High energy density physics with intense ion beams

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Abstract

We review the development of High Energy Density Physics (HEDP) with intense heavy ion beams as a tool to induce extreme states of matter. The development of this field connects intimately to the advances in accelerator physics and technology. We will cover the generation of intense heavy ion beams starting from the ion source and follow the acceleration process and transport to the target. Intensity limitations and potential solutions to overcome these limitations are discussed. This is exemplified by citing examples from existing machines at the Gesellschaft für Schwerionenforschung (GSI-Darmstadt), the Institute of Theoretical and Experimental Physics in Moscow (ITEP-Moscow), and the Institute of Modern Physics (IMP-Lanzhou). Facilities under construction like the FAIR facility in Darmstadt and the High Intensity Accelerator Facility (HIAF), proposed for China will be included. Developments elsewhere are covered where it seems appropriate along with a report of recent results and achievements.

1. Introduction

This millennium experienced a fast-paced development of High Energy Density Physics (HEDP). This evolved parallel to the advancements in driver technology. Most prominent is the development of high power and high-energy lasers, where the National Ignition Facility (NIF) is an outstanding example [1–3]. Also pulsed power devices like the Z-Machine at Sandia National Laboratory, Albuquerque, and Angara-5-1 in Troitsk reported towering progress [4–8]. Along with laser and pulsed power devices, high explosives [9,10] and intense particle beams [11–13] are suitable and commonly used drivers to induce high energy density states. The expressions High Energy Density-matter, Hot Dense Matter or Warm Dense Matter (WDM) are often used interchangeably and are not defined unambiguously; however, we are talking about matter of temperature at least in the eV/kB-regime and above (where kB is the Boltzmann constant, which we will omit in future when we talk about a temperature stated in eV). The density is about solid-state density and higher, and finally owing to these parameters, depending on the equation of state of the material, the pressure is above the GPa range. Thus

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matter with such properties takes up a large area of the respective phase diagram, and is of interest in diverse domains of physics, such as astrophysics, planetary physics, power engineering, controlled thermonuclear fusion, material science and more.

The National Ignition Campaign [14] was supposed to show ignition of a fusion target in the laboratory by the end of 2012. However, even though the laser worked perfectly up to the design parameters and even outperformed them with respect to the total energy delivered to the target, ignition of the fusion target did not occur. Of course one may debate that the fusion energy output measured in terms of neutron yield [15], which is on the order of some 10 kJ, is equivalent to the energy that finally reaches the compressed fuel, and therefore in some respect one may speak of scientific breakeven. The reason why ignition did not occur is still under debate within the scientific community and most probably a number of sources play a role, among them turbulent mix of the fuel during the compression phase. During the compression phase the fuel heats up and passes through the Warm Dense Matter regime. Here the properties of matter as expressed by an Equation of State (EOS) are widely unknown. In the high compression regime we have to deal with degenerate matter. Energy loss of charged particles in degenerate matter is practically unexplored, which was pointed out by RD Petrasso in his Teller-award lecture during IFSA 2013 at Nara, Japan (International Conference on Inertial Fusion Science and Applications).

Since the perspectives of fusion energy are very important and very promising, we think it is time to review alternative inertial fusion driver concepts. Such an alternative to intense laser beams is constituted by intense high energy heavy ion beams. They can be produced efficiently, where the conversion of electric power to kinetic energy of heavy ions is on the order of 25% and accelerators by design work at high repetition rate. Thus swift, heavy ions are very efficient carriers of energy. Moreover their specific interaction properties also make them ideal candidates to generate high energy densities in matter.

2. Accelerator issues of high energy density physics

2.1. High current ion sources

As well as even the longest journey starts with the first step (Chinese wisdom), an efficient accelerator depends on the ion source and here we start our discussion.

Inertial Fusion Energy (IFE) and similarly the generation of high energy density matter generated by ion beams require considerably more ions per pulse, than classical ion sources are able to deliver [16]. One way to overcome this problem was the suggestion that was already made in the early system studies for heavy ion driven fusion like HIBALL (Heavy Ion Beams and Lithium Lead) and HIDIF (Heavy Ion Driven Ignition Facility) [17–19]. It was proposed to have multiple ion sources, and to increase the intensity by beam funneling as shown in Fig. 1. This of course causes the beam emittance to grow, which we will discuss later. Alternative solutions to
decrease the number of funneling stages, as well as the necessity to overcome the Child Langmuir space charge limitations, had to be investigated. In a conventional electron- or ion source (see Fig. 2) the current density $J$ is limited to

$$J \propto \frac{U^{3/2}}{d^2} \quad (1)$$

where $U$ is the extraction voltage and $d$ is the gap distance between the ion source electrodes. For a given gap distance the voltage $U$ is limited by the electric breakdown, which leads to a general limit for a given geometry. Laser-produced plasmas may partially overcome this limit. Today high power laser interaction with plasma does generate intense high energy particle beams [20–22]. However, these kinds of beams have not yet been effectively coupled to accelerator structures. Several institutes are currently working on this problem, among them CERN and GSI-Darmstadt. On the other hand laser generated plasmas have been used very efficiently as ion sources. One of the first examples is the laser plasma ion source at CERN [23]. This ion source was later moved to
ITEP-Moscow, where it served for many years as ion source for highly charged ions [24]. The original CO$_2$ laser was later tried to be replaced by an Nd-laser to produce helium like ions up to medium and high Z-targets, however, there was no significant advantage with respect to technology and repetition rate, thus for the whole project the CO$_2$ laser was used. The expanding laser plasma (see Fig. 3) is funneled by an aperture system into the extraction system operated at 120 kV and an adjacent low energy beam transport system with gridded electrostatic lenses. A final double aperture simulates the acceptance of the RFQ-accelerator section (Radio-Frequency-Quadrupole). The expanding plasma is still quasi-neutral. However, after the extraction system there exists a beam with space charge. In order to match this beam to the accelerator structure, space charge compensation by injecting electrons from a thermionic tungsten cathode was applied. By this technique a current density increase of up to a factor of 25 was achieved [25]. H. Riege and co-workers (1998) used electron beams emitted from ferroelectric materials for space charge neutralization with pulsed electron beams [65]. Even though the offline experiments showed very good results, this technique never entered the testing phase in an actual accelerator [65]. A typical charge state spectrum obtained for Pb is shown in Fig. 4, with the most intense charge state Pb$^{27+}$ and Pb$^{28+}$. A similar charge state spectrum is obtained from stripping lead ions at an energy of 1.4 MeV/u after a gas stripper. This is the situation which is common at the GSI accelerator where a stripping section exists at 1.4 MeV/u after a total acceleration length of about 50 m, which is necessary for a powerful low energy accelerator system to handle ions of low charge state. The advantage of a laser-plasma ion source is thus obvious. In the example shown in Fig. 4, a CO$_2$-laser of 92.5 J and a power density of $P = 3 \times 10^{13}$ (W·cm$^{-2}$), with the parameters indicated there was used. For non-resonant photoionization the laser intensity $I$ necessary to obtain the charge state distribution with a maximum charge state $q$ of an element with atomic number $Z$ and ionization energy $E_{\text{ion}}(Z)$ is approximately given by:

$$I \approx 4 \times 10^9 \frac{E_{\text{ion}}(Z)^4}{q^2}. \quad (2)$$

The charge state spectrum, under the assumption of local thermal equilibrium in the expanding laser plasma, represents the relative abundance of ionization states given by the Saha equation, where $\frac{n_{z+1}}{n_z}$ is the ratio of the particle numbers in different ionization states $z$ and $z+1$. This ratio is then multiplied by the electron density $n_e$:

$$\frac{n_{z+1}n_e}{n_z} = \frac{g_{z+1}}{g_z} e^{-\frac{w_z}{\pi}} \cdot \frac{(2m_e)^{1/2}}{\pi^2\hbar^3} \int_0^\infty \sqrt{E} \cdot e^{\frac{-E}{\pi}} dE$$

$$= \frac{g_{z+1}}{g_z} \cdot \frac{2(2\pi m_e kT)^{1/2}}{\hbar^3} e^{-\frac{w_z}{\pi}} \quad \text{(3)}$$

![Fig. 3. Laser Plasma ion source at CERN and ITEP.](image-url)
In this equation $g$ are the statistical weights of the quantum states, $W_{iz}$ is the ionization energy, $m_e$ is the electron mass at rest, $k$ is the Boltzmann constant, $h = \frac{p}{c}$ is Planck's constant divided by $2\pi$, and $T$ the temperature. In the expanded laser plasma this equation approximately presents the situation. Observed deviations from the charge state ratio point to a situation which is not fully in equilibrium. Moreover the ion charge state distribution does not remain “frozen” during plasma expansion as long as the density is high enough to allow for three-body recombination. This process, however scales with $n_e^2$. Therefore at the later stage of expansion, the equilibrium is determined by collisional ionization and radiative recombination, a situation which is called corona equilibrium.

At the GSI radio frequency quadrupole accelerator RFQ-Maxilac matching of a laser ion source to this accelerator was demonstrated [26]. A 10 J/μs CO₂ laser has been used to produce a hot plasma plume, from which highly charged tantalum ions were emitted. For the charge state Ta$^{10+}$, a current of 1.8-mA was measured after acceleration to 45 keV/u.

Laser-plasma ion sources are today used in many places, Refs. [27,28] give just two examples of currently ongoing research in this field.

2.2. Low energy beam transport

Space charge limitations are especially serious at low energy. Therefore special attention is necessary to match the low energy beam, which was produced from the ion source, to the low energy accelerator section. In 1979 Alfred Maschke at Brookhaven National Laboratories developed a set of equations to determine the transport limit for a generalized linear accelerator [29]. The current density $J$ is thus determined by:

$$J \left[ \text{mA/cm}^2 \right] \propto \frac{A}{Z} (\beta \gamma)^3.$$  

(4)

This equation shows that at low energy the beam is severely subjected to space charge, and strong focusing forces are necessary to overcome this effect. Therefore the invention of radiofrequency quadrupole focusing and acceleration (RFQ) by Kapchinsky and Teplakov in 1970 [30], represented a major progress to increase the beam intensity of particle accelerators. Later under the guidance of Kapchinsky and Koshkarev at ITEP in Moscow [59,60], and even a bit later at GSI Darmstadt under the leadership of R. Müller [31] RFQ accelerators for heavy ions were built and used for early high energy density physics experiments. The machine at GSI was designed to accelerate heavy ions up to an energy of 45 keV/u. The accelerator was called MAXILAC and was used to generate the first heavy-ion beam induced plasma with a temperature of 0.75 eV.

Phase space limitations are not only a concern during low energy transport. Intensity limitations are less restrictive at high energy due to the scaling proportional to $(\beta \gamma)^3$, as indicated in Eq. (4). At the end of the linear acceleration the beam is injected into the synchrotron. At GSI-Darmstadt this is a synchrotron for beams with a maximum rigidity of 18 Tm. If the beam may be described by a distribution function $f(x, v, t)$, which fulfills the conditions of kinetic plasma theory, that is, we deal with non-interacting particles and local thermal equilibrium then we obtain the Vlasov equation with

$$\frac{df(x, v, t)}{dt} = 0$$

(5)

The physical interpretation of this result is, that a particle in a considered volume does not experience any change of the distribution function in its local frame of reference as long as it is subjected to conservative (non-dissipative) forces only. This amounts to the fact that the local distribution function is conserved, and it is an invariant. This holds equally true for the phase space and this result is also known as the Liouville theorem (Conservation of phase space), which has direct consequences for the beam properties.

2.3. Multi-turn injection and Liouville limitations

For most experiments and applications that request high intensities, especially for high energy density plasma physics, the beam is first accumulated in the synchrotron by filling it over many turns before it is accelerated (see Fig. 5). This technique is known as multi-turn injection. Due to the above mentioned Liouville theorem it is not possible to inject into an already occupied phase space volume for a second time without losing the particles. This means that the phase space ellipsoid of the injected beam must be well adapted to the partial ellipsoids that are already present inside the machine. The phase space matching is done using the beam transport system before injection (Fig. 5(b)). The equilibrium trajectory (shown in red) is disturbed by means of a number of bumper magnets (in Fig. 5 two are shown). They cause a local bump and deviation from the ideal trajectory. The SIS-18 injection system uses a total of four bumper magnets located close to the septum magnet. The magnitude of deflection is maximum at the start of the injection process and is gradually tuned to zero. As indicated in Fig. 5(c), the acceptance of the synchrotron (150 mm mrad) shown as red ellipse is filled from the inside to the outer rim. This method requires, that the emittance of the injected beam is smaller than the acceptance of the synchrotron (transverse stacking method).

The intensity and beam quality obtained by multturn injection is not sufficient for a cost effective inertial fusion driver based on rf-linac and synchrotron. A more effective stacking method therefore was tested at the Terawatt Accumulator of ITEP-Moscow (TWAC) [32]. This method is based on Non-Liouvillian Stacking by Charge exchange injection.

To overcome the limitations set by the Liouville theorem the circulating particles and the injected particles are of different species, thus they are allowed to occupy the same phase space volume. This is possible by changing the charge state of the injected species when the injected beam is combined with the circulating beam. The original idea of G.I. Budker in 1963 was put forward on an accelerator conference and was later published in a journal [33]. The process was first
tested with H$^{1+}$ circulating in a storage ring with weak focusing. The injected beam was neutral hydrogen H$^{0+}$. After H$^{0+}$ and H$^{1+}$ were combined both species had to pass a gas jet serving as stripper target. The stripping process yields a combined pulse of H$^{1+}$. The same scheme may in principle also applied for heavy ions. However, the stripping process at the stripper target usually results in the production of a charge state spectrum and hence results in a loss of beam intensity. A different situation arises when the energy of the circulating and injected beam is high enough that stripping produces predominantly fully ionized ions. This situation is depicted in Fig. 6. The incoming beam $Z^q$ consists of the ion species $Z$ with charge state $q$. The nuclear charge of these ions is also $Z$ and we have the condition $q \leq Z$, which means that $q$ is smaller, but in the vicinity of $Z$. Therefore a high charge state $q$ is already necessary, which may be obtained by a laser-plasma ion source or by an ECR-source (Electron Cyclotron Resonance) [66]. In Fig. 6 the dashed red circle represents the ideal trajectory of the fully stripped circulating beam. At the injection the beam is in a lower charge state, ideally helium like. In the overlap region the fully stripped and the helium like beam occupy the same phase space. In a thin stripper foil the helium like beam is transformed to the fully ionized state. The stripper foil must be sufficiently thin, in order to minimize beam degradation during the stacking process. This case was successfully realized at the ITEP-TWAC accelerator system [32,34]. The scheme is shown in Fig. 7. The accelerator system at ITEP consists of two rings. In the UK booster ring the respective ions are accelerated to a maximum energy of 0.7 GeV/u and then transferred to the U-10 accumulator ring. In this ring already bare nuclei are circulating. After the transfer from the booster ring where ions are not yet fully stripped to the accumulator ring, ions are injected into the same phase space volume as the already circulating, fully stripped ions. Then both bunches pass the stripper target and after the stripper target all ions with minimal loss of intensity and energy are fully stripped. The inset of Fig. 7 shows the example of Carbon at 213 MeV/u and the accumulation of intensity after each injection step. The final intensity is approximately $N_{\text{ions}} \approx (4 - 5) \times 10^{10}$.

The laser-plasma ion source described above was used to produce helium like charge states C$^{4+}$, S$^{16+}$, Ca$^{18+}$, and Co$^{25+}$. The maximum stripping energy was 0.7 GeV/u. In the ideal case one would use lower charge states due to space charge considerations. In fusion scenarios even Pb$^{4+}$ or Bi$^{1+}$ are discussed. In this case one needs a very powerful laser to resonantly ionize to charge state 2+. Such lasers are currently not available to produce intense beams, but there is certainly a development path. Finally the limit for the maximum intensity is set by the appearance of beam instabilities, like:

### 2.4. Incoherent tune shift limit

Ion driven inertial fusion, as well as experiments of High Energy Density physics require highest beam intensities. Therefore a synchrotron has to be operated up to the space charge limit. As shown in Fig. 8, this limit was reached for moderately heavy ions up to $^{58}$Ni$^{4+}$ and $^{86}$Kr$^{4+}$ already in 1999. This amounts to approximately $(3 - 4) \times 10^{10}$ particles of this ion species per ion pulse. For Uranium ions of charge state 73+ this limit has not yet been reached. Before we...
discuss the reasons let us take a quick look at the physics underlying this space charge limit. The Coulomb repulsion, due to the positive charge of the ions constituting the beam pulse, is offset by focusing forces of the electromagnetic quadrupoles. Close to the ideal trajectory of the beam the focusing force increases linearly with the distance from the beam center. The individual beam particles, however, do not follow the ideal trajectory, but they do perform oscillations as shown in the schematic drawing of Fig. 9. If the number of betatron oscillations per circulation \( Q \) is an integer or close to it, the particle will come to the same position after an integer number \( m \) of circulations. The resonance condition is 
\[
m \cdot Q = \text{integer}.
\]
Thus any positioning error of the beam transport system will amplify and the beam is lost within a few circulations. Therefore the number \( Q \) of betatron oscillations must be chosen carefully to stay off any of these resonances. An increase in beam intensity tends to reduce the number of betatron oscillations and hence a shift \( \Delta Q \) occurs. If this shift causes a resonance condition, the beam experiences a resonance condition and is lost. In heavy ion synchrotrons the beam is stored only for a relatively short time during multi-turn injection, therefore a tune shift of up to \( \Delta Q \approx 0.5 \) is possible [36]. The reason why until now the space charge limits for heavy ions at low charge state has not yet been reached is due to the problem of the dynamic vacuum.

### 2.5. Dynamic vacuum

Up to very recently (2014) all experiments at the High Energy Density Physics area at GSI were performed with a maximum of \( 4 \times 10^9 \) beam ions. The bunch length may presently be varied between 80 ns (minimum, lower intensity) and 120 ns (maximum intensity). A higher intensity for \( \text{U}^{73+} \) was achieved in 2014 by measures that we will discuss here. Eventually, even still higher intensities may be expected for a lower charge state e.g. \( \text{U}^{28+} \). However the problems encountered with the higher charge state will turn out to be even more severe in the low charge state case. To prove the feasibility, experiments at the SIS-18 were conducted to test high intensity uranium operation with low charge states [37]. During these injection experiments, a varying number of \( \text{U}^{28+} \)-particles up to \( 7.4 \times 10^9 \) were injected and stored at the injection energy of 11.4 MeV/u. The results (see Fig. 9) showed...
extremely fast and intensity-dependent particle losses. Moreover the more intensity was injected, the faster the beam was lost as can clearly be seen from Fig. 10. With this injection experiment the pressure at various locations of the synchrotron was measured. This required the possibility of fast pressure measurements. Simultaneously with the loss of beam a dynamic increase in the residual gas pressure was observed. Therefore we concluded that the beam was not lost due to space charge instabilities since the intensity was still well below this limit. The effect was, however, a result of desorption effects. The inset of Fig. 10 shows schematically a section of the synchrotron with a bending magnet. Even at ultra-high vacuum conditions there are still $10^6 - 10^7$ particles per cubic centimeter. Charge changing collisions have a high cross section and therefore the probability of a collision that results in a change of charge state of the beam ion is quite high. If such a collision occurs, the ion is removed from the ideal trajectory and will hit the beam pipe at some later position. Kinetic energy of the beam ion is deposited into the surface of the beam pipe where a multitude of molecules are adsorbed. The sudden input of energy causes desorption and per original beam ion up to $10,000$ desorbed ions may be released into the vacuum of the synchrotron. Thus more beam-ions undergo a charge changing collision, which sets off an avalanche with the consequence of total beam loss. Ultrahigh vacuum is therefore mandatory for high intensity heavy-ion synchrotrons and it is the main reason for superconducting magnets, since the cold surface also serves as a cryo-pump to keep the vacuum low. Currently sticking coefficients are measured to gain more knowledge about adsorption and absorption effects. The results will help to design optimum parameters for the FAIR facility, which is under construction. Therefore, a quantitative description of the observed effects, which affect the lifetime of intermediate charged ion beams need to include calculation of the interaction of the beam particles with rest gas molecules/atoms and particle trajectories with aperture limits in the ring structure.

A design concept for the SIS-100 synchrotron of the FAIR facility must have residual gas pressure stabilization. The idea was to develop a dedicated ion catcher system and strong pumping of cold surfaces where effects of desorption are expected to occur. Thus a careful analysis of the beam transport system and proper alignment of all magnets is paramount to the success. Then it is possible to place a properly designed system of catchers at places with high desorption probability. This was done by Lars Bozyk in his thesis work: “Design and test of a prototype cryo-collimator to control the dynamic vacuum problem” [38]. This collimator must be placed at the appropriate position, indicated in Fig. 11. Moreover the angle of incidence should be as close to $90^\circ$ as possible, in order to minimize desorption effects.

The result of the design study is shown in Fig. 12. Currently this model has been tested and designed and a number of these collimators have been ordered to be built into the SIS-100 at FAIR.

Once the intense beam is in the synchrotron it has to be extracted and transported to the experiment. In order to do this without beam loss a very efficient beam diagnostic is necessary, which we will discuss in the following section.

2.6. Non-interceptive beam diagnostic

The most applied method to do beam diagnostic of intense beam is associated with beam induced fluorescence (BIF). A BIF-monitor exploits fluorescence light emitted by residual gas molecules after atomic collisions with beam ions. Fluorescence-images are recorded with an image-intensified camera system, and beam profiles are obtained by projecting these images. Such monitors are already in operation at GSI's LINAC since some years ago [39]. However, this method needs further investigation and development, to employ it also for high intensity accelerators as the new machines under construction at the moment.

We will here present a different non-invasive diagnostic method for the experimental determination of the transverse profile of an intense ion beam which is called electron beam imaging (EBI). This technique has been developed and was investigated theoretically as well as experimentally for employment at the FAIR facility. The method is based on the deflection of electrons passing the potential generated by an ion beam (Fig. 13). To achieve this, an electron beam is generated with a specifically prepared transversal profile.

This distinguishes this method from similar ones which use thin electron beams for scanning the electromagnetic field [40]. First of all the influence of the electromagnetic field of the ion beam on the electrons has been analyzed theoretically. It was found that the magnetic field causes a shift of the electrons along the ion beam axis, while the electric field causes a shift in a plane transverse to the ion beam. Moreover, in the non-relativistic case the magnetic force is significantly smaller than the Coulomb one and the electrons experience a shift due to the magnetic field and continue to move parallel to their initial trajectory. Under the influence of the electric field $E_{\text{lin}}$, the electrons are pushed off from the ion beam axis, their resulting trajectory shows a specific angle $\theta$ compared to the original direction. This

![Fig. 10. Injection into the SIS-18 with varying intensities. At the highest injection intensity the beam's lifetime in the synchrotron is the lowest.](image-url)
deflection angle practically depends just on the electric field of the ion beam. Thus the magnetic field has been neglected when analyzing the experimental data. The deflection angle follows from:

\[
\frac{dv}{dt} = -\frac{e}{m_e} E_{x,y} \to \theta = \frac{v_y}{v_x} \to \theta = -\frac{e}{m_e v_x} \int E_y \, dx,
\]

\[\text{(6a)}\]

and

\[
v_x = \sqrt{\frac{2E_o}{m_e} \left(1 + \frac{E_p}{E_o}\right)} \to (\text{with } E_o \gg E_p) \to \theta = \frac{-e}{2E_o} \int E_y \, dx
\]

\[\text{(6b)}\]

In these equations \(v\) is the non-relativistic electron velocity, \(E_{x,y}\) the electric field components, \(E_o\) is the non-relativistic kinetic energy of the electron and finally \(E_p\) is the potential energy of the electron in the field of the ion beam [41].

The theoretical model provides a relationship between the deflection angle of the electrons and the charge distribution in the cross section of the ion beam. The model however, can only be applied for small deflection angles. This implies a relationship between the line—charge density of the ion beam and the initial kinetic energy of the electrons (Method is shown in Figs. 13 and 14).

Numerical investigations have been carried out to clarify the application range of the EBI diagnostic method and to benchmark the theoretical model. Different charge distributions were considered and the simulation results have been compared with the theoretical model. Numerical investigations have shown a very good agreement with the theoretical model for deflection angles up to 20 mrad. This value defines the limit for the applicability of the theoretical model. Moreover, the magnetic field of the ion beam has also been taken into account in the simulations. The results show that at high ion beam currents — starting at about 1 A — the electrons experience a non-negligible displacement along the ion beam.
axis, which has to be taken into consideration in experiments with intense heavy ion beams. The electrons suffer practically the same displacement under the influence of the magnetic field, regardless of their offset. At an offset of 10 mm the deviation from the shift at the ion beam axis is less than 3%. For the experimental investigations of the EBI diagnostic method an offline experiment had been set up at the HHT experimental area at GSI in Darmstadt. The Coulomb field of the ion beam had been simulated by electrostatically charged wires. In case of a single wire, the experimental results are in good agreement with the theoretical model for deflection angles up to 20 mrad. This confirms the results of the numerical studies. To simulate the field within an ion beam, several wires have been clamped parallel to each other within a plane perpendicular to the electron beam. The electrons thus could pass through the spaces between the wires. The results of these experiments have quantitatively confirmed the prediction of the theoretical model that the derivative of the deflection angle with respect to the offset is proportional to the charge distribution in the cross section of the ion beam. Quantitatively, however, deviations from the theoretical model have been observed, which can be explained by the imprecise modeling of the charge distribution of an ion beam by the charged wires.

The EBI diagnostic method has been applied for the first time in collaboration with the group of Professor Ulrich Ratzinger at the FRANZ accelerator at the Goethe University Frankfurt am Main for low-energy, DC ion beams — $^4\text{He}^+$ at 13.5 keV and a current of approximately 1 mA.

The transverse charge distribution of these beams has been successfully determined by this diagnostic method. The results are displayed in Fig. 15. It is a difficult procedure, but we are sure that this method will be very useful to diagnose intense ion-beams at future high intensity accelerators.

Once the intense ion beam is available from the accelerator and can be diagnosed along the beam-transport system to the target without loss, it must be focused in order to achieve high energy density. Due to the high magnetic rigidity focusing of ion beams is a larger challenge than the focusing of high energy electrons. Superconducting magnets are envisioned as a final focus system at FAIR. However previous experiments showed that plasma technology may show another solution to the focusing problem.

3. Beam plasma interaction

3.1. Plasma lens focusing

High energy density physics requires beam bunches of high intensity. This is usually achieved through bunch compression in the synchrotron. This technique, however, leads to an increase in longitudinal emittance. Along with the transverse emittance this poses a problem for the final focusing system. The focusing effect of conventional quadrupole doublets is a second order effect. Each quadrupole focuses in one plane and defocuses in the transverse plane. Thus the performance of quadrupole lens focusing is limited by field strength considerations and limitations are severe in cases where extremely small focal spots are necessary for the experiment. Here a high focusing gradient and a large aperture for the quadrupole system is necessary. Moreover space charge considerations may play a role in cases of extreme intensity like ion beam focusing for inertial fusion. Before we started our experiments at GSI, part of our team has successfully tested a plasma lens to capture antiprotons from the
production target at CERN [42]. In that case a divergent beam, originating from a production point had to be adapted to a beam transport system. We had to deal with the reverse problem, to focus a beam to a small spot size to induce high energy density. The starting point was a cylindrical discharge that produced a homogenous wall stabilized plasma, which was also used for beam plasma interaction experiments, which we discuss later.

Fig. 17 shows the result of a focusing experiment where the beam was focused down to a 300 µm spot size from originally 10 mm. The focus period was 300 ns. This is sufficient since typical beam bunch lengths are on the order of 100 ns or less. In this discharge we used a 10 kV discharge with a maximum current of 22 kA and a total energy of 200 J was stored in the capacitor bank. Due to the success of this experiment a much larger Z-pinch plasma was built where the stored energy went up to 2.1 kJ, the maximum current to 150 kA at a discharge voltage of 32.5 kV [43]. The high current plasma lens based on the Z-pinch principle is shown in Fig. 16.

During different times of the discharge the current distribution changes from homogenous, which results in a linear B-field to inhomogeneous, which produces a non-linear B-field and leads to an annullar focus. This feature became interesting for the planned experiments at the future FAIR facility, which we will discuss in a later chapter.

Now that we have followed the beam from the ion source to the focusing point we are ready to address:

3.2. Beam-plasma interaction physics

Soon after the discovery of alpha-decay, nuclear physics addressed the problem of energy loss of ions in matter. The interest in energy loss of heavy ions started, when energetic ions became available from fission processes. Investigation of particle energy loss problems has since then become a

Fig. 16. Wall-stabilized plasma to serve as a plasma lens. The focal spot of the ion beam is observed with a fast CCD camera on a scintillator screen (NE 102A).

Fig. 17. High current (150 KA, 32.5 kV, 2100 J) Z-pinch plasma lens with linear and nonlinear B-field configuration.
traditional topic of nuclear physics with application mainly in detector development, but not only there. Tumor therapy with swift heavy ions started at Berkeley laboratories and today we see many places where energetic protons, alpha particles and heavy ions like carbon and oxygen are used in radiation therapy treatment. Interaction processes of intense ion beams are also 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 deep 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 they allow to draw conclusions for the plasma target properties [44].

All institutes involved in this review (GSI-Darmstadt; ITEP-Moscow and IMP-Lanzhou) carried out experiments to measure the energy loss of ions in ionized matter. Examples are given in Refs. [45–47]. In all reported cases the energy loss of ions in plasma is higher than the energy loss in normal matter that we are used to. In this review we suggest to change our frame of reference and consider the case of a free electron gas as the reference case. This case is experimentally realized in a fully ionized hydrogen plasma, and this state is the most prevalent in the visible universe. Energy loss of ions in plasma is predominantly due to collisions with electrons. Only at very low velocity the nuclear stopping is important. The interaction is mediated by the long range Coulomb force. Impact parameters up to the Debye shielding length contribute to the energy loss. This implies that also collisions at large impact parameter with low energy and momentum transfer contribute to the energy loss process. This is different when we deal with energy loss and stopping processes in ordinary “cold” matter. Here we have bound electrons and in general only those collisions contribute to the energy loss of the ions, where the ionization energy or at least some excitation energy is transferred in the collision process. If this is not possible due to a large impact parameter then quantum mechanics rules out any energy loss. Therefore a vast part of the collisions is without effect and hence the total energy loss is lower than in the equivalent amount of fully ionized matter. In inertial fusion, the target will end up in a highly degenerate state and fusion generated alpha particles are supposed to deposit their kinetic energy in degenerate matter. Since in degenerate matter all states up to the Fermi-edge are occupied, only those collisions may contribute to the energy loss where an electron is moved across the Fermi edge. Here again at large impact parameters with low energy transfer, much less electrons are available for effective collisional energy transfer, and hence we expect a lower energy deposition in the target. This effect may add to the problems we currently see in fusion physics. It may not be the main problem, compared to turbulent mix of the fuel, however it adds to the general problem and is an interesting question of basic physics.

Information on heavy-ion beam—plasma interaction experiments, became available, when first experiments at GSI were started. In order to have clean boundary conditions the first beam—plasma interaction experiments at GSI, were performed with hydrogen. Already at moderate temperature and density conditions, which are easily obtained in a discharge plasma, a state of almost fully ionization may be obtained for the duration on the order of microseconds. Later a dense Zpinch plasma was used to extend the measurements to higher density and higher temperature [48–50]. These experiments made it possible to compare the stopping power of hydrogen gas and fully ionized hydrogen plasma in one experimental set-up. In total, the plasma parameters of these first experiments ranged in density from \( n_e = 10^{16} \text{ cm}^{-3} \) to \( n_e = 10^{19} \text{ cm}^{-3} \), with \( 2 \text{ eV} \leq T_e \leq 20 \text{ eV} \). The experimental results clearly demonstrated the high stopping power of fully ionized plasmas, due to the interaction of beam ions with free electrons in plasma as compared to lower stopping power, where bound electrons are involved.

At high energy (left part of Fig. 18) the energy loss in cold gas is a factor of 2–3 lower than in the case of fully ionized hydrogen. At low energy (right part of Fig. 18) the experiment was performed at 45 keV/u where the ion velocity is close to the average electron velocity in the plasma, and thus the stopping power is close to the maximum. For heavy ions also the charge state plays an important role. An electron capture process of the beam ion requires momentum and energy conservation. This is difficult to fulfill for the capture of free electrons. Therefore a heavy ion traversing a fully ionized plasma shows a high charge state, since capture processes are reduced but ionization by target nuclei and plasma electron...
continues at the cross section determined by the respective velocities. In the energy range considered, the well-known Bethe-formula without polarization correction describes the energy loss in hydrogen ($Z = 1$) quite well:

$$\frac{dE}{dz} = \frac{Z_{\text{eff}}^2 \cdot 1 \cdot e \cdot \omega}{v^2} \cdot \ln \Lambda$$

$$A_{\text{bound}} = \frac{2m_e v^2}{T} A_{\text{free}} = 0.76 \frac{4v}{b_{\text{min}}}$$

In Eq. 7(a), (b), $z$ denotes the direction of ion beam movement inside the target, $Z_{\text{eff}}$ is the effective nuclear charge of the projectile, $e$ is the electron charge, $m_e$ the electron rest mass, $\omega$ the plasma frequency, which is a function of the density, and finally $v$ is the ion velocity. We distinguish the Coulomb logarithm $\Lambda$ for the case of free and bound electrons respectively. Therefore in the case of bound electrons, which refers to non-ionized matter, this term contains the average ionization energy $I$, and for the case of free electrons, which refers to fully ionized matter, the denominator contains the minimum impact parameter. This may be in some cases, due to Debye shielding, the respective Debye length, which is indicated by the index $\omega$.

In total, the beam energy in these first experiments was varied between 1 and 6 MeV/u for different ion species from carbon to uranium and the stopping power of fully ionized matter exceeded that of cold matter always by roughly a factor of three. This enhancement, as seen in Fig. 17 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 behavior is even more dramatic. An enhancement factor close to 40 was measured [51], and the main contribution in this case is the higher effective charge state $Z_{\text{eff}}$ of the beam 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 [52].

The experimental challenge was to extend the investigation towards plasma parameters with higher temperature and density, in order to have conditions that are more close to a fusion plasma. Such conditions can be generated by high power, high energy lasers.

The diameter of a laser focus usually is in the submillimeter range and the limit is determined by diffraction effects. One characteristic of laser plasma is the existence of strong gradients in density and temperature and a short lifetime. The diameter of ion-beam bunches is usually on the order of 1 mm. The experimental task was to match these conditions. As shown in Fig. 19, the ion beam diameter was narrowed down by a 500 $\mu$m aperture and the laser spot size was increased to 1 mm and thus the effect of strong laser-plasma gradients was minimized. Nevertheless, due to the coherent nature of laser light a laser focus always contains speckles consisting of intensity variations up to a factor of 4. This effect is usually minimized by random phase plates (see Fig. 19). Also the problem of time mismatch could be minimized. The longest possible laser pulses of up to 10 ns duration were used. The beam bunches from the accelerator arrive at the target with a frequency of 109 MHz. Therefore they constitute a pulse train with one ion pulse every 9.9 ns. The duration of each micro bunch of the beam pulse ranges from less than 1 ns up to 4 ns. With this set of measures laser and ion beam were matched to each other to the best of available experimental technique. However, there remains the fundamental problem of laser plasma generation. Light may penetrate matter only up to the critical surface. Therefore, soon after the onset of the laser pulse a plasma is created on the
surface of the target and the critical density moves away from the target surface, thus creating a diffusion zone. Finally the target experiences ablative pressure and a shock wave is generated, heating the bulk matter of the target. When finally the ion beam passes through these different zones, each zone contributes differently to the measured total energy loss. Plasma diagnostic, based on optical spectroscopy as shown in Fig. 19 can only analyze the plasma up to the critical density [53]. For the rest we until now have to rely on simulations. Therefore in future experiments penetrating radiation must be used to analyze the dense part of the target. This is a task where the teams are currently working on.

The experiments show the expected effect that after the plasma generation (see Fig. 20) the energy loss rises from the initial energy loss in the cold target material (≈ 2 MeV), up to some maximum (≈ 4 MeV) and decreases with the hydrodynamic expansion of the target material. Latest measurements [54] indicate however, that the increase effect is lower than expected from available simulations. Since at the moment we have to rely on simulations, we do not speculate here on the reasons. It may eventually be an effect attributed to the properties of warm dense matter that is generated in the bulk material of the target.

4. Dense plasma and high energy density matter

4.1. Generating high energy density with intense ion beams

The quest for a deeper understanding of dense plasma phenomena and properties of matter under extreme conditions is the driving motivation for High Energy Density Physics at many laboratories worldwide.

Among all methods to generate high energy density states of matter, heavy ion beams hold a unique position.

The total kinetic energy of heavy ions is determined by the acceleration process in the accelerator system and can therefore be tailored exactly to the experimental conditions and needs. Fig. 21 shows the penetration of a 300 MeV/u Ar-ion beam into a Krypton crystal. The number of Ar ions is measured with high precision by fast beam transformers, the initial energy is 300 MeV/u with an uncertainty well below 1%. Therefore we have the situation that the initial conditions of the spatial and temporal distribution of the energy deposition is very well known. High energy density states that are reached during the heating process can then easily be traced back to the initial conditions. With this kind of precision for the initial conditions no other method is able to compete. Moreover the resulting gradients with respect to temperature and density extend over macroscopic dimensions of some millimeter up to centimeter. Therefore the starting conditions are quite homogeneous.

In Fig. 22 we see the result of one of the first high energy density in matter experiments. At $t = 0$ the beam bunch is deposited deep inside the bulk matter of solid Ne at cryogenic temperature. The deposition region is clearly visible on the first frame. Heating of the crystal changes the bulk properties of matter. The first sign of it is that the previously clear and optically transparent crystal is now opaque. Moreover the onset of hydrodynamic response to the energy deposition is revealed on the second frame. The contour of the crystal now follows the energy deposition profile. The onset of motion starts close to the maximum energy deposition region at the end of the range of the ion beam. This region is commonly denoted as Bragg peak region. After 186 μs this feature is even more distinct (third frame of Fig. 22). The expansion velocity is connected to the bulk properties of matter by the respective equation of state. A measurement of the expansion velocity therefore yields equation of state data. From this early experiment it is clear that, for target material like lead or other metals, it is necessary to have penetrating radiation as a diagnostic tool. We will discuss this later.

The figure of merit for laser matter interaction experiments to induce high energy density is the laser intensity $I$ measured in W/cm² and the total energy. Due to the nature of ion matter interaction, where ions penetrate deep into the target volume, the important parameter is the energy $E_s$, deposited per gram of matter [J/g] and the deposition power $P_s$, measured in W/g. Hence the physics of beam induced high energy density matter is governed by three equations (Eqs. (8)–(10)):

$$E_s = \left(1.6 \cdot 10^{-19}\right) \frac{dE/dx}{\pi r^2} \frac{N}{J/g},$$

where $dE/dx$ is the stopping power of the material, $N$ is the number of beam ions delivered by the accelerator $\pi r^2$ 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 it may be a very different situation if the matter is in an ionized state.
The time $t_H$ to deliver this energy is limited, due to the hydrodynamic response of the beam heated material, and is approximately given by:

$$t_H \propto \left( \frac{L^2}{P} \right)^{1/3}, \quad (9)$$

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 (Eqs. (8) and (9)) yields the total deposition power $P_s$:

$$P_s = \frac{E_s}{t_H}. \quad (10)$$

From Eq. (10) the necessity arises to have beam bunches that are shorter in time $\tau_{bb}$ than the limit for the heating time set by hydro-motion ($\tau_{bb} \leq t_H$). The time scale is set by the sound speed $C_S$ which defines the time for a rarefaction wave to travel across the distance of the focal spot radius. By the time the rarefaction of the target material has reached the outer edge of the focal spot the effective heating of the target material stops. Thus the heating $t_H$ time is given as the upper limit of the integral (Eq. (11)):

$$r_o = \int_0^{t_H} c_s(T(P_s)) \, dt$$

(11)

The effective heating time ($t_H$) therefore depends on the equation of state of the material. In the limit of a mono-atomic ideal gas with the adiabaticity coefficient $\kappa = 5/3$ this can be written as:

$$r_o = \int_0^{t_H} \sqrt{\kappa} \cdot E_s \cdot dt = \int_0^{t_H} \sqrt{\kappa} \cdot P_s \cdot dt$$

(12)

Note that $E_s$ is given in J/g. The focal spot radius $r_o$, the specific energy deposition $E_s$, and the beam bunch length $\tau_{bb}$ are therefore interrelated through:

$$r_o = \sqrt{\kappa} \cdot P_s \cdot \tau_{bb} \cdot \frac{2}{3} \cdot \frac{1}{t_H^3}. \quad (13)$$

For the experiment this result has important consequences: The beam intensity, the bunch length and the minimum focal spot cannot be chosen independently from each other. As an example we calculated a focus radius of 250 $\mu$m for $E_s = 0.1$ TW/g [55].

In Fig. 22 we present the high energy density states that are available with heavy ion beams of different intensity. The left inset of Fig. 23 shows the available temperature as function of

![Fig. 22. Hydrodynamic motion induced by heating matter with an intense beam of heavy ions.](image)

![Fig. 23. Available high energy density states as function of deposited energy [J/g] and entropy [J g$^{-1}$ K$^{-1}$]. SIS-18 is the synchrotron currently in operation at GSI-Darmstadt. SIS-100 is the first stage of the planned FAIR facility in Darmstadt.](image)
deposition power. The quantity $E_s$ used in the equations above is given in MJ/g. Since the temperature which is obtained depends on the equation of state we used the SESAME library. In the high temperature limit they approach the ideal gas equation of state. Current experiments are carried out in the region of 1 kJ/g. This corresponds to the lower left end in Fig. 23 (0.001 MJ/g). The two red horizontal lines mark the region of Warm Dense Matter. Above a temperature of 10 eV, we expect strong hydrodynamic motion and the onset of a radiation regime. Above 100 eV, we surely enter the radiation dominated regime, where every additional input of energy is very efficiently converted to radiation. The aim of future facilities must be to enter this regime, since it is relevant for ion driven fusion. The right part shows the pressure as function of entropy. Shock wave experiments generally produce data along the Hugoniot line (black). Our experiments are aimed to achieve sudden heating with a state on the HI-HEX quasi isochoric heating line and then have the matter expand to explore the region below. Current experiments center close to the indicated critical point (CP). The example is taken for lead.

The most favorable beam ion for high energy density physics experiment is Uranium due to its high nuclear charge. Experiments were able to be operated with up to $4.4 \times 10^9$ particles per bunch in approximately 100–125 ns. The intensity limitations have been discussed in the previous section. It is important to investigate thermophysical properties and hydrodynamic response of various materials including Pb samples. The samples under investigation endure a rapid heating process, in some experimental conditions $2.2 \times 10^{10}$ (K/s) were obtained. This takes the sample into the two-phase liquid–vapor region near the critical point.

The diagnostic tools are at the moment limited to optical diagnostic. As mentioned above the expansion velocity can be

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**Fig. 24. Irradiating a cylindrical target volume (cryogenic, solid Ne) inside bulk matter.** The irradiation time is 1000 ns with a U beam of 190 MeV/u. Density, temperature and phase of the target material are indicated from left to right. The density scale is from 0.2 g/cm$^3$, temperature scale from 10 K to 2000 K.
measured. Another method is to measure the impact of the expanding material onto a sapphire window. The displacement of the back surface of the sapphire window can be measured and from this the pressure can be inferred. A very elegant method was developed with a fast multi-channel radiation pyrometer. This is now one of the key diagnostic tools [56]. Brightness temperature profiles were measured for lead samples. The results show that the state of matter achieved by heavy ion beam heating is equivalent to samples that were initially shocked up to 1.51, 1.80 and 2.23 Mbar. In our experiments using ion beams to heat samples, the physical temperature was obtained from the pyrometer measurements, and fitting a gray-body model to the data. The pyrometer had six different channels for a simultaneous measurement at six different wavelengths. In the beam-driven experiment, the total duration of the heating pulse was about 1 μs with full width at half maximum (FWHM) of 125 ns. During the heating phase, the sample foil is driven to the melting point and started to evaporate at the free surface. While expanding, the lead vapor is rapidly cooling down and at the moment when its temperature becomes sufficient for homogeneous nucleation (near the vapor spinodal line), liquid droplets appear inside the vapor and a boiling wave is formed. After this moment, the expansion dynamics is governed by surface evaporation processes.

The heating ion beam itself may also be used as a diagnostic source. Due to the hydrodynamic response of the ion-beam heated target matter, the target density changes as time progresses.

Therefore the penetration depth of the beam or if a penetrating beam is used, the change in energy loss of the emerging beam is a measure of the target density along the interaction region. By this technique which was developed by D. Varentsov as part of his dissertation work [57] first experimental results on measurements of energy loss dynamics of uranium beams in neon using different initial energy and intensity were obtained. The energy loss dynamics measurements were then complemented by two-dimensional hydrodynamic simulations. A comparison between the experimental data and simulations resulted in the development of a new wide-range equation of state for neon [57]. In the low temperature region none of the measured results were compatible with existing data on the equation-of-state. However in the high energy regime simulations agreed with the data within error limits. This points to the fact that, in the low temperature warm dense matter, part of the phase diagram we still are in an unchartered area.

The energy deposition characteristics of high-energy heavy ion beams in dense matter favor a cylindrical geometry. A simple experimental scenario is therefore a quasi-cylindrical plasma volume produced from focusing an intense ion beam into an extended target volume. A simulation of such experiment is shown in Fig. 24. The beam of U-ions at 190 MeV/u is deposited inside the target volume(cryogenic, solid Ne) over a time span of 1000 ns. After 300 ns the hydro motion is clearly visible showing compressed states of matter. The density along the interaction zone of target material and the ion beam decreases due to hydro motion. Therefore the beam penetrates further and finally exits the target at the rear end. Now the energy of the beam behind the target can be measured. At the end the beam will fully evaporate the target. This way the time it takes for the beam to appear at the rear end and the dynamic energy loss as well as the surface expansion are indications of the high energy state that is reached during the interaction process.

A different experimental scenario, which we use in our experiments, is called HIHEX-heavy ion beam heating and expansion. Fig. 25 shows the diagnostic set-up for the experiment. As a matter of fact in these experiments we use a slightly elliptical beam shape and irradiate a complete sample in order to heat a bulk piece of matter as homogeneously as possible. This way we may in first or zero order approximation assume that we have low gradients in temperature and density as starting conditions, before hydrodynamic motion sets in. The diagnostic tool is then to observe the radiation from the surface with the fast pyrometer, the expansion velocity and the impact onto the sapphire window.

A more complicated scenario with higher compression yields can be achieved with a special beam focus geometry, e.g. a hollow cylindrical beam focus at the target position, as sketched in Fig. 25.

This scenario has at the moment not yet been tested. It is part of the collaborative effort of the HEDgeHOB collaboration at FAIR. To achieve an annular focus is a challenging problem. The example shown in Fig. 26 was obtained with a non-linear field distribution of the plasma lens. Problems that will arise are obvious from this figure. The intensity distribution is not evenly distributed and will eventually not lead to the cylindrical compression. Therefore in addition to a plasma lens at ITEP [62,63] we are currently building at ITEP a wobbler system to achieve a homogeneous annular distribution [64].

The working principle as sketched in Fig. 27 is like that of an old TV tube, using rf cavities for the deflecting electric field. In order to achieve sufficient homogeneity it is necessary...
to have at least 10 circulations during the beam bunch length of 100 ns. This sets the requirements for the applied rf-frequency. Nevertheless it is a very challenging problem for the beam transport and focusing system. Applying an additional magnetic field, the heating of target material, can be enhanced by more than an order of magnitude. If an external magnetic field is introduced (see Fig. 25), the effect of magneto-thermal insulation may allow to reach even keV temperatures in the compressed inner cylinder consisting of deuterium gas. The experimental conditions for these experiments require, however, the maximum beam intensities available from the new facility together with a high initial magnetic field. Therefore this is not an experiment to be performed during the start-up phase of FAIR. This experiment also requires to diagnose the conditions inside the outer high-Z cylinder during the compression phase. Therefore penetrating radiation is necessary and we started to develop radiography based on high energy protons and we call it: the PRIOR-Project.

4.2. Advanced diagnostic methods: the PRIOR-project

To the best of our knowledge a breakthrough for radiography with protons was achieved at Los Alamos National Laboratories using 800 MeV protons. We follow this concept and have designed a proton microscope for experiments at GSI and FAIR [58]. With a special set-up of four quadrupoles as shown in Fig. 28. Focusing as a function of scattering angle is achieved in a Fourier plane. This allows to get rid of high angle scattering events that lead to excessive blur of the resulting picture. The final two quadrupoles achieve a point to point imaging with some magnification. A number of effects contribute to image blur. These are Coulomb scattering, chromatic aberration and detector blur. All these effects may be minimized by using high energy protons. At GSI we currently use 4 GeV and an energy up to 10 GeV will be available at FAIR.

In a collaborative effort of ITEP-Moscow, GSI-Darmstadt, TU-Darmstadt and Los Alamos National Laboratory, a proton microscope was constructed and successfully tested in July 2014. Fig. 29 shows the proton microscope with four quadrupoles made of permanent magnets and the test picture, demonstrating the radiographical capabilities of this device.

We strongly believe that with the completion of FAIR at GSI in a couple of years, high energy density physics with heavy ion beams will enter a new era.

5. Conclusion and outlook to the future

We believe that it is fair to say that in the recent past there were 4 accelerator laboratories leading the research in high energy density physics with ion beams: GSI-Darmstadt, ITEP-Moscow, LBNL-Berkeley and IMP-Lanzhou (see Fig. 30), not to forget TIT-Tokyo and Universite de Paris Sud.

Here it would lead too far to list the achievements of the different laboratories. However two of these laboratories have remarkable plans for the future. At the site of GSI-Darmstadt they currently are in the middle of constructing the FAIR facility, and in China there are plans for a new heavy ion accelerator facility with intense beams (HIAF). The leading laboratory here is the Institute of Modern Physics, Lanzhou. While there are still plans awaiting approval and further detailing, it is obvious that beam matter interaction with intense beams will have a future that probably will give us more insight into the prospects of intense beams as drivers
Fig. 28. Beam transport system of the proton microscope.

Fig. 29. The PRIOR proton microscope and the first test result with a 4 GeV proton beam at GSI.

Fig. 30. Leading laboratories in HEDP with ion beams: Helmholtzzentrum für Schwerionenforschung GSI-Darmstadt, Institute for Theoretical and Experimental Physics (ITEP-Moscow, now part of Kurchatov Institute), Heavy Ion Fusion Science-Virtual National Laboratory (Berkeley, the national laboratories at Princeton, Livermore and Berkeley constitute this laboratory), Institute of Modern Physics, Lanzhou (Chinese Academy of Science).
for inertial fusion. Experiments at GSI are currently carried out at $E_n = 1 \text{ kJ/g}$, and this number will rise to $120 \text{ kJ/g}$ at FAIR and the first estimations for HIAF range from $300 \text{ kJ/g}$ up to eventually $1 \text{ MJ/g}$. With these numbers it will be possible to enter the radiation dominated regime. It is still not enough to ignite a fusion target, but scaled experiments will be possible not only for target physics but also provide a better basis to scale the properties of accelerators up to a fusion driver.

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