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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Heavy-ion fusion activities at ITEP

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Abstract

An overview of current activities on Heavy-Ion Fusion at ITEP is presented. A project called TWAC (TeraWatt Accumulator) is in progress now, aiming at the production of TeraWatt power level (100 kJ/100 ns) of intense heavy-ion beams, concentrated on experimental targets [1]. The project is based on the use of the existing accelerator chain at ITEP: A 2 MV/2.7 MHz heavy-ion injector I-3, a 13 Tm booster ring UK, a 34 Tm synchrotron U-10, a system of beam transfer lines and a laser ion source of He-like medium mass ions. Volume energy deposition of the heavy-ion beam in a target is expected to generate hot, strongly compressed matter with extremely high energy density ($>$ 1 MJ/g) in dense plasmas. The scientific program includes a number of challenging issues on accelerator physics, the physics of high energy density in matter and relativistic nuclear physics. The results of numerical simulations relevant to the suggested high energy density in matter experiments with TWAC beams are discussed. A survey of current experiments on beam–plasma interaction using the ITEP 3 MeV proton linac is given here. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

On the long path towards a Heavy-Ion Ignition Facility a number of important physical issues exist, both in accelerator physics and in physics of dense, strongly compressed plasma, which can be studied in simple geometry with lower power and without actual fusion burn. In the field of accelerator physics considerable research on techniques leading to the increase of the final phase space density of heavy-ion beams is necessary. Issues like phase space density dilution processes due to resonances and instabilities in rings, space charge effects in beam transport lines, pulse compression and pulse shaping, final focusing and matching the beams to experimental targets etc. can be investigated by making use of existing accelerator facilities. Application of non-Liouvillean techniques [2–4] in an existing accelerator facility based on a heavy-ion synchrotron becomes essential for its adaptation to HIF related experiments: it opens a possibility to match the relatively low-current techniques in the front end of the facility to high-current requirements of the target drive. The basic requirements for matter and radiation studies are intense ion beams, which produce a specific deposition power of more than 1 MJ/g. Since the efficiency plays a minor role in high energy density and

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radiation physics experiments, it is possible to use very high energy beams, which deposit only a small fraction of their energy in the target. Furthermore, the use of relativistic ions reduces the effect of space charge and makes it possible to take advantage of only one beamline to heat the target material. All these arguments were a strong motivation for the modification of an already existing heavy-ion accelerator complex at ITEP since February 1997, established now as the Project ITEP-TWAC.

2. The project ITEP-TWAC

The procedure pursued in the ITEP-TWAC project is the stacking of many pulses accelerated in a synchrotron into a storage ring. Full stripping of helium-like medium atomic mass ions is used to provide a high efficiency of the non-Liouvillean stacking process, but special efforts are undertaken to prevent scattering and straggling effects in the stripping foil. The choice of the ion species for our project is a result of optimizing a number of competitive demands and constraints:

- the requirement to use as heavy-ions as possible;
- the capability of the ion source to produce a sufficiently high number of helium-like ions;
- the requirement to minimize the intensity losses due to vacuum conditions in the rings;
- the requirement to provide a high (close to 100%) stripping efficiency of ions by non-Liouvillean stacking.

The most suitable type of ion source is the laser ion source, capable of producing a sufficiently high number (10^{10}–10^{11}) of highly charged ions with atomic mass $A \sim 40$–60 in a 1 Hz repetition rate operation mode [5]. The principle of the laser ion source is based on plasma generation by a laser beam focused by a mirror system (or a lens) on a solid movable target. A powerful CO_2 rep-rate laser is found to be the best choice to deliver sufficent energy to evaporate the target material producing a plasma of He-like ions. The production of helium-like ions from medium-A elements with ionization potentials of about ~ 1 keV requires a rather high plasma temperature [6]. Therefore, the development of an efficient laser ion source is one of the crucial requirements of the project. A number of candidate ion species like ${}_{32}S^{14+}$, ${}_{40}Ca^{18+}$, ${}_{59}Co^{25+}$ are now under consideration.

The whole acceleration-accumulation scenario is as follows. A laser ion source produces about 5×10^{10} Co^{25+} ions, which are accelerated in the pre-injector I-3 up to 1.6 MV/u and are then injected into the 13 Tm booster ring UK (see Fig. 1). After acceleration up to 0.7 GeV/u, a 250 ns long bunch is injected in a single-turn mode to the synchrotron ring U-10, using a non-Liouvillean stripping process. The charge state of the ions changes from Co^{25+} to Co^{27+} by passing through a solid foil of about 5 mg/cm^2. Cobalt nuclei are accepted by the synchrotron, which serves as a storage ring, while no further acceleration of the Co nucleii is provided. To minimize the effect of the stripping foil, the accumulated beam circulating in the storage ring is directed on the stripper target only during the injection of the next ion beam pulse coming from the UK booster. For this purpose, a kicker-system for the beam, based on two fast coherent deflectors has to be installed. Since the cross-section of the accumulated beam is at least 25 times larger than the surface-area of the stripper target, the beam quality is not deteriorated significantly by the scattering in the foil. Repeating this process a 1000 times provides ion accumulation in the coasting beam until the Laslett space-charge limit ($\Delta Q \approx 0.16$) is reached in the synchrotron ring at 1.2×10^{13} ions, corresponding to about 100 kJ stored energy in the beam. A rapid switch of the RF in the synchrotron ring causes ballistic compression of the accumulated bunch from a length of 1000 ns down to ~ 100 ns. Such a compression of the beam requires a rather low longitudinal momentum spread $\Delta P/P \sim 4 \times 10^{-4}$. On the other hand, the suppression of coherent microwave instabilities requires to keep the momentum spread not below $\sim 2 \times 10^{-3}$. To solve this problem, a special shaping of the beam momentum distribution can be applied by slightly changing the initial energy of the injected beams. After compression, the bunch is extracted, transported and focused onto the target. The beam emittance of 5 cm mrad enables focusing to a spot-size of ~ 1 mm in diameter.

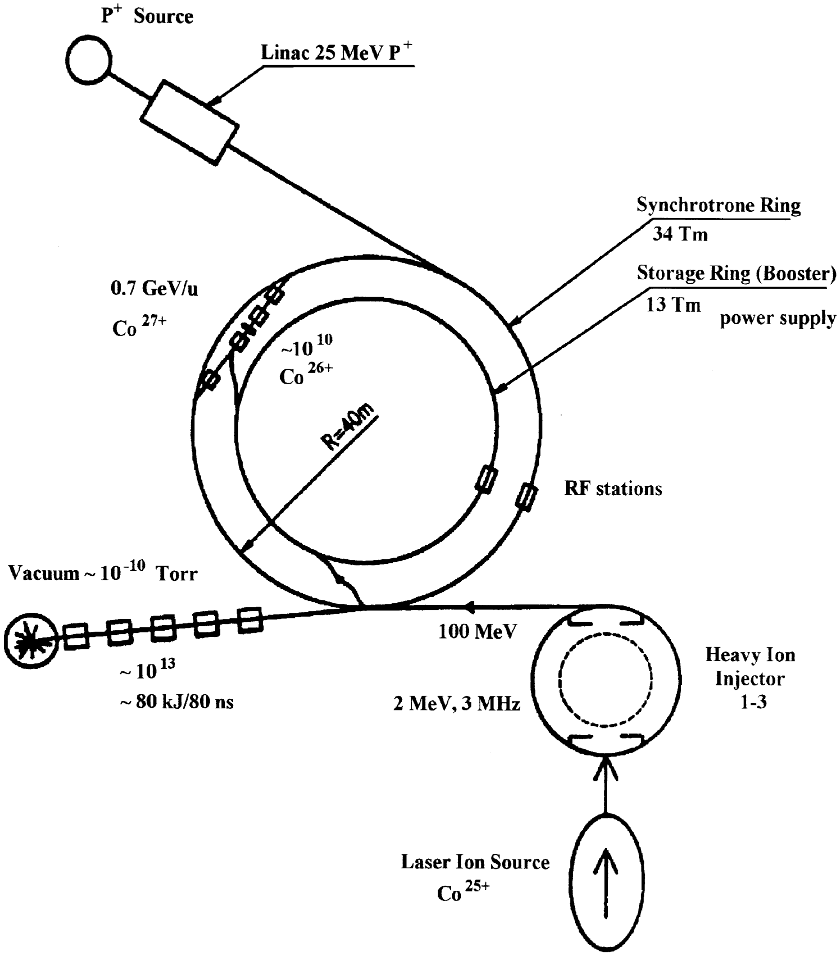

Fig. 1. Layout of the ITEP accelerator–accumulator complex (ITEP-TWAC).

3. TWAC-related high energy density in matter physics

The expected output parameters of the ITEP-TWAC facility are: an energy of 100 kJ deposited on the target in 100 ns, corresponding to a deposition power ∼ 1 TW, while the specific deposition power is ∼ 10 TW/g, in a spot of 500 μm radius. The temperature reached in a solid Au target is calculated to be up to 40 eV. This set of parameters opens up the opportunity for

(1) experiments addressing some fundamental issues of the physics of dense plasmas, like EOS, thermodynamics of strongly compressed matter, plasma phase transitions, etc., and

(2) experiments related to the physics of HIF targets, especially cylindrical targets with magnetized fuel.

Volume energy deposition of the heavy-ion beam in a target causes generation of hot strongly compressed matter with extremely high energy density (>1 MJ/g), producing uniform intense shock waves in solids and plasmas. The expected pressure region between 10 and 100 Mbar provides the possibility to investigate also thermodynamic and kinetic properties of etalon metals (Al, Cu, Fe) in regions of phase diagrams that are difficult to reach with other methods [7]. A combination of the simple geometry of the energy deposition region (inherent for TWAC beams) with geometrical shape of the target gives a wide variety of different experimental schemes. A hollow beam combined with a hollow cylindrical target can produce much higher densities and pressures because of the converging shock waves on the axis of the cylinder. Due to the relatively large (1 mm) target spot size and 100 kJ of pulse energy, it should be possible to carry out experiments with TWAC where magnetically insulated cylindrical targets are directly driven [8]. Two-dimensional simulations predict that some fusion neutrons could be obtained which would be sufficient for diagnostics.

If the proposed TWAC acceleration-accumulation scheme succeeds in determining the planned high output parameters of heavy-ion beams, its upgrade (TWAC-2) towards higher capabilities might be considered. Adding several superconducting storage rings to be filled by the synchrotron would increase many times the available energy and beam power on the target. The expected parameters for the facilities TWAC and TWAC-2 are shown in Table 1. Such an upgrade can be considered as a realistic goal for the ITEP accelerators complex. Even if the TWAC-2 facility does not provide conditions required for the ignition of a hohlraum target, for the parameters required to drive magnetized fusion targets [8] the possibility to obtain significant thermonuclear burn seems to exist despite the low gain of $G \approx 10^{-2}$. The design of a ~ 2 cm long cylindrical target would be a possible match for the requirements of the density distribution along the radius, as presented in Ref. [9].

Table 1
Output parameters of the TWAC and TWAC-2 facilities

	TWAG	TWAC-2
Ions	Co_{27}^{+}	Co_{27}^{+}
ε_i	40 GeV	40 GeV
N_{sr}	1	10
E_0	0.1 MJ	1 MJ
P_{ow}	1 TW	10 TW
τ	100 ns	100 ns
J_s	120 TW/cm^2	30 TW/cm^2
J_m	6 TW/g	1.5 TW/g

4. TWAC related accelerator physics

The progress of the TWAC project initiated preliminary theoretical studies of the collective effects in the accumulation ring. It is clear that the intention to prevent the development of beam instabilities by keeping the momentum spread as large as possible is in contradiction with the requirement to compress the accumulated beam down to 100 ns. The contributions of several effects have been investigated both analytically (linear theory) and numerically (PIC-code). The influence of the space charge tune shift ($\Delta Q \sim 0.16$) and the development of the longitudinal microwave instability have been found to be of no importance. On the other, the transverse coherent instabilities and intra-beam scattering processes have been found to be real limitations for the final phase space density of the beam as well as the straggling and the varying energy losses of the ions in the stripper foil. As a result a specific momentum spread distribution (80% of ions within $\Delta P/P \leq 4 \times 10^{-4}$ and the wings within $\Delta P/P \leq 2 \times 10^{-3}$) is suggested. A number of technical efforts to provide the required output parameters of the beam are under consideration.

Table 2
Parameters of the charge symmetrical driver for high gain and ignition experiments

	High gain	Ignition
Driver energy (MJ)	9.6	3.2
Ion energy (GeV)	10	10
P max (TW)	960	1000
Emittance (cm mrad)	4	3.4
Focal spot (∅ mm)	4	2.2
N beams	12	8
Current per beam (kA)	8	12
N of rings	96	6
Ion species	Pt^{+}/Pt^{-}[a]	Au^{+}/Au^{-}
Req. source current (mA)	130	45

[a] Four isotopes.

5. HIF driver design and target physics

The activities on the design of a HIF Charge Symmetric Driver, pursued at ITEP since 1991 [10], are in progress. The main issues of the research are:

- beam dynamics of the charge-compensated beam in all stages of acceleration, beam transfer, compression, funneling of positive and negative ions, final transport onto the target;

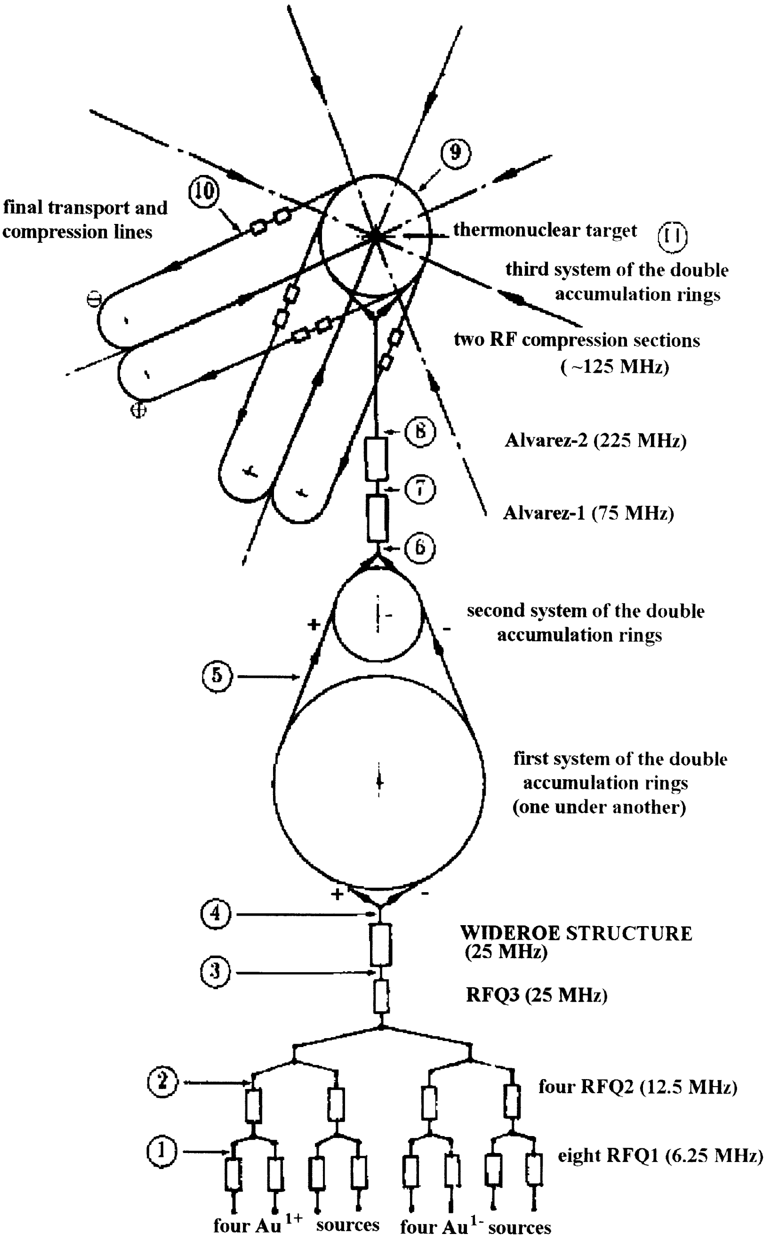

Fig. 2. Charge symmetric driver for 3.2 MJ beam pulse energy.

- design of the 10 GeV linac for simultaneous acceleration of positive and negative ion species;
- the effect of intra beam scattering on the beam losses during the funneling stage and final beam transport to the fusion target.

It has been shown that the most important feature of the charge symmetric scheme is the possibility to obtain a final current of up to 10 kA per beam and to provide the power density of 1000 TW/cm^{-2} on the target converter. The next step forward has been made by applying similar ideas to the design of the driver with an output energy $\sim$ 3.2 MJ for an Ignition Facility (low gain option in Table 2). Only two ion species Au$^+$ and Au$^-$ are considered to be accelerated. The beam compression is started already at an ion energy $\sim$ 600 MeV in four rather small accumulation rings. After the acceleration to the final energy of about 10 GeV, the beam is compressed five times in one ring for each species and 16 bunches are compressed 100 times in the final beam transport line, then they are funneled and focused onto the thermonuclear target. Therefore, only six rings are used in the whole beam manipulation scheme (Fig. 2). A schematic view of an indirectly driven target which could be ignited with the driver parameters mentioned above, is shown in Fig. 3. The fusion capsule is similar to the one proposed for the NIF project [11]. The main characteristics of this target have been calculated with the 2D view-factor code VF2 and with the 1D radiation hydrodynamics code DEIRA. About 50% of the ion beam energy, deposited in the eight converters, is transformed into thermal X-rays, of which 150 kJ are absorbed by the capsule. The time-integrated peak-to-valley non-uniformity of the X-ray drive on the capsule has been calculated to be below 1%.

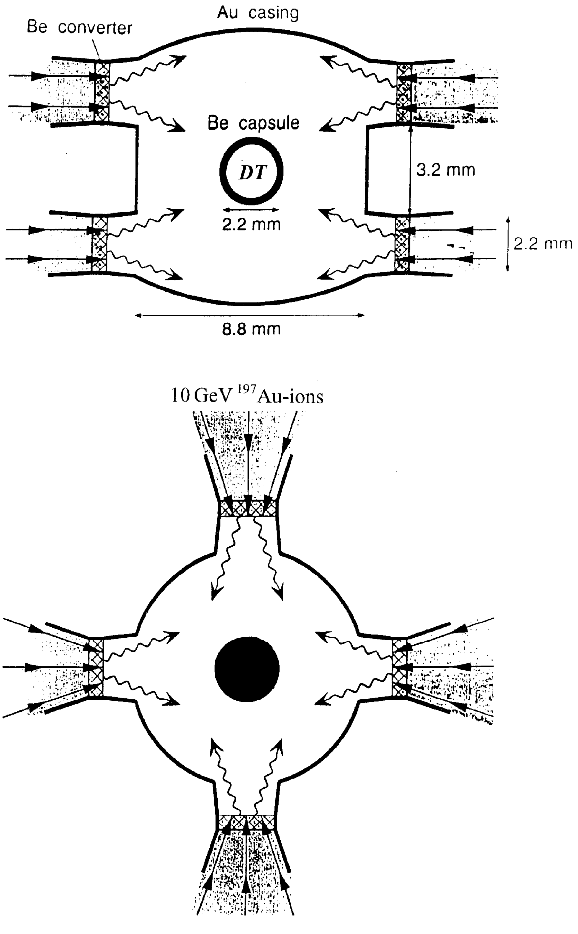

Fig. 3. Schematic view of the target.

6. Beam–plasma interaction experiments

The investigation of interaction processes of ion beams with dense plasmas is already a well-etablished issue in physics of IFE driven by heavy-ion beams. In series of experiments the effect of the plasma on the Coulomb stopping power of fast ions has been studied. The recent experiment performed at ITEP introduces the Coulomb energy losses of fast protons as a method of plasma density diagnostic, particularly important for the case of hot dense ($N_e > 10^{19}$ cm^{-3}) plasmas, where most of the other techniques fail. In our experiment the 7 μs long pulses of 3 MeV protons delivered by the 148.5 MHz ISTRA-36 RFQ linac have been used for plasma diagnostics. The plasma was generated by an electrical discharge inside a 50 mm long cylindrical capillary channel bored in a polyethylene slab [12]. The total effective Coulomb logarithm of an atomic–ionic mixture of composition CH2 has been calculated with the SAHA-4 code [13] by taking into account several independent measurements of the plasma pressure. As a result the density of free electrons has been measured with good accuracy to be $n_e = (6.4 \pm 1.1) \times 10^{19}\ \mathrm{cm}^{-3}$.

7. Conclusion

Upgrading of the ITEP accelerator complex to a powerful heavy-ion facility promises to provide a very valuable tool for experiments in high energy density in matter physics, in relativistic nuclear physics and accelerator physics as well. If the basic scientific ideas of the TWAC acceleration–accumulation scheme will provide the desired output parameters, a new challenging path to ignition, based on the use of heavy-ion synchrotrons, has become apparent.

Acknowledgements

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