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Experiments on extreme states of matter towards HIF at FAIR

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ABSTRACT

The Facility for Antiproton and Ion Research in Europe (FAIR) will provide worldwide unique accelerator and experimental facilities allowing for a large variety of unprecedented frontier research in extreme state of matter physics and applied science. Indeed, it is the largest basic research project on the roadmap of the European Strategy Forum of Research Infrastructures (ESFRI), and it is cornerstone of the European Research Area. FAIR offers to scientists from the whole world an abundance of outstanding research opportunities, broader in scope than any other contemporary large-scale facility worldwide. More than 2500 scientists are involved in setting up and exploiting the FAIR facility. They will push the frontiers of our knowledge in plasma, nuclear, atomic, hadron and applied physics far ahead, with important implications also for other fields in science such as cosmology, astro and particle physics, and technology. It includes 14 initial experiments, which form the four scientific pillars of FAIR. The main thrust of intense heavy ion and laser beam-matter interaction research focuses on the structure and evolution of extreme state of matter on both a microscopic and on a cosmic scale.

1. International FAIR

Construction of a new accelerator facility called FAIR (Facility for Antiproton and Ion Research) was started in 2010 as an international research project in Darmstadt, Germany. This new accelerator complex will consist of two powerful heavy ion synchrotrons and a number of storage rings and experimental facilities for various research projects [1,2]. The centerpiece of the accelerator assembly will be a 100 Tm superconducting heavy ion synchrotron SIS-100 (see Fig. 1). FAIR will provide compressed beam pulses with an intensity that exceeds the current beam intensities by two orders of magnitude. This will extend the available beam deposition power from the current level of 10 GW/g by at least two orders of magnitude up to 3 TW/g. Many aspects of high power beam physics associated with inertial confinement fusion driven by intense heavy ion beams will be addressed there, even though this facility will not provide enough beam power to ignite a fusion pellet [3]. Due to the unique feature of the energy deposition of heavy ions in dense matter – volume character of heating – it is possible to generate extreme states of matter that cannot be accessed with other drivers. This will open up the possibility to explore the thermo-physical and transport properties of high energy density (HED) matter in a regime that is very difficult to access using the traditional methods of shock compression [4].

2. HED physics with intense heavy ion beams at FAIR

Recent progress and the expected future developments [5–7] in the technology of high quality, strongly bunched, well focused intense heavy ion beams have provided a very efficient tool to research HED physics in the laboratory.

In case of shock compression, matter is irreversibly heated and this generates states of high pressure, high entropy in the sample material. Intense particle beams, on the other hand, deposit their energy over extended volumes of matter and are thus capable of inducing these exotic states in the target material directly, without generation of shocks. The main advantages of using intense beams include high repetition rate of the driver, high beam–target coupling efficiency and rather large samples of HED matter with fairly uniform physical conditions (no sharp gradients).

Due to these reasons, a dedicated experimental program on HED physics has been proposed for FAIR [2], which is going to be one of the most powerful accelerators in the world with respect to the beam power and quality. Extensive experimental and theoretical work has been carried out over the past years to assess the potential of intense heavy ion beams to research this important field. This work has shown that one will be able to perform different types of experiments on HED physics at FAIR as described below.

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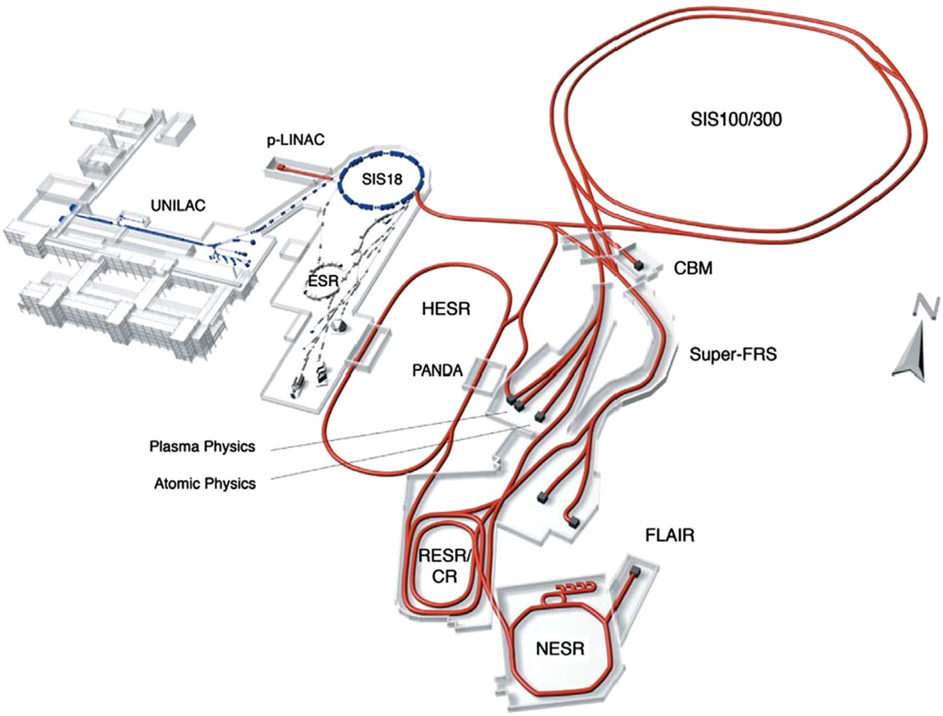

Fig. 1. The FAIR facility. The main components of the facility relevant to the HED physics experiments are the UNILAC (uranium beams) and p-LINAC (proton beams) linear accelerator injectors followed by the SIS-18 and SIS-100 synchrotron rings. The SIS-100 beam transport line and the perpendicular SIS-18 proton beam line coming to the "Plasma Physics" experimental area are shown as well. The other components of the facility prominent for high energy nuclear physics, particle physics and atomic physics are ESR (Experimental Storage Ring), HESR (High-Energy Storage Ring), NESR (New Experimental Storage Ring), RESR (Recycled Experimental Storage Ring), CR (Collector Ring) and Super-FRS (Super Fragment Separator) as well as large experimental installations PANDA (AntiProton ANnihilation at DArmstadt), CBM (Compressed Baryonic Matter) and FLAIR (Facility for Low Energy Antiproton Ion Research).

2.1. Studies on equation of state of HED matter

An intense focused heavy ion beam heats large-volume targets uniformly and quasi-isochorically, thereby generating states of high pressure and high entropy. The heated material can then expand isentropically and depending on the deposited energy, will reach different physical states of HED matter. These include an expanded hot liquid, the region near the critical point, two-phase liquid-gas region, strongly coupled (non-ideal) plasmas and warm dense matter (WDM) regions. Such ion-beam generated samples can be used to study the Equation of State (EOS) properties of different phases of HED matter. This scheme is named HIHEX (Heavy Ion Heating and Expansion) [4,8] and is an important part of the experimental program at FAIR. It is to be noted that some of the above HED states are either very difficult to achieve or are inaccessible using the traditional methods by shock in the limited region of the principal and porous Hugoniots (shock adiabats).

The thermodynamic path followed by the material in a HIHEX experiment can be accessed by depositing the corresponding amount of the specific energy and the subsequent expansion of the heated material. Therefore, using this technique, one will be able to study a wide region of the HED phase diagram of all the materials of interest at FAIR.

2.2. Planetary physics research at FAIR

Theoretical work has shown that an intense heavy ion beam can be efficiently employed to isentropically implode a sample material like hydrogen or water that will generate physical conditions which are expected to exist in the interiors of the giant planets in our solar systems as well as in exoplanets [9–12]. An experiment based on this scheme, named LAPLAS (Laboratory Planetary Sciences) has been proposed to study planetary physics at FAIR [9].

In a LAPLAS experiment, the target consists of a cylinder of the sample material (e.g., frozen hydrogen or water) that is surrounded by a thick shell of a heavy material, like gold or lead. One face of the target is irradiated with an intense heavy ion beam that has an annular (ring-shaped) focal spot, and the target length is less than the range of the driver ions so that the energy deposition in the longitudinal direction is uniform. Such a hollow heavy ion beam can be generated using a RF fast beam rotator (wobbler) system [13]. It is assumed that the inner radius of the annulus is larger that the radius of the sample material which is a necessary condition to avoid direct heating of the sample by the ion beam. A layer of cold material from the outer shell known as "pusher" or "payload", is thus created between the sample material and the beam-heated region. The payload plays an important role in placing the compression on the desired adiabat.

This scheme generates a low-entropy compression that leads to a very high material density with a relatively low temperature. Simulations have shown that using the parameters of the SIS-100 beam at FAIR, one would achieve hydrogen density of 1–3 g/cm^3, pressure of 3–30 Mbar and temperature on the order of ten thousand Kelvin. These are the predicted physical conditions in the interior of Jupiter.

2.3. Relevance to heavy ion IFE

Cylindrical implosion suggested in LAPLAS experiments is relevant to the Heavy Ion Fusion Energy concept, based on the high-energy ion beams drive of a cylindrical target developed in Refs. [14,15].

Direct drive of cylindrical DT-target by intense ion beam in fast ignition mode and wetted liquid wall reactor chamber design with