INDUCTION LINACS

Keefe, D.

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UNIVERSITY OF CALIFORNIA

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D. Keefe

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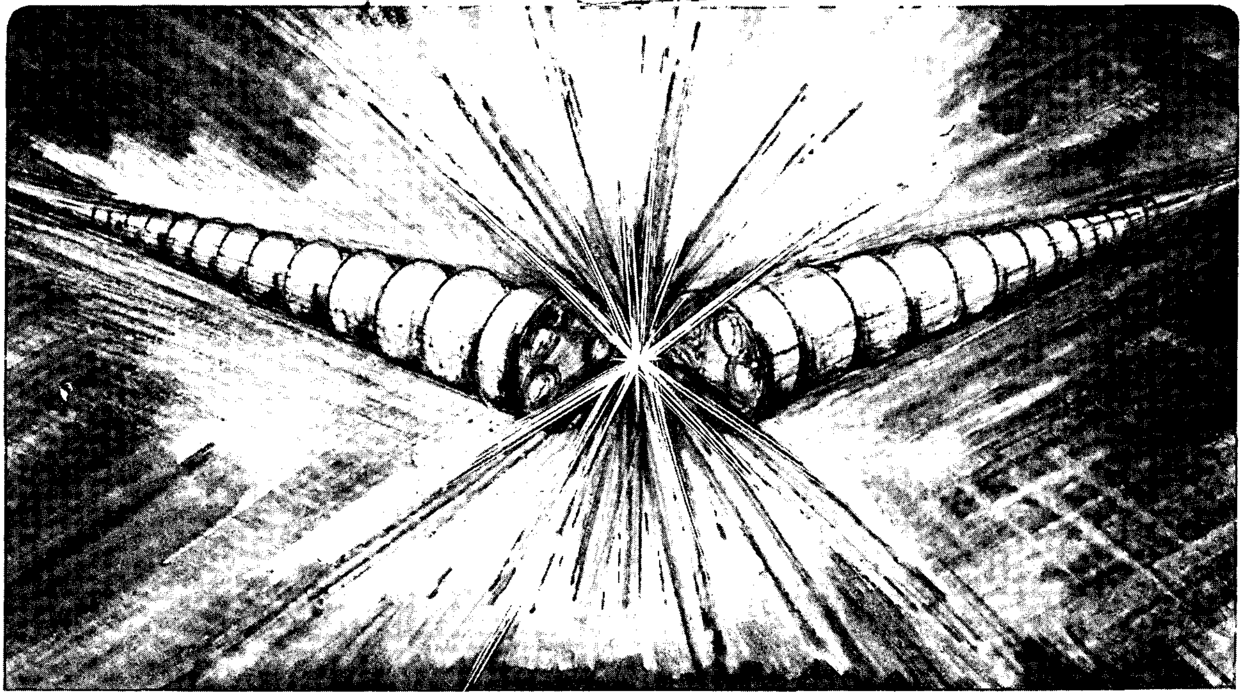

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Denis Keefe

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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Denis Keefe
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University of California
Berkeley, CA 94720 USA

1. INTRODUCTION

Induction acceleration -- in a circle as in the betatron, or in a straight line as in the induction linac -- has a venerable history. The idea of using the electric field produced by a time-varying magnetic field to accelerate particles (exclusively electrons, until recently) were first actively explored in the 1920's. The relationship between the electric and magnetic fields is

$$\oint \underline{E} \cdot \underline{d\ell} = -\frac{1}{c}\oint \frac{d\underline{B}}{dt} \cdot \underline{dS} \tag{1}$$

where the line integral is taken around the circular orbit in the betatron or along the core axis in an induction linac. The surface integral is over the orbital area in the first case, and over the core cross-section in the second. Betatron acceleration of electrons was first suggested by Slepian in 1922, and the famous "two-to-one" betatron condition for an orbit of constant radius was discovered independently by Wideroe in 1928 and Walton in 1929. Nonetheless, development of a working betatron -- despite many experimental efforts in the meantime -- had to wait over a decade more, until the classic analysis and experiments by Kerst and Serber (1941).

Bouwers (1939) discusses clearly the principle of linear induction acceleration. He points to the fact that in a betatron the time-varying magnetic field is in the poloidal direction leading to a toroidal electric field. In the induction linac case the time-varying magnetic field is toroidal around the axis and the electric field is poloidal. He claims to have proposed this method in 1923, referring to it as "reversal of the transformer method". (Why he chose these words escapes me.) Again decades were to elapse before Christofilos and his coworkers (1964) were to demonstrate a multi-gap working induction linac.

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2. Principle of the Linear Induction Acceleration Unit

In a familiar low-frequency analogy, an induction accelerating unit can be thought of as a torus of ferromagnetic material which acts as a transformer core surrounding the beam, a primary (pulsed) power supply providing excitation by means of a one-turn primary winding looping the core, and the beam acting as the secondary.

More insight can be obtained by examination of the transmission line analogy pictured in Fig. 1(a). (See Keefe (1981).) This shows a bent coaxial line, with a hollow inner-conductor, which is driven from the side and shorted at the end. Acceleration occurs across the gap (two holes allow passage of the beam) and will continue from the time the start of the voltage pulse, V, arrives at the gap until its inverted reflection arrives back at the gap and cancels the field. Thus the accelerating pulse lasts only as long as the double transit time from the gap to the short-circuit. If V were 1 MV and the length of the axial part of the line were 1 meter, the gradient would be 1 MV/m and the pulse duration 6 nanoseconds. To provide for this "transit-time isolation" for longer pulses would involve increasing the line length, and hence would soon lead to a serious reduction in gradient.

One way of avoiding this problem is to load the line with either ferromagnetic (μ) or dielectric (σ) material to slow the speed of propagation. Figure 1(b) illustrates how the physical size, axially, can be reduced by this means. Ferromagnetic material, in the form of tape-wound cores to allow for rapid field penetration, is preferred over dielectric because it presents a higher electrical impedance to the driving source. Enough cross-sectional area in the core is required that so that saturation does not occur before the end of the desired pulse duration. See Humphries (1986) for details.

A second way around the gradient problem for moderately short pulses is to flare the coaxial line to form a radial line as in the Radlac (see below); this leads to a transversely bulky structure if carried too far.

Several cores can be driven in parallel to provide increased gap voltage. They may be stacked axially (Fig. 1(c)) or radially (Fig. 1(d)); the latter was the choice for the NBS 2 μ-sec induction linac built by Leiss et al. (1980).

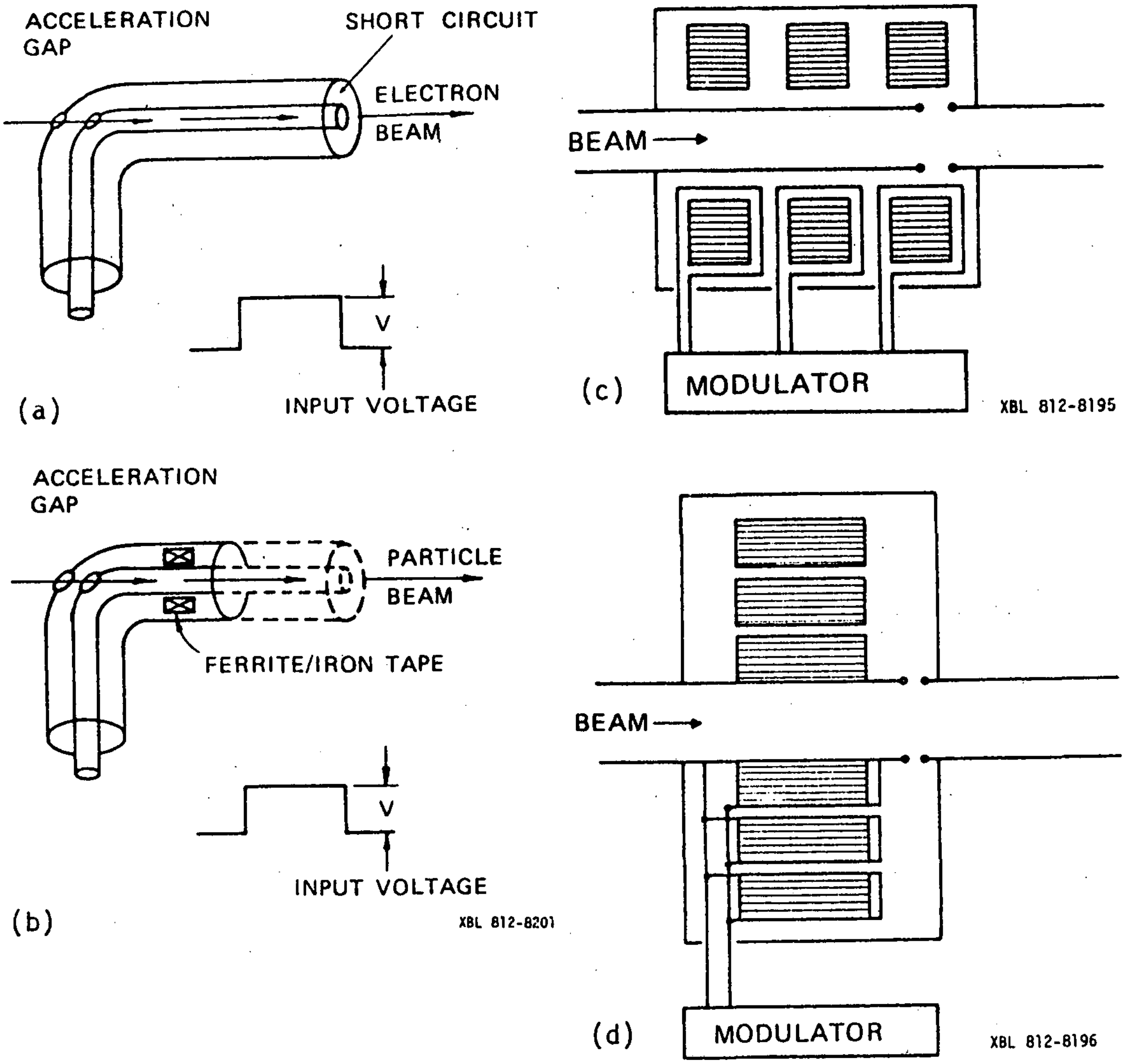

Fig. 1. Evolution of the induction linac geometry. See text.

3. Practical Configurations for Induction Linacs; Examples

A practical induction linac is made up of a succession of small pulse-power modules each timed to give an energy increment to the particles at the moment of passage of the beam. Pulse-power devices have the special advantage that the peak power capacity can exceed the average power rating by a factor of 10^4 to 10^6. (By contrast the size and cost of a pulsed radio-frequency system designed for a certain peak power turns out to be roughly the same as one that could deliver about one-tenth as much power on a cw basis.) Since, therefore, it is reasonable to supply power to each module at the gigawatt level and above -- usually at a voltage level in the 100 kV range -- the induction linac is ideally suited (and efficient) for accelerating very large beam currents (100-100,000 Amps.). Most often, a Marx generator is used to charge a pulse-forming network or transmission line, the geometry of the line being so arranged that voltage of only one polarity (accelerating) is seen by the beam. For short beam pulses a vacuum or dielectric line can be used provided the double-transit time is adequately long; for long pulses a high impedance termination (ferromagnetic toroid) is used to exclude the unwanted polarity from the beam for as long as it takes the magnetic material to saturate. Table I shows a listing of a number of induction linacs that have been constructed or proposed. Figure 2 shows a schematic of the system (top) and a practical configuration used in the LBL ERA injector and in ETA, and ATA.

Advanced Technology Accelerator (ATA). At present under construction at Lawrence Livermore Laboratory, this 50 MeV ferrite-loaded linac is intended to deliver 10,000 Amps of electrons in 50 nsec pulses. The average repetition rate is 5 Hz with a burst-mode capability of 1 kHz for 10 pulses. Water-filled Blumleins are used for the pulse-forming lines. The 2.5 MeV gun of the 5-MeV injector (ETA) has been completed and has so far delivered of the design current at the desired repetition rate. About 10 kA of beam has been accelerated through further induction module stages to an energy of 4.5 MeV. The development of reliable high-voltage (250 kV) spark-gap switches to operate at 1,000 times per second was a significant technological advance.

Long Pulse Induction Linac. For pulse durations much longer than 100 nsec large volumes of ferromagnetic material are needed and ferrite becomes unduly expensive. The National Bureau of Standards had a program (now discontinued) to address the problem of using thin (1-mil) inexpensive iron sheet, insulated layer to layer, as a core material suitable for a pulse duration of 2 μsec (Leiss et al. (1980)). In addition, this design included the novel feature of stacking several (n) nested ferromagnetic toroids of successively larger radii. These can all be driven in parallel from a single pulse line (of voltage V) so that an accelerating voltage nV can be developed across a single gap. Units with n = 4 and 5 were successfully built. Such an arrangement leads to a reduction in the overall length of the accelerator at the expense of a more bulky transverse dimension. [See Fig. 1(d)].

The NBS machine was operated at 0.8 MeV and 1000 Amps electron beam current. Experiments with this beam gave a striking demonstration that a gas-focused beam can propagate for long distances in low pressure gas (1 to 30 Torr) and can even be bent through 360° with dipole magnets

TABLE I. High Current Linear Induction Accelerators

ACCELERATOR	ASTRON INJECTOR (ORIG.)	ASTRON INJECTOR (UPGRADE)	ERA INJECTOR	ERA INJECTOR "SILUND"	NEP2 INJECTOR	PROPOSED	ETA/ATA	PROPOSED	PAVLOVSKI	HIF REQUIREMENTS
LOCATION YEAR BUILT PROPOSED, OR PUBLISHED	LIVERMORE 1963	LIVERMORE 1968	BERKELEY 1971	DUBNA 1969	DUBNA 1971*	NBS** 1971	LIVERMORE 1978*	LIVERMORE FXR* 1978	USSR 1975	BERKELEY 1976
PARTICLE	E	E	E	E	E	E	E	E	E	HEAVY ION, $A > 100$
KINETIC ENERGY	3.7 MEV	6 MEV 1975: 7 MEV	4 MEV	2.4 MEV	30 MEV	100 MEV	5 MEV/ 50 MEV	15-24 MEV	10-12 MEV	10-26 GEV
BEAM CURRENT ON TARGET	350 AMPS	800 A	900 A	700 A	250 A	2000 A	10,000 A	1200-4000A	100,000 A	10,000-50,000 A
PULSE DURATION	300 NS	300 NS	2-45 NS	20 NS	500 NS	2 μS	30 NS/50 NS	60 NS	20-40 NS	10 NS 20-50 μSEC AT INPUT, DECREASING TO 50 NS
PULSE CHARGE	100 μC	240 μC	30 μC	14 mC	125 μC	4 MC	300/500 μC	700-240 μC	2-4 MC	30-300 μC
PULSE ENERGY	390 J	1 KJ	100 J	5 J	3.75 KJ	400 KJ	1.5 KJ/ 25.0 KJ	1-5 KJ	20-50 KJ	> 1 MJ
REP RATE, PPS	0-60 1400 BURST	0-60 <5> 800 BURST	0-5		50	1	5 1000 BURST	1		1-10
MOMENTUM		$<10^{-3}$	$<10^{-3}$							$< 10^{-2}$
NUMBER OF SWITCH MODULES	300	496 (~550 BY 1975)	17	160 ?	1500 ?	250	10/200	62	24	~ 10,000
CORE TYPE	NI-FE TAPE	NI-FE TAPE	FERRITE	FERRITE	NI-FE TAPE	STEEL TAPE	FERRITE	FERRITE	WATER	TAPE AND FERRITE
SWITCH	THYRATRON	THYRATRON	SPARK GAP	THYRATRON	THYRATRON	SPARK GAP	SPARK GAP	SPARK GAP	SPARK GAP	SPARK GAP
MODULE VOLT.	250 KV	250 KV	250 KV	180 KV	250 KV	400 KV	250 KV	250-400 KV	500 KV	20-500 KV
CORE VOLT.	(12.5 KV)	12.5 KV		15 KV	22 KV					
ACCELERATOR LENGTH	~10 M	30 M	14 M	~10 M	210 M	~250 M	~10/53 M	40 M		~5 KM

*UNDER CONSTRUCTION
**PROPOSED, PROTOTYPE MODULE BUILT

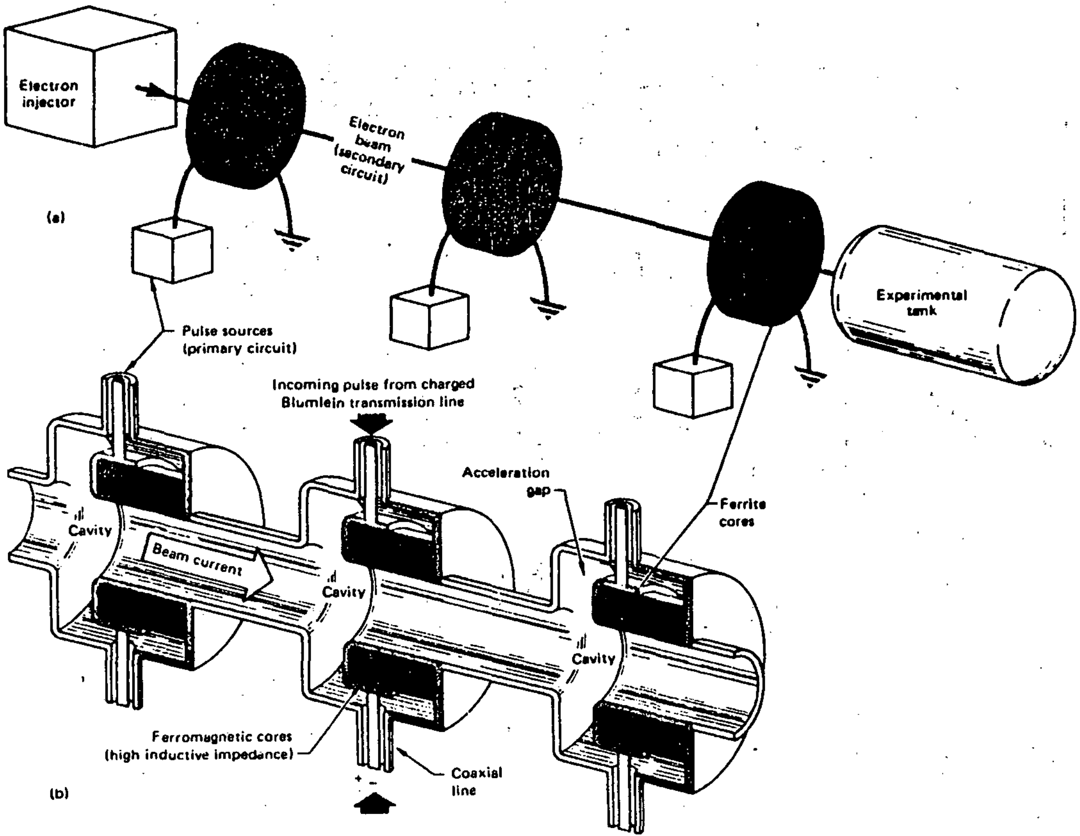

Fig. 2. Two diagrams of the accelerator modules in the ATA. (a) Generalized representation of the relationship of the two circuits in the accelerator, the electron beam and the pulsed power that drives it through the ferrite cores. (b) A more specific drawing (longitudinal section) of the accelerator module. This structure is essentially a long metal tube consisting of a series of chambers, or cavities, containing ferrite rings that prevent the current n the coaxial line from shorting. Blumlein transmission lines deliver a high-voltage pulse to each cavity just as one of the electron clusters that make up the beam reaches the cavity. The electron clusters thus pass from one cavity to the next, increasing in momentum each time.

only (no additional focusing lenses are needed) for recirculation through the accelerating cavity.

Radial Line Accelerator (RADLAC). For short pulses (~ 20 nsec) the pulse-forming line can be a radial transmission line closed at the outer radius and, if one wishes to minimize the transverse size, it can be filled with dielectric. Such a device was first assembled in the USSR by Pavlovskij (1975). The RADLAC-1 consisted of 4 such radial lines each supplying 2 MV across a 2-in. gap (Miller et al. (1981)). With the use of a 2-MV pulse-power relativistic electron-beam (REB) diode as an injector,the final performance was intended to be acceleration to 10 MeV of a 50-kA annular electron beam with a pulse length of 15 nsec.

If one analyzes a transmission line initially charged to voltage V, which is suddenly shorted by a fast switch at one end, one finds the following voltage behavior at the open-circuit end. The voltage remains at the value V for a single transit-time after switch closure; the and reflects at the open circuit end, with the voltage doubling to -2V. The resultant voltage amplitude is (V-2V) = -V which persists for a double-transit time 2τ, by which time the pulse has returned from the shorted end, and is now inverted to +V. Thus it can be seen that, in the absence of losses, the output voltage will be a train of square pulses each 2τ long and alternating in amplitude from +V to -V. The only exceptional pulse is the first one, which is only τ in length. For acceleration one can choose to use either the first pulse or, if the longer pulse length is desired, one of the later pulses.

Figure 3 shows how the radial lines are arranged in the RADLAC. Each consists of a flat inner conductor flanked on either side by slightly conical outer conductors to form a tapered line of constant impedance (~ 10 ohms). It is a "folded" geometry with both the switch and gap located at the inner radius. The oil-filled cavities are 3 m in diameter and of fairly simple sheet-metal construction. A circular hole in the center is surrounded by a graded insulator (which provides the oil-vacuum envelope) and allows for passage of the beam. Arranged symmetrically around the cylindrical insulator are eight self-closing oil switches that fire in synchronism as the potential on the inner conductor is brought up rapidly. During the passage of the beam, no field is present on the (shorted) switch side of the line, while the other side acts as an accelerating gap.

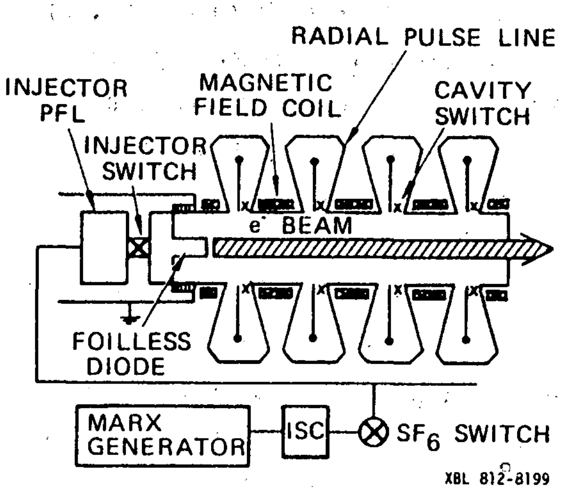

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Fig. 3. The RADLAC comprises four folded radial pulse lines that are filled with oil. The taper is chosen to provide constant characteristic impedance in the radial direction. The 2 MeV injector is an E-beam generator and diode.

Solenoid lenses provide magnetic focusing. The injector and the four cavities have operated as to produce a 25-kA beam at 9 MeV, with current losses of only 10%. The average accelerating gradient is 3MV/m.

Magnetically-Insulated Electron-Focussed Ion Linac (PULSELAC): Results to date from this program are very promising. The basic acceleration scheme is a conventional one using pulsed drift tubes to accelerate a long slug of ions. Ions are accelerated into a drift tube and when the head of the beam reaches the downstream end the voltage is removed from the drift tube and the succeeding one switched on. Instead of using conventional focusing, Humphries et al. have arranged to inject electrons into the drift tubes to provide transverse focusing of the ion beam; a convenient arrangement is an array of field emission points. The key feature of the scheme, however, is to prevent the electrons from crossing the accelerating gap between successive drift tubes so that they do not constitute an inordinate current drain on the power supply. This is accomplished by magnetic insulation whereby a magnetic field is applied in such a direction that the electrons perform magnetron orbits (with an E x B drift) but can never cross the gap and so drain the voltage generator. Obviously, fresh electrons must be injected into successive drift tubes.

Creating such a situation requires the drift tube to consist of two concentric tubes with an annular ion-beam contained between them (Fig. 4b). Conductors wound around the outer radius at the tips of the outer tube, and around the inner radius of the inner tube can provide a magnetic field to meet the requirement of magnetic insulation. A useful feature of this arrangement is that the E x B drift can carry the electrons around the axis again and again; thus charge-accumulation, which can be troublesome in other geometries, is avoided.

A set of plasma guns arranged in an annulus supplies about 3,000 to 4,000 Amps of carbon ions for injection; a 5-gap pulsed drift-tube system now in operation produces at its exit an impressive 3,000 Amps of carbon ions at an energy of 600 keV, with good emittance. These results seem to indicate that the mobile electron species can adjust its distribution in a benign way to provide focusing that is both strong and, as far as one can judge, reasonably linear.

4. A Related Concept: The Auto Accelerator

Auto-Accelerator: This program is an ingenious effort to exploit the high-current electron-beam technology that has been developed in the sub-10 MeV region to produce electron-beams at very much higher

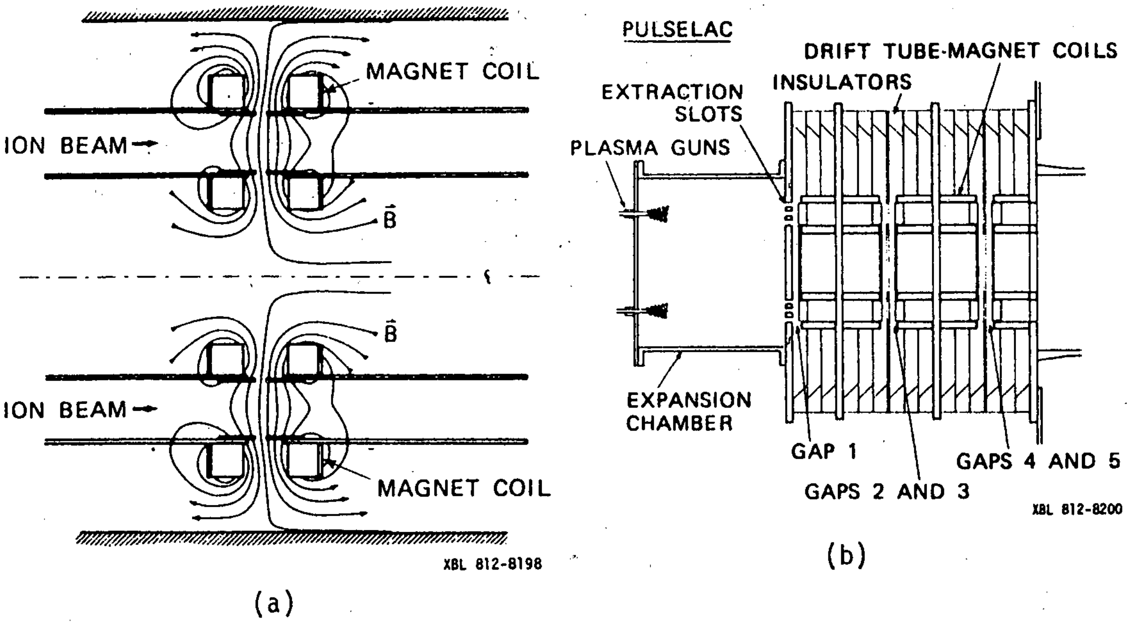

Fig. 4. (a) The arrangement of the four field coils to produce the desired magnetic field in an accelerating gap of the Pulselac. Note that the ions form a hollow cylindrical beam situated in the space between the two coaxial conductors that make up a drift tube. (b) A schematic of the Pulselac that shows the three pulsed drift tubes and the annular carbon ion source.

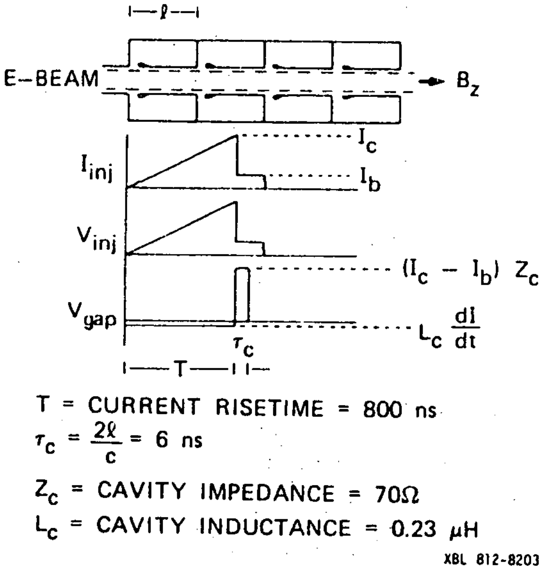

Fig. 5. The NRL auto-accelerator concept. From top to bottom the figures show: Cavity structure; injected current i(t); voltage developed across each gap showing the time averaged retarding voltage L_c di/dt during the current rise, and the accelerating voltage during the current drop.

energies, perhaps in the range 100-1000 MeV. In contrast to the RADLAC geometry, the cavities have their long dimension (~ 1 m) in the axial, not the radial, direction (Fig. 5). Each cavity acts as a transmission line with a double transit time, $2\tau = 6$ nsec. The mode of operation is highly novel; an intense electron beam passing through the pipe is arranged to charge the cavities with magnetic energy on a slow time scale and this energy is later extracted quickly, in a double-transit time, to accelerate a 6-nsec pulse of electrons near the tail of the beam pulse.

The relativistic electron "charging" beam rises linearly from zero to $I = 30$ kA in a time of 800 nsec. The beam current $i(t)$ acts as a current source for the transmission line and instantaneously contributes a voltage, $Z_0 i(t)$, at the gap. If one follows how each such signal increment reflects back and forth along the line with inversion at the shorted end, a doubling at its first return to the open-circuit end and, in the absence of losses, repeated reflections of alternating sign thereafter, one can synthesize the voltage waveform developed across the gap. This turns out to be a linear rise to a value $Z_0 i(2\tau)$, followed by a linear fall to zero at $t = 4\tau$ and a repetition of this triangular form as long as the current rise continues. Thus, the average value of the gap voltage is $1/2\ Z_0 i(2\tau)$. Bearing in mind that $Z_0 = (L/C)^{1/2}$ and $c = 1/(LC)^{1/2}$, we find that this voltage is equal to $(Lc\tau)\ dI/dt$, where $Lc\tau$ is the lumped-element (long time-scale) inductance of the coaxial cavity. The sign of this voltage is such as to provide a slight <u>deceleration</u> of the electron beam.

If the current rise is halted at $i(t) = I$ and the electron-beam current returned to zero, the destructive reflections that keep the gap voltage at this low value are suddenly removed and it can quickly be verified that a large <u>accelerating</u> voltage, $Z_0 I$, appears on the gap for a time 2τ. In the NRL auto-accelerator the electron-beam current is switched not to zero but to $I/5$, so that the accelerating voltage per gap is $0.8\ Z_0 I$. (See Fig. 5).

What is distinctive about this device is that it circumvents two of the major problems of pulse-power accelerators--the switches and the insulators. Since the magnetic energy release from a cavity begins just when the downward step in beam-current occurs at the gap location, the accelerator is automatically self-synchronized from gap to gap; jitter is eliminated because switches are not needed. Insulators at the acceleration gaps are also not required; for short pulses, very high voltages (~ 3 MV) can be achieved across just a few centimeters in vacuum. Finally, the accelerator can be designed to have relatively high efficiency from the wall plug to the beam, perhaps in the region of 30%.

In the experiments, the injector is an E-beam generator, with a transmission line for pulse forming, which produces a 30 kA, 1.5 MeV, hollow beam from a foiless diode. This beam is transported in a uniform-field solenoid magnet (15 kG) through a sequence of coaxial cavities. Six cavities were planned for the proof-of-principle experiment but only two installed. Electrons were accelerated from 0.3 MV to 3 MV with 4 kA beam current. Some "cross-talk" was encountered between the two cavities, but it was eliminated by reducing the Q-factor of the cavities.

It is tempting to call this device a collective accelerator in which electrons are used to accelerate other electrons, but in fact the electromagnetic field occurs as an intermediary between the action of one set of electrons and the reaction of the other set. (Note, for comparison, that in a conventional rf accelerator electron-beam tubes create rf fields that are coupled via wires or waveguides to cavities and thence to the beam. The Two Beam Accelerator shares similar properties.)

5. Induction Linacs for Ions

The very intense (20 kA) short-pulses (10 nsec) of heavy ion beams needed for a heavy-ion driver for inertial fusion led to the proposal that an induction linac could provide a suitable solution (Keefe (1976)). The non-relativistic nature of ions beams makes for considerable difficulties with transverse focussing, but also allows for the interesting strategy of current amplification. The special application to fusion drivers is discussed in a later talk in this series.

Another application of a current-amplifying ion induction linac was pointed out by Keefe and Hoyer (1982) namely the acceleration of protons to the 50-250 MeV range to generate an intense short burst of spallation neutrons.

An interesting result of their studies was that when the beam energy was fixed at 10 kJ per pulse it was advantageous, from both capital and operating cost considerations, to choose low kinetic energy and high beam charge (125 MeV, 80 μC) rather than high kinetic energy and low beam charge (2 GeV, 5 μC). The initial pulse length was typically 5 μsec and the final pulse length 20 nsec.

6. Efficiency

When the beam accelerated in an induction linac is in the range of a few hundred amperes to many kiloamperes, the energy transfer efficiency can be very high. This is illustrated by a somewhat simplified analysis presented by Faltens and Keefe (1977). In constructing an equivalent circuit for an induction linac, Faltens has repeatedly stressed that the beam should be treated as a current source not an impedance. The analysis uses the concept of "gap impedance", Z_g, which for high frequencies (see Faltens and Keefe (1981)) can be written as:

$$Z_g = 60\ g/a \text{ ohms} \ , \tag{1}$$

where g is the gap length and a is the gap radius. The voltage across the gap will result from three terms: the incident voltage from the feed line V_o^+, the voltage reflected from the gap, $V_r^- = V_o^+(Z_g-Z_o)/(Z_g+Z_o)$, and the voltage wave generated by the beam current $V_b^- = I_b(Z_gZ_o)/(Z_g+Z_o)$ since the beam "sees" the gap impedance paralleled by the transmission-line impedance. The efficiency of the induction-linac module can be defined as the ratio of the power delivered to the beam to the power delivered to a matched load. This efficiency is

$$\eta = \frac{V_{gap}I_b}{(V_o^+)/Z_o} = \frac{(V_o^+ + V_r^- + V_b^-)I_b}{V_o^{+2}/Z_o} = \frac{\left(V_o^+\left(\frac{2Z_g}{Z_g+Z_o}\right) - I_b\,\frac{Z_gZ_o}{Z_g+Z_o}\right)I_b}{V_o^{+2}/Z_o}$$

$$= \frac{Z_g}{Z_g + Z_o}\left(2 - \frac{I_bZ_o}{V_o^+}\right)\left(\frac{I_bZ_o}{V_o^+}\right) . \tag{2}$$

When maximized, this efficiency is

$$\eta_{max} = \frac{Z_g}{Z_g + Z_o} \ , \tag{3}$$

which can be made close to unity by choosing $Z_o \ll Z_g$. The achievement of such a high efficiency, however, would require a precise matching of the voltage and current waveform, and a specific design value of the beam current.

7. Conclusions

The induction linac represents well-established technology for efficient acceleration of beams with currents in the range of hundreds and thousands of amperes. The lifetime can be long and the repetition rate high, because the linac is engineered as a multigap device with low energy per stage (a few kilojoules) but very high power per stage (gigawatts).

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LAWRENCE BERKELEY LABORATORY
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UNIVERSITY OF CALIFORNIA
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