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INDUCTION LINEAR ACCELERATORS AND THEIR APPLICATIONS

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Abstract

A growing number of applications of particle accelerators require combinations of beam current, beam energy, and beam quality which are not readily achieved with conventional types of particle accelerators. Induction linear accelerators promise to fill some of these needs. A general description is presented of linear induction accelerator principles, various types of linear induction accelerators and their status, and possible future developments.

Introduction

The historical development of particle accelerators has concentrated on efforts to satisfy needs for extremely high-current low-energy accelerators, very high energy low -current accelerators, or low-current moderate energy accelerators. This historical development in these three areas has been driven by user needs primarily in transient radiation effects studies, high-energy physics, and nuclear physics respectively. Beam quality likewise has been developed according to the needs of these various applications of accelerators.

These user needs, until recently, have been satisfied by conventional accelerator types such as electrostatic accelerators, pulsed diodes, microwave linear accelerators, cyclotrons, synchrotrons, etc. However during the last few years a number of accelerator users have expanded their needs, and a number of new accelerator applications have developed which are not easily satisfied by the more usual accelerator types. The linear induction accelerator appears to be capable of satisfying some of these new needs and is therefore receiving renewed interest.

Table I lists a number of areas of accelerator application for which linear induction accelerators seem suitable and in some cases unique. A discussion of a few of these areas will illustrate the nature of these needs.

Table I

POTENTIAL USES OF INDUCTION ACCELERATORS

- PRODUCTION OF INTENSE NEUTRON PULSES
- TRANSIENT CHEMISTRY
- TRANSIENT RADIOGRAPHY
- NUCLEAR DEVICE SIMULATION
- BEAM PLASMA STUDIES
- RADIATION EFFECTS
- LASER EXCITATION
- COLLECTIVE ACCELERATOR STUDIES
- FUSION RESEARCH
- FREE ELECTRON LASER DRIVER
- HEAVY ION FUSION
- TUNNEL BORING
- WEAPONS RESEARCH

Intense pulsed electron beams with energies of 30-100 MeV are commonly used to produce secondary pulsed neutron beams through development of electromagnetic showers and subsequent photoneutrons in the accelerator target. Such neutron sources are characterized by good neutron source geometry and good neutron source time resolution. Peak electron beam currents with conventional high repetition rate microwave electron linear accelerators are at present limited to about 20 amperes or less. Electron accelerators of 30-100 MeV energy, few kiloamperes of pulsed beam current, and adequate repetition rates would allow large expansion in the capabilities of such sources. If high current pulses of protons or deuterons could be accelerated in such an accelerator, major increase in neutron source strength would result and many new applications would be possible in the study of neutron material interactions.

Bremsstrahlung beams from pulsed electron accelerators are commonly used in radiography of transient phenomena. Microwave electron linear accelerators are most commonly utilized. Research needs for finer spatial resolution, shorter time resolution, and radiography through relatively thick samples results in demands for pulsed electron beams with 30-50 MeV energy and peak pulse currents of a few kiloamperes. Sufficient beam quality is required to ensure good x-ray source focal spot size. Needs for free-electron-laser research are very similar, although extremely high beam quality is required.

The most demanding application for which linear induction accelerators are suggested is in the area of heavy ion fusion. The possibility of providing sufficient energy of heavy ions in a few nanoseconds to a small target pellet appears to be an attractive alternative to pulsed laser beams as a driver for inertial fusion. Typical accelerator requirement would be for beams of heavy ions of several kiloamperes, pulse lengths of about 10 nanoseconds, and ion kinetic energy of about 20 GeV. Beam quality must be sufficiently good to allow a beam focal spot at the pellet of a few millimeters dimension in a several meter diameter reactor chamber. The attraction of heavy ion drivers for inertial fusion derives from the relatively well developed accelerator technology, the high efficiency of accelerator drivers relative to lasers presently developed, and the ease with which accelerators can be operated at the required few pulses per second repetition rate.

The above examples illustrate needs for development of accelerators which simultaneously have relatively high beam currents (several kiloamperes) and beam energies (20 MeV to several GeV) well above those available from pulsed diodes. Such beam parameters are not generally available from conventional accelerator technology. Figure 1 schematically illustrates the status of conventional accelerator technology. For energies below about 10 MeV, pulsed diode accelerator technology is well developed and capable of pulsed beam currents of about 10^6 amperes. For higher energies microwave linear accelerators and synchrotrons are capable of very high kinetic energy but are limited in general to relatively small beam current. These capabilities do not match the needs of many applications, although the possibility of accelerating lower beam currents and accumulating the beam in a high current storage ring appears feasible for heavy ion fusion drivers. An alternative approach is direct acceleration in a linear induction accelerator.

Induction Acceleration

The linear induction accelerator or linear betatron principle is derived from Maxwell's equation

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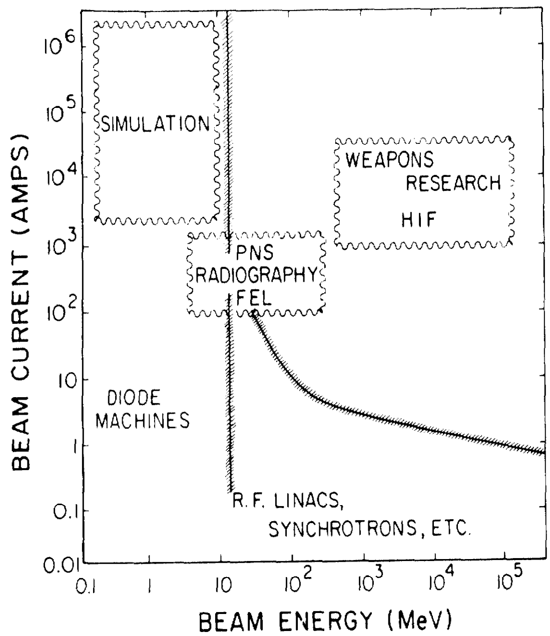


Fig. 1. Schematic illustration of the limitations of conventional accelerator technologies and the parameter needs of some accelerator applications. Diode machines operate to the left of the dashed line at about 15 MeV. RF linacs, synchrotrons, etc. operate below the dashed line of a few amperes or less. PNS indicates pulsed neutron source, FEL--Free electron laser, HIF--heavy ion fusion.

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t} \quad (1)$$

from which one can derive using Stokes' Theorem the line integral

$$\oint E \cdot d\ell = -\frac{1}{c}\frac{d}{dt}\int_S B \cdot \hat{n} da \quad (2)$$

and the voltage around a conductor loop

$$V_{Loop} = -\frac{1}{c}\frac{d(BA)}{dt} \quad (3)$$

where A is the cross sectional area enclosing magnetic induction B. This is the same principle used in the transformer and in the betatron.

A unique feature of the induction electric field is that the voltage induced in a conductor depends upon the changing magnetic flux enclosed by the conductor as indicated in the line integral of Eq. (2). If the conductor encloses changing magnetic flux a voltage is induced. If no changing flux is enclosed by the conductor, voltage is not induced. As a direct result, linear induction accelerators can be built in modular manner with the modules and their interconnecting plumbing held at ground potential. The total voltage gain is the sum of the voltage gains of the individual modules. This is illustrated in fig. 2.

As indicated in Eq. (3) the induction voltage is induced by change in either the magnetic induction B or the cross sectional area containing this induction A. In discussing different types of linear induction accelerators below we will identify two classes of induction linear accelerators. Those in which B changes and the area A stays constant we will identify as core-type induction accelerators. Those in which B stays constant and A changes we will identify as line-type induction accelerators. While this distinction is artificial it is convenient in illustrating the common induction acceleration principle of seemingly different accelerator concepts.

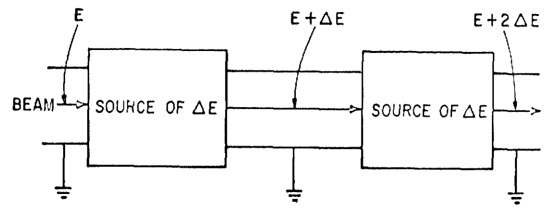
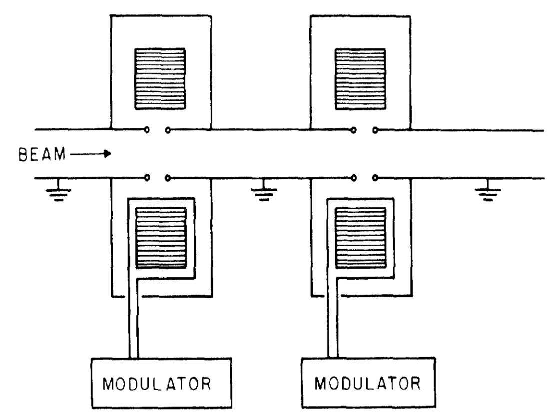


Fig. 2. Illustration of modular nature of induction linear accelerators, allowing repeated increments of energy gain while maintaining the space between modules at ground potential.

Core-Type Induction Accelerators

In core-type induction accelerators a large change in magnetic induction B is induced by discharging a modulator in current carrying conductors surrounding a core of magnetic material such as iron or ferrite, as indicated in fig. 3. The induced voltage V_{Loop}



SCHEMATIC OF INDUCTION LINEAR ACCELERATOR

Fig. 3. Schematic illustration of modulator drive of core-type induction linear accelerators.

appears across a second conductor surrounding the core. If metallic magnetic materials are used in the core, the core is wrapped as a toroid using thin foil to minimize eddy current losses. If the core is made of ferrite material, the ferrite is of sufficient resistivity that eddy current losses are negligible.

During the pulsing of the magnetic core the core material is driven from its original magnetic induction B_r to its saturation value, B_S as indicated in fig. 4. Before the next accelerator pulse it is necessary to reset the core to its original magnetization B_r. Thus a core type induction accelerator pulsing system as illustrated in fig. 5 is required.

Figure 5 also indicates the need for pulse compensation networks in order to obtain uniform accelerating voltage pulses. The major need for pulse compensation results from the non-constant eddy current loading in tape wound cores. Figure 6 gives expressions for the amount of magnetic material required for a given energy gain and pulse length. The eddy current load, $i_c(t)$ in the core rises linearly during the pulse. The value of this eddy current load at the end of the pulse $i_c(t_s)$ is shown in fig. 6 and increases as the square of the

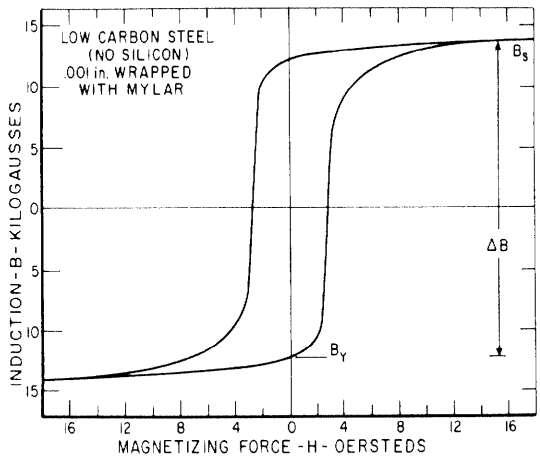
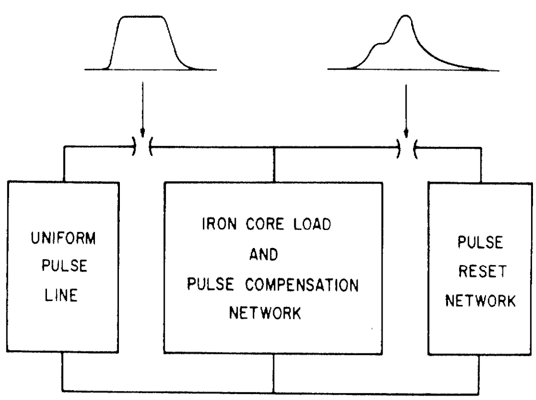


Fig. 4. Typical hysterisis curve for magnetic tape wound induction accelerator cores. During pulsing the total available change in magnetic induction B is from Br to Bs. Between pulses the core must be reset to Br.



INDUCTION LINAC PULSING SCHEMATIC

Fig. 5. Block diagram of core-type induction linear accelerator pulsing system. A uniform pulse line is provided for the acceleration pulse. A second pulser is required to reset the magnetic cores. Pulse compensation networks are required to compensate for rapidly changing core losses.

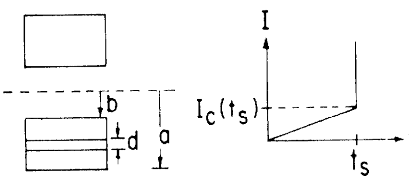
magnetic foil thickness and inversely as the foil resistivity. Thus designers of induction accelerators desire to use cores constructed of the thinnest foil and highest resistivity material which is available. Since there is large variation in the price of different thin foil magnetic materials selection of the appropriate material for a given accelerator requires detailed cost optimization analysis including magnetic material cost, pulse power cost, and building cost. In some cases accelerator power conversion efficiency is an important consideration.

For higher energy linear induction accelerators the number of pulse modulators can be very large if one modulator is provided for each magnetic core as shown in fig. 3. To reduce the number of modulators and to allow impedance matching between modulator and beam load several magnetic cores can be driven from a single modulator. Two configurations have been demonstrated, longitudinal stacking of cores and radial stacking of cores as indicated in figs. 7 and 8. The voltage step-up and impedance relations are shown in fig. 6.

CORE EQUATIONS

$$V\tau_s = \Delta B A \left[\frac{2b^{1/2}}{a^{1/2}+b^{1/2}}\right] \quad \text{VOLT-SECONDS}$$

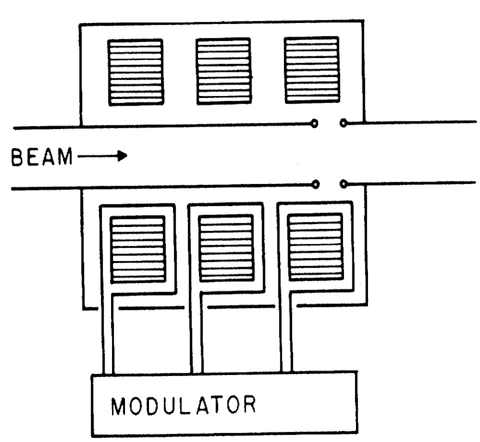
$$I_c(t_s) = \frac{\pi d^2}{4\rho A}\left[(ba)^{1/2}+b\right] \quad \text{CORE CURRENT}$$



VOLTAGE STEP-UP $V_s = NV_p$

IMPEDANCE $R_s = N^2 R_p$

Fig. 6. Design equations for core-type induction accelerators. τ_S is the time at which the magnetic material saturates. $V\tau_S$ determines the required cross sectional area, A of the magnetic core. The eddy current load in the core at saturation $i_c(\tau_S)$ rises linearly during the pulse and is determined by foil thickness, d, and material resistivity, ρ. If N cores are driven from a single modulator, the voltage across the accelerating gap is N times the individual core voltage. The load impedance, R_S, is N^2 times that of a single core.



LONGITUDINAL STACKING OF ACCELERATOR CORES TO ACHIEVE VOLTAGE STEP-UP

Fig. 7. Illustration of longitudinal stacking of induction accelerator cores driven by a single modulator.

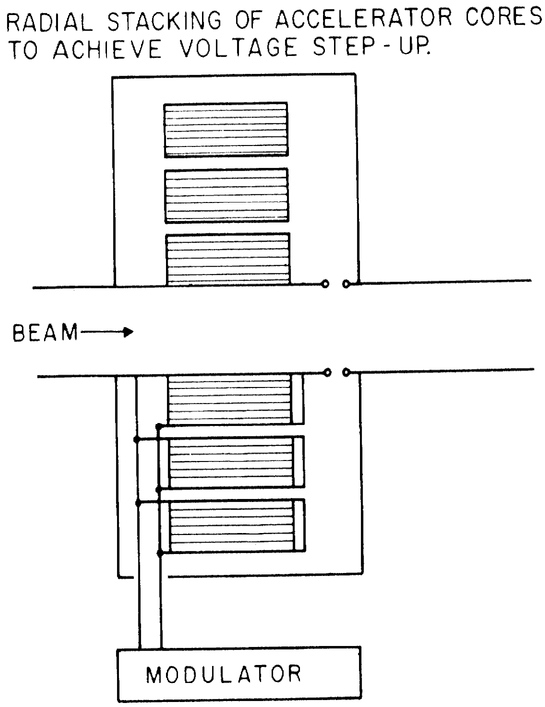


Fig. 8. Illustration of radical stacking of induction accelerator cores driven by a single modulator.

Development of core-type linear induction accelerators has been carried out at Lawrence Livermore Laboratory[1,2,3], Lawrence Berkeley Laboratory[4,5], the National Bureau of Standards[6], and the Dubna Laboratory in the USSR[7]. The linear induction accelerator was originally developed at the Lawrence Livermore Laboratory[1] for the Astron plasma physics experiment. Use of ferrite cores was introduced by the Lawrence Berkeley Laboratory[4] in development of the injector for their Electron Ring Accelerator. Tables II and III give parameters of a number of core-type induction accelerators which have been built or are under construction or have been proposed.

Line-Type Induction Accelerators

In line-type induction accelerators change in magnetic flux results from moving electromagnetic waves in pulse lines. For constant impedance lines, the change in flux results from the changing area containing magnetic induction. Two general classes of induction accelerator of this type are being investigated, pulse line accelerators and electron autoaccelerators. The two differ primarily in the manner in which the energy is initially stored in the pulse line and the manner in which high power switching is accomplished.

Electrostatically charged pulse lines are being investigated in the USSR[8], at Sandia Laboratories[9], and at the U.S. Army Ballistic Research Laboratory[10,11].

TABLE II

HIGH CURRENT LINEAR INDUCTION ACCELERATORS

Operating Accelerators

Accelerator	Astron Injector (Orig.)	Astron Injector (Upgrade)	ERA Injector	ERA Injector "Silund"	NBS (Prototype)
Location	Livermore	Livermore	Berkeley	Dubna	
Year Built, Proposed, or Published	1963	1968	197L	1969	1971
Particle	e	e	e	e	e
Kinetic Energy	3.7 MeV	6 MeV 1975:7 MeV	4 MeV	2.4 MeV	0.8 MeV
Beam Current on Target	350 Amps	800 A	900 A	700 A	1000 A
Pulse Duration	300 ns	300 ns	2-45 ns	20 ns	2000 ns
Rep Rate (PPS)	0 - 60 1440 burst	0 - 60 800 burst	0 - 5		< 1
Number of Switch Modules	300	496(~550 by 1975)	17		2
Core Type	Ni-Fe Tape	Ni-Fe Tape	Ferrite	Ferrite	Steel Tape
Switch	Thyratron	Thyratron	Spark Gap	Thyratron	Spark Gap
Module Volt.	250 kV	250 kV	250 kV	180 kV	200 kV
Core Volt.	(12.5 kV)	12.5 kV		15 kV	40 kV
Accelerator Length	~10 m	30 m	14 m	~10 m	1.3 m

TABLE III

HIGH CURRENT LINEAR INDUCTION ACCELERATORS UNDER CONSTRUCTION OR PROPOSED

Accelerator	NEP2 Injector	Design Study	ETA/ATA	Proposed	Design Study	Pavlovski	HIF Requirements
Location Year Built, Proposed, or Published	Dubna 1971	NBS 1971	Livermore 1978	Livermore FXR 1978	NBS 1978	USSR 1975	Berkeley 1976
Particle	e	e	e	e	e	e	Heavy Ion, A > 100
Kinetic Energy	30 MeV	100 MeV	5 MeV/ 50 MeV	15-24 MeV	3-36 MeV	10-12 MeV	10-26 GeV
Beam Current on Target	250 A	2000 A	10,000 A	1200 - 4000 A	2000 A	100,000 A	2000 - 10,000 A
Pulse Duration	500 ns	2 μs	30 ns/50 ns	60 ns	5-60 ns	20-40 ns	10 ns 20-50 μsec at input, decreasing to 50 ns
Rep Rate (PPS)	50	1	5 1000 burst	1	180		1 - 10
Number of Switch Modules	1500 ?	250	10/200	62	72	24	~10,000
Core Type	Ni-Fe Tape	Steel Tape	Ferrite	Ferrite	Ferrite	Water	Tape and Ferrite
Switch	Thyratron	Spark Gap	Spark Gap	Spark Gap	Spark Gap	Spark Gap	Spark Gap
Module Volt. Core Volt.	250 kV 22 kV	400 kV 40 kV	250 kV	250-400 kV	500 kV 250 kV	500 kV	20-500 kV
Accelerator Length	210 m	~250 m	~10/53 m	40 m	54 m		~5 km

Two line configurations which have been investigated are shown in figs. 9 and 10 in which constant impedance spherical and coaxial pulse lines are shown respectively. The lines are initially charged electrostatically. Closure of the spark gap switches as shown in figs. 9 and 10 initiates a travelling electromagnetic wave in the lines and consequent induction electric field across the accelerating gap. A number of different pulse line configurations of this general type are possible and have been investigated.

Probably the most difficult technical problem in the electrostatically charged pulse line accelerator is the spark gap switch, which is imbedded in the accelerator structure and must close reliably and completely around the beam line to avoid large transient transverse accelerating fields and to preserve good accelerating pulse shape. Some success in developing this type of accelerator has been reported[8]; however detailed experimental accelerator performance properties have not been reported. One program to develop a very high current accelerator of this type in the Soviet Union is indicated in Table III.

A second type of pulse line induction accelerator is the electron beam charged autoaccelerator. This type accelerator has been studied in the Soviet Union[12], at Lawrence Livermore Laboratory[13], and at the Naval Research Laboratory[14,15]. The configuration used at the Naval Research Laboratory is shown in fig. 11. A slowly rising low-energy charging electron beam is passed through a series of coaxial cavities. Wall return currents equal to the charging electron beam current are induced in the coaxial cavities, storing energy magnetically in the inductance of the cavities. When the charging beam current has reached a value I_c, it is suddenly reduced in value to a new level I_b. An electromagnetic wave is induced in the coaxial pulse lines and an accelerating voltage

$$V_A = Z_o (I_c - I_b) \qquad (4)$$

is induced across the gap of each coaxial line. Expressions for pulse length and accelerator efficiency are given in fig. 11, assuming that all of the energy of the charging beam is expended in storing energy in the cavities.

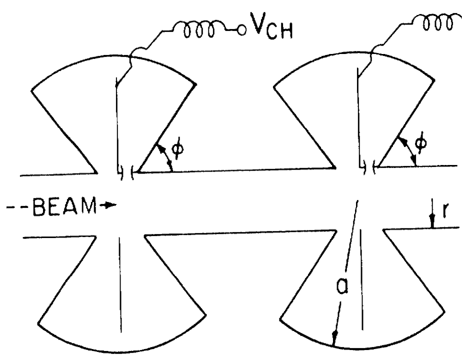
The electron autoaccelerator has the potential advantage of large accelerating voltage gradient and considerable simplicity since the only switches are those associated with the charging electron beam. The most serious difficulties are associated with possible beam instabilities of the large low energy charging electron beam and with the interaction of the charging electron beam with the accelerator structure.

Some success in demonstrating the electron autoaccelerator has been achieved at NRL[15]. In particular, appreciable energy gain has been observed; however achieving stable beam transport of the charging beam has been difficult.

Future Induction Linear Accelerator Development

A number of induction linear accelerators which have been built, are under construction or are proposed are

RADIAL PULSE LINE
CONICAL



$$Z_0 = 120 \ln \cot\left(\frac{\theta}{2}\right) \text{ OHMS}$$

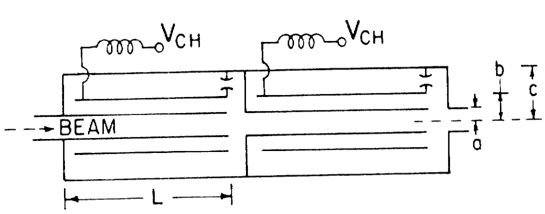
$$\theta = \frac{90° + \phi}{2}, \quad a >> r$$

$$V_A = \frac{V_{CH}}{2} \text{ for } I_B = \frac{V_{CH}}{2Z_0}$$

$$\tau = \frac{2a}{c}$$

Fig. 9. Illustration of pulse line accelerator using constant impedance conical cavities of characteristic impedance Z_0. The accelerating voltage V_A is one-half the charging voltage V_{ch}. The impedance matched beam current is I_b, pulse length τ.

RADIAL PULSE LINE
CYLINDRICAL



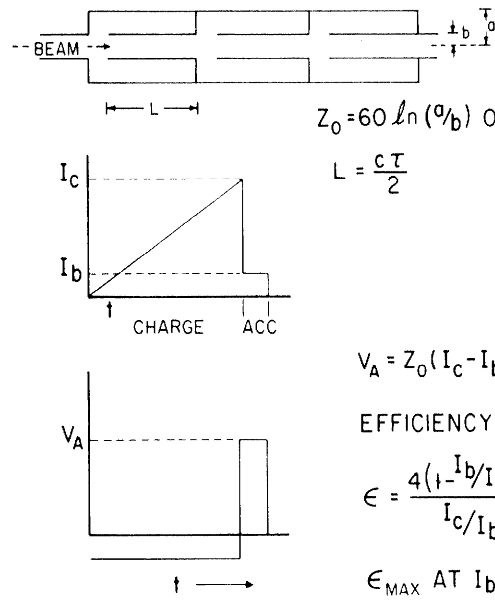
$$Z_0 = 60 \ln (b/a) = 60 \ln (c/b)$$

$$V_A = -\frac{V_{CH}}{2} \quad \text{for} \quad I_b = \frac{V_{CH}}{2Z_0}$$

$$\tau = 2L/c$$

Fig. 10. Illustration of pulse line accelerator using constant impedance coaxial cavities. Nomenclature is the same as for fig. 9.

AUTO ACCELERATOR
COAXIAL



$$Z_0 = 60 \ln (a/b) \text{ OHMS}$$

$$L = \frac{c\tau}{2}$$

$$V_A = Z_0 (I_c - I_b)$$

EFFICIENCY:

$$\epsilon = \frac{4(1 - I_b/I_c)}{I_c/I_b}$$

$$\epsilon_{MAX} \text{ AT } I_b = I_c/2$$

Fig. 11. Illustration of electron beam charged autoaccelerator. ϵ is the efficiency of converting charging beam power to accelerated beam power. Other nomenclature is the same as for fig. 9.

indicated in Tables II and III. Those accelerators which have been built and operated have demonstrated good performance and justify a number of excellent accelerator properties listed in Table IV which can be expected from induction linear accelerators. However as Table II indicates all of the induction linear accelerators whose performance has been reported are of low energy. New accelerators now being planned or are under construction listed in Table III will considerably expand our experimental experience. Problems requiring the greatest attention are those of transport of intense beams and especially the suppression of various types of beam instabilities. Further development of long life, high reliability pulse power components, especially high voltage, high current switches is needed. For some applications high repetition rate switches are not available. For core-type induction linear accelerators improved magnetic materials, e.g. high resistivity glassy metals with good magnetic properties, are under development and promise both improved accelerator cost and efficiency. Line-type induction accelerators are at a much earlier state of development than core-type induction accelerators. For line-type accelerators the greatest need at present is for more experimental demonstration of these accelerator types so that performance can be assessed.

It is an inherent aspect of induction linear accelerators that they are relatively low gradient, low impedance accelerators compared to most other accelerators. Their effective accelerating gradient could be substantially increased if the beam could be recirculated through the accelerator several times, as in the race track microtron. That this might be feasible is based upon the fact that large accelerator apertures are available and the fact that no rf phase stability requirements exist as in the usual microtron. Some initial success in linear induction accelerator beam recirculation has been achieved at NBS[16].

TABLE IV

Properties of

INDUCTION LINEAR ACCELERATORS

- o HIGH CURRENT > 1 kA
- o HIGH POWER
- o MODULAR CONSTRUCTION
- o VERSATILE - WIDE RANGE OF PARAMETERS
  - Pulse Length ns - μs
  - Pulse Repetition Rage 1 - 1000 cps
  - Energy 10 keV - 1000 MeV
  - Particle-Type Electrons, Light, Heavy Ions
- o GOOD ENERGY SPREAD
- o GOOD BEAM EMITTANCE

Linear induction accelerators are equally applicable for acceleration of electrons and heavy ions. Present plans for heavy ion fusion utilizing induction linear accelerators require acceleration at low energies with very long pulses because of large beam space charge forces, with the beam pulse gradually shortened as the energy increases. Efforts to demonstrate electron space charge neutralization of intense proton and heavy ion beams are underway at Sandia[17]. If successful, these techniques could be directly applied in induction linear accelerators and would greatly expand the number of uses for these accelerators.

Acknowledgments

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