LINEAR INDUCTION ACCELERATORS

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I. Introduction

The development of linear induction accelerators has been motivated by applications requiring high-pulsed currents of charged particles at voltages exceeding the capability of single-stage, diode-type accelerators and at currents too high for r.f. accelerators. In principle, one can accelerate charged particles to arbitrarily high voltages using a multi-stage induction machine, but the 50-MeV, 10-kA Advanced Test Accelerator (ATA) at LLNL is the highest voltage machine in existence at this time.[1] The advent of magnetic pulse power systems[2] makes sustained operation at high-repetition rates practical, and this capability for high-average power is very likely to open up many new applications of induction machines in the future.[3]

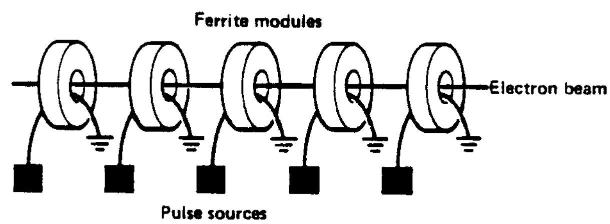
In this paper, we survey the U.S. induction linac technology with primary emphasis on electron machines. A simplified description of how induction machines couple energy to the electron beam is given, to illustrate many of the general issues that bound the design space of induction linacs. A key issue in all high-intensity linacs is that of beam instability; progress in this area in induction linacs is covered in detail in a companion paper in these proceedings.[4]

II. Survey of Electron Induction Machines

The invention of linear induction machines followed naturally from the observation that the coupling of energy into a high-current beam was best accomplished by relatively low-impedance structures (e.g., ~ 1-100 ohms). This impedance is well matched to simple pulselines and transmission lines, without any need for resonant cavity structures (which basically act as an impedance transformer to couple megaohm-class beam impedances to the transmission lines carrying electromagnetic energy to the beam acceleration region). To apply pulseline output voltages to a beam in a multi-stage configuration, magnetic core materials are generally used to isolate the accelerator module sections in a sequence of 1:1 transformers (Fig. 1). The induction machines that have been built over the past decades differ mainly in the type of core materials used (principally a function of pulselength) and the switch/pulseline technology (which advanced steadily in this period.)

The absence of resonant structures in the acceleration cavity is also a significant benefit in controlling the excitation of spurious modes connected with beam breakup instability,[4] and this was a key factor in the achievement of 10-kA performances in ATA (for example.)

The Lawrence Livermore and Berkeley Laboratories have pioneered the linear induction accelerator technology since its origination by N. C. Christofilos in the late 50s.[5] A summary of the applications that motivated these developments from 1960 to the present is given in Fig. 2. The Astron controlled-fusion concept required very high pulsed currents of relativistic electrons, and the development of electron injectors for the experimental studies of this concept culminated in the sequence of Astron accelerators at LLNL in the 1960-70 timeframe. At Lawrence Berkeley Laboratory, a program to investigate the electron ring accelerator concept, following the successful initial experiments in the USSR by Sarentsev and his group, led to the development of the ERA injector.[6] National defense programs studying charged particle beam propagation in air at LLNL led to a need for even higher current capabilities, and the ETA machine that was developed for these studies utilized many of the innovations made at LBL in the ERA injector development, such as the use of ferrite core cavities.[7] The ETA advances were subsequently exploited in a flash radiography machine (FXR) and the Advanced Test Accelerator (ATA) at LLNL in the 1980s. Meanwhile, interest in using the induction linac technology for accelerating heavy ion beams as a driver for inertial fusion applications has been explored at LBL from the late 70s to the present.[8]



- An induction linac works as a series of 1:1 pulse transformers threaded by the electron beam
- Each module generates an increment of beam acceleration

Fig. 1. Linear induction accelerator concept.

1960's

Astron injector — create electron ring for fusion plasma confinement and heating

1970's

ERA injector — create electron ring for collective ion acceleration

ETA — electron beam propagation studies (now used for microwave FEL experiments)

1980's

FXR — flash radiography of fast processes

ATA — electron beam propagation studies and IR wavelength FEL experiments

Heavy ion fusion driver development at LBL

Fig. 2. Motivations for linear induction accelerator developments at LLNL/LBL

A summary of the parameters of the induction machines that have been built in the U.S. (of the magnetic-core type) is given in Fig. 3. Note that the early machines operated at currents less than a kiloamp, and at relatively long pulselengths, consistent with the use of tape-wound magnetic cores. The high-repetition rate "burst" capability of Astron was developed to study the "stacking" of electron pulses in this magnetic confinement experiment, while ETA and ATA have a similar burst-mode capability to study various aspects of beam propagation. As mentioned, all machines following the ERA injector used ferrite "disks" as the inductive core, and operated at voltages per stage of 200-300 keV (about 20 times the Astron voltage of 12 keV.) The gradient of these machines is correspondingly higher. The last machine listed is the first embodiment of magnetic pulse power drivers on an induction machine,[2] replacing the Blumlein/spark-gap pulseline technology used on the earlier short-pulse machines. (The Astron/NBS machines employed gas thyratrons, consistent with their longer pulselengths and low-stage voltage.)

	Kinetic energy	Beam current	Pulse length	Avg. rep. rate (max)	Burst rep. rate
Astron injector, LLNL Original (1963)	3.7 MeV	350 A	300 ns	60 Hz	1440 Hz for 100 pulses
Upgrade (1968)	6 MeV	800 A	300 ns	60 Hz	800 Hz for 100 pulses
NBS prototype (1971)	0.8 MeV	1,000 A	2,000 ns	1 Hz	–
ERA injector, LBL (1971)	4 MeV	1,000 A	45 ns	5 Hz	–

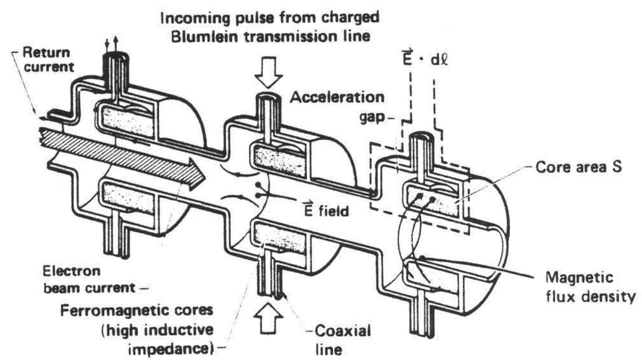
	Kinetic energy	Beam current	Pulse length	Avg. rep. rate (max)	Burst rep. rate
ETA, LLNL (1979)	4.5 MeV	10,000 A	30 ns	2 Hz	900 Hz for 5 pulses
FXR, LLNL (1982)	18 MeV	3,000 A	70 ns	0.3 Hz	–
ATA, LLNL (1983)	45 MeV	10,000 A	60 ns	5 Hz	(1,000 Hz for 10 pulses)
HBTS, LLNL (1984)	1.5 MeV	2,000 A	60 ns	100 Hz (1,000 Hz)	

Fig. 3. Parameters of core-type induction linacs built in the USA. Parameters in parentheses are pulse-power capabilities, not yet demonstrated with the stated beam parameters.

III. Physical Principles of Induction Linac Operation

As illustrated in Fig. 1, a linear induction accelerator can be thought of as a series of 1:1 transformers where the electron beam acts as the secondary. A key point about this configuration is the absence of a "voltage" on any of the cables or structures that exceeds the voltage supplied to a single accelerator module driven by the pulse source. The electrons, in effect, do the "integration" of the axial electric field in the vacuum beam pipe to achieve a final energy "N" times the module voltage (for N modules.)

These ideas can be more clearly understood by considering the sketch in Fig. 4 of a geometry similar to the ETA/ATA accelerator modules. A voltage pulse is supplied to the accelerator module by coaxial cable transmission lines (driven from two sides in a balanced mode to avoid deflection forces on the electron beam.) A cylindrical core of ferromagnetic material (e.g., ferrite) located in the cavity as shown presents a very high impedance to the drive transmission lines at their junction point with the cavity. Without any electron beam present, the acceleration gap then has a "voltage" ($\int E \cdot dz$) impressed across it equal to the transmission line voltage at its output (junction point with the cavity.) This statement is a good approximation only for pulse lengths much longer than the transit time of electromagnetic waves throughout the cylindrical radial line structure (~1 nsec typically), so that the electromagnetic fields can be treated in a quasistatic approximation. Capacitive and inductive effects of the gap, coaxial leads, etc., can particularly affect the electromagnetic field distribution during the rise and fall times of the voltage (beam current) pulse. Note that the electric field in the vicinity of the gap is "quasistatic" in shape (see sketch in Fig. 4) and there is no coupling of adjacent modules as long as a beam pipe of reasonable length (> pipe diameter) separates the acceleration gaps.



$$\oint \vec{E} \cdot d\vec{\ell} = -\int_S \frac{d\vec{B}}{dt} \cdot d\vec{S}$$

Fig. 4. The magnetic induction module.

The ferromagnetic core will present a high impedance for only a limited time, of course, and the "volt-sec" capability of the material determines the core area S for a given module voltage and pulse-length. In actual fact, in the operation of ferrite-type modules, the wave propagation aspects of the penetration of the electromagnetic fields through the ferromagnetic material cannot be ignored, and the ferrite region is often not accurately represented by lumped circuit models. This is not a crucial feature for zero-order modeling since the role of the ferrite is to present a sufficiently large impedance to the drive lines, which it does in cases of interest (since $(\mu/\epsilon)^{1/2}$ is large compared to the free space impedance).

In the presence of an electron beam pulse proceeding down the axis of the accelerator, as illustrated in Fig. 4, a return current in the wall will flow up the gap and "load" the drive transmission line as shown. Once again, this simple picture applies when the current pulse is relatively long (e.g., 50 nsec ~ 50 ft) compared to the transit time of EM waves up the gap (~1 nsec).

The pulse generation is done with a "pulse forming line" (PFL); an elementary schematic of such a system is illustrated in Fig. 5. The output of the line is applied to the transmission line as shown (in actuality it is a balanced pair of lines in ETA/ATA to drive the cell.) The transmission lines are long enough to provide "transit time isolation" of the PFL/switch and the cell (the cable transmission time is longer than the pulse length). In this case, the simple equivalent circuit of the drive system shown in Fig. 5 is applicable, where $V_0(t)$ is the pulse waveform supplied to the transmission line by the PFL. The ideal "square wave" shown in the figure is, of course, in practice modified by switch inductances, etc., and these aspects can limit the minimum pulse-lengths that have enough of a "flat top" on the waveform to be useful in induction accelerators.

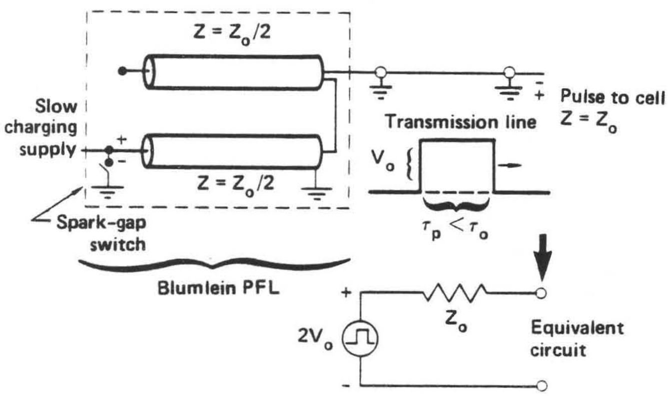


Fig. 5. Simplified picture of an accelerator cell driver.

From all of these considerations, we can deduce the circuit schematic shown in Fig. 6. The beam current load on the transmission line is accurately represented by a current source, since the current is not dependent on the voltage of that stage as it is in a diode region. External compensation circuits at the transmission line output are often used to help flatten the acceleration voltage pulse, and to absorb energy from the transmission lines when the beam is absent (prevent "ringing" of the energy on the cables.) In practice, resistors are used on ATA to absorb half of the drive power with a 10-kA beam.

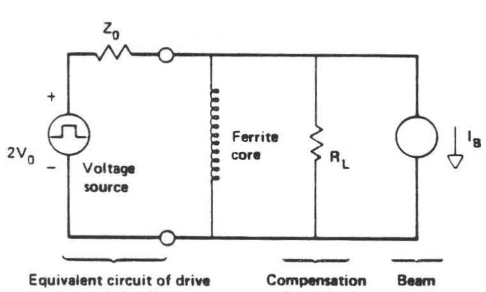


Fig. 6. Simplified schematic of induction unit.

Many observations are readily apparent from this circuit schematic. For example, for optimum efficiency, the transmission line impedance should be matched to the beam $Z_0 = V_0/I_B$ (in the absence of resistor compensation). Since pulse power system efficiencies can be quite high (~50% on ATA and 60-70% with the latest magnetic modulator systems,) induction machines can have good overall efficiencies. Parameter choices can compromise this potential for high efficiency; in particular, with long pulse-lengths, compensation of voltage "droop" due to finite ferrite inductance in the compensation circuitry will waste some of the drive current.

It can also be appreciated from this simple schematic that it is very difficult to avoid beam energy variation in the head and tail of a heavily loaded (relatively efficient) induction machine, where I_B is changing (matching $V_0(t)$ and $I_B(t)$ waveforms are possible in principle, but difficult in practice). As a consequence, beam transport systems in induction machines must often accommodate a relatively broad energy variation through the electron beam pulse. Operational experience with ATA, for example, has often exhibited difficulties traceable to the problems of handling a time-varying energy on the beam head.[9]

IV. Concluding Remarks

We have discussed linear induction machines of the "core" type only in this paper. An alternate approach that does not involve any magnetic material for isolation of the accelerator modules is represented, for example, by the RADLAC technology described in the paper by Mazarakis, et al., in these proceedings.

The magnetic power systems mentioned earlier should make a wider range of applications of linear induction accelerators possible in the future (Fig. 7). Application of these machines for radiation processing is, in one sense, the least obvious one to consider since the high-peak-current capability is not required in contrast to the other applications listed in Figure 7. Nonetheless, the "rugged" nature of this solid-state pulse power technology, the practical features of system simplicity arising from only having to deal with very short pulses of high voltage on electrodes (modest vacuum requirements, etc.), and the relatively low cost per watt do warrant serious examination of its applicability even in these areas.

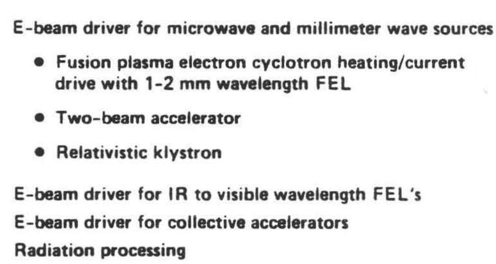


Fig. 7. Magnetic power compression systems enable high repetition rate operation; these developments should have a significant impact on potential future applications on LIA's.

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