HEAVY ION INERTIAL FUSION RESEARCH
Towards a European Programme

A report [*] on heavy ion inertial fusion research to be presented at the World Energy Congress in September offers some insights into the way international collaboration in the field may evolve.

Europe

Fusion research in western Europe is mainly funded by a European Community fusion energy programme in the Framework programme for science and technology. It is oriented towards magnetic devices, partly because inertial confinement research is classified in France and the UK, thus inhibiting cooperation. There are, however, very substantial national inertial confinement fusion (ICF) related programmes using both laser and heavy ion beams.

Considering the basic research programmes with institutional or government funding, **Germany** established a federal (BMFT) programmme in 1979 to investigate key issues including systems, accelerator components for high intensity ion beams, the generation and dynamics of beams with high phase space density, beam-target interaction, and the physics of dense plasmas. Milestones are the HIBALL design studies, construction of the SIS/ESR synchrotron/storage ring facility for heavy ion beams at GSI, Darmstadt (see page 86), the develoment of low-velocity accelerator structures and some beam handling devices (*e.g.*, plasma lenses), and ICF relevant atomic physics experiments.

GSI remains Germany's centre for heavy ion beam — plasma interaction research, with contributions from Frankfurt and Giessen Universities and Z-pinch experiments at the Fraunhofer Institute, Aachen. The MPI für Quantenoptik is the leading laboratory for target physics, with contributions from TU Darmstadt and Frankfurt University on dense plasmas and certain physics aspects. Three other universities collaborate with GSI on atomic physics studies.

In **Italy**, INFN Frascati has a long tradition of research on target physics, with the latest work directed towards simulations of target design, compression physics and free-electron laser (FEL) design. The INFN laboratory at Legnaro is the main nuclear physics laboratory with experience in accelerator physics: it is presently working on beam-target interactions along with INFN Cagliari. Accelerator physicists at the Sincrotrone synchrotron light source now under construction near Trieste participate in accelerator design studies for a fusion driver and for a FEL proposed for an ingenious, and potentially revolutionary, non-Liouvillean injection scheme (see page 88). Several universities are also active (Padua and Genoa on acceleration at high beam intensities; Milan on plasma diagnostics and on FEL design and development).

A recent Italian study project (see page 92) has recommended the development of non-Liouvillian stacking schemes and energy transfer modelling.

Groups in **France** based at Orsay and Orléans are involved in the theoretical and experimental aspects of target physics, notably ion stopping with laser-heated plasmas. ICF simulations are performed at the CEA, Limeil, home of PHEBUS, Europe's most powerful laser (20 kJ) but much smaller than the 70 kJ NOVA laser in the USA. Indeed, numerical simulations remain a feature of most countries efforts, notably the UK with codes developed at the Rutherford Appleton Laboratory and at Imperial College, London.

In **Spain**, the Institute of Nuclear Fusion, Madrid, concentrates on the theory of target design, target dynamics and reactor neutronics, neutron transport calculations, and in the last decade has developed hydrodynamic computer codes for direct-drive fusion targets.

In **Russia**, there is a large HIF group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow working on accelerator and target problems and operating heavy ion accelerators, but not dedicated ICF facilities. The Kurchatov Institute operates large electron linacs while ICF theoretical and experimental studies, are carried out at the Lebdev Institute and elsewhere.

USA

The Heavy Ion Fusion Accelerator Research Program that was transferred from the DoE to the Office of Fusion Energy (OFE) aimed to establish if heavy ion accelerators can be used for commercial energy production. It was terminated without completing all the planned expriments. The main part of the OFE's Inertial Fusion Energy (IFE) Progam, which depends upon the larger, defense oriented Inertial Confinement Fusion (ICF) Program, now involves driver research based on induction linacs at the Lawrence Berkeley Laboratory (LBL). The first experimental test of a multiple beam concept has been carried out at the Multiple Beam Experiment (MBE-4) using four beams. A 30 M$US, 10 GeV Induction Linac System Experiment has been proposed as a next step to tackle all the key issues for a full-scale driver. The LBL is backed by a major collaboration with the Lawrence Livermore National Laboratory (LLNL) which is carrying out a 50 M$US/year project to determine driver requirements for a high-gain target. Laser beams are being used as the physics results are believed to be applicable to heavy ion drivers. There are smaller collaborations with NRL, SLAC, SNL, and the Universities of New Mexico and Maryland.

A European HIF Programme?

The ICF community has a tradition of international cooperation (see table). For example, GSI, western Europe's main centre for HIF research, works with the ITEP, Moscow, and with universities at Orsay and Orléans (France) on ion-plasma interactions, plasma lenses, plasma diagnostics, target physics, ion sources, and accelerator development. The GSI also collaborates with groups in the USA and the UK.

A working group involving CERN, GSI, Sincrotrone, and ENEA and INFN laboratories in Italy was set up in 1990 under the auspices of Professor C. Rubbia, CERN's Director-General, to develop a strategy for building a new-technology HIF Demonstration Accelerator, based on either a dedicated facility or as the first stage of a larger installation. This would enable significant target-beam experiments and to demonstrate accelerator technology and non-Liouvillian (NL) stacking. Study groups have been meeting regularly to discuss driver options based on NL techniques, target design, and system studies exploiting advanced concepts.

To realise some of the goals, stronger national collaborations are envisaged, notably between Germany and Italy. This fits in with

Overview of Heavy Ion Inertial Fusion Activities in Europe

	accelerator	target	system studies	other topics
Germany	structures & tech. development UNILAC & SIS/ESR experiments beam dynamics studies	ion stopping in plasmas beam-target interactions physics of dense plasmas	HIBALL I (1982) HIBALL II (1985)	ion-ion charge exchange x-sections atom physics x-sections
STUDY GROUPS	Non-Liouvillean driver scenarios	target design issues	systems studies based on advanced concepts	
Italy				FEL studies & design
CIS	RFQ development synchrotron facility	ion stopping theory	driver study	vacuum breakdown on sputtering
France		ion stopping theory (laser heated plasma)		
Spain		target physics target design (direct driver mainly)	reactor design	

the conclusions of the symposium report [*]. The HIF field is not yet sufficiently well-developed to define a large, multinational, central facility that would become the focus for a global-scale project akin to the International Thermonuclear Reactor (ITER) project for magnetically confined fusion. Instead, work should continue to be coordinated informally between laboratories on problems of mutual interest.

Nonetheless, a 1991 report of the US Fusion Policy Advisory Committee has established a schedule for ICF research with a driver decision for an Experimental Test Facility set for around the year 2000. In the absence of an equivalent European inertial fusion programme, this timetable is an additional reason for reinforcing national-level collaborations so as to keep pace with developments.

Bilateral agreements and multinational laboratories already exist for accelerator research as there is little commercial interest. For target research, it is clear that a European facility to test inertial targets is at least 10 years away. But can people in the meantime collaborate effectively while much information is classified? The report thinks classification is not a serious problem as the overall goals for key parameters are known. For reactor issues, the topics are so diverse that there must surely be plenty of room for collaboration. But would not cooperation at the national level be more effective with an European HIF programme?

Worldwide Collaboration

The symposium report offered some guidelines for international collaboration. First, it is important to avoid splintering as happened for magnetic fusion where the US alone now has ten torroidal confinement devices in nine different institutions. Second, the greatest technical challenge is to develop a low-cost driver. To illustrate the problem, an induction linac for high-gain target HIF experiments would cost 1000 M$US, and a RF

The main hall of the 70 kJ NOVA laser facility at the Lawrence Livermore National Laboratory, USA.

device probably even more. Moreover, system studies in Germany, the USA and Japan all show that the accelerator driver is the most expensive component of an electricity generating plant. The US has opted for a linear induction accelerator approach as it appears simpler and cheaper than approaches based on RF systems with which Europe has more experience.

The report suggests establishing common ground for collaboration by combining elements of both approaches in a new concept, namely a circulating induction accelerator proposed in 1988 by the MBE-4 team (see page 83).

The European consensus (see below) appears to be that there should be a determined effort to collaborate on target issues. Meanwhile, one must continue development of the main accelerator alternatives for several more years before making the choice for a large demonstrator.

[*] Herrmannsfeldt W.B. *et al.*, *SLAC Report* **SLAC-PUB-5457** (1991).

European Programme Recommended

R.A. Ricci of the Laboratori Nazionale di Legnaro, Italy, and President of the Italian Physical Society summarises the results of an evaluation of heavy ion driven inertial fusion.

An Italian study of inertial confinement fusion (ICF) driven by heavy ions began in 1989 following an agreement between Ente Nazionale Energie Nucleare e Alternative (ENEA) and the Società Italiana di Fisica (SIF). In considering the possibility of a national research programme on heavy ion beam driven ICF, the evaluation was largely motivated by:

– The international scientific community's renewed interest in the physics of ICF, driven either by lasers or by charged-particle beams.

– Increased confidence in the feasibility of commercial energy generation.

– The possibility of a common effort by Italian and German research groups in establishing a joint programme in the field, taking into account that until now European efforts have been almost exclusively devoted to magnetic confinement. This might has been justified up to now for the priority programme of the European Community, but it presently seems that new, joint initiatives concerning inertial confinement should also be considered.

Starting Points

The starting points for the study project, which also comprise the working scheme being considered for a specific Italian-German collaboration, were:

– The initial systems study HIBALL which provides the basic parameters for a reactor driver [1].

– A novel driver concept exploiting non-Liouvillian stacking as an essential technique for providing heavy ion beams of, *e.g.*, Bi or Ba, with suitable intensity and energy [2].

– Studies of driver chains for achieving the beam parameters required for ignition. These parameters have to be considered as being determined by non-Liouvillian stacking and by the reactor requirements, for both direct or indirect drive.

– Investigations of beam-target interaction, target geometries and related issues, for both direct and indirect drive, involving both computational and/or experimental studies.

Status

Reference parameters for a heavy ion ICF scheme started from HIBALL's basic data for the principle non-Liouvillian option [1]. Reviewed below is the status of various aspects of ion driven ICF following more recent evaluations reported by Italian groups.

Non-Liouvillian stacking

There is a consensus that non-Liouvillian stacking is an advanced and efficient tool for accumulating high current heavy ion beams without the usually unavoidable increase in phase space volume. A possible problem could arise in attempting to optimise the requirement of not exceeding space charge limits during high power ($\approx$ 500 TW) deposition into a pellet of reduced size ($\approx$ 3 mm). This is related to the choice of the accelerating scheme in which photo-ionisation is performed.

Driving chain

The driving chain can adopt several different arrangements. A generic design would be as follows [4]:

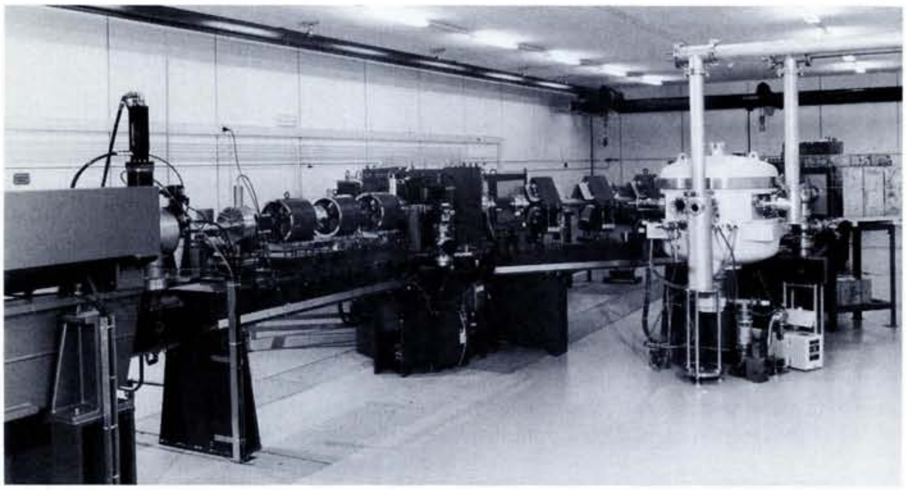
– Bi^+ source + RF quadrupole.

– Acceleration (20 KeV $\rightarrow$ 1-2 MeV) including a non-Liouvillian stacking ring (NLS) connected to the FEL inducing the photo-ionisation of Bi^+ to Bi^{++} (*i.e.*, photo-ionisation in the storage phase) and eventually a transit-time linac if further acceleration from 1 MeV to 1 GeV is carried out after the NLS.

– Further storage, acceleration (transit-time linac: 1 GeV to 10 GeV) and pulse compression to Δt = 10 ns).

A version which now seems to be more acceptable involves full acceleration (1 $\rightarrow$ 10 GeV) before the NLS with the $Bi^+ \rightarrow Bi^{++}$ photo-ionisation at the compression phase (see page 88).

The final beam parameters would be: $\approx$10 GeV kinetic energy; pulse time Δt = 10 ns; $\approx$5 MJ input energy; 500 TW beam power; number of ions per pulse N = 3.125×10^{15} ions. Taking into account the efficiency of the NLS and losses, one



This linac-driven free-electron laser (FEL) at the FOM "Rijnhuizen" Institute for Plasma Physics, The Netherlands, became last year the first in Europe to produce radiation. Bending magnets and quadrupole lenses feed electrons from the linac (on the left) into a single-stage undulator/resonator structure hidden behind the vacuum tank housing one of the cavity mirrors. Infrared radiation with a wavelength of 2 μm is produced at the 25 GeV maximum energy. Storage rings are normally used instead of linacs for drivers at energies above 50-100 GeV (wavelengths ≲ 500 nm to 1 μm). In a proposed [3] scheme for photo-ionisation injection for HIF, the idea is to use a conventional 215 MeV linac-driven undulator/ resonator generating 240 nm radiation as the first stage of a two-stage device. This approach allows one to retain the most important advantage of a linac driver, namely the high brightness.

arrives at $N = 4 \times 10^{15}$ ions. It is worthwhile to note, however, that a modified design allowing for more comfortable beam intensities ($N = 10^{12}-10^{13}$) is being studied at CERN.

FEL photo-ionisation

Photo-ionisation by a FEL appears possible because one would be operating in the UV region. What is needed is to work in the self-amplified spontaneous emission (SASE) regime. There are several alternatives for obtaining the 84 nm wavelength required for the $Bi^+ \rightarrow Bi^{++}$ photo-ionisation process starting with the 240 nm wavelength of a standard (*e.g.*, KrF) laser. One can use a frequency tripling device, and another possibility which is being explored is to employ an electron beam from a conventional linac of 200-400 MeV to obtain output UV parameters as follows: 80 nm wavelength, 3 MW power, 40 mm rad emittance. The third harmonic of light emitted by a conventional magnetic undulator structure is amplified at a resonance phase in a second undulator [3] and a three-dimensional simulation of this process is already giving reliable results.

Beam interaction and pellet design

Beam-target interaction and the pellet design seem to be major issues needing further investigation, not only by computation and/or model calculations but also experimentally.

Depositing a specific power of 10^{15}-10^{16} W/cm^2 in an ICF target pellet to achieve ignition conditions poses serious problems. These are, of course, determined by fluid instabilities as well as by imperfections in the target design and illumination symmetry. The consensus seems to favour indirect drive because of superior uniformity, provided the X-ray conversion efficiency remains sufficient, which seems to be the case.

Target design and the corresponding physical issues are under study at the INFN, Frascati [5], taking into account the expertise acquired in the context of a laser fusion programme. The investigations have been and continue to be focussed on implosion symmetry and stability for both direct and indirect drive.

In the case of heavy-ion beam driven generators, preliminary analyses of thermal X-rays suitable for indirect drive have been performed and analytical models for evaluating the efficiency of radiators suitable for use in ICF target chambers are being developed [5].

Perspectives

The main elements of a future research programme should include:

1) *Energy transfer modelling* involving further studies (both theoretical and experimental) of the feasibility of ignition and of the amount of energy to be transferred from the beam to the fuel to achieve a net energy gain. Studies of phenomena arising in beam-target interaction using techniques based on either lasers (photon transfer into the target) and/or accelerators (uniformity, efficiency for ion to X-ray conversion) are essential.

2) *Development of high-performance accelerators,* where the design of non-Liouvillian stacking schemes including the photo-ionisation mechanism, *i.e.*, the type of accelerating sequence, is the principle concern (as will be the case for the Italian-German collaboration).

It is the scientific community's hope that such a programme will be considered in the near future as an issue at the *European level* in working towards a new nuclear energy source.

[1] Badger B. *et al.*, *KIK-3202* (1981); *KIK-3840* (1985).

[2] Rubbia C., *Nucl. Inst. & Methods* **A278** (1988) 253.

[3] Bonifacio B. *et al.*, Proc. AIP Conf. (AIP, New York, NY) 1984.

[4] Puglisi M. and Wrulich A., Workshop Report, Varenna (1989).

[5] Atzeni S., *Europhys. Lett.* **11** (1990) 639.

Make ICF Safe and Environmentally Acceptable

H. Schopper, a member of the Board chaired by Prof. U. Colombo that evaluated Europe's fusion research in 1990, comments on the importance of considering the environmental aspects of inertial confinement fusion.

Inertial confinement fusion (ICF) is the only appropriate alternative to magnetically confined approaches. Original hopes centered on laser or light-ion drivers whereas there is now general agreement that heavy ions might provide a better solution. ICF offers several advantages, *e.g.*, no magnetic coils, simple geometry of the reactor vessel, separation of driver and reactor vessel, and most important, no radioactive actinides. But these disadvantages have to be set against some drawbacks, *e.g.*, sophisticated drivers, complex target technology linked with military applications (which is the reason why ICF is given great importance in the USA, where it is financed to a large extent from the defense budget), the activity induced in structures by fast neutrons, and finally the sizable tritium inventory.

So far, the world-wide effort both in inertial and magnetic confinement has concentrated on the physical and technical problems: these will eventually be solved. However, considering the history of fission reactors its seems urgently necessary to devote a comparable effort to safety and environmental problems (this is one of the major recommendations of the European Community's Evaluation Board). It is particularly important to demonstrate for ICF that the worst possible accident will present no major hazard to the population; that