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Differential acceleration in the final beam lines of a Heavy Ion Fusion driver

Alex Friedman [a,b,*]

[a] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[b] The Virtual National Laboratory for Heavy Ion Fusion Science, USA

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ABSTRACT

A long-standing challenge in the design of a Heavy Ion Fusion power plant is that the ion beams entering the target chamber, which number of order a hundred, all need to be routed from one or two multi-beam accelerators through a set of transport lines. The beams are divided into groups, each of which has a unique arrival time and may have a unique kinetic energy. It is also necessary to arrange for each beam to enter the target chamber from a prescribed location on the periphery of that chamber. Furthermore, it has generally been assumed that additional constraints must be obeyed: that the path lengths of the beams in a group must be equal, and that any delay of "main-pulse" beams relative to "foot-pulse" beams must be provided by the insertion of large delay-arcs in the main beam transport lines. Here we introduce the notion of applying "differential acceleration" to individual beams or sets of beams at strategic stages of the transport lines. That is, by accelerating some beams "sooner" and others "later," it is possible to simplify the beam line configuration in a number of cases. For example, the time delay between the foot and main pulses can be generated without resorting to large arcs in the main-pulse beam lines. It is also possible to use differential acceleration to effect the simultaneous arrival on target of a set of beams (*e.g.*, for the foot-pulse) without requiring that their path lengths be precisely equal. We illustrate the technique for two model configurations, one corresponding to a typical indirect-drive scenario requiring distinct foot and main energies, and the other to an ion-driven fast-ignition scenario wherein the foot and main beams share a common energy.

1. Introduction

A long-standing challenge in the design of a Heavy Ion Fusion power plant [1–4] is that the ion beams entering the target chamber, which number of order a hundred, all need to be routed from one or two multi-beam accelerators through a set of transport lines. After emerging from the accelerator(s) and undergoing conjoined transport over some distance, the beams are separated. They are divided into groups, each of which has a unique arrival time and may have a unique kinetic energy. It is also necessary to arrange for each beam to enter the target chamber from a prescribed location on the periphery of that chamber. Furthermore, it has generally been assumed that additional constraints must be obeyed: that the path lengths of the beams in a group must be equal, and that any delay of "main-pulse" beams relative to "foot-pulse" beams must be provided by the insertion of large delay-arcs in the main beam transport lines.

Here we introduce the notion of applying "differential acceleration" to individual beams or sets of beam at strategic stages of the transport lines. That is, by accelerating some beams "sooner" and others "later," it is possible to simplify the beam line configuration in a number of cases. For example, the time delay between the foot and main pulses can be generated without resorting to large arcs in the main-pulse beam lines. In some cases, *e.g.*, when two accelerators are arranged at opposite sides of the chamber, this can reduce the need for beam bending, known to be a source of emittance growth in space-charge-dominated beams.

It is also possible to insert "trim" accelerating elements into the individual final beam lines. These can enable differential acceleration to provide for the simultaneous arrival on target of a set of beams (*e.g.*, for the foot-pulse) without requiring that their path lengths be precisely equal. This can dramatically simplify the design of the three-dimensional "railroad yard" leading to the chamber, and reduce its cost. It may also be possible to reduce some components of the required geometrical precision by this means, though we have not assessed this.

The layout of this paper is as follows. Section 2 reviews typical final beamline layouts for indirectly driven [5,6] and directly driven [7] targets, and some earlier work on their overall configurations.

* Correspondence address: Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94550, USA.
E-mail address: af@llnl.gov
URL: https://www-pls.llnl.gov/fesp/hifs

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Section 3 presents the differential acceleration concept and the simple calculation used to generate the examples. Section 4 illustrates the technique for two model configurations. One corresponds to a typical indirect-drive scenario, requiring distinct foot and main energies [5,6]. The other corresponds to an ion-driven fast-ignition target (the "X-target") [8,9] which requires only single-sided drive, and in which the foot and main beams share a common energy. Finally, Section 5 offers a few closing comments.

2. Final beam line layouts

In a "traditional" indirect-drive HIF power plant concept, clusters of beams approach the target chamber from two sides; each cluster fans out into a set of cones. To simplify the final beam routing, the cone angles are kept as small as possible, consistent with final focusing magnet shielding requirements and other constraints. The "Robust Point Design" (RPD) is an example of such a system [10]. The general geometry is illustrated in Fig. 1.

Other concepts involve directly driven targets [7]. The most straightforward approaches assume that the beams come in from ports distributed uniformly around the periphery of the chamber in some regular pattern; these, however, complicate the chamber design, and seem to preclude the use of neutronically thick liquid walls of, *e.g.*, FLiBe. Alternatively, a "polar direct drive" approach keeps the beams on cones (typically with a larger cone angle than for indirect drive); the beams are aimed and otherwise specified so as to give uniform target drive (in some cases this may require sweeping the nominal focal spot positions during the target drive). A representative layout showing some of the beams in a direct-drive scenario is shown in Fig. 2.

To maintain a longitudinally quiescent beam, "ear" fields (additional components of the accelerating waveforms designed to counteract the space-charge-induced blow-off of the ends) are needed, both in the accelerator and in the transport lines.

In almost all scenarios, the beams also undergo (non-neutral) drift compression during some portion of their final transport toward their final-focusing lenses (typically, magnetic quadrupole multiplets). In this process, a head-to-tail velocity gradient or "tilt" is imparted to a beam, which then shortens and temporally compresses as it drifts. Ultimately, the inward motion in the beam frame of reference is halted by space-charge forces, leaving the beam nearly mono-energetic. This "stagnation" is beneficial because minimization of the coherent energy spread along the beam reduces the deleterious effects of chromatic aberrations on the focal spot [11].

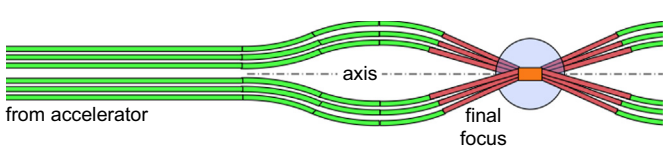

Fig. 1. Conceptual layout of a final beam layout for an HIF driver intended to work with indirectly driven targets.

Pulse shaping of individual beams is sometimes assumed [12]. This is accomplished by imposing a non-uniform velocity tilt on the beam, so that it compresses in a manner which is not nearly self-similar. In contrast, the RPD builds up the pulse shape required by stacking building-block pulses. In either case, some beam pre-configuration in advance of the final drift compression is likely to be needed, requiring additional transport length.

In power plant concepts employing a single, multi-beam linac but targets requiring two-hemisphere drive, it is necessary to use at least a pair of arcs to carry the beams from the accelerator to the vicinity of the target chamber. This is the case for both indirect-drive and direct-drive scenarios; see Fig. 3.

The late Dr. David Judd developed a conceptual design of the transport lines for an HIF power plant [13]. It is documented in a draft report, left incomplete and unpublished by Dr. Judd. More recently, a commentary on that work was developed, necessarily also as an unpublished Laboratory report [14]. In the scenario examined therein, the arcs are ~ 600 m long, while the drift distance should be < 240 m. Thus, the velocity "tilt" must be imposed in the arcs, or upon exit from the arcs (requiring longer transport lines). In order to produce the required time delay between foot and main pulses, Judd's work assumed separate arcs for those two groups of beams. Fig. 4 shows the layout, which includes a significantly longer path length for the main-pulse beams. Note also how the beam clusters fan apart so as to enable the beams to enter at positions on their respective cones.

3. Differential acceleration

We now turn to the concept of differential acceleration. The linac is assumed to accelerate all beams in tandem to some intermediate kinetic energy, $\mathcal{E}_0$ (considered to be specified in eV). At that point, which we consider the starting point $z_0 = 0$ for our calculations, the main-pulse beams and the foot-pulse beams split from each other, forming two separate beam bundles. Since they are to arrive first at the target, the foot-pulse beams are immediately accelerated to their final kinetic energy, $\mathcal{E}_{\text{foot}}$. This acceleration is complete when the foot beams reach the station $z = z_1$, the location of which is determined by $\mathcal{E}_0$, $\mathcal{E}_{\text{foot}}$, and the acceleration "gradient" (rate) $\mathcal{G}$ in V/m. Thenceforth, the foot beams race ahead of the main beams. The acceleration of the main beams from $\mathcal{E}_0$ to their final kinetic energy $\mathcal{E}_{\text{main}}$ begins at station z_2, and is completed by station z_3. Beyond this point, the beams begin drifting. Though the main beams are now faster than the foot beams, the latter have a large head start and the main beams never catch up. See Fig. 5, which is schematic.

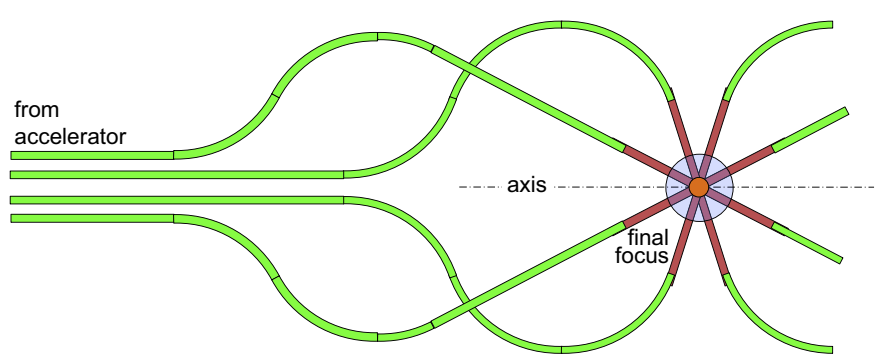

Fig. 2. Conceptual layout of a final beam layout for an HIF driver intended to work with directly driven targets.