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INDUCTION LINAC PLANS

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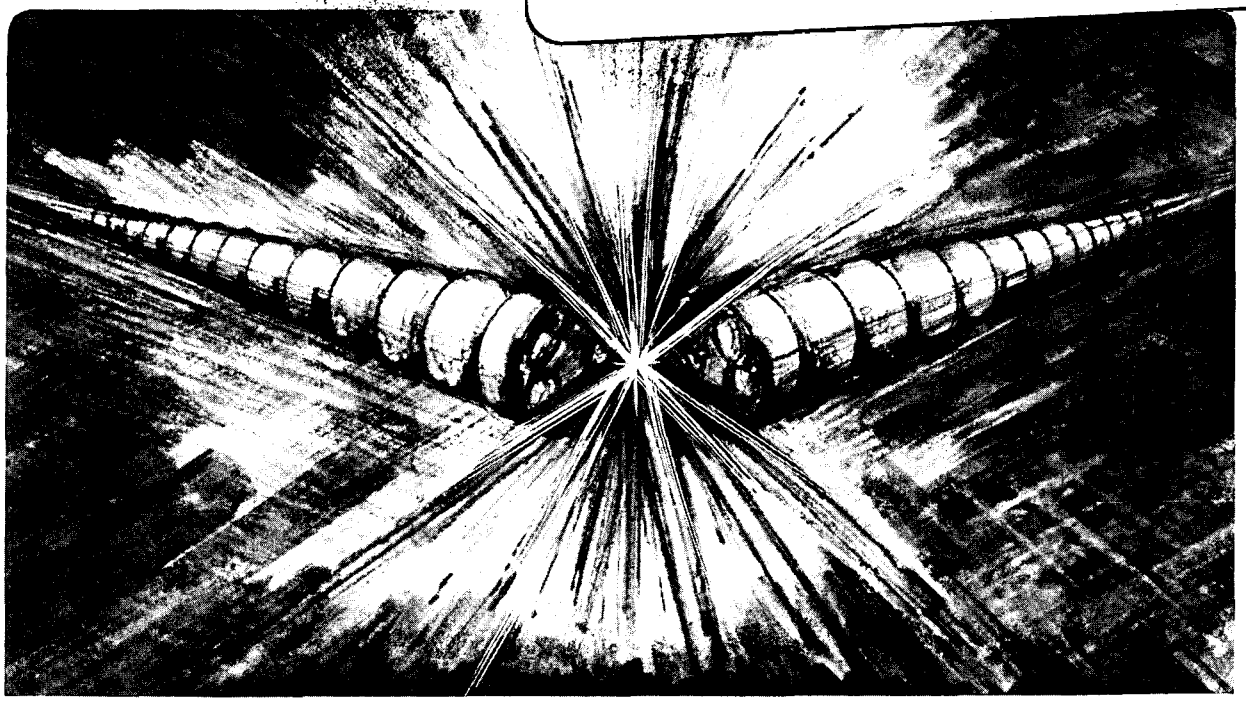

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Introduction

Some of the other papers at this workshop are devoted to what is generally called the big picture: how do we get from here to fusion or to a high temperature spot heating experiment (HTE) which demonstrates the suitability of the induction linac approach. This paper is devoted to the more limited topic of what the near term developmental plans and problems are, with emphasis on component development. Of necessity it is a mix of physics, technology, and economic considerations. Very good technical solutions are available for almost every requirement which are not being pursued because of cost. While costs are not the most important consideration for the near term multiple beam experiment (MBE), they appear to be for driver and probably for HTE scale machines, consequently it is important to find the physics and technological limits and design close to them. The general sequence followed in this paper is to start with the focusing system and accelerating column, which alternate axially at the interior of the accelerator, and work outwards to the induction core, pulser, and accelerator control system.

Ever since the first HIF workshop[1], at other workshops and in the test bed proposals, and in the present National Plan[2], the need to first develop some induction modules and then pass a high current ion beam through them has been emphasized and reiterated. At previous meetings we have shown the various induction modules which have been developed in different laboratories in the past and where they would relate to HIF driver needs. While this experience is extremely valuable and accounts for most of the technology which has been developed, none of the modules is directly suited for

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a heavy-ion high-current induction linac. The principal differences arise from the technological limitations on focusing heavy ion beams and from the non-relativistic longitudinal dynamics of the ions. The differences are greatest at the low energy end, where the accelerator is transport limited. Now, the LBL-LANL HIF group has started the required developmental program which should culminate in a High Temperature Experiment.

Accelerating Column and Beam Focusing

In practically all HIF cases, the beam hole must be much larger than previously because of the focusing limitations, approaching 1 m in some conceptual designs. Starting with a given total charge and a reasonable transport channel for a beamlet, that is, one with modest focusing fields and with clearances around the beamlet for injection errors, mismatches, and misalignments, the transportable current will increase with the beamlet number n, the radius of the beamlet cluster approximately as $n^{1/2}$, and the induction core volume decreases approximately as $n^{-1/2}$ for n not too small, in a densely packed array, and neglecting accelerating pulse rise and fall times. When the latter are included, the core volume at first decreases and then increases again. Different, usually weaker-n dependences result if the total emittance of the beamlets is kept constant, or a different packing geometry is used, or if the channel is reoptimized for cost purposes. The larger than usual hole diameter, which we are trying to minimize, results in a larger required core for otherwise equal pulse duration and voltage requirements, and requires a more powerful pulser.

The large cluster diameter, coupled with the requirement of low background gas pressure leads to the unsolved technical problem of finding a suitable insulator for a driver. At the required driver pressure of 10^{-8} Torr, alumina would be the material of choice, but is not readily available in the U.S. in sizes larger than 26" ID, 28" OD, and is expensive, especially when many closely spaced gradient rings are included along the accelerating column. We have maintained a small ongoing effort to find alternative insulators, with the hope of finding or developing one which has no size limitations and into which the gradient rings can be cast directly, instead of requiring a separate joining operation. Two promising materials are Polysil^R, an EPRI developed polymer concrete, and Re-X^R, a G.E. developed castable glass that recrystallizes into a ceramic; both of these

materials are being investigated now. For the near term, the HTE and MBE accelerators have less of an insulator problem both from a reduced pressure requirement of 10^{-7} Torr and a cluster size well within existing alumina sizes, although lower cost remains a goal.

The currently favored HTE design is based on an array of beamlets arranged in a 5x5 pattern from which the four corners have been removed to approximate a circular shape and the inner 5 beamlets have been left out. For the remaining 16-beamlet cluster a 14" clear aperture is required. Assuming 1" for the protrusion of the gradient rings, an insulator ID of 16" is satisfactory; this is just slightly larger than the 16" OD insulators used on the 1A 2 MeV drift tube Cs beam experiment at LBL. The transport system is designed for a 50% occupancy factor, which translates into 2/3 of the physical length being devoted to the focusing quads and their support system, and the remaining 1/3 to the accelerating column. In the HTE the half period of the lattice would increase along the machine. The focusing is with electrostatic quads in the low energy end and permanent magnet quads in the high energy end and in the subsequent bunching lines. The final focusing elements would be pulsed conventional magnetic quads.

As detailed in the National Plan, the first tasks are the determination of attainable focusing and accelerating fields and their tolerances, from which an accelerator design could follow. Before this determination, the design has been based on the following estimated limits:

$\langle E \rangle < 300$ kV/m,	average accel. field in the electrically focused portion.
$\langle E \rangle < 500$ kV/m,	same, in the magnetically focused portion
$V_q < 0.5\ V_{BR}$,	electric quad operating voltage less than half the breakdown voltage.
$B_q < 0.5$ M,	magnetic quad pole field less than half the permanent magnet magnetization.
$\eta = 0.5$,	hard-edge equivalent focusing field occupancy.
$\sigma = 60^\circ - 12^\circ$,	transport tune window

$V_{injector} = 2$ MV

$I_{injector} = 5A\ Na^+$

$\epsilon_N/\pi = 4\times10^{-7}$ m per beamlet

Δx, $\Delta y < 0.25$ mm, focusing element mechanical alignment tolerance

$D < 24''$, max beamlet cluster diameter

Already in the preliminary design stages it has been expedient to exceed or modify these limits. In particular, the tune window was enlarged in both directions -- higher single particle tune and lower depressed tune -- as simulations and the beam transport experiment have shown that nothing disastrous occurs at the old limits. The least known, and therefore most serious limit, is whether the injector can provide the desired voltage, current, and emittance, therefore it is given a high priority in the development program. Possible fallback positions are to change ion species to K^+ and Ne^+, which would require a machine redesign, therefore early injector results are essential.

Both the electric and the magnetic quads are designed to produce a good two-dimensional quadrupole within their interior, that is, away from the ends, using simple electrode or permanent magnet geometries. The criterion selected is the vanishing of the next highest allowable multipole component, $n = 6$, with the assumption that the following multipole, $n = 10$, is unimportant. For round electrodes this occurs when the distance from the center to the electrode, R, is 7/8 of the radius of the electrode. For rectangular blocks of permanent magnet material of the rare-earth type which have essentially unity relative permeability, the desired geometry is a function of field strength, but lies in the vicinity of width = 1.5 R, depth = 0.5 R for a pole field of 0.4 T.

One of the earlier concerns had been the interaction of the beamlets with each other. At that time, the electric quad electrodes envisaged were small compared with the lattice spacing, and a "good field" region where beam could be placed extended only about half way to the electrode. The present design has good field out to the pole tip, using electrodes that are close to half the lattice spacing in diameter, leaving a narrow channel between them through which the beamlets see each other. Consequently, the beamlets are well shielded within the focusing structure. The estimated field strength from one beamlet to the next is < 1% of the beamlet's own field at the edge of beamlet. In the acceleration gap, which takes up one third of the physical space, the field from the neighboring beamlet is esti-

mated to be 10% of the direct field; if this proves excessive, it too can be reduced to the < 1% level by inserting transverse baffles connected to the gradient rings. Besides shielding the beamlets, this would also reduce the peak electric fields on the gradient rings. Because the beamlets are or can be made almost independent, most of the physics-of-beam-transport questions will be resolved in the well instrumented existing single beam transport experiment while the engineering and systems integration questions are emphasized in the multiple beam experiment.

Induction Cores

Our hopes for induction cores are based on the Allied Corporation pioneered Metglas[R] material, an amorphous metallic glass which appears to be ideally suited for the appliation. The material is cast directly from a molten mix onto a cold, spinning wheel, where it is quenched before the constituents can recrystallize. Because of the rapid quenching requirement, it can at present only be made in the form of thin ribbons, roughly 10-100 μm in thickness, and we hope this doesn't change. Before this new development, thin ferromagnetic tapes were made by repeatedly annealing and rolling the tape, in a relatively slow and expensive process whose cost increased as thickness decreased. A similarly favorable circumstance is that the magnetic properties of metallic glasses tend to be best when the composition is 80% metal, 20% insulator, resulting in a resistivity of about 125 μΩ cm, which is much higher than, say, the silicon steels, which become brittle if the silicon content is a little greater than the standard 3.25%, at a resistivity of 50 μΩ cm. As most of the core losses, due to eddy currents, are proportional to ρ/t^2, 1 mil Metglas has the promise of decreasing core losses by an order of magnitude below those of the presently most economical choice: 2 mil silicon steel. The present yearly production of Metlgas is about 100 Tons, with the quanitity increasing and price decreasing dramatically with time, to a projected level of $2/lb in large quantities for the as-cast material.

A substantial amount of work remains to be done in applying Metglas to HIF uses. The essential problem is preservation of good magnetic properties in a finished core with adequate interlaminar insulation. During this year, in cooperation with Allied, we are investigating a matrix of magnetic annealing, winding, and insulating possibilities. The principal choices are

SiO_2, Kapton^R, and Mylar^R insulation, with or without annealing, and with or without rewinding where possible. Because the actual insulation requirements vary by more than an order or magnitude depending on pulse duration, it is quite possible that different solutions will be best for different locations in the accelerator.

Pulsers

The pulsers are one of the components where an almost ideal solution exists in the form of a hard tube with feedback, which could provide the desired specially shaped accelerating voltage waveforms while at the same time eliminating jitter, presenting a low coupling impedance to the beam, and allowing a smaller core to be used due to its ability to be turned on and off rapidly. Unfortunately it is too expensive an option and the alternatives all are lacking in one or more of the attributes listed. For long pulses, greater than a microsecond, we have been developing an ignitron pulser because it is a low cost and efficient closing switch able to handle kiloampere currents and pass coulombs of charge per pulse. The major shortcoming of ignitrons for this application, jitter, was reduced to 50 ns total in a developmental gridded tube, but in the first long test of a representative module, the grid eroded and caused tube failure at 5×10^6 pulses. This test was begun after successful operation of one tube driving a single induction core encouraged us to drive two cores in parallel. Now we are life testing a one-core configuration again, and expect much more than twice as much life. For pulses below 1 μs, thyratrons are superior because of their shorter risetime and nanosecond jitter. Both of these low pressure gas discharge switches have to be protected from large reverse currents; in our case this is accomplished with a series saturated choke which comes out of saturation and presents a high impedance when the current reverses. This protective device more than doubles the circuit leakage inductance and slows down the rise and fall times. Because the ignitrons and thyratrons probably can be made to meet the near term requirements, other pulser options, such as spark gaps and magnetic modulators have not yet been seriously considered, the first because of their more powerful trigger requirement, and the second because of their long delay time.

Waveform Synthesis and Control

Ideal waveforms required for acceleration of the ion bunch, while preserving constant space charge density except at the ends of the bunch, have been worked out on the basis of single particle kinematics assuming the fields are applied continuously in z. The actual waveforms will be applied at 1/3 meter intervals and approximated in piecewise fashion with discrete pulsers. The space charge field of the beam at the bunch ends is about 1% as large as the acceleration field, and can be approximately counteracted with 3 of the nominally 300 pulsers; the rather low space charge field longitudinally is also a consequence of the shielding by the focusing and accelerating electrodes. In the frame of the beam the average electric field is almost uniform in space and increasing in time. In space, at any location the required applied voltage is most nearly a step plus a ramp. The waveforms will be controlled and synthesized by varying the firing times of the individual pulsers.

The very slow speed of the ions makes it possible to detect simple forms of malfunction and correct for them before the beam has left the machine. For example, at the injection energy in the MBE and HTE designs of 2 MeV, the ions travel about 4 meters in a microsecond. With both thyratron and ignitron pulsers, the output pulse at the core appears less than a microsecond after a low level trigger starts the triggering sequence. A correcting pulser, located 4 meters downstream and held in reserve, could correct for some errors such as prefires or misfires before the bunch has slipped too far out of its acceleration program or the waveforms have changed too much; in this example, with nominal 25 kV pulsers, particle trajectories longitudinally would have changed by about 3 cm before an energy correction could be applied. The same process at higher energy, say 8 MeV, as at the exit of the MBE, would require the correcting element to be located twice as far downstream, but the trajectories would differ by only half as much as at 2 MeV so the correction would be slightly better. Something like 5% of the total pulsers held in reserve would greatly increase the overall reliability, both for error correction and for temporary replacement of modules which have failed. For both physics and engineering purposes we are trying to determine the maximum allowable step size.

Conclusion

The most important developmental information for near term needs will be in hand after an example of an electric quad lattice and a permanent magnet quad lattice have been built and measured, and after prototype acceleration modules have been built for about 5 representative locations along the accelerator. This work has started. Longer term, for a driver, the same process should be repeated for a physically much larger beamlet cluster where the focusing elements are superconducting quads.

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