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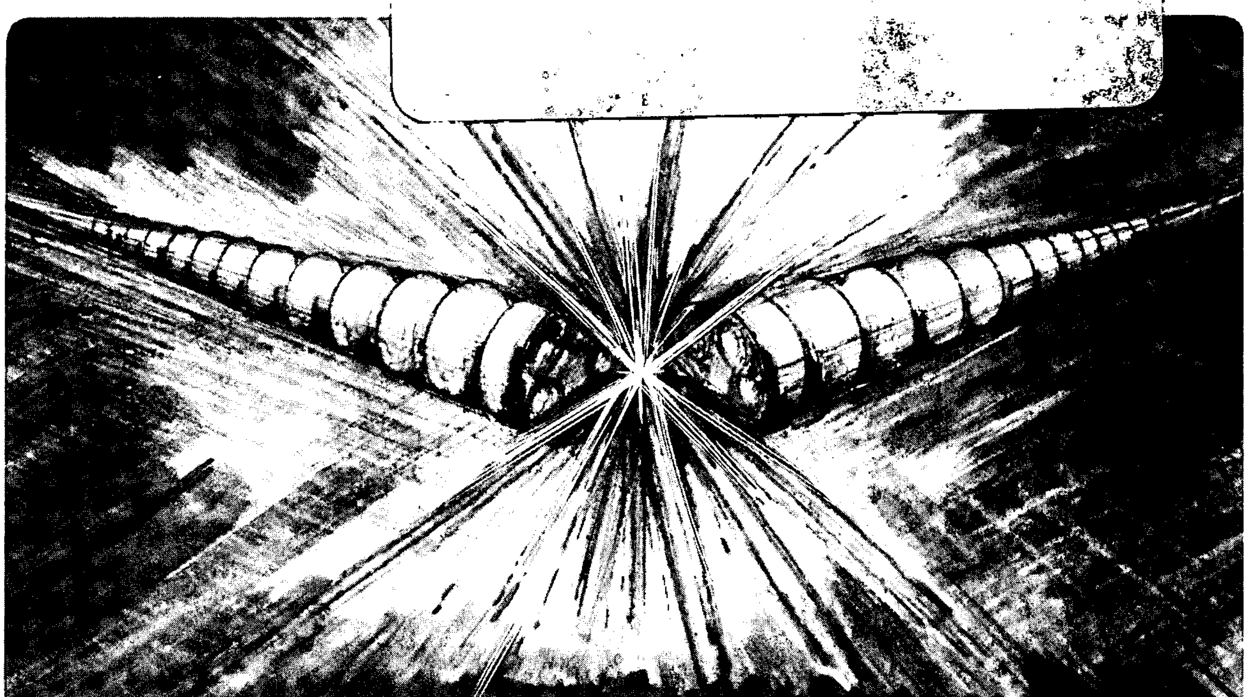

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Abstract

In this report we compare two physics designs of the low energy end of an induction-linac-ICF driver: one using electric quadrupole focusing of many parallel beams followed by transverse beam combining; the other using magnetic quadrupole focusing of fewer beams without beam combining. Because of larger head-to-tail velocity spread and a consequent rapid current amplification in a magnetic focusing channel, the overall accelerator size of the design using magnetic focusing is comparable to that using electric focusing.

Introduction

The induction linac is an efficient accelerator for high current beams with short pulse durations. Unfortunately, the transportable current for a low energy heavy ion beam in a conventional alternating-gradient focusing channel is severely limited by space-charge forces. For the Inertial-Confinement-Fusion (ICF) application, in which the total number of particles is fixed, the requirement for current amplification can reduce the acceleration rate and makes the linac longer. One way to alleviate this problem and increase the efficiency of the accelerator is to use many parallel beams individually focused in electric quadrupole channels. After a significant acceleration, these multiple beams are combined transversely into a fewer number of beams and injected into magnetic quadrupole focusing channels. A conceptual design using this method was described in the Heavy Ion Fusion Accelerator Research Outline Plan [1], in which 64 beams are combined to 16 beams at an energy of 100 MeV. A schematic diagram of the conceptual design is shown in Fig. 1. In the present study we limit ourselves to the region below 100 MeV.

In order to benefit from the multiple-beam idea, one can use a great number of beams with very small channel diameters [2]. The required mechanical tolerances and beam manipulations associated with bending and combining are not a trivial task. In bending the beams, it is necessary that either a time dependent bending field should be used or the head-to-tail velocity spread has to be removed before bending. Also, recent studies have shown that the transverse emittances tend to grow during the combining operation as the beams see each other's space charge forces [3]. The purpose of the present study is to find what penalties, if any, we need to pay to eliminate the beam combining operation.

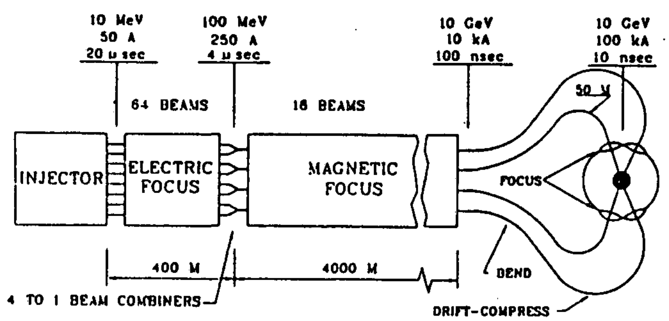

Fig. 1. A schematic diagram of a conceptual induction-linac-ICF driver using mass number 200 and charge state 3. (Adopted from ref. 1)

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An alternative design presented here uses magnetic quadrupole focusing of fewer beams and does not require beam combining. This simpler option has received less attention so far because the overall size of the accelerator was considered to be too large. However, magnetic focusing channels accept larger head-to-tail velocity spread than electric channels and thus current amplification can take place more rapidly. By taking advantage of these properties, the size of the lower energy end of the driver and the injector can be greatly reduced.

Design Considerations

At injection, the zero-intensity phase advance of the betatron oscillation per lattice period (betatron tune or σ_0) is chosen to be 80 degrees. This value of σ_0 is maintained constant for the head of the beam by increasing the lattice period along the linac. (One can also get the same result by keeping the lattice period constant and increasing the pole-tip field strength provided that the field gradient has not reached the technological limit set by insulator flash-over. Current amplification is faster for this option.). The value of σ_0 for the tail of the bunch decreases as it gets more acceleration than the head of the bunch. The acceleration and bunching schedule is adjusted in such a way that, for the tail of the beam, the tune is allowed to drop as low as 40 degrees but not below this value. This range of values for σ_0 corresponds to a head-to-tail velocity tilt of about 30 per cent for electric focusing channels and 60 per cent for magnetic focusing channels.

Quadrupole occupancy factor is assumed to be 0.5, that is, the physical length of quadrupoles are about one half of the lattice-half period. For higher energy regions beyond 100 MeV, the occupancy factor is decreased to make room for more accelerating units.

The quadrupole-bore radius is kept constant for simplicity. The center-to-center beam separation is also assumed to be constant to avoid beam bending. The pole-tip fields are kept constant along the linac.

Other common design parameters are listed below.

Mass Number	200
Charge State	+3
Injection Energy	10 MeV
Final Energy	100 MeV
Final Current	250 A (Electrical)
Final Pulse Duration	4 micro-seconds
Max Gradient	0.4 MV/m
Max Flux	0.5 Vs/m (Set by size)
Total Charge	1000 micro-Coulombs (electrical)

Description of the Designs

The current amplification schedule is determined by requiring that the maximum beam radius (in the middle of the focusing lenses) remains approximately constant. For the transport channels described in the previous section, beam current should be amplified linearly with the velocity of the beam for electric focusing and linearly with the kinetic energy for magnetic focusing [4]. For the electric focusing design however, the initial and final currents given in reference 1 require that the current should amplify approximately as velocity to the 1.4-th power. As a result, the beam radius increases along the linac and the quadrupole bore radius is somewhat under-utilized at the injection point. The current amplification schedules adopted in this report are shown in Fig. 2(a) for electric and 3(a) for magnetic focusing.

The total current required at injection is twice higher for electric design (50 A total), but the current per beam at injection is twice higher for magnetic focusing (1.56 A per beam). A design tradeoff can be made for an even smaller injection current with a longitudinal drift compression.

The accelerating voltage waveforms are calculated according to the design procedure described by Kim and Smith [5]. This procedure is based on the current self-replicating scheme where the current pulse shape at a given location is self-similar at subsequent locations. The accelerating voltage waveforms should provide not only the acceleration but also the velocity tilt necessary for current amplification. Two types of voltage waveforms are used; "square" waveforms for accelerations and "triangular or trapezoidal" waveforms for generating the head-to-tail velocity spread for the desired current amplification. Typical waveforms selected at intervals of every 15 meters are shown in Fig. 2(b) for electric and 3(b) for magnetic focusing. Space-charge effects and corrections for the accumulated errors can be added to these waveforms as demonstrated in the LBL multiple beam experiment [6].

At a given location the beam radius may change in time because of the velocity tilt. If the beam current is constant in time, the major radius of the beam cross section (ellipse) remains approximately constant for electric focusing. The same is true for magnetic focusing if the line charge density is constant in time. In the present study, we will consider the constant current distribution for both eletric and magnetic focusing.

The head-to-tail velocity tilt as a function of distance (z) is shown in Figs. 2(c) and 3(c). Velocity spread of up to 30% has been tried in MBE-4 successfully [7]. High velocity tilt in magnetic focusing has not been tried experimentally but calculations using beam envelope equations showed no ill effects. In these calculations, a constant current (at a given location) was assumed for electric focussing and a constant density (at a given location) waa assumed for magnetic focussing [4]. The overall length of the linac depends sensitively on the maximum allowable velocity tilt.

The kinetic energies for the head, center and the tail of the beam bunch are shown in Figs. 2(d) and 3(d) for the two designs. In both designs rapid acceleration happens only after the pulse is significantly compressed.

Other beam parameters are summarized in Table I. The space-charge depressed betatron tune (σ) for magnetic focusing is 15 degrees at the beginning and drops to 7 degrees at the end (for a normalized emittance of $2\times10^{-7}\ \pi$ radian-meters).

The half-lattice period can be increased in steps in combination with some variations of the pole-tip field. Although the required volt-seconds are less for the

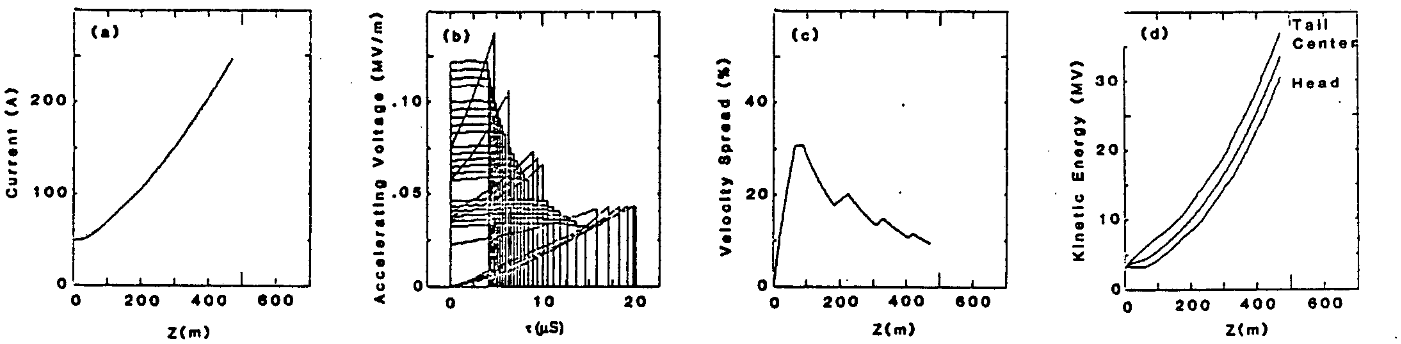

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Fig. 2. Design using electrical quadrupole focusing: (a) Current amplification, dotted line shows a schedule which is proportional to $\beta^{1.4}$; (b) Accelerating voltage waveforms selected at every 15 meters; (c) Head-to-tail velocity tilt; (d) Kinetic energies of the head, center, and tail of the beam.

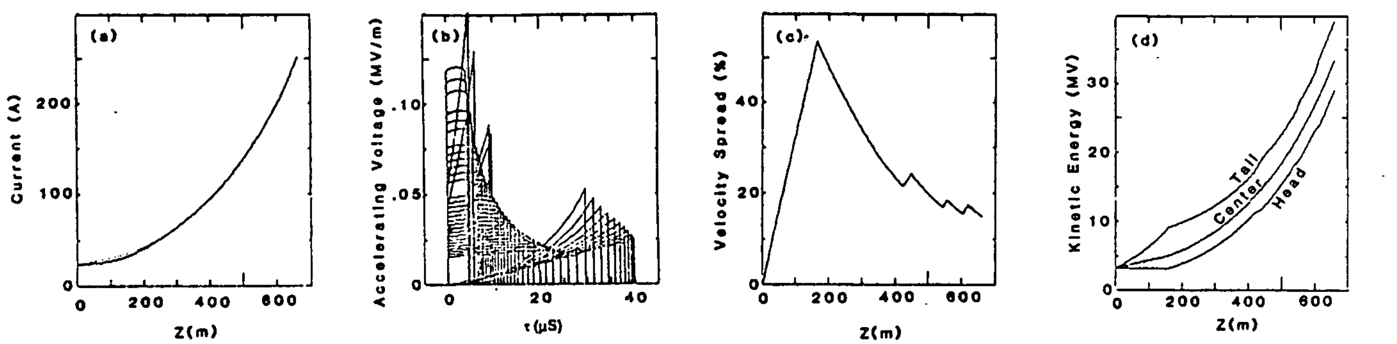

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Fig. 3. Design using magnetic quadrupole focusing: (a) Current amplification, dotted line shows a schedule which is proportional to β^2; (b) Accelerating voltage waveforms selected at every 15 meters; (c) Head-to-tail velocity tilt; (d) Kinetic energies of the head, center, and tail of the beam.

Table I. Summary of parameters for the two designs

	Electric	Magnetic
Current at injection	50 Amperes	25 Amperes
Number of beams	64	16
Pulse duration	20 microsec	40 microsec
Beam radius (max)		
Initial	2.7 cm	4 cm
Final	3.4 cm	4 cm
Bore radius	5 cm (constant)	7 cm (constant)
Bunch length		
Initial	62 m	124 m
Final	39 m	39 m
Pole-tip Voltage/field	100 kV (constant)	1.5 T (constant)
Half-lattice period		
Initial	50 cm	50 cm
Final	163 cm	100 cm
Max velocity tilt	30 %	55 %
Total flux required	227 Volt-sec	330 Volt-sec
Total length of Linac	471 meters	660 meters

electrical design the amount of core material is about the same for both designs because the total diameter of the transport structure is bigger for the electrical design.

Beam combining adds some additional length to the electric design. An additional two-bunch lengths of linac is needed if the velocity spread is to be removed before combining and to be restored thereafter.

Possible Improvements

A possible way to improve the electrical design is to increase the injection current by increasing the number of beams and decreasing the individual quadrupole-bore diameter at the same time. However, better alignments are needed [4], the core ID becomes larger, and the combining operation becomes more complex.

A possible way to improve the magnetic design is to use higher pole-tip field. The field at injection can not be increased much because the quadrupoles become too short, but it can be increased linearly with the beam velocity if the half-lattice period is fixed. This scenario allow much faster current amplification (as velocity to the third power) and more rapid acceleration. The tune depression is very strong but may not cause any ill effects if the beam pipe has a round cross section. [8].

Summary

Judging from the size and complexity of the accelerator the design using magnetic focusing appear to be more attractive than that using electric focusing. However, a detailed cost analysis is required to make a final decision. Some of the assumptions made for the magnetic design require further investigation: Magnet-winding techniques for short quadrupoles need to be developed; beam transport with a high velocity tilt need to be experimentally demonstrated.

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