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THE NEW HEAVY ION FUSION ACCELERATOR RESEARCH PROGRAM*

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Abstract

This paper will briefly summarize the concepts of Heavy Ion Fusion (HIF), especially those aspects that are important to its potential for generating electrical power. It will also note highlights of the various HIF programs throughout the world. Especially significant is that the US Department of Energy (DOE) plans a program, beginning in 1984, aimed at determining the feasibility of using heavy ion accelerators as drivers for Inertial Confinement Fusion (ICF). The new program concentrates on the aspects of accelerator design that are important to ICF, and for this reason is called HIF Accelerator Research.

Introduction

Among the attractions of Heavy Ion Fusion (HIF) are:

1. The extensive world-wide experience with building and using large charged-particle accelerators.
2. The physical separation between the accelerator and the target chamber which simplifies the engineering (as compared, for example, to magnetic fusion).
3. The possibility of achieving reasonable electrical efficiency from the accelerator system. This is a necessary condition for economic power generation that is not achieved by any laser system that is known to have the other requirements of repetition rate, high pulse energy, wavelength, etc.

The first workshop for accelerators for Inertial Confinement Fusion (ICF) was held at the Claremont Hotel in Oakland/Berkeley.[1] There have been four workshops since then; at Brookhaven in 1977, at Argonne in 1978, at the Claremont Hotel again in 1979, and most recently in 1982, at the Gesellschaft fur Schwerionenforschung (GSI).[2] Happily, the next symposium in this series will be hosted by our program chairman for this meeting, Professor Hirao, and will be held at the Institute for Nuclear Studies in Tokyo next January.

In this paper, I will try to give a general introduction to the field of Heavy Ion Fusion. The arguments in favor of HIF are quite persuasive. For example, from the utility viewpoint, it is obviously desirable to make an early model of a fusion power plant as small as is practical. Consider the minimum fusion yield necessary to make a power plant that could be economically feasible. The requirement for economic feasibility is essentially that the recirculating power supplied to the driver be less than about 30% of the total generated power. Assuming a thermal-to-electric conversion efficiency of 33%, this requires a product of driver electrical efficiency times target gain of ten or greater. Figure 1 shows fusion yield as a function of driver energy according to published gain curves.[3] The threshold for economic operation is shown for driver efficiencies of 5% and 25%, which are typical for lasers (e.g. KrF) and accelerators, respectively. The advantage of the higher efficiency expected from a heavy ion accelerator results in;

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1. The ability to employ the simpler, single shell targets.
2. Driver energy a factor of about two smaller.
3. Fusion yield per shot an order of magnitude less.
4. A factor of conservatism that leaves a margin for the uncertainties in target and driver performance.

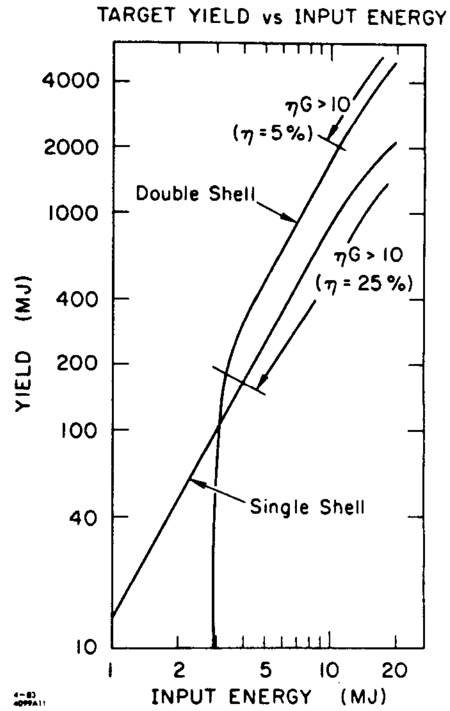


Fig. 1. Pellet yields are plotted according to published gain curves.[3] The range for each curve for which the condition for economic fusion power is valid (driver efficiency times target gain > 10) is indicated.

A demonstration reactor operating near the lower end of the economic range shown in Fig. 1, with, for example, a yield of 300 MJ and a pulse rate of 1 pps, could generate about 100 MWe of power. Assuming a 25% efficient accelerator and 5 MJ of beam power per pulse, this power plant would have a net output of about 80 MWe. Considering the capital cost of the facility, especially for the accelerator, this is too small an electrical output to be economically attractive. However, because the accelerator should be capable of a much higher repetition rate, the full capacity of such a facility would be much greater. A combination of higher repetition rate reactor chambers and/or several chambers operating from one accelerator, would result in net power produced in the range of 2-3 GWe.

Of course, it would not be necessary to start with a multi-megajoule accelerator facility. A 1 MJ accelerator should be able to implode targets to yield breakeven, or slightly better, and could be used as a driver for a "target development facility."

Ion Beam Requirements

Heavy ions were a late entry in the driver technology race; lasers and light ion diodes were already well established. The targets that were suggested for use with heavy ion accelerators were originally adaptations from short wavelength laser targets. The result was that the predicted gain for an ion beam target was usually lower than that for a laser target at the same input energy. Bangerter[3] showed how this gap has been partially bridged. With the proper, rather stringent, beam conditions, gain curves for heavy ion targets are about the same as for the "best estimate" laser targets. By "best estimate," the designers mean that the design code is being run in two dimensions, (2-D instead of 1-D), and imperfections in fabrication and beam uniformity are included. The beam conditions that are of special significance are the ion mass and kinetic energy (which must be chosen so that the ions stop in the pellet), the target size, and the peak beam power. Usually the pulse length will be longer than the ratio of total energy to peak power because of the need for some pulse shaping: it is desirable to begin imploding the target at a lower power level and then to apply the peak power near the end of the pulse. A significant number of final transport lines, typically 16-24 lines, are needed to conduct the required current to the target chamber. Usually this number of beams is more than adequate to meet the requirement for symmetry of illumination at the target.

Table 1. Typical Beam Parameters

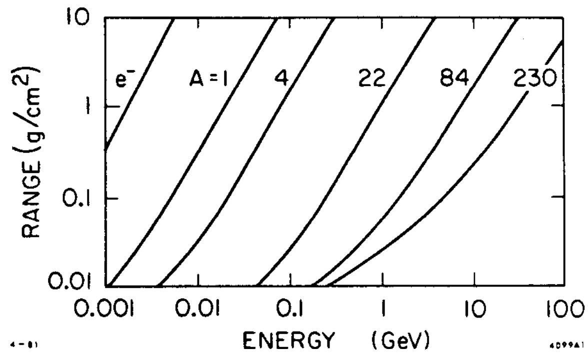
Kinetic Energy	10	GeV
Beam Energy	4	MJ
Peak Beam Power	200	TW
Pulse Length	40	ns
Beam Spot Radius	2-3	mm
Number of Beams	$\sim$ 20	
Peak Particle Current per beam	$\sim$ 1	kA
Emittance (10 cm radius lens, 10 m away)	20	mm-mrad

Let us examine a typical set of beam parameters as shown in Table 1. The range-energy curves for ions stopping in hot, high-Z material are shown in Fig. 2. These curves do not depend strongly on the target temperature or on the target material, (up to a factor of two shorter for a low-Z target). However, as can be seen, there is a strong dependence on the atomic number of the incoming ion beam. The advantage of heavy ions is in the much lower current that it is necessary to transport to the target at high kinetic energy. At 10 GeV and above, where the incoming ions are highly stripped, this advantage results in a need for a factor of 1000 times lower peak current for the heaviest ions compared to proton beams.

Calculations show that a specific energy deposition of about 20 MJ/g is needed for the target implosion. The mass in which the beam is deposited is $4\pi r^2 R$, where r is target shell radius and R is ion range. The specific energy requirement can be met for a target of about 4 mm radius with a 4 MJ beam. The beam spot radius could be 2 or 3 mm for a 4 mm radius target.

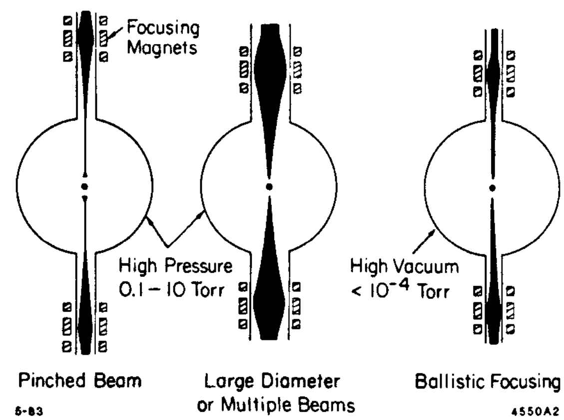
The pulse length can be found from the requirement that the implosion velocity must be of the order of 3×10^7 cm/s, i.e., corresponding to the energy needed to create a fully degenerate plasma. For a target a few millimeters in radius, the implosion time is limited to a few tens of nanoseconds. A larger target, which permits a longer pulse and lower beam power, has a drawback of requiring more energy because of the higher mass. The larger target also has tighter requirements on surface finish, illumination uniformity, and hydrodynamic instabilities; all factors that can affect the yield of the target. It is reasonable to hope that continued development of targets for ion beams will both improve the target performance and reduce the difficulty of the specifications for the accelerator system. It would be especially beneficial if the peak power requirement were relaxed.

Fig. 2. Range as a function of kinetic energy for a high-Z target at a temperature of about 200 eV and density of about 2 g/cm^2.



The emittance requirement is determined by characteristics of the final transport system to the target. It depends on the number of beamlines, the design of the final focusing lenses, and the distance to be covered to the target. Assuming ballistic focusing from a final lens with 10 cm aperture, 10 m from the target, the emittance shown in Table 1 results in a 2 mm spot if space charge is neglected. Because the current is not constant during the pulse, and especially because of the initial transient, it is important to design the transport system with a large enough angle of convergence so that the perturbing effect of space charge is small and is confined to the last few centimeters of travel to the target. Experience shows that the ion beam is certain to be at least partially neutralized by electrons that come from the residual gas or that are deliberately injected to aid neutralization. Several different transport schemes have been considered depending on variations in reactor design and the first-wall protection scheme. Some final transport modes are illustrated in Fig. 3.

Fig. 3. The transport schemes shown are appropriate for reactors with different residual pressures. With adequate vacuum, the ballistic focusing concept is the "classical" approach. A single, large diameter beam probably would not be feasible at high pressure because of the lack of good vacuum in the final lens area, but it could work if a cluster of beamlets were used with an aperture plate to give adequate differential pumping. The self-pinched concept is attractive because it requires smaller penetrations through the reactor side wall.



Accelerator Technology for HIF

Even though the field of HIF was originated by accelerator physicists from the field of high energy physics, the accelerator technology needed is very different from that used in any existing research accelerator. Especially significant when one considers the cost of an accelerator, or any other ICF driver, is the total amount of beam power needed for a power plant. A 4 MJ beam pulse at 30 pps would have an impressive 120 MW of beam power; this is about 150 times that possible with the SLAC electron linac running at 360 pps.

The two principal accelerator technologies for HIF are illustrated in Fig. 4. They are:

1. The radio-frequency (rf) linear accelerator (which supplies the energy to the system), injecting into a system of storage rings which perform the function of current multiplication, and

2. The linear induction accelerator (LIA) which performs the dual functions of energy gain and current multiplication in the same structure.

Both types of accelerator systems can inject multiple beams into one of the final transport systems illustrated in Fig. 3. They can both use ramped pulses in linear induction modules at the beginning of the final transport line to perform a final longitudinal compression of the beams. For storage ring multipliers, this final compression can be started in the rings if the beam is then quickly extracted.

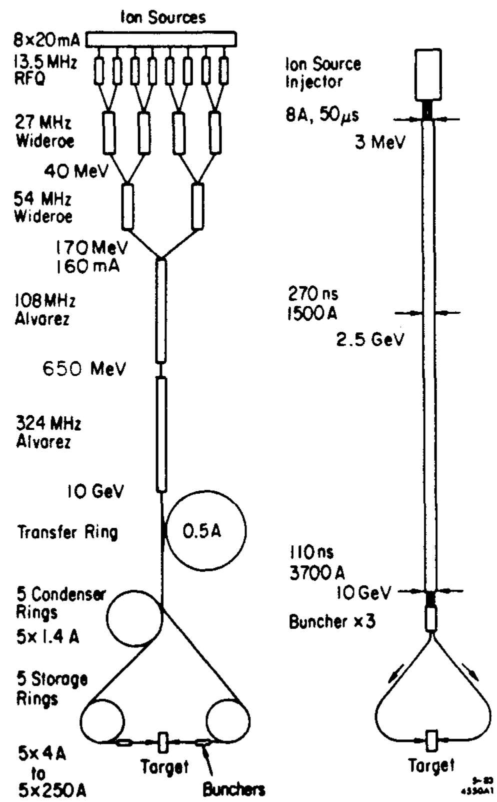


Fig. 4. On the left is shown the rf linac injecting into a system of charge-accumulating which are used to multiply the linac current. On the right is an illustration of the single-pass linear induction accelerator which uses multiple beams and longitudinal bunching to increase the current.

The degree to which these two accelerator types have different technologies can be judged by comparing the requirements on corresponding elements. The ion sources both must be high current, high brightness (low emittance) sources, but with substantial differences. For the rf linac, a long pulse ($\sim$ 1 ms) at 100-1000 mA is needed. Usually this requirement is met by some type of multi-aperture gas discharge source. The first stage of acceleration for rf linacs has traditionally been a high-voltage generator. Recently, the radio-frequency quadrupole (RFQ) has been studied for this application because of its combined acceleration and focusing, including longitudinal focusing (bunching). For heavy-ions, it is impossible to achieve the required high currents from a single ion source and injection accelerator. As shown in Fig. 4, a number of ion sources and injectors are placed in parallel in a linac "tree."

For the LIA, it is also necessary to split the injector into a number of parallel, lower current beams. The ion source requirement is for high current, low emittance, short pulses (a few microseconds), and is best achieved with a conventional Peirce diode with a fixed thermionic emitter. Such devices have been under development for some time at the Lawrence Berkeley Laboratory (LBL). The first stage of acceleration for the LIA is made difficult because of the need for relatively long pulses which results in a low energy gain per unit length. With careful attention to pulse shape and jitter, it is possible to compress the pulse in the LIA longitudinally so that the current increases faster than v/c and the pulse time is significantly shortened. Since the LIA is more efficient for short, high current pulses, this approach becomes more economic at higher kinetic energies.

For both types of accelerators, the current is limited by the transverse space charge forces. For periodic focusing (quadrupoles), the focusing strength is limited by a requirement that the zero current single particle motion (which is the sort of motion that will occur at the ends of the pulse) should not encounter a resonance, or stop band, in the focusing system. As space charge is added, the phase advance per period is depressed toward zero. If an instability occurs at a lower current, then the growth rate and type of instability needs to be known to design a HIF driver. Space charge limited transport has been studied theoretically since the first HIF workshop, but only recently have experimental results become available. Some of these results will be noted in the next section.

For either approach, it is the linac that puts the kinetic energy into the ion beam. In some recent scenarios for the the rf linac, currents are required to be very high so as to avoid complications in the storage rings. One should note carefully the implications of accelerating 0.5-1.0 A to 10 GeV; this requires 5 to 10 GW of rf power into the beam. The cost of such a system could be prohibitive even for a low duty cycle accelerator. Interestingly, a very good case can be made that future accelerators for High Energy Physics will also need very large amounts of rf power; perhaps the mutual interests of these two research areas will continue in the future.

The storage ring accumulators for the rf linac approach are specialty devices that do not have corresponding components in the LIA. They require debunching of the rf structure of the pulse, multiple turn storage, and then rebunching in the storage rings. The current that can be stored in this way is limited by the transverse space charge forces in the same way as in a linear transport system, but by a more stringent requirement, known as the Laslett tune shift, that measures the tune depression due to space charge for an entire turn around the ring. If a safe limit for this tune shift is exceeded, then for long storage times, instabilities can cause the emittance of the stored beam to grow. Other sources of emittance dilution in storage rings are the debunching and rebunching, scattering from residual gas and from ion-ion interaction in the stored beam, and from the extra phase space needed for multiple turn injection. For both approaches, the crucial factor is the final emittance of the beam in six-dimensional phase space. If the emittance is too large, the efficiency of the system will be compromised by a low percentage of beam actually reaching the target pellet. A final transport system designed to accommodate large emittance beams must have very large aperture magnets that are both very expensive and are prone to introduce aberrations that place upper limits on their ability to focus the beam to the target pellet.

The International HIF Community

During the last few years, world interest in HIF has grown in spite of budget difficulties and shrinking programs in the US National Laboratories. The following is not presented as a comprehensive review of all HIF activity, but it does show that there is significant international interest in HIF.

The West German program, with help from the University of Wisconsin, produced the HIBALL[4] report which is the best self-consistent fusion power park scenario yet written for inertial fusion. The innovative reactor system for HIBALL (the acronym stands for Heavy Ion Beams and Lithium Lead) uses woven tubes of silicon carbide to conduct streams of lithium lead, thus providing thin films of the liquid to absorb the products of the microexplosion that would damage a solid first wall of a reactor chamber. The reactor chamber for HIBALL is illustrated in Fig. 5. By inhibiting the flow, as compared to a free fall or pressurized spray, the use of the silicon carbide tubes greatly reduces the energy needed to pump the heavy material. One advantage of lithium-lead is the much lower vapor pressure which eliminates problems caused by poor vacuum in the final transport of the ion beams to the target pellet. A second advantage is its greater safety compared to pure lithium in the event of a catastrophic leak.[5]

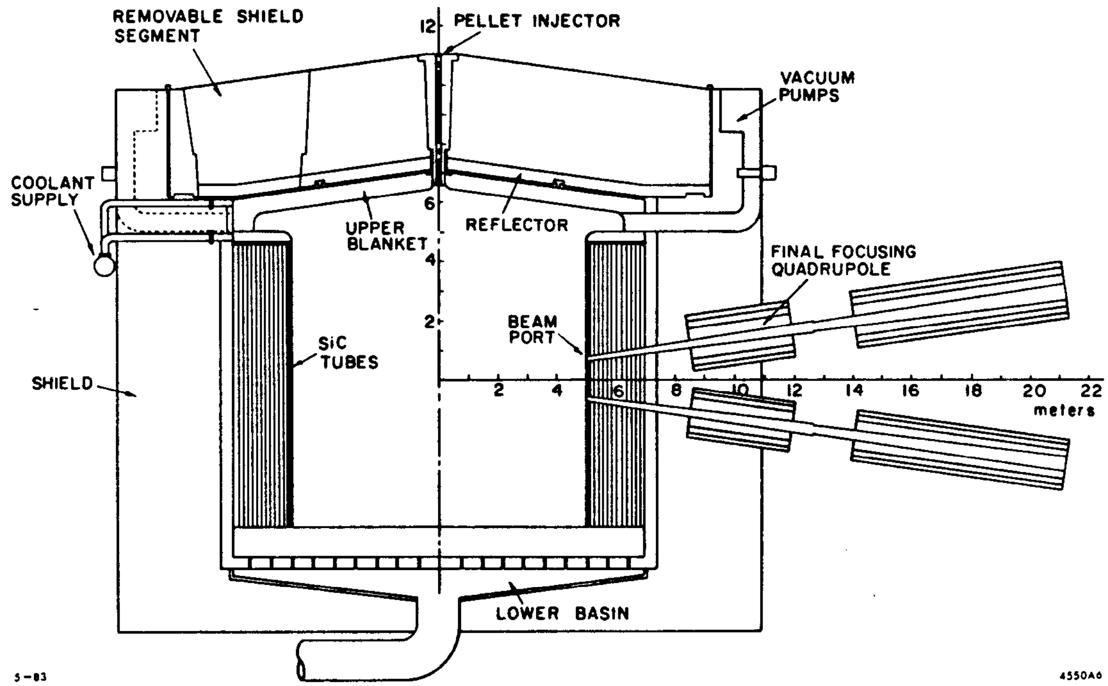


Fig. 5. The reactor chamber for the HIBALL reactor uses SiC tubes to conduct liquid lithium-lead down along the walls of the chamber. This scheme protects the the walls of the chamber and results in a low vapor pressure for the final beam transport to the target.

The heavy ion accelerator for HIBALL was originally based on a rf linac for $Bi+2$. The doubly charged ion makes it possible to achieve 10 GeV with a less expensive linac than would be required for singly charged ions. The HIBALL accelerator system was studied at the most recent HIF workshop at GSI.[2] The general conclusion of the workshop was that the storage rings for HIBALL were required to store currents in excess of expected limits. The designers had previously identified some problems with the final focus system. Since the workshop, they have modified the accelerator system to use singly charged ions, thus improving both the final transport efficiency and reducing the requirements on the storage rings. The redesigned system would cost significantly more, but could be used to run four or more reactor chambers. Thus the cost of the driver system (reported to be around $ 3 billion) would be about one-third or less of the total cost of the power park of capacity 4 GWe or more.

The heavy ion beam currents that must be contained in the HIBALL storage rings are expected to be significantly above the threshold for longitudinal instability. Generally, in order that the estimated cost of a power plant system should not be excessive, all heavy ion storage ring scenarios have been designed to push the stability limits. A major issue, therefore, is whether the growth rate of the instability is small enough to avoid significant loss of beam quality during the time that the current must be stored. The first machine which could test the relevant instability threshold and growth rate in the parameter space needed for HIF is the Spallation Neutron Source (SNS) under construction at Rutherford Appleton Laboratory (RAL) in Great Britain.[6]

The transverse stability limits for the beam current in a linear transport system are also important to the economics of HIF, especially for the induction linac which should be designed as nearly as practical to the space charge limit throughout its length. This problem has been studied analytically and numerically for several years and, most recently, experimental efforts have been started at several laboratories. Early experimental results from Maschke,[7] from the Univ. of Maryland-RAL collaboration,[8] from Klabunde et al., at GSI,[9] and from the work at LBL,[10] all seem to confirm numerical studies predicting that such instabilities as do occur will not grow in a way that reduces beam brightness.

As was pointed out above, the linear induction method has only recently been used for accelerating unneutralized ion beams. One of the first tests of such an application was reported from Japan at Nagoya University.[11] The group at LBL has also begun beam tests accelerating $Cs+$ in a long-pulse induction module.[12] Previously, in the US, induction linacs have been proposed for accelerating neutralized ion beams for ICF. Tests have been reported by Humphries[13] (in a program that was funded for HIF but was a casualty of the budget cuts) and by Nation's group at Cornell University.[14]

The Electric Power Research Institute, which obtains its funding from the utility industry, has sponsored a number of studies in inertial fusion related topics. One of these is the Technical Risk Assessment of Inertial Fusion performed under contract with TRW, Inc. This study uses interviews with scientists to identify critical problems and then uses this information to develop an R & D plan leading to a demonstration power plant by the year 2010. Another EPRI contract[15] has studied the use of "advanced" fuels, specifically D-D, with a small tritium fraction, which eliminates the need for a thick lithium blanket to breed tritium. Because of the energy demands and lower yields of D-D targets, this approach requires the efficiency and economy-of-scale possible with heavy ion accelerator drivers.

The US Energy Research Plan

The Los Alamos National Laboratory has the role of "lead laboratory" for HIF. Funding for the Los Alamos ICF program has always come from the Office of Inertial Fusion (OIF) in the Defense Programs (DP) part of the USDOE. Heavy Ion Fusion is viewed as an energy strategy, not essential to the mission of DP, and thus funding has been greatly inhibited. By agreement between officers of the DOE at the Assistant Secretary level, a transfer of the HIF program to the Office of Energy Research (ER) was arranged, effective in October 1983.

The new objective was to establish a base of experience with high-brightness, high-current, heavy-ion accelerators that could be used to evaluate this technology for application for an ICF driver for civilian power. With help from contributions from other laboratories, Bangerter (LANL) compiled a draft program plan described in "Accelerator Inertial Fusion – A National Plan for the Development of Heavy-Ion Accelerators for Fusion Power."[16]

The National Plan calls for a two-stage program in which Stage I would use three years to do the necessary R & D to design a suitable test accelerator. Stage II would be to build the test accelerator and to perform a "High Temperature Experiment" (HTE). The National Plan acknowledges that it is impractical to expect to obtain funding to pursue both the induction linac and the rf linac/storage ring technologies. Thus, the Plan calls for concentration on one approach, the induction linac, while maintaining a small effort, mostly to observe developments from other programs, in the rf linac/storage ring method. Some of the justification for this choice lies in a technical argument; that the number of beam manipulations is less for the induction linac, resulting in a greater likelihood of preserving the necessary beam quality. Another argument stresses the eventual cost of an accelerator for a power plant which is generally predicted to be somewhat lower for conceptual designs using the the induction linac approach. It is likely that innovative developments will further reduce the cost of the induction linac system. This potential is documented in a report from LBL[17] in which a list of cost-cutting developments is given.

As this was written, the choice of technology had not been made, but realistically it would require a major program reversal to switch back to the rf linac system. The decision, which should be made soon, could still be reversed before the Stage II construction phase starts. The fact that the European HIF research is oriented toward the rf linac method effectively amounts to a program which is complementary to the induction linac program in the US.

Stage II of the National Plan calls for the construction of an accelerator facility which would be used to demonstrate the accelerator concepts needed for a full scale fusion driver. The facility has been named the "High Temperature Experiment" because it could be used to heat a small target or foil to temperatures in the range of 50-100 eV. It is important to recognize that the HTE is an accelerator demonstration project, and that achieving some tens of electron volts by around 1988-89 is not expected to provide especially new information for the physics of solid density plasmas. The importance will be in demonstrating that the intense heavy ion beam can be produced and focused in such a way as to reach significant temperatures. The high temperature is, in other words, primarily a beam diagnostic.

The one piece of high temperature physics that should be accomplished by the HTE is the experimental confirmation of the beam-target interaction. Due primarily to the surprisingly complex target interaction physics that was uncovered by the high-power laser experiments, there has always been some concern that the ion beam deposition physics may conceal some nasty surprises. For example, one worries about processes that could preheat a target pellet before the compression occurs. Among the possible causes of preheat that have been studied are fission fragments, knock-on electrons, various plasma instabilities in the target, etc. Preliminary results from light-ion experiments confirm predictions of some range shortening in hot matter. Range shortening is generally helpful, but it is not obvious that this effect will be great enough to improve target performance significantly.

As part of the preparation for the transfer of the HIF program to Energy Research, the DOE arranged for a special review of the physics issues of ICF that are peculiar to heavy ions. The final report[18] was generally very favorable with conclusions that contained the especially significant statements that "..the uncertainties in coupling physics for high energy heavy ions are minimal," and "The proposed National Plan for HIF seems to be a sensible and minimal next step in HIF." The report of this review does not contain a great deal of technical information; more details can be found in a recent review article by Bangerter.[19]

The Heavy Ion Fusion Staff at LBL has prepared a plan[20] to develop the Induction Linac to meet the requirements of the National Plan. They propose a multiple beamlet structure to accelerate sodium or potassium ions to around 100 MeV for the HTE. The lighter ions are chosen because the target physics of a full scale reactor is simulated better with ions of similar velocity than by just having ions of similar atomic mass. Stripping, focusing and energy deposition are all better studied under conditions of similar velocity. Also, for the HTE it is necessary to get high instantaneous power, which is very difficult if the ions move too slowly. In anticipation of a much stronger program beginning with the new Energy Research budget, the LBL group has three major thrusts underway:

1. Conceptual design work for the HTE.
2. An experimental test of current transport limits.[10]
3. The development of induction linac modules for heavy ions.[12]

Conclusion

In conclusion, it is now possible to say that heavy ions are being accelerated, that high current beams are being transported, and that there is a DOE program to evaluate the feasibility of using heavy-ion accelerators for the civilian energy application of ICF. It seems to me that HIF has turned an important corner and is starting to study the critical issues in a program that can lead to a new energy option.

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