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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.

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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, Albuquerqe, 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/k_B-regime and above (where k_B 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

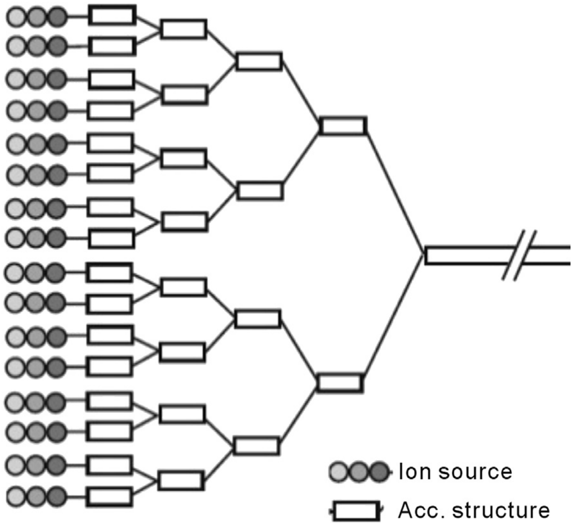

Fig. 1. Multiple ion sources and beam funneling to achieve high intensity as proposed by the HIDIF study [18,19].

$$J \propto \frac{U^{3/2}}{d^2} \tag{1}$$

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

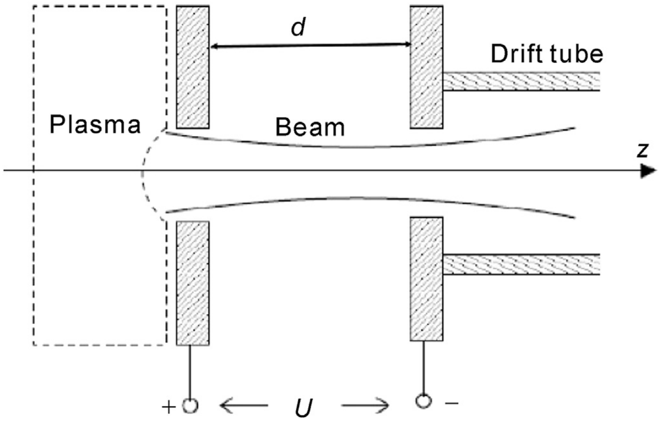

Fig. 2. Schematic set-up of a plasma ion source. The ions are emitted from the concave plasma sheath, which forms an equipotential surface.