HIF Driver Point Designs

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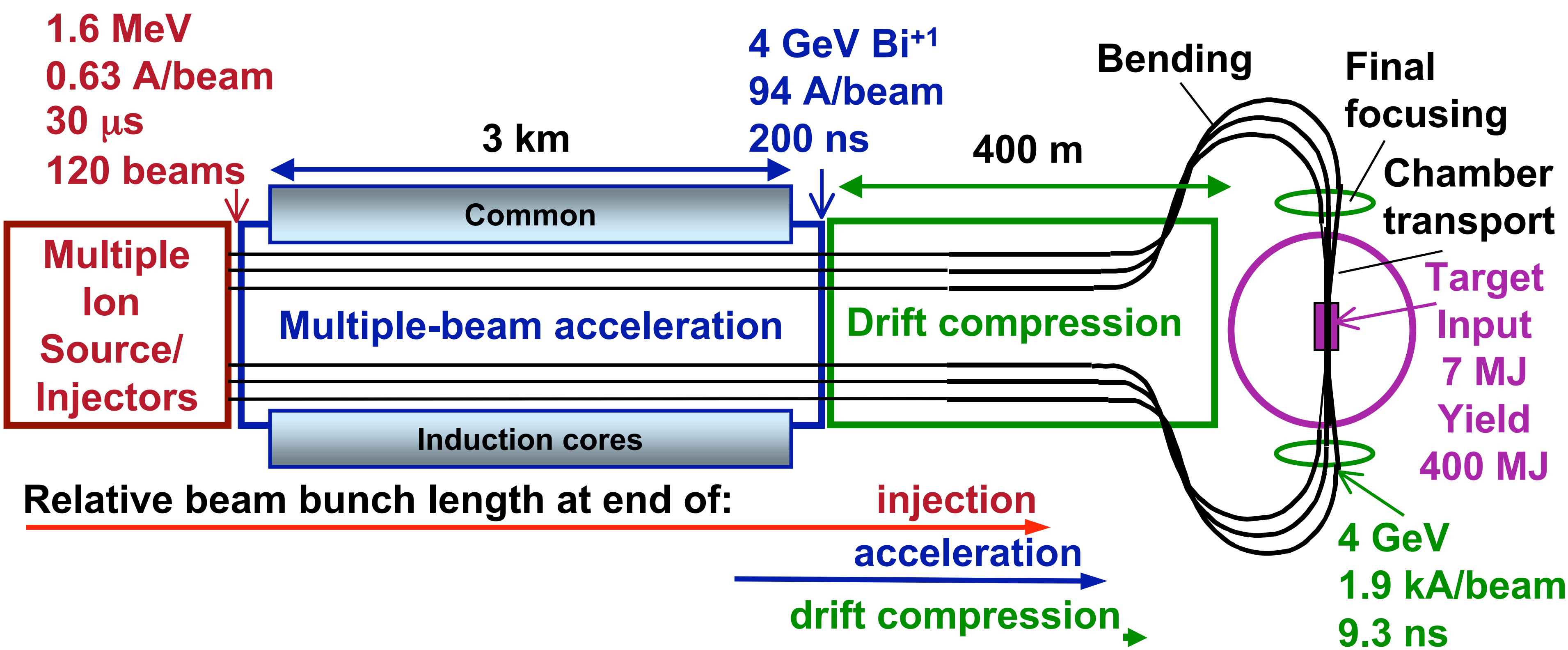
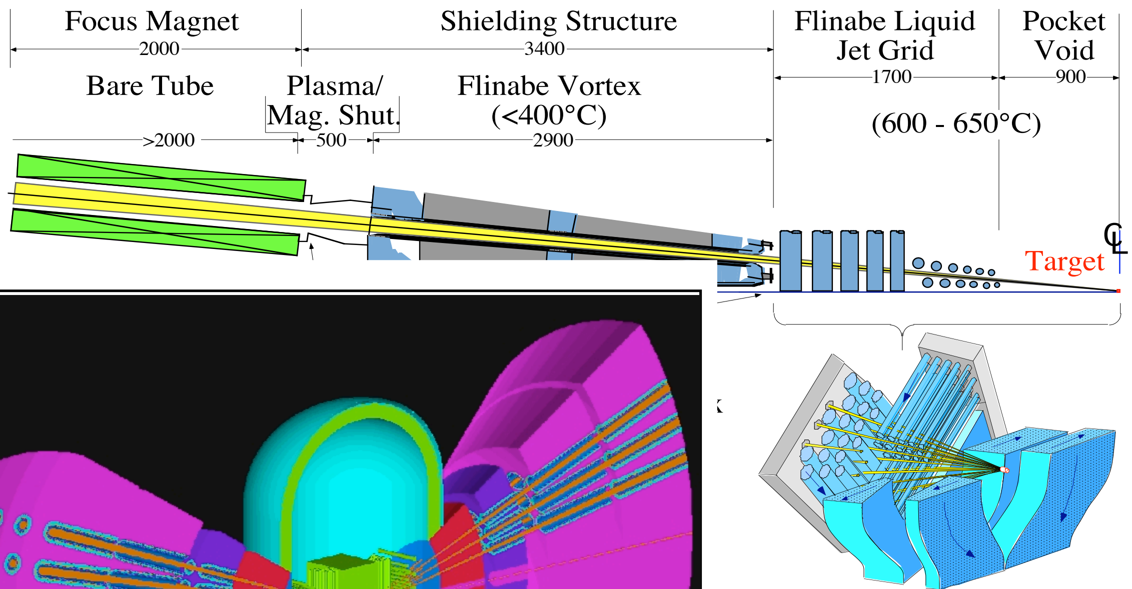
Summary

- An HIF driver point design must be an integrated system that is self-consistent from injector to target
- The Robust Point Design (RPD) is an integrated system based on a single accelerator with multiple beams
- Ongoing Modular Point Design (MPD) study seeks a self-consistent integrated solution based on 10-20 accelerator modules with single beam/module

A Robust Point Design study established a baseline for a multiple-beam quadrupole induction linac HIF driver



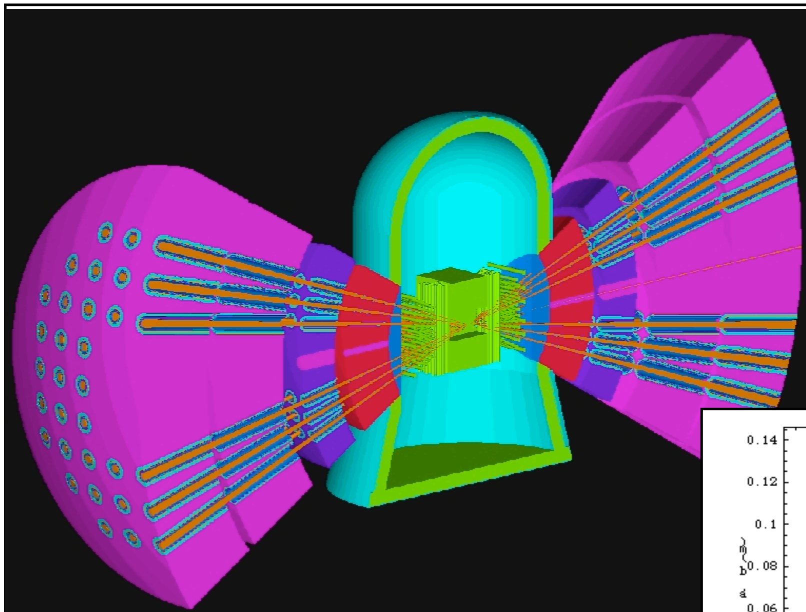
Integration of target, chamber, and accelerator requirements led to the self-consistent point design



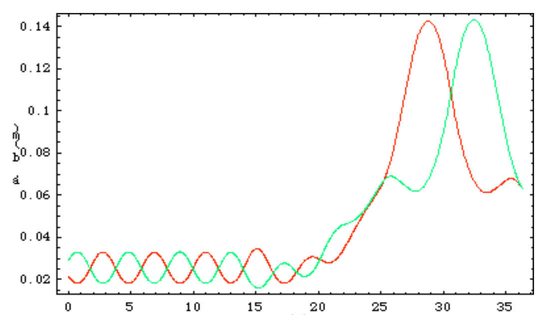
Schematic Liquid Jet Geometry

Chamber dynamics

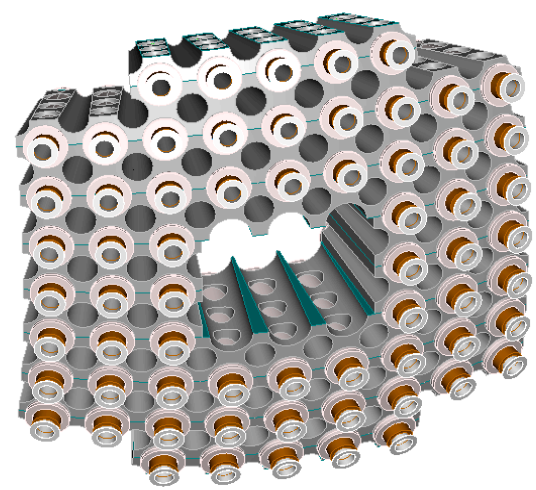
Ion: Bi^{+} (A=209)
Main pulse: 4 GeV
Foot pulse: 3.3 GeV
120 beams total (72 main, 48 foot)
Pulse energy: 7 MJ
Final spot radius: 2.2 mm



3 D neutronics calculations



Final beam optics

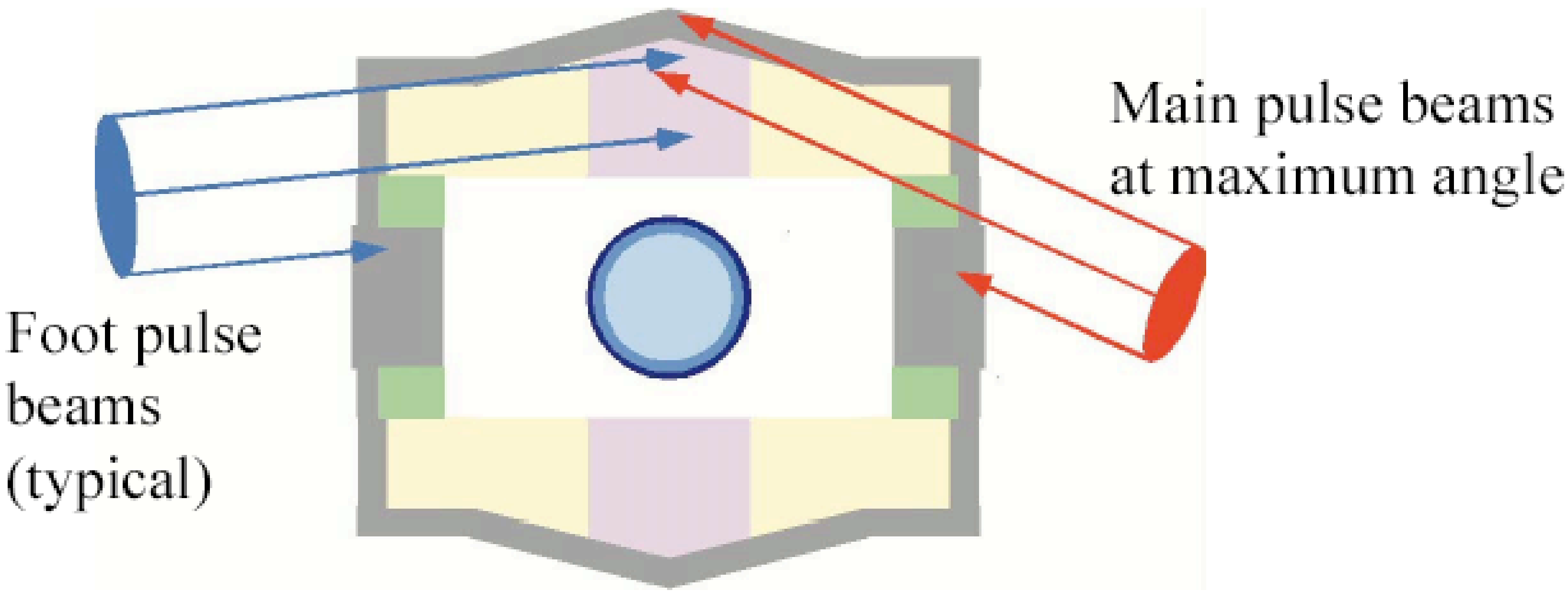


Mechanical engineering

+ target physics + chamber propagation

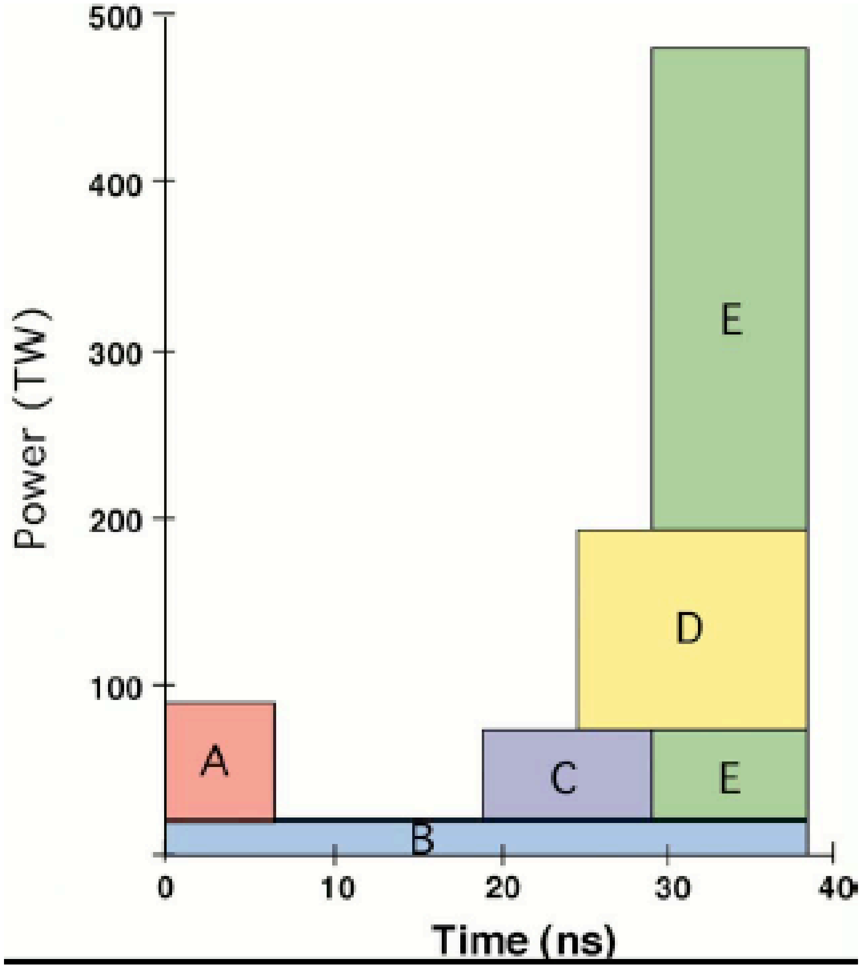
Length: 2.7 km; Efficiency 28%
Total cost: 2.8 B$

Target design is a variation of the distributed radiator target (DRT)



- This new design allows beams to come in from a larger angle, up to 24 degrees off axis.
- Yield = 400 MJ, Gain = 57 at E_{driver} = 7 MJ

A building block pulse shape is used



Beam and Pulse Shape Requirements

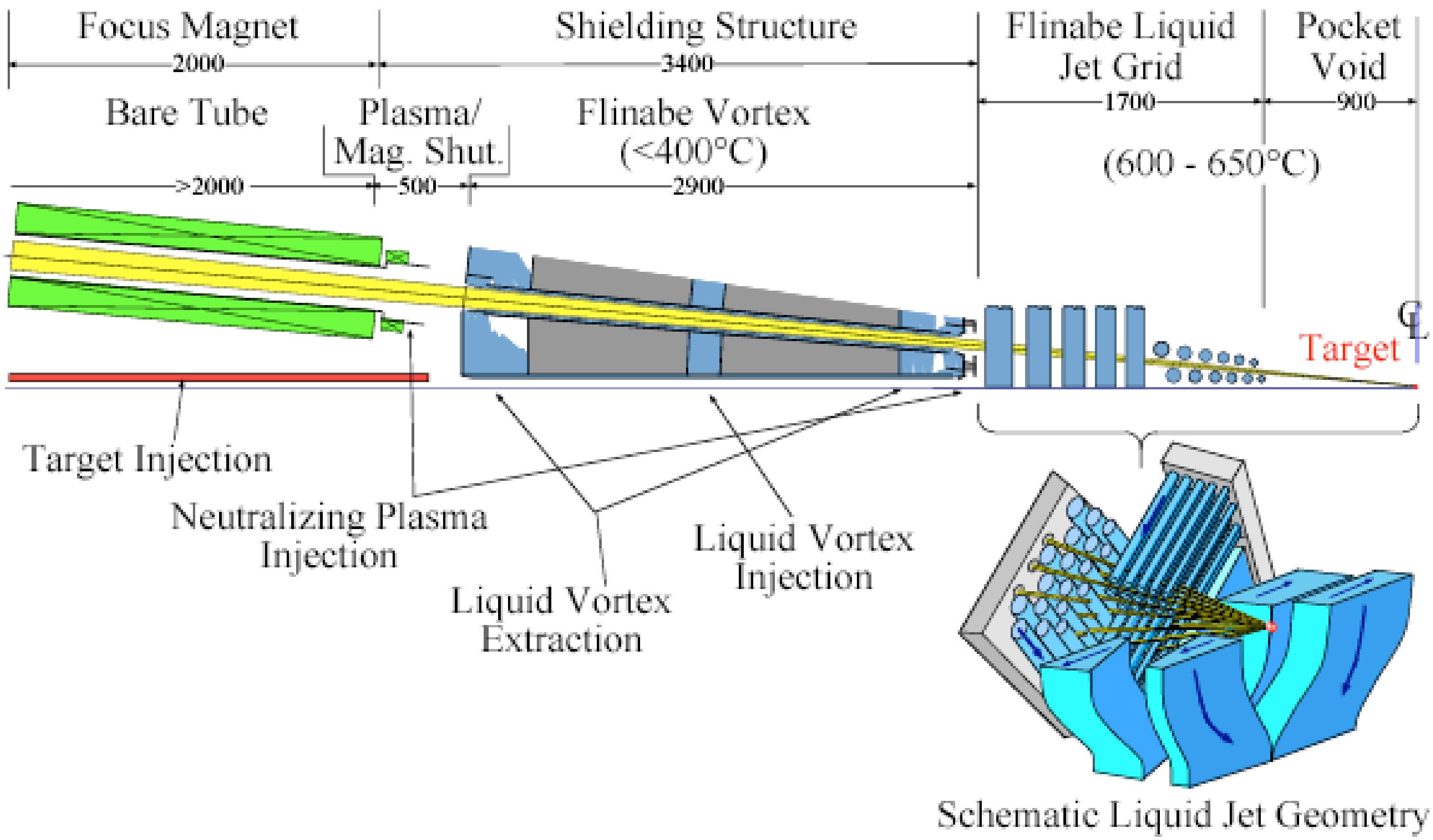
Block	No. of Beams	Power, TW	Pulse width, ns	Energy, MJ
A (Foot)	16	70	6.5	0.46
B (Foot)	16	20	38.3	0.77
C (Foot)	16	53	10.1	0.54
D (Main)	24	120	13.7	1.64
E (Main)	48	388	9.3	3.61

48 foot pulse beams:
T = 3.3 GeV, E_F = 1.76 MJ

72 main pulse beams:
T = 4.0 GeV, E_M = 5.25 MJ

120 total beams:
E_D = 7.0 MJ

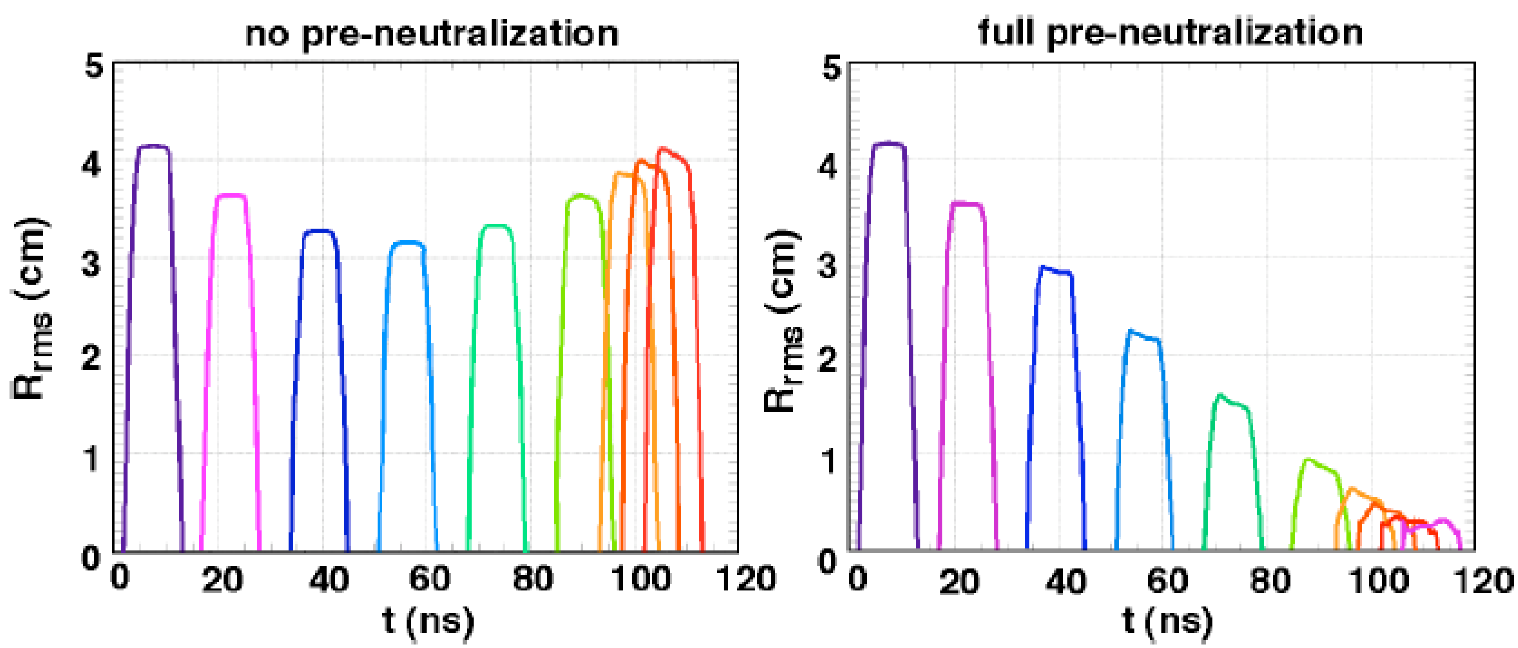
The Robust Point Design (RPD) beam line



Neutralization is required for small spot sizes

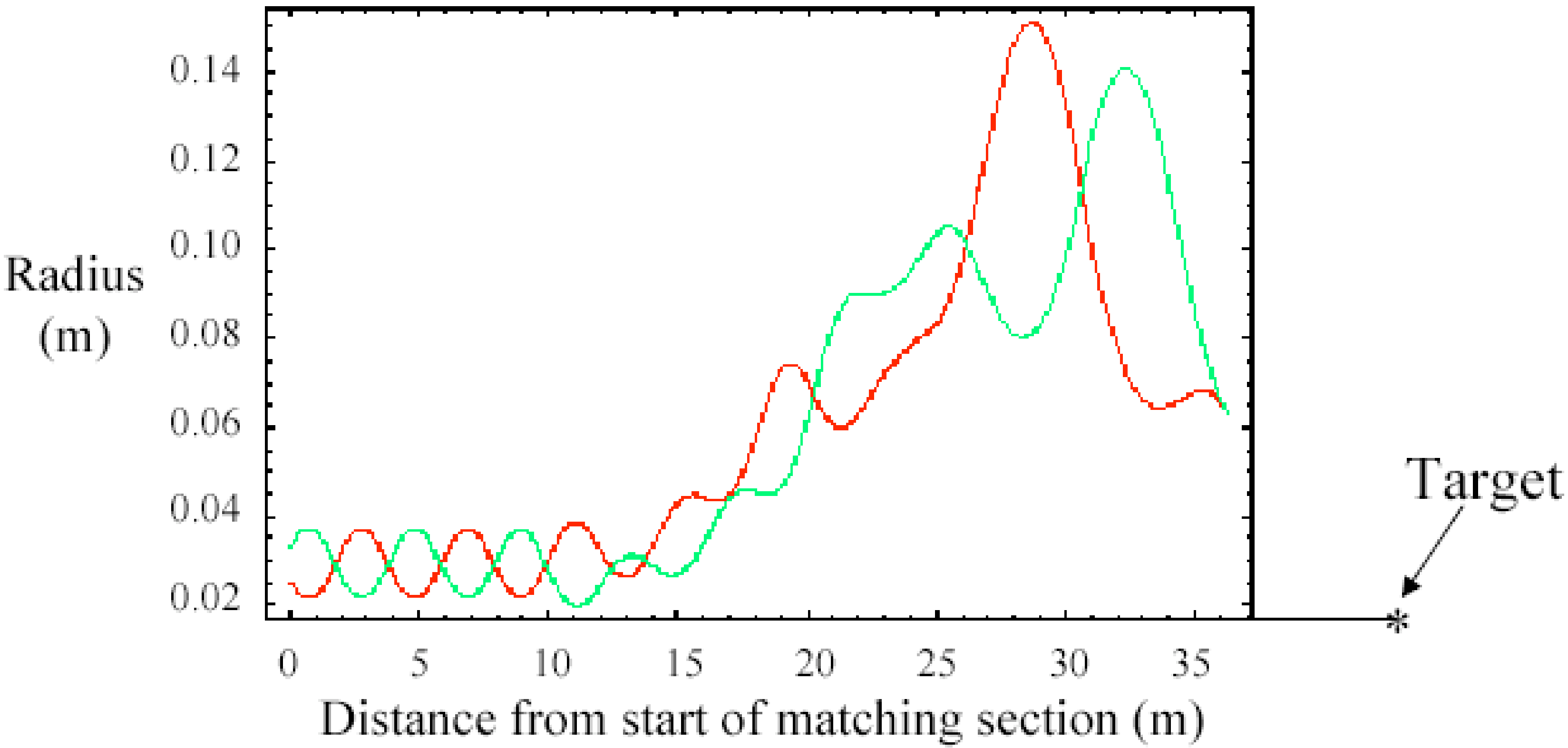
Results for standard Xe main pulse

- time histories of rms radius at selected axial positions
- plasma is electrically connected to wall by images and emission



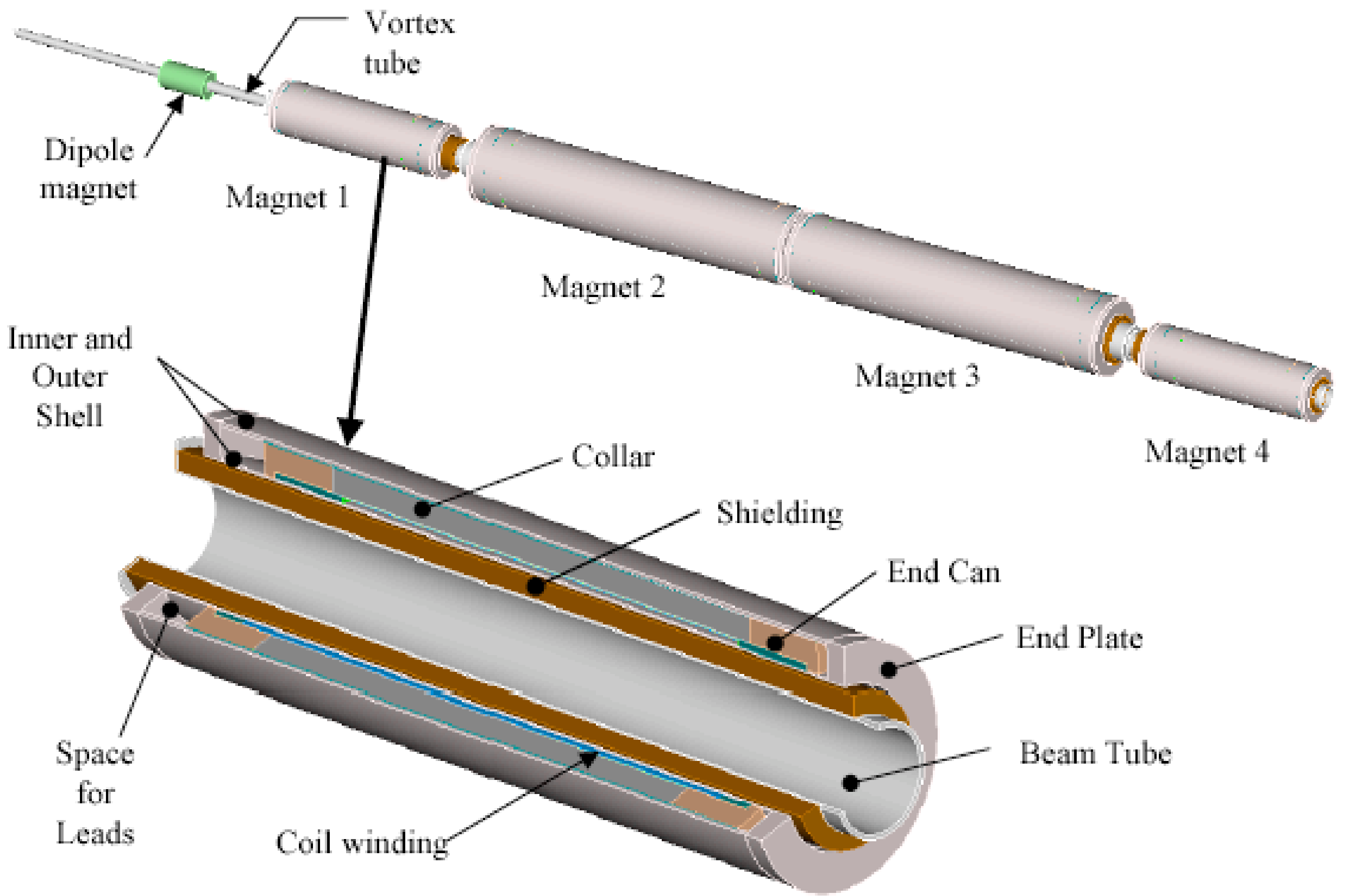
- 2.5 mm waist is close to value needed by distributed-radiator target
- Bi is easier to focus and meets spot requirement

Beam envelop in final focus region



x- and y- envelopes for the Block E main pulse beams in the final focus system. The target is to the right.

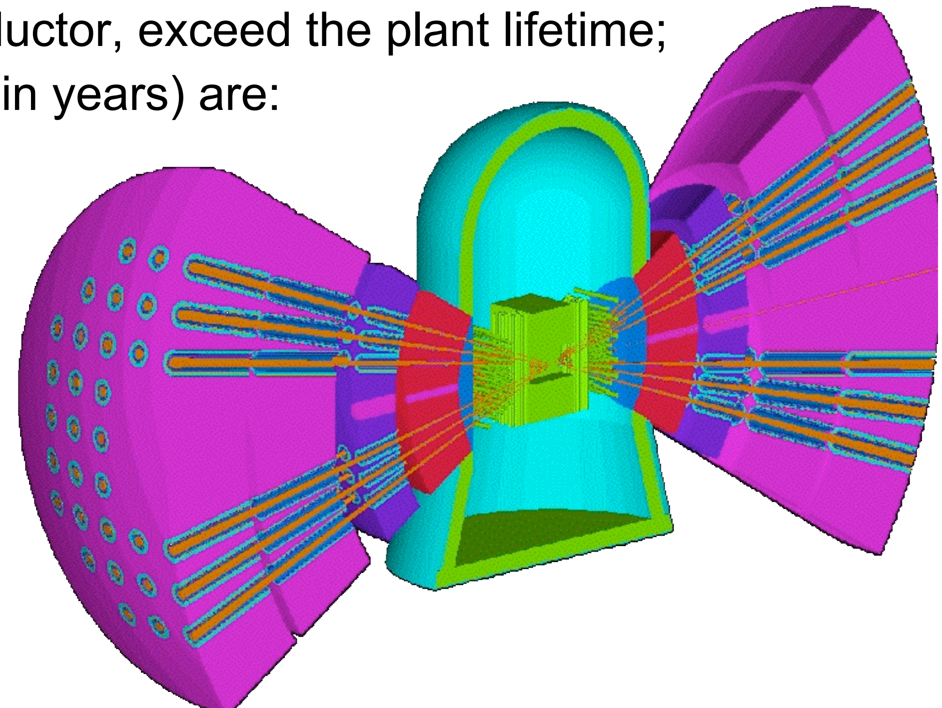
Final focus configuration uses four magnets



Magnet Lifetime: Sufficient material has been added to make the shielding & activation results very robust

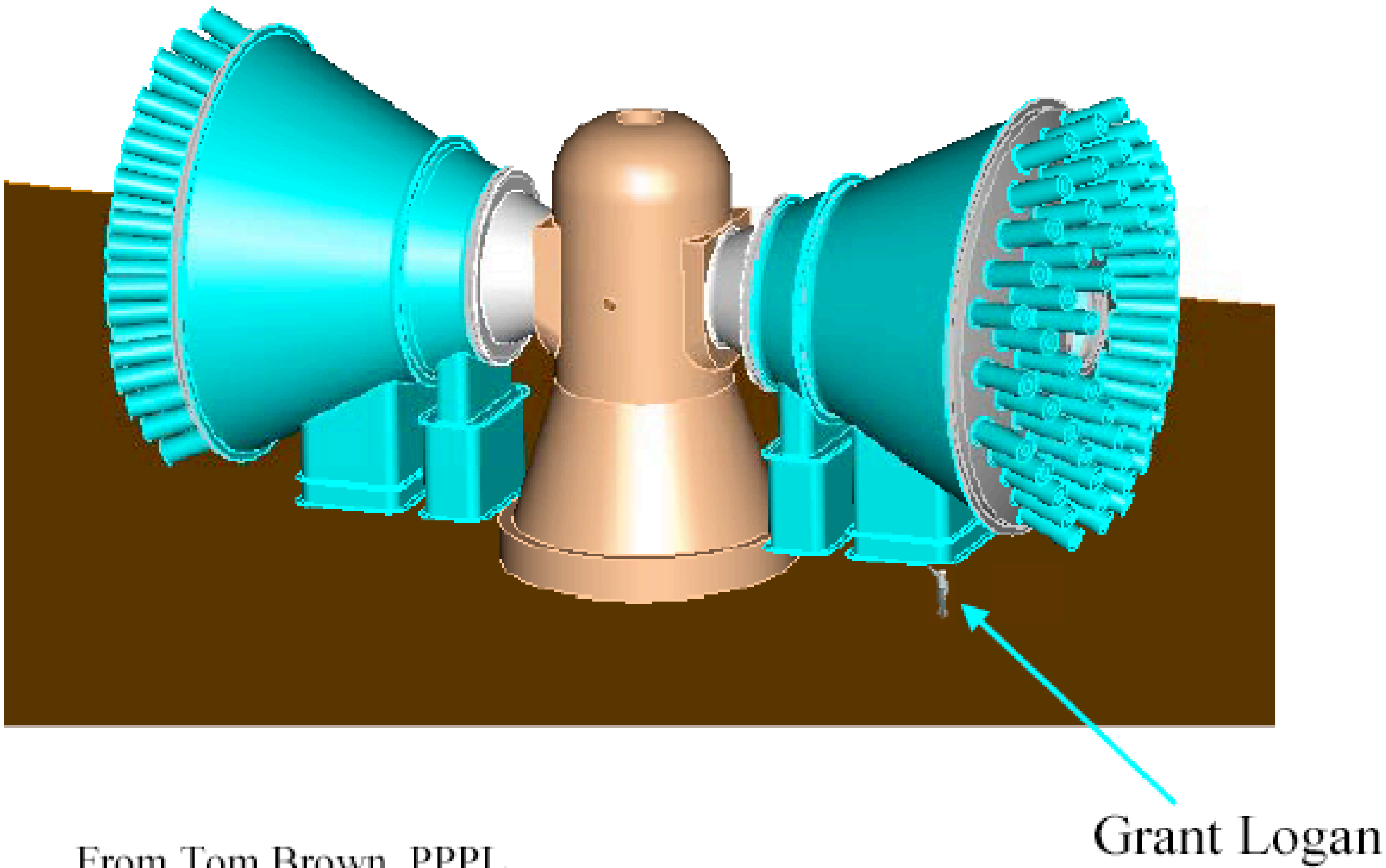
Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime; Insulator & superconductor lifetimes (in years) are:

- Last magnet: 230/260
- 2nd magnet: 410/1580
- 3rd magnet: 100/610



- Waste disposal ratings are significantly reduced from previous work: 1.7, 0.5, 0.4 (^{94}Nb)
- Increasing liquid stand-off distance in vortices (from 1→5 mm) will reduce lifetimes by ~2x
- Optimizing shielding to increase neutron effectiveness (at cost of gamma-ray shielding effectiveness) should enable all magnets to qualify for disposal as lowlevel waste; adequate margin exists for magnet lifetime to exceed plant life.

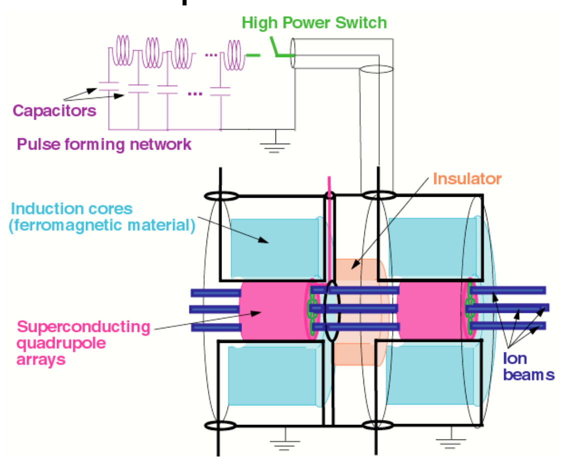
Illustration of final focus arrays is a real eye opener



From Tom Brown, PPPL

Example of critical physics issue: drift compression of bunch length by factors of 10 to 30

Induction acceleration is most efficient at τ_{pulse} ~100 to 300 ns



Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

Target capsule implosion times require beam drive pulses ~ 10 ns

Drift compression line

Final Focus

The beam must be confined radially and compressed longitudinally against its space-charge forces

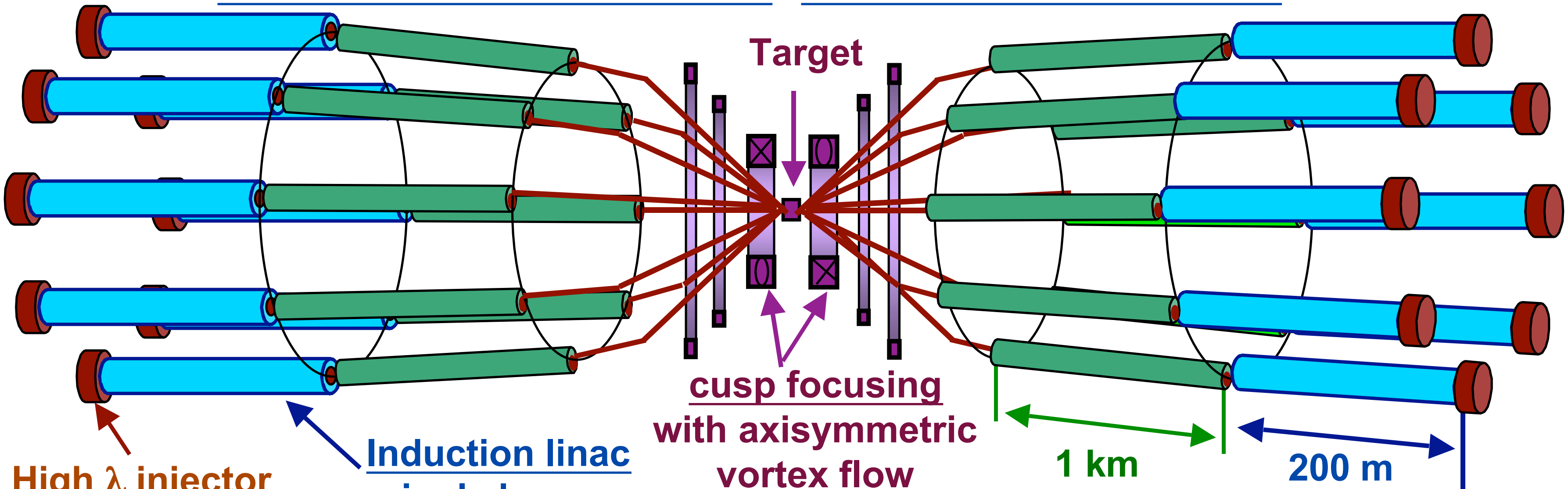
Issues that need more study and experiments:

1. **Matching beam focusing and space-charge forces during compression.**
2. **Beam heating due to compression (conservation of longitudinal invariant)**
3. **Chromatic focus aberrations due to velocity spread**

Modular Point Design Example: A 16 module, 1 beam/module solenoid focus option[1]

Pulse energy ~ 6.7 MJ

V~ 200-300 MV: T~ 2.5 GeV Xe^{+8} ions or T ~ 200 MeV for Ne^{+1}



High λ injector

Merging beamlet source/injector

or

accel/decel injector

Induction linac

single beams

r_p ~ 15 cm

B_s ~ 9T

I ~ 6.7 kA

T ~ 2.5 GeV

Δt ~ 100 ns

double pulsed for foot and main pulses

cusp focusing with axisymmetric vortex flow

or

adiabatic plasma lense assisted pinch with cross-jet flow. liquid walls

Neutralized drift compression

Δv/v ~ 0.01

(no space charge stagnation)

1. B.G. Logan, "A chamber integrated, ...multi-beam, heavy ion power plant ..," Draft, June 17, 2002.

Solenoids can transport high line charged density at beam low energies

Maximum transportable line charge density has a different scaling than quadrupoles on key quantities:

$$\lambda \approx \left(10\frac{\mu C}{m}\right)\left(\frac{\mathrm{B}}{10T}\right)^2\left(\frac{r_p}{10cm}\right)^2\left(\frac{133}{A/q}\right)\left(\frac{\eta}{1.0}\right)\left(\frac{a/r_p}{1.0}\right)^2$$

Advantage for large B, r_p,
Advantage for small A/q ($cf.$ extensive experience with e^- induction linacs)

Note λ is independent of energy , so very low energy transport is possible

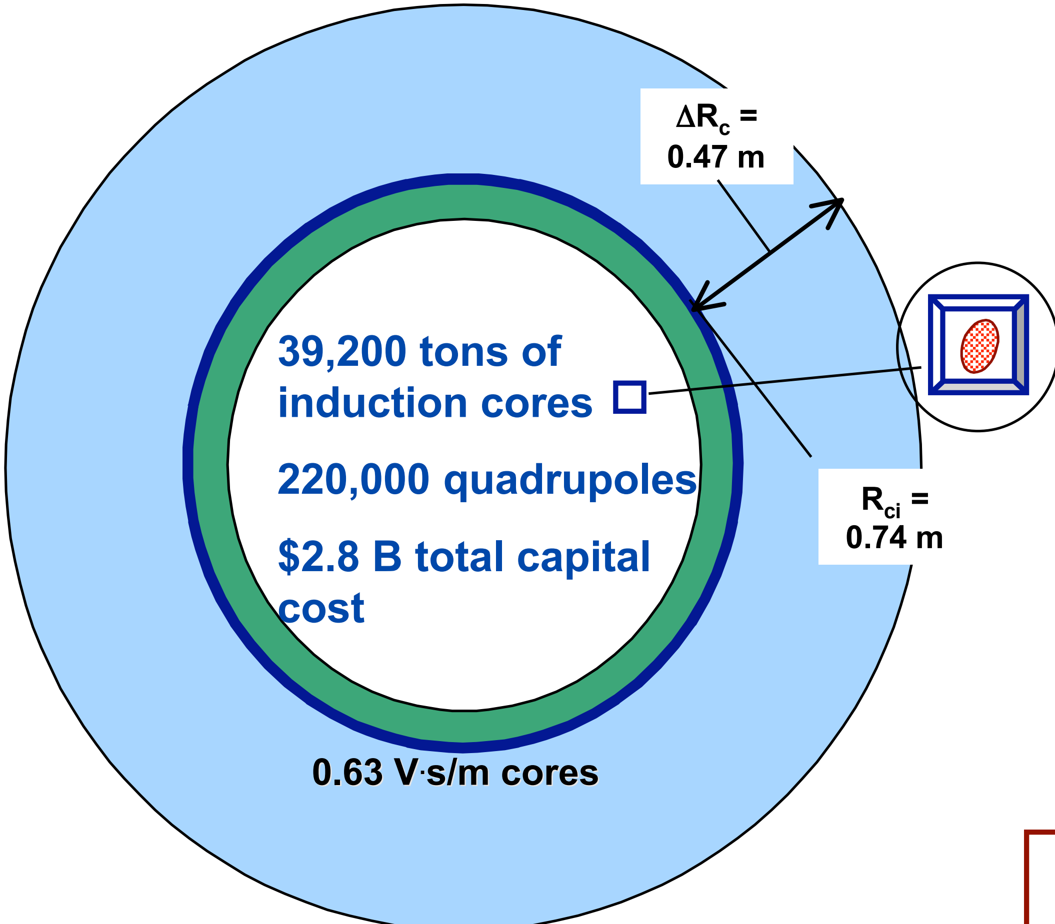
For magnetic quadrupoles,

$\lambda \sim (q/A)^{1/2}\beta\, r_p$, favoring small beams and high energy.

For electric quadrupoles,

$\lambda \sim$ independent of q/A, r_p, and β (except at very low energy when $\lambda \sim \beta^2$), favoring small beams and low (but not too low) ion energy and heavy ions

RPD and MPD accelerators have different scalings



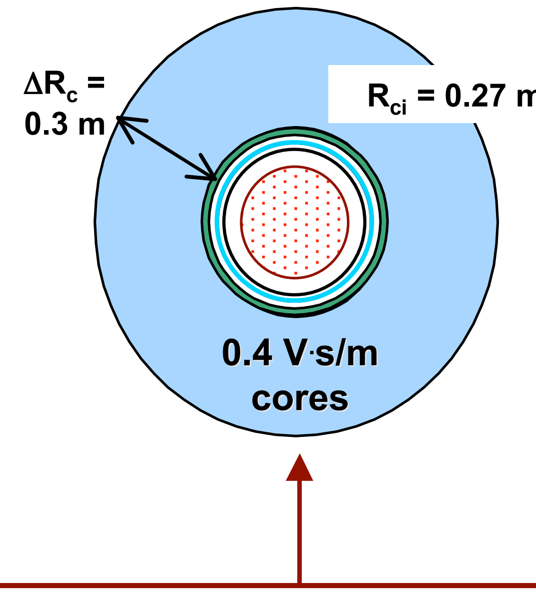
One 120-beam x 3 km

= 3 km total length of linac

7,000 tons of induction cores

4000 solenoids

$750 M total capital cost



16 single-beam modules x 200 m

= 3.2 km total length of linacs

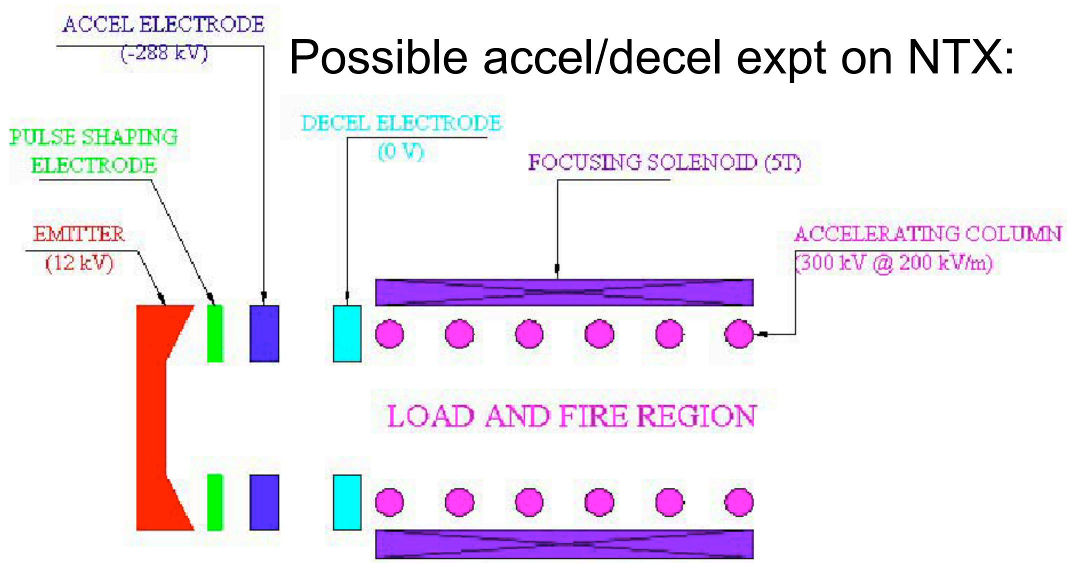
Injector Options

Three injector options have been suggested so far:

1. Standard injector with aggressive bunch compression within the accelerator. $\lambda \sim 0.25\ \mu$C/m compressed to ~ 25-60 μC/m requires large initial pulse duration. (May require high gradient to increase initial λ and minimize initial pulse duration.)

2. Accel/decel injector: Use high voltage diode to obtain large current; immediately decelerate, to reduce bunch length; use load-and-fire acceleration to rapidly decrease pulse duration and minimize core volume.

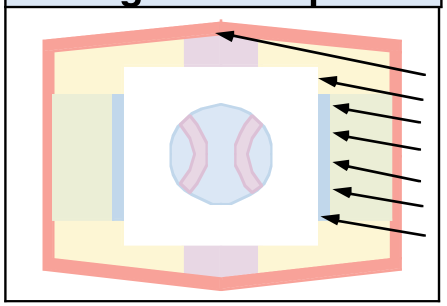
Possible accel/decel expt on NTX:



3. β=0 injector: Inject plasma into solenoid. Apply a longitudinal electric field to separate ions from electrons. Utilize velocity independence of solenoids to confine low velocity beam.

Target will be "hybrid" design, allowing larger focal spots[1]

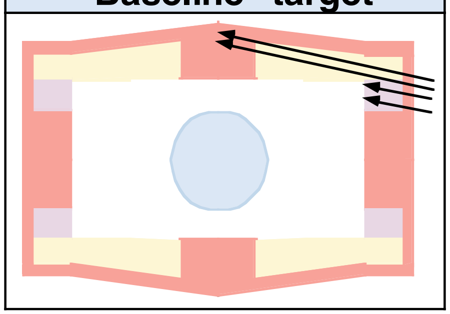
"Hybrid design" for Modular Point Design:



Spot radius: ~5.0 mm round (or ~5.4 x 3.8 mm elliptical)
Pulse energy: 6.7 MJ
Minimum 8 beams per side
Ion range equivalent to 4.5 GeV Pb (main) and
3 GeV Pb (foot)

New task: define the allowable velocity spread that maintains high target performance

In contrast, Robust Point Design used "Distributed radiator design"

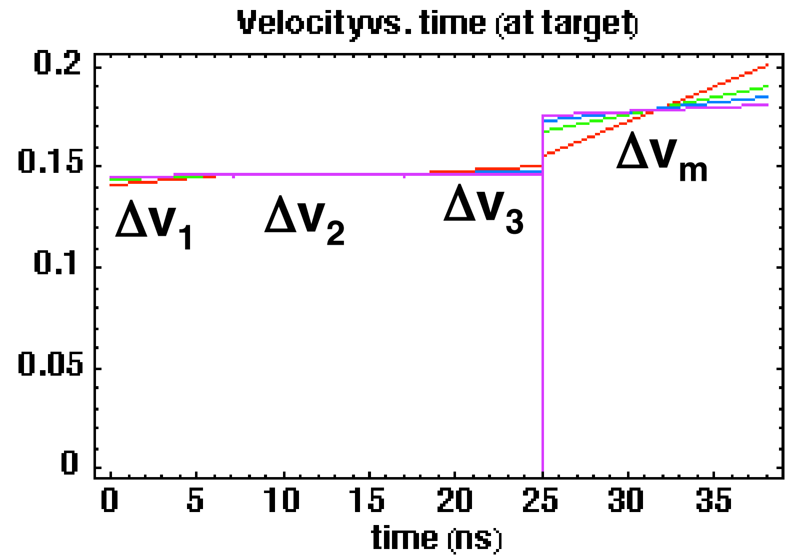


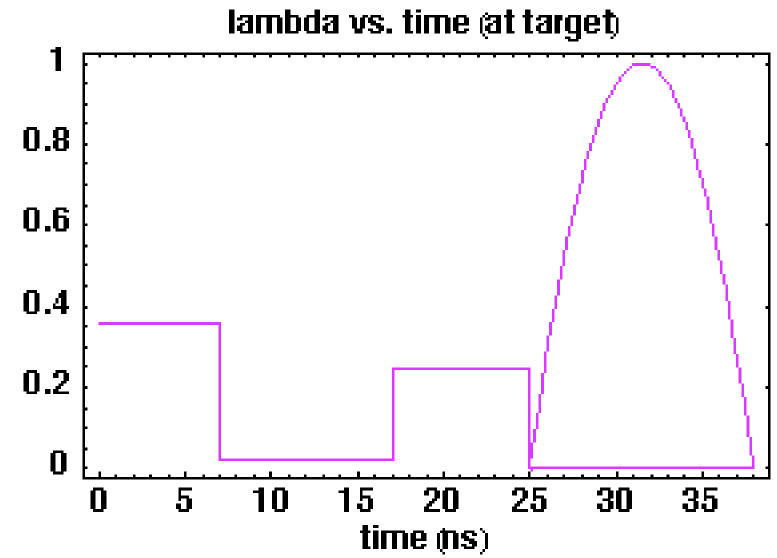
Spot radius: 1.8 mm x 4.2 mm (main)
Pulse energy: 6.5 MJ
Ion range equivalent to 4 GeV Pb (main) and 3.3 GeV (foot)

1. D.A. Callahan, M.C. Herrmann, and M. Tabak, Laser and Particle Beams, *20*, 405 (2002).

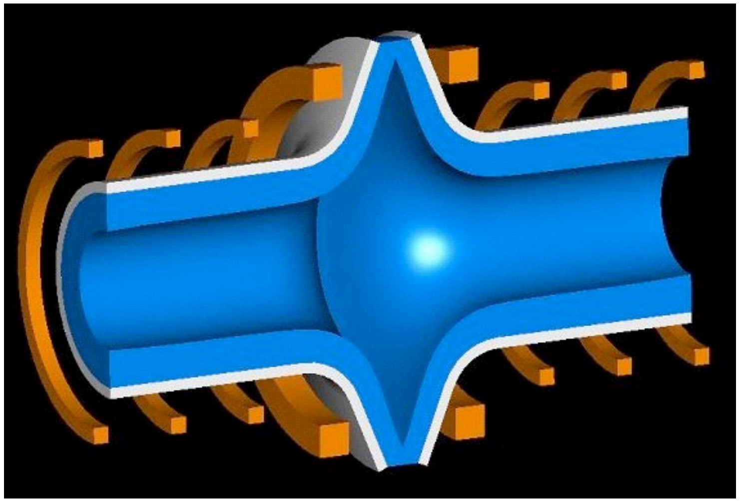
The drift length for NDC is determined by how much velocity tilt the target can accomodate

Drift length	$\Delta v_1 / v_1$	$\Delta v_m / v_m$
134 m	.037	.256
268 m	.0188	.128
536 m	.0095	.0638
1032 m	.0048	.0319



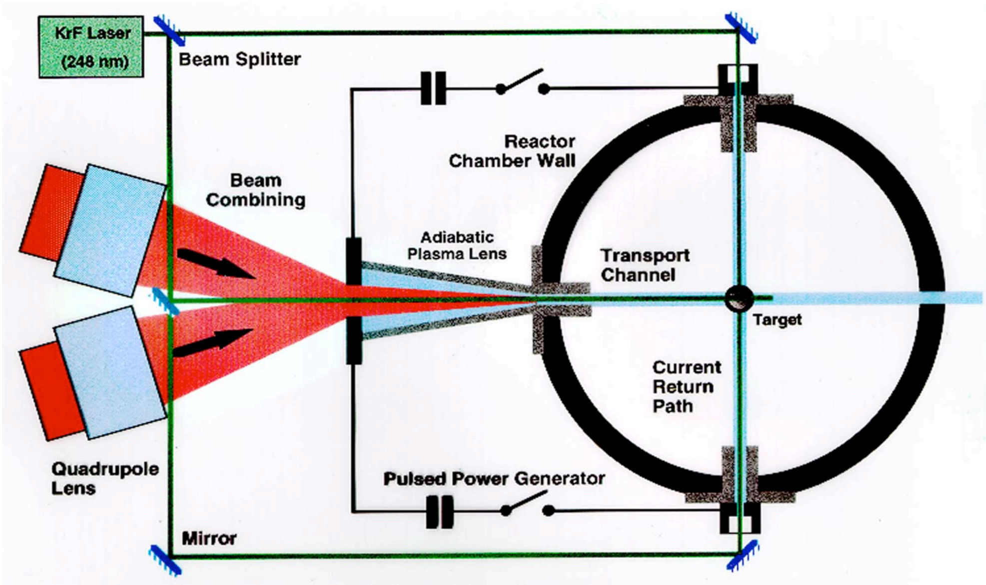


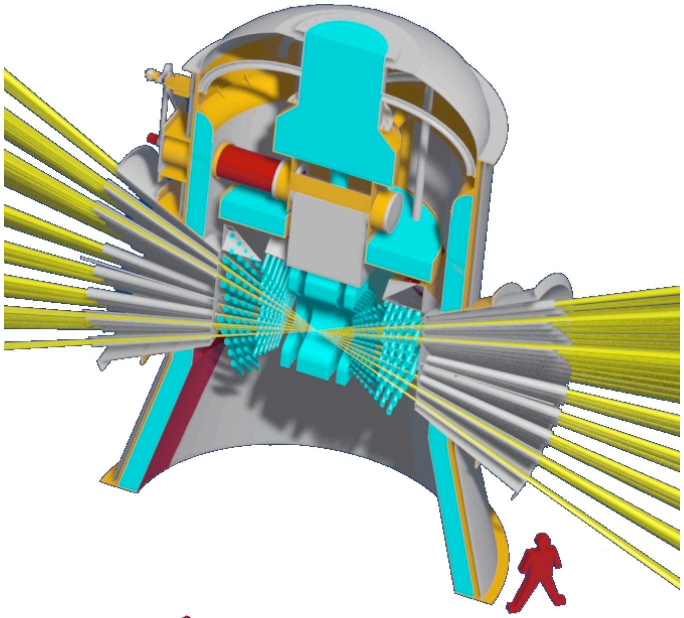
Chamber Options



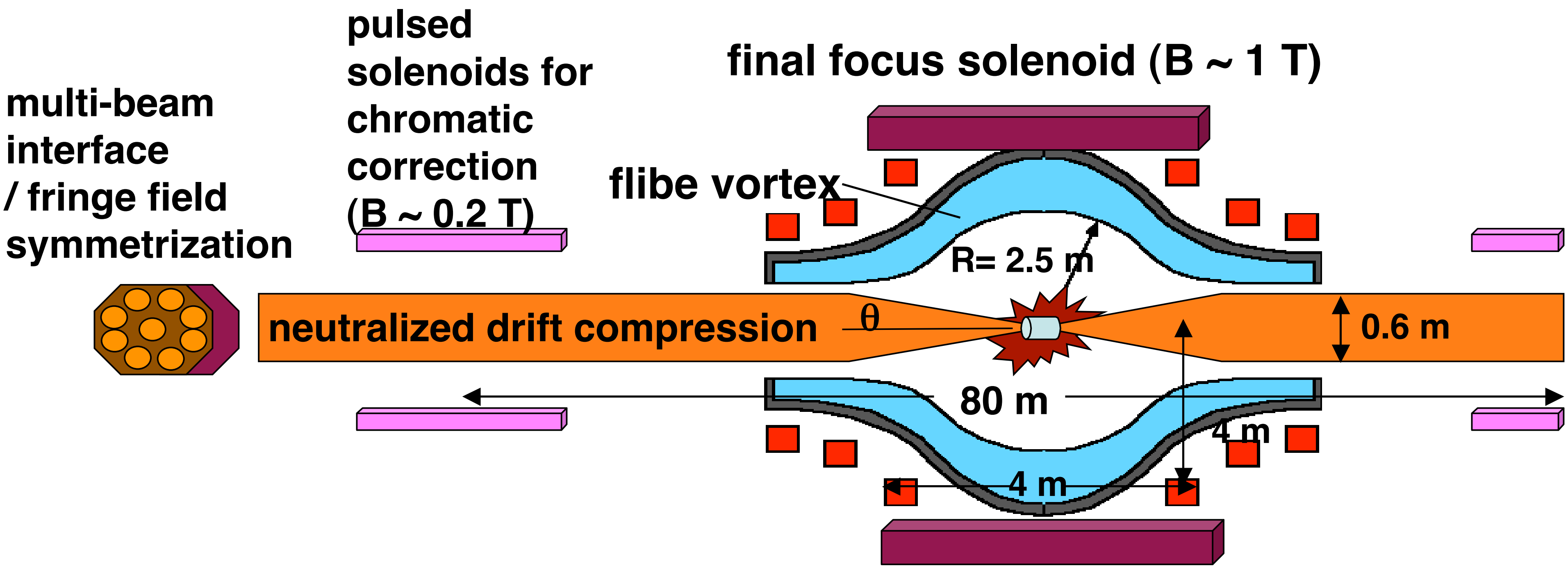
Vortices with liquid FLiNaBe or FLiBe serving as wall protection, and heat absorbing fluid, may be well suited for cusp or solenoidal focusing options (upper left).

Hi-life-like chamber protections schemes (as in the RPD design, lower right) may be extendable to assisted pinch designs (lower left)





A solenoid-based final focus system for a modular driver has attractive features

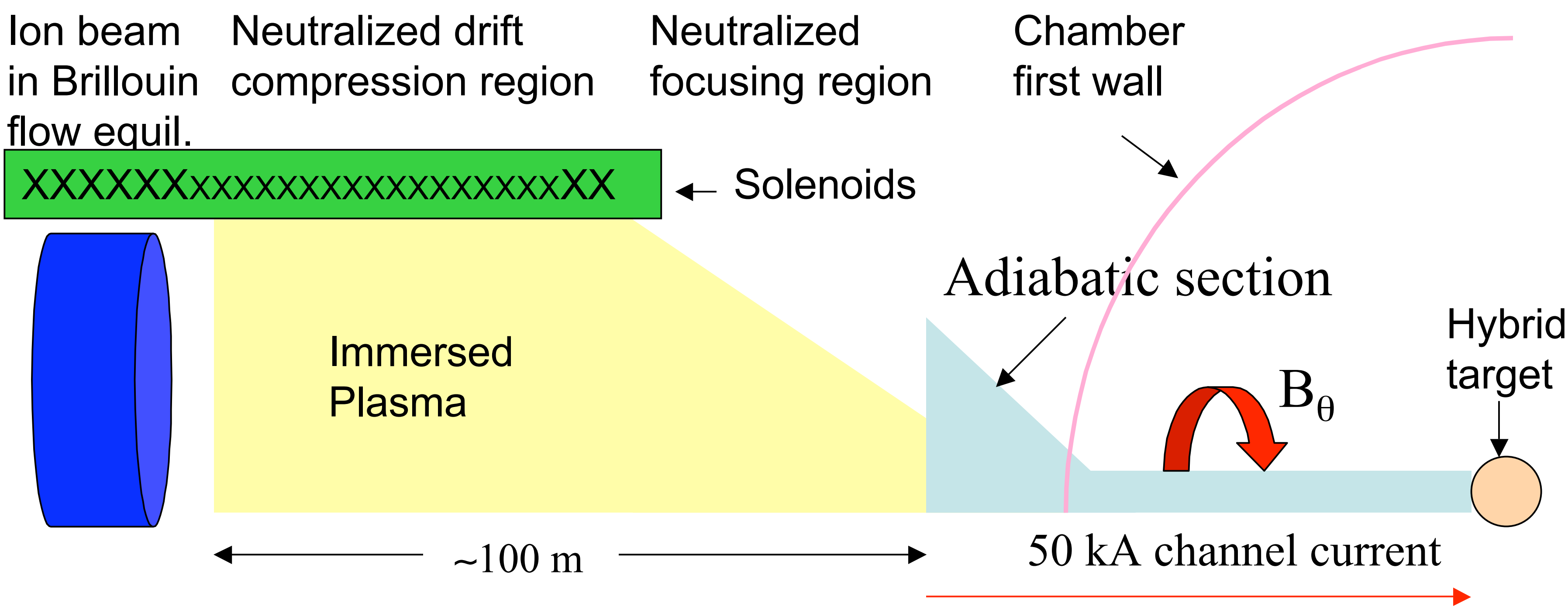


- Large cone angle θ ~ 100 mr produces a small spot (~ 5 mm) on target for $\varepsilon \sim 4\times10^{-4}$ m-rad
- Moderate fields allow normal magnets
- Highly stripped ions (200-300 MeV Ne^{+10})
- Fringe field aberrations minor

Self-consistent target / chamber / drift compression: an example

Hybrid Target	Solenoid / NDC	Assisted Pinch
Pulse shape Range shortening	Controlled by initial velicity shaping at entrance to NDC Beam at exit of NDC maintains initial velocity tilt	Independent of Beam current Can accommodate large energy variations
Spot size (~5mm radius)	Driver optimized with high Q/M Some stripping can occur in NDC	Tighter focusing with high Q/M Insensitive to Z-variation
Symmetry	Few beam driver	Anharmonic focusing in Z-pinch symmetries
Shallow entrance angle	Nearly parallel beamlines	Beam merging in adiabatic lens

An integrated PIC Simulation (LSP) from Accelerator Exit to Target Demonstrates 92% energy deposition within required 5mm spot



The RPD and MPD have distinctly different architectures

Driver components	RPD (M beams M=120)	MPD (N modules N=10-20)
Accelerator/Pulse Power System (PPS)	1 accelerator/1PPS	N accelerators/1PPS
Ion species	Heavy - Bi (Xe possible)	Medium (Ne to Ar)
Injector	M compact injectors	N high λ injectors
Transport	Multiple quad array for M beams	Solenoid/hybrid (1 solenoid/module)
Drift Compression	M vacuum drift compression beamlines	1 Neutralized drift compression beamlines/module
Final focus / chamber transport	Quad focusing / neutralized ballistic transport	Solenoid in plasma or assisted pinch
Chamber	HYLIFE II	Vortex chamber or modified HYLIFE
Target	Distributed Radiator Target With Large Angle	Hybrid Target

Summary

- An HIF driver point design must be an integrated system that is self-consistent from injector to target
- The Robust Point Design (RPD) is an integrated system based on a single accelerator with multiple beams
- Ongoing Modular Point Design (MPD) study seeks a self-consistent integrated solution based on 10-20 accelerator modules with single beam/module

BACKUP

A 7 MJ induction linac driver using Bi+ is the baseline

	Along Accelerator		
	Injector Exit	Ti – 3.3 GeV	Ti – 4.0 GeV
Ion energy, GeV	0.0016	3.3	4.0
Pulse duration, μs	30	0.2	0.2
Ion speed/light speed	0.004	0.18	0.20
Pulse length, m	36.5	10.9	12.0
Beam current, A*	0.63	94	94
Beam radius, cm*	3.8	1.9	1.9
Bore radius, cm	5.3	2.9	2.9
Field gradient, T/m	62	106	106
Core inner radius, m	1.29	0.77	0.62
Core build, m	0.48	0.47	0.47
Quad Occupancy, %	0.75	0.090	0.075
Half lattice period, m	0.30	3.83	4.43
Acc. gradient, MV/m	0.026	1.5	1.5
Dist. from injector, km	0	2.39	2.86
*For max current beams (Block E)			

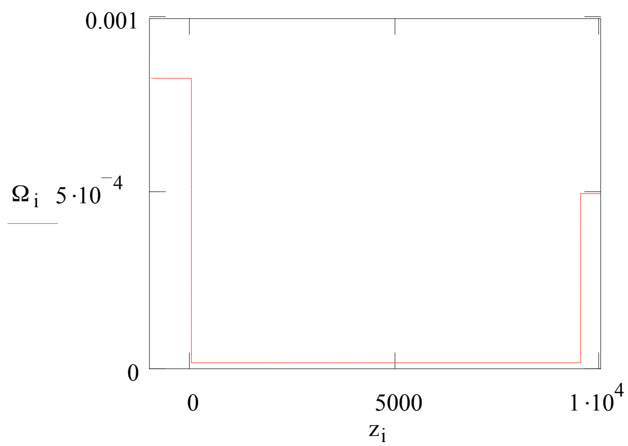
Accelerator parameters at:

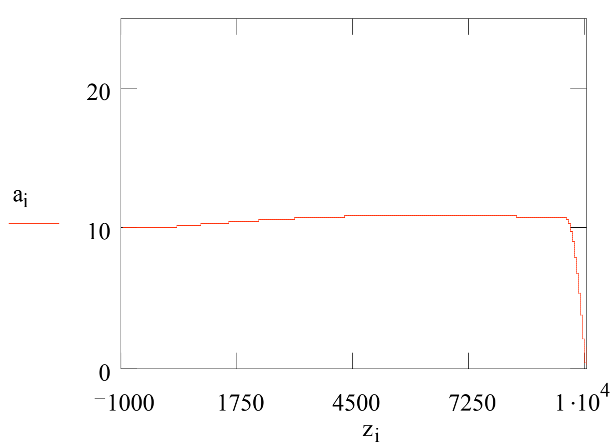
- Injector
- Foot pulse final energy (3.3 GeV)
- Main pulse final energy (4.0 GeV)

- Ion = Bi+ (A = 209 amu)
- Length = 2.9 km
- Driver efficiency = 38%
- Total cost = $2.8B

147 J beam energy transport design with 105 m drift length

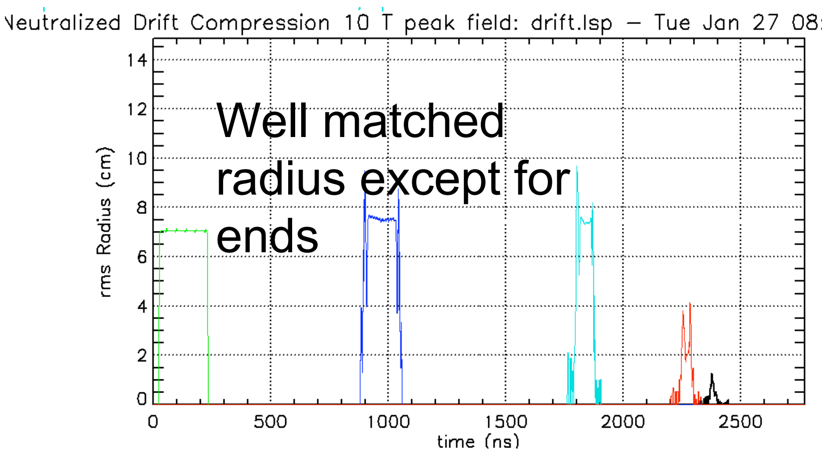
- 3.35-kA, 10-cm, 8-mm-mrad, 231-MeV, 210 ns Ne^{+1} beam (147 kJ) with a 20% perfect energy tilt to axially focus at L=104.5 m
- Injected Billouin Flow equilibrium into 10 T
- Transition to neutralized drift ($\sigma=10^{12}\ s^{-1}$) with .14 T at z = 2.4 m
  - $n_p/n_b = 10$, $r_L/\lambda_{sd} \approx 0.01 \ll 1$ (no self fields)
- 5 kG dipole field at 2.2 m, no plasma electron transport
- Focusing solenoid at 90-100 m (2.7 T)
- 50-kA, discharge channel z>101 m: 2-0.5 cm radius in 1.5 m adiabatic channel; 3-m long, .5-cm radius straight channel

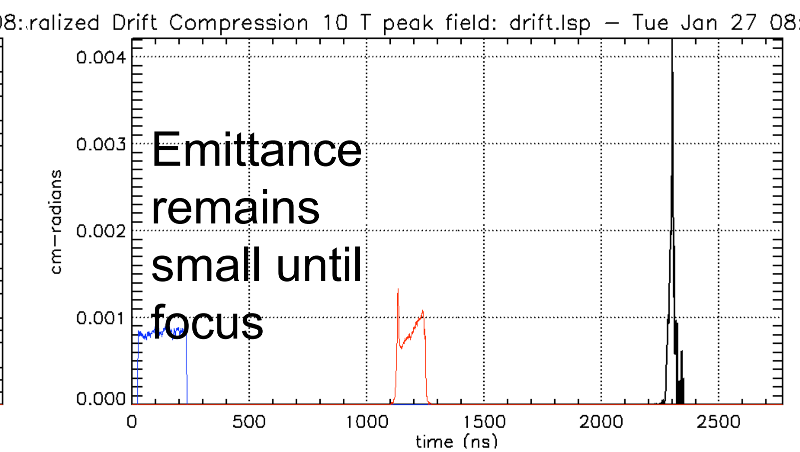


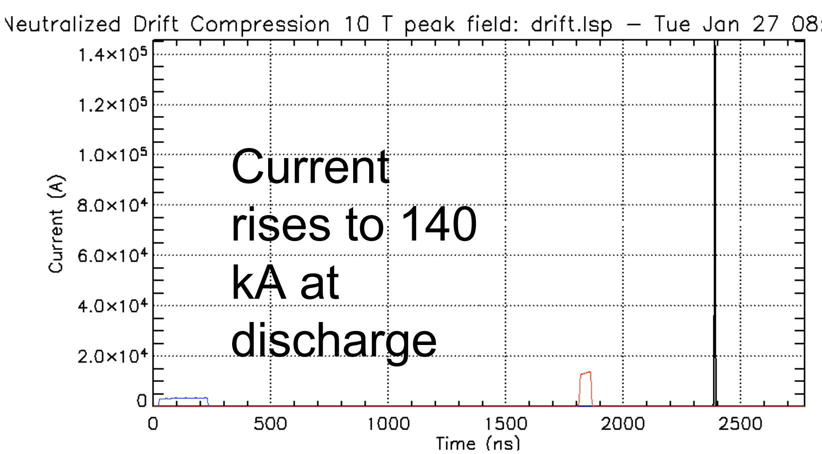


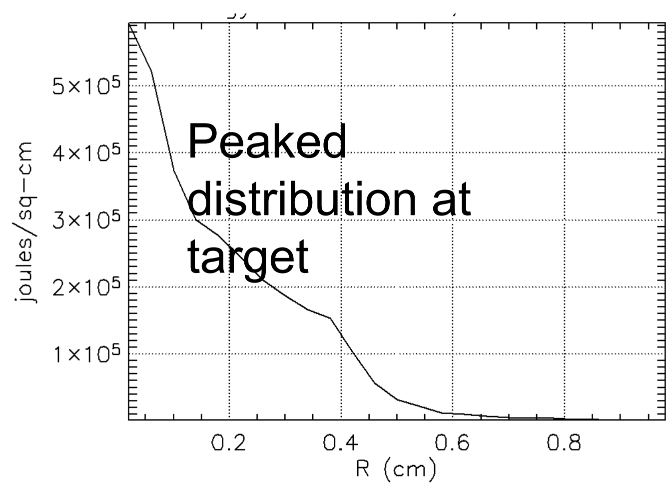
Good energy transport to target

- 92% of 147 kJ energy strikes target within 5 mm radius
- Halo forms from lack of “ears” and due to filamentation (s model dependent)



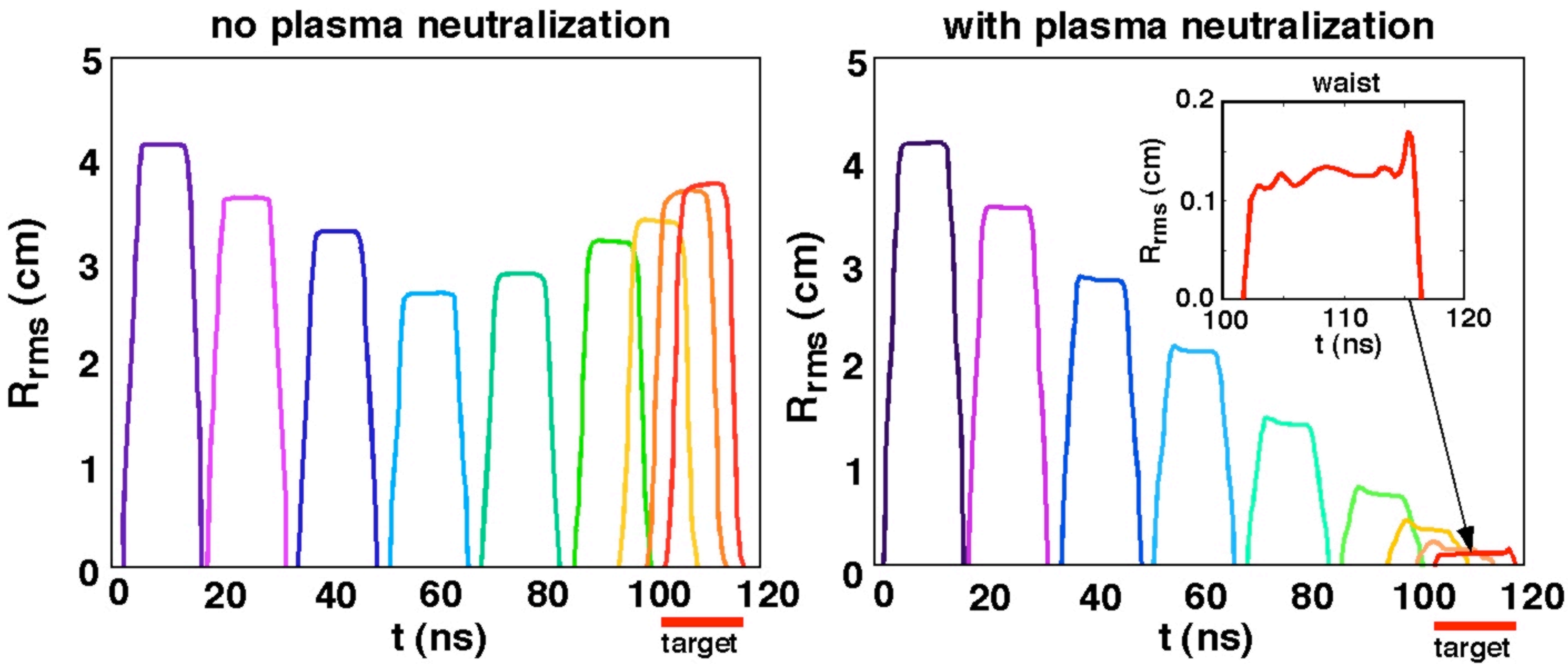






Neutralization of beam space charge in fusion chamber is critical to focusing of driver beams

Plots show 3.2-kA beam of singly charged 2.5-GeV xenon ions
Beam radius vs time is shown at selected points over a 6-m focal length



Without plasma neutralization, the ion kinetic energy would have to *triple* to recover the 2-mm focal spot for the target, increasing the linac voltage, length, and cost