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 booster accelerators, 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-Liouvillean stacking is included. New collider scenarios based on non-Liouvillean 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 SI/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-Liouvillean beam manipulations and to research all related techniques, e.g., FEL development, should be a priority.
- A new conceptual design study, replacing HIBALL, including 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-Liouvillean 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-Liouvillean 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

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. 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 indispensable for studies with very heavy ions (about 10¹¹ 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 Ar¹⁸² beams have already shown [2, 3] that the beam current threshold (the Kell-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 driven 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-negligible role among the various charge-changing processes.

ICF relevant atomic physics experiments include beam-plasma interactions and intra-beam scattering to provide data for stopping power and beam loss in heavy ion storage rings. One of the important technologically spin-offs is the focussing of a heavy ion beam by the plasma lens properties of an enhanced 2-pinch effect. This has been demonstrated 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 intra-beam scattering in the 1% region for a the driver scheme (4 ms storage time) considered in the HIBALL scenario.


**Prospects for Heavy Ion Inertial Fusion**

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