BEAM DYNAMICS FOR HEAVY ION INERTIAL FUSION

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Intense and heavy ion beams of concern for driving the targets in future heavy-ion inertical fusion reactors are strongly affected by space-charge forces. This is true for both the r.f. linear accelerator compressor ring scenario as well as for the induction accelerator system. The low current ($I \geq 1$ A), long-pulse (about a millisecond) beams from several ion sources must be accelerated, merged and compressed longitudinally to achieve the peak power (20kA, 10GeV, 10ns) required at the target. To achieve fuel ignition, the final beams must be focused to a small spot of only a few millimeters. This in turn requires careful control of the six-dimensional phase-space volume of the beams during the entire acceleration and final transport process. The major effects that can lead to increases in the transverse and longitudinal emittances will be reviewed.

1 Introduction

The charged-particle beams in future accelerators ("drivers") for heavy-ion inertial fusion (HIF) (r.f. linear accelerators (linacs)-storage rings or induction linacs-recirculators) differ from conventional beams in two ways: (1) special manipulations such as beam merging, funneling, bunching, compression and pulse shaping are necessary to achieve the high peak currents (about 20 kA) and short pulse duration (about 10 ns) at a final beam energy of about 10 GeV or less required for igniting the target; (2) space-charge forces are significant or dominant in many accelerator stages or througout the entire accelerator system and play a major role in the target chamber where charge and current neutralization may be required [1]. This topic will be covered at the end of this paper.

Another important aspect of HIF driver design is the trade-off between cost and beam physics. On the one hand, one could utilize the existing (conventional) technology of high energy physics colliders and build a system with a large number of manipulators (accelerators, rings, beam lines etc.), producing many beamlets with sufficiently low intensity to stay below the various current thresholds, but the costs of such a system might be prohibitive. One the other hand, one can reduce the number of manipulators by investing in non-conventional technology and new beam physics at potentially significant cost savings that could make HIF an economically more attractive option for future power generation.

The r.f. linac-storage ring scenario is building on existing technology, but a major goal is to minimize the number of manipulators by exploring possibilities of increasing the beam currents beyond the limits in convention rings (space-charge tune shift, longitudinal instability etc.) via rapid resonance traversal, non-liouvillean injection, beam cooling and other techniques. The induction linac-recirculator approach, in contrast, involves the development of substantially new technology and new beam physics aimed at understanding the behavior of the space-charge-dominated beams inherent in such systems.

The main focus of this review paper is to highlight the specific features encountered in the manipulation of the space-charge dominated heavy ion beams from ion sources to target.

2 Heavy ion driver concepts

Various driver candidates for intertial fusion have been investigated during the past decades: Several kinds of laser facilities, light ion pulse-power devices and heavy ion accelerators. With respect to the requested beam pulse energy, laser and light ion facilities are most advanced. It is the repetition rate and the efficiency —an inherent property of heavy ion accelerators— which makes heavy ions the superior choice for a reactor driver. In addition, operation of accelerators has been shown to be very reliable over long periods. Other attractive features are the ballistic transport of heavy ion beams through the reactor chamber and the excellent beam-target coupling, which is well understood from basic physics [2,3].

2.1 The driver concept

Among the various types of accelerating structures used for the acceleration of heavy ions, two accelerator concepts have turned out to be especially appropriate as inertial fusion drivers. Based on existing experience, the European inertial fusion community has decided for the investigation of rf-structures combined with storage rings [3,4], the US community for the induction linac [5]. At the present stage of modest expenses, research on both concepts has to be continued until a clear advantage for one or the other will become evident. Since the technology of the two accelerators is quite different, there is a clear sharing of tasks.

The acceleration is achieved by a linear accelerator consisting of various types of rf-structures, delivering a continuous beam of singly charged very heavy ions of about 10 GeV. This accelerator is followed by a system of transfer and storage rings to achieve the necessary current multiplication, the formation of the required pulse sequence and the final bunching (Fig. 1). Because of space charge limits at low velocities the front end of the linac starts with 8 parallel channels which are combined stepwise by funneling connected with a frequency doubling at each step. The major part of the linac up to a length of about 5 km consists of Alavarez structures. Ion source development at GSI has shown that sufficient intensity and emittance can be achieved.

An important design parameter is a restriction on the allowed maximum storage time due to the beam loss and the longitudinal instability. For the HIBALL scenario a storage time of 4 ms had been adopted which is a compromise with a reasonably low injector linac intensity in two sets of rings by horizontal and vertical stacking in the transfer and storage rings, respectively. When the filling of the 4 transfer rings is completed, the 4 beams are extracted simultaneously, are combined and transferred to the set of 20 storage rings. After filling and bunching all the beams are extracted and transferred to the target, as indicated in Fig. 1.

According to our present knowledge on beam dynamics and accelerator technology the driver concept described here is supposed to meet the required specifications of 5 MJ for both direct and indirect drive. In case of indirect drive, however, more stringent conditions are requested for the focusing and bunching in order to reach the specific deposition power of 10^{16} W/g instead of 5×10^{14} W/g for direct drive. If it should turn out that with this concept the beam quality requested for indirect drive cannot be reached, non-Liouvillean techniques would have to be applied at the injection into the storage rings.

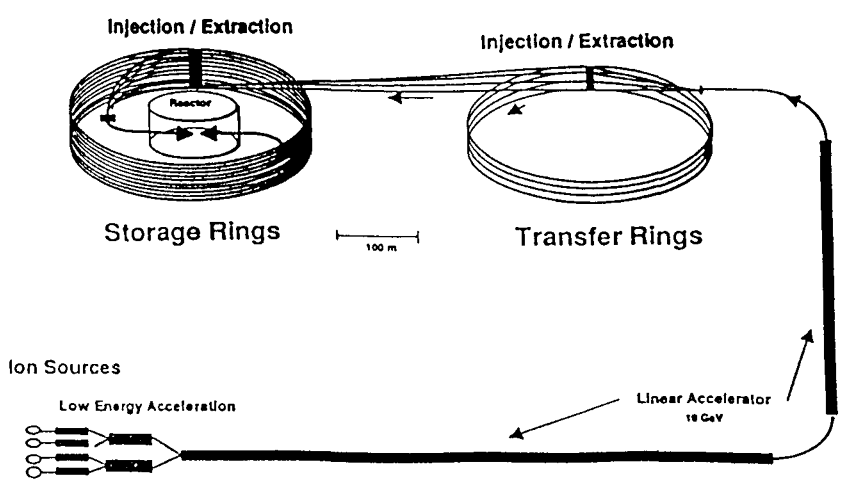

Figure 1: Heavy ion driver accelerator based on an rf-linac with storage rings (Hofmann *et al.* [4]).

2.2 Key issues and present accelerator research

The present driver concept is based on a wide experience with existing accelerators and on computer simulation on beam dynamics at high intensity and high phase space density. Many problems have been studied during the last decade, some of them are considered to be solved. Among the remaining problems some key issues need further investigation, such as [3]:

- high current performance of linac structures
- emittance growth by funneling and by multi-turn injection
- instabilities in storage rings with phase space dominated beams, in particular the longitudinal microwave instability
- fast bunching and, as a consequence, resonance crossing in storage rings
- beam losses at injection and extraction
- final focussing and repulsive forces between beamlets near the target.

Most of them are under investigation at various existing accelerators, mainly at GSI and at CERN.

The heavy ion accelerator facility at GSI (Fig. 2) has a kind of prototype function for the investigation of many of these problems. It consists of an injector linac (UNILAC) and a combination of two rings, a synchrotron (SIS) and a storage and cooler ring (ESR). It became fully operational some years ago and has been used for the investigation of microwave instabilities. Research on specific driver problems will be continued on a broader scale.

Some preliminary results of ongoing experiments are quite remarkable and shall be briefly mentioned:

- Experiments at the ESR in Darmstadt as well as at the TSR of the MP1 in Heidelberg and at LEAR (CERN) have shown that beams in storage rings remain stable up to a factor 10 beyond conventional phase space density limits (Keil-Schnell limit). Stability limits for bunched beams are under investigation.
- The crossing of an integer resonance due to space charge was demonstrated for the first time recently at the CERN PS with only a slight increase of emittance.
- Experiments at SIS have reached $5x10^{10}$ Ne^{5+} equal to 50J. Extrapolation to Bi^{+} give evidence that design parameters for a driver accelerator can be reached.

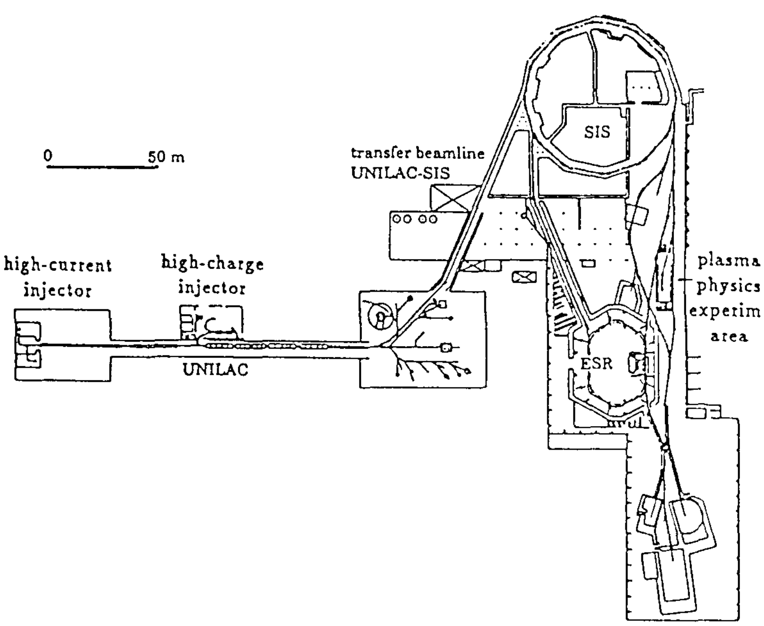

Figure 2: The GSI 2-ring heavy-ion accelerator facility SIS/ESR with UNILAC as an injector for all ion species up to Uranium. The injector energy is 11.9 MeV/u, the maximum energy of SIS 2 GeV nucleon. Ions can be stored and cooled (up to 10^{10} ions) in the ESR and reinjected in the SIS. The target cave on the right hand side is dedicated to beam-target interaction experiments.

2.3 Induction linacs [5]

This type of accelerator is unique in its ability to continuously amplify both the beam current and energy during the acceleration process. In a conceptual driver, many beams are accelerated in parallel through common induction cores. As the beams gain energy, the beam focusing system can transport higher currents. Therefore, in the linac approach, the multiple beams are combined in groups of four to produce a final total of typically 10 beams. In the recirculating induction approach, several beams are accelerated by a series of accelerator rings to the final energy. During acceleration, the current of each beam increases by a factor of 200 or more, mostly as a result of an increase in ion velocity but also due to the transverse beam combination and a decrease in the length of the beams. A beam power increase by an additional factor of 10 is achieved by drift-compression current amplification between the accelerator and the target. Fig. 3 is a sketch of the induction linac driver concept.

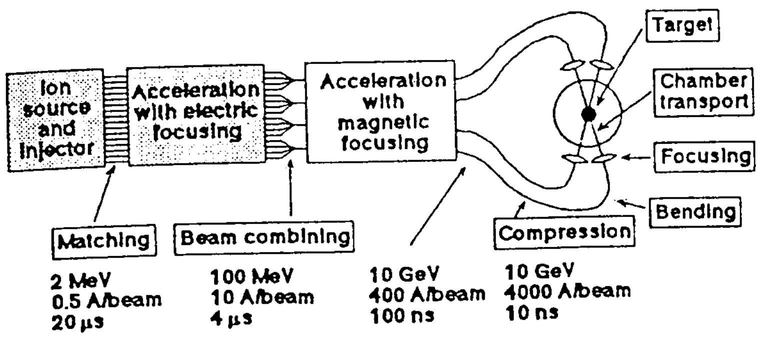

Figure 3: The multiple-beam heavy ion induction linac concept. The shaded areas indicate driver areas that have been investigated by technology developments and/or model physics experiments.

2.4 Ion Sources

One of the first experiments demonstrated that heavy ion sources of the required quality, intensity and lefetime are available. A multiple-beam induction linac will need 50 or more sources of heavy ions able to emit heavy ions at currents near one Ampere. The quality or normalized emittance of each beam must be much less than the 10 or 20 π mm-mrad limit set by the requirements of focusing the beams onto the inertial fusion target. The source shown in Fig. 4 was developed at LBNL and provided up to 2 Amperes of Cesium^{+1} as a quality approximately 100 times better than required. The Cs^+ was obtained by contact ionization from a tungsten plate that was heated to approximately 1000°C. Cesium beams from this source were subsequently accelerated to 1.5 MeV in a drift tube linac. Experiments since 1980 have obtained beams of Cs^{+1} and Potassium^{+1} at very low emittance from alumino-silicate (zeolite) sources heated to similar temperatures. Fig. 4 shows measurements of Potassium emission as a function of the extraction voltage from a zeolite source developed for use with the ILSE experiments. The experiments showed that this source is able to provide several times the current density required for the ILSE experiments.

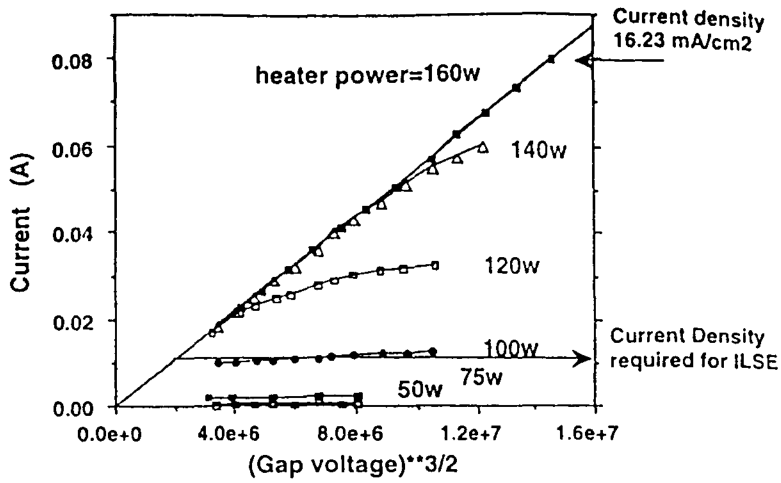

Figure 4: Measurements of Potassium^{+1} emission from a zeolite ion source as a function of applied voltage and heater power [5]

2.5 Beam transport

Beam of Cs^{+1} at energies near 125 kV and currents up to 20 mA were transported through 85 electric quadrupoles. Measurements of beam quality versus distance for various adjustments of the focusing volltages showed that much lower emittance ion beams could be transported than initially estimated. These results gave us confidence that high quality ion beams can be transported and accelerated with no loss of quality. This confidence has significantly reduced cost estimates of multiple-beam induction linac drivers for commercial fusion.

MBE-4 addressed, in a scaled manner, the physics associated with the low energy portion of a much longer induction linac driver. Four space-charge-dominated Cs^+ beams were injected at 0.2 MeV and accelerated to a peak energy of nearly 1 MeV over a distance of approximately 15 m. Experiments were conducted between 1986 and 1992 when the experiment was completed. A diagram of the apparatus is shown in Fig. 5.

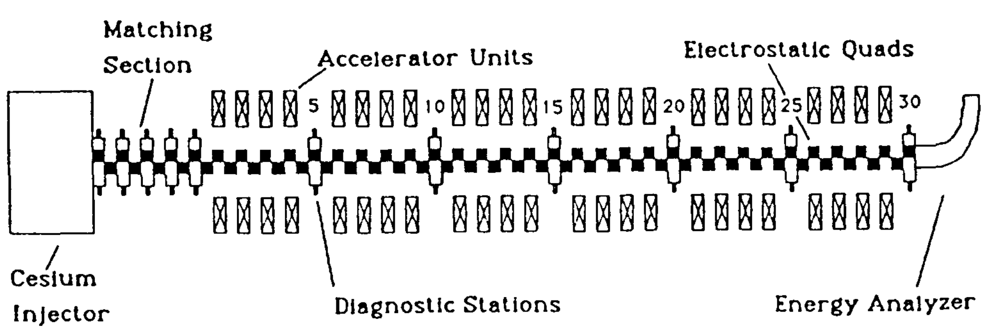

Figure 5: Schematic of the MBE-4 current amplifying induction accelerator

Early MBE-4 experiments with 12 of the 24 accelerator sections showed for the first time that simultaneous acceleration and current amplification of multiple, space-charge-dominated ion beams can be accomplished in an induction linac with adequate beam control and no perceptible degradation of beam quality (increase in normalized emittance). In more recent experiments with the completed facility, current amplification of from 10 to as much as 90 mA/beam has been studied.

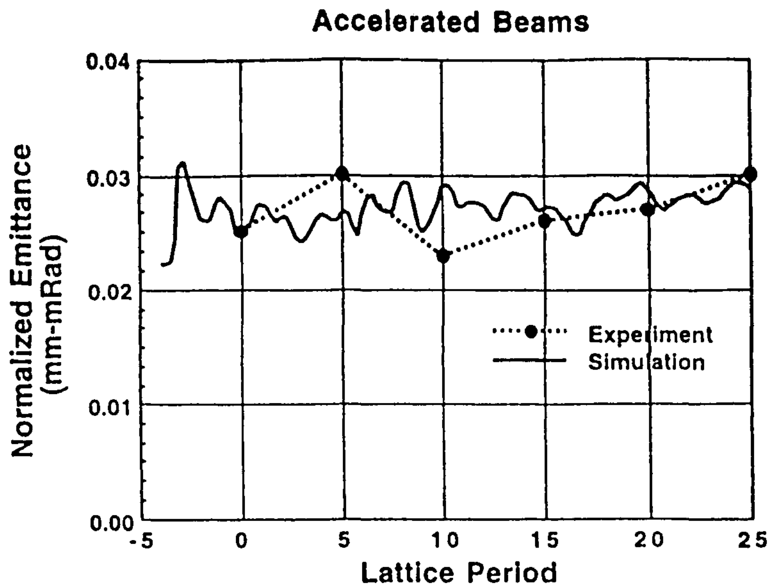

Figure 6: Measurement and simulation of the normalized emittance of a Cs^{+1} beam during acceleration through MBE-4. With care acceleration and current amplification were achieved with no degradation in beam quality.

One important experiment demonstrated that the ion beams could be accelerated with current amplification while adequately preserving the transverse and longitudinal beam quality. Fig. 6 shows both measurements and calculations of the beam emittance or quality during acceleration through MBE-4. In an ideal accelerator this quantity at best remains constant and does not increase. This result required that the beam be carefully centered and matched in the focusing channel.

These experiments showed that the acceleration waveforms can control beams longitudinally and simultaneously increase the beam energy and current without a loss in beam quality. For these intense beams, space charge reduces but does not eliminate effects due to acceleration errors. However, for the degree of control required in a full-scale driver, better and more agile pulsers than used in MBE-4 will be required.

3 Reaction chamber propagation [6]

Whatever the approach used for the accelerator (recirculation induction linear accelerator (LINAC) for the US or radio frequency program (r.f.) LINAC/Storage ring for the European and the Japanese programs) and for the illumination of the pellet (direct or indirect with a hohlraum, or cavity), a crucial issue concerns the transport of the beam in the reaction chamber.

In the Hylife II project [7], through a Flibe gas-protecting wall, the beam has to be focused ballistically from the entrance of the chamber to a pellet a few millimeters in size that is 5m away. Although several theoretical studies have been carried out on beam propagation and interaction with gas and plasma, the complexity that results from the large number of particles generates unsolved problems. Experiments with heavy ion beams of several kiloamps are not yet available and the only approach up to now has been to use large computer simulations.

A primary test using a 60x60x60 grid and 100000 particles has been run to simulate the propagation of the beam in the reaction chamber through a vacuum. The envelope equation and the simulation included both electromagnetic and emittance effects for a beam with cylindrical symmetry. The envelope equation is

$$\frac{\partial^2 r}{\partial z^2} = \frac{K}{r} + \frac{\varepsilon^2}{r^3}$$

with K is the permeance, ε is the non-normalized emittance and r is the envelope radius of the beam.

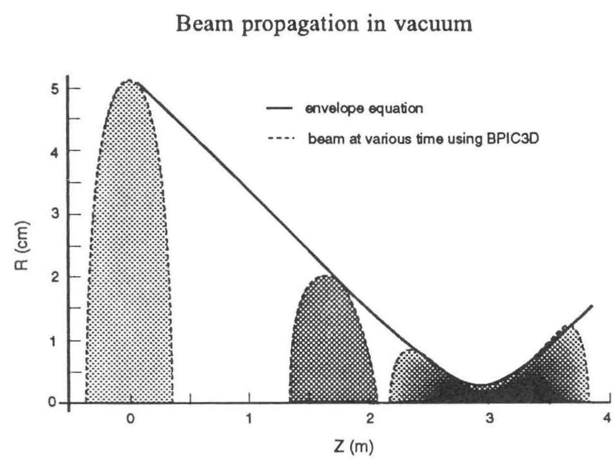

Figure 7: Comparison of the envelope equation and the BPIC3D code results for the propagation of the beam through a vacuum. The beam is plotted at six successive times.

With these parameters used the beam had an initial radius of 5.2 cm and converged to a radius of 3.3 mm. At the same time, the transverse length of the grid converged from 13 to 1.4 cm.

As can be seen in Fig. 7, the results show a good agreement between the BPIC3D particle-in-cell simulation and the theoretical envelope equation.

4 HIDIF project [3,4]

Results in heavy ion inertial fusion research achieved during the last decade, in particular the progress in accelerator technology, have greatly increased our confidence that the heavy ion accelerator is the superior choice among the driver candidates for a power reactor. During the last years the European Inertial Fusion Community had a series of meetings and workshops in which these achievements and the future strategy and prospects were discussed. It was realized that —after more than a decade of exploratory work in Europe— it is now timeley to establish a coherent European program. In a final workshop at CERN with participants from several European countries the concept of a dedicated facility to achieve ignition with low thermonuclear gain was defined as the next logical step.

The studies to be launched shall be concerned with critical issues of the design of the heavy ion driver, of the targets and the means of their production and of the required reaction chamber. The main task of the Study Group is to develop a coherent set of parameters for the driver, the target and the reaction chamber of a future Ignition Facility. According to present knowledge this requires a pulse energy of 1-2 MJ delivered onto a target of a few mm diameter within 6-7 ns, the specific deposition power being of the order of 10^4 TW/g. In a recent workshop it was concluded that a MJ driver can be realized with a 6 GeV/nucleon linac and possibly a single storage ring for beam accumulation (Fig. 8).

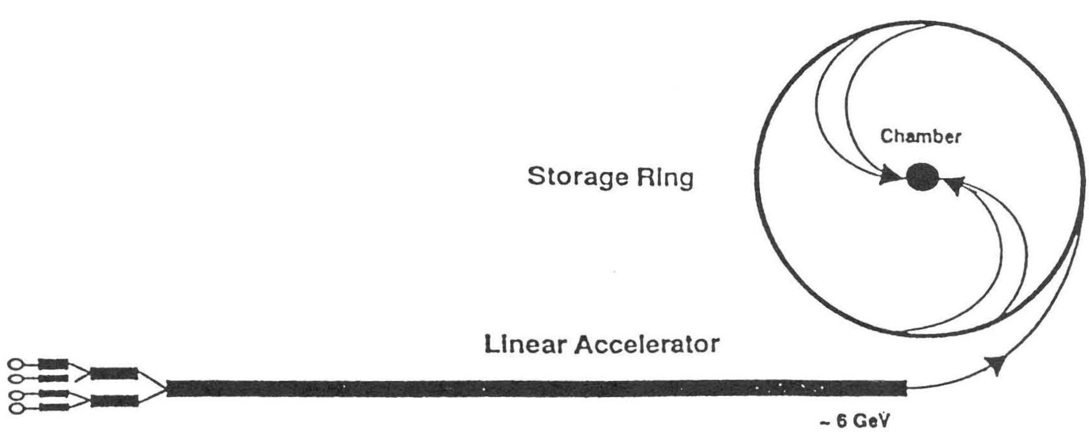

Figure 8: Concept of a heavy ion driver accelerator for an ignition test facility (I. Hofmann *et al.* [4]

In the field of target physics, the implosion symmetry and hydrodynamic instabilities represent the key issues for igniting targets. Indirect drive which is accepted as the most appropriate approach to heavy ion induced fusion, relies on radiation symmetrization inside a target capsule to ensure spherical implosion of the fusion pellet. Extensive numerical studies have to be carried out in order to determine the parameters necessary for the accelerator design.

Beam transport and focussing between the accelerators and the reaction chamber are essential issues of the study where existing systems designs (such as HIBALL) will be adapted to new progress and new concepts. The design of an appropriate reaction chamber for experiments at low repetition rate can be developed on the basis of present knowledge about the response of materials and structures to radiation and pulsed mechanical load. The development of diagnostic tools will be of crucial importance.

The proposed study shall result in a feasibility report with a preliminary design of an ignition facility. Beyond the goal of ignition, however, the proposed facility has a larger potential. Due to its high repetition rate the accelerator can be used in connection with several reaction chambers addressing various aspects of an ICF development plan. It is obviously a great advantage of the heavy ion approach that the accelerator technology of an ignition driver is nearly identical with that envisaged for a final power reactor. Heavy ions therefore offer a direct route toward fusion energy production.

Acknowledgements. Le Laboratoire de Physique des Gaz et Plasmas est associé au CNRS (URA 073).

References

[1] M. Reiser, *Fus. Eng. Des.* **32-33**, 133 (1996).

[2] C. Deutsch, *Ann. Phys.* (Paris) **11**, 1 (1986).

[3] R. Bock, *GSI report 95-15* (Féb. 1995).

[4] I. Hofmann, *et al.*, Plasma Physics and *Controlled Nuclear Fusion Research*, 1994.*Proceedings of the Fifteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Seville, Spain, 26 Sept.- 1er Oct. 1994 (Vienna, Austria: IAEA, 1995), p.279.

[5] R.O. Bangerter and T.J. Fessenden in *Current trends in International Fusion Research*, ed. E. Panarella (Plenum Press, New York, 1997) p. 279.

[6] J.L. Vay and C. Deutsch, *Fus. Eng. Des.*, **32-33**, 467 (1996).

[7] R. Moir, *Fusion Technol.*, **29**, 306 (1991).