Longitudinal and Transverse Neutralized Beam Compression

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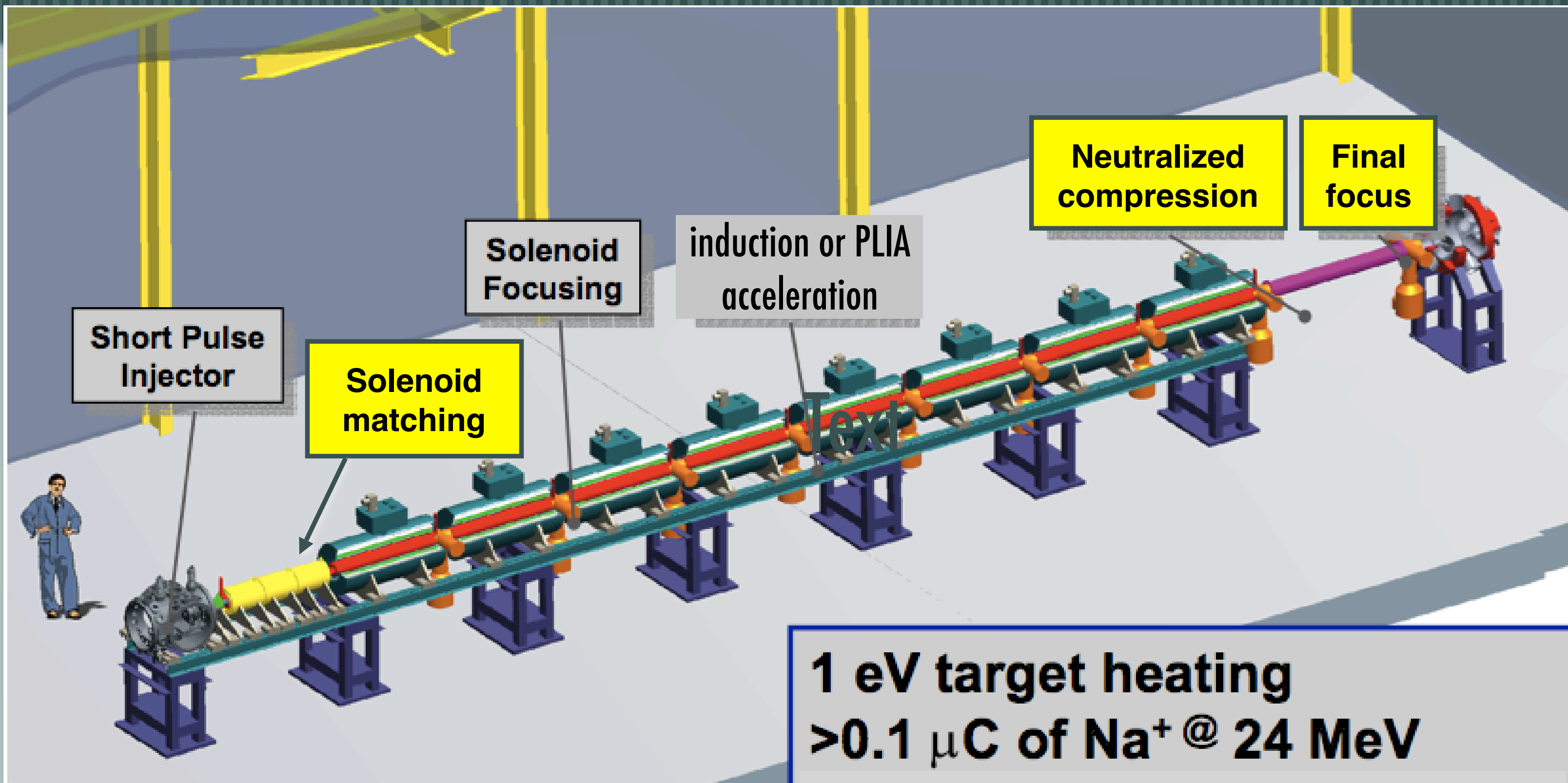
The Heavy Ion Fusion Science Virtual National Laboratory

Outline

- motivation - warm dense matter studies
    - beam requirements
- summary of previous measurements
    - transverse focusing of a neutralized ion beam
    - longitudinal compression of a neutralized ion beam
- first simultaneous and longitudinal compression experiments
- e-cloud studies in solenoid transport channels
- next steps: final focusing solenoid + plasma

Before WDM user facility, we plan a modest upgrade ... NDCX-2



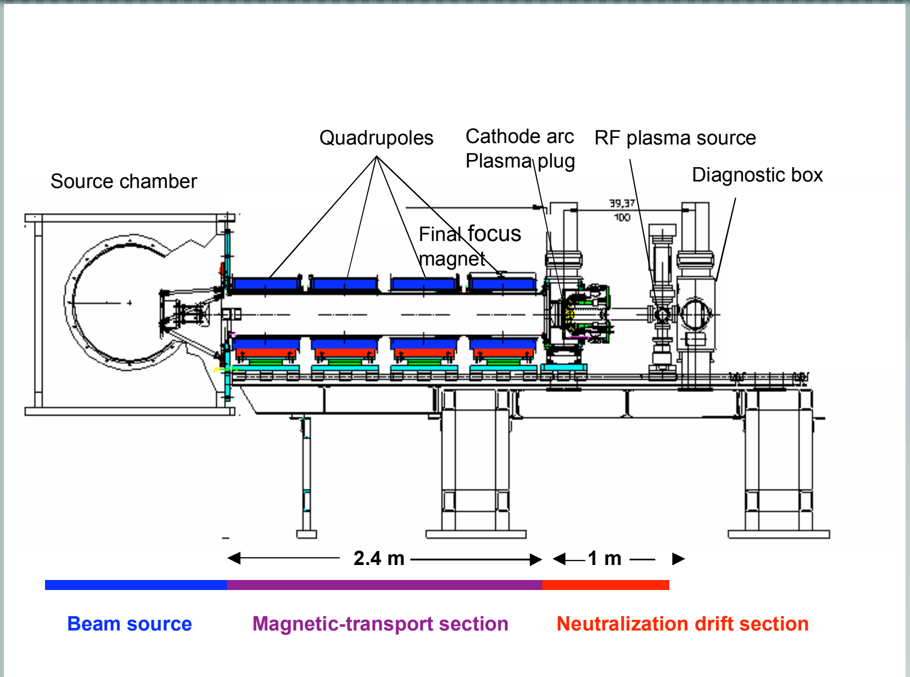
1 eV target heating
>0.1 μC of Na^+ @ 24 MeV
heating @ peak of dE/dx
+ $5M hardware

2.8 MeV Li^+ -- Possibly less costly.
Issues: source, beam formation, higher ϕ_{beam} at injection, $T_{||}$

Neutralized drift compression

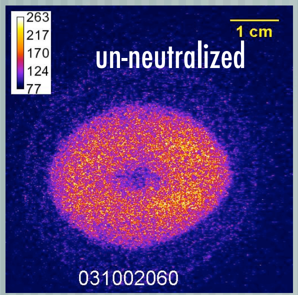
- Acceleration and velocity ramp for compression
  - induction core(s) or other (Pulse Line Ion Accelerator?)
- Need to cancel out space charge
  - plasma column with $n_p >> n_b$

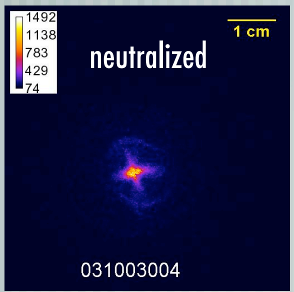
Neutralized Transport Experiment (NTX) demonstrated fusion driver issues

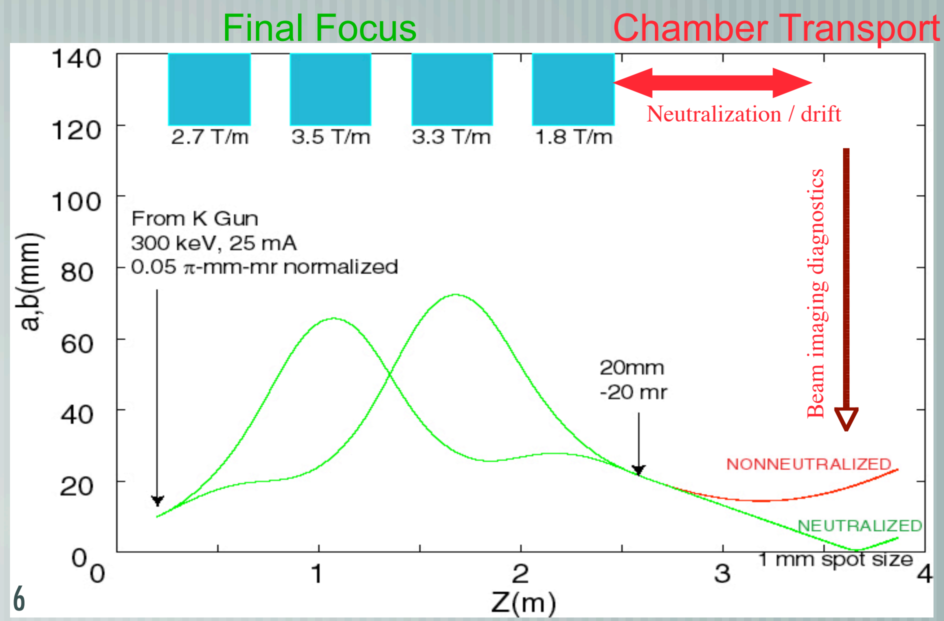


Perveance is the key parameter for final focus and neutralization. NTX covered range of perveance relevant to the driver

$$K = \frac{2qI_B}{4\pi\varepsilon_o m(\beta\gamma c)^3} \leq 10^{-3}$$

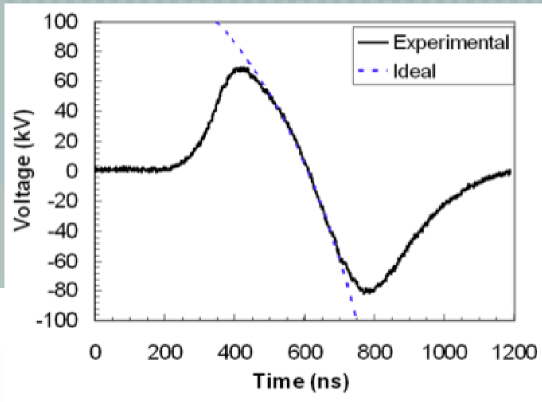


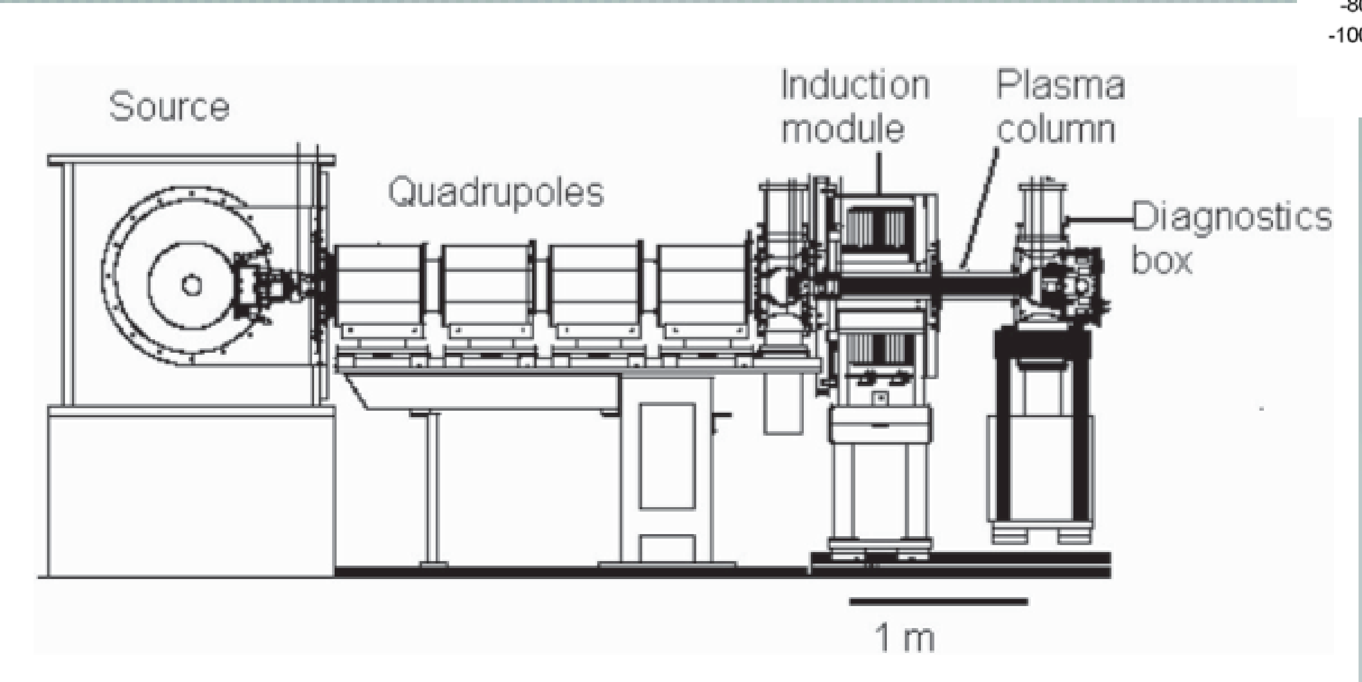




First round of neutralized drift compression experiments...

injected 10-μsec, K^+, 280-310 keV, 22-26 mA,
bunch a portion of beam with induction module
head to tail velocity ramp, $\Delta v/v \approx 15\%$ (≈0.2 s)
Plasma column neutralizes space charge





If T_L limits compression, bunch duration:

$$t = \frac{L}{v^2}\sqrt{\frac{2kT_L}{M}}$$

Huge advantage of neutralized compression for high perveance ($K \approx 10^{-3}$)

E = 300 keV, K^+

I = 44 mA

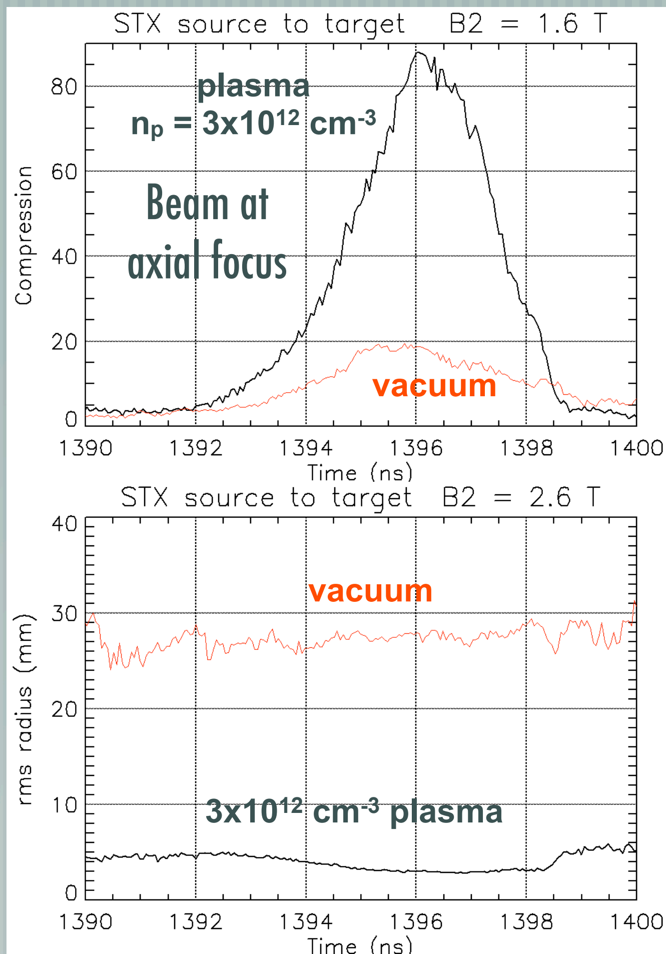
Solenoids

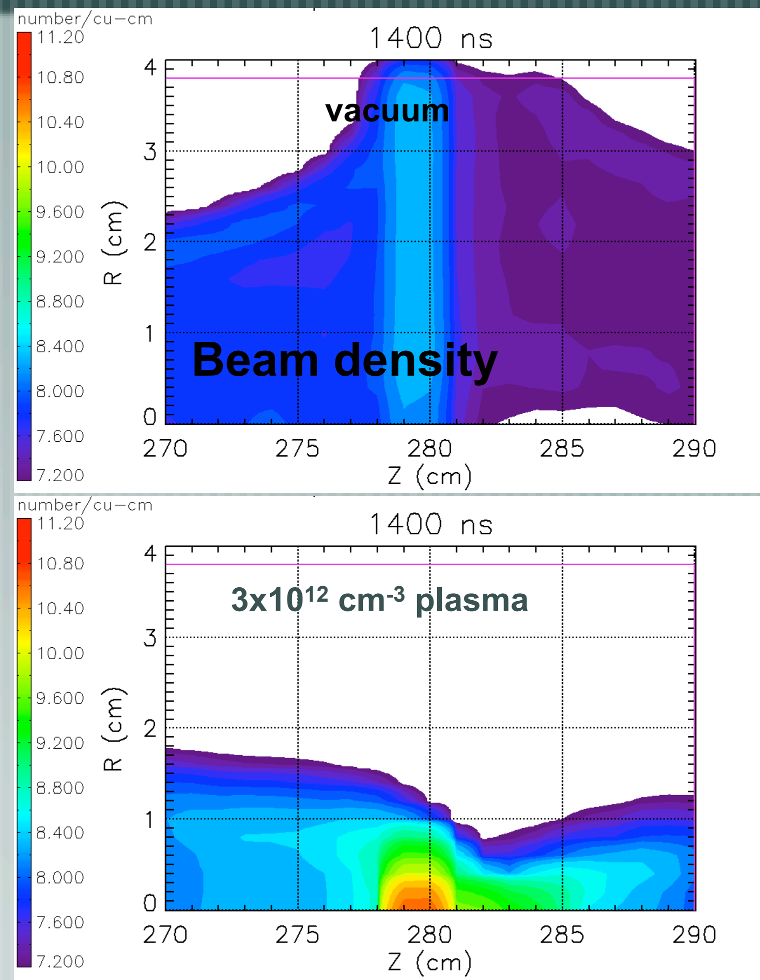
B1=2.445 T

B2 = 2.6 T

Bunching core

200 kV, 200 ns

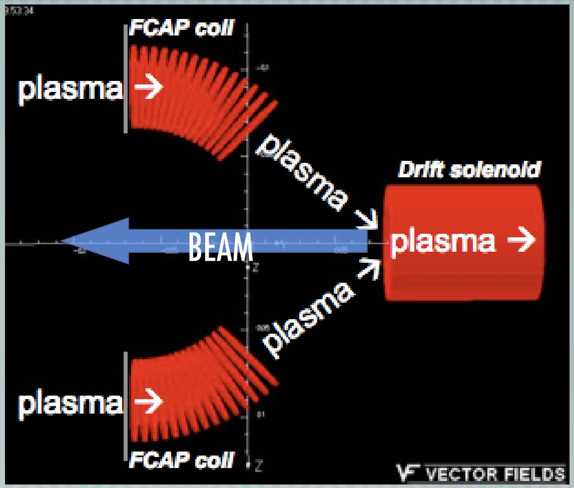


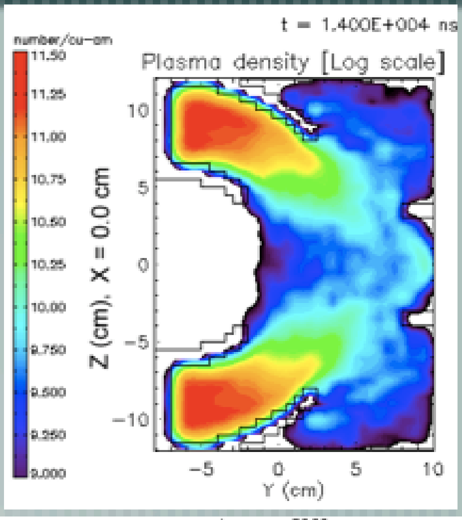


~500 x enhancement of intensity on target is possible

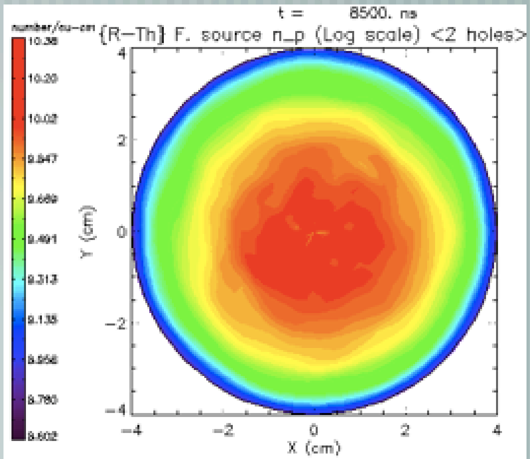
plasma sources for 1-2 meter drift compression.

- Filter cathode arc plasma source
- Injection from end into weak solenoid
- $n_e \approx 5 \times 10^{11}$ cm^{-3} measured



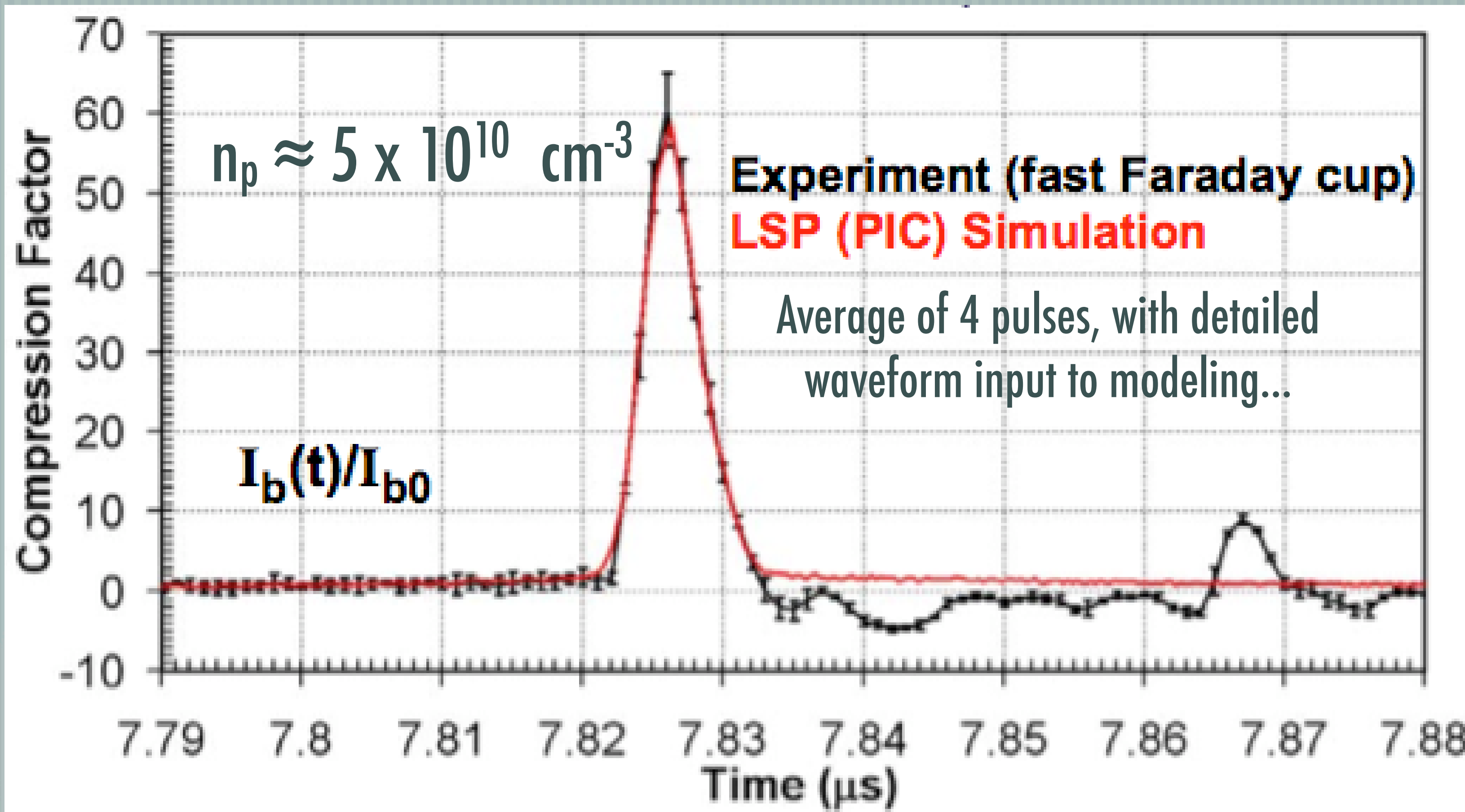


Ferro-electric plasma source
Generated from cylindrical surface
$n_e \approx 2\text{-}8 \times 10^{10}$ cm^{-3}



Both approaches not yet optimized, higher density possible.

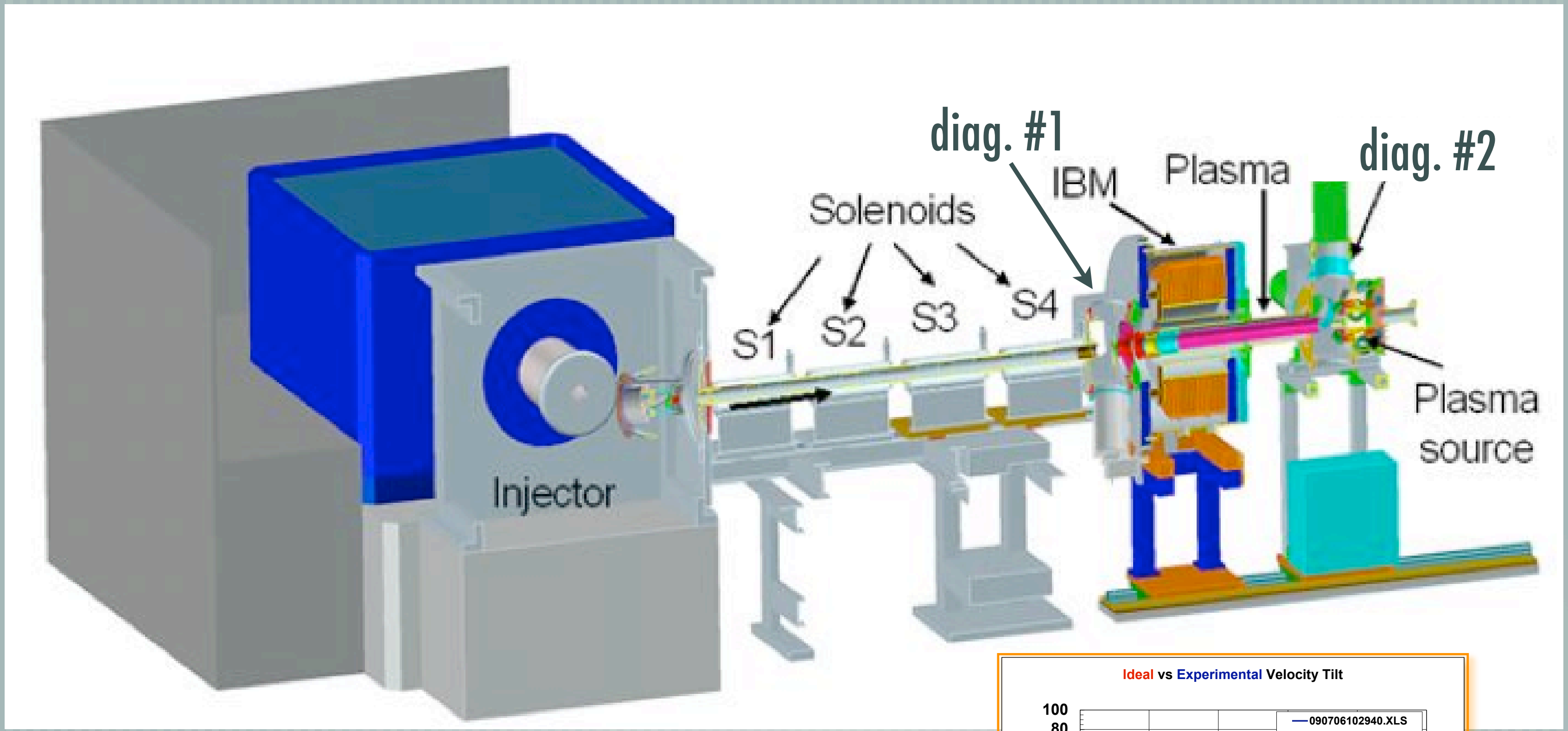
...observed 50x compression in a 1-meter neutralized drift experiment. Good agreement with EM-PIC model

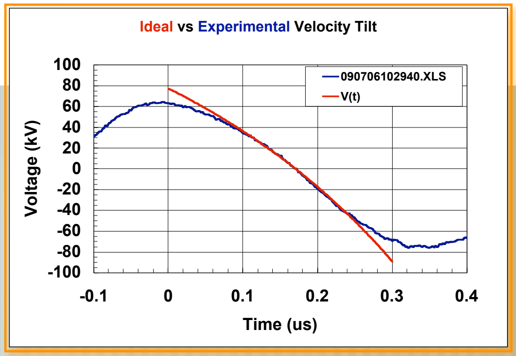


LSP*: EM - PIC code including plasma modeling and beam plasma interaction.

*Voss Scientific, www.vosssci.com

Next step: Simultaneous transverse focusing and longitudinal compression (Sept 2006)



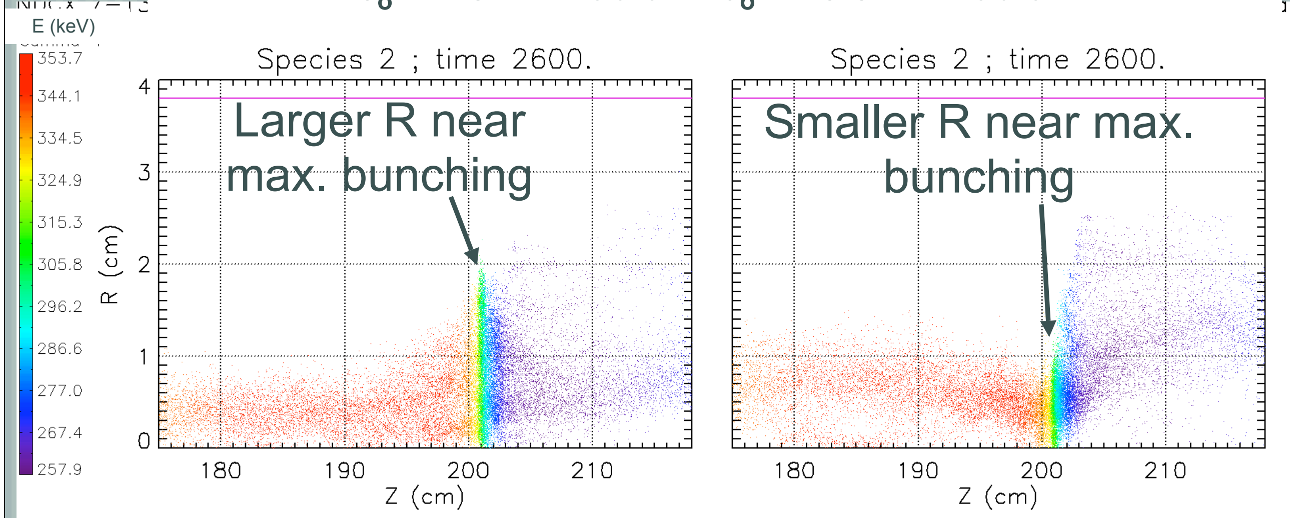


- $E_i = 0.3$ MeV K^+, $I_i = 25$ mA

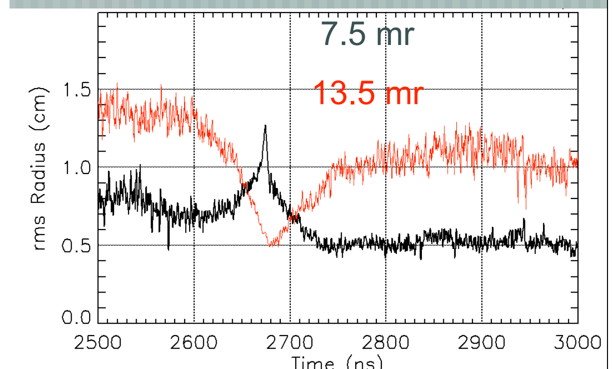
Required **modeling** of the defocusing in bunching module gap due to energy change, time-dependent E_r

Angle at entrance to bunching module

θ_o = 7.5 milliradian θ_o = 13.5 milliradian

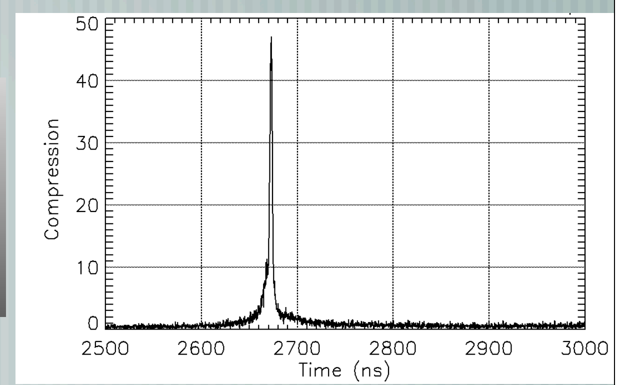


Beam radius at z=210 cm



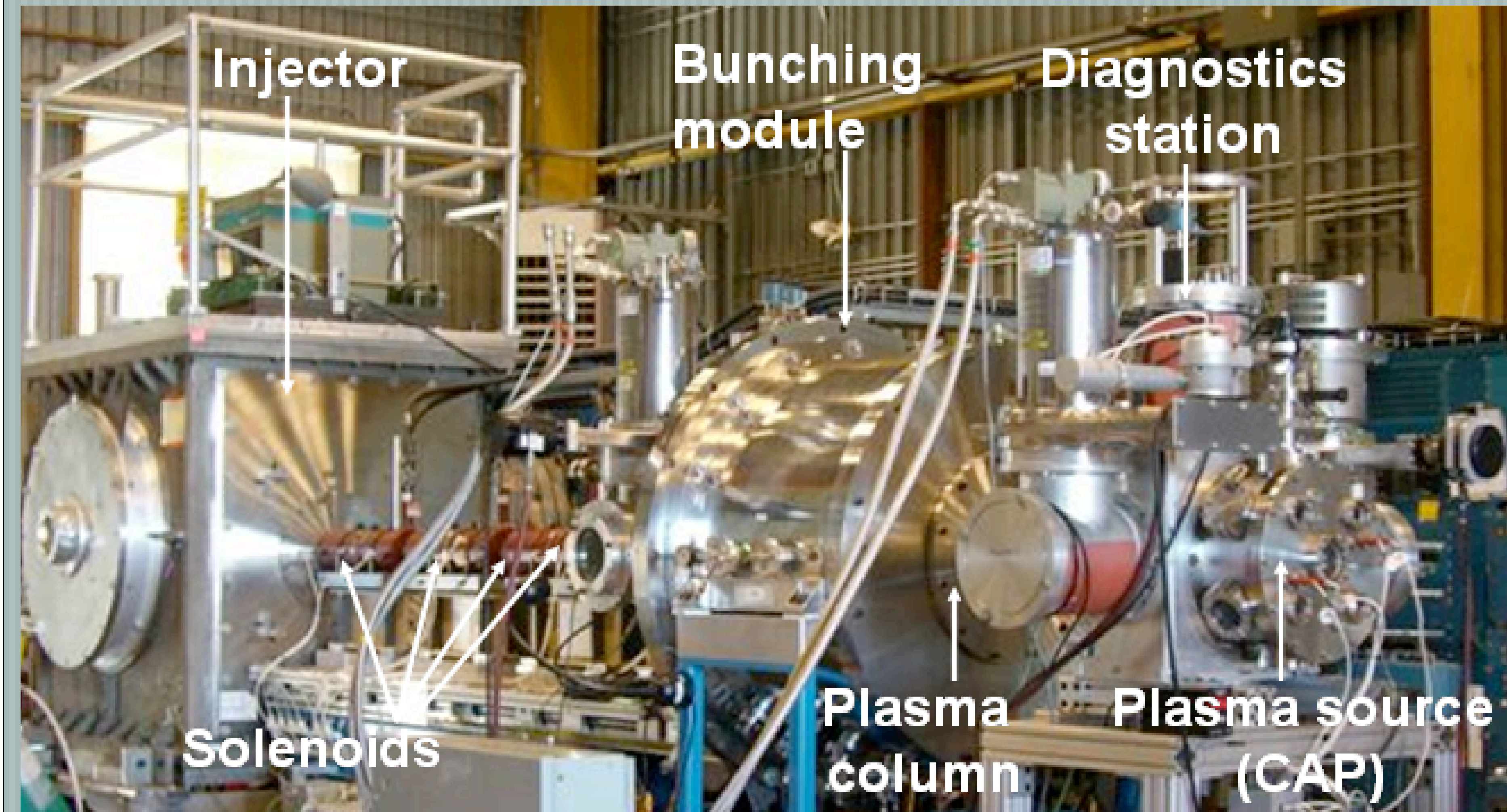
Compensation of transverse focusing effect in induction gap

Compression I/I_o

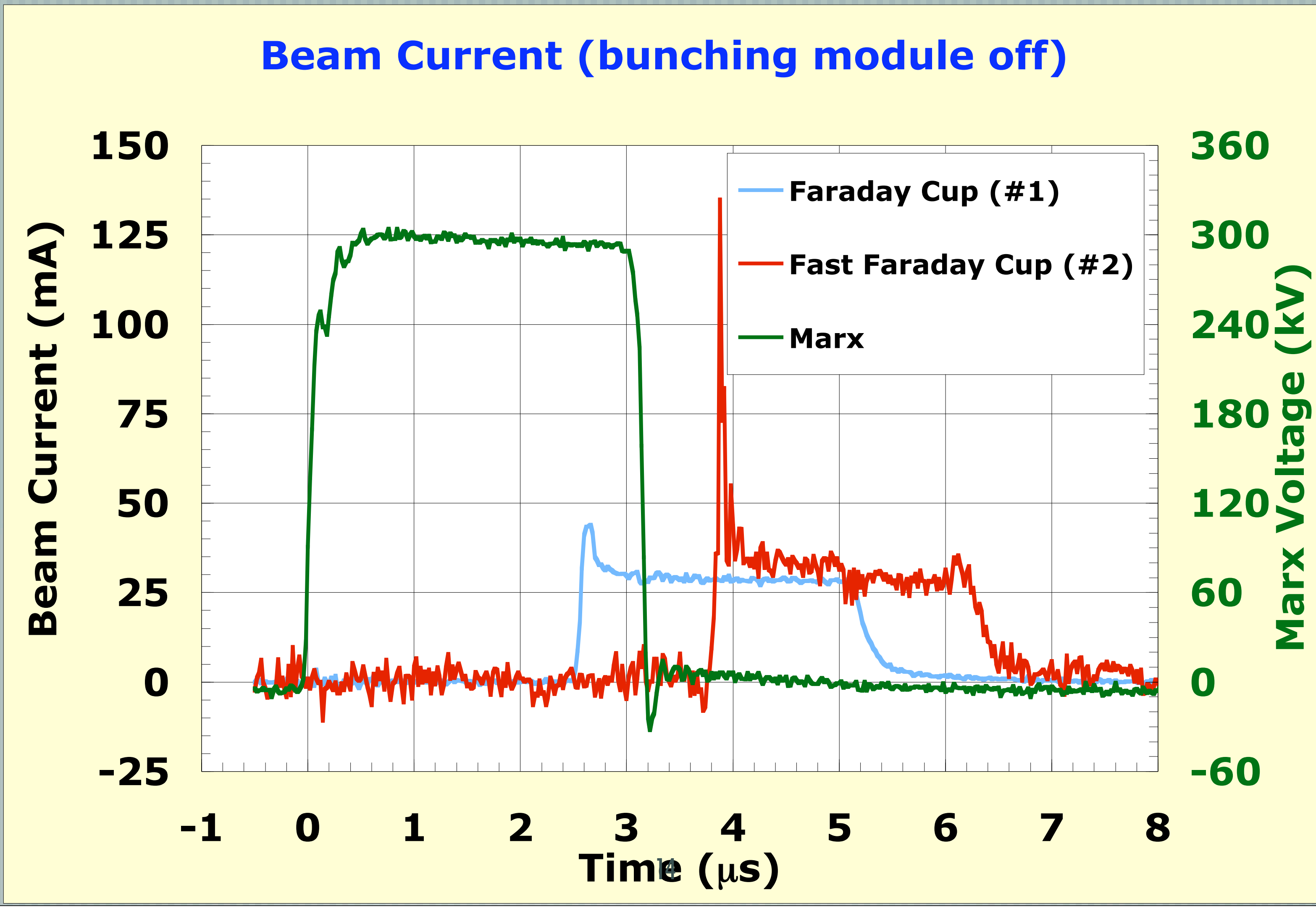


The simulations implied that simultaneous longitudinal compression and transverse focusing on NDCX should be possible, increasing the compressed beam intensity ≈4x.

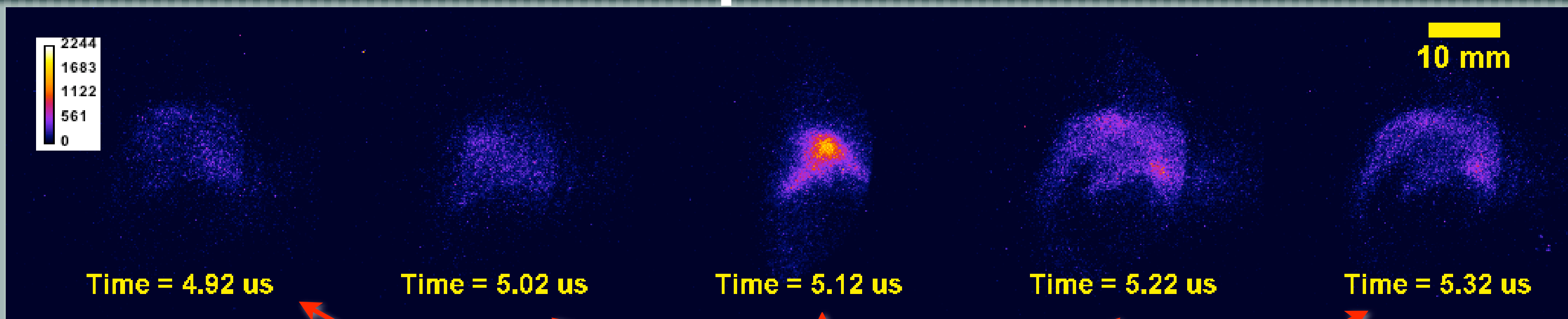
Most recent NDCX setup

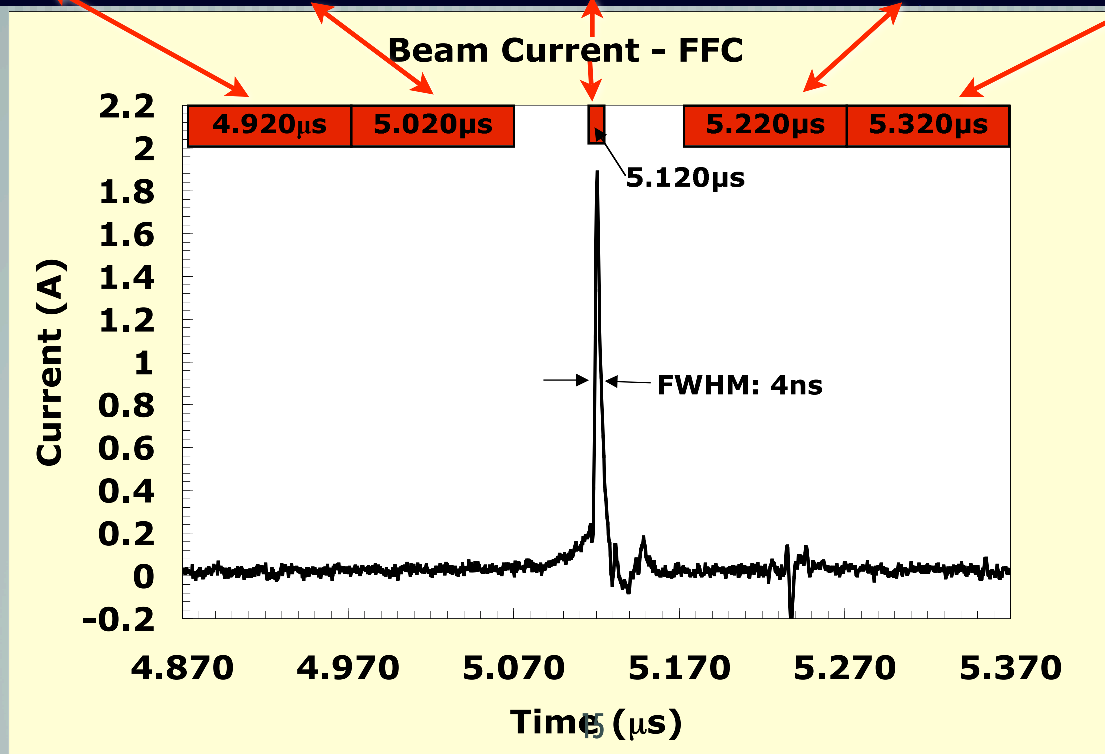


Beam current – no velocity tilt

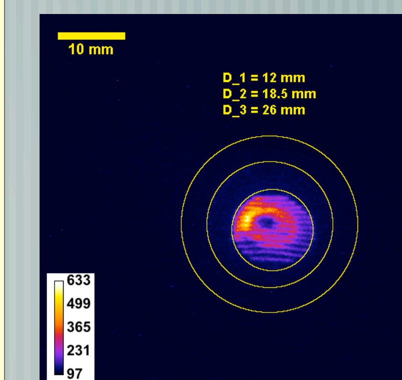


Simultaneous and longitudinal compression experiments

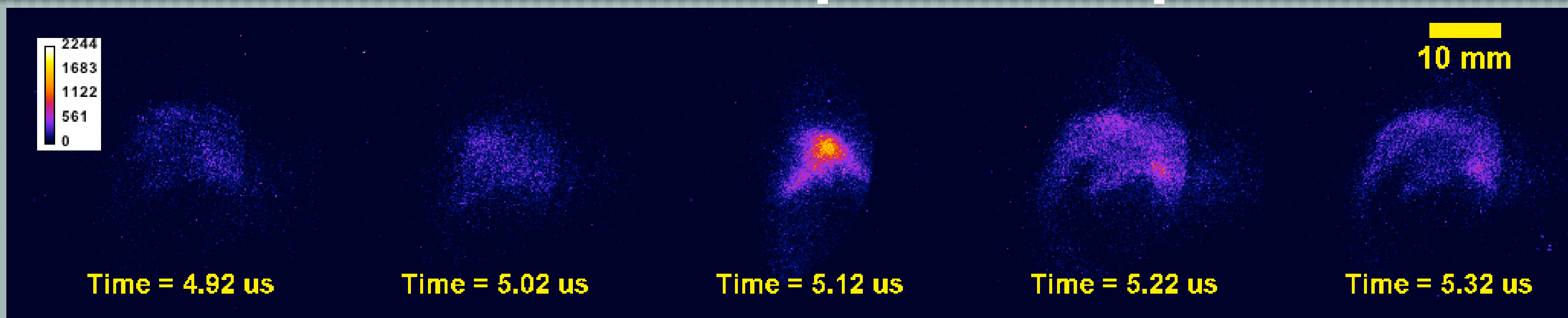




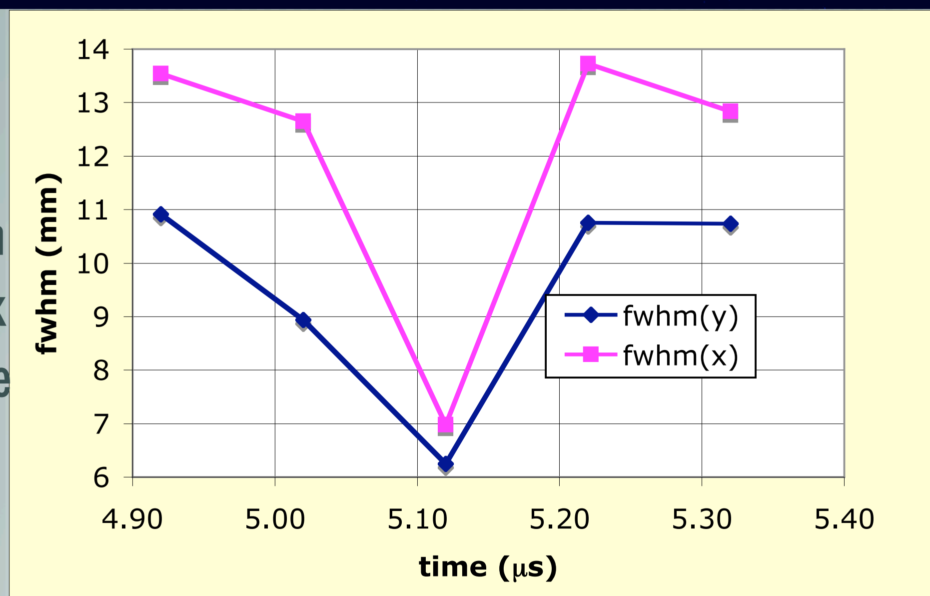
non-uniformity? Might be partly caused by non-ideal beam upstream of IBM



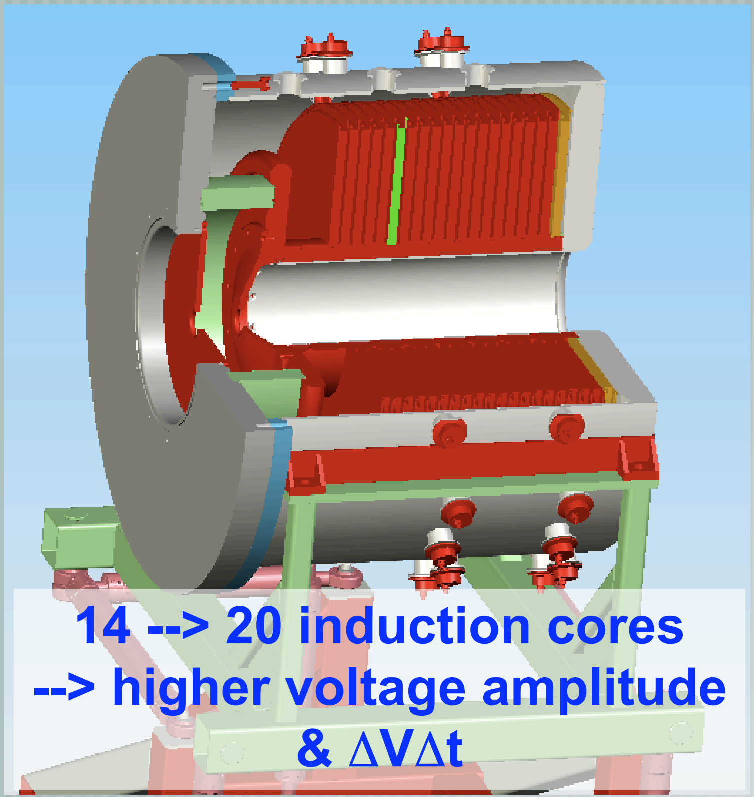
Minimum spot size @ same time as peak compression

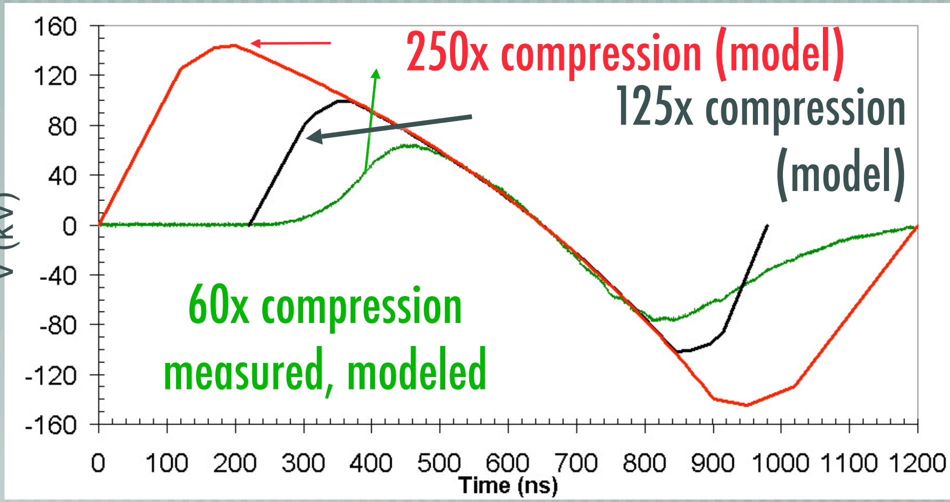


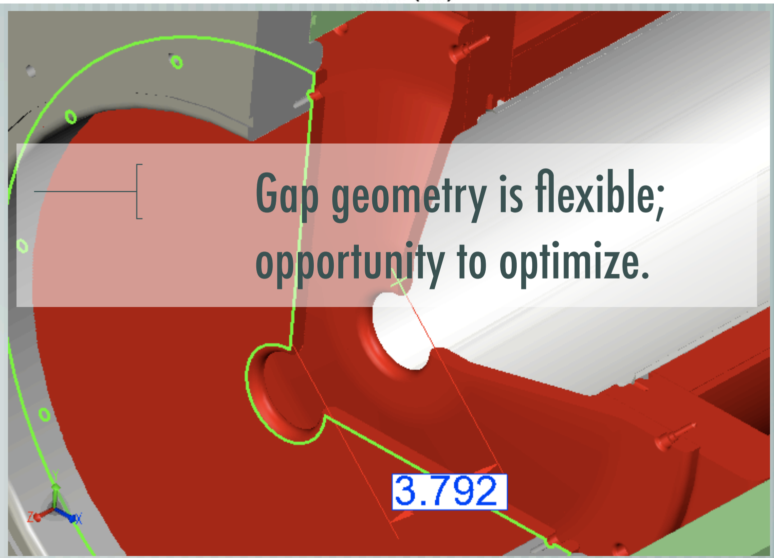
2X reduction in the spot size (4X increase in beam intensity) brings the peak beam density to the range $n_b \approx 10^{11}\text{-}10^{12}\ \mathrm{cm}^{-3}$.



A new bunching module will increase the voltage amplitude and voltage ramp duration

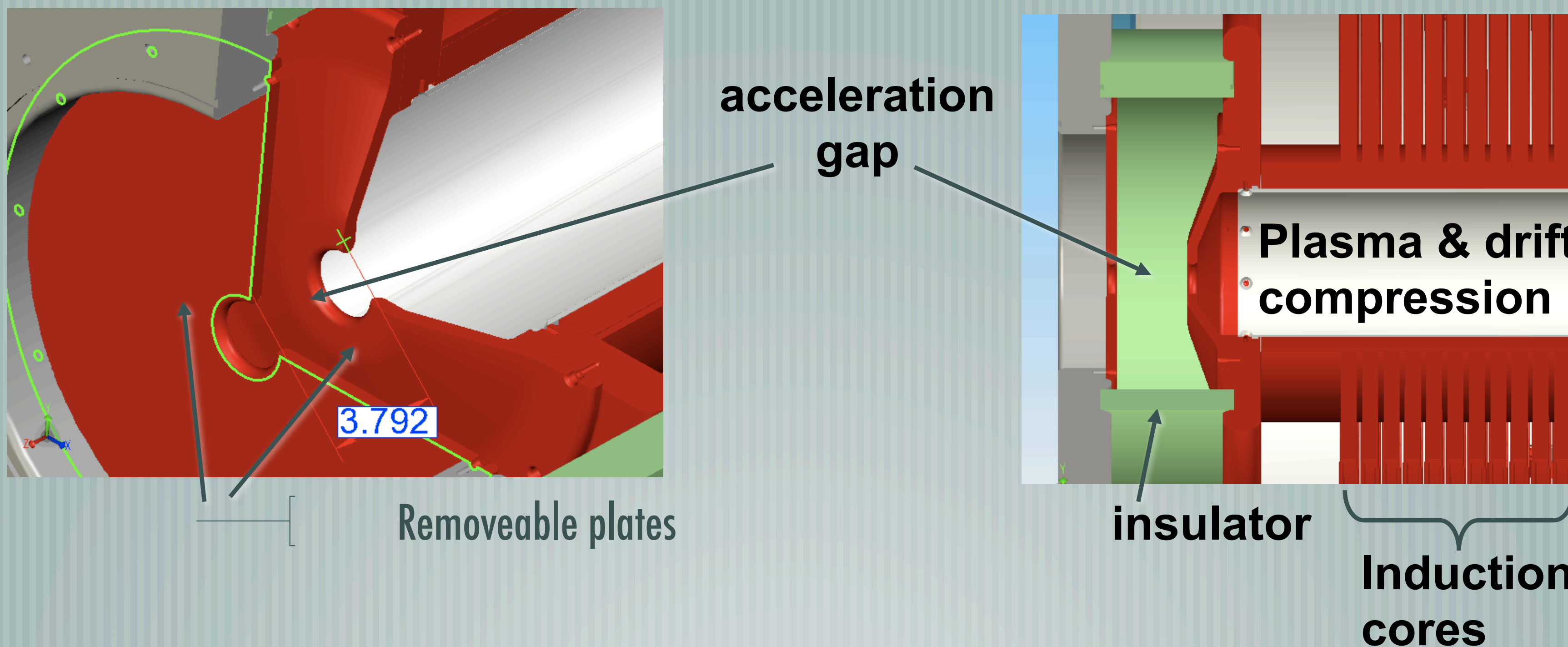




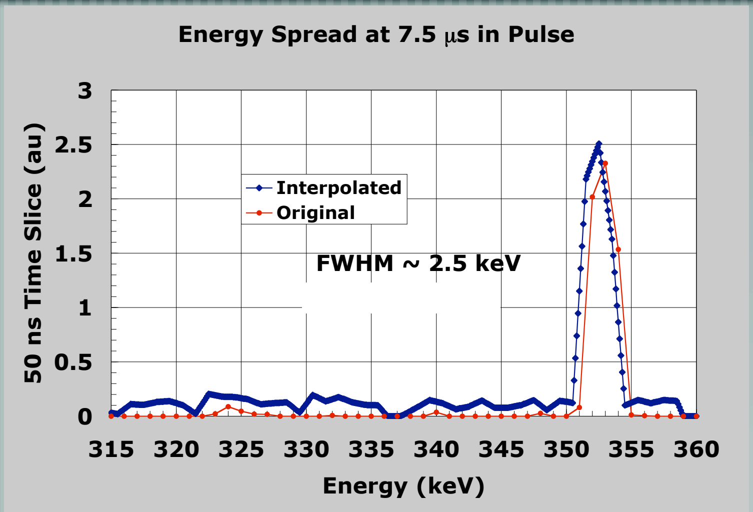


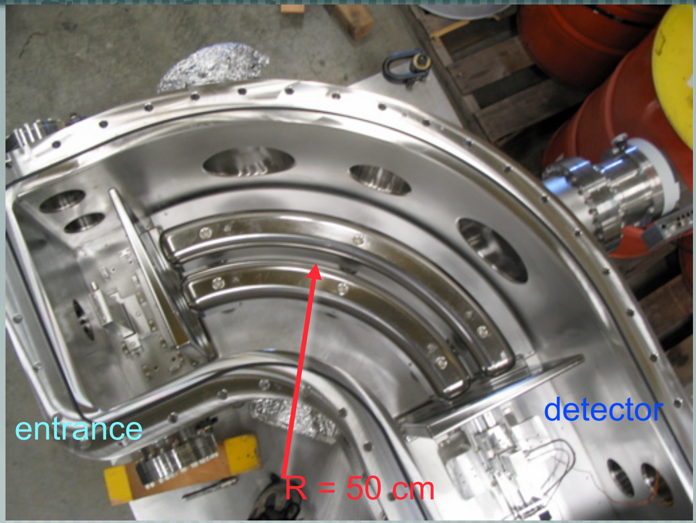
Beam experiments in 2007.

Gap geometry - design allows for straightforward modifications



1st NDCX longitudinal energy spread measurement $T_l \approx 1.5$ eV (new electrostatic energy analyzer)

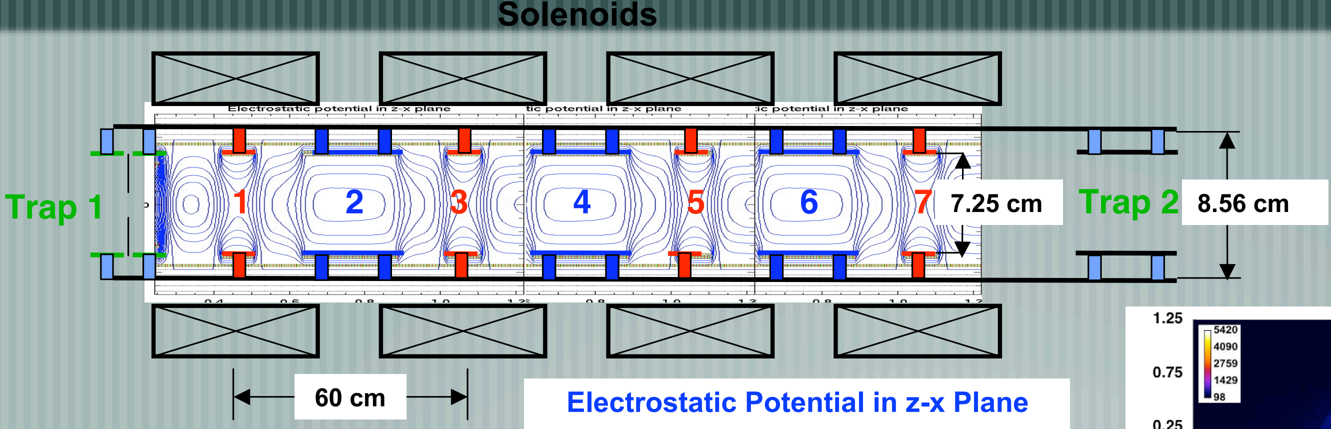




- $T_{//} \leq (\Delta E)^2/(2E) \leq 1.5$ eV.
- Upper limit due to coarse measurement intervals, uncertainty of instrumental resolution.
- broadening due to finite entrance slit = 1 mm –> 8%.
- New analyzer can measure up to 1 MeV ions, with resolution few x 10^{-4}.
- It was used to verify ion acceleration and beam dynamics of the prototype Pulse Line Ion Accelerator module.

valuable for disentangling contribution to focusing limits from initial beam conditions and bunching waveform fidelity.

Electron and gas desorption may degrade the beam quality $\rightarrow$ Conducting experiments with e⁻-cloud diagnostic rings in solenoids



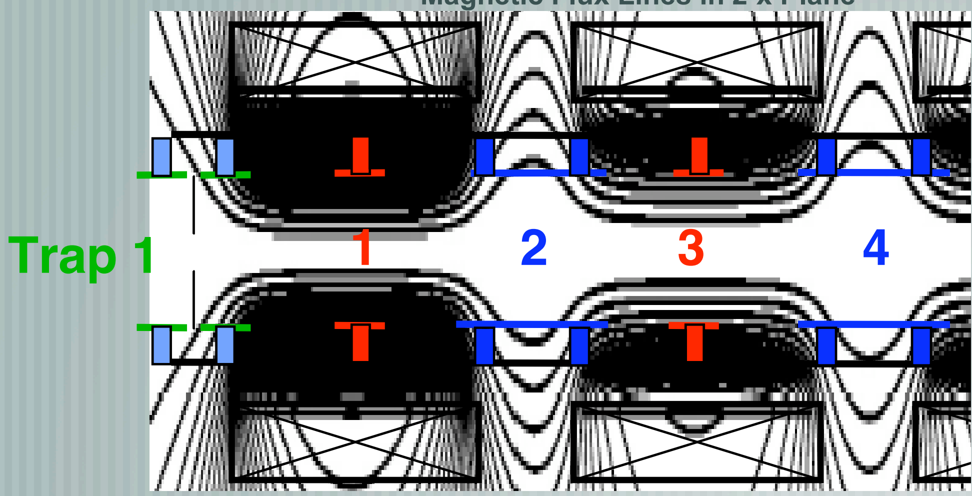
Electrostatic Potential in z-x Plane

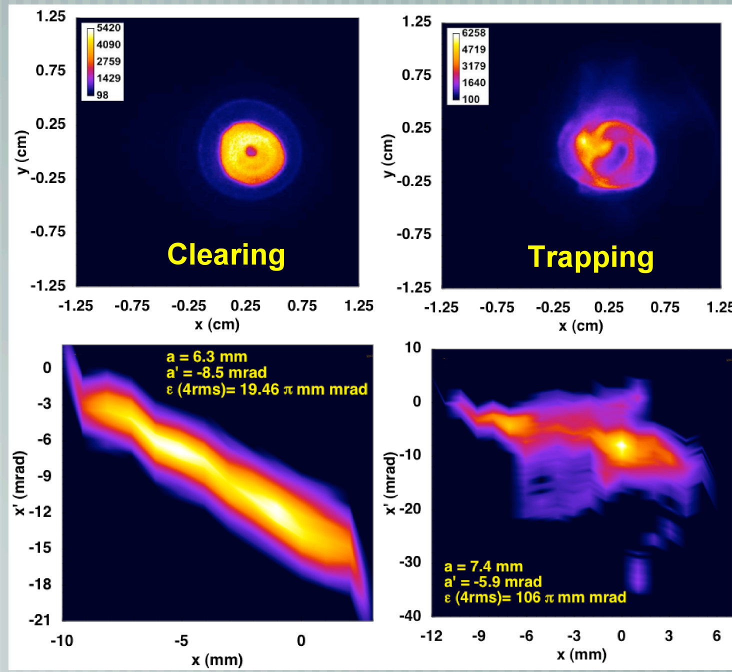
Radial Beam Potential

$$\psi = \int \vec{D} \cdot d\vec{a}$$

$$\Delta V = \frac{\lambda}{2\pi\epsilon_o} \ln\left(\frac{r_{beam}}{r}\right)$$

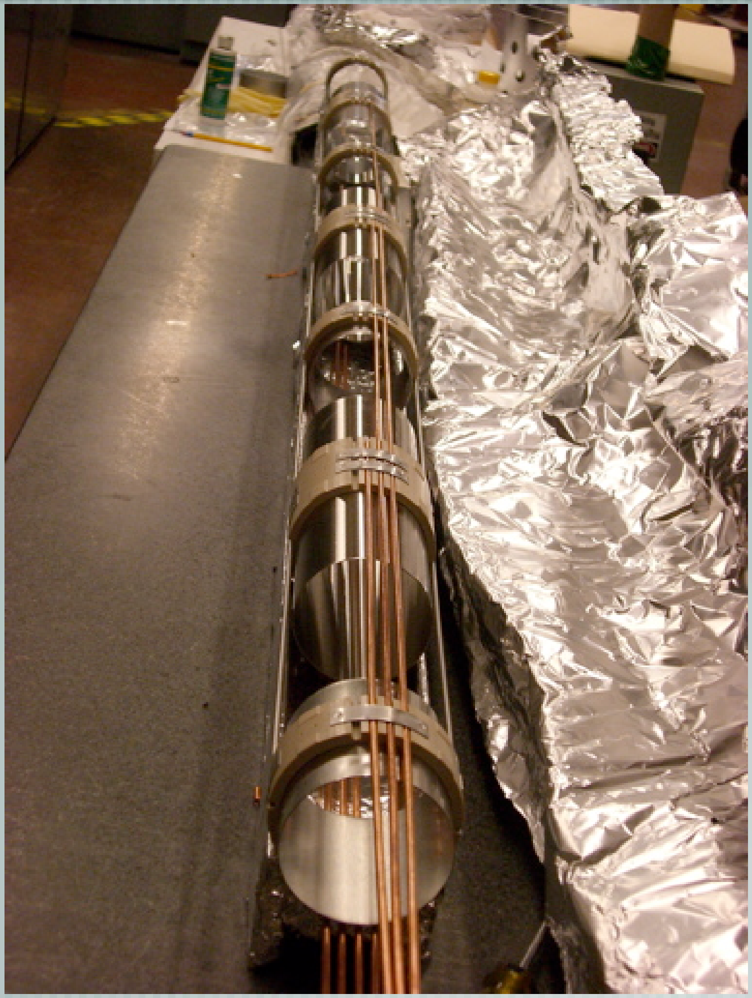
Magnetic Flux Lines in z-x Plane

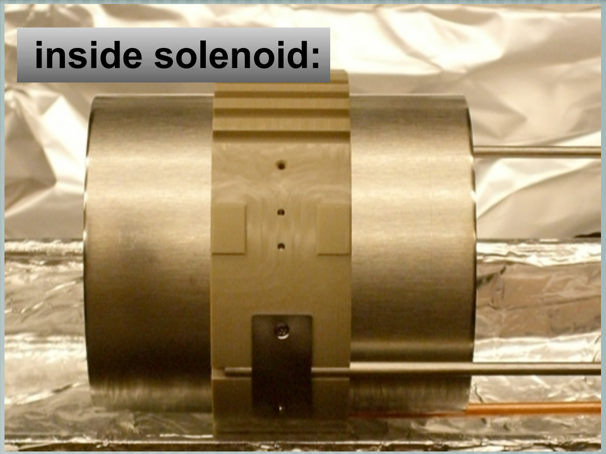




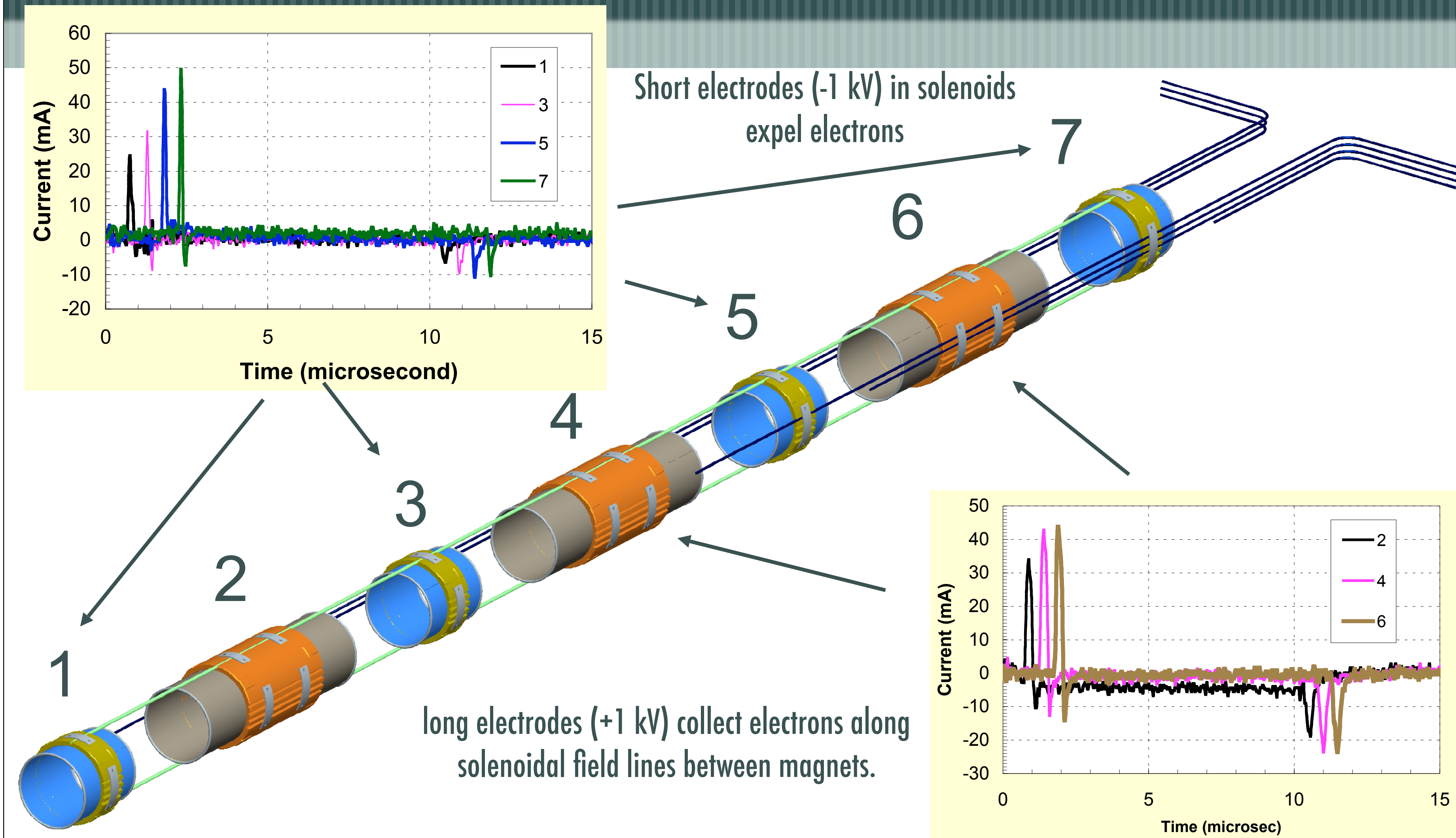
Negative electrode inside solenoid: suppress e⁻. **Positive electrode** between solenoids :collect e⁻. Reverse bias to emit and trap e⁻.

e-cloud diagnostics for solenoid beamline



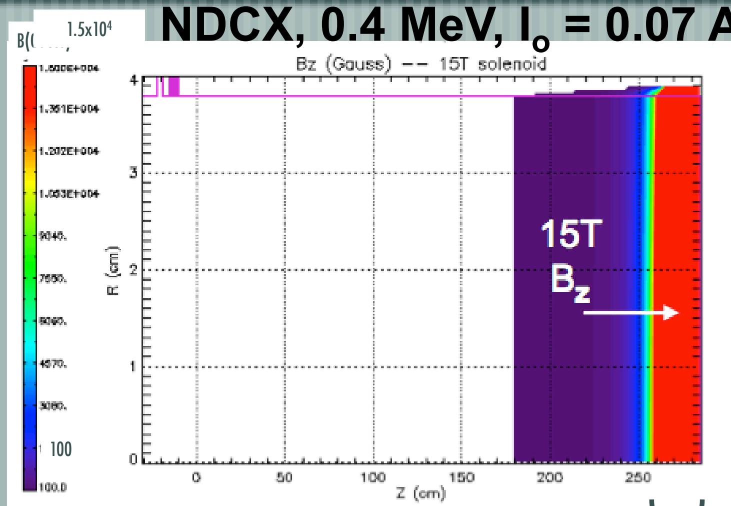


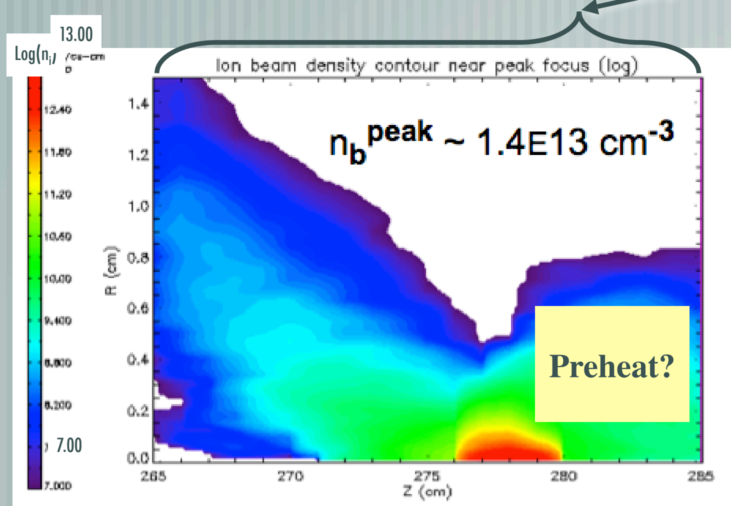
Preliminary results from e-cloud diagnostics



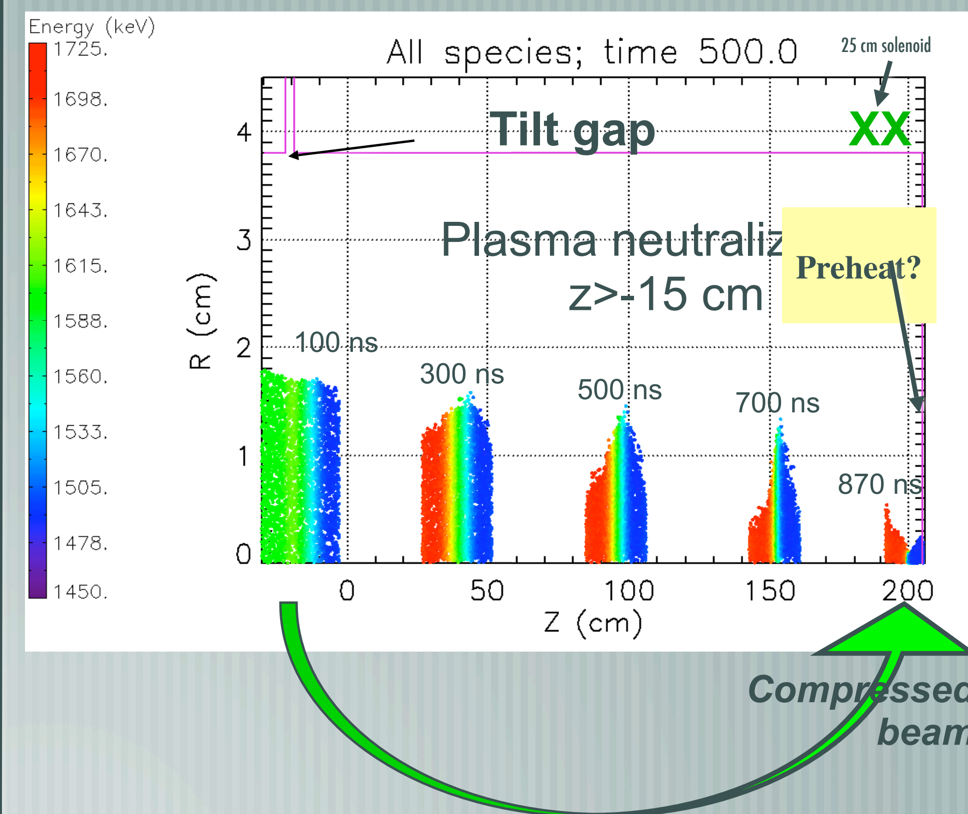
A final focus solenoid is needed to achieve $T_{tgt} \approx 1$ eV. Modeling for NDCX and HCX input beams

NDCX, 0.4 MeV, I_o = 0.07 A





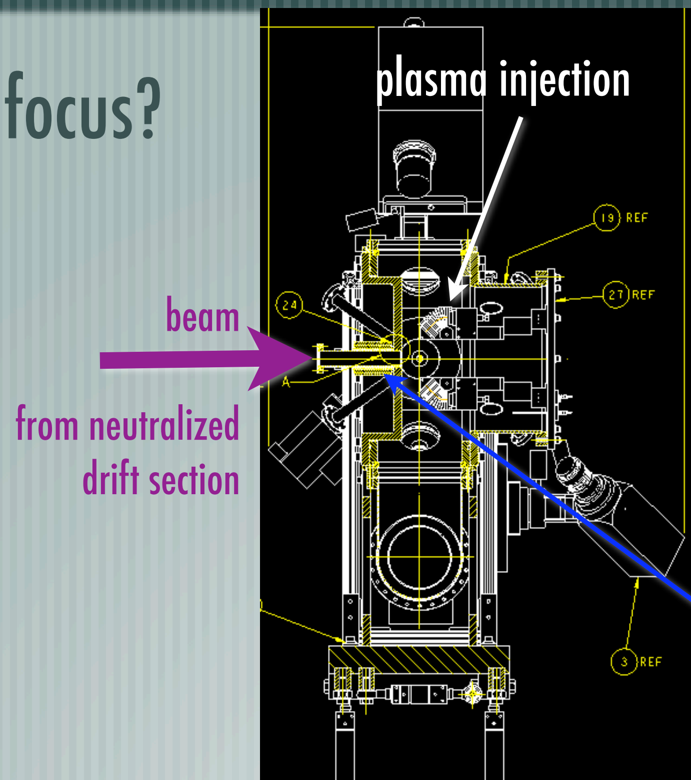
HCX, 1.6 MeV, I_o = 0.36 A

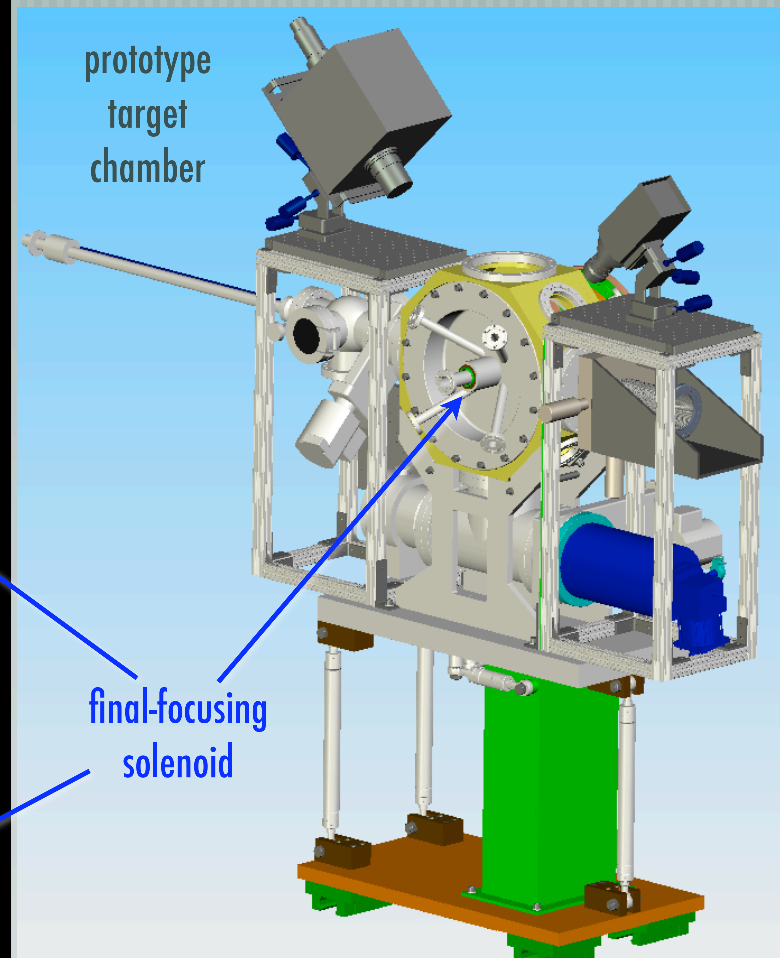


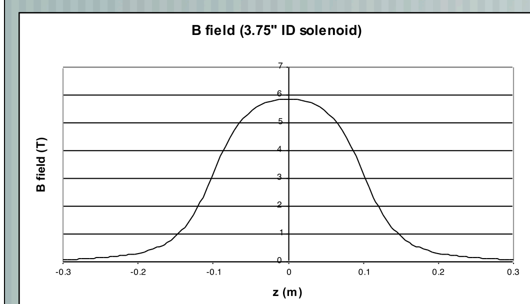
Simulations: D. Welch (Voss Sci.) & A. Sefkow (PPPL)

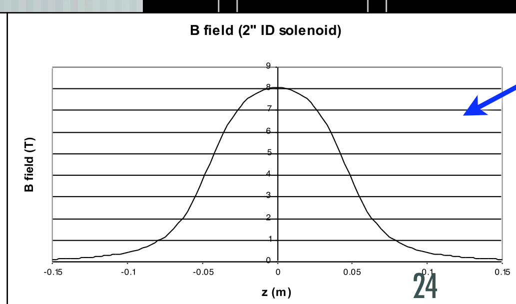
Final focusing solenoid + plasma will be tested on on NDCX in 2007.

$n_p > n_b$ near focus?









beam pipe ID(inch)	beam pipe OD (inch)	G10 pipe ID(inch)	G10 pipe OD (inch)	solenoid ID (inch)	solenoid OD (inch)	length (cm)	current (Amp)	B field (T)	stored energy (J)
1.26	1.5	1.75	2	2	2.5	9	21260	8.05	5.080E+03

Summary

Neutralized drift compression:

- Demonstrated longitudinal beam compression with transverse compression
- $T_I \approx 1$ eV: inferred from compressed pulse width & also consistent with uncompressed beam through new energy analyzer. More measurements planned, valuable for disentangling contribution to focusing limits from initial beam conditions and bunching waveform fidelity.
- A new induction bunching module may provide compression up to 200x.
- 5-15 Tesla final focus solenoid is planned to increase transverse compression to < 1 mm.

Solenoid transport

- Injected and matching high-perveance beam into solenoid channel. Beam dynamics studies, gas and electron effects...