Heavy Ion Inertial Fusion

STATUS AND PERSPECTIVES

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Research during the past decade has strongly increased our confidence that the heavy ion accelerator is the superior driver candidate for economic power generation by inertial confinement fusion. The European Community nonetheless concentrates nearly all its fusion research spending on thermonuclear fusion using magnetic confinement techniques.

Results achieved with high intensity laser beams and systematic theoretical studies have provided the necessary reference data for implosion of a fuel pellet, the most crucial issue in inertial confinement fusion. With respect to the conditions for ignition and continuous burning, experiments with laser beams are about as close to break-even as those using magnetic confinement. For example, a 20 kJ beam at the NOVA facility at Livermore in the USA has obtained 150 times liquid density for the deuterium (D)-tritium (T) fuel mix, while Japan's GEKKO XII laser facility has achieved a compression factor of 600. Experimental results for pellet implosions in underground nuclear explosions confirm theoretical predictions that a pulse energy of about 5 MJ is necessary for implosion.

Unfortunately, laser facilities as drivers, while indispensible for future target research, have serious shortcomings for electricity generating power plant, notably low efficiencies and repetition rates such that it is hard to imagine how the necessary orders of magnitude improvements could be obtained to meet commercial requirements. The principle alternatives are heavy ion accelerators as both the efficiency and the repetition rate are not critical and other requirements such as final focussing and beam-target coupling appear satisfactory. Enormous progress in accelerator technology and experience with operational reliability at complex accelerator facilities also place heavy ion drivers in a favourable light noting, of course, that the required beam intensities exceed by a wide margin those of existing accelerators.

In view of the progress, our aim here is to review the development of heavy ion drivers for inertial confinement fusion and consider some perspectives.

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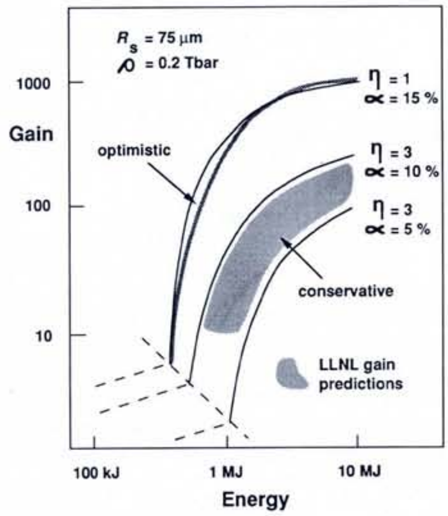

Fig. 1 — Conservative and optimistic predictions of the pellet gain as a function of the deposited energy obtained at Lawrence Livermore National Laboratory (LLNL), USA, compared with calculations by Meyer-ter-Vehn [3]. The model parameters are the radius of the hot spot R_s, the fuel pressure at ignition ρ, the isentrope of the compressed fuel α, and the hydrodynamic efficiency η.

Inertial Confinement Fusion

Inertial confinement fusion (ICF) involves confining a D-T mixture of a few milligrams in a pellet of up to 10 mm diameter, which is heated and compressed by ablation to ignition conditions: energy can be supplied using either laser or heavy ion beams. The inertial forces of the implosion keep the compressed pellet together for a few nanoseconds, long enough to burn a substantial fraction of the fuel. At an ignition temperature of about 5 to 10 keV, a level of high compression has to be reached in order to fulfill the Lawson criterion $\rho R > 3$ g/cm^2 where ρ is the fuel density and R the fuel radius at ignition. The criterion tells us that, *e.g.*, for an amount of fuel which can be handled in a reactor chamber (up to a few milligrams), a compression of about 1000 times liquid density (200 g/cm^3) is needed.

An ICF power plant consists of three major components: the driver, the reactor cavity (including the conventional electrical installations) and the pellet factory. One of the great advantages of the ICF scenario as compared to magnetic confinement is the separation of the driver and the reactor cavity, thus facilitating construction and maintenance as well as extraction of the energy generated.

To evaluate heavy ion ICF, three aspects have to be investigated: the pellet, the driver and the concept for a power plant. Implosion of the pellet, as one of the most critical issues for ICF, has been and will remain over the next years a domain of laser experiments. An upgrade of the NOVA laser facility has been recently recommended. In summarising on-going investigations in the field of heavy ion driven inertial fusion and the status of accelerator facilities we shall concentrate on the two other areas, namely systems studies and the driver.

Reactor

The HIBALL system study [1] started in 1980 and upgraded in 1985 demonstrated for the first time the feasibility of a commercial heavy ion driven power plant. It also identified key issues in a systematic way. The study envisaged injecting fuel pellets into a reactor chamber (9 m in diameter × 10 m in height) where they are imploded using multiple heavy ion beams. The chamber has a wetted first wall consisting of an eutectic mixture of PbLi used as a coolant and breeder. The advantage of this mixture is its extremely low vapour pressure which facilitates beam insertion and focussing at a rapid cycling rate. The flow of the PbLi along the walls is guided by an array of porous SiC tubes. The tritium breeding ratio is 1.25, and the low solubility of tritium in the liquid PbLi results in less than 100 g of tritium inventory in the blanket and fuel processing system.

Drivers

A qualitative evaluation of various driver candidates for electric power production [2] shows a clear preference for heavy ion accelerators. Most important are the excellent properties with respect to repetition rate, efficiency (about 25%), and beam-target coupling. An efficient driver is essential: with a 5% driver efficiency some 60 % of the energy would circulate for an assumed power gain of 100 for the ignited pellet ("pellet gain"), whereas with a 25% efficiency only about 10 % circulates.

A heavy ion pulse of 5 MJ has to be delivered to a D-T filled pellet for about the 10-20 ns required by the dynamics of pellet implosion in order to achieve ignition and a significant burn. Consequently, the pulse power is 250-500 TW. The pellet gain is plotted in Fig. 1 as a function of the

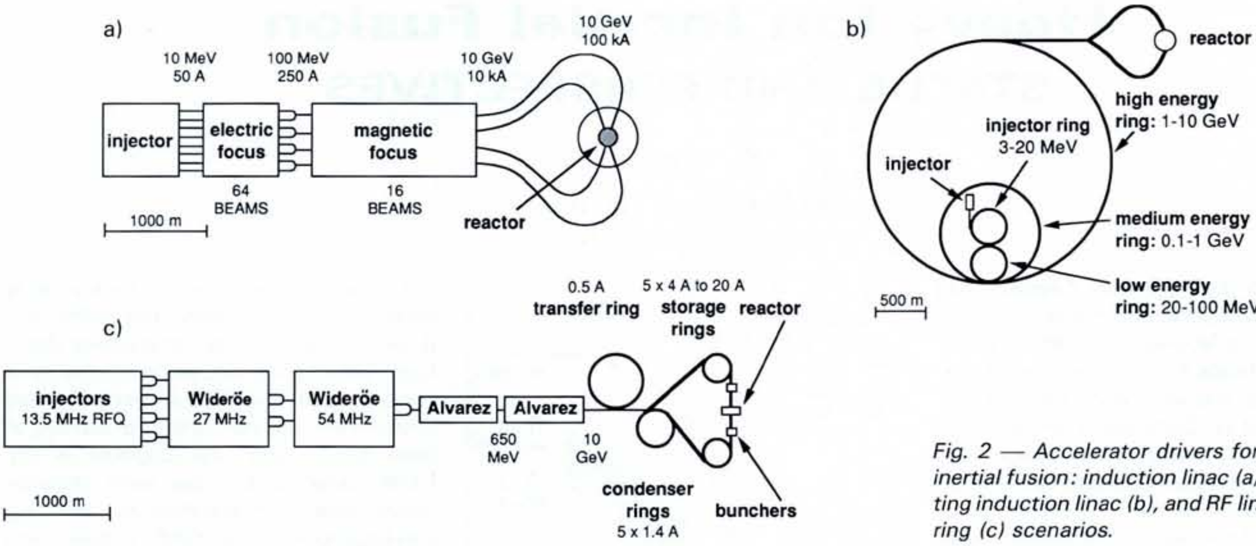

Fig. 2 — Accelerator drivers for heavy ion inertial fusion: induction linac (a), recirculating induction linac (b), and RF linac/storage ring (c) scenarios.

deposited energy, where for a heavy ion beam, the pulse power is a product of the heavy ion kinetic energy and the beam current [3]. Since the kinetic energy is limited to about 50 MeV/nucleon by the ion range in the pellet (10 GeV for the heaviest ions), the current in the heavy ion pulse must reach 25-50 kA. Based on a 5 MJ pulse and a pellet gain of 100 (which from theoretical considerations — Fig. 1 — is realistic), the output energy of a single pulse would be 500 MJ. Assuming a pulse rate of 20 pulses per second, a thermal power of 10 GW would be obtained — equivalent to an electrical output of about 3 GW. Other problems, notably those connected to the beam-pellet interaction, pulse shaping, range shortening in a plasma, and pellet design have been studied but will not be discussed in detail.

Heavy Ion Accelerators

We shall now consider 1) whether an accelerator can meet the requirements discussed above; and 2) the design of an accelerator-driven power plant. Two types of accelerators look promising, namely, the induction linac [4] and the RF-linac with storage rings [1]. The latter was investigated in our HIBALL concept study: other systems studies undertaken in Japan, the US and the former USSR confirm the favourable prospects.

In spite of some common features such as the transport and handling of space charge dominated beams, the technical problems associated with both concepts are quite different, especially with respect to the pulse structure. For an induction linac, the pulse sequence of the linac can be accommodated to the needs of the reactor right from the ion source: transformation of the pulse structure is not needed. An extremely high intensity from a pulsed ion source is necessary, with pulse compression during acceleration of many orders of magnitude.

A high-current RF-linac, on the other hand, can deliver a continuous heavy ion beam of up to several hundred mA. However, accumulator and buncher rings are required for current amplification; storage rings must hold the pulses for several milliseconds in order to create the final pulse structure and pulse currents before feeding the reactor.

Induction linac

The pioneering research on heavy ion induction linacs was carried out during the last decade at the Lawrence Berkeley Laboratory (LBL), USA [4]. The basic idea is to inject a long beam bunch of high intensity and to achieve current amplification by ramping the inductive acceleration fields as each bunch passes. Pulses are compressed from 20 μs at injection down to 10 ns at the target, the current being increased from amperes to kiloamperes. One important conceptual improvement was the splitting of a single high-intensity beam into a large number of parallel beamlets, each being separately focussed inside the same accelerating structure. This concept improves focussing because of a smaller emittance: it has been shown to be cost-effective if the number of beamlets is in the range of 8-16. The latest concept for a driver starts with 64 beamlets at injection which later, when space charge forces decrease, are combined to a final 16 beams. For a Bi^{3+}, the whole length of the accelerator is about 5 km (Fig. 2a).

Recent work at LBL concentrated on a prototype experiment for the multi-beam concept (MBE-4) consisting of 4 beamlets [5]. In spite of being limited to the front-end components of the accelerator, the prototype will allow many critical issues to be investigated because the front-end and the initial pulse formation represent the most critical aspects. A 30 M$ Induction Linac System Experiment (ILSE) has been proposed [6] as a next step that is intended to address all key issues of a full-scale driver, including the transport of space charge dominated beams, combining and bending of beams, compression and pulse shaping as well as fine focussing. Construction would take 4-5 years and it may be necessary to have an intermediate step before designing and constructing a full-scale driver. A new concept, the recirculating induction linac [7] first proposed in 1988 (Fig. 2b) is being also considered in order to reduce the cost of a full-scale driver. It combines elements of both the RF and induction approaches.

RF linac

The RF linac/storage ring concept looks more conventional than the induction linac because nearly all the accelerator and beam handling elements are known from operating facilities. However, there exists little experience of their operation in a regime of space charge dominated, non-relativistic beam dynamics, where various types of instabilities may occur and where the beam transport and any beam manipulations may be associated with severe emittance growth and intensity loss.

We undertook the HIBALL conceptual design study [1] to identify major problems: the similar studies performed in the US, the former USSR and Japan tackled the same issues. In HIBALL, a 5 km RF-linac provides acceleration at constant current using RFQ, Wideröe and Alvarez accelerating structures (Fig. 2c). Because of space charge limitations, the charge state of the ions is chosen to be 1+. Bismuth was chosen as a beam because it is mono-isotopic, but other heavy elements could be used. The front-end starts with eight parallel channels owing to space charge limits at low velocity. By funnelling connected with frequency doubling, the parallel channels are combined stepwise over a length of about 500 m. Sufficient intensity of Bi^{+} with a normalised emittance of 0.2×10^{-6} m rad has already been obtained using sources developed at GSI to allow a design value of 165 mA for the linac current. One of the remaining problems in this area is the question of emittance growth by funnelling. ►

Transfer, storage and buncher rings are necessary for current multiplication (by a factor of about 10^4) and for producing the required pulse length and pulse sequence for the reactor. The storage time of 4 ms which was adopted is a compromise between the longitudinal microwave instability in the storage rings (requiring a short storage time) and the beam intensity provided by the linac. If the microwave instability turns out to be less serious, longer storage times could be permitted and, consequently, the beam intensity of the linac could be further decreased. On the other hand, because of the short storage time, the driver can provide a much higher pulse frequency ($\approx$ 100 Hz) than a single reactor chamber could make use of (5 Hz): a single driver accelerator therefore can serve a number of reactor chambers. The HIBALL study assumes four cavities but more would be possible, thus further reducing the cost of the electricity output.

A number of problems have been identified for the ring system and for injection into the reactor. Many of them will be accessible to experimental investigation in the near future at the SIS/ESR two-ring synchrotron facility at GSI (see page 86). Most important are the longitudinal (microwave) instabilities, the phase space dilution in multi-turn stacking and in all kinds of beam manipulations, the ion-ion charge exchange (intrabeam scattering), and final focussing and bunching.

For beam stacking, the method proposed by Rubbia (see page 88) will be used to reduce phase space dilution and improve beam quality during beam accumulation: non-Liouvillian stacking is achieved by photo-ionisation at injection into a storage ring [8]. A photon energy of 14.5 eV, the ionisation potential of Bi^+, corresponding to a wavelength of 84.8 nm, is needed to ionise Bi^+ to Bi^{++}. Other ion species with higher ionisation cross-sections (*e.g.*, Ba) are under consideration. A photon beam with the necessary power can only be provided by a free-electron laser (FEL). Such an FEL appears not to be beyond present-day technology.

Perspectives

The principle uncertainties for heavy ion inertial fusion are:

– Pellet: radial symmetry of the implosion drive, its consequences for the growth rate of hydrodynamic instabilities and for the beam quality; conversion efficiency in the case of indirect drive.

– Accelerator: the growth rate of longitudinal microwave instabilities in storage rings, final focussing and final bunching.

Pellet

The symmetry of implosion drive has been investigated recently by Atzeni [9] using a two-dimensional simulation code. Driving forces on the fuel capsule must be extraordinarily uniform owing to the development of Rayleigh-Taylor hydrodynamic instabilities (cover illustration) and upper limits for the deviation from symmetry in terms of Legendre polynomials have been determined. Heavy ion beams with sufficient intensity will definitely not be available in the near future to experimentally confirm these calculations. However, laser beams may give useful information, so high-power laser experiments are thought to be essential.

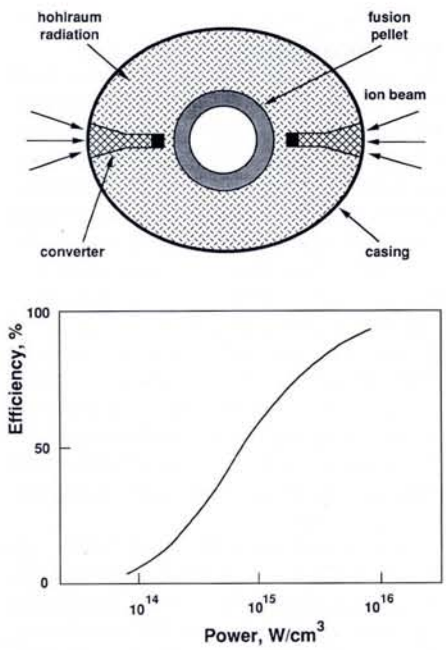

Fig. 3 — An example of an indirect-drive target for heavy ion ICF [10]. The kinetic energy of the beam is converted into soft X-rays which implode the inner shell filled with D-T fuel. Radiation confinement is achieved with a high-Z material. The conversion efficiency η depends strongly on the specific deposition power (lower) such that a total efficiency of 5-10% requires 10^{16} W/g.

Based on present knowledge, it is generally believed that the symmetry requirements for pellet implosion might not be achieved with a reasonably small number of heavy ion beams. If this is so, an indirect drive would be a necessary ingredient of a pellet implosion concept. Two additional issues are then absolutely crucial, namely, the conversion efficiency and radiation confinement.

Various types of indirect-drive pellets with two converters have been suggested and investigated by computer simulation by Meyer-ter-Vehn [10] and others: an example is shown in Fig. 3. To achieve high conversion efficiency of kinetic energy into the soft X-rays (which generate radiation pressure to implode the fuel capsule) the required deposition power must be about 10^{16} W/g: the total efficiency of the pellet is found to be 5-10%, which should be adequate for a high-gain target. The required deposition power of 10^{16} W/g calls for more severe conditions for the final focussing and bunching capacity of the driver.

However, the symmetry obtained from two converters might be insufficient. Recent analyses have therefore investigated various configurations of indirectly driven targets (some options are illustrated in Fig. 4 [11]).

Non-Liouvillian techniques

Non-Liouvillian techniques, in helping overcome the driver's final focussing and bunching capacity, become an essential ingredient of any driver concept. For example, the specific deposition power can be increased by more than an order of magnitude by using non-Liouvillian techniques. So if non-Liouvillian injection works as expected, the deposition power seems not to be beyond what is feasible, even for the enhanced requirements of indirect drive.

Since C. Rubbia first suggested non-Liouvillean injection by photo-ionisation in 1988 quite a number of different injection schemes and accelerator scenarios have been discussed, both for a driver accelerator and for a test facility based on the requirements for indirectly driven targets. In addition to schemes proposed by Rubbia, non-Liouvillian bunch compression was suggested by I. Hofmann for a driver accelerator by pre-bunching coasting beams in a stack of storage rings and depositing these bunches on top of each other, by non-Liouvillian injection, into a stack of 20 compression rings for final bunching. Moreover, instead of changing the charge at injection, the mass can be changed by accelerating a molecular ion and dissociating it at injection. This concept was considered by Arnold and Müller for a test facility, the advantage being that a more convenient laser wavelength is needed for the photo-dissociation. Some preliminary results of all these considerations are encouraging, but much work has to be done in order to prove the feasibility of proposed schemes. ►

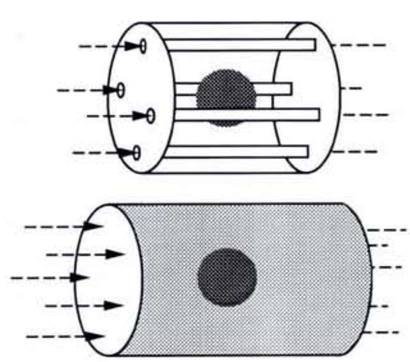

Fig. 4 — Some indirectly driven targets for heavy ion ICF [11]. a) The multiple filamentary converters can be designed for very high ion energies but the position of the fuel capsule (shaded) is critical. b) The hohlraum casing is completely filled with converter material, attractive from the implosion symmetry point-of-view but restricted to low energy ions.

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.

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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.

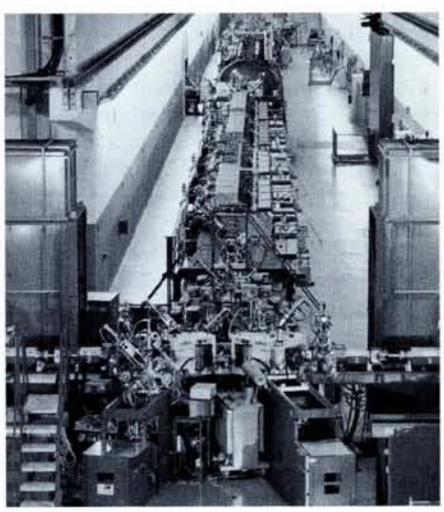

Fig. 1 — GSI Darmstadt's UNILAC RF-linac.

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^{182} 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