Eur. Phys. J. D **44**, 293–300 (2007)
DOI: 10.1140/epjd/e2006-00125-0

THE EUROPEAN PHYSICAL JOURNAL D

Particle accelerator physics and technology for high energy density physics research

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Received 2nd January 2006 / Received in final form 8 April 2006
Published online 13 June 2006 –

Abstract. Interaction phenomena of intense ion- and laser radiation with matter have a large range of application in different fields of science, extending from basic research of plasma properties to applications in energy science, especially in inertial fusion. The heavy ion synchrotron at GSI now routinely delivers intense uranium beams that deposit about 1 kJ/g of specific energy in solid matter, e.g. solid lead. Our simulations show that the new accelerator complex FAIR (Facility for Antiproton and Ion Research) at GSI as well as beams from the CERN large hadron collider (LHC) will vastly extend the accessible parameter range for high energy density states. A natural example of hot dense plasma is provided by our neighbouring star the sun, and allows a deep insight into the physics of fusion, the properties of matter at high energy density, and is moreover an excellent laboratory for astroparticle physics. As such the sun's interior plasma can even be used to probe the existence of novel particles and dark matter candidates. We present an overview on recent results and developments of dense plasma physics addressed with heavy ion and laser beams combined with accelerator- and nuclear physics technology.

PACS. 51.30.+i Thermodynamic properties, equations of state – 52.20.-j Elementary processes in plasmas – 52.25.Fi Transport properties – 52.57.-z Laser inertial confinement

1 Introduction

In the familiar environment we live in, matter occurs predominantly as baryonic matter in the solid, liquid or gaseous phase. This is, however, not common to the situation in the universe at large, where most of the matter is in the form of dark matter [1] or dark energy and we don't know anything about their nature except that the gravitational interaction is observable. Only 4% of the total mass of the universe is made up of baryons that we are familiar with and most of the visible matter exists as plasma.

Very often plasma is called the fourth state of matter, following the idea that as heat is added to a solid, it undergoes a phase transition to a liquid. If more heat is added the phase transition to a gas occurs. The addition of still more energy leads to a regime, where the thermal energy of the atoms or molecules forming the gas is so large, that the electrostatic forces which ordinarily bind the electrons to the atomic nucleus are overcome. The system then consists of a mixture of electrically charged particles like ions and electrons and neutral particles as well. In this situation, the long-range Coulomb force is the factor that determines the statistical properties of the sample. On earth plasmas occur naturally only as a transient phenomenon in lightning or in the aurora. The practical application of man made plasmas is very extensive and ranges from material modification, surface cleaning, and micro fabrication of electronic components to the future prospects of energy production in fusion plasmas.

There are a number of methods to produce plasma, like electrical discharges in a gas or laser irradiation of a sample. Intense heavy ion beams add on to the previously

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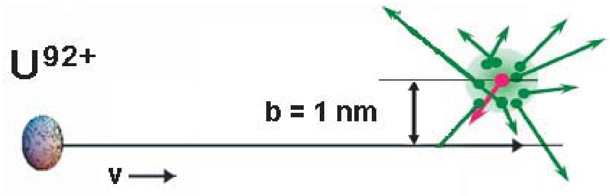

Fig. 1. A highly charged heavy ion incident on a target atom at low impact parameter produces an intense pulse of electromagnetic radiation.

existing methods since they became available from powerful ion accelerators. They contribute a number of interesting features to plasma research because they are of dual use, in the sense that they can produce the plasma by irradiation of the sample and they also provide at the same time excellent diagnostic methods to analyze the plasma properties [2–4] Moreover, they are a unique tool to generate plasma at high density. The quest for a deeper understanding of dense plasma phenomena that govern the properties of matter under extreme temperature and density conditions is the driving motivation for high energy density plasma physics research with intense heavy ion and laser beams at GSI.

2 Energy deposition of heavy ions in matter

Inertial fusion driven by powerful heavy ion beams was the motivating force to investigate heavy ion interaction processes with ionized material. Energy deposition of heavy ions in matter is a nuclear physics topic since decades, and there still are unchartered regimes, that attract the attention of many research groups. Since the interaction is mediated by the well-known Coulomb force, the presence of collective phenomena of beam target coupling still leads to surprising results, for example the unexpectedly high energy loss of ions in dense ionized matter [5–10].

The ion energy deposition is extremely high, since a single atom can well be excited up to and above 20 eV. The electromagnetic pulse experienced by the target atom is extremely short like 10^{-17} s to 10^{-13} s, depending on the energy of the ion. Only ultra-short laser pulses are comparable with this process. The relaxation process then leads to heating of a macroscopic sample of matter and the timescale involved here is 10^{-13}–10^{-11} s and is often associated with particle emission. Moreover ions penetrate deep into the bulk of the target material, and the penetration depth can be fine tuned with the particle energy. This method is so precise and effective that it is even used in medical applications for radiotherapy with high energy beams of carbon ions [11]. Here also the high directionality of the energy deposition process serves as an advantage, as well as the energy deposition characteristic wit a Bragg peak at the end of the particle range. This is not found with any other ionizing radiation.

The phenomena get even more exciting with relativistic heavy ions. If we consider, as shown in Figure 1 an electron as part of a target atom which is passed by a completely ionized uranium ion at an impact parameter of 1 nm, then the interaction time may be as short as 10^{-19} s. If the ion energy corresponds to a relativistic velocity of $\gamma = 5$ (4 GeV/u), then the intensity of the electromagnetic pulse experienced by the target electron is on the order of 10^{21} W/cm^2. This corresponds to the highest intensity of modern high power lasers, and it can still be increased easily at higher ion energies which will be available at high energy heavy ion accelerators. These are dynamic electromagnetic fields of ultra-short duration and extreme intensity.

Another property associated with heavy ion matter interaction, though of minor importance to the topics discussed here, are the static electromagnetic fields of highly charged ions, which are experienced by the few electrons that are present in highly charged ionic systems. The electron in the hydrogen atom moves in an electric field of 10^{10} V/cm at a binding energy of 13 eV. Already at a nuclear charge of 10 the 1s binding energy is of the order of 3×10^{12} V/cm which corresponds to an intense laser field of 10^{22} W/cm^2. In hydrogen-like uranium (U^{91+}) the field is 1.8×10^{16} V/cm and this is way above the limit that is accessible with current laser fields. This is the realm of quantum electrodynamics (QED), where perturbation theory is no longer applicable since the expansion parameter αZ is of the order of unity.

3 Accelerator and laser facilities at GSI-Darmstadt

The GSI-heavy ion accelerator laboratory in Germany operates the most powerful and versatile heavy ion accelerator worldwide and in addition to this there is an approved project to build a new accelerator facility at GSI called FAIR (Facility for Antiproton and Ion Research). This new accelerator (see Fig. 2) will consist of two powerful heavy ion synchrotrons and a number of storage rings and experimental facilities for various research projects [12,13]. The main part of the accelerator assembly will be a 100 Tm heavy ion synchrotron. This will extend the available beam deposition power from the current level of 50 GW/g by more than two orders of magnitude up to 12000 GW/g. Many aspects of high power beam physics associated with inertial confinement fusion driven by intense heavy ion beams can be addressed there, even though this facility will not provide enough beam power to ignite a fusion pellet.

GSI-Darmstadt is also the first accelerator laboratory worldwide where in addition to a powerful and intense heavy ion beam a high-energy laser beam is available for experiments using laser and particle beams simultaneously. The already existing laser facility *nhelix* (**n**anosecond **h**igh **e**nergy **l**aser for **i**on e**x**periments) [14] is currently complemented by a new laser using the acronym *PHELIX* for **P**etawatt **H**igh **E**nergy **L**aser for **I**on E**x**periments [15]. This is a laser system in the kJoule regime with the option to produce ultra-short, high-intensity light pulses with a total power above 1 PW

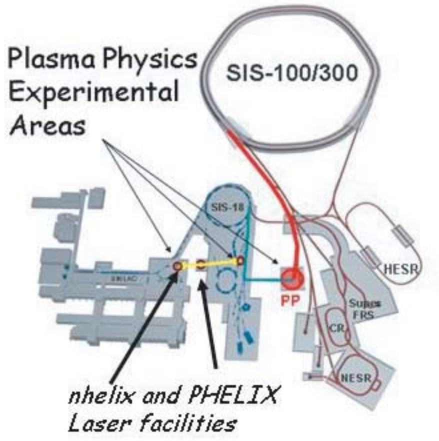

Fig. 2. Schematic layout of the planned FAIR accelerator facility at GSI with the experimental areas for plasma physics. The FAIR project at GSI will greatly improve the options for beam-plasma experiments. The arrows point to the existing experimental areas of plasma physics and the future installation at FAIR. Each experimental area is already, or will in the future be served with heavy ion beams from the accelerator and an intense laser beam.

(10^{15} Watt). It will be able to produce a light pulse pressure exceeding the pressure in the interior of the sun. The full potential of the PHELIX laser will be exploited in high energy density physics experiments with the high intensity heavy ion beams of the future accelerator at GSI. The unique combination of ion and laser beams facilitates novel and pioneering beam-plasma interaction experiments to investigate the structure and the properties of matter under extreme conditions of high energy density, which are similar to those deep inside stellar objects with keV temperatures and more than 100 times solid density. Recent advances in the understanding of absorption mechanisms of high intensity laser radiation [16] will improve the experimental skill to produce high energy heavy ions from laser plasma [17–19] and to achieve intense beams of high energy ions and electrons accelerated in the intense laser field of high power lasers [20–22]. This has initiated a program at GSI to investigate this phenomenon in applications to serve as an ion injector for conventional accelerator systems.

4 Studies of strongly coupled plasmas at the future FAIR facility

Plasmas are often characterized by the ratio $\Gamma = e^2/(4\pi\varepsilon_0 dkT)$ of the Coulomb potential energy ($e^2/4\pi\varepsilon_0 d$, where d is the interparticle distance and ε_0 the dieeletric constant of the vacuum) over the thermal energy (kT, where k is the Boltzmann constant and T the temperature). For ideal plasmas this ratio is very small compared to unity, strongly coupled coulomb systems show a plasma parameter $\Gamma \geq 1$.

Such strongly coupled plasmas are ubiquitous in nature in general, but not in our environment. They are found in stars, brown dwarfs and giant planets. A study of the physical properties of this special kind of ionized matter in the laboratory, under controlled conditions is therefore of great importance to our understanding of the building blocks of the solar system. Another very important problem associated with strongly coupled plasmas is the interaction of charged particles with such systems. There are theoretical predictions that the stopping power of strongly coupled plasmas is lower than that of ideal plasmas [23,24]. If this turns out to be true, it will have very important implications for the design of inertial confinement targets, since in the compression phase the fuel material has to go through the parameter regime of warm dense matter and strongly coupled coulomb systems. Due to the specific nature of energy deposition, intense heavy ion beams are a very unique tool to create states of High-Energy-Density (HED) in matter including strongly coupled plasmas [25–27].

In laser matter interaction experiments it is the intensity I measured in W/cm^2 and the total power which are the relevant experimental parameters. Due to the nature of ion matter interaction, where ions penetrate deep into the target volume, the important parameter is the energy E_s, deposited per gram of matter [J/g] and the deposition power P_s measured in W/g. Hence the physics of beam induced high energy density matter is governed by three equations:

$$E_s = \left(1.6 \times 10^{-19}\right) \frac{(dE/dx)N}{\pi r^2} \quad [\mathrm{J/g}] \tag{1}$$

where dE/dx is the stopping power of the material, N is the number of beam ions delivered by the accelerator πr^2 is the focal spot area. In order to achieve high deposition energy the accelerator has to provide the maximum beam intensity and the experiment has to care for an effective focusing. The stopping power is given by nature. The time t_H to deliver this energy is limited, due to the hydrodynamic response of the beam heated material, and is approximately given by:

$$t_H \propto \left(\frac{L^2}{P_s}\right)^{1/3}, \tag{2}$$

where, L is the target dimension. For a cylindrical target this is the target radius and t_H is essentially given by the time a rarefaction wave needs to travel over the distance L.

Combining these two equations yields the total deposition power P_s:

$$P_s = E_s/t_H. \tag{3}$$

Thus it is obvious, that high energy density induced by heavy ion beams requires that an intense, bunch of short time duration is focused into a sample with a small focal spot size.

The experimental situation is sketched in Figure 3, where the intense ion beam passes through a cylindrical target. Since the range of the ion beam is large compared to the target length, this configuration is called a sub-range target. Moreover the energy deposition characteristic is not changing much over the whole target length.

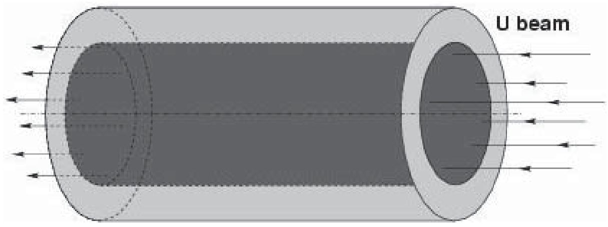

Fig. 3. Beam-target geometry, for the cylindrical target with a length much smaller than the ion beam range.

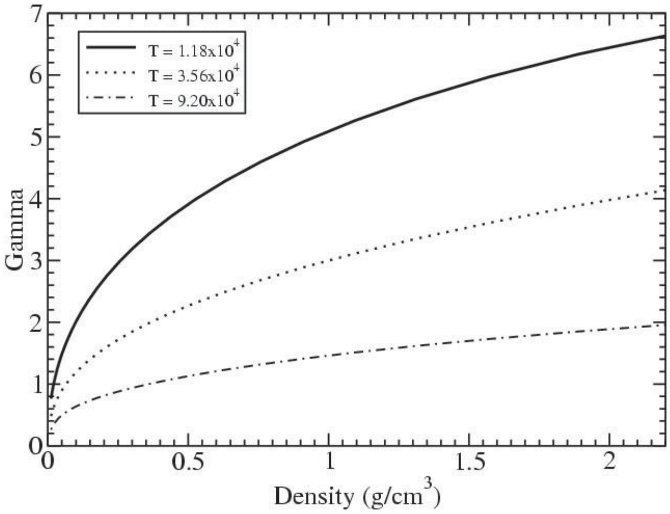

Fig. 4. Plasma coupling parameter $\Gamma = e^2/4\pi\varepsilon_0 dkT$ vs. density at different.

Due to the high energy of the beam the stopping power variation from one end of the target to the other can be kept to a few percent, guaranteeing a uniformly heated sample with small gradients. This is in extreme contrast to the energy deposition by photons, where the absorption is always exponential, causing large differences in energy deposition between the front- and backside of the target already in very thin target layers.

A temperature of a few eV is generated in the deposition region that leads to a high pressure. The high pressure launches a shock wave in the transverse direction that drives material outwards, thereby creating a sub solid density region that is converted to a high density, low temperature plasma. Employing a two-dimensional hydrodynamic computer code, BIG-2 [28], we have carried out numerical simulations of hydrodynamic and thermodynamic response of solid lead targets that are irradiated with an ion beam that will be available from the planned accelerator facility FAIR. Our calculations show that one would be able to generate strongly coupled plasmas with a coupling parameter, Γ of up to 6. Further details can be found in reference [29].

In Figure 4 we present the calculated Γ values for lead as a function of density at different temperatures. These calculations have been done using the code SAHA-IV which is especially designed for calculations of thermodynamic properties of multicomponent plasma with strong interparticle interactions. The physics ingredients for the simulation are based on a chemical picture of the plasma [30,31]. Coulomb interaction of charged particles, short range repulsion of atoms and ions at close distances, degeneracy of free electrons, and up to 20 states of ionization were taken into account. Further details can be found in reference [32].

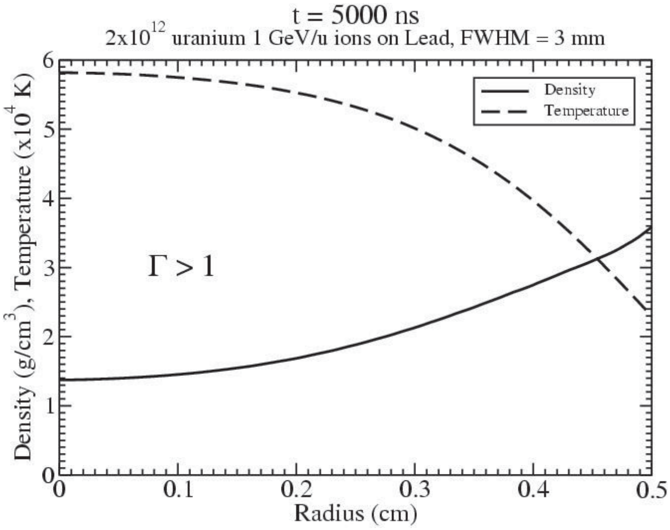

Fig. 5. Density and temperature vs. radius at the middle of the cylinder.

Next we consider again a lead target and the results are presented in Figure 5. The density and temperature are shown as a function of the radial distance from cylinder center at $t = 5000$ ns, using a beam intensity of 2×10^{12} ions with a beam focus of FWHM = 3 mm. It is interesting to note that the temperature achieved in low-Z materials using the same beam parameters is much lower than that in the high-Z materials.

5 LAPLAS: laboratory planetary science with intense heavy ion beams

Properties of matter under conditions of high density and pressure are often summarized by an equation that relates the pressure or energy density to the matter density of the sample. Such an equation is called the *equation of state* (EOS) of the material. The determination of the proper equation of state is a topic of intense research effort experimentally as well as theoretically with ion and laser beams. Especially interesting is the occurrence of phase transitions in cold compressed material, e.g. the insulator to metal transition of diamond at 10 Mbar, the insulator to metal transition of solid hydrogen above 5 Mbar, or the plasma phase transitions at temperatures of about 1 eV [33]. Moreover, the interior structure of giant planets, like Jupiter, Saturn, Uranus and Neptune provide conditions that are very similar. Therefore laboratory investigation of matter under the conditions of high pressure and high energy density will provide insight into this very interesting subject. The first two planets are believed to

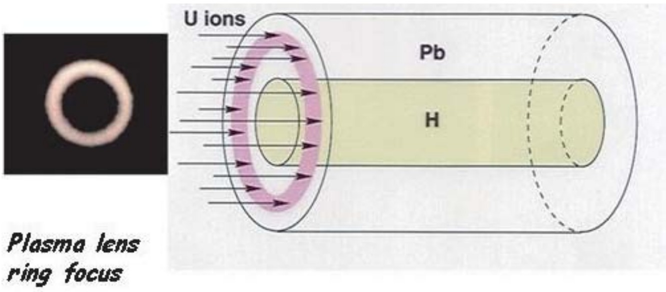

Fig. 6. Beam-target configuration for LAPLAS (Laboratory Planetary Science) [38] experiments. An annular beam focus, achieved by plasma lens focusing is used to compress a hydrogen sample.

be made mainly of hydrogen that exists under extreme conditions, while the latter two are expected to contain large quantities of water (ice) in very exotic states. Development of high power lasers has made possible laboratory astrophysics. Recent advancements and planned future developments in the technology of intense bunched beams of heavy ions have lead to the idea of laboratory planetary sciences using these beams. The proposed beam-target geometry is shown in Figure 5. The target consists of a solid cylinder of hydrogen that is enclosed in a thick shell of a heavy material like lead or gold. One face of the target is irradiated by the beam so that the beam axis coincides with the target axis. The range of the particles is again much larger than the target length to provide uniform energy deposition along the particle trajectory.

As most of the previous experiments to study high energy density matter were based on shock wave techniques starting from ambient pressure and solid density, these phase transitions were not accessible because in a single planar shock only fourfold compression is possible. Higher compression ratios require multiple shocks or even isentropic compression. Heavy ion heated systems with their intrinsic large time and length scales offer a promising alternative to explore these phase transitions in precision experiments [34]. To illustrate this capability two-dimensional numerical simulations have been carried out with respect to the parameters for hydrogen metalization. The experimental scenario makes use of the inherent cylindrical beam geometry where the compression is achieved by imploding multi-layered cylindrical targets. In the simulation the target is irradiated with an intense uranium beam at an energy of 1 GeV/u with a total number of 5×10^{11} particles. Our simulations show that hydrogen metalization is well within reach for the new accelerator facility [35]. This however is only possible if the heavy on beam can be focused well enough and the total intensity is matched to the hydrodynamic response time of the target [35–37].

A more complicated scenario with higher compression yields can be achieved with special beam focus geometry, e.g. a hollow cylindrical beam focus at the target position, as sketched in Figure 6. This is a very challenging problem for the beam transport [39] and focusing system. However, a ring focus was demonstrated experimentally, which was achieved by carefully tuning nonlinear field gradients of the plasma lens [40]. Thus hollow cylindrical implosions become possible, and the simulations show that in such case the initial pressure, which is generated by the direct heating of target material, can be enhanced by more than a factor of 10. Alternative schemes to achieve a hollow beam are based on high frequency rotation of a beam spot on target. A careful analysis of the rotation frequency as a function of beam bunch length is has shown that it is possible to overcome initially imprinted beam irradiation inhomogeneities [41].

6 Potential of the CERN large hadron collider to study high energy density states in matter

It is obvious that the motivation to build the Large Hadron Collider (LHC) at CERN was not derived from plasma physics issues but rather from fundamental problems in particle physics. The LHC is being installed in a tunnel with a circumference of 26.8 km that was previously used for the Large Electron Positron Collider (LEP). Two counter rotating proton beams will be made to circulate in separate beam pipes and will be accelerated to particle energies of 7 TeV. Each beam will consist of a bunch train with every bunch consisting of 1.15×10^{11} protons. The total number of bunches will be 2808, so that the total number of protons in each beam will be 3×10^{14}. The bunch length will be 0.5 ns and two neighbouring bunches will be separated by 25 ns while the radial power profile in the beam spot will be Gaussian with a standard deviation of 0.2 mm. The total duration of the beam is of the order of 89 μs. The energy content of the beam is high enough to melt approximately 500 kg of copper. This initiated the idea the LHC could be used to induce high-energy-density (HED) states in bulk matter, including expanded as well as compressed hot liquid states, the two-phase liquid-gas region, critical point region and strongly coupled plasma states. To this we carried out numerical simulations of thermodynamic and hydrodynamic response of a solid copper target that is irradiated with one of the LHC beams. The simulations used the two-dimensional computer code BIG-2 [28] which is based on a Godunov type numerical scheme. A multiphase semi empirical EOS model [42] is used to treat different phases of the target material. Our simulations show that the first bunch deposits about 2.5 kJ/g specific energy in the target. The specific energy deposition increases as the subsequent bunches deliver their energy to the target. In addition to coulomb collisions, the 7 TeV protons, will generate particle cascades in all directions and one needs to calculate the energy deposited by all these different particles in the target. For this purpose we used the well-known particle interaction and transport Monte Carlo code, FLUKA2 [43]. This code is capable to calculate all components of particle cascades in matter ranging from TeV energies down to those of the thermal neutrons. The energy deposition profile calculated by the FLUKA code is used as input

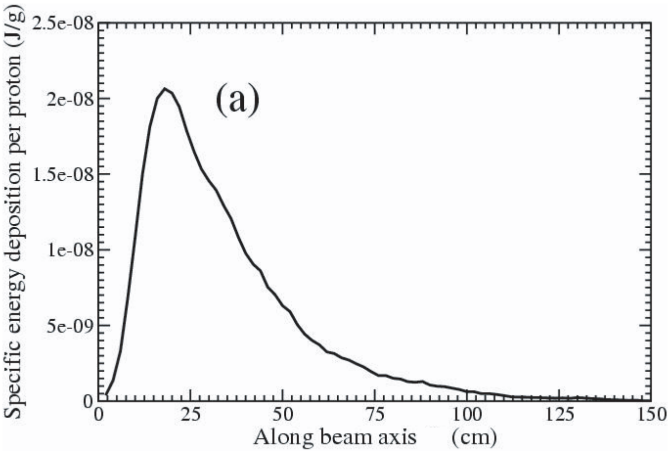

Fig. 7. Specific energy deposited by one bunch along the target axis.

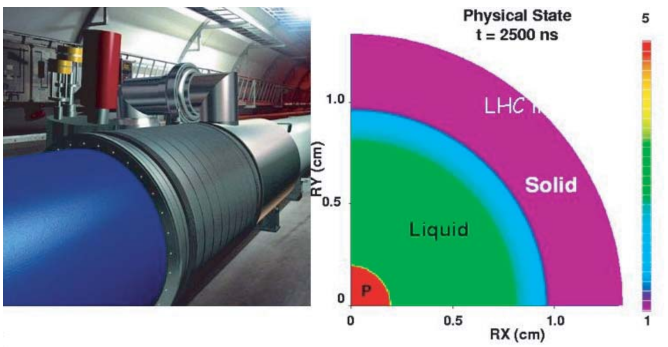

Fig. 8. (Color online) The left insert shows an LHC magnet. The right insert shows the material state at $t = 2.5$ μs.

to the BIG-2 code. The target geometry for the FLUKA simulations is considered to be a cylinder of solid copper that is 5 m long and has 1 m radius. The energy deposition profile along the target axis per bunch (after 1 ns) is shown in Figure 7.

The longitudinal peak of energy deposition occurs at about 15 cm and the deposited energy is a factor 1250 lower than the peak value at about 1.5 m. For the BIG-2 calculations we consider a cylinder made of solid copper with a radius of 5 cm and the beam is incident along the axis. Due to the three dimensional nature of the energy deposition calculated by the FLUKA code, and the limitation that the BIG-2 code is two-dimensional, we simulate target heating and expansion in the transverse plane at different longitudinal positions, L. Here we only report results corresponding to $L = 16$ cm where the maximum of the energy deposition occurs.

Calculations of the plasma coupling parameter Γ have been performed using the code SAHA-IV [31]. At the central part of the target (see Fig. 8), strongly coupled plasma with a plasma parameter of the order of 2–5 is created. An LHC beam will therefore be a very efficient tool to create states of an expanded hot liquid and strongly coupled plasmas with life times of the order of ten μs, as shown in Figure 8 for 2500 ns. We note that at $t = 10$ μs, only about 400 out of 2808 LHC bunches have been delivered. However, by this time the target density becomes extremely low, the rest of the bunches will encounter little mass and will therefore pass through this region of the target without any significant interaction and will penetrate deeper into the target. The time for investigation may therefore be limited to 10 μs, which is sufficiently long to carry out experimental investigation. Diagnostics of such samples of HED matter will be a very challenging problem. A complete set of diagnostic tools will be needed to measure density, temperature and pressure of the sample to fully determine the EOS. The simulations show a temperature of the order of 10 eV that corresponds to a maximum of the Planck radiation of a wavelength of about 30 nm that will make pyrometry in the VUV region a possibility to measure the temperature. Piezoelectric polymer stress gauges (PVDF) immersed in the target can be used to measure the pressure. The density can be measured using X-ray backlighting and shadowgraphy technique as well as proton radiography. Further details about this work can be found in [44,45].

7 Probing the hot dense interior plasma of the sun using a decommissioned CERN-LHC-magnet

In this section we describe a recent experiment that was initiated for a number of reasons. Plasma physicists are interested to study the properties of the sun's interior plasma, nuclear physicists like to find out why in contrast to the weak force, strong interactions do not violate CP-symmetry, and but not least astro-particle physicists are driven by the quest for the nature of dark matter. The Cern Axion Solar Telescope (CAST) experiment provided the opportunity to combine these three efforts. The central plasma of the sun provides an example of a gravitationally (inertially) confined fusion plasma and allows a deep insight into the physics of fusion. This hot, dense plasma is also an excellent laboratory for astroparticle physics. As such the sun can be used to probe the existence of novel particles and dark matter candidates like the axion. The yet undiscovered axion is a direct consequence of the theoretical solution of the CP problem in strong interaction to explain why in contrast to the weak interaction it does not, to our current experimental evidence, violate the CP-symmetry (Charge-Parity), and was proposed by Peccei and Quinn [46].

Inside the core of the sun axions could be produced by conversion of thermal photons interacting with the electromagnetic field of charged particles of the solar plasma (Primakoff effect). With the CAST experiment at CERN, we aim to detect such solar axions on earth by converting them back to X-ray photons inside a strong transversal magnetic field (see Fig. 9). The conversion probability of axions to photons is proportional to the square of the strength of the magnetic field and its length. Thus, a strong magnetic field is essential to achieve a high sensitivity of the experiment.

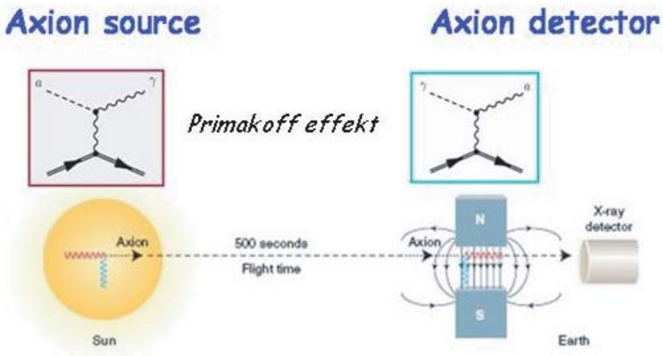

Fig. 9. (Color online) Solar axions are predicted to be created in the hot dense plasma of the solar interior via interaction of a real photon and a virtual photon of the electric field of an atomic nucleus. In a magnetic field the axion is converted back into a photon and may be detected with the proper X-ray detector.

The heart of the CAST experiment is accelerator equipment, a prototype of CERN's Large Hadron Collider (LHC) superconducting magnet providing a dipole magnetic field of approximately 9 T in the interior of two parallel pipes over a distance of 9.26 m. On both ends of the magnet X-ray detectors are looking for a potential axion signal as an excess signal over detector background. A TPC detector covers two magnet bores on one end looking for axions during sunset. On the opposite side of the magnet, a micro mesh gas detector and an X-ray telescope with a pn-CCD detector are looking for axions at sunrise. The magnet can be pointed towards the sun for about 1.5 h during sunrise and sunset, resulting in 3 h observation time per day. The remaining time is used for systematic background studies. The most sensitive detector system of CAST is the Wolter I type X-ray telescope which enhances the signal-to-background ratio significantly by concentrating the potential signal flux on a small spot on the pn-CCD detector. During the last two years CAST was taking data for about twelve months, six months during 2003 and during 2004. The analysis of the 2003 data reveals no significant excess signal over background and allows us to set a new upper limit on the axion to photon coupling of $g_{a\gamma}(95\%) < 1.16 \times 10^{-10}$ GeV^{-1} [47].

Figure 10 shows the corresponding combined upper limit of all three detector systems derived from the analysis of the 2003 data. The analysis of the 2004 data is still in progress and will further improve the upper limit, such that we can surpass the best astrophysical limits in the CAST axion sensitive mass range ($m_a < 0.02$ eV, see Fig. 10). Due to coherence effects, the CAST helioscope in its current configuration is sensitive for axions with masses $m_a < 0.02$ eV.

To extend the sensitivity to the higher mass regime up to $m_a < 1.2$ eV the refractive index of the conversion volume has to be changed. Then, the photon acquires an effective mass ($m = m_a$) and the momentum exchange during the Primakoff effect becomes negligible. This is foreseen for the second phase of CAST which started to be prepared in 2005, in order to be ready to fill the magnet pipes with an adequate buffer gas. If successful this experiment will provide a new method to measure the plasma parameters of the sun's interior plasma, since the back-conversion to photons in the CAST experiment will yield the original photon which has been transported by the axion.

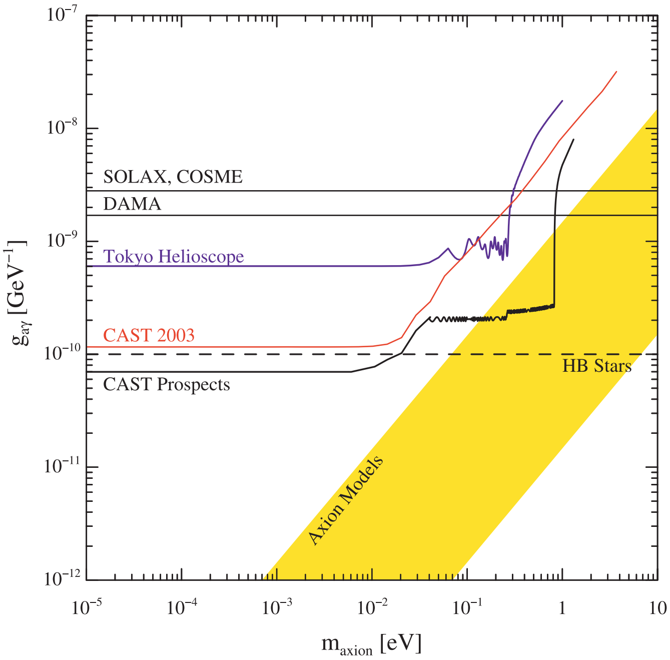

Fig. 10. (Color online) Upper limit (95%) of the axion to photon coupling depending on the axion mass m_a derived from the data of 2003. The shaded area represents the parameter range of theoretical axion models. The results of earlier experiments SOLAX, COSME, DAMA, and the Tokyo helioscope are shown for comparison. The best astrophysical limit based on evolutionary models of horizontal branch stars in globular clusters is indicated.

8 Conclusion

Investigation of interaction processes of heavy ion beams with ionized matter had originally been motivated by inertial fusion physics, where intense heavy ion beams were proposed to ignite a fusion target [48]. Inertial Fusion Energy today is an area of active basic research while some aspects of the fusion scenario are already technically feasible. Currently the two big laser facilities under construction in the US and in France are the main projects towards inertial fusion. Accelerator laboratories like CERN in general, and heavy ion laboratories such as GSI-Darmstadt are continuously increasing the beam power for experiments. Failure of beam transport components in this case may cause already serious problems since the energy contained in a beam pulse is sufficient to melt an appreciable amount of material and even transform it into high energy density matter. With a high power laser beam from the PHELIX laser and the intense heavy ion beam key issues of high energy density physics can be addressed to study the properties of matter under extreme conditions of temperature and pressure. The detailed knowledge about interaction phenomena of intense fields with matter will certainly also influence the development towards inertial fusion [49]. Moreover, the combination of plasma physics-nuclear physics- and astroparticle physics using accelerator equipment and technology opened the gate to search for new particles and helped to address the dark matter problem.

The authors like to acknowledge the support of various funding agencies: DFG, INTAS; WTZ, and the ILIAS (Integrated Large Infrastructures for Astroparticle Science) project funded by the EU under contract EU-RII3-CT-2004-506222. The authors also want to acknowledge the contribution from the CAST collaboration, the PHELIX laser team at GSI and all members of the Plasma Physics Department at GSI

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