Title
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DESIGN/COST STUDY OF AN INDUCTION LINAC FOR HEAVY IONS FOR PELLET-FUSION*

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Introduction and Background

For electrons, the induction linac has been well-established as a high-current (≈1 kA) accelerator with high repetition rate, good electrical efficiency and high operational reliability.[1] In such systems the electrons are injected at relativistic speed so that the beam current, I, and pulse duration τ, remain constant along the accelerator. The design procedure thus becomes one of designing a single accelerating module (appropriate to the chosen I and τ) and iterating such modules until the final beam particle energy has been reached.

For a non-relativistic ($\beta < 0.5$) heavy ion induction-linac driver, however, the design procedure is much less transparent. For instance, the particle mass and charge can have a range of values - also the final beam voltage, V_f, (kinetic energy/charge-state, q), is a matter of choice since only the product, $I\tau \ V_f = Q$, is specified for a driver delivering Q joules. An important degree of freedom is available in such a machine - namely, the ability to achieve pulse compression by modest differential acceleration (slightly-ramped voltage pulses); this comes at the price - to the designer - of allowing a free choice of beam current over a wide range at any point along the machine. The upper bound on current is set by the transverse space charge limit; on the lower side, while there is no physical bound, in general one finds that a decrease in current is accompanied by a decrease in electrical efficiency and an increase in cost.

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The physics of the pellet implosion sets stringent conditions on the accelerator driver. The beam energy should be > 1 MJ, the beam power > 100 TW (implying a pulse length ≈ 10 ns), and the specific energy deposition in the pellet > 20 MJ/g.

Thus, considerable current amplification is required, e.g. from some 10 amps at the source to perhaps 10 kiloamps at the pellet. Most of this amplification can be accomplished continuously along the accelerator and the remainder achieved at the end by bunching in the final transport lines to the target chamber.

Design Approach

A conceptual schematic of an Induction Linac Fusion Driver is shown in Figure 1, which includes an injector, an accelerator-buncher, and a final transport system. Here only the accelerator portion of the driver is discussed.

The essence of the design approach is to pick a specified total beam charge $[I\tau]$, one value in a sequence, and examine the differential cost, ΔC, required to add an increment of voltage $\Delta V = 1$ MV to the beam at each voltage point, V, along the accelerator. In general, there is a minimum value of $\Delta C/\Delta V$ at each voltage point, V, which in turn determines the exact design for the accelerating modules, pulsers and magnets at that point; if one seeks for example, a minimum-cost accelerator, the entire design is determined and the cost -- except for the injector and final beam manipulation sections -- is given by

$$[C_{min}]_{[I\tau]} = \left[\int_{V_{inj}}^{V_f} \left(\frac{\Delta C}{\Delta V}\right)_{min} dV\right]_{[I\tau]}$$

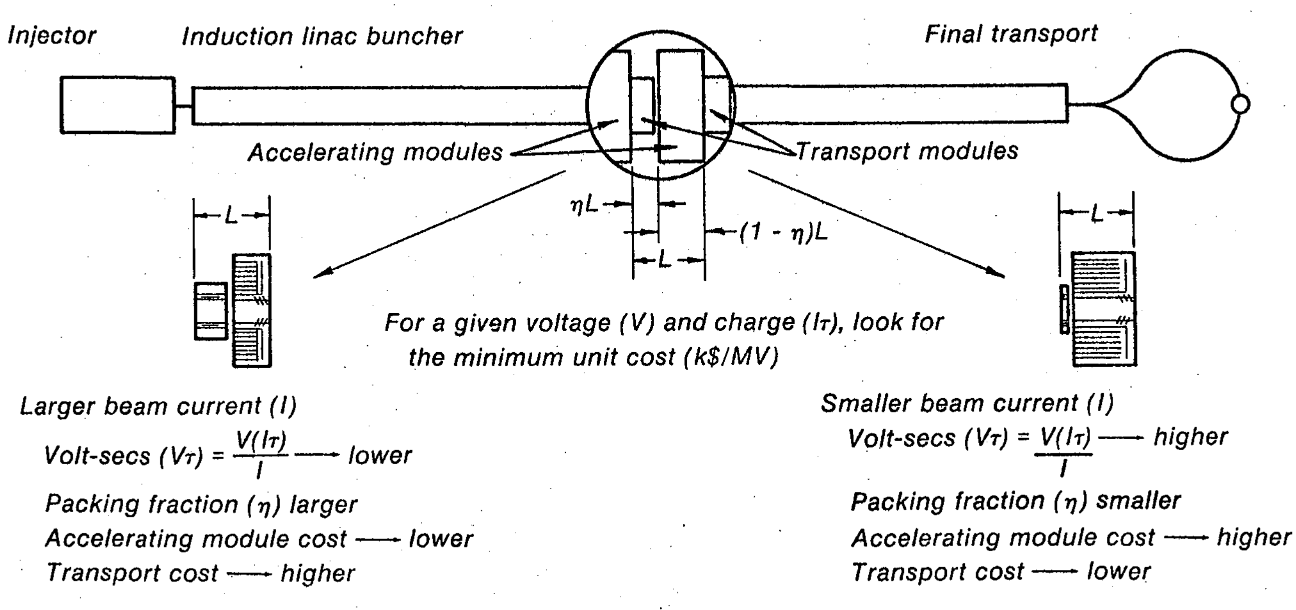

FIG. 1 - INDUCTION LINAC FUSION DRIVER

Some departure from the minimum-cost design, particularly at the higher voltage points, is probably desirable for electrical efficiency reasons and for meeting the final longitudinal space charge requirements. Thus it is important to have detailed information concerning the nature of the $\Delta C/\Delta V$ variation, i.e., whether it is a broad or narrow stationary minimum or if it is a non-stationary minimum arising from a constraint. See Fig. 3 for an example of a $\Delta C/\Delta V$ curve.

Methodology

We have simplified the problem in studying drivers by assuming:

(i) A suitable injector at V_{inj} = 50 MV is available.

(ii) The final rapid-buncher section costs about the same as if it were composed of a pure accelerating section with modest bunching.

To address the main part of the system, viz. the Induction Linac, a computer program (LIACEP) has been developed to sort through the possible engineering options at each voltage point, V, along the machine and to generate the desired cost and design information. In Figure 2 a simplified flow chart of the LIACEP Program is shown.

We start by specifying an ion species with atomic weight, A, charge state, q, transverse emittance, ε_N, Betatron tune shift, $\Delta\nu$, and rep. rate f. Next, an electrical beam charge $[I\tau]$ is specified with a sequence to be explored -- 30 μC, 60 μC, 90 μC..., etc. Then at any voltage point, V, along the accel- erator the cost consequences of adding a further 1 MV are examined. The independent variable is chosen to be the current, I, with the magnet occupancy factor, η, for a symmetrical FODO lattice, as a separately set and varied parameter (e.g., η = .5, .33, .17, .10, .05, etc.). In this way a set of curves for each value of η can be generated to display differential cost versus current and so to arrive at a minimum or indicate the cost/benefit ratio of departing from the minimum as shown in Fig. 3.

Key ingredients of the optimization process include: (1) Engineering design options and constraints, (2) Cost data base which can affect the trade-off among design choices, (3) Physics assumptions about (i) the desirable beam emittance determined by the pellet and transport requirements, or the realizable beam emittance set by the source performance, and; (ii) the transverse space charge limiting current.

The program cycles through three design configurations, see Figure 2, and consider four different core materials: ferrite, low carbon steel, nickel steel, and amorphous iron. Superconducting transport elements are considered. Cost data information is given in Reference 2.

The sensitivity of cost efficiency to the space-charge limited current seems a general feature and it becomes important to have a good understanding of what betatron tune depression can be safely tolerated in the transport system. Extensive studies of this question have been carried out by Laslett using computational techniques for a Kapchinskij-Vladimirskij distribution[3] and by Haber using numerical simulation codes.[4] At present a tune depression of 60° 24° is used for a K-V distribution (60° with no current down to 24° at maximum current).

Example 1 MJ Driver

Results from the LIACEP program are shown in Figures 3 through 6 for a 1 MJ Driver with the following set conditions:

U^{+4} $\qquad \varepsilon_N = 3.0 \times 10^{-5}$ meter radians

$I\tau$ = 210 μC $\qquad \Delta\nu = 60° - 24°$

f = 1 Hz

Unit costs versus current for various packing fractions at a fixed beam voltage V are shown in Figure 3. Adopting the minimum cost options at

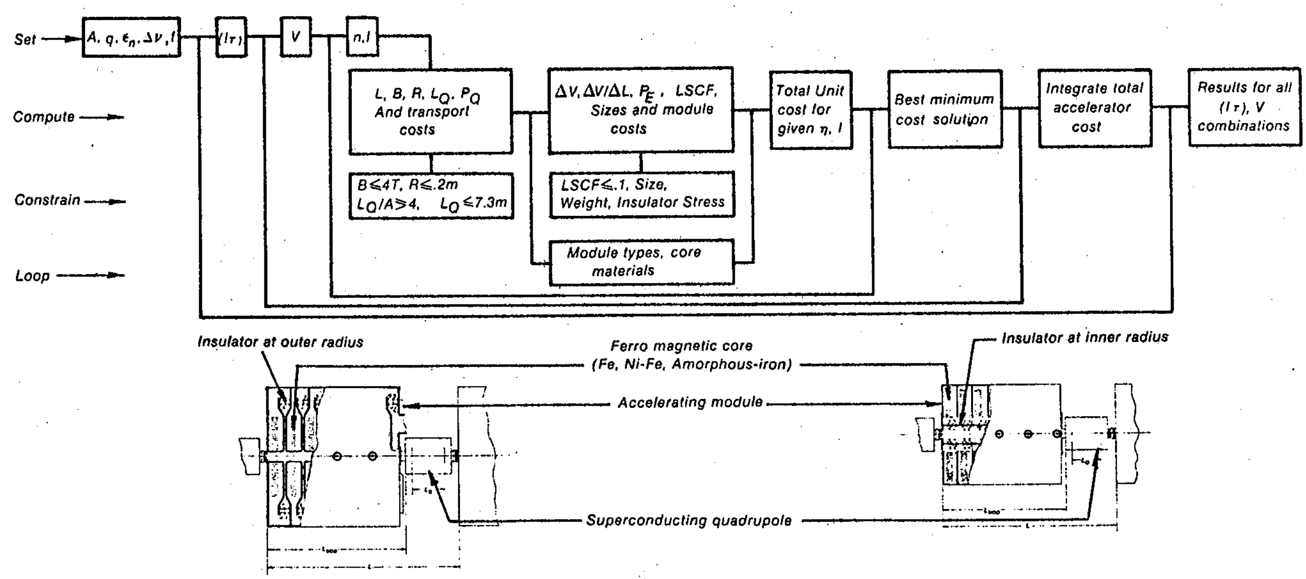

FIG. 2 - PROGRAM LIACEP FLOW CHART

various beam voltages, the minimum unit cost curve in Figure 4 is obtained. Integrating the unit cost curve with voltage yields the minimum accelerator cost also shown in Figure 4. Figures 5 and 6 show various accelerator parameters, namely, current, pulse duration, transport magnet field, and radius, for the minimum cost accelerator.

It must be emphasized that these cost studies are useful as a design guide and as a tool for identifying the cost sensitivity to any of the input assumptions and engineering options and costs. Thus the absolute value of the cost figures should be treated with considerable caution and attention focussed on the trends suggested by the data; reliable costs can be derived only when a particular case is settled upon and an <u>ab initio</u> design carried through in detail for that case.

We wish to acknowledge the help of Mr. Victor Brady in performing much of the computational work.

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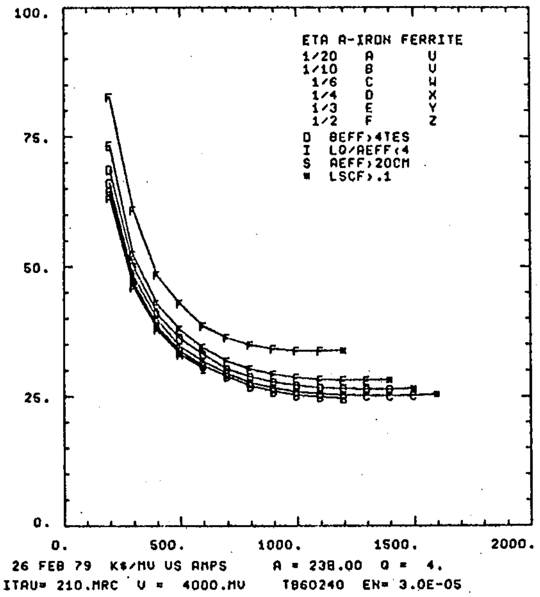

FIG. 3 - EXAMPLE COST CURVE

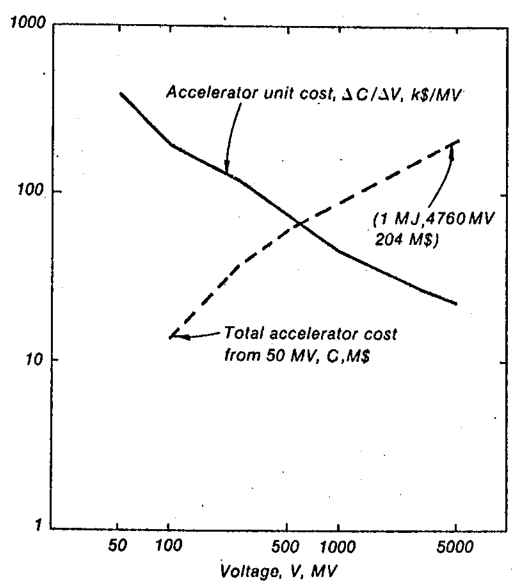

FIG. 4 - MINIMUM UNIT COST AND ACCELERATOR COST

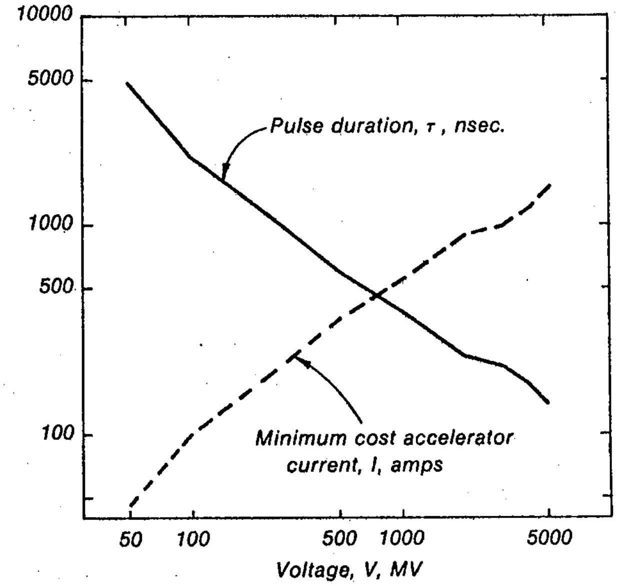

FIG. 5 - ACCELERATOR CURRENT AND PULSE DURATION

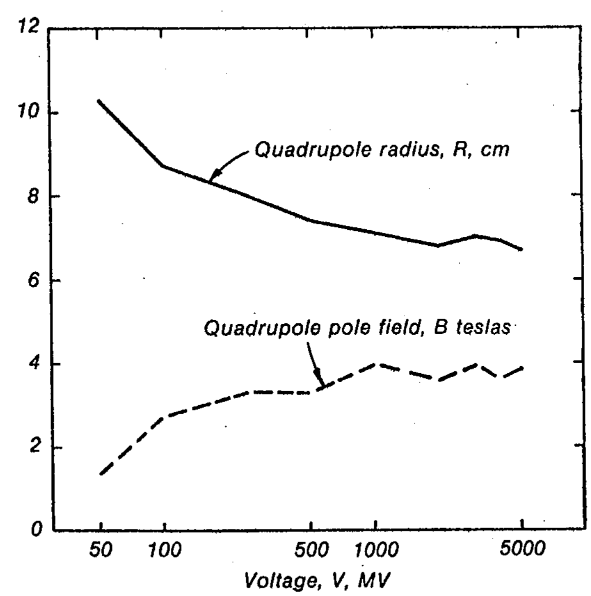

FIG. 6 - TRANSPORT MAGNET FIELD AND RADIUS