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Summary report on:

Beam Target Interaction and Chamber Propagation

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Since the first conference in this series held 1982 at GSI Darmstadt, especially the field of beam plasma interaction physics has experienced a significant development. While in those days heavy ion inertial fusion was almost an entirely theoretical subject we see today a large experimental program being performed in many laboratories worldwide. It was obvious to the scientific community from the very beginning that beam plasma interaction processes do play an important role in heavy ion inertial fusion. There were, however, a few very outstanding theoretical contributions between 1978 and 1991 which really initiated the amount of research work as we could see it being presented on this conference. Two contributions by Nardi, Peleg and Zinamon in 1978 [1] and by Nardi and Zinamon in 1982 [2] made us aware of the fact that energy deposition processes of heavy ions in hot, ionized plasma may be quite different from those processes in cold matter. Mehlhorn in 1981 [3] published simulations of ion-plasma interactions which in many cases is still the basis for many beam-plasma interaction codes. Continuous contributions that led to a deeper understanding of heavy ion - plasma interactions were made by Deutsch and his coworkers [4]. In 1991 Peter and Meyer-ter-Vehn published a comprehensive treatment, that gave very close guidance to the first experiments. As a matter of fact all these authors made again significant scientific contributions to this conference. The first experiment to investigate the energy loss of ions in a plasma was carried out in 1982 by Young et al [6], using an intense proton beam from an ion diode. At the same time a very difficult experiment was started by Dei Cas [7] in Bruyere-le-Chatel investigating the energy loss of protons in a laser plasma. This experiment was especially difficult due to the short lifetime and small dimensions of the laser plasma. The final results of this experiment were presented by Deutsch on this conference. The first experimental results of energy loss experiments with alpha-particles from laser induced fusion reactions were reported in 1988 [8], and in the same year beam plasma interaction experiments were started by the Orsay-GSI collaboration, and enhanced energy loss of heavy ions in fully ionized hydrogen plasma was demonstrated for the first time [9-13]. Today beam-plasma interaction experiments are also pursued in a large number of research institutes like ITEP-Moscow, TIT-Tokyo, and Erlangen University with heavy ions, FZ-Karlsruhe, Sandia Laboratories-Albuquerque, and INP-Alma Ata with light ions and protons. A remarkable development in beam plasma interaction experiments is starting at Orsay. Deutsch reported about investigations using cluster ion beams for ICF and the start of experiments analyzing interaction processes of cluster beams with cold and ionized matter.

The typical set-up for energy loss measurements of heavy ions in a plasma as it is used in most of the laboratories is such that the heavy ion beam from an accelerator is injected through a differential pumping system into a discharge plasma. The interaction of the beam with the plasma results in energy loss and in a change of the heavy

ion charge state. These parameters are measured with magnetic and electrostatic spectrometers and time-of-flight systems. The predominant energy loss mechanism is the electronic energy loss. In hydrogen plasmas it is possible to achieve a fully ionized plasma state for a time span of some nanoseconds up to the mikrosecond regime, depending on the plasma target. In this case only free electrons are present. Due to the efficient energy transfer in collisions with free electrons this results in an enhanced energy loss. In general free and bound electrons are present in a plasma target and thus the total energy loss $(dE/dx)_{\text{tot}}$ is the sum of the energy loss due to collisions with bound electrons $(dE/dx)_{\text{Bethe}}$, and with free electrons $(dE/dx)_{\text{free}}$ [3].

In the case of free electrons the average atomic binding energy in the logarithmic term of $(dE/dx)_{\text{Bethe}}$ is replaced by the plasma excitation energy $\hbar\omega_p$ and thus

$$\left(\frac{dE}{dx}\right)_{\text{free}} = \frac{Z_{\text{eff}}^2 e^2 \omega_p^2}{v_p^2} \cdot G\left(\frac{v_p}{v_{\text{th}}}\right) \cdot \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{\hbar\omega_p}\right). \quad (1)$$

This equation shows the same structure as the Bethe formula except for the term $G(v_p/v_{\text{th}})$, which is Chandrasekhar function, and accounts for the coupling of projectile energy loss to the free electrons, where v_p is the projectile velocity and v_{th} the free electron thermal velocity. The energy loss of heavy ions depends, however, also on the effective charge state Z_{eff} of the heavy ions. Generally in heavy ion experiments it is very difficult to distinguish between the effect of the enhanced logarithmic term and effects due to the charge state of the ion. Sharkov et al. presented therefore a very important contribution, measuring the energy loss of protons in a hydrogen plasma of medium density. Details of this experiment were also presented in a poster by Golubev et al. and Belyaev et al. In this kind of experiment charge state effects do not play a role and thus the measured enhanced energy loss is attributed to the difference in the logarithmic term of $(dE/dx)_{\text{Bethe}}$ and $(dE/dx)_{\text{free}}$ of eq. 1, representing the difference in energy loss for interaction processes between free and bound electrons. A typical result is measured for uranium ions slowing down in a hydrogen plasma [9,12,13]. The observed difference for the plasma and cold gas case is approximately a factor of three and is thus due to the enhanced energy transfer in collisions with free plasma electrons. The experiment by Sharkov et al. now proves that our understanding of the energy loss phenomena in low and medium dense plasmas is basically right and the replacement of the average ionization energy $\bar{I}$ by $\hbar\omega_p$ in the logarithmic term of the Bethe formula reproduces the experimental results. In heavy ion experiments the charge state effects at low projectile energies can be dominant, as was demonstrated in the talk by Chabot et al. about the charge exchange between chlorine ions in a deuterium plasma at MeV/u energies. Recent experiments [15] have shown that in cases where the projectile velocity is close to the thermal electron velocity, the observed energy loss of heavy ions in a plasma is almost a factor of 40 higher than in cold gas of the same density. This definitely is a result of the enhanced charge state of ions passing through a fully ionized plasma. Due to the low capture cross section for free electrons, the fully ionized plasma tends to strip the ion to high charge states. This effect has been demonstrated in the experiments discussed by Chabot et al. and has been pointed out earlier by Alton et al., [16] and Dietrich et al. [17].

Zinamon and Nardi pointed out the importance of the charge state effect in interaction processes of heavy ions with the fusion converter. A low Z material like Be will finally be fully ionized, due to the high temperatures of 200 - 300 eV expected in the converter target. Therefore a decrease in the ion range is to be expected. An addition of small amounts of high Z material for radiation purposes adds, however, also bound electrons, thus decreasing the projectile ion charge state, with the effect, that the effective range will be longer than in the pure low Z converter. The theoretical approach to predict the charge state of heavy ions has also been taken up at the Russian Federal Nuclear center by Ovezov. Based on an improved version of the original Bohr Lamb criterion [18,19] he is able to reproduce experimental results of charge state measurements of ions passing through cold matter as well as the Betz-formula [20]. For lead ions passing through air at a temperature of 1 keV, where one expects the target ions to be fully ionized, he also predicts an increased charge state of the heavy ion projectile. For a high Z target like gold the effect is reduced due to the fact that there are still bound electrons left at a temperature of 1 keV.

Wang and Mehlhorn are developing a unified self consistent field model for ion energy deposition in ion-driven targets. Whereas in most theoretical approaches until now the effect of free and bound electrons is considered separately and finally added up to result in the total energy loss, the new concept treats the target ion in the background field created by the free electron density. It thus provides a self consistent treatment of bound and free electrons as well. This model reproduces quite well the experimental results of stopping power measurements in cold matter and it resolves a long standing controversy about range lengthening effects in dense hot plasmas, which have been predicted earlier [21, 22].

Beam plasma interaction experiments have been performed in the regime of ideal plasmas, with densities up to 10^{19} cm^{-3} and plasma temperatures of some 10 eV. First experiments have been reported of laser plasma targets (Coullaud and Deutsch) and new experiments with fully ionized high Z laser plasma targets are being designed at ITEP-Moscow, GSI-Darmstadt and the University of Erlangen. There is, however, also a path to dense, non ideal plasmas. Stetter and Dornik presented experiments showing a rare gas crystal (Kr, Xe) being heated by an intense ion beam, investigating the hydrodynamic motion of the heated material. These experiments will finally lead to interaction experiments with dense, non ideal plasmas of relatively low temperature. The theory group at University of Erlangen represented by Toepffer, reported about the properties of matter under extreme conditions and the energy loss of ions in strongly coupled plasmas. Due to the non-linear shielding a deviation from the usual Z^2 dependence of the stopping power is predicted under these conditions. This will also strongly effect recombination rates and is thus important for investigations addressing the production of coherent radiation from dense plasmas. Quantum effects will become important when the interparticle distance is on the order of the thermal wavelength, in this case Toepffer et al. predict a considerable decrease in the stopping power. It will be very interesting to subject these models and predictions to an experimental test and due to development of the experimental programs worldwide we will probably soon be able to improve our understanding of dense plasma phenomena by interpreting and analyzing experimental results.

Chamber propagation physics turns out to be an issue that is studied and addressed now experimentally with great vigour. Of course, looking into the details of the mechanisms, now physics- and technical problems turn up. I regard this as a very good sign, since this means that we are sure that the basic problems to ignite a target with sufficient gain and to generate the necessary beam intensity are assumed to be solved, or at least a solution is within reasonable reach, so that we can now start to deal with the details. D. Callahan in her invited paper gave an overview of the current status of chamber propagation physics for heavy ion fusion. To be able to focus the beam down to the spot size required by target design considerations, partial or even complete neutralization of the beam in the chamber is necessary to counteract the strong space charge forces. Ho (Livermore) suggests to pass the beam through a thin film of submicron thickness to draw electrons, which co-move with the beam and autoneutralize the beam in the vicinity of the target, where due to the required strong focussing space charge forces are largest. This idea works probably quite well, but only during the last part of ballistic beam transport to the target. As long as active beam transport is still considered this method is not applicable, due to the resultant charge state spectrum of the beam ions. Self pinching of the beam is investigated by Welch and Olson (C.1), which involves propagating the beam in a background gas at pressures up to 200 mTorr. Beam propagation under these conditions is simulated and studied with the hybride code IPROP at Sandia. The problem of beam propagation is also addressed by Vay and Deutsch at Orsay, who developed a 3D electromagnetic PIC-code. Employing a dynamic grid they are able to follow the beam focus from an initial radius of 5cm down to 3 mm. Olson et al. point out the importance of small charge clumps on the emittance growth and the space charge neutralisation of intense beams. Gas neutralization at pressures of about 1 Torr and plasma shielding may take care of this effect. Another beam transport experiment is under way at LBL-Berkeley by Tauschwitz et al. The concept of the experiment is to apply the well known effect of plasma lense focussing and combine this with the plasma channel propagation to transport a well focussed beam to the target. A wall stabilized, tapered discharge of about 100 kA is suggested. For the present experiment the 2 MeV beam from the LBL ESQ-injector is used.

Chamber propagation and beam target interaction physics has made large progress since the last meeting and the results are of immediate relevance and importance for the proposal that is currently discussed in Europe to investigate a heavy ion ignition facility.

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