Ion beams and Inertial Fusion Energy

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Executive summary

Heavy Ion Fusion (HIF) is a well vetted approach for inertial fusion energy (IFE) [1, 2]. In HIF, fuel compression, heating and ignition is achieved with beams of heavy ions, complementary to laser driven IFE [1, 2]. Proton (or ion) fast ignition is one option to support reliable ignition in laser driven IFE [3]. Over the last decade, (heavy) ion fusion and driver R&D has progressed, but at a slower rate compared to laser driven IFE and pulsed power approaches which have made tremendous progress at NIF and other facilities. Here, we propose a three pronged approach to advancing science and technology of ions for IFE that can lead to the ion driver and fast ignition capabilities needed for economical fusion power.

First, we propose to conduct scaled experiments, including with new high power, high energy heavy ion pulses (>10 kJ, ~100 ns) that are coming online soon to benchmark target and reactor designs with new data at high pressures and target temperatures up to tens of eV [4].

Second, we propose to take advantage of recent developments in modeling and simulation capabilities to find conditions for efficient focusing and beam propagation in a reactor chamber [5, 6].

Third, we propose to leverage recent advancements in ion accelerator R&D. Exciting progress has been made recently including in lower cost pulsed power for induction linac components [7, 8], massively scaled multi-beam RF linacs made by additive manufacturing [9], and laser-plasma based ion acceleration [10]. We propose to leverage these new directions and develop high power ion accelerator components for a new ion driven fusion power plant blueprint.

1. Introduction

Charged particle accelerators offer great promise as potential drivers for IFE, and as a component in fast ignition approaches [1-3, 11]. This is due to the known properties of ions and particle accelerators, including:

- the ability to deliver high energy pulses more directly to a fusion target (based on the physics of ion energy loss processes in collisions with target electrons and nuclei)
- the high efficiency of particle accelerators (>20% wall plug to beam in some cases)

- favorable final optics protection in a future reactor chamber
- demonstrated long life of accelerator components
- examples of stored beam energy in the 1 MJ range as required for future heavy ion fusion driver beams
- relatively high repetition rates (>10 Hz)
- multi-GeV heavy ions minimize the beam current required with an ion range in matter consistent with high gain fusion target dimensions
- HIF drivers also seem well suited to flowing liquid protection of the structural components of the reactor vessel
- finally, ion beam driven ICF targets are not subject to the laser-plasma interactions that have challenged some NIF and other experiments.

Nonetheless, the required beam currents of ~1 MA during a few ns at ~5 GeV to deliver ~5 MJ are still daunting [1, 2], as are requirements for fast ignition pulses (e. g. 10 kJ in 20 ps) [3].

2. Proposed technical R&D

Beam intensities required for IFE have not yet been achieved in conventional particle accelerators (nor in laser-plasma based ion accelerators). The achievable intensity of space-charge dominated beams, propagating through thousands of focusing magnets in parallel with tens of periodically interacting beams, all undergoing confinement and compression, remains to be confirmed experimentally. This beam physics challenge is amenable to highly accurate, predictive, first principles particle simulations as well as detailed analytic theory. Results from theoretical analysis and simulations to date are promising [2]. Propagation through the final target chamber, in which a background plasma may be employed to neutralize the beam space charge, requires a detailed understanding of collective beam/plasma and beam/beam interactions. Scaled experiments at relevant beam intensities have not been possible to date. The FAIR heavy ion facility in Darmstadt, Germany, will soon (2025+) operate with high intensity heavy ion pulses and a kinetic energy range that is highly relevant for IFE experiments. Pulses with up to $5x10^{11}$ uranium ions at HIF relevant energies in the tens of GeV range are predicted for heating of targets to temperatures up to ~30 to 50 eV (estimate) in ~100 ns pulses, with the possibility to combine ion and ns-laser laser pulses for plasma target formation, heating and compression [4]. These ion pulses will enable a new class of experiments where ion beam - plasma coupling can be studied at unpreceded intensities. The experiments will provide new data to benchmark driver parameters, fusion target and reactor chamber designs**. We propose that the US IFE community engage with FAIR to participate in selected experiments on ions for IFE.**

The attractive aspects of and challenges for a series of approaches for IFE, including heavy ion fusion, were summarized in the National Research Council report “An Assessment of the Prospects for Inertial Fusion Energy” from 2013 [12]. The report identifies the recent successes of the HIF program which have put to rest many critical issues, and listed the remaining outstanding challenges. Important issues are associated with the physics of intense beams in the accelerators themselves, rather than the target physics that can be addressed on NIF

and other high power laser facilities. The intense beams are non-neutral plasmas. Their study benefits from, and contributes to, the broader area of plasma science. One particularly successful example of mutual benefit has been the development and sharing of computational codes and techniques. Our ability to model and simulate particle accelerators has increased tremendously in recent years, due to advances in physics understanding, the development of more efficient codes, and increases in computational power [5]. **We propose a targeted modeling and simulation program that addresses key challenges of IFE based on heavy ion drivers, including final focusing and beam propagation in a future reactor chamber.**
Such a program can identify show stoppers, retire risks and open new pathways for ion driven IFE at modest cost while also delivering new discovery science results relevant to the broader high energy density science community. Detailed descriptions are presented in companion white papers [5].

In the early 2000s, DOE placed the energy mission of IFE on hold. Today, there are new opportunities to address critical challenges that had already been identified in the 2013 NRC report and do so efficiently at relatively modest funding levels. Intense bursts of ions produced by high-intensity laser beams and accelerators, including at high power laser facilities across LaserNetUS [13] and at facilities overseas, like FAIR [4], can now be used to test advanced plasma and beam physics models. Ion pulses and other secondary beams from laser-plasma acceleration can also advance diagnostics for IFE experiments. **We propose a program in HEDP for IFE at US and selected international high-power laser and ion beam facilities.**

Intense ion beams offer unique features for studying high energy density plasmas and provide data that support the quest for IFE. Energetic ions directly deposit energy in matter of any density. There is no critical density. The development of accelerators for high energy density physics, and ultimately power production, is synergistic with accelerators for other purposes such as particle physics and nuclear physics. It also has synergistic aspects with the development of other drivers utilizing pulsed power. Accelerator science and technology has advanced over the last ten years, as has laser and pulsed power technology.

We propose to assess recent accelerator science and technology developments, including laser-plasma, pulsed power and multi-beam ion accelerators (recently demonstrated with over 100 beams) and invest in new developments that can drastically change the economics equation for ion beam drivers and fast ignition approaches for IFE. Higher performance pulsed power switches based in SiC have enabled a new high-power induction linac designs [8]. RF linac components were recently made using additive manufacturing techniques (Figure 1) [9]. Optimized laser-ion acceleration promises efficient acceleration of intense pules of high energy ions and protons [10]. While at proof-of-concept stages today compared to driver requirements (or fast ignition pulses), these are examples of new directions in accelerator R&D that can now be advanced for the development of cost competitive fusion drivers. Newly available high-power switches offer the promise of increased performance and lifetime at reduced cost with benefit for multiple driver approaches. For ion drivers, these could reduce induction cell cost and enable shorter pulses in a more efficient driver (where wall-plug efficiencies as high as 50% seem possible.

We propose to invest in these promising development paths and scale demonstration components to high beam power at orders of magnitude reduced cost compared to currently deployed technologies. If successful, the result will be a new class of high-power ion accelerators for economical fusion power.

This proposed effort would include the development of a multi-parameter systems optimization code – from the source to the target – including the known scaling of target physics yield with beam energy and focal spot intensity [14]. Our goal is to identify a combination of drivers and targets that is leading to a compelling development path for a range of power plant outputs, from sub-GWe power plants [15] to multi-GWe power plants, with a significant reduction in overall cost.

Finally, much of the needed progress in target physics, power plant studies, target fabrication and systems integration are common to most drivers and can be supported by many, if of not all, members of the emerging IFE community.

Table 1 shows the fusion parameter space that is open to exploration and optimization. If successful, the "Ions for IFE" program we envision will inform new learning curves for intense, pulsed (heavy) ions beams that can enable and support new paths to economic fusion power.

Parameter	**Value**
Target fusion gain	50-300
Driver pulse energy	1-10 MJ
Driver wall plug efficiency	30-50%
Power output	0.3 to > 2 GW (switchyard , multiple chambers)
Pulse repetition rate	5-10 Hz
Ion mass	Ar - U (40 to 238)

Table 1: Summary of key heavy ion fusion driver parameters [1, 2, 16-19].

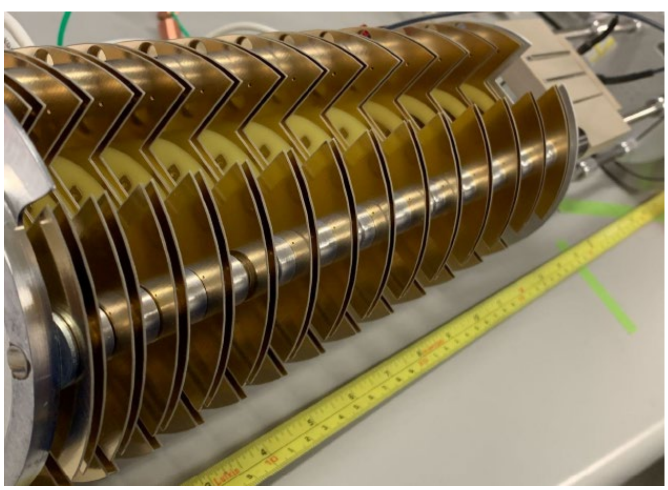

Figure 1: Photo of a multi-beam RF linac built from low cost wafers [9].

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