# Propagation of Ion Beams in a Heavy-Ion Inertial Fusion System

## Topical area: Chamber and Drivers

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# Executive summary

In the baseline case of a Heavy-Ion Inertial Fusion reactor using two-sided indirect drive targets, an array of ion beams will be focused onto both ends of a cylindrical hohlraum. The hohlraum contains a DT fuel capsule, along with converter material designed to stop the ion beams and generate x-rays. The focusing of a single beam has been extensively studied numerically and benchmarked against scaled experiments, showing proper focusing to the intended radius, for realistic physical parameters. Of order a hundred beams must be focused onto, and overlap at, the ends of the hohlraums. However, the modeling, generally carried out using Particle-In-Cell (PIC) codes, has yet to be extended to multiple beams, due to the high computational cost of such simulations.

We highlight how progress in PIC codes will enable the modeling of arrays of ion beams as they are focused by magnetic lenses at the entrance of an HIF reaction chamber, then propagate and overlap before reaching the target. The planned simulations will incorporate multiple physical processes, including the ion beams' electromagnetic fields, the ionization of residual background gas in the chamber, the stripping of beam ions by the gas, interactions among the beams via their mutual electromagnetic fields, as well as their interactions with electrons and photons emitted by the target.

This research will be of high value and relatively low cost. It will provide crucial information on the validity of ion beam focusing, as well as compatibility with the desirable feature of neutronically thick liquids to protect the chamber wall, and with a wide range of target designs from direct to indirect drive. It will either retire significant components of the risk related to HIF, or show that past modeling and scaled experiments were too optimistic and thus guide concept modifications.

Building on earlier research, this effort will also include detailed HIF driver simulations (including ion beam generation, acceleration, and focusing upstream of the target chamber). Considerable earlier work concerned such simulations, and related studies in support of experiments on beam generation, acceleration, merging, and temporal pulse compression ("drift compression"). Extensions of this work will include coupling to simulations of HIF target physics.

# Introduction

In the baseline case of two-sided indirect drive targets, an array of ion beams is focused onto both ends of a cylindrical hohlraum. The hohlraum contains a DT fuel capsule, along with converter material designed to stop the ion beams and generate the x-rays that drive the capsule implosion [1–4]. In direct drive, the beams are distributed as evenly as possible over the surface of a spherical DT capsule.

The focusing of one beam, from a radius of around 4 cm (RMS) to around 1 mm over the distance from the final magnetic lens to the target, has been extensively studied [5] numerically and benchmarked against scaled experiments, showing proper focusing of the beam to its intended radius at the ends of the hohlraum, for realistic physical parameters. The modeling was generally done using Particle-In-Cell codes to account for the interaction of the beam with residual gas filling the chamber, as well as with regions filled with plasmas to provide a reservoir of electrons to help neutralize the beam space charge. Due to the high computational cost of these simulations, the work has yet to be extended to multiple beams. Since of order a hundred beams may be employed, and (in both the driver and the chamber) these beams will exert electromagnetic forces on each other, additional studies are warranted.

The target sets the requirements for the ion beams, and design of an HIF system is centered on meeting those requirements. Thus in this discussion we first consider the beams in the fusion chamber, and then their acceleration and their transport in the final beam lines.

## 1 Physics of beam propagation in an HIF chamber

The most thoroughly developed HIF chamber concept is the HYLIFE-II design [6], featuring liquid protection of the inner chamber walls via a mix of fluorine, lithium and beryllium ($Li_2BeF_4$ or "FLiBe"). A thickness of about 1 m of FLiBe is needed to absorb fusion neutrons and to breed sufficient tritium for continued operation. The HYLIFE-II design meets this requirement with a combination of FLiBe curtains and jets. Oscillating nozzles produce rippled FliBe curtains that overlap to provide a series of falling horizontal tube-like cavities. Synchronizing with the alignment of each cavity with the center of the target chamber, an HIF target is injected along the axis, and a cone of ion beams converges on the target from each end to heat the hohlraum. The space between the beams is protected by a lattice of crisscrossed FLiBe jets. This wall protection is found to be adequate for chamber survival over the projected lifetime of a HIF power plant [2].

The array of ion beams on each side of the hohlraum is focused by magnetic optics before entering the chamber; each beam undergoes transverse compression by a factor larger than 10 as it travels from the chamber entrance to the target. Obtaining the final longitudinal and transverse compression required of HIF beams is a key requirement of any chamber design. In addition to the beams' own space charge, there are a number of processes that limit the spot radius. The ions' transverse thermal motion (transverse temperature) limits the minimum spot radius. Similarly, the longitudinal temperature (velocity spread) limits the minimum spot size as different ion energies have different focal lengths (chromatic aberrations). The longitudinal temperature also limits the minimum pulse duration, as different particles arrive at the target at different times.

The beam also interacts with some amount of residual gas emanating from the FLiBe jets, leading to some amount of stripping of the beam ions, which increases its space charge and sensitivity to it, and also leading to impact ionization of some of the gas, which provide electrons that can help neutralize the beam space charge. The net effect depends on the density of residual gas, the cross-sections of stripping and ionization, leading to better or worse focusing than in vacuum [5].

Simulations have shown that, depending in part on the chosen ion, the kinetic energy, the target design, and the chamber environment, (FLiBe vapor or other), a plasma may be needed to provide a reservoir of electrons to help neutralize the beam space charge and obtain the required spot size at the target. [7, 8]. With the experimental demonstration of the neutralization technique on scaled experiments, neutralized chamber transport of high-current ion beams became the preferred approach to managing the space-charge problem [2].

In addition, as early pulses heat an indirect-drive HIF hohlraum, soft x-rays emitted by the hohlraum photoionize the surrounding background gas. For the gas densities expected in liquid wall chambers, the resulting plasma improves neutralization near the target for main pulses and the late-arriving foot pulses. This additional neutralization is partly offset, however, by photostripping of the beam and by enhanced collisional stripping by the photoionized background gas. Together, these effects lead to a modest improvement in the beam focal spot [5].

Finally, as multiple beams converge to one side of the hohlraum in the chamber, they can interact through electric and magnetic fields, and final beam aiming must account for these forces. A tailored temporal pulse shape must be imposed on the beam currents if the target capsule is to implode and ignite; any resulting time-varying inter-beam forces (mutual attractions) must be understood and compensated for by time-dependent pre-steering. As the beams interact together and with the background gas, ions and electrons, there is the possibility for instabilities, e.g., two-stream, that must also be accounted for [9–13].

## 2 Integrated modeling of multiple beams physics with modern computer software and hardware

The method of choice for the modeling of the beam propagation and interaction with gas and/or plasma in an HIF reaction chamber is the electromagnetic Particle-In-Cell (EM-PIC) technique [14]. Codes based on EM-PIC self-consistently follow the evolution of charged macroparticles via the Newton-Lorentz equations and the associated electromagnetic fields, described using Maxwell's equations. The field is typically discretized on a Cartesian grid. Because of the high computational cost of an EM-PIC simulation of multiple beams, with the grid having to cover a very large region toward the entrance of the chamber, simulations have so far been limited to a single beam.

With the advances in computer hardware and PIC codes that have occurred in the last decade, the modeling of arrays of tens of beams is now at hand and is the natural next step in the study of beams propagating in an HIF chamber. Fortuitously, the PIC code WarpX [15, 16], the modern successor of one of the workhorse codes of the U.S. HIF program Warp [17–19], has been selected for the sole particle accelerator project of the U.S. DOE Exascale Computing Project (ECP), which is to deliver over the coming year the hardware and software for computing at Exascale in the U.S.

WarpX includes all the electromagnetic PIC algorithms that were implemented over the years in Warp, augmented by new algorithms and additional physics (e.g., Coulomb collision and QED effects). Like Warp, it also contains an electrostatic PIC mode and the implementation of the many features that Warp contains in this mode are progressively being implemented. WarpX is built around the (ECP) AMReX library [20], which provides state-of-the-art support for both CPUs and GPUs, multiple levels of parallelism, dynamic load balancing of parallel tasks, and adaptive mesh refinement. Thanks to these features, WarpX is much faster and scales better to tackle large problems on many nodes of computer clusters or supercomputers.

We propose to leverage the computational power offered by WarpX and the new U.S. supercomputers to perform computational studies of the dynamics of single and multiple ion beams propagating in the environment of an HIF reaction chamber. The study will involve the following tasks:

1. Benchmark WarpX against selected past results from single beam propagation studies.
2. Ensure that all the physics processes that are needed for a comprehensive study have been implemented; upgrade as needed.
3. Determine sets of optimal algorithms (e.g., type of field solver), spatial and time resolution and grid adaptivity.
4. Select set of configurations to extend studies of beam propagation, with a range of options for, e.g., the ion beams kinetic energy, number and density of ion beams, residual gas composition and density.
5. Perform computational studies of single and multiple beams propagation for the selected configurations.
6. Build a database of ion beam distributions at the ends of hohlraums for computational studies of energy deposition and heating of hohlraums and targets driven by heavy-ion beams.

Based on the results, the community will reassess the range of options and associated risks related to ion beam propagation in HIF chambers. For the range of configurations that exhibit a credible path toward an HIF reactor design, the next step will be to extend the modeling upstream of the chamber, from the generation of the ion beams, along their acceleration and propagation in the driver, and through the final focusing optics, thence into the reaction chamber.

# 3 Beams' phase space configuration at the chamber entrance - start-to-end modeling of the driver

In addition to the various physics processes that were discussed above, the successful deposition of the ion beam arrays on the target will depend on the 6D distribution of each beam at the entrance of the reaction chamber, which is determined by the entire history of the beam, from its generation at the source to its final focusing.

It is thus essential to extend the modeling to account for (a) the generation of each beam at the source, (b) the beam-beam interaction in the accelerating gaps of the induction linac, (c) the loading of the induction modules, (d) the transverse beam transport in FODO (transverse confinement via alternating-gradient focusing) cells described with realistic aberrations from multibeam quadrupole arrays, (e) the potential interaction of the beams with gas and stray electrons produced by beam halo striking the walls, and (f) errors in alignment, external longitudinal and transverse focusing and accelerating fields.

The sequence of tasks that were enumerated above for the chamber propagation studies will apply similarly here, with benchmarking of WarpX modeling of a single beam from start-to-end of the particle accelerator against previous results and/or Warp. Leveraging the computational power and scalability of WarpX, the studies will then be extended to beam arrays from source to target. The new results will augment the database with new, more realistic, ion beam distributions at the focus, and also at selected key locations (e.g., exit of injector, entrance of final focus region). The work here will also be coupled to technology developments and systems optimizations that aim to significantly improve the development path and lower the fusion energy driver cost [21].

# 4 Connections to other IFE topics

WarpX is also well suited to the modeling of fast ignition, and of laser-plasma instabilities in the target and its immediate vicinity. It can be used for modeling, e.g., microscopic physics and hot electron generation (two plasmon decay, langmuir wave decay, etc) to inform large scale physics simulations.

Other white papers being submitted for this Workshop describe related approaches to Inertial Fusion Energy. These include electron- or ion-driven fast ignition. The latter scheme uses an igniter ion beam generated by impinging a short-pulse laser beam on a suitably shaped foil. Other means of generating such an igniter beam may involve an advanced version of conventional accelerator technology. Indeed, such fast ignition could also be married to ion-beam compression of the capsule. WarpX is well suited to model the electron or ion beam transport and its interaction with the plasma, as well as their generation and acceleration to the desired energy, for these two fast ignition scenarios. The WarpX simulations for the HIF program that are described in this document would, in addition, inform on ion intense transport and simulation methods of relevance to fast ignition research.

# Conclusion

The progress in software and hardware computational power now enables the detailed study of the propagation of ion beams arrays in a heavy-ion inertial fusion chamber. These studies will provide crucial information on the validity of our understanding, with regard to ion beam focusing, compatibility with the desirable feature of thick liquids to protect the chamber wall, and the suitability of a wide range of target designs from direct to indirect drive. This work will either retire some risk related to HIF, or show that past modeling and scaled experiments were too optimistic.

The ultimate goals of this work include the coupling of driver simulations to the modeling of ion beam propagation in the target chamber, and thence to HIF target simulations, with the end goal of truly predictive self-consistent source-to-target modeling of an HIF system.

This work is also complimentary and synergistic with other activities (e.g., studies of fast ignition and laser-plasma instabilities) within the IFE community.

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