Parametric Studies for Recirculating Induction Accelerators as Drivers for Heavy-Ion Fusion

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Abstract

A computer model for the cost and performance of a recirculating induction heavy-ion accelerator for driving inertial fusion reactions has been developed. This code has been used to examine the driver design space in an effort to reduce driver costs while maintaining high driver efficiency and target gain. The driver model is described, and the results of parametric studies are reported. The design parameters examined include driver energy, maximum magnetic field allowed at the superconducting windings, maximum bending field in each ring, axial quadrupole field packing fraction for the focusing magnets in each ring, and ion mass.

I. INTRODUCTION

Inertial fusion energy (IFE) power plant concepts produce energy by compressing and heating a target made of heavy hydrogen isotopes (D-T or D-D) until the nuclei become close enough that fusion occurs. The driver used to compress and heat the target must deliver a large amount of energy (MJs) in a very short period of time (10s of nanoseconds). Both particle accelerators (using light ions or heavy ions) and lasers have been proposed as drivers for IFE, with particle accelerators having the advantage of higher inherent efficiency.

Heavy-ion fusion (HIF) driver research in the U.S. has focused on induction accelerators. Recirculating induction accelerators (RIAs) have been proposed as a less-expensive alternative to linear induction accelerators (linacs) for IFE drivers [1].

II. DESCRIPTION OF AN RIA

An induction accelerator accelerates an array of ion beams through transformer action and continually focuses the beam using a lattice of alternating focusing and defocusing quadrupoles. In a multiple-beam accelerator, the cost of the acceleration systems can be reduced if a single ferromagnetic induction cell surrounds all of the beams to provide an acceleration voltage for all of them. Each beam still requires its own focusing lattice, so compact arrays of quadrupoles are required along the length of the accelerator.

An RIA adds arrays of dipole magnets between the quadrupoles in each half-lattice period in order to bend the beams in a circle and allow the beams to pass through each induction cell up to a few hundred times. An RIA generally consists of one to four rings. Because each quadrupole array and inductor is used many times per shot, the required focusing and acceleration costs are greatly reduced. The added costs for the dipole magnets are more than offset by the cost savings for the acceleration and focusing systems. Driver efficiency is kept high (>30%) by using combined function (CF) superconducting focusing magnets (quadrupoles with a constant dipole offset) in high energy rings and by using energy recovery circuits for all pulsed resistive dipoles.

There are additional design constraints on an RIA that are not relevant to a linac. Because the lattice period must remain constant in each ring, the undepressed tune of the beam will decrease as the ion energy increases. This defocusing effect limits the useful energy gain per ring and leads to designs which use several rings (three rings were used in LLNL's most cost-effective "C" design [1]). Rapidly pulsed injection and extraction systems are needed for each ring. The need for dipoles between the quadrupoles limits the space available for acceleration gaps. Constraints on available circumferential space lead to designs which use induction cores surrounding the quadrupoles. Each induction core uses voltage leads to connect it to the narrow acceleration gaps located between quadrupole arrays.

III. DESCRIPTION OF RECIRC CODE

The RECIRC code was created to model three ring RIA drivers and examine the dependence of driver cost and target gain on the large number of available driver design parameters. The driver includes an injector, a low-energy ring (LER), a medium-energy ring (MER), a high-energy ring (HER), and a final compression and focusing section. For a given driver energy and set of input driver parameters (see Table 1), the code calculates the final ion energy and beam current. The injection and extraction beam parameters for each ring are then calculated, and the cost of the driver is calculated. The final beam parameters are used to give ion ranges (gm/cm^2) and spot sizes (mm) needed to calculate target gain. Spot sizes are calculated assuming auto-neutralization of the ion pulse by co-injected electrons following the final focusing magnets [2].

A. Beam Modeling

The models used for transportable current in an alternating-gradient lattice are improvements to those first studied by Maschke [3], the improved approximations were derived by Lee, Fessenden, and Laslett [4] at Lawrence Berkeley Laboratory. The four equations used are:

$$2\,(1 - \cos(\sigma_0)) = \left(1 - 2\,\eta/3\right)\eta^2\left(B'/[B\rho]\right)^2 L^4$$

$$\varepsilon_n = \beta\gamma\,\sigma/(2\,L)\,\bar{a}^{\,2}$$

$$2\,(1 - \cos(\sigma)) = 2\,(1 - \cos(\sigma_0)) - \kappa\left(2\,L/\bar{a}\right)^2$$

$$\kappa = 2\,I\Big/\left[(\beta\gamma)^2\,[\beta\rho]\left(4\pi\,\varepsilon_0 c^2\right)\right]$$

where

σ_0 = the undepressed phase advance per lattice period,
σ = the depressed phase advance per lattice period
η = the occupancy factor for the quadrupole fields,

B' = the field gradient in the quadrupoles,
$B\rho$ = the ion beam rigidity,
L = the half-lattice-period length,
$\bar{a}$ = the average beam radius,
κ = the dimensionless line charge,
ε_n = the normalized emittance,
$\beta\gamma$ = the relativistic velocity, and
I = the transportable current.

B. Determining Ring Parameters

The relations in the previous section can be used to give the transportable beam current as a function of the cumulative acceleration voltage, V. For a constant current beam, the transported power is given by P = I(V) V, so the final voltage needed for a given final driver energy, E, and pulse duration, τ, can be obtained by solving the final power balance,

$$P_{beam} = V\,I(V) = \frac{E}{N\tau}$$

for V. The final beam current can then be obtained from I(V). The injection voltage and current for the HER and the injection and extraction voltage and current for the MER are then calculated from the transport parameters and energy gain (V_{ext}/V_{inj}) for each of these rings. The energy gain for the LER is obtained by dividing the injection voltage for the MER by the 3 MV injection voltage for the driver. The required beam size and injection current for the LER are then determined by the required injection current for the MER. The diameters for the MER and HER are given by the bending strength of the dipoles and the beam rigidity; the diameter of the LER is set by the assumption that the LER circumference must be twice the injected beam length to allow time to reset the acceleration cells.

C. Component Costing and Scaling

The number and size of the quadrupole arrays, dipole arrays, and induction cores in each ring are calculated from the packing fractions, ring diameters, injection and extraction pulse durations, and the input magnetic fields allowed in each component. The size and cost scaling for the acceleration and bending systems are taken from the "C" design in Reference [1], but the scaling of the quadrupole array is given by a more detailed model [5] taken from an earlier study of linac drivers [6,7]. The more detailed quadrupole model gives slightly larger quadrupole arrays and thus slightly increases the cost of the quadrupoles and inductor cells relative to those estimated in [1].

Key cost assumptions are a unit cost of \$5/kg for the Metglas used in the inductor cells and a wound cost of \$300/kg of NbTi and \$50/kg of Cu in the quadrupole or CF magnet windings.

D. Key Driver Parameters

Key driver parameters which may be varied in parametric studies are given in Table 1.

Table 1
Key Input and Output Parameters

Input Parameters	driver energy final pulse duration ion mass and charge state quad field gradients quad packing fractions dipole fields in CF magnets max dipole field in LER pulse compression exponents for each ring, ($\tau \sim \beta^{-n} \sim V^{-n/2}$) ion energy gain ratio (E_{ext}/E_{inj}) for MER and HER
Output Parameters	dipole packing fractions Max. dipole fields in MER and HER Inj. and Ext. beam parameters: ($E_{ion}, I_{beam}, \tau_{pulse}$) for each ring ring diameters total direct cost for driver estimated target gain

IV. RESULTS OF PARAMETRIC STUDIES

Two parametric studies were done. First the "C" design assumptions were scaled through a range of energies; then a parameter search was done to find lower cost options for 1.5, 4, and 6 MJ three-ring drivers. In the second study, all parameters were varied except final pulse duration and ion charge state. Figure 1 shows the direct costs (including installation and controls), target gain, and pulsed-power efficiency for the drivers in both studies. Table 2 compares the parameters used for the low-cost 4 MJ driver with those used in the "C" design.

Only drivers with three rings and four beams were considered. Although these are reasonable assumptions for 4 MJ drivers, the range of energies examined was large enough that other design choices may be more cost effective at different energies. At 1.5 MJ, two-ring drivers may have lower costs and less emittance growth. Drivers with more beams (e.g., 12) will give lower ion energies and smaller rings; they may give higher gains (because of the lower ion ranges) at comparable costs for higher-energy drivers.

The pulsed-power efficiency is the ratio of the driver beam energy to the total pulsed energy for the inductors and dipoles. The actual driver efficiency will also include constant power terms for refrigeration, vacuum pumps, etc.

Minimizing driver cost is only one way of choosing a driver design. The eventual goal will be to optimize figures of merit, such as cost of electricity, for IFE plants. Better figures of merit will include the effects of target gain and driver efficiency on reactor and plant scaling and costs.

Innovative and aggressive magnet design may also lower the estimated cost of RIA drivers. The quadrupole (or CF) arrays assumed in this study are very conservative in that each magnet NbTi winding is surrounded by a structural collar and enough iron to isolate it from the fields of adjacent magnets.

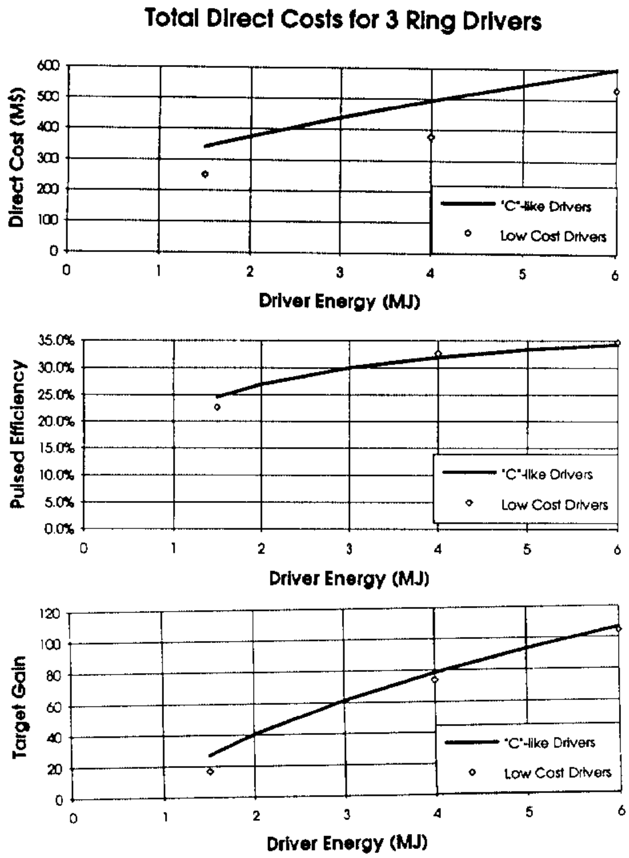

Figure 1. Cost and Performance Parameters

Table 2
4 MJ Driver Parameter Comparison

Parameter	"C"-Like 4 MJ Driver	Low-Cost 4 MJ Driver
Ion Mass (amu)	200	140
Ion GeV-HER	1.1-11	0.73-8.76
Ion MeV -MER	55 - 1,100	61 - 730
Ion MeV-LER	3 - 55	3 - 61
HER Diameter	615 m	252 m
MER Diameter	259 m	176 m
LER Diameter	245 m	391 m
CF Dipole Field-HER	1.0 T	1.5 T
CF Dipole Field-MER	0.75 T	0.62 T

More aggressive designs using high-performance superconductors (such as Nb_3Sn), using less iron, and/or using less structural material may be possible. More compact magnet arrays would reduce the dimensions and costs of the inductor cells as well as the focusing magnets.

V. RESULTS AND CONCLUSIONS

A. Cost Reductions for Three Ring Drivers

Parametric studies on 3 ring RIA drivers ranging from 1.5 to 6 MJ gave a cost reductions of 11 to 27%. Cost reductions resulted from

- using lower ion masses,
- using higher bending field in the CF magnets, and
- using smaller energy gains in the MER and HER.

B. Potential Future Studies

This study was limited in scope to the analysis of three ring recirculating drivers. Other work that would be of great interest includes

Examination of low-energy RIAs with one or two rings and examination of high-energy RIAs with more beams.

Examination of hybrid drivers: Cost savings may be possible if a linac is used before the first recirculating ring. The cost and performance of such "hybrid" drivers should be examined.

Sensitivity Studies: The effect of significant changes in anticipated beam performance (e.g., emittance growth) or unit cost (e.g. superconductor cost) on optimum designs and costs should be explored.

Cost comparisons between optimized linacs and RIAs: A comparison of optimized drivers using consistent assumptions has yet to be done.

VI. REFERENCES

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