

# Integrated Experiments for Heavy Ion Fusion<sup>\*</sup>

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## Abstract

We describe the next set of experiments proposed in the U.S. Heavy Ion Fusion Virtual National Laboratory, the so-called Integrated Beam Experiment (IBX). The purpose of IBX is to investigate in an integrated manner the processes and manipulations necessary for a heavy ion fusion induction accelerator. The IBX experiment will demonstrate injection, acceleration, compression, bending and final focus of a heavy ion beam at significant line charge density. Preliminary conceptual designs are presented and issues and tradeoffs are discussed. Plans are also described for the step after IBX, the Integrated Research Experiment (IRE), which will carry out significant target experiments.

Keywords: Fusion; Heavy Ion; Inertial fusion; Driver; Accelerator; Systems model

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## I. Introduction

The U.S. program in heavy ion fusion is currently embarking upon an ambitious set of experiments [1] which focus on critical areas of a heavy ion fusion driver. Sources and injection (on the Source Test Stand, STS500, Ref. [2]), transport at high line charge density (on the High Current Experiment, HCX, Refs. [3,4]), and neutralized final focus (on the Neutralized Transport Experiment, NTX, Ref. [5]) will each be studied. This paper focuses

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- <sup>\*</sup>Work performed under the auspices of the US Department of Energy under contract DE-AO33-76F0098 at University of California LBNL, contract W-7405-ENG-48 at University of California LLNL and contract DE-FG02-95ER40919 at PPPL.
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on the next set of proposed experiments, the so-called Integrated Beam Experiment (IBX). In Section II, we will discuss the purpose of IBX, which broadly-speaking is to investigate in an integrated manner the processes and manipulations necessary for a heavy ion fusion induction accelerator. These experiments will demonstrate injection, acceleration, compression, bending and final focus of a heavy ion beam at significant line charge density. The scientific goals of IBX came about as a result of two workshops, whose conclusions are briefly discussed. In Section III, two point designs from the second workshop are described and some design considerations are discussed which outline some of the constraints on the proposed accelerator. In section IV, the design equations are presented. In section V, we discuss plans for the step after IBX, the Integrated Research Experiment (IRE), which will carry out significant target experiments, and which will provide the basis, along with results from the inertial confinement fusion program, to proceed to an engineering test facility for inertial fusion energy.

## **II. The scientific goals of the IBX**

Two workshops were held in 2001 that helped define the IBX scientific mission: The first was the Heavy Ion Fusion Science Workshop held May 30-31, 2001 at Lawrence Berkeley National Laboratory which examined the critical issues facing heavy ion fusion generally. The workshop comprehensively identified and prioritized the scientific and engineering issues of the induction linac approach to heavy ion fusion. In the second workshop (theso-called IBX workshop) held October 9-10 (cf. Ref. [12]), the discussion began regarding the IBX science mission and beam parameters. Prior to the IBX workshop, study groups were formed, focusing on specific physics and engineering areas and two illustrative designs were worked out (Refs. [6] and [7]).

Not all of the goals given high priority in the science workshop will be addressed on IBX, as many will be addressed in the near-term experiments, HCX, STS-500, and NTX, or later on the IRE. The main goals to be achieved on IBX can be divided into three broad areas: Integrated physics, longitudinal physics, and transverse/longitudinal coupling physics. integrated physics includes a demonstration of injection, acceleration, compression, bending, and focusing of a heavy ion beam at line charge density similar to the initial stages of a driver, so that physics involving interactions of beam ions with walls, residual gas and stray electrons may be assessed. In parallel, simulations of a 3D beam from source-to-target, predicting final spot radius and current profile on target would demonstrate an integrated theoretical understanding. Longitudinal physics includes the physics of drift compression and stagnation. Stagnation here means the process whereby the longitudinal electric field of the beam's space charge is used to

remove the velocity tilt at precisely the point where the beam passes through the final focus and hence minimizes chromatic aberrations of the spot. Measurement of the velocity tilt and velocity spread remaining after compression by a factor of  $\sim 10$ , will be a key goal. The physics of longitudinal heating during acceleration and compression will be another focus. The third area to be explored is transverse/longitudinal coupling physics. The large velocity tilt required to compress the beam also manifests itself in the transverse dynamics, and so a number of topics related to coupling will be examined: matching and beam control with velocity tilt and acceleration; time dependent final-focus correction physics; bending physics; the transverse/longitudinal temperature anisotropy instability; and beam “end” physics.

### **III. Two Illustrative Conceptual Designs for IBX**

In designing an accelerator with the physics goals described in Section II, certain practical decisions need to be made. In carrying out the "straw man" or preconceptual designs in Refs. [6] and [7] these decisions translate into certain design strategies. Among these are: maximize driver-relevant manipulations and beam physics to the extent possible; configure the machine to be able to carry out compression experiments in the drift section, but also to be flexible enough to carry out bunch compression and acceleration experiments in the accelerator itself; physics experiments are to be given higher priority than engineering demonstration (so technology limits are not pushed); and finally, simplicity should be stressed, maximizing modularity, in order for the project to fall within a cost envelope of approximately \$50 M, the expected available project cost for a proof-of-principle experiment at this stage of fusion energy development. Using these considerations, and the design equations in Section IV the two teams independently obtained illustrative point designs. Figure 1 illustrates some of the more important parameters of the two point designs.

#### **a. Commonalities of the two designs**

There are many commonalities to the accelerator point designs in Refs.[6] and [7]. The designs each consist of a number of sections where the beam undergoes a particular manipulation (such as the imposition of a velocity tilt or acceleration). Following the injector, there is a section which imposes an initial velocity tilt on the beam needed for bunch compression in the accelerator. This is followed by the main accelerator, followed by a shaping and velocity-tilt section where the current and velocity profiles are tailored to provide the correct initial conditions for the transfer of the beam into the drift compression section. The beam is then bent and compressed in the drift compression section, before it passes through the final focusing magnet section. Here the beam is expanded before its final convergence in the chamber section, where the beam space charge is neutralized before it arrives at the target with a spot size of a few mm. Both designs allow for testing of virtually

all of the beam manipulations required in a driver, at line charge densities comparable to the initial line charge densities found in a driver. The discreteness of the sections in these point designs is largely due to conceptual simplicity. In more mature designs, the transitions would be more seamless, and for example, the velocity tilt and shaping that follow acceleration, would more like occur in the accelerator itself.

Both preconceptual designs assume an ion species of singly-charged potassium (atomic mass 39), an initial injection energy of 1.7 MeV, and an initial current of 0.69 A. This is based on extensive experience with potassium sources and the 2 MeV ESQ injector, together with the desire to create a single beam with the line charge density similar to what will be needed for a driver beam. Magnetic-quadrupole transport was chosen throughout both accelerators, as this choice has been made for the medium-to-high-energy end of driver accelerators, and has largely been unexplored at these large line charge densities.

The principal difference in the two preconceptual designs is the initial pulse length, and the consequences on the accelerator, arising from this difference. Some induction linac heavy ion fusion power plant driver designs require initial pulse lengths as long as 20  $\mu$ s. However, electron induction linacs have pulse lengths of order 10's of ns. In this paper, "short" is relative to the pulse length of present experiments that have pulse durations of a few  $\mu$ s. The "longer" pulse design, although still shorter than a driver or many present experiments, has an initial flat-top pulse duration of 1  $\mu$ s, and a total pulse duration of 2  $\mu$ s, whereas the "short" pulse design has an initial flat-top pulse duration of 200 ns, and a total pulse duration of 300 ns.

### **b. Arguments in favor of short pulse**

There are two principal arguments in favor of a short pulse. A short pulse allows a shorter drift compression section; and short pulse requires fewer volt-seconds for a fixed final ion energy (and hence smaller induction cores). To understand the first argument, we may examine the scaling of a pulse with an initial parabolic distribution of current, and hence perveance  $Q$ :  $Q = Q_{\max} (1 - 4z^2/l_{\text{bunch}}^2)$ , where  $Q_{\max}$  is the perveance at the center of the bunch and hence is an evolving function of time,  $z$  is the longitudinal position relative to the bunch center, and  $l_{\text{bunch}}$  is the full length of the bunch. The longitudinal electric field  $E_z$  is assumed to be approximately given by  $E_z = -\left(g/[4\pi\epsilon_0]\right)\partial\lambda/\partial z$  where  $g$  is the line charge density,  $\epsilon_0$  is the free-space permeability,  $g = 2 \ln r_p/a$ ,  $r_p$  is the radius of the beam pipe, and  $a$  is the average beam radius. For these estimates,  $g$  is assumed to be constant, and it is also assumed that the space charge removes the velocity tilt at the end of the drift distance (to help mitigate the effects on the spot size of chromatic aberrations). A self-similar integration

of the cold 1-D fluid equations, yields a required velocity tilt  $\delta v/v$  at the beginning of drift compression given by

$$\delta v/v = (8Q_a g (C-1))^{1/2}, \quad (1)$$

and a required drift distance  $d$  given by

$$d = l_a (1 - 1/C) / (\delta v/v). \quad (2)$$

Here,  $Q_a$  and  $l_a$  are the perveance and bunch length at the end of the accelerator, respectively, and  $C$  is the ratio of bunch length at end of accelerator to final bunch length. Although, the actual pulse format used may not be parabolic, the scaling of velocity tilt and drift length are likely to be similar to a more exact calculation. Our science goals suggest that a final accelerator perveance  $Q_a$  of  $10^{-4}$ , and a minimum compression ratio of 10 would be desired. With the variation of  $g$  limited, the initial velocity tilt will be of order 10% and will be insensitive to the pulse length, but the drift distance is directly proportional to the bunch length. Hence, cost savings can be accrued in the drift compression if the physics goals can be met with a shorter pulse.

The second advantage of short pulse, is that fewer induction core volt-seconds are required for fixed final ion energy. From Faraday's law, the core cross-sectional area  $A$  times the material saturation magnetic field  $B$  is proportional to the applied voltage times the pulse duration. The volume of the cores, and hence the mass of ferromagnetic material, is proportional to  $A$  for small outer radii and  $A^2$  if the outer radius becomes large compared to the inner radius. The engineering design is greatly simplified when the cores are smaller and more manageable, and the cost of the core material itself is greatly reduced. Although the loss rates per unit volume,  $L_{\text{loss}}$ , increase as  $t$  decreases (at worst being proportional to  $(dB/dt)^2 t \sim 1/t$ ), the volume of magnetic material decreases as the pulse duration is decreased, thereby decreasing the total loss and reducing the total stored energy required for the pulsed power.

There are also some issues raised by going to very short pulse. The short-pulse option would reduce the ability to study potential electron/gas problems, since ions desorbed from the pipe walls require a large fraction of a  $\mu\text{s}$  to reach the beam. The long-pulse portion of the driver (the low energy end) would not be modeled well by this experiment, but it does model well the high energy portion of the driver. (The issues for the low energy end of a driver are well studied in HCX and STS500 so the need to study them again in IBX may be minimal.) Some have argued that the diagnostics for a pulse length less than 100 ns may be expensive. Detailed cost estimates need to be made, but the time regime for the short pulse design is very similar to electron induction accelerators. There are differences between electron and ion diagnostics, but it does not appear to be a fundamental problem. The most serious

concern for the short-pulse design is the simultaneous requirement of a 200 ns flattop pulse and the requirement of a current of 0.69 A of  $K^+$  at 1.7 MeV. For a simple planar diode, the Child-Langmuir law, yields a current of  $(1/9)(4\pi\epsilon_0)(q/m)^{1/2}(a/d)^2V^{3/2}$ , where  $q$  and  $m$  are the ion charge and mass, respectively,  $a$  is the radius of the source,  $d$  is the gap distance, and  $V$  is the voltage across the gap. Optics considerations generally require  $a/d < 0.5$  (Ref.[8]), so to obtain a current of 0.7 A of  $K^+$  requires a voltage of at least 280 kV. To avoid breakdown, an empirical expression (cf. Ref. [8]) relating the maximum voltage  $V_{\max}$  allowed for a given gap separation  $d$  is commonly employed. This expression is

$$V_{\max} = \begin{cases} V_b (d/d_b) & \text{for } d < d_b \\ V_b (d/d_b)^{1/2} & \text{for } d > d_b \end{cases}, \quad (3)$$

where  $V_b = 100$  kV and  $d_b = 0.01$  m. This relation suggests that for a 280 kV gap, the minimum distance  $d$  for this diode would be 0.078 m. Generally, to avoid transients in the current pulse, the flattop pulse duration must exceed the transit time of a particle through the gap (cf. Ref [9]), given by  $t_{\text{trans}} = 3d(m/2qV)^{1/2}$ . For  $d=0.078$  m,  $V=280$  kV, and singly charged  $K^+$ ,  $t_{\text{trans}} = 200$  ns, so controlling transients and forming a flat usable current pulse needs to be carefully studied. One way to minimize transients, would be to reduce the gap length (reducing the transit time), keeping the voltage constant. This would increase the voltage gradient beyond what is given in Eq. (3). But this has been successfully carried out on the injector for the RTA electron induction linac experiment at LBNL, possibly as a result of incorporating a solenoidal field to help prevent breakdown. This type of injector, is planned to be investigated in more detail in fiscal year 2003, to see if a short pulse, single source injector would be feasible for IBX.

Another option, which would be manifestly compatible with short pulse, would be a multiple-beamlet injector, currently being investigated for use on an a heavy ion fusion driver or Integrated Research Experiment (Ref.[8]). Each beamlet would be millimeter-scale in radius, so transients would occur on a much shorter time scale. The development time for the multiple beamlet injector, however, will perhaps be longer than would acceptable for inclusion in the IBX.

### c. Additional differences between the two preconceptual designs

Besides pulse duration, the two reference designs differed in other ways.

**Doublet versus Singlet:** In Ref. [7], the initial lattice period was based on the actual magnet design of the HCX (Ref. [3,4,10]), so a syncopated lattice was introduced which allows for one longer drift space per lattice period for diagnostics, with minimal current reduction. This

doublet configuration was maintained until 4.58 MeV, after which normal FODO (focus-drift-defocus-drift) focusing was used with equal drift spaces between quads. In Ref. [6], a longer initial lattice period was chosen to accommodate separate cryostats for superconducting magnets, and a larger pipe radius was chosen to accommodate the reduced focusing.

**1 versus 4 beams:** The Ref [6] design is a single-beam accelerator for simplicity and cost savings, whereas in the Ref. [7] design there are four beams in order to gain additional experience with multiple beams. The number of beams was not fundamental to either design and costing has been estimated in Ref. [11] for versions with both one and four beams. The consensus of the IBX workshop was that the IBX should initially be a single beam facility, but that the induction cores should have a large enough inner radius to accommodate four to nine beams, for a possible future upgrade.

**Identical half-lattice period versus variable lattice:** As the beam energy increases in a magnetic focusing system, the lattice period can be increased, as the focusing requirements are reduced. In Ref.[7] the lattice period increases as  $V^{1/2}$  until 4.58 MeV, and then increases as  $V^{1/4}$  to 18.34 MeV. In Ref. [6], modularity was taken to a greater extreme, as the lattice half-period was held constant throughout the accelerator. This allowed identical magnets, as well as identical induction cells. This modularity advantage would be traded off against more half-lattice periods. More detailed estimates of engineering effort and fabrication costs required for different magnet and cell designs will be needed before choosing which of these strategies would be employed.

**Compression schedules:** In Ref. [7] a single compression schedule is suggested in which the line charge density was constant in the doublet section, and increased by a factor of two in the FODO section and by a factor of six in the drift section. In Ref [6], the strategy is to use different compression schemes, when studying different aspects of accelerator physics. Each compression scheme can be characterized by the exponent  $\alpha$ , where the bunch length  $l \sim V^{-\alpha}$  (see Tables 2 and 3). For example, to examine drift compression, the accelerator itself may operate with a simple "compression" scheme such as constant current ( $\alpha=0.5$ ). Under that scenario the current and pulse duration would remain constant, and so the bunch length would actually increase within the accelerator. But in the drift compression section, a factor of 10 bunch compression can take place, with a final perveance that would still be no higher than  $10^{-3}$ . On the other hand, to investigate acceleration and compression within the accelerator, bunch compression (with  $\alpha=-0.25$ ) by a factor of 0.64 would take place within the accelerator, but compression of a factor of only 3 in drift compression would be possible. The scenarios were constructed such that only the voltage waveforms needed to be modified for different compression schedules, the focusing would accommodate all four of the scenarios.

**Cost:** In Ref. [11], an approximate estimate of the costs of the short and longer pulse design was obtained. Estimates of the amount of ferromagnetic core material were made, and total cell costs were assumed proportional to weight, with the proportionality constant set by adopting the same coefficient as was found in the Dual Axis Hydrodynamic Radiography Test (DAHRT) accelerator now undergoing commissioning tests, and the Relativistic Two beam Accelerator experiments at LBNL, and detailed engineering costs of a previously proposed accelerator ILSE. Superconducting quadrupole and cryostat costs are based on work done in Ref [10]. Pulsed magnet options were also costed. Pulsed power costs were based on the sum of stored energy and switching costs. Energy requirements were estimated from core losses, based on calculated core volumes and pulse durations. Spark gaps were chosen as the high power switch based on lower cost. The higher price of capacitors per Joule in the short pulse case was included in the estimate. The cost estimates suggested that the one-beam short pulse design would have a total project cost (TPC) of ~38 M\$, whereas the four beam longer pulse design would have a TPC ~66M\$ and the one beam version of the longer pulse design would have a TPC of 57M\$, Since pulse duration was not the only variable in the two designs, and the costs and designs are very rough, one should only infer that the cost and physics goals are not unrealistically out of line.

#### IV. Design equations

In both Refs. [6] and [7], algebraic relations were used to specify the lattice elements. We summarize below the major equations that specify the lattice. (See, for example Ref. [13]). The lattice parameters are related to the undepressed phase advance  $\sigma_0$  per lattice period approximately by the relation (Ref.[14])

$$\hat{\sigma}_0 = (2[1 - \cos \sigma_0])^{1/2} = \frac{\eta B' L}{[B\rho]} \left(1 - \frac{2\eta}{3}\right)^{1/2}. \quad (4)$$

Here,  $B'$  is the magnetic quadrupole gradient,  $L$  is the fraction of the half-lattice period occupied by the effective magnet length,  $L$  is the half-lattice period, and  $[B\rho]$  is the ion rigidity. Stability for space-charge-dominated beams requires  $\sigma_0$  to be less than  $\sim 85^\circ$ .

The equilibrium envelope equation relates the mean beam radius to  $\sigma_0$ ,  $L$ , the unnormalized beam emittance  $\epsilon$ , and the generalized perveance  $Q$ . (In the non-relativistic limit,  $Q = \sqrt{4\sigma_0 V}$ , where  $qV$  is the ion energy). This gives:

$$Q = \frac{\hat{\sigma}_0^2 a^2}{4L^2} - \frac{\epsilon^2}{a^2} \quad (5)$$

The velocity tilt  $\Delta v = v_t - v_h$  is defined as the difference between the velocity of the tail  $v_t$  and the velocity of the head  $v_h$ , at a fixed location,  $z$ , along the accelerator. If it is assumed that



the bunch length varies continuously with the ion energy, and the energy varies continuously with  $z$ , then  $v$  is related to the voltage gradient  $dV/ds$  and pulse length  $l$  by

$$\frac{v}{v_0} = \frac{dV}{ds} \frac{\ell}{V} \frac{1}{2} - \frac{V}{\ell} \frac{d\ell}{dV} \quad (6)$$

Here  $v$  is the velocity of the midpulse.

In the continuous half-lattice approximation, the number of half-lattice periods  $n$  increases as:

$$\frac{dn}{ds} = \frac{1}{L} \quad (7)$$

and the energy  $qV$  is related to the voltage gradient through the equation:

$$V(s) = \frac{v}{v_0} \frac{dV}{ds} ds \quad (8)$$

The total number of Volt-seconds required to accelerate the flattop of the pulse, per half-lattice period is:

$$\frac{d(V \ell)}{dn} = \frac{dV}{ds} L \left( \frac{\ell}{v} \right) \quad (9)$$

The additional voltage added to the beginning and end of the acceleration voltage required to keep the beam confined longitudinally against its own space charge is known as the "ear" voltage. Using the "g-factor model," applied to a current pulse with quadratic current falloff the required voltage increment per half-lattice period is given by:

$$V_{ear} = \frac{2g \lambda_{flat} L}{4\pi\epsilon_0 \beta c \ell} \quad (10)$$

To maintain the velocity tilt implied by eq. (6), a voltage increment of the tail relative to the head per half-lattice period must be applied, given by:

$$V_{tilt} = \frac{d(2V \ell / v)}{ds} L \quad (11)$$

To obtain a specific physics design additional assumptions are made. The voltage gradient, bunch length, and half-lattice period are all assumed to vary as a power of the voltage (defined as the beam energy/ion charge):  $dV/ds \sim V^{-1}$ ,  $\ell_{bunch} \sim V^{-2}$ ,  $L \sim V^{-3}$ . Using the

equations above, constraints can then be placed on the exponents  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ . Also, the pipe

radius  $r_p$  has been held constant (in both designs) for engineering simplicity, but this assumption has been relaxed in the drift compression section. The magnet length  $L$  has also been assumed (in both designs) to be constant to allow for more modularity and hence reduced engineering and fabrication costs. In the short pulse design, this modularity was extended to include a constant lattice period, and a constant cell design. Thus  $d(V \ell)/dn$  is constant in the short-pulse design so the voltage increment per half-lattice period is held constant (single cell flavor). Tables 1 summarize major parameters of the linac portion of the

illustrative designs based on these scaling laws, and table 2 illustrates major beam parameters for the short-pulse design of Ref.[6].

### **V. Parameter ranges for the IBX**

The two point designs in Ref. [6] and Ref. [7] give some confidence that a machine capable of carrying out the scientific goals of Section II, can be carried out within the expected cost envelope. At the IBX workshop a “consensus” based on scientific goals was obtained by three independent working groups on the energy (10-20 MeV), the ion species ( $K^+$ ), the final line charge density (1-2  $\mu A/m$ ), the minimum bunch compression needed ( $>\sim 10$ ), a final perveance of  $<\sim 10^{-3}$ , and initial pulse duration of between 0.2 and 2  $\mu s$ . In some sense, the two point designs spanned the “consensus” parameter space.

### **V. Looking beyond the IBX: the IRE**

With the insertion of an additional experiment (the IBX) into the experimental sequence leading to a heavy ion driver, the planned final pulse energy for the Integrated Research Experiment (IRE) has been increased, to allow for more substantial target heating experiments. In Ref. [15], a possible 200 MeV, 32 beam,  $K^+$  30 kJ IRE is described. Recent considerations (Ref. [16]), have suggested that a considerable benefit to the target experiments could be achieved by going to a 800 MeV,  $Rb^+$ , 250 kJ IRE. The total induction cell volt-seconds of such a machine might be  $\sim 3$  times that of Ref. [15], even though the pulse energy was increased by nearly an order of magnitude. Detailed cost and physics designs of a more advanced IRE have not yet been carried out.

### **VI. Summary and conclusions**

We have begun the process of defining the scientific goals and major accelerator parameters for the next heavy ion fusion induction accelerator, the IBX. The IBX will be an integrated test of most beam manipulations now being considered for an induction HIF driver. The energy will likely be between 10-20 MeV, with final line charge density  $\sim 1$ -2  $\mu C/m$ , and a bunch length compression by a factor of approximately 10. The beam will be focused to a spot, and the broadening of the beam spot from all of the processes which could potentially degrade the beam quality including errors in acceleration, compression, focusing and neutralization will be assessed. It will be the first integrated experiment to carry out such a complete set of operations needed for HIF. The IBX will set the stage for the second integrated experiment on a larger scale, the IRE, where target heating experiments will be carried out. The IRE would lay the ground work for the first engineering test facility on the pathway to a heavy ion driven inertial fusion energy power plant.

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Table I. Summary of parameters for "short" and "longer" pulse conceptual design

Parameter	Short Pulse Design [Ref. 6]	Longer Pulse Design [Ref. 7]
Accelerator length (m)	25	25
Number of half-lattice periods	84	192
Volt-seconds per meter (current flattop)	0.0667	0.40
Initial pulse duration (flattop) (ns)	200	1000
"Ear" rise and fall time (ns)	50	500
Voltage increment per hlp (kV)	100	45
Half-lattice period (m)	0.3	0.225
dV/ds (average gradient) (MV/m)	0.3333	0.200
Quad occupancy	0.449	0.449
Quad length (effective) (m)	0.1347	0.101
Pipe radius (m)	0.04	0.0295
Quadrupole gradient (T/m)	40.9	60
B at beam pipe radius (T)	1.61	1.77

	Short Pulse Design [Ref. 6]		Long Pulse Design [Ref. 7]	
	Initial	Final (end of accelerator)	Initial	Final (end of accelerator)
Energy (MeV)	1.71	10.04	1.71	18.4
Phase advance per period ( $\phi_0$ ) (degrees) (midpulse)	72	28.07	67.5	67.5
Velocity/c	0.0097	0.0235	0.0097	0.0318
Rigidity [B ] (T-m)	1.176	2.8495	1.176	3.85
Current (A)	0.692	0.69 - 2.6	0.692	6.56
Beam radius (cm)	1.83	1.2 - 2.3	1.24	1.24

Table 2: Parameters for different compression schedules in the accelerator for the short pulse design (Ref. [6])

	Constant current	"Parabolic pulse shaping"	Constant bunch length	Bunch compression
1: $dV/ds \sim V^{-1}$	0	0	0	0
2: $l_{\text{bunch}} \sim V^{-2}$	0.5	0.25	0	-0.25
3: $L \sim V^{a3}$	0	0	0	0
Initial pulse duration (ns)	200	200	200	200
Final pulse duration (ns)	200	128	83	53
Final bunch length (m)	1.41	0.91	0.58	0.37
Final perveance $/(10^{-4})$	0.88	1.367	2.12	3.31
Final beam radius (cm)	1.23	1.49	1.83	2.26
Initial velocity tilt	0	0.0283	0.0567	0.085
Final velocity tilt	0	0.0075	0.00965	0.0093
Initial Voltage tilt (kV)	0	96.9	193.9	290.8
Initial Voltage tilt ( $V_{\text{head}} - V_{\text{tail}}$ ) (maintenance) (kV)	0	1.4	0	-4.25
Final Voltage tilt ( $V_{\text{head}} - V_{\text{tail}}$ ) (maintenance) (kV)	0	0.38	0	-0.465
Initial ear voltage per half lattice period (kV)	13.6	13.6	13.6	13.6
Final ear voltage per half lattice period (kV)	3.49	3.18	8.47	13.2

**Figure caption**

Figure 1: Layout and parameters of the two illustrative physics designs for the IBX. Parameters for the short pulse design in Ref.[6] are above that sketch, and parameters for the longer pulse case in Ref. [7] are below the sketch. Also note, that in Ref. [7], the bend extends for 180 degrees, rather than 90 degrees as indicated in the figure.

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