# REVIEW OF INDUCTION LINACS

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## Summary

There has been a recent upsurge of activity in the field of induction linacs, with several new machines becoming operational and others in the design stages. The performance levels of electron machines have reached 10's of kiloamps of current and will soon reach 10's of MeV's of energy. Acceleration of several kiloamps of ion current has been demonstrated, and the study of a 10 GeV heavy ion induction linac for ICF continues. The operating principles of induction linacs are reviewed with the emphasis on design choices which are important for increasing the maximum beam currents.

## Introduction

The previous review of induction linacs[1] by J. Leiss at the 1979 Particle Accelerator Conference occurred at a time when several new machines had been proposed or were in the early stages of construction. By now the ETA,[2] Radlac,[3] and FXR[4] machines have been completed and are in various stages of becoming operational, and the ATA machine is midway in construction with operation scheduled a year from now. These machines have increased the operational experience level from the 1kA level of the first generation of induction electron linacs built a decade ago, to the 10kA or higher level, and will soon extend the particle energies from a few MeV to a few tens of MeV. In addition to the progress made with the electron machines, protons[5] and light ions[6] have been accelerated with induction machines and steady progress has been made in the conceptual design of a heavy ion induction linac[7] inertial confinement fusion driver, for which the goal is acceleration of a kiloamp of current to energies near 10 GeV. The desired currents of the relativistic electron accelerators and the nonrelativistic ion accelerators have now reached the levels where further progress will depend in large part on the understanding and control of the transverse and longitudinal collective instabilities.

Undoubtedly the principle of induction acceleration was evident decades ago, because an induction linac is just a straightened out or linear betatron, but the first large device embodying most of the features of the present machines was the Astron injector[8] built by N.C. Christofilos. The radial line version of the induction linac was considered for electric acceleration of electron rings at LBL and for production of high power electron beams for radiography in the U.S. and the U.S.S.R. independently in the 1960's. In the U.S. there was a hiatus of nearly a decade in new developments during which the two biggest machines at LBL and LLNL were scrapped, leaving the NBS long pulse prototype[9] as the lone survivor. The developments in the USSR appear to have continued during this time, with the MEP 30[10] and LIU 10[11] machines being particularly impressive. Table 1, which is an updated version of Table III of reference 1, lists some of the parameters of the present generation of machines. In addition to the efforts aimed at obtaining higher currents, there is a possibility to attain higher voltages by recirculating a beam through an induction module, similar to but with more energy gain per turn than a betatron.[12]

## Principles, Problems, and Limits of Induction Acceleration

Induction acceleration is a process of acceleration by nonresonant acceleration modules and pulsed or modulator type of power sources, rather than by the, until now, more common resonant cavity and rf source combination, in a configuration which may be iterated to high energies, even though both types of acceleration work by induction. In the ensuing discussion, emphasis is placed on acceleration instead of on source or transport problems. An induction module of the type under consideration is shown in Fig. 1. It consists of some metallic conductors which define the electric field in the accelerating gap region, a vacuum insulator separating the gap from the region marked "core", and the modulator or pulsed power source. The quotation marks around core are used because in some applications the core is a magnetic material toroid while in others it may be vacuum or a dielectric. Unlike the drive to an rf cavity which is lightly enough coupled to allow the cavity to resonate near its unloaded frequency, the drive connection to the induction module gap is very tight—directly across the gap—and therefore it has a dominant influence on the module.

Because the "core" occupies a major portion of an induction module and accounts for much of its cost, one is tempted to think that it is the seat of some very important physical processes. This misleading view is encouraged by often heard statements such as "the accelerating field is caused by the changing magnetic field in the core." It is more illuminating, however, to think of the core as an ac open circuit, with nothing occurring within it; core size is large simply because the available materials are far

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Table 1. High Current Linear Induction Accelerators

| Accelerator | MEP 2 Injector | Design Study Prototype | ETA/ATA | FXR | LIU 10 | RADLAC | HIF Requirements |
|---|---|---|---|---|---|---|---|
| Location | Dubna | NBS | LLNL | LLNL | USSR | Sandia | LBL |
| Year Built, Proposed, or Published | 1971 | 1971 | ETA full op.81 ATA schd. 82 | 1981 | 1975 | 1980 | 1981 |
| Particle | e | e | e | e | e | e | $Hg^{+1}$ |
| Kinectic Energy | 30MeV | 100MeV | 5/50MeV | 20MeV | 13.5MeV | 9MeV | 10GeV |
| Beam Current | 250A | 2kA | 10kA | 4kA | 50kA | 25kA | 15kA total on target, 1kA max per beam |
| Pulse Duration | 500ns | 2μs | 30ns/50ns | 60ns | 20-40ns | 15ns | 50μs at source decreasing to 100ns in accel and 20ns on target |
| Rep Rate (PPS) | 50 | 1 | 5 1000 Burst | 1 | | | 1-10 |
| Number of Switch Modules | 1500 | 250 | 10/200 | 54 | 24 | 4 | $10^4$ |
| Core Type | Ni-Fe Tape | Fe Tape | Ferrite | Ferrite | Water | Oil | Tape Ferrite |
| Switch | Thyratron | Spark Gap | Spark Gap | Spark Gap | Spark Gap | Spark Gap | Ignitron and Spark Gap |
| Module Volt | 250kV | 400kV | 250kV | 400kV | 500kV | 1.75MV | 20-500kV |
| Core Volt | 22kV | 40kV | 250kV | | | | |
| Accel. Length | 210m | 250m | 10/53m | 40m | | 3m | 5km |

from ideal and a large volume is needed to create a high impedance approximation of an open circuit. In the limit of an open-circuit core it is immediately apparent that the voltage appearing across the accelerating gap is simply whatever voltage is applied at the drive terminals. By Faraday's Law of Induction,

$$\phi = \int V \, dt \, , \qquad (1)$$

the applied voltage causes a flux change some-where within the volume marked "core", the details of which are usually of little interest.

What is significant is the total drive current going into the "core" region, because it is a measure of the difficulty of establishing the accelerating field. It is also noteworthy that the voltage across the gap can be constant in time and in space, therefore being indistinguish-able in that region from a static voltage distri-bution, with the very important difference that this voltage may be added up along the beam direction without requiring large voltages at any one location. Conceptually, an induction linac is equivalent to a dc accelerating column. The energy associated with a magnetic field in a core is inversely proportional to the magnetic permeability — opposite to the behavior of
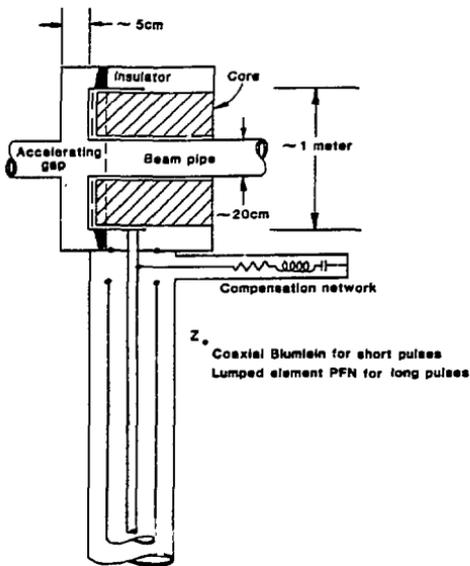
Fig. 1    Induction Acceleration Cavity
and Voltage Generator

the beam; the energy that does go into the "core" is usually lost. The energy supplied to the beam never passes through a state where it is all magnetic energy, as in the oscillating fields of an rf cavity, and most of the energy bypasses the core on its way to the beam.

A substantial part of the design of an induction module is addressed to making the core behave more nearly as an open circuit, or require less excitation current. Figure 2 shows examples of core currents for approximately constant voltages. The core current is rarely like that which would flow into a linear inductor because of eddy currents, magnetic viscosity, and saturation in magnetic cores, and transmission line effects in dielectric cores. A compensation circuit is often used to match the accelerating
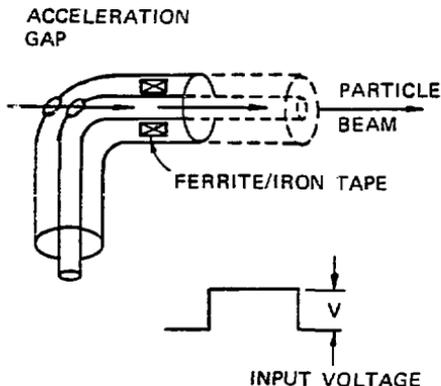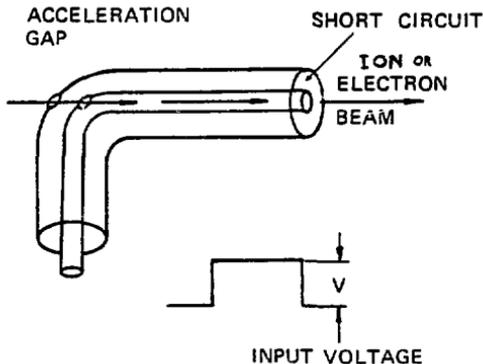
dielectrics for which the field energy increases with the dielectric constant—and for a high current accelerator is much less than goes into
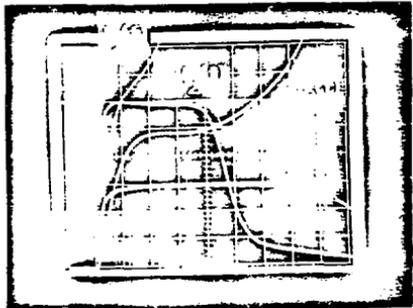


Fig. 2    Example of core currents and their change as the applied voltage is doubled.



Fig. 3    Circuit model of an induction module.

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Table 2

Effects of various core materials on the pulse duration and core current in
the module of Fig. 3 at an acceleration rate of 1 MV/m for a module 1 meter long.

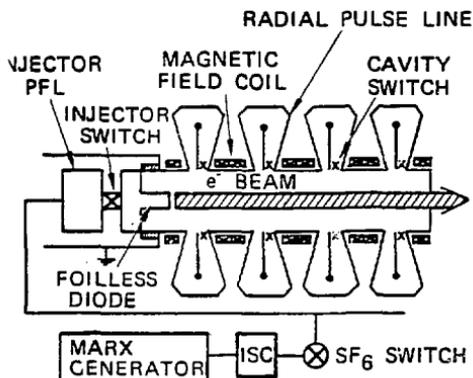| | Magnetic Core | | Nonmagnetic "Core" | |
|---|---|---|---|---|
| | Iron | Ferrite | Vacuum | Dielectric |
| Permeability | $10^3$–$10^5$ | $10^3$ | 1 | 1 |
| Dielectric Constant | 1 | 10 | 1 | 100 |
| $Z_0$,$\Omega$ | NA | 600 | 60 | 6 |
| T pulse travel | NA | 600 ns | 6 ns | 60 ns |
| T pulse saturation | 3$\mu$s | 500ns | NA | NA |
| I core | 2kA | 1.6kA | 16kA | 160kA |

module to its power source, which is usually a pulse forming line or network of either constant or tapered impedance. An important point to note is that the energy and current going into a core must be judged in relation to the beam current being accelerated and the value of that beam current to the user. Not every application requires an efficient accelerator. The core current in an induction linac with a magnetic core and an average acceleration rate of 1MV/meter is of the order of 1kA, therefore acceleration would be inefficient for currents of amperes and efficient for kiloamperes. Depending on the intended application the required current levels a choice may be made as to the geometry and filling material of the region marked "core." The circuit in Fig. 3 is helpful in clarifying the operation of an induction module and the choice of the core.

The transmission line in Fig. 3 either transit-time isolates the short circuit from the gap region or provides, for a time, a high impedance to the drive line. Although several geometrical variations and embellishments are possible, especially in combining the pulse forming line and the required acceleration geometry, such as shown in Fig. 4, the basic choices may be summarized in Table 2 by considering the bent transmission line model of Fig. 3, with various core materials.

It is obvious that the efficiency increases as the beam current increases. For acceleration of very high currents the geometries of the type shown in Fig. 4, become preferable in that the power going into the core is not wasted. Additional transmission line geometries are discussed by Eccleshall and Hollandsworth in Ref. 13. The usual currents which are accelerated are more modest than those required for a good match to the dielectric core geometries because of either the output current requirements or the limits due to the beam transport system.

The reduction of the core current is a desirable goal in the majority of applications. The magnetic materials which make such reductions possible are ferrite and ferromagnetic alloys. Insofar as the magnetic properties of ferrite are well understood, the prospects of further improvements are based more on the possibility of manufacturing larger toroids than on fundamental materials improvements, even though some properties such as permeability keep improving. There is one fairly recent development in ferromagnetic materials which is extremely interesting: the amorphous glassy metals. These glasses are typically composed of 80% magnetic metal such as iron and 20% insulator such as boron. Because of the large fraction of insulator and the amorphous structure, their resistance is approximately 150$\mu\Omega$-cm or about three times greater than that of transformer silicon steel. A hysteresis curve for one of the metallic glasses is shown in Fig. 5. These materials are particularly well suited for induction linac uses because the present manufacturing technique requires the material to be rapidly cooled from a melt before recrystallization can take place,



RADIAL PULSE LINE

INJECTOR PFL
MAGNETIC FIELD COIL
CAVITY SWITCH
INJECTOR SWITCH
e⁻ BEAM
FOILLESS DIODE
MARX GENERATOR — ISC — ⊗ SF₆ SWITCH

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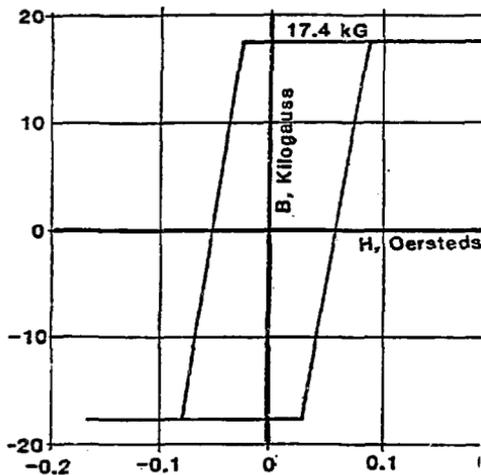
Fig. 4   Radlac: radial line geometry

Fig. 5  Hysteresis curve of 2605 CO metallic glass.

and this is possible only with material thicknesses of about 1 mil; eddy current losses, which are proportional to the thickness squared divided by the resistivity, are therefore reduced. Tests on small samples at LLNL, LBL, and elsewhere have shown that these materials are competitive with the best previously available materials such as 50% Ni 50% Fe–1 mil tape, with the promise of becoming better technically and considerably less expensive.

## Collective Effects

The preceding discussion has been devoted to the "core" part of the induction module. Now, let us assume that the core is an ideal open circuit or that its impedance is folded in with the generator impedance, and consider the circuit formed by the gap electrodes and the power input line. This circuit is essentially on open-circuited transmission line with the open circuit at the gap. Looking from the gap towards the generator, there are several possibilities regarding the impedance presented to the beam: if the voltage source or generator is very stiff, it acts as a short circuit across the transmission line and the impedance has the familiar behavior of resonances when the line length is an odd number of quarter wavelengths long; if the generator impedance matches the line, then for all frequencies the beam sees a constant impedance; and if the generator impedance is higher than the line impedance, the line tends toward an open circuited transmission line behavior, with impedance peaks when the line length is an even number of quarter wavelengths.

Usually the generator source impedance is chosen because of other considerations, with little regard of the module geometry. Unless very high currents are to be accelerated the situation may be completely acceptable. At high currents however, that is, currents near the maximum possible in the structure, the details of the gap geometry, the connections to the generator, and the stiffness of the generator become paramount.

Because almost all of the induction linacs built thus far have been for the acceleration of electrons, which are rather easily deflected by magnetic fields, a module conductor geometry consisting of a single strap threading the core is unsatisfactory because of the large transverse magnetic fields caused by currents in the strap. Instead, three or more symmetrical straps or a continuous metal conductor have been used in the gap region to minimize the steering effects from the core excitation current and the beam image current. In the limit of a continuous conductor in the gap region, the core current flows on the core side of the conductor and is well shielded from the beam, and the image current flows on the opposite side, reasonably symmetrically near the gap. Both currents combine near the drive terminals, and effectively function as sources of higher multipole fields from there, depending on the number of drive points. While alleviating the low frequency deflection and beam sweeping problem, the additional conductors introduce the possibility of harmful high frequency resonances of a new type.

The simplest equivalent circuit for the high frequency behavior of the accelerating module is a transmission line as shown in Fig. 6, where $Z_g$ includes the core, compensation, and generator impedances, and $Z_0$ is the impedance of the short length of line from the gap to the drive terminals. For $Z_g < Z_0$, this line has resonances when its length equals an integral number, $n$, of half-wavelengths, similar to the resonances of a line short-circuited at both ends but with lower Q. The odd-n modes result in a high longitudinal impedance and are the same as for the single strap example. The even modes are new, and yield a high transverse impedance. The characteristic length, $l$, is of the order of the module diameter—about 1 meter — therefore the lowest longitudinal and transverse resonances could occur near 150 MHz and 300 MHz respectively. If $Z_g > Z_0$, the resonances occur at similar frequencies except that the even-n modes have high longitudinal and the odd-n modes have high transverse impedances, similar to the behavior of an open-circuited line. It is unfortunate that because the induction modules resemble resonant cavities from the outside, they have been called cavities, and that the internal conductor resonances, which are due to avoidable mismatches, are confused with the resonances in empty circular cylinders whose resonant frequencies happen to fall in the same vicinity because of similar dimensions. The usual mathematical description of the interior fields in terms of normal modes appears particularly difficult to
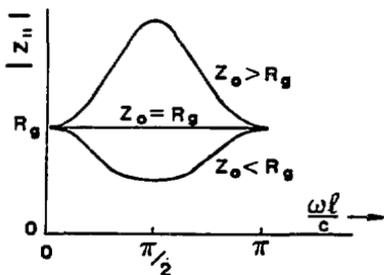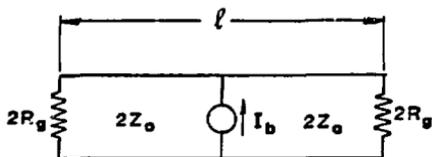
Fig. 6   Equivalent circuit for two drive point
         induction module.

apply to the induction modules because of the
point-like drive connections and because the
boundary of a magnetic core such as ferrite
saturates and recedes during the pulse.
Fortunately, a small amount of ferrite inserted
discontinuously—so as not to be saturated by the
beam current or present a high inductance to it—
is almost the perfect rf absorber for high fre-
quencies, and can be used to damp the resonances
caused by geometrical and material mismatches in
all of the different cavity types, thereby allow-
ing the coupling impedance to the beam to be
determined by the generator impedance at low
frequencies and the gap geometry at high
frequencies.

Neglecting the self-field effects, which are
negligible for relativistic electrons but impor-
tant for nonrelativistic ions, the stability of
the beams or, more importantly, the growth rates
of instabilities depend on the impedances seen
by the beam at the accelerating gaps. Beam sta-
bility is the subject of the paper by Lloyd Smith
in these proceedings. The problems are very
similar to those facing circular machine design-
ers about a decade ago, when they started to
realize that their instabilities were dominated
by the various boxes and similar objects places
in the beam line and resonating or reacting on
the beam at frequencies much higher than the
revolution or rf frequencies. In the induction
linacs, the real or resistive part of the longi-
tudinal impedance should be kept small for
acceleration of ions whereas the transverse

impedance should be minimized for acceleration of
electrons. For both types of modes the generator
small-signal impedance can be kept small at low
frequencies by regulating the output voltage; at
high frequencies, the transmission line from the
acceleration gap to the drive terminal can be
made lossy, thereby approximating a matched line.
The best one could hope for the longitudinal
impedance is a smooth increase from essentially
zero at low frequencies to the characteristic
impedance of the gap, $Z_{11} \approx 60g$ /a $\Omega$ per
module at high frequencies, where $g$ is the gap
length and $a$ is the gap radius. The longitudi-
nal impedance,

$$Z_{11} = \frac{\int \epsilon_z \, dz}{I}$$

is the usual electrical impedance which could be
measured across the accelerating gap, including,
most importantly, the drive circuitry. The
transverse impedance, for which several alternate
definitions are possible, in most common usage is

$$Z_\perp = \frac{\int (\epsilon + v \times B)_{perp} dz}{\beta I \Delta}$$

which is a measure of transverse impulse per
unit of beam displacement, $\Delta$. At low frequen-
cies, $Z_\perp = 60$ $g/a^2$ per module, at high fre-
quencies in a geometry which supports a $TM_{110}$-
like mode of oscillation, $Z_\perp = 377$ $gQ/b^2$ per
module; where $b$ is of the order of the module
radius.

For all of the geometries discussed thus
far, which are similar to the geometry of Fig. 1
and apply to most of the induction linacs built
or contemplated, it is clear from the preceding
that one would like a short accelerating gap $g$
and a large vacuum chamber radius $a$. Insofar
as the peak electric field across a gap is usu-
ally a decreasing function of the gap distance,
the accelerators for maximum current should be
constructed of a large number of high-field short
gaps rather than a few high-voltage long gaps,
for example, 200 kV gaps of 1 cm spacing, and the
impedance of the gap region smoothly transformed
to the drive terminals or other high frequency
absorbing material. Theoretical work is in pro-
gress now to look at the transverse instability
in electron machines in the limit where a single
resonant mode description is not a good model for
the cavity interaction; similarly, work is in
progress at analyzing the longitudinal instabil-
ity of a single bunch of heavy ions. The param-
eters shown in Table I for ATA and HIF are near
the maximum which may be obtained from machines
of the "standard" type, and further progress will
depend in part on the ability to understand and
lower the coupling impedances.

### Applications of Induction Linacs
### to Heavier Particles:

Insofar as particle beams have been men-
tioned earlier we have been mainly referring to
high-current relativistic electron beams. From
the description of the technology, however, it

is clear that an induction module can be used to accelerate charged particles other than electrons —for example, protons, heavy ions, or charged macroparticles, if need be. For much of an accelerator system such beam particles are non-relativistic and the beam current that can be handled is limited by the capabilities of the beam focussing system and typically will be much smaller than the values quoted earlier for electrons. For transport of a beam in vacuum by means of magnetic quadrupole lenses the maximum current is give by Maschke's formula

$$I_M \le K \left(\frac{A}{Z}\right)^{1/3} \left(\epsilon_N \, B\right)^{2/3} \left(\beta\gamma\right)^{5/3} , \quad (2)$$

where $\epsilon_N$ is the normalized emittance and B is the maximum "pole-tip" field. In the early stages of an ion induction linac this condition – which corresponds to the near-cancellation of the magnetic restoring force by the electrostatic defocussing space-charge force – will limit the ion-beam current to the range 1-10 amps.

If one wishes, one may choose to increase the beam-current as the kinetic energy (qV) is increased and still satisfy equation 2. (Note that, non-relativistically, $I_M \propto V^{5/6}$). This can be accomplished by arranging for an effective ramp on the accelerating voltage profiles so that at any point in the accelerator the rear particles in the bunch will have received somewhat more energy than the particles near the front. This strategy of current amplification is possible because the ions remain nonrelativistic for a long way down the accelerator; it is not an option for electrons since they usually emerge from the gun with relativistic speeds. An effective ramp can be arranged to maintain the physical length of the bunch to be constant, in which case $I \propto \beta \propto V$; alternatively the current can be increased as $V^{5/6}$ by arranging for the physical length to decrease appropriately during acceleration.

Since Equation 2 applies to a single beam (in vacuum), another way to achieve higher current is simply to accelerate several beams in parallel, each contained by its own separate transport system but all threading the individual induction cores. There are, of course, practical limitations to this approach since addition of more beams in parallel will increase the aperture of the induction module and hence its cost. Nonetheless, studies have shown that, by judicious choice of the transverse beam (or beamlet) size and the number of such beams, a cost-effective solution exists that can accelerate greater current than that permitted by Eq. 2.

A good example of an ion induction linac design in which maximum current – handling capacity is desired is that for a heavy-ion driver for inertial fusion[10]. Here, the accelerator system must ultimately deliver some 15kA of heavy ions (A = 200), with a stored energy in the ions of 3MJ, that can produce implosion of a deuterium-tritium-filled pellet

and achieve useful gain. Apart from this physics requirement, the accelerator system is also required to operate with as much beam-loading as possible in order to achieve high electrical efficiency (~ 20%); thus it is desirable to maximize the beam current at all points in the accelerator – within reasonable cost limits. A typical scenario for 10 GeV heavy ions (~ 50 MeV/amu) utilizes both current amplification and independent transport of multiple beams. The degree of current amplification that can be obtained during acceleration is limited not by the single-particle dynamics of this maneuver but by the independent condition that the longitudinally-defocussing forces at the front and rear of the bunch remain within tractable limits. Figure 7 shows results of an example calculation of the current amplification that could be attained in a reference driver design; in this case, four magnetically focussed beamlets were assumed to be accelerated and attention was paid to keeping the capital cost near a minimum. One can see that the beam-current can be increased from a few amperes from the source to a few kiloamperes at the end of acceleration and that a final more drastic beam compression section is needed to obtain the last factor of
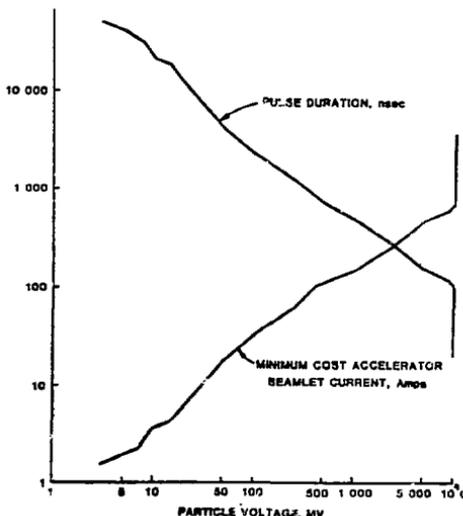
ACCELERATOR BEAMLET CURRENT AND PULSE DURATION

Fig. 7    Desirable current amplication of heavy ion pulse.

five, or so, in current as demanded by the needs of the pellet physics.

A feature of induction linacs designed to meet the needs of inertial fusion is that the capital cost is, in lowest approximation, set by the number of megajoules of beam energy that is desired. Thus if one chooses to double the beam charge and halve the particle kinetic energy to achieve the same number of megajoules, the capital cost is not drastically altered. A different situation obtains, however, in the case of a proton induction linac that might be used for producing an intense pulsed spallation-neutron source.[14,15] In this case, it was found that the accelerator had relatively lighter beam-loading and the cost was dominated more by the kinetic energy desired than by the number of joules delivered. An interesting feature of this possible application is that the final proton energy (~ 500-1000 MeV) is in the relativistic region and significant current amplification can be achieved only in the earliest part of the accelerator.

Another way of obtaining high beam-current at low ion kinetic energy is to depart from conventional vacuum beam-transport systems (quadrupoles or solenoids) and to appeal to collective focussing methods in which the electrostatic space-charge forces are off-set by neutralizing the beam with electrons. In any such scheme, it is clear that the electrons should be prevented from experiencing the accelerating field for several reasons; otherwise, because of their much greater mobility, the electrons could provide a large current-drain on the drive generator and fluctuations in the electron-current could cause erratic accelerating fields; furthermore, large currents of electrons accelerated backwards in the accelerator could result in serious component damage.

One approach could be to use Gabor lenses between induction modules and arrange for the lenses to be electrically shielded from disturbance by the pulsed accelerating field. Humphries has proposed an ingenious alternative to the Gabor lens in the form of two coaxial cylinders with the space between them occupied by electrons[6]. In this case the ion-beam must have an annular cross-section that fits in the space between the cylinders. At the ends of each pair of coaxial cylinders a radial magnetic field is provided by two circular coils, one on the inside tip of the inner cylinder and the other on the outside tip of the outer cylinder. An accelerating voltage can be supplied by an induction module across the gap between sequential cylinder pairs. The application of an axial accelerating electric field in the presence of the radial magnetic field gives rise to magnetic insulation by preventing the electrons from crossing the gap and, instead, forcing them to execute an $E \times B$ drift azimuthally around the axis. In a five-gap system Humphries et al. have demonstrated that neutralization can be achieved by injection of electrons from a pulsed plasma sources, that magnetic insulation can be

effective, and that some three kilomperes of carbon ions can be accelerated to 600 keV.

It has yet to be shown what are the limitations of such a magnetic insulation scheme. The placement of cylinders and field coils internal to the hollow beam requires that conductors must intersect the beam; how much beam-interception they cause and the magnitude of the azimuthal emittance will limit the number of accelerating stages that can be allowed. The electrons must be supplied to each pair of cylinders independently and must be replenished every pulse; since the electron charge distributions at the cylinder tips contribute to the focussing it is crucial to understand how reproducible and time-independent their behavior can be, if serious degradation of the ion-beam emittance is to be avoided.

Finally, it should be noted that the first use of an induction module to accelerate protons has been reported recently by Ivers et al.[5]. They used a low-impedance electron-beam generator to pulse both an ion-diode - to supply the protons - and a downstream induction acceleration gap. A few hundred amperes of proton current was obtained in the presence of a large reverse electron stream that provided neutralization; the drive current was so large that the drain on the generator was of no consequence. This device is being modified to produce a hollow ion beam that can employ magnetic insulation in the manner proposed by Humphries.

## Acknowledgments

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