Heavy Ion Beams for Inertial Confinement Fusion and Recent Experimental Results

D.H.H. Hoffmann, K.-G.Dietrich, E. Boggasch[1], J. Jacoby[1], K. Mahrt-Olt[1], B. Heimrich[2], M. Winkler[2], V. Dubenkov[3], A. Golubev[3]

GSI-Darmstadt, Postfach 110552, 6100 Darmstadt, Germany

[1] Max-Planck-Institut für Quantenoptik, Garching, Germany
[2] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Germany
[3] Institute for Theoretical and Experimental Physics Moscow, USSR

Introduction

The production of safe and abundant energy from thermonuclear fusion processes was a major aim of intense research programs that have been launched since the 1950s in many countries. Both methods to confine the fuel during the burn phase, magnetic confinement fusion (MCF), and inertial confinement fusion (ICF), are now believed to be technically feasible. Though the ICF approach to fusion was addressed about two decades later than the MCF path, it is today a serious competitor and offers a high potential to turn into an industrial source of energy. It is a well known fact that ICF works, e.g. in the interior of stars, and it has been demonstrated to work in a large number of thermonuclear explosions. Today we know, through information from the Centurion Halite program, that it is indeed also possible to produce sufficiently high fuel densities and temperatures in a small fusion pellet to achieve ignition and even high gain . The question about an efficient, reliable, and affordable driver is, however, still open.

Recent advances in laser fusion [1,2], and the progress toward high gain laser fusion [3] considerably raise the probability, that it will be a laser driver to ignite the first high gain fusion pellet under laboratory conditions. However, for a competitive commercial power reactor heavy ions offer a number of most favorable properties. The high efficiency (25%) and proven reliability of accelerators, as well as their ability to deliver high intensity beam pulses at a high repetition rate ($\geq$ 1 Hz) are main assets of ion driven fusion. Also the problem of coupling the beam energy to the target is advantageous for heavy ion beams. Due to the high nuclear charge (Z) heavy ions have a high deposition power ($\propto Z^2$) in matter, and the energy is deposited in the target volume rather than in a thin surface plasma layer. Even multi-TW pulses can be transported ballistically and can be focused to a small spot size.

The demands on a heavy ion driver are, however, very severe if we consider for a moment the key figures that are involved in ion driven fusion. It is expected that the energy delivered to the target in a 10 ns pulse has to be in the range of 5 to 10 MJ, which amounts to a pulsed power of 10^{15}W. The symmetry requirements of ICF pellets during the heating and compression process are difficult to meet with directly driven targets and make it appear likely that the indirect drive approach will be pursued. In this case it is necessary to heat a hohlraum to temperatures of approximately 300 eV to obtain a circulating flux of 10^{15} W/cm^2. Thus the ion beam kinetic energy has to be absorbed and converted into thermal radiation in a small amount of matter like 100 mg of high Z material (e.g. Au). Using these figures the order of magnitude for the specific deposition power P_ρ (measured in W/ g), which is the key parameter for heating matter with heavy ion beams can be estimated to be 10^{16} W/g. The advanced state of present day accelerator technology, and novel techniques and ideas to produce high intensity beam pulses [4] make it appear possible that this parameter regime can be reached. Though the most critical issues of ion driven fusion have to be addressed and resolved by the accelerator physics community a number of basic physics issues like interaction phenomena of intense beams with ionized matter need to be investigated.

High Energy Density in Matter Induced by Heavy Ion Beams

An experimental program to investigate beam plasma interaction phenomena was initiated at GSI almost five years ago [5], when it became clear that the accelerator facilities at GSI would provide the most powerful heavy ion beams worldwide and offer outstanding experimental conditions to address key issues of inertial confinement fusion. The entire experimental program was geared to lay the foundations for a dedicated research program using the new accelerator scenario consisting of the SIS and ESR (fig. 1), and a high current injector for UNILAC which will be added later.

Heavy ion beams from the SIS are now available for experiments, and all ions provided by the UNILAC with an intensity of at least 1 μA electrical pulse current can be accelerated up to the design energy [6]. Currently the

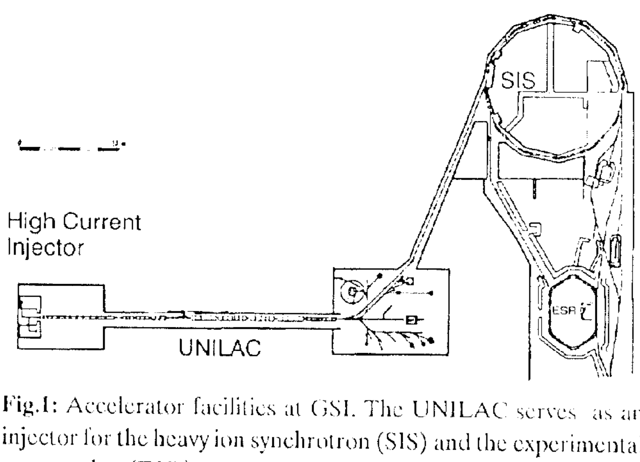

Fig.1: Accelerator facilities at GSI. The UNILAC serves as an injector for the heavy ion synchrotron (SIS) and the experimental storage ring (ESR). At the right hand side is the target cave for intense beam experiments. A high current injector for the UNILAC will be installed after 1991.

maximum number of particles per pulse for light ions like neon or argon is in the 10^8 range, but w expect the machine soon to deliver 10^9 particles per pulse in 100 ns. Focused on a small sample of matter it will then be possible to produce a high density plasma with intense heavy ion beams, investigate interaction processes of heavy ions with hot ionized matter, and address key issues of inertial confinement fusion (ICF).

The potential of heavy ion beams to heat matter to extreme conditions of temperature and pressure is expressed by the specific deposition power P_p :

$$P_p = (E \times I) / (a \times r) \qquad [TW/g] \qquad (1)$$

with the total particle energy (E), the particle intensity (I), the focal spot area (a), and the range of the ion beam in matter (r). A calculation by Arnold & Meyer-ter-Vehn [7] shows (fig. 2) the range of temperature that can be obtained in heavy ion beam heated targets as a function of the specific deposition power P_p. The result of our first intense beam experiment with the RFQ accelerator is just at the low temperature, low deposition power limit of this range, where we were able to produce a beam heated plasma just below 1 eV in a gas target. With the SIS at its full potential (10 TW/g), temperatures above 10 eV in solid state targets will are possible. For an indirectly driven fusion pellet a thermal radiation field at a temperature of 200-300 eV is necessary for ignition, and thus a deposition power above 10^3 TW/g is required to achieve this goal.

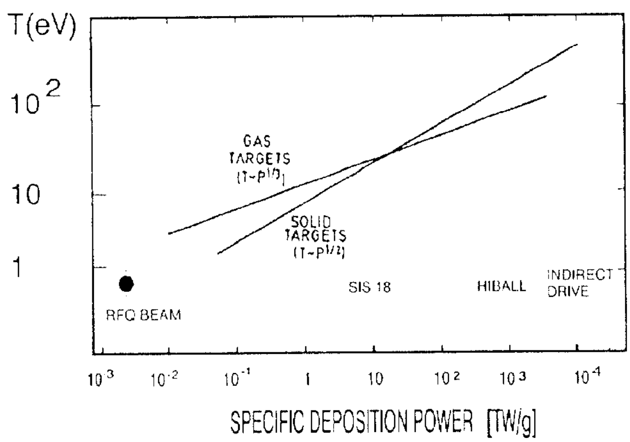

Fig. 2: Matter temperatures of ion beam heated plasmas as a function of specific deposition power [7]. The first experimental result of ion beam heated plasmas with the intense beam from the RFQ accelerator is shown. The plasma temperature was just below 1 eV.

High Energy Density Target Area at SIS

For the intense beam-target experiments the high energy density (HED) target area has been designed. Beam pulses of maximum intensity from the SIS, bunched to 100 ns pulse length are focused to a spot size of about 100 μm radius by a lens array of five magnetic quadrupoles. In the early operating phase of SIS the maximum intensity for Ne^{3+} pulses will be merely above 10^9 particles at 300 MeV/u, which is just sufficient for a well focused beam to heat the target spot to 1 eV for high Z material and a few eV for low density material.

New diagnostic techniques specific to ion beam induced plasmas have been developed during the intense beam experiments at the RFQ accelerator, and the experimental equipment will now be set up at the new experimental area. A major aim of the experiments is to understand the hydrodynamic response of the target material and compare this to numerical simulations. Therefore the target response will be diagnosed by means of optical and x-ray spectroscopy, to measure time and space resolved the spectral emission of the expanding target. For this purpose the spectrometers are coupled to high resolution streak cameras with digital readout systems (CCD camera). One specific way to analyze density fluctuations of the expanding target is to measure the energy loss of the ions after target passage. A spectrometer consisting of a dipole magnet for momentum dispersion and a position sensitive detector (PSD) is currently being designed by a group of the IPN Orsay, and will soon be available for experiments to measure the energy loss of heavy ions in beam heated plasmas.

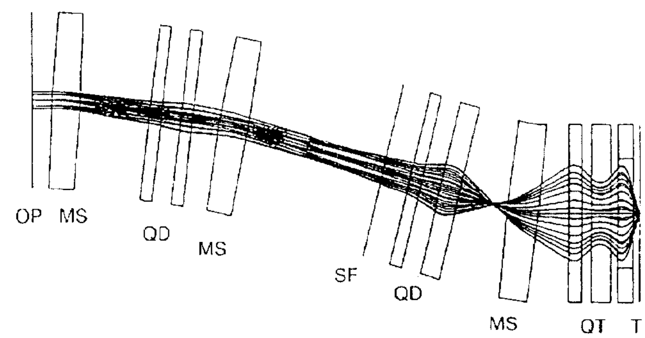

Fig. 3: Final focus system at the Target area for intense beam experiments (OP - takeover point; MS - magnetic sector; SF - stripper point; QD - quadrupole doublet; QT - quadrupole triplet; T - target).

Magnetic Fine Focus System

Centerpiece of the experimental set-up is the final focus system, to achieve the smallest possible focal spot size of the beam. The design of the system has been calculated with the GIOS code [8] , assuming the following beam parameters: emittance ε = 1.5 πmm mrad, momentum spread $\Delta p = 0.4\%$, and beam energy E/A = 300 MeV/u. In fig. 3. the magnetic beam guidance system from the take over point (OP) to the focal spot at the target (T) is shown.

From the take over point, up to the stripper foil (SF) the magnetic system is designed to handle beam pulses up to the maximum value of the magnetic rigidity of 18 Tm. Downstream of the stripper foil the charge state of the ions is increased (Ne^{3+} Ne^{10+}), and the demands on the focusing system are reduced to a maximum magnetic rigidity of 6 Tm, which is necessary to keep the magnetic flux density of the last quadrupole below 0.7 T. The electrical beam current, however, increases by the same factor, causing space charge effects to play a more important role, and up to 10% of the focusing power is used to compensate space charge effects.

Development of Plasma Lenses for Focusing of Heavy Ion Beams

Experiments to produce high energy density in matter will have to make use of the highest possible specific deposition power of the ion beam. Increasing the particle intensity is one way to achieve this aim and it is therefore a very intense research topic for accelerator physicists.Novel ideas and non conventional techniques will be necessary for the final focus of an advanced ICF test facility, or even more for the envisioned power reactor, to make full use of the increased particle intensity.

For our current experimental program focusing systems consist of electric and magnetic quadrupoles only. Plasma lenses are presently under discussion as an attractive focusing device [9].

In a Plasma lens the plasma serves as an almost transparent current-carrying and space-charge neutralizing medium. If a homogeneous current density distribution is obtained it will result in a linearly rising magnetic field. In contrary to quadrupoles these cylindrically symmetric "wire lenses" provide simultaneous focusing in both planes with very high field gradients of several hundred Tesla per meter.

One possibility for producing the plasma is realized by a z-pinch discharge, similar to the device we currently use in our stopping power experiments. Plasma lenses based on z-pinch discharges have been successfully used earlier for focusing of high-energy charged particle beams at Berkeley [10] and Brookhaven [11]. At CERN a plasma lens designed for antiproton collection is presently being tested off-line and is planned to be installed in the target area of the Antiproton Collector Ring in 1991 [12]. Along with the planned stopping power experiments this year on our z-pinch plasma we will also investigate the plasma lens effect and perform focusing experiments by simultaneous observation of the downstream beam profile. These experiments will provide further information needed for design and construction of a future SIS plasma lens.

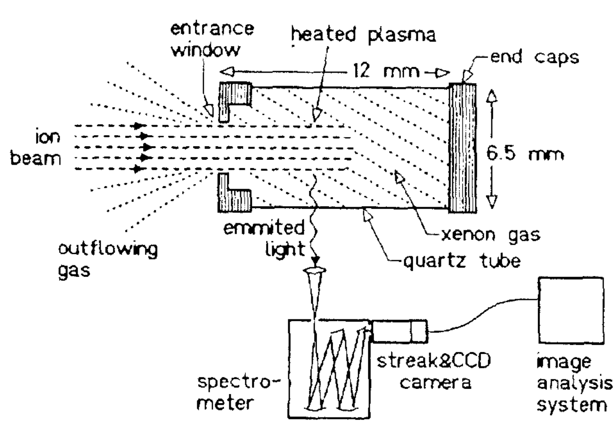

Fig. 4: Set-up of the intense beam experiment at the RFQ accelerator. A closed gas target is heated with an intense ion beam.

Intense Beam Experiments at the RFQ Accelerator

First intense beam-target experiments have been performed, using the five module RFQ accelerator at GSI [13]. A 45 keV/u heavy ion beam is available at this machine. A Kr^+ ion beam current just above 5 mA was transported to the target and focused to a spot size of 1 mm^2. Due to the short range (1 mg/cm^2) of Kr at this low energy the beam power (19 kW) amounts to a specific deposition power P_p of about 2 GW/g transferred to the target. The aim of this experimental program

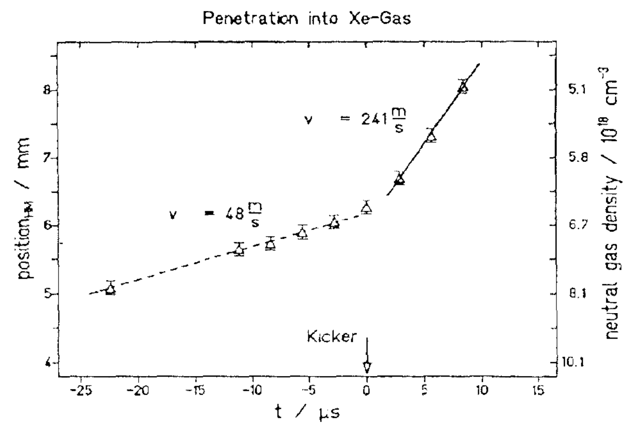

Fig. 5: Penetration velocity of a high and a low intensity beam into a Xe gas target.

at the intense low energy beam accelerator was to develop new diagnostic techniques, specific to ion beam heated plasmas, and to test basic beam target interaction theories. The set-up of the experiment is shown in fig. 4. It shows the design of a closed gas target, and the beam is impinging on the target from the left side, where an aluminum lid closes the quartz tube. The beam is focused to an entrance aperture (1.5mm x 4mm) in the aluminum lid, which is sealed by a thin polypropylene foil (80 $\mu g/cm^2$). The total beam pulse consists of a long train (500 μs) of micropulses (10 ns width) separated by intervals of 74 ns. Light emitted during the irradiation process indicates the beam-gas interaction region.

Already the first few micropulses destroy the entrance window, causing the Xe target gas to stream out of the quartz tube through the aperture. The range of the Kr beam at 45 keV/u is approximately 3.7mm in Xe gas at the filling pressure of 600 mbar, taking into account the energy loss in the entrance foil. Thus we expect the beam initially to be stopped left of the gas cell center. From then on the beam successively penetrates to the end of the quartz tube, as the density inside the beam-gas interaction region decreases.

With a streak camera image of the penetration process, the penetration velocity of the beam inside the gas target was measured. Our experimental set-up allows to send a low intensity beam pulse first, and then by activating an electrostatic kicker the full intensity beam is focused onto the target. Time zero in fig. 5 corresponds to this point in time, when the kicker is fired. The low intensity beam corresponds to about 1% of the full intensity.The penetration velocity of the high intensity beam (241 m/s; solid line in fig. 5) is increased by more than a fact or 5 as compared to the low intensity beam (48 m/s; dashed line in fig. 5) . Both measurements can be explained with the decrease in target gas density due to gas streaming out through the entrance aperture into the vacuum of the target chamber.

The low intensity beam does not heat the gas considerably and we find that the penetration velocity is in agreement with the reduction in target density due to the mass outflow of cold Xe gas. The intense beam, however, heats the gas in the interaction region, and we have to deal with the mass flow of a hot gas.

In a very simple model the higher velocity going along with the intense beam, is consistent with a temperature of 0.65 eV of the outstreaming gas. The plasma temperature has also been determined by spectroscopic methods and by a comparison of the observed radial hydrodynamic motion of the beam heated target gas [14], to results of a two dimensional hydrodynamic model calculation [15]. All methods have produced consistent results from which we deduce a mean temperature value $T = 0.75 \pm 0.15$ eV for this first example of an intense beam induced plasma.

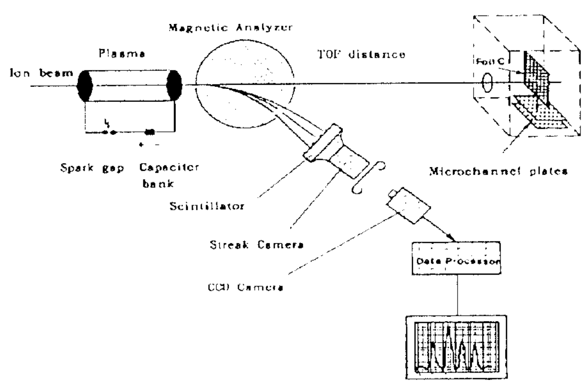

Fig. 6: Set up of the beam plasma interaction experiment with a z-pinch plasma. Time of flight technique is applied to measure the energy loss in the plasma, and a detector system with magnetic analyzer serves for charge state analysis of the ion beam.

Energy Loss of Heavy Ions in a Dense Z-Pinch Plasma

Energy deposition of heavy ions in hot ionized matter is an important issue in the design of high gain fusion pellets. In our earlier experiments [16,17] we established experimentally an enhanced stopping power of plasma targets for heavy ion beams. The enhancement factor reported from the experiments with a low density ($n_e = 3x10^{17} cm^{-3}$) hydrogen discharge plasma [18] varied between 2.0 and 2.6 for ion species from ^{40}Ca to ^{238}U. Therefore the aim of our recent experimental activity was to extend the energy loss measurements into the density regime above $n_e = 10^{18} cm^{-3}$. Using the experimental set-up described earlier [19], we measured the energy loss of Pb^{30+} ions at an energy of 1.4 MeV/u, in a hydrogen z-pinch plasma that was designed especially for this experiment by our colleagues from the FHG Institute for Laser technique in Aachen [20]. In fig. 7 we present

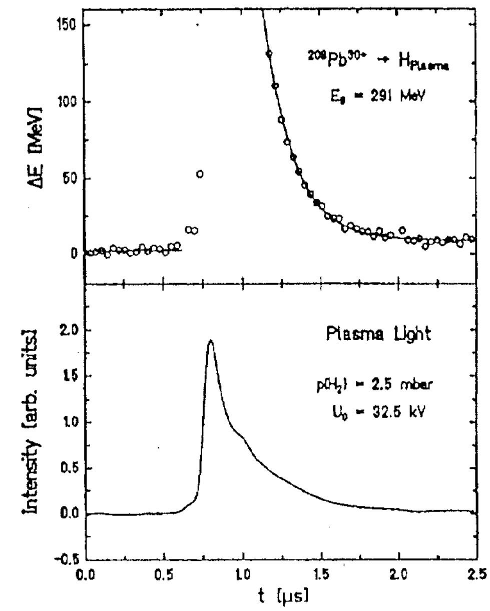

Fig. 7: Energy loss of Pb ions in a dense hydrogen z-pinch plasma (upper part), and the plasma light output signal from the z-pinch measured along the pinch axis.

the results of the energy loss measurement as a function of time (upper part of fig. 7) together with the light output signal of the plasma (lower part of fig. 7). Up to 600 ns the data correspond to the energy loss (2 MeV) in the cold hydrogen gas target (length = 20cm, p = 2.5 mbar). At that point the pinch reaches the beam axis and the target density and the associated energy loss rises steeply, exceeding the range accessible to our time of flight spectroscopy.

The plasma light signal is measured through the exit aperture of the z-pinch cathode, thus the line of sight for this signal is along the beam plasma interaction zone at the center of the pinch column. The intensity of this signal is correlated to the free electron density of the plasma and therefore it shows the same features as the energy loss measurements, with a very steep rise of the intensity, when the pinch collapses on the axis. At this time the plasma density is above $5x10^{18} cm^{-3}$ and the ions are stopped completely inside the plasma column and a time of flight energy measurement is no longer possible. This explains the lack of energy loss data between 0.8µs and 1.2µs in the upper part of fig. 7. During the expansion phase of the pinch the energy loss is again within the limits accessible for time-of-flight spectroscopy and we observe an energy loss corresponding to 45% of the incident beam energy of 291 MeV.

The plasma density diagnostics was performed with laser interferometry in Mach-Zehnder geometry along the z-pinch axis [21]. The plasma temperature was determined by spectroscopy of the emitted light. During the pinch phase it is above 5 eV and for the whole range between 1 and 2.5 µs the temperature is high enough to guarantee a degree of ionization above 99%.

Combining energy loss measurements and the results of the plasma free electron density diagnostics, the observed energy loss can be displayed as a function of the areal density ($\int n_e dl$) of the plasma target (fig. 8). The energy loss for cold hydrogen

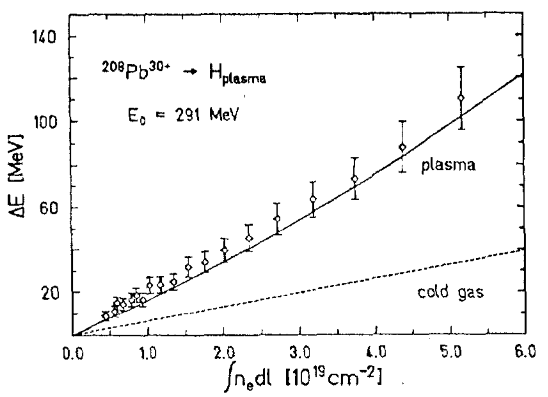

Fig. 8: Energy loss of Pb ions as a function of the free electron density. The dashed line represents the energy loss derived from data tables [22].

gas is indicated as a dashed line and it is derived from the tables of Northcliffe and Schilling [24]. Our measurements at low density [19], prove that these tables are in good agreement with experimental data. The observed energy loss in the plasma is almost a factor of 3 higher than the energy loss in the cold gas. We compare our data to a calculation in the standard stopping power model, which takes into account the difference in the Coulomb logarithm due to collisions with free electrons and a higher effective charge state of the ion in a plasma environment, due to reduced capture cross sections [23]. The evolution of the charge state was modelled by a Monte-Carlo simulation taking into account the relevant charge exchange cross sections. This calculation predicts an increase of the Pb ion charge state from 30 + to 38 +, causing the energy loss to rise stronger than in the case of a constant charge state. The agreement of the calculation with the experimental data is very good. This experiment is therefore the hitherto best evidence for the higher effective charge of heavy ions in a completely ionized plasma.

The experiment has now been moved to an experimental hall of the UNILAC in order to have access to all ion species with energies up to 20 MeV/u as well as increased beam intensity. We will now be able to measure energy loss data even in the most dense phase of the pinch. It is also planned to directly measure the ion charge state after its passage through the plasma target.

Acknowledgement

The experiments reported here are performed at GSI in an international collaborative effort of a number of institutes including also MPQ-Garching, TH Darmstadt, IPN Orsay, GREMI-CNRS Orleans, LPGP Orsay, FHG-ILT Aachen, Univ. Giessen, and ITEP Moscow.

We want to thank especially Dr. R.W. Müller (GSI). His successful efforts to provide an intense beam from the RFQ accelerator made the first experiments with heavy ion beam induced plasmas possible. The close collaboration as in this case between accelerator research and development and target experiments is an important condition for the development of this research field. The funding for the German institutes collaborating with GSI in this experimental program was provided by the federal ministry for research and technology (BMFT).

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