Title
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Publication Date
1981-06-01

Peer reviewed

LBL-12409

Presented at the 4th International
Topical Conference on High-Power
Electron and Ion-Beam Research and Technology,
Palaiseau, France, June 29 - July 3, 1981

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June 1981

*This work was supported by the Director, Office of Energy Research, Office of Inertial Fusion, Research Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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ABSTRACT

The initiation of inertial confinement fusion reactions with a heavy ion particle beam has been under intensive study since 1976, and the progress of this study is principally documented in the proceedings of annual workshops held by U.S. National Laboratories.[1,2,3,4] At this time a 3MJ, 150TW, ion beam is a good choice to initiate microexplosions with energy gain of 100. The Lawrence Berkeley Laboratory has made systems studies based on a Linear Induction Accelerator to meet the beam requirements. The accelerator system, expected performance and cost, and technical problems to be addressed in the near future are discussed.

INTRODUCTION AND DESIGN PROCEDURE

The accelerator system consists of an ion source, the induction linac, a final transport section, beam splitters, and a final focussing system. The beam parameters are determined jointly by the target requirements and by the final focussing and transport systems. It has been found advantageous to use a number of beamlets to irradiate the target, typically 16 or more, to decrease the emittance per beamlet and to reduce geometric aberrations in the final focussing lenses. Similarly, in the last few hundred meters of the system, it has been found advantageous of use four or more final transport lines to increase the transportable power. The computer-aided design program LIACEP has been modified to sort through the many possible options, including beam splits and combinations, to arrive at some desirable configurations.

The machine design process has been described previously[3,5]. Essentially, it consists of varying the local current at any particular location in an induction accelerator until a true cost minimum is found or some technical limit is encountered. For any trial current, the required focusing and accelerating components are calculated and costed for several physical configurations. The entire machine is the sum of all of the minimum cost designs. All ion types are assumed to be equally available, and a large variety of particles has been already systematically examined. Since the first reference designs of two years ago, the major changes in the HIF scheme have been an increase in the preferred energy on target from 1MJ to 3MJ, and the consideration of multiple beams separately focused but passing through common cores.

As yet, there is no automatic tie-in with source or target requirements within the program and these have to be inputted manually. At this time the beam parameters shown in Table 1 meet target requirements, and a satisfactory source would be one similar to the Cs^{+1} and Hg^{+1} several ampere ion sources which were developed in the 1960's for ion propulsion in space, and the 1 ampere Cs^{+1} source[6] developed for HIF experiments at LBL.

The code has been expanded to consider electric or magnetic focussing choices at any location, but for reasons to be given below the minimum cost design was not chosen for the 3MJ reference design, which is an all-magnetically focused 4-beam system, as shown in Fig. 1. (see, also, Table I)

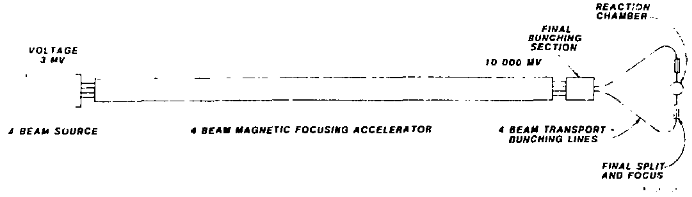

Fig. 1 4 Beam Reference Design System

TABLE I - Reference Design Parameters

Ion mass, type, and charge state	200, Hg^{+1}
Final particle energy and beamlet emittance	10 GeV, 8.3×10^{-6} m-rad
Total beam energy and power	3 MJ, 150 TW

The initial design equations and limits were partly based on the assumption that the actual accelerating modules would be similar to the modules of the previously built induction linacs for high current electron beams,[7,8,9] with the pulse duration at any location mainly determining the appearance of the module at that point, which in most previous cases has been a physically and electrically independent box with an end-to-end voltage of a few hundred kilovolts. The transport system for the ion beam is a major part of the accelerator, instead of subsidiary as in the case of electrons, and this results in the minimum cost designs having tightly packed modules with diameters, especially for multiple beam, which are several times greater than those of the corresponding electron machines and end-to-end voltages of several megavolts. The voltage and field limits which are used in the program are safe for independent modules, but the tight packing and large diameters tend towards making the modules interdependant and the initial assumptions questionable. Consequently, we have not used the minimum cost designs such as 16 parallel beamlets passing through a 1+ meter diameter aperture, and instead have chosen a 4 beam case where the aperture for the array is only half a meter; at the same time we have halved the maximum permissible insulator fields to approximately 10 kV/cm.

THE ELECTROSTATIC ARRAY OPTION

In principle, the current passing through a given aperture such as an induction core could be increased substantially by subdividing the beam into a large number of independent beamlets focused by electrostatic quadrupoles. Some of the practical problems to be solved for this approach to work are the very precise manufacturing tolerances and alignment which are necessary to make the clearances small relative to the beam dimensions, and the development of very precise beam diagnostics to detect and correct errors near their point of origin. Unlike in low current machines, where the coherent oscillation tune is constant along the bunch, the heavy ion beamlets have a large space charge tune variation along the bunch and it is not permissible to accumulate errors over a substantial distance and then correct them. With manufacturing tolerances affordable at present the apertures are significantly increased by clearance requirements, and some of the advantage of going to a very large number of beams is lost.

Another complication is due to the large ionization cross sections ($\sigma \approx 10^{-15}$ cm^2) of the heavy ions, which translate into a pressure requirement of better than 10^{-8} torr in the vacuum chamber. One solution to the problem of pumping through a maze of focusing electrodes is to provide a large central hole through the array for pumping, but this tends to negate the original goal. A related consideration is that ions hitting the chamber wall desorb an appreciable amount of gas, especially when the beam is able to heat impulsively the surface to a high enough temperature to boil off some of the adsorbed gases; in this instance a few millimeters clearance is required to keep the gas from reaching the beam.

The most serious limits to the use of large electrostatic arrays may turn out to be electrical. In order to keep the focusing voltages independent of the beam, it is necessary to supply as much current to the array as given by the difference between the beam entering and leaving it, and to do so in a nonresonant manner. This implies the use of some filtering capacitors and low inductance interconnections, with sufficient damping. As a result, a large amount of electric energy must be stored locally. The probability of a breakdown increases with the area of the array, and the stored energy required increases with the size of the array and with the beam current. When the energy in a discharge is of the order of one joule, the electrodes tend to condition towards holding higher voltages; as the energy is increased however, the sign of this effect eventually reverses. At the stored energy levels required for some of the conceptual designs - about 100 joules per meter of length-it is not obvious in which direction the array would condition.

For the various considerations discussed above, the multiple electrostatically focused beam array has not been used in this 3 MJ design, even though such an array would be several times less expensive at low energy than the magnetically focused array and would lead to almost 20% savings in the accelerator. Instead, we have relegated it to the list of developmental projects for the future which can lead to significant savings.

BEAM CONTROL

The control of the magnitude of the beam current at any point within the accelerator is accomplished by ramping of the accelerating voltages in the preceding modules. To gain a perspective of the problem, neglecting here the space charge forces, the bunch traveling through a constant average electric field structure, starting with a monoenergetic beam, would elongate as $L_f = \sqrt{V_f/V_i}\, L_i$. If, however, the beam bunch were injected in such a way that the front and back particles have the same starting velocities, then the bunch would remain at constant length throughout the machine. In the actual accelerator designs one almost never utilizes the constant electric field scenario for the following reason: the product of the electric field multiplied by the pulse duration determines the core cross-sectional area, which for the long pulse durations is proportional to the core outer radius and results in the average core volume (and losses) being proportional to the square of the pulse duration. It is more economical and efficient to use the same volume of core material by arranging it axially, thereby decreasing the acceleration rate and requiring, on the average, more focusing elements. The tradeoffs are examined computationally and result in a prescribed acceleration profile, as shown in Fig. 2a and 2b.

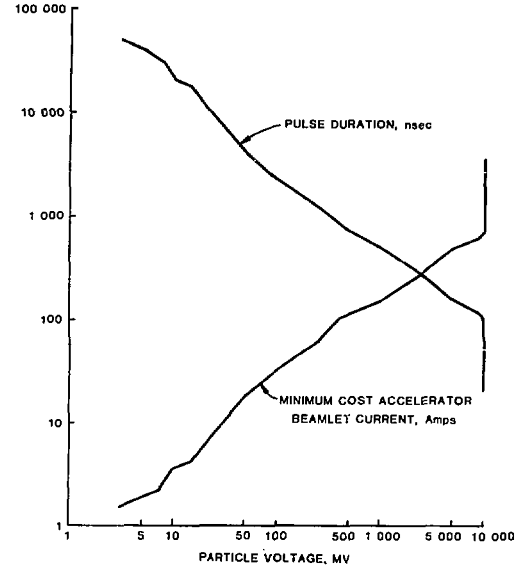

Fig. 2a ACCELERATOR BEAMLET CURRENT AND PULSE DURATION

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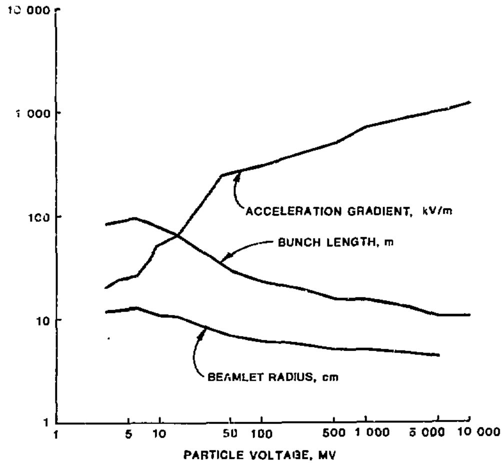

Fig. 2b ACCELERATOR BEAM RADIUS, BUNCH LENGTH AND ACCELERATION GRADIENT

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For the desired acceleration profile, the physical bunch length should decrease by a factor of seven, with most of the decrease occuring in the first 100 MeV. Through the rest of the accelerator the bunch length is about 20 meters, which may be attained by accelerating the rear of the pulse by about 20 MV more than the front. When the beam energy is high, the required energy ramps are small. At the low energy end the desired fractional energy tilt is about 30% but the usable tilt is limited by the requirement of having to keep both ends of the bunch within the stable transverse focusing limits. The acceleration recipe at the front of the machine essentially consists of waiting until the entire bunch is within the accelerator before turning on fields which in the frame of the bunch are the sum of a constant field working equally on all particles plus a linear ramp which causes a uniform compression. Because the accelerating field can be increased by an order of magnitude in the first 100 MeV, largely because of the very rapid decrease of the pulse duration at the low energy end, the actual waveforms which must be generated there are more elaborate than elsewhere in the machine. The two test beds previously proposed by LBL were largely aimed at the elucidation of the bunch control problem.[10]

Near the end of the accelerator, it is necessary to provide a tilted momentum distribution which will result in the bunch reaching its minimum duration at the final focusing magnets. There are numerous bunch shape – momentum distribution pairs which would work for final beam bunching, some of which have been examined with a 1-D computer code. The space charge forces become dominant only after acceleration and bunching have ceased, in the final transport lines to the target, where they remove the momentum tilt placed on the bunch by the bunching section. The compression of the bunch from 110 nsec at the exit of the accelerator to 20 nsec at the target requires a ± 1% momentum tilt for a final drift distance of 400 meters. The required energy tilt of ± 2% may be accumulated in the last two kilometers of the machine with a 20% tilt of the voltages.

WAVEFORM GENERATION AND ELECTRICAL CONSIDERATIONS

There are three different regimes in the accelerator regarding the required voltage waveforms and their generation. From 0–100 MeV may be regarded as the initial matching section, from 100 MeV to 8 GeV as the pure acceleration section, and the interval from 8 GeV to 10 GeV as the buncher, even though acceleration is the main function in each.

In the matching section beam loading is negligible. One solution for generating the required waveforms and fields, which vary from a few kV per meter up to 300 kV per meter and change from being s-shaped to almost flat in this interval, is to use a large number of low voltage pulsers which are independently fired, to generate a piecewise approximation to the ideal waveforms. A satisfactory pulser type for this application is a lumped element PFN switched by an ignitron and charged to 25 kV. Approximately 5000 such circuits are required for the first 100 MeV, allowing a great deal of flexibility in waveform generation; because of the large number of pulsers required, the coarseness in generating any specific waveform or the errors due to a few misfirings are acceptable.

In the accelerator section, which is the largest part of the machine, the total current is 130 amps at the entrance and 2.3 kamps at 8 GeV. In addition to compensating the space charge fields, allowance must be made for the voltages generated by the beam current in passing through the accelerating module. The module impedance as seen by the beam is well approximated by a parallel RC circuit, where the R is the combined effect of the induction core losses and PFN characteristic impedance, and the C is the equivalent capacity of the accelerating gap and module electrodes. If necessary for longitudinal stability reasons, the small signal or incremental resistance can be made much smaller than the R above, which is in the range of 100 Ω/meter. The gap capacity, C, is adjusted to allow a voltage pulse risetime of one tenth of the pulse duration. The bunch length must be decreased from 27 to 13 m in a distance of about 8 km, therefore little bunching is required. For the longer pulses lumped element PFN's are satisfactory; because the voltages in this region are essentially flat, one pulser may drive several cores in parallel within each induction module. As the pulse duration decreases and the required drive current increases, the required PFN impedance drops to the 1 Ω level, below which it is preferable to drive the modules with higher-voltage, higher-impedance devices such as water Blumleins switched by spark gaps.

The appearance of the accelerator and the pulsers in the final bunching section are identical to those in the short-pulse end of the accelerating section with the exception that the voltage pulses would be ramped about 20 through a combination of tapering the Blumlein impedance and using a compensation circuit at the module terminals.

CONCLUSION

The reference design described has a total estimated cost of close to $\$10^9$. There are obvious steps which may be taken to reduce this cost, and futher parameter optimizations such as those shown in Fig 3 will lead to substantial savings. Obviously, all such avenues would be explored before a machine of even $\$10^8$ would be constructed. Some of the calculable savings which have been examined are listed in Table II, along with others for which no quantitative amount can be assigned. It is likely that a concerted developmental effort aimed at the high payoff areas would reduce the risks associated with the higher risk options, and would eventually yield a $\$5\times10^8$ machine. Intermediate experimental accelerators at the $\$5\times10^7$ level would answer many of the physics and engineering questions and serve as prototypes for the future.

The present experimental program has been running at less than a $\$10^6$ level, and has demonstrated that a high voltage ion source for heavy ions with acceptably low emittance for currents in the ampere region is attainable. This was one of the major uncertainties at the start of the HIF program. The experiments in progress now will check the theoretical transport limits.

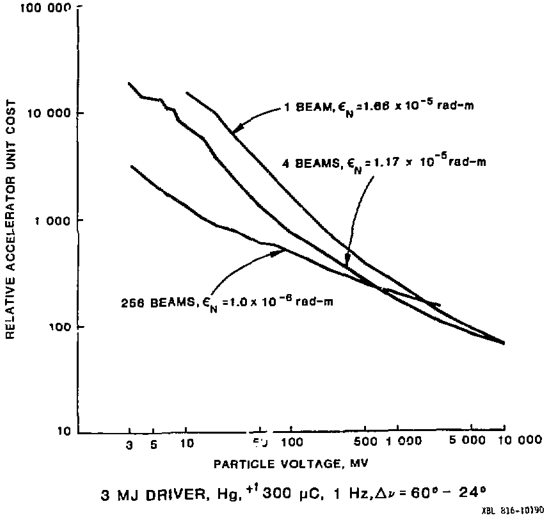

Fig. 3 Relative costs of accelerating different numbers of beamlets

TABLE II: Cost Reduction Examples Contigent on Development

ITEM	COST REDUCTION
-- Using 256 Electrostatically Focussed Beams for the 3-500 MV Region	19
-- Increasing Emittance $\sqrt{2}$ Times	10
-- Doubling Allowable Insulator Fields	11
-- Increasing Tune Depression, 60°-12°	12
-- Thinner Interlaminar Core Insulation	
-- Higher Charge State Ions (e.g., +2, 5 GeV, 600μC.)	20
-- Economies from Mass Production and Learning Experience	

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ACKNOWLEDGEMENT

This work was supported by the Director, Office of Energy Research, Office of Inertial Fusion, Research Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.