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RECENT PROGRESS AND PLANS FOR HEAVY ION FUSION

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Abstract

The heavy ion inertial fusion community has completed two years of conceptual designs, cost estimates, theoretical analyses and a modest experimental effort in ion sources and preaccelerators. Designs have narrowed to rf linacs (with storage rings) and induction linacs. Considerable progress has been made in the theory of high current beam handling. Ion sources at levels appropriate to both linac types have been demonstrated. Attention is turning to more detailed accelerator designs appropriate to a three-stage program, the first stage involving demonstration of high current beam techniques, the second stage aimed at ion-pellet deposition experiments, the third stage being a megajoule class pellet driver. In this paper progress is reviewed, with emphasis on program implications.

1. Introduction

Inertial confinement fusion is being pursued in the Department of Energy using two basic pellet "driver" technologies: lasers and particle beams.[1] Lasers are divided into three groups: glass, for near term target physics; CO_2 gas laser because of its higher efficiency and more advanced technology; and several advanced lasers aimed at high efficiency at various short wavelengths. Particle beam fusion can also be divided into three main branches according to the particle: electrons, light ions, and heavy ions. Assuming for the sake of comparison that the theory of pellet compression and ignition yields a peak power requirement of 100 terawatts for adequate pellet gain,[2] then the differing beam energy and current requirements are illustrated in Table I.

Table I - Typical Energy and Current vs Particle

	Kinetic Energy	Peak Current
Electrons	1 MeV	100 MA
Protons	5 MeV	20 MA
Heavy Ions	20 GeV	5 kA*

*Particle current; electrical current greater by ratio of charge state.

These differing requirements result from a consideration of the known range/energy relation of each particle in matter. Between electrons and heavy ions the requirements differ by more than four orders of magnitude, resulting in the use of vastly different technologies. For electrons or very light ions, a single high voltage diode with low impedance design can produce a 1-2 TW beam in a single pulse mode. Thus the DOE sponsored program at Sandia Laboratories, Albuquerque, is based on construction of an Electron Beam Fusion Accelerator (EBFA) which, in its final version, is expected to produce the required total beam power using 72 beams.[3] This style of pulsed power technology, originally developed for nuclear weapon simulators by the Defense Nuclear Agency, is characterized by very high electric field stresses placed on capacitors and dielectrics, the use of inexpensive spark gaps, and low current charging supplies. High performance is obtained at relatively low cost with reliability of 10-100 shots considered adequate. While ideal for the near term goal of scientific experiments, to adapt the same technology to commercial power may require major modifications to achieve long-lived high-repetition-rate performance. To that end the Sandia group is conducting a parallel R&D program in high repetition rate components.

The heavy ion program has emerged from a technology, that of high energy accelerators, which has of necessity emphasized high reliability at full repetition rate for many years. High energy accelerators are characterized by modest capacitor ratings, use of relatively expensive thyratron or high vacuum switches, and inherent design for high average power including cooling systems. They are characterized by a much larger number of energy-adding modules, each with relatively small peak power handling capacity. For the equivalent single pulse performance, they are therefore more expensive than their pulse power counterparts.

The chief attraction of the heavy ion method is in the drastic reduction in the peak current requirement to the order of 5 kiloamps (particle current). This reduction is allowed by the high energy per particle. Using a typical number of beams of 10-20, this means that each beam is less than one kiloamp. Studies during the past two years indicate that, as expected at the initial workshop, such currents can be handled, transported, and focused to the required spot size using conventional methods. Self-fields are in general perturbations to ballistic trajectories. By contrast, the electron and proton methods are dominated by self-field effects. Transport of e-beams or light ion beams is a serious technical issue and a significant fraction of the Sandia effort is aimed at studying methods of transport, the chief one being the use of plasma channels. In addition, DOE supports the Naval Research Laboratory in plasma channel transport.[4]

Before moving to the main heavy ion topics, a development worth noting is the rapid progress in various types of light ion sources. Following early work at Cornell (1974-75),[5] the NRL group achieved proton currents of several hundred kiloamperes in 1976.[6] Recently the Sandia group has achieved similar intensities and a current density on target of 100 kA/cm^2 together with a foil implosion velocity of 10^7 cm/sec.[3] In addition, considerable attention is being given to the use of pulse compression of light ion beams by means of voltage ramping of the diode to provide time-of-flight bunching.[7] These results underscore the possibility that pulsed power methods present a promising path to target experiments in the early-to-mid eighties. For example, if the required plasma channelling and beam overlap occur as hoped, then EBFA II might provide 10 MA of ions as follows: 300 kA per diode x 72 diodes x 3 compression, with a safety factor of 6 for beam focusing and overlap efficiency. Developments in this field are certain to be followed closely.

2. Beam Target Interaction

In a paper contributed to the Argonne Workshop, R. O. Bangerter reviews the present understanding of

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heavy-ion/matter interactions.[8] The subject is important because experimental verification of the expected "classical" nature of heavy ion deposition at fusion intensities is clearly some years away and the accelerator design depends on the expected energy loss per unit length dE/dx. For example, if accelerator cost varies as $(\text{energy})^{0.4}$ as expected, then a 25% decrease in energy loss would require a performance and cost increase of roughly 10%. The level of sensitivity is thus significant but not crucial unless some sort of radically unexpected behavior decreases dE/dx below that level. In any case, it is important to examine the details of intense heavy ion deposition in hot, dense matter.

Bangerter argues that dE/dx is well understood and that fundamental considerations place a lower boundary on energy loss. In his calculation of a minimum (dE/dx) he makes the following points:

- Brown and Moak in 1972 showed that one important parameter of deposition, the effective charge due to stripping, Z_{eff}, depends only on the incident ion velocity ($\beta = v/c$) and charge Z.[9] For a variety of projectiles and targets they fitted the data to form

  $$Z_{eff}/Z = 1 - 1.034 \exp(-137\beta/Z^{0.69})$$

  to high accuracy. Apparently an ion is stripped to the point at which the orbital velocities of the remaining electrons are equal to or greater than the velocity of the ion. Thus, for example, with $\beta > 0.3$, heavy ions are more than 80% ionized and the dependence of Z_{eff} on β is weak. Bangerter argues that although the data refers to cold matter, the same situation should apply in the dense plasma case provided the same relative velocities apply. In fact, β is an order of magnitude larger than the electron velocity (except at very low ion energies) which in turn is 2 or 3 orders of magnitude larger than target ion thermal velocity.

- For typical beam/target parameters, the actual beam density is low, about nine orders of magnitude less than the electron density in the target. The average distance between ions is about 1000 Debye lengths.

- A large fraction of the total dE/dx can be accounted for by binary collisions involving impact parameters less than a Debye length ($\sim 10^{-8}$ cm).

- Nuclear interactions are negligible at incident energies of current interest (< 20 GeV).

With these arguments and others, Bangerter concludes that the lower limit on dE/dx is not significantly different from the "classical" value. This conclusion, if upheld on further examination, will clearly have a bearing on the relative importance of this question as a technical issue.

3. Conceptual Designs

The basic contention of the original proponents of the heavy ion method, that a technology exists which appears to be capable of being adapted to deliver the requisite beam to a target, has been largely verified to the extent that conceptual design effort and supporting studies can verify that contention. Figures 1, 2 and 3 show in schematic form the accelerator system designs which were given the highest confidence ratings at the HIF workshop held at Argonne in September 1978. Since they are described in detail in available reports, only cursory descriptions are given here.

Figure 1 shows a conservatively designed reference 10 MJ reactor driver due to A. Maschke.[10] The beam on target is 20 GeV, 200 TW, U^{+2}, using 8 final rings and beam lines. Maschke proposes the unusually low frequency of 2 MHz for the first Wideroe linac in order to substantially increase the space charge limiting current. Succeeding Wideroe sections operate at 4 and 8 MHz, respectively. Three succeeding Alvarez linacs operate at 48, 96, and 192 MHz, with the last one being folded to occupy the same tunnel as the large "multiplier" ring. The latter ring has a (racetrack) circumference of 6 km, while the small multiplier ring and the accumulator rings each have a circumference of 600 m. Using multi-turn injection and bunching, the total cycle time to fill eight rings is about 6 msec. With a repetition rate of 15 Hz, the rf duty factor is 10%. Beam transport lines 1 km in length are proposed to allow longitudinal bunching of ions on the way to the target chamber located in the center of the system. Maschke suggests that the inherent high average beam power of this kind of system, 150 MW for his design, is suitable for driving several reactor chambers. With an estimated overall efficiency of 37%, the system would be suitable for low gain targets or for a breeding scenario.

Figure 2 shows an Argonne reference design for a 1 MJ fusion driver based on an rf linac but using somewhat different methods.[11] In this system 128 mA (electrical) of Hg^{+8} are accelerated with a 2.5 GV linac to 20 GeV. Transverse beam stacking of (4 x 4) x (4 x 4) = 256 is performed using intermediate "delay" rings. Ion currents of 24 A are then accumulated in 18 storage rings. One extraction beam line per storage ring is used, with external linear-induction bunchers, to supply a final compression factor of 74. A spot size on target of 1 mm is calculated, with a reaction chamber radius of 5 m and a port radius of 21 cm, providing a specific energy deposition of 20 MJ/g. In this design the momentum spread on target is very small (dp/p) = 0.035%.

As in other designs, linac frequency upshifts are performed in stages, the final Alvarez frequency being 200 MHz. To conserve most of the momentum resolution inherent in the linac, a set of debuncher cavities and associated drift space is employed. The transverse beam stacking is accomplished by combining four beams after each of a sequence of four delays, which are based on beam transport lines ranging in steps up to 1.4 km long. Hence the (4 x 4) factors noted above. Emittance dilution is included based on previous experience with protons.

The rings in each array are filled sequentially; then the beams are simultaneously extracted, combined with the beam from the previous array using four septum magnets, and the combined beam is used to fill successive rings in the next array. The 18 final storage rings are filled sequentially and extracted simultaneously into beam lines that pass through linear induction cavities for final bunching.

Figure 3 shows the Lawrence Berkeley design based on a linear induction accelerator (LIA).[12] It is a "single-pass" method, by far the simplest conceptually, but one which has the least engineering, operating, and cost experience. The inherent low impedance, high current capability of the LIA eliminates the need for storage rings. Simultaneous acceleration and bunching is performed. The beam must be split at the output as shown in Figure 3 not only for more symmetric irradiation on target but because the final beam current after bunching is above the space charge limit for transport. A recent more highly optimized design uses 20 GeV instead of 26 GeV as shown, combined with 16 beams for final transport. Beam splitting is performed with septum magnets.

The Berkeley group has developed a computer program which enables them to optimize and compare the cost and performance of the LIA designs as a function of the rather large number of independent variables. These include (all as a function of axial distance) the beam radius, core material and size, location and strength of focusing magnets, space charge "phase shift," accelerating gradient, degree of bunching, and other parameters. Experimentally, they have demonstrated a Cs^{+1} ion source of the contact ionization potential type which produces 1 ampere at 500 kV with acceptable emittance.

The principal technical uncertainty in the LIA method is preservation of the beam emittance through the low velocity region in the "injector." The principal cost uncertainty is the cost of the core material in mass production. New core materials are being actively studied by the Berkeley group.

Meaningful cost estimates for heavy ion drivers could not be made until the accelerator design effort reached an acceptable level of completeness. Although a firm consensus has not been reached on cost estimates, it is clear that the cost of an optimized driver scales roughly as the 0.4 power of the total pulse energy because of the rapid increase in beam power capability vs kinetic energy. For planning purposes an estimate good to about 25% appears to be: cost = 350 M (energy in MJ)$^{0.4}$ dollars. This formula does not include indirect costs and is for the driver only. In addition, the estimate is in the context of high energy R&D accelerators and has not been studied for cost-cutting techniques.

4. Program Planning

It would not be appropriate to attempt a discussion of detailed program plans which have been neither thoroughly discussed nor approved. However, a few broad concepts and several technical issues have emerged from the program thus far and are worthy of comment in a review paper.

Much of the recent thinking about long range plans has emphasized the concept of a three-stage program along the following lines. A first stage is envisioned whose primary purpose would be to demonstrate, on a small scale, as many of the accelerator technology issues as possible, including beam handling and beam multiplication techniques. We will dub this stage the Accelerator Demonstration Facility (ADF), recognizing that it is more of an R&D program than a construction project and will not necessarily be termed a "facility."

The second stage, by virtue of its size and expected cost, would be a major facility. It would produce an output in the range of 50-100 kJ and has been called HIDE, for Heavy Ion Demonstration Experiment. This output would be sufficient to perform validating target experiments as a major intermediate step on the path to a megajoule class reactor driver. The third stage, designated Engineering Test Facility (ETF) in recent policy documents of the DOE, would have a repetition rate adequate for initial studies of reactor design and pellet injection as well as pellet design optimization. The ETF is envisioned as a full scale upgrade of HIDE, in the sense that the HIDE linac would be lengthened, the number of beams would be increased and, in the rf case, more storage rings would be added. Thus HIDE would be located at a site suitable for the ETF. On the other hand the smaller ADF, with its emphasis on accelerator R&D could be sited at a wider variety of locations.

Table II - Possible Three Stage Program for a Linac-Based Heavy Ion Driver

	Total Energy (kJ)	Peak Power (TW)	Kinetic Energy (GeV)	Beam Current* (kA)	Ion
ADF (Ind)	0.5-2	0.01	0.03	0.1-0.2	$Cs^{1,2}$
ADF (rf)	1-4	0.1-0.4	1-2	1-2	Xe^{+8}
HIDE	20-100	2-10	5	1-4	U^{+2}
ETF	0.6-3MJ	60-300	20	6-30	U^{+2}

*Electrical current.

Typical beam parameter objectives for the above facilities are summarized in Table II. Separate objectives are given for the induction linac ADF and rf linac ADF and follow recent proposals of LBL and ANL, respectively. The Berkeley group propose a "test bed" consisting of several Marx-driven drift tubes with electrostatic focusing followed by a number of induction cavities with magnetic focusing. The Argonne group propose to obtain high performance by employing a high charge state, +8, which would not necessarily be used in HIDE or the ETF. Neither ADF would exceed 200 meters in length. At the HIDE level and above, the performance objectives are similar for the two linac types.

The main uncertainties in the detailed designs are in preservation of transverse and longitudinal phase space in the presence of space charge effects somewhat greater than employed in conventional accelerators. Prudent designs allow for a factor of safety, up to a factor of two, in the emittance increase at each major beam manipulation. In the case of the induction linac, considerable effort is being devoted to the lowest energy part of the system where conventional single-pass methods are inadequate, and to the final bunching and focusing. In the case of the rf linac/storage ring method, attention is centered on the "funnel loading" technique (combining two beams into one with frequency jumping between linacs) and on bunching, debunching, and rebunching (at different frequency) techniques, in addition to the final transport and focus. In each case the main body of the linear accelerator, where power is imparted to the beam (and where most of the cost lies), presents few technical problems.

A possible ADF or HIDE system schematic is shown in Figure 4 for the rf linac/storage ring method. It contains all of the basic subsystems necessary to demonstrate the method at a fraction of the projected cost of an ETF driver. The choice of the Xe^{+8} ion as proposed by the Argonne group involves a tradeoff between the cost savings resulting from its use and the likely use of a lower charge state in larger systems. For smaller systems, it appears to provide greater performance per unit cost.

5. System Studies

What effect, if any, do the projected characteristics of heavy ion technology have on ICF system studies? W. B. Herrmannsfeldt of the Stanford Linear Accelerator Center has made a preliminary parametric analysis appropriate to HIF drivers.[13] Unlike some previous studies, he allows the driver energy and repetition rate to be free parameters, within limits. After consultation with the LLL pellet design group, Herrmannsfeldt chooses the pellet gain to be $G = 200\ (E^{0.4} - 0.5)$ where E is the beam energy on target in megajoules. From the recent two years of design and cost analyses, he chooses for the cost of a HIF driver the expression $C_d = 0.7\ E^{0.4}$ billion dollars where the factor 0.7 includes a factor of two for indirect costs (interest, EDIA and contingency). The exponent 0.4 is believed to be unique to HIF drivers, as noted elsewhere. Plant size is fixed at 1 GW electric and 1.2 billion dollars is added for the related equipment. With assumptions about the thermal efficiency (33%), annual fixed charge rate (15%), capicity factor (65%), and operating "tax" (10%), the projected power cost as a function of efficiency or driver energy is calculated. A portion of the results is shown in Figure 5. All costs are in FY 1979 dollars.

While the results in absolute terms are questionable at this early stage of development, nevertheless the parametric trends are interesting. Perhaps the most surprising result of the curves of Figure 5 is the relatively weak dependence on driver energy in the efficiency range of 12-25% and, for E > 3 MJ, also for lower efficiency. This implies some degree of freedom in choosing other parameters. As noted above, the repetition rate in this model is a free parameter and ranges from about 1 Hz at 10 MJ to a high of 40 Hz at 1 MJ. (In one model variation Herrmannsfeldt includes a capital cost penalty for the highest repetition rate ranging up to 20%.)

Not surprising is the strong dependence on efficiency. One must "pay" for the cost of running the driver. The curves exhibit the desirability for at least 6% and show diminishing returns at 25%. This result depends strongly on the gain function assumed, with higher gain alleviating the need for high efficiency.

Also interesting is the sensitivity of the best result, about 50 mills/kWh for E = 1-3 MJ, to variation of assumptions. For example, if the capital cost is 1 billion dollars higher than assumed, the power cost is 50% higher; if the driver cost is halved, the power cost is reduced by 20%. Surprisingly, if the pellet gain is doubled or halved, the power cost is affected only ± 5%. (This statement of course does not apply to cases involving low efficiency.) Finally, Herrmannsfeldt points out, in agreement with the approach adopted by A. Maschke,[10] that in the HIF case the effective driver cost can be greatly reduced by powering two or more reactor chambers with one driver. Such a scheme puts a greater burden on driver reliability but appears to be eminently suited to any ICF driver which is capable of high repetition rate, has reasonably high efficiency and uses beams which can be rapidly shifted to an alternate reactor.

6. Ion Sources

Progress in appropriate ion sources has been substantial. Two sources have been demonstrated at the Lawrence Berkeley Laboratory. For the induction linac method, they developed a pulsed contact ionization potential source which delivers 1.2 A of cesium ions at 0.5 MV. A scale-up to about 4 A is ultimately required. For the rf linac method, the LBL group adapted and modified a multiaperture plasma source normally used for heating Tokamak and mirror plasmas. This source fitted with a Cockcroft-Walton preaccelerator delivered 60 mA of xenon ions at 0.5 MV. Initial measurements of optical quality were adequate.

At Argonne, a NASA-surplus commercial Dynamitron high voltage generator has been modified to accelerate 30 to 50 mA at 1.5 MV. To date the generator has been operated up to 900 kV. A high brightness Xe^{+1} source built by Hughes Research Laboratories is being mounted in the Dynamitron together with a new high-gradient column especially designed for this purpose. In general, the ion sources do not appear to be a limiting factor in the development of high-current heavy ion accelerators.

The author is indebted to numerous people in the heavy ion program for assistance and discussions. A number of topics not included in this review, such as beam transport in vacuum and in low pressure gas, development of ion sources, final-focus optics, and ion-atom and ion-ion cross-sections, may be found in the heavy ion workshop proceedings[2,8] and in part in a previous review.[14]

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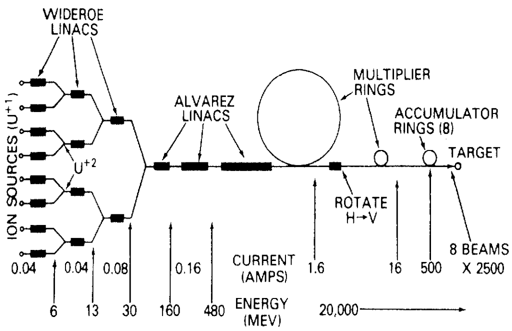

Fig. 1 Conceptual design in schematic form of a 10 MJ, 200 TW system developed at Brookhaven National Laboratory based on an RF linac/accumulator rings method.[10] Multi-turn injection and bunching is employed in two intermediate "multiplier" rings.

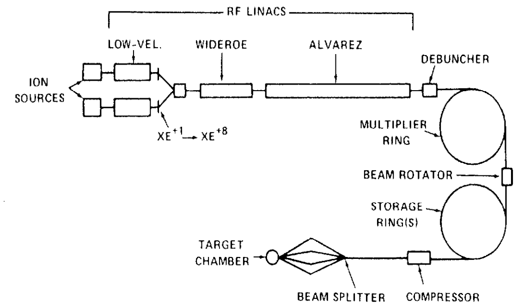

Fig. 4 Preliminary schematic of an Accelerator Demonstration Facility appropriate to the RF linac/storage ring method. For a linac voltage gain of 100-200 MV, a pulse energy on target of 1-4 kJ is projected.

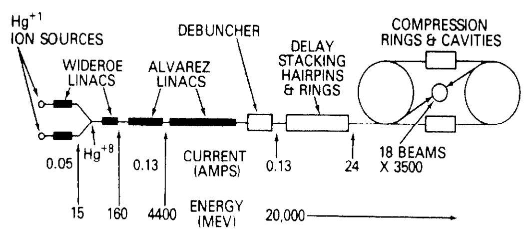

Fig. 2 Schematic of RF linac-based conceptual design proposed by the Argonne National Laboratory group.[11] Transverse beam stacking is performed using intermediate "delay" rings prior to accumulation in 18 storage rings. Induction cavities, shown above and below the target chamber, are used to bunch each beam to 3.5 kA on target.

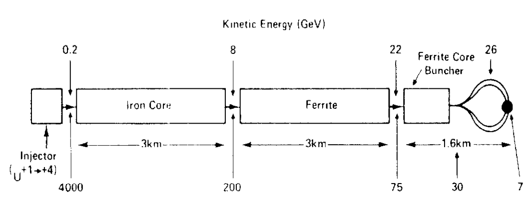

Fig. 3 Induction linac conceptual design by Lawrence Berkeley Laboratory.[12] The "injector" consists of a 2 MV, 4 A, 40 μsec source, pulsed drift tubes to 13 MeV, and low-gradient induction cavities to the 200 MeV point as shown. Stripping from U^{+1} to U^{+4} is done at 5 MeV. Beyond that point the peak (electrical) current can be obtained from I(amperes) = 240/pulse duration in μsec. Final beam on target is 1 MJ, 160 TW, 2 cm-mrad.

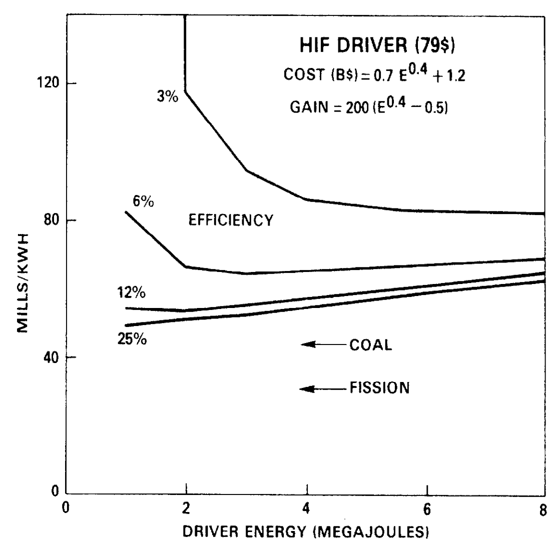

Fig. 5 Preliminary calculation of electricity cost for a 1 GW (electric) plant employing a heavy ion driver, based on a model due to Herrmannsfeldt.[13] In this model the driver efficiency and pulse beam energy are independent variables, while the repetition rate is a free parameter.