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LINEAR INDUCTION ACCELERATOR FOR HEAVY IONS *

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Abstract

There is considerable recent interest in the use of high energy ($\gamma \approx 1.1$), heavy ($A \gtrsim 100$) ions to irradiate deuterium-tritium pellets in a reactor vessel to constitute a power source at the level of 1 GW or more. Various accelerator configurations involving storage rings have been suggested. This paper discusses how the technology of Linear Induction Accelerators--well known to be matched to high current and short pulse length--may offer significant advantages for this application.

1) Technology

The Linear Induction Accelerator (LIA) utilizes a sequence of singly pulsed accelerating cavities arranged in a straight line. Each cavity is loaded with ferromagnetic material (thin-laminated iron or ferrite) driven by a modulator (pulse forming network and spark gap/thyratron switch) and acts as a transformer in which the particle beam plays the role of the secondary winding. The phasing of the pulsed cavities is adjusted to accelerate a particle of particular q/m in correspondence with the mean accelerating field $\overline{E}$ (MV/m). Thus, only a portion of the structure is energized at one time, and this region propagates down the accelerator in synchronism with the particle bunch.

The technology is relatively simple but not widely known simply because only four machines have been built in this country [Astron I, (2 MeV), Astron II (5 MeV), ERA (4 MeV) and NBS (0.25 MeV)]. In addition, two other electron machines are in the planning stages at LLL, while conceptual designs for LIA's for very special purposes have appeared in the literature [1,2]. (See Table I.)

Table 1

Linear Induction Accelerator
Parameters Achieved (or Designed)

Machine	I	τ	Rep. Rate	V/gap	$\overline{E}$
	amp	ns	Hz	kV	MV/m
Astron II	1000	300	30	10	≈0.3
ERA Inj.	1-5000	50	1(10)	250	0.3
NBS	1000	1700	1(10)	250	≈0.5
ERA(des)[1]	--	10	200	750	5.5
Excav(des)[2]	5000	1000	360	80	0.11

Basically the technology seems best matched to applications where a very high current (100 - 10,000 A) is required for a short time (10 - 2,000 ns) with rather precise voltage control. In addition, the ability to run at repetition rates up to 100 Hz or so seems to come naturally for very little extra expenditure on additional charging supplies. If the beam current can be matched to the cavity voltage and impedance, the pulsed energy conversion efficiencies can approach 50% in the absence of eddy-current and hysteretic losses. Achievement of high-impedances for accelerating low-current beam is an outcome of the NBS work on parallel driven cores.

2) The LIA as an Ignition Source for Pellet Fusion

The short-pulse, high-current features make the LIA worthy of consideration as an igniter for D-T pellets, and a preliminary set of workable self-consistent parameters were presented in Ref. 3. That example was explored, however, in the context of a scientific breakeven experiment to deliver 0.2 MJ to the pellet, and has the features shown in the first row of Table II.

The work at the ERDA Summer Study Group has been directed on the other hand to parameters appropriate to a power plant of ≥ 1 GW. Because the number of parameters that can be varied is rather large, and some of the correlations somewhat subtle, the focus of attention was on just two examples which, in hindsight, are almost certainly not optimum. The second row of Table II shows the case studied. Note that repetition rate up to 10 Hz certainly and ≤ 100 Hz probably can be considered as a free parameter and this point will not be addressed further.

Comparison of the two rows of Table II will reveal that the increased requirements of energy (Q) and power (P) by a factor of 15 to 20 over the Ref. 3 example have forced one in the direction of lower charge state and hence a longer accelerating column.

In addition, it will emerge that the increased power will impose rather special requirements on the beam handling in the front 1-2% of the accelerator column which were not in the earlier example. The remaining 98-99% of the accelerating column, however, is a good match to the characteristic features of pulse length and current inherent in the LIA technology.

3) Limiting Features and Choice of Parameters

A convenient approach to setting parameters is

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Table II

Example Parameters Considered for 25 GeV Uranium Ions

Example	Charge q	Energy Q (MJ)	Power P (TW)	Current (amps) Initial / Final	Gradient $\overline{E}$ (MV/m)	Overall Length (km)	τ_{final} (nsec)
Ref. 3	+10	0.2	20	84 / 8400	3.0	0.8	10
ERDA Summer Study	+3 (+1)	3.0	450	≈10 / 18,000	2.5	3.3 (10)	7

3) Cont'd.

to consider the end point of the accelerator when acceleration is essentially complete and before the beam is subdivided and the segments finally compressed in time to 7 nsec for delivery to the target. The most strongly limiting effect is the beam power transmission limit discussed by Maschke [4] and later by Courant [5]. Courant's expression for the power is

$$P \approx 2.6 \times 10^{15}\, \beta^{11/3}\, \gamma^{5/3}\, (B_o{}^{2/3})/q^{4/3} \text{ watts} \qquad (1)$$

for an emittance $\pi\varepsilon$ of 6π cm mrad at $\beta\gamma = 1$. For a practical pole-tip field strength of $B_o = 1$ Tesla, this yields a maximum transmitted power and current

$$P_3(q=3) = 35 \text{ TW} - I_3 = 4.2 \text{ kA},\ \tau = 85 \text{ nsec}$$

$$P_1(q=1) = 150 \text{ TW} - I_1 = 6.0 \text{ kA},\ \tau = 20 \text{ nsec}$$

at the 25 GeV end point. (How these powers can be transformed up to the goal of 450 TW on target will be discussed later). These currents are within the comfortable range for induction acceleration and as one proceeds backward up the accelerator, it is desirable to maintain the current as high as possible. However

$$P(\beta) = I(\beta)\ V(\beta) = 1/2\ \frac{M\beta^2}{qe}\ I(\beta). \qquad (2)$$

Combining this with Equation (1) it is clear that one can remain everywhere within the power limit if $I(\beta)$ is made to vary as $(\beta)^{5/3}$. This would require a pulse-length variation of

$$\tau \sim 1/\beta^{5/3} \qquad (3)$$

How close this can be approached with reasonable ramping voltages remains to be studied in detail. Since Eqn. (3) impresses only a lower limiting condition, larger values of τ are permitted if desired; in particular, in the case of $q = 1$, it is undesirable to compress all the way to $\tau_1 = 20$ ns but instead to maintain a constant value after $\tau = 50$-70 nsec has been reached in order to avoid the steep gradients needed to counterbalance space-charge effects in the bunch.

For a major fraction of the machine (≥95%) both the currents and pulse lengths are in ranges that are well adapted to the L.I.A. technology, and it is possible therefore to achieve rather good efficiency in converting electrical energy into the beam energy. As pointed out by J. Leiss [6], it is important to examine the engineering trade-off between the capital cost and the efficiency desired.

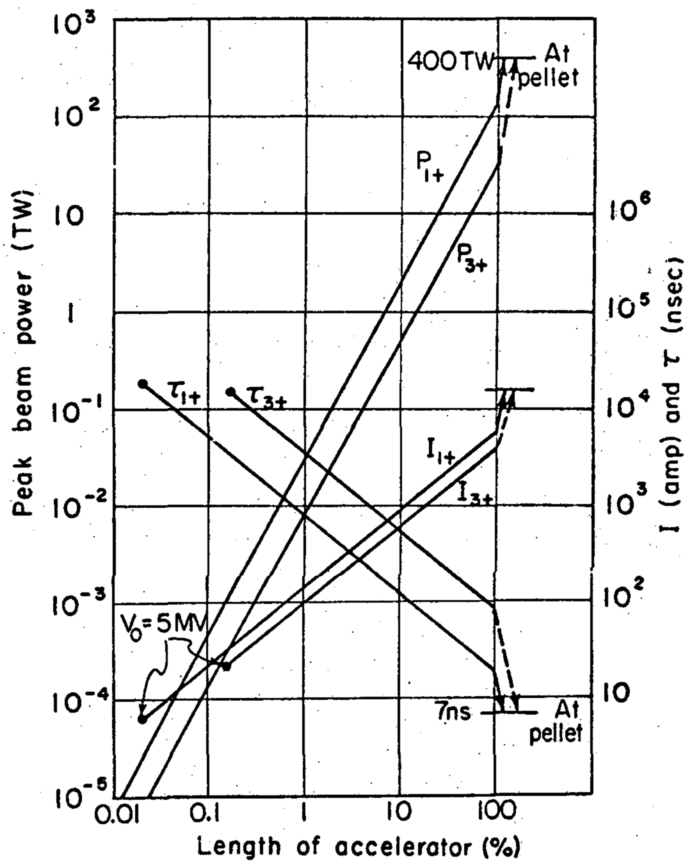

Fig. 1: Beam power limit as function of length along accelerator for 25 GeV Uranium Ions (q = +1 and +3). Required peak current and minimum pulse length shown on right-hand scale [note log-log plot].

From Fig. 1 it can be seen that the Maschke power transmission-limit formula imposes a requirement that the pulse length should be rather long and the current quite low (tens of amperes) in the front few percent of the machine (referred to for convenience as the Power Matching Section).

This then leaves three sections of the system for special consideration:

(i) Ion source; (ii) Front few percent of accelerator - "Power Match Section;" (iii) Transmission and bunching between the end of the accelerator and the target.

(i) Source: For the ion source there are several choices: magnetically-insulated diode, reflex diode, or stacked conventional sources [7]. The high-voltage diodes have the outstanding advantages of creating the ions at high-energy and of having very large current density. They have not yet, however, been studied enough to be sure that they can provide adequate brightness. Since the currents needed are in the range of a few tens of amperes (compared with kiloamperes available), there is considerable hope of achieving this goal by operating with larger spacing and with more careful control of the anode plasma conditions. At this time--still early in the development history of these diodes--there seem to be some reasons for anticipating that the magnetically insulated diode is to be preferred. The geometry allows electrons to drift (by $\bar{E} \times \bar{B}$) indefinitely around without having a preferred location for accumulation of charge, thus giving hope of operation on the microsecond, and longer, time scale. Also, the magnetic field is transverse to the direction of motion of the ions and so leads to a deflection in one plane which can be corrected for exactly. In the reflex diode there is some concern about instabilities of the virtual cathode that could lead to energy modulation of the ions: this situation could be ameliorated by using a second image cathode pierced to allow ion extraction; a more fundamental objection, however, is that the magnetic field in which the ions are born is parallel to the direction of motion of the ions, which leads to an undesirable coupling of the two transverse degrees of freedom, and hence a dilution of useful emittance in the later transport system of the accelerator. This dilution seems not to be serious at the 1 kG level but could become so at the 10 kG (or more) level required.

Stacked conventional sources can give adequate brightness if operated in the range of 30-100 mA. The size required is rather large but not unduly so ($\sim$15 - 30 cm radius). There is a considerable body of experience in operation and performance to be drawn upon, and long-pulse operation is assured. A slight disadvantage is the relatively low-voltage ($\approx$ 100 kV) which will cause the front-end low-energy transport and acceleration system to become longer.

(ii) Power Matching Section: Reference to Fig. 1 shows that for q = 3, the pulse length needed in the first few percent of the accelerator exceeds the 2 μsec or so that seems most suitable for LIA cavities. Possible methods of handling this problem include using a conventional rf linac to inject about 100 bunches into an accumulator ring at a few hundred MeV and accelerating thereafter in the LIA [8]. Alternatively, five or so beams of lesser current could be extracted from a magnetically insulated diode or parallel conventional sources, separately accelerated to a few hundred MeV and reassembled via magnetic septa into the required high-current beam. Appeal to various neutralization schemes would, of course, provide other solutions; these are, as yet, unexplored. Long pulse lengths up to 20 μsec are certainly feasible--at the expense of decreased accelerating field--and may well be a viable method of proceeding. At the present level of investigation, however, it seems prudent to suggest that other methods should be considered. It should also be pointed out that the Maschke formula is based on conditions that are not valid at low energies. In other words, a realistic transport and accelerating system still needs to be studied and defined in detail.

(iii) Bunching: Pulse-shaping can be rather easily accomplished in the LIA (c.f. ERA injector experience where a ramped cavity could be turned on to produce a programmed ramp in the energy of the beam with time). For instance, towards the end of the accelerator it is envisioned that addition of an $\dddot{E}$ term (or higher-order odd derivative) to the $\dot{E}$ ramp will be required to contain the space-charge forces at the beam ends, and so establish a moderately uniform transverse space-charge force throughout most of the length of the bunch. This need not be accomplished by detailed shaping of pulses in every cavity but simply by adding occasional short-pulse ferrite kickers.

Splitting of the beam into 2 or 4 channels, say, for separate transport to the target can be accomplished in a number of ways. Fast kickers provide one approach; alternatively, modest differential acceleration of sequential portions of the beam can be used to create a momentum spread later to be transformed into spatial spread by passage through a d.c. bending magnet.

In the final compression and transport of individual beams to the target a design pole-tip field larger than 1T is assumed. To bunch to 7ns and transmit 450 TW on target thus requires:

q = 1	2 beams	B_o = 1.85 T
q = 3	4 beams	B_o = 5.2 T.

These "pole-tip" fields are within the state of the art for superconducting magnets.

For the final stages of time compression it is essential to use ferrite because of its fast time-response. Values of $\dot{E}$ in excess of 10^8 MV/meter-sec are easily obtainable. A factor of two is available by employing bi-polar pulses.

Finally, the ability to tailor pulse shapes (within reason) on the nanosecond time scale permitted by ferrite allows one to consider ramping the beam power and approach to some degree the most desirable profile for optimum pellet efficiency.

Conclusion

At this time the LIA seems to be a worthwhile candidate for an efficient pellet igniter (c.f. 6) A comprehensive conceptual design is needed in order properly to evaluate its promise.

References

1) A. Faltens, E. Hartwig, D. Keefe, W. Salsig: IEEE Trans. Nucl. Sci. NS-18, 484 (1971)

2) R. T. Avery and D. Keefe: Proc. Int. Topical Conf. on Electron Beam Research and Technology SAND 76-5122, Vol. II, p.61 (1976).

References (Continued)

3) D. Keefe: Linear Induction Accelerator to Produce Intense Short Pulses of Heavy Ions. Lawrence Berkeley Laboratory Report Bev-3201, April 22, 1976.

4) A. Maschke: Proceedings of the ERDA Summer Study of Heavy Ions for Inertial Fusion (Berkeley, July 19-30, 1976), to be published.

5) E. D. Courant, ibid.

6) J. Leiss, ibid.

7) J. Osher, ibid.

8) T. Godlove, ibid.

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