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HEAVY ION DRIVERS FOR INERTIAL CONFINEMENT FUSION

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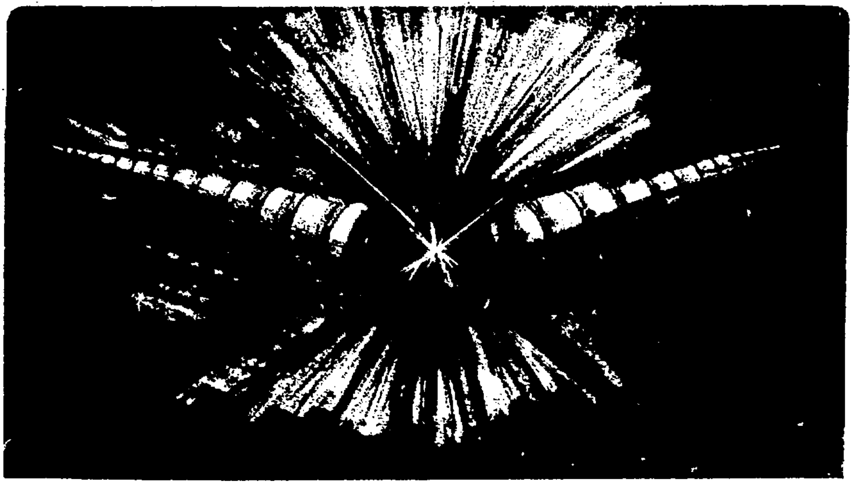

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Abstract

The advantages of heavy ion beams as a way of delivering the needed energy and power to an inertial fusion target are surveyed. The existing broad technology base of particle accelerators provides an important foundation for designing, costing, and evaluating proposed systems. The sequence of steps needed for the verification of the heavy ion approach is described; recent research results are even more encouraging than had been assumed hitherto.

1. The Advantages of Heavy Ions for a Particle Beam Driver

Whereas laser beams deposit their energy in the surface layers of an inertial fusion target, particle beams – whether of light or heavy ions – deposit energy volumetrically beneath the surface to a depth equal to their range. Fairly straightforward arguments(1) lead to the conclusion that, like laser beams, particle beams must deliver several megajoules per pulse with an irradiance approaching 1000 TW/cm^2. In addition, the specific energy delivered must be some 20-40 MJ/gram which leads to a rather closely defined preferred particle range in matter, namely $R = 0.1$ to 0.2 gm/cm^2.

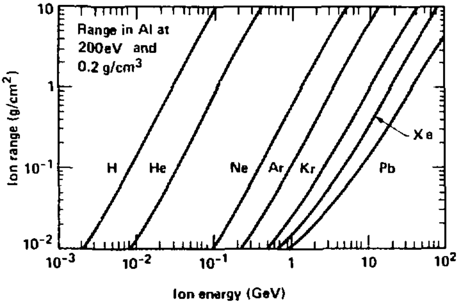

Fig. 1 The range-energy relation for several ion species in hot matter (200 eV). The ion range of interest for inertial fusion is about 0.1-0.2 g cm^{-2}.

Referring to the range energy relations for different ions (Fig. 1), we observe that a suitable kinetic energy for protons is ~10 MeV, and for heavy ions ~10 GeV. Thus while 15 MA of protons would be needed to deliver the required beam power (150 TW), a very much smaller current, 15 kA, of heavy ions will suffice. Moreover, at very high beam currents collective instabilities can disturb both the propagation of the ion beam across the reaction chamber to the target and the energy deposition in the hot plasma near the target surface(2). The heavier the ion, the less responsive it is (in proportion to its mass) to the nasty effects of collective instabilities, leading to a further factor of 200 in advantage for heavy ions over protons. Since high-current collective phenomena are indeed of concern, heavy ion beams could be viewed as having an advantage of a factor of 10^5 over protons because of the reduced current and reduced response.

When he first drew attention to the effectiveness of heavy ion beams for heating ICF targets, Maschke(3) also recognized that an extensive technology base existed in the form of large accelerator systems developed over decades for high-energy and nuclear physics. Thus, three essential ingredients – often considered to belong to the later years in development of many fusion approaches – were already to hand: Repetition Rate, Availability, and Long Life. In addition, a significant body of experience existed in the engineering design, costing and scheduling of accelerator systems on the scale of the several kilometers of technical components that will be needed for an ICF driver.

Finally, a very significant advantage of deploying conventional accelerator technology became apparent when certain designs were scaled up to the high-current regime necessary for Heavy Ion Fusion (HIF). The fraction of electrical power being communicated to the beam ("beam-loading") could be such that the electrical efficiency (η) of the accelerator system could lie in the 15 – 30 percent range, with important consequences for reactor application (see below).

On the negative side, three important concerns soon emerged. First, the heavy ion beam currents needed were very much greater than those typical of nuclear physics accelerators. Second, the beam quality, measured by accelerator physicists in terms of emittance which is related to the product of beam size and intrinsic thermal spread, was required to be maintained throughout the entire acceleration process at an uncomfortably small value. Historically, research accelerator users have not, usually, placed strong demands on maintaining superb optical quality; in contrast, the need to deliver essentially all the beam to a target focal spot only 5 mm in diameter in the center of the reaction chamber, requires that all manipulations of the beam during acceleration result in only minimal dilution of the phase-space density of the beam. Third, the speed of the heavy ions needed is in the non-relativistic region (at the peak energy, 10 GeV, $\beta = v/c$ is about 0.3) and the transport of high-current beams at low speed is a major problem. (Notice that the restoring force in a magnetic quadrupole transport system is proportional to vB, where B is the magnetic field, and is inevitably small for low-speed particles.) Thus, in two example accelerator systems to be discussed later, the limitations of the transport system, due to available peak magnetic — or electric — fields create novel design constraints. This occurs at both the low- and high-energy ends in one case (rf-storage rings), and sets a consistent design limit throughout, in the other (induction linac).

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In summary, then, extension of two features of accelerator physics needs verification for the success of the accelerator approach:

(i) Ability to achieve high currents of heavy ions

(ii) Ability to maintain small emittance, i.e., good optical quality.

2. Fusion Reactors

Figure 2 shows the power-flow diagram for an ICF plant. The thermal energy recovered from the thermonuclear burning of a D-T pellet or target exceeds the delivered beam input energy by a factor G, referred to as the target "gain". If the driver has an overall electrical conversion efficiency denoted by η then, in order to make up for the thermo-electric conversion efficiency ($\simeq 1/3$) and to ensure that only a small fraction of the total electrical energy produced ($\lesssim$ 25 percent) is consumed by the driver, we must ensure the following inequality:

$$\eta G > 10.$$

Thus, the entire promise of an ICF power plant based on pure fusion, rests on the estimates of the efficiency η for different drivers, and the expected values of gain, G, based on different target designs. Fig. 3 shows estimates of G for two different target designs; the "single-shell" type is of relatively simple construction whereas the "double-shell" type, which offers the promise of higher gain, needs a larger investment of energy per pulse and is more costly to fabricate(1).

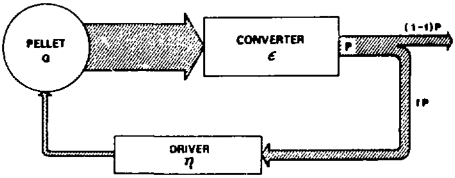

Fig. 2 Electrical power flow in a reactor. The recirculating power fraction is f.

Explicitly marked in Fig. 3 (right-hand ordinate) are the values of gain that must be reached to achieve $\eta G = 10$ for drivers of $\eta = 5$ percent and $\eta = 25$ percent. The lower value of $\eta = 5$ percent could correspond to that achievable with a short-wave-length laser and implies that a double-shell target must be used with an energy investment per pulse of ~ 7 MJ. The higher value of $\eta = 25$ percent can be realized with a heavy ion accelerator driver, and Fig. 3 indicates that the simpler and cheaper single-shell targets would be adequate with an energy investment per pulse of about 3 MJ. Yet another feature of the high-efficiency driver deserves mention: in the above examples, the yield per pulse is 120 MJ, compared with 1400 MJ for the low-efficiency driver, resulting in less thermal shock per pulse in the reaction chamber. To produce an equivalent electric power output, however, a high repetition rate is needed for the high-efficiency driver; this seems well within the range of accelerator experience.

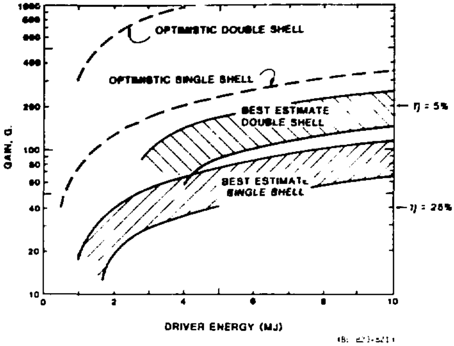

Fig. 3 Calculated gain for single- and double-shell targets as a function of driver input energy. The lines marked $\eta = 5\%$, 25% indicate the gain needed for drivers with these respective efficiencies.

An important distinction between Inertial Fusion and Magnetic Fusion systems lies in the reactor design. To a considerable degree the design choices for the ICF reactor and the design choices for the driver can be made in a quasi-independent way. The technical components of the driver lie well outside the reaction chamber and the design coupling between the two systems occurs only when one considers the final beam optics to bring the beams to the target (for a heavy-ion driver the final elements will be magnetic quadrupole lenses). The use of liquid metals, either lithium or lead-lithium, to protect the wall of the chamber from the microexplosion of the target seems attractive, although dry-wall solutions are not ruled out by any means.(4)

Fig. 4 shows an example concept, Inport(5), in which liquid lead-lithium alloy flows through open-weave silicon carbide tubes to provide protection of the first wall.

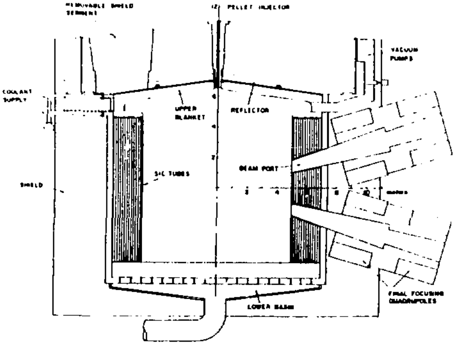

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Fig. 4 The Inport reactor concept.(5) Ten ports through which the heavy-ion beams enter are arranged in five pairs around the chamber; one pair is shown.

3. Accelerator Systems as Drivers

Two example systems, one based on rf linac/storage ring technology, the other on induction linac technology, are depicted in Figure 5. [Soon after Maschke first pointed to the advantage of using the heaviest possible ion species, Martin and Arnold(6) proposed using a synchrotron as a cheaper alternative than an rf linac for loading the storage rings. In time, the optimum ion kinetic energy needed was significantly revised downwards by target designers, thereby diminishing the role of the synchrotron to the point that it no longer offered advantages].

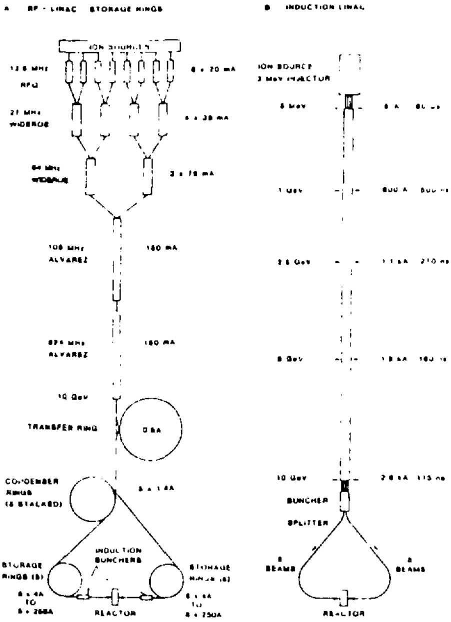

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Fig. 5 Schematic of two proposed accelerator driver systems: (1) A proposed 7-MJ driver of the rf/storage-ring type.(5) (b) A single-pass four-beam induction linac (3 MJ).(8)

An rf linac operates at constant beam current; the object then is to use the linac to supply the full kinetic energy, 10 GeV, to the beam at a relatively low current — a fraction of an ampere. Next, the current is amplified by injecting multiple turns into each of a number of storage rings (about twenty of them). Next, the circulating ring currents are further amplified by radio-frequency bunching, the bunches are extracted from the rings, and are further bunched by passing through a ramped electric field, supplied by an induction linac section. The momentum tilt thereby imparted causes longitudinal implosion of the bunch as it drifts to the reaction chamber. To accomplish all this, a significant number of beam manipulations is needed at both *the front end of the main linac* — *where* beams from many low energy linacs must be funnelled together because of the transport limits — and, also, at the high energy end where the space-charge limiting properties of storage rings (much more stringent than linacs) dictate the use of a large number of rings. Throughout all the manipulations, strict attention is needed to maintain adequate optical quality of the beam.

The induction linac system is conceptually much simpler insofar as it is a single-pass system from source to target. A suitable pulsed high-voltage injector delivers an ion beam, or beams, with a few amperes for some tens of microseconds; the total beam is then accelerated in an induction linac by transformer action(7) to the full energy of 10 GeV. Because the individual accelerating units are separately pulsed, conditions can be arranged to maintain the bunch at a constant length. In this case the beam current becomes amplified, as the bunch proceeds along the accelerator, in proportion to the ion speed. By small adjustments, the bunch length can actually be shortened slightly during acceleration to provide still further current amplification. Thus, both current and energy enhancement proceed hand-in-hand during acceleration. How fast the current amplification can occur is determined by the limitations of the transport system alone; the large beam current of a few kiloamperes at the end does not unduly stress the pulse-power induction linac technology. Apart from the beam transport elements, the high-energy half of the linac would not appear very dissimilar to existing multi-kiloamp electron linacs (c.f. Fig. 6).

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Fig. 6 A view of the FXR induction linac at the Lawrence Livermore National Laboratory. It accelerates 4 kA of electrons with a pulse width of 60 ns; components toward the high-energy end of an ion induction linac would look very similar.

The driver example sketched in Fig. 5b relied on accelerating four beams, each with its individual transport lenses, to full energy, 10 GeV.[8] A further splitting operation by means of septum magnets would then be required to create the 16 beams needed at the target. This operation can result in some dilution of emittance; to avoid this, later concepts have included consideration of starting with 16 beams from the injector which then would be accelerated commonly, but transported individually from source to target without any splitting operations. Some cost studies indicate that the induction linac may have a cost minimum for 4 or 8 beams; while a very slight cost penalty would be incurred for 16 beams, the increased safety margin on maintaining optical quality could, however, be well worthwhile.

4. Program Research and Development Plan

Beginning in this fiscal year, FY 84, the heavy ion fusion program will be funded from the DoE Office of Basic Energy Sciences. (Previously it had been supported at a modest level by the Office of Inertial Fusion which is in charge of the large laser and light-ion programs). The thrust of the program is in Accelerator Research -- to establish a suitably extensive base of accelerator physics and accelerator engineering and technology, to allow evaluation of the usefulness of the accelerator approach for fusion to be made in a convincing way.

We have identified a highly significant experiment called the High Temperature Experiment (HTE) that could be prepared in the time-frame FY 87-89 which, if successful, could provide considerable assurance about proceeding later with a larger facility capable of using thermo-nuclear targets. The HTE would consist of a multiple-beam induction linac with beam-current amplification, and a final-focussing system to deliver all the beams to overlap at a common focal spot on a slab target. If the accelerator system performs as we hope, the spot temperature could be in the range of 75 eV, about one-third of that needed for an ablatively driven target and sufficiently high to test any unsuspected problems in energy deposition due to collective effects in the target. Tentative parameters for the HTE are given in Table I.

Table I - Tentative Parameters for HTE

Ion : Na^+ (A = 23)
Kinetic Energy : 125 MeV
Beam Charge : 30 μC
Number of Beams : 16
Beam Energy : 3.75 kJ
Final Pulse Direction: 30 nsec

After so much earlier discussion of the advantages of using the heaviest of ions, the choice of an ion as light as sodium (A = 23) for HTE may seem surprising. For fusion drivers the cost is related, in lowest order, to the number of megajoules of beam energy and, indeed, the heaviest ions are preferred. This is not so when we drop down to the kilojoule region where the kinetic energy, not the joules in the beam, is the leading cost determinant. Folding in other scaling laws leads to a choice of A ~ 20 - 30 as optimum for this level of experiment.

The R and D program over the next three years will concentrate on component development for the HTE and an integrated system test of a multiple-beam induction linac system of modest scale. (Multiple Beam Experiment, or MBE). The aim is to develop and test as many as possible of the engineering and physics questions, e.g. current amplification, that are expected to be encountered in the HTE. This effort is being jointly conducted by LBL and LANL.

Apart from the conceptual design of MBE and HTE, present experimental activities at LBL are concerned with development of a multi-module long-pulse accelerating unit, which has already successfully accelerated heavy ions (cesium), and a single-beam transport experiment (SBTE). The latter consists of a long alternating-gradient transport system consisting of 87 electrostatic quadrupoles to test the propagation features of a very intense cesium-ion beam. An extensive body of theory on the matter has emerged over the last several years, and has warned of potential trouble, i.e. degradation in quality, when certain predicted currents were exceeded. The ongoing experiments have already shown that indeed, for certain settings of the transport channel parameters, violent effects do occur as predicted. On the other hand the experiments have also shown (in agreement with some simulation results) that under other conditions the beam current can be pushed to values well beyond the feared danger zones without deleterious effects on beam quality. It is therefore probable that much of the previous work on driver studies, including the example shown in Fig. 5b, were based on overly conservative assumptions on the beam current transport limits. While we draw considerable comfort from the implications of these new results for drivers, exactly how much comfort is going to take more work to establish.

References

1. Keefe, D., Ann. Rev. Nucl. Part. Sci., 32, 391 (1982)
2. Olson, C. L., J. Fusion Energy, 1, 307 (1982).
3. Maschke, A. W., Brookhaven National Laboratory Internal Report: BNL 19008 (1974).
4. Monsler, M.J., Hovingh J., Cook, D.L., Frank, T.G., Moses, G.A., Nucl. Techn. Fus. 1, 302 (1981).
5. Badger, B. et al., Univ. Wis. Rep. UWFDM-450 (1980).
6. Martin, R.L., Arnold, R.C., Argonne National Lab. Intern. Rep., RLM/RCA-1, and U.S. Patent 4069457.
7. Faltens, A., and Keefe, D., Proc. 1981 Lin. Accel. Conf., Sante Fe, N.M., LANL Rep. LA-9234-C, 205 (1982).
8. Faltens, A., Hoyer, E., Keefe, D., Proc. Beams IV Symp. (Palaiseau, France), 751 (1981).