IL NUOVO CIMENTO Vol. 106 A, N. 11 Novembre 1993

Recirculating Induction Accelerators for Heavy-Ion Fusion (*).

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(ricevuto il 18 Giugno 1993; approvato il 21 Giugno 1993)

Summary. — A two-year study of recirculating induction heavy-ion accelerators (recirculators) as low-cost drivers for inertial-fusion energy power plants has recently been completed. A summary of that study and other recent work on recirculators is presented.

PACS 28.52.Av – Theory design, and computerized simulation.
PACS 29.20 – Cyclic accelerators and storage facilities.
PACS 41.80.Gg – Ion beams and ion optics.
PACS 84.70 – High-current and high-voltage technology.

1. – Introduction.

Heavy-ion accelerators have been identified as leading candidates for Inertial Fusion Energy (IFE) power plant drivers. The induction accelerator is the leading U.S. candidate for heavy-ion fusion (HIF) due to its inherent ability to transport high current, and favorable cost projections for induction linac drivers. Additionally, the development path of induction accelerators begins with high-current, lower-energy accelerators, and so complements the European radio-frequency approach which initially focuses on higher-energy, lower-current machines.

In this paper we present a synopsis of the major results of a two-year study of recirculating induction accelerators (recirculators) and also our most recent work on the subject. The complete recirculator report may be found in ref. [1], and a recent review of the critical issues facing a recirculator can be found in ref. [2]. The potential

(*) Paper presented at the International Symposium on Heavy Ion Inertial Fusion, Frascati, May 25-28, 1993.

for cost reduction motivates our studies. In ref. [1], a few design examples of recirculators were produced, from which we made concrete cost and efficiency estimates. In addition, the designs allowed us to determine some of the major physics and engineering issues of the recirculator.

Recirculators are induction accelerators in which the components are arranged in one or more nearly circular rings so that they are reused up to 100 times. The resulting reduction in the number of components offers the possibility of a large savings in cost. The length of a linear induction accelerator is determined by the maximum average accelerating gradient achievable, which is about 1 MV/m. For a 10 GeV heavy ion this results in a length of $10\,\mathrm{km}/q$, where q is the charge state of the ion. In contrast, the circumference of the recirculator is determined by the bending radius of a 10 GeV ion in an average bending magnetic field of about 1 T. This suggests a minimum ring circumference of about $1.3\,\mathrm{km}/q$ for the highest-energy ions (with atomic mass 200). Since the components are used repeatedly the accelerating gradient may be reduced by an order of magnitude. This reduced gradient results in induction cores which are smaller than those of a linear accelerator. The combination of smaller cores and fewer components has a major impact on reducing the driver cost. However, ramped magnetic dipoles, increased induction core pulser repetition rates, and longer path lengths traversed by the beam are all more demanding in the recirculator, and therefore the impact of these issues on the design must be considered.

2. – Recirculator overview.

Figure 1 schematically depicts the layout of one of our recirculator designs. The final pulse energy is 4 MJ carried by ions at an energy of 10 GeV, and an atomic mass of 200 a.m.u. This design consists of three rings, each with four beamlines. The beams make 100 laps through each ring. The beams are injected into the low-energy

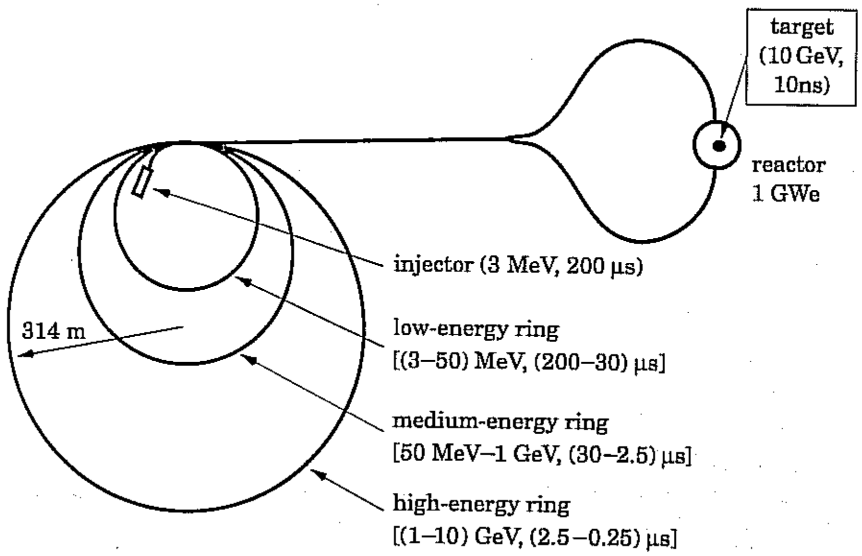

Fig. 1. – Schematic layout of a recirculating induction accelerator.

ring at 3 MeV with a pulse duration of 200 μs. This is a long pulse for an induction accelerator, and can be achieved because of the low voltage gradient, which permits a reasonable size induction core. The beam is initially half the circumference of the low-energy ring (LER). After increasing the energy to 50 MeV and decreasing the pulse duration to 30 μs, the beam is extracted from the LER and injected into the Medium Energy Ring (MER), where the energy increases to 1 GEV and the pulse duration decreases to 2.5 μs. The beam then transfers to the High Energy Ring (HER) where the final energy of 10 GeV is reached, but the pulse duration is still 250 ns long. There is a final linear bunching section, which imparts a head to tail velocity «tilt» to further compress the beam so that when it reaches the target the pulse duration is 10 ns. A reactor based on this design produces approximately 1 GW of electric power.

Each ring consists of a number of lattice elements, arranged in a large circle, interrupted only by the linear injection/extraction/transition sections. The lattice arrays consist of induction modules for acceleration, dipole magnets for bending the beam, and quadrupole magnets for focusing the beam. Additional space is allotted for vacuum, control, and diagnostics.

The induction cores are composed of annular cylinders of ferromagnetic material. A voltage pulse is received from the pulsers, and, as in a transformer, an electric field is produced across the acceleration gap to provide an increment in energy to the beam. The product of the voltage and pulse duration is, by Faraday's law, proportional to the cross-sectional area of the induction cores. The efficiency of the cores is maximized when the cell voltage is minimized and when the core cross-sectional area is optimized. That is, as the core cross-section is incrased from its minimum value, initially the change in magnetic-flux density decreases (increasing the efficiency), but as the cross-section is further increased, the increasing core volume eventually increases the core losses, decreasing the efficiency. Since the voltage gradient in the recirculator is smaller than in a linear accelerator, the cell voltage can be smaller, and so the core cross-section can be reduced substantially to minimize cost, or reduced less to increase efficiency by reducing the magnetic-flux swing from its maximum (saturated) value.

The dipole field is produced by two types of bending magnets: a time-independent superconducting component (for high efficiency) and a temporally ramped conventional component (to accommodate the increasing energy of the beam) which varies from -0.8 T to $+0.8$ T. By including the time-independent component, we minimize the magnitude of the ramped part and thus increase the efficiency of the dipoles.

The superconducting quadrupoles comprise the third major element in a lattice period. In our conceptual design the superconducting quadrupoles and dipoles are united into a combined function magnet. The quadrupoles are placed within the induction cores to reduce the overall circumference of the recirculator. Since the quadrupole field is constant in time the betatron frequency of the beam changes as the beam is accelerated.

3. – Cost and efficiency results.

A system code which used the design equations to determine the specifications of each component was developed. The \$500 M total cost was the sum of component costs. That is, individual quadrupoles, dipoles, induction modules, etc., were designed and their costs determined on the basis of material quantities and assumed manufacturing costs. The result is a significant reduction in cost from the conventional linac which was estimated in the Heavy Ion Fusion System Assessment studies [3] to be about $ 1000 M. However, other recent studies [4, 5] have suggested similar cost reductions, using a variety of cost-saving techniques, including higher-charge state, different material for superconductors, and multipulsing a linac into a set of storage rings. Present studies by W. J. Schafer Associates (in collaboration with LLNL) are in progress, comparing linacs and recirculators using identical costing algorithms [6]. In addition, both the linacs and recirculators are being optimized from injector to target, so that a fair comparison can be made between the two concepts.

In addition to estimating costs, the energy requirement of each component was calculated and a summation was made over all components. The energy budget was divided among three major elements: the beam recived 35% of the supplied electrical energy, losses in the acceleration modules accounted for another 31% and losses in the ramped dipole magnets accounted for another 24% of the energy. An additional 10% was lost in miscellaneous sources such as vacuum, refrigeration, and beam injection and extraction. The efficiency of 35% compares favorably to that of linear induction accelerators. This result is at first glance surprising since the addition of ramped dipole magnets provides energy consumption which does not occur in the linear machine. However, the lower voltage gradient allows smaller cores with lower individual voltages, making the induction cells much more efficient. In addition, the decomposition of the dipole field into an efficient time-independent component and a temporally-ramped, energy-consuming component helps to minimize losses in the dipole magnets.

4. – Physics and engineering issues.

The principal technology issues identified include energy recovery of the ramped dipole magnets, which may be achieved through use of ringing inductive/capacitive circuits [1, 7], and high repetition rates of the induction cell pulsers, which may be accomplished through arrays of Field Effect Transitor (FET) switches [1, 8]. Principal physics issues identified include minimization of particle loss from interactions with the background gas and from beam-beam interactions [1], and more demanding emittance growth and centroid control requirements associated with the propagation of space-charge–dominated beams around bends and over large path lengths. The amount of emittance growth from two major sources was estimated: from bend/linear transitions [9, 10] and from misaligned quadrupoles [1]. These estimates indicated that emittance growth would meet the target requirements. Centroid control will be possible with present-day alignment capabilities if steering with feedback is used to correct errors in beam position. In addition, instabilities such as the longitudinal resistive instability and beam–break-up instability were found to be controllable with careful design. The betatron-orbit instability, which limits the tune shifts in other circular machines, was found to be benign also, because of the relatively rapid change in betatron frequency, arising from the increasing beam energy and constant quadrupole field. (The number of betatron periods per orbit changes by an average of 0.4 periods in the HER, which is an average phase change of 144°. This effectively causes a given misalignment to give a random kick to the beam centroid, producing a random walk off axis, as if the recirculator were a long linear accelerator.)

5. – Summary and conclusions.

We find that a 4 MJ recirculator driver would have a projected cost of about $ 500 M and would have an estimated efficiency of 35%. The crucial technology issues include the high-repetition-rate pulsers and efficient energy recovery in the ramped dipole magnets. Small-scale experiments are in progress to validate the solutions to these engineering challenges. The principal physics issues are the maintenance of high vacuum, beam centroid control and beam emittance control. Estimates to date show no insurmountable hurdles, although critical desorption data are required to validate our assumptions concerning the vacuum design. To provide a test of the recirculator concept, we plan to add a recirculator ring at the output end of the Induction Linac Systems Experiments facility, which is now being planned at the Lawrence Berkeley Laboratory, in collaboration with LLNL. We find the recirculator to be a promising candidate for reducing the cost of an inertial-fusion driver and believe merits further theoretical, computational, and experimental study.

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In addition to the authors of this paper many people contributed to our recirculator studies. These people include W. A. Barletta, A. L. Brooks, R. Bieri, D. Callahan, J. P. Clay, F. Coffield, J. DeFord, W. M. Fawley, T. J. Fessenden, W. L. Gagnon, A. R. Harvey, J. R. Heim, D. W. Hewett, D. C. Ho, W. J. Hogan, C. A. Hurley, A. B. Langdon, E. J. Lauer, J. L. Miller, R. W. Moir, H. G. Patton, G. E. Russell, C. Shang, S. Shen, D. S. Slack and L. Smith. This work was performed under the auspices of the U.S. Department of Energy at Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and at Lawrence Berkeley Laboratory under contract DE-AC03-76SF00098.

REFERENCES

[1] J. J. Barnard, A. L. Brooks, J. P. Clay, F. Coffield, F. Deadrick, L. V. Griffith, A. R. Harvey, D. L. Judd, H. C. Kirbie, V. K. Neil, M. A. Newton, A. C. Paul, L. L. Reginato, G. E. Russel, W. M. Sharp, H. D. Shay, J. Wilson and S. S. Yu: *Study of Recirculating Induction Accelerators as Drivers for Heavy Ion Fusion,* LLNL Report UCRL-LR-108095, September, 1991.

[2] J. J. Barnard, F. Deadrick, A. Friedman, D. P. Grote, L. V. Griffith, H. C. Kirbie, V. K. Neil, M. A. Newton, A. C. Paul, W. M. Sharp, H. D. Shay, R. O. Bangerter, A. Faltens, C. G. Fong, D. L. Judd, E. P. Lee, L. L. Reginato, S. S. Yu and T. F. Godlove: *Recirculating induction accelerators as drivers for heavy ion fusion, Phys. Fluids B,* in press (1993).

[3] J. Hovingh, V. O. Brady, A. Faltens, D. Keefe and E. P. Lee: *Fusion Technol.*, 13, 255 (1988).

[4] R. F. Bourque, W. R. Meier and M. J. Monsler: *Fusion Technol.*, 21, 1465 (1992).

[5] L. M. Waganer: IEEE/NPSS *Symposium on Fusion Engineering, October 1991.*

[6] R. L. BIERI: *Parametric studies for recirculating induction accelerators as drivers for heavy-ion fusion*, in *Proceedings of the 1993 Particle Accelerator Conference, 17-20 May 1993, Washington, D.C.*
[7] L. REGINATO, M. NEWTON and S. S. YU: *Part. Accel.*, 37-38, 335 (1992).
[8] M. A. NEWTON and H. C. KIRBIE: this issue, p. 1575.
[9] J. J. BARNARD, H. D. SHAY, S. S. YU, A. FRIEDMAN and D. P. GROTE: *Proceedings of the 1992 Linear Accelerator Conference, August 24-28, 1992, Ottawa, Ontario, Canada*, AECL-10728, Vol. 1 (Scientific Document Distribution Office, AECL, Chalk River, Ontario, Canada, 1992), p. 229.
[10] A. FRIEDMAN, D. A. CALLAHAN, D. P. GROTE, I. HABER, A. B. LANGDON and S. M. LUND: this issue, p. 1649.