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UCRL-JC-128679
PREPRINT

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This paper was prepared for submittal to the
17th IEEE/NPSS Symposium on Fusion Engineering
San Diego, CA
October 6-10, 1997

September 30, 1997

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Systems Modeling for Heavy Ion Drivers — An Induction Linac Example

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Abstract — A source-to-target model for a induction linac driver for heavy ion fusion has been developed and is described here. Design features for a reference case driver that meets the requirements of one current target design are given, and the systems analyses supporting the point design are discussed. Directions for future work are noted.

I. INTRODUCTION

The authors' organizations have been working together to develop a systems model for a heavy ion driver based on induction linac technology. The emphasis at this point has been on drivers for future heavy ion fusion (HIF) power plants, but the tools being developed will also be used to evaluate candidates for more near-term experimental facilities. Previous systems modeling and conceptual design studies for HIF drivers can be found in [1-4]. The model described here is an integrated source-to-target model that includes the key interdependencies of the major subsystems in terms of cost, performance and constraints. We begin with a brief description of the general features of the code, including some example parametric studies, present the reference case design parameters, and conclude with the results of some cost sensitivity studies and direction for future work.

II. MODEL DESCRIPTION AND EXAMPLE PARAMETER STUDIES

The code is written using a commercial scientific/engineering software package (Mathcad) that incorporates text and graphics in an easily readable and user-friendly format. The reference case induction linac driver architecture includes a multi-beam injector feeding an electrostatic transport section, four-to-one beam merging and transition to a magnetic transport section at some higher energy (e.g., ~100 MeV). The main accelerator is followed by final transport and final focus sections. The final transport section provides the distance needed for drift compression (to get the required pulse length on target) and re-alignment of the beams for two-sided illumination. The final focus section models the final focus quadrupoles (four per beam) that are used to first expand the beam radially and then focus it to a small spot on target. Calculation of the spot size on target is included.

A. Inputs, Assumptions, and Constraints

The code includes numerous inputs, assumptions and constraints for the models of the various subsections. Typical

assumptions would be cost scaling dependencies in cases where these have not been established in actual practice, and component unit costs (e.g., \$/kg of various materials). Examples of constraints include the source current density limit (A/m^2) and the acceleration gradient limit (V/m). A key input is the specification of beam characteristic that the driver must deliver to the target. Table I gives the target requirements for one current HIF target design [5]; other target designs will be investigated in future work. Note that the target requires a prepulse with a lower ion energy than the main pulse.

Table I
Target Requirements

	Pre-Pulse	Main Pulse
Ion mass, amu	200	200
Ion energy, GeV	3.0	4.0
Beam energy, MJ	1.6	4.3
Total charge, mC	0.53	1.07
Pulse duration on target, ns	30	8
Spot radius on target, mm	2.7	2.7

B. Injector

The multi-beam injector delivers ions at 2 MeV simultaneously to each beam channel in the low-energy, electrostatic transport section. The total charge (C) per beam is simply calculated from the given total beam energy on target (J) divided by the final ion energy (eV). The initial current (A) per beam at the exit of the injector is this charge per beam divide by the initial pulse duration (s), which is one of the design variables we optimize. In our model, the number of prepulse and main pulse beams is set such that each beam carries the same charge. In this way, the entire accelerator up to 3 GeV is identical for prepulse and main pulse beams. The source radius for each beam depends on the achievable source current density (A/m^2), which is a function of diode gap as described by the Child-Langmuir law and is constrained by emission limits for the particular ion source. Since the diode gap is proportional to the source radius, there is a unique combination of source radius, diode gap, and diode voltage that gives the required current per beam. For example, the reference case design with 192 beams at the low energy end, has a source radius of 29 mm, diode gap of 73 mm, and a diode voltage of ~300 kV providing a current of 0.3 A per beam at a 30 μ s pulse duration.

*Work performed under the auspices of U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

C. Electrostatic Transport Section

The electrostatic quadrupoles are used at the low energy end of the accelerator, from the 2 MeV injector energy to ~100 MeV in our reference case design. The general configuration of the multi-beam array is illustrated in Fig. 1. The beam size depends on the current per beam coming from the injector. Electrode dimensions are scaled from the beam size and in turn determine the outer radius of the multi-beam array and the inner radius of the induction cores. Fig. 2 show the inner radius of the cores as a function of the number of beams for three different initial pulse durations: 20, 30, and 40 μ s. The inner radius decreases with increasing number of beams and initial pulse duration. For our reference case of 192 beams and 30 μ s, the inner radius of the cores is 0.37 m.

Fig. 1. Configuration of electrostatic quad array.

Fig. 2. Inner radius of cores in electrostatic section as a function of the number of beams for initial pulse durations of 20, 30, and 40 μ s.

The acceleration gradient increases from an initial value of ~50 kV/m to 330 kV/m at 100 MeV; it is limited by the maximum allowable radial build of the cores, which is a user specified constraint (1.0 m in this case). This then determines the length of accelerator required to achieve a given ion energy, which is 492 m to an ion energy of 100 MeV.

The cost of the electrostatic quads is broken down into six subsystems: electrodes, end plates, insulators, power supplies, vacuum vessel, and articulation. The cost of the accelerator modules (or cores) includes the cost of metglas, cell housing and structural support. The electrostatic transport cost is the sum of the costs for quads, cores, pulsed power and the vacuum pumping systems. To this we add the cost of the injector to get the cost of the front end. Cost scaling relationships have been developed for all these subsystems.

Fig. 3 shows the cost for the front end as a function of the initial pulse duration. The cost have been normalized to the minimum, which occurs at 30 μ s. The cost is strongly dominated by the cost of cores for pulse durations greater than 30 μ s. At lower pulse durations, the injector cost rises rapidly due to the higher initial current per beam and correspondingly high source area requirements.

The cost of the front end also decreases with increasing number of beams, but reaches diminishing returns beyond 150-200 beams. The cost of our 192-beam reference case design is only 10% higher than a 300 beam case.

Fig. 3. Relative cost of front end (up to 100 MeV) as a function of initial pulse duration for 192 beam case.

D. Magnetic Transport Section

At the transition from electrostatic to magnetic focusing, the multi-beam array undergoes a 4-to-1 beam merging, which gives 48 beams in the magnetic section. The transition energy is a design variable that is chosen to minimize the overall driver cost (including front end, magnetic transport section, final transport and final focusing). As will be shown later, the cost is rather insensitive to this transition energy over 10's of MeV, with the optimum at ~ 100 MeV.

As in the electrostatic section, all of the beams in the magnetic quadrupole section share common cores. Each quad occupies a square unit cell, illustrated in Fig. 4, consisting of an inner vacuum pipe (bore) wall, a 0.5-cm-thick layer of superinsulation, a support wall on which the superconductor is wound, and regions (primarily the corners of the square) for superconductor and associated cooling. The entire package is surrounded by a stainless steel (SS) box on the outer edge. The inner radius of the bore is scaled from the beam size which depends on the current per beam and the magnetic field of the quad. The thicknesses of the stainless steel walls and the outer box scale in proportion to the beam size and are set by stress considerations. One half a unit cell thickness of conductor surrounds the entire array to provide a flux return path for the quads on the outer edge.

Fig. 4. Configuration of magnetic quads

The overall radial dimension of the array determines the inner radius of the induction cores. Fig. 5 shows the core radius as a function of the quad field at the winding, B_w , for several different initial pulse durations. The minimum inner radius occurs at 6 T in each case. At higher fields, extra space is needed for conductor, and the quad unit cell and overall array dimension increase. While 6 T gives the smallest core radius, the minimum cost for the driver occurs at $B_w = 4$ T. This illustrates the importance of an integrated model.

The acceleration gradient in the magnetic transport section increases rapidly to 1 MV/m and then rises slowly to a maximum of nearly 2 MV/m. As the acceleration gradient is increased, the core axial packing fraction is decreased to reduce capacitance and prevent breakdown. Once the ions reaches 3 GeV, the array is split into two parallel multi-beam arrays, one for the prepulse (16 beams) and one for the main pulse (32 beams). As the main pulse beams continue to

Fig. 5. Core inner radius as a function of quad field at the winding for initial pulse durations of 20, 30 and 40 μ s.

accelerate to 4 GeV, the prepulse beams are simple transported to the end of the accelerator.

E. Final Transport and Focusing

At the end of the accelerator, the prepulse and main pulse have pulse duration of 140 and 110 ns, respectively. These must be shortened prior to focus on target to 30 and 8 ns, respectively. A simple model is used to calculate the required velocity tilt and drift length to accomplish this [6]. Secondly, we determine the transport length needed simply to redirect the beams to a two-sided illumination geometry as a function of the field in the dipole bending magnets. The larger of the two distance sets the final transport length. The final transport cost includes the costs of quads, dipoles, and a vacuum system. In our reference case, a dipole field of 4.5 T gave the minimum cost and resulted in final transport length (from the end of the accelerator to the end of the final focus magnets) of 415 m. Note that as the pulses are compressed, the current per beam rises rapidly, and the bore radius and quad fields are increased in order to transport the higher currents.

The final focus geometry is based on a simple point-to-point lens model consisting of four quadrupoles for each beam [7]. Magnet dimensions and costs scale with the beam size at the middle of the final quad which is equal to the product of the beam focusing half angle, θ_f , and the final focus length, L_f (distance from the middle of the last quad to the target). An allowance for neutron shielding inside the bore of the final focus quads is included, although more detailed work is needed on this aspect of the design. The inner radius of the bore is also constrained by voltage breakdown between the beam and bore wall using a limit of 200 kV/m.

III. REFERENCE CASE PARAMETERS

Table 2 shows several parameters of the reference case design which delivers the required 5.9 MJ to target. The overall length of the accelerator is 3250 m plus an additional 420 m for the final transport and focusing. The current per beam increase from 0.3 A at the exit of the injector to 1.1 kA for the prepulse and 4.2 kA for the main pulse. The beam radius is less than 7 mm in both the electrostatic and magnetic section, and the bore radius is ~ 13 mm.

Table II
Reference Case Design

Number of beams (electrostatic / magnetic)	192 / 48			
Initial pulse duration, μ s	30			
Transition to magnetic transport, MeV	100			
Accelerator quad field at winding, T	4.0			
Final transport quad field at winding, T	4.5			
Final focus length, m	5.0			
Beam focus half angle, mrad	10			
Parameters Along Accelerator				
	Injector Exit	End of EQT ^a	Pre-pulse	Main Pulse
Ion energy, GeV	0.002	0.1	3	4
Pulse duration, μ s	30	4.2	0.14	0.11
Pulse length, m	41.7	41.7	7.6	6.6
Beam current, A	0.3	2.0	230	310
Beam radius, mm	6.6	6.6	6.9	6.9
Bore radius, mm	12.6	12.6	12.9	12.9
Core inner rad., m	0.37	0.37	0.29	0.25
Core build, m	0.92	1.0	0.89	0.4
Acc. gradient, MV/m	0.05	0.33	1.77	1.77
Dist. from injector, m	0	490	2220	3250
Parameters at last final focus quad				
	Prepulse		Main Pulse	
Pulse duration, ms	30		8	
Pulse length, m	1.6		0.5	
Beam current, A	1110		4170	
Beam radius, mm	50		50	
Bore radius, mm	70		70	

^aEQT = Electrostatic quad transport

IV. COST RESULTS

A. Cost Breakdown

The total direct cost of the 5.9 MJ reference case driver is ~ \$1.4 B. The contributions to this total are: injector (2%), electrostatic transport (10%), magnetic transport (48%), final transport (6%), and final focus (3%). We include an allowance for instrumentation and control (6%) and assembly (23%). We note that these results are preliminary and work continues on refining the cost scaling models and accelerator architecture in order to reduce this cost.

If we examine the cost of the magnetic transport section in more detail, we find that its cost is dominated by the cost of cores (40%) and pulsed power (40%). The quads account for 14% and the vacuum system the remaining 6%.

B. Cost Sensitivity

Fig. 6 shows the sensitivity of the driver cost (normalized to the reference point cost) as a function of changes in reference point design variables. As indicated, the cost is relatively insensitive to parameter variations over a rather broad range. The driver cost is most sensitive to reducing the initial pulse duration (+17% going to 15 μ s) and reducing the number of beams (+13% for half as many beams). Changing the quad field over the range of 2 to 6 T increases the cost by 5% or less. The transition energy from electrostatic to magnet transport has very little impact over the range of 50 to 150 MeV.

Fig. 6. Sensitivity of cost to changes in reference case parameters.

V. FUTURE WORK

This work is still in progress and several things are planned for the future. First, we will conduct studies with the current architecture to find optimum designs and costs for different ions, ion energies and targets, including higher charge-to-mass ratio ions. We work to improve the cost basis and cost scaling models, develop a better treatment of emittance growth along the accelerator, and provide more detailed on the final focusing model. Technical solutions, such as using fewer, more powerful thyatrons for the pulsed power, will also be incorporated. Finally, we to evaluate other architectures (e.g., an all magnetic front end, elimination of merging, replacing part of the magnetic section with a recirculating linac).

ACKNOWLEDGMENTS

We would like to thank John Barnard, Debra Callahan-Miller, Alex Friedman, and Grant Logan of LLNL as well as Joe Kwan and Ed Lee of LBNL for their reviews of various parts of the model and useful suggestions.

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