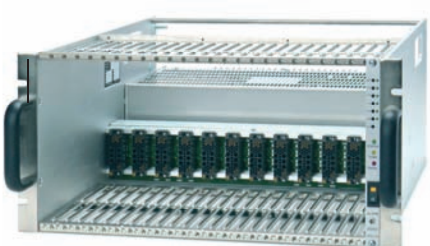

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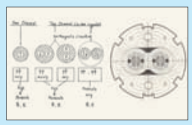


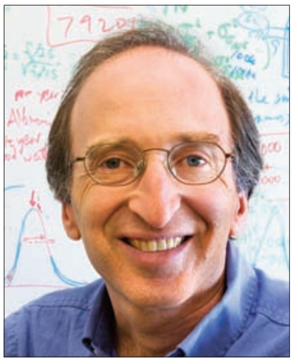
On the cover: A small magnet levitates above superconducting material in one of the most entrancing demonstrations of superconductivity, a phenomenon that was discovered 100 years ago and now underlies many of the recent advances in particle accelerators (p5).

News

LHC NEWS

Discovery of accelerating universe wins Nobel prize

Saul Perlmutter, Brian Schmidt and Adam Riess have been awarded the 2011 Nobel Prize in Physics "for the discovery of the accelerating expansion of the universe through observations of distant supernovae". Perlmutter, professor of astrophysics at the Lawrence Berkeley National Laboratory and University of California, Berkeley, receives half of the prize, with the other half being shared between Schmidt, distinguished professor at the Australian National University, and Riess, professor of astronomy and physics at Johns Hopkins University and the Space Telescope Science Institute. Their finding led to a dramatic change in perception of the universe by providing evidence for what has become known as "dark energy".



Left to Right: Perlmutter, Schmidt and Riess. (Image credits: Lawrence Berkeley National Laboratory; B Schmidt/ANU; W Kirk /Homewood Photographic Services.)

In 1997 the Supernova Cosmology Project (SCP), led by Perlmutter and the High-z Supernova Search Team, led by Schmidt, were working independently on observations of distant Type 1a supernovae, using them as "standard candles" to measure cosmological distances as a function of time. (All such supernovae have similar intrinsic brightness, so their apparent brightness gives a measure of distance.) They expected to find evidence for a gradual slowdown in the expansion of the universe, resulting from the influence of gravity on the matter it contains.

Instead, the measurements revealed around 50 distant supernovae that appeared to be dimmer than predicted by calculations based on the gravitational effects of matter. In 1997 Gerson Goldhaber – well known in the particle-physics community – was the first person in the SCP team to notice the unexpected effect while plotting the brightness against redshift for Type Ia supernovae that the project had discovered. The same year, Adam Riess, then a research fellow at UC Berkeley who was leading an analysis of supernovae detected by the High-z project, uncovered a similar effect.

The observations pointed to the surprising conclusion that the expansion of the universe is not slowing under the influence of gravity, but is instead accelerating. This in turn implies the existence of some form of gravitationally repulsive "substance", uniformly distributed across the universe, which counteracts the gravitational attraction of matter. This unknown substance has become known as "dark energy" (*CERN Courier* September 2003 p23).

The two teams published their results in 1998–1999 and since then their findings have been confirmed not only by further observations of supernovae but also by detailed measurements of fluctuations in the cosmic microwave background radiation and of baryon acoustic oscillations, i.e. clustering of baryonic matter in the early universe that also serves as a "standard ruler" for cosmological distance scales. All of the evidence suggests that dark energy contributes as much as 73% of the mass-energy content of the universe, with 23% from dark matter and only about 4% from normal baryonic matter – but the nature of both dark matter and dark energy remains unknown.

100 years of superconductivity

In November 1911, Heike Kammerlingth Onnes reported on the abrupt disappearance of resistance in mercury at 4.20 K. To mark the centenary of the discovery of superconductivity, this issue of *CERN Courier* looks at some of the aspects of its application – in particular in the context of particle accelerators – and at some more anniversaries. It is 75 years since type-II superconductivity was first observed in Kharkov (p17). Although sadly overlooked for 25 years, this made superconducting magnets a real possibility and led to the Tevatron – the first superconducting synchrotron – (p28) and most recently the LHC, with its particular challenges (p21), as well as to applications in medical scanners (p39). First proposed 50 years ago, RF superconductivity also has an important role in many accelerators (p33), exemplified in several of the applications of superconductivity at KEK, founded 40 years ago (p36).

Sommaire en français

Neutrinos

OPERA reports time-of-flight anomaly

The OPERA experiment in Italy's INFN Gran Sasso Laboratory has sent ripples round the world with its findings that neutrinos created 730 km away at CERN arrive at the detector slightly earlier than if they were travelling at the speed of light.

The result is based on the observation of more than 15 000 neutrino events measured by the experiment, which observes the beam produced by the CERN Neutrinos to Gran Sasso (CNGS) project (*CERN Courier* November 2006 p20). Using high-statistics data taken in 2009, 2010 and 2011, the collaboration has measured the velocity of the muon-neutrinos reaching the detector with much higher accuracy than previous studies conducted using accelerator neutrinos. Upgrades to the CNGS timing system and to the OPERA detector, as well as the use of high-precision geodesy to measure the neutrino baseline, allowed the collaboration to achieve comparable systematic and statistical accuracies.

To perform the study, the OPERA collaboration teamed up with experts in metrology from CERN and other institutions to make a series of high-precision measurements of the distance between the source and the detector, and of the neutrinos' time of flight. The distance between the origin of the neutrino beam and OPERA was measured with an uncertainty of 20 cm over the 730 km travel path. The neutrinos' flight time was determined with an accuracy of less than 10 ns by using sophisticated instruments, including advanced GPS systems and atomic clocks. The time responses of all of the elements of the CNGS beamline and of the OPERA detector have also been measured with great precision.

The results indicate that neutrinos from CERN arrive early at Gran Sasso by 60.7 ± 6.9 (stat.) ± 7.4 (sys.) ns compared with the time that would be taken assuming the speed of light in vacuum. This anomaly corresponds to a relative difference of the muon-neutrino velocity, v, with respect to the speed of light, c, $(v-c)/c = (2.48 \pm 0.28$ (stat.) ± 0.30 (sys.)$) \times 10^{-5}$.

Given the potential far-reaching consequences of such a result, independent measurements are certainly needed before the effect can either be refuted or firmly established. While OPERA continues to gather more data, the MINOS collaboration in the US is planning to improve its measurement of the neutrino time of flight with the beam from Fermilab to the Soudan Underground Laboratory, about 370 km away.

Further reading

The OPERA collaboration T Adam *et al.* arXiv:1109.4897v1 [hep-ex].

Collaboration

Israel to become an associate member of CERN

Aharon Leshno-Yaar, left, and Rolf Heuer shake hands after signing the agreement.

On 16 September, CERN's director-general, Rolf Heuer, and the Israeli ambassador and permanent representative of Israel to the United Nations Office and other international organizations in Geneva, Aharon Leshno-Yaar, signed a document admitting Israel to associate membership of CERN, subject to ratification by the Knesset. Following ratification, Israel will become an associate member for a minimum of 24 months. Following this period, CERN Council will decide on the admission of Israel to full membership, taking into account the recommendations of a task force to be appointed for this purpose.

Israel has a strong tradition in both experimental and theoretical particle physics, with a major involvement at CERN during the 1990s in the OPAL experiment at the Large Electron–Positron (LEP) collider. Israel's accession to observer status in 1991 followed an agreement to contribute funds to the CERN budget to support Israeli scientists, as well as providing equipment to CERN. The Israeli fund also contributed to running LEP and supported LHC construction and R&D for future accelerators. During its association with CERN, Israel has in addition supported Palestinian students at CERN, notably sending mixed Israeli–Palestinian contingents to CERN's summer-student programme.

"It is a vital part of our mission to build bridges between nations. This agreement enriches us scientifically and is an important step in that direction," says CERN director-general, Rolf Heuer. "I am very pleased that CERN's relationship with Israel is moving to a higher level."

In 2009, Israel was accepted as a special observer state, with the right to attend restricted Council sessions for discussions of LHC matters. Israel currently has strong involvement in the ATLAS experiment at the LHC and participates in a number of other experiments at CERN.

Les physiciens des particules du monde entier sont invités à apporter leurs contributions aux CERN Courier, en français ou en anglais. Les articles retenus seront publiés dans la langue d'origine. Si vous souhaitez proposer un article, faites part de vos suggestions à la rédaction à l'adresse cern.courier@cern.ch.

CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

ASTROPARTICLE PHYSICS

Gravitational waves: European detectors keep up the pace

For several years the European gravitational-wave detectors GEO600 (a collaboration between Germany and the UK), close to Hanover, and Virgo (a collaboration between Italy, France, the Netherlands, Poland and Hungary), close to Pisa, have been performing data-taking runs together with the LIGO detectors in the US. About a year ago the LIGO collaboration turned off its detectors to start an important upgrade, so this summer the European detectors joined forces to step up their search for gravitational waves in a last three-month data-taking run before Virgo also shuts down for its own upgrade.

GEO600 and Virgo had the good fortune to be on with an impressive 82% duty cycle at the time of the recent nearby supernova explosion (*CERN Courier* October 2011 p12). Unfortunately, the event on 24 August was too far away and of Type 1a, so releasing only a small amount of energy as gravitational waves. Analysis is nevertheless continuing at full speed.

These detectors are kilometre-scale Michelson laser-interferometers that work by measuring tiny changes caused by a passing gravitational wave in the lengths of their orthogonal arms. Laser beams sent down the arms are reflected from mirrors, suspended under vacuum at the ends of the arms, to a central photodetector. The periodic stretching and shrinking of the arms is then recorded as varying interference patterns.

The worldwide detector upgrades that are just starting will be a fundamental step forward. With current sensitivities, the probability of detecting a gravitational-wave burst in one full year of data-taking is estimated to be of the order of a few per cent. The upgrades aim to improve the sensitivities by a factor of 10 with respect to the present values, which should then extend the "listening" distance by a factor of 10. This will increase the volume of universe explored and the detection probability by a factor of 1000, offering the "certainty" of catching several gravitational-wave events a year.

The non-detection of gravitational waves so far has nevertheless allowed the derivation of several important scientific results. For example, important limits have been established on the production of gravitational waves of cosmological origin and by known pulsars. Improving the spin-down limit of the Crab and Vela pulsars should put limits on the ellipticity of the stellar mass-distributions, which are expected to be related to the magnetic asymmetries in these systems.

"Multimessenger" astrophysics has meanwhile begun, looking for coincidences of candidate gravitational-wave signals with gamma-ray bursts and signals from space-borne cosmic-ray detectors as well as neutrino and optical telescopes. Such clues will have paramount importance in studying the sources as soon as genuine gravitational-wave detection becomes routine after 2015, when detector upgrades are expected to be completed.

EXOTIC ATOMS

Kaonic hydrogen casts new light on strong dynamics

Hadronic bound systems with strange quarks, such as kaonic hydrogen, are well suited for testing chiral dynamics, especially in view of the interplay between spontaneous and explicit symmetry breaking. Effective field theories with coupled channels based on chiral meson–baryon Lagrangians have become well established as a framework for describing $\bar{K}$–nucleon interactions at threshold, including much disputed $\Lambda(1405)$ resonances and deeply bound antikaonic nuclear clusters lying just below the respective thresholds.

A recent precision measurement at the Laboratori Nazionali di Frascati of the strong-interaction-induced shift and width of the 1s level in kaonic hydrogen sheds new light on these basic problems in strong-interaction binding and dynamics. Kaonic hydrogen, in which a $\bar{K}$ replaces the electron, is produced by the capture of stopped $\bar{K}$ from the decay of ϕ mesons in hydrogen gas. The ϕ mesons are generated nearly at rest at the DAΦNE e^+e^- collider, operating in a new, high-luminosity collision mode.

The SIDDHARTA collaboration with the apparatus. (Image credit: C Curceanu.)

The shift and width of the kaonic 1s state is deduced from precision X-ray spectroscopy of the K-series transitions in the kaonic hydrogen. The emitted K-series X-rays, with energies of 6–9 keV, were detected by the recently developed Silicon Drift Detector for Hadronic Atom Research by Timing Application (SIDDHARTA) experiment, which performs X-ray–kaon coincidence spectroscopy using microsecond timing and the excellent energy resolution of about 180 eV FWHM at 6 keV of 144 large-area (1 cm^2) silicon drift detectors that surround the hydrogen target cell. This method reduces the large X-ray background from beam losses by orders of magnitude. It has led to the most precise values for the 1s level shift, $\varepsilon_{1s} = -283 \pm 36\,(\text{stat.}) \pm 6\,(\text{syst.})$ eV, and width $\Gamma_{1s} = 541 \pm 89\,(\text{stat.}) \pm 22\,(\text{syst.})$ eV for kaonic hydrogen (Bazzi *et al*. 2011).

A recent study using next-to-leading-order chiral dynamics calculations of the shift and the width has shown excellent agreement with these measurements (Ikeda *et al*. 2011). Further measurements with similar accuracy are planned for the K-series X-rays from kaonic deuterium, using an improved SIDDHARTA-2 set-up to disentangle the isoscalar and isovector scattering lengths.

● **Further reading**
M Bazzi *et al. Phys. Lett.* **B704** (2011) 113.
Y Ikeda, T Hyodo and W Weise 2011 arXiv:1109.3005[nucl-th].

News: LHC experiments

ALICE revolutionizes TOF systems

The ALICE detector is optimized to investigate collisions of heavy-ions – in practice lead–lead (Pb–Pb) – in which the production of quark–gluon plasma (QGP), a new state of matter, will provide invaluable insight into the "quark–gluon coloured world". Many aspects of this new state make particle identification an obligation, especially in the study of strangeness enhancement and heavy-flavour production. One technique developed for ALICE is based on relatively "low-tech" detectors, considering the many areas of frontier technology employed at the LHC, but its performance is proving surprisingly good.

Time-of-flight (TOF) is one of several methods that ALICE uses to identify particles. In the mid range of momenta (0.5–2.5 GeV/*c*) the TOF array shows an excellent performance in separating pions from kaons. The system is based on the multigap resistive plate chambers (MRPCs), first developed in 1996. When built with small gas gaps, this type of detector shows exceptionally good intrinsic time resolution, below 50 ps – and full efficiency.

The ALICE TOF is made of 1593 MRPCs, each of which is 120 cm long and consists of a double-stack MRPC, with a total of 10 gaps 250 μm wide. The unusual feature of the device, however, is that even though the time resolution is at the cutting edge, the technology itself is relatively low-tech.

The resistive plates are made out of thin (400–550 μm thick) sheets of "soda-lime" glass (window glass) and fishing line is used to create the 250 μm spacing between the sheets. The simplicity of the construction and the relatively low cost allowed the collaboration to build a very large area TOF (around 140 m^2) that covers the full ALICE barrel region, with 152 928 read-out pads.

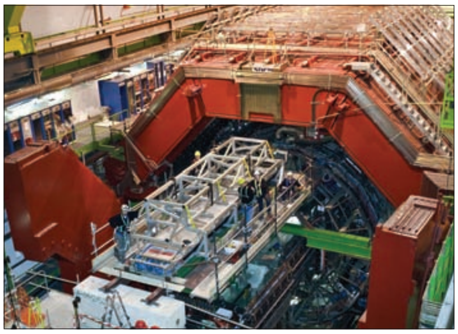


Fig. 1. The installation of a TOF sector in the ALICE detector.

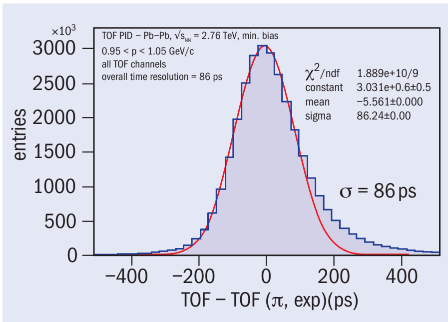


Fig. 2. TOF global time resolution in Pb–Pb collisions in ALICE.

Full exploitation of the extraordinary time resolution of the MRPC requires a suitable electronics chain. For this purpose, the "NINO" chip was developed in collaboration with CERN's microelectronics group. The chip consists of an ultrafast amplifier and discriminator, which also provide charge information (needed for time-slewing corrections) by means of the time-over-threshold technique.

In addition to its extremely precise time response, the MRPC has low noise (singles rate of 0.06 Hz/cm^2), which allows the TOF to be used as a trigger device for both cosmic rays and for collider physics. Another advantage is that all of the MRPC modules are operated at the same voltage and all of the thresholds of the front-end electronics are the same. This is in contrast to TOF arrays based on scintillators, where the high voltage of each phototube has to be carefully tuned.

At present the global time resolution achieved in Pb–Pb collisions is 86 ps, including fluctuations on the time-zero of the event and the track length (see figure). This value matches the design goals and provides a fundamental contribution to the particle identification analysis, which is the prominent feature of the ALICE experiment. The time resolution is still being improved and the collaboration is highly motivated to exploit all the possibilities of this extremely precise and stable detector.

Meanwhile, the MRPC has revolutionized TOF technology and many research laboratories and experiments have quickly followed ALICE's lead. These include the HARP experiment at CERN, the STAR experiment at the Relativistic Heavy Ion Collider and the FOPI experiment at GSI.

The ALICE TOF was built by the University and Sezione INFN of Bologna, the University of Salerno, the Institute for Theoretical and Experimental Physics in Moscow and the Department of Physics at Kangnung National University.

Further reading

A Akindinov *et al.* 2009 *Nuovo Cimento B* **124** 235.
E Cerron-Zeballos *et al.* 1996 *Nucl. Instrum. Meth.* **A374** 132.

ATLAS looks at vector bosons plus jets…

While searches with 2011 LHC data for the Higgs and new physics caught the headlines over the summer, detailed studies of 2010 data continue to yield high-precision physics. For example, the ATLAS collaboration has published a number of results on the production of vector bosons (W and Z) based on the full 2010 dataset of 37 pb^{-1}, including measurements that require additional jets in the final state.

The challenge of precision measurements of Standard Model vector-boson production is to understand and control the systematic uncertainties; this contrasts with many analyses that are still dominated by statistical uncertainties and can thus "simply" wait for more data. This challenge will increase in analyses of the larger 2011 data set, where ATLAS will probe higher jet-multiplicities and higher jet transverse-momenta. In addition to precise measurements of electroweak parameters, the study of W and Z bosons at the LHC tests perturbative QCD (pQCD) and it constrains the distribution of partons (quarks and gluons) inside the proton. W and Z bosons are also studied as background to other Standard Model signals and to look for new physics.

Two recent ATLAS results have focused on the production of a vector boson together with jets from b-quarks. The Z measurement is still statistically limited, while the W measurement is dominated by systematic uncertainties. The cross-section for inclusive Z + b-jets production agrees with next-to-leading-order pQCD calculations. For the

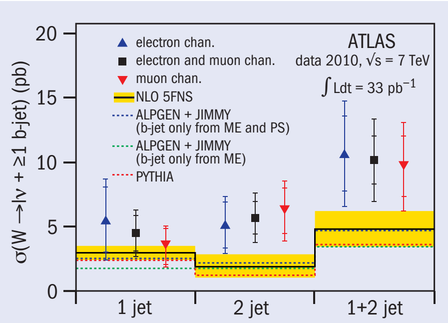


Fig. 1. Cross-section of W with 1 b-jet, 2 b-jets and 1 or 2 b-jets, for the electron, muon and combined channels.

production cross-section of a W with one or two b-jets, the results are again consistent within uncertainties, although the value observed is slightly higher than predicted (Fig. 1). These measurements with b-jets not only test pQCD for heavy quarks, they also assess what is a significant background source in searches, for example for associated Higgs production, where $H \rightarrow b\bar{b}$.

Considering the ratio of cross-sections rather than their absolute value has the advantage that many sources of systematic uncertainty cancel. ATLAS has recently published a measurement of the ratio of W and Z cross-sections with exactly one associated jet, complementing measurements of the individual channels. The ratio is measured as a function of the jet transverse-momentum. The systematic and statistical uncertainties are of comparable size, thereby providing the basis for a precision test of the Standard Model (Fig. 2). The results are in reasonably good agreement with a number of Monte Carlo predictions.

● Further reading

ATLAS collaboration arXiv:1109.1403, arXiv:1109.1470, arXiv:1108.4908.
ATLAS collaboration ATLAS-CONF-2011-042, ATLAS-CONF-2011-060.

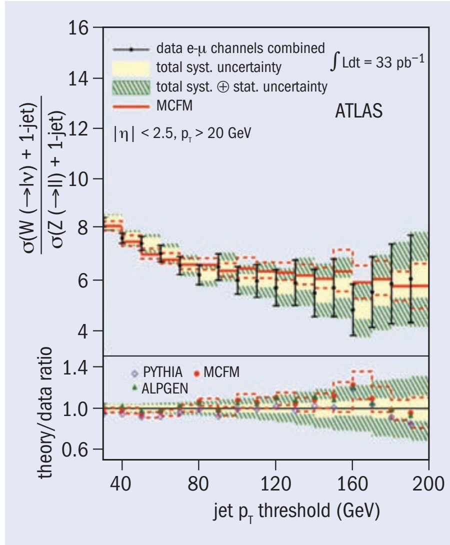


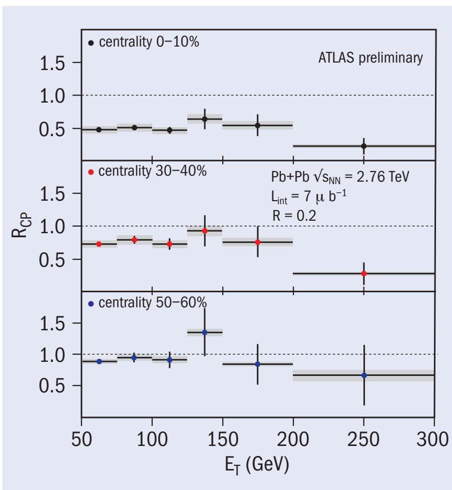
Fig. 2. Combined electron and muon result for the ratio of the W and Z cross-sections with one jet.

...and measures suppression of single jets in heavy-ion collisions

While primarily designed for proton–proton collisions, the ATLAS detector is also an excellent tool to perform measurements in the hot, dense environment of heavy-ion collisions, where temperatures reach tera-kelvin scales. So far, results include detailed measurements of collective properties of the system, such as "elliptic flow", as well as of "hard probes", such as jets, quarkonia and vector bosons.

Using the initial 2010 heavy-ion collision data from the LHC, the ATLAS collaboration published the first direct evidence that jets lose energy as they pass through the hot, dense medium, a process called jet "quenching", leading to event-by-event asymmetries in the energies of the two jets (*CERN Courier* January/February 2011 p6). To characterize the effects of quenching from a different perspective, the next major jet measurement in lead–lead collisions undertaken by ATLAS was to establish the overall reduction in the rate of jets in more "central" collisions, where the two nuclei overlap more completely.

For the Quark Matter 2011 conference, ATLAS compared the rates for central events with those in more peripheral events that consist primarily of a few simultaneous nucleon–nucleon collisions. One surprising result is that, for jets above 100 GeV, the measured jet-suppression factor is independent of the measured jet energy. An even more surprising finding is that this result is the same for jets reconstructed with different "cone" radii, implying that the suppression is not accompanied by a substantial modification of the distribution of energy within a jet. By contrast, an ATLAS measurement of W boson yields using single muons showed no suppression at all.



R_{CP} for jets as a function of jet transverse-energy measured by ATLAS for three selected centrality intervals, where zero centrality means the most "central" collisions.

This comparison, shown in the figure, was quantified using the variable R_{CP}, the ratio of yields measured in central and peripheral collisions, each yield normalized by the relevant number of binary collisions. This quantity is unity if jets are produced in proportion to the number of binary collisions, but falls below one if the yields are suppressed in more central collisions.

The higher luminosities expected in 2011 will provide increased jet statistics, allowing the measurement of jets with even higher energies. At the same time, a more precise understanding of the fluctuations of soft particles, mainly from a rich spectrum of collective modes, will allow the measurement of lower-energy jets, which in preliminary results from the Relativistic Heavy Ion Collider show stronger modification from passage through the medium.

● Further reading

ATLAS collaboration ATLAS-CONF-2011-075.
ATLAS collaboration http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults.

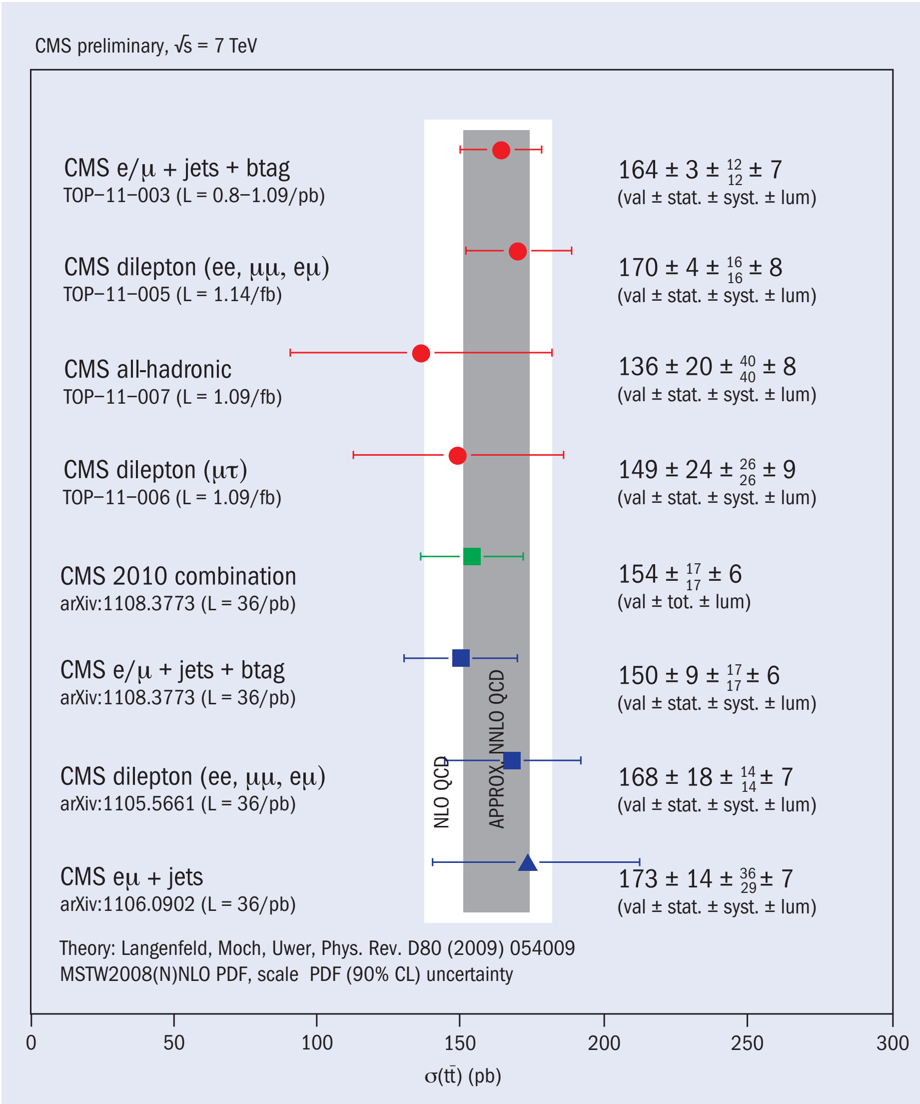
New results from CMS on top quarks

About a year ago, the CMS collaboration released its first publication on studies of the top quark – the measurement of the $t\bar{t}$ production cross-section at 7 TeV. The measurement was based on a data set of only 3 pb^{-1} of integrated luminosity and the top quarks were identified through the leptonic decay channels of the W boson. Now, a plethora of results on the top quark based on luminosities of 1–2 fb^{-1} have been released for the summer conferences, in particular for the TOP2011 workshop, held at the end of September at Sant Feliu de Guixol, Spain.

Top quarks decay almost exclusively into a W boson and a b-flavoured quark jet, leading to different event final states that can be used for selecting tops. Figure 1 gives an overview of the CMS results, which use more or less all of the decay modes. The most precise single measurement is the analysis where one W boson decays into leptons while the second W decays into hadrons and b-quark identification is used, giving a cross-section of 164.4 ± 14.3 pb, i.e. a precision of 8.5%. Precise measurements of the cross-section can also be converted into measurements of the top quark's mass, within a given theoretical scheme. Currently, the CMS cross-section measurements allow for a precision on the top mass of about 7–8 GeV in such data extractions.

Further new analyses include a measurement of the difference in mass of the t and $\bar{t}$, which is an interesting test of CPT invariance. For this study, data are used where one of the W bosons decays into a muon, allowing the event to be classified as t or $\bar{t}$ decay, depending on the charge of the muon. The difference in mass between the t and $\bar{t}$ is found to be 1.2±1.3 GeV, i.e. the result is compatible with equal mass within the uncertainty. This is the most precise result on this quantity to date.

Another interesting measurement concerns the charge asymmetry in top production. The experiments at Fermilab's Tevatron reported asymmetries that are larger than expected. At the LHC, $t\bar{t}$ production is also slightly asymmetric in rapidity as a result of the different roles that the valence and sea quarks play in the production. CMS has studied this asymmetry by measuring the different widths of the rapidity distribution for t and $\bar{t}$. The result gives an asymmetry of 1.6% with an uncertainty of about 3.5%; an asymmetry of about 1.3% is expected from theory. The agreement with the Standard Model is good within the measured uncertainties.



Cross-section measurements for $t\bar{t}$ pair production in CMS in various top-selection channels. The grey bands show the theoretical predictions and their uncertainties (NLO and NNLO).

Finally, a challenging new measurement on the electroweak production of single top has been undertaken, namely tW associated production. While single top production in the top-quark channel was reported by the LHC experiments earlier this year, this measurement analyses a different final state; also, this channel is not accessible at the Tevatron. CMS finds an excess over expected background events with a significance of 2.7 σ, and is compatible with the expectation for tW production.

With several tens of thousands of top-quark pairs recorded so far, the detailed study of the properties of the heaviest quark is merely starting. Results based on the full 2011 data sample should be ready in time for the 2012 winter conferences.

● Further reading

For more information, see the CMS papers:
CMS-TOP-11-003.
CMS-TOP-11-008.
CMS-TOP-11-014.
CMS-TOP-11-019.
CMS-TOP-11-022.

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Sciencewatch

COMPILED BY JOHN SWAIN, NORTHEASTERN UNIVERSITY

Tsunamis: why the first wave is not the tallest

Tsunamis usually consist of multiple waves and it has long been a puzzle why the first wave is often not the tallest or most damaging. Now, Frederic Dias of University College in Dublin and colleagues have found the answer in a resonance effect.

As the first wave crashes on the shore, the water level behind it drops, resulting in a stored potential energy analogous to a compressed spring. If the second wave arrives at the right time it can pick up the energy of the rebounding water to give a larger and more powerful second wave. Subsequent waves can be even more powerful, which explains the puzzle.

In simulations of a perfectly smooth beach the researchers found enormous amplifications in strength, up to a factor of 60. More realistic simulations of the tsunami that struck the Mentawai Islands in October last year showed smaller yet still large enhancements. Predictions of where such enhancements are expected to be large in size could improve how people are warned when future tsunamis hit.

Further reading

T S Stefanakis 2011 *Phys. Rev. Letts.* **107** 124502.

The first wave of the "tsunami monster" is not necessarily the most damaging. (Image credit: Andart/dreamstime.com.)

Memory that stays cool

A new nonvolatile memory device could use 99% less energy than current FLASH technology and lead to laptops that do not heat up your lap. Saptarshi Das and Joerg Appenzeller of Purdue University in Indiana have demonstrated a proof-of-concept of a new ferroelectric transistor random-access memory, or FeTRAM.

Earlier ferroelectric RAM devices destructively read out bits stored in a capacitor. By contrast, the new device stores bits in a memory transistor – the capacitor being replaced by a transistor with an organic ferroelectric, which can be read out nondestructively. Unlike earlier attempts of this kind, the device is compatible with current CMOS technology. Some cool memory could be coming soon.

Further reading

S Das and J Appenzeller 2011 Nano Letts. 11 4003.

Weird particles in graphene

Graphene – a single layer of carbon atoms from graphite – has displayed a variety of unusual properties, including having effectively massless charged quasiparticles. Igor Zaliznyak of Brookhaven National Laboratory and colleagues have recently shown that if three layers are properly stacked, massive I = 3 chiral quasiparticles appear, with the novel property that their masses depend on energy going to infinity as the energy level decreases.

In the normal world of particle physics such particles would be unstable against decay, but chirality protects these from doing so. They could be the basis for completely novel electronic and spintronic devices.

Further reading

X L Zhang *et al.* 2011 *Nature Physics* doi:10.1038/nphys2104

The origin of lager

Beer drinkers may have Argentina to thank for the lager that they have drunk, even if it is German. José Paulo Sampaio of the Universidade Nova de Lisboa in Caparica, Portugal, and colleagues were researching the genetics of yeast when they came to the surprising conclusion that the cold-resistant yeast that makes lager – first brewed in the 15th century – must originate from beech trees in Patagonia. The yeast is not indigenous to Europe, Japan or North America, and how it travelled to Europe is not clear. It could possibly have come on wood that was used to make a barrel. Whatever route, however, it seems to have been an amazing, but happy, accident.

Further reading

D Libkind *et al.* 2011 *PNAS* **108** 14539.

An antiviral with potent potential

Viral illnesses are notoriously difficult to treat, but now a new approach could hold the promise of cures for almost all of them. The trick is in noticing that nearly all viruses generate double strands of RNA with more than 30 base pairs – something healthy mammalian cells do not. The immune system has an enzyme called protein kinase R (PKR) that blocks them, but many viruses have ways round it.

Todd Rider of the Massachusetts Institute of Technology in Lexington and colleagues bonded PKR to a protein that triggers cell suicide, or apoptosis. The result, called DRACO (for "double-stranded RNA activated capsase oligimerizer") makes a cell die as soon as the viral RNA is produced. The researchers showed it to be effective against rhinovirus, which causes the common cold, as well as the H1N1 virus. While clearly dangerous if too many cells are infected, this appears to be a novel approach to treating a range of viral infections.

Further reading

T H Rider *et al.* 2011 *PLoS ONE* **6(7)**: e22572.

Magnetic cloaking

Invisibility cloaking has been a hot topic in recent years and now a related twist is the development of a magnetic cloak. Alvaro Sanchez and colleagues at the Universitat Autònoma de Barcelona have shown how an "antimagnet" made using superconductors and isotropic magnetic materials can conceal the magnetic response of a volume from the outside. Such devices could be useful, for example in allowing magnetic resonance imaging of people with pacemakers or cochlear implants.

Further reading

A Sanchez *et al.* 2011 New *J. Phys.* 13 093034.

Astrowatch

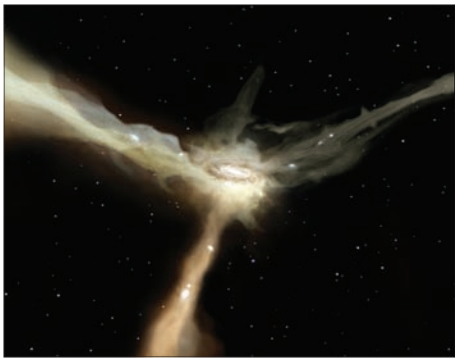
COMPILED BY MARC TÜRLER, ISDC AND OBSERVATORY OF THE UNIVERSITY OF GENEVA

Herschel favours quiet galaxy build-up theory

Did most galaxies form their stars through violent and tumultuous merging events or via more steady and gentle processes? A study of deep-field observations by the Herschel Space Observatory favours a quiet build-up for most galaxies, which is in contradiction with preconceptions.

The Herschel and Planck missions of the European Space Agency were launched together by an Ariane 5 rocket on 14 May 2009 (*CERN Courier* July/August 2009 p12). While Planck is scanning the whole sky with its prime objective to study the cosmic microwave background, conversely Herschel is performing accurate, deep observations of specific regions of the sky. Named after William Herschel, who discovered infrared radiation in 1800, it observes a variety of far-infrared sources – from the formation of stars and planets in the Milky Way to faint galaxies in the distant universe (*CERN Courier* September 2010 p11).

There are basically two routes to star formation: one involves a rather slow and steady process in spiral galaxies; the other is via short-lived starbursts that are thought to be driven by the interactions and mergers of galaxies. Starburst galaxies are known to be more frequent in the early universe and – with their stronger star formation rate (SFR) – they are thought to be prime contributors to the build-up of the stellar content of galaxies. The Herschel mission offers an unrivalled opportunity to test this hypothesis by determining the relative contribution of the two modes to the global SFR of the universe.



Artist's impression of a galaxy with gentle, steady star formation supplied by rapid, narrow streams of cold gas. (Image credit: ESA/AOES Medialab.)

To have a statistically significant sample of galaxies over a broad range of distances Herschel turned its 3.5-m mirror – the largest space telescope – to fields already observed by the Hubble Space Telescope and other facilities, namely the northern and southern fields of the Great Observatories Origins Deep Survey (GOODS) and the wider COSMOS (Cosmic Evolution Survey) field. The GOODS-North and GOODS-South fields each cover a region of about 10 × 15 arcminutes (around a quarter of the size of the full moon), whereas the COSMOS field of 2° square is 50 times larger.

A first study by David Elbaz from CEA Saclay and colleagues from Europe and America has investigated the SFR in more than 2000 galaxies that were identified in the GOODS fields. These were found to have surprisingly similar infrared properties despite spanning the past 11 billion years, or 80% of the history of the universe. Starburst galaxies can be identified as outliers with a relative deficit of emission at a wavelength of about 8 μm. The origin of the difference would lie in the destruction of 8-μm emitting molecules – known as polycyclic aromatic hydrocarbons – by UV radiation in galaxies with compact starburst regions.

Elbaz and colleagues find that starburst galaxies contribute only about 20% to star formation in the universe. The result is corroborated by a second study led by Giulia Rodighiero of the University of Padova and European colleagues, which concentrated on the cosmic peak of the star-formation activity about 10 billion years ago – at a redshift of around $z = 2$ – using the GOODS-South and the wide COSMOS fields.

This evidence that most galaxies in the universe formed their stars in a gentle and steady fashion triggers a new question: how could such a process be more efficient in the early universe than now? A possible solution is that early galaxies are fed by rapid, narrow streams of cold gas, providing them with continuous flows of raw material for star formation. This scenario has not yet been observed but is suggested by computer simulations in which massive galaxies form in the knots of the cosmic web of dark matter and gas filaments that pervades the universe (*CERN Courier* September 2007 p11).

Further reading

D Elbaz *et al.* 2011 *A&A* **533** A119.
G Rodighiero *et al.* 2011 *ApJ* **739** L40.

Picture of the month

This image marks the opening of a new window on the submillimetre universe with the Atacama Large Millimeter Array (ALMA). The first released image from ALMA is overlaid here with a beautiful view of the Antennae Galaxies taken by the Hubble Space Telescope (*CERN Courier* December 2006 p14). The on-going merger of the two spiral galaxies (NGC 4038 and 4039) triggers intense star formation producing bright, blue stars out of dense clouds of cold gas, which are now revealed for the first time by ALMA at wavelengths of 0.87 mm (in yellow) and 2.6 mm (in red). The quite clumpy view by ALMA – taken with "only" 12 antennae in a compact arrangement – is just a taster for what is to come and does not reflect the array's potential to surpass Hubble in sharpness by 2013, when the full array of 66 antennae built in Europe, North America and East Asia will be installed at 5000 m altitude in the desert of Chajnantor, Chile (*CERN Courier* March 2009 p11). (Image credits: ALMA (ESO/NAOJ/NRAO); visible light image: the NASA/ESA Hubble Space Telescope.)

CERN Courier Archive: 1968

A look back to CERN Courier vol. 8, November 1968, compiled by Peggie Rimmer

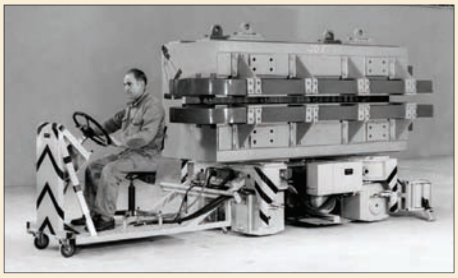
CERN

Beam-transfer gymnastics at the ISR

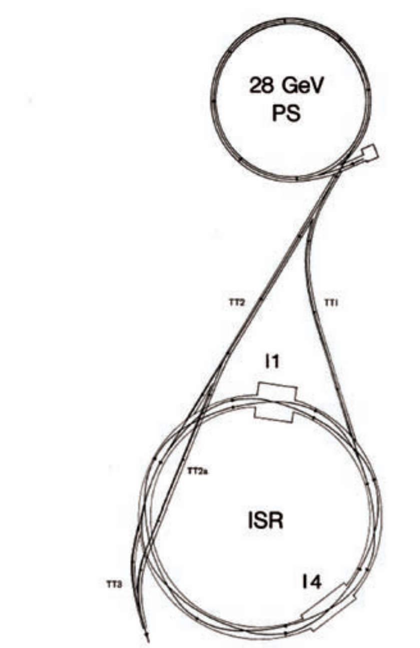
The level of the ISR site is up to 25 m higher than the PS site. To limit the cost of excavation and access roads, the beam level of the ISR was chosen as high as possible, subject to the requirement that the ISR tunnel floor should rest directly on the molasse practically everywhere. This resulted in a beam level 445.46 m above sea level for the ISR compared with 433.66 m for the PS. Thus the conception and alignment of the transfer channels is a three-dimensional problem.

Just after the beam emerges from the PS, a small vertical deflection takes it over the linac beam; it then continues horizontally at a level of 434.24 m. Over the last 110 m to the ISR there is an upward slope of about 10%, so that the transferred beams approach the ISR from below on the inside of the rings. The channel to the West Hall passes at a level of 434.24 m under the ISR and then rises, with a slope of 12%, to the beam level of 448.06 m in the West Hall.

A special vehicle (see photograph) was designed entirely by the General Engineering Group to transport some 130 bending magnets, weighing up to 20 tonnes, inside the beam-transfer tunnels where no overhead cranes are available. Some of the design parameters were extremely severe. The vehicle has to protect the magnets from any shock that would disturb precise assembly, and descend slopes equivalent to the steepest mountain passes. When it reaches the desired position, it stops with a precision of 1 mm, the wheels are turned through 90° and it then moves exactly at right angles to its initial direction. It stops again with millimetre precision and jacks are inserted to lift the magnet clear. It then moves out and the proper magnet supports are put in position.



The extraordinary transport vehicle designed to carry magnets down the ISR transfer tunnels.



To the West Hall and the 3.7 m hydrogen bubble chamber.

● Compiled from texts on pp276–277.

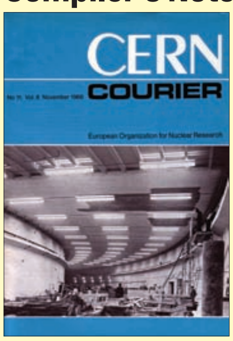
Beam stacking

With the present PS proton beam intensities, several hundred pulses have to be accumulated – or "stacked" – to reach the design intensity of 20 A circulating current in each storage ring. The stacking is done in "longitudinal phase-space", which means that particles of successively injected pulses are made to differ by a small amount of energy so that protons of different cycles are put side by side in the ISR vacuum chamber. This is achieved by means of the r.f. system. The bunches of particles arriving from the PS are captured at the injection orbit near the inner wall of the vacuum chamber and accelerated to the stacking orbit where they are deposited by turning off the r.f. voltage. The r.f. system then prepares to receive the next pulse and the same cycle is repeated every time a new set of particles is injected.

Since the circumference of the ISR is 1½ times that of the PS, one beam pulse transferred from the PS fills only ⅔ of the ISR circumference. Therefore, if nothing special is done, 10 out of the 30 r.f. "buckets" generated by the ISR r.f. system would remain empty, resulting in a corresponding loss in the maximum intensity which could be attained in the stacked beam. It was originally intended to fill the missing part of the beam by means of a second injection from the PS prior to starting each stacking cycle. This idea has now been abandoned and instead, a device that suppresses the unwanted empty buckets by switching off 10 out of every 30 r.f. waves will be incorporated in the r.f. system. This is possible since it needs to be done only towards the end of each stacking cycle, when the r.f. voltage is relatively low.

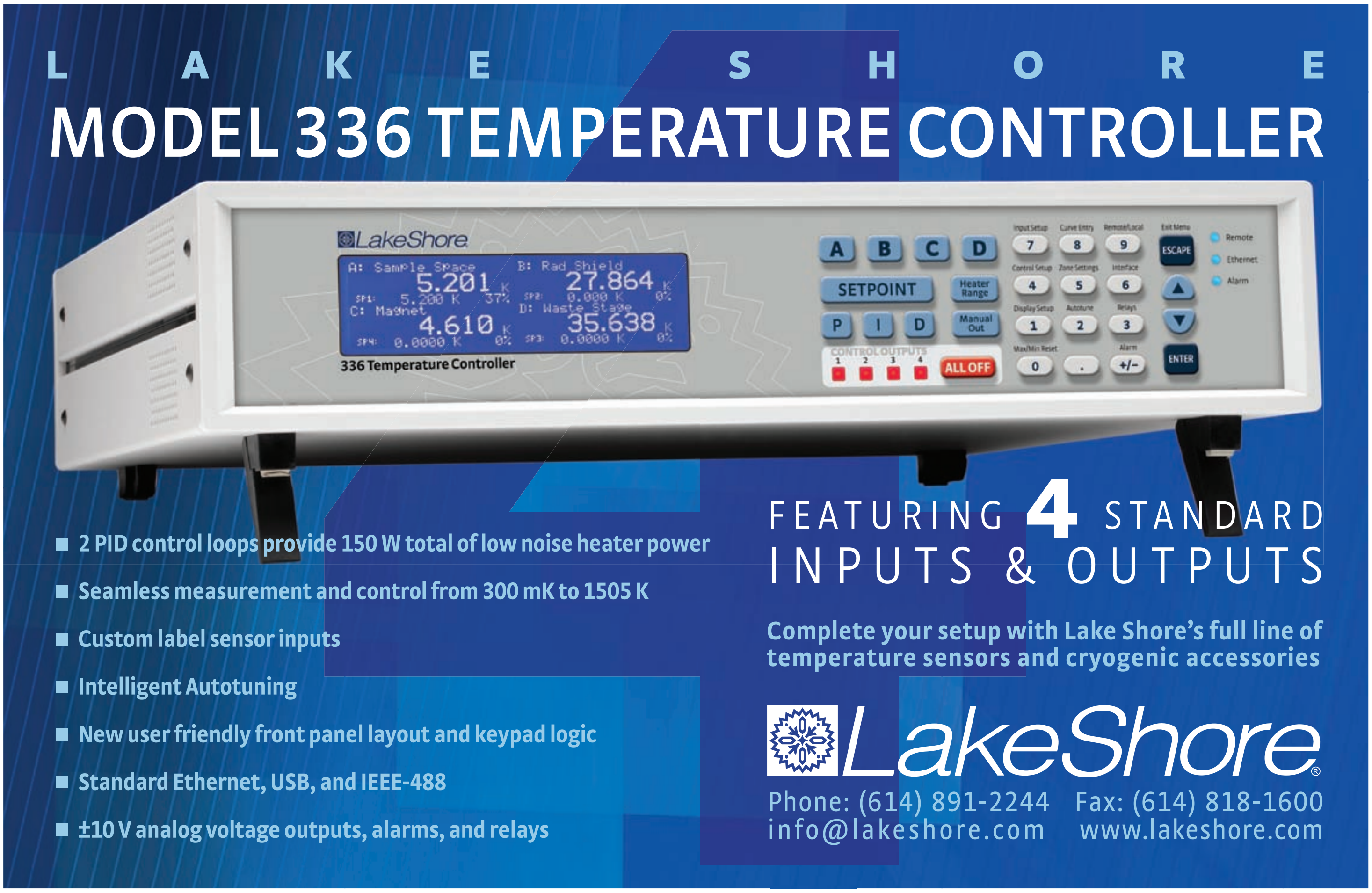
● Compiled from texts on pp239–241.

Compiler's Note



In the autumn of 1968 construction of the ISR was at the half-way stage and the November issue of the *CERN Courier* was devoted exclusively to the project, with a star-studded lineup of authors: K Johnsen, L Resegotti, W Schnell, E Fischer, B de Raad, S van der Meer, H Horisberger, G Schaffer, F Bonaudi and J Gervaise. The machine produced the world's first proton–proton collisions in January 1971 and proton–antiproton collisions a decade later, before being shutdown in 1984 (*CERN Courier* January/February 2011 pp27–42 and 62).

The ISR was also the first CERN machine to be built on French territory and pioneered what has become a CERN hallmark, namely the use of existing research machines to fill each new generation of accelerator. These two anecdotes from the November 1968 issue of *CERN Courier* highlight problems that can arise when coupled machines are not in the same horizontal plane and, if circular, are not of the same circumference.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The discovery of type II superconductors

Type II superconductivity allows the superconducting state to exist in high magnetic fields, making possible the high-field magnets for particle accelerators and other applications. Behind its discovery, however, lies a tragic tale.

Clockwise from top left: L V Shubnikov; V I Khotkevich; G D Shepelev; Y N Rjabinin. (Image credit: A Shepelev.)

Regular readers of *CERN Courier* are well aware that the LHC depends on some 10 000 magnets made of type II superconductor, which remains superconductive in high magnetic fields. Many will also recall that the era of superconducting magnets began 50 years ago when John "Gene" Kunzler and colleagues at Bell Telephone Laboratories showed that a primitive Nb_3Sn wire could carry more than 1000 A/mm^2 in a field of 8.8 T. What is much less well known is that the path to type II superconductors had already been demonstrated a quarter of a century earlier by Lev Shubnikov, Vladimir Khotkevich, Georgy Shepelev and Jury Rjabinin in Kharkov (Shubnikov *et al*. 1936a, 1936b and 1937). So how was it that this understanding was lost for 25 years and rediscovered only by accident in 1961?

From the beginning

The huge value of superconducting wires for high-field magnets was clearly understood by Heike Kamerlingh Onnes, the discoverer of superconductivity. In his report submitted to the 3rd International Congress of Refrigeration in Chicago of 1913, he described his design for a 10 T superconducting solenoid. He had recently passed almost 500 A/mm^2 through a lead wire, although his first attempt at a silk-insulated lead wire was not so successful, no doubt because of some "bad places in the wire" (Kamerlingh Onnes 1913). Sadly, just one year later, he found that pure-metal superconductors lose their superconductivity at a critical magnetic field, H_c, that is much less than 0.1 T. His interest then languished when the First World War intervened.

Work restarted in the 1920s, by which time laboratories in Leiden, Toronto, Oxford and Kharkov all had liquid helium and work on the superconductivity in metal alloys was taken up again. The initial results were complex because the loss of diamagnetism occurred at fields much lower than those at which resistance was restored. In the best cases, traces of superconductivity by transport were seen at almost 2 T. Kurt Mendelssohn in Oxford put forward the "sponge hypothesis", which hypothesized that the small supercurrent densities observed at high fields were associated with a fine, filamentary network of tiny relative volume (Mendelssohn 1935). Because most samples had poorly controlled homogeneity and cold work state, metallurgical inhomogeneity was, indeed, a contributor to the large variation in properties.

The huge value of superconducting wires for high-field magnets was clearly understood by Kamerlingh Onnes.

This plausible but fundamentally and decisively wrong hypothesis was soon to get its rebuttal by the experiments on lead–indium and lead–thallium alloys made by Shubnikov's group in Kharkov. This seminal work of 1936 was characterized by its use of well annealed single crystals that in principle completely invalidated the premise of the "sponge ▷

100 years of superconductivity

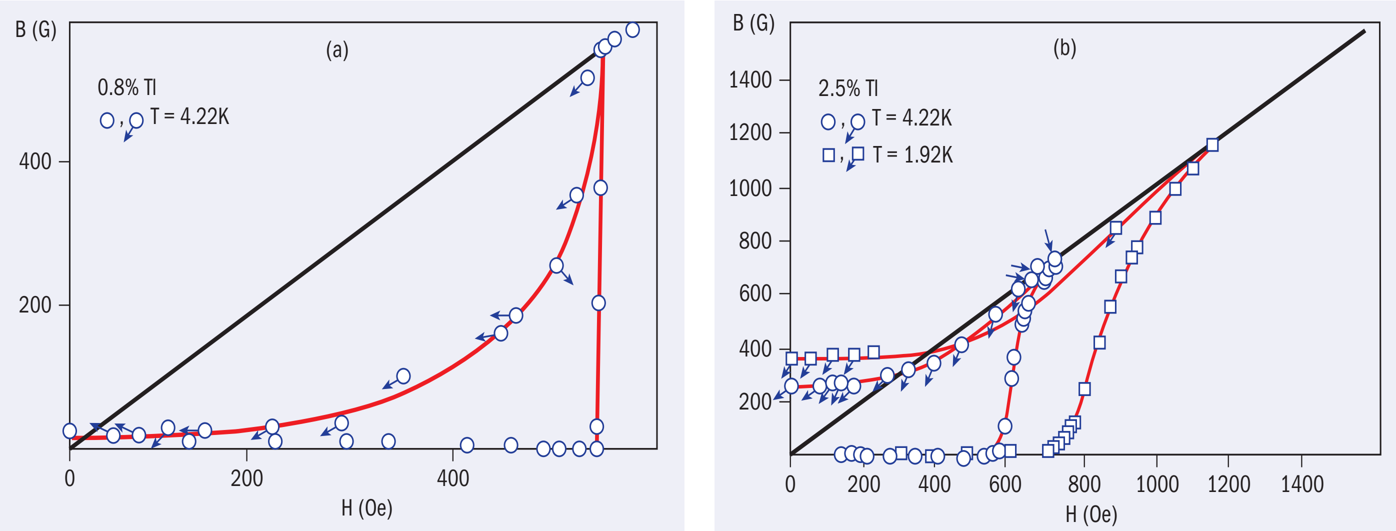

Fig. 1. Variation of magnetic induction B with field H in well annealed, homogeneous single-crystal alloys of a) Pb 0.8 wt% Tl and b) Pb 2.5 wt% Tl in decreasing (arrows) and increasing (no arrows) field. B=H indicates normal conductivity and B=0 for complete flux exclusion. (a) is a type I superconductor, (b) is type II. The almost reversible behaviour shows the samples' high uniformity.

model". The experiments showed three main features:

1. There is a critical alloy concentration, x_c, below which alloys behave as pure superconductors with a full Meissner effect and abrupt loss of superconductivity at a critical field, H_c (figure 1a).

2. Increasing the alloy concentration beyond x_c, for example from 0.8 to 2.5% by weight of Tl in figure 1b, drastically changes the equilibrium magnetic properties, separating the loss of superconductivity, which occurs at an increasingly higher critical field H_{c2}, from the onset of flux penetration at the lower critical field H_{c1}.

3. With increasing x_c, H_{c1} becomes smaller, while H_{c2} grows larger (figure 2). Shubnikov realized, however, that the energy of the superconducting state in his well annealed, almost reversible (i.e. low current density) single crystals was almost independent of alloy content.

In all normal circumstances, the high quality of the Kharkov crystals, their evident homogeneity and above all the finding that their superconductivity must have been a bulk effect incapable of being explained by a small filament network should have undercut the sponge hypothesis and instigated much greater attention to the thermodynamic properties of the new type II superconducting state.

Regrettably, this discovery occurred against a backdrop of bitter conflict and human tragedy. Shubnikov's friend Lev Landau, who was "held captive" by the "Mendelssohn sponge", did not recognize this discovery either in 1936 or in 1950, when he and Vitaly Ginzburg created the phenomenological theory of superconductivity that, as Alexey Abrikosov later found, provided a beautiful description not just of the type I superconductors that they considered but also of the type II superconductivity discovered by Shubnikov. It is clear that their parameter κ describes perfectly the transition from type I to type II behaviour at the critical value 1√2. However, Landau still did not recognize the discovery by Shubnikov's group, even though their results and the published paper were presented by Martin Ruhemann at the 6th International Congress of Refrigeration in The Hague in 1936. For reasons that appear quite mystifying in 2011, none of the scientists present either supported or continued the Kharkov work, even though a number of contemporary references cite it.

The real tragedy occurred a year later. Shubnikov, the director of the Low Temperature Laboratory in Kharkov, who had come under suspicion and been confined to the Soviet Union in 1936, was arrested in 1937 on charges of spying (the laboratory was well connected to Western laboratories, Shubnikov having spent several years in Leiden). He was summarily shot dead without any legal process. The following year, Landau was arrested and held in prison for a year, being released only on the advocacy of Pyotr Kapitza. The Soviet Union was experiencing a difficult time.

The dormant period

The results of Shubnikov and his co-workers remained generally unknown for another 25 years, even though Abrikosov drew attention to the work in the 1950s when he predicted the vortex state in high κ ($\gg 1/\sqrt{2}$) superconductors. In his 2003 Nobel address describing his work explaining type II superconductivity, Abrikosov said: "I compared the theoretical predictions about the magnetization curves with the experimental results obtained by Lev Shubnikov and his associates on Pb–Tl alloys in 1937, and there was a very good fit" (Abrikosov 2004). However, as he has pointed out, his paper came out just as the Bardeen–Cooper–Schrieffer theory of superconductivity was published and all interest became focused on the superconducting mechanism, rather than on what some regarded as an esoteric vortex state. So work on high-field magnets lay dormant until the totally unexpected discovery by

Shubnikov, far left, with Lev Landau, centre. (Image credit: UPhTI, Kharkov.)

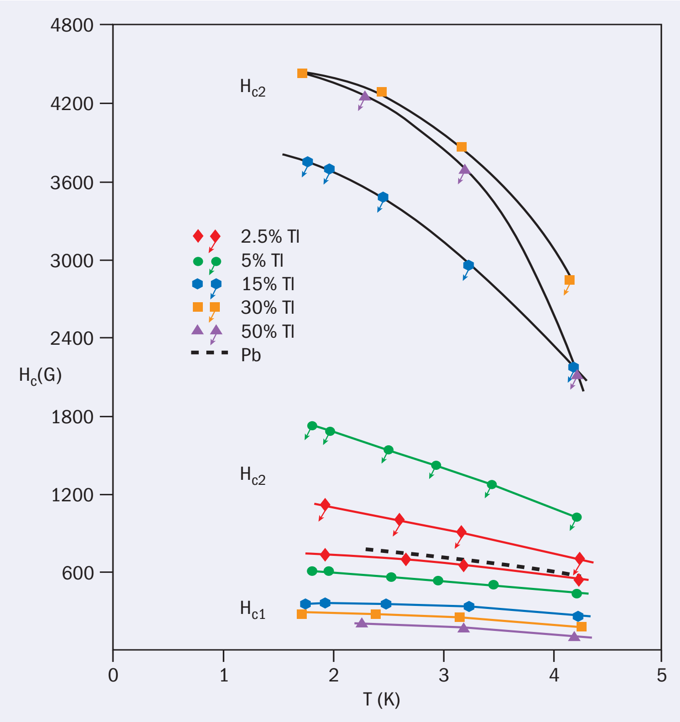

Fig. 2. Temperature dependence of H_{c1} and H_{c2} for single-crystal alloys of Pb–Tl with Tl contents ranging from 2.5–50 at.% Tl as compared with H_c for pure Pb. Alloying depresses H_{c1} well below H_c and raises H_{c2} well above H_c. The critical field of Pb (H_c around 800 G) is raised to above 4500 G by alloying (H_{c2}).

Kunzler's group, which connected all of the disconnected sightings of high-field and high-current-density superconductivity that had been impossible to explain by the Mendelssohn sponge. Ted Berlincourt has written fine recollections of this fertile period in the 1950s when finally things began to gel (Berlincourt 1987).

After 1961, Shubnikov's seminal role in this extraordinary advance in science and technology was finally recognized, in particular at the International Conference on the Science of Superconductivity held in Hamilton, New York, in 1963, where several speakers praised the research. The conference chair, John Bardeen, and the secretary, Roland Schmitt, stated formally in the proceedings: "It should be noted that our theoretical understanding of type II superconductors is due mainly to Landau, Ginsburg, Abrikosov and Gor'kov, and that the first definitive experiments were carried out as early as 1937 by Shubnikov" (Bardeen and Schmitt 1964). Soon after, future Nobel laureate Pierre-Gilles de Gennes introduced the designation the "Shubnikov phase" for the mixed-vortex state that is stable between H_{c1} and H_{c2} (de Gennes 1966). It is also the case that the first doctoral dissertation on type II superconductors was that written by G D Shepelev under Shubnikov's guidance.

Finally, we may note that the long, 25-year period of 1936–1961, in which the sponge hypothesis held sway, was also a period in which many new superconductors – such as NbN and Nb_3Sn – were discovered. Like the more recent discoveries of cuprates, organics, MgB_2 and the new iron-based systems, all are type II superconductors. What might have been if only the poignant politics of the Soviet 1930s had not so tragically entwined the studies and fate of Shubnikov's group in Kharkov?

• Further reading

For a longer version of the story, see: A G Shepelev 2010 *Superconductor* A M Luiz (ed.) (InTech), www.intechopen.com/books/show/title/superconductor.

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Résumé

La découverte des supraconducteurs de type II

La supraconductivité de type II permet à l'état supraconducteur d'exister dans des champs magnétiques élevés. Elle rend possible l'obtention d'aimants de forte intensité pour les accélérateurs de particules et d'autres applications, mais derrière cette découverte se cache une histoire tragique. En 1936, Lev Choubnikov et ses collègues, à Kharkov, observaient un nouveau type de comportement supraconducteur dans des échantillons d'alliages métalliques de grande qualité. Mais c'était une époque troublée en Union soviétique. Choubnikov fut arrêté en 1937, puis fusillé. La recherche dans ce domaine devait stagner jusqu'à ce que la supraconductivité de type II soit découverte aux États-Unis en 1961, ouvrant la voie à la production d'aimants à champ élevé.

Anatoly Shepelev, Kharkov Institute of Physics and Technology, and **David Larbalestier**, National High Magnetic Field Laboratory, Florida State University.

Superconductivity and the LHC: the early days

With 9 T dipole magnets of a new 'twin' design and superfluid helium cooling, the LHC took the use of superconductivity in accelerators to a new level. **Lucio Rossi** looks at some of the first challenges that had to be overcome.

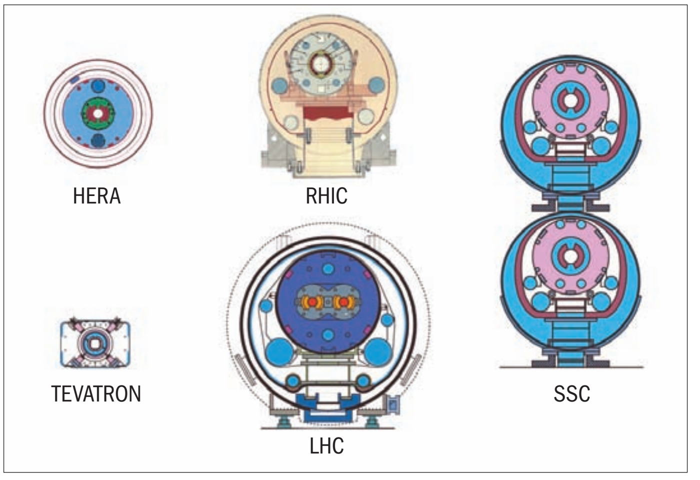


Fig. 1. Comparison of dipoles from the Tevatron to the LHC.

As the 1970s turned into the 1980s, two projects at the technology frontier were battling it out in the US accelerator community: the Energy Doubler, based on Robert Wilson's vision to double the energy of the Main Ring collider at Fermilab; and Isabelle (later the Colliding Beam Accelerator) in Brookhaven. The latter was put in question by the difficulty in increasing the magnetic field from 4 T to 5 T – which turned out to be much harder than originally thought – and eventually gave way to Carlo Rubbia's idea to transform CERN's Super Proton Synchrotron into a p–$\bar{p}$ collider, allowing the first detection of W and Z particles. Based on 800 superconducting dipole magnets with a field in excess of 4 T, it involved the first ever mass-production of superconductor and represented a real breakthrough in accelerator technology. For the first time, a circular accelerator had been built to work at a higher energy without increasing its radius.

When the Tevatron began operation at 540 GeV in 1983, Europe was just starting to build HERA at DESY. This electron–proton collider included a 6 km ring of superconducting magnets for the 820 GeV protons and it came into operation in 1989. The 5 T dipoles for HERA were the first to feature cold iron and – unlike the Tevatron magnets, which were built in house – they were produced by external companies, thus marking the industrialization of superconductivity.

Meanwhile the USSR was striving to build a 3 TeV superconducting proton synchrotron (UNK), which was later halted by the collapse of the Soviet Union, while at CERN the idea was emerging to build a Large Hadron Collider in the tunnel constructed for the Large Electron–Positron (LEP) collider (*CERN Courier* October 2008 p9). However, the US raised the bid with a study for the "definitive machine". The Superconducting Super Collider (SSC), which was strongly supported by the US Department of Energy and by President Reagan, would accelerate two proton beams to 20 TeV in a ring of 87 km circumference with 6.6 T superconducting dipoles. With this size and magnetic field, the SSC would require decisive advances in superconductors as well as in other technologies. When the then director-general of CERN, Herwig Schopper, attended a high-level official meeting in the US and asked what influence on the scientific and technical goals the Europeans could have by joining the project, he was told "none, either you join the project as it is or you are out". This ended the possibility of collaboration and the competition began.

To compete with the SSC, the LHC had to fight on two fronts: increase the magnetic field as much as possible so as to reduce the handicap of the relatively small circumference of the LEP tunnel; and increase the luminosity as much as possible to compensate for the inevitable lower energy. In addition, CERN had to cope with a tunnel with a cross-section that was tiny for a hadron collider, which many considered a "poisoned gift" from LEP. However, the interest for young physicists and engineers lay in the "impossible challenges" that the LHC presented.

To begin with, there was the 8–10 T field in a dipole magnet. Such a large step with respect to the Tevatron would require both the use of large superconducting cable to carry 13 kA in operating conditions of 10 T – almost double the capability of existing technology – and cooling by superfluid helium at 1.8–1.9 K. Never previously used in accelerators, superfluid helium cooling had been developed for TORE Supra, the tokamak project led by Robert Aymar but on a smaller scale. Then, to fit the exiting LEP tunnel, the magnets would have to be of an innovative "two-in-one" design – first proposed by Brookhaven but discarded by US colleagues for the SSC – where two magnetic channels are hosted in the iron yoke within a single ▷

100 years of superconductivity

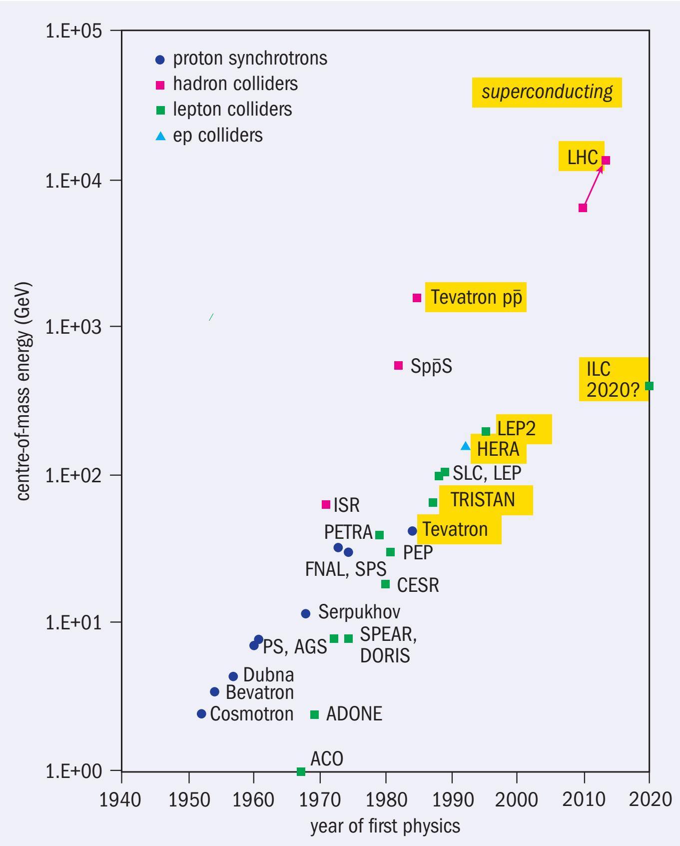


Fig. 2. Evolution of accelerators with those making use of superconductivity highlighted in yellow.

cold mass and cryostat. In this way, a 1 m diameter cryostat could house two magnets, while the geometry of the SSC (with separate magnets but with 30% lower field than the LHC) simply could not fit in the LHC tunnel. Figure 1 (p21) shows the various main-dipole cross-sections for the various hadron machines.

A critical milestone

In 1986 R&D on the LHC started under the leadership of Giorgio Brianti, quietly addressing the three issues specific to the LHC (high field, superfluid helium and two-in-one), while relying on the development done for HERA and especially for the SSC for almost all of the other items that needed to be improved. The high field was the critical issue and had to be tested immediately. Led by Romeo Perin and Daniel Leroy, CERN produced the first LHC coil layout and provided the first large superconducting cable to Ansaldo Componenti. This company then manufactured on its own a 1-m long dipole model – single bore, without a cryostat – that was tested at CERN in 1987. Reaching a field of 9 T at 1.8 K, it proved the possibility of reaching the region of 8–10 T (*CERN Courier* October 2008 p19). This was arguably the most critical milestone of the project because it gave credibility to the whole plan and began to lay doubt on the strategy for the SSC.

These results were obtained with niobium-titanium alloy (Nb-Ti), the workhorse of superconductivity. CERN had also a parallel development with niobium-tin (Nb_3Sn) that could have produced a slightly higher field at 4.5 K, with standard helium cooling. This

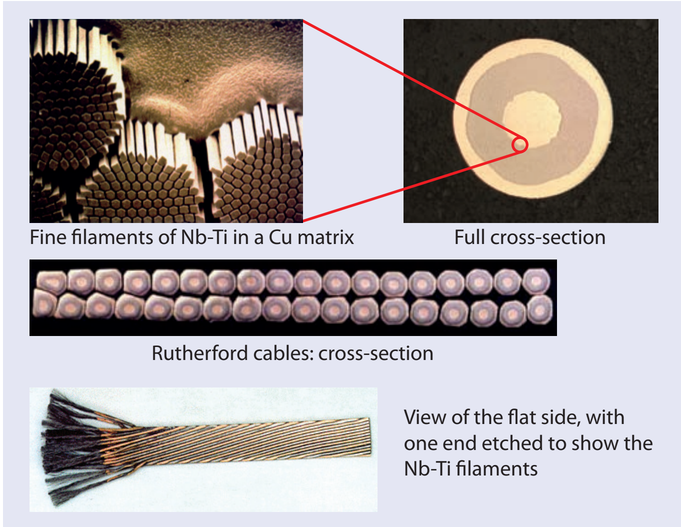


Fig. 3. Structure of the superconducting cable used in the LHC – from Nb-Ti filament to final cable.

development, pursued with the Austrian company Elin and led by CERN's Fred Asner, produced a 1-m long 9.8 T magnet and also a 10.1 T coil in mirror configuration, the first accelerator coil to break the 10 T wall. However, in 1990 the development work on Nb_3Sn was stopped in favour of the much more advanced and practical Nb-Ti operating at 1.9 K. This was a difficult decision, as Nb_3Sn had a greater potential than Nb-Ti and would avoid the difficulty of using superfluid helium, but it was vitally important to concentrate resources and to have a viable project in a short time. The decision was similar that taken by John Adams in the mid-1970s to abandon the emerging superconducting technology in favour of more robust resistive magnets for CERN's Super Proton Synchrotron. Figure 2 shows how the performance of superconducting accelerators has increased since that time.

For the development of the superconducting cable there were three main issues. First, it should reach a sufficient critical current density with a uniformity of 5–10% over the whole production, which also had to be guaranteed in the ratio between the superconductor and the stabilizing copper matrix, illustrated in figure 3. The critical current was to be optimized at 11 T at 1.9 K, maximizing the gain when passing from 4.2 to 1.9 K (figure 4). The second issue was to reduce the size of the superconducting filaments to 5 μm without compromising the critical current. This required, among other features, the development of a niobium barrier around Nb-Ti ingots. Third was to control the dynamic (ramping up) effect in a large cable, as some effects vary as the cube of the width.

It was vitally important to concentrate resources and to have a viable project in a short time.

Again, the strategy was to concentrate on specific LHC issues – the large cable, the critical current optimization at 1.9 K – and rely on the SSC's more advanced development for the other issues.

100 years of superconductivity

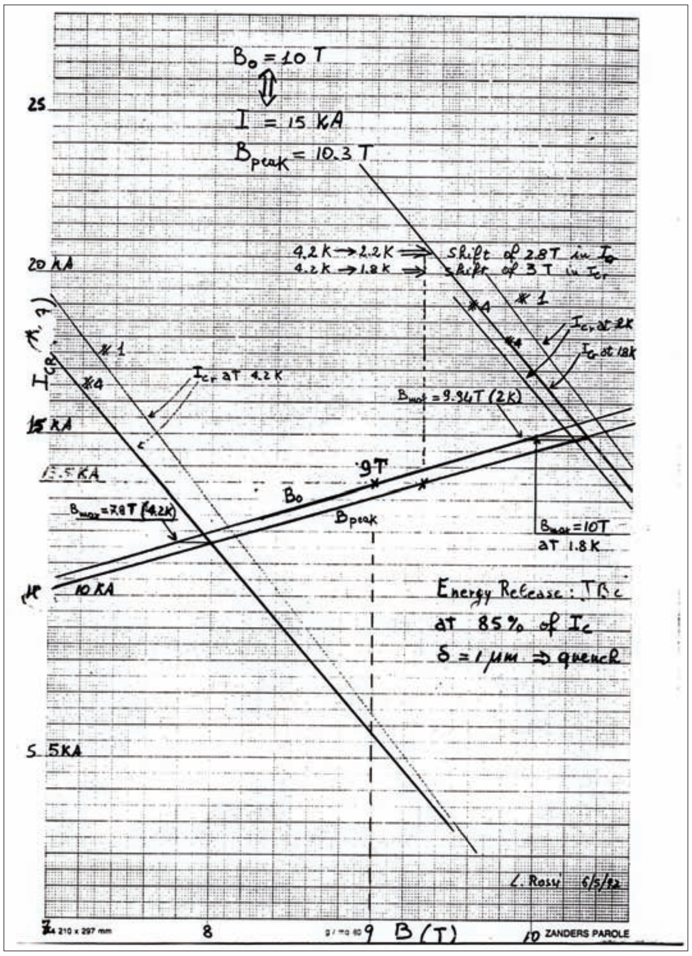


Fig. 4. Page from a notebook showing the first measurement of the critical current of LHC cables (courtesy of M Garber, BNL) and the load line of the LHC dipole. The shift of the I_{cr} curves towards high fields when moving from 4.2 K (left) to 1.8 K allows the maximum theoretical performance of the magnet increases from 7.8 T to 10 T.

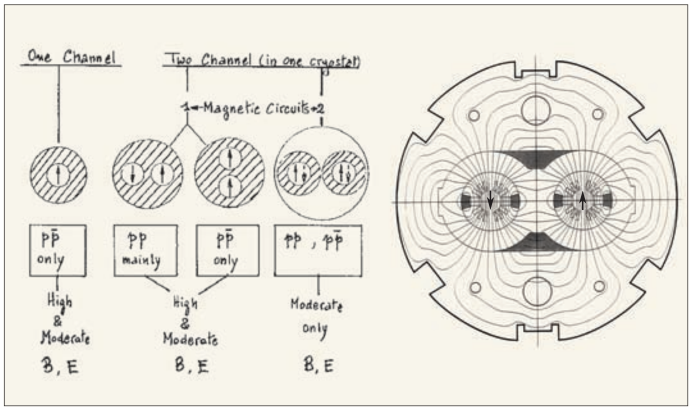


Fig. 5. A workshop in Lausanne in 1984 looked at several early options for the LHC dipole, left, the second of which was retained in the final "twin" design, far right.

There is, indeed, a large debt that CERN owes to the SSC project for the superconductor development. However, when the SSC project was cancelled in 1993, the problem of eliminating the dynamic effect arising from the resistance between strands composing the cable was still unresolved – but it became urgent in view of the results on the first long magnets in 1994 and after. Later, CERN carried out intense R&D to find a solution suitable for mass production relatively late, at the end of the 1990s. This involved controlled oxidation, after cable formation, of the thin layer of tin-silver alloy with which all the copper/Nb-Ti strands were coated – a technology that was a step beyond the SSC development.

Returning to the magnet development, after the success of the 1987 model magnet, which was replicated by another single-bore magnet that CERN ordered from Ansaldo, the R&D route split into two branches. One concerned the manufacture of 1-m long full-field LHC dipole magnets to prove the concept of high fields in the two-in-one design, with superconducting cable and coil geometry close to the final ones. A few bare magnets, called Magnet Twin Aperture (MTA), were commissioned from European Industry (Ansaldo, Jeumont-Scheinder consortium, Elin, Holec) under the supervision of Leroy at CERN.

The second line of development lay in proving the two-in-one concept in long magnets and a superfluid-helium cryostat. This involved assembling superconducting coils from the HERA dipole production, which had ended in 1988, in a single cold mass and cryostat, the Twin Aperture Prototype (TAP). The magnet, under the supervision of Jos Vlogaert with the cryostat and cold-mass, under Philippe Lebrun, tested successfully in 1990, reaching 5.7 T at 4.2 K and 7.3–8.2 T at 1.8 K – thus supporting the choices of the two-in-one magnet design, of the superfluid helium cooling and the new cryostat design.

At the same time, the LHC dipole was designed in the years 1987–1990, featuring an extreme variation: the "twin" concept, where the two coil apertures are fully coupled, i.e. with no iron between the two magnetic channels (figure 5). We now take this design for granted, but at the time there was scepticism within the community (especially across the Atlantic); it was supposed to be much more vulnerable to perturbations because of the coupling and to present an irresolvable issue with field quality. It is to the great credit of the CERN management and especially Perin, who for a long time was head of the magnet group, that they defended this design with great resilience – because among many advantages it also made an important 15% saving in the cost.

The result of the first sets of twin 1-m long magnets came in 1991–1992. Some people were disappointed because they felt that the results fell short of the 10 T field "promised" in the LHC "pink book" of 1990. However, anyone who knows superconductivity greatly appreciated that the first generation of twins went well over 9 T. This was already a high field and only 5–10% less than expected from the so-called "short sample" (the theoretical maximum inferred by measuring the properties of a short 50–70 cm length of the superconducting cable); accelerator magnets normally work at 80%, or less, of the short-sample value. The results of the 1 m LHC models also made it clear that the cable's mechanical and electrical characteristics and the field quality of the magnet (both during ramp and at the flat top) were not far from the quality required for the LHC.

A final step would be to combine the two branches of the ▷

development work and put together magnets of the twin design with a 10 m cold mass in a 1.8 K cryostat to demonstrate that full-size, LHC dipoles of the final design were feasible. However, the strict deadline imposed by the then director-general, Rubbia, dictated that the LHC should have the same time-scale as the SSC and be ready at the end of 1999. This meant that CERN was forced to launch the programme for the first full-size LHC prototypes in 1988, i.e. well before the end of the previous step, the construction in parallel of 1 m LHC MTA models and the 10-m long TAP.

At this point, CERN was just finishing construction of LEP and beginning work on industrialization of the components for LEP2; it was a period of shortage of personnel and financial resources (not a new situation). So Brianti and collaborators devised a new strategy: for the first time CERN would seek strong participation from national institutes in member states in the accelerator R&D and construction. In 1987–1988 the president of INFN, Nicola Cabibbo, and CERN's director-general, Schopper, agreed – with a simple exchange of letters (everything was easier in those days) – that INFN would given an exceptional contribution to the LHC R&D phase. The total value was about SwFr12 million (1990 values) to be spread over eight years.

Towards real prototypes

In 1988 and 1989, INFN and CERN ordered LHC-type superconducting cables for long magnets and in 1989 INFN ordered two 10-m long twin dipoles from Ansaldo Componenti in Italy, some nine months before CERN had the budget to order three long dipoles, one from Ansaldo and two from Noell, a German company that had been involved in the construction of HERA quadrupoles. A fourth CERN long magnet, without the twin design, was ordered from the newly formed Alstom-Jeumont consortium (even at CERN some people still doubted the effectiveness of the twin design). The effort was decisive in being able by 1993 to have the magnets qualified by individual tests and then put into a string, consisting of dipoles and quadrupoles connected in series to simulate the behaviour of a basic LHC cell.

Parallel to the INFN effort, the French CEA-Saclay institute established collaboration with CERN and took over the construction of the first two full-size superconducting quadrupoles for the LHC. While CERN provided specifications and all of the magnet components (including superconducting cable), CEA did the full design and assembly of these quadrupoles, for a value a few million Swiss francs over the eight years of R&D (*CERN Courier* January/February 2007 p25). This was the start of a long collaboration; the French also continued to support the project after the initial R&D, throughout industrialization and construction phases, with an in-kind contribution on quadrupoles, cryostats and cryogenics for about SwFr50 million (split between CEA and CNRS-IN2P3).

The challenge of the prototyping was hard and covered many aspects. In particular for the dipoles, CERN first had to convince industry to pay enough attention and to invest resources in the LHC; the allure of the SSC, a much larger project (6000 main dipoles of 15 m length, 2000 quadrupoles, etc), was difficult to ignore. CERN's project was much more challenging technically, with the required accuracy of the tooling a factor of five or so higher than for the HERA magnets. There was also the usual fight in a prototyping phase: good results required building expensive tooling for one or two magnets, with insufficient budget and no certainty that the project would be approved and the tooling cost thus paid for.

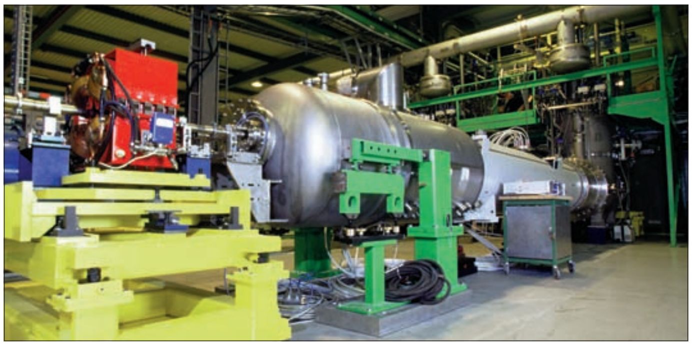


Fig. 6. A short straight section, containing a prototype LHC main quadrupole from the CEA, on its test bench at CERN.

A delay of one year was the price to pay for the many developments and adjustments. Meanwhile, in 1993 the project had to pass a tough review devoted to the cryo-magnet system led by Robert Aymar, who as CERN's director-general 10 years later would collect the fruit of the review. With the review over and completion of the long magnet prototypes approaching, the credibility of the LHC project increased. In autumn 1993, the SSC came to a halt – certainly because of high and increasing cost (more than $12 billion) and the low economic cycle in the US, but also because the LHC now seemed a credible alternative to reach similar goals at a much lower cost ($2 billion in CERN accounting). Rubbia, near the end of his mandate as director-general, which was the most critical for the R&D phase, led the project without rival. In a symbolic coincidence, the demise of the SSC occurred at the same as leadership of the LHC project passed from Giorgio Brianti, who had led the project firmly from its birth through the years of uncertainty, to Lyn Evans, who was to be in charge until completion 15 years later. The end of the SSC and the green light for the LHC was marked by the delivery to CERN of the first INFN dipole magnet in December 1993, just in time to be shown to the Council. This was followed four months later by the second INFN magnet and then by the CERN magnets, as well as by the two CEA quadrupoles designed and built by the team of Jacques Perot and later Jean-Michel Rifflet (figure 6).

Returning to the first dipole, which had been delivered from INFN at the end of 1993, a crash programme was necessary to overcome an unexpected problem (a short circuit in the busbar system – a problem that in a different form would later plague the project), so as to test it by in time for a special April session of the Council in 1994. The magnet passed with flying colours, going above the operational field of 8.4 T at the first quench, beyond 9 T in two quenches, and a first quench above 9 T after a thermal cycle i.e. full memory (figure 7). Its better-than-expected performance was actually misleading, giving the idea that construction of the LHC might be easy; in fact, it took a long six years before another equally good magnet was again on the CERN test bench. However, the other 10-m long magnets performed reasonably well and with the two very good CEA quadrupoles (3.5 m long), CERN set up the first LHC magnet string, to test it thoroughly and finally receive the

Fig. 7. On 14 April 1994 the first 10 m LHC dipole prototype from INFN was successfully powered at CERN for the first time. This magnet is now operating in the CAST experiment at CERN.

approval of the project in December 1994.

Many other formidable challenges were still to be resolved on the technical, managerial and financial sides. These included: the nonuniformity of quench results and the problem of retraining that plagued the second generation of LHC prototypes; the unresolved question of the inter-strand resistance; the change of aluminium to austenitic steel as the material for the collars, implemented by Carlo Wyss; and the lengthening of the magnets from 10 m to 15 m with the consequent curvature of the cold mass, etc.

Looking back at the period 1985–1994, when the base for the LHC was established, it is clear that a big leap forward was accomplished during those years. The vision initiated by Robert Wilson for the Tevatron was brought to a peak, pushing the limit of Nb-Ti to its extreme on a large scale. New superconducting cables, new superconducting magnet architectures and new cooling schemes were put to the test, in the constant search for economic solutions that would be applicable later to large scale production. This last point is an important heritage that the LHC leaves to the world of superconductivity: the best performing solution is not always going to be really the best. Economics and large-scale production are very important when a magnet is part of a large system and integration is critical. "The best is the enemy of the good" has been the guiding maxim of the LHC project – a lesson from the LHC for the world of superconductivity in this 100th anniversary year.

Résumé

La supraconductivité et le LHC : les débuts

Le LHC s'est inspiré de la conception du Tévatron et a mis à profit les travaux réalisés pour le collisionneur HERA, à DESY, et pour le projet SSC (non achevé), aux États-Unis, pour porter l'exploitation de la supraconductivité pour les accélérateurs à un niveau inédit. Les principaux défis concernaient le gros câble supraconducteur nécessaire pour transporter le courant électrique destiné aux dipôles de 8 à 10 T, le système de refroidissement à l'hélium superfluide, et la structure exigeant deux aimants en une même culasse pour que le collisionneur s'intègre dans le tunnel construit pour le LEP (le grand collisionneur électron–positon). Lucio Rossi revient sur la manière dont ces défis ont été relevés.

Lucio Rossio, CERN, head of the Magnet and Superconductor group, 2001–2011.

Farewell to t

Installation of the world's first superconducting synchrotron began at Fermilab 30 years ago, but now the Tevatron has finally seen its last beam. **Roger Dixon** looks back at the intriguing story of this pioneering machine.

On 30 September 2011, Helen Edwards aborted the beam and dumped the ramp for the last time on what has for the past 28 years been one of the most productive physics machines in the world. The world's first superconducting particle accelerator represented a major advance in both technology and physics reach. The Tevatron's place in history is secure. During its life it provided fixed-target beams as well as colliding beams that resulted in numerous discoveries, including the first observations of the τ neutrino and top quark (*CERN Courier* September 2011 p20).

The concept of a superconducting accelerator predates the establishment of the National Accelerator Laboratory (NAL), later renamed Fermi National Accelerator Laboratory in 1974. In 1967 NAL's first director, Robert R Wilson, discussed the possibility of using superconducting technology soon after the new laboratory moved into temporary offices in Oakbrook, Illinois. He recognized that it was premature to begin developing the concept of a new machine before construction of the planned 500 GeV accelerator at NAL had even begun. Nevertheless, superconducting technology held the promise of higher energies and lower operating costs. Not only would a superconducting accelerator in the Main Ring tunnel double the energy of the fixed-target beams, it would also enable collisions between beams. The Intersecting Storage Rings at CERN had at that stage already proved the feasibility of colliding proton beams at 62 GeV in two conventional storage rings (*CERN Courier* January/February 2011 p27). It would be a huge leap to go from conventional accelerator technology with one beam at NAL to a superconducting accelerator with colliding beams, but the thought was too tempting to dismiss completely.

The superconducting challenge

The Main Ring was commissioned in 1972. It was completed under budget and on schedule even though many difficult problems were encountered – and then resolved – during construction. The laboratory's staff had demonstrated a desire to persevere and clearly had the talent to succeed in the face of tight budgets and enormous technical challenges. The Main Ring extended the energy reach by more than a factor of five over existing accelerators. The first 200 GeV beam to the fixed-target programme was a major accomplishment. Eventually, beams at 400 GeV with 3×10^{13} protons per pulse were delivered and split between up to 15 experiments, resulting in many physics results, including the discovery of the Υ in 1977.

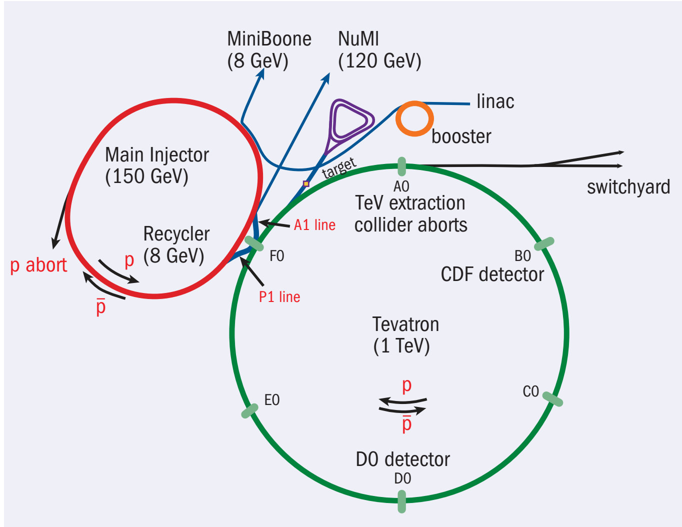
The Fermilab site. The Tevatron is the large ring to the right and the Main Inj

Once the Main Ring was commissioned the laboratory answered the call of the superconducting machine, initially known as the Energy Doubler/Saver because Wilson's vision was to reach an energy of 1000 GeV while also saving the cost of acceleration to lower energies. In 1973 work began in earnest to develop a superconducting accelerator magnet. Superconducting magnets had been built and used since the late 1940s and early 1950s – their primary use in particle physics being in bubble chambers. However, a new accelerator in the Main Ring tunnel would require approximately 1000 high-quality dipoles and quadrupoles: a reproducible magnet of accelerator quality would prove to be a major challenge.

Alvin Tollestrup played a key role in the effort to design such a magnet. After testing short magnets with monolithic superconductor, a design was chosen based on a warm-iron, collared coil of

the Tevatron

Injector ring is to the left. (Image credit: Fermilab Visual Media Services.)



The Fermilab accelerator complex during Tevatron Run II.

the niobium-titanium multifilament-strand cable developed at the Rutherford Laboratory in the UK. The first 20-ft (6.1-m) magnet was ready for tests in 1974 and by 1977 full-sized magnets were being produced and tested. However, many of these would be relegated to beam lines because further design improvements were still being implemented while magnet testing continued on test stands and in the beam lines.

It would be a huge leap to a superconducting accelerator with colliding beams.

An active quench-protection system had been developed and was exercised extensively during the early magnet testing phase – in which the people conducting the tests were ensconced behind the "dewar deflector". This experience led to a robust system that has worked well over the years.

Towards construction

In 1979, energy-deposition studies were carried out to measure the quench behaviour of two Energy Doubler dipoles in 350 GeV and 400 GeV beam extracted from the Main Ring. These measurements provided an early opportunity to use the MARS Monte Carlo shower simulation software that Nikolai Mokhov wrote at the Institute of High Energy Physics, Protvino, in 1974 and is now widely used for many accelerator and beam-related applications. Mokhov began visiting Fermilab with MARS in 1979. He helped to collect the data from the tests and used his software to determine that a superconducting collider should be feasible. A fixed-target machine was more uncertain; the extraction system would have to have better loss properties than the extraction system from the Main Ring. Helen Edwards and Mike Harrison came to the rescue with a modified design that moved the electrostatic extraction septa halfway round the ring from the extraction point, while Curtis Crawford developed a way to make the wire planes in the electrostatic septa straighter, so as to reduce losses.

Construction of the superconducting ring was authorized that same year and a final design for the magnets was in place by 1980. Because Wilson had anticipated building a second accelerator in the Main Ring tunnel, he left space underneath the Main Ring and designed its magnet stands to allow the magnets of a new machine to slip through them. The first step was to install magnets in one sector for a test in 1982. Concurrently, a large cryogenic refrigeration system was being built to provide the necessary cooling for the new accelerator. The cryogenic plant included 24 satellite ▷

100 years of superconductivity

The Tevatron ring with red dipoles fit neatly beneath the original Main Ring with its blue dipoles, as Robert Wilson had foreseen. (Image credit: Fermilab Visual Media Services.)

The Main Injector ring, below, with the green magnets of the Recycler suspended from the ceiling. (Image credit: Fermilab Visual Media Services.)

refrigerators located in the service buildings that were spaced around the Main Ring tunnel. A large helium-liquefaction plant fed helium to the satellite refrigerators.

The completed accelerator was ready to be commissioned in 1983. It was a hectic and exciting time. Many challenges had been encountered and overcome, but many of those working on the project were still sceptical that it would succeed. Nevertheless, they made an incredible effort that brought the first superconducting synchrotron to life.

Beam was injected for the first time on 2 June 1983. It took less than a day to make the first turn all of the way round. On 3 July the Energy Doubler reached 512 GeV. Resonant extraction was established in August and the fixed-target programme at 400 GeV was underway in the autumn. By 1984 the energy had reached 800 GeV and the Energy Doubler was renamed the Tevatron. Five experiments took beam during the initial 400 GeV fixed-target run.

Construction of an antiproton source began in 1981, led by John Peoples. Antiprotons were stochastically cooled in the source using the technique that Simon van der Meer had first proposed at CERN (*CERN Courier* June 2011 p24). Work also began to construct a collision hall in the BØ straight section that would accommodate the proposed CDF detector. The antiproton source was completed in 1985 and in October the first proton–antiproton collisions were observed in a partially complete CDF detector. The first collider-physics run began in 1987 using only the CDF detector. DØ came online in 1992 with a detector in the DØ straight section.

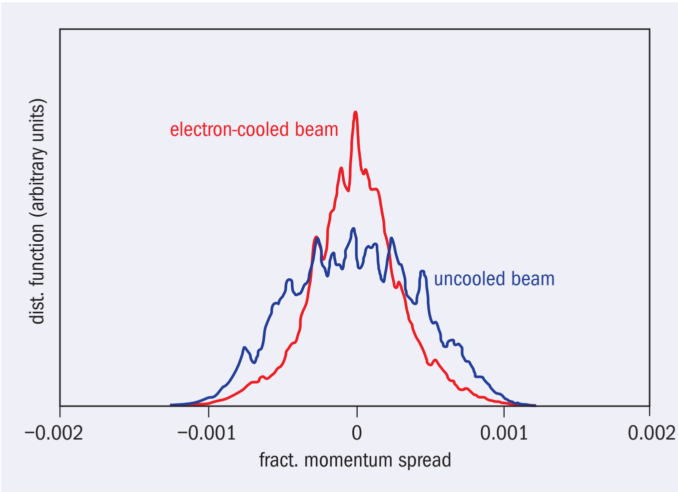
The Main Ring was still being used as an injector during the early collider runs, so it had to be accommodated in the collision halls. The CDF experiment had a Main Ring bypass that passed over the top of the detector, while the DØ collaboration had to learn to live with a Main Ring beam that went through the detector. In 1999 a new 150 GeV synchrotron, the Main Injector, was completed that replaced the Main Ring and provided more protons for both the collider and antiproton production. Built in a separate enclosure, it remedied the bypass problem. It would eventually enable simultaneous fixed-target and collider running, which had alternated until 1999.

In 1989 US President Bush awarded the National Medal of Technology to Helen Edwards, Rich Orr, Dick Lundy and Alvin Tollestrup for their work in building the Tevatron. Not only were they instrumental in solving the technical problems associated with building the forefront machine but they had also succeeded in maintaining an enthusiastic technical team in the face of problems that often seemed insurmountable.

High luminosities

The design luminosity for the early running of the collider programme was $1 \times 10^{30}\ cm^{-2}s^{-1}$ at 1800 GeV. During the first physics run in 1988 and 1989, $1.6 \times 10^{30}\ cm^{-2}s^{-1}$ was achieved. By the end of Run I in 1996, initial luminosities were typically $1.6 \times 10^{31}\ cm^{-2}\ s^{-1}$ – a factor of 16 higher than the initial design luminosity. By this time a total integrated luminosity of 180 pb^{-1} had been delivered to the two detectors – and the top quark had been discovered.

By 2001, when Run II began, many improvements to the accelerator complex had been made, including the addition of electrostatic separators to create helical orbits that prevented collisions at locations other than BØ and DØ, where the two detectors were situated. Antiproton cooling systems were also improved and the linac was upgraded from 200 MeV to 400 MeV to improve injection into the



The effect of the electron beam on the energy spread of the antiproton beam; electron cooling was a major improvement in Run II.

8 GeV booster. Cold compressors were also added to the satellite refrigerators in 1993 to lower the operating temperature by 0.5 K, making it possible to raise the beam energy to 980 GeV. However, the new compressors were not used until the beginning of Run II in 2001.

The Main Injector had a larger aperture and could deliver more protons with higher efficiency. When Run II began, this enabled the delivery of more protons to the antiproton target and better transfer efficiencies for protons and antiprotons. There were also improvements to the Antiproton Source and the incorporation of a new permanent magnet ring, the Recycler, in the Main Injector tunnel. Initially meant to recycle antiprotons, it was never used for this purpose; instead it was used to stash and cool antiprotons delivered from the antiproton source.

Initial luminosities at the beginning of Run II were in the region of 2×10^{31} cm^{-2} s^{-1}. A luminosity improvement "campaign" was initiated and implemented concurrently with the physics programme. Improvements continued to be made over most of the Run II period. Significant improvements were made to the antiproton source resulting in an increase in the stacking rate from 7×10^{10} to 26×10^{10} antiprotons per hour. The Tevatron lattice was improved and magnets were reshimmed to correct problems with the "smart bolts". Slip stacking was developed in the Main Injector, which resulted in more protons on the antiproton target.

However, the largest single improvement made during Run II was the development and implementation of electron cooling in the Recycler. This effort, led by Sergei Nagaitsev, was commissioned in 2005 and resulted in smaller longitudinal emittances. Using the Recycler to stash and cool also increased the stacking rate in the antiproton source because protons could be off-loaded to the recycler often, making the cooling more efficient. The net increase from electron cooling was more than a factor of two. Other improvements included a reduction of the β^* in the two interaction regions and there was a vigorous programme to improve the reliability of the entire complex. Altogether the improvements resulted in initial luminosities a factor of 350 better than the original design.

The National Medal of Technology (inset) awarded by US President George Bush to Helen Edwards, Dick Lundy, Rich Orr and Alvin Tollestrup in 1987 for their leading roles with the Tevatron. (Image credit: Fermilab Visual Media Services).

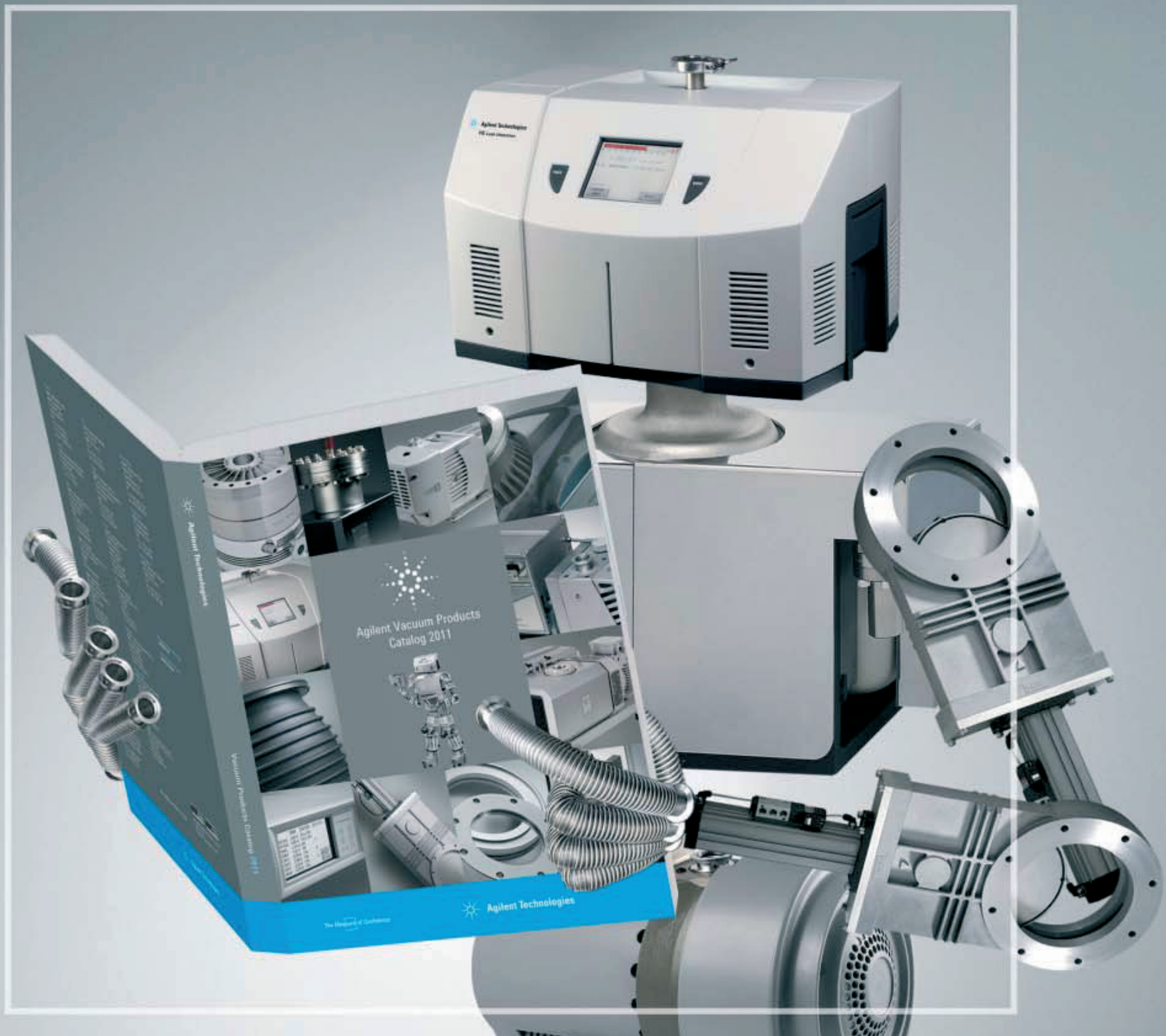
During Run II, the Fermilab accelerator complex consisted of seven accelerators that together delivered beam for the collider programme, two neutrino beams and one test beam. It has performed magnificently over the years. All but the Tevatron will now continue operating to carry Fermilab into the future (*CERN Courier* September 2011 p54). Nevertheless, the Tevatron defined the laboratory for 30 years. It has been an incredible experience for those of us fortunate enough to work on it.

Résumé

Adieu au Tevatron

L'installation du premier synchrotron supraconducteur du monde a commencé à Fermilab il y a 30 ans. Aujourd'hui, le Tevatron a fait circuler son dernier faisceau. Au cours de son exploitation, il a fourni des faisceaux pour cible fixe, ainsi que des faisceaux en collision, ce qui a amené de nombreuses découvertes. L'idée d'un synchrotron supraconducteur a commencé avec Robert Wilson en 1967, avant la mise en place de ce qui est maintenant Fermilab. Les travaux menant au développement de la machine ont commencé sérieusement en 1973 et, dix ans plus tard, le « doubleur d'énergie », comme on l'appelait, accélérait son premier faisceau. Robert Dixon nous raconte l'histoire de l'accélérateur qui a été, pendant de nombreuses années, le champion du monde des hautes énergies.

Roger L Dixon, Fermilab.



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The Measure of Confidence

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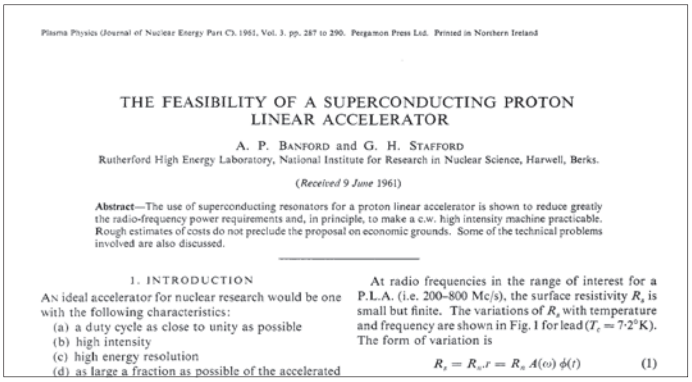
Advances in acceleration: the superconducting way

2011 marks the 50th anniversary of the launch of RF superconductivity, which is now the key technology for accelerators at the high-energy and luminosity frontiers. **Hasan Padamsee** describes some of the key developments in the field and surveys its widespread use today.



Plasma Physics (Journal of Nuclear Energy Part C). 1961, Vol. 3, pp. 287 to 290. Pergamon Press Ltd. Printed in Northern Ireland

THE FEASIBILITY OF A SUPERCONDUCTING PROTON LINEAR ACCELERATOR

A. P. Banford and G. H. Stafford

Rutherford High Energy Laboratory, National Institute for Research in Nuclear Science, Harwell, Berks.

(*Received 9 June* 1961)

Abstract—The use of superconducting resonators for a proton linear accelerator is shown to reduce greatly the radio-frequency power requirements and, in principle, to make a c.w. high intensity machine practicable. Rough estimates of costs do not preclude the proposal on economic grounds. Some of the technical problems involved are also discussed.

1. INTRODUCTION

An ideal accelerator for nuclear research would be one with the following characteristics:

(a) a duty cycle as close to unity as possible
(b) high intensity
(c) high energy resolution
(d) as large a fraction as possible of the accelerated

At radio frequencies in the range of interest for a P.L.A. (i.e. 200–800 Mc/s), the surface resistivity R_s is small but finite. The variations of R_s with temperature and frequency are shown in Fig. 1 for lead ($T_c = 7{\cdot}2°$K). The form of variation is

$$R_s = R_n . r = R_n A(\omega)\, \phi(t) \qquad (1)$$

The first proposal to use superconducting cavities for a high-intensity, high duty-factor proton linear accelerator was put forward 50 years ago.

In a seminal paper published in June 1961 A P Banford and G H Stafford described how a future superconducting proton linear accelerator could run continuously, instead of at the 1% duty cycle of the 50 MeV proton accelerator that was operating at the time at the Rutherford High Energy Laboratory in the UK. The basic argument was that, because ohmic losses in the accelerating cavity walls increase as the square of the accelerating voltage, copper cavities become uneconomical when the demand for high continuous-wave (CW) voltage grows with particle energy. It is here that superconductivity comes to the rescue.

The RF surface resistance of a superconductor is five orders of magnitude less than that of copper. The quality factor (Q_0) of a superconducting resonator is typically in the billions (i.e., a billion oscillations before the resonator energy dissipates). After accounting for the refrigerator power needed, the net gain in the overall cooling power remains a factor of several hundred. It became clear that the higher-voltage, shorter superconducting structures can also reduce the disruptive effect that accelerating cavities have on the beam, resulting in better beam quality, higher maximum current and less beam halo (less activation). By virtue of low losses in the walls, a superconducting RF (SRF) cavity design can also afford a large beam aperture, which further reduces beam disruption and beam halo.

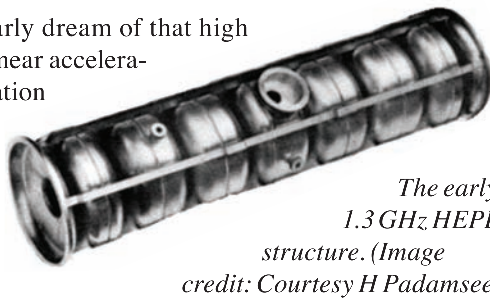
It took nearly 40 years for the early dream of that high duty-factor, high-intensity proton linear accelerator to be fulfilled. Today, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory runs at 6% duty cycle with 88 m of superconducting cavities providing 1 MW of beam power with a 1 GeV, 10 mA beam. The success of the SNS has stimulated the construction of the European Spallation Source (ESS), with 5 MW of beam power, to be completed in 2016.

Pioneering work

In the early 1960s, Stanford University, under the leadership of William Fairbank, pioneered the development of superconducting cavities for electron accelerators. By 1968 they achieved a Q value of more than 10^{10} at 1.7 K for an 8.5 GHz TM010-mode single-cell pill-box resonator built of solid niobium. The first niobium cavity also demonstrated the exciting prospect of gradients of more than 30 MV/m.

However, with the more practical, lower frequency (1.3 GHz) accelerator structures that were built in the 1970s, the performance level fell to 2–4 MV/m. The primary roadblock was multipacting – the spontaneous resonant production of electrons. By the mid-1980s, the physics of multipacting was understood. It turned out that the limiting field-levels scale with the RF frequency, so the high-frequency cavities of the 1960s had been fortuitously exempt.

The next three decades saw several layers of gradient problems being uncovered, the underlying physics understood and solutions developed. Cavity performance then ratcheted up at a steady pace, as did accelerator applications. The development of the anti-multipacting, spherical (and elliptical) cavities was a breakthrough moment. With multipacting overcome, thermal breakdown of superconductivity became the next limiting mechanism, at 4–6 MV/m. Local heating at surface imperfections led to thermal ▷

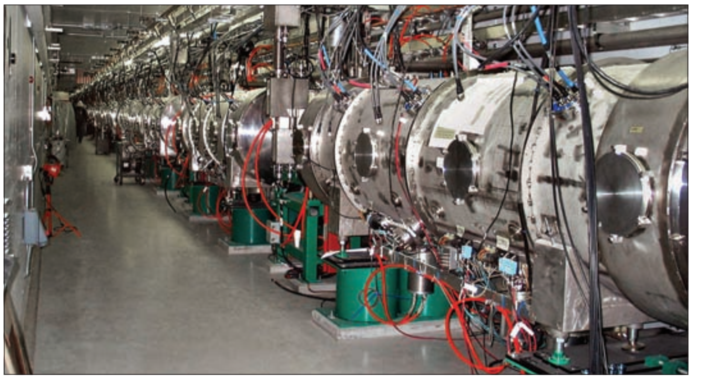


The early 1.3 GHz HEPL structure. (Image credit: Courtesy H Padamsee.)

runaway and a quench of superconductivity. The cure was to switch to niobium of high-purity – high residual-resistance ratio (RRR) niobium. With the co-operation of industry, RRR improved by an order of magnitude and cavity gradients rose on average by a factor of three. Another cure for thermal breakdown was to sputter a micron-thin film of niobium onto a copper cavity-substrate, which also had the benefit of reduced material costs – especially for the cavernous, low-frequency (0.35 GHz) cavities.

With the corresponding rise in surface electric fields, electron emission became the next limit to gradients, at 10–15 MV/m. Global R&D revealed microparticle contamination to be the dominant source of field emission, so the solution demanded better preparation techniques, such as powerful surface scrubbing with high-pressure (100 atm) water and assembly in Class 100 clean rooms. With these advances, cavity gradients climbed to 20 MV/m.

Above 20 MV/m, however, RF losses began mysteriously to rise exponentially with the field. The physics of such losses is still under investigation but pragmatic countermeasures are already in place. Electro-polishing has replaced the standard chemical etching to obtain a smoother surface, followed by mild baking at 120 °C for two days. There is now excellent prognosis for reaching 35–40 MV/m. Many nine-cell, 1 m-long niobium structures have demonstrated performance above 40 MV/m in qualification tests, while basic research continues to push towards the theoretical limit of 55 MV/m.



The proposal for a high-intensity proton linac, first made in 1961, finally came to fruition at the SNS, commissioned in 2005 at Oak Ridge National Laboratory. (Image credit: ORNL.)

Cornell/Jefferson Lab cavities run CEBAF at 7–10 MV/m. (Image credit: Jefferson Lab.)

SRF takes off

As gradients improved steadily from the mid-1980s, RF superconductivity grew into a key technology for accelerators at the energy and luminosity frontiers, as well as at the cutting edge of low- and medium-energy nuclear physics, nuclear astrophysics and basic materials science. SRF cavities are now routinely accelerating electron, proton and heavy-ion beams in a variety of frontier accelerators.

It was in the early 1990s that SRF took off to push the energy frontier in storage rings, with TRISTAN at KEK and HERA at DESY. In the late 1990s the energy of the Large Electron–Positron collider at CERN doubled, with 500 m of superconducting cavities built by sputtering niobium on copper. Nb-Cu superconducting cavities now meet the voltage and high current demands of the LHC at CERN. At the luminosity frontier, high-current, high-luminosity electron–positron storage rings have operated and continue to operate with SRF cavities for copious production of c and b quarks at the Cornell Electron Storage Ring in the US, the KEKB facility in Japan and the Beijing Electron Positron Collider in China.

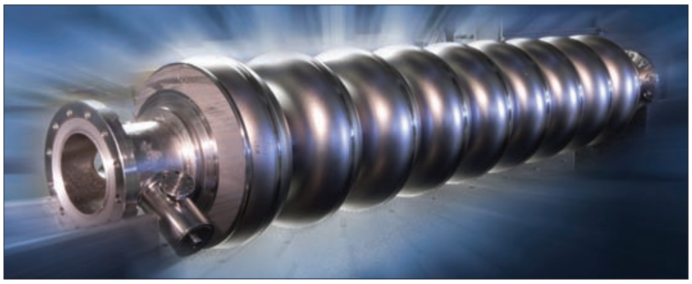
At the cutting edge of nuclear physics, Jefferson Lab has installed a 1 GeV superconducting linac to achieve 6.5 GeV beam by recirculation. The laboratory's Continuous Electron Beam Accelerator Facility (CEBAF) has been operating for 15 years with more than 150 m of SRF cavities, the largest number in operation at one facility. Looking ahead, Jefferson Lab has also developed 20 MV/m cavities to upgrade CEBAF's energy from 6.5 GeV to 12 GeV.

For heavy ions, the CW superconducting accelerator provides an optimized array of independently phased resonators, to accelerate a variety of ion species with different velocities and charge states. The Argonne Tandem Linac Accelerator System at Argonne National Laboratory and the ALPI machine at the Legnaro National Laboratory have been operating for several decades. TRIUMF has expanded its radioactive-beam facility ISAC by adding a superconducting heavy-ion linac to supply more than 40 MV. Heavy-ion linacs in New Delhi and Mumbai have also come online. More than 250 superconducting resonators are currently operating around the world. New radioisotope beam (RIB) facilities are under construction with the SPIRAL2 project at the GANIL laboratory, HIE-ISOLDE at CERN and the ReA3 re-accelerator at Michigan State University (MSU).

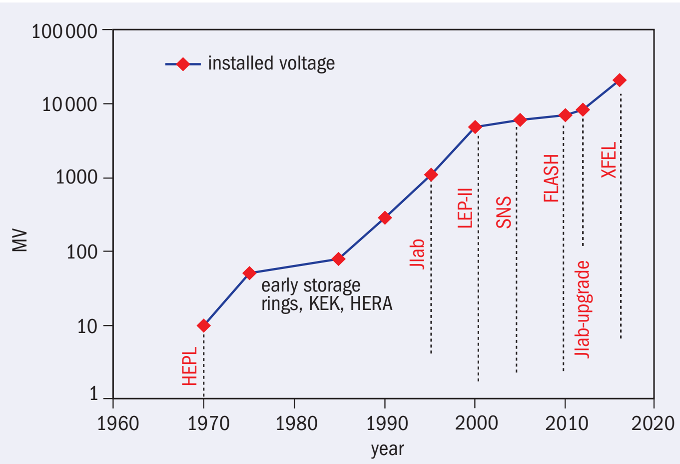
Electron storage rings working as light sources are having an enormous impact on materials and biological science. SRF accelerating systems have been used in upgrading storage-ring light sources, such as the Cornell High Energy Synchrotron Source and the Taiwan Light Source. The Canadian Light Source, DIAMOND in the UK, the Shanghai Light Source in China and SOLEIL in France also operate with SRF; the National Synchrotron Light Source II at Brookhaven and the Pohang Light Source in Korea are planning to use SRF cavities. The Swiss Light Source at PSI and ELETTRA in Trieste have both installed third-harmonic superconducting cavities to improve beam lifetime and stability.

Free-electron lasers (FELs) based on SRF linacs provide tunable, coherent radiation over a wide range of wavelengths. The Jefferson Lab FEL generates 14 kW of CW laser power in the infrared, with energy recovery by recirculating nearly 1 MW of beam power. This is an important milestone toward the use of energy-recovery

100 years of superconductivity



XFEL cavities reach 30–40 MV/m and will be used for the ILC. (Image credit: Fermilab Visual Media Services.)



Superconducting cavities have operated routinely in a variety of accelerators with a range of demanding applications. The total installed voltage is on the path to increase from 7 GeV at present to near 20 GeV with the completion of the European XFEL.

linacs (ERLs) for future light sources and electron-cooling applications. SRF-based FELs have operated at the Japan Atomic Energy Research Institute and at the ELBE project in Germany. FLASH at DESY is a short-wavelength FEL based on the self-amplified stimulated emission (SASE) principle, delivering 6 nm wavelength light. Its SRF linac uses more than 60 cavities, each 1 m long to accelerate a 1 GeV electron beam. A variety of innovative linac-based light sources are also under study for FELs and ERLs to deliver orders of magnitude higher brightness and optical beam quality. High-intensity beams for ERLs have spurred explorations for electron-cooling applications and for electron-ion colliders, for example to upgrade the Relativistic Heavy Ion Collider at Brookhaven.

With many exciting prospects on the horizon, the world SRF community has expanded to include many new laboratories where extensive SRF facilities have been installed. In all, more than 1 km of superconducting cavities have been installed worldwide to provide more than 7 GeV of acceleration. The next big jump of 16 GeV is already under construction, with the largest SRF application underway on a superconducting linac for the European XFEL at DESY. It will be based on nearly 700 niobium cavities operating at a gradient of more than 22 MV/m. When completed in 2016 it will provide X-ray beams of unprecedented brilliance at sub-nanometre (Ångström) wavelengths.

A new Facility for Rare Isotope Beams (FRIB) is underway at MSU to allow the study of exotic isotopes related to stellar evolution and the formation of elements in the cosmos. FRIB will be based on more than 330 low-velocity resonators, doubling the number currently in operation.

The most ambitious future application under study is for the International Linear Collider (ILC), a 500 GeV superconducting linear accelerator. It will require 16 km of superconducting cavities operating at gradients of 31.5 MV/m. Intense research is underway to reach a high yield for high gradients: 30–40 MV/m. New vendors for niobium, for cavities and for associated components are being developed around the world. Improved techniques for performance reliability and cost reduction are emerging. New assembly and test facilities are coming together at DESY, Saclay, KEK and Fermilab; the experience of the DESY XFEL will be a key stepping stone. Future ILC energy upgrades toward 1 TeV would benefit from even higher gradients that would push niobium towards its ultimate potential of 55 MV/m and thus open the door for new materials with gradients of 100 MV/m. Nb_3Sn is the most promising candidate offering the prospect of 100 MV/m gradients, but substantial research is needed to verify this potential and guide the development necessary to harness it.

With the success of the SNS and the upcoming ESS, high-intensity proton linacs are likely to fulfil future needs in a variety of arenas: upgrading injector chains of proton accelerators at Fermilab's Tevatron (Project X) and CERN's LHC (the SPL), transmutation applications for treatment of radioactive nuclear waste, nuclear-energy production using thorium fuel, high-intensity neutrino beamlines, high-intensity muon sources for neutrino factories based on muon storage rings and eventually a muon collider at the multi-tera-electron-volt energy scale. All of these far future prospects will of course depend on the success of on-going efforts.

The 2011 International SRF conference in Chicago hosted more than 350 SRF enthusiasts. We can remain confident that the RF superconductivity community has both the creativity and determination to face the upcoming challenges and successfully bring these exciting prospects to fruition.

Résumé

Améliorer l'accélération par la supraconductivité

Un article pionnier publié en 1961 proposait l'utilisation de la supraconductivité pour les cavités radiofréquence (RF) pour permettre le fonctionnement en continu d'un accélérateur de protons linéaire. Il a fallu près de 40 ans pour que ce rêve devienne réalité, mais, pendant ce temps, le recours à la supraconductivité pour les cavités RF dans les accélérateurs de particules s'est développé progressivement. Cette technologie est maintenant très utilisée, non seulement en physique des particules, mais aussi pour d'autres applications s'appuyant sur des linacs de protons de haute intensité, ainsi que pour les sources de lumière synchrotron et les lasers à électrons libres. C'est à présent la technologie essentielle pour les accélérateurs aux limites des hautes énergies et des hautes luminosités, comme l'explique Hasan Padamsee.

Hasan Padamsee, Cornell.

Progress in applied superconductivity at KEK

The application of superconductivity in accelerators and particle detectors at KEK has progressed hand in hand with the research programme ever since the laboratory was founded 40 years ago.

Fig. 1. The interaction-region quadrupole (IRQ) magnet integrated into the BELLE detector and its solenoid magnet at KEKB, top. Fig. 2. The IRQ magnet system installed in the LHC accelerator, bottom.

The Japanese High-Energy Accelerator Research Organization, or KEK, was established (originally as the National Laboratory for High Energy Physics) in Tsukuba in 1971, around the same time that superconductivity – discovered 60 years earlier – was just beginning to find large-scale applications in physics. The laboratory became involved in superconducting technology almost from the start and KEK has continued to push frontiers in the field as its research programme has evolved. Two pioneering scientists, the late Hiromi Hirabayashi and Yuzo Kojima, deserve particular mention for their leading roles in starting research and development at KEK in the mid-1970s – on superconducting magnets and RF superconductivity for accelerator science, respectively.

Superconducting-magnet technology was first put to practical use at KEK in a secondary-particle beamline at the 12 GeV proton synchrotron. Two cosθ dipole magnets and one superconducting septum magnet formed major components in the beamline, while a large-aperture "window-frame" superconducting spectrometer-magnet was built for one of the physics experiments. Hirabayashi not only took the lead in this milestone project, he also used it to train the next generation of magnet scientists and engineers. They would take forward the various superconducting-magnet projects that were subsequently carried out at KEK and in collaborative international programmes, including R&D on the Superconducting Super Collider in the US and LHC project at CERN.

Frontier projects with superconducting magnets

The frontier project for the 1980s was an electron–positron collider, TRISTAN, which had a maximum beam energy of 30 GeV and operated between 1987 and 1995. KEK successfully developed large-aperture insertion-quadrupole magnets for the four interaction regions, to bring high-brightness beams into collision in the physics experiments.

Following on from TRISTAN, KEK constructed the accelerator for the B-factory, KEKB – an energy-asymmetric electron–positron collider with two rings handling 3.5 GeV positrons and 8 GeV electrons – built in the TRISTAN tunnel. Superconducting interaction-region quadrupole (IRQ) magnets were again developed. Based on a sophisticated coil design, with corrector-coils in additional coil layers, they were very closely integrated with the collider detector, BELLE (figure 1). The IRQs contributed to the highest beam luminosity ever achieved, as described later, enabling the KEKB accelerator and the BELLE experiment to help in establishing the Kobayashi-Maskawa theory for which the Nobel prize was awarded in 2008 (*CERN Courier* November 2008 p6). A further sophisticated multiple-magnet system is now being developed for the interaction region at Super-KEKB, the upgraded B-factory, which was approved in 2010.

The experience acquired in these projects was to allow KEK to make important contributions to the LHC, in particular in a fundamental study of high-field dipoles to reach 10 T and in the

Fig. 3. J-PARC primary proton beam line and the superconducting combined-function magnet string.

Fig. 4. The superconducting cavity string used for beam acceleration in TRISTAN.

construction of insertion quadrupoles with a design field gradient of 215 T/m at a coil aperture of 70 mm (figure 2). The quadrupole magnets were developed and supplied in collaboration with Fermilab.

More recently, KEK developed a primary proton-transport line at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, in a collaboration between KEK and the Japan Atomic Energy Agency (JAEA). To create and direct a neutrino beam towards the Kamioka neutrino observatory nearly 300 km away, an internally extracted proton beam from J-PARC has to bend through around 90°, with a much smaller bending radius than that of the main-ring accelerator. This requirement has been achieved using a series of uniquely fashioned superconducting magnets with combined-function coils having dipole and quadrupole field components within a single-layer coil (figure 3). The experience accumulated in the earlier projects contributed to achieving this distinctive superconducting-magnet design, which also involved important co-operation with Brookhaven National Laboratory. At J-PARC superconductivity has taken an essential role in providing high-intensity pulsed muon beams in the meson-science laboratory, as well as the superconducting solenoid beamlines for muon science and a superconducting magnetic spectrometer for particle physics.

For the future, KEK intends to contribute to upgrade programmes for the LHC, to the application of advanced high-field superconductors in co-operation with the National Institute of Materials Science and to high-temperature superconductors in co-operation with other laboratories and industry. Fundamental research on the effect of stress-strain on superconductor performance is crucially important for high-field superconducting magnets. Experimental studies of structural and stress analysis are in progress using neutron-diffraction techniques at the J-PARC neutron-beam facility in co-operation with JAEA.

KEK has also applied superconducting-magnet technology to particle-detector magnets. The TRISTAN collider's three major particle detectors – TOPAZ, VENUS and AMY – and the BELLE detector at KEKB were based on superconducting solenoid magnets to provide the magnetic fields for momentum analysis in particle spectroscopy. In particular, these involved a great deal of development work on aluminium-stabilized superconductor technology.

The key feature of this technology is that it allows the maximum magnetic field for the minimum material – an important step in matching the physicists' dream of having only a magnetic field, without additional material, in an experiment. It therefore leads to the possibility of "thin-walled" superconducting coils that are in effect transparent to particles passing through. The use of aluminium stabilizer instead of ordinary copper stabilizer allows for low density and low resistance but requires sufficiently high strength. It has become a fundamental technology in the construction of magnets for large-scale particle detectors, including – most recently – the magnet systems of the ATLAS and CMS experiments at the LHC. KEK provided the ATLAS central solenoid magnet, which had the extremely demanding requirement that it should be installed in a common cryostat with the liquid-argon calorimeter system in addition to employing the advanced high-strength aluminium-stabilized superconductor technology to meet the physics requirement for the magnetic field to be as transparent as possible (*CERN Courier* September 2006 p5).

KEK has also applied this technology in a variety of global collaborations, including the muon g-2 parameter measurement experiment (E-821) at Brookhaven National Laboratory and the WASA experiment at Uppsala University (now transferred to the Cooler Synchrotron (COSY) ring at the Forschungszentrum Jülich). A more extreme application is in the field of astroparticle physics. The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) has successfully flown twice over Antarctica to search for primordial antiparticles in the universe, in collaboration with NASA in the framework of Japan–US co-operation in space science.

Superconducting acceleration

Turning now to RF superconductivity, TRISTAN was the first high-energy particle accelerator in the world to use superconducting RF cavities as the main acceleration components with a frequency of 500 MHz in the routine operation of the accelerator (figure 4). This is where Kojima took the lead and established a milestone by using superconducting RF to provide a high continuous-wave accelerating gradient in storage rings. He also trained many next-generation scientists in RF superconductivity, who have since extended the application in a variety of subsequent projects and global collaborations. ▷

100 years of superconductivity

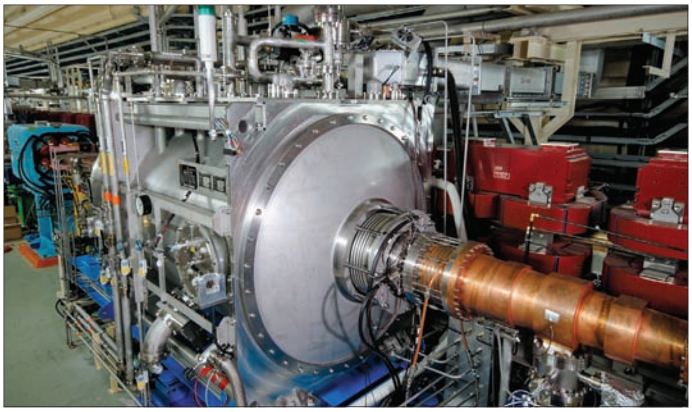


Fig. 5. A superconducting crab cavity installed in the KEKB accelerator. (Image credit: KEK and MHI Ltd.)

Fig. 6. The international superconducting cavity-string test, S1-Global, hosted by KEK, has participation from DESY, INFN, Fermilab, and SLAC. (Image credit: KEK.)

The technology pioneered at TRISTAN was extended for the KEKB accelerator, which was commissioned in 1998 with superconducting RF cavities as a major accelerating component. Eight single-cell cavities with sufficiently damped higher-order modes (HOM) accelerated the electron beam of 1.4 A, delivering the RF power of 350 kW per cavity. This technology was also applied to the Beijing Electron–Positron Collider II in co-operation with the Institute for High-Energy Physics in Beijing. Furthermore, collaboration with the National Synchrotron Radiation Research Center is under way to apply superconducting RF technology to its new synchrotron-light source, the Taiwan Photon Source. At the same time, a unique superconducting RF cavity, called the "crab cavity", was successfully developed as a key component to maximize the peak luminosity of KEKB (figure 5). It was designed to reach the optimum beam-interaction efficiency by tilting the beam and then compensating the crossing angles (*CERN Courier* September 2007 p8). Once installed at KEKB, the crab cavity contributed to the facility's world-record luminosity of 2.11×10^{34} cm^{2}s^{-1} achieved in 2009. KEKB shut down in June 2010 to be upgraded to Super KEKB, so as to allow operation with a peak luminosity of 8×10^{35} cm^{-2}s^{-1}.

Looking to future applications of RF superconductivity in accelerator science, KEK is now undertaking research and development in two major directions. Energy-recovery linacs (ERLs), which in effect recycle energy from the beam, will inevitably be required for efficient acceleration, especially in applications of intense electron beams and in photon science. KEK is building a compact ERL facility as a prototype for a potential future ERL accelerator.

Aiming towards the high-energy frontier, research and development for the International Linear Collider (ILC) is being carried out in a global co-operation led by the Global Design Effort (GDE) (*CERN Courier* September 2011 p9). The design, based on RF superconductivity, foresees more than 16 000 superconducting 9-cell 1.3 GHz cavities in series, operating with an average field gradient of 31.5 MV/m, to achieve a linear electron–positron collider based on two 250 GeV linear accelerators.

KEK is contributing to developing the advanced superconducting RF cavity technology for the ILC within the global collaboration. There has been successful progress towards demonstrating a field gradient of more than 40 MV/M in 9-cell cavities, based on accumulated long-term fundamental research and development. In a unique global effort, KEK has hosted a cavity-string test (the so-called S1-Global) with a cavity-string and a cryomodule system jointly contributed by DESY, Fermilab, INFN, SLAC and KEK (figure 6). The test facility has demonstrated how international collaboration can be possible in providing a plug-compatible cavity-string assembly, which would inevitably be required in constructing the ILC accelerator.

Once installed at KEKB, the crab cavity contributed to the facility's world-record luminosity.

Applied superconductivity has been an essential and fundamental technology in all of the major experimental facilities for accelerator science and for physics programmes that have and will be carried out at KEK, as well as for international co-operation programmes, including the LHC and the ILC. The hope is that KEK will continue both to play an important role in contributing to advanced technology and to be a centre of excellence in applied superconductivity for fundamental physics and accelerator science.

Résumé

Supraconductivité appliquée au KEK

Deux pionniers de la physique – Hiromi Hirabayashi et Yuzo Kojima – ont joué un rôle majeur dans le démarrage de la recherche et développement sur les aimants supraconducteurs et la supraconductivité RF, respectivement, au Laboraboire japonais de recherche sur les accélérateurs de haute énergie (KEK). L'application de la supraconductivité aussi bien dans les accélérateurs de particules que dans les détecteurs de particules a depuis progressé au même rythme que le programme de recherche du KEK. Akira Yamamoto évoque les principales réalisations, y compris le développement de supraconducteurs stabilisés à l'aluminium pour les aimants des détecteurs de particules et les cavités RF « en crabe » qui ont permis au collisionneur KEKB d'atteindre un record mondial de luminosité.

Akira Yamamoto, KEK.

PET and MRI: providing the full picture

A new hybrid medical-imaging technique places photodetectors in a strong magnetic field, just as experiments are doing in particle physics.

Modern medical imaging of the human body often provides not only anatomical detail but also functional information or the biochemical status of a particular region of the body. The first example of the combined use of anatomical and functional imaging, now known as "hybrid imaging", put positron emission tomography (PET) together with computed tomography (CT). David Townsend, a former CERN scientist working at the University Hospital in Geneva, first thought of incorporating an X-ray-based CT scanner in the same instrument as a PET camera in 1991 (*CERN Courier* June 2005 p23). The first such instrument was in operation by the end of the 1990s and now all PET cameras that are commercially available from the major international companies are combined PET/CT scanners.

Although PET/CT has proved its value in oncology, CT still has some serious limitations related to soft-tissue contrast, which often needs additional injections of contrast agents for the patient. In CT imaging, high levels of radiation exposure are also a concern, particularly in paediatrics, in repeated scanning for therapy monitoring and in other non-oncology pathologies. An alternative approach for hybrid imaging has arisen recently with the emergence of systems that combine PET with magnetic-resonance imaging (MRI). The advantages of a PET/MRI scanner is evident from the table below, which illustrates the merits of the different medical-imaging techniques.

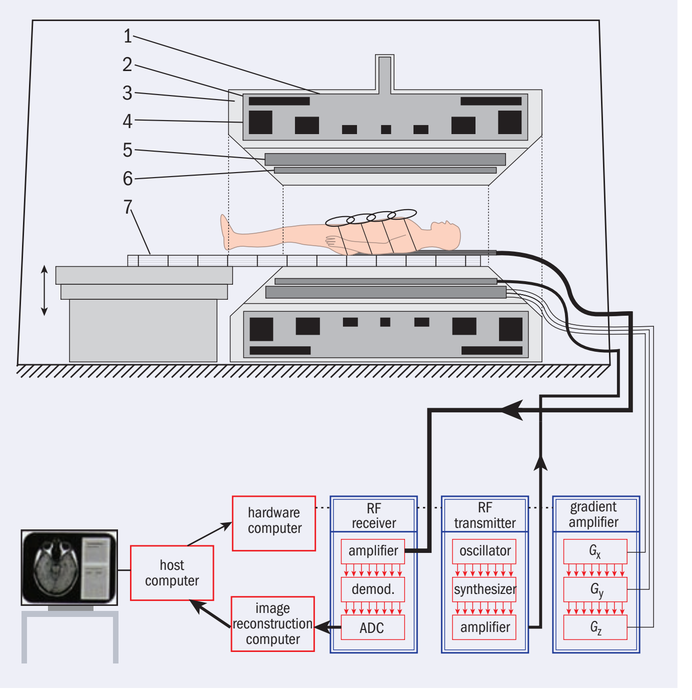


Fig. 1. Illustration of a general MRI imaging system (adapted from Bock 2008); 1 is the cryotank containing liquid helium, 2 is the active magnetic shielding, 3 is a vacuum tank, 4 the B_0 coil, 5 are the gradient coils and 6 the RF body coil, while 7 is the couch. The elements positioned on the patient represent various RF-receiver body coils. (Image credit: Springer Science+ Business Media: Magnetic Resonance Tomography *by M F Reiser, W Semmlar and H Hricak (eds) 2008 p77.)*

Unlike CT, MRI provides good contrast in soft tissue. This technique involves aligning the magnetic moments of hydrogen ▷

Parameter	Ultrasound	Optical imaging	CT scanner	MRI scanner	PET camera
Anatomical detail	OK	Good	Good	Excellent	Poor
Spatial resolution	OK	Good	Good	Excellent	OK
Clinical penetration	OK	Poor	Excellent	Excellent	Poor
Sensitivity	Poor	Poor	Poor	Poor	Excellent
Molecular imaging	Poor	Poor	Poor	OK	Excellent

Industry

Fig. 2. The Philips PET/MRI scanner at the University Hospital Geneva. (Image credit: Philips Healthcare.)

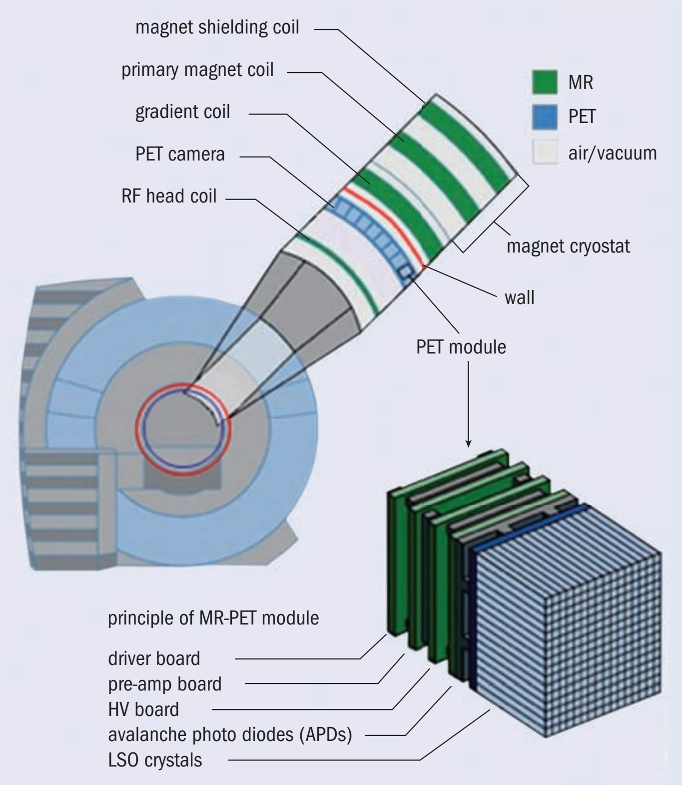


Fig. 3. Schematic of the Siemens whole-body PET/MRI scanner. (Image credit: Siemens Healthcare. Based on the diagram in Medical Solutions *September 2005 p28.)*

nuclei in a strong magnetic field and then using a temporary RF field to flip the spin of some of them. When these nuclei revert to their former state, they radiate at the same radio frequency. The key to providing an image is to apply an additional magnetic-field gradient so that the resonant frequency varies with position. A typical MRI scanner comprises a strong magnet to produce a static, homogeneous, longitudinal magnetic field (B_0), three "gradient" coils that can be switched on and off, an RF transmitter, RF receiver coils and a computer-control and data-acquisition system (figure 1, p39).

Superconducting magnets offer the optimum way to provide the necessary field strength over the volume required in a whole-body scanner and the commercial development of these magnets from the 1970s onwards has led to the wide medical use of MRI. Modern systems have fields of 1.5–3 T, although some with fields up to 7 T already exist. The gradient coils generate magnetic-field gradients in x, y and z directions and are used to encode position, while the RF-transmitter coil is used to excite nuclei by dragging longitudinal magnetization from the B_0 direction to a desired predefined angle. Several RF-receiver coils are used – one is integrated into the MRI scanner and several "surface" coils can be placed closer to the patient to improve signal-to-noise ratios. These coils receive RF pulses transmitted from nuclei when they lose their excitation and their re-alignment with B_0. Recently, the RF receiver–transmitter system has evolved to accommodate two parallel transmitters that improve the spatial homogeneity of acquired signals – this is important in 3 T systems for whole-body imaging.

A PET camera, by contrast, is used to detect and measure the distribution in the body of radioisotopes decaying via positron emission. For every positron annihilation event in tissue, an almost coplanar pair of 511 keV gamma-ray photons is produced. A PET detector consists of a pixelated scintillator ring connected to banks of photomultiplier tubes (PMTs) via optical guides. The PMTs convert the photons of visible light from the scintillators into voltage and the relative output voltages of pairs of PMTs determine the position of the photon pairs at the detector surface. To identify photon pairs, the PMTs operate in coincidence using a timing window of a few nanoseconds. The detected coincident pair defines a line-of-response (LOR), somewhere along which a positron annihilation event happened. Detectors with fast timing-resolution, typically less than 600 ps, can localize the annihilation on the LOR using time-of-flight technology (TOF).

PET meets MRI

PMTs, however, are inherently unable to operate inside a magnetic field. Early attempts to develop smaller animal PET/MRI scanners produced several innovative prototypes using different approaches to overcome the cross-talk between the PET and MRI systems. In 2008, both the Philips and Siemens medical companies developed their first PET/MRI prototypes for humans. The Philips system had two independent scanners and additional shielding to contain the magnetic field from its 3 T magnet, with a coaxial distance between the PET detector and the MRI scanner of 4.2 m (figure 2). Furthermore, each PMT was individually shielded and its photocathode aligned along the flux lines of the magnetic field. Apart from this change the PET detector was the same as the commercially available TOF scanner and this PET/MRI system was capable of acquiring whole-body images in a sequential fashion. The Siemens prototype had a PET scanner integrated into an MRI system with a 3 T scanner. A retractable PET detector used avalanche photodiodes (APDs) which are solid-state photon detectors coupled to lutetium oxyorthosilicate scintillator crystals (LSO). The system was designed to acquire simultaneous PET and MRI pictures of the brain.

Today, three large-imaging companies have PET/MRI whole-

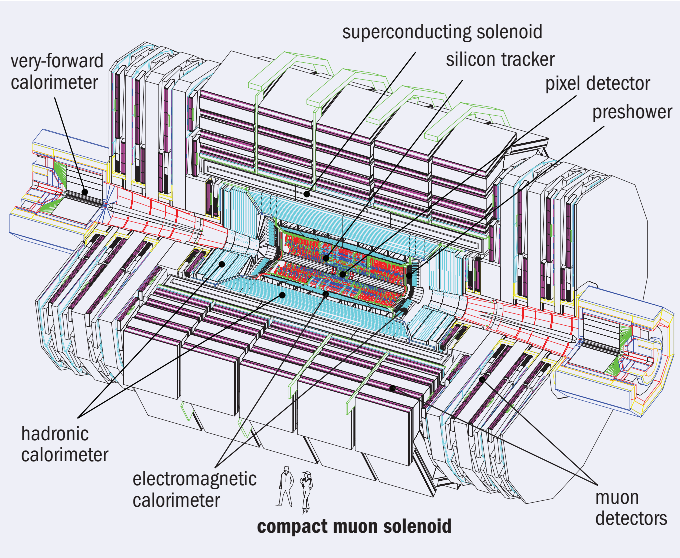


Fig. 4. The CMS experiment at the LHC has its calorimeters inside the 12.5 m long, 4 T superconducting solenoid.

body scanners in their portfolios, although all three are significantly different. In 2010, Siemens announced a whole-body simultaneous PET/MRI scanner based on their original technology and this has already received medical devices registration (CE mark for Europe and 510(k) for the US). This latest model comprises a 70 cm diameter 3 T magnet with an integrated PET detector ring 60 cm in diameter. The PET detector consists of pixelated scintillators coupled via optical guides to an array of APDs (figure 3). APDs are insensitive to magnetic fields and have high gain (10^2–10^3) and timing resolution of the order of 1 ns (Lewellen 2008). The APD arrays are connected to front-end electronics for pre-amplification and digitization and have a cooling circuit to maintain constant temperature because their gain is temperature sensitive. Meanwhile, Philips has commercialized its sequential whole-body TOF-PET/MRI system (CE mark already received and 510(k) approval pending). A third company, General Electric, is proposing an arrangement where an MRI scanner is placed in a room adjacent to a PET/CT scanner and the patient is transferred from one system to the other using a shuttle couch arrangement.

Some concerns remain about the integration of MRI and PET. Photons travelling through a patient's body are absorbed or attenuated and are not registered. In PET/CT systems, this is compensated for by using a low-dose CT scan, which provides an accurate attenuation map of the object being imaged; this CT attenuation map can then be used for attenuation correction of the PET image. This is not possible in PET/MRI systems and various methods for estimating attenuation coefficients are still under development. Another problem is cross-talk between PET and MRI because RF pulses from the MRI may cause the PET electronics to lose counts during transmission of the RF pulses. Nevertheless, the latest commercial systems seem to have overcome most of the problems and fine-tuning of the designs continues. Industry and the medical-imaging community are now actively collaborating to use and improve this new medical technology, as well as to demonstrate a true clinical utility for PET/MRI scanners. This has already resulted in a multitude of scientific publications on these topics in both journals and conferences on PET and MRI.

There is a remarkable similarity in design between these integrated PET/MRI clinical scanners and the large, general-purpose detector systems developed in particle physics. For example, the CMS experiment at the LHC in CERN has a central detector of 4 m × 15 m within an axial magnetic field of 4 T (figure 4). This can be compared with a commercial whole-body PET/MRI scanner, with a field of view of 0.6 m × 0.26 m and magnetic fields of up to 3 T. It is therefore reasonable to expect that the latest technologies now being used in particle physics detectors – e.g. silicon photomultipliers – will soon be incorporated by industry into newer and more sensitive combined PET/MRI scanners, with timing-resolution capabilities superior to even those of today's state-of-the-art PET/CT scanners that are based on PMTs.

• Further reading

M Bock 2008 *Magnetic Resonance Tomography* M F Reiser, W Semmlar and H Hricak (eds.) Springer 77.

T K Lewellen 2008 *Phys. Med. Biol.* **53** R287–R317.

Résumé

TEP et IRM : la vision d'ensemble

Les techniques modernes d'imagerie médicale sont capables de montrer le détail anatomique d'une région du corps, et aussi de donner des informations biochimiques fonctionnelles, mais pas toujours les deux à la fois. Dans une nouvelle approche, on combine les effets de la tomographie par émission de positons (TEP) avec ceux de l'imagerie par résonance magnétique (IRM). Le scanner IRM fournit des images donnant un bon contraste dans les tissus mous, alors que la caméra TEP mesure la distribution des radio-isotopes se désintégrant sous l'effet de l'émission de positons. Aujourd'hui, trois grandes sociétés proposent des scanners TEP/IRM pour l'ensemble du corps. Ces systèmes hybrides s'appuient sur des photodétecteurs placés dans un fort champ magnétique, exactement comme les expériences le font dans le domaine de la physique des particules.

Dewi M Lewis, CERN, and **Antonis Kalemis**, Philips Healthcare.

Faces & Places

Honours

Italian Physical Society honours Gargamelle physicists with Fermi award

The 2011 Enrico Fermi prize of the Italian Physical Society, for work in the field of experimental particle physics, has been awarded to Dieter Haidt of DESY and Antonino Pullia of the University of Milano Bicocca and INFN, "for their fundamental contribution to the discovery of weak neutral currents with the Gargamelle bubble chamber at CERN". They received the award at the opening session of the society's 97th National Congress, at the University of L'Aquila, Coppito, on 26 September.

The prize is awarded yearly to members of the society who especially honour physics with their discoveries. It was first awarded in 2001, to commemorate the centenary of Enrico Fermi's birth.

Dieter Haidt (left) and Antonino Pullia, rewarded for their incisive work in the discovery of weak neutral currents. (Image credit: Italian Physical Society.)

The discovery of neutral currents in the Gargamelle bubble chamber at CERN has been honoured with many prizes, including the High-Energy and Particle Physics Prize of the European Physical Society in 2009. The key results were published in September 1973 after an intense period of work that had commenced nearly two years earlier.

A particular problem concerned background coming from neutrons, which could imitate the neutral-current signal from the interaction of a neutrino with a proton or neutron. Haidt and Pullia contributed in an essential way to the difficult data analysis that was necessary to make a final assault on the neutron background and reach the conclusion that substantiated the discovery before it was announced (*CERN Courier* October 2004 p21 and September 2009 p25).

Moscow State University awards Rolf Heuer with an honorary degree

The Lomonosov Moscow State University (MSU) traditionally opens its doors to the new generation of students on 1 September, welcoming some 7000 newcomers. This year, CERN's director-general, Rolf Heuer, was invited to join the celebration to be awarded the title of honorary doctor of Moscow University. The rector of MSU, Victor Sadovnichy, handed over the diploma of honorary doctor and the MSU medal at a ceremony attended more than 1000 people.

Heuer receives the honour in recognition of his prominent contribution to the development of fundamental research and education in Europe and for his support for the fruitful scientific relations with MSU that ensured the successful participation of the university's teams in research and educational programmes at DESY and at CERN. In the afternoon he gave the traditional lecture at the Main Auditorium of the MSU Faculty of Physics, talking on "The search of a deeper understanding of our universe at the Large Hadron Collider: the world's largest particle accelerator".

The rector of Moscow State University, Victor Sadovnichy, right, hands the diploma of honorary doctor to Rolf Heuer. (Image credit: MSU.)

Buras elected to Cracow academy

Andrzej Buras. (Image credit: facesbyfrank.)

Andrzej Buras, professor of theoretical elementary particle physics at the Technische Universität München (TUM), has been elected a foreign member of the Polish Academy of Arts and Sciences in Cracow. A leading researcher in applied quantum field theory, he is elected on the basis of his studies of strong-interaction (QCD) effects in deep-inelastic processes, calculations of higher-order QCD effects in weak and rare meson decays and extensive studies of the physics beyond the Standard Model in flavour-changing neutral-current processes.

The academy in Cracow has its roots in the Cracow Learned Society, formed in 1815. In the 1950s, a merger with other institutions formed the Polish Academy of Sciences. It regained its independence in 1989.

LABORATORIES

Brookhaven becomes an APS Historic Site

The American Physical Society (APS) has named the US Department of Energy's Brookhaven National Laboratory (BNL) as an APS Historic Site. The APS president, Barry Barish of Caltech, presented a plaque in recognition of the honour in a ceremony on 23 September.

Since it began honouring sites of historic significance in 2004, the APS has recognized some 20 other individuals and the laboratories where their work was conducted, as well as locations of important physics events. However, this is the first time that an entire national laboratory has received this prestigious recognition.

The official APS Historic Site citation recognizes Brookhaven's broad-based contribution to science: "At this laboratory, over many years, scientists and engineers have made numerous fundamental discoveries in the fields of nuclear and high-energy physics; the physics and chemistry of materials; energy and environment; biology and medicine. Among many landmark experiments are: establishing the spin direction (helicity) of the electron neutrino; the first observation of solar neutrinos; proof of more than one species of neutrino; the first observation of a lack of symmetry between matter and antimatter; and the principle of strong focusing that led to more compact and powerful accelerators."

Barry Barish, right, hands the plaque to BNL's director, Samuel Aronson. (Image credit: BNL.)

● For more about Brookhaven's physics discoveries, see www.bnl.gov/historicsite/timeline.php.

OUTREACH

Call for International Year of Light

The need to promote improved public and political understanding of the central role of light in the modern world has motivated the European Physical Society to co-ordinate a proposal for the proclamation of an International Year of Light in 2015 under the auspices of the United Nations. As well as celebrating the anniversaries of important milestones in the history of science that fall in 2015, the International Year of Light project will include important aspects of education and development, focusing specifically on how the science of light can improve the quality of life in the developing world and in emerging economies.

The project involves many international partners, representing major international scientific societies from all branches of physics. The release of the prospectus will be followed by a formal request for endorsement at the International Union of Pure and Applied Physics General Assembly in November. This is the important first step in the process of approaching the United Nations.

The project prospectus can now be downloaded at www.eps.org.

Faces & Places

WORKSHOP

Quantum mechanics in the 21st century

Quantum mechanics has existed for more than 100 years but some long-standing debates are still alive and waiting for a solution. The field calls for creativity and exceptional skills, in both theory and experiment. Now, new experimental techniques and a new theoretical understanding hold the tantalizing promise of future breakthroughs, as was evident at a recent workshop at the European Centre for Theoretical Physics (ECT*) in Trento.

The international workshop "Speakable in quantum mechanics: atomic, nuclear and subnuclear physics tests", devoted to the hot topics of quantum mechanics, took place on 29 August – 2 September. Some 40 scientists participated, with a well balanced mix of theoreticians and experimentalists. Several young scientists gave interesting talks and contributed to the discussions – an extremely good sign for the future of research in quantum mechanics.

Talking quantum mechanics. Workshop participants at the ECT. (Image credit: J Marton.)*

The workshop opened with a session that addressed possible probes of decoherence in quantum gravity and tests of quantum mechanics with facilities such as the DAΦNE collider at the Frascati National Laboratory, where pairs of neutral kaons are copiously produced in an entangled state. In particular, it is now possible to test the predictions of quantum mechanics in these massive kaon systems, where the effects of quantum gravity might became important and alter the predictions of nonrelativistic quantum mechanics. Bell-type inequalities can also be checked in such systems. Other sophisticated experiments that probe quantum entanglement with photons, neutrons and even complex molecules were also discussed.

The mystery that still shrouds the collapse of the wave function has been addressed in recent years by novel theories, such as the Ghirardi–Rimini–Weber model, which modifies the Schrödinger equation by adding a nonlinear term. No experimental tests have been performed to date and part of the discussion in the workshop was focused on this important topic, with many ideas for possible future experiments.

One session was entirely devoted to experimental tests of the spin-statistics connection, in particular to searches of small violations of the Pauli exclusion principle. Because the principle is tightly embedded in the very essence of modern field theory, it is quite difficult to build conceptual frameworks that allow for a violation, and thus it is difficult both to conceive experiments and to give a consistent interpretation of the experimental results. Nonetheless, experimentalists go boldly forward and test the principle to a high accuracy in atomic and nuclear systems. Experimental results from the VIP, DAMA and Borexino experiments in the Gran Sasso National Laboratory were presented and discussed, together with their theoretical implications and future perspectives.

In a special talk, Angelo Bassi of the University of Trieste presented the EU Cost Action "Fundamental Problems in Quantum Physics", which is dedicated to items that are closely related to those discussed during the workshop (*CERN Courier* June 2011 p32). This encounter may help to create a closer and long-standing collaboration between the scientists present at the meeting, including the possibility of using the Short Term Scientific Missions promoted by this Action.

The workshop was organized by Catalina Curceanu (LNF-INFN, Frascati), Johann Marton (SMI and TU Vienna) and Edoardo Milotti (University and INFN Trieste). Its ultimate success owed much to the session chairs, F de Martini, A di Domenico, B Hiesmayr, H Rauch and N Zanghí, as well as to all of the participants who contributed to the lively discussions.

NEW PRODUCTS

Cobham Technical Services has announced a new release of the Concerto electromagnetic design software for RF and microwave applications from its Vector Fields Software product line. Many enhancements of the Concerto v7.5R1 centre on the powerful 3D geometric Modeller that forms an integral part of all Concerto configurations. This has new meshing options for the finite element Eigenvalue solver, with significantly shorter solution times, and the Modeller now provides access to a range of additional features in Concerto's finite-difference, time-domain simulation engine. For more information, contact Julie Shephard, tel +44 1865 370 151, e-mail vectorfields.info@cobham.com or visit www.cobham.com/technicalservices.

Heason Technology has introduced Delta Tau's Geo Brick LV family of packaged 8-axis motion and machine controllers. The Geo Brick LV and the newly announced 19-inch rack-mount version, the LV-PC, is supplied with eight user-configurable 250 W drives for linear or rotary brushed and brushless servos, ceramic motors or stepper motors in any combination with feedback interfaces that include practically all types commercially available today. For more details, contact Jon Howard, tel +44 1403 755 800, e-mail jhoward@heason.com or see www.heason.com.

Faces & Places

Hiden Analytical Ltd has expanded its HPR series of mass spectrometer-based gas analysers to include analysis of static offline gas samples in addition to the more routine conditions of dynamic flow. New additions include the HPR-70 benchtop system for gas-composition measurement of individual, discreet samples as small as 0.1 sccm; the gas-preparation stage includes selectable cascade volumes for pressure optimization over a wide spread of sample volumes and sample pressures. The HPR-90 system uses similar mass-spectrometer stages together with a customized inlet system specifically configured for analysis of gases trapped within enclosed volumes. For additional information, tel +44 1925 445 225 or e-mail info@hiden.co.uk.

Keithley Instruments Inc has launched five new general-purpose programmable DC power supplies designed to complement the company's existing lines. The Series 2200 combines superior voltage and current output accuracy at a cost-effective price, with flexible operation and features designed to enhance ease of use. It has also introduced a low-cost addition to its popular Series 2400 SourceMeter instrument. The new model 2401 is optimized for high-precision test applications, such as current vs voltage characterization of photovoltaic (solar) cells, high-brightness LEDs, low-voltage materials and semiconductor devices. For more details, tel +1 440 248 0400, e-mail info@keithley.com or visit www.keithley.com.

Meetings

The **2012 John Adams Lecture**, organized by the CERN Accelerator School, will take place at CERN on 18 November. In "LHC – Bold Beginning", Mike Lamont, head of the Operations Group at CERN, will take a look at what has contributed to the collider's current success. He will also discuss existing and future challenges. For further information, see https://indico.cern.ch/conferenceDisplay.py?confId=157547.

The conference on **Primordial QCD Matter in LHC Era: implications of QCD results on the early universe** will take place in Cairo on 4–8 December. Organized by the Egyptian Center for Theoretical Physics at the Modern University for Technology and Information, it will bring together cosmologists and particle physicists to discuss the implications for the two fields of recent LHC results on QCD matter. For further information and registration, see www.mti.edu.eg/mti/page.aspx?pageID=434.

Visits

Ryoji Chubachi, centre, executive member of the Council for Science and Technology Policy, cabinet office, government of Japan and vice-chair, representative corporate executive officer and member of the board of the Sony Corporation, was welcomed to CERN by **Peter Jenni**, former ATLAS spokesperson, left, and **Taka Kondo**, ATLAS collaboration member from KEK, on 31 August. They visited the ATLAS underground experimental area and the ATLAS visitor centre.

On 6 September **José Lino Barañao**, Argentinian minister of science, technology and innovation, left, visited the CERN Control Centre with **Michael Benedikt**, from CERN's Beams Department. During his time at CERN the minister also toured the LHC superconducting magnet test hall, the ATLAS visitor centre and the *Universe of Particles* in the Globe of Science and Innovation.

Fernando Schmidt Ariztía, undersecretary for foreign affairs for Chile, visited CERN on 12 September. His tour of CERN included the ATLAS visitor centre, the LHC superconducting magnet test hall, the CERN Control Centre and the AMS control centre. He also met CERN's director-general, Rolf Heuer.

On 13 September, **Kofi Annan**, president of the Kofi Annan Foundation and former secretary-general of the United Nations, centre, was welcomed to CERN by the director-general, **Rolf Heuer**, right, and **Felicitas Pauss**, CERN's head of international relations. His tour of CERN included the LHC superconducting magnet test hall, the ATLAS visitor centre and the exhibition *Universe of Particles*.

Faces & Places

BSI2011

Balkan Summer Institute 2011 convenes by the blue Danube

The 2011 Balkan Summer Institute for 2011 (BSI2011) – this year's core meeting of the South-eastern European Network in Mathematical and Theoretical Physics (SEENET-MTP) – took place on 19 August – 1 September in Donji Milanovac, in the heart of the Djerdap National Park, with an introductory seminar in Niš, Serbia. A total of 178 participants attended the institute from 28 countries.

BSI2011 was composed of four complementary events: "Trends in Modern Physics" (BSS2011), a seminar for physics teachers; the "Summer School on Cosmology and Particle Physics" (BS2011), for MSc and PhD students; and two workshops entitled "Scientific and Human Legacy of Julius Wess" (JW2011) and "Particle Physics from TeV to Planck Scale" (BW2011). A number of social activities were also organized during the institute.

Participants at the 2011 institute. (Image credit: M Milosevic/SEENET-MTP.)

The main goal of the BSS2011 seminar was to improve the quality of teaching, the promotion of science and new approaches in education. Lectures were followed by computer sessions, a CERN video link, laboratories and hands-on exercises. Sofoklis Sotiriou demonstrated the ideas and experience of the European teachers' programmes "Pathway" and "Discover the Cosmos", which provided the opportunity to interact with working scientists and receive data from sources, such as CERN.

The BS2011 school gathered six renowned experts as lecturers (Fred Adams (Michigan), Ignatios Antoniadis (CERN), Tao Han (Wisconsin), Neil Lambert (CERN), Viatcheslav Mukhanov (Munich) and Goran Senjanović (ICTP)), two tutors (Miha Nemevšek (ICTP) and Alexander Vikman (CERN)) and around 50 students, mostly from Europe. An introduction and a summary were given by Goran Djordjević (Niš).

The JW2011 workshop was dedicated to the scientific and human legacy of Julius Wess. One of the founders of SEENET–MTP in 2003, he contributed much to facilitate research and return physicists and scientists from the former Yugoslavia to international science. His associates, students and admirers met at the lower course of his favourite river Danube to discuss the state of art in the scientific fields to which he had made important contributions, in particular noncommutative physics.

At the by-now traditional workshop BW2011, 25 invited lecturers presented their latest results on dark matter and its role in cosmology, astrophysics, particle physics and related fields. Luis Álvarez-Gaumé opened the workshop with a talk on "minimal inflation", which is based on the general properties of supersymmetry-breaking in supergravity models.

Among the highlights that followed, Dejan Stojković reviewed the "vanishing dimensions" paradigm. It appears that experimental evidence of lower-dimensionality at higher energies may already exist – a statistically significant planar alignment of events with energies higher than a tera-electron-volt has been observed in some cosmic-ray experiments. The LHC should be able to see effects associated with the dimensional crossover. Glenn Starkman gave a talk on large-scale anomalies in the cosmic-microwave background (CMB), which suggest that either something is wrong with the understanding of the large-scale properties of the universe or that the low multipoles of the CMB data are not of cosmic origin.

Sezen Sekmen (CMS) and Takanori Kono (ATLAS) presented the latest results and ongoing experimental and technical constraints of their detectors at the LHC. Both lectures were great opportunities for a number of researchers and advanced students to get a good insight into the current research of both collaborations. In his talk, Goran Senjanović pointed out that neutrino mass is the only established physics beyond the Standard Model and as such provides a great window into new physics. This is especially true if the neutrino is a Majorana particle, which is automatic in the case of the seesaw mechanism.

A round table "Balkan Forum" focused on (inter)regional co-operation through SEENET–MTP in science and education. The network will soon consist of 19 nodes from 10 Balkan countries, with around 250 individual members and numerous partners from Europe and the world. The publication of a number of scientific issues originating from BSI2011 is planned for the beginning of 2012.

The directors of BSI2011 were: E Dudas (Palaiseau), G Dvali (Munich/CERN), D Lüst (Munich), G Senjanović (Trieste), D Stojković (Buffalo) and G Djordjević (Niš). The institute was organized by the Faculty of Science and Mathematics (FSM) and SEENET–MTP office in Niš, in co-operation with ICTP Trieste, LMU and MPI Munich, CPHT Palaiseau, the Faculty of Physics Craiova and the Physical Society Niš as a local co-organizer.

The main support for BSI2011, as a whole or for some of its events, came from ICTP and its partner CEI, DAAD and the Serbian Ministry for Education and Science. Co-sponsors of BSI2011 were UNESCO Venice Office as a permanent supporter of the SEENET–MTP, EPS, ESF, EU and CERN (UNILHC Network and MassTeV grant), the French Embassy in Belgrade, the Perimeter Institute, Project BELISSIMA and FSM Niš.

● For more details, see the SEENET–MTP site at www.seenet-mtp.info and the BSI2011 site at http://bsi2011.seenet-mtp.info.

● *G Djordjević and I Antoniades.*

Recruitment

ELEKTA

Elekta is a human care company pioneering significant innovations and clinical solutions for treating cancer and brain disorders. The company develops sophisticated state of the art tools and treatment planning systems for radiation therapy and radiosurgery, as well as workflow enhancing software systems across the spectrum of cancer care.

We have a number of vacancies for **Physicists** to join our R&D Physics group in Crawley. The Physics group is responsible for providing support to the business and contribute with designs and measurements in the following areas: Physics of Radiotherapy Systems, including beam generation and dosimetry (electron beams, MV and kV photon beams), general Radiation Physics, Monte Carlo simulations and other computational modelling methods, Control Systems for experiments, Microwave components and theory, Waveguide testing and tuning, Optics, Physics of Detectors and Imaging Systems.

Successful applicants will take a leading role in supporting the development of new products and will be involved on a number of projects including both computational and experimental activities. Ideally candidates will have experience of medical accelerator systems and the ability to contribute in several of the areas that the Physics group is responsible for. Projects will often offer interaction with Research Hospitals and other Institutions, therefore exceptional written and spoken communication skills will be required. Our preference is for candidates to be educated to MSc or PhD level or equivalent. The ability to work to tight deadlines and within a successful team is also essential for these roles.

Current vacancies include:

- **Radiotherapy System Physicist**: You will take a leading role in designing, planning, implementing and managing test programmes in order to produce performance data for Elekta Linac systems. You will be involved in a variety of R&D projects. You will ideally have an MSc or a PhD degree in Medical Physics, Radiation Physics or closely related discipline and experience working within the Medical Devices industry or a Radiotherapy Hospital department (although experience as a Radiation Physicist in another area will be considered). Experience with international compliance standards and/or Physics QA programmes will be an advantage.

- **Accelerator Physicist**: You will provide the business with technical support of Elekta RF electron linear accelerators and associated developments, with particular focus on beam generation, transport, control and monitoring. This role will require an understanding of periodic accelerating structures, particle-in cell modelling, electron sources, RF sources and electron beam dynamics. Ideal candidates will have a PhD degree in Physics, Accelerator Physics, Particle Beam Physics or closely related discipline. Candidates will have experience as an accelerator physicist, involved with modelling aspects of accelerating structures as well as beam experiments, either in a research or industrial environment. However applicants with less experience yet exceptional skills will also be considered.

- **Imaging Physicist**: The aim of this position is to provide physics support for the research and development of Elekta systems for Image Guided Radiotherapy. The Imaging Physicist contributes to the design and experimental evaluation of new developments of kV and MV imaging systems, define technical specifications and address issues related to acceptance, quality assurance and regulatory requirements. The role involves both computational and experimental tasks.

To be successful in this role a thorough understanding of the physics of X-ray imaging, X-ray sources and detectors is required. Candidates should have an MSc or preferably a PhD in Physics, Medical Physics, Radiation Physics, Medical Imaging or closely related discipline. Candidates will be expected to have experience as an X-ray Imaging Physicist, either in an industrial, research or clinical environment, having developed significant knowledge in several of the following areas: design and evaluation of planar or tomographic X-ray imaging systems, imaging detector electronics, image reconstruction algorithms, scatter correction methods, modelling of imaging systems, dosimetry of kV and MV photon beams.

To apply for these vacancies please visit our website **www.elekta.com** and apply via the careers section.

INDIANA UNIVERSITY

FACULTY POSITION Accelerator and Beam Physics

The Department of Physics at Indiana University invites applications for a faculty position in accelerator and beam physics for appointment beginning Fall 2012. We are seeking to make this appointment at the tenured full professor level, however outstanding candidates at the assistant or associate professor level will be considered.

Scientists from all areas of accelerator physics are encouraged to apply. We seek an outstanding scientist who is interested in building a vibrant accelerator and beam physics research program that will complement and extend our ongoing efforts in accelerator design, nonlinear beam dynamics, development of beam manipulation and detection techniques, polarization preservation, and the development of novel instrumentation. We are particularly interested in scientists who may collaborate with the condensed matter and subatomic physics groups at the IU Center for the Exploration of Energy and Matter, which houses facilities such as a pulsed neutron source (LENS) and a compact electron storage ring (ALPHA). More information about the group may be found at **http://www.iub.edu/~iubphys/research/ accelerator.shtml**

The successful candidate is also expected to demonstrate a commitment to excellence in teaching at both the undergraduate and graduate levels.

Applicants should submit a curriculum vitae, a statement of research plans, a description of teaching experience and philosophy, and contact information for six references to **physsrch@indiana.edu** or by mail to: **Faculty Search, Department of Physics, 727 E. 3rd St., Bloomington, IN, 47405-7105, USA**.

Applications received by January 1, 2012 will be given full consideration. Further information about the IU Physics Department can be found at **http://physics.indiana.edu**. Indiana University is an Affirmative Action, Equal Opportunity Employer committed to excellence through diversity. The University actively encourages applications of women, minorities, and persons with disabilities.

NATIONAL TAIWAN UNIVERSITY

Leung Center for Cosmology and Particle Astrophysics

Distinguished Junior Fellowship

The Leung Center for Cosmology and Particle Astrophysics (LeCosPA) of National Taiwan University is pleased to announce the availability of several Post-Doctoral or Assistant Fellow positions in theoretical and experimental cosmology and particle astrophysics, depending on the seniority and qualification of the candidate. Candidates with exceeding qualification will be further offered as LeCosPA Distinguished Junior Fellows with competitive salary.

LeCosPA was founded in 2007 with the aspiration of contributing to cosmology and particle astrophysics in Asia and the world. Its theoretical studies include dark energy, dark matter, large-scale structure, cosmic neutrinos, and quantum gravity. The experimental investigations include the balloon-borne ANITA project in Antarctica and the ground-based ARA Observatory at South Pole in search of GZK neutrinos, and a satellite GRB telescope UFFO that will slew in to the burst event within 1sec.

These positions are available on August 1, 2012. Interested applicant should email his/her application with curriculum vitae, research statement, publication list and three letters of recommendation before December 1, 2011 to

Ms. Yen-Ling Lee ntulecospa@ntu.edu.tw

For more information about LeCosPA, please visit its website at http://lecospa.ntu.edu.tw/

Three letters of recommendation should be addressed to

Prof. Pisin Chen, Director
Leung Center for Cosmology and Particle Astrophysics
National Taiwan University

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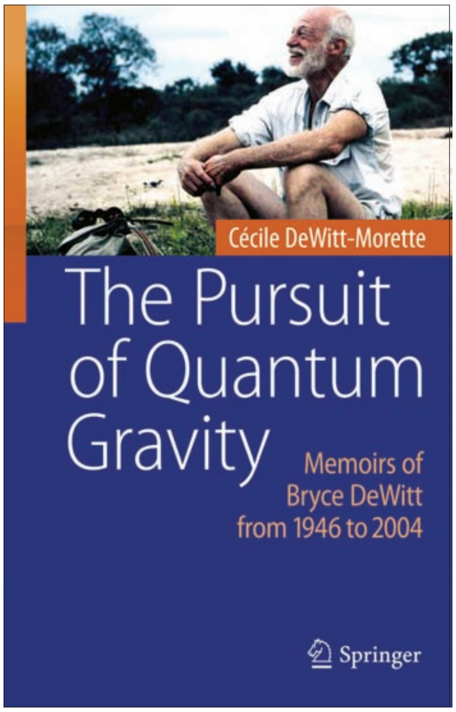
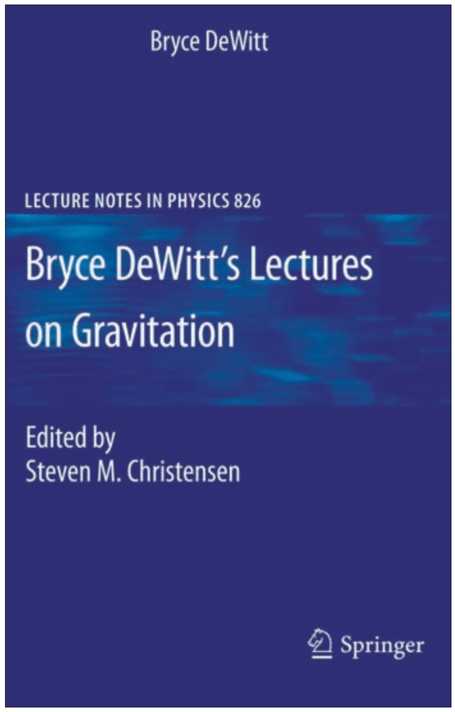




The Pursuit of Quantum Gravity: Memoirs of Bryce DeWitt from 1946 to 2004
By Cécile DeWitt Morette
Springer 2011
Hardback: £31.99 €36.87 $49.95

Bryce DeWitt's Lectures on Gravitation
By Bryce DeWitt (ed. Steven M Christensen)
Springer 2011
Paperback: £62.99 €73.80 $89.95

Bryce DeWitt made many deep contributions to quantum field theory, general relativity and quantum gravity. He generalized Richard Feynman's original approach to quantum gravity at the one-loop level, to a fully fledged, all-order quantization of non-abelian gauge theories, including ghosts. The formalism that he developed also transformed the way that we think about quantum field theory, although it took some time before his ideas percolated the community.

The Pursuit of Quantum Gravity is a charming and remarkable book put together by Cécile Morette, who became his wife and was to share his life for more than 50 years. Here we meet the man and his science. It is a remarkable story of vision, passion, independence and determination that led this scientist along such a difficult road, against all odds.

The material in the book is difficult to find elsewhere and it is not only highly informative but also a pleasure to read. For instance, the way that he organized an expedition to Mauritania to check the deflection of light by the Sun and thus verify the results from the 1919 eclipse by Arthur Eddington *et al*. There are also documents that are not easily accessible elsewhere, such as the essay that won him the first prize of the Gravity Research Foundation in 1953. It is quite remarkable how many aspects of the vision laid out in that paper that he was able to accomplish.

This book makes us aware of how much we owe Bryce DeWitt, and how deep and broad his influence has been. It pays homage to a truly great man – through the words of the person who knew and understood him best.

Back in 1971, he delivered a series of lectures on gravitation at Stanford University, before moving to the University of Texas at Austin. It has taken 40 years for them to be available to the physics community, but finally they are here as *Bryce DeWitt's Lectures on Gravitation*, thanks to the efforts of his former student Steven M Christensen. Anyone who has seen the original realizes how grateful we should be to the editor for the large amount of work required in carrying out this task.

These lectures do not represent a standard introduction to the subject but rather DeWitt's unique way of presenting it. Along with standard topics that include special relativity, continuous groups and Riemannian manifolds, one finds a remarkable treatment of the study of asymptotic fields, the energy–momentum of the gravitational field, and above all the dynamics of the production and propagation of gravitational waves.

Many of the results found here cannot be found in other books or review articles on the subject, despite the number of years that have elapsed since they were presented. Take, for example, the treatment of the angular momentum carried by gravitational waves, where a cursory look at the relevant chapters shows why this book is different. The complexity of the algebra involved requires a combination of tenacity, wizardry and understanding that is difficult to find in any other master of general relativity. DeWitt's head-on, uncompromising approach is unique.

The book also has high historical value, showing how this maverick maven thought of the subject. It is a great tribute to his scientific legacy.

● *Luis Álvarez-Gaumé, CERN.*

Gravitation: Foundations and Frontiers
By T Padmanabhan
Cambridge University Press
Hardback: £50 $85
E-book: $68

The general theory of relativity – the foundation of gravitation and cosmology – may be as widely known today as Newton's laws were before Einstein proposed their geometric interpretation. That was around 100 years ago, yet many unanswered questions and issues are being revisited from the current perspective, such as: why is gravity described by geometry and why is the cosmological constant so extraordinarily fine-tuned in comparison with the scale of elementary particles?

In an active research field – where the universe at large meets the discoveries in particle physics – there is much need for textbooks based on research that address gravity in depth. Thanu Padmanabhan's book fills this need well and in a unique way. Within minutes of opening the rich, heavy, full, yet succinctly written 728 pages I realized that this is a new and personal view on general relativity, which leads beyond many excellent standard textbooks and offers a challenging training ground for students with its original exercises and study topics.

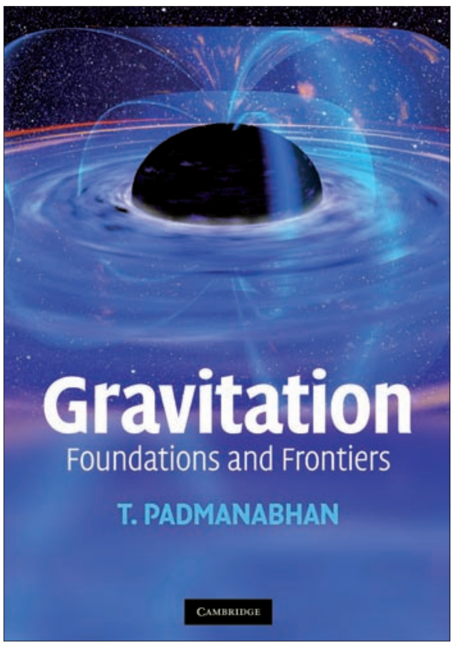
In the first 340 pages, the book presents the fundamentals of relativity in an approachable style. Yet, even in this

Bookshelf

"standard" part the text goes far beyond the conventional framework in preparing the reader in depth for mastering the "frontiers". The titles of the following chapters speak for themselves: "Black Holes", "Gravitational Waves", "Relativistic Cosmology" and "Evolution of Cosmological Perturbations", all of which address key domains in present-day research. Then, on page 591, the book turns to the quantum frontier and extensions of general relativity to extra dimensions, and to efforts to view it as an effective "emergent" theory.

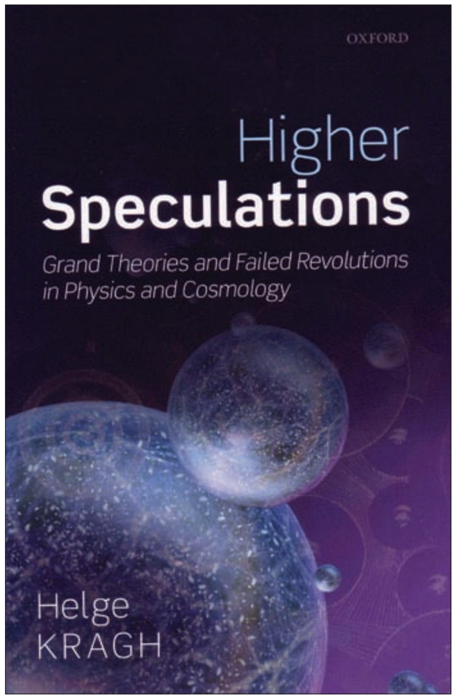
This research-oriented volume is written in a format that is suitable for a primary text in a year-long graduate class on general relativity, although the lecturer is likely to leave a few of the chapters to self-study. "Padmanabhan" complements the somewhat older offerings of this type, such as "The Big Black Book" (*Gravitation* by Charles Misner, Kip Thorne and John Wheeler, W H Freeman 1973) or "Weinberg" (*Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, Wiley 1972).

Naturally, this publication differs greatly from "text and no research" offerings, such as Ta-Pei Cheng's *Relativity, Gravitation and Cosmology: A Basic Introduction* (OUP 2009) or Ray d'Inverno's *Introducing Einstein's Relativity* (OUP 1992). Any lecturer using these should consider adding "Padmanabhan" as an optional text to offer a wider view to students on what is happening in research today. In comparison with "Hartle" (*Gravity: An Introduction to Einstein's General Relativity*, Addison-Wesley 2003), one cannot but admire that "Padmanabhan" does not send the reader to other texts to handle details of computations; what is mentioned is also derived and explained in depth. Of course, "Hartle" is often used in a "first" course on gravity but frankly how often is there a "second" course?



"Padmanabhan" is, as noted earlier, voluminous, making it an excellent value for money because it contains the material of three contemporary books for the price of one. So who should own a copy? Certainly for any good library covering physics, the question is really not if to buy but how many copies. I also highly recommend it to anyone interested in general relativity and related fields because it offers a modern update. Students who have already had a "first" course in the subject and are considering taking up research in this field will find in "Padmanabhan" a self-study text to deepen their understanding. If you are a bookworm like me, you must have it, because it is a great read from start to finish.

● *Johann Rafelski, University of Arizona.*



Higher Speculations: Grand Theories and Failed Revolutions in Physics and Cosmology
By Helge Kragh
Oxford University Press
Hardback: £35 $63

Over the past 60 years, high-energy physics has gone through various stages of development characterized by a varying degree of speculation. The bootstrap programme (based on the S-matrix approach) of the early 1960s was thought to be empirically more motivated than a field-theoretical description of strong interactions. Today, gauge theories are at the heart of strong interactions even if confinement and the transition between partonic and hadronic degrees of freedom are not completely understood. The development of science is full of speculations, conjectures and useful mistakes.

The themes touched on in this book by historian Helge Kragh are certain to be of interest to the current generation of physicists, even if the inspiration of the author is more historical and, to some extent, philosophical. In some parts, the text might have been more terse and synthetic but, overall, the author's reflections are timely.

The first part (consisting of six chapters) starts with the cosmological vision of René Descartes and ends with an interesting account of the bootstrap programme. The second part deals with comparatively modern speculations such as the varying constants of nature (invoked by Paul Dirac, Robert Dicke and others), the cyclic models of the universe, the anthropic principle and the multiverse. Chapter 11 focuses on string theory and quantum gravity while chapter 12 deals with astrobiology.

Even without this book, every particle physicist would subscribe to the suggestion that the criteria for the validity of a physical speculation seem to become experimentally less demanding as time goes by. Some theorists are now studying models having, in the most conservative cases, thousands of parameters and zillions of vacua. To select the right vacuum (i.e. our universe) in this multiple universe, the techniques of statistical mechanics are employed together with the tenets of the so-called anthropic principle. While some practitioners claim that the anthropic principle is simply a new name for what used to be called fine-tuning, the themes that Kragh discusses are often taken seriously and become the subject of heated debates, even in the popular press.

A general and panoramic historical view, such as the one conveyed here by Kragh, might help physicists to understand that the potential threats of modern science are not the conjectures or even the bold theoretical mistakes. There are healthy speculations (which are motivated empirically) and "failed revolutions" i.e. those conjectures that lose the character of falsifiable hypotheses but remain a fashionable way of thinking. While healthy speculations can be ruled out by experiments, failed revolutions have many analogies with religious belief. The historical overview suggests, in this respect, that science has made tremendous progress in the past century not only thanks to the healthy speculations, but also despite the failed revolutions. There are no reasons to doubt that the same will happen in the years to come.

● *Massimo Giovannini, CERN and INFN Milan-Bicocca.*

Books received

Dynamical Symmetry

By Carl E Wulfman

World Scientific

Hardback: £75 $109

E-book: $142

Whenever systems are governed by continuous chains of causes and effects, their behaviour exhibits the consequences of dynamical symmetries – many of them far from obvious. *Dynamical Symmetry* introduces the reader to Sophus Lie's discoveries of the connections between differential equations and continuous groups that underlie this observation. It develops and applies the mathematical relations between dynamics and geometry that result. Much material is new and some has only recently appeared in research journals.

Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry

By V Alan Kostelecký (ed.)

World Scientific

Hardback: £77 $118

E-book: $153

The 5th Meeting on CPT and Lorentz Symmetry focused on tests of these fundamental symmetries and related theoretical issues. Topics included searches for CPT and Lorentz violations, ranging from studies of birefringence and dispersion from cosmological sources, through laboratory and gravimetric tests of gravity to spectroscopy of hydrogen and antihydrogen. Theoretical discussions included physical effects at the level of the Standard Model, general relativity and beyond; the possible origins and mechanisms for Lorentz and CPT violations; and issues in field theory, particle physics, gravity and string theory.

An Introduction to String Theory and D-brane Dynamics with Problems and Solutions (2nd edition)

By Richard J Szabo

Imperial College Press

Hardback: £42 $68

E-book: $88

This book provides both an introduction to the rudiments of perturbative string theory and a detailed introduction to the more current topic of D-brane dynamics. The rapid but coherent introduction to the subject is perhaps what distinguishes this text from others on string theory or D-branes. The presentation is pedagogical, with material based on mini-courses in theoretical high-energy physics delivered by the author at various summer schools. This second edition includes an appendix with solutions to the exercises and expands on some of the technical material.

Heisenberg's Quantum Mechanics

By Mohsen Razavy

World Scientific

Hardback: £74 $120

Paperback: £42 $61

E-book: $156

This detailed account of quantum theory puts the emphasis on the Heisenberg equations of motion and the matrix method. It features a deep treatment of fundamental concepts, such as the rules for constructing quantum-mechanical operators and the classical-quantal correspondence; the exact and approximate methods based on the Heisenberg equations; the determinantal approach to the scattering theory and the LSZ reduction formalism. The uncertainty relations for a number of different observables are derived and discussed. There is also a chapter on the quantization of systems with nonlocalized interaction.

Lectures on Gravitation

By Ashok Das

World Scientific

Hardback: £61 $99

Paperback: £30 $48

E-book: $129

This compilation covers the lectures for a one-semester course on gravitation given at the University of Rochester. Starting from a simple description of geometry, the topics are systematically developed through to the big-bang theory with a simple derivation of the cosmic-background temperature. Several informative examples are worked out in detail.

Polarized Sources, Targets and Polarimetry: Proceedings of the 13th International Workshop

By G Ciullo, M Contalbrigo and P Lenisa (eds.)

World Scientific

Hardback: £82 $126

E-book: $164

Recent experimental results, new ideas and prototypes in the field of nuclear gaseous and solid polarized targets and polarimetry feature in these proceedings from the biennial meeting on the topics of polarized sources, targets and polarimetry. The topics covered include polarized electron sources, polarized proton and deuterium sources, polarized internal targets, polarized ^{3}He ion sources and targets, polarimetry (e, p, d) at low and high energy, polarized antiprotons and polarized solid targets.

Practical Guide to Computer Simulations

By Alexander K Hartmann

World Scientific

Hardback: £67 $108

Paperback: £40 $64

After working through this book, the reader will possess the background knowledge, starting from program design, programming in C, fundamental algorithms and data structures, random numbers and debugging, all of the way to data analysis, presentation and publishing. The reader will be equipped to perform complete projects from the first idea to final publication. All techniques are explained using many examples in C. The C codes and solutions are readily available in the accompanying CD-ROM.

Predicted and Totally Unexpected in the Energy Frontier Opened by the LHC: Proceedings of the International School of Subnuclear Physics

By Antonino Zichichi (ed.)

World Scientific

Hardback: £148 $238

Paperback: $309

These are the proceedings from the International School of Subnuclear Physics held in Erice on 29 August – 7 September 2008. Topics include: "Predicted signals at the LHC from technicolour"; "How supercritical string cosmology affects the LHC"; "Progress on the ultraviolet finiteness of supergravity"; "Quantum gravity from dynamical triangulation"; "Status of superstring and M-theory"; "Strongly-coupled gauge theories"; "'Strongly interacting matter at high energy-density"; "The nature and the mass of neutrinos, Majorana vs Dirac"; and "The anomalous spin-distributions in the nucleon".

Wavefronts and Rays: As Characteristics and Asymptotics

By Andrej Bóna and Michael A Slawinski

World Scientific

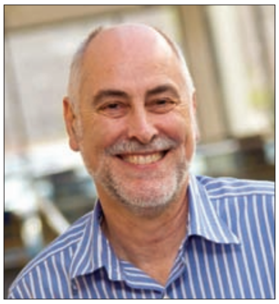
Hardback: £62 $90

The purpose of this text book is to provide a background of physics and underlying mathematics for the concept of rays. The emphasis on and presentation of the theory of characteristics, which defines the rays, accentuate the beauty and versatility of this theory. The mathematical rigour of the formulation is played down to highlight the physical meaning and make the subject accessible to a wider audience.

Viewpoint

Accelerator-driven systems for nuclear energy

Jefferson Lab's **Andrew Hutton** surveys prospects for transmuting waste and generating electricity.



Andrew Hutton. (Image credit: G Adams/ Jefferson Lab.)

Some years after Ernest Rutherford invented nuclear physics, he expressed a wish for "a copious supply of atoms and electrons which have an individual energy far transcending that of the α and β particles" available from natural sources so as to "open up an extraordinarily interesting field of investigation". He was calling for the invention of the particle accelerator, but probably had no idea that by 2011 – the centenary of his famous publication on the nuclear atom – some 30 000 of them would operate worldwide, mostly for applications outside discovery science. And given that he famously dismissed as "moonshine" all talk about someday extracting useful energy from atoms, he surely did not foresee what might conceivably become one of the most important practical applications of accelerators: accelerator-driven systems, or ADS, for transmuting nuclear waste and generating electricity.

How would an accelerator replace a nuclear reactor? Today's reactors include a core in which the composition and configuration of the nuclear fuel are such that there are enough neutrons to maintain a fission chain reaction. An ADS system involves a fuel configuration where the neutrons necessary to establish a sustainable fission chain reaction are produced by spallation of a target by an accelerator. Because the neutrons that maintain the chain reaction are produced by the accelerator – and are thus external to the core of the ADS reactor – an ADS reactor has a lot of flexibility in the elements and isotopes that can be fissioned in its core.

Among the fission products of uranium-235 are the minor actinides (mainly americium and californium), which are radioactive with extremely long half-lives. Their presence in nuclear waste drives the storage requirements for spent fuel: 100 000 years to return the radioactivity to its initial levels. These isotopes could be fissioned (burnt) in a conventional reactor, but given the characteristics of their delayed neutrons there is a maximum concentration of these materials that can be consumed in existing reactors. With ADS, however, the minor actinides can be a much larger fraction of the fuel because an ADS core is subcritical and the fission neutrons are produced by the accelerator externally to the core. Thus, core kinetics and stability do not come into play as much as they would in a conventional reactor. So, ADS can burn up a much greater quantity of the minor actinides than a typical commercial reactor, and can return the radiation to its initial level in "only" 300 years.

Nobel laureate Carlo Rubbia and others have been advocating ADS for two decades – and for good reason. By efficiently burning the minor actinides, ADS could conceivably transform the landscape of the waste-disposal and storage problem. And to paraphrase a US white paper from September 2010, additional advantages are flexibility of fuel composition and potentially enhanced safety. With ADS, nonfissile fuels such as thorium can be used without incorporating uranium or plutonium into fresh fuel. An ADS can be shut down simply by switching off the accelerator. With a large enough margin to criticality, reactivity-induced transients cannot cause a supercritical accident and power control via beam-current control allows fuel burn-up compensation. However, as we have learnt from Fukushima, it remains necessary to address the problem of long-term removal of the residual decay heat left in the fuel once the fission reaction has been shut down.

The overall potential of ADS has been understood for two decades, but technological evolution during that time has improved the outlook for actual implementation. As early as 2002, a European study concluded that "beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible".

It is important to highlight the ADS prospects for power production using thorium-based fuel. Even though thorium has no current market value, it is known to be plentiful. Thorium can absorb a neutron to become ^{233}U, which is fissile. Its potential benefits for nuclear energy are proliferation resistance, minimized production of radiotoxic transuranics, avoidance of the need to incorporate fissile material in the fuel and the potential to operate nearly indefinitely in a closed fuel cycle.

Interest has been growing worldwide. Thorium particularly interests India, Norway and China, all with programmes investigating the ^{233}U-thorium fuel cycle. India, which has little uranium but much thorium, sees ADS as part of its energy future. China is rapidly building reactors, but not having identified a stable geological waste repository is investigating ADS for transmutation of minor actinides. Perhaps most notably, Belgium is planning MYRRHA, an 85 MW ADS prototype to be built at the Belgian Nuclear Research Centre, SCK.CEN. The projected total capital cost is €950 million, with a construction start set for 2015.

Some 200 of us are gathering on 11–14 December in Mumbai for the 2nd International Workshop on Accelerator-Driven Sub-Critical Systems & Thorium Utilization. The first conference was held last year at Virginia Tech, in Blacksburg, Virginia. Considerable effort has been spent to get a world-class International Advisory Committee that includes Rubbia as well as Srikumar Banerjee, chair, Atomic Energy Commission, India, and Hamid Aït Abderrahim, director, MYRRHA. For more about the conference, see www.ivsnet.org/ADS/ADS2011.

● **Further reading**

For the US white paper see http://science.energy.gov/~/media/hep/pdf/files/pdfs/ADS_White_Paper_final.pdf.

For the European report see www.nea.fr/ndd/reports/2002/nea3109.html.

● *Andrew Hutton, associate director, Jefferson Lab.*