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Systems analysis for modular versus multi-beam HIF drivers

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Systems Analysis for Modular Versus Multi-Beam HIF Drivers*

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Abstract

Previous modeling for HIF drivers concentrated on designs in which 100 or more beams are grouped in an array and accelerated through a common set of induction cores. The total beam energy required by the target is achieved by the combination of final ion energy, current per beam and number of beams. Economic scaling favors a large number of small (~1 cm dia.) beams. An alternative architecture has now been investigated, which we refer to as a modular driver. In this case, the driver is subdivided into many (>10) independent accelerators with one or many beams each. A key objective of the modular driver approach is to be able to demonstrate all aspects of the driver (source-to-target) by building a single, lower cost module compared to a full-scale, multi-beam driver. We consider and compare several design options for the modular driver including single-beam designs with solenoid instead of quadrupole magnets in order to transport the required current per module in a single beam, solenoid/quad combinations, and multi-beam, all-quad designs. The drivers are designed to meet the requirements of the hybrid target, which can accommodate a larger spot size than the distributed radiator target that was used for the Robust Point Design. We compare the multi-beam and modular driver configuration for a variety and assumptions and identify key technology advances needed for the modular design.

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1. Introduction

The most developed and studied concept for a induction accelerator driver for heavy ion fusion (HIF) is the multi-beam design in which a hundred or more beams are grouped in an array and accelerated through common induction cores [1,2]. The designs use quadrupole-focusing magnets over the entire length of the accelerator, or in some cases use electrostatic quads at the low energy end. After acceleration, the array must be split into two and the beams redirected to provide two-sided illumination of the hohlraum target. Drift compression occurs during this final transport section. Recently we have been exploring an alternate architecture, the modular driver, in which the driver is subdivided into many (>10) independent accelerators (modules) with one or more beams each. A key objective of the modular driver approach is to be able to demonstrate all aspects of the driver (source-to-target) by building a single, lower cost module compared to a full-scale, multi-beam driver. We have developed a system model to compare several design options for modular drivers. The drivers are designed to meet the requirements of the hybrid target [3], which can accommodate a larger spot size (~5 mm radius) than the distributed radiator target that was used for the Robust Point Design (RPD) [4]. In Section 2 we describe a driver option that uses solenoid instead of quadrupole magnets in order to transport the required current per module in a single beam. In Section 3 we show potential benefits of transitioning from solenoid to quad magnets at some point along the accelerator. Section 4 discusses the potential advantages that neutralized drift compression and relaxed target spot size requirements can have for the mult-beam all-quad designs we have studied in the past, and Section 5 gives conclusions and plans for next steps in the systems modeling work.

2. All-Solenoid Modules

In considering modular drivers, it is quickly apparent that it is not practical to simply take the multi-beam driver and divide it into hundreds of modules (like lasers can do). The main obstacle is that each module needs a set of induction cores. To be practical we need fewer, high-current beams. This led to the consideration of using solenoid magnets instead of quads since the scaling with beam current is favorable especially at low ion energy [5]. Table 1 gives accelerator and beam parameter for an optimized, modular driver using solenoid focusing. The total driver energy is 6.7 MJ, which is divided into 24 single beam modules. Each module, however, is double pulsed, giving 48 beam pulses (140 kJ/pulse) to provide the necessary symmetry and pulse shaping required by the target. (We have not worked out all the pulse shaping details at this stage.) The ion is Ne^{+1} and the final ion energy is 200 MeV, which gives the correct range when deposited in the target radiator material. In order to maximize commonality of parts we assume that the bore and winding radii are constant along the entire accelerator. Key accelerator and beam dimensions as a function of ion energy are given in Fig. 1. The optimum initial pulse duration is 20 μs accounting for an 8× bunch compression prior to acceleration, or 2.5 μs into the accelerator (at 0.9 MeV). The bunch length is held constant (7.2 m) during acceleration, giving a final pulse duration of 0.17 μs. The acceleration gradient grows from 0.28 MV/m to 2.4 MV/m by the end of the accelerator resulting in a total acceleration length of only 125 m. Note that as the acceleration gradient increases, the acceleration gap between adjacent solenoids increases to prevent breakdown, so the occupancy factor decreases and the beam radius grows slightly for the assumed fixed field (5.6 T at the winding). The beam edge, however, is always > 3 cm from the bore. The constant core radial build of 0.62 m was chosen to minimize overall cost. The quad spacing is limited to 1 m to prevent the gap voltages from becoming excessive.

The total cost for this particular design is ~\$1.75B (excluding neutralized drift compression and final focus magnets – expected to be small), which is significantly less than the \$2.8B for the RPD driver. Figure 2 shows how this cost scales with the number of modules. A smaller number would be better, but target symmetry and pulse shaping will likely require the 24 modules (48 pulses) used in this example. Figure 3 shows the scaling with ion mass. Clearly lower mass ions, with corresponding low final ion energy (scales as A), are more attractive. The key then is to develop the ability to do pulse compression and focusing of these high current, low mass ions. Neutralized drift compression is the chosen approach coupled with either plasma channel (assisted pinch) or compensated neutralized ballistic focusing [6,7].

3. Solenoid/Quadrupole Modules

Since quad focusing becomes more efficient with increasing ion energy, we next consider the option of using solenoid magnets at the start of the accelerator modules and then switching to quad focusing at some higher energy to be optimized. Figure 4 shows the results of the 32-module driver. Plotted are the cost of the injector (constant), solenoid region, quad region and total as a function of the solenoid-to-quad transition energy (T_{SQ}). The benefits of solenoids at lower energy are evident as the total cost decreases with increasing transition energy. The optimal point at which to switch to quads is ~ 120 MeV, but the driver cost is quite insensitive to T_{SQ} between ~100 MeV and the final ion energy of 200 MeV. That is a half-solenoid, half-quad module is comparable in cost to an all solenoid module.

A variation of this architecture is to combine a single beam solenoid section at the start followed by a multi-beam quad region beyond T_{SQ}. The feasibility of splitting the beam while maintaining adequate beam quality is uncertain. Also, if a mask with multiple holes is used for beam splitting (as has been done in some single shot experiments), the mask would experience significant ion heating and possible ablation which could interfere with subsequent pulses. None-the-less, Fig. 5 shows the cost if the beam was split into four beams at the transition. In this case, the optimal transition occurs at ~ 50 MeV. The four-beam array in the quad section is more compact (by ~2×) than a single quad beam (20 vs. 30 cm), leading to a lower cost per meter and lower transition energy.

4. Mutli-Beam, All-Quad Linacs with Low Mass Ions

A natural question is how the multi-beam, all-quad linac design would be affected by the ability to use neutralized drift compression with high current, low mass ions. For this study, we used the IBEAM case with slightly different assumptions (6.4 MJ). We found an optimal design using ~ 150 beam (somewhat high than the 120 RPD design) with a cost of ~ $1.4B, a factor of two lower than the $2.8B for the 7 MJ RPD driver. So clearly, developing the science and technology for neutralize drift compression and demonstrating focusing schemes for high current, low mass ions would be broadly beneficial. Recall, however, that a key motivation for considering modular drivers is the ability to demonstrate the source-to-target driver design at lower cost.

5. Conclusions and Future Work

Based on our preliminary systems analysis of modular drivers for HIF, we conclude that: a) modular drivers are a potentially attractive option with low mass ions (< 40 amu), using 10's of modules (not 100's), neutralized drift compression, and combined targets that can accept larger spot size beams; b) combined solenoid/quad modules are also attractive with optimal transition energies of ~120 MeV for single beam modules; c) if feasible, beam splitting at transition to quads would be beneficial and results in a lower optimal transition energy; and d) neutralized drift compression and larger spot size targets also benefit standard multi-beam, all-quad linacs.

Future system modeling work is needed to: a) improve the injector model (which is a significant cost component for these high current beams); b) include final transport and focusing models; and c) determine target gain scaling with achievable spot size (which will allow us to compare high-current modular drivers using large spot size targets to low-current multi-beam linacs using smaller spot size targets).

References

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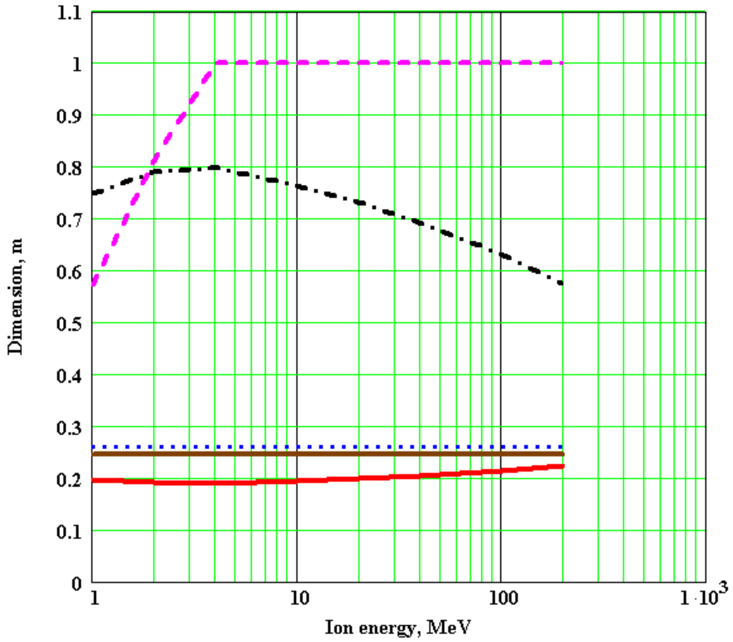

Fig. 1. Key solenoid accelerator dimensions as a function of ion energy: beam radius (red solid), bore radius (brown solid), winding radius (blue dotted), occupancy factor (black dash-dot), and magnet spacing (magenta dash).

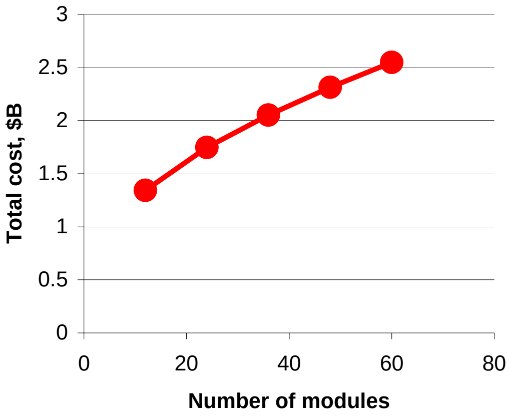

Fig. 2. Total drive cost versus number of modules (A = 20 amu, E = 6.7 MJ).

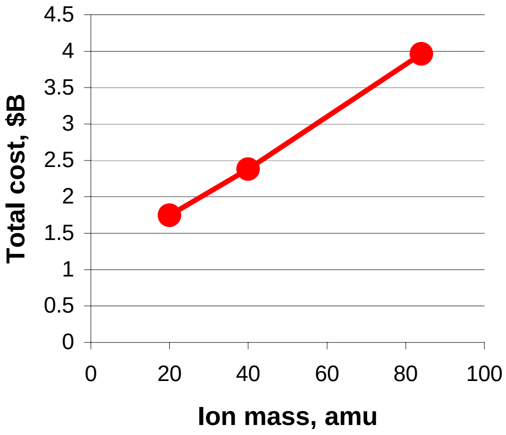

Fig. 3. Total driver cost versus ion mass (N = 24 modules, E = 6.7 MJ).

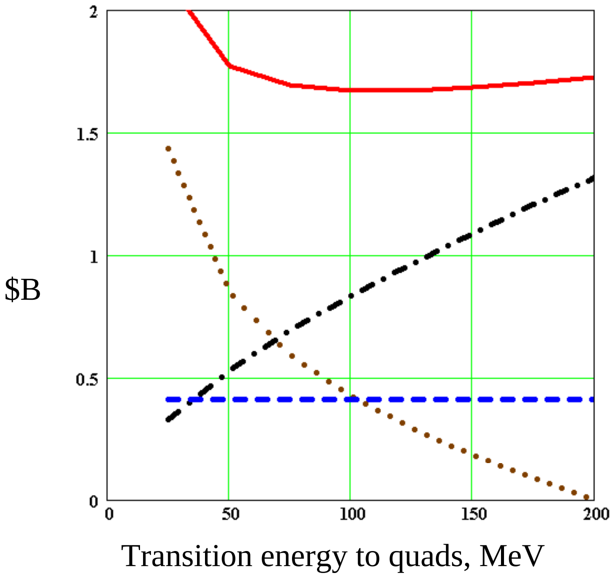

Fig. 4. Cost ($B) of injector (blue dash), solenoid region (black dash-dot), quad region (brown dot), and total (red solid) as function of the ion energy (MeV) for transition to quads: Modules with a single beam in both regions.

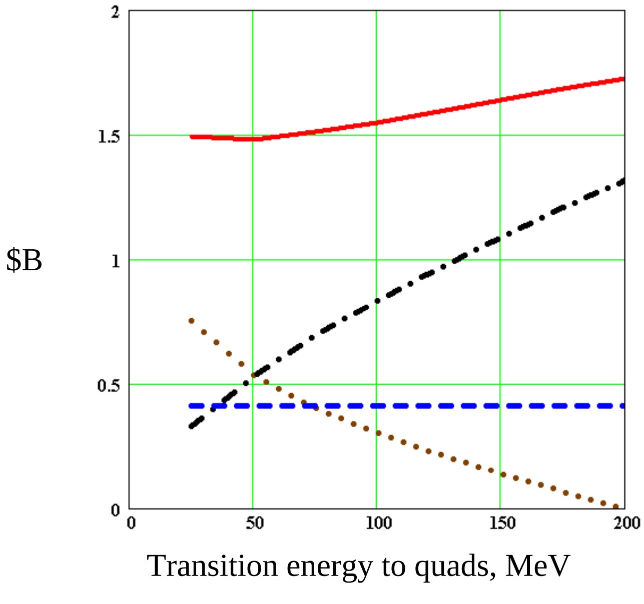

Fig. 5. Cost ($B) of injector (blue dash), solenoid region (black dash-dot), quad region (brown dot), and total (red solid) as function of the ion energy (MeV) for transition to quads: Modules with a single beam in solenoid region and four beams in quad region. Optimum transition is ~50 MeV.

Table 1. Accelerator and Beam Parameter for Example All-Solenoid Modular Driver.

Total driver energy	6.7 MJ
Number of modules	24
Total pulses	48
Energy per pulse	140 kJ
Ion / mass	Ne^{+1} / 20 amu
Final ion energy	200 MeV
Core radial build	0.62 m
Max gradient	2.4 MV/m
Accelerator length	125 m
Accelerator efficiency	33%
Initial ion energy	0.9 MeV
Final ion energy	200 MeV
Charge per pulse	0.70 mC
Initial pulse duration	20 μs
Bunch compression	8x (2.5 μs)
Initial beam current	280 A
Pulse length (constant)	7.2 m
Line charge density	97 μC/m
Final pulse duration	0.17 μs
Final beam current	4.1 kA