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THE INTEGRATED BEAM EXPERIMENT – A NEXT STEP EXPERIMENT FOR HEAVY ION FUSION

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ABSTRACT

The U.S. Heavy Ion Fusion Virtual National Laboratory is proposing as its next experiment the Integrated Beam Experiment (IBX). All experiments in the U.S. Heavy Ion Fusion (HIF) program up to this time have been of modest scale and have studied the physics of selected parts of a heavy ion driver. The mission of the IBX, a proof-of-principle experiment, is to demonstrate in one integrated experiment the transport from source to focus of a single heavy ion beam with driver-relevant parameters-- i.e., the production, acceleration, compression, neutralization, and final focus of such a beam. Present preconceptual designs for the IBX envision a 5-10 MeV induction linac accelerating one K^+ beam. At injection (1.7 MeV) the beam current is approximately 500 mA, with pulse length of 300 ns. Design flexibility allows for several different acceleration and compression schedules, including the possibility of longitudinal (unneutralized) drift compression by a factor of up to ten in pulse length after acceleration, and neutralized drift compression. Physics requirements for the IBX, and preliminary physics and engineering design work are discussed in this paper.

I. INTRODUCTION / MOTIVATION

A heavy ion fusion driver requires production of intense, high-brightness heavy ion beams; acceleration of these beams in parallel to several GeV; longitudinal compression of each beam pulse by a factor ~60; transport through the fusion chamber environment; and focusing of the beams on a few-millimeter spot at the target. Over the next few years, the U.S. Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) will be completing a series of small experiments that have explored the physics of most of these processes. Presently, five different VNL experimental facilities are investigating intense ion beam transport limits, neutralization of intense beams, finalfocus aberrations, solenoid-focused beam transport, and ion source and injector physics.[1,2] When these experiments have been completed, most areas of driver physics will have been explored individually on a small scale. The next step in the program is to integrate all of these processes into a single proof-of-principle experiment.

This integration is essential for reasons evident from the physics. As the beams propagate through the accelerator, their distribution functions integrate the effects of sequential beam manipulations and errors. So while it is important to study each manipulation first in isolation in order to have a controlled experiment which can explore a single physical process, it is vital then to combine these manipulations into a system, an “integrated experiment” where the evolution of the beam through all of the manipulations can be observed. The “Integrated Beam Experiment” (IBX) would be the first of these integrated experiments for Heavy Ion Fusion.

The present IBX concept is shown in Figure 1. A single-beam heavy-ion induction linac would accelerate ions of K^+ or Ar^+ to 5-10 MeV, then longitudinally compress the beam by a factor of up to 10 in the “drift compression” section. A final focusing section, including beam neutralization experiments, would follow the drift compression. A neutralized drift compression experiment would also be included. A bend could be added as an upgrade. This design integrates all aspects of beam production and transport in the driver, with the exception of multiple-beam and high-energy effects. It is particularly noteworthy that the drift compression and final focus, including neutralization, would be done for the first time as an integrated experiment, since beam compression actually overlaps and stagnates within the final focus section for standard driver designs, requiring that these processes be studied together.

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Along with its mission of integrating the physics of heavy ion beam transport from source to target, the IBX offers access to important physics which has not previously been experimentally addressed. For reasons of cost, HIF experiments up to this point have been limited in length, number of beams (≤4), and final beam kinetic energy (≤2 MeV). Because the relevant parameter for most of the stability, focusing, and transport physics is the dimensionless perveance, which is proportional to the ratio of the beam space charge potential energy to the kinetic energy, it has been possible to study issues in the correct (driver-relevant) regime in low energy experiments, by scaling λ ($\lambda \equiv$ beam charge per unit length) down proportionately with the kinetic energy, thus testing this physics on low-current, low-energy, relatively low-cost experiments. Recent experiments have increased λ, duplicating the parameters of a driver-scale beam at low energy, in order to study phenomena (such as interaction with stray electrons) which are sensitive to beam electrostatic potential.

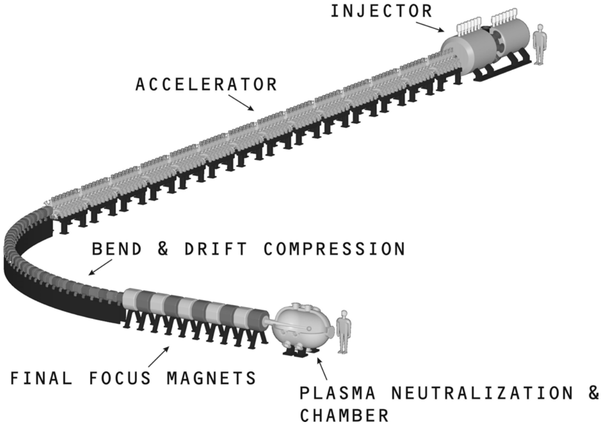

Fig 1. Schematic of the IBX

What could not be addressed with these experiments was issues which require a long accelerator, multiple beams, or medium-to-high energy. The IBX, by making a modest increase in accelerator length and energy, will be able to access significant new areas of beam physics. These include longitudinal wave physics, beam halo production, the effects of accumulating electrons and gas on beam transport, temperature anisotropy modes, collimation experiments, and possible electron-ion two-stream instabilities. All of these effects occur on long length or long time scales compared to the transit time of the beam through previous HIF experiments. The increase in energy also enables new experiments. The drift compression, for instance, occurs in the driver at the high energy end, where the perveance has been reduced by acceleration. In order to observe drift compression in the same regime of perveance as the driver, with large enough λ to have significant effect on stray electron physics, acceleration to at least 5-10 MeV is necessary.

II. DESIGN DETAILS AND FLEXIBILITY

The design for the IBX was derived from the physics mission described in Section I, particularly the goal of integrating the source-to-target physics of a single intense ion beam. Maximal flexibility was also considered to be desirable, in the light of the variety of physics to be explored. However cost was also an issue, and some design choices were made with a view to capturing the essential physics for minimal expense. These will be explained below. Details of the design scaling and choices can be found in Barnard et. al.[2]

The IBX linac will accelerate the beam to 5-10 MeV. This energy range is the minimum required to produce a beam perveance in a driver-relevant regime while keeping λ also driver-relevant. The design current exiting the injector is 364 mA of K^+ or Ar^+ (depending on the source technology chosen—aluminosilicate hot-plate, or plasma source) at 1.71 MeV for a 6 MeV case. For a higher final energy, the initial perveance would be increased proportionally to the final energy, in order to keep the same final perveance of 10^{-4}, which is desirable for drift compression and final focus experiments. Acceleration is accomplished, as in the driver, using induction. The alternating-gradient focusing lattice may use either superconducting or room temperature magnets. Superconducting magnets are preferred, since this is the technology of the driver, and the low temperature environment produces vacuum conditions which are important to some experiments. However room temperature magnets are somewhat cheaper (see below), and it may be possible to study vacuum-dependent issues in a small section of the accelerator fitted with superconducting magnets. The acceleration and focusing technology choices will be described more completely below.

An initial pulse duration of 200 ns (flattop) with 50 ns rise and fall times is the choice of the current design. This short pulse (the pulse length of the driver beam at injection is ~20 μs) greatly decreases the cost of the accelerator, since the cost of the acceleration roughly scales as the pulse length. The engineering design is also considerably simplified, since the size of the induction cores is reduced. The short pulse length has the further beneficial effect on the cost of the experiment, in that the length of the drift compression section is proportional to the pulse length when the beam enters this section.

However the short rise and fall times present a challenge to the injector, since the beam transit time through the diode for the higher-current designs is longer than the desired pulse length. During the transit time, the space charge forces on the head and tail of the pulse are not the same as those for the constant-current section of the pulse. Specially-tailored voltage waveforms for the head and tail must compensate for this effect. If the transit time is long, so that both the head and tail are in the diode gap simultaneously, correction in the diode is probably impossible. The waveform must then be optimized to produce a pulse which is correctable by time-dependent acceleration after the injector. Another possible solution is a multibeamlet injector (see ref. 1, 2), where the initial acceleration gap, and thus the transit time, is much smaller than in the standard large diode.

It is very desirable to also have the capability for long-pulse (~2-4 μs) operation of the injector. Due to the cost considerations for acceleration mentioned above (i.e., cores have approximately a fixed volt-second product), the acceleration of the long pulse would be much less than for the short-pulse case. Long pulses are necessary for experiments to measure the effect on the beam of gas desorbed from the vacuum wall by beam halo—the timescale is given by the time necessary for the gas to travel from the aperture to the beam interior. The ability to pulse the experiment at 5 Hz for ≥ 5 pulses ("burst" capability) to look at degradation of the vacuum over multiple pulses is another requirement on the injector. The beam can ionize background gas, the ions of which are expelled and desorb gas from the wall. This will increase background pressure if pumping is not adequate.

Longitudinal spatial compression of up to a factor of 2 will be done in the accelerator. Solid state switches on induction cores used to provide the compression velocity profile will enable variability of the compression schedule, thus giving a large amount of flexibility in the exploration of the compression physics. Details of the compression schedule flexibiliy can be found in reference 2. The drift compression section will longitudinally compress the beam by up to a factor of 10, depending on the beam energy and amount of compression imposed upstream.

A design choice that greatly enhances the flexibility of the IBX for physics experiments is the use of a constant focusing period (i.e., constant distance between magnets) throughout the accelerator. This is not the economic optimum for a driver, and therefore not the design choice of previous experiments. But it allows experiments with beams which are not accelerated, or accelerated at any rate up to full acceleration, adjusting only the focusing magnet strength, thus offering the possibility of studying acceleration rate limits, and of comparing physics effects with and without acceleration. It also opens up the possibility of using the whole accelerator for lower-perveance drift compression experiments, where longer drift length is required for the compression. A final advantage of constant focusing period is that construction of the IBX can be staged—i.e., the experiment can be constructed without the acceleration cores, and most of the physics above can be addressed first for the simpler case of drifting beams. Acceleration can then be added later, as an upgrade.

The experiments mentioned in Section I require certain ranges of beam and accelerator parameters. As mentioned above, studying drift compression (and final focus) in the range of both perveance and λ appropriate for driver-relevant physics requires beam acceleration to at least 5-10 MeV (giving perveance ~$10^{-5} – 10^{-4}$), and injected current (at 1.7 MeV) of 35-350 mA. This is a good range also for the neutralization and stray electron experiments. Most of the physics experiments to be done on the IBX also require a minimum length of the machine. These requirements, along with the IBX cost for various technology choices, are shown in Figure 2 in terms of "half lattice periods"—i.e., the distance between focusing magnet centers in the IBX.

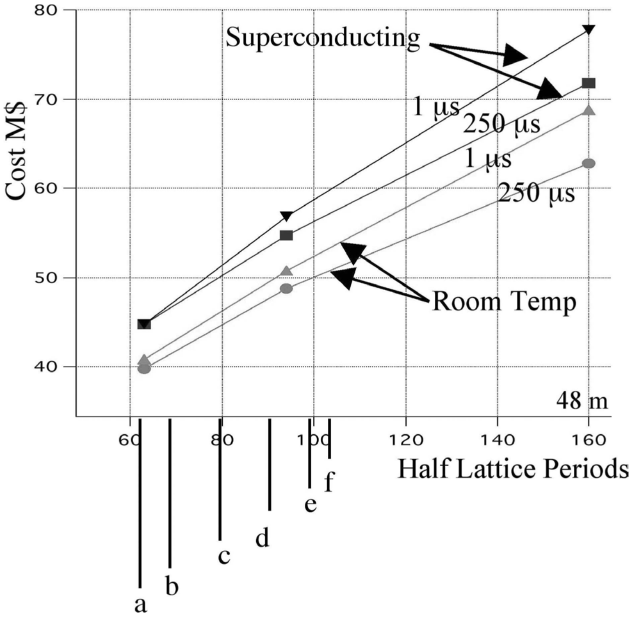

Fig. 2 Cost of the project (TEC, without the injector) for various choices of magnet technology and pulse length, with notations showing the minimum length, in half-lattice periods, required for the main experiments (a. integrated source-to-target experiment; b. effect of "ear"core acceleration/confinement of beam ends; c. two-stream instability, halo; d. temperature anisotropy instability; e. density oscillations, misalignments; f. longitudinal wave propagation.

III. IBX TECHNOLOGY CHOICES

The IBX accelerator is a current-amplifying heavy-ion induction linac with an alternating-gradient magnetic-quadruple transport lattice. The accelerator is built from individual modules as indicated in Figure 1. Figure 3 displays schematically the main components of such an IBX accelerator module. A broad range of design alternatives has been examined during IBX preconceptual costing studies.

IBX has the choice of using either pulsed room-temperature (RT) or steady-state superconducting (SC) quadrupoles for the beam focusing magnets. Ultimately, for an HIF driver, superconducting magnets will be more effective than RT magnets in terms of field quality, efficiency, and reliability. Furthermore, SC magnets are significantly more cost-effective in large quantity. However, to date mainly RT pulsed magnets have been used for HIF-VNL experiments because of their significantly lower cost if used in small quantity.

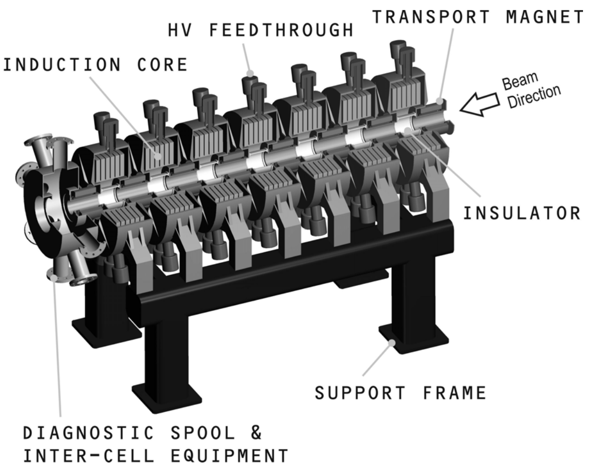

Fig.3 Components of an IBX acceleration module. A half lattice period consists of a quadrupole magnet and an induction acceleration gap. Every several half-lattice periods an induction cell is replaced by a vacuum spool for diagnostics, pumping and auxiliary access.

Figure 4 shows cross-sectional views of RT and SC versions of IBX acceleration cells. As can be seen in the figure, the cryostat for the SC case takes up additional radial space, leading to larger induction cores and consequently higher costs. IBX will need approximately 100 focusing magnets, which appears to be slightly below the turning point where SC magnets become more cost effective. For this reason present effort is focused on a tradeoff study comparing the two technologies.

The current IBX baseline design integrates three separate induction core types into a single induction cell:

(1) Each half-lattice period in IBX will include an induction acceleration gap. The main acceleration pulse (+100 kV/gap) is generated by bulk Metglas® cores with a lumped-element pulse-forming network.

(2) An initial velocity tilt (i.e., v_z vs. z, where z is distance along the accelerator), used for longitudinal bunching, which is applied to the ion beam in the beginning of the accelerator, must be maintained throughout the accelerator by applying a small tilt voltage (~5 kV) on top of the main acceleration pulse. This tilt voltage will be generated by smaller Finemet® cores and linear solid-state amplifiers.

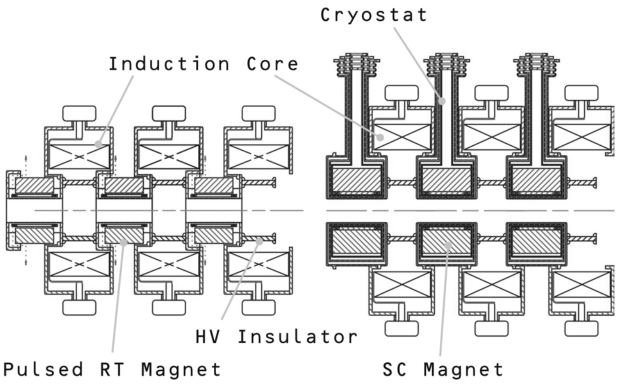

Fig 4. Comparison between a room-temperature (RT) version and a superconducting version (SC) of IBX.

(3) "Ear" voltage pulses (± 5 kV) confine the head and tail of the high-current bunch longitudinally against space-charge forces. Since the ear voltage pulses are relatively small and short, solid-state pulsers together with a third core component using either Finemet or ferrite material is utilized.

Solid-state switch technology for the ear and tilt cores (compared to a lumped-element pulse forming network) constitutes an important aspect of IBX, which will allow enough flexibility for different longitudinal beam physics experiments, each with different high voltage waveform schedules.

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