INSTITUTE OF PHYSICS PUBLISHING PHYSICA SCRIPTA
Phys. Scr. **T123** (2006) 1–7 doi:10.1088/0031-8949/2006/T123/001

Frontiers of dense plasma physics with intense ion and laser beams and accelerator technology

D H H Hoffmann[1], A Blazevic[1], O N Rosmej[1], P Spiller[1], N A Tahir[1], K Weyrich[1], T Dafni[2], M Kuster[2], M Roth[2], S Udrea[2], D Varentsov[2], J Jacoby[3], K Zioutas[4], V Mintsev[5], V E Fortov[5], B Yu Sharkov[6] and Y Maron[7]

[1] Gesellschaft für Schwerionenforschung, GSI-Darmstadt, Plasmaphysik, Planckstr. 1, 64291 Darmstadt, Germany
[2] Institut für Kernphysik, Technische Universität Darmstadt, Schloßgartenstr. 9, 64289 Darmstadt, Germany
[3] Universität Frankfurt, Institut für Angewandte Physik, D-6000 Frankfurt, Germany
[4] European Organization for Nuclear Research (CERN), Geneve, Switzerland
[5] Russian Academy of Sciences, Institute of Problems of Chemical Physics, Chernogolovka, 142432 Russia
[6] Institut for Theoretical and Experimental Physics (ITEP), Moscow, 117259 Russia
[7] Department of Particle Physics, Weizmann Institute of Science, Rehovot, IL-76100 Israel

E-mail: D.Hoffmann@gsi.de

Received 6 June 2005
Accepted for publication 5 September 2005
Published 17 March 2006
Online at stacks.iop.org/PhysScr/T123/1

Abstract
Interaction phenomena of intense ion and laser radiation with matter have a large range of application in different fields of science, from basic research of plasma properties to application in energy science. The hot dense plasma of our neighbouring star the Sun provides 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 numbers: 51.30.+i, 52.20.−j, 52.25.Fi, 52.57.−z, 52.58.Hm, 52.29.−f

(Some figures in this article are in colour only in the electronic version.)

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 or dark energy and we do not know anything about their nature except that the gravitational interaction is observable [1]. 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 such as 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, such as electrical discharges in a gas or laser irradiation of a sample. Intense heavy ion beams add on to the previously 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 analyse 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. 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 the facility for antiproton and ion research (FAIR). This new accelerator (see figure 1) will consist of two powerful heavy ion synchrotrons and a number of storage rings and experimental facilities for various research projects [5]. The centrepiece 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^{-1} by at least two orders of magnitude up to 12000 GW g^{-1}. 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 [6].

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 **n**anosecond **h**igh **e**nergy **l**aser for **i**on e**x**periments (*nhelix*) is currently complemented by a new laser *PHELIX* (**P**etawatt **H**igh **E**nergy **L**aser for **I**on E**x**periments) [7]. 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 (10^{15} W). 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.

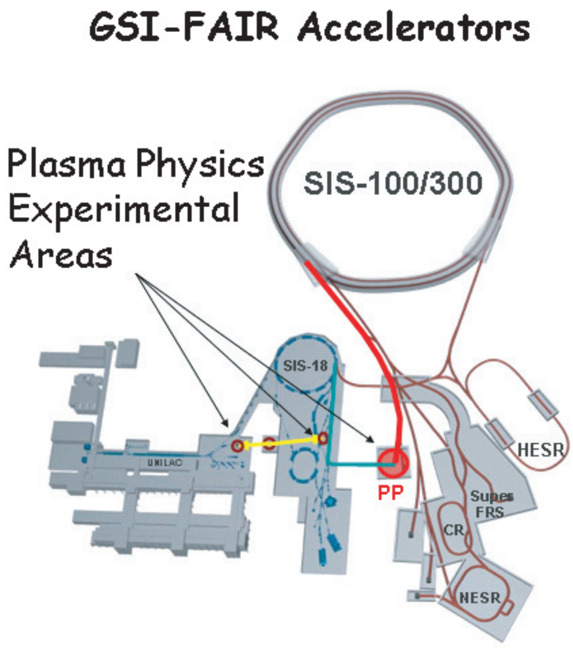

Figure 1. Schematic layout of the planned FAIR accelerator facility at GSI with the experimental areas for plasma physics. The FAIR project at GSI will greatly improve the experimental option for beam–plasma experiments. The arrows point to the existing experimental areas of plasma physics and the future installation at FAIR. Each experimental area is already served, or will in the future be served, with heavy ion beams from the accelerator and an intense laser beam.

3. High energy density physics

The 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 [8–11]. 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 [12].

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^{-1}] and the deposition power P_{s} measured in W g^{-1}. Hence the physics of beam induced high energy density matter is governed by three equations:

$$E_{\mathrm{s}} = (1.6 \times 10^{-19}) \times \frac{(\mathrm{d}E/\mathrm{d}x)N}{\pi \times r^2}\,(J/g), \qquad (1)$$

where $\mathrm{d}E/\mathrm{d}x$ is the stopping power of the material, N is the number of beam ions delivered by the accelerator, and 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 and we will show later that

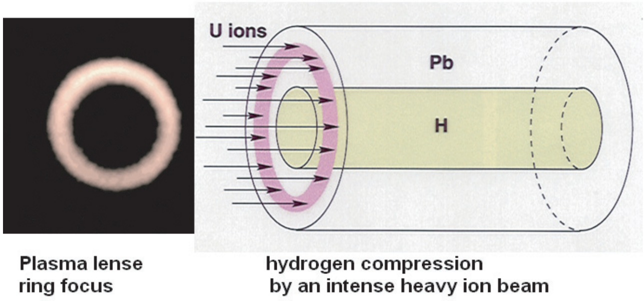

Figure 2. An annular beam focus, achieved by plasma lens focusing is used to compress a hydrogen sample [12, 16].

it may be a very different situation if the matter is in an ionized state or not. The time τ_H to deliver this energy is limited, due to the hydrodynamic response of the beam heated material, and is approximately given by:

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

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 be focused into a sample with a small focal spot size. The presently available beam from the SIS 18 is focused by a fine focus system. Until recently a plasma lens was in operation and a beam spot radius of 250 μm was achieved by a 400 kA discharge current of the plasma lens [13, 14]. A specific power deposition up to 10 GW g^{-1} is achieved and results in a pressure inside the investigated target of about 10 kbar [15].

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. To illustrate this capability, two-dimensional numerical simulations have been carried out with respect to the parameters for hydrogen metallization. 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^{-1} with a total number of 5×10^{11} particles. Our simulations show that hydrogen metallization is well within reach for the new accelerator facility [12, 16].

The energy deposition characteristics of high energy heavy ion beams in dense matter favour a cylindrical geometry. A simple experimental scenario is therefore a quasi-cylindrical plasma volume created by focusing an ion beam. 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 2. This is a very challenging problem for the beam transport and focusing system. However, a ring focus was demonstrated experimentally, which was achieved by carefully tuning nonlinear field gradients of the plasma lens [13]. 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 [16]. Alternative schemes to achieve a hollow beam are based on high-frequency rotation of a beam spot on target. Are 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 [37, 38, 41].

4. Interaction experiments of heavy ion beams with plasmas

The investigation of interaction processes of high energy heavy ion beams with matter is a research topic with a long tradition at accelerator laboratories. At least for simple collision systems a basic understanding of the dominant atomic and nuclear interaction mechanisms has been achieved. However, energy loss and charge exchange reactions with dense, ionized matter have added new and interesting aspects to this field [17]. Interaction processes between intense ion beams and plasmas are an ideal tool to probe high energy density plasmas and to investigate their properties. The kinetic energy of the heavy ions can exactly be tailored to the experimental conditions. The ions penetrate deeply into the volume of the plasma target. Energy loss and the final charge state distribution of the ions are the typical signals which reveal the beam–plasma interaction processes, and which allow us to draw conclusions for the plasma target properties [18]. The general interest in these measurements is the determination of the deposition power with high accuracy, an analysis of recombination and charge exchange processes, and the hydrodynamic response of matter irradiated with high-intensity heavy ion beams [19–22].

First beam–plasma interaction experiments at GSI have been carried out to compare the stopping power of hydrogen gas and fully ionized hydrogen plasma. Plasmas in linear discharge geometry and a dense z-pinch plasma [23] have been employed to cover the density regime from $n_e = 10^{16}$ to 10^{19} cm^{-3}. These experiments clearly demonstrated the increased stopping power of fully ionized plasmas, due to the interaction of beam ions with free electrons in plasma.

The beam energy in these first experiments was varied between 1 and 6 MeV u^{-1} for different ion species from carbon to uranium and the stopping power enhancement accounted for was roughly a factor 3. This enhancement, as seen in figure 3, was mainly attributed to the efficient energy transfer to free electrons in small angle collisions. For lower kinetic energies, where the projectile velocity is comparable to the thermal velocity of the plasma electrons, the energy loss behaviour is even more dramatic. An enhancement factor close to 40 was measured [22], and the main contribution in this case is the higher effective charge state Z_{eff} of the beam

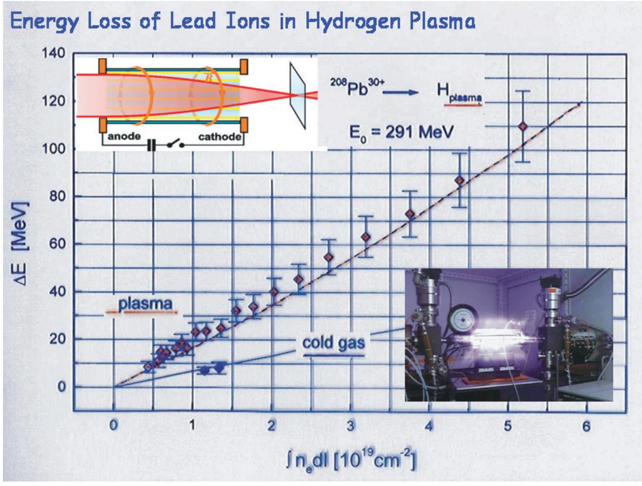

Figure 3. Energy loss of Pb ions in hydrogen gas and hydrogen plasma. The plasma was generated by a discharge.

Bethe - Bohr - Bloch stopping theory

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \frac{16\pi {a_0}^2 {I_H}^2 Z_p^2}{m_e v_p^2}\left[\sum_{Z=0}^{Z_K}(Z_K - Z)n_z \ln\left(\frac{2m_e {v_p}^2}{I_Z}\right) + n_e \ln\left(\frac{2m_e {v_p}^2}{\hbar\omega_P}\right)\right]$$

effective projectle charge

bound electron contribution

free electron contribution

Figure 4. The stopping power of an ionized medium is described by contributions from bound and free electrons to the electronic energy loss. For a fully ionized plasma the bound electron contribution is zero.

ions, due to the reduced recombination processes in highly ionized plasma. The dynamic equilibrium between ionization and capture processes is shifted towards higher charge states. Free electrons are difficult to capture for the beam ions, since energy and momentum conservation requirements are difficult to be fulfilled at the same time with free electrons. With bound electrons, however, momentum conservation is generally no problem due to the strong binding energy. The resulting reduction in electron capture cross-section depends strongly on the ionization degree of the plasma. Therefore hydrogen gas was the first choice as a plasma target, because it is the only material which can be transformed from a solid to a liquid, a gas, a plasma and finally a completely ionized plasma with only a negligible amount of remaining bound electrons. Charge state analysis of beam ions penetrating the fully ionized hydrogen plasma clearly showed the effect of an enhanced average charge state [24]. The effect is well understood and described for ideal plasmas by the well known Bethe–Bohr–Bloch stopping theory as shown in figure 4.

Laser heated plasmas provide higher temperatures and densities than gas discharges. Consequently, a powerful Nd:YAG/Nd:glass laser system at the Z6 experimental area of GSI has been installed [25–27]. With this device it was possible to investigate plasmas of the critical density 10^{21} cm^{-3} corresponding to the laser wavelength (1064 nm). The temperatures of these plasmas exceeded $kT = 60$ eV.

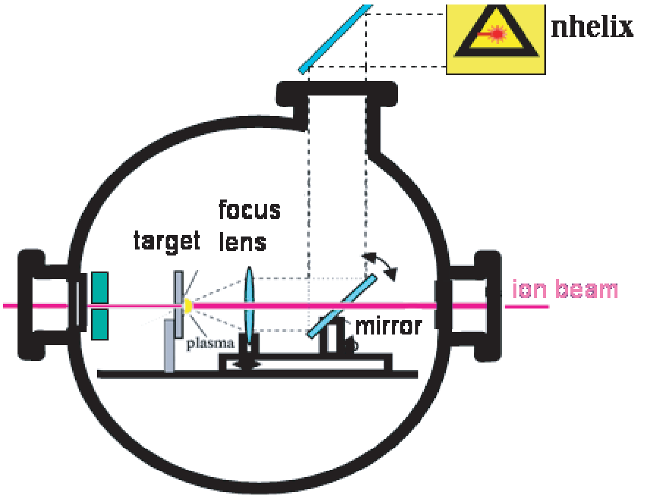

Figure 5. Experimental setup. The laser beam from above is focused on to the target, while the ion beam is guided through apertures to the laser plasma. The energy loss of the ion beam is measured by time-of-flight methods.

Because of the difficulty to focus heavy ion beams and the restriction that the target plasma size has to exceed the ion beam radius, the laser irradiated area had to be larger than 1 mm^{-2}. This constraint led to the necessity of a high energy pulse laser. The laser system consists of an Nd:YAG oscillator providing a laser pulse of 15 ns FWHM operating in a master oscillator/power amplifier (MOPA) scheme. The pulse is amplified in six amplification stages of up to 64 mm diameter until it has a maximum energy above 100 J.

In the experimental setup shown in figure 5, both the laser and the heavy ion beam are transported to the target in parallel, which is possible because the ion beam is penetrating the final focusing optics through small apertures. As the laser heated area of the target is much larger in diameter than the target thickness, the expansion of the laser heated target is mainly normal to its surface. Thus during the first phase of expansion the ions face an almost constant line density. The mainly one-dimensional expansion of the target was recently confirmed by high-resolution spectroscopy experiments [28]. It could be shown that strongly collimated jets emerge out of the plasma. This collimation is probably enhanced by strong magnetic fields, which can be generated by high gradients in the target plasma. The plasma jets contain ions of kinetic energies in the MeV range, as spatially resolved x-ray spectroscopy has shown [29].

Future interaction experiments will benefit from planned improvement of the laser performance at the experimental area. Within the next few years the installation of the Petawatt/kJoule system ‘PHELIX’ will be completed and can provide target plasmas of improved homogeneity, higher temperatures and higher densities. Fully ionized plasmas with atomic numbers up to and above 6 (carbon) will then be available. New target materials and designs give access to a more precise spectroscopic determination of the plasma parameters and new fields of investigation. Thus the development of thin cryogenic hydrogen films for laser plasma–ion beam interaction experiments will extend the stopping power studies for hydrogen plasmas to densities of almost solid state density. An improvement of spectroscopic techniques

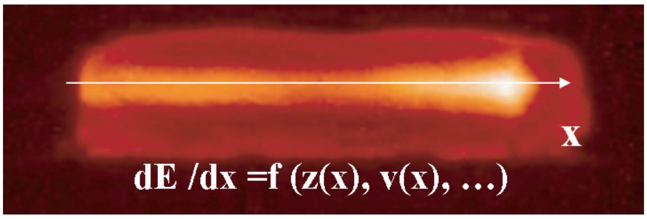

Figure 6. A 300 MeV u^{-1} Ar beam is penetrating into a Kr crystal. The aim of the experiment is the investigation of the stopping process of ions inside matter and to determine the dynamics of the energy loss as a function of penetration depth and velocity.

and new models of calculation will enable us to find more precise descriptions of the interaction of heavy ion beams with high-density plasmas, answering the questions that have been raised in the recent experiments.

Laser plasmas even in the high-density regime close to solid state density are usually ideal plasmas with a plasma parameter Γ much smaller than 1. The regime of dense, strongly correlated plasmas where Γ exceeds 1, will be addressed in shock wave experiments, using high explosives to compress the target material at low plasma temperatures. A collaboration between the Institute of Chemical Physics (Chernogolovka), the ITEP (Moscow), and GSI has just been started to characterize the plasma target. First experiments with low-energy proton beams at ITEP impinging on explosively driven plasmas have just been successfully completed. For detailed calculations of the energy deposition profile in heavy ion targets the total range of the ions has to be known. Usually the total range is obtained from differential energy loss measurements by integration procedures. Tabulated results differ by as much as 30%. A project to measure the total range of ions in an energy range from 5 MeV u^{-1} up to 300 MeV u^{-1} with a precision better than a few per cent has been initiated using novel techniques of highly efficient spectroscopy and calorimetric measurements [30].

5. Dynamic charge state evolution of the projectile ion

Inertial fusion energy requires intense laser or particle beams to heat matter to high temperatures on the order of 300 eV. Interaction processes of photons and ions with ionized matter are therefore an important ingredient for the process of inertial fusion. For this reason, GSI as an accelerator laboratory for heavy ions takes specific interest in the investigation of interaction phenomena of heavy projectile ions with ionized matter as well as solid and gaseous targets. Figure 6 shows a situation where the target thickness did exceeds the ion stopping length and thus the ions were fully stopped inside the target material.

The main goal of this experiment is to understand the details of the energy deposition of the fast heavy ion penetrating solid matter. This depends on the charge state distribution and velocity of the ion inside the target volume as well as on the target density. The availability of intense ion beams from the GSI accelerator, combined with improved spectroscopy methods made it possible for the first time to observe the dynamic evolution of the projectile ion velocity inside extended solid targets. We measured the K-shell projectile and target atom radiation in the photon energy region of 1.5–4 keV. Due to high spectral and spatial resolution, we were able to analyse the ion charge and velocity along the ion beam interaction path in extended solid targets [31].

In figure 7, the principal setup of the experiment is shown. Ionization and electron capture processes lead to the emission of characteristic radiation from target ions and atoms as well as from the projectile. Due to the high initial energy of 11.4 MeV u^{-1} the projectile velocity is approximately 10% of the speed of light in vacuum. Under these conditions the relativistic Doppler shift is observable also at observation angles perpendicular to the ion trajectory. The spatial resolution was 50–70 μm and we observed the ion penetrating into the solid target for almost 10 mm. Moreover, we made use of the variation of the projectile Kα-satellite's Doppler shift due to the ion deceleration to determine the ion velocity as a function of penetration depth.

Aerogel targets of SiO_2 with a low mean density of 0.15 g cm^{-3} allowed us to extend the ion stopping length more than 10 times as compared to a solid quartz target and it was therefore possible to increase spatial resolution of the method.

In figure 8, K-shell projectile spectra show the long lasting radiation of the highly charge Ar ions down to the energies of 2 MeV u^{-1}. The fact that the high charge states are obviously preserved down to very low energies is in disagreement with measurements of the ion charge state distribution measured after passing through solid carbon foils. In these measurements, the charge state is measured with detectors far away from the last interaction process, whereas the current method allows observing the charge state *in situ*. With these new measurements and the new technique, it will be possible to address the question why the charge state distribution of ions measured behind a gaseous target or a solid foil are so different, while the specific energy loss does not differ significantly.

6. Probing the hot dense interior plasma of the Sun

In this section we describe a recent experiment that was initiated for a number of reasons. Plasma physicists are interested in studying the properties especially 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 last but not least astroparticle 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.

Thus our neighbouring star, the Sun, provides a deep insight into the physics of fusion, the physics of hot plasmas and it is 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 axion is a direct consequence of the theoretical solution of the CP problem in strong interactions proposed by Peccei and Quinn [32]. 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

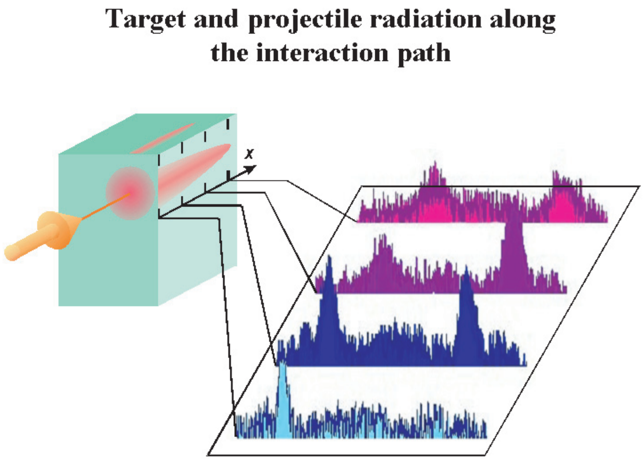

Figure 7. Along the interaction path the projectile and the excited target atoms or ions emit radiation, which is recorded with high spectral and spatial resolution.

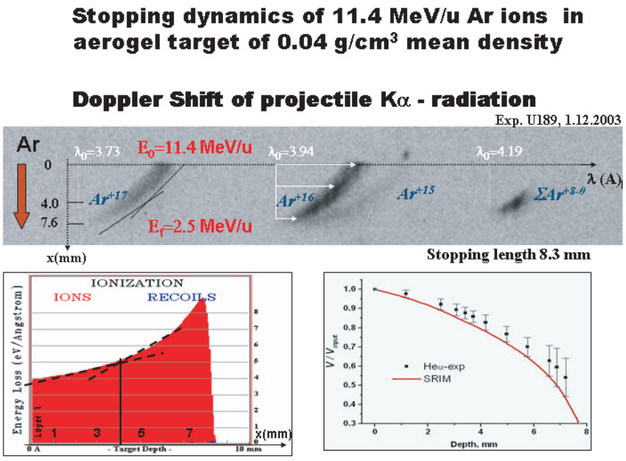

Figure 8. The upper insert shows the radiation spectra of Ar projectiles of different charge states from H-like (Ar + 17), He-like (Ar16+) and Li-like (Ar15+) down to the radiation of the lower charge state ions, which are not resolved. The lower left insert shows the derived energy loss as a function of penetration depth which is then compared to (lower left) standard stopping calculations.

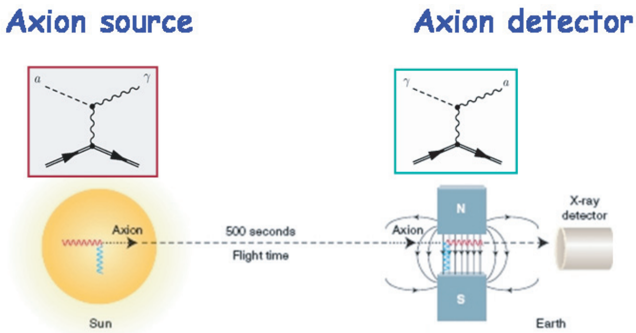

Figure 9. Solar axions are predicted to be created in the hot dense plasma of the solar interior via interaction of a real photon and a virtual photon of the electric field of an atomic nucleus. In a magnetic field the axion is converted back into a photon and may be detected with the proper x-ray detector.

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 figure 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.

The heart of CAST is a prototype of CERN's Large Hadron Collider (LHC) superconducting magnet providing a dipole magnetic field of 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

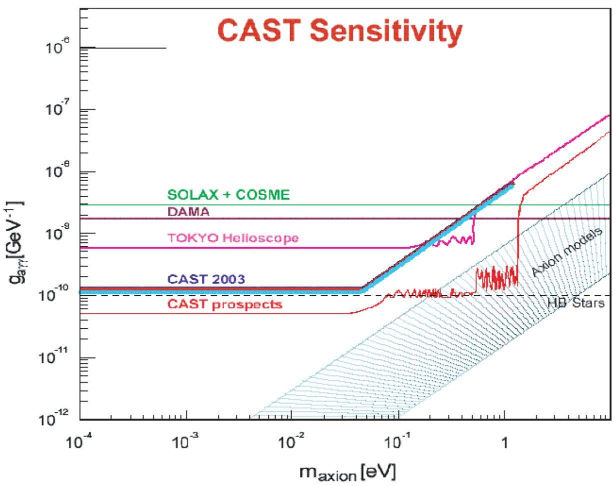

Figure 10. Upper limit (95%) of the axion to photon coupling depending on the axion mass m_a derived from the data of 2003. The shaded area represents the parameter range of theoretical axion models. The results of earlier experiments SOLAX, COSME, DAMA and the Tokyo helioscope are shown for comparison [33]. The best astrophysical limit based on evolutionary models of horizontal branch stars in globular clusters is indicated.

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 by a factor of $\sim$100 by concentrating the potential signal flux on a small spot on the pn-CCD detector. During the last 2 years CAST was taking data for about 12 months, 6 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 $g_a(95\%) < 1:16 \times 10^{-10}\,\mathrm{GeV}^{-1}$ [33].

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 figure 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 $m_a < 1:2$ 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 starting mid-2005, by filling the magnet pipes with an adequate buffer gas.

7. 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 [34–36]. 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 [39, 40]. 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 [42]. The detailed knowledge about interaction phenomena of intense fields with matter will certainly also influence the development towards inertial fusion. 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.

Acknowledgments

The authors would like to acknowledge the support of various funding agencies: German–Israeli Project (DIP), INTAS;WTZ. 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 team at GSI.

References

[1] Zioutas K, Hoffmann D H H, Dennerl K and Papaevangelou T 2004 *Science* **306** 1485
[2] Golubev A *et al* 1998 *Phys. Rev.* E **57** 3363–7
[3] Hoffmann D H H *et al* 2002 *Phys. Plasmas* **9** 3651–4
[4] Varentsov D *et al* 2003 *Europhys. Lett.* **64** 57–63
[5] Henning W F 2003 *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. Atoms* **204** 725–9
[6] Hoffmann D H H *et al* 2005 *Laser Part. Beams* **23** 47–54
[7] Neumayer P *et al* 2005 *Laser Part. Beams* **23** 385–9
[8] Dewald E *et al* 2003 *IEEE Trans. Plasma Sci.* **31** 221–6
[9] Tahir N A *et al* 2000 *Phys. Rev.* E **62** 1224–33
[10] Constantin C *et al* 2004 *Laser Part. Beams* **22** 59–63
[11] Godwal B K *et al* 2003 *Laser Part. Beams* **21** 523–8
[12] Tahir N A *et al* 2001 *Phys. Rev.* E **63** 016402
[13] Neuner U *et al* 2000 *Phys. Rev. Lett.* **85** 4518–21
[14] Stetter M *et al* 1996 *Fusion Eng. Design* **32** 503–9
[15] Constantin C *et al* 2004 *Rev. Sci. Instrum.* **75** 1268–73
[16] Tahir N A *et al* 2004 *Laser Part. Beams* **22** 485–93
[17] Hoffmann D H H *et al* 1990 *Phys. Rev.* A **42** 2313–21
[18] Hoffmann D H H *et al* 2000 *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. Atoms* **161** 9–18
[19] Jacoby J *et al* 1990 *Phys. Rev. Lett.* **65** 2007–10
[20] Boggasch E *et al* 1991 *Phys. Rev. Lett.* **66** 1705–8
[21] Wagner T *et al* 1996 *Phys. Rev. Lett.* **76** 3124–7
[22] Jacoby J *et al* 1995 *Phys. Rev. Lett.* **74** 1550–3
[23] Tauschwitz A *et al* 1995 *Laser Part. Beams* **13** 221–9
[24] Dietrich K G *et al* 1992 *Phys. Rev. Lett.* **69** 3623–6
[25] Roth M *et al* 2000 *Europhys. Lett.* **50** 28–34
[26] Roth M *et al* 1999 *Phys. Scr.* **T80A** 40–2
[27] Iwase O *et al* 1998 *Phys. Scr.* **58** 634–5
[28] Schaumann G *et al* 2005 *Laser Part. Beams* **23** 503–12
[29] Rosmej F B *et al* 2002 *J. Exp. Theor. Phys.* **94** 60–72
[30] Bakhmetjev I E *et al* 2003 *Laser Part. Beams* **21** 1–6
[31] Rosmej O N *et al* 2005 *Laser Part. Beams* **23** 79–85
[32] Peccei R D and Quinn H R 1977 *Phys. Rev. Lett.* **38** 1440
[33] Zioutas K *et al* 2005 *Phys. Rev. Lett.* **94** 121301
[34] Hora H 2004 *Laser Part. Beams* **22** 439–49
[35] Barnard J J *et al* 2003 *Laser Part. Beams* **21** 553–60
[36] Ratzinger U *et al* 2003 *Laser Part. Beams* **21** 627–32
[37] Piriz A R *et al* 2003 *Plasma Phys. Controlled Fusion* **45** 1733–45
[38] Temporal M *et al* 2003 *Laser Part. Beams* **21** 609–14
[39] Tahir N A *et al* 2005 *Phys. Rev. Lett.* **94** 135004
[40] Tahir N A *et al* 2005 *J. Appl. Phys.* **97** 083532
[41] Temporal M *et al* 2005 *Laser Part. Beams* **23** 137–42
[42] Tahir N A *et al* 2005 *Phys. Rev. Lett.* **95** 035001