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MEGAPIE, a 1 MW pilot experiment for a liquid metal spallation target[☆]

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Abstract

Megawatt pilot target experiment (MEGAPIE) is an initiative launched by Commisariat à l'Energie Atomique, Cadarache (France) and Forschungszentrum Karlsruhe (Germany) together with Paul Scherrer Institut (Switzerland), to demonstrate, in an international collaboration, the feasibility of a liquid lead bismuth target for spallation facilities at a beam power level of 1 MW. Such a target is under consideration for various concepts of accelerator driven systems (ADS) to be used in transmutation of nuclear waste and other applications world wide. It also has the potential of increasing significantly the thermal neutron flux available at the spallation neutron source SINQ for neutron scattering. SINQ's beam power being close to 1 MW already, this facility offers a unique opportunity to realize such an experiment with a reasonably small number of new ancillary systems. The paper describes the basic features of the experiment and its boundary conditions, the technical concept of the target and underlying research carried out at participating laboratories. © 2001 Elsevier Science B.V. All rights reserved.

1. Background and goals

Megawatt pilot experiment (MEGAPIE) is a joint initiative by six European research institutions and JAERI, Japan, to design, build, operate and explore a liquid lead–bismuth spallation target for 1 MW of beam power, taking advantage of the existing spallation neutron facility SINQ at PSI, Switzerland.

A liquid metal spallation target based on the lead–bismuth eutectic mixture with a melting point as low as 125°C and a boiling point as high as 1670°C is the preferred concept in several studies aiming at utilising accelerators to drive subcritical assemblies (ADS). The main goal in these efforts is to transmute long lived radioactive species into shorter lived isotopes in an effort to ease problems of long term storage and final disposal of nuclear waste [1–3]. However, to date, such a target has never been operated. This lends a speculative element to all of these designs, which must be eliminated if serious consideration is given to the implementation of a demonstration facility. Apart from ongoing research into several of the underlying issues, a full demonstration of a working system is highly desirable. For obvious reasons such a feasibility demonstration should be carried out on an existing accelerator with suitable design features.

More specifically, the current orientation in France is a step by step approach towards a possible ADS demonstration experiment, as visualised in Fig. 1. In this context the test of a 1 MW liquid metal target is a crucial milestone, even if the final choice of the type of target (solid vs liquid) has yet to be made. The MEGAPIE experiment will be an important ingredient in defining and initiating the next step, a dedicated ADS-quality accelerator plus irradiation oriented target plus (at a later substage) a low power, subcritical blanket.

Operation of a liquid metal target in an intense proton beam is essentially a materials issue. Not only are

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[☆] Present partners of the MEGAPIE collaboration are: CEA (France), CNRS/SUBATECH (France), ENEA (Italy), FZK (Germany), PSI (Switzerland), SCK*CEN (Belgium) with other institutions having expressed interest to join.

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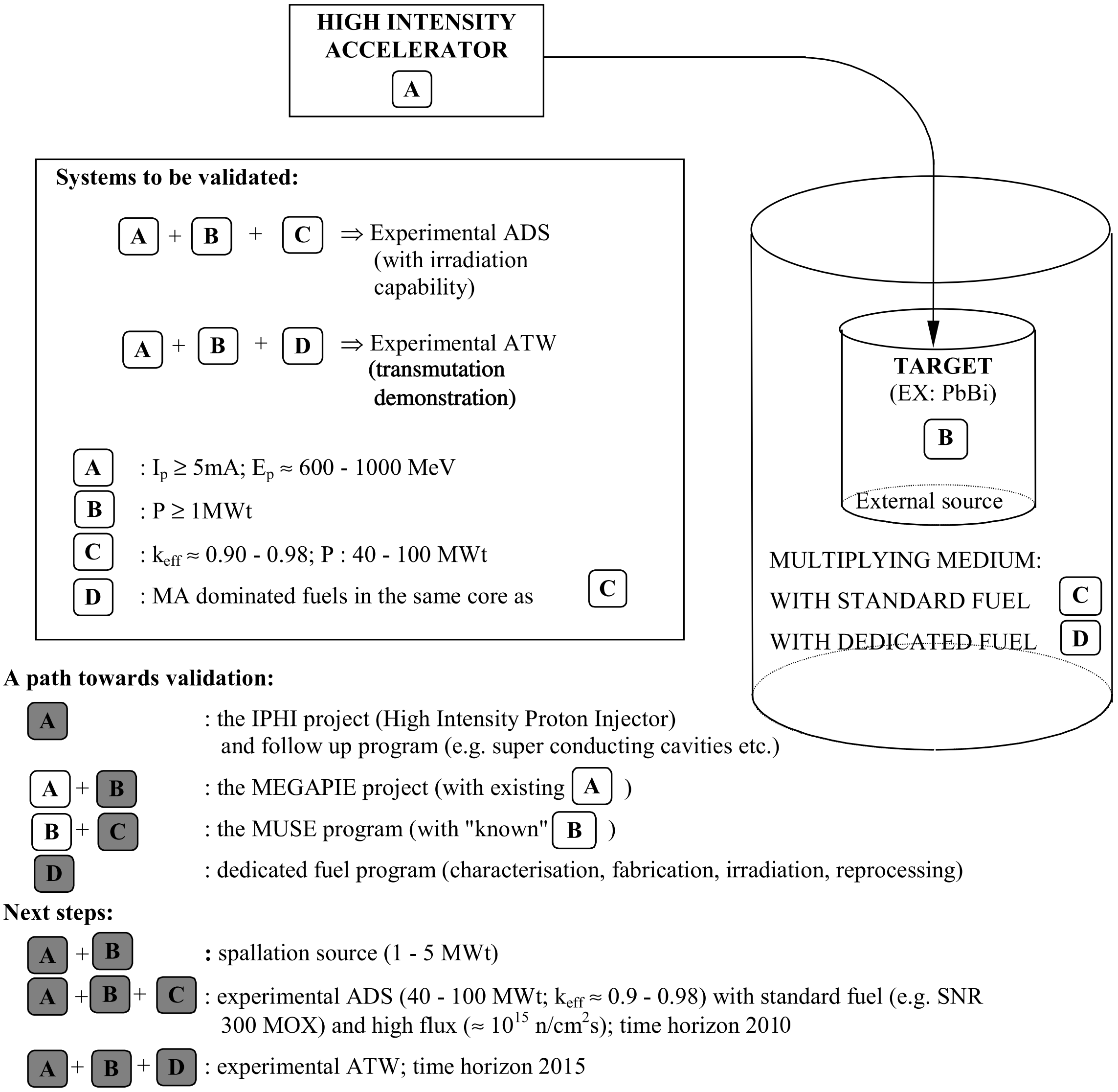


Fig. 1. A step by step approach towards the validation and demonstration of the ADS concept. Several key elements the program relies on are under way, such as the development of $a > 5$ MW high power proton accelerator with super conducting cavities for the European Spallation Source, ESS, and an experiment to couple a subcritical core to an external neutron source in a critical facility (MUSE at Cadarache). There is also an independent program to develop reactor fuel that can be based on minor actinides (MA). MEGAPIE will help to fill an important gap in the early validation program.

radiation effects in the structural materials, especially in the target window, still a largely unexplored issue, given the particular conditions they are exposed to, but also other, related questions are of similar importance. These include liquid metal corrosion and possible ways for its mitigation, liquid metal embrittlement and the possible effect of radiation on it, hydrogen retention in the matrix in case of simultaneous helium production and others.

It is the goal of this experiment to explore the conditions under which such a target system can be licensed, to accrue relevant materials data for a design data base for liquid lead–bismuth targets and to gain experience in operating such a system under the conditions of present day accelerator performance. Furthermore, design validation by extensive monitoring of its operational behaviour and post irradiation examination of its components are integral parts of the project. An extensive pre-irradiation materials R&D program will be carried out in order to maximise the safety of the target and to optimise its layout.

The only accelerator in Europe which has a sufficiently high proton beam power to make the installation of such a target a meaningful experiment is the ring cyclotron at PSI with 590 MeV proton energy and a continuous current of 1.8 mA, being in the process of an upgrade to 2 mA. It is used for a large range of scientific research tools, the most prominent one being a spallation neutron source (SINQ) with its large number of different user facilities. Furthermore, the very existence of this spallation source with its heavy shielding and complete suite of ancillary systems makes this experiment much more easily affordable.

2. Opportunities and boundary conditions at PSI

2.1. Accelerator facilities and proton beam line

A large complex of research facilities at the Paul Scherrer Institut is based on a cascade of three accelerators that deliver a proton beam of 590 MeV in energy at a current up to 1.8 mA. A schematic floor plan of these facilities is shown in Fig. 2. The proton beam is pre-accelerated in a Cockroft–Walton column to an energy of 800 keV and is brought up to an energy of 72 MeV in the 4-sector injector cyclotron. This has replaced the original Philips injector cyclotron (Inj. 1) also shown in the figure, which is currently operating for different applications and is intended to be utilised also in the underlying research efforts for MEGAPIE, as discussed below (LiSoR experiment). Final acceleration to 590 MeV occurs in the 8-sector main ring cyclotron, from which the beam is transported through the experimental hall in a shielded tunnel.

A small fraction of the beam (20 μA) is split off early on to serve a proton irradiation and cancer therapy test facility. (PSI is in the process of providing a separate accelerator for the cancer therapy facility in the near future, thus removing some operational restrictions on the main accelerator system that result from this additional use.) The main beam passes through two pion production targets (M and E), whereby its energy is reduced to 575 MeV. After passing through target E the beam can either be dumped in a beam stopper or can be recaptured and bent downwards for onward transport to the spallation neutron source SINQ. Target E, which is a 4 cm long graphite target, causes some scattering of the beam. After this target 2/3 of the beam current (1.2 mA) can be recaptured and transported to the SINQ target. The beam power presently available for SINQ thus is roughly 0.7 MW but is expected to increase to 1 MW by 2004, the period for which the operation of the MEGAPIE target is planned. This is due to ongoing efforts to increase the beam current in the accelerator.

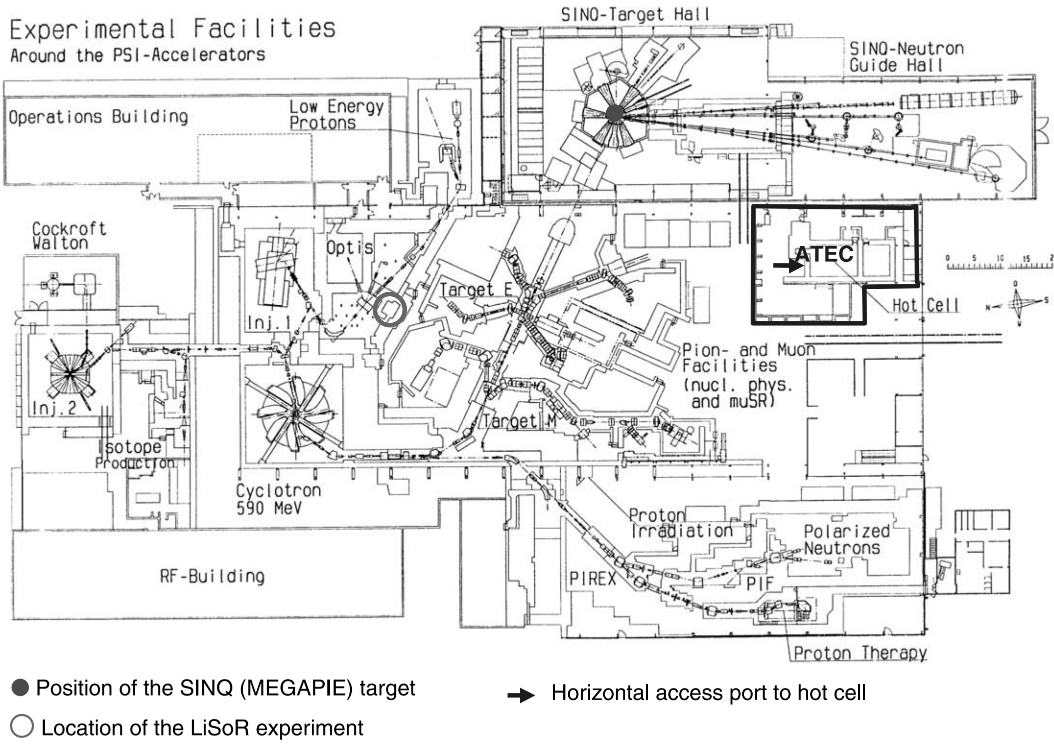


Fig. 2. Schematic floor plan of the PSI accelerator complex and associated research facilities.

2.2. The spallation neutron source SINQ and its ancillary equipment

SINQ is designed as a neutron source mainly for research with extracted beams of thermal and cold neutrons, but hosts also facilities for isotope production and neutron activation analysis. Except for its different process of releasing the neutrons from matter, it resembles closely a medium flux research reactor for most of its users, since the neutron beams are extracted from a 2 m diameter heavy water moderator surrounding the target, as shown in Fig. 3. Beam injection into SINQ is from underneath and the target is inserted from the top and is suspended from the upper edge of the target shielding block.

Although the beam interaction region in the target is only about 30 cm long, the target unit is a 4 m long structure with 20 cm diameter in its lower 2 m, which widens to 40 cm in the upper half. These dimensions must also be adhered to with the MEGAPIE target. The present target is an array of solid rods cooled in cross flow by heavy water. It is shown in Fig. 4. Since it is essential to minimise neutron absorption in the region of the moderator tank in order to obtain a high neutron flux, the part of the target unit extending into the moderator tank is filled with heavy water, except for the rod bundle, which is about 40 cm long and is located in the centre of the moderator tank. In the first two SINQ targets the rods were from solid Zircaloy. Materials testing samples were embedded in the second target in the frame of an international collaboration (STIP, see below) to examine the effect of the realistic SINQ operating conditions on a variety of different candidate structural and solid target materials for SINQ and other future spallation neutron sources, including MEGAPIE. The arrangement of these test rods is also shown in Fig. 4, together with a photograph of the rod array after removal of the container shell in the hot cells. At this point the target had been charged with 6800 mA h of protons.

The lower half of the target unit is enclosed in a double walled shroud with separate heavy water cooling. This shell is presently made of aluminium alloy. Although it will be necessary to have such a shroud surround the liquid metal container also in the case of the MEGAPIE target, it remains to be decided whether aluminium alloys are still suitable or whether a material with higher strength at elevated temperatures needs to be chosen in order to maintain a safe containment if the inner liquid metal container breaks and the target material gets in contact with the water cooled inner wall of the shroud.

The water cooling loop for the target has a heat removal capacity well above what is needed for either the solid or liquid metal target. It is, however, limited to operating temperatures below some 80°C and is not

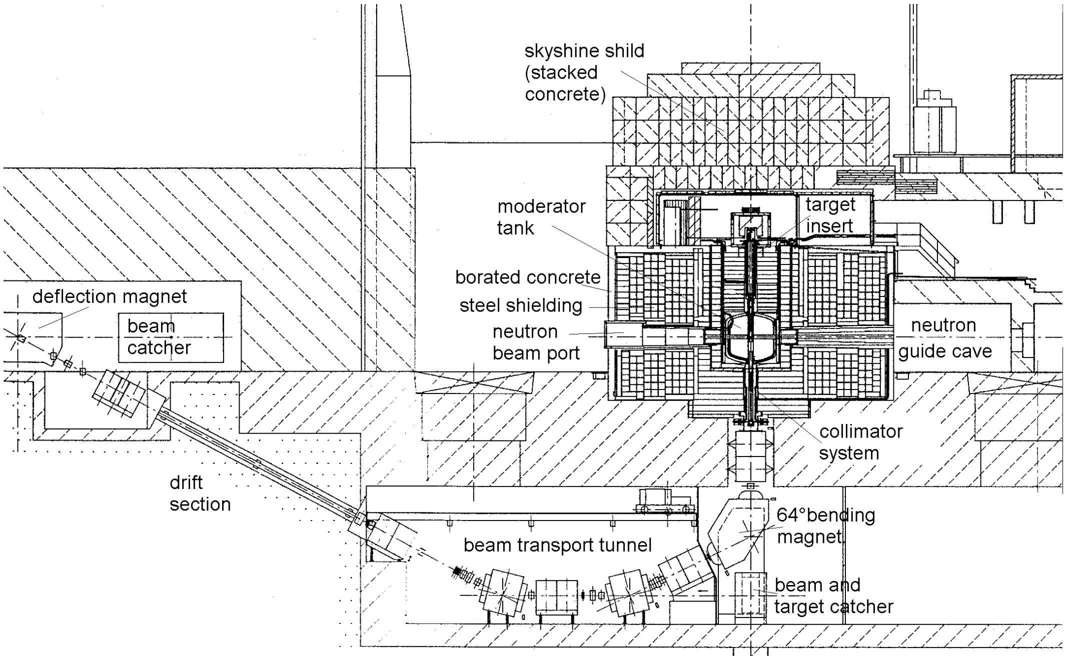
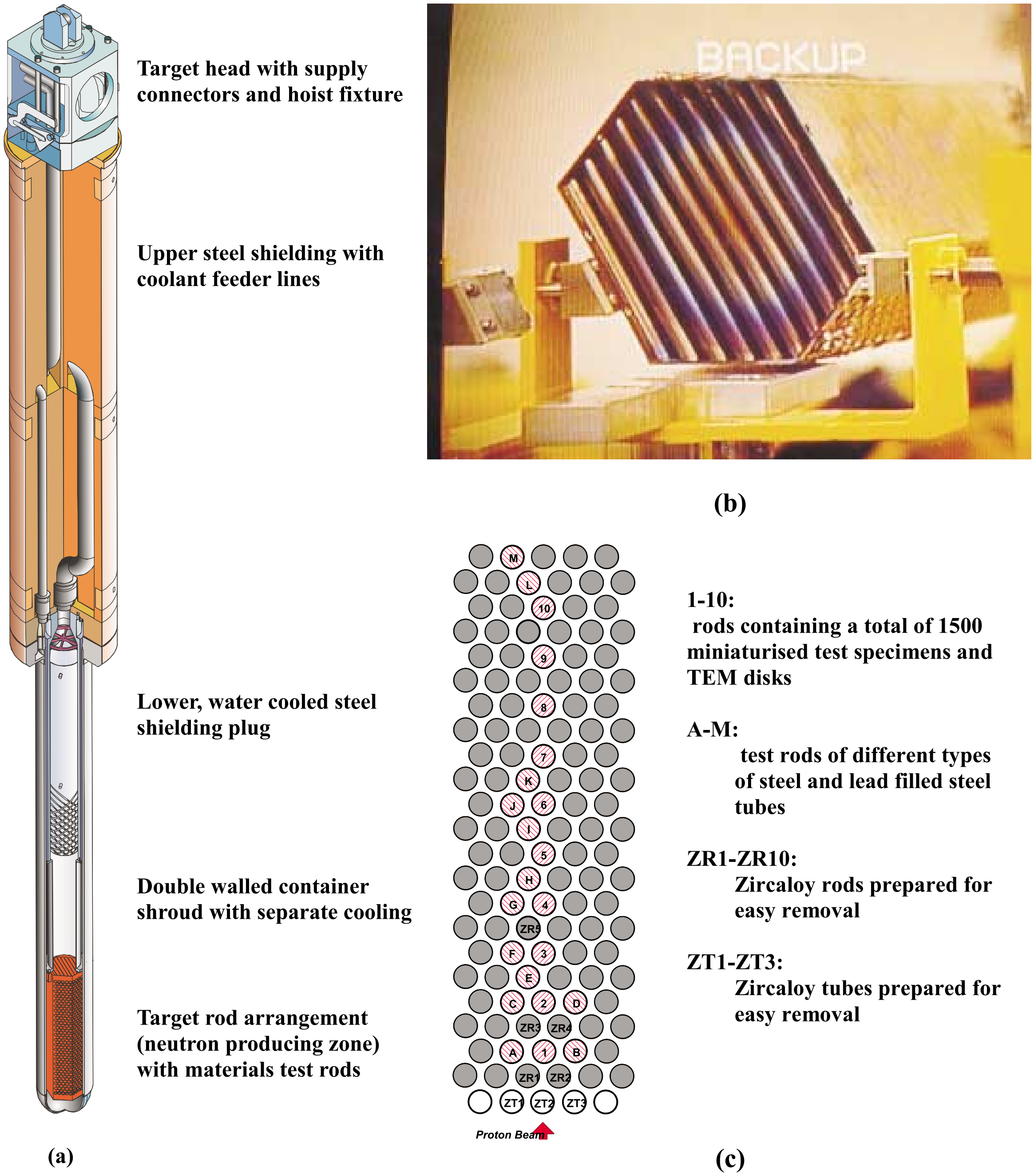


Fig. 3. Vertical cut through the target block and part of the proton beam transport line of SINQ.



Target head with supply connectors and hoist fixture

Upper steel shielding with coolant feeder lines

Lower, water cooled steel shielding plug

Double walled container shroud with separate cooling

Target rod arrangement (neutron producing zone) with materials test rods

(a)

(b)

1-10: rods containing a total of 1500 miniaturised test specimens and TEM disks

A-M: test rods of different types of steel and lead filled steel tubes

ZR1-ZR10: Zircaloy rods prepared for easy removal

ZT1-ZT3: Zircaloy tubes prepared for easy removal

(c)

Fig. 4. (a) The SINQ target is a 4 m long structure with 20 cm diameter in the lower, 2 m long section and 40 cm diameter in the upper half. Proton injection id from underneath into a water cooled array of rods of 11 mm diameter. (b) The rod assembly of target Mark 2 having received a total of 6500 mA h of beam in SINQ. The footprint of the beam is clearly visible. (c) Schematic of the lower part of the rod assembly showing the arrangement of materials testing samples in the matrix of Zircaloy rods.

suitable for pressurisation to more than about 0.8 MPa. Hence, the water temperature of this loop cannot be raised to more than 125°C in order to prevent freezing of the PbBi. A different solution must be found for this problem.

The target is inserted into and removed from its operating position by means of a specially designed exchange flask which has an internal hoist to lift the target. This flask is transported by means of the overhead crane in the SINQ target hall, whose capacity is limited to 60 tons. The shielding of this flask is currently optimised for the solid target, which has its radioactivity concentrated in the bottom region. Although the specific activity of the liquid metal target will be much lower due to its significantly larger target mass, it remains to be examined whether the shielding in the upper part of the flask is sufficient. Possibilities for back-fitting of the present flask are very limited, due to both its design and the weight limitations on the overhead crane.

2.3. The active handling area ATEC

The area in the PSI experiment hall immediately adjacent to the SINQ neutron guide hall (Fig. 2) is designed and equipped to handle large radioactive components and is generally used to service, repair and prepare for disposal all kinds of radioactive parts used in the operation of the facility. Its hot cell is equipped with a power manipulator, master-slave manipulators and a movable heavy duty working table as well as several other items such as radiation monitoring, video cameras, etc. Although access to the hot cell is possible through its roof, a specially designed port for horizontal access (arrow in Fig. 2) is used to insert the SINQ target, because limitations in height prevent vertical insertion with sufficient clearance for the manipulations required. The SINQ targets no. 1 and 2 were successfully dismantled and prepared for disposal in this cell. Samples from the target material and container shell were removed and one target was also reassembled in this hot cell. In principle this cell and its special equipment prepared for the handling of the SINQ solid target should also be suitable to dismantle the liquid metal target. There are, however, some severe boundary conditions, the most important one being the fact that this hot cell is not equipped and licensed to handle α-activity. Thus, even if a method is developed to drain the liquid metal from the target before opening it, as is desirable for a variety of reasons, one must still be able to guarantee that no α-active isotopes are released into the cell during the manipulations foreseen. Alternatively, the cell might be retrofit for handling α-active parts, but this would not only mean a significant additional expense, it would also make access much more difficult and would shut down the area for an extended period of time. The latter is a particular problem because the cell is more or less continuously utilised and must be available on short notice in case any of the vital components in the accelerator or beam transport systems fail. It shall, therefore, be an important task in the MEGAPIE design phase to develop a procdure for use inside the hot cell that guarantees that no α-activity is released into the cell when the target is opened to remove those parts on which post use examinations are foreseen.

2.4. PSI hot cell facilities and PIE equipment

PSI is operating well equipped hot cells in which post irradiation examinations (PIE) can be carried out with a large variety of different methods. Final definition of the PIE program will be a relevant part of the project activity during the R&D and engineering design phase.

2.5. Operation of the MEGAPIE target

The MEGAPIE target will, for a period of time of up to one year, replace the neutron production target in SINQ while utilisation of the facility will continue. This means that a high reflector flux and reliable operation are important issues in the project.

2.6. Target development for SINQ in view of the MEGAPIE initiative

As mentioned above, the first target (Mark 1) used for commissioning the SINQ facility was made up from simple Zircaloy rods. While this is a relatively well proven material in nuclear applications, its neutron yield is not optimum. It has, therefore, been an important goal of the SINQ target development program to improve the neutron flux in the moderator and to maximise the time of reliable operation of the targets. In order to establish a data base for the design and operation of future targets, the first target was removed after half a year of operation (500 mA h total charge delivered). It was replaced by another one (Mark 2) which, while still being essentially a Zircaloy rod bundle, incorporated several test elements designed to provide data for future target concepts (cf. Fig. 4). Apart from a large number of test specimens which will allow examination of radiation effects in a mixed proton-fast and thermal neutron spectrum under varying load for the first time (STIP-collaboration, see below), the target also contained rods made from lead filled steel tubes. Although results from post irradiation examinations are not yet available, the fact that no problems [1] were encountered up to a total charge of 6.8 A h (at which point the target was removed) seemed to justify the use of a target made up of lead filled steel tubes. In this way the thermal neutron flux increased by a factor of 1.45 relative to Zircaloy. This target (Mark 3) is again loaded with test specimens. Following the investigation of the material from the Mark 2 target it is intended to decide whether or not

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[1] The target even survived an inadvertent brief focusing of the beam which drove the temperature in some of the sample rods to above the melting point of aluminium and, unfortunately, rendered some of the test samples useless.

Zircaloy can be used as a tube material for the lead rods, in which case another gain factor of 1.3 would be expected for the thermal flux. Currently the projected operating life for each target is two calendar years.

As for the MEGAPIE target, a period of two years (2000 and 2001) has been allotted to carry out the research and engineering work necessary to decide what the final design should be and to prepare the preliminary safety analysis report. At the end of this period a decision will be made whether to go ahead with the detailed design and construction, for which another two years are foreseen, including testing without beam. This sets the beginning of the year 2004 as the goal for putting the MEGAPIE target into SINQ. A standby target will be ready in case some unforeseen difficulty arises in the last minute. This target will be used at the end of the operating period of the MEGAPIE target, unless a follow up liquid metal target will be available. The duration of the irradiation period will be decided upon, based on the results obtained up to that point from supporting research, but the design goal was set to 6000 mA h, which corresponds to one year of full power operation at 1 MW. A rough schedule of the MEGAPIE project is shown in Fig. 5.

3. Level 0 baseline of the MEGAPIE project

The overall (level 0) project baseline as agreed upon as a basis to draw up an agreement of collaboration between the partners is as follows:

1. MEGAPIE is an experiment to be carried out in the SINQ target location at the Paul Scherrer Institut and aims at demonstrating the safe operation of a liquid metal spallation target at a beam power in the region of 1 MW. It will be equipped to provide the largest possible amount of scientific and technical information without jeopardising its safe operation. The minimum design service life will be 1 year (6000 mA h).
2. MEGAPIE is an international collaboration in pursuit of common interests and in order to pool existing know how and resources. The experiment will not constitute a major disruption to the primary mission of SINQ, namely the supply of neutrons to the user instruments. No specific new requirements will result for the operation of the PSI accelerator system.
3. The maximum incremental total project cost (ITPC, total project cost over and above efforts going on in the participating laboratories or funded by other sources, e.g., EU-programs), to be shared by the par-

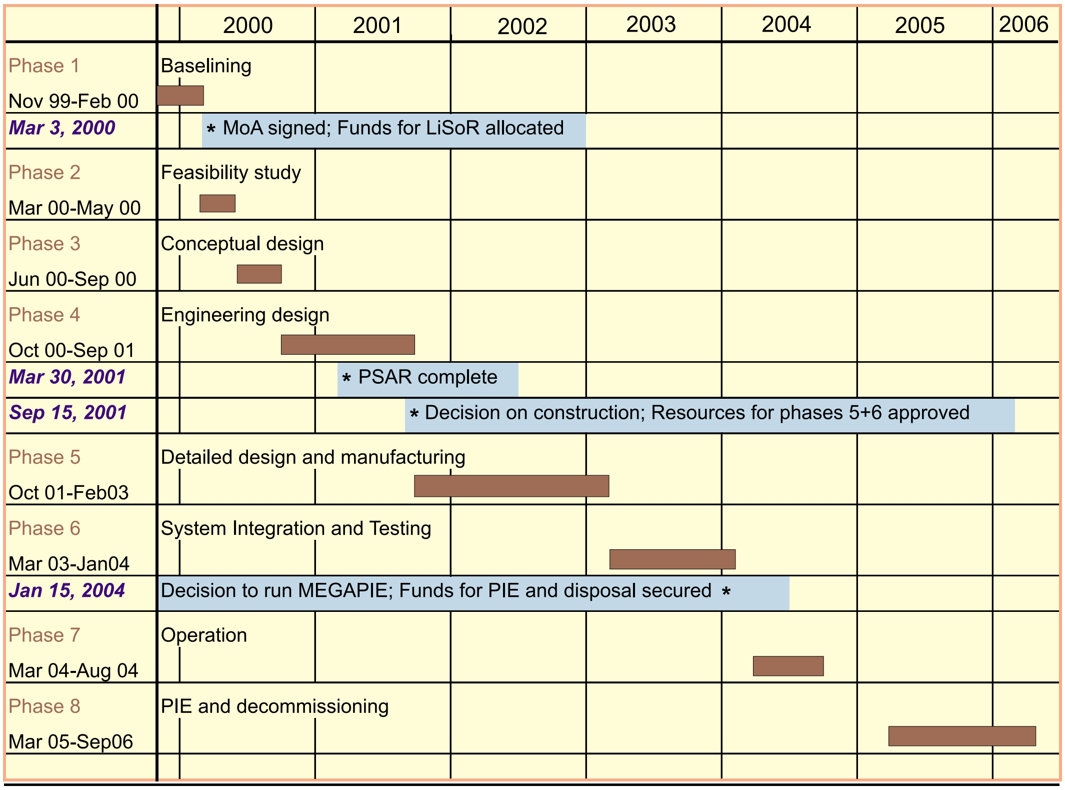

Fig. 5. The MEGAPIE project phases and major mile stones.

ticipants, shall be 10 MSFr, including final disposal. No charge will be levied by PSI for the proton beam. Start of irradiation will be March 2004; the duration of the project will be though 2006, including PIE and decommissioning.

4. Target material will be the PbBi eutectic mixture. The design beam power is 1 MW at 600 MeV. Existing facilities and equipment at PSI will be used to the largest possible extent. Cooling water loops of the target station will be left largely unchanged and will be ready for use with a solid target again within less than 1 month after termination of the MEGAPIE irradiation.
5. The overall project leadership rests with CEA, while PSI takes charge of the technical co-ordination, since the experiment will be licensed under Swiss authority. The project will be overseen by a Project Steering Committee (PSC), in which the participating laboratories are represented. Each participating laboratory will nominate a responsible Local Co-ordinator (LC), who will be a member of the Project Management Group (PMG) and will be given the executive power to see to it that the laboratory fulfils its technical commitments in accordance with the overall project needs. The PMG will be chaired by the Project Director (PD). Task leaders (TL) will be nominated for specific sub-units of the project. The TL and the PMG will form the Project Control Team (PCT).

4. The MEGAPIE collaboration

Originally proposed by three laboratories, CEA Cadarache (F), FZ Karlsruhe (D) and PSI (CH), the MEGAPIE collaboration has since been joined by four more institutions, namely ENEA (I), SCK-CEN (B), JAERI (J) and CNRS (F) – jointly with SUBATECH. An agreement of collaboration (AoC) was worked out in which the terms of the collaboration are laid down. In accordance with the general project baseline (see above), a Project Steering Committee (PSC) was formally established as the controlling body of the project. All participating institutions are represented in the PSC. Its main tasks are to ensure the necessary support from the different parties, approve the project planning, authorise the project spending plan, monitor progress and decide on corrective actions. The Collaboration is open to new members who are willing to contribute actively to the funding and realisation of the project. The PSC will decide on the use of additional funds from new partner or research programs.

In order to cover the cost for designing, building, running, post irradiation examining and decommissioning of the target a 'common funding' was agreed upon as joint funding for the project. These common funds will be controlled by the PSC. While a fixed key has been agreed upon for contributions to the common funds, the supporting R&D work is carried out on a best effort basis by the participating laboratories and all results are made available to all participants.

5. Boundary conditions and technical baseline of the MEGAPIE target

The MEGAPIE target will be used in the existing target block of SINQ. A vertical cut through this target block and through parts of the proton beam line is shown in Fig. 2.

The beam enters the target block from underneath and passes through a collimator system which, on the one hand prevents the proton beam from hitting the central tube of the moderator tank surrounding the target and, on the other hand limits the intensity and angular divergence of the evaporation neutrons streaming back from the target into the beam transport system. A special, heavily shielded catcher device is located beneath the last bending magnet to avoid soil activation by the remaining neutrons and, in case of a catastrophic target failure, to hold the debris that would eventually fall down. This part of the beam line is designed for use with a solid target only and some retrofitting will become necessary for use with a liquid metal target. Apart from this, the fact that an existing target location is used clearly constitutes a significant advantage in terms of cost and time, but, together with the fact that the primary mission of SINQ remains to provide neutrons to a user community, also results in a number of boundary conditions that are listed in the following.

5.1. Boundary conditions

5.1.1. General

The target and its handling operations must be conceived such that α-contamination of accessible areas in the SINQ facility is excluded under all conceivable conditions.

The target design shall follow the present SINQ target philosophy that includes a separately cooled safety enclosure around the regions affected by radiation damage.

The safety shell shall be able to withstand a spill of the target material into the interspace until solidification of the target material has occurred.

The interspace between the safety shell and the target container shall be surveyed for leakage of either one of the two components.

Double enclosure of all volatile or potentially volatile radioactive materials shall be foreseen.

Decisions about PIE and disposal (what, where, how) must be final before test operation of the target with beam is started.

Permission of the regulatory body responsible for PSI must be obtained, based on a safety analysis report (SAR); prior to installation of the pilot target in SINQ.

5.1.2. Mechanical

The target's outer dimensions must be such that it fits into the target position of the SINQ facility, the existing target exchange flask including its contamination protection devices and the existing target storage positions.

Sufficient shielding must be provided towards the top of the target to allow personnel access for disconnecting the coolant piping, electrical supplies and other media transport lines prior to removal of the target from its operating positions.

Space around the target position required for access to perform maintenance or handling operations must not be obstructed by auxiliary or ancillary equipment.

It must be possible to reverse changes made to any of the existing equipment for the solid target operations within one month after the end of the liquid metal target test operations.

5.1.3. Thermal-hydraulic

Pressure level, pressure drop and temperature level at the secondary side of the heat exchanger must be within the specifications of the existing cooling loops. The operating parameters of the present cooling loops are listed in Table 1.

5.1.4. Proton beam

The target will be designed for 1 MW of beam power at a proton energy of 575 MeV, i.e., a total beam current of $I_0 = 1.74$ mA. The beam on target has elliptical distribution with Gaussian intensity profiles characterised by $\sigma_x = 19$ mm and $\sigma_y = 33.1$ mm. The Gaussians are truncated at 2σ. The beam distribution in x and y direction then becomes

$$I(r)_{x,y} = I_0 \exp(-(r_{x,y}/\sigma_{x,y})^2/2)/(2\pi\sigma_x\sigma_y(1-\exp(-c^2/2))) \quad \text{with } c = 2. \tag{1}$$

For scoping calculations an average σ of 25.08 mm $(= \sqrt{(\sigma_x\sigma_y)})$ can be used.

A graphical representation of the different beam profiles is given in Fig. 6.

It is also important to realise that the stability of beam delivery cannot be guaranteed at all times. The MEGAPIE heat removal system must be able to cope with frequent short beam trips and occasional unstable operation (an example is given in Fig. 7) up to days long shutdown periods.

5.1.5. Time limitations

Installation of the target can be made only during the annual accelerator shutdown period which starts the day before Christmas and usually lasts until end of February of the following year. An extension of no more than two weeks is acceptable. It is currently planned to operate each solid target for two years, which makes the beginning of even-numbered years the preferred periods for installation of the pilot target. If the year 2004 cannot be met, installation will be delayed by at least one year.

5.1.6. Neutronic

Although MEGAPIE is an experiment aiming at the demonstration of a liquid metal target, it will also serve as the neutron production target for SINQ during its operation time. For this reason care should be taken in its design and construction to optimise the resulting neutron flux in the surrounding reflector. This relates to the diameter of the target (within the maximum limit given above) as well as to elements present in the part that protrudes into the reflector. Here, elements with low thermal neutron absorption are to be preferred and strongly absorbing elements should be avoided.

Table 1
Operating parameters of the SINQ cooling loops ($I_{\text{SINQ}} = 1.030$ mA at 575 MeV)

Parameter	Loop			
	Target	Target enclosure	Moderator	Shielding
Medium	D_2O	D_2O	D_2O	H_2O
Forward flow temperature (°C)	34	34	32	33
Return flow temperature (°C)	43	35	36	35
Forward flow pressure (MPa_{abs})	*0.7*–1.1	*0.7*–1.1	0.35	0.4
Return flow pressure (MPa_{abs})	0.5	0.5	0.2	0.2
Mass flow (kg/s)	*10*–15	2.2	3.1	7.2
Purification bypass (kg/s)	0.4	0.08	0.55	0.28
Coolant volume (l)	3400	460	5710	2480
Approx. actual power (kW)	375	7	60	55
Nominal power rating (kW)	650	35	111	210

Where ranges are given, italics indicates the values actually used.

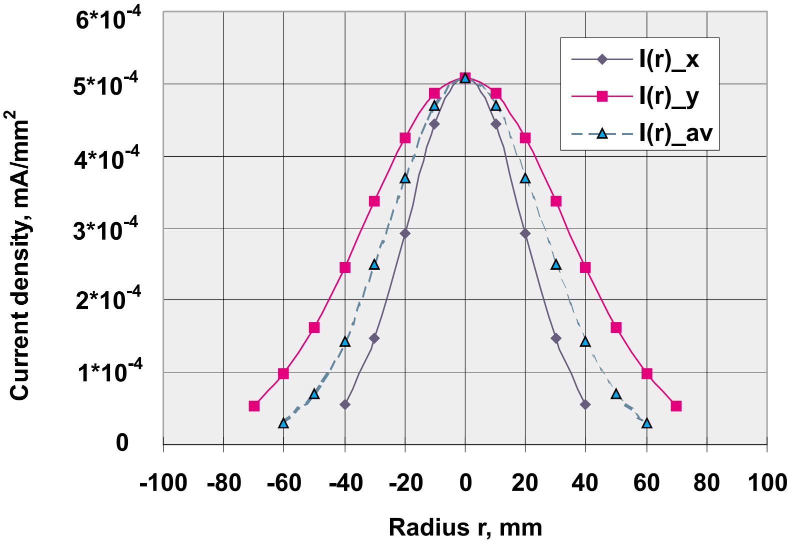

Fig. 6. Reference beam intensity distribution for the design of the 1 MW MEGAPIE target ($I_{\mathrm{SINQ}} = 1.74$ mA at 575 MeV).

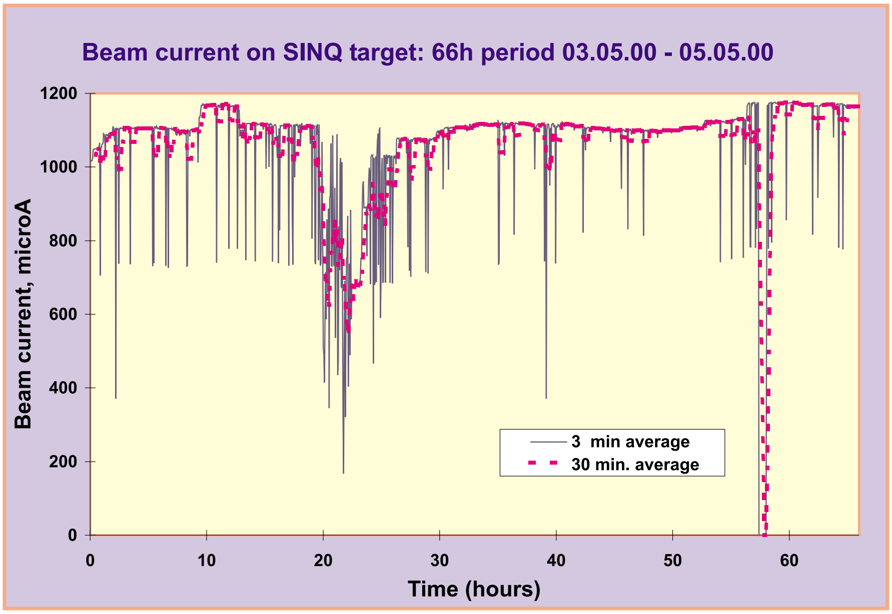

Fig. 7. Example of beam stability problems the MEGAPIE target will have to cope with. Solid line: 3 min average; dashed line: 30 min average.

Examples (not a complete list) of

'Excellent' elements ($\sigma_{\mathrm{abs}} \leqslant 100$ mb) are:	Be, C, D, O, F, He, Ne, Mg, Bi
'Good' elements ($100 \leqslant \sigma_{\mathrm{abs}} \leqslant 500$ mb) are:	Si, P, Zr, Pb, H, Al, Ca, Rb
'Tolerable' elements ($500\sigma_{\mathrm{abs}} \leqslant 1000$ mb) are:	Na, S, Ar, Ce, Sn,
'Undesirable' elements ($1000 \leqslant \sigma_{\mathrm{abs}} \leqslant 5000$ mb) are:	N, Ba, Cr*, Cu, F, Ga, Ge, Fe*, Ni*, Nb, Ti, V
'Bad' elements ($\sigma_{\mathrm{abs}} \geqslant 5000$ mb) are:	Sb, B, Cd, Cl, Co, In, I, Ir Au, Hf, Li, Mn, Hg, Mo, Pt, Re, Rh, Se, Ag, Ta, W, Xe

*The main constituents of steel have: Fe – 2.6, Cr – 3.1 and Ni – 4.6 barn.

Therefore, from a neutronic point of view, it is desirable to have a thin container and central guide tube with low nickel content.

5.2. Technical baseline

The technical baseline of the MEGAPIE target developed in view of the above boundary conditions is schematically represented in Fig. 8, showing the main components of the target unit and the required new auxiliary systems.

5.2.1. The target unit

The original concept for the SINQ target was to move the liquid metal from the beam interaction zone to the heat exchanger by natural convection [4]. This has the benefit of being a completely passive system and it was shown that, in an equilibrium situation, is also sufficient to establish the necessary flow of about 4 l/s/MW. However, the situation during transients is difficult to control. In order to avoid the risk of local overheating it would be necessary to restart the beam after each trip with a carefully controlled ramp. In particular the flow configuration at the beam entrance window becomes very unpredictable. In order to rectify this latter problem tests were carried out at the large mercury loop of the University of Latvia in Riga, using a pumped bypass flow across a hemispherical window in a full scale mock-up of the SINQ target [5,6]. It was shown that, even in a non-wetting condition with a pumped bypass flow inverse heat transfer coefficients of $0.5\ \mathrm{K}/(\mathrm{W}/\mathrm{cm}^2)$ could be obtained, which is a factor of 5 better than without a bypass flow. For this reason the concept of a pumped bypass flow of 1 l/s to cool the window was adopted as a reference for MEGAPIE. Although this flow from the bypass pump might be sufficient to avoid overheating during transients, the technical baseline for MEGAPIE was chosen to include a pump also for the main flow. Its estimated capacity should be 4 l/s at a pressure head as require by the flow resistance in the target. Although an EM-pump has been selected as reference concept, other alternatives will still be evaluated.

The heat exchanger system must be designed such that freezing of the liquid metal can be safely avoided everywhere in the system even in cases of variable beam power or extended shutdown periods (e.g., the weekly 1–2 days of accelerator maintenance and beam development). Several options to achieve this have been identified, but a final selection will depend on detailed evaluations of all aspects involved.

Since the existing target exchange flask is shielded to handle solid targets, i.e., has most of its shielding in the lower part, it is important to keep the amount of PbBi in the upper part of the target small. To this end displacement bodies of steel are foreseen around the heat exchanger pins and in all locations not needed to ensure sufficient cross-section for the liquid metal flow. The main flow guide tube which serves to separate the upward flow in the centre of the target from the downward flow in the outer annulus is planned to form one unit together with the pump system. A ceramic insulated heater system inside the target will facilitate initial filling and will serve as a second means of preventing the liquid metal from freezing. A gas filled expansion volume will be located above the liquid metal level.

The structural material for the target container is foreseen to be martensitic (French designation T91 type) steel, at least in its lower part. For the upper part the use of austenitic (316 L type) steel is being considered, which is more readily available and easier to weld. This is contingent upon sufficiently high liquid metal corrosion resistance, because the highest temperature gradient in the system will occur along the heat exchanger. In order to facilitate the transition between two different materials the two parts will be joined by a flange system. The whole target container will be surrounded by a second enclosure with an insulating vacuum between. In the lower part this enclosure will be double walled with heavy water cooling as is the present target shell. The material for this part will be chosen for minimum neutron absorption and sufficient strength at any temperature the shell might reach in the case of a breach of the target container. Presently Zircaloy 2 is the favoured material, but this needs to be studied in detail. Again, as in the present target concept, the upper and lower parts of the outer shell will be joined by a flange. The upper part of the outer shell will be stainless steel. Sufficient shielding shall be provided in the top part of the target to avoid excessive radiation levels in the target head room from direct gamma radiation from the liquid metal. Whenever possible, the feeds through this shield should be designed to avoid direct sight.

5.2.2. Auxiliary systems

While changes to existing auxiliary systems of the SINQ target shall be kept to a minimum, there will be a number of additional auxiliary systems required for the safe operation of the MEGAPIE target. They are schematically indicated in Fig. 7.

Cover gas and spallation product handling system. Volatile spallation products will enter the cover gas of the expansion volume during operation of the MEGAPIE target. This will include light species (isotopes of hydrogen, helium) as well as noble gases and possibly mercury. An assessment of the production rates can be found in [7]. All condensable species should be trapped either inside the expansion volume (e.g., by a water cooled baffle) or in a specially enclosed cover gas handling system. The question of tritium treatment needs still to be evaluated. It can either be released under

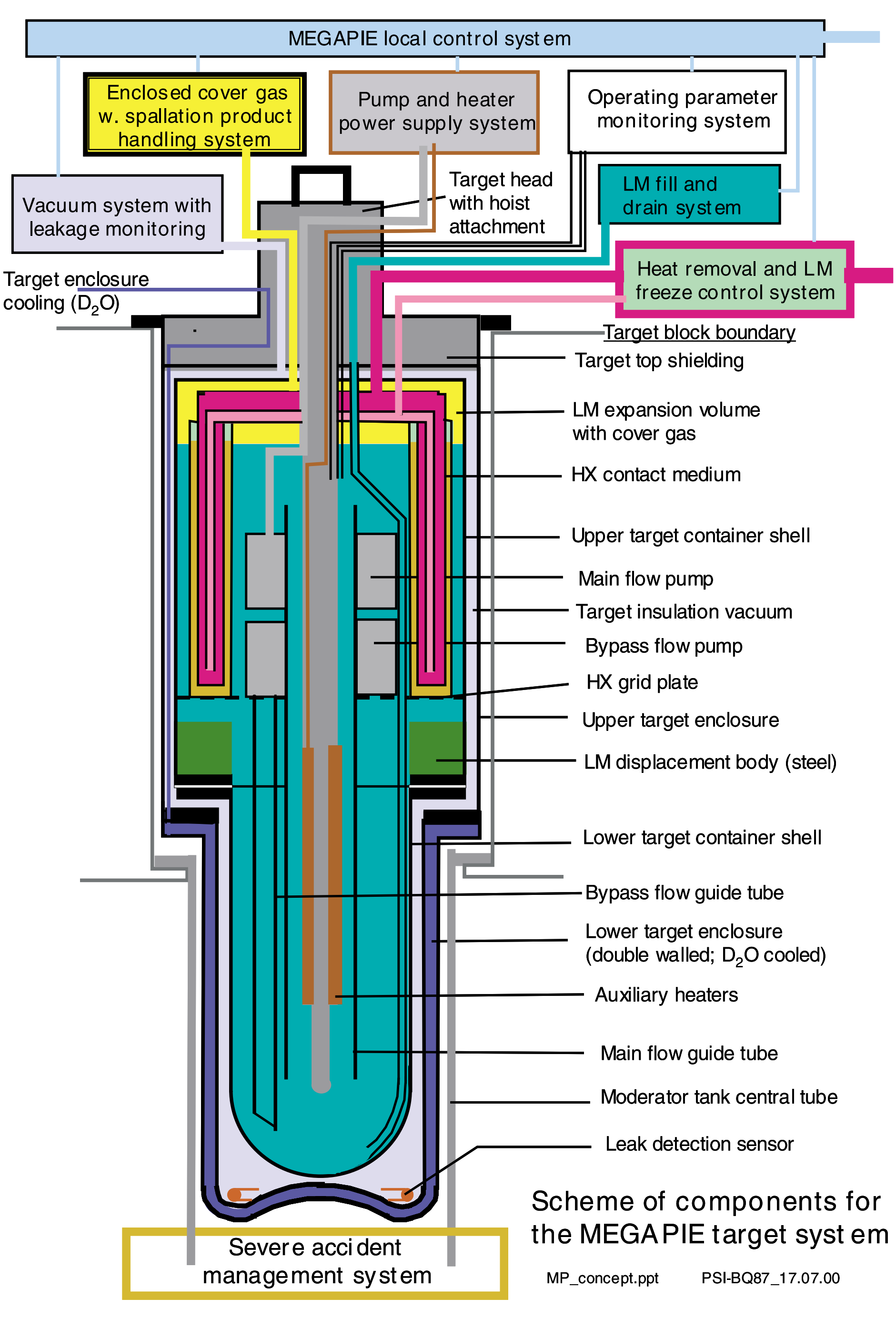

Fig. 8. The basic concept (left) and conceptual design (right) of the MEGAPIE target.

controlled conditions into the ventilation system or retained in special getters.

Liquid metal fill and drain system. Filling the target must be effected in a very careful manner, making sure that all surfaces and the target material are in the required conditions. It remains to be decided whether the PbBi will be drained from the target or whether it will be allowed to solidify after the end of the irradiation period. This decision will have a strong effect on the design and location of the LM fill and drain system. In any case this work package will include the liquid metal technology system. There will also be a close interrelation with the expansion room cover gas system, since this will be used to preheat the structure for filling and, eventually, to push the PbBi out of the container.

If a heat exchanger with an intermediate heat transfer fluid is used, filling and draining must also be provided for this fluid with precautions taken for potential radioactivity after use.

Vacuum and leakage monitoring system. A new vacuum system with controlled exhaust will be required to maintain the insulating vacuum between the LM container and the outer target shell. This vacuum will be continuously monitored for spallation products and water vapour in order to detect any leaks in the system. The question, whether or not a continuous stream of a small amount of carrier gas is desirable to speed up the response time of this monitoring system needs yet to be decided. It is intended to have also other, redundant, leakage monitors such as electrical contacts in this volume.

Heat removal and liquid metal temperature control system. As mentioned before, heat removal from the target needs to be closely controlled in order to avoid freezing of the LM anywhere in the system. Various concepts have been identified which can be implemented individually or in combination. These include:

- activating the auxiliary heater system in the guide tube;
- using an economiser-second heat exchanger, eventually with water preheating in a bypass stream, to keep the water temperature level in the heat exchanger pins higher than in the existing cooling loop;
- controlling the heat transfer in the primary heat exchanger, for example by varying the level of an intermediate heat transfer fluid;
- varying the efficiency of the EM-pump through the frequency of its current supply.

The economiser-secondary heat exchange system will have to be installed in the room above the target head.

Pump and heater power supply system. The power supplies for the pumps and heaters will have to be installed outside the target head room for easy access and space. This requires new cabling into the target head room.

MEGAPIE local control system. All additional parameter monitoring and controlling required to operate the MEGAPIE target will be handled by a local control system which will be located outside the target head room and will be connected to the main SINQ control system.

Operating parameters monitoring system. All operating parameters that need to be monitored (temperatures, pressure, flow rates, etc.) in order to verify design predictions but are of no or little safety relevance will be collected in this system and will be transferred to the SINQ control system for data logging. Details of the parameters to be surveyed need yet to be defined.

Severe accident management system. Every possible precaution will be taken to avoid severe accidents during the operation of the MEGAPIE target. As far as the target block is concerned, the necessary precautions against the consequences of an earth quake or an air plane crash have already been implemented. A breach of the outermost shell or both shells of the lower, D_2O cooled enclosure is equivalent to the same accident in the present situation and need not be discussed further. Similarly, a breach of the LM container alone would not constitute a severe accident because the target could still be removed by the normal procedure. The one potential severe accident that needs to be studied in detail for the liquid metal target as opposed to the solid target is the simultaneous breach of all three shells separating the liquid metal from the beam line vacuum.

Since the three shells of the target containment are exposed to different environments during operation and are likely to be made of different materials, the only credible common cause of failure would be an inadvertent focusing of the proton beam and consequent overheating of all three shells. The collimator below the target and several monitors along the beam line are in place to guard against this situation, but there is no passive system to avoid it in the event of a loss of target E. In this case liquid metal would enter the proton beam vacuum and would severely contaminate parts of the beam vacuum tube. While this is not an accident that would pose an immediate risk to the public, its consequence might be a very long shutdown of SINQ and significant radiation exposure of workers during the cleanup operation. It is, therefore, a question of risk management within PSI, whether and to what extent modifications to the existing system (vacuum pipe, catcher and collimator below target) shall be implemented to shorten a potential shutdown period in the unlikely case of such an event. The present position is to study possible measures and their implications and to decide about their realisation on the basis of a serious analysis. This decision will have to be made at latest in the early months of the engineering design phase before submission of the safety analysis report.

6. Supporting R&D at the participating laboratories and in international collaborations

While the MEGAPIE collaboration aims directly at designing, building and testing a PbBi liquid metal pilot target in a 1 MW proton beam, it is embedded in and will profit from a variety of different related research activities its members are involved in and which cover most of the questions of more fundamental nature related to this endeavour. The most important of these collaborations and activities are listed below. Furthermore, a proposal to fund design support and integral testing of the MEGAPIE target has been submitted for the second call of the 5th EU framework programme of research funding.

6.1. The STIP collaboration

As mentioned above, the unique opportunity of investigating the radiation effects from a perfectly realistic spectral mix of the different particles in a spallation environment in the SINQ target is being taken advantage of in an effort to broaden the data base for a variety of materials considered as candidates for target and structural materials in future spallation facilities. A collaboration was formed supported by laboratories from all over the world. Different types and materials were assembled in 10 of the SINQ target rods and embedded in the Zircaloy target Mark 2 (cf. Fig. 4) that went into operation in the beginning of the year 1998. At the end of the target's service life (end of 1999), the peak radiation damage from protons alone was of the order of 10 dpa in steel, with a somewhat smaller contribution resulting from the fast neutron flux. The specimens were removed from the spent target during the summer of 2000 and will be shipped to the participating laboratories for examination by different methods such as tensile testing, tear testing, bend bar and Charpy testing as well as electron microscopy. Due to the rather large range of radiation damage levels and irradiation temperatures, which the specimens experienced in different positions of the SINQ target, a large parameter space will be covered by the data obtained.

Furthermore, 13 rods were made up either of different types of steel as bulk material or of steel tubes filled with lead. In addition to five Zircaloy rods designed for easy removal from the target, these are available for non-destructive and destructive testing using, among others, neutron small angle scattering, neutron radiography and internal strain measurements with neutrons at SINQ.

With this first round of sample irradiation (STIP-1) completed in December 1999, the follow-up target, which went in operation in March 2000, was equipped in a similar way but predominantly with materials and materials combinations in which interest has arisen more recently (STIP-2). Furthermore, this target now has a higher neutron yield due to the use of lead as spallation material and experiences a higher peak current density as a consequence of the shorter target E (4 cm as compared to previously 6 cm). This new target also contains capsules in which steel is irradiated in contact with stationary liquid metal (PbBi and mercury).

6.2. The LiSoR experiment

One of the major unknowns in liquid metal target development is related to the question, whether liquid metal–solid metal reactions (LiSoR) in the presence of (static or cyclic) stress are enhanced under irradiation. Since this is a problem that must be solved before a liquid metal target can be irradiated in a proton beam for an extended period of time, an experiment has been initiated to use PSI's 72 MeV Philips cyclotron to irradiate stressed steel specimens in contact with flowing liquid metal. Scoping calculations showed that, while much less radioactivity is produced, the damage levels and gas production in thin specimens by 72 MeV protons are, within reasonable limits, comparable to those on the inside of the proton beam window at 600 MeV. Also, the beam parameters can be adjusted in such a way that relevant heating rates at the solid–liquid interface are obtained. A proposal to carry out such an experiment has been received positively by the Experiment Review Committee and irradiation time has been set aside for the operating period of the year 2001. Currently the rig is being designed by SUBATECH and PSI with support from CNRS and CEA. LiSoR was originally planned as a stand alone investigation. Due to its immediate relevance for MEGAPIE it was incorporated into the project, but, for the time being, is still pursued on an largely independent basis. This is mainly due to temporal restrictions which result from PSI's intention to discontinue operation of the Philips cyclotron after 2001, and from the time when results are needed to affect the MEGAPIE design. Support for LiSoR has been granted under the first phase of the EU 5th framework programme (TECLA Programme, see below).

6.3. The TERM experiments

In a quest to study some of the unresolved problems related to the design of liquid metal targets in the context of the ESS project and in preparation of a data base for thermal hydraulic studies for a possible later SINQ liquid metal target, a test experiment at the Riga mercury loop (TERM) was set up. The main goal was to study experimentally questions of heat transfer between the window and the fluid and related flow distributions in various geometrical configurations. The first phase, which used the geometry of the SINQ target has been finished. Methods developed and used include ultrasonic velocity probes (UVP), based on a though the wall measurement of the Doppler effect in the fluid, heat emitting temperature sensitive surfaces (HETSS) and infrared surface thermography. Data from this phase of the experiment are still being evaluated, but it is obvious that a jet flow accross the target window improves the heat transfer to the liquid metal by roughly a factor of 5 in the SINQ geometry [6,7]. Ongoing experimental work now concentrates on the geometry of the ESS target and the effect of gas in the fluid on the coolability of the beam window. The full scale SINQ target model is also still available for further investigations.

6.4. The PSI lead bismuth loop

In order to be able to carry out experiments even more realistic for SINQ than were possible at the Riga Mercury Loop, a PbBi-loop has been constructed and is being commissioned at PSI. Without a test section attached, the loop contains 0.12 m^3 of PbBi and has a total height of 5.1 m. Operating temperatures are rated at 250°C and below. It is equipped with an EM-pump (32–58 kVA) with a head of 1.5 m LBE and a capacity up to 200 l/min. The pressure rating of the loop is -1 to 2 bar. Test sections can be added to the loop depending on the problem under investigation. The loop is intended for both, testing of individual components as well as studies of flow configuration and heat transfer problems.

6.5. The Karlsruhe lead laboratory KALLA

Within the German HGF-Strategy Fund Project 99/16 entitled ‘Reduction of Radiotoxicity’, the Karlsruhe lead laboratory KALLA is being planned and constructed at the Forschungszentrum Karlsruhe. KALLA comprises three different experimental loops, each emphasising different specific objectives, briefly summarised in Table 2, together with the main data.

6.6. The SPIRE programme

As part of the SPIRE programme funded under the first phase of the EU 5th Framework Programme irradiation effects in structural materials under a proton neutron mixed spectrum will be investigated. Within this framework, CEA has taken leadership in a programme the objectives of which are to (i) determine the in service properties of the selected structural steels: tensile properties, fracture toughness, irradiation creep and swelling, (ii) provide the basic understanding and modelling of the observed phenomena induced by atomic displacements and production of spallation elements, and (iii) contribute to a validated data base. The programme includes studies aiming at the understanding of the effects of spallation elements production (He, H, Ca, P, S, Ti) on the physical metallurgy, microstructure and mechanical properties of the selected steels, neutron irradiation in Phénix (Antarès up to 40 dpa) and Bor60 (Altaïr up to 30 dpa) to complement the existing data base, post irradiation examination (PIE) of conventional martensitic steels included in SITP-1, and basic studies to predict the hardness and the cohesion energy of segregated boundaries.

6.7. The TECLA programme

Corrosion, quality control in Pb–Bi and associated technology will be investigated as part of the programme ‘Technologies, Materials, Thermal-Hydraulics for lead alloys’ (TECLA) also funded under the first phase of the EU 5th framework programme. The objectives of this corrosion programme are to provide a validation of the envisaged structural materials under varied experimental conditions: (i) quantify the corrosion kinetics under different chemical (oxygen and spallation elements contents) and hydraulic (Pb–Bi velocity) conditions and (ii) identify and assess structural materials protection methods against corrosion. Corrosion kinetics vs oxygen

Table 2
Investigations and capabilities at KALLA

Technology loop	Thermal-hydraulic loop	Corrosion loop
	Single-effect investigations:	
Oxygen measurement	Solid beam window Windowless design	Corrosion mechanisms
Oxygen control	Closed target module	Protection layers
Measurement techniques	Fuel element	Mechanical tests
Heat transfer and turbulence	Steam generator	
High-performance heaters	Heat exchanger	
	Integral investigations: Core heat removal Decay heat removal	
Fluid volume: 0.1 m^3	Fluid volume: 0.5–4.0 m^3	Fluid volume: 0.03 m^3
Temperature: max 550°C	Temperature: max 550°C Power: 0.3–4.0 MW	Temperature: max 550°C
Flow rate: max 5 m^3/h	Flow rate: max 100 m^3/h	Flow rate: max 3.5 m^3/h

potential of the various selected materials will be evaluated within a co-operation with IPPE Obninsk. This experimental effort will result in a data base that will allow the comparison between the selected materials and offer a reference baseline to anticipate the behaviour of the MEGAPIE window. Different devices, static and rotating probes, will be used in CEA to assess the effect on corrosion of flow velocity and of spallation elements introduced as chemical impurities. This includes initial impurities before start-up, corrosion products, spallation products, impurities, such as air, introduced during operation, etc. After identifying sources and nature of impurities and establishing functional specifications of purification systems, selected processes (cold traps, getters, filters, EM traps,...) have to be qualified. A benchmark is being organised to provide a standard for the laboratories involved in physico-chemical studies in order to be able to compare results from various laboratories. CEA is working on a chemical specification for lead bismuth in collaboration with its European partners.

Research activities are also foreseen to validate a strategy to maintain a constant oxygen concentration: various processes will be elaborated to maintain the oxygen concentration at a constant value, in order to protect the structures against corrosion. The oxygen value will be defined from corrosion studies. The processes of gas control cold trapping, equilibration method, ‘electrochemical pump’ will be investigated and compared. The most promising processes will be tested on the available experimental facility. Thermal hydraulic investigations will be performed at FZK (within KALLA), ENEA (within CIRCE) and FZR.

6.8. The French GEDEON network (groupement de recherche)

The GEGEON ‘groupement de recherche’ is a joint initiative of CEA, CNRS, EdF and FRAMATOME, which co-ordinates the R&D activities on ADS in France as a contribution to the research on innovative options for waste management. GEDEON has launched a number of research projects in the fields of materials for targets and beam windows (radiation effects, physico-chemical properties and behaviour), neutronics of subcritical systems, spallation physics, nuclear data, accelerator requirements and system studies. The CEA/CNRS participation in the MEGAPIE project will be co-ordinated through GEDEON.

7. Conclusions

The MEGAPIE project will be an essential step towards demonstrating the feasibility of coupling a high power accelerator, a spallation target and a subcritical assembly. It will specifically address one of the most critical issues, namely the behaviour of a liquid metal target under realistic operating conditions. As an intensely instrumented pilot experiment it will provide valuable data for benchmarking of frequently used computer codes and will furnish important experience in the safe handling of components that have been irradiated in contact with PbBi.

The supporting R&D activities focus ongoing research and streamline efforts in several European laboratories.

MEGAPIE will also be a valuable contribution to potential collaborations with partners outside Europe, and can help to establish an effective sharing of work.

The envisaged target date (irradiation in 2004) is consistent with development plans in the accelerator driven system domain and with the milestones of the 5th and 6th European Union Framework Programs, as well as with upgrade plans in the SINQ facility.

The results obtained in this pilot experiment will also help PSI to decide whether or not it wants to go ahead with the development of a liquid metal target for routine use in its spallation neutron source. If the answer is positive, this will be a continuous source of experience and information which will benefit the ADS activities of all participating parties.

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The MEGAPIE initiative and concept are the result of the joint efforts and know how of many colleagues from all participating laboratories. While it is impossible to list every single name, it is a pleasure to acknowledge the wide spread support and enthusiasm this project has generated and the readiness of the directorates of the various collaborating institutions to support this initiative. Special thanks go to R. Eichler, PSI, M. Boidron, CEA, F. Dupont, CNRS, G. Gherardi, ENEA, G. Heusener, FZK, and P d'Hondt, SCK.CEN for their willingness to serve on the Project Steering Committee. Last but not least, the support of part of the work through grants from the European Commission and the Swiss Bundesamt für Erziehung und Wissenschaft is highly appreciated.

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