APPLICATIONS OF INDUCTION LINAC TECHNOLOGY TO HEAVY ION FUSION

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I Introduction: A summer study sponsored by the U.S. Energy Research and Development Administration was held a year ago to evaluate the use of high-energy heavy ions produced by a conventional accelerator system to ignite D-T pellets. The study group concluded that accelerators could offer a very promising solution to the pellet-igniter problem./1/ Several advantages were perceived -- the possibility of high repetition rate (1 - 10 Hz), good electric efficiency (>10%), and considerable past experience in the physics, engineering and operational control of complicated accelerator systems some kilometers in length. The required ion kinetic energy (50 - 400 MeV/a.m.u.), the beam stored energy (1 to 10 MJ) and average power ($\gtrsim$1 MW) are each in a range already experienced. There are difficulties to be overcome stemming from pellet and reactor considerations, e.g. the high specific energy needed in the pellet surface (10-30 MJ/gm), the huge beam power (100-600 TW), the wish for a target larger than $\approx$ 1 mm, and the desire that the openings in the reactor through which the final beams pass be small compared with the reactor dimension. These considerations imply final beam pulses of a few nanoseconds, with currents of order 10 kA, and special care in maintaining good beam quality (e.g. normalized emittance $\epsilon_N = \epsilon\beta\gamma \approx 2 \times 10^{-5}$ rad-m). Maschke has pointed out the stringent requirements on the transport system needed to handle this very high beam power./2/

An adequate igniter will probably comprise an assembly of sub-systems which may span a wide-variety of particle-accelerating and/or storage techniques. One can categorize various systems that have been discussed in terms of the accelerating device that is viewed as supplying the major part of the beam kinetic energy viz. (a) synchrotron, (b) rf linac, and (c) induction linac./3,2,4/ All of these approaches require special strategies for injection at the beginning, and bunching and beam delivery at the end.

Each system has its advantages and disadvantages. Intensive efforts are underway at ANL, BNL, and LBL, to weigh them against each other and to evaluate expected system performance and cost. Compared with either of the linear accelerators (b,c) the synchrotron (a) has a very high rate of energy delivery per meter of structure (MeV/m). Its current will be limited by the betatron tune shift condition, $\Delta\nu < 0.25$, and perhaps also by charge-exchange interactions of the ions within the bunch which lead to beam loss; the design is also sensitive to repetition rate and the pulsed power needs. Both the synchrotron (a) and rf linac (b) are envisioned as being used to feed a number of d.c. storage rings in which current amplification (by transverse stacking) and beam-bunching are accomplished before delivery to the pellet. With the induction linac it is hoped to avoid the use of storage rings and achieve truly a single-pass system.

Here we discuss applications of induction-linac technology to pellet ignition. In the past such machines have been used only for electron beams but have the inherent attraction of operating in the high current (1 to 100 kA) and short pulse-length (20-2000 nsec) regime, which are close to the ion-beam needs. Also there is demonstrated experience of operating at high repetition rate, 5 Hz[5] to 30 Hz,[6] over long time-spans with high-quality voltage control, and the feature intrinsic to this form of pulse-power technology that large instantaneous power (>1 GW) can be delivered to the beam at low average power (<1 kW) with good electrical efficiency.[7] Dimensional tolerances are not stringent and a variety of inductive loading materials are available that are suited to different pulse lengths -- iron laminations in the 1000 ns region,[6,8] and ferrite in the 100 ns region[10] -- whereas vacuum or dielectric radial lines[10,11] are appropriate in the 10 ns range. The overall concept to be discussed relies upon an injector (Sec. III) to supply a current of a few hundred amperes in a pulse time $\tau \approx 2$ μsec, which is then accelerated and compressed in time (hence increased in current) by suitably-ramped voltages, throughout the length of the induction linac, to a few tens of nanoseconds before splitting and delivery to the pellet without resort to storage/accumulator rings. The strategy for pulse compression and current amplification is determined by the design of the transport system, which will be pushed close to its space charge limit. In this way the total cost of ferromagnetic loading material can be minimized. An important question, therefore, is to establish a realistic space charge limit for a linear transport system which will then determine the scenario for the continuous current amplification.

II. <u>The Transport-Limited Current</u>: Several beam-current limiting phenomena can be identified. One that can cause trouble at ion-source energies ($\beta \sim 10^{-3}$) is the space-charge limiting current -- well-known for electron beams -- in which a virtual anode is formed. Another arises at high lens-magnetic-field when off-axis ions are reflected and cannot enter the lens. A third effect arises in a quadrupole focusing channel where the current can be increased by making the aperture larger; a limit occurs when the magnet aperture-to-length ratio attains its maximum allowed value (0.5). These three limits all have a velocity dependence like β^3, are of concern in the early part of all machines but can be ignored when the velocity significantly exceeds $\beta = 0.01$. Thereafter the important limit, I_T, is set by the transport system.[2] The properties of this limit have been explored for quadrupole and solenoid systems by means of the Kapchinsky-Vladimirsky envelope equations.[12] For quadrupoles $I_T \propto (\beta\gamma)^{5/3}$, while for solenoids $I_T \propto \beta\gamma$; the coefficients are such that quadrupoles have a higher limit for $\beta \gtrsim 0.01$, at least for low charge states.

If a strong-focusing system has a phase-shift μ_0 per period, then at high current the defocusing space charge will change the betatron phase shift to a lower value, μ. To transport all currents from zero to the maximum desired, both μ_0 and μ must lie in the interval 0-180°. In principle very large currents can be transported by increasing the lens aperture and allowing μ to become very small; in practice non-linearities in the space charge will set a lower limit to μ.[12] This value is unknown but may be in the region of 30°. Recent work suggests, further, that one choose $\mu_0 < 90°$ to avoid instability of the beam envelope.[13] The transport-limited current for the special case of U^{+4} at 40 GeV (not an optimum) is shown in Fig. 1 for a variety of lens pole-tip fields as a function of the integrated voltage, V(MV), experienced by the ions. The magnets are assumed to occupy half the available length. If one remains close to I_T, then the beam radius is roughly 0.07m. It can be seen that to begin the induction linac with a pulse length of $\tau \approx 2$ μsec (laminated iron cores) the injector must supply 500A (electrical) at 160 MV if the magnets at this point have a pole-tip field of 3T. When the ions have gained another 200 MV the pole tip field can be decreased gradually to 1 T and below, with the pulse-length roughly constant. In the latter half of the the machine the pulse can be further compressed and the core material changed from iron to ferrite.

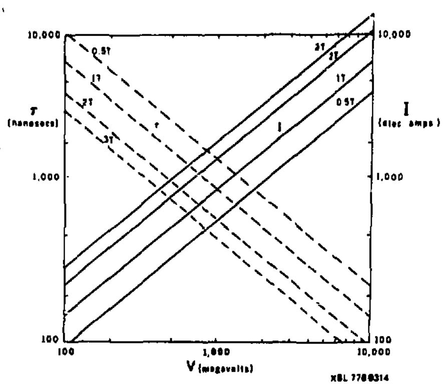

Fig. 1: Transport-limited current and pulse length versus voltage (see text for example parameters)

Basically then, the strategy involves specifying the pole-tip field strengths of the lenses to keep the current close to $I_T(B)$ in such a way as to match the injector output and also the economically-optimum pulse lengths for the ferro-magnetic loading materials available. The transport system is assumed superconducting, which would require some 1.5 MW of room-temperature power per kilometer of structure; conventional copper and iron magnets would require very high power.

Solenoids can perhaps be used at beam voltages $V \gtrsim 200$ MV if the charge-state is very high. For example, for charge state q = 10 beams of 200 amperes can be transported by means of solenoid lenses.

A sharp contrast between the strategy for an induction linac (c) and other systems (a,b), is that one seeks throughout to remain close to the current limit, I_T, by adjusting the pole-tip field. For the synchrotron the space-charge limit is approached for injection and for full-energy bunching but not in between; in the r.f. linac the limit is only at the beginning and not afterwards; in the accumulator rings final bunching demands proceeding to the space charge limit.

III. Injection Into the Induction Linac: A suitable injector must produce a pulse-length of $\tau \approx 2$ μsec, which implies $\dot{I} \sim 500A$, and qVe~ 700 MeV for q = 4. Many [illegible]ilities are being considered, and briefly summarized below, but there has not yet been time to decide on an optimum system. General considerations that bear on such a choice will become apparent in Section 4.

Some general types of strategy can be identified as follows:

(A) Stripping: If charge state q = 1, 2, or 3, is desired it is best obtained directly from the ion-source. A high charge-state is best obtained by accelerating ions with q = 1 and then passing them through a gas-stripper. Thus for q > 3 a two-stage injector, pre-stripper plus post-stripper, is needed. (B) Transverse Stacking: One can use a single "conventional" source ($10^{-3}m^2$area) and later stack at some intermediate or full energy, or use a small number (perhaps 10) of multi-aperture sources ($10^{-2}m^2$) with later more modest stacking, or a single multi-aperture source ($10^{-1}m^2$) with no later transverse stacking. In principle, the resulting emittance will be the same in all cases, in practice the stacking manipulations will lead to dilution in phase space and involve extra hardware, such as large kicker magnets; (C) Longitudinal Stacking: If pulsed non-resonant (Sec. IV) drift-tubes are used their length can become unduly long ($\ell_{dt} \gtrsim 20m$) if the amount of charge to be accelerated in a single large sausage-shaped bunch is large. In that case it seems preferable to accelerate a train of shorter bunches by multiple-pulsing the drift-tubes and later drifting the train together to assemble a final 2 μsec bunch at entry into the induction linac.

With these alternatives in mind we list briefly some injector options:

1) Conventional source + r.f. linac + low-energy accumulator ring[14]; this involves substantial transverse stacking.

2) Several parallel drift-tube structures with transverse stacking at the appropriate point.

3) Pulsed non-resonant drift-tubes which are attractive for a few MJ beam energy but unduly long for 10 MJ pulses.

4) Pulsed drift tubes as in (3) but pulsed several times at 5 μsec intervals

to accelerate a short train (≤10) of pulses which are re-assembled by differential acceleration later.

5) Pulsed drift tubes with re-circulation by means of pulsed bending magnets. A racetrack configuration of four drift tubes with fixed focussing but pulsed bending seems capable of recirculating particles for 20 turns, or so./15/

6) Collective methods or magnetically-insulated space-charge-neutral accelerators; these schemes hold great promise for providing an injector with the right features, but are not well-enough developed to permit proper evaluation.

Singly-pulsed drift-tubes seem acceptable at a beam energy of 1 MJ, but need multiple-pulsing for 10 MJ. Study of the best injector approach may well determine how best to choose the combination of beam-energy and repetition rate (e.g., 10 MJ at 1 Hz, or 1 MJ at 10 Hz) to meet the needs of a power-plant.

IV Non-Resonant Acceleration Systems: While a number of acceleration and accumulation schemes might work, the most direct and rapid is a single-pass system in which the current is increased along it to suit the acceleration and transport systems. In a single-pass system a typical accelerating gap voltage might be 1/2 MV, which, multiplied by the total beam charge of about 1 mC, requires 500 J to be added by each of 20,000 gaps to reach the higher (10 MJ) energies needed for fusion. If the energy is supplied at a low rate, then an r.f. system with high shunt impedance cavities is satisfactory. At low β the choice of accelerating frequency tends toward a few MHz, and the usual structures, Figs. 2a, 2b, become grotesquely large.

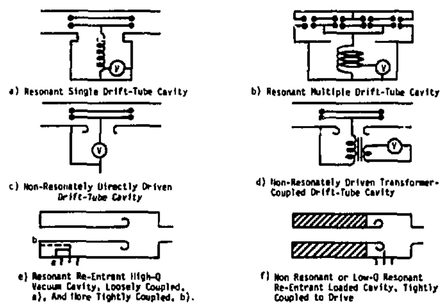

Fig. 2 - Resonant and Non-Resonant Structures

In this region most of the power goes into the structure, specifically the lossy inductance of the circuit, so a reasonable structure is one in which the inductance is a coil with high mutual inductance between turns, resonating with a few drift tubes which have minimal capacity away from the beam hole, as in Fig. 2b. Increasing the beam current, to improve electrical efficiency, leads to the following: use of the highest power r.f. sources available, about 1 MW cw and 10 MW pulse, allows acceleration of 2A and 20A respectively, with one expensive source per gap, so that r.f. accelerated currents must be kept low and the current amplified downstream. This drive-power limit is insensitive to gap-voltage.

The stored energy in the cavity fields, at the practical limit of ~100 kV/cm, is usually much less than the 500 J per gap required by the beam. At this field strength, the energy density is ~500 J/m³. If a large fraction of the stored energy is extracted, successive beam bunches will gain decreasing amounts of energy, so the stored energy must be increased, but this increases dissipation and the likelihood of serious damage in case of a spark.

To accelerate the beam at currents near the transport limit non-resonant accelerators have been developed which, relative to r.f., are able to supply higher peak power flows and higher total energy for short pulses. These are distinguished from resonant ones in that the required energy is stored externally from the accelerating structure, for example in capacitors, and means are provided for transmitting it at very high power to the beam. Some contrasts are listed in Table 1 and some characteristics of switching devices in Table 2. Some non-resonant structures are shown in Figures 2c, d, f. Combinations of energy storage networks, switches, and accelerating structures exist which are able to accelerate the entire beam charge at the highest currents envisioned (10 kA) without voltage droop.

At low β, individually pulsed large drift tubes are suitable, as they have unlimited pulse duration capability. Their length is determined by $\ell_{dt} \approx \beta c(t_{beam\ pulse} + t_{switching}) + 2r_{bore}$, with the beam current and duration determined by the transport limits. The applied waveform is slightly ramped to provide continuous current amplification, with shaping at the ends of the pulse to counteract the longitudinal space-charge defocusing field,

$$E_{z\ sp.chg.} = \sqrt{\frac{\mu_o}{\varepsilon_o}}\ \frac{1}{4\pi\beta\gamma^2}\left(1 + 2\ \ln\frac{r_{enclosure}}{r_{beam}}\right)\frac{dI}{dz}$$

At high β, drift tubes become too long because of switching time limitations, and the re-entrant cavity structure, Fig. 2f, becomes preferred. This is similar to proton synchrotron tuned cavities, except that the magnetic material (ferrite, laminated iron, or a mixture depending on pulse duration) is swung from $-B_{remanent}$ to almost $+B_{saturation}$ in one pulse, and for very short (~10 ns) times and high currents a vacuum radial-line cavity is sufficient. In most of these non-resonant structures, the longitudinal coupling impedance is dominated by the tightly-coupled source-impedance, Z_0, which is in parallel with the structure impedance, . The voltage across the accelerating gap is the sum of an incident wave, V^+, a reflected wave, V^-, and a beam-generated outgoing wave, $V_b^- = I_b Z_0 Z_s/(Z_0+Z_s)$, where the impedances are taken to be real for the beam spectrum of interest. The efficiency, η, of power transfer from the pulse source to the beam is:

$$\eta = \frac{[V^+ + V^- - I_p\ Z_0 Z_s/(Z_0+Z_s)]I_b}{(V^+)^2/Z_0} = \left(\frac{Z_s}{Z_0 + Z_s}\right)\left(2 - \frac{I_b Z_0}{V^+}\right)\left(\frac{I_b Z_0}{V^+}\right)$$

which for $I_b Z_o = V^+$ has a maximum value, $\eta_{max} = Z_s/(Z_o + Z_s)$, near 100%.

Table 1 - Usual Characteristics of Resonant and Non-Resonant Accelerating Structures

Resonant Structure	Non-Resonant Structure
Acts as a voltage step-up transformer	Does not necessarily step up the applied voltage
Sinusoidal waveform	Arbitrary waveform
Reactive power circulating within cavity large compared to either the drive power or the power taken out by the beam	Drive power comparable to power to beam. Reactive power may be comparable or small compared to drive power.
May act as an energy storage element	Energy storage undesirable
Cavity dissipation a major concern	Cavity dissipation can be unimportant
Dimensional tolerances critical	Dimensional tolerances not critical
Drive power expensive (~$1/W cw; $0.10/W pulse)	Drive power inexpensive (≤$.0001/W pulse)
Operation may be limited by wall heating, multipactor, damage caused by sparks, insulator dielectric heating and breakdown.	Operation may be limited by insulator breakdown, fault currents may be damped without much effect on electrical efficiency, to reduce damage.

Table 2 - Representative Switch Tube Characteristics

Type	Voltage	Current	Power	Cost	Recovery Time	Notes
Spark Gap	>30 kV	>30 kA	$>10^9$ W	$3k	>3 ms	Lifetime limited by electrode erosion
Thyratron	~30 kV	~5 kA	1.5×10^8 W	$5k	~10μsec	Faster recovery with clearing fields Lifetime limited by gas cleanup, cathode
Hard Tube	~30 kV	~1 kA	3×10^7 W	$30k	0	Lifetime limited by cathode

V. Bunching and Final Focusing: Pulsed radial-line cavities can supply the fields needed to compress the bunch to the final duration of $\tau \approx 10$ nsec./10,11/ In practice, however, a differential voltage applied between the head and tail of the bunch toward the end of the accelerator, followed by a drift distance is more convenient. The momentum-spread permissible to avoid chromatic aberration problems in the final lenses is less than 1%; this value can be exceeded at the start of bunching because space-charge will tend to remove momentum differences as the bunch collapses in size.

The final focusing constraints are somewhat uncertain as yet. If the reactor conditions correspond to a high vacuum, focusing of U^{+4} creates no problems./16/ If the background pressure is significant it may help in providing neutralization or may be harmful in generating instabilities./17/

VI. Activities at LBL: We are developing conceptual designs for accelerator-igniter systems and comparing the relative advantages of the different approaches. Because of past experience with pulsed non-resonant systems we are intensively examining how best to match such systems to heavy-ion fusion needs. In addition, we are constructing two experiments on low-energy ion acceleration: (i) a one-ampere Cs^{+1} beam to study beam-propagation limits; and (ii) a 5 particle-mA Xe^{+3} beam accelerated to 15 MeV in a Wideröe structure. Reference to Sec. III will make clear the application of these experiments to the injector problems not just for the induction linac, but for other proposed systems as well.

References

1) ERDA Summer Study of Heavy Ions for Inertial Fusion: July 1976, p. 35: LBL-5543.
2) A.W. Maschke: unpub. report July 1976.
3) R.L. Martin and R.C. Arnold, ANL Report RLM/RCA, Feb. 1976.
4) D. Keefe, LBL report BeV 3201, April 1976; Ref. 1, p. 21.
5) A. Faltens and D. Keefe: (unpublished, 1970).
6) J.W. Beal, N.C. Christofilos, R. Hester, Proc. IEEE Accel. Conf. p. 294 (1969).
7) J.F. Leiss, Ref. 1, p. 81.
8) J.F. Leiss, Proc. Proton Linac Conf. (1972) p. 197.
9) R.T. Avery, et.al., Proc. IEEE Accel. Conf. NS 18, 479. (1971).
10) A. Faltens, E.C. Hartwig, H.P. Hernandez, ERA Symposium, UCRL-18103, 332, (1968).
11) A.I. Pavlovskij, et.al., Dokl. Akad, Nauk SSSR, 222, 817 (1975).
12) G.R. Lambertson, L.J. Laslett, L. Smith, Proc. IEEE Conf. on Part. Accel. (Chicago, March 1977) to be published.
13) L.J. Laslett and L. Smith (private communication June 1977).
14) T. Godlove, Ref. 1, p. 83.
15) D. Keefe and L.J. Laslett (unpublished Nov. 1976).
16) A.A. Garren, Ref. 1, p. 102.
17) R.N. Sudan and D.A. Tidman, Ref. 1, p. 86.

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