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PRELIMINARY DESIGN FOR A RECIRCULATING INDUCTION ACCELERATOR FOR HEAVY ION FUSION†

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Substantial savings in size and cost over a linear machine may be achieved in an induction accelerator in which a heavy ion beam makes many (~50) passes through one or more circular accelerators. We examine a point design for such an accelerator, consisting of four rings. We discuss the consequences of this design on emittance growth, longitudinal instability growth, vacuum requirements, pulser requirements, pulsed-magnet requirements, acceleration schedule, and cost.

The concept of recirculating induction accelerator as a fusion driver has been known ever since the early days of heavy ion fusion. The potential cost advantages of such a machine are obvious. Multiple passes through induction cores (N_{lap} times) lead to a reduction of core material by a factor of $1/N_{\mathrm{lap}}$. In contrast to a linear machine whose length is limited by the maximum accelerating gradient (~1 MV/m), the circumference of a circular machine is limited by the effective radius of curvature for bending. The savings in length is about a factor of 5 for a given charge state. The cost for focusing magnets and structures could be expected to be reduced correspondingly. In addition, multiple use of induction cores eases the constraints on minimizing the total volt-seconds. One can then generally consider pulses with longer duration. For a given charge per bunch, this implies new freedom in reduced current and/or number of beamlets. The transverse dimensions of circular machines could be expected to be much smaller.

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TABLE 1
4-ring Recirculator Design Example

	IR	LER	MER	HER
Ion Energy	3–20 MeV	20–100 MeV	0.1–1 Gev	1–10 Gev
Pulse Duration (μs)	115–32.5	32.5–3.5	3.5–0.55	0.55–0.10
Circumference (m)	335	283	921	2591
Current/beam (A)	0.9–3.1	3.1–29	29–182	182–1000
No. of Beams	4	4	4	4
No. of Laps	50	50	50	50
Pipe Radius (m)	0.084	0.075	0.068	0.068
Lattice Half Period (m)	0.80	0.87	1.26	3.03
Induction Modules:				
Inner radius (m)	0.295	0.263	0.236	0.237
Outer radius (m)	0.565	0.583	0.565	0.598
Length (m)	0.404	0.481	0.591	0.542
No. of Cores	224	221	607	1580
Bends (Magnetic Dipoles):				
Length (m)	0.23	0.31	0.54	1.6
Max. Mag. Field (T)	0.7	1.5	1.1	1.0
No. of Bends	1424	1100	2712	3200
Superconducting Magnetic Quadrupoles:				
Length (Eff. Length) (m)	0.52 (0.40)	0.49 (0.39)	0.59 (0.48)	1.08 (0.96)
Max. Mag. Field (T)	1.3	2.8	3.2	2.1
No. of Quads	1560	1184	2800	3304

Offsetting the potential cost advantages described above, recirculators were expected to have a more complex pulse-power system to accommodate the variable lap-to-lap format in the induction cells, along with time-varying dipoles to match the lap-to-lap increase in beam energy. The cost reduction potential of recirculators could be realized provided that the pulsers are not prohibitively expensive. In addition, new issues associated with the dynamics of space-charge dominated beams going around bends and with possible beam loss due to long resident times must be addressed.

These considerations have led to an intensive study by a team from LLNL and LBL over the last few months. Our goals were to ascertain whether the recirculator concept is indeed technically viable, and to construct a realistic cost estimate on the basis of a concrete point design.

The present study focuses on a 4 MJ system, consisting of ions of mass 200 and charge state +1, accelerated to final energy of 10 GeV. The driver design example consists of 4 rings. Acceleration from 100 MeV to 10 GeV is accomplished in the high-energy ring (HER) and the medium-energy ring (MER), each ring incrementing the beam energy by one decade. The low energy end consists of the injection ring

(IR), which is fed by a 3 MeV injector, and accelerates ions to 20 MeV, and the low-energy ring (LER), which provides transition from IR to MER. The key parameters of the 4-ring driver are shown in Table 1.

Conceptual designs of the dipole and induction core pulsers for the 4-ring driver have been constructed. The dipole field must be ramped to its peak value of 1–2 T in ~1 millisecond. Very efficient energy recovery is required since the energy stored in the dipole fields is about ten times the total beam energy. A sinusoidally ringed circuit with appropriate switching for energy recovery[1] is expected to be ~95% efficient. Multiple pulsing of the induction cells is accomplished in the IR and LER by means of hard-vacuum tubes and in the MER and HER with pulse-forming-networks together with appropriate switching, using thyratrons and magnetic devices.[2]

The recirculating induction accelerator, like the linear version, requires multiple beam operation to accommodate space-charge effects. To minimize the complexities of beam manipulation around the rings, we have chosen a design which consists of four parallel beams from injector to final extraction. No beam merging is required.

The 4-beam configuration at the low energy end is made possible by operating at very low currents, and therefore long pulses. At the 3 MeV injection into the IR, the beamlet current is 0.87 A and the pulse duration is 115 μs. With this low current, the beamline consists of half lattice periods (L) which are ten times longer than the pipe radius (R). This aspect ratio allows adequate room for focusing, bending and extraction/injection without resorting to extremely short magnets. The beam is accelerated at constant beam size to 20 MeV, at which point the current is 3.1 A, and the pulse duration is 32.5 μs. In our design, the acceleration in the IR (as well as in each of the other rings) is achieved in 50 laps. The core material required is therefore quite reasonable even though the pulses are long.

The LER is designed to accommodate a relatively large pulse compression factor. The pulse duration at exit is 3.5 μs. The hard-tube switches in the LER provide the flexibility required for the somewhat more delicate beam manipulations needed during compression. Other constraints on focusing and bending are also eased by designing for only a fivefold increase in beam energy in the LER.

The acceleration schedules in the MER and HER are both tailored for the switching available. Since the pulse-forming-network can produce only one voltage waveform with a fixed duration (although it can be repetition-rated for variable intervals) the beam pulse duration is fixed during acceleration. After acceleration is complete in each of the rings, the pulses are compressed to the desired pulse length in the last couple of laps. The velocity tilt required for compression is induced by judiciously delaying some of the pulsers.

The design of the MER and HER is by no means unique. We strive to maintain a balance between the dual goals of low cost and high efficiency. As an example, our cells are designed with four times more Metglas than is required by the maximal flux swing. This measure reduces the core losses drastically. The dipole fields employed reach a maximum of only 1 T. This design increases the number of dipoles (as compared to a higher field design) but reduces the field energies required. Cost reductions were achieved by employing low-field superconducting magnets (2 to 3 T), and embedding them inside the induction cores. On the basis of our first bottoms-up estimate, the efficiency of this driver is calculated to be 24%, and substantial savings in cost over a linear machine appear to be borne out.

The longitudinal instability for our recirculator point design is much milder than its linear counterpart, primarily because of a much reduced impedance per unit length due to the lower accelerating gradient. The low-frequency gain is calculated to be 5 or 6 e-folds even before capacitative effects are taken into account. The transverse beam breakup instability can be kept quite small as long as care is taken to minimize the quality factor Q of the induction cells. Although detailed calculations of the resonance crossing instability have not yet been performed, it is expected to be insignificant because of the large changes in tune ($\Delta\nu > 1$) from revolution to revolution.

Our point design is based on 50 passes per ring. The long residence time can lead potentially to beam loss due to charge exchange and stripping by background gas. Charge exchange losses turn out to be exceedingly sensitive to beam radius ($\propto a^{-4}$). By a judicious choice of focusing strengths, beam radii are kept to no less than 3 or 4 cm in all rings, yielding $\sim 1\%$ loss due to charge exchange over the millisecond residence. Vacuum requirements imposed by beam stripping are somewhat more difficult to determine. The primary unknowns are related to the generation of background gas as beam and background ions impinge upon the accelerator walls. Based on our best estimate of the ionization cross sections and desorption coefficients, beam loss could be kept small[3] for background pressure of $\sim 10^{-10}$ Torr.

Emittance growth of space charge dominated beams around bends is an area of active studies. Analytic work by Ed Lee and V. Kelvin Neil and numerical simulations by A. Friedman have not to this point discovered mechanisms for major brightness degradations for matched beams, but further theoretical and experimental work is required to understand this central issue.

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