THE GERMAN HEAVY ION INERTIAL FUSION ACTIVITIES

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Problems of heavy-ion inertial fusion are investigated in the framework of a basic research program at German research laboratories and universities. The SIS/ESR facility at GSI became operational recently and will provide excellent conditions for studies on beam dynamics and beam-target interaction. In collaboration with other European laboratories, advanced accelerator scenarios are investigated which include concepts of non-Liouvillean beam handling techniques and indirect drive.

1 INTRODUCTION

This is a brief overview of the German research activities in Heavy Ion Inertial Fusion and their objectives, recent achievements, and near-term goals. Some more-detailed information is given in these proceedings.

After a decade of research on issues of accelerator and target physics, two aspects will strongly influence the direction of our future research: (1) the commissioning of the new accelerator facility SIS/ESR at GSI, and (2) the consideration of non-Liouvillean techniques for future concepts of driver or test facilities.

1) The new two-ring facility at GSI, a heavy-ion synchrotron and a storage and cooler ring, which recently became fully operational, will provide excellent and unique conditions for systematic accelerator and target investigations. Key issues of the dynamics of high-intensity beams at high phase-space density, in particular the limits for beam instabilities, will be addressed in an experimental research program at this facility, as well as problems of beam-target interaction and the physics of dense plasmas. In addition, the future high-current feature of SIS/ESR for very heavy ions will provide an excellent basis for advanced technological developments.

2) The inclusion of non-Liouvillean techniques in the concept of a heavy ion driver, as proposed by Rubbia[1] some years ago, will considerably improve the performance of such a facility with respect to final focussing and final bunching. Even in case of indirect drive, non-Liouvillean techniques still seem necessary to provide sufficient beam quality. Stimulated by these observations, other non-Liouvillean concepts have been considered and will be an important aspect of our forthcoming activities.

Research presented in this paper was carried out by a number of groups at some German research institutes (GSI, Max-Planck-Institute for Quantum Optics Garching, Fraunhofer Institute Aachen) and universities (Darmstadt, Frankfurt, Giessen, München and Stuttgart). It is funded by the German Federal Ministry for Research and Technology. In addition, collaborations exist for some years already in some areas with a French group of Orsay/Orléans and a group from ITEP in Moscow. It is obvious that the future program needs a stronger European effort. A new Italian-German collaboration will be active in research on target and driver issues, predominantly those emerging from proposed new driver concepts. After some meetings in Varenna 1989 and 1990 arranged by the Italian Physical Society and with an international participation, joint study groups have been established and are going to discuss new scenarios and the new framework of activities.

2 OBJECTIVES AND SOME RECENT RESULTS

The main objectives of the program are the generation and investigation of high intensity heavy ion beams with high phase-space density, and the investigation of the interaction of these beams with matter. It is a basic physics- and technology-oriented research program[2] and can be subdivided into the following topics:

- Experiments and theory on dynamics of space-charge dominated beams
- Experiments on beam plasma interaction
- Generation of dense plasmas, and radiative and hydrodynamic response
- Development of special accelerator structures and components
- Driver-relevant atomic-physics issues
- Development of equipment and diagnostics
- Systems studies and future accelerator concepts

Much work done since the last symposium in 1988 has been devoted to preparations for the research at SIS/ESR. In this section we concentrate on some selected results, mainly achieved in collaborations with university groups.

Stopping of Ions in Plasma and Plasma Lens Focusing (D. H. H. Hoffmann *et al.*[3]). The experiments on the interaction of heavy ions with plasma were extended to higher plasma density and to higher beam energy with an improved Z-pinch device. Previous results of roughly 3 times enhanced stopping power in plasma were confirmed. In addition, measurements on the charge state distribution of the beam ions showed for the first time the shift to higher charge states in the plasma. These results are in excellent agreement with a novel theory of Peter and Meyer-ter-Vehn[4], which predicts that the high charge state remains until the end of the range, where the ion gets suddenly neutralized. Furthermore it shows the influence of dielectric recombination on stopping. With the same device, focusing of heavy ions by the Z-pinch plasma has been demonstrated for the first time.

First Heavy-Ion-Generated Plasmas (Jacoby *et al.*[5]). The high-current RFQ, MAXILAC, was used for the development of techniques and for preliminary target experiments. For the penetration of a high-intensity Kr beam in a Xe gas target, the gas was heated up to the eV region and the hydrodynamic response was measured. Good agreement with simulations[6] was observed.

Electron Capture Cross Section (A. Müller *et al.*[7]). An experiment has been assembled to measure atomic cross sections for the interaction of a heavy ion beam with an electron beam at very low relative velocity using merging-beam techniques. Measured cross sections for radiative capture are found to be much higher than those predicted by theory. With this new device, an "electron target", atomic processes relevant to heavy ion inertial fusion can be measured.

Ion-ion Charge Exchange Cross Sections (Salzborn *et al.*[8]). Intra-beam scattering is a critical issue for beam loss. Figure 1 shows a compilation of measured cross sections, including the recently measured case of $Cs^+ + Cs^+$, a closed-shell ion. The effect of closed shells is not so dramatic as was expected; the loss of beam intensity in storage rings of a HIBALL scenario still remains in the region of 1%.

Accelerator Development (H. Klein *et al.*[9]). Systematic work on RFQ structures has been continued at Frankfurt University. A new prototype of a 27-MHz high-current injector for UNILAC has been designed and will be delivered in June 1991

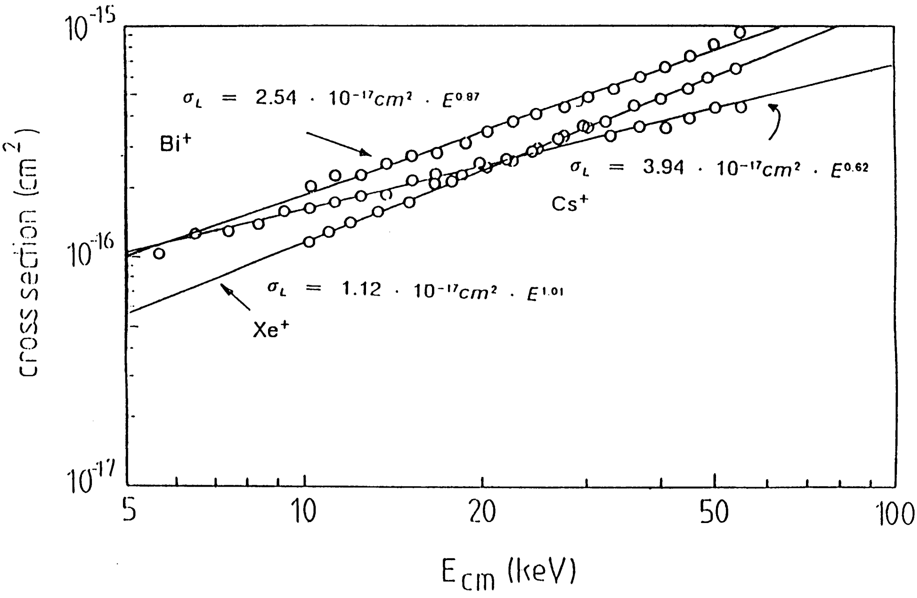

FIGURE 1 Results of a crossed-beam experiment: charge-change cross sections for $Bi^+ + Bi^+$, $Cs^+ + Cs^+$ and $Xe^+ + Xe^+$ as a function of velocity. The velocity range corresponds to the relative velocity of ions in a beam bunch in storage rings. The loss rate by charge-changing intrabeam scattering as determined from these cross sections is in the order of 1% for a storage time of 4 ms. The case $Cs^+ + Cs^+$ (closed shells) is by a factor of 2–3 better than $Bi^+ + Bi^+$. The measurements were made by Salzborn *et al.*[8] at Giessen University.

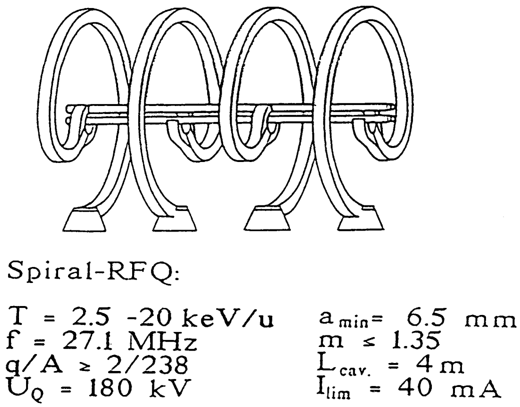

FIGURE 2 Spiral RFQ structure for the 27-MHz high-current injector for UNILAC (developed at Frankfurt University[9]).

(Figure 2). Work on some crucial issues is making progress—in particular studies of funneling, of neutralization of ion beams, and of diagnostics for measuring beam profiles.

Theoretical Work is going on at MPQ Garching on beam target interaction and a number of topics concerning indirect-drive targets; in Frankfurt on target hydrodynamics and on radiation efects; and in Darmstadt on stability limits of ICF targets, Langmuir waves, implosion and burn of indirect drive targets and on targets for SIS experiments. Recent progress concerns in particular the stopping of ions in plasma, hydrodynamic response of beam-heated plasmas, and the conversion of beam energy in radiation.

3 THE SIS/ESR FACILITY AND THE FUTURE EXPERIMENTAL PROGRAM

The synchrotron SIS has been in operation since autumn 1989. The storage ring ESR had its first cooled beam in May 1990, as shown in Figure 3. The high-current injector—an integral part of the whole facility—is delayed by two years. As mentioned before, it will be a 27-MHz RFQ structure developed at Frankfurt University. A set of performance parameters for the whole facility and its expected realization is given in Table 1.

The first experiments will be devoted to heating of material of various densities up to solid-state density with heavy ion beams. Problems of interest are

- the energy deposition in plasma
- the hydrodynamic response of matter at high energy densities
- thermal radiation processes
- equation-of-state physics

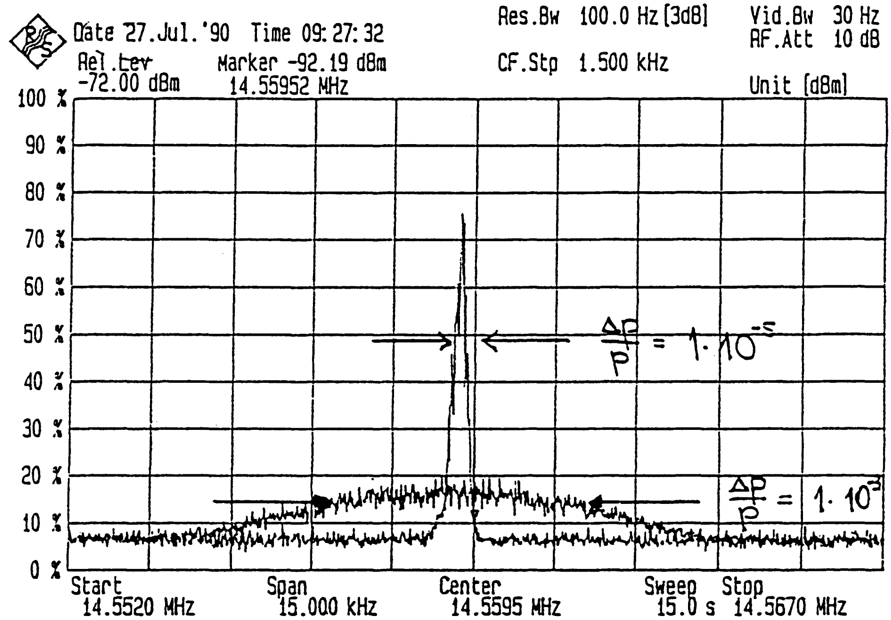

FIGURE 3 First results of electron cooling at SIS/ESR[14]. The measurement shows the Schottky noise spectrum of the cooled and uncooled beam. The momentum spread is improved by cooling by a factor of 10 to 100.

The focusing of the heavy ion beam down to a diameter of about 0.2 mm should result in a specific energy density up to about 10 TW/g, resulting in temperatures of about 20 eV at solid-state density. In diluted matter it might even be higher. Shock waves of up to 4 times solid density are expected. Concerning the thermal processes, radiation cooling and the conversion efficiency into soft X-rays is of great interest. The time schedule for the experimental investigation of these issues very much depends on the achieved beam intensity, e.g., on the schedule for full commissioning of the facility, including the high current injector.

TABLE I

Beam performance with SIS/ESR for accelerator and target experiments within the next 3 years (Hofmann[12])

Ion	Ne^{3+} single turn no cooling	Xe^{44+} 25 turns cooling	Xe^{44} cooling + high-current	Upgraded
N	1.6×10^{9}	3.2×10^{10}	1.2×10^{11}	1.2×10^{11}
Energy (MeV/u)	300	300	1100	1100
Pulse Length (ns)	100	35 or >	70	10
Total Energy (J)	1.5	30	2500	2500
Specific Power (TW/g)	0.003	0.12 or >	8	60
Temperature (eV)		1.4	20	50

The first experiments on the dynamics of space-charge-dominated beams will concentrate on issues like:

- space-charge effects in multi-turn injection
- longitudinal micro-wave instability
- fast bunching and resonance crossing

As a result of recent experiments[14] the Keil-Schnell limit for microwave instabilities has been overcome by more than a factor of 6, good news for the lifetime of stored beams. The results of these experiments, some of them have already started, will provide the basis for further considerations on driver concepts.

4 PERSPECTIVES

In our present understanding, the primary uncertainties of heavy ion inertial fusion are:

for the pellet

- the radial symmetry of implosion drive
- hydrodynamic instabilities

for the accelerator

- longitudinal microwave instabilities
- final focusing
- final bunching

Theoretical investigations about the necessary symmetry of implosion drive indicate that, with a small number of heavy ion beams, sufficient symmetry might not be achieved. Taking this for granted, indirect drive would be a necessary ingredient of a pellet implosion concept. In this case two more target issues are important: the conversion efficiency and the radiation confinement.

Various types of indirect-drive pellets have been investigated[10]; an example is shown in Figure 4. In order to achieve high conversion efficiency the required deposition power needs to be about 10^{16} W/g, as indicated in the inset of Figure 4. Indirect drive would impose much more severe conditions upon final focusing and final bunching.

Table 2 shows a comparison of parameters for direct and indirect drive[11]. The necessary increase of the specific deposition power is more than an order of magnitude. At this point non-Liouvillean techniques are getting to be an essential ingredient of a driver concept.

Since Rubbia suggested non-Liouvillean injection in 1988, a number of different injection schemes and accelerator scenarios (both driver and test facilities) have been considered. The compilation of Table 3 shows several basic possibilities[13]. Some examples should be mentioned, including non-Liouvillean bunch compression which

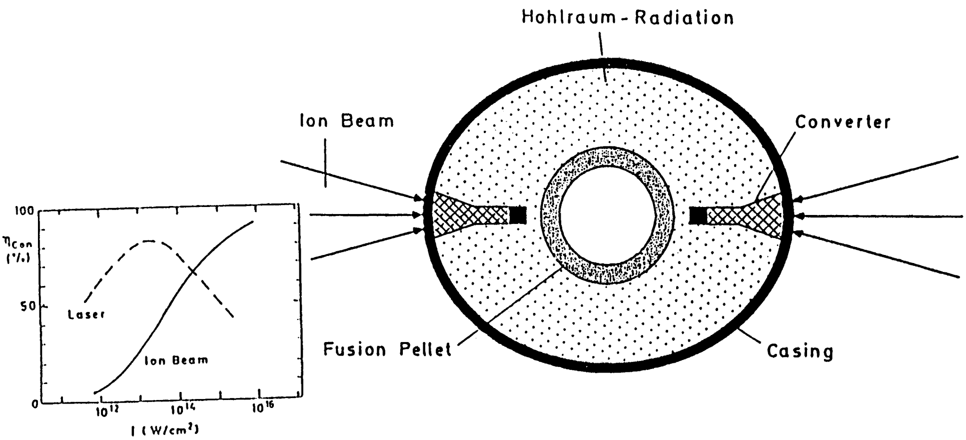

FIGURE 4 Configuration of an indirect-drive target for heavy-ion inertial fusion. The kinetic energy of the beam is converted into soft X-rays which implode the inner shell filled with DT fuel. The conversion efficiency depends strongly on the specific deposition power, as plotted in the insert. For comparison also the conversion efficiency of a short wave-length laser beam ($\lambda = 0.35\ \mu m$) is given. The radiation confinement is achieved by the high-Z casing (Meyer-ter-Vehn[10]).

TABLE II

Beam parameters for direct vs. indirect drive (Hofmann[12]).

	Direct drive (HIBALL)	Indirect drive
Beam power	250 TW	500 TW
Absorber mass	400 mg	45 mg
Spot diameter	8 mm	2.7 mm
Final pulse duration	20 ns	10 ns
Specific power	$6 * 10^{14}$ W/g	10^{16} W/g

TABLE III

Various possibilities for non-Liouvillean beam handling techniques.[13]

Candidate reactions for non-Liouvillian beam manipulation		
"In-beam chemistry"	Examples	Problems/remarks/status
Molecular dissociation	$HI^+ + h\nu \rightarrow H^0 + I^+$ $I_2^+ + h\nu \rightarrow 2I^+ + e^-$	Low dispersion Unknown branching (I^0?)
Photoionization	$Bi^+ + \Sigma h\nu \rightarrow Bi^{++} + e^-$	Space-charge problem with Bi^{++}
Stimulated recombination	$Bi^{++} + e^- + h\nu \rightarrow Bi^+ + 2h\nu$	To be studied ideal candidate *if it works*
Cluster or macromolecule formation		
Multiple-photon ionization of negative ions	$Au^- + \Sigma h\nu \rightarrow Au^+ + 2e^-$	Ideally good dispersion; best available data; best known overall case

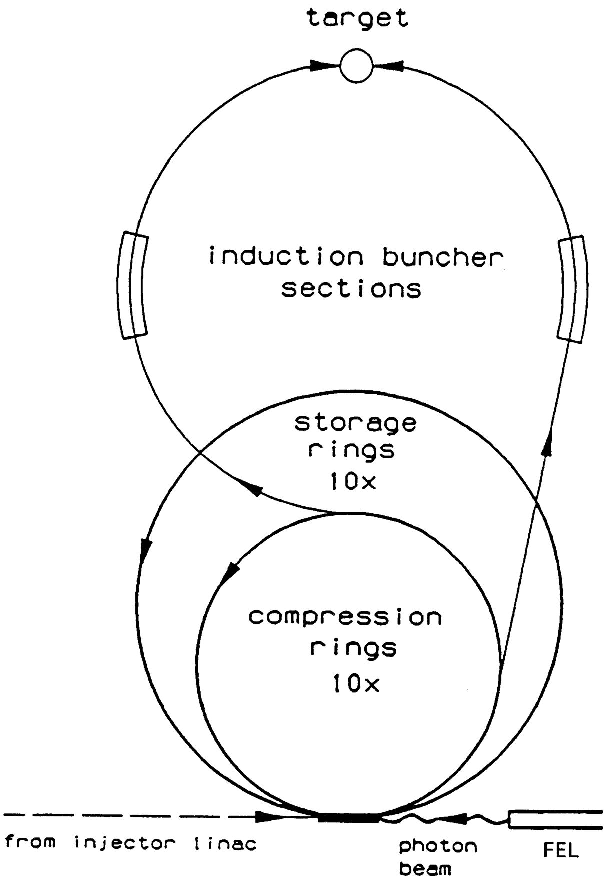

FIGURE 5 Advanced driver scenario, including non-Liouvillean bunch compression using photo-ionization with a free electron laser (I. Hofmann[12]).

was recently suggested by I. Hofmann[12] for a driver accelerator) in which short pieces of a coasting beam are cut off by short laser pulses. The short heavy-ion bunches are deposited on top of each other in a compression ring without increasing the momentum width (Figure 5). Instead of changing the charge state at injection, the mass can be changed by dissociating a molecular ion at injection[13] (Figure 6). Some preliminary results look quite encouraging. These possibilities have to be investigated in much more detail.

5 CONCLUSIONS

The rf linac with storage rings provides a challenging driver option for inertial confinement fusion. Also, for the enhanced requirements of indirect drive, the

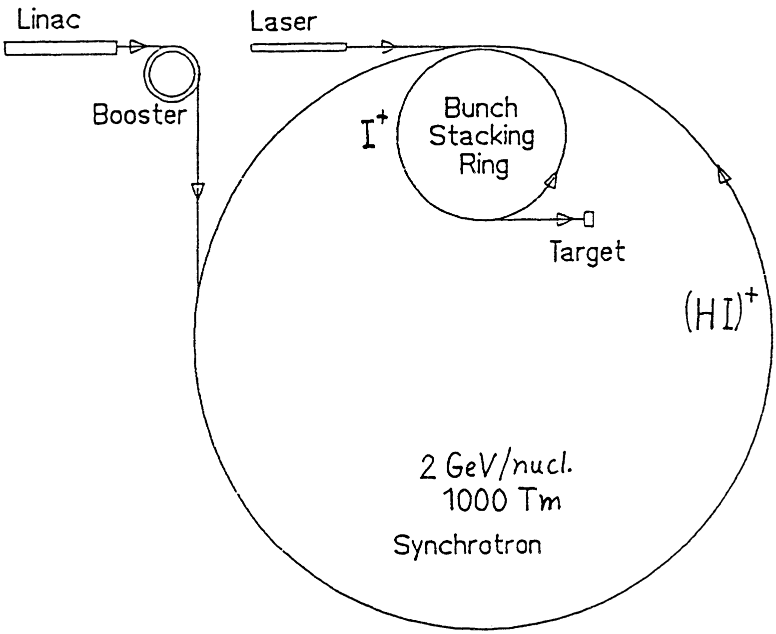

FIGURE 6 Suggested scenario for a test facility using non-Liouvillean stacking by photodissociation of a molecular beam (Arnold and Müller[13]).

heavy-ion accelerator continues to be the best driver candidate if non-Liouvillean stacking is included. The goals for a near-term research program are three fold:

1) There is a serious lack of experimental data on many key issues, in particular in beam dynamics and in the physics of dense plasmas. The new 2-ring accelerator SIS/ESR will be a unique facility for such investigations. Related theoretical work needs to be continued as well. All possibilities for the investigation of non-Liouvillean beam manipulation and research on all related techniques, e.g., FEL development, have to be pursued with emphasis (time schedule ~5 years).

2) A new conceptual design study, replacing HIBALL, has to be elaborated, including the new concepts of indirect drive and non-Liouvillean techniques as essentially new ingredients (time schedule ~1 year).

3) A strategy for building an HIF Demonstration Accelerator has to be developed. It should enable

- significant beam-target experiments
- a feasibility prove of accelerator technology
- non-Liouvillean stacking

Either a dedicated test facility (i.e. with low repetition rate) or the first stage of a larger facility might be considered; it should be based on the new technology (time schedule ~3–4 years).

Obviously the scope of such activities will exceed the framework of national programs. Stimulated by Carlo Rubbia and Renato Ricci, a series of meetings have been arranged in Varenna under the sponsorship of the Italian Physical Society and of ENEA, in order to discuss goals for an Italian-German collaboration. Meanwhile working groups have been established to analyse existing experience and to co-ordinate future activities. Some more collaborations exist with ITEP in Moscow and with Orsay/Orleans. In the long run it needs to be an integrated European effort. Recently Fusion Committees in the US have recommended relaxing classification in this field in the United States, which, if realized, would greatly improve international collaboration.

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