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The Modular Approach to Heavy Ion Fusion

By

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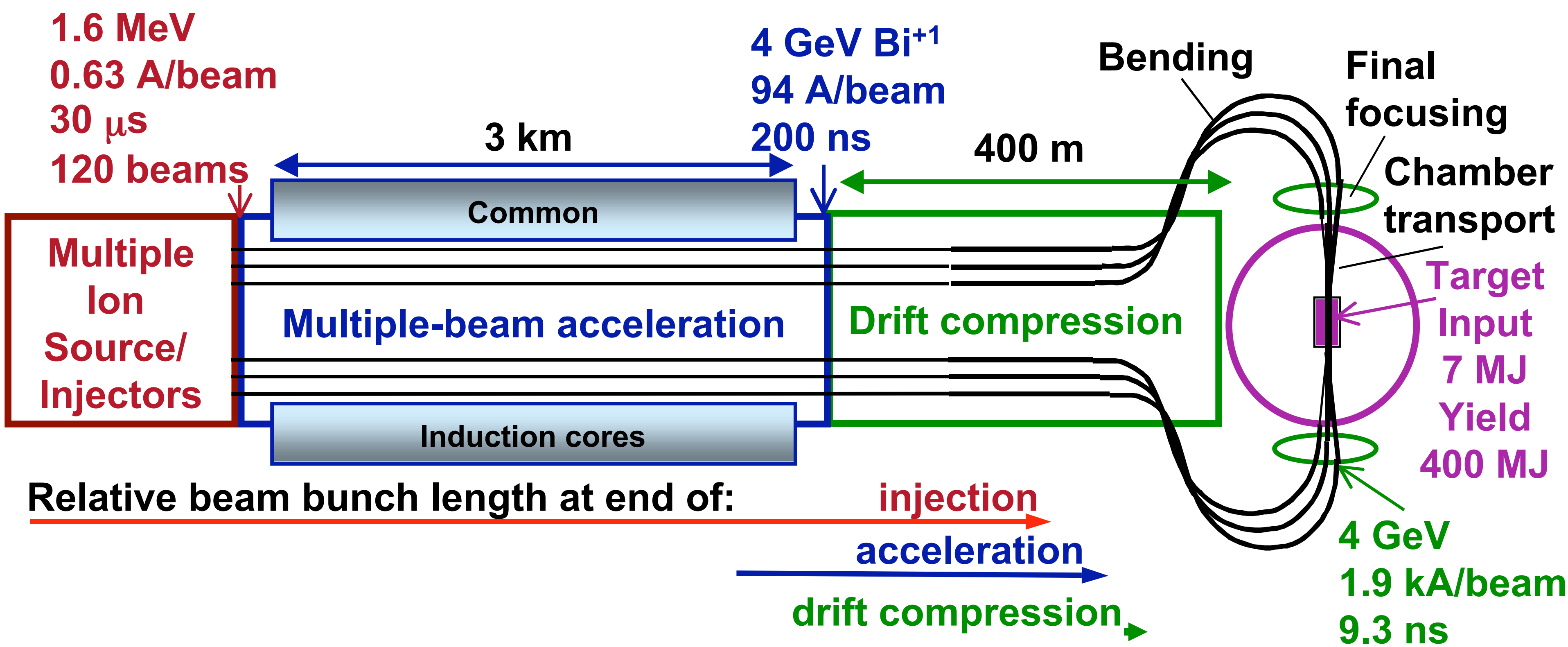
Summary

- The new approach to Modular Heavy Ion Fusion Drivers offers possibilities of architectural simplicity, direct development path, and perhaps lower cost.

- New technical concepts to accommodate high line charge densities are studied by simulations and a two year plan for scaled experiments (NDCX-I , FY05-6)

- The same technical approach can lead to near-term applications in High Energy Density Physics.

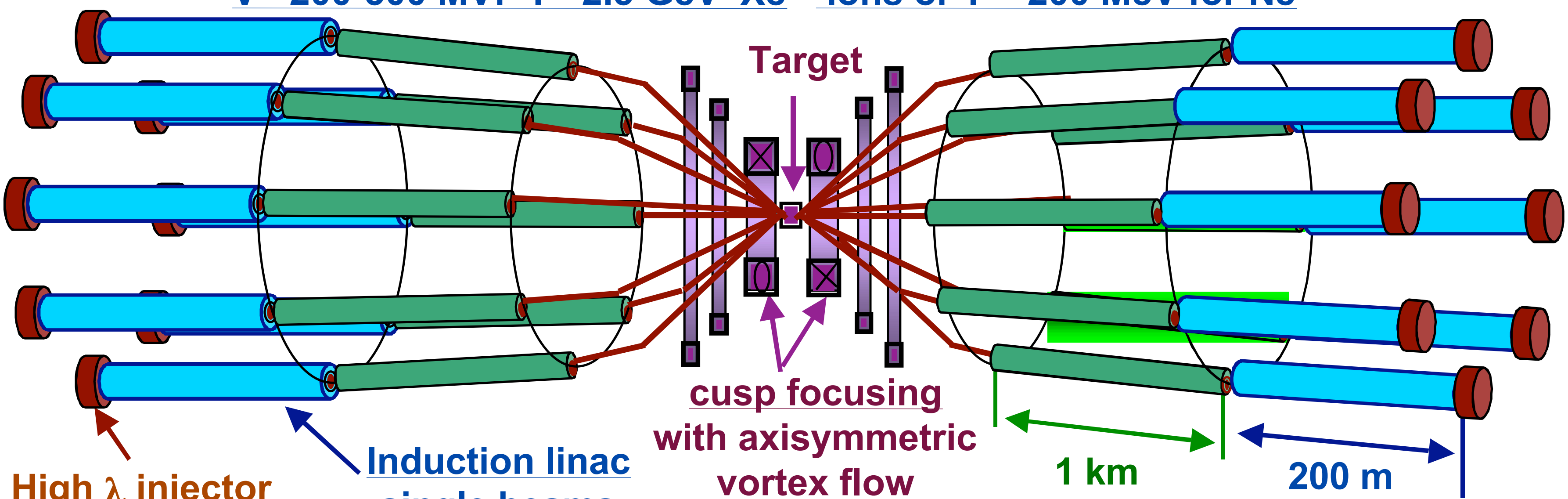
A Robust Point Design study established a baseline for a multiple-beam quadrupole induction linac HIF driver



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

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 lens 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.

High Line Charge Density requires new innovations for the Modular Point Design

- Transport
- Drift Compression
- Injector
- Target
- Final Focus and Target Chamber
  – Solenoid focusing and vortex chamber
  – Assisted pinch

Solenoids can transport high line charged density at low beam energies

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

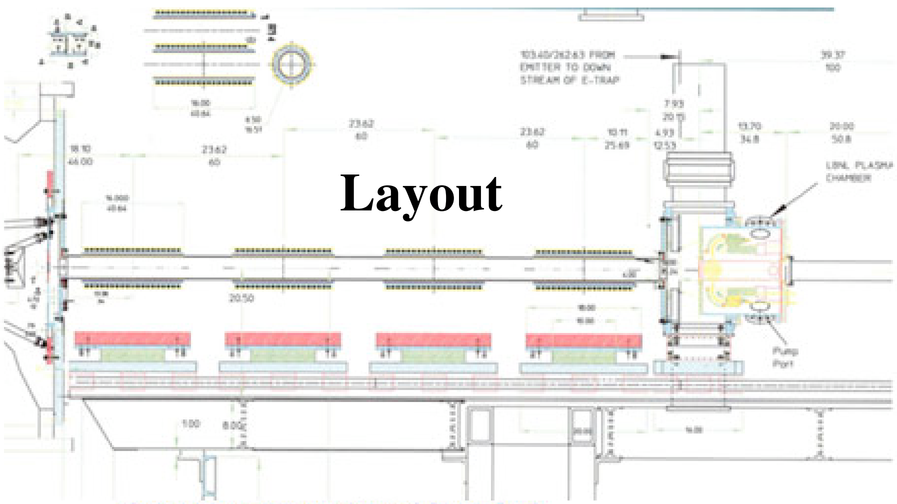
$$\lambda \approx \left(10\frac{\mu C}{m}\right)\left(\frac{B}{10T}\right)^2\left(\frac{r_p}{10cm}\right)^2\left(\frac{133}{A/q}\right)\left(\frac{\eta}{1.0}\right)\left(\frac{a/r_p}{1.0}\right)^2$$

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

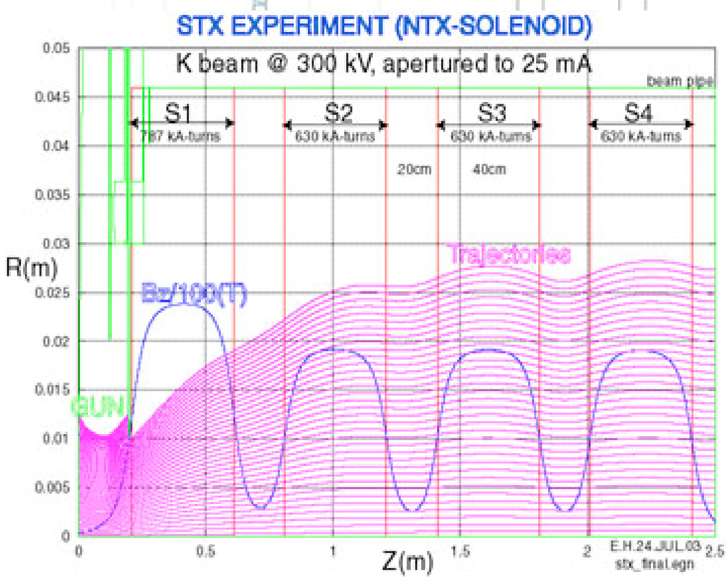
Note λ is independent of energy , so very low energy transport is possible

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

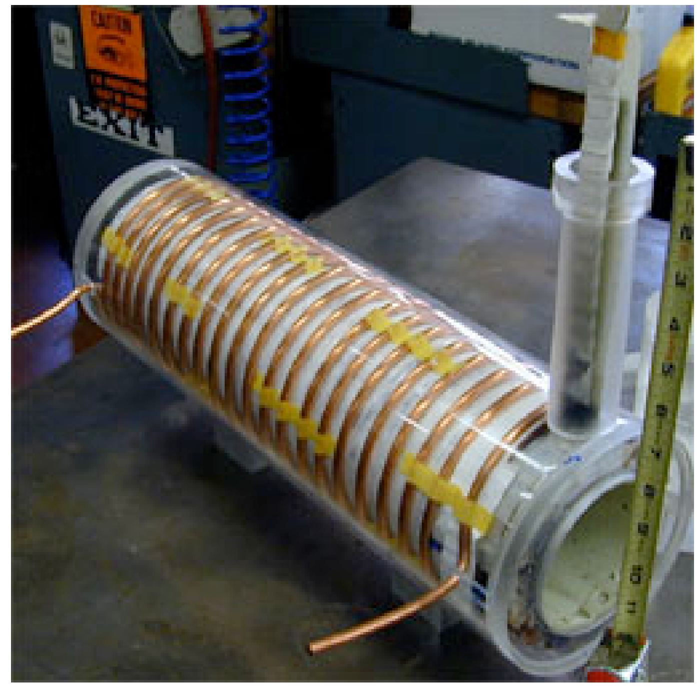
The Fundamental Scalings of Solenoid Transport will be tested in a scaled experiment (NDCX-Ib) in FY05



Layout



Simulation



Solenoid

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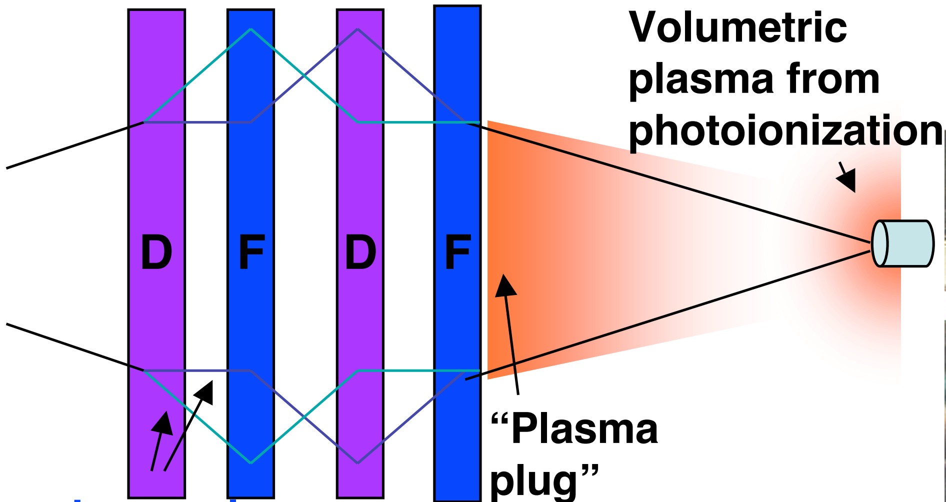
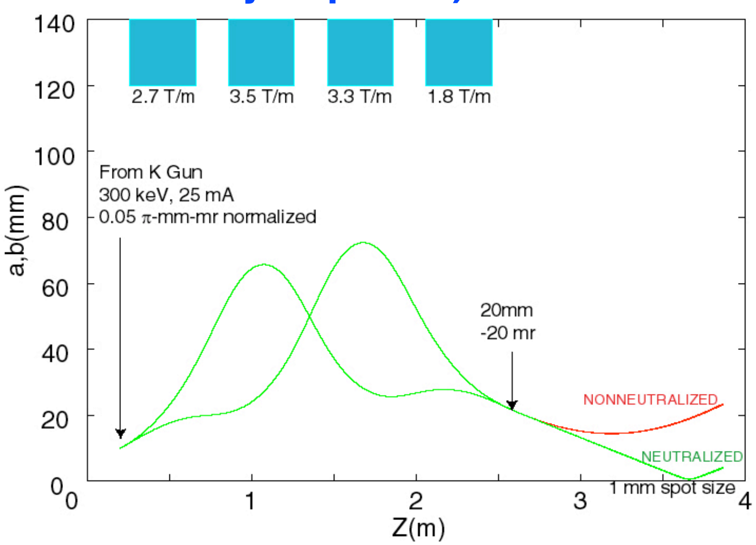
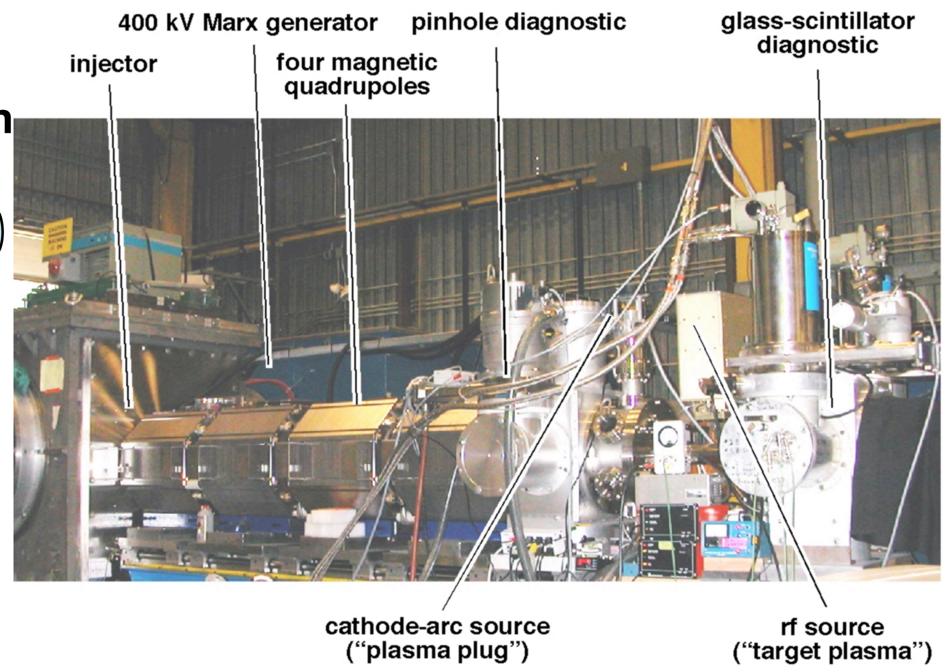
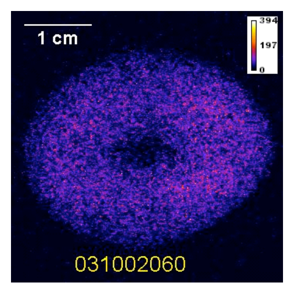
The Neutralized Transport Experiment (NTX) has demonstrated significant reduction of spot size with plasma neutralization



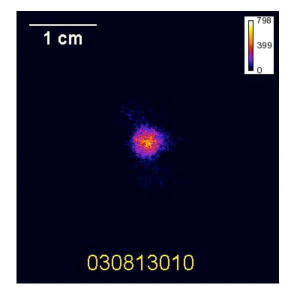
x and y envelopes (schematically depicted)





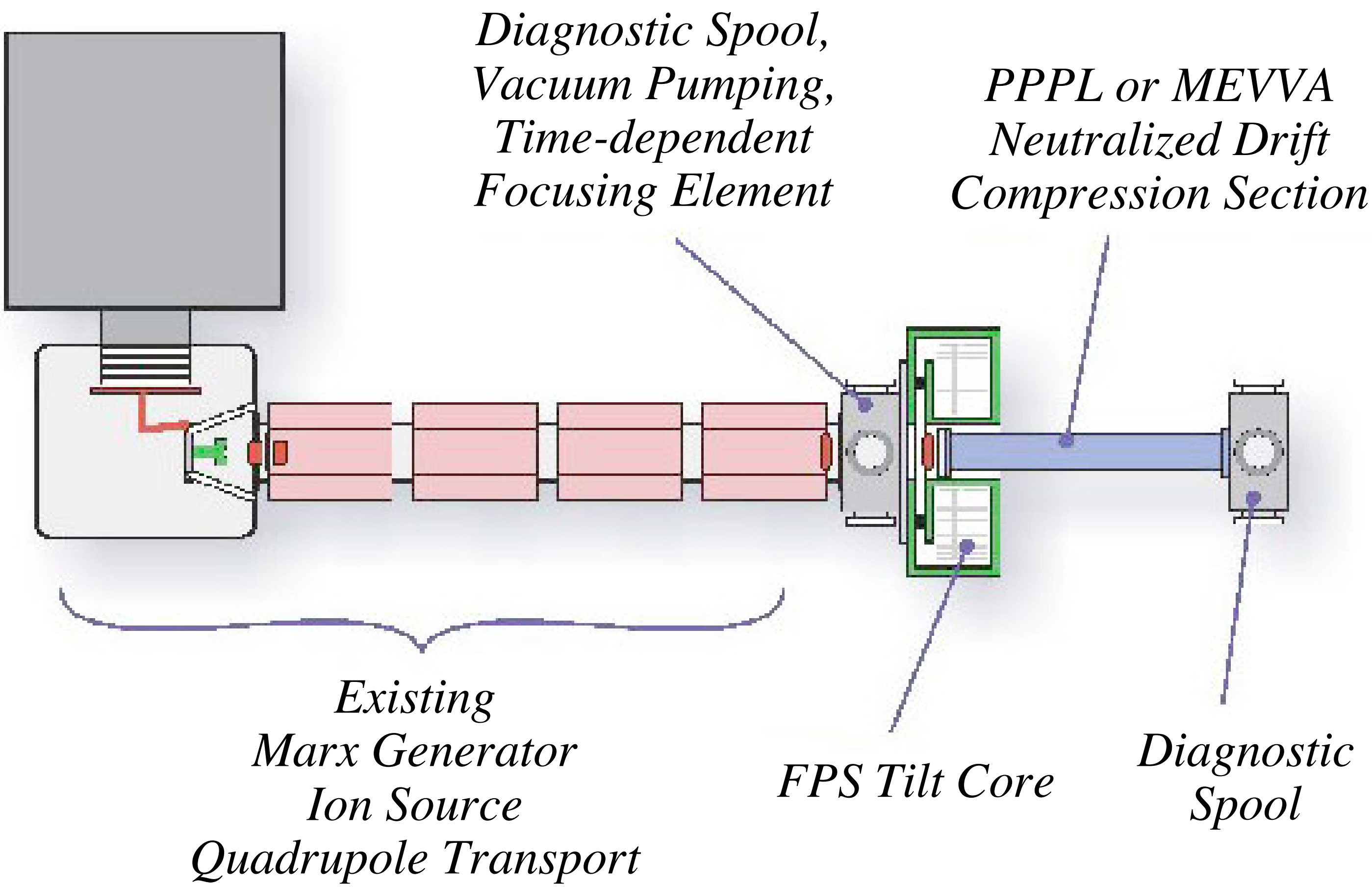


Non-neutralized FWHM=27 mm

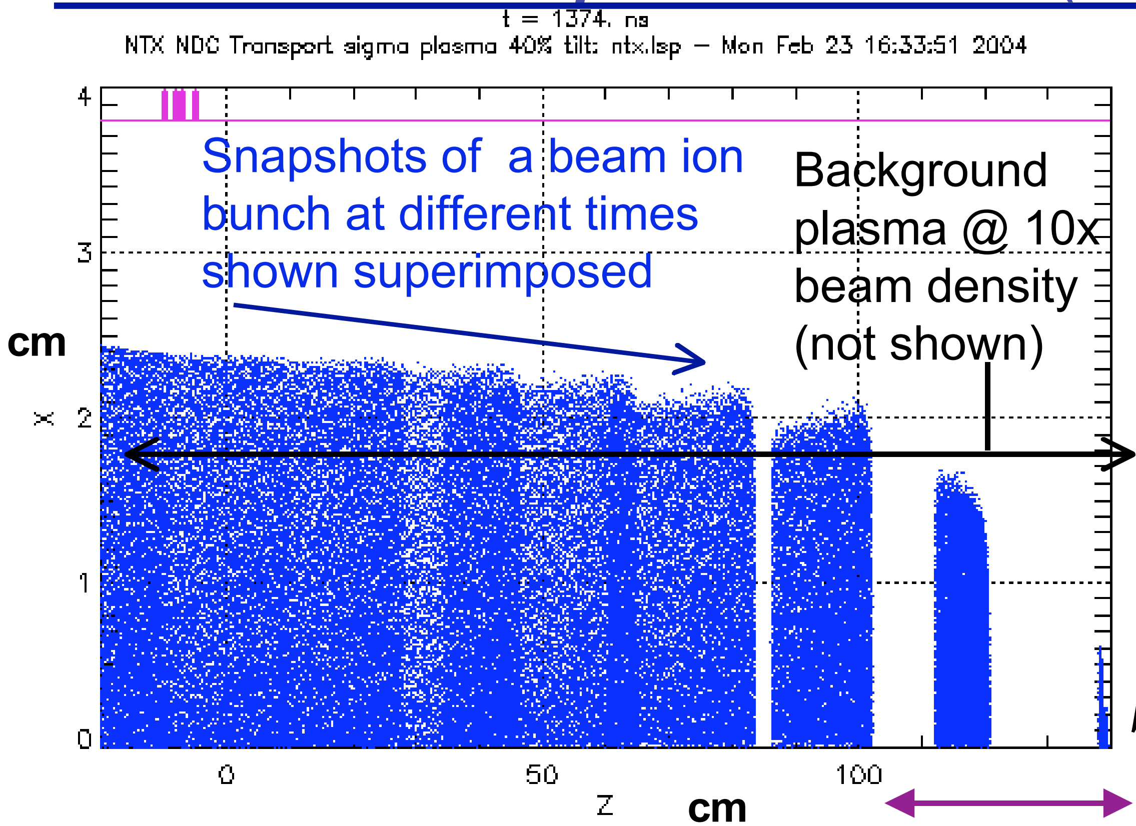


Neutralized FWHM=2.1 mm

First Neutralized Drift Compression Experiment (NDCX-Ia)



Preliminary LSP-PIC simulations of proposed NTX experiment show dramatically larger compressions of tailored-velocity ion beams *inside a plasma column* (Welch, Henestroza, Yu 3-11-04)

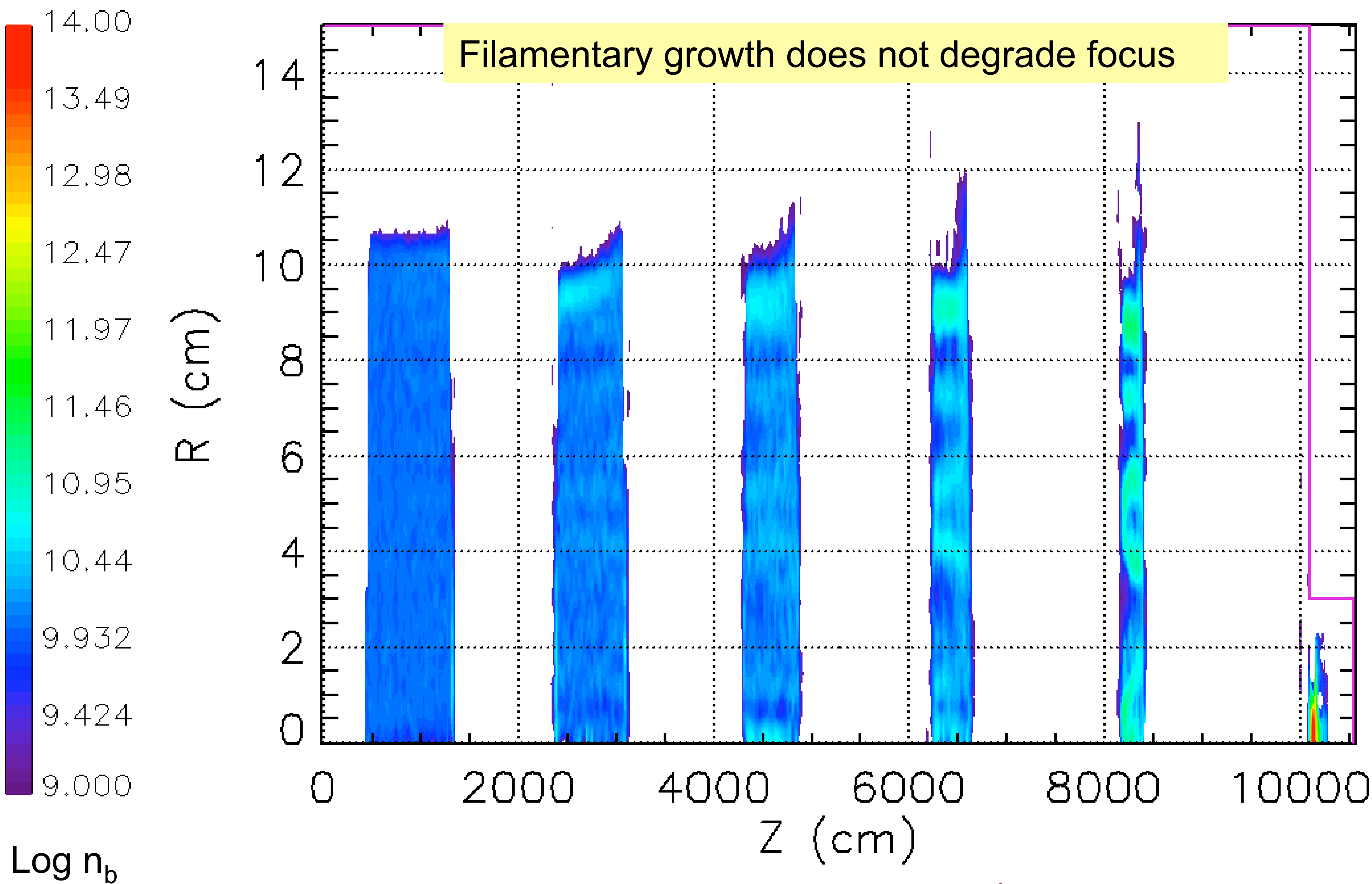


Ramped 220-390 keV NTX K^+ ion beam injected into a 1.4-m -long plasma column:

- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X*.

- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with $n_p >> n_b$, and B_z field (Welch, Rose, Kaganovich)**

A 100 -m LSP Simulation of Neutralized Drift Compression for a Modular Driver



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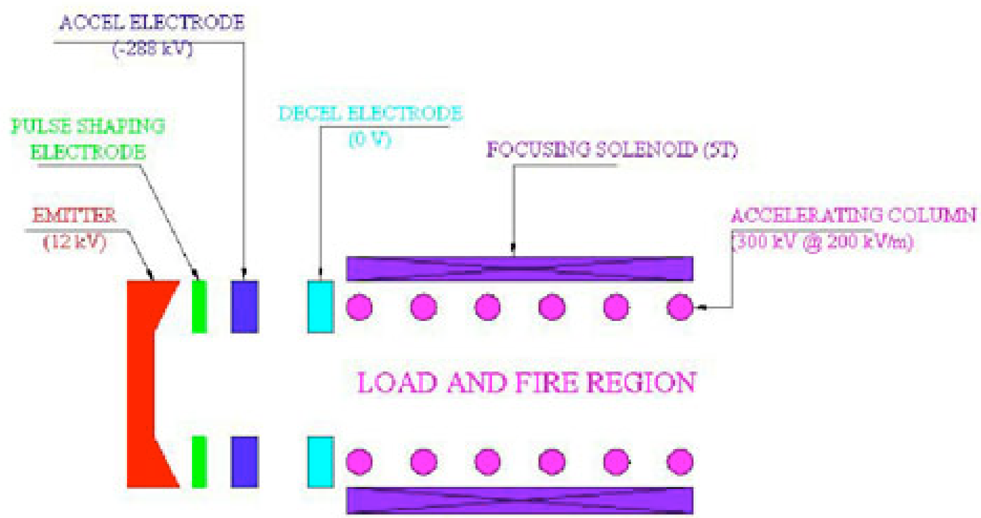
A High Line Density Injector will be tested

Three injector options have been suggested so far:

1. Standard injector with aggressive bunch compression within the accelerator. λ ~ 0.25 μC/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.)

Possible accel/decel expt on NTX:

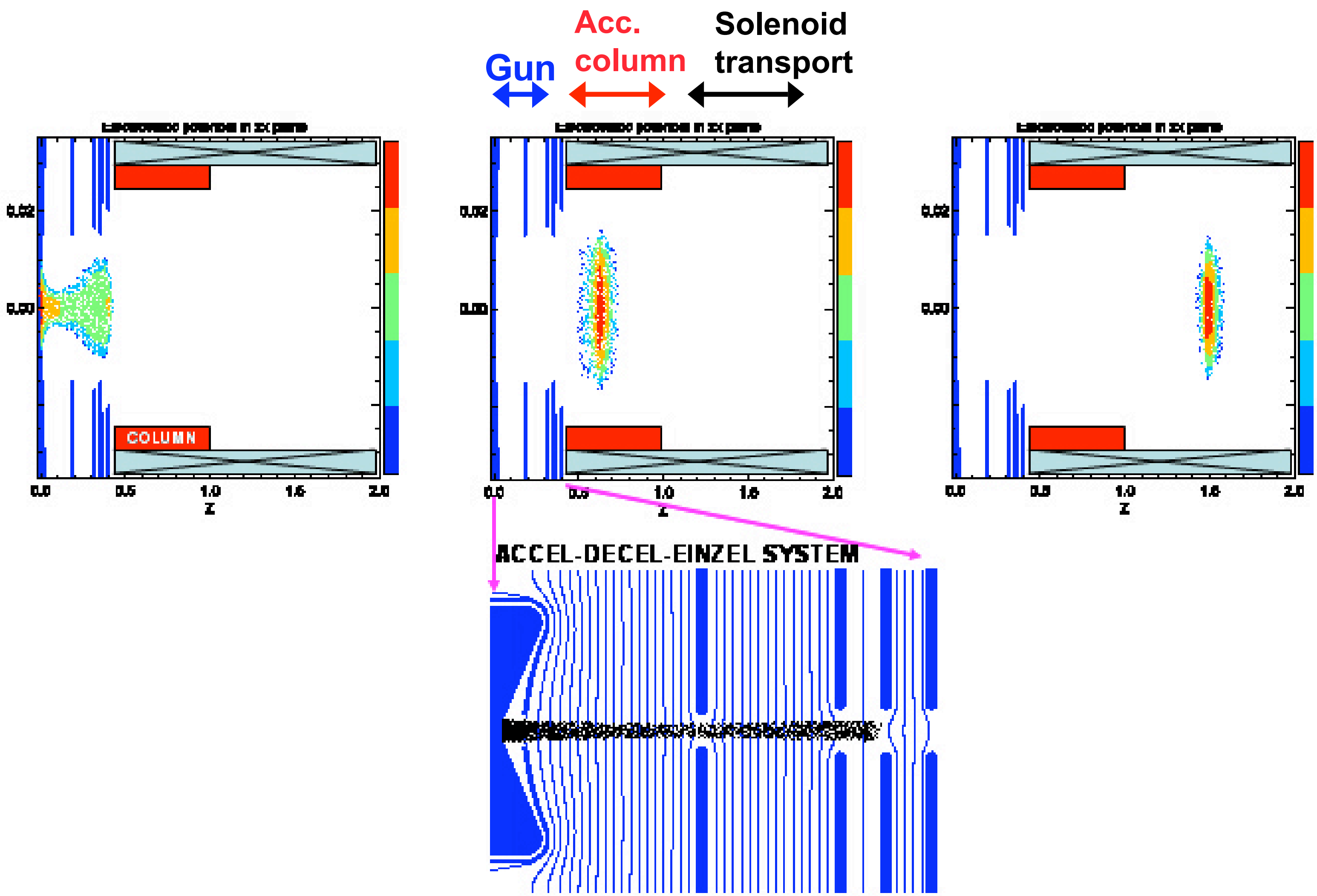
2. Accel/decel injector: Use high voltage diode to obtain large current; immediately decelerate, to reduce bunch length; use load-and-fire acceleration to rapidly decrease pulse duration and minimize core volume.



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.

Simulation of a scaled experiment of a High Line Density Injector (NDCX-1c)

(Fully Self-Consistent WARP3D Calculation of an ACCEL-DECEL-LOAD-AND-FIRE SYSTEM)



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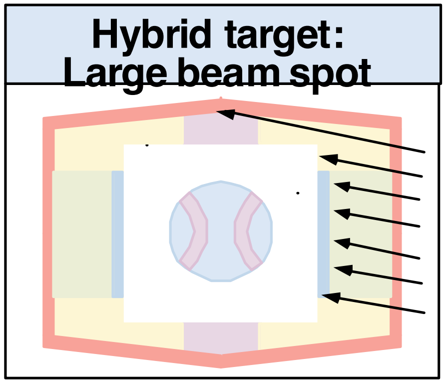
Target will be "hybrid" design, allowing larger focal spots[1]

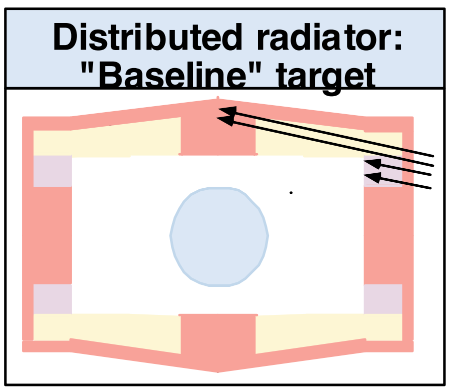
"Hybrid design" for Modular Point Design:



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"

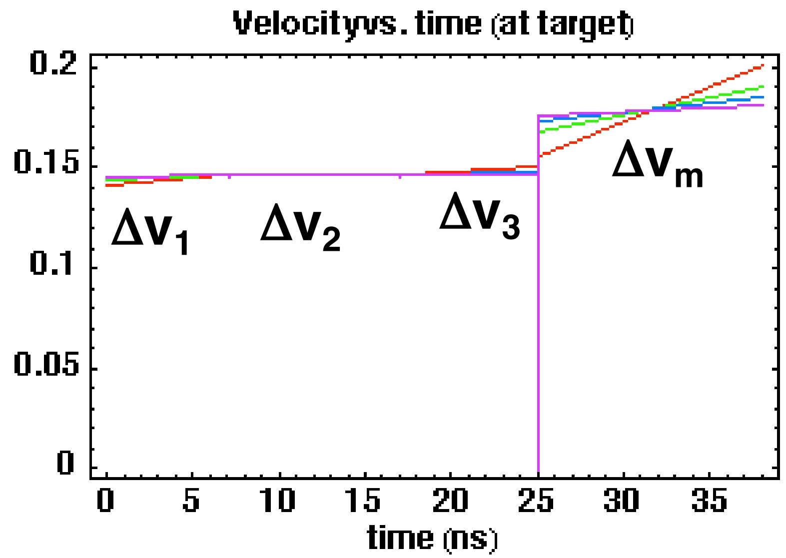


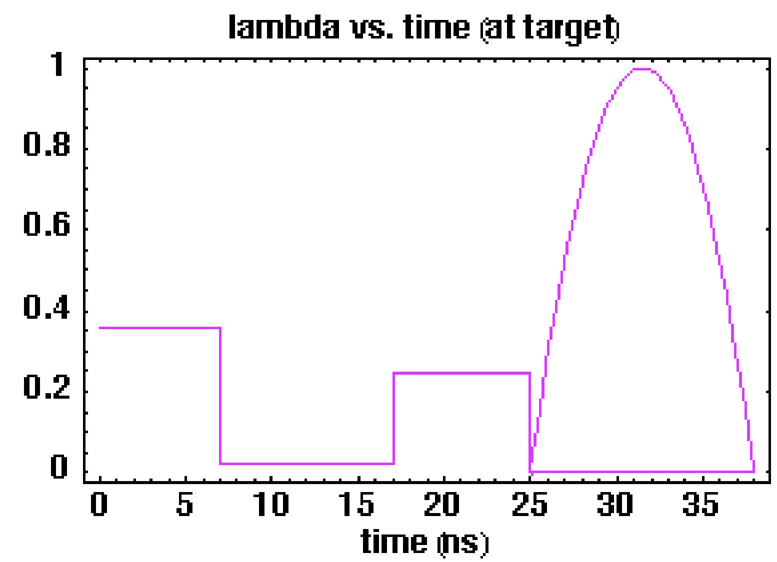
Spot radius: 1.8 mm x 4.2 mm (main)
Pulse energy: 6.5 MJ
Ion range equivalent to 4 GeV Pb (main) and 3.3 GeV (foot)

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 accommodate

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





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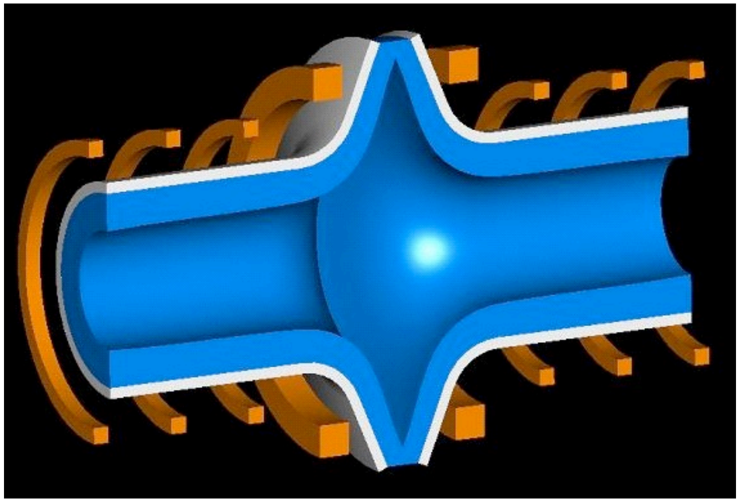
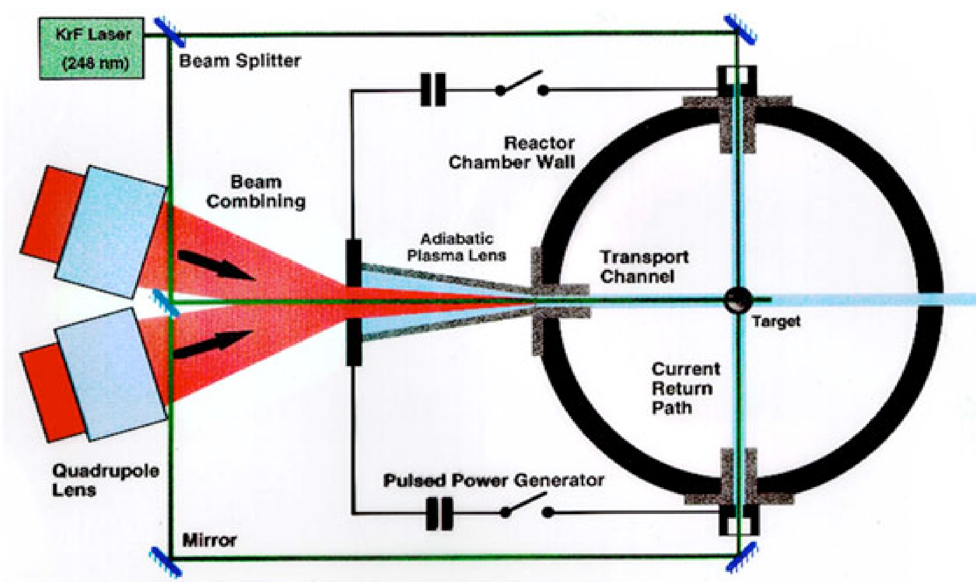
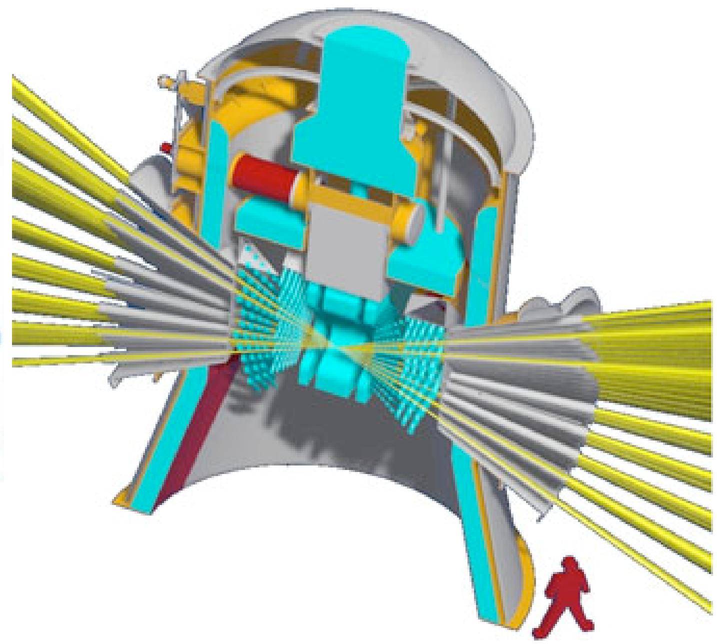
Two Final Focus and Chamber Options are under study



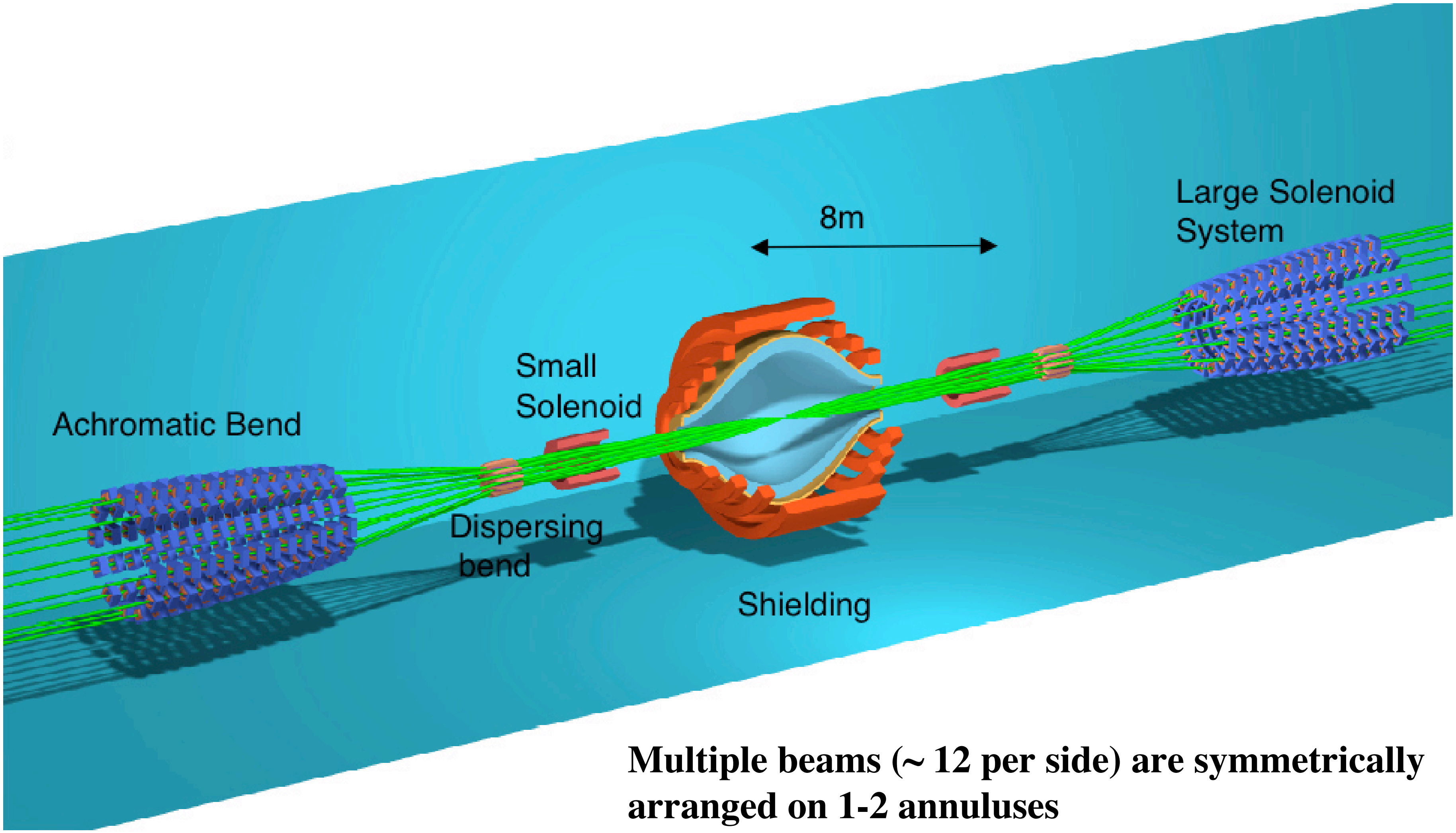
Vortices with liquid FLiNaBe or FLiBe serving as wall protection, and heat absorbing fluid, may be well suited for cusp or solenoidal focusing options (upper left).

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





Solenoidal Final Focus for a Modular driver must accommodate multiple (off-axis) beam and the vortex chamber configuration



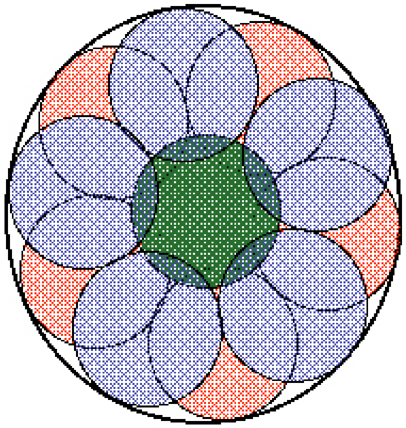
Multiple beams (~ 12 per side) are symmetrically arranged on 1-2 annuluses

A numerical study shows multiple beam spot radius ~5.5mm is achievable with ~1T solenoids around a vortex chamber

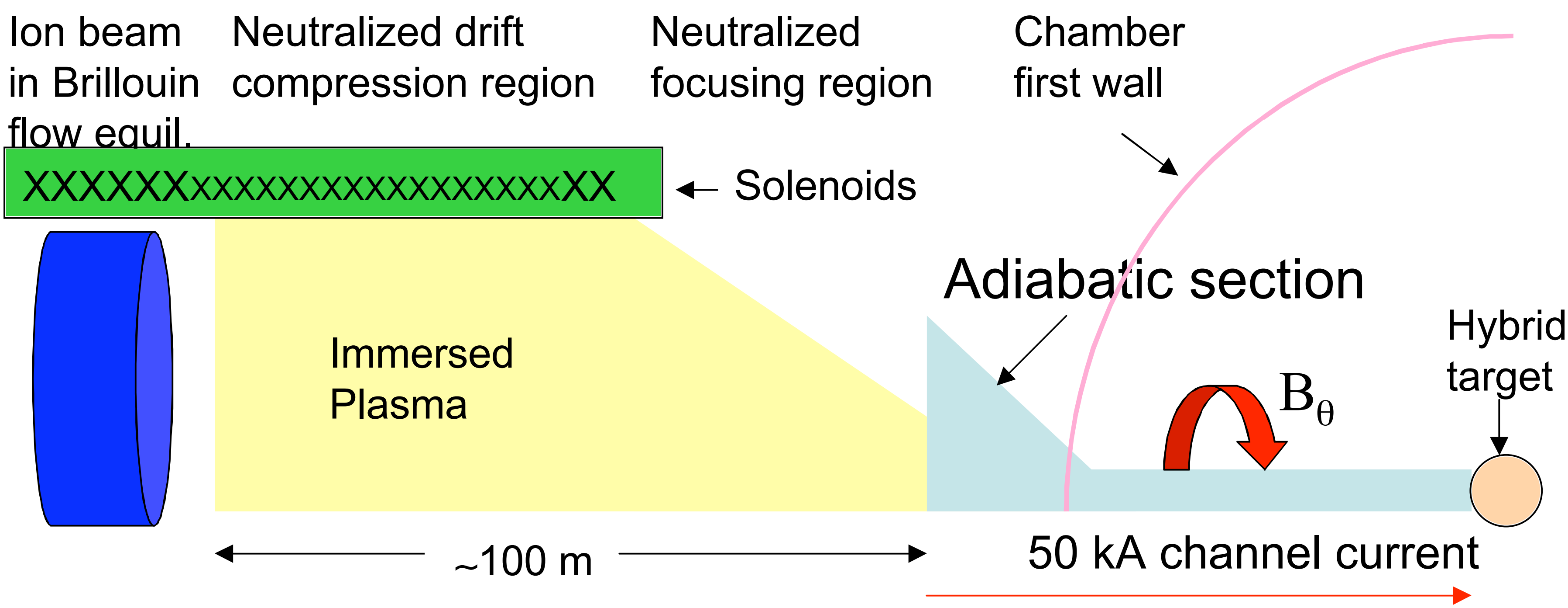
- **Geometric and fringe field aberrations are minimized by 4 cm initial radius beam when design orbit is corrected for Δ*P***
- **Without dispersion single beam radius ≈3mm for $\varepsilon=10^{-4}$ *m-r***
- **Dispersion (±4%) produces a moving annulus of beam spots:**

ΔP/P	χ
-.05	3.8mm
-.04	2.3
-.03	1.1
0	.00
.03	1.9
.04	3.2
.05	4.7

blue = pulse head
green = center
red = tail

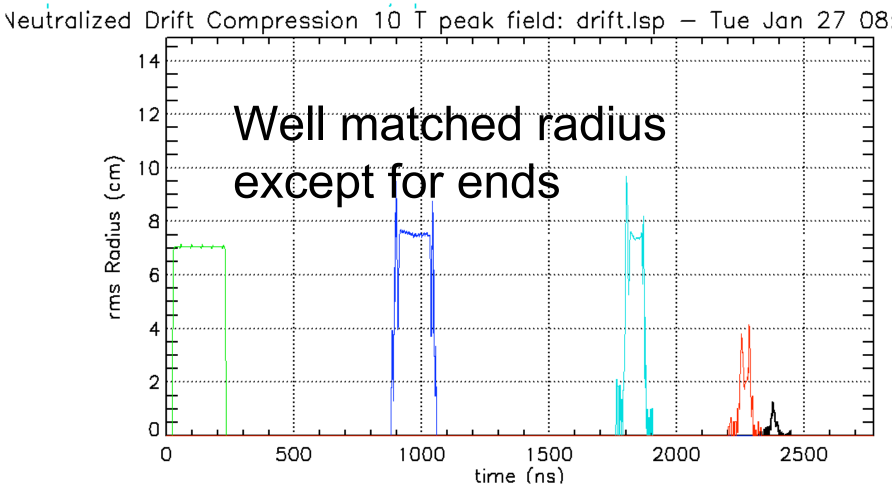


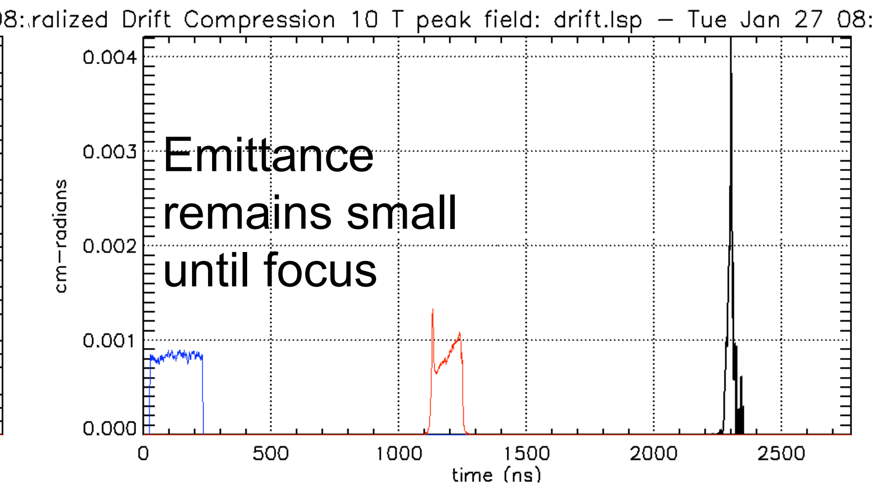
An integrated Assisted Pinch Simulation (LSP) from accelerator exit to target demonstrates 92% energy deposition within required 5mm spot

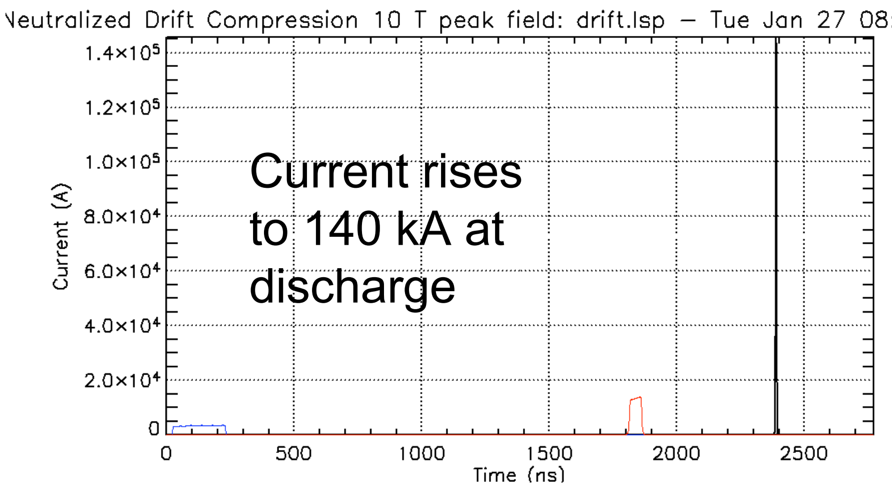


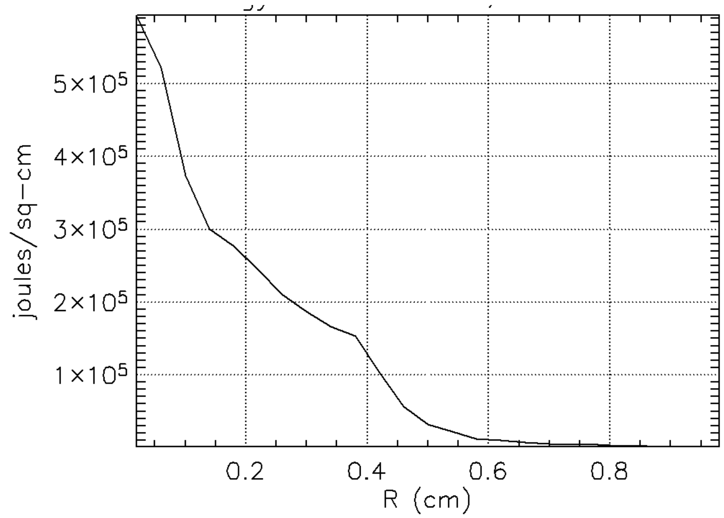
Good energy transport to target

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

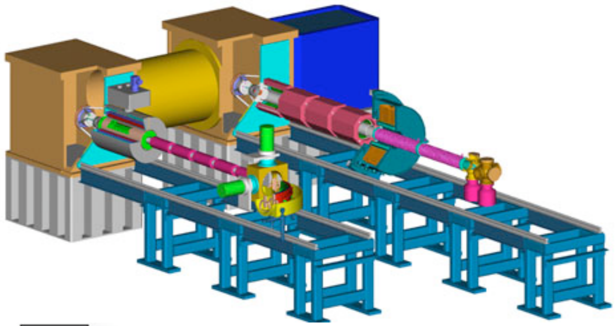




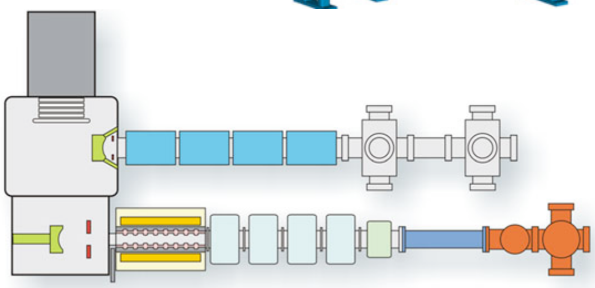




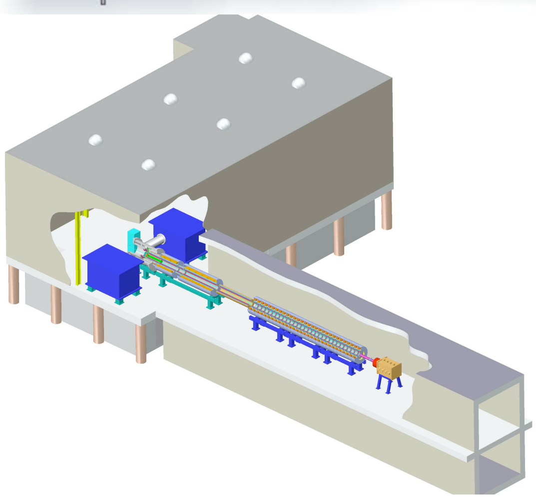
The New HIF Plan Envisions Three Steps in Neutralized Drift and Focusing to an HEDP-Capable Facility in 10 Years



♦**NDCX-I (FY06) First experiments using existing NTX equipment for drift compression (Ia), solenoid transport (Ib), and accel-decel injection (Ic).**



♦**NDCX-II (FY09) First integrated compression and focusing experiment with a *$4M* upgrade of NDCX-I, designed to reach 500MW, 1 MeV in 1 ns, (1 eV) to begin developing/testing target diagnostics.**



♦**NDCX-III (FY15) An *50M$* class HEDP-user facility capable of 10eV targets with 30-60 GW, 1 ns beams at 30 MeV Neon Bragg peak.**

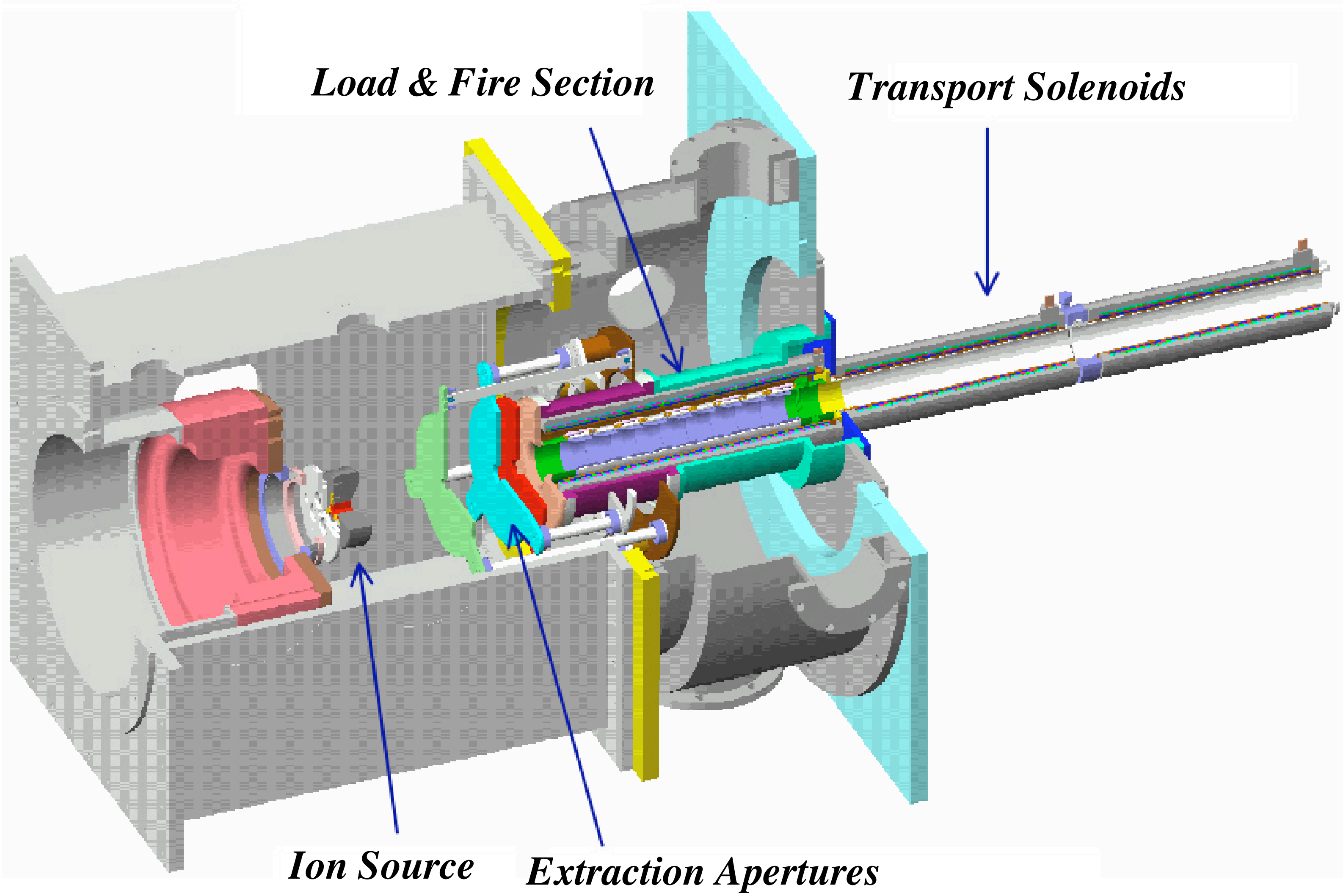
All must accelerate beams with high perveance 0.1 to 0.01 solenoid transport preferred.

Summary

- The new approach to Modular Heavy Ion Fusion Drivers offers possibilities of architectural simplicity, direct development path, and perhaps lower cost.
- New technical concepts to accommodate high line charge densities are studied by simulations and a two year plan for scaled experiments (NDCX-I , FY05-6)
- The same technical approach can lead to near-term applications in High Energy Density Physics.

Backup

Short Pulse Injector (Accel/decel + Load & Fire)



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