Concluding Remarks

The heavy ion accelerator is the most promising driver candidate for the production of electrical energy by inertial confinement fusion. The HIBALL design study showed for the first time that the concept of an accelerator driven fusion reactor should be technically and economically feasible.

However, heavy ion beams represent a challenging driver option for ICF. Two accelerator designs, an RF-linac with storage rings and an induction linac, both investigated in the framework of national programmes during the last decade, are candidates. Two accelerator facilities, SIS/ESR and MBE-4/ILSE, will study key issues of both driver concepts.

For the enhanced requirements of indirect drive, the heavy ion accelerator also continues to be the preferred candidate if non-Liouvillian stacking is included. New accelerator scenarios based on non-Liouvillian beam manipulations have been proposed and promise greatly improved beam quality and intensity to meet the requirements.

Regarding the most important immediate research objectives:

– There is a serious lack of experimental data on many key issues, in particular, beam dynamics and the physics of dense plasmas. The SIS/ESR two-ring accelerator will be a unique facility for such investigations, and related theoretical work must be continued. Any opportunity to investigate non-Liouvillian beam manipulations and to research all related techniques, *e.g.*, FEL development, should be a priority.

– A new conceptual design study, replacing HIBALL, involving workers at CERN (accelerator aspects) and Sincrotrone Trieste (FEL) has been launched recently (see page 91) in order to include the novel concepts of indirect drive and non-Liouvillian techniques.

– A strategy for building an heavy ion fusion demonstration accelerator has yet to be developed to enable significant beam-target experiments and to demonstrate the feasibility of accelerator technology and non-Liouvillian stacking. Either a dedicated test facility (*e.g.*, with low repetition rate) or the first stage of a larger facility might be considered. It should, however, be based on new technology.

REFERENCES

[1] Badger B. *et al.*, HIBALL: *KfK Report* **3202** (1981); HIBALL II: *idem.* **3840** (1989).
[2] Hogan W.J., *LLNL Report UCRL* **50021-86** (1986).
[3] Meyer-ter-Vehn J., *Nucl. Fusion* **22** (1982) 561.
[4] *Proc. Conf. on Heavy Ion Inertial Fusion,* Washington DC, Eds. M. Reiser, T. Godlove and R. Bangerter (AIP, New York, NY) 1986.
[5] Fessenden T., *Nucl. Inst. & Methods* **A278** (1989) 13.
[6] Keefe D., [5] p. 266.
[7] Godlove T. and Yu S., Symp. Heavy Ion Inertial Fusion, Monterey, USA (1991).
[8] Rubbia C., [5] p. 253.
[9] Atzeni S., *Europhys. Lett.* **11** (1990) 639; *Laser Part. Beams* **9** (1991) 232.
[10] Murakami M. and Meyer-ter-Vehn J., *Nucl. Fusion* **31** (1991) 1315.
[11] Meyer-ter-Vehn J. and Murakami M., *Particle Accelerators* **37-38** (1992) 519.
[12] Hofmann I., *Drivers for Inertial Fusion,* Vol. I (IAEA, Vienna) 1991.

SIS / ESR

A Nuclear Physics Facility for Heavy Ion Inertial Fusion Research

A German government funded programme on the fundamental issues of heavy ion inertial fusion (HIF) began with an exploratory phase in 1979 and was devoted mainly to the HIBALL system feasibility study (see page 83), to theoretical investigations of accelerator and target issues, and to research on some key HIF aspects such as development of high-brilliance sources, RFQ's and other accelerator relevant components. Gesellschaft für Schwerionenforschung (GSI) - Darmstadt, KfK - Karlsruhe, the Max-Planck-Institut für Quantenoptik in Garching, and a number of German universities participated in the programme which concentrated on the front-end of a RF linac driver approach.

The major achievements were a full-scale, high-brilliance ion source for Bi ions which meets inertial confinement fusion (ICF) driver specifications, and a low-frequency (13.5 MHz) RFQ prototype injector for high-current injection into GSI's existing UNILAC linear accelerator (Fig. 1). Based on this experience, a prototype of a new 27 MHz injector for high beam currents is under construction at Frankfurt University, with delivery of a prototype planned for 1992.

The HIBALL study showed that the existing experimental database is too narrow for deciding upon critical HIF issues. Consequently, in the second half of the programme, starting in 1983, a concept for an experimental facility was developed, partly based on the nuclear physics community's plans for a heavy ion synchrotron at GSI.

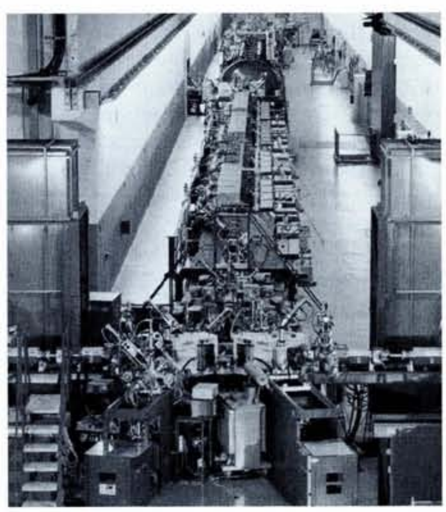

Fig. 1 — GSI Darmstadt's UNILAC RF-linac.

Two additional devices of particular relevance to HIF are:

– a high-current injector for high intensity operation of the synchrotron;

– a storage ring for beam dynamics studies at space charge limits, with a beam cooling facility for generating low-emittance beams to create high energy density in a target, and to allow investigations of beam instability at phase space densities beyond beam stability limits.

The SIS/ESR Facility

The two-ring, heavy ion synchrotron (SIS)/storage ring (ESR) accelerator facility (Fig. 2) became operational in 1990 and accelerator experiments using the available low intensities started a few months later [1]. The electron cooling capability was demonstrated in May 1990. Installation of the high-current injector indispensible for studies with very heavy ions (about 10^{11} uranium ions will be injected per spill) has unfortunately been delayed. The facility incorporates in principle all the accelerating structures of a complete driver accelerator for HIF based on a RF linac/storage ring concept and offers excellent opportunities for dedicated research on key HIF issues in the field of driver and target physics. Most driver relevant issues should be accessible to experimental investigation, except non-Liouvillean stacking.

Experimental Programme

Experiments in **beam dynamics** will cover issues affecting the acceleration, storage and other manipulations of high intensity beams at high phase space density. Experimental data are of fundamental interest as well as being urgently needed to design future facilities.

Schottky noise measurements with Ar^{18+} beams have already shown [2, 3] that the beam current threshold (the Keil-Schnell limit) for the longitudinal microwave instability can be exceeded by a factor five without any loss of stability. The appearance of a double-hump structure in the Schottky spectrum at the highest phase space densities marks the transition from single particle to collective behaviour.

For **beam-target** interactions, the objectives are the generation and investigation of dense (heavy ion) plasmas of solid state density produced with a well-defined geometry by a heavy ion beam of high phase space density. This new area of research has been opened up by the ESR's beam cooling facility, and many results of fundamental significance can be expected. The field spans a broad spectrum of problems such as beam-plasma interaction and the dynamics of hot dense plasmas. The generation of plasma samples of solid state density, well defined in time and geometry, also offers new possibilities for spectroscopic investigations and for studying the physics of non-ideal plasmas, related to stellar plasma, under controlled experimental conditions. Owing to the bunched beam, evolution with time can be investigated. With a specific power density in matter of 10 TW/g, plasma temperatures of ten or several tens of eV should be obtainable at the designed beam intensities, depending on the target configuration.

Concerning ICF relevant issues, ion deposition and equation of state physics arising at power densities of 10-100 TW/g will be explored, while studies on thermal radiation processes need higher temperatures that might be reached using special target arrangements. Thus, issues of beam-target interaction can be investigated at a reasonable level of power deposition (several tens of eV) but, unfortunately, still far from the requirements for fusion implosion driving plasmas (300 eV). Crucial issues of implosion dynamics will therefore remain open, although many relevant problems can be investigated, such as deposition power, the equation-of-state, conversion to thermal radiation, opacities at low temperatures, and shock compression.

The SIS/ESR beam line that first operated in June 1991 includes a dedicated lens for fine focussing to a 0.2 mm diameter beam on the target. Beam-plasma interaction experiments have been carried out up to now at 1.4 and 6 MeV/nucleon using beams from the UNILAC accelerator with an improved Z-pinch device for the generation of a fully-ionised hydrogen plasma [4]. The stopping power for heavy ions in a plasma was measured for the first time and showed an enhancement by a factor of 2 to 3 as compared to cold matter [5]. Charge state distributions for an ion traversing a plasma have also been determined for the first time. As predicted, the equilibrium charge states are much higher than in a cold gas. This is the first direct experimental proof of an enhanced effective charge of heavy ions in ionised matter. Detailed measurements show that the dielectronic recombination plays a non-neglegible rôle among the various charge-changing processes.

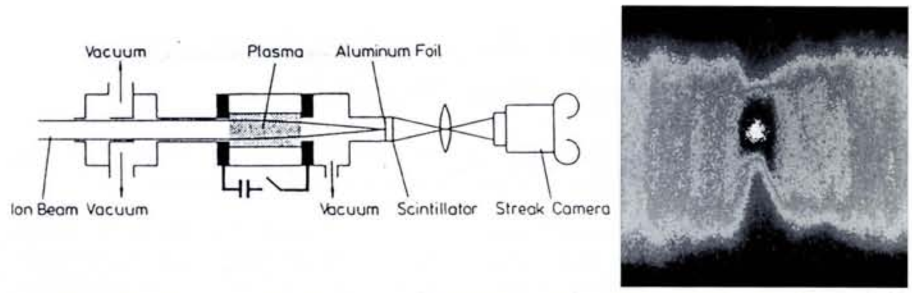

Fig. 3 — Schematic representation of a GSI plasma lens focussing experiment (on the left) and the streak camera image showing compression (Z-pinch) of a 10 mm 11.4 meV/nucleon Ar beam on igniting the plasma for ≈ 1 μs. The image is seen to contract with time (horizontal coordinate) and then recover.

ICF relevant **atomic physics** experiments include beam-plasma interactions and intrabeam scattering to provide data for stopping power and beam loss in heavy ion storage rings. One of the important technological spin-offs is the focussing of a heavy ion beam by the plasma lens properties of an enhanced Z-pinch effect. This has been demonstrated for the first time as a proof-of-principle [6] using a 460 MeV argon beam from UNILAC injector (Fig. 3). The technique will be improved further using SIS/ESR. The focussing properties of another plasma lens, a discharge tube with a five-times higher magnetic gradient (100 T/m), is presently being investigated with promising results.

An experiment (Salzborn *et al.*) deals with intrabeam scattering in the storage rings of a driver accelerator. Ion-ion collisions for the Bi^+ on Bi^+ heavy ion system have been investigated using a crossed-beam arrangement for the first time in the relevant energy range of 10-100 keV, corresponding to the relative motion of the beam particles in a bunch. Two other systems (Xe^+ on Xe^+ and Cs^+ on Cs^+) have been examined recently with similar results. A rough estimate gives a loss rate owing to charge-changing intrabeam scattering in the 1% region for a the driver scheme (4 ms storage time) considered in the HIBALL scenario.

[1] Bock R., *Drivers for Intertial Confinement Fusion*, Vol.1 (IAEA, Vienna) 1991; Int. School of Physics "Enrico Fermi" — CXVI Course (Varenna) 1990.
[2] Franzke B., Proc. Particle Accel. Conf., San Francisco (1991) 2880.
[3] Hofmann I., *ibid.*, p. 2492.
[4] Hofmann I. *et al.*, *Particle Accel.* **37-38** (1992) 371.
[5] Dietrich K.G., *Z. Phys. D* **16** (1990) 229.
[6] Boggasch E. *et al.*, *Particle Accel.* **37-38** (1992) 89.

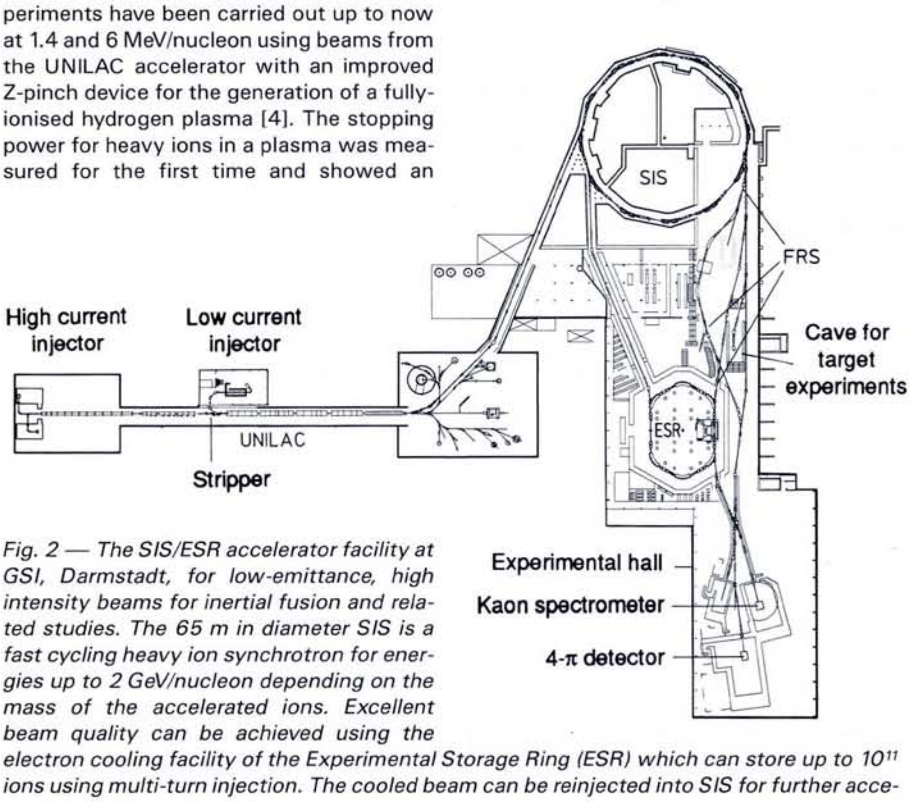

Fig. 2 — The SIS/ESR accelerator facility at GSI, Darmstadt, for low-emittance, high intensity beams for inertial fusion and related studies. The 65 m in diameter SIS is a fast cycling heavy ion synchrotron for energies up to 2 GeV/nucleon depending on the mass of the accelerated ions. Excellent beam quality can be achieved using the electron cooling facility of the Experimental Storage Ring (ESR) which can store up to 10^{11} ions using multi-turn injection. The cooled beam can be reinjected into SIS for further acceleration and bunching. The target cave on the right is dedicated to beam/target interaction experiments with an anticipated 10^{11} Xe ions/bunch using a new high-current injector. The original UNILAC RF-linac injector handles all ions up to uranium.