Engineering Issues in the Design of a Recirculating Induction Accelerator for Heavy Ion Fusion

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Abstract

Despite additional complexity, a recirculating induction accelerator system has potential for achieving significant cost reductions over linear induction accelerators. A study is being conducted to evaluate the feasibility and cost of a recirculating induction accelerator for heavy ions. This study has identified the major cost components of the recirculator system, evaluated the engineering feasibility of various accelerator sub-systems and estimated overall system efficiency. System studies have been conducted to evaluate the dependence of system costs and efficiency on various system parameters and configurations. This paper will present the results from some of the system studies along with an evaluation of the engineering feasibility issues for a specific system design. The discussion of engineering feasibility will include evaluation and analysis of technical feasibility as well as cost and efficiency of the accelerating pulse power systems and the beam bending systems.

1. Introduction

For the last several years, the U.S. effort to develop heavy ion drivers for inertial fusion has focussed on linear induction accelerators. [1] As part of this comprehensive effort, systems studies have been conducted to assess the cost and feasibility of heavy-ion induction linacs and to identify potential scenarios for reducing the size and cost of power-plant scale drivers. [2,3] An old idea for cost reduction that has not been as aggressively investigated, is to use the linear induction accelerator technology in a recirculating configuration. The recirculating induction accelerator reuses the induction cells many times to accelerate an ion beam by bending the beam in a closed path. In contrast, a linear induction accelerator must use many more induction cells to achieve the same particle energy. This potential to realize significant cost reductions with induction accelerator technology has motivated an extensive evaluation of recirculating heavy-ion induction accelerators for inertial fusion drivers by the Beam Research Program at Lawrence Livermore National Laboratory in cooperation with the HIFAR Program at Lawrence Berkeley Laboratory.

The basic operating principles of a recirculating induction accelerator are the same as a linear induction accelerator with a few significant differences. Both accelerators use induction cells to couple the drive energy to the ion beam, and quadrupole focussing to transport the beam through the accelerator. Unlike the linear accelerator, the beam in a recirculator must follow a closed path which requires dipole magnets to bend the beam. The dipole magnetic field must increase as the ion beam recirculates through the accelerator because the beam gains energy from lap to lap. The induction cell system in a recirculator must have a much higher peak and average repetition rate capability than a linear accelerator. An accelerating potential must be applied to the beam on every lap resulting in peak repetition rate requirements equal to $\beta c/L$, where βc is the ion velocity and L is the circumference of the ring. The average repetition rate requirements are equal to $N_l f_o$ where N_l is the number of laps the beam makes in a ring and f_o is the repetition rate required at the target. The alignment and vacuum systems may also significantly impact the cost of a recirculator but they will not be addressed here. For a recirculator to be economically advantageous, the additional cost of the higher performance accelerating system, the dipole system and other potentially more complex systems, must be small relative to the cost reductions realized by the reduced size of the induction cell system and quadrupole system.

This recirculator study effort has focussed on evaluating the feasibility, efficiency and cost of heavy-ion, recirculating induction accelerator drivers for inertial fusion power generation. Critical physics and engineering issues have been identified and are being studied to evaluate the feasibility of the recirculator concept. A systems model has been developed and used in the initial studies of a 4 MJ driver for mass=200 and charge state=+1 ions. These parameters were chosen because they appeared to be a reasonable starting point based on past systems studies. This paper will present initial results of an engineering systems assessment of the recirculator concept for a 4 MJ driver. Future work will certainly explore a wider parameter space.

2. Recirculator Conceptual Design

There are many possible recirculator configurations for a 4 MJ, mass=200, charge state=+1 driver. For the purposes of this paper, the discussions will be limited to a single example because most of the engineering systems issues considered are applicable to recirculators in general. This particular configuration is not an optimum design but was chosen as an example because it has been thoroughly evaluated. [4]

To date, all of the 4 MJ recirculator configurations that have been evaluated consist of multiple acceleration rings (3 - 4) to accelerate the ions to 10 GeV. In general, each ring accelerates the ions by approximately one order of magnitude in single particle energy. Table I lists the significant parameters for the example recirculator configuration. A one-line drawings of the accelerator layout is shown in figure 1.

Four ion beams are injected into the injection ring (IR) at low current (.5 A) and low particle energy (3 MeV). After a specified number of laps, the ion beams are extracted from the IR and injected into the next accelerating ring which is the low energy ring (LER). This scenario is repeated from ring to ring until the beams are extracted from the high energy ring (HER). At this point the ion beams enter a final drift compression section where the ion bunches are compressed to 10 ns by inducing a velocity tilt on the beams.

Each accelerating ring is composed of three major components, the induction accelerating cells, quadrupole focussing magnets and dipole bending magnets. The configuration of a typical section of the accelerator which was used for these studies is shown in figure 2.

The accelerating systems provide the energy to accelerate the ion beam to the required energies. These systems consist of pulsed modulators that generate and deliver the accelerating potential to induction accelerating cells. In a recirculator system, these pulsed modulators must be capable of supplying the accelerating potential to the ion beam every time it makes one complete lap around the recirculator. The time required for an ion beam to make a lap varies from 100's of µs to as short as 10's of µs in a single accelerating sequence depending on the exact configuration of the recirculator. In addition to supplying the accelerating potential, each pulsed modulator must also supply a potential for reseting the induction core material between acceleration pulses. Feasible methods for generating the accelerating potentials have been identified using mature technologies.[5] More advanced solid state technologies are also being investigated.

The quadrupole magnet system that is necessary to transport the ion beam through the accelerator is a dc superconducting system. Superconducting magnets were chosen for the system studies because reasonable accelerator efficiencies were not possible with conventional quadrupole magnets. The superconducting quadrupoles are configured in an array of four magnets, one per beam. A critical parameter for the quadrupole magnets is the radial size of the array. Because the induction cell surrounds the quadrupole array, the array size affects the quantity of the magnetic material which impacts the cost and efficiency of the recirculator.

The dipole magnet system consists of dipole magnets and pulsers that generate a time varying magnetic field to bend the ion beam in a constant radius as the beam energy increases. The energy stored in the dipole magnetic fields is on the order of 100's of megajoules. Greater than 90% of this dipole field energy must be recovered to achieve a reasonable driver efficiency (≥ 20%). This requires careful design of low-loss pulsed dipole magnets and the use of energy recovery schemes in the dipole pulser system. [6]

3. System Studies

The recirculating heavy ion accelerator is a complex system with many possible configurations. In a system where cost and efficiency are crucial to feasibility, it is important to understand the dependence of cost and efficiency on various system parameters. A system model was developed for a recirculating accelerator to identify the major cost components and to evaluate tradeoffs between various system parameters. This systems model uses the physics and engineering design equations to identify a feasible recirculator configuration. System costs and efficiencies are then estimated based on conceptual designs for each of the major components. Three objectives of these systems studies were to identify the major cost components of a 4 MJ driver system, identify the major power consumption components of the system and to evaluate some of the tradeoffs between various system parameters.

A relative cost breakdown of the recirculator system which includes only direct costs, is shown in figure 3. The three major lattice components of this particular example, the accelerator systems, the quadrupole magnet systems and the dipole magnet systems account for > 57% of the total direct driver costs. Typically these are the major components of any recirculator configuration, only the percentages may vary. A breakdown of the total power consumption of the recirculator is shown in figure 4. The efficiency of the recirculator is dominated by two major systems, the induction accelerating system and the dipole magnet system. Most of the remaining discussions will focus on these two systems.

The losses in the induction accelerating system are primarily due to magnetic material losses in the induction cell. The volumetric losses in a Metglas ™ loaded induction cell can be expressed as shown in equation 1 where ΔB_m is the flux density used in the magnetic material, Δt is the pulse width, and K, m and n are constants that depend on the type of Metglas. For 2605 S-2, m≈-.8, n≈1.8 and K≈139.

$$\frac{E_m}{V} = K\,\Delta t^m\,\Delta B_m^n \quad (1)$$

Equation 1 shows that the magnetic losses can be decreased by lowering the ΔB_m used in the induction core. This can be done by increasing the cross-sectional area of the induction core as seen in equation 2 where V_c is the cell voltage, A_m is the cross sectional area of the induction core, Δt is the

$$\Delta B = \frac{V_c\,\Delta t}{A_m\,PF} \quad (2)$$

pulse width, and PF is the packing fraction of the magnetic material in the core. However, the magnetic material losses cannot be decreased indefinitely by increasing the cross-sectional area. There is a point where the increasing core volume begins to increase total losses faster than the corresponding decrease in ΔB reduces losses. Fortunately the recirculator core configuration is in the range where increasing the cross-sectional area can significantly reduce core losses.

The recirculating configuration has the advantage over the linear machine in that the cost of the magnetic material does not dominate the overall cost of the machine. This allows a flexibility to use more magnetic material than is actually required. Figure 5 shows the impact that extra core material has on the cost and efficiency of the high energy ring. The addition of 400% more core material than is required by the accelerating voltage waveform results in a decrease in total system power consumption of ≈ 50% for a corresponding increase in system cost of ≈ 11%.

A large amount of energy (>100 MJ) is required to generate the magnetic fields that bend the ion beam. A large percentage (>90%) of this energy must be recovered after each accelerating sequence in order to maintain a driver efficiency of greater than 20%. The dipole energy, E_d, is expressed by the relationship shown in equation 3 where B_d is the magnitude of the dipole field, A_c is the cross-section of the dipole field volume, μ_o is the permeability of free space and [Bρ] is the particle rigidity. It is a temptation to make the dipole field as high as possible in order to shorten the overall length and presumably reduce the cost of the accelerator, but one must be careful to balance any cost savings with a decrease in system efficiency because the losses go up linearly with B_d as shown in equation 3.

$$E_d = \frac{\pi B_d}{\mu_o} A_c [B\rho] \quad (3)$$

Figure 6 is a plot of the normalized recirculator system cost and efficiency as a function of dipole field strength. As would be expected, the cost of the recirculator decreases as the dipole field is increased, but a price is paid in efficiency. Above 1 tesla, the decrease in cost becomes insignificant but the power consumption continues to increase linearly with dipole field.

There are a number of other tradeoffs to evaluate that provide valuable insight for a recirculator system. One of the most obvious parameters to vary in a recirculator is the number of laps that the beam will traverse the ring to gain the required energy. After all, achieving cost eduction by recirculation is the main objective of this concept. Figure 7 shows the normalized cost of he highest energy ring of this recirculator point design example as a function of the number of laps ısed for acceleration. There are large reductions in cost for the range of 10 to 50 laps. After ıpproximately 50 laps, the incremental cost reductions become much smaller. For this particular lesign example, there is not much cost incentive for increasing the number of laps above 100. Vacuum :onstraints may limit this number to something smaller than 100. The recirculator power :onsumption shown in figure 7, which assumes a constant pulse duration acceleration schedule, is ınly weakly dependent on the number of laps.

ı.0 Conclusions

The systems studies that have been conducted to date have provided considerable insight nto designing a low cost recirculating driver for inertial fusion. No absolute costs have been quoted ecause the overall system costs are very dependent upon the particular system configuration that ıas been chosen. Global optimization of the recirculator including everything from the wall plug to he target has not been attempted. Our systems studies have been limited to a 4 MJ driver using nass=200 and charge state=+1 ions. Several configurations for this particular driver size have been nvestigated each having varying degrees of risk associated with them. The total costs of these ystems, including both direct and indirect costs range from 500 M$ to 1.5B$. Significantly more vork is needed to identify optimum systems with an acceptable balance between risk and cost.

ı.0 References

1] POLANSKY, W.M., U.S. accelerator research program for heavy-ion fusion, Fusion Technology 13 (1988) 201.

2] DUDZIAK, D.J., U.S. heavy-ion fusion systems assessment project overview, Fusion Technology 13 (1988) 207.

3] HOVINGH, J.,BRADY, V.O., FALTENS, A. , KEEFE, D., LEE, E., Heavy-ion linear induction accelerators as drivers for inertial fusion power plants, Fusion Technology, 13 (1988) 255.

4] YU, S.S., et al., "Preliminary design for a recirculating induction linac for heavy ion fusion", Heavy Ion Inertial Fusion 1990 (Proc. Int. Symp., Monterey, 1990).

5] NEWTON, M., REGINATO, L., YU, S.,"High repetiton rate pulser concept for a recirculating linac HIF driver," Heavy Ion Inertial Fusion 1990 (Proc. Int. Symp., Monterey, 1990).

6] REGINATO, L., NEWTON, M., YU, S.,"An energy recovery concept for powering the dipole magnets in a recirculating induction accelerator for HIF," Heavy Ion Inertial Fusion 1990 (Proc. Int. Symp., Monterey, 1990).

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	IR	LER	MER	HER
Ring energy (GeV)	.003 - .01	.01 - .1	.1 - 1	1 - 10
Beam pulse duration (μs)	200 - 40	40 - 4	4 - .75	.75 - .25
Number of laps	50	50	50	50
Number of beams	4	4	4	4
Circumference (m)	600	500	1400	3100

Table I. Example parameters of a recirculating induction accelerator driver.

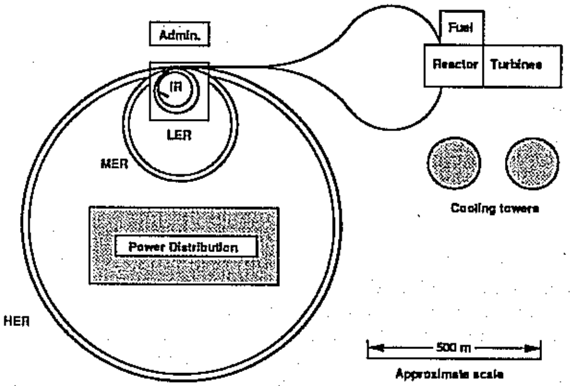

Figure 1. Example of a 4 MJ recirculator driver.

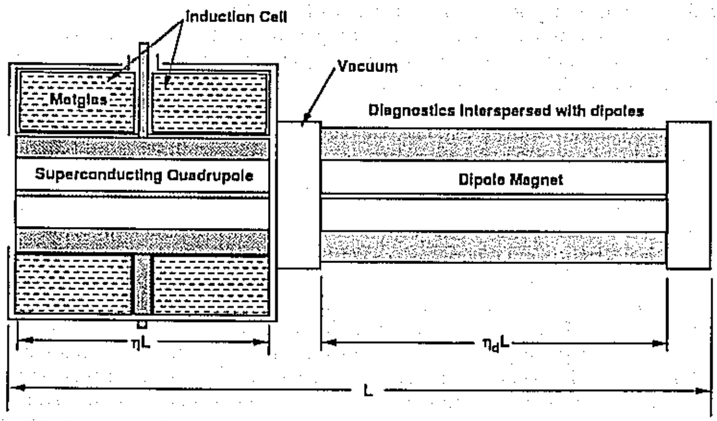

Figure 2. Typical half-lattice period section.

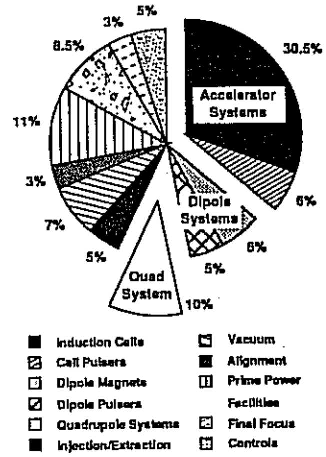

Figure 3. Breakdown of recirculator costs.

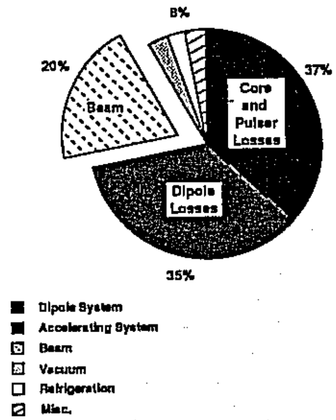

Figure 4. Breakdown of recirculator power consumption.

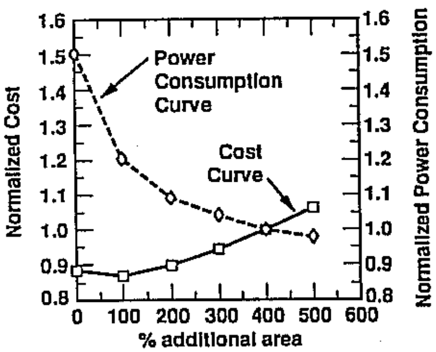

Figure 5. Graph of cost and power consumption vs. additional magnetic material cross-section area.

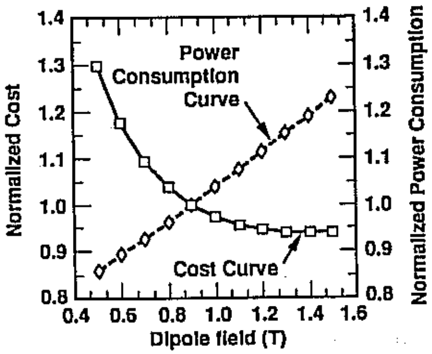

Figure 6. Graph of cost and power consumption vs. dipole field strength.

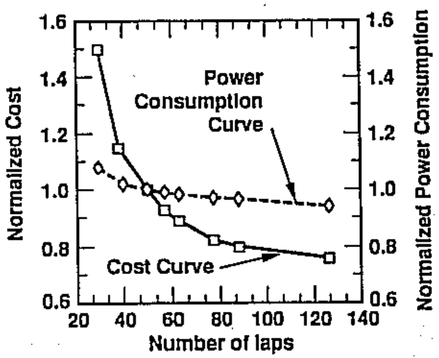

Figure 7. Graph of cost and power consumption. vs. number of recirculation laps