

INERTIAL FUSION WITH ACCELERATORS

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Abstract

The status of heavy ion accelerators studies to heat and compress matter to the conditions required for inertial fusion energy is discussed. We focus on the work of the European Study Group on an "Ignition Facility" with the goal of studying the feasibility of an RF heavy ion driver for ignition of a low-gain pellet. A key issue in the envisaged current multiplication scheme studied so far is the control of space charge effects in the storage rings to minimize emittance growth and beam loss.

1 INTRODUCTION

Thermonuclear fusion promises a relatively clean and abundant long-term source of energy supply, which could replace large-scale burning of fossil fuels and nuclear fission reactors. Research on controlled fusion has followed two complementary approaches, namely the quasi-steady *magnetic confinement fusion*, and the alternative approach based on successive implosion of small pellets, *inertial confinement fusion*. A major advantage of ICF is the decoupling of driver and reactor, whereas in MCF all processes involved are contained in the same unit. Both laser and particle beams - light or heavy ions - are studied to drive the implosion of the pellet. In recent years ICF with glass lasers (the leading NOVA facility in Livermore, and GEKKO in Japan) has come about as close to ignition as magnetic confinement fusion with tokamaks [2]. It is expected that pellet ignition will be demonstrated in the year 2005 with the planned "National Ignition Facility" (NIF) in Livermore, which is based on glass lasers. The goal of the tokamak based "International Thermonuclear Experimental Reactor" (ITER; construction approval expected in 1998) is to achieve a burning plasma in the year 2008. NIF (and a similar facility in France) is designed on a single-shot basis with a scope in the defense program. With respect to energy production, heavy ion accelerators as drivers are the most promising approach as they are based on a technology, which can provide the high efficiency and repetition rate necessary for a reactor [1].

Heavy ion fusion research in Europe is based on the RF linear accelerator and storage ring concept. An alternative scheme is the linear induction accelerator, which is the approach chosen by the US community. The characteristic feature of the induction linac is that the large power required for igniting a pellet can be achieved in a single pass through a structure with induction modules, which provide

simultaneously acceleration and bunch compression. A recent modification is the induction "recirculator", which makes repeated use of the structure by a large number of laps (for recent reviews see Refs. [3, 4]).

Both concepts have in common that substantial efforts are needed to understand and control the effects of space charge on beam quality. After discussing some basic features in Section 2, we shall concentrate in this paper on the RF linac and storage ring approach for the "Ignition Facility" feasibility study (Section 3). We also shortly discuss non-Liouvillian concepts which may have a potential for improving the final phase space density (Section 4).

2 HEAVY ION DRIVEN ICF

2.1 Basic Requirements

The fusion reaction with the most favorable cross section and temperature is the D-T reaction, which generates 17.6 MeV energy carried away mainly by the 14 MeV neutron. A plasma temperature of 5 keV is required to obtain the necessary reaction rate. The D-D reaction would get along without the tritium, but requires an order of magnitude higher plasma temperature. While this is practically impossible in the steady-state plasma of MCF it cannot be excluded in ICF as a more advanced fuel option with little or no tritium content. The criterion for thermonuclear burn with D-T is $n\tau T \approx 5 \times 10^{15} \text{ cm}^{-3} \text{ s keV}$, where n is the number of particles per unit volume, τ the confinement time and T the plasma temperature. In magnetic confinement this is reached by $n \approx 10^{14}$, in ICF by $n \approx 10^{25}$, which requires over 1000-fold compression of solid D-T.

2.2 Why Heavy Ions?

The driver repetition rate and efficiency (η) in conjunction with the pellet gain (G) play a crucial role in the argument why heavy ions give the most promising driver for *energy production*. The key issue is that the recirculating power in the reactor should not exceed 25-35%, which requires $\eta \times G \geq 7 - 10$. With practically achievable accelerator efficiencies of 25% this requires a pellet gain of 30-40, which is reasonably moderate and avoids the risks of very high-gain targets needed in alternative schemes with much lower efficiency (for instance the proposed KrF lasers with at best 5-10% efficiency). Along with repetition rates of 10 Hz (or even better) this efficiency cannot be achieved by any other presently known scheme. The choice for the heaviest ions

comes from the fact that the stopping power scales with Z^2 , where Z is the charge state of the (nearly fully stripped) ion in the converter. Classical stopping in the target material - with no anomalous effects like in laser deposition - and the option of ballistic focusing in a 10^{-3} – 10^{-4} Torr vacuum in the reactor chamber are further attractive features of heavy ion beams. To reach the typical power of 600 TW necessary for ignition, a particle current of 60 kA is required for 10 GeV heavy ions with mass $A \approx 200$. The schematic of the RF accelerator concept is shown in Fig. 1, which indicates the problem of phase space dilution occurring in parallel with the current multiplication.

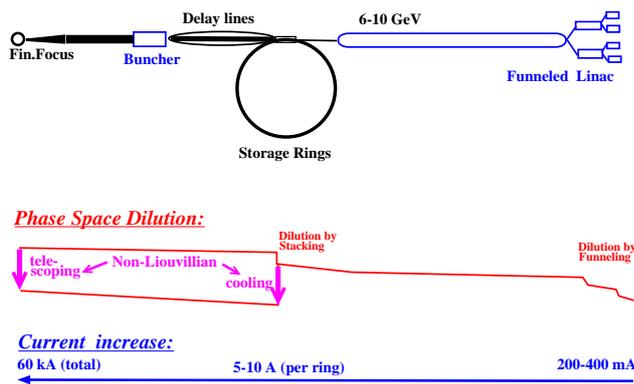


Figure 1: Schematic of RF linac and storage ring concept.

2.3 Target and Chamber Issues

The physics of target compression up to the point of ignition and burn is extremely complex due to the interplay of hydrodynamic motion, electron and radiation transport, equations of state under extreme conditions, and the appearance of instabilities, like the Rayleigh-Taylor-instability driven by non-spherically symmetric implosion of the pellet. The symmetry problem can be solved more easily by *indirect drive* of a pellet in a hohlraum. In this scheme the beams hit a converter which is heated to a temperature of about 300 eV, when it irradiates soft x-rays at high efficiency. Repeated absorption and re-emission at the hohlraum walls lead to a uniform radiation field, which is absorbed by the pellet and drives the implosion [5, 6, 7]. A specific power deposition in the converters of $P \geq 10^{16}$ W/g is needed for this process, which requires a small beam focal spot of 2-3 mm radius and at the same time a short pulse length of 5-10 ns. To provide the necessary beam power density is the challenging task of the driver accelerator.

The result of a 2-D calculation of a heavy ion driven hohlraum target with the code MULTI-2D for simulation of radiation hydrodynamics [8] is shown in Figs. 2, 3. The initial configuration prior to arrival of the ion beams is shown in Fig. 2 with the two cylindrical beam stoppers (converters) right and left. The cavity is surrounded by a cylindrical gold casing. Radiation shields have been placed between converters and pellet to avoid direct heat-

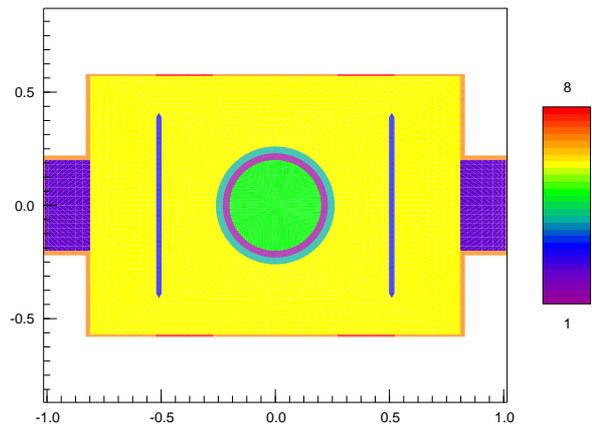


Figure 2: Initial configuration of a heavy ion driven hohlraum target showing a cut through the cylindrical cavity with different materials indicated by the grey scale (courtesy of J. Meyer-ter-Vehn and R. Ramis).

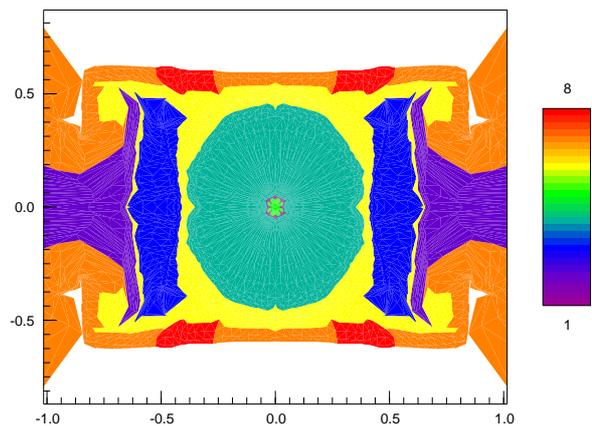


Figure 3: Final configuration at point of maximum compression of pellet core showing hydrodynamic expansion of all other materials.

ing of the pellet. It is noted that the outer shell of the pellet has expanded due to ablation, whereas the D-T fuel has imploded in the center showing some amount of Rayleigh-Taylor-instability due to the non-perfect spherical symmetry of this preliminary design.

In a *power plant* the energy released by the pellet must be contained in a reactor chamber, which provides a safe containment of the radiation, transformation of the energy into heat and breeding of tritium. In most ICF reactor concepts the debris and x-rays from the fire-ball are absorbed by a thin liquid metal film, which protects the first wall. The neutrons are absorbed in a liquid metal "blanket" containing also the lithium required for tritium breeding. A heat exchanger transfers the thermal energy from the blanket to an electrical generation system. Behind the blanket a shield is used for protection against neutrons. In this context a

major advantage of inertial fusion as compared with magnetic fusion is the decoupling of the reactor from the driver, which allows easier maintenance. For a discussion of recent heavy ion fusion power plant studies see Ref. [9, 10]. The ignition facility is based on single shots, which relaxes substantially the protection requirements and allows to use concepts presently developed for laser ignition facilities. Issues of special concern are the minimum distance target to last focusing magnet, which is expected to be inside the reaction chamber (for easier focusing) and requires some protection (see Section 3.3).

3 STATUS OF “IGNITION FACILITY” DESIGN

The European Study Group to design an Ignition Facility based on heavy ions has set its goal to demonstrate the feasibility of the concept on the basis of presently available knowledge about target requirements for ignition with low-gain, in a reaction chamber to be designed on a “single-shot” basis. As reference parameters we have chosen 3 Megajoules to be delivered within 5 ns pulse duration on a spot of 2.5 mm (converter radius). These parameters are based on results published by the Livermore group [12].

In the following we discuss key issues, which will determine largely the driver scenario to be defined as goal of the study group. So far the emphasis has been on the storage rings and final bunching and focusing requirements, which determine largely the necessary linac performance to be studied in a next step.

3.1 Linac and De-bunching

The linac is required to deliver 400 mA of 10 GeV Bi⁺ (or similar heavy ion) at an emittance of 4π mm mrad (unnormalized, full area of equivalent KV-beam). The relatively small emittance is needed to satisfy the final focusing requirements. An appropriate funneling scheme for combining of beams from 16-32 ion sources into one main linac at 216 MHz is being developed [13]. At the high energy end structures allowing high acceleration gradients, like the IH-structure, must be studied and tested under extreme space charge conditions [14]. The linac beam is chopped in macro-pulses of 250 ns, which are captured in the RF barrier-bucket of the storage rings.

The linac momentum spread is largely determined by the short final pulse requirement, and by space charge during de-bunching in the transfer line to the ring and the first few revolutions in the ring. A computer simulation result (particle-in-cell simulation with r-z Poisson solver for self-consistent space charge force calculation) is shown in Fig. 4. It is noted that the initial de-bunching of the short linac bunch is only little influenced by space charge. After applying the rebuncher voltage, a much longer bunch is obtained (assuming $\pm 135^\circ$ phase width) at correspondingly smaller momentum spread. It is thus subject to an enhanced space charge effect in the further drift in the rings and leads to an

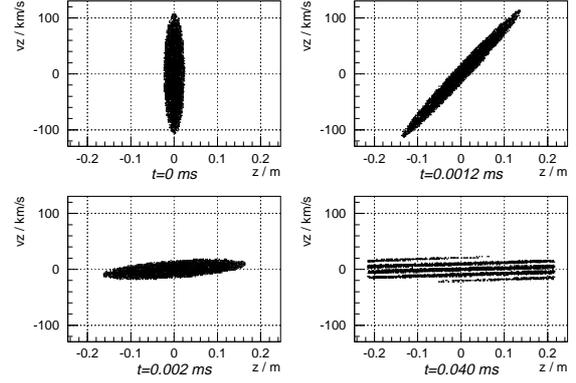


Figure 4: De-bunching process of the linac beam in longitudinal phase space: initial, de-bunched, re-bunched and final state (in SR with several bunches overlapping).

increase of the momentum spread by about 50% to the final value of $\pm 2.3 \times 10^{-4}$.

3.2 Storage Rings

Their main task is the accumulation of the required total number of heavy ions ($2-3 \times 10^{15}$) by stacking procedures, and current multiplication by RF bunch compression. We have chosen a lattice with 3-fold symmetry and 6 Tesla dipole magnets (50% filling) in the arcs (Fig. 5).

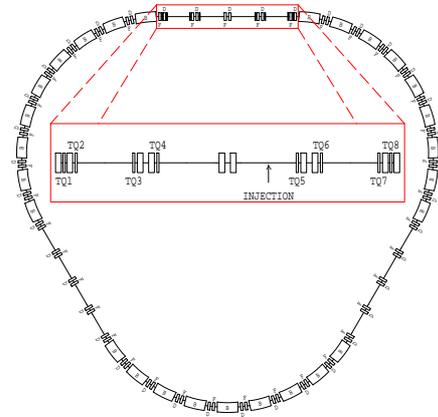


Figure 5: Storage ring lattice with doublet focusing and sc dipoles arranged in three super-periods and 443 m circumference (enlargement showing the injection straight with trim quadrupoles to adjust beta-functions for multi-turn stacking).

The straight sections with zero dispersion are for injection/extraction kickers and the demanding RF systems. A three-fold symmetry was chosen to keep the ring circumference as small as possible. Four super-periods with achromatic arcs (4π phase advance each) would have required a 33% larger circumference; for two super-periods only the area in the tune diagram free of systematic resonances would have been too small. A key issue not yet finalized is the minimum kicker rise time, which determines

the number of bunches in the ring. Extrapolations from standard technology suggest typical rise-times of $\approx 1\mu\text{sec}$ [15]. This would allow only 3-4 bunches per storage ring. The subject is under further investigation in order to establish the maximum possible number of bunches per ring. Control of space charge effects requires substantial efforts in computer simulation, including code development, and verification by experiments. Besides emittance dilution it is also necessary to keep beam loss at a minimum. Due to the short range in matter, beam loss concentrated on small spots must be avoided to the extent that material is not melted. Appropriate measures to deal with this problem are under investigation.

Multi-turn Injection in Two Planes: Simultaneous injection into the horizontal and vertical phase space by using a corner septum or an inclined straight septum and bumping the equilibrium orbit away from the septum in both planes has been studied [16]. Results are shown in Fig. 6 for a working point of $Q_h=8.78$ and $Q_v=8.66$, which is found to allow 15 turns of injection without loss on the septum. Preliminary calculations including space charge show significant distortions of the injected elliptical phase space boundaries, which lead to septum losses of the order of several percent. Further optimization is needed. It should be mentioned that the intrinsic incoherent space charge tune shift of the injected beam is 0.03.

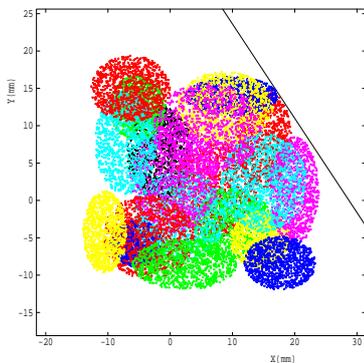


Figure 6: Two-plane multi-turn injection scheme (20 turns) with inclined septum in x-y plane (space charge ignored).

Barrier Bucket: Capture of linac macro-pulses in a barrier-like RF potential well during the multi-turn injection, where space charge cancels up to 90% of the applied RF potential has been studied by simulation [17]. Results have been obtained for a linac pulse of 250 ns length injected into a bucket with five Fourier harmonics (basic harmonic is the 12th, corresponding to 400 ns period). We find that good longitudinal matching and nearly loss-free trapping is possible, if the bucket is 20% longer than the injected pulse, hence 300 ns.

RF Cavities: RF systems for several harmonics (3-5) are required to provide the stationary barrier-like bucket,

and to perform a pre-bunching by bunch rotation prior to extraction. Preliminary Super-fish calculations have been carried out. Results have shown that a voltage of 250 kV (required for fast pre-bunching) at 2.5 MHz can be achieved with one cavity of a high-Q ($=10^4$) capacitively loaded pill-box structure of 3.6 m diameter [18]. Strong RF feedback is needed for such a cavity. Work is in progress to determine the distribution of higher harmonics needed to optimize the bunch rotation voltage and to adjust it to the compensation of space charge forces.

Instability Studies: The longitudinal instability, which is primarily of concern here, has been studied by computer simulation and experiment [19]. The instability due to interaction with the higher harmonic RF cavity impedances requires suppression of the cavity impedance by means of feedback. Our estimates suggest that at the 5-th harmonic of the fundamental RF frequency the impedance must be suppressed from the estimated R_p value of 350 k Ω by an order of magnitude [17]. Experiments to confirm the results from simulation need to be carried out under different impedance environments and for barrier-like buckets.

3.3 Final Bunching and Focusing:

Bunches extracted from the rings after pre-bunching are compressed to their final length of 5 ns; at the same time they need to be synchronized in time for arrival at the target. This requires delay lines with length differences that correspond to the bunch distance in the rings. We assume that the final compression is carried out in an RF buncher linac, after bunch synchronization. Due to pre-bunching in the rings the buncher linac can operate at 10 MHz, where it needs to provide a gradient as high as 1 MV/m over a length of 250 m. A Super-fish calculation has shown that a 1 MV cavity with 1 m length and 3.6 m diameter is at the limit of technical feasibility, if a Kilpatrick-factor of 1 is assumed [18].

A candidate for a final focusing scenario showing illumination of one converter is given in Fig. 7. Here we have assumed that six beam lines from a stack of six storage rings go through each one of the three buncher linacs (for bunches going through different delays). After this linac they are spread out in a 2x3 arrangement (vertical x horizontal) to allow focusing through individual lenses, assuming an emittance of $50\pi\text{mm mrad}$. Confinement of the bundle of 18 beam lines (from each side) to an opening angle as large as $\pm 37^\circ$ can be realized only with pulsed quadrupoles inside the reactor chamber at a distance of 2 m from the target. A larger total opening angle would reduce considerably the beam converter overlap. It should be mentioned that this geometric arrangement with a total of 36 beam lines is consistent with an assumed total number of 144 bunches, if each beam line is shared by four different “telescoping” bunches. The feasibility of this non-Liouvillian method is presently examined (see Section 4).

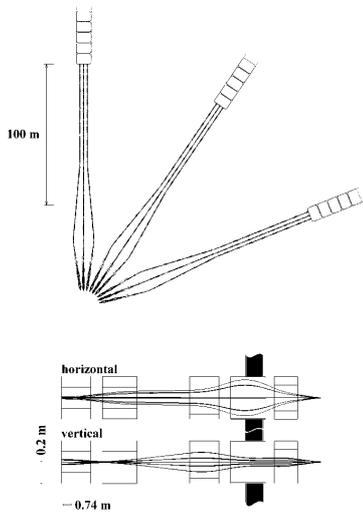


Figure 7: Layout of final transport assuming three buncher linacs and 18 beam lines from each side and focusing on target (enlarged, with indication of chamber wall).

4 NON-LIOUVILLIAN TECHNIQUES

The various beam manipulations and the effects of space charge lead to undesirable reduction of the final phase space density. This leaves little margin with respect to the very stringent requirements from final bunching and focusing. Phase space dilution can be reversed only with non-Liouvillian techniques like cooling or stripping. Most techniques amenable to heavy ions involve considerable additional complications, but they could lead to an overall reduction in the number of storage rings and beam lines, which helps the final focusing in the reaction chamber.

Telescoping of Different Ion Species: The idea is to generate bunches with different mass ions (neighboring elements), but identical magnetic rigidity, which then differ in velocity. A bunch with the faster species can be injected into the final transport line at a distance behind the slower bunch such that both arrive at the target simultaneously. Thus they fully overlap in momentum space, which is only possible as they are different particles species, and Liouville is only valid in the respective phase space. The issues presently investigated are funneling of different ion species into one linac, acceleration with rapid (few MHz) switching to different species, and mutual space charge effects for beams overlapping in real space in the storage rings and final transport lines. Preliminary results indicate that 3-4 different species varying by 2% mass differences are a promising candidate. Nonlinear space charge effects between bunches require special attention to avoid degradation of the phase space density.

Laser Cooling of Ions: This process is based on spontaneous absorption of photons in the beam direction and re-emission into 4π . This thus leads to a net momentum transfer of $h\nu/c$ per process and to a cooling effect during that part of the synchrotron motion where the ion moves against the laser beam. It has been shown recently to work very effectively in a small ion storage ring with bunched beams of Mg^+ [20]. We have estimated cooling of Hg^+ with the transition $6s2s \rightarrow 6p2p$ corresponding to a wavelength of 194 nm in the ion frame and roughly 250 nm in the lab frame. If a typical life-time of 2 ns is assumed for the excited state, the maximum absorption rate is 5×10^8 photons/s (saturation). One thus finds that for cooling of an injected momentum spread of 2×10^{-4} about 2×10^6 photons are needed, which leads to cooling times of 10-20 ms. Here it is assumed that half of the ring circumference is used for laser interaction. It should be mentioned that intra-beam charge exchange losses are expected to be substantial on this time scale, hence for this application it is of interest to search for other transitions leading to cooling times shorter by about an order of magnitude. An experiment to study cooling of high-intensity Mg^+ bunched beams is planned in the near future at the ESR storage ring at GSI.

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