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Multiple beam induction accelerators for heavy ion fusion

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ABSTRACT

Induction accelerators are appealing for heavy-ion driven inertial fusion energy (HIF) because of their high efficiency and their demonstrated capability to accelerate high beam current (≥10 kA in some applications). For the HIF application, accomplishments and challenges are summarized. HIF research and development has demonstrated the production of single ion beams with the required emittance, current, and energy suitable for injection into an induction linear accelerator. Driver scale beams have been transported in quadrupole channels of the order of 10% of the number of quadrupoles of a driver. We review the design and operation of induction accelerators and the relevant aspects of their use as drivers for HIF. We describe intermediate research steps that would provide the basis for a heavy-ion research facility capable of heating matter to fusion relevant temperatures and densities, and also to test and demonstrate an accelerator architecture that scales well to a fusion power plant.

1. Motivation

The three main types of heavy ion drivers for inertial fusion energy are synchrotrons, RF linear accelerators (usually with storage rings) and induction linear accelerators. RF accelerators are appealing because of the extensive experience in high energy and nuclear physics; induction accelerators, because of their higher efficiency and experience accelerating high beam current (≥10 kA in some applications). The US effort has focused on induction accelerators because of the high efficiency at high beam current and because there is no need to accumulate charge in storage rings; their non-resonant character allows pulse compression during acceleration. Baseline driver design in the US consists of a multiple beam induction linear accelerator, accelerating beams to a final kinetic energy of 1 GeV per ion, or higher. Because of the high charge per bunch, transport, or transverse control of the beam, is the limiting consideration at low ion kinetic energy. The approach is to accelerate a longer bunch near the transport limit and gradually decrease its length within the accelerator – as allowed by beam dynamics – by small voltage ramps. The transport limit for current increases with velocity because of the increasing strength of the $v \times B$ force. Near the exit of the accelerator, a larger ramp is applied to compress the bunch. This final bunch compression occurs mainly at the end of the accelerator and in the drift lines leading to the target, resulting in the required short pulse at the target.

To put the driver objectives and components in context, Fig. 1 shows a typical layout of a multi-beam induction linear accelerator driver for heavy ion fusion. Operating at 5–15 Hz, many ion beams are injected into an induction accelerator, with the bundle of beams passing through common induction accelerator cores. Other induction accelerator architectures have been studied, for example, separate accelerators for each beamline, and recirculating induction accelerators. Initially motivated by their potential to lower cost, studies showed additional beam physics and technical issues, as described in Ref. [18], Chapter 10.

Singly charged ($q=1$) ions are often chosen because higher charge state ions create proportionally more space charge which would be much more difficult to produce and match to the alternating gradient lattice. Other favorable aspects of $q=1$ ions are the ability to create low-emittance beams of sufficiently high current with essentially no admixture of $q \geq 2$ ions, and the lower longitudinal confinement fields required for bunch containment. Of course, a disadvantage is the proportionally lower acceleration rate. Ion sources and injectors for HIF are reviewed by Kwan [1]. The accelerator front end may use electrostatic focusing quadrupoles at the front end, followed by a transition to superconducting magnetic quadrupoles for most ($>90\%$) of the accelerator.

A velocity ramp is applied to the beam near the end of the accelerator. The beam ($\beta = 0.2–0.3$) is not highly relativistic, thus the bunch length shortens by an order of magnitude or more to meet the 1–10 ns bunch duration required by the target. This drift-compression section and the final focusing system are reviewed by Kaganovich et al. [2] in these proceedings. A part of the drift compression section includes dipoles for each beamline to aim each beam at the target according to the required illumination geometry.

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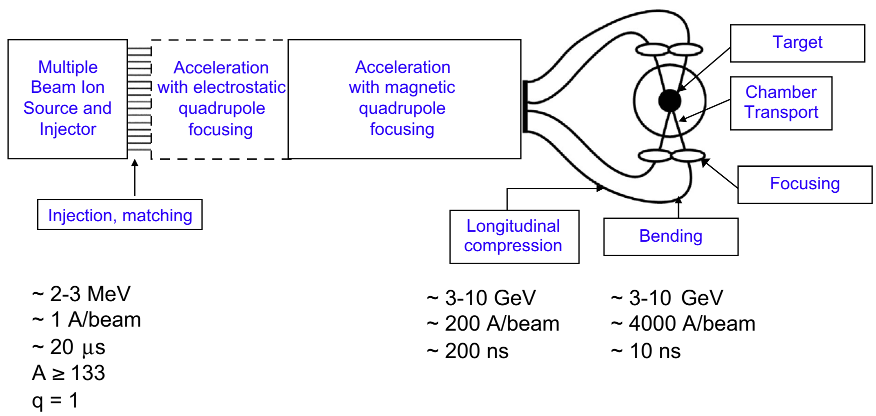

Fig. 1. Schematic of an induction accelerator driver for heavy ion fusion.

The propagation of the beams in the reactor chamber is reviewed by Olson [3]. The ends of each beamline must penetrate the reactor chamber wall while leaving sufficient solid angle for a viable tritium breeding blanket and heat extraction. This blanket design is usually a flowing thick layer of liquid, molten salt containing lithium, which protects the structural wall and focusing magnet coils from radiation damage [4]. This is a very desirable feature that is compatible with ion-beam driven IFE. Not shown in Fig. 1 are the essential tritium extraction, target factory, heat recovery and electricity generation systems.

Fundamental aspects of the fusion target designs (ignition mode, target size, energy coupling) have a great influence on the final beam parameters and target illumination geometry [5] and therefore on the accelerator design. The required beam energy per pulse may vary among target designs by a factor of several, which will influence the number of parallel beams and other aspects of the accelerator design. Also, the beam pulse duration depends on the ignition mode, with "fast-ignition" targets requiring sub-nanosecond ignition pulses, and indirectly driven targets requiring ~ 10 ns main pulses. Most targets generally require a low power prepulse, with 20–100 ns duration to efficiently compress the fusion fuel prior to the main pulse. Since the driver is considered to be the most costly aspect of the IFE system, the target design has a tremendous impact on the system cost and feasibility. In this paper, we assume final beam parameters of approximately 5 ± 2 MJ/pulse (total of the foot and the main pulse), 5 ± 3 GeV ion kinetic energy, and an ignition pulse of 10 ± 5 ns and a final beam radius at the target of 5 ± 3 mm. These values correspond to a variety of indirectly driven hohlraum target designs. At the end of the accelerator the overall bunch duration is assumed to be 0.1–0.2 μs. Hypothetically, if considerably greater beam energy (>7 MJ/pulse) were required for ignition and satisfactory target gain, the capital costs significantly increase even though the cost of electricity scales favorably for higher yield targets requiring higher energy driver pulses.

As will be described below, these beam parameters are at once somewhat conservative in their demands on the accelerator, but still require the development of novel accelerator components, and the understanding and mitigation of various beam physics that can dilute the beam emittance. Target designs requiring a much shorter ignition pulse (<1 ns), or a smaller radius at the target (<1 mm) usually force a higher beam phase space density at the target, corresponding to stricter tolerances throughout the accelerator. Lee reviews beam dynamics in induction accelerators for HIF in these proceedings [6].

The trade-offs between target physics and accelerator physics must be resolved with an overall HIF design optimization. For example, to simplify some target design challenges, a few driver designs have two ion kinetic energy beams striking the target for different parts of the pulse [8]. This invokes additional accelerator design challenges—to separate a group of beams for further acceleration, implementation of needed delay lines [7], and the necessity to determine the economic costs of these features.

Common to laser and ion beam IFE development plans is a demonstration power plant (DEMO) that should produce fusion power, breed tritium and demonstrate all key scientific and engineering points [9]. To develop the science and technology for HIF, several intermediate step induction accelerators have been suggested or built. These may be categorized by low (<100 J/pulse) and high (10–100 kJ) energy per pulse. The purpose of the low energy (<100 J) experiments, included developing and testing injection and transport of a high space-charge beam while preserving the low emittance that would be needed for ultimate focusing onto a small fusion target. While the kinetic energy and beam current in some of these experiments was often much lower than needed at any stage of a driver, the transport lattices were designed so that the dimensionless perveance and betatron phase advance matched those in a driver. Thus the relative importance of space charge to emittance mimicked a driver. An example is the Single Beam Transport Experiment [10] that demonstrated space-charge dominated transport through 87 electrostatic quadrupoles with very little emittance growth. In other experiments, for example the 2 MV injector experiment [11] and the High Current Experiment [12], the beam current (0.2–0.7 A) and energy (1–2 MeV) were characteristic of an injected ion beam to the low energy end of an induction linac. These experiments demonstrated the needed low emittance from the source and injector at driver scale, as well as the ability to control the high initial space charge and match the beam to an alternating gradient quadrupole lattice. Other experiments are summarized in a review article by Sharp et al. [13]. The objective of the proposed 10–100 kJ accelerator and research facility is to definitively demonstrate all the key driver beam manipulations at or near full scale, and to enable HIF relevant target physics experiments. It is usually considered a prerequisite to the DEMO. For example, in the late 1970s the Heavy Ion Demonstration Experiment proposal was for a 50–100 kJ/pulse facility for which RF and induction accelerator designs were developed [14]. The more recent proposals are the Integrated Research Experiment (IRE) [15] and the Heavy Ion Driver Implosion Experiment (HIDIX) [16], both based on multiple-beam induction linear accelerator with quadrupole focusing to create 10–100 kJ beam bunches.

2. Induction linear accelerators

An induction linear accelerator is a non-resonant (low-Q) structure in which the acceleration field is established by a high