Beam Physics Goals and Issues in the Integrated Beam Experiment (IBX)

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Workshop on Recent Progress in Induction Accelerators

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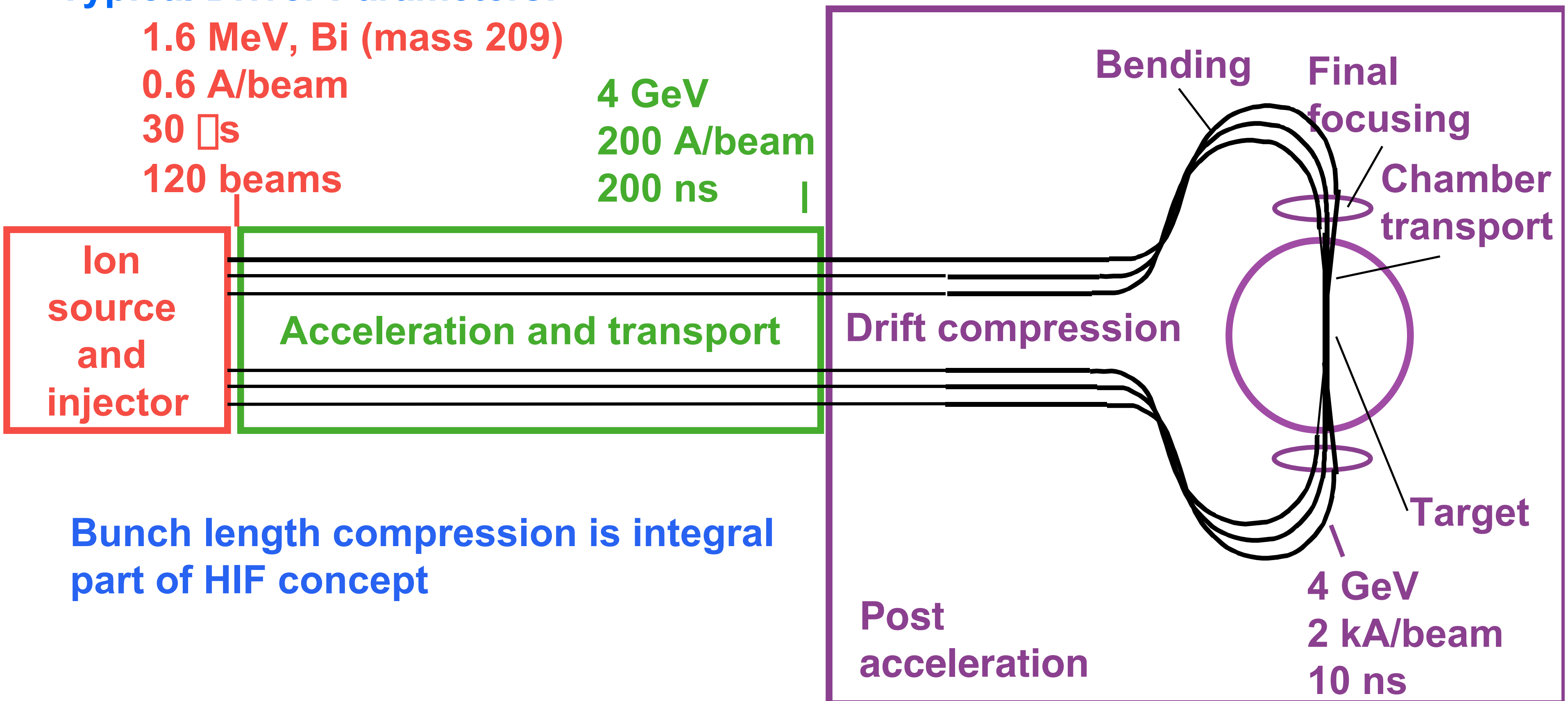
The IBX will address most of the physics issues found in an induction HIF driver

Typical Driver Parameters:

1.6 MeV, Bi (mass 209)
0.6 A/beam
30 μs
120 beams



Bunch length compression is integral part of HIF concept

Relative bunch length at end of: injector / accelerator / drift compression

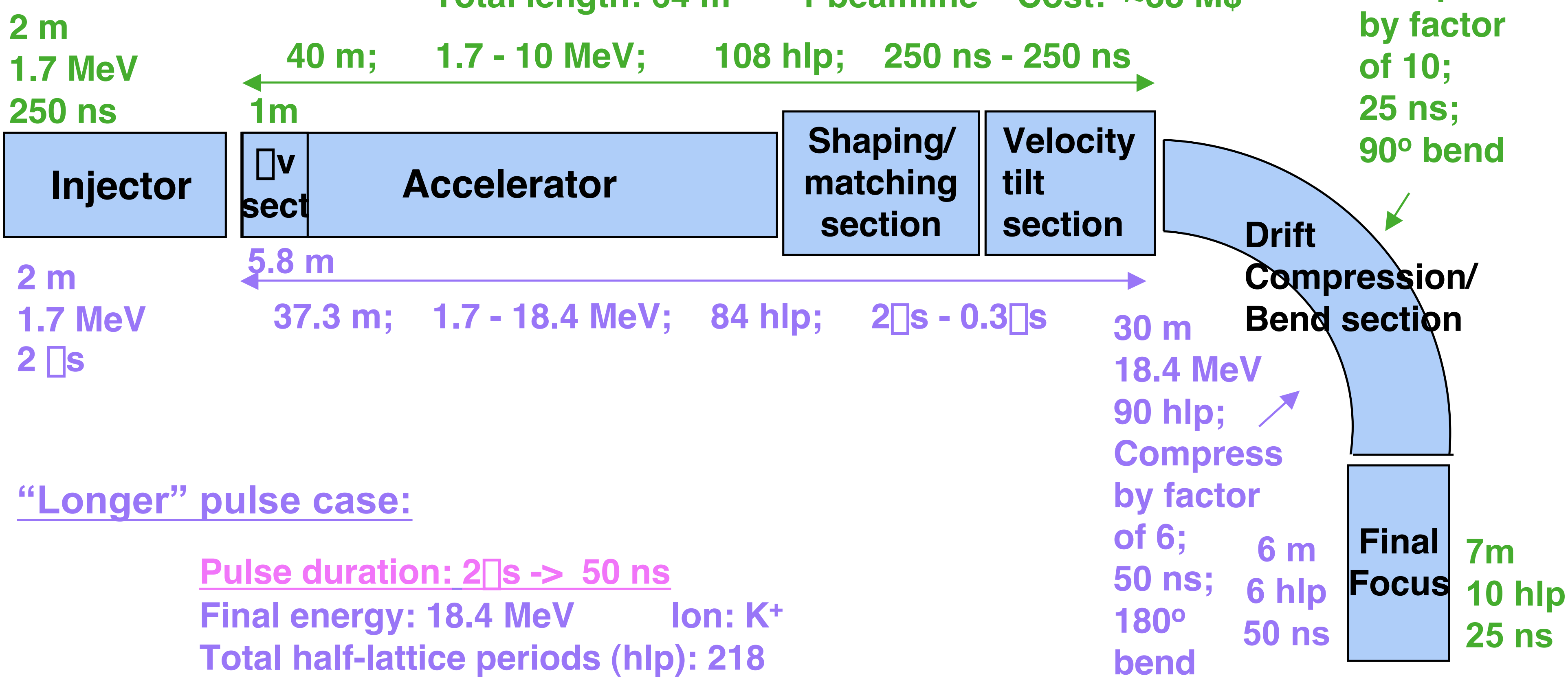
Several workshops have prioritized the science issues of HIF and derived the goals of the IBX

1. Integrated physics
   - Inject, accelerate, compress, bend, and focus a heavy ion beam at “significant” line charge density
   - Simulate a 3D beam from source-to-target, predicting final spot radius and current profile on target
2. Longitudinal physics
   - Physics of drift compression and space charge stagnation:
     Measure residual velocity tilt and spread after compression by factor ~10
   - Physics of longitudinal heating during acceleration and compression
3. Transverse/longitudinal coupling physics
   - Matching and beam control with velocity tilt and acceleration
   - Time dependent (upstream) final focus correction physics
   - Bending physics
   - Transverse/longitudinal temperature anisotropy instability
   - Beam “end” physics

Two cases for IBX were initially considered

Short pulse case:

Pulse duration: 250 ns -> 25 ns
Final energy: 10 MeV Ion: K^+
Total half-lattice periods (hlp): 148
Total length: 64 m 1 beamline Cost: ~38 M$

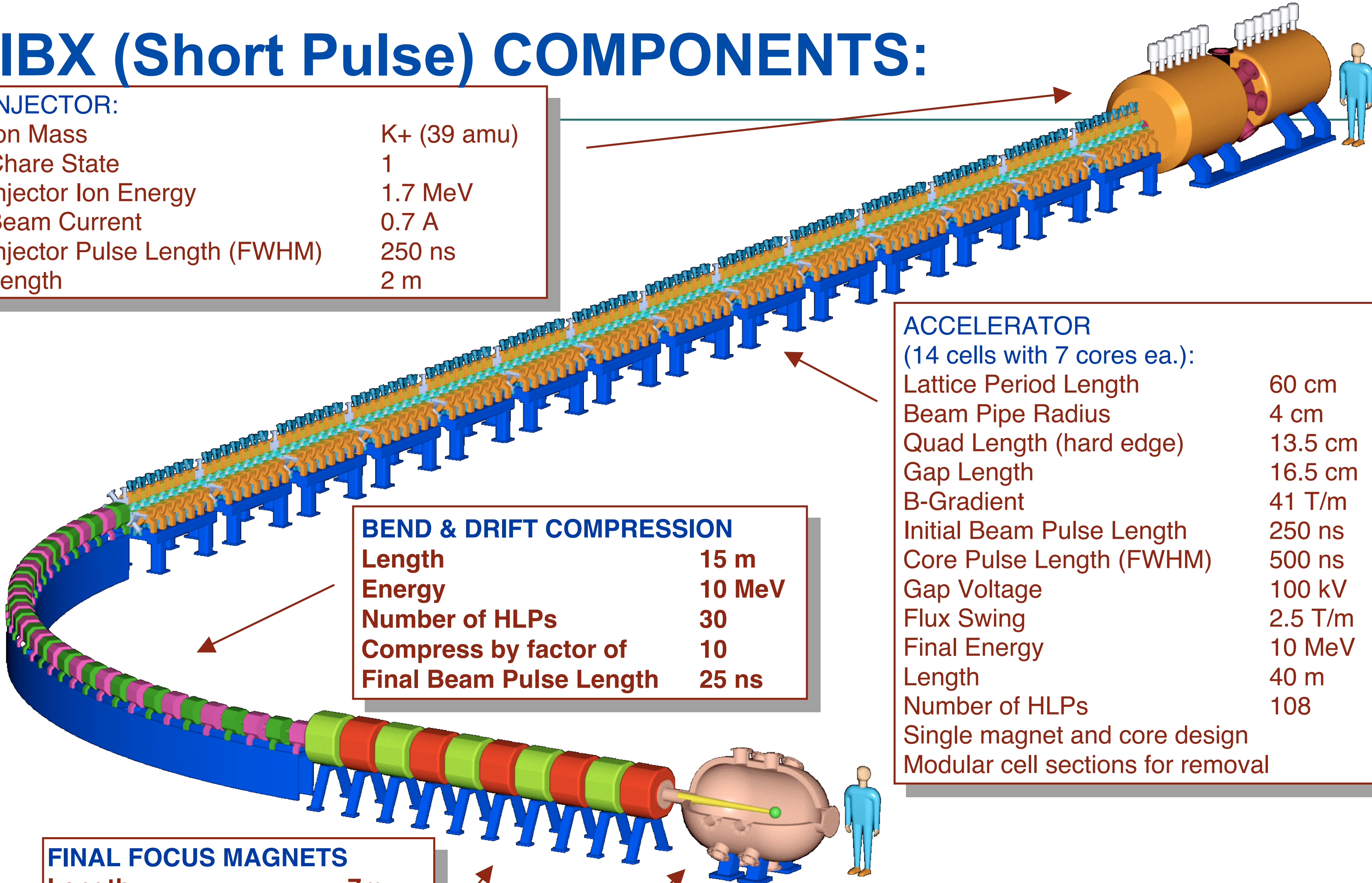


"Longer" pulse case:

Pulse duration: 2 μs -> 50 ns
Final energy: 18.4 MeV Ion: K^+
Total half-lattice periods (hlp): 218
Total length: 75.3 m 4 beamlines Cost: ~66 M$

IBX (Short Pulse) COMPONENTS:

INJECTOR:	
Ion Mass	K+ (39 amu)
Chare State	1
Injector Ion Energy	1.7 MeV
Beam Current	0.7 A
Injector Pulse Length (FWHM)	250 ns
Length	2 m



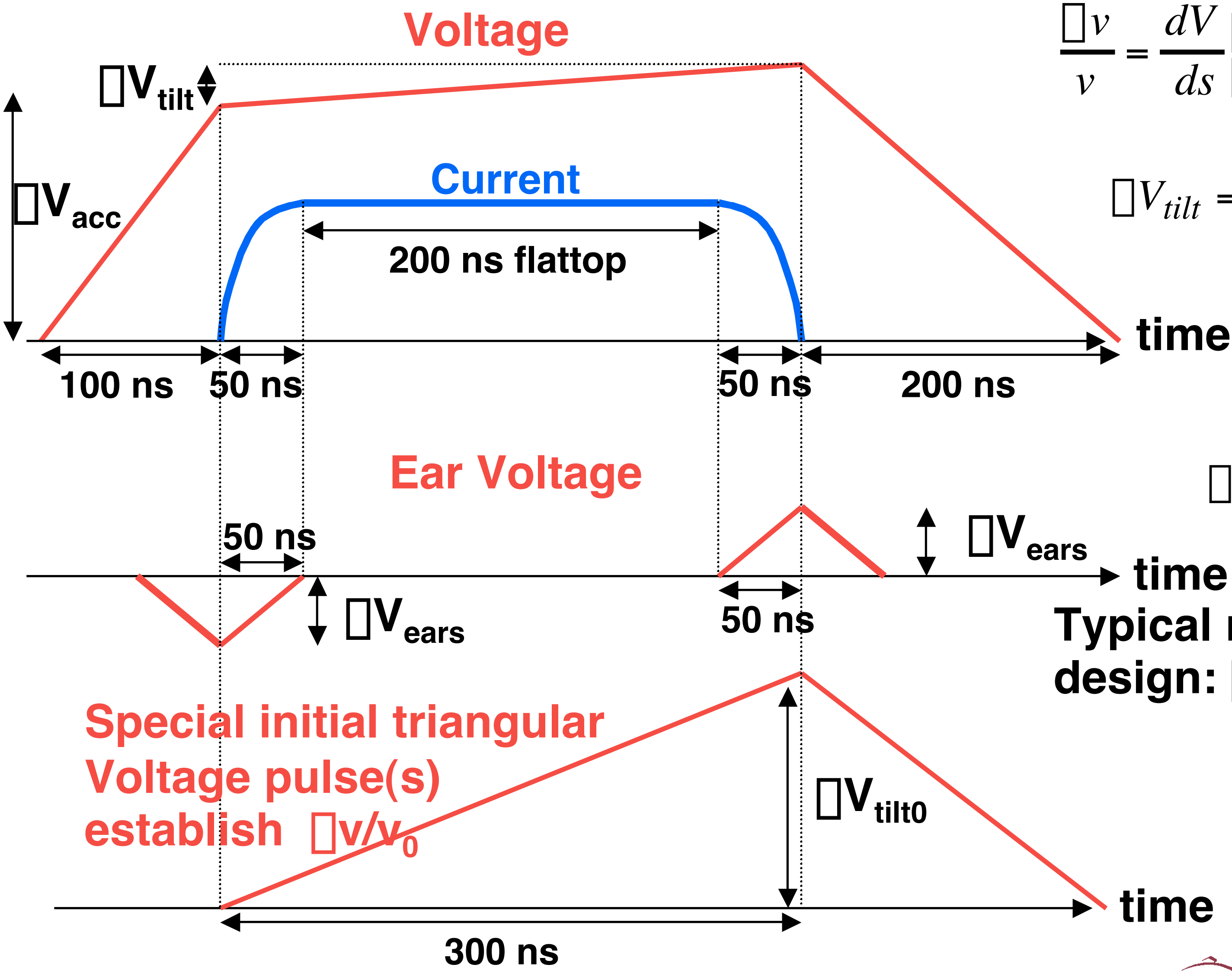
ACCELERATOR (14 cells with 7 cores ea.):	
Lattice Period Length	60 cm
Beam Pipe Radius	4 cm
Quad Length (hard edge)	13.5 cm
Gap Length	16.5 cm
B-Gradient	41 T/m
Initial Beam Pulse Length	250 ns
Core Pulse Length (FWHM)	500 ns
Gap Voltage	100 kV
Flux Swing	2.5 T/m
Final Energy	10 MeV
Length	40 m
Number of HLPs	108
Single magnet and core design	
Modular cell sections for removal	

BEND & DRIFT COMPRESSION	
Length	**15 m**
Energy	**10 MeV**
Number of HLPs	**30**
Compress by factor of	**10**
Final Beam Pulse Length	**25 ns**

FINAL FOCUS MAGNETS	
Length	**7m**
Number of HLPs	**10 hlp**
Beam Pulse Length	**25 ns**

PLASMA NEUTRALIZATION & CHAMBER

Voltage and Current Wave forms



$$\frac{\Delta v}{v} = \frac{dV}{ds}\left(\frac{\ell}{V}\right)\left(\frac{1}{2} - \frac{V}{\ell}\frac{d\ell}{dV}\right)$$

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

$$\Delta V_{ear} = \frac{2g\lambda_{flat}L}{4\pi\varepsilon_0\beta c\Delta t}$$

Typical numbers from design:

- ΔV_{tilt0} ~ 100 kV
- ΔV_{tilt} ~ 1 kV
- ΔV_{ears} ~ 14 kV
- ΔV_{acc} ~ 100 kV

Accelerator would be flexible enough to explore different compression schedules

	Constant current	"Parabolic pulse shaping"	Constant bunch length	Bunch compression
alpha1: dV/ds ~ V^alpha1	0	0	0	0
alpha2: Ibunch ~ V^alpha2	0.5	0.25	0	-0.25
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 (maintenance) (kV)	0	1.4	0	-4.25
Final voltage tilt (maintenance) (kV)	0	0.38	0	-0.465
Initial ear voltage per hlp (kV)	13.6	13.6	13.6	13.6
Final ear voltage per hlp (kV)	3.49	3.18	8.47	13.2

Why short pulse?

1. Cross sectional area of core proportional to voltage x pulse duration

=> Core size can be reduced

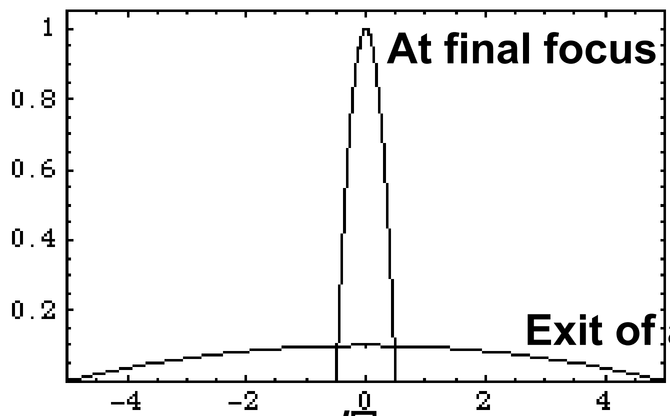
0.43 m | **1.9 m**

250 ns, 100 kV RTA cell | **2 μs, 200 kV DARHT cell**

Why short pulse (cont'd)?

2. Length of drift compression **directly** proportional to bunch length

Perveance



Q/Q_f (vertical axis), $z/\Delta z_{final}$ (horizontal axis)

$Q = Q_{max}(s)\ (1-4\Delta z^2/l_{bunch}^2)$

Assume parabolic profile (for purposes of obtaining rough scaling)

$\Delta v/v = (8Q_a\, g\, (C-1))^{1/2} \quad \sim \quad (8Q_f g)^{1/2}$ **Velocity tilt**

$d = l_a\,(1 - 1/C)\ /\ (\Delta v/v) \quad \sim \quad l_a\ /\ (\Delta v/v)$ **Drift length, d**

Here C = compression ratio = l_a/l_f = (bunch length at accelerator end)/
(bunch length at final focus)

Q_a = Peak perveance (Q_{max}) at end of accelerator; Q_f = peak perveance at target;

g = longitudinal "g-factor" = 2 ln r_p/a

Issues for short pulse design

I. Injector transients need to be assessed.

For a single beam injector, $I \sim (q/m)^{1/2} (a/d)^2 V^{3/2}$; for K^+, a/d~0.5, and I~0.7 A, V~280 kV; for breakdown voltage V~100 kV(d/1cm)$^{1/2}$; d ~7.8 cm

For minimal transients in injector, flattop pulse length > transit time $t_{transit}$

But $t_{transit}$~200 ns for these parameters, so study needed.

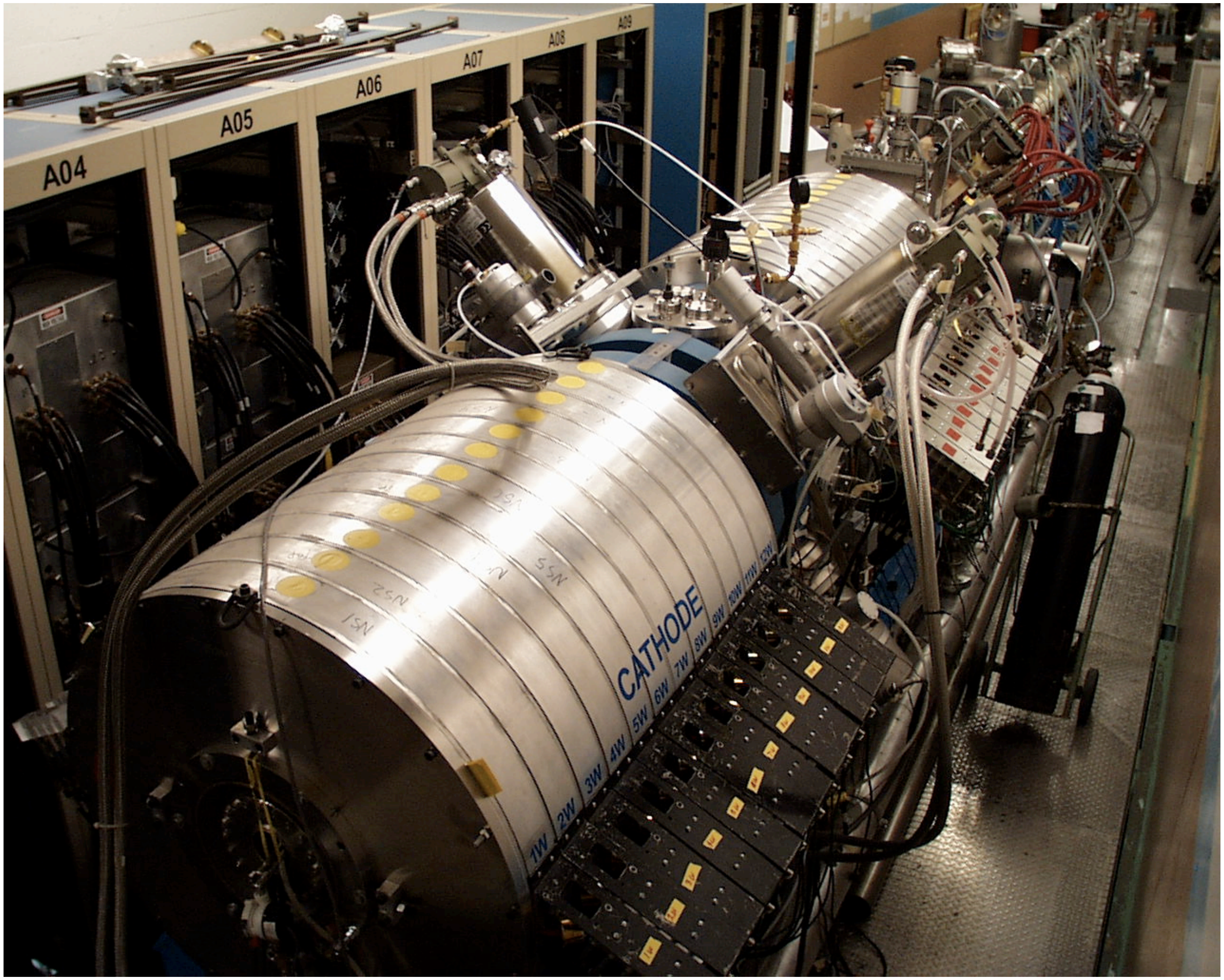
Two solutions:

1. Reduce d, V, I (transit time is reduced)
2. Use multiple beamlet approach as is being studied on test stand (but may not be ready for IBX)

II. Potential electron/gas problems not as well studied (Investigation of long pulse effects will be carried out on HCX and Injector test stand)

III. Diagnostics need to be costed. (But regime is very similar to induction electron accelerators.)

The RTA Injector (1 MeV, 375 ns) is a working example of a short-pulse induction-driven electron injector



Other design differences were not fundamental to short or long pulse option

Doublet vs. singlet: Long pulse design based on doublet superconducting magnet work for HCX, with syncopated lattice; short pulse design lengthened lattice period, but increased pipe radius for FODO design

1 vs. 4 beams: Long pulse option was designed with 4 beams; current view: multiple beam option should be costed and perhaps carried as upgrade option; single beam mainline

Identical half-lattice period vs. variable lattice: Short pulse design carried identical lattice periods throughout accelerator; Very modular, and would allow drifting beam experiments; cost penalty

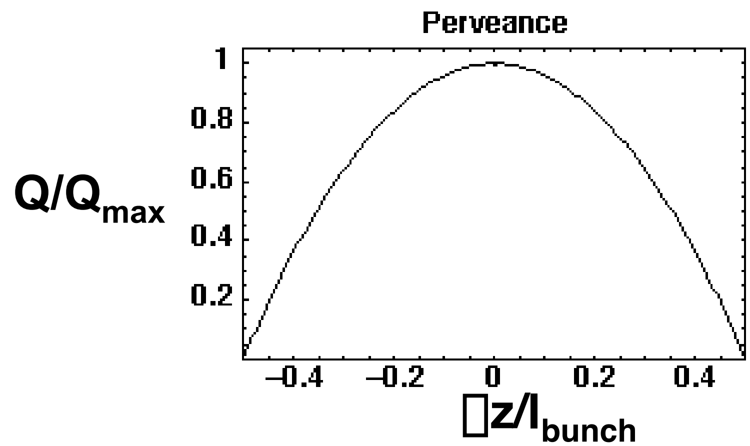
Compression schedules: short pulse design used constant current schedule in accelerator to achieve factor of 10 compression in drift compression; Bunch compression in accelerator uses different voltage waveforms; Not as “integrated” as long pulse design.

"Fluid dynamics" of drift compression

Assume parabolic profile (for purposes of obtaining rough scaling)
Perveance $Q = \lambda/4\pi\epsilon_0 V$ = **space charge potential energy/beam kinetic energy**

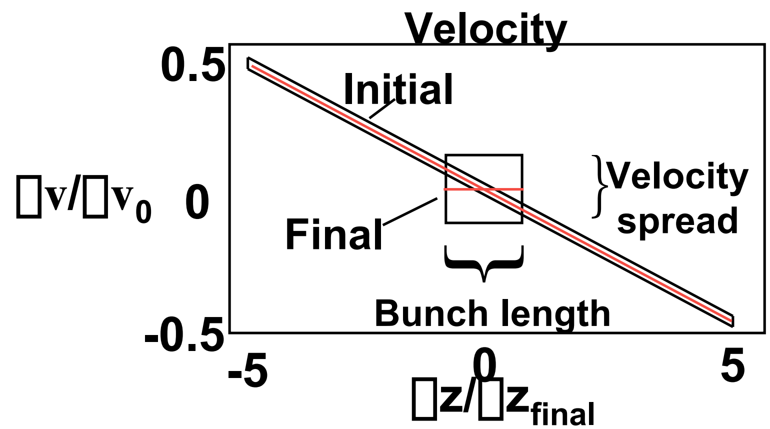
1D fluid equations can be employed to obtain rough scaling of requirements
In comoving frame:

$$\frac{\partial \lambda}{\partial t} + \frac{\partial \lambda v}{\partial z} = 0 \qquad \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial z} = -\frac{qg}{4\pi\epsilon_0 m}\frac{\partial \lambda}{\partial z}$$



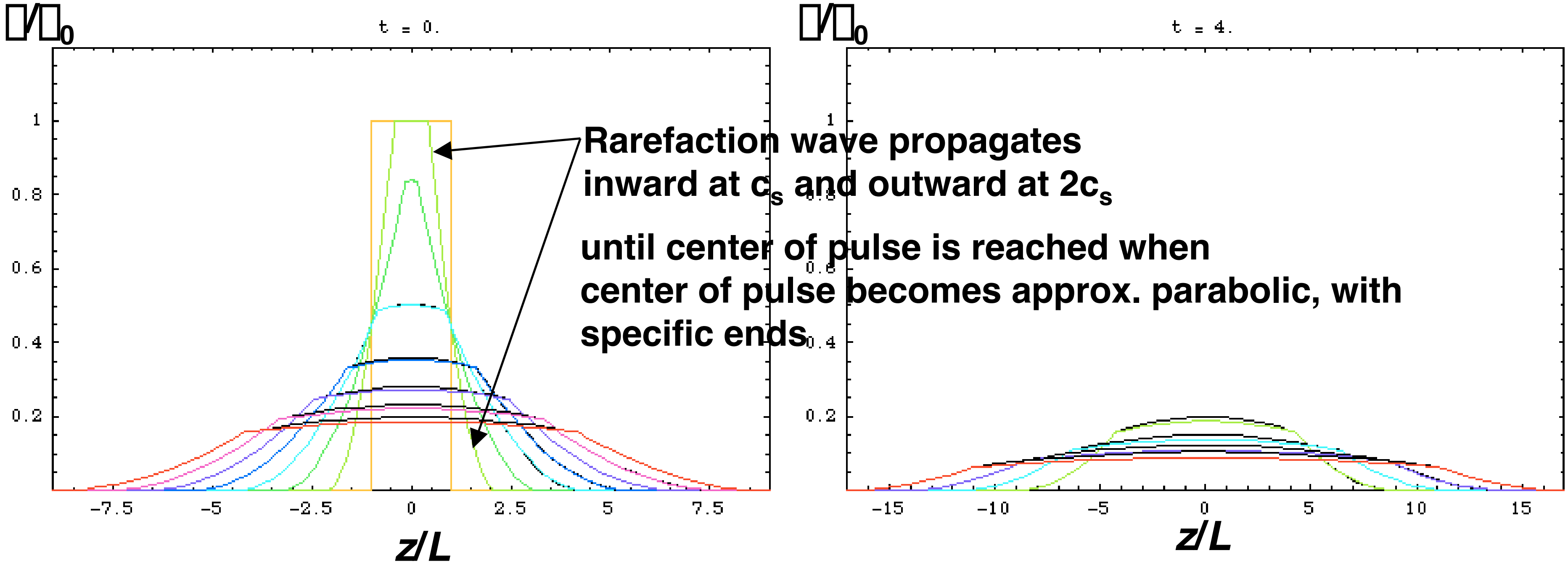
Similarity solution:

$$Q = Q_{max}(t)\,(1-4\Delta z^2/l_{bunch}(t)^2);$$
$$v = \Delta v_{tilt}(t)(2\Delta z\,/l_{bunch}(t))$$



$\Delta v/v = (8Q_a\, g\, (C\text{-}1))^{1/2}$ ~ $(8Q_f g)^{1/2}$ **Velocity tilt**
$d = l_a\,(1 - 1/C)\ /\ (\Delta v/v)$ ~ $l_a\,/\,(\Delta v/v)$ **Drift length,** d

A second illustrative example: a rectangular current pulse at final focus



(first four wave crossing times, L/c_s)   (second four wave crossing times. L/c_s)

Two timescales exist: 1. Crossing time of rarefaction wave to pulse center, $L/(2c_s)$

2. Pulse compression time, d/v_0

Ratio of timescales ~ *C*= bunch length before/after drift compression

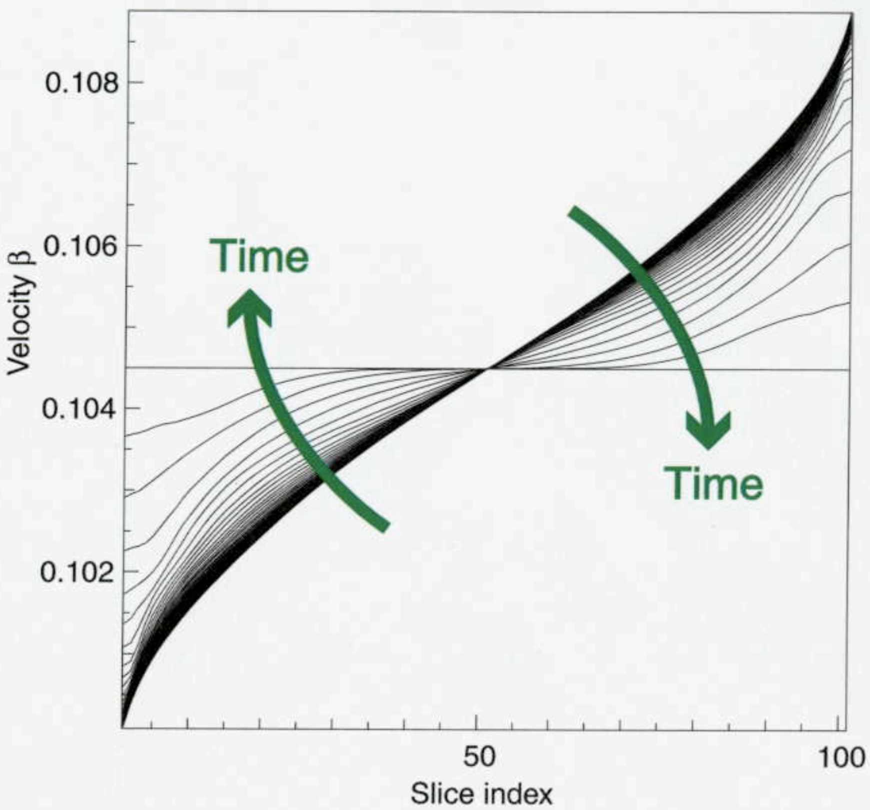
(Here $c_s = (gQ/2)^{1/2}\, v_0$; $2L$= final bunch length; *d*=drift distance; v_0=beam velocity)

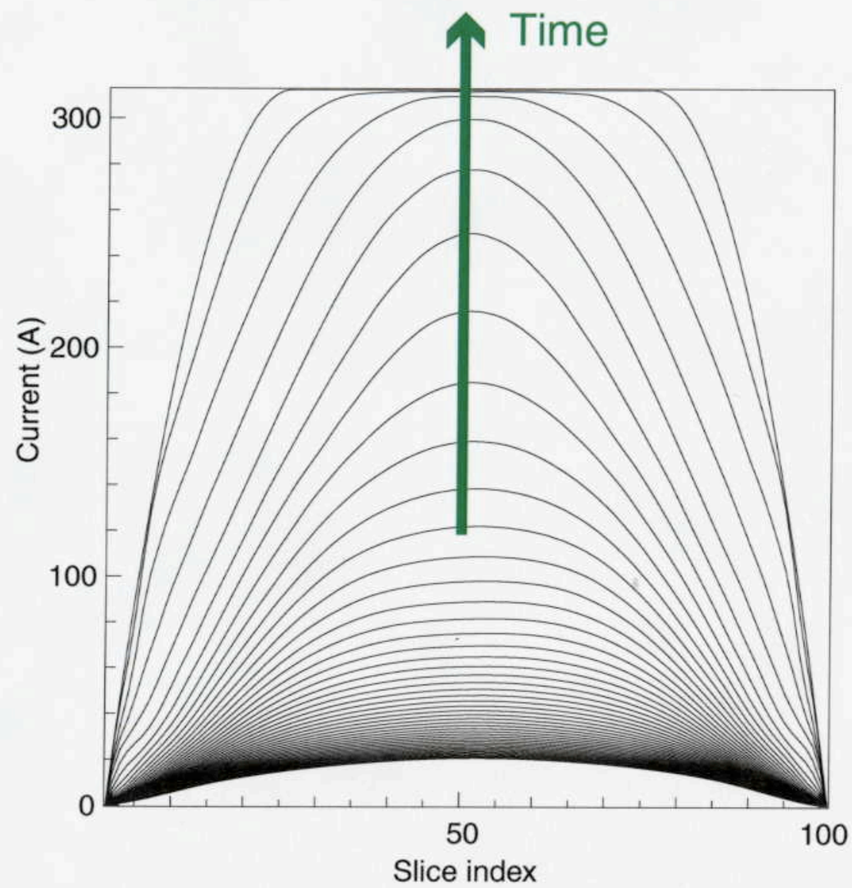
(cf. Ho et al, 1991, also Faltens and Lee, 1987, Landau and Lifshitz, Fluid Mechanics, 1959)

The HERMES code was used to model a final current pulse that is flat with parabolic ends

15 ns final pulse duration

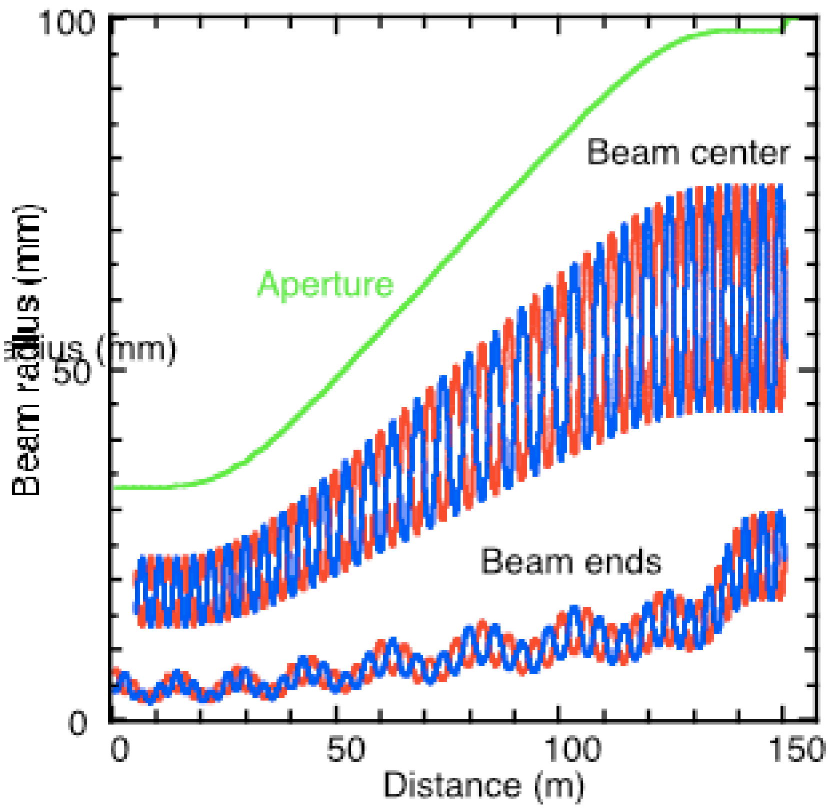
The initial tilt on the beam is about 4% (compare to ~30% at the beginning of the accelerator)



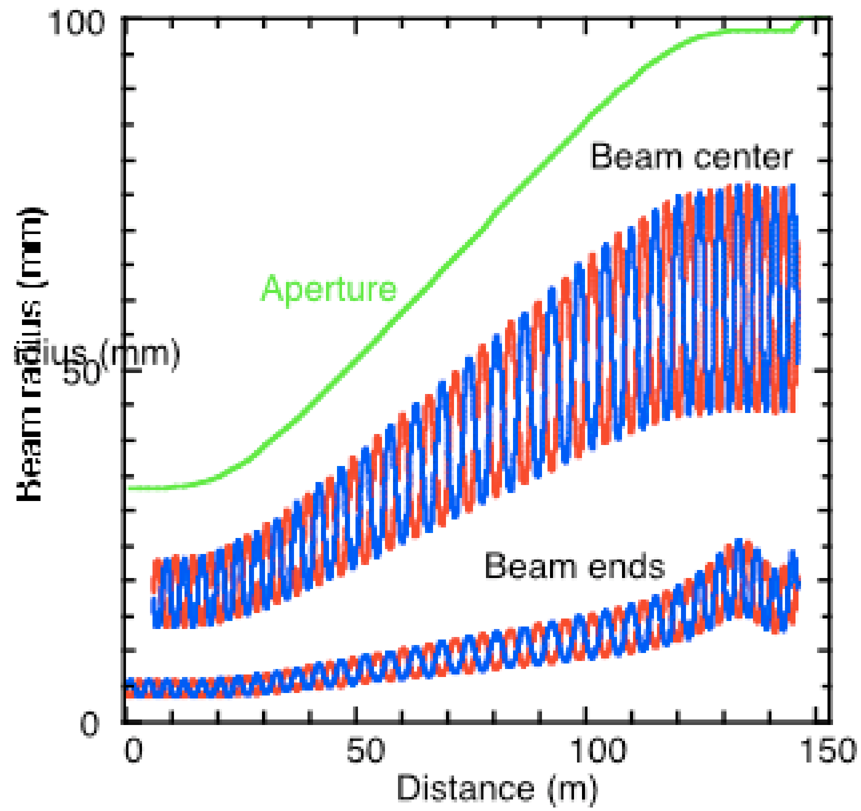


Although the final beam profile is flat, it is parabolic for most of the drift compression

Drift compression section is designed by running code first backwards from target, then forwards after rematching



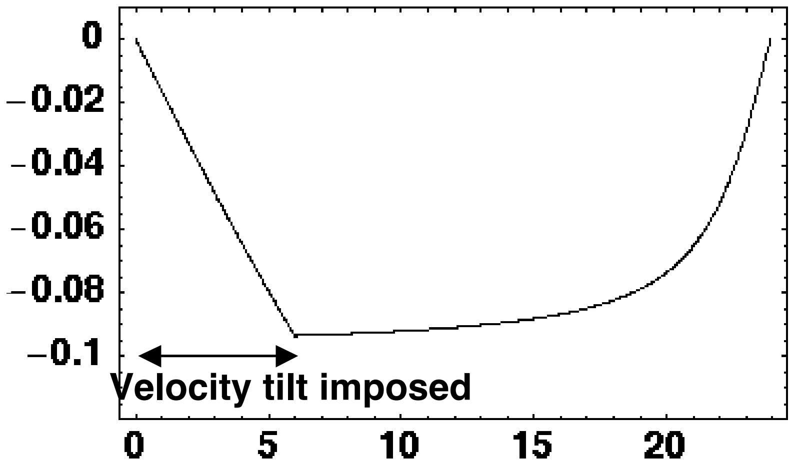
Begin with a desired 20ns, constant-energy pulse at end of compression, track backwards, design lattice for central slice; beam end becomes mismatched early on



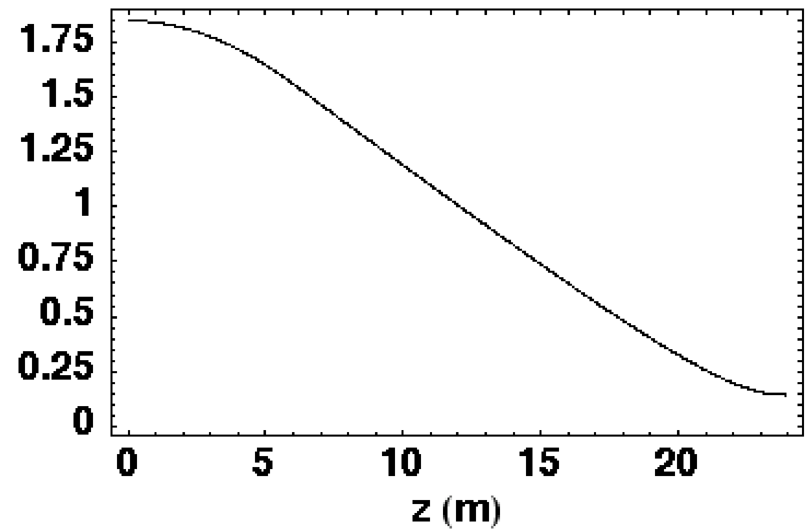
“Rematch” at entrance to compression section, by adjusting a,a’,b,b’; then track forward

Details of the drift compression/bunching section (short pulse option) in IBX

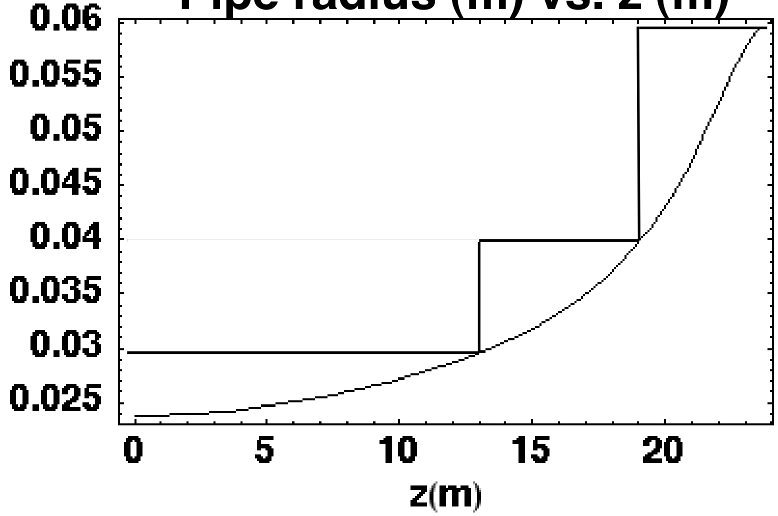
d(Bunch Length)/dz vs. z (m)



Bunch length (m) vs. z (m)



Pipe radius (m) vs. z (m)



Half-lattice period: 0.5 m

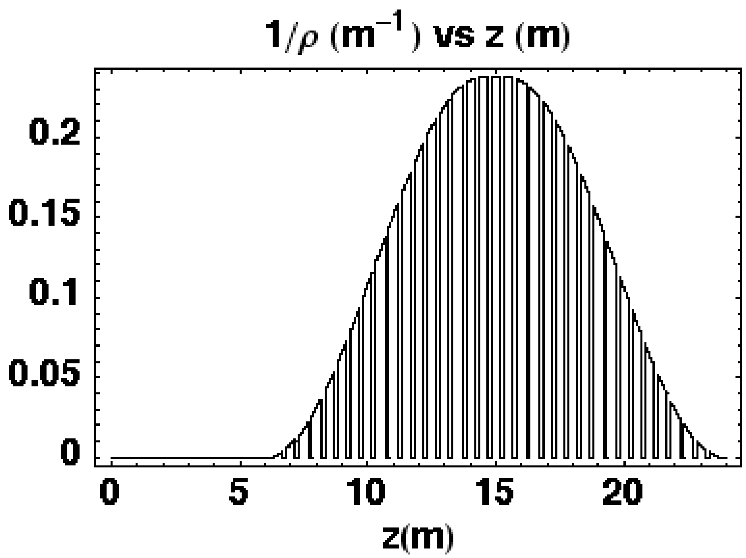
Gradient: 26 T/m

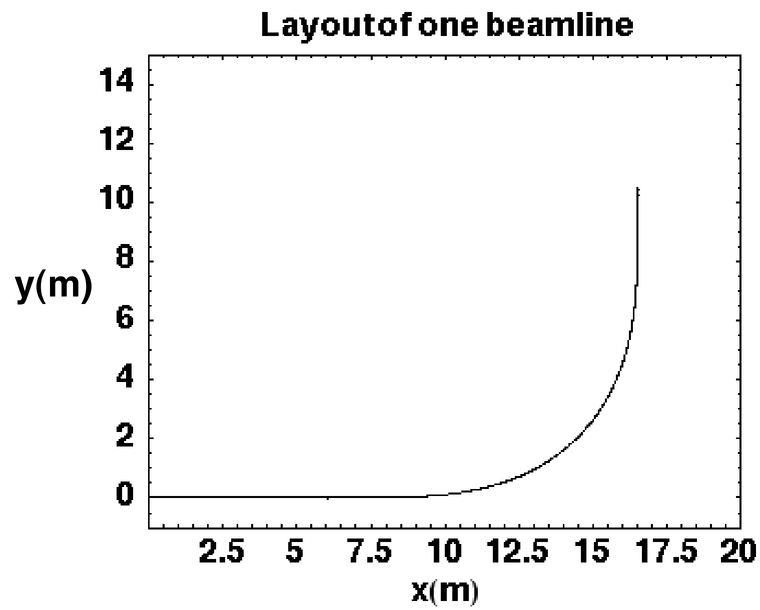
Occupancy: 0.7

Field at bore radius: 1.04 T (4 cm)
1.56 T (6 cm)

Number of hlp: 48 (includes velocity tilt imposition section and 3 m of final focus section)

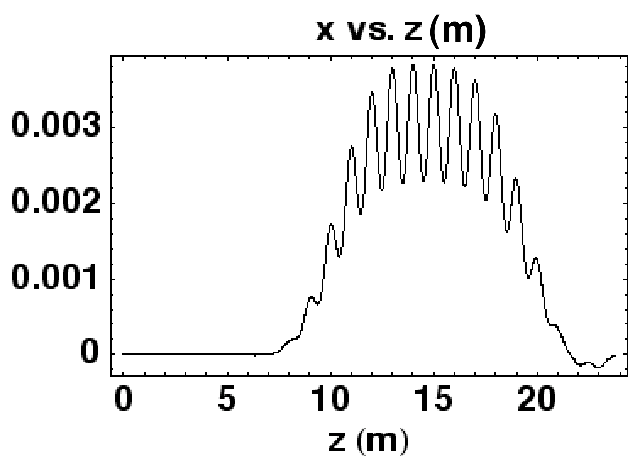
During drift compression beam would simultaneously be bent, exploring dispersion and emittance physics





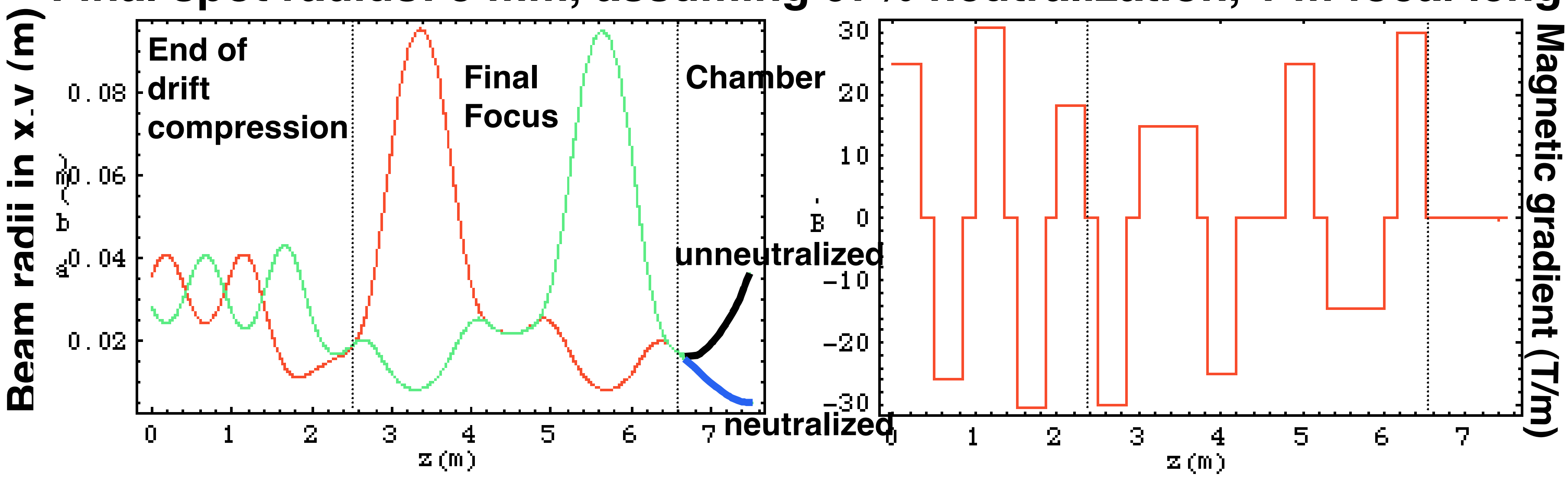
Rigidity of 2.85 T/m requires .54 T dipole field

Centroid of slice, (halfway between end and center of pulse)



Final focus section

Example final focus section for the parameters of this design
Final spot radius: 5 mm, assuming 97% neutralization, 1 m focal length



Final focus section is approximately 7 m long consisting of 6 final focus quads plus 4 matching quads

B-fields required at bore radius: 1.8 T (penultimate magnet)
1.5 T (last magnet)

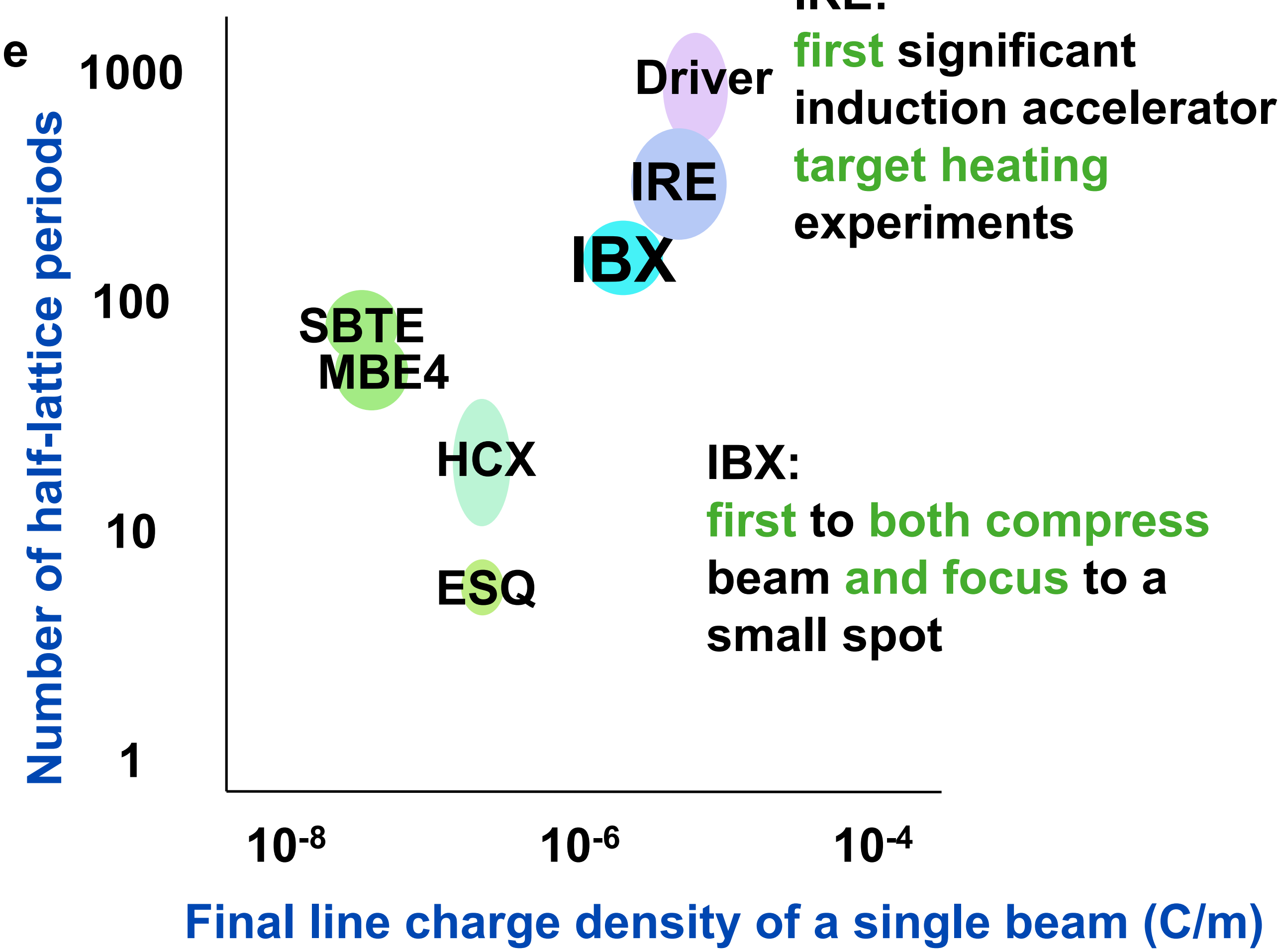
Max beam radius: 9.5 cm; bore radius: 15 cm; magnet length: 70 cm

IBX is a logical step in a progression of HIF experiments

SBTE:
stability of space-charge dominated beams

MBE-4:
multiple beams and simple pulse compression

HCX and ESQ:
line charge comparable to initial line charge in driver; electron effects



IRE:
first significant induction accelerator
target heating experiments

IBX:
first to both compress beam and focus to a small spot

Conclusion

The scientific goals of IBX are:

- Demonstrate an integrated system,
  - using same manipulations as driver
- Accelerate, compress and focus beam to a spot at significant □
- Assess longitudinal physics of bunch compression and brightness preservation
- Investigate transverse/longitudinal coupling physics

The IBX parameters, based on IBX workshop consensus, are:

- Ion energy: 5-20 MeV
- Final line charge density: ~1-2 □C/m
- Bunch length compression in drift section: 10 x.

Point designs indicate broad parameter space where scientific goals can be met within cost envelope

The IBX will set the stage for the IRE, where target heating experiments at 50-100 eV will first be carried out with ions