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

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Abstract

Recirculating induction accelerators offer the potential of providing a driver for a heavy ion fusion reactor at a lower cost than a linear induction accelerator. We discuss some of the design issues facing a recirculator and we compare induction recirculators with induction linacs, rf-linac/storage rings, and synchrotron/storage rings. We briefly discuss two critical physics issues, in common with the rf-linac approach, emittance growth and beam interactions with the residual gas.

I. INTRODUCTION

Heavy ion accelerators hold the promise for meeting all of the requirements for an inertial confinement fusion (ICF) reactor for the production of electrical power. These requirements include efficient beam-target coupling, high repetition rate (~1-10 Hz), high reliability, and long stand-off focusing. Previous design studies, have focused on the linear induction accelerator (e.g. Ref. [1]), the rf-accelerator/storage ring approach (e.g. Ref. [2]), or the synchrotron-accelerator/storage ring approach (e.g. Ref. [3]). A substantial cost savings over a linear induction accelerator may be achieved in an induction accelerator in which a heavy ion beam makes many (~50-100) passes through one or more circularly shaped accelerators. We are examining a few point designs for such an accelerator, consisting of three to four accelerating rings, each of which increments the energy by a factor between 3 and 20. In section I, we discuss some of the similarities and differences between our studies and previous studies, and describe some aspects of our design. In sections II and III we identify two of the critical issues which face the recirculator, viz, emittance growth and vacuum/gas interactions and indicate preliminary estimates of their impact on our design.

II. BRIEF OVERVIEW OF RECIRCULATORS

The induction recirculator shares some common features with each of its brethren, the induction linac, the rf-linac/storage ring, and the synchrotron/storage ring. As in the induction linac, the acceleration is accomplished by a set of induction modules, each of which increases the energy of the ion beam by an increment of up to several hundred kilovolts. In the recirculator case the modules are arranged in a circular array. Since the induction modules are used up to one hundred times, the size of the accelerator and the number of cores used can be much smaller, resulting in a possible large cost reduction over the induction linac. The ion beam is focused by alternating gradient super-conducting magnetic quadrupoles with constant magnetic field. As is done in the synchrotron approach, the beam is bent in a circle by means of a set of temporally ramped magnetic dipoles. The acceleration time (and hence residence time) in each ring is several milliseconds. This is similar to the residence time of the ion beams in the storage rings envisioned in the rf-linac/storage ring approach. This is much shorter than the one second residence time in the synchrotron approach. Synchrotrons are not currently as actively being pursued because of this long residence time (Ref. [4]). The potential problems of the heavy ions interacting with residual gas, or with other beam heavy ions, or of the beam emittance growing due to non-linear forces in a space-charge dominated beam being transported around bends are shared both in the rf-linac and recirculator approach.

One advantage of induction acclerators is the ability to accelerate larger currents than the rf-linacs per beam line. This translates to an absence of storage rings in the induction accelerator designs. One potential problem that is absent in the recirculator approach as a result is the so-called "black cloud" effect (Ref. [5]). This is the interaction of the beam with a septum upon entrance of the accelerated beam into a storage ring. A septum is necessary since the current is built up over time in the storage ring. In the recirculator, the beam is "kicked" into and out of each ring by a set of temporally ramped dipole magnets and oversized quadrupole magnets and so no septum is necessary.

An advantage of the recirculator over the linear induction machine is the reduced accelerating gradient that is possible arising from the reuse of the cores. Since the cross-sectional area of each core is proportional to the product of voltage and pulse duration, the lower gradient allows longer pulses at the low energy end of the accelerator, than a comparable linear machine. This longer pulse duration translates to lower currents for a given amount of charge and thus fewer beams, since the transport equations translate into limits on current.

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However, the introduction of varying magnetic dipole fields, higher peak repetition rate of the induction cells, and the varying voltage pulse format lead to new technical complexities which must be studied before the feasibility of the recirculator can be evaluated. Many of these engineering challenges are addressed in Ref. [6].

In the course of our recirculator studies, a number of designs are being considered, with variations arising in order to achieve the simultaneous goals of low cost, high efficiency, and high probability of both high beam quality at the target and technological achievability. As an example, we summarize the accelerator parameters of one of our designs in Table 1 below. The design consists of three rings: the Low Energy Ring (LER), Medium Energy Ring (MER), and High Energy Ring (HER). Further details may be found in Ref. [7].

Table 1. Ring Summary

	LER	MER	HER
Ion Energy (GeV)	.003-.05	.05-1	1-10
Pulse Duration (μs)	200-30	30-2.5	2.5-.25
Circumference (m)	700	885	1934
Current/Beam (A)	0.5-3.3	3.3-40.0	40.0-400.0
No. of Beams	4	4	4
No. of Corelines	1	1	1
No. of Laps	100	100	100
Pipe Radius (m)	.078	.066	.061
Lattice Half Period (m)	.85	1.54	3.50
Induction Modules:			
Inn. radius (m)	.313	.314	.404
Out. radius (m)	.448	.631	.552
Length (m)	.384	.729	.962
No. of Cores	785	535	1050
Bends (Magnetic Dipoles):			
Eff. Length (m)	0.15	0.50	1.50
No. of Bends	2680	1800	1920
Max. B-Field (T)	0.90	1.80	1.80
Super-Conducting Magnetic Quadrupoles:			
Length (Eff. L.) (m)	.47 (.23)	.81 (.62)	1.58 (1.40)
No. of Quads	3140	2140	2100
Max. B-Field (T)	2.0	1.5	1.2

III. EMITTANCE GROWTH CONSIDERATIONS

One of the most serious unresolved issues that confronts the recirculator is the question of how much the normalized emittance will increase on passage of the beam from injector to target. This question is being addressed on many levels: from crude estimates, through more sophisticated analytic theory to fully 3-dimensional code work, as well as experimentally. For example, an estimate can be made (Ref. [7]) in which it is assumed that alignment errors give rise to betatron oscillations, which are phase mixed, due to non-linearities, and thus give rise to emittance growth. Using the approximation of constant focusing (and a number of other simplifying assumptions) the increased emittance $\Delta\epsilon$ can be written:

$$\Delta\epsilon \cong \frac{\sigma_o^2}{\sigma}\frac{\delta x_{rms}^2}{L^2} n_{lap} L_{rec} \qquad (1)$$

Here (with example numbers from the High Energy Ring of the example point design), $\sigma_o \cong 1.4$ is the undepressed tune, $\sigma \cong .14$ is the depressed tune, the half lattice period $L = 350$cm, the number of laps the beam makes in the ring $n_{lap} = 100$, the circumference $L_{rec} = 1.9 \times 10^5$ cm. We find a $\Delta\epsilon = 2.2 \times 10^{-3}$ cm rad if the rms alignment error $\delta x_{rms} = 10\mu$. This compares to an average emittance of about 3.8 $\times 10^{-3}$ cm rad in the design for the High Energy Ring. This is a pessimistic estimate assuming that all centroid oscillation energy is converted into emittance growth. Steering will minimize such oscillations before phase mixing occurs, so that eq. (1) indicates that alignment tolerances may not be unreasonable in a driver. Thus far, estimates of non-linearities and preliminary numerical work have yet to demonstrate that emittance growth will be unmanageable (Ref. [7]), but work in this area is just beginning.

IV.VACUUM CONSIDERATIONS

The vacuum requirements for the recirculator are somewhat more demanding than for the induction linac approach. The larger residence time of the ion beam in the recirculator by a factor of 10 or so, requires an average background gas density that is smaller by the same factor. Further, gasses that are desorbed from the walls, will make a larger contribution to the pumping load in the recirculator than in the linear case. (See Refs. [7], [8] and references therein for a more complete description.)

The fractional beam loss x_{ce} from charge exchange alone is approximately written:

$$\begin{aligned} x_{ce} &= \sigma_{ce} n_b v_{cm} \Delta t \\ &\cong .025\left(\frac{A}{200}\right)^{.62}\left(\frac{\epsilon_N}{.001\text{ cm rad}}\right)^{2.24}\left(\frac{Q_b}{100\ \mu\text{C}}\right)\times \\ &\times\left(\frac{7\text{ cm}}{r_p}\right)^{4.24}\left(\frac{\eta_p}{2}\right)^{4.24}\left(\frac{30\text{ m}}{l_b}\right)\left(\frac{\Delta t}{3\text{ ms}}\right)^{.62} \end{aligned} \qquad (2)$$

Here we have assumed the cross-section for a heavy ion to change charge states due to an interaction with another heavy ion $\sigma_{ce} \cong 2.1 \times 10^{-16}(E_{cm}/10\text{keV})^{.62}$ cm^2 (cf. Ref. [9]). Also, n_b is the heavy ion beam number density; A is the heavy ion atomic mass; ϵ_N is the normalized emittance; $E_{cm} = A m_H v_{cm}^2/2$; $v_{cm} \cong \epsilon_N c/a$; Q_b is the charge in each ion bunch, the beam radius a is a fraction η_p of the pipe radius r_p,l_b is the bunch length, and Δt is the residence time of the bunch within the recirculator. Note the steep dependence of the charge exchange loss on the pipe radius.

The required background gas density can be determined by consideration of the mass continuity equation of the heavy ion beam, which approximately yields,

$$n_g \cong \frac{x_{strip}}{\sigma_s n_{lap} L_{rec}}. \tag{3}$$

Here x_{strip} is the fractional beam loss due to stripping, σ_s is the cross section for a background gas molecule to strip an electron off of a heavy ion, n_{lap} is the number of laps of the recirculator of circumference L_{rec}, satisfying $n_{lap} L_{rec} \cong v_i \Delta t$, where v_i is the heavy ion velocity. Eq. (3) indicates the scaling that the required gas density is approximately inversely proportional to the residence time.

By consideration of the continuity and momentum equations of the background gas the total pumping rate may be obtained (cf. Refs [7], [8] and references therein):

$$S_{lin} L_{rec} \cong N_b n_{lap} L_{rec} \left(\frac{\sigma_s Q_o A_{sp}}{x_{strip}} + \frac{(\eta_G \sigma_i + \eta_{HI} \sigma_s) Q_b}{q e t_r} \right) \tag{4}$$

Here S_{lin} is the average pump rate per unit distance along the accelerator, Q_o is the intrinsic gas desorption rate per unit area, N_b is the number of beams; η_G is the number of molecules desorbed from the pipe inner wall per incident gas molecule; η_{HI} is the number of molecules desorbed from the pipe inner wall per incident heavy ion; qe is the ion charge; t_r is the repetition time for pulses in the recirculator, and $A_{sp} = 2\pi r_p L_{rec}$ is the total surface area of a single beam pipe. Eq. (4) is approximately true when appropriate averages are made over cross sections and desorption coefficients and also when the beam induced wall desorption is not undergoing an exponential growth. This condition can be expressed as a condition on r_p as:

$$r_p >\sim \left(\frac{(\eta_G \sigma_i + \eta_{HI} \sigma_s) Q_b n_{lap}}{\pi q e} \right)^{1/2} \tag{5}$$

From eqs. (4) and (5) we can see that the total pumping rate decreases as r_p decreases (as the intrinsic gas desorption decreases) but then increases with further decrease of the pipe radius as the beam induced desorption begins to take off. As an example, in the High Energy Ring of one point design, $N_b = 4$, $n_{lap} = 100$, $L_{rec} = 1.9 \times 10^5$ cm, $Q_o \sim 10^{-11}$ torr l s^{-1} cm^{-2}, $x_{strip} = .01$, $\eta_G \sim 5$, $\sigma_i \sim 5 \times 10^{-16}$cm^2, $\eta_{HI} \sim .01$, $\sigma_s \sim 5 \times 10^{-17}$cm^2, $Q_b = 100$ μC, $qe = 1.6 \times 10^{-19}$ C, $t_r = .1$ s, so that $S_{lin} L_{rec} = 2.2 \times 10^6$ liters s^{-1}, which translates into a pumping cost of \$ 22 M assuming a unit cost of \$ 10 l^{-1}s. The required background gas density would be then be about 3×10^{-10} torr. The minimum pipe radius from eq. (5) would be about 7 cm.

V. CONCLUSIONS

Recirculators have the potential for significantly reducing the cost of a heavy ion fusion driver. As in other driver scenarios, beam quality issues must be well understood before the success of a proposed driver can be evaluated. We have given two examples of how our present understanding of these issues helps constrain recirculator design, and have indicated how accelerator parameters depend on physical parameters.

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