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THE USE OF HEAVY IONS FOR INERTIAL CONFINEMENT FUSION

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THE USE OF HEAVY IONS FOR INERTIAL CONFINEMENT FUSION*

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Programs are underway at Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley Laboratory to develop the application of high energy heavy ions to inertial confinement fusion. Experimental programs are in progress at each of the laboratories as well as conceptual designs of accelerator systems as drivers of large power plants with pellet fusion as the heat source. The requirements for these drivers are stated as a total energy of 1 MJ at a peak power of 100 TW in a shaped pulse with a repetition rate $\gtrsim$ 1 Hz and an energy deposition rate of 20 MJ/g of target material. To date, Argonne has concentrated on accelerator systems which utilize rapid cycling synchrotrons with storage rings, Brookhaven and Argonne have designed systems with conventional rf linacs and storage rings, and Berkeley has developed the design for linear induction accelerators. These conceptual designs for accelerator systems were reviewed in a workshop, the third in an annual series, held at Argonne in September 1978. It is the stated plan of the U.S. Department of Energy to support construction of a Heavy Ion Demonstration Experiment (HIDE) beginning in October 1981. This facility is to be some part of the accelerator configuration represented by one of the conceptual power plant driver designs with the primary goal being to demonstrate the credibility of the entire driver design. This report will review these conceptual designs as well as indicate the status of the experimental programs.

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Introduction

The use of high energy heavy ions as the ignition source for the fusion reaction in small pellets[1] appears most promising. This promise results from the direct application of the existing mature technology of high energy accelerators. Existing machines have demonstrated (with protons) accumulation of adequate total beam energy, repetition rates of 30 Hz or more, a reliability in excess of 90% over long periods of time, transport of beams over long distances, and focussing on millimeter targets. Efficiencies of linacs of 40-50% appear straightforward, and coupling of ion energy into the pellet appears to be classical and highly advantageous compared to that of other forms of energy. Competing ignition sources for pellet fusion (lasers, e beams, light ions) have some of these characteristics; none presently have all of the required characteristics suitable for producing useful energy from inertial confinement fusion. The adaption of the high energy accelerator technology to intense beams of heavy ions appears only to involve engineering problems and not any fundamental issues. Thus the expectation for success in the high energy accelerator field seems particularly high.

These ideas were examined by accelerator and pellet physicists in a summer study in 1976[2] in Oakland, California. The results were positive and led to initial substantial funding of three accelerator laboratories in April 1977.

At a second workshop in October 1977 at Brookhaven National Laboratory,[3] the requirements for a first demonstration experiment (HIDE) were discussed. This was to be a heavy ion facility of approximately 100 kJ beam energy, which would demonstrate all the accelerator technology involved in a full scale facility capable of driving a fusion power plant.

It thus became a leading question as to an optimum driver configuration and even what were to be the criteria to optimize; was it cost, performance, or credibility? It is at the same time one of the strengths of the program and a problem: that so many choices of ions, charge states, configurations, and accelerator parameters exist which can meet the requirements conceptually.

A third in the annual series of workshops on heavy ion fusion was held at Argonne National Laboratory on September 19-26, 1978. The goals of the workshop were to provide a preliminary review of accelerator design concepts submitted by the laboratories active in this program, to disseminate status reports on progress in the R&D program and related studies, and to broaden the awareness of this program to university and industrial participants. Accelerator design concepts were submitted by Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley Laboratory. Status reports were also presented by each of these laboratories and will be summarized here.

None of the accelerator laboratories view the accelerator designs presented as a final solution. They were presented in the spirit of requiring a specific design in order to get specific comments from the accelerator community. While they are surely not optimized, the designs, perhaps modified, will now permit examination in detail of individual components for feasibility, practicality, and cost. From this study and the parallel experimental program should emerge a more clear idea of an appropriate first demonstration facility.

Accelerator Design Concepts for Heavy Ion Fusion

Brookhaven National Laboratory has presented an accelerator design utilizing a conventional rf linac with eight accumulator rings to store 10 MJ of beam energy.[4] The beam would be delivered in two clusters of four beams each to a 3 mm diameter target in 50 nsec for a peak beam power of 200 TW. The system would use U^{+2} ions accelerated to 20 GeV and would have a capability of operating at 15 Hz.

Components in the design are shown schematically in Fig. 1. Eight sources of 40 mA of U^{+1} are utilized. Each is to be accelerated through a preaccelerator to 500 kV followed by a 2 MHz Wideroe to reach 6 MeV. An output current of 20 mA from each unit is anticipated. The ions would be stripped at this stage to U^{+2} with 50% efficiency, thus preserving the electrical current and pairs of beams combined into 4 MHz Wideroe linacs. Combination of pairs of beams is continued into 8 MHz Wideroe linacs and finally into a 48 MHz Alvarez linac. Further frequency transitions take place in Alvarez linacs to 96 MHz and 192 MHz with the bulk of the acceleration to 20 GeV occurring in the latter. At this point, the current would be 160 mAe in bunches at a 16 MHz rate (1 bucket in 12 of the 192 MHz linac containing beam). The beam is then injected into a large radius multiplier ring with 10 turn injection to give 1.6 A circulating. Upon extraction, the horizontal and vertical planes are interchanged to allow 10 turn horizontal injection into a second multiplier ring of 1/10 the radius of the first for a final circulating current of 16 A. The process is repeated eight times to accumulate 10 MJ of beam energy. Compression to the final bunch length is begun in the accumulator rings and completed in the transport line to the target. The accumulator rings are arranged in two clusters so that two clusters of four beams each are transported.

Argonne National Laboratory has presented two accelerator systems. HEARTHFIRE Reference Concept No. 2 is a conventional rf linac system with accumulator rings.[5] Hg^{+8} ions would be accelerated to 20 GeV to store 1 MJ of beam energy in 18 rings arranged in two clusters of 9 rings each. Eighteen beams would be transported to the target with a final bunch length of 6 nsec to give a peak power of 160 TW. Two sources of 50 mA of Hg^{+1} would be employed with acceleration to 1.5 MeV in modified Dynamitrons. First and second harmonic bunchers would give 80% capture in 12.5 MHz linac structures to provide 40 mA of beam current in each. The ions would be stripped to charge +8 at an appropriate energy between 10 and 20 MeV with an assumed particle efficiency of 20%. The electrical current would then have been increased to 64 mA and the two beams combined into a single Wideroe linac at 25 MHz with 128 mA of average current. Transitions to Alvarez linacs at higher frequencies would follow with acceleration to 20 GeV. At this point, strong debunching of the beam is required to preserve the longitudinal emittance of the beam. Current multiplication would then be accomplished through a series of delay stacking bypasses and rings to combine beams in the transverse plane, four at a time, using thin septum magnets. A transmission efficiency of 93% with emittance dilution of 1.45 at each combination is assumed. A total of four such manipulations is contemplated, two in each transverse plane, to give a current multiplication of 256. Coupled with an overall efficiency of 75%, this process would result in an average beam current of 24 A for injection into each of the accumulator rings. At this point, the 25 MHz bunch structure of the linac would have been preserved so that the beam would require adiabatic debunching and rebunching to a single bunch in the accumulator rings. Longitudinal compression by a factor of 74 would be accomplished by linear induction cavities external to the accumulator rings followed by 1/2 turn around another ring for transport to the target.

The synchrotron based system,[6] HEARTHFIRE Reference Concept No. 3, is shown schematically in Fig. 3. This accelerator system would accelerate Xe^{+8} to 20 GeV for storage of 1 MJ of beam energy in 16 accumulator rings. The total accumulation time is 1 sec. The choice of Xe^{+8} is related to this factor in that the ion has a closed electronic shell and the charge exchange cross section between xenon ions should then be an order of magnitude lower than for xenon ions of lower charge. Beam losses due to this effect should then be no more than 10% during this accumulation time. The system begins with two Xe^{+1} sources of about 20 mA captured with 50% efficiency in special 12.5 MHz structures followed by Wideroe linacs. Stripping to a +8 charge state is to take place with $\sim$ 20% efficiency at 11 MeV, and the two beams combined in a 25 MHz Wideroe to give 30 mAe of average beam current. Further frequency transitions take place in Alvarez linacs to produce 30 mAe of Xe^{+8} at 4.4 GeV with a bunch structure of 25 MHz. Debunching by a factor of 16 is required to preserve the longitudinal emittance and produce the required 0.075 bunching factor in the rapid cycling synchrotron. Nine turn injection is proposed. Both transverse planes are to be filled equally with considerable emittance dilution allowed in order that the space charge limit of the synchrotrons be as high as possible. The beam is accelerated to 20 GeV and transferred to a rebuncher ring. Since at this point the 25 MHz bunch structure has been preserved, the beam must be adiabatically debunched and rebunched to a harmonic number of two after two synchrotron pulses are injected synchronously into the rebuncher ring. Sixteen pulses from the rebuncher ring are injected into the storage ring (with the horizontal and vertical phase planes interchanged in a solenoid in the transport line in order to allow horizontal injection). Of these 16 pulses, two turns are injected into the transverse plane and eight into the longitudinal plane, resulting in 16 beam bunches circulating in the storage rings, adiabatic rebunching to two bunches per ring in half the storage rings, and one bunch per ring in the other half. This procedure, with 16 storage rings, results in 24 beams transported to the target and provides some degree of pulse shaping. Thirty-two synchrotron pulses are required to fill each storage ring. At a synchrotron repetition rate of 64 pulses/sec, eight synchrotrons are required to complete the accumulation in 1 sec. Four rebuncher rings are necessary to complete the adiabatic operations in this period of time.

Lawrence Berkeley Laboratory has presented an accelerator design utilizing the linear induction accelerator.[7] This concept is shown schematically in Fig. 4. The source would be the contact ionization type producing 4 A (at 2 mA/cm^2) of U^{+1} for a duration of 40 μsec. The beam would be accelerated in a series of drift tubes to 5 MeV, at which point it would be stripped to U^{+4} with 37.5% particle efficiency resulting in an electrical current of 6 A. In addition to further acceleration in drift tubes to 200 MeV, the beam would also be compressed to a duration of 4 μsec and a current of 60 A for injection into the iron core induction cavity section. The process of current multiplication by beam compression simultaneously with acceleration is continued in the iron core induction cavities to produce an 8 GeV beam of 1200 A with 200 μsec duration. Ferrite core induction cavities then are employed to accelerate the beam to 19 GeV with a final current of 3200 A and a duration of 75 nsec. A final stage of induction cavities would be a ferrite core buncher with a gradient ± 1 MV/m. This buncher would provide the impulse to compress the beam in a relatively long drift distance to its final duration of 7 nsec and 34 kA. However, before the current has achieved this value, the beam would be split by septum magnets into 16 beams and transported to the target in two clusters of eight beams each such that the maximum current in any one beam is 2.125 kA.

Experimental Program

Preliminary experiments with an existing source and preaccelerator have been carried out at Brookhaven National Laboratory. Xenon gas was introduced into a duoplasmatron and a beam of xenon ions accelerated to 750 kV in a Cockcroft-Walton preaccelerator. Initial studies of beam neutralization, transport, and acceleration in a 16 MHz cavity containing 11 accelerating gaps have been performed. Of particular interest is the investigation of strong focussing of ion beams using a trapped electron cloud (Gabor lens).[8] Possible uses of such lenses would be in the source terminal to isolate the source from the column, in the transport line between the preaccelerator and the linac, and in the early sections of the low beta linac. In all of these regions, strong focussing is required to counteract the defocussing forces of the space charge dominated beams.

The experimental program in heavy ion fusion at Brookhaven is presently being moved into a new area with adequate space for a longer range program. Under construction is a preaccelerator for a voltage of 400-500 kV and a parallel plate transmission line to drive 2 MHz Wideroe structures. Surplus industrial transmitters are being modified to drive this linac at 2 MHz.

Argonne National Laboratory has been experimenting with a high brightness xenon source obtained from Hughes Research Laboratories, Malibu, California. The source is a Penning discharge, Pierce extraction type and delivers 2.5 mA of Xe^{+1} with 80 kV extraction. The beam has been transported with 90% efficiency over a distance of 3 m and its emittance measured to be about 1 cm mrad (0.001 cm mrad normalized). This source is then about an order of magnitude brighter than that required for the heavy ion fusion driver (although not high enough current). A scaled-up version of this source, with a single aperture of 3 cm diameter, has delivered 100 mA at a current density of 15 mA/cm^2 at Hughes. No emittance measurements have been made on this source, and it is to be delivered to Argonne in October of this year. A second version of this source is being modified to produce a mercury beam.

The modifications to a surplus Dynamitron have been completed and the Dynamitron installed and power tested at Argonne with a dummy load. The existing rf power supply will drive a continuous current of 30 mA at 1.5 MV so that this current will be the initial goal of the program with xenon ions. A column for the Dynamitron is nearing completion and will be installed in November.

Two single drift tube cavities of different types at 12.5 MHz are nearing completion. One will serve as a buncher and a second as the initial accelerating cavity. Three other cavities are on order to extend the accelerated energy.

In initial experiments, Lawrence Berkeley Laboratory has achieved a cesium beam of 400 mA at 200 kV from a contact ionization source. The time of flight was consistent with this beam being Cs^{+1}. The goal of this program is to produce 1 A of Cs^{+1} at a current density of 2 mA/cm^2 and to accelerate the beam to 2 MeV in three drift tubes as a preliminary test of drift tube accelerators as an injector for a linear induction accelerator.

Also developed at Berkeley is a multiaperture (13 apertures over 2.5 cm diameter) xenon source. Extraction is at 20 kV, and the normalized emittance measured at 1.5 m from the source with 40 mA of beam current was 0.03 cm mrad. The source was mounted in the terminal of a Cockcroft-Walton and the beam transported to the column through a pair of quadrupole triplets. A current of 60 mA at 475 kV has been attained to date. No emittance measurements have yet been made on this accelerated beam.

Discussion

The subject of transport and focussing of intense beams continues to be actively pursued. The question of instabilities leading to beam emittance growth in space charge dominated transport lines is not yet fully resolved, but analytic theory and computer simulation are tending to converge. Such instabilities could easily be avoided but would place some constraints on design of the transport line. Questions of chromatic and geometrical aberrations in the transport line and in the final focussing system, and their correction with pairs of sextupole and octupole lenses, are also receiving considerable attention.

The consensus of individual working groups of the workshop, and of a committee charged with coordinating the comments of these groups, was that encouraging progress in this program had been made in prototype R&D and in theoretical and computational studies. None of the reference designs were judged sufficiently complete to allow a detailed comparison nor do they address a common parameter regime. Furthermore, none of the designs are optimized. Differences in many aspects related more to preferences of the designers rather than to any fundamental issues. Nevertheless, some comparisons were made and some general conclusions drawn.

There was a clear consensus that at least one accelerator configuration, that of conventional rf linacs with accumulator rings, could meet the target requirements with high confidence, based on current knowledge. The linear induction accelerator remains attractive because of the simplicity of the concept. However, it could not be given high marks at this time because of the fact that acceleration of ions by linear induction accelerators has not been demonstrated. Considerable development would be required to bring this configuration to the level of credibility that presently exists with conventional linacs. Synchrotron based accelerator systems are now thought to be less promising than originally perceived. The apparent cost advantage over conventional linac systems has narrowed because of the recognition that at high $\dot{B}$ the bunching factor must be kept low to maintain a small momentum spread. Hence, the space charge limit is reduced and more synchrotrons are required. In addition, a special ion of significantly lower charge exchange cross section is required, the more difficult vacuum requirements remain at the border of technical feasibility, and the required repetition rate might press the state of the art. For these reasons, use of synchrotron based accelerator systems for heavy ions as drivers for fusion power plant applications appears significantly more difficult than systems based on acceleration in conventional linacs.

Acknowledgment

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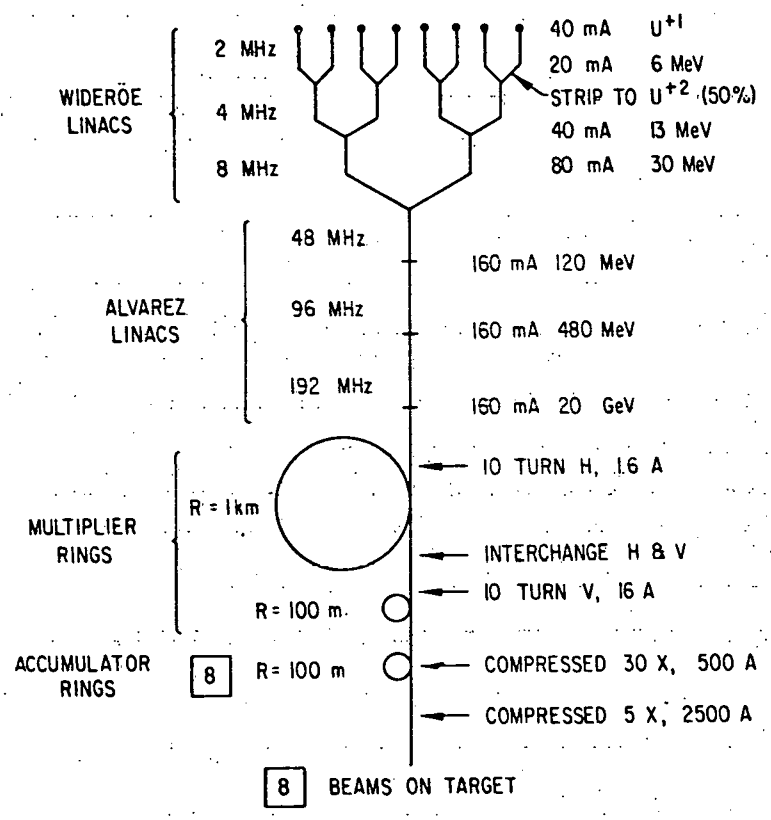

Fig. 1 BNL (10 MJ, 200 TW)

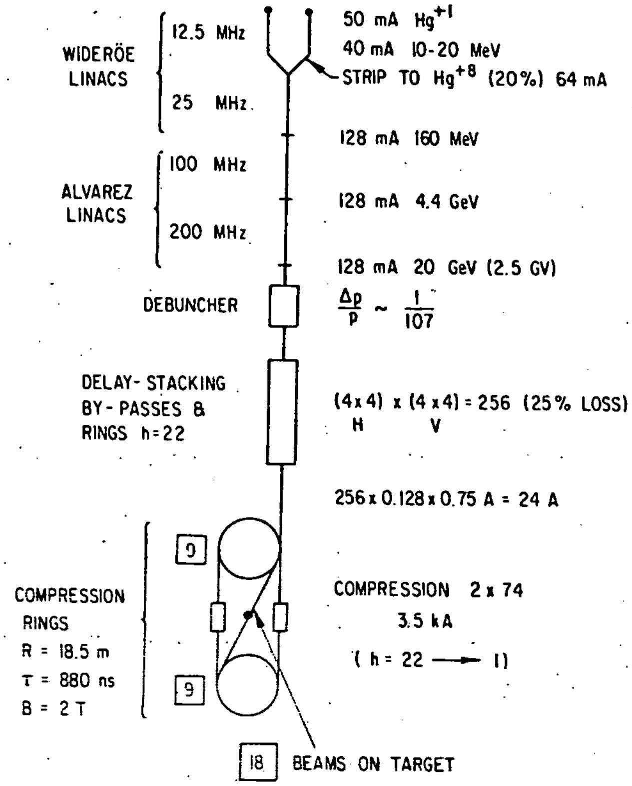

Fig. 2 ANL-HEARTHFIRE #2 (1 MJ, 160 TW)

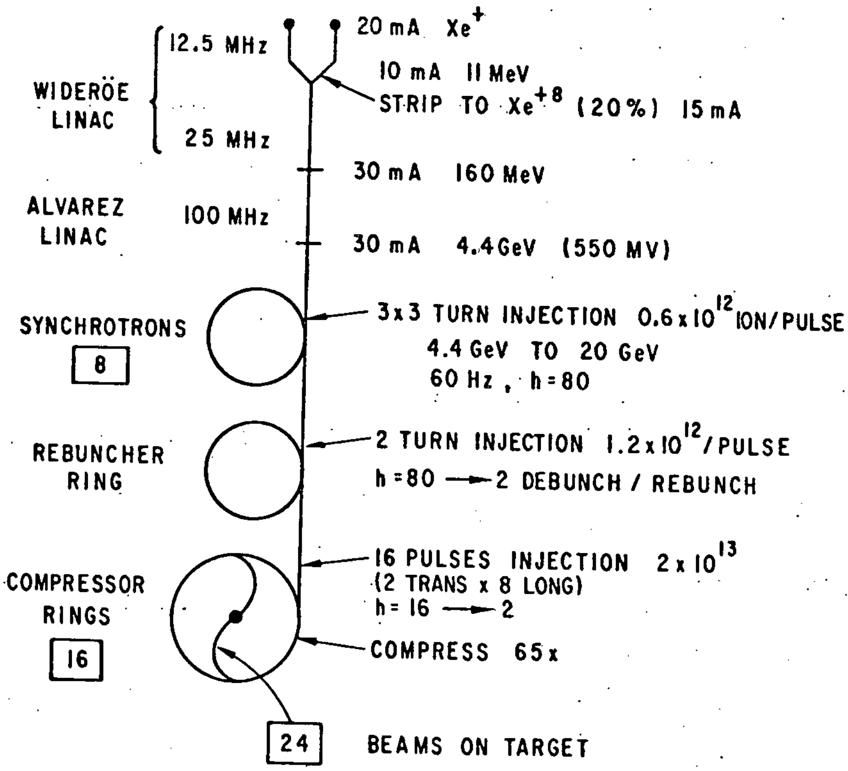

Fig. 3 ANL-HEARTHFIRE #3 (1 MJ, 160 TW)

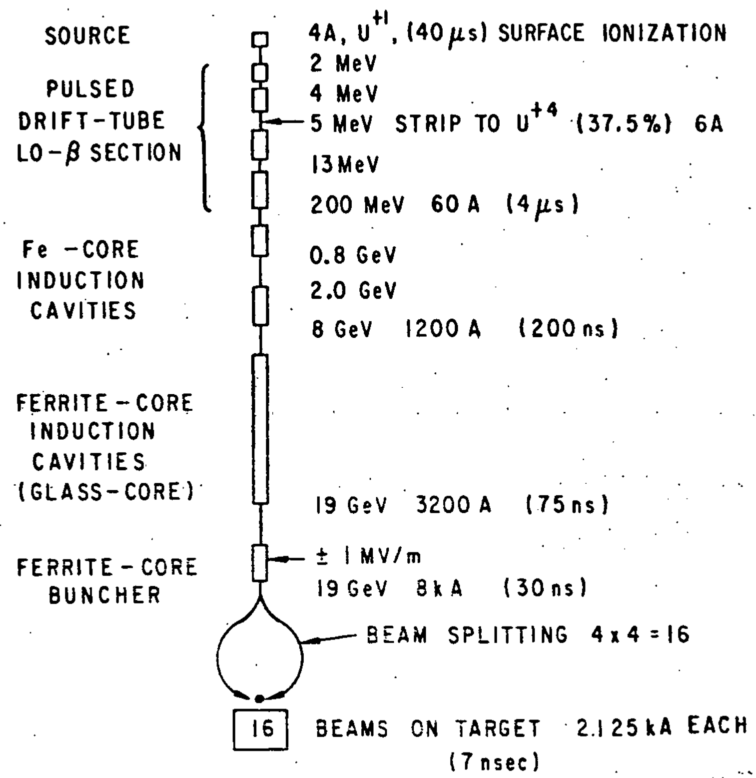

Fig. 4 LBL (1 MJ, 160 TW)