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DESIGN CHOICES FOR THE INTEGRATED BEAM EXPERIMENT (IBX)*

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Abstract

Over the next three years the research program of the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL), a collaboration among LBNL, LLNL, and PPPL, is focused on separate scientific experiments in the injection, transport and focusing of intense heavy ion beams at currents from 100 mA to 1 A. As a next major step in the HIF-VNL program, we aim for a complete "source-to-target" experiment, the Integrated Beam Experiment (IBX). By combining the experience gained in the current separate beam experiments IBX would allow the integrated scientific study of the evolution of a high current (~1 A) single heavy ion beam through all sections of a possible heavy ion fusion accelerator: the injection, acceleration, compression, and beam focusing.

This paper describes the main parameters and technology choices of the proposed IBX experiment. IBX will accelerate singly charged potassium or argon ion beams up to 10 MeV final energy and a longitudinal beam compression ratio of 10, resulting in a beam current at the target of more than 10 Amperes. The different accelerator cell design options are described in detail, in particular the induction core modules incorporating either room temperature pulsed focusing-magnets or superconducting magnets.

INTRODUCTION

The U.S. Heavy Ion Fusion program is supporting several key experimental programs to validate the attractiveness of a heavy ion accelerator as a candidate for an inertial fusion energy driver. Over the next few years, the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) will complete a set of small experiments addressing scientific key questions related to heavy ion fusion drivers [1]. The goal of these experiments is to demonstrate the feasibility of such driver beam manipulations, which can be investigated in separate small-scale experiments as initial step.

As the logical next step, the HIF-VNL proposes a fully integrated beam physics experiment. This intermediate-scale experiment, the Integrated Beam Experiment (IBX), will allow important access to significant areas of heavy ion fusion physics [2]:

- The longitudinal properties of a driver-scale beam under induction acceleration, its profile and the manipulation of that profile, and the resultant emittance changes, will be studied for the first time.
- Limits of acceleration and longitudinal beam compression can be examined for the first time.
- In particular, IBX will be the first experiment to allow exploration of all post-accelerator manipulations of the beam found in a future driver - drift compression, final focus, and chamber transport.
- Electron dynamics with acceleration will also be addressed, with the opportunity for the first time to see the effect on beam transport.
- The final focus spot size on target depends on the accumulated beam phase-space changes through each region along the accelerator system. The crucial integration role of the IBX will be to test the ability to achieve a high beam brightness (focusability) from source to target.
- A key strategic goal in the HIF-VNL theory/simulation program is an integrated and detailed source-to-target simulation capability. The IBX will provide a well-diagnosed experiment to benchmark integrated beam dynamics simulation codes for a single beam through the injection, acceleration, longitudinal drift compression, and final focus, with sufficient beam current to include important gas/electron interactions.

This integrated source-to-target experiment will have a final kinetic energy ≤ 10 MeV. The charge-per-unit length will be 1-2 μC/m in order to produce the space charge potential necessary for electron dynamics and final transport neutralization studies. The final perveance (measure of the ratio of space charge potential energy to kinetic energy) of the beam after longitudinal compression of a factor of 10 will be ~10^{-3}. The option of such aggressive beam compression will enable exploration of a wide range of final focus transport and final compression alternatives, including the opportunity to employ a variety of schemes to correct geometric and chromatic beam aberrations.

IBX COMPONENTS AND SPECIFICATIONS

The IBX project is currently in a pre-conceptual design stage. As required by the physics program [2] the minimum final beam energy of IBX will be 5 MeV, but depending on funding level should preferably approach 10 MeV. Main performance parameters for a 10 MeV IBX scenario are listed in the following table:

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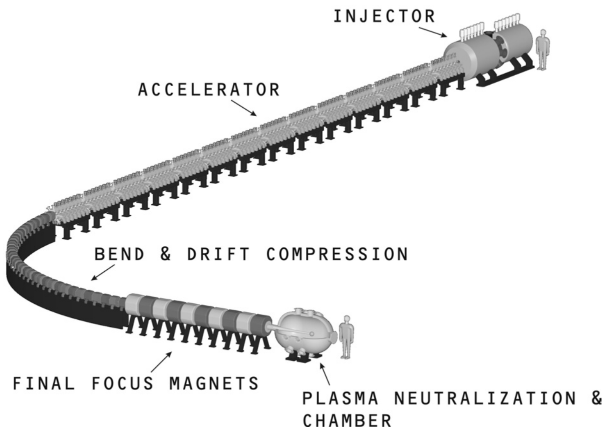

Figure 1: Schematic layout of the Integrated Beam Experiment (IBX).

INJECTOR	
Ion:	K+ or Ar+
Current:	0.6 A
Energy:	1.7 MeV
Pulse Length:	0.25 μs
ACCELERATOR:	
Number of Half Lattice Periods:	~ 120
Half Lattice Period Length:	30 cm
Final Energy:	10 MeV
BEND & DRIFT COMPRESSION:	
Number of Half Lattice Periods:	~ 30
Compression Ratio:	10
Beam Pulse Length at End of Drift Compression:	25 ns
FINAL FOCUS & PLASMA NEUTRALIZATION:	
Number of Half Lattice Periods:	~ 10
Final Beam Pulse Length:	~ 15 ns
Final Perveance:	$1.4 \cdot 10^{-3}$
Final Space Charge Density:	1.4 μC/m
Final Current:	~ 10 A

Figure 1 shows the mechanical layout of a 10 MeV IBX version. To advance the integrated heavy-ion beam physics program in a time- and cost-effective manner IBX will rely mainly on the use of existing technology, in particular induction core- and superconducting magnet-designs developed in the heavy ion fusion program.

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 2 displays schematically the main components of such an IBX accelerator module. A broad range of design alternatives has been examined during IBX pre-conceptual costing studies.

Transport Magnets

IBX has the choice of using either pulsed room-temperature (RT) or steady-state superconducting (SC) quadrupoles for the ion beam transport magnets. Ultimately, for a 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, up to today mainly RT pulsed magnets have been used for HIF-VNL experiments because of their significantly lower cost if used in small quantity.

Figure 3 shows a cross-sectional view of a RT and a SC version of IBX acceleration cells. As demonstrated 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 is slightly below the turning point where SC magnets become more cost effective. For this reason present effort is focused on a tradeoff study comparing both technologies.

The use of superconducting magnets in IBX has three major advantages over pulsed RT magnets: First, they are steady state, eliminating eddy current problems. Secondly, the magnet cryostats can provide a cold pumping surface in the beam tube. Third, a HIF driver will also be built with SC cold bore magnets. Therefore, IBX could simulate more closely the vacuum environment seen by the heavy ion beam in a HIF driver.

Having the same vacuum and especially beam-pipe wall conditions compared to a HIF driver allows exploring limitations associated with magnetic focusing, in particular the onset of instabilities or focusing effects due to electrons trapped in the potential well of the ion beam (electron cloud effect).

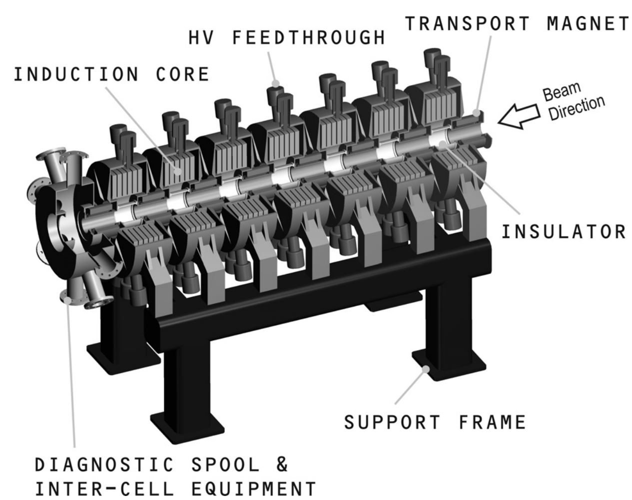

Figure 2: Components of an IBX acceleration module. A half lattice period consists of a quadrupole magnet and an induction acceleration gap. Every several half-lattice periods an induction cell is replaced by a vacuum spool for diagnostics, pumping and auxiliary access.

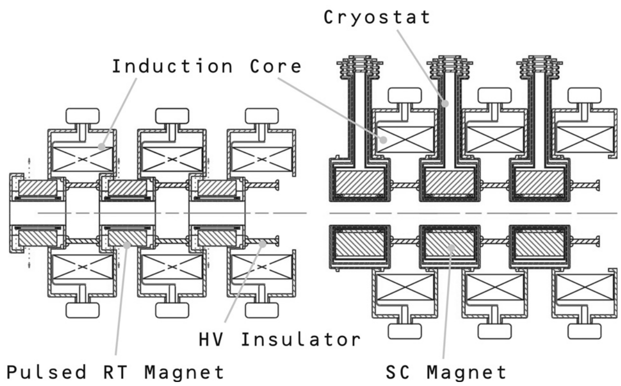

Figure 3: Comparison between a room-temperature (RT) version and a superconducting version (SC) of IBX. The cryostat for the SC case takes up additional radial space, leading to larger induction cores.

Induction Cores & Pulsers

Figure 4 shows the different voltage waveforms that have to be generated by a single IBX induction cell. Consequently, the current IBX baseline design integrates three separate induction core types into a single induction cell:

(1): Each half-lattice period (i.e. quadrupole magnet) 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 (see figure 4a).

(2): An initial velocity tilt (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 (see figure 4a). This tilt voltage will be generated by smaller Finemet cores and linear solid-state amplifiers. Since solid-state pulsers are extremely flexible, the tilt voltage can be modified easily for different longitudinal beam physics experiments. Regulation of the main acceleration waveform to less than 1% can also be achieved using these same cores and pulsers.

(3): Ear voltage pulses (± 5 kV, see figure 4b) confine the head and tail of the high-current bunch from spreading out longitudinally due to space-charge forces. These ear waveforms require the highest magnetization rate. 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 technology (compared to a lumped-element pulse forming network) constitutes an important component of IBX, which will allow enough flexibility for different longitudinal beam physics experiments, each with different high voltage waveform schedules. As a further advantage, solid-state pulsers can be easily integrated into the accelerator control system. Since the waveform is generated by arbitrary waveform generators, feedback loops can correct errors in the applied voltage pulses even during a single beam shot in subsequent cells.

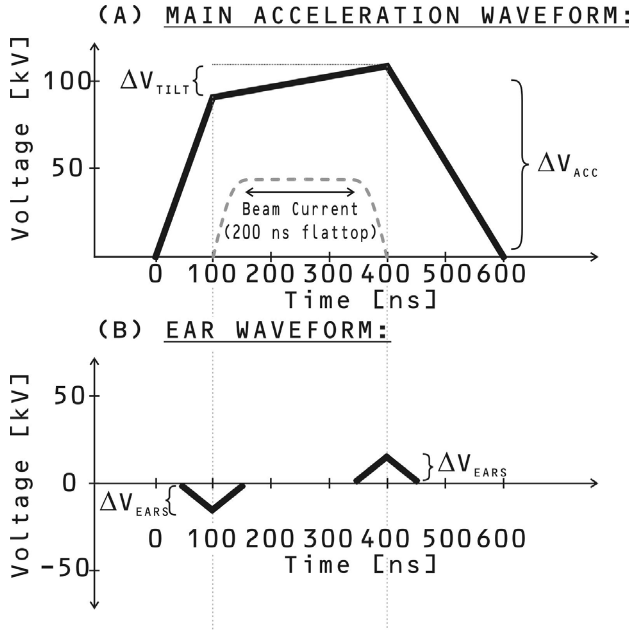

Figure 4: IBX will incorporate agile waveform control utilizing solid-state pulser technology and different core materials to produce flexible pulse waveforms as indicated in this figure.

SUMMARY

Main parameters and the most consequential technology choices of the planned Integrated Beam Experiment (IBX) pursued by the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) have been described. The total project cost including R&D is currently expected to be in the range of 80 M$. Following project approval and a one-year conceptual design effort IBX's first operation could begin after a 5-year design and construction schedule. The unique IBX capability for integrated injection, acceleration, compression and focusing of high-current, space-charge-dominated heavy-ion beams would unfold a completely new field for investigating and exploring heavy ion fusion concepts.

REFERENCES

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[2] J.J. Barnard, et al.: "Integrated Experiments for Heavy Ion Fusion", Laser and Particle Beams , in press (2003)