PROGRESS IN BEAM FOCUSING AND COMPRESSION FOR WARM-DENSE MATTER EXPERIMENTS

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The 17th International Symposium on Heavy-Ion Inertial Fusion
Tokyo Institute of Technology
Tokyo, Japan
3-8 August 2008

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Outline

Beam requirements

Method: bunching and transverse focusing

Beam diagnostics

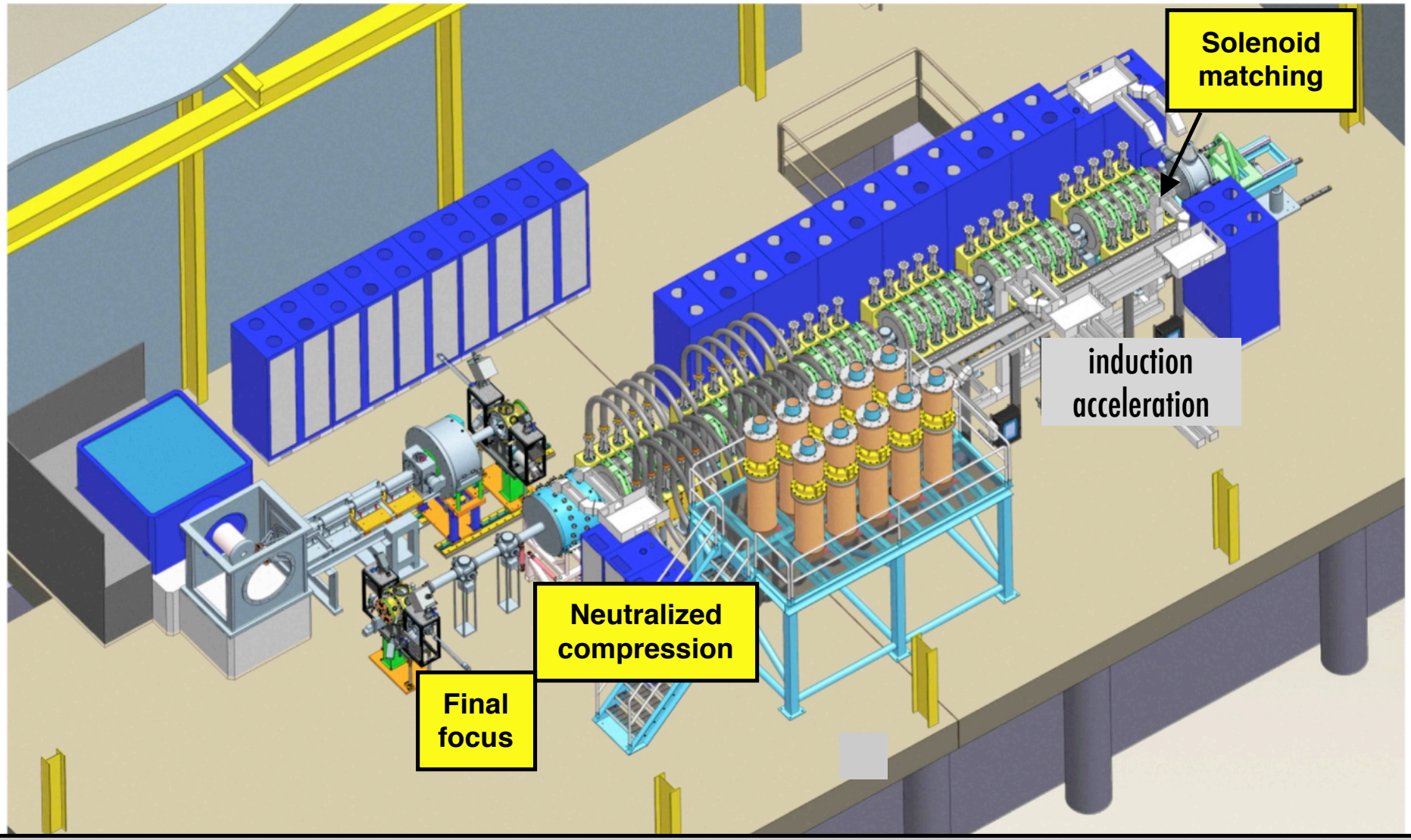
Recent progress:

- simultaneous and longitudinal compression, longitudinal phase space measured
- improved centroid control via beam steering dipoles;
- enhanced plasma density in the path of the beam

Next steps toward higher beam intensity & target experiments

- greater axial compression via a longer-duration velocity ramp
- time-dependent focusing elements to correct chromatic aberrations

Before WDM user facility, we plan an intermediate step: NDCX-2
Beam requirements: intensity, short pulse (τ_{beam} ~ 1 ns < τ_{hydro})



E= 3 MeV Li^+

Final focus: ~15 J/cm^2 beam deposition for T ≈ 1 eV, $n_{b\text{-}max}$ ≈ 4x10^{13}/cm^3.

Challenges: source, beam formation, ϕ_{beam} at injection, $T_{||}$

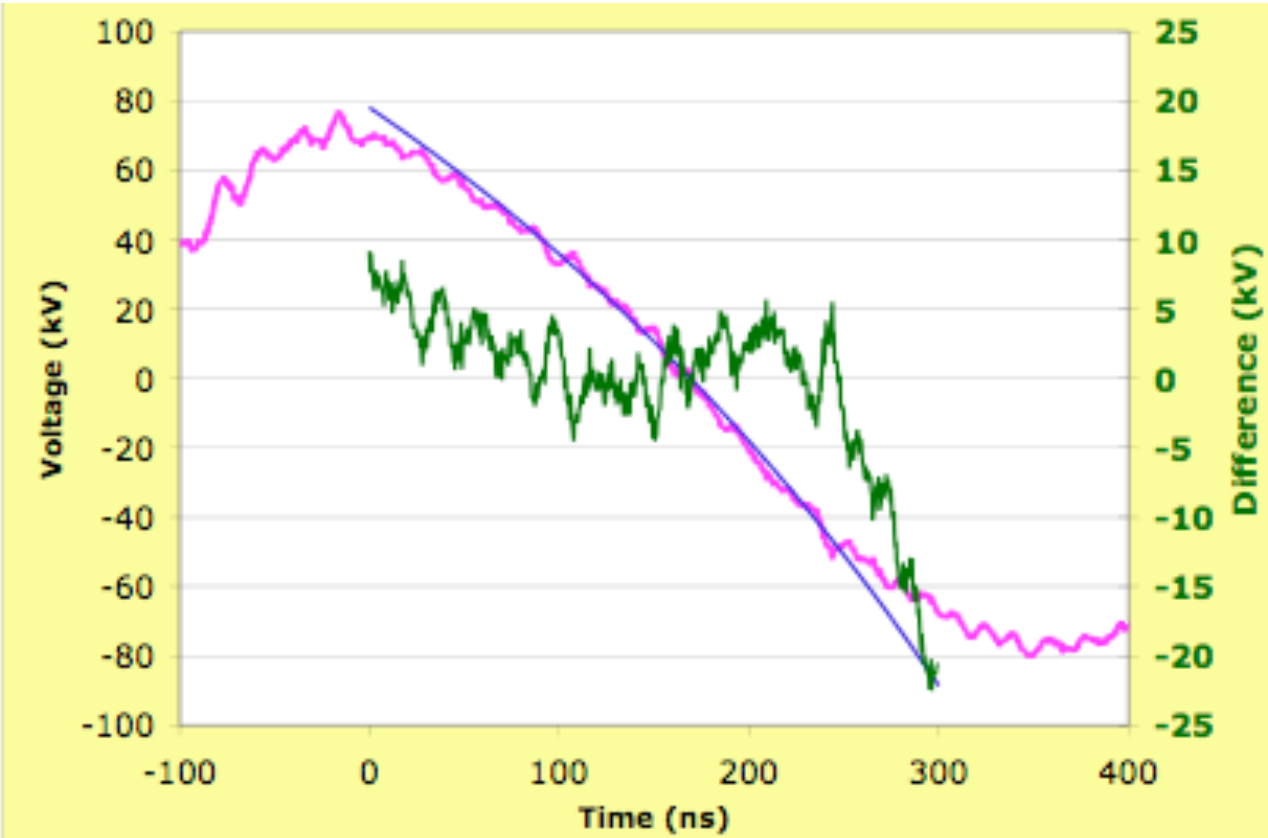
Approach: High-intensity in a short pulse via beam bunching and transverse focusing

The time-dependent velocity ramp, v(t), that compresses the beam at a downstream distance L:

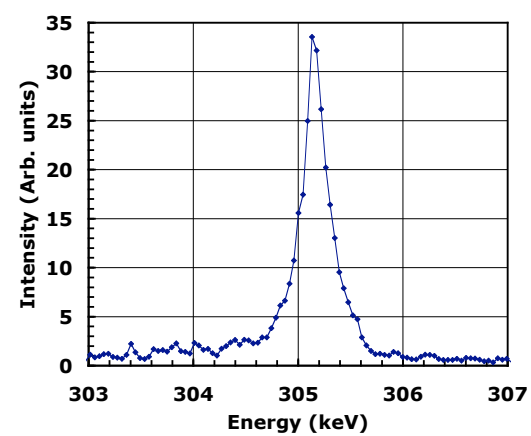
$$v(t) = \frac{v(0)}{(1 - v(0)t/L)}$$

IBM voltage waveform producing this ramp: ($e\phi_o$ = ion kinetic energy.)

$$V(t) = \frac{1}{2} m v^2(t) - \phi_o \qquad t_p = \frac{L}{v_L^{\,2}} \sqrt{\frac{2kT_L}{M}}$$



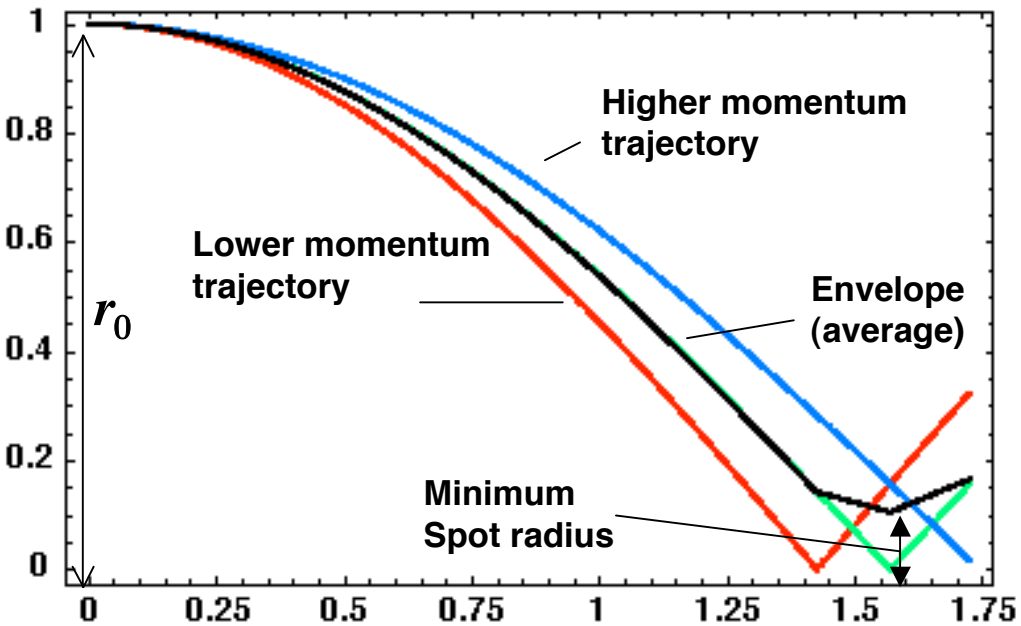
Energy analyzer, unbunched be



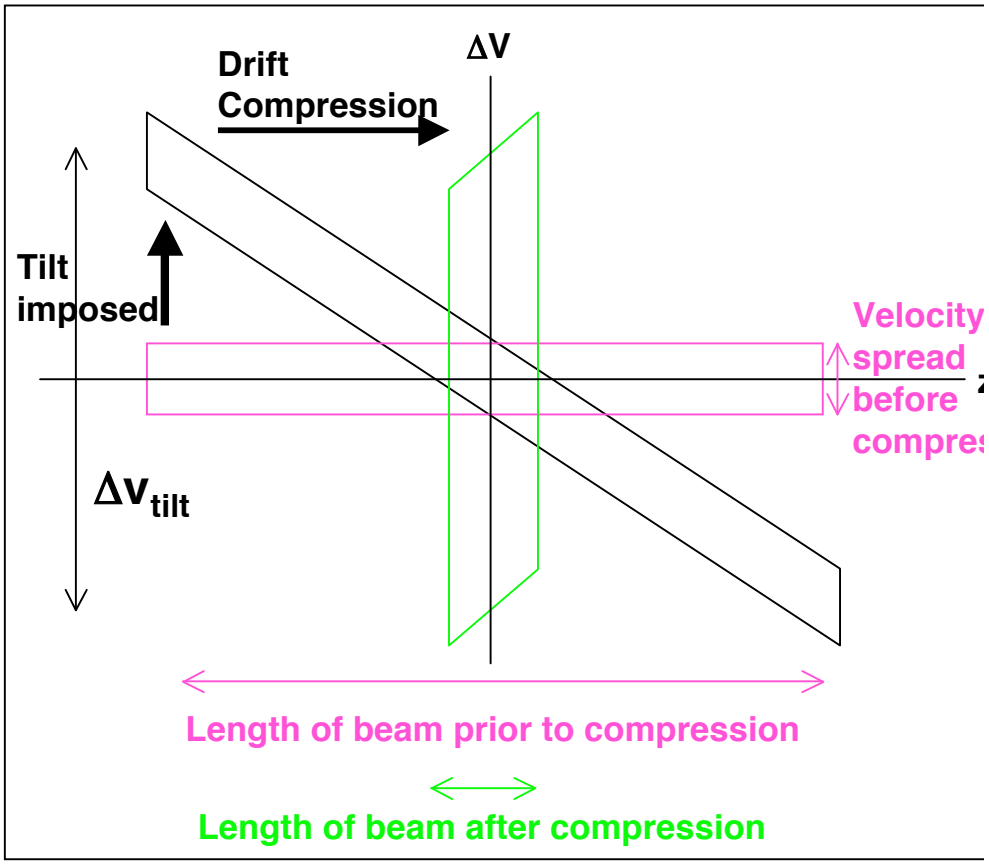
FWHM	keV	0.30
σE	keV	0.13
T_z	eV	2.6E-02

Increasing velocity tilt increases the peak current. Chromatic effects --> larger spot radius.

Transversely, spot radius determined by emittance + chromatic aberrations



Longitudinally, phase space undergoe rotation during drift compression; $<(\delta v/v)^2>^{1/2}$ limits final bunch length



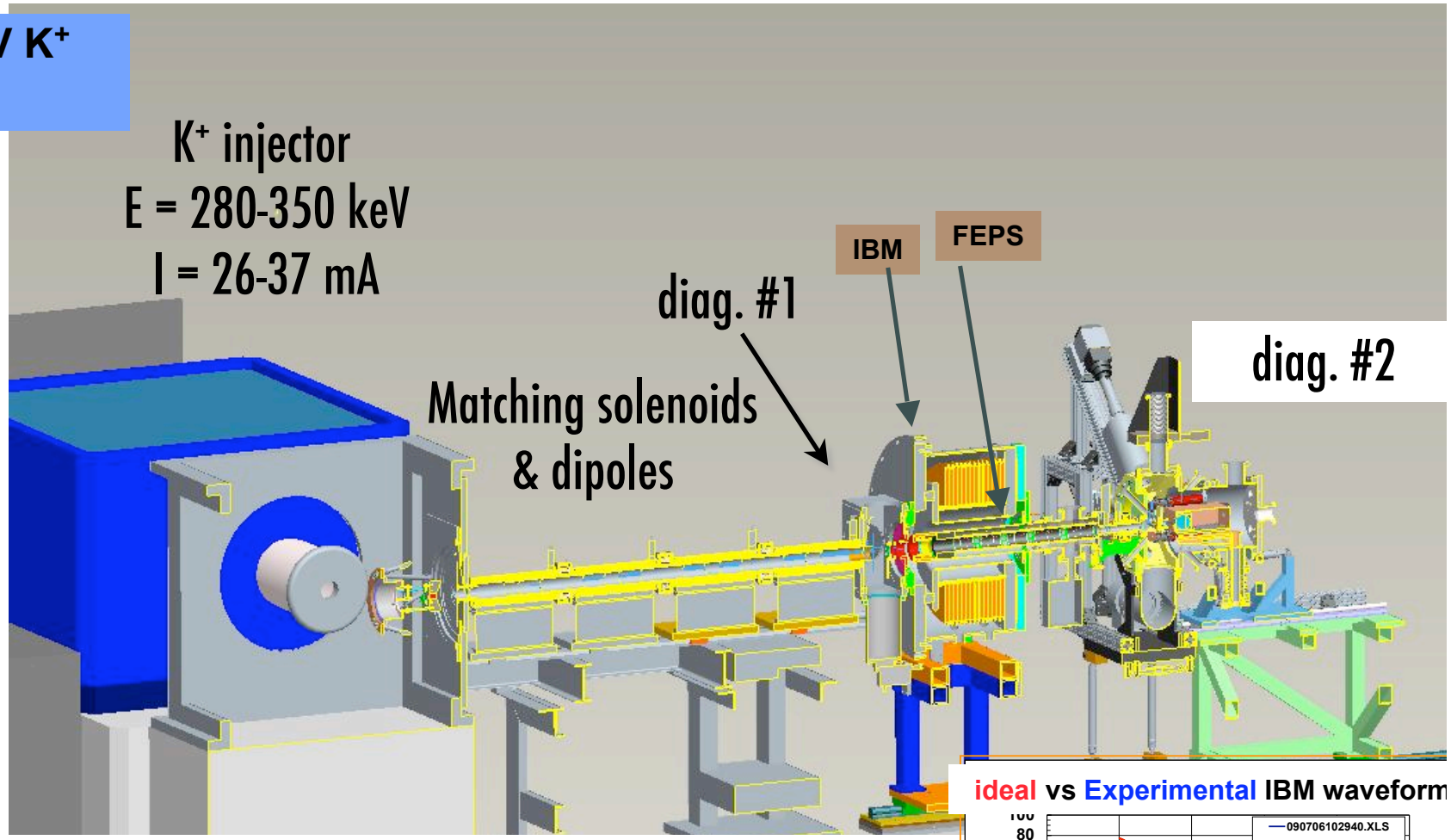
Energy deposition (J/cm²):

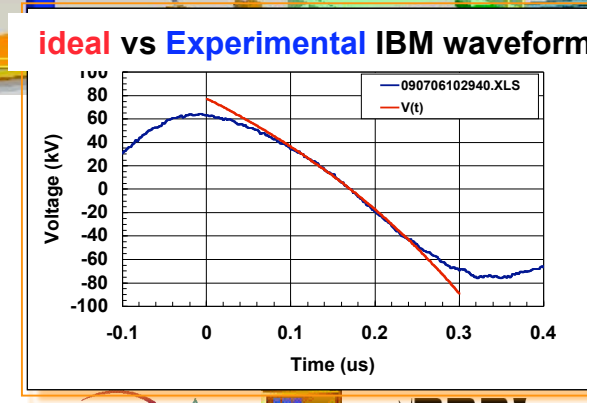
$$E = \frac{4e\phi I\tau}{\pi\varepsilon f\Delta} F_1(\eta)\tan^{-1}\left(\frac{F_2(\eta)r_0^2\Delta}{2f\varepsilon}\right) \propto \sim \frac{e\phi I\tau}{\varepsilon f\Delta}$$

$\Delta = \delta v/v$, $e\phi$ = beam energy, f = final solenoid focal length

On NDCX-1, we recently demonstrated simultaneous transverse focusing and longitudinal compression

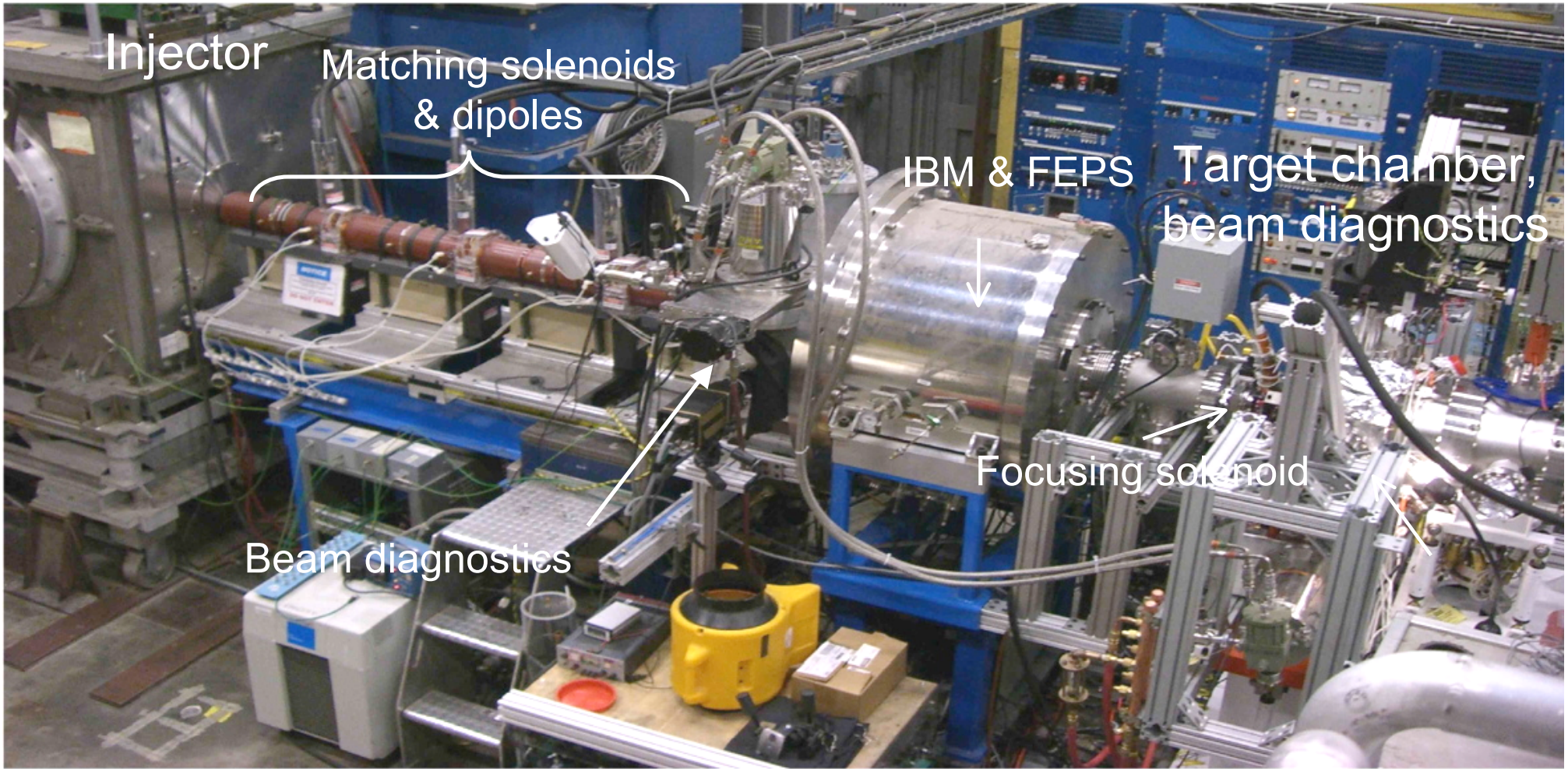
E_i = 0.3 MeV K^+
I_i = 25 mA





<u>Objectives:</u> Preservation of low emittance, plasma column with $n_p > n_b$,
($n_{b\text{-init}} \approx 10^9$ /cm^3,
$n_{bmax} \approx 10^{12}$ /cm^3 now, later, $\approx 10^{13}$ /cm^3)

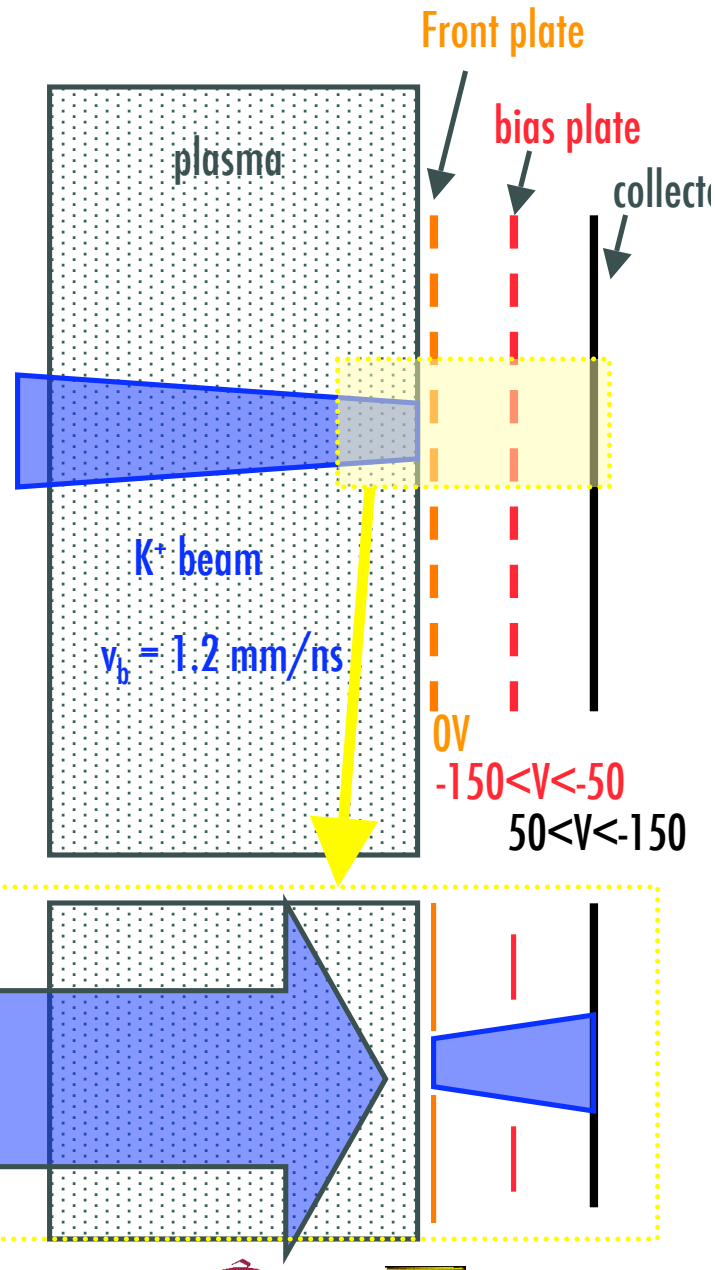
Present configuration of the experiment



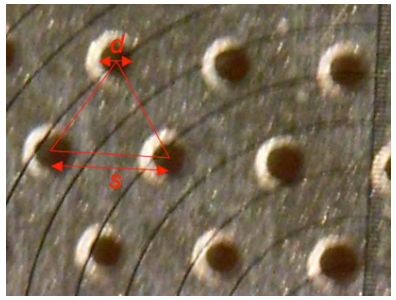
New: steering dipoles, focusing solenoid (8T), target chamber, more diagnostics

To measure the bunched current waveform, the Faraday cup needs:

- Fast time response (~1 ns)
- Immunity from background neutralizing plasma
- 2 hole plates, closely spaced for fast response.
- Hole pitch & diameter small → blocks most of the plasma

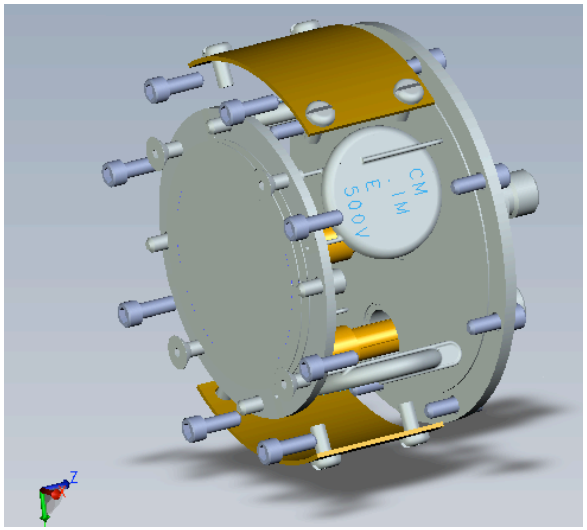


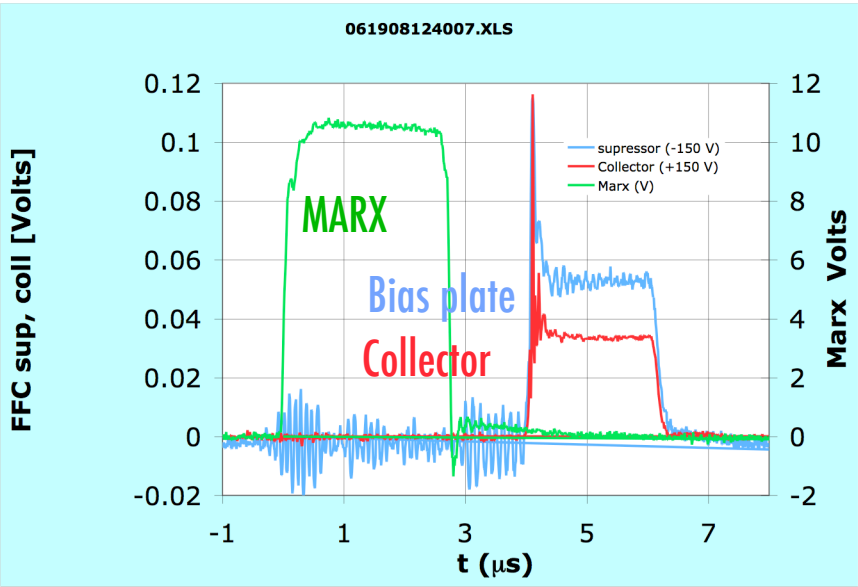
Hole plate front view

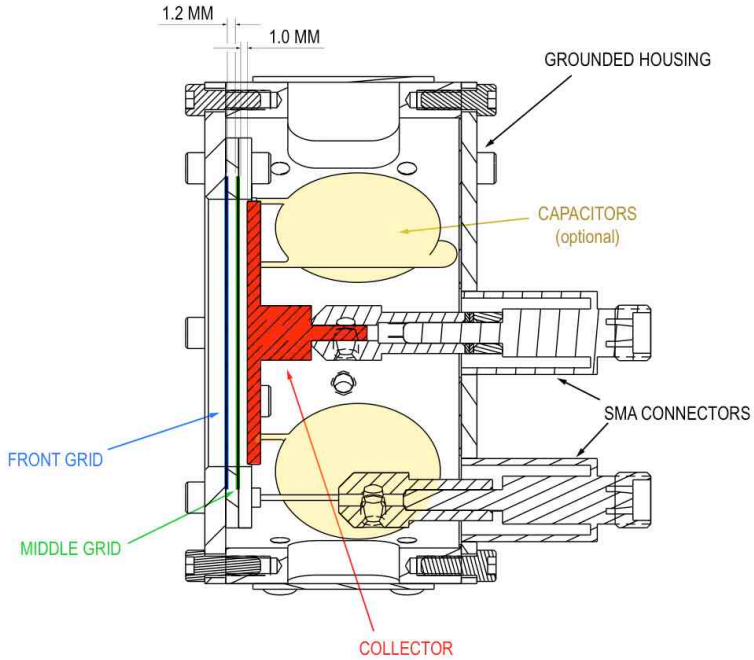


Beam diagnostics - improved Fast Faraday Cup: lower noise and easier to modify

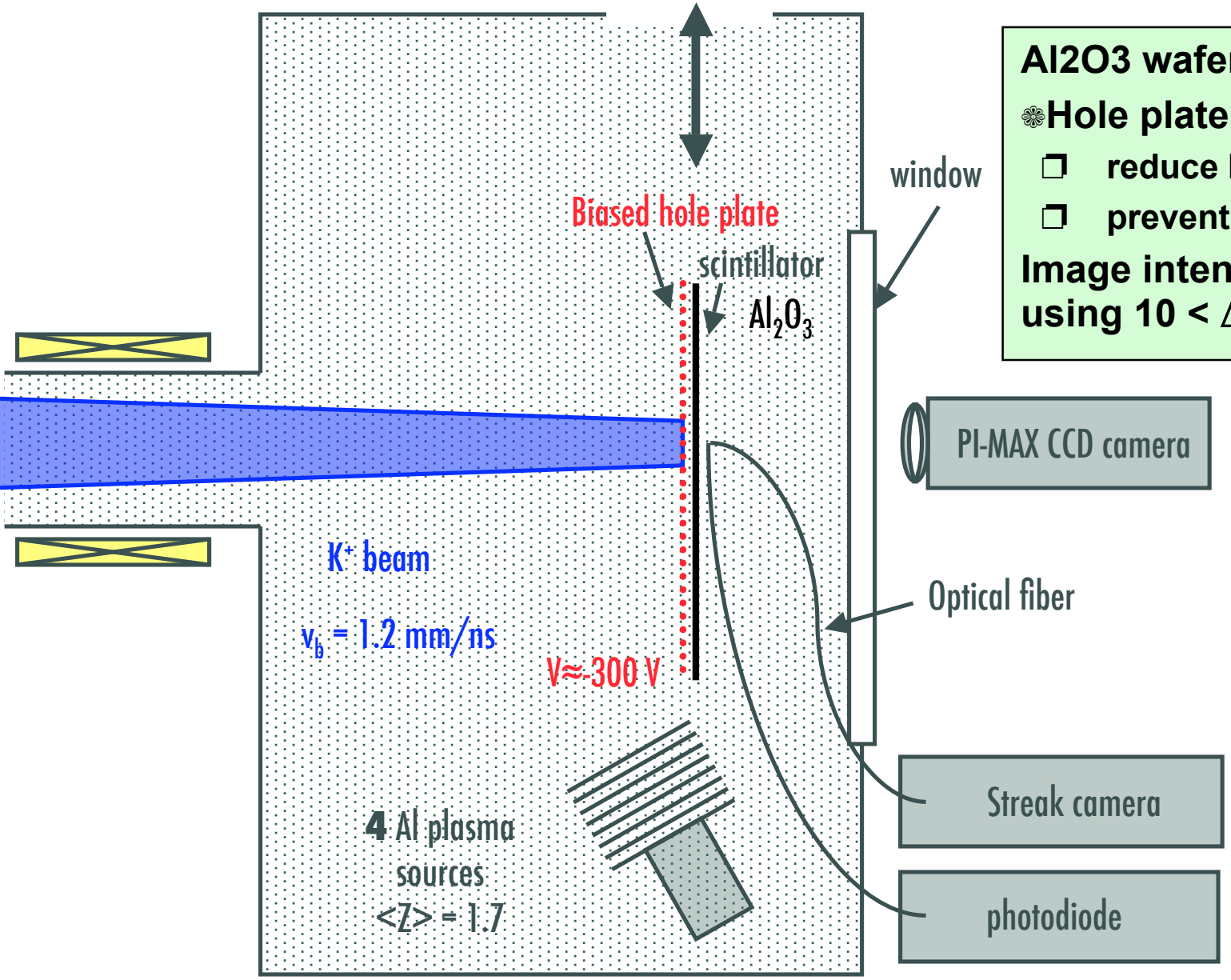
- **Metal enclosure for shielding.**
- **Easier alignment of front hole plate to middle (bias) hole plate.**
- **Design enables variation of gaps between hole plates, and hole plate transparency.**







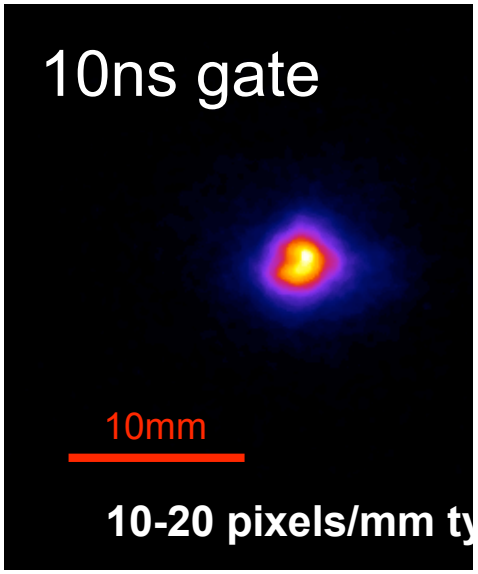
Beam diagnostics in the target chamber: scintillator + CCD or streak camera, photodiode



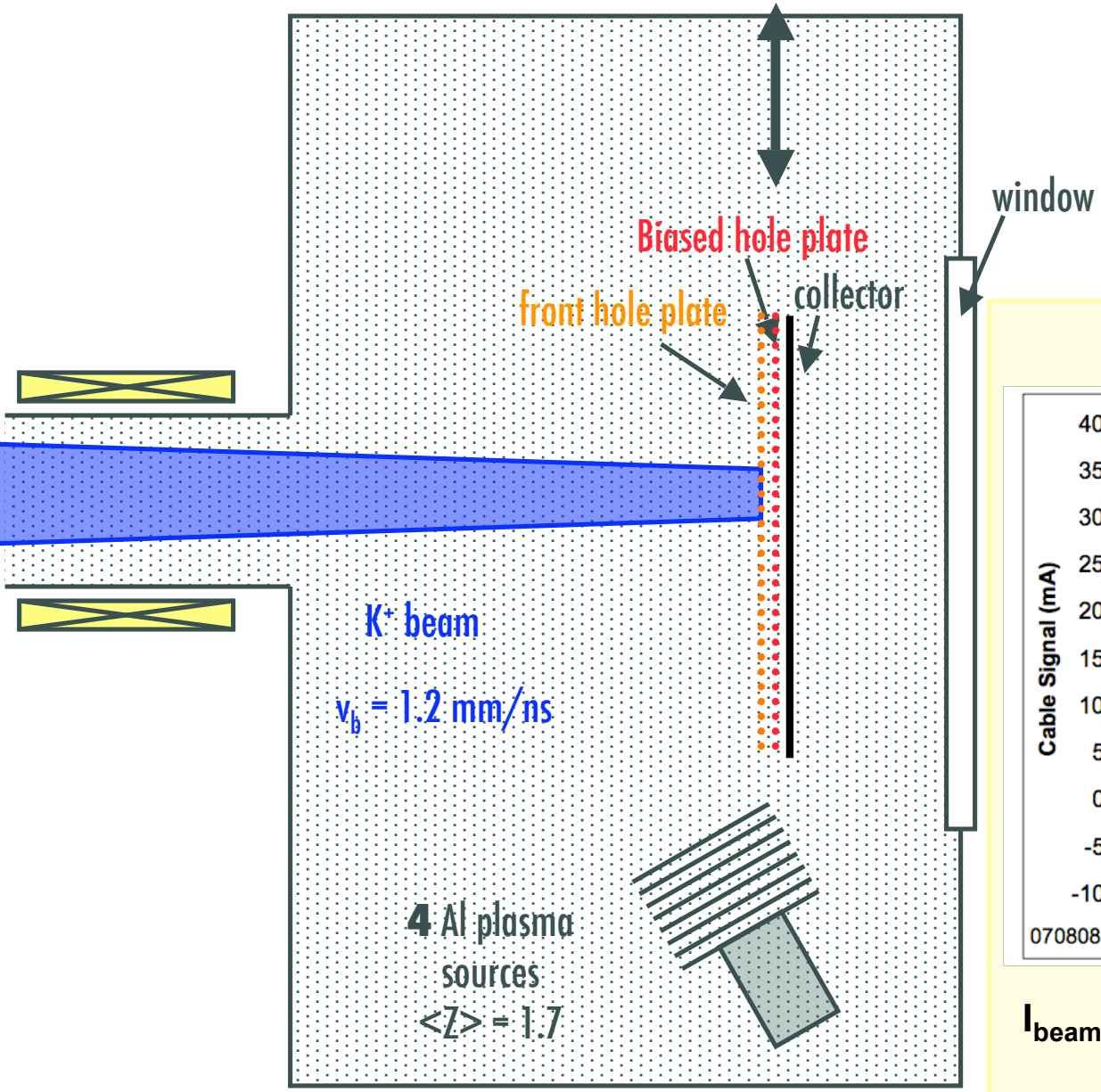
Al2O3 wafer with hole plate:

- **Hole plate to**
  - **reduce beam flux: less damage**
  - **prevent charge buildup.**

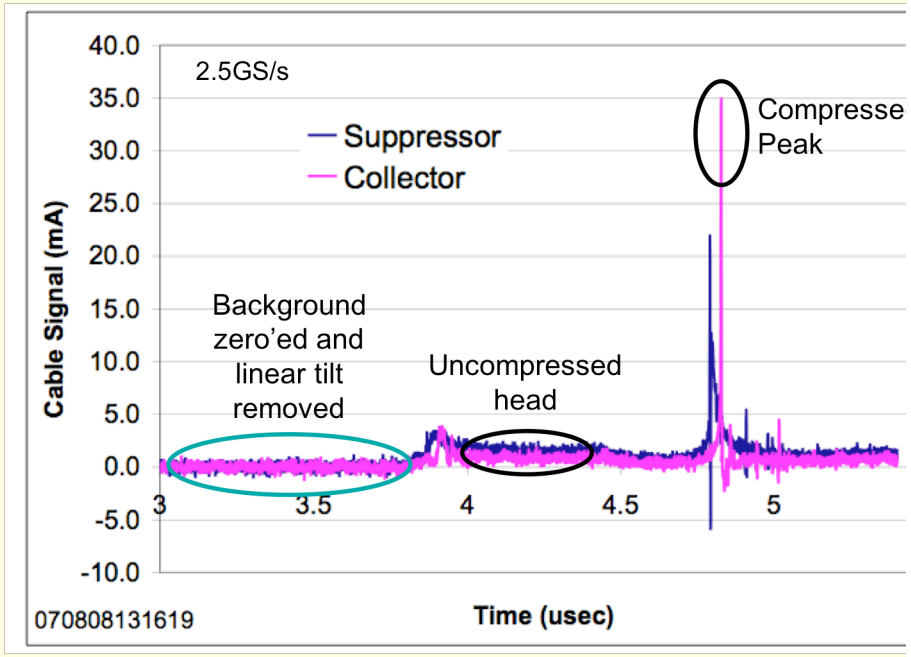
Image intensified CCD camera using 10 < Δt <500 ns gate.



Beam diagnostics in the target chamber: Fast faraday cup



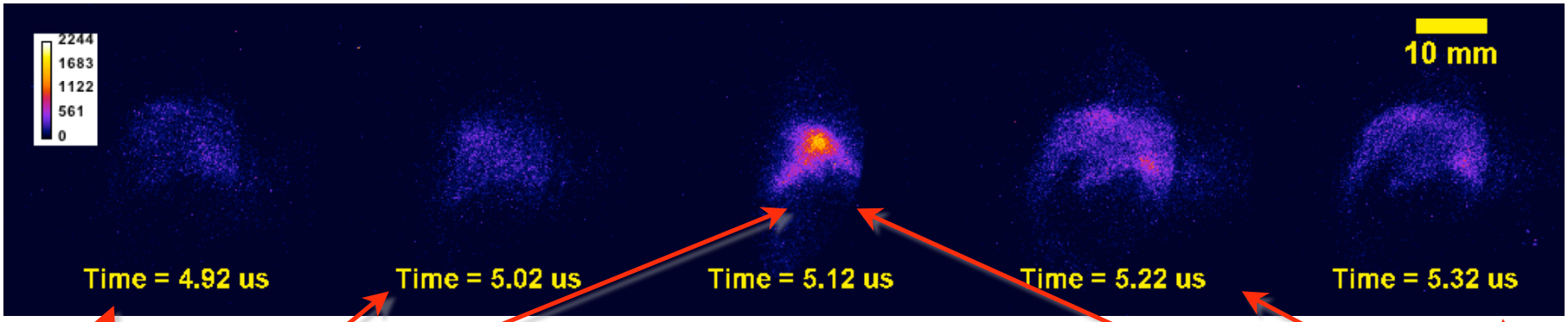
Example waveform

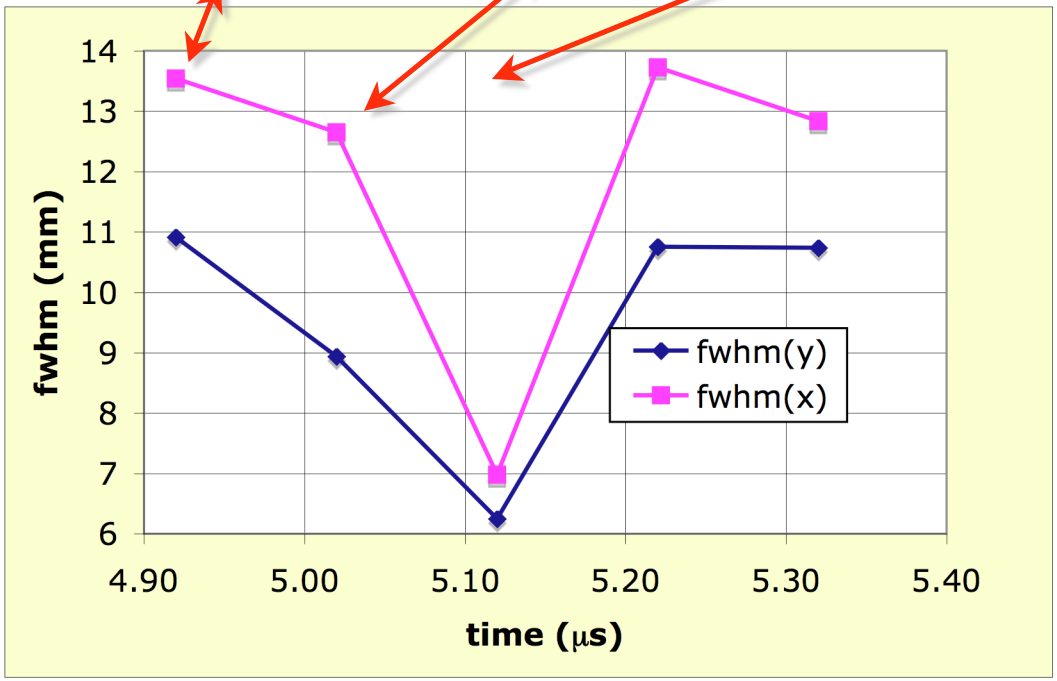


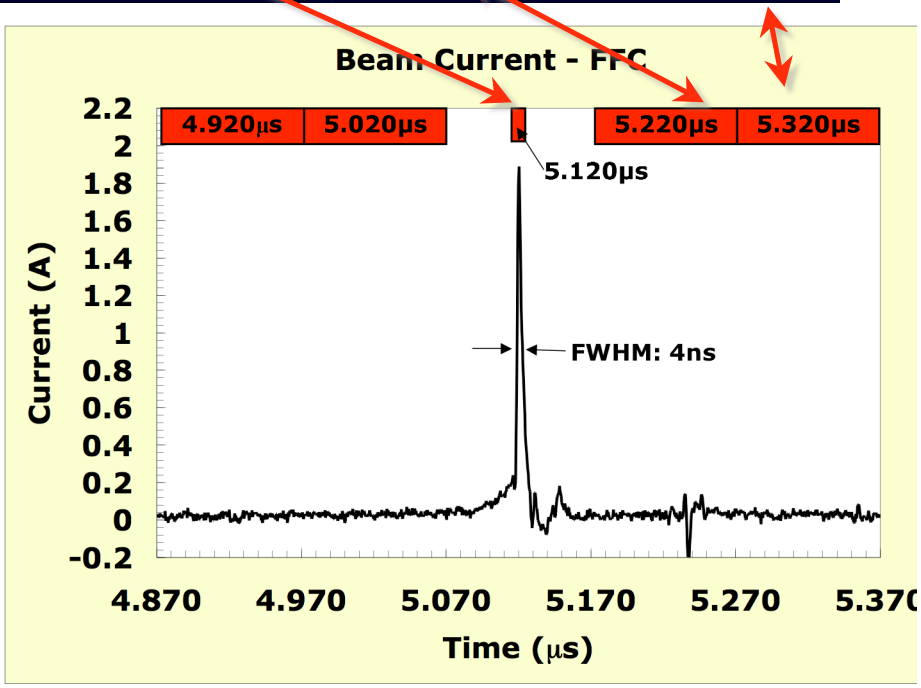
$I_{beam} = I_{collector} \times (\text{transparency})^{-1}$

$= 35\ \text{mA} \times 44 = 1.5\ \text{A pea}$

Minimum spot size @ same time as peak compression



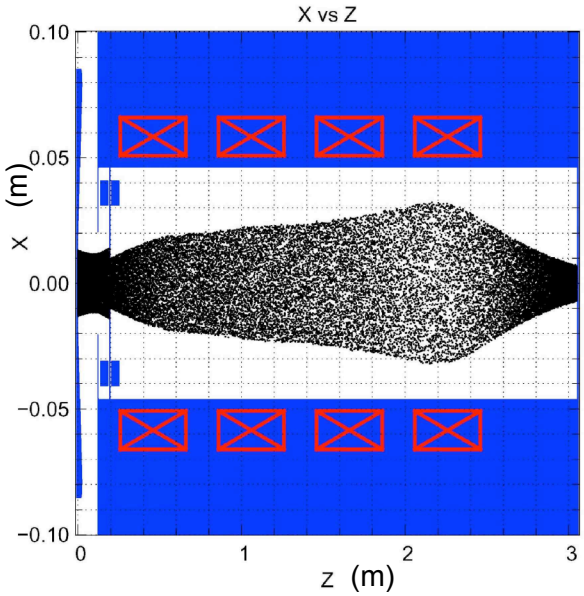


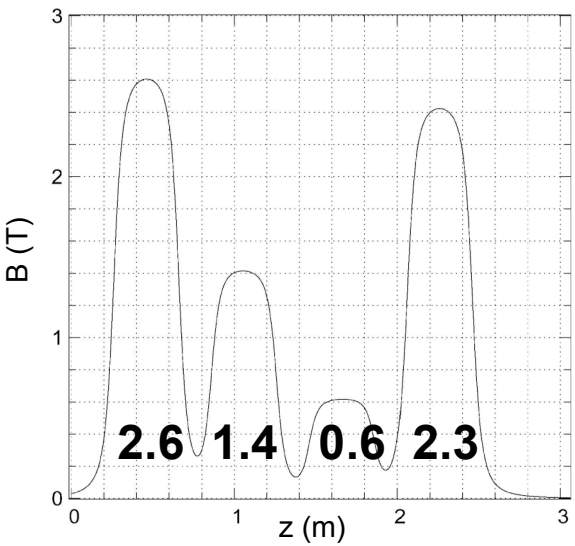


2X reduction in the spot size (4X increase in beam intensity) brings the peak beam density to the ra

$n_b \approx 10^{11}$-10^{12} cm^{-3}.

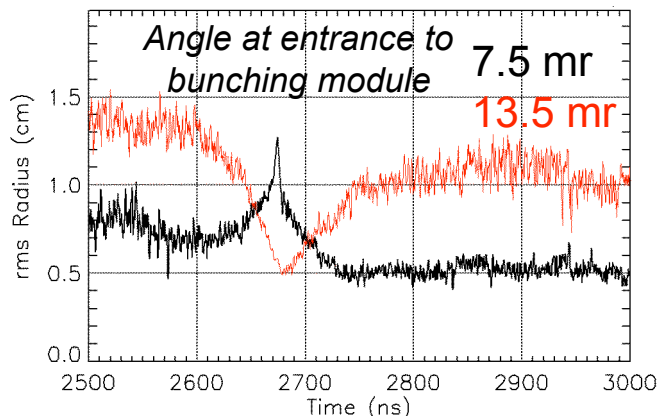
simultaneous longitudinal compression and transverse focusing, compared to simulation.

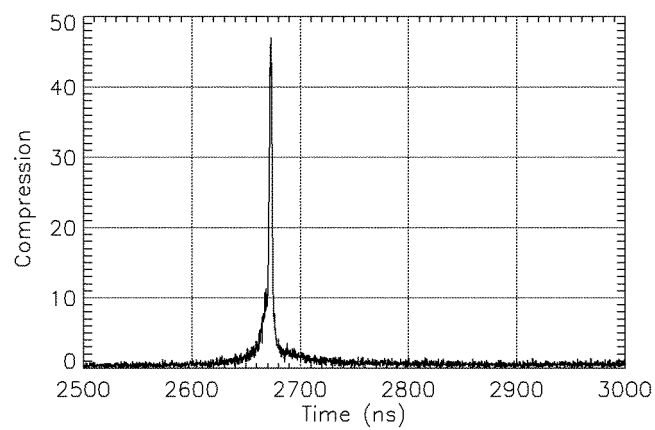




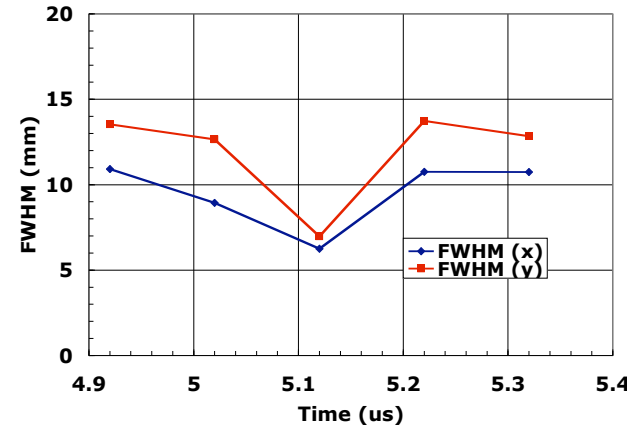
Net defocusing in gap due to energy change, E

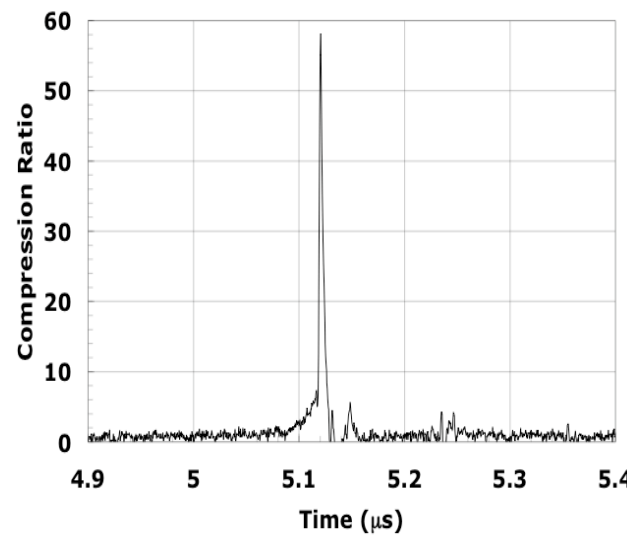
LSP Calculation



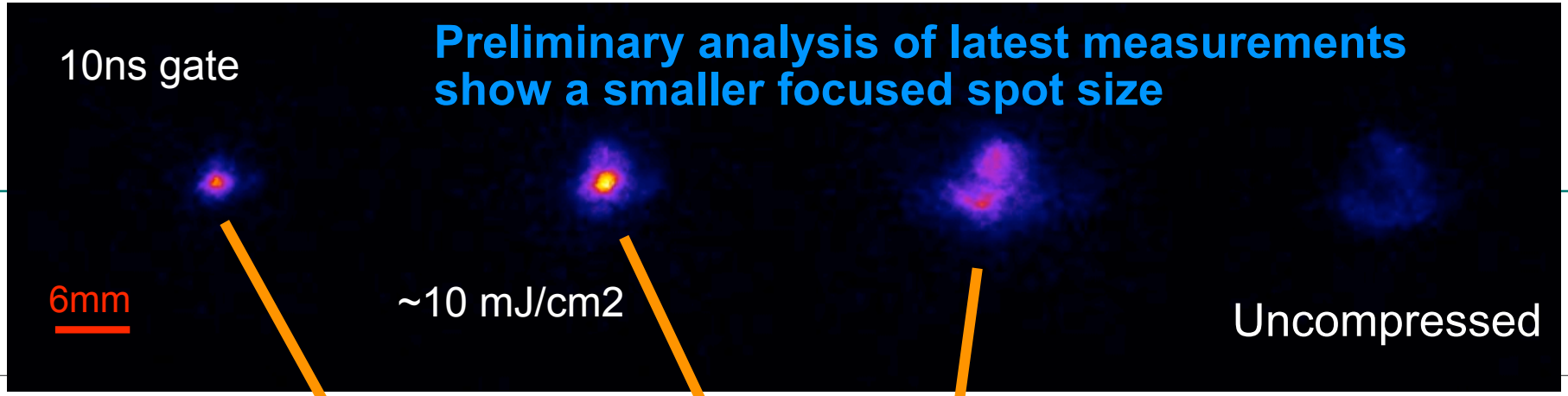


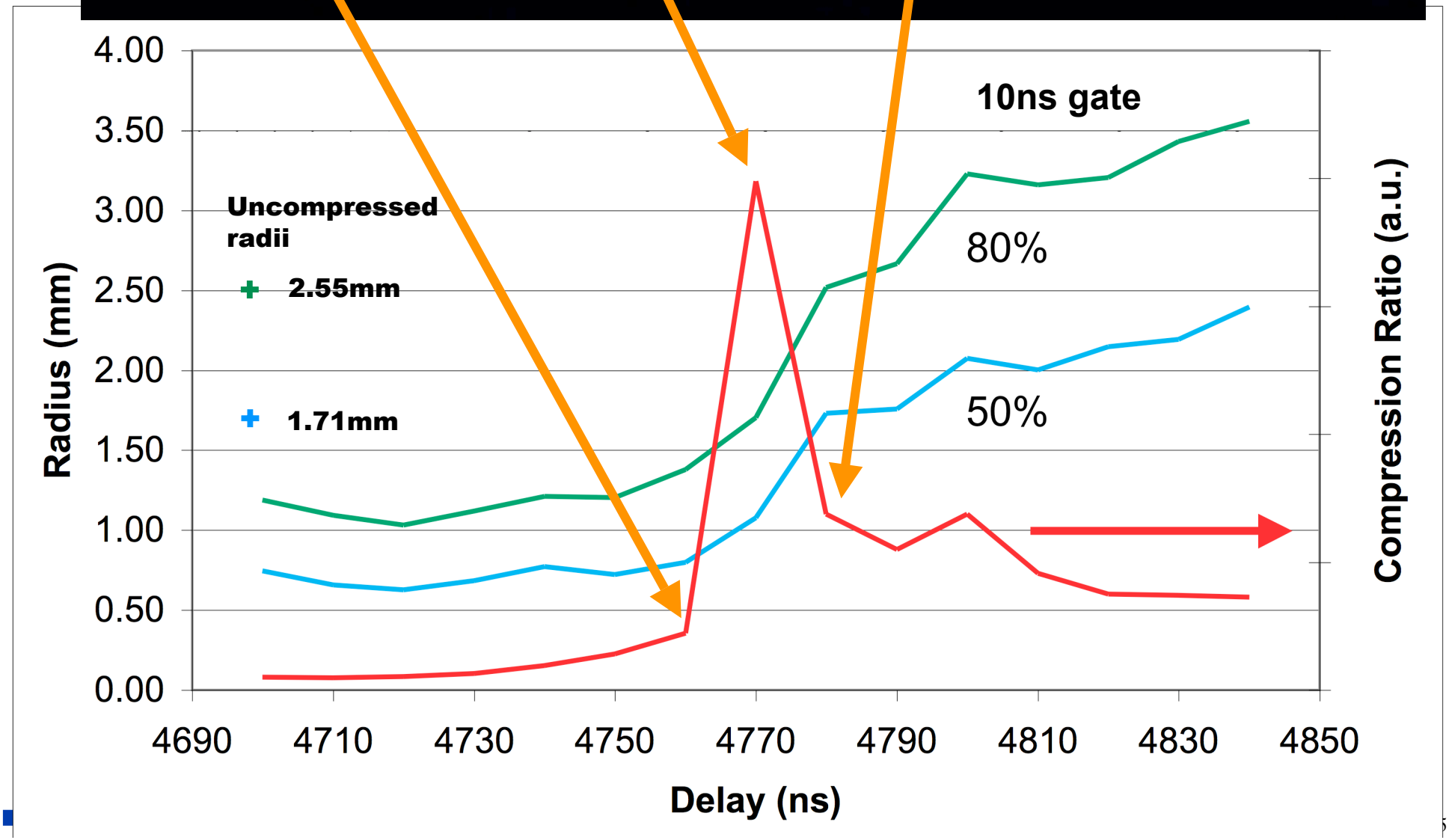
Experiment





Preliminary analysis of latest measurements show a smaller focused spot size



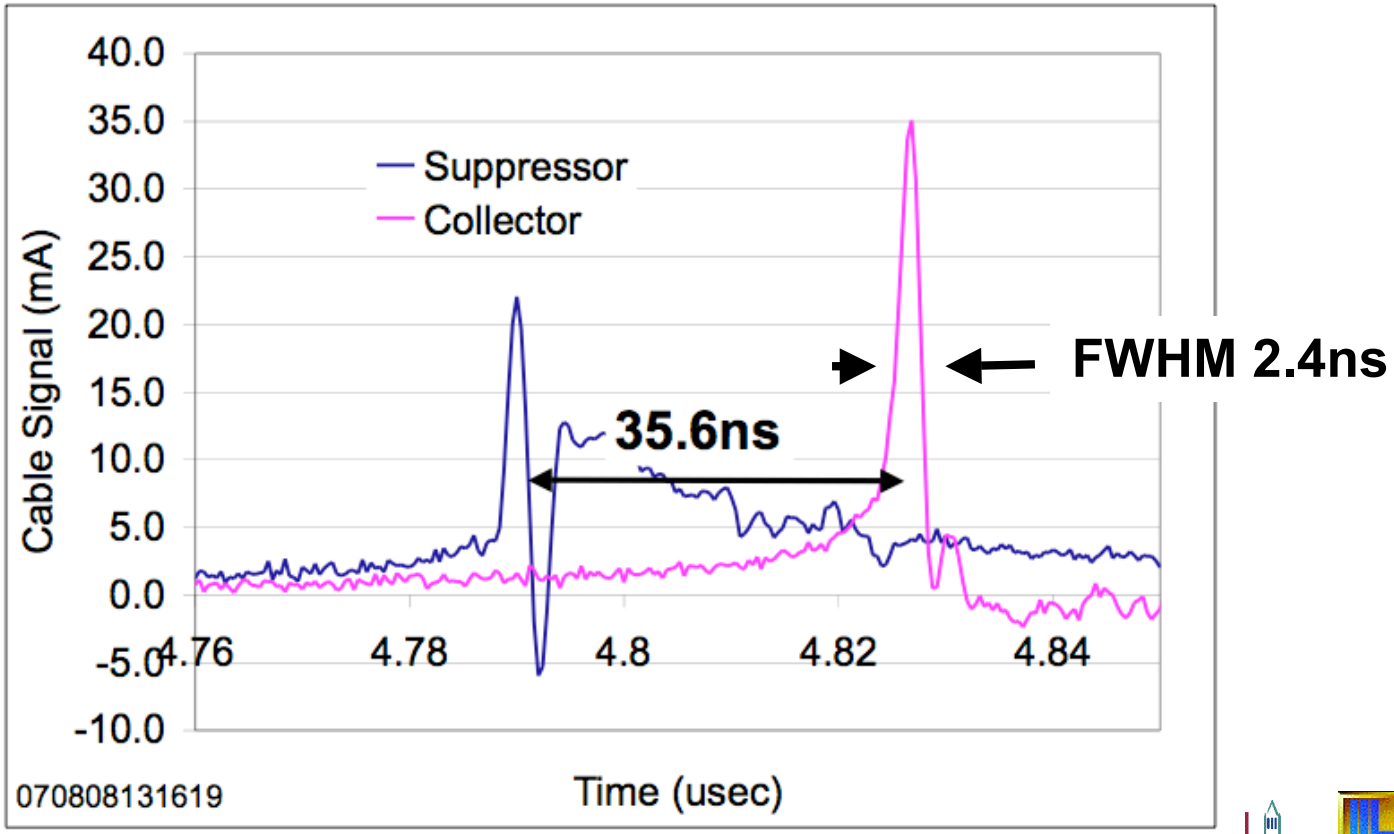


Improved focusing can be expected due to…

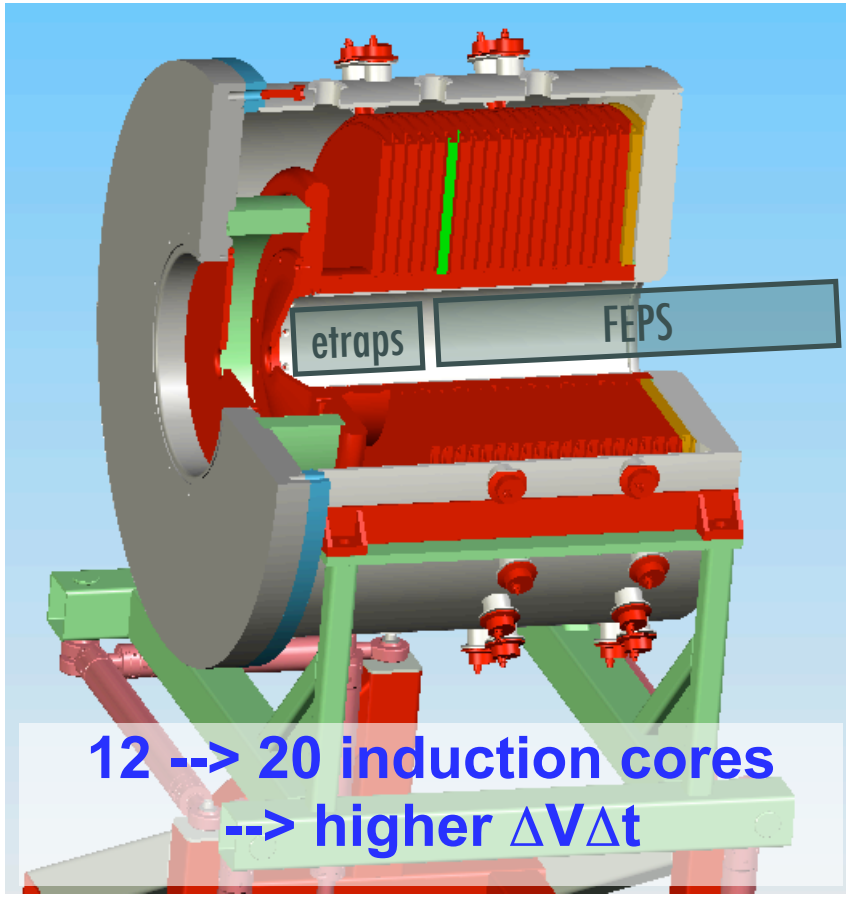
Higher plasma density near the focal plane.

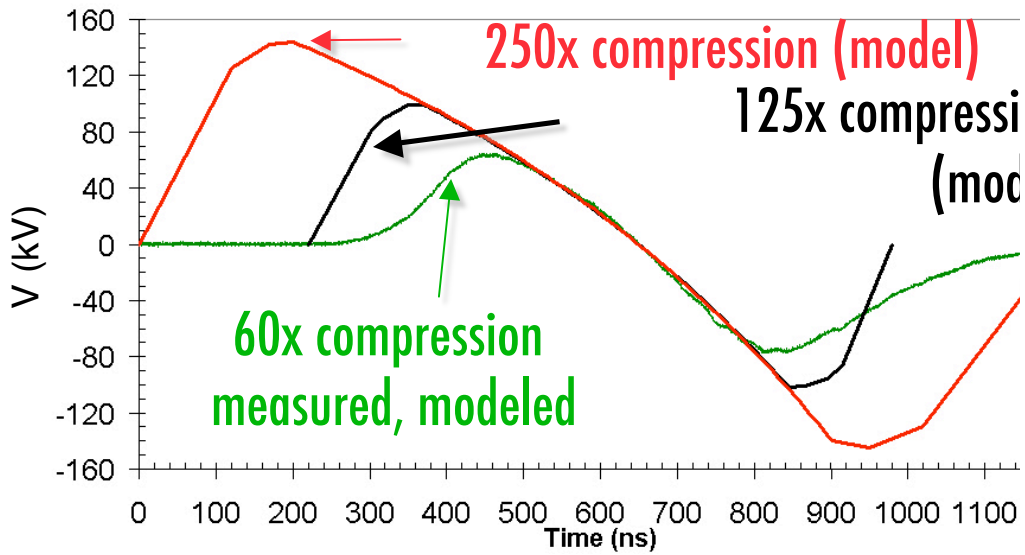
5 Tesla --> 8 Tesla final focusing solenoid.

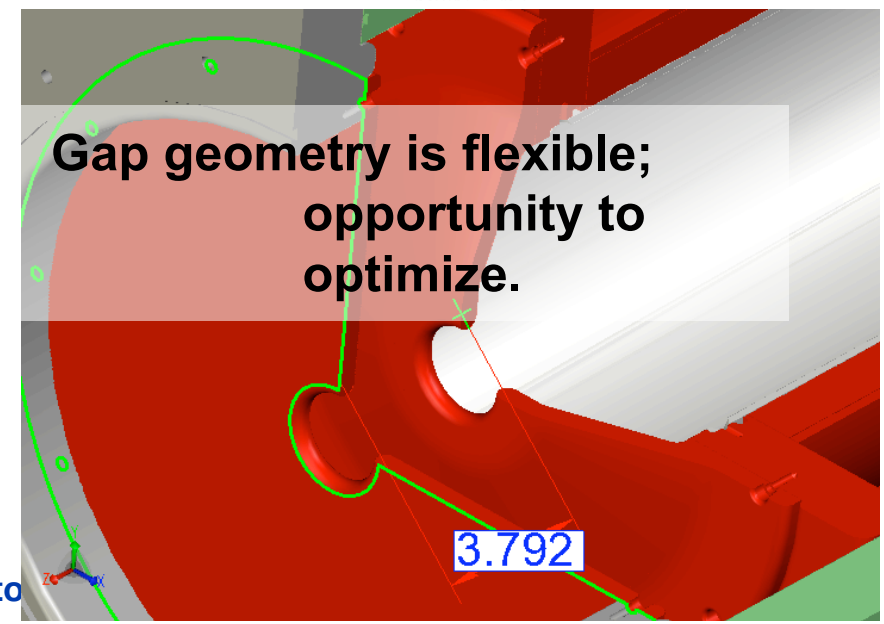
We need to compare models and experiments.



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



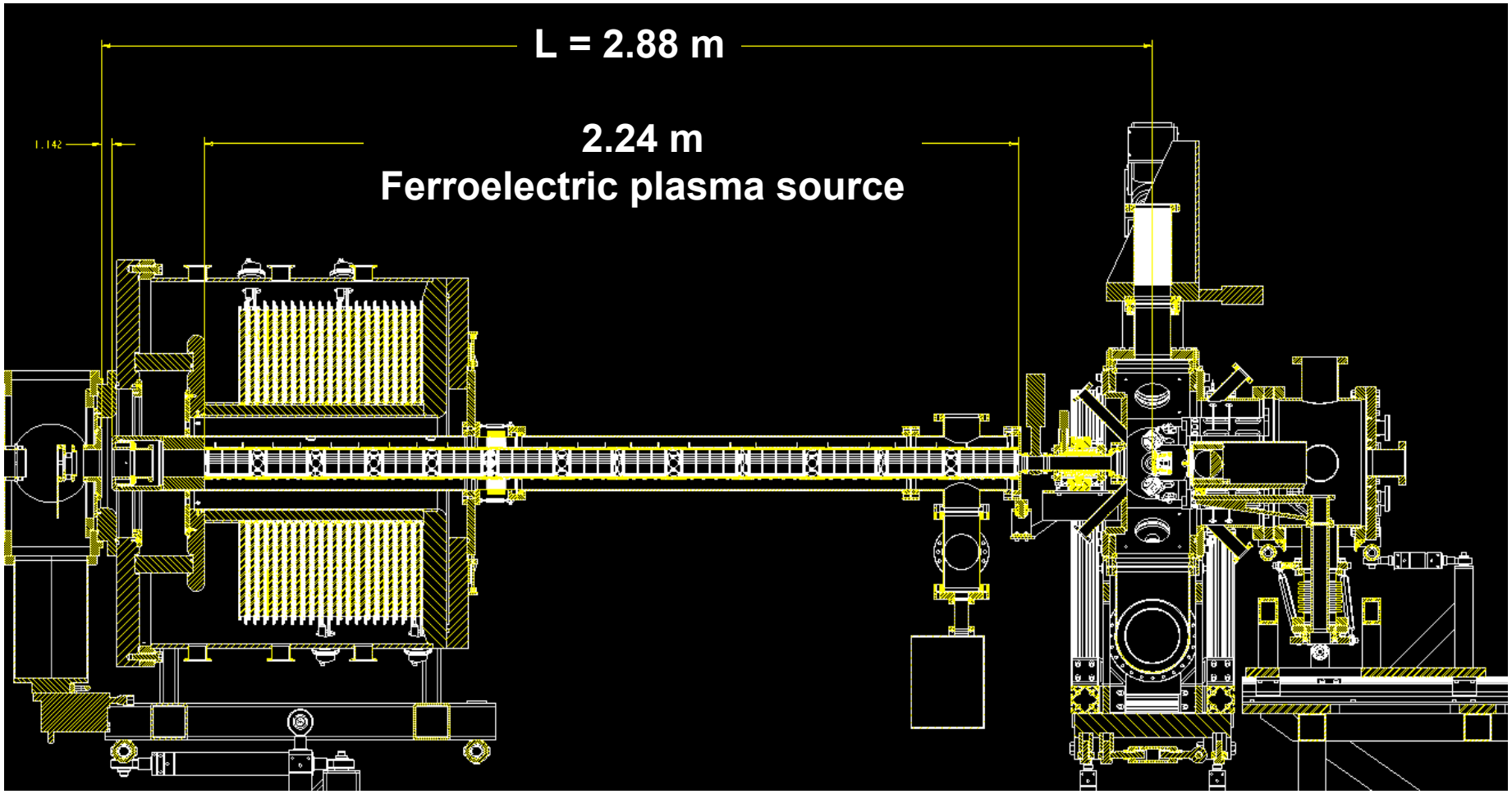




FEPS = ferro-electric plasma source

Beam experiments in 2008.

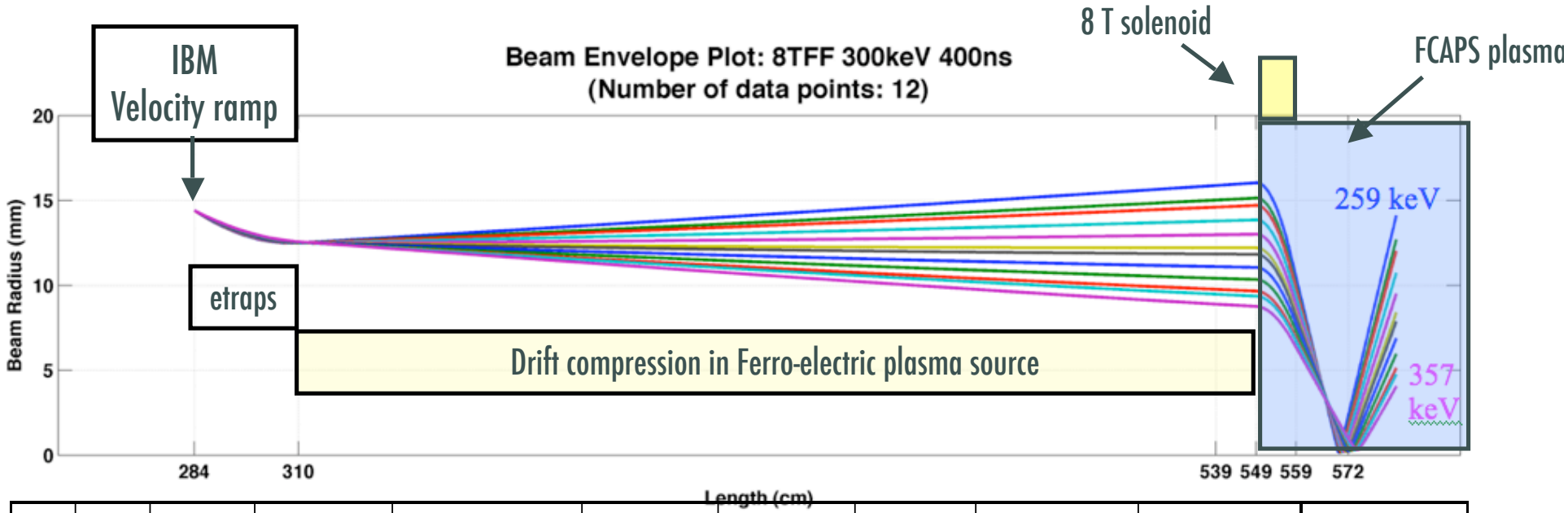
New drift compression section, L=2.88 m, Longer to cap ΔV_{peak} & chromatic effects



It is advantageous to lengthen the drift compression section by 1.44 m via extension of the FEPS

Po-5 Efthimion et al., Ferro electric plasma source

chromatic effects - as represented by slices of beam of different energy



	FF (T)	t (ns)	initial kinetic energy (keV)	a(z=284) (mm)	a' (mrad)	Current at focus (Amps)	pulse width @ focus (ns)	E (J/cm2) envelope	E (J/cm2) LSP2	E (J/cm2) (Eq. 1)
a)	0	200	300	21.50	-23.80	3.08	1.69	0.06		
b)	8	282	300	9.55	-9.82	4.01	1.83	0.39	0.30	0.59
c)	8	400	300	14.40	-13.70	3.23	3.22	0.82	0.69	0.94

Comparison of LSP, the envelope-slice model, and the simple analytic model.

(a) no final focusing solenoid.

(b) New IBM, the final focusing solenoid (B_{max} = 8 Tesla) L_{drift} =144 cm, **<u>present setup</u>**

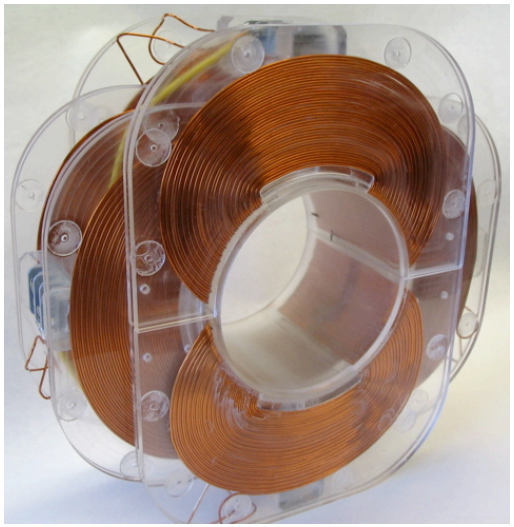
(c) with twice the drift compression length (L=288 cm) as the present setup.

Alignment: Beam centroid corrections are required to minimize aberrations in IBM gap & for beam position control at the target plane

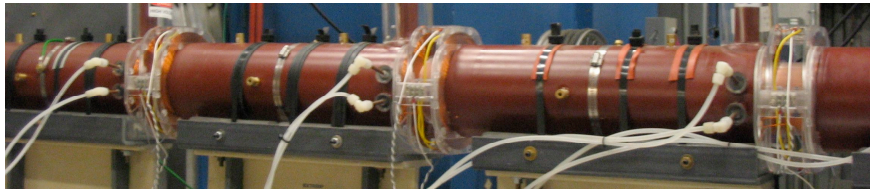
Alignment survey: mechanical structure aligned within 1 mm.
Manufacturing imperfections (coil w.r.t support structure) not included.

Observe < 5 mm, <10 mrad offsets at exit of 4 solenoid matching section without steering dipole correction.

We can correct the centroid empirically with steering dipoles at the exit of the solenoid matching section.

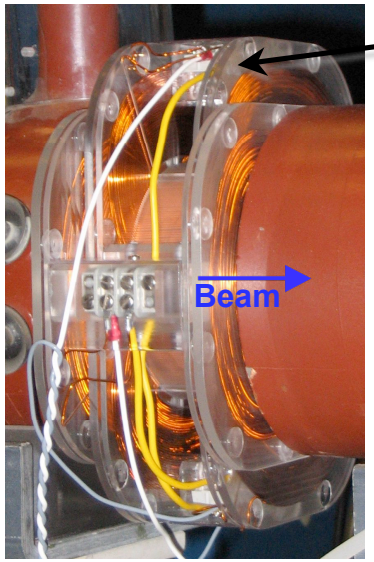


3 dipole pairs between solenoids



$I_{max} \sim 200$ A

$B_{max} \sim 0.5$ kG



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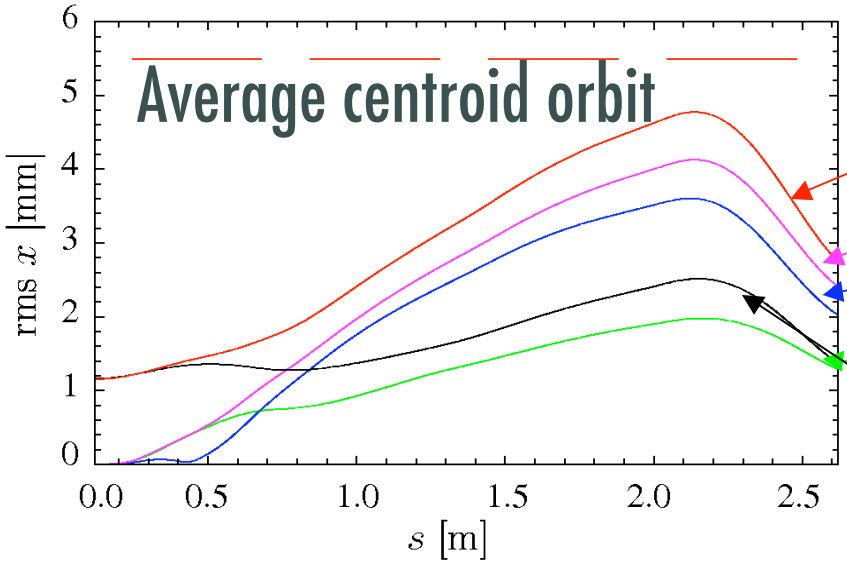
Next step: Minimization of the centroid betatron amplitude. Requires knowledge of the absolute offsets.

Ensemble of 10,000 random error combinations to estimate sensitivity, Lund, Po-24



Errors:

All

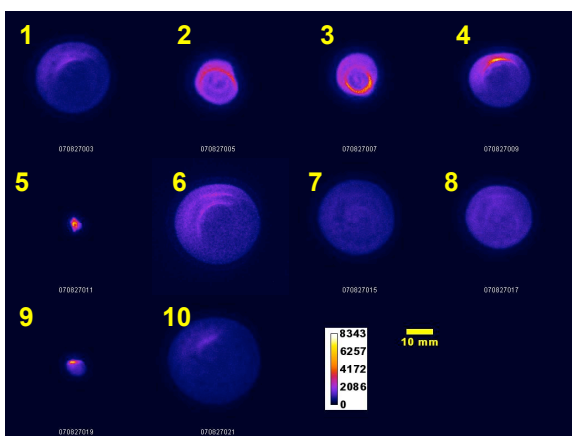
Solenoids: Dispacements +tilts

Solenoids: tilts only

Solenoids: displacements only.

Initial conditions only (ion source)

Beam centroid measured without dipoles will be used to solve for beamline offsets

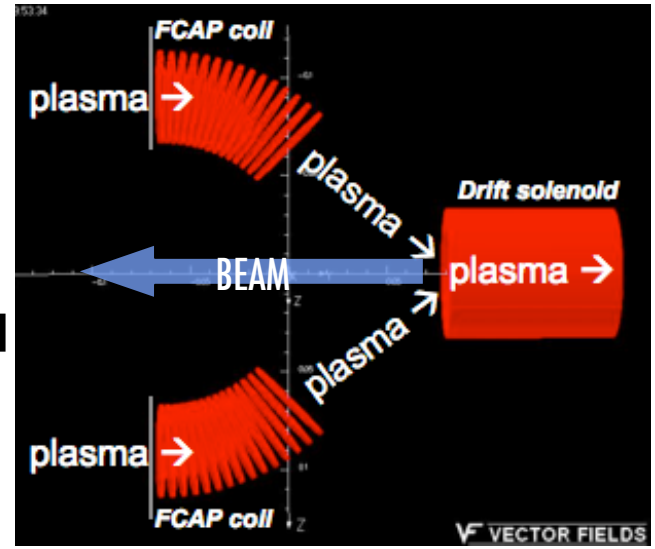


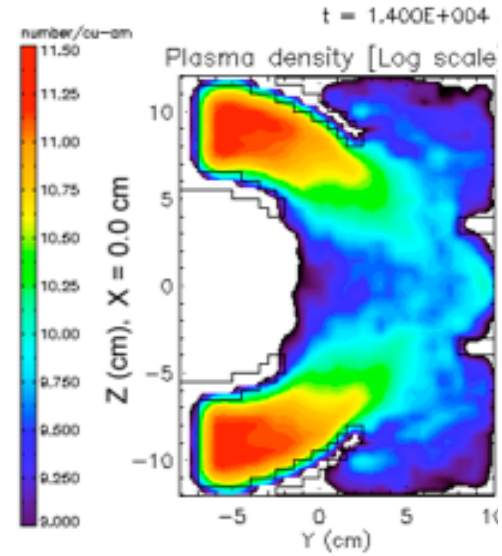
Beam distribution J(x,y) at exit of 4 solenoid matching section. We plan more measurements to verify this method

Cathodic arc and ferro-electric plasma sources for neutralized drift compression.

Filtered cathode arc plasma source (FCAPS)

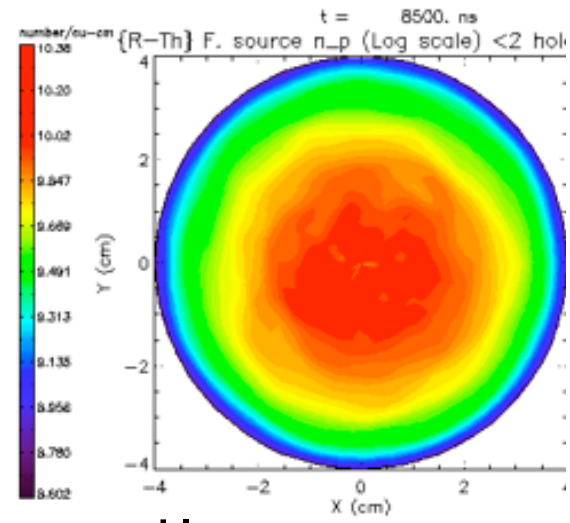
- Injection from end into region upstream of target plane and into final focusing solenoid
- $n_e \approx 5 \times 10^{11}$ cm^{-3} measured with "bent" filters designed to limit neutral particle flux.





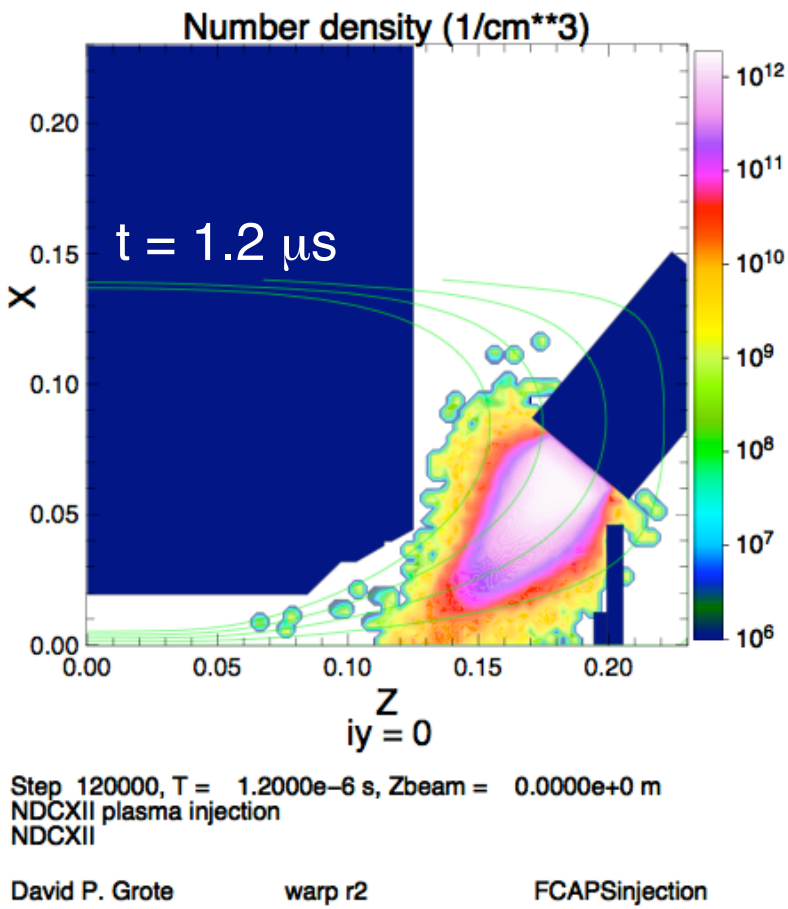
Ferro-electric plasma source (FEPS)

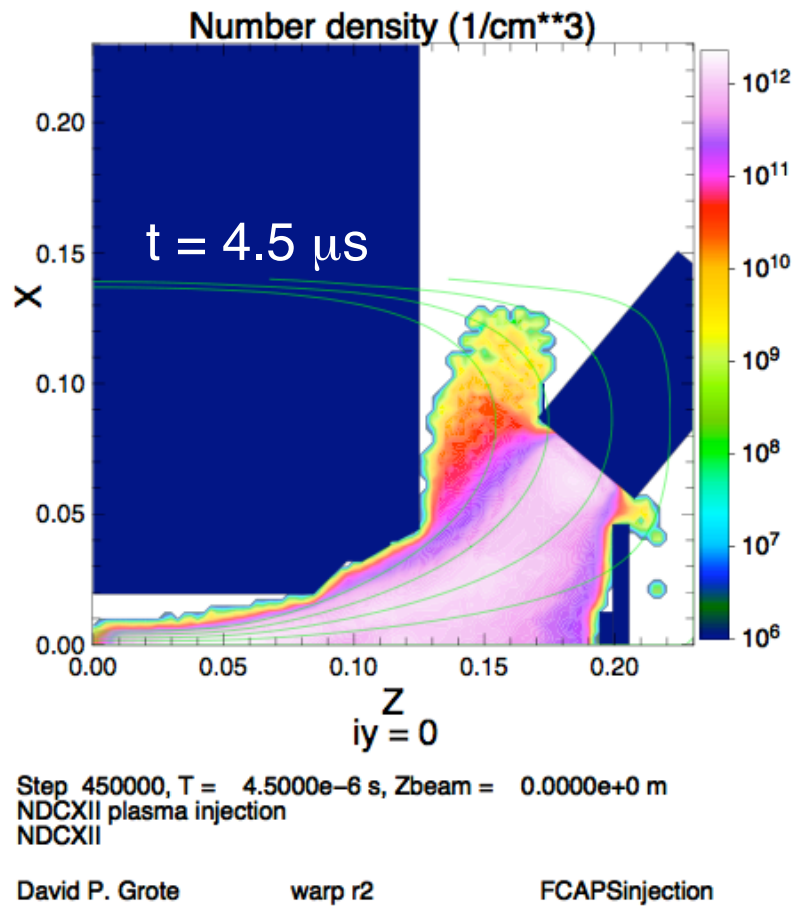
- Generated from cylindrical surface
- Installed downstream of IBM
- $n_e \approx 2\text{-}8 \times 10^{10}$ cm^{-3}



Both approaches are not yet optimized, higher density possible.

Warp can now simulate injection from Cathodic-Arc Plasma Sources





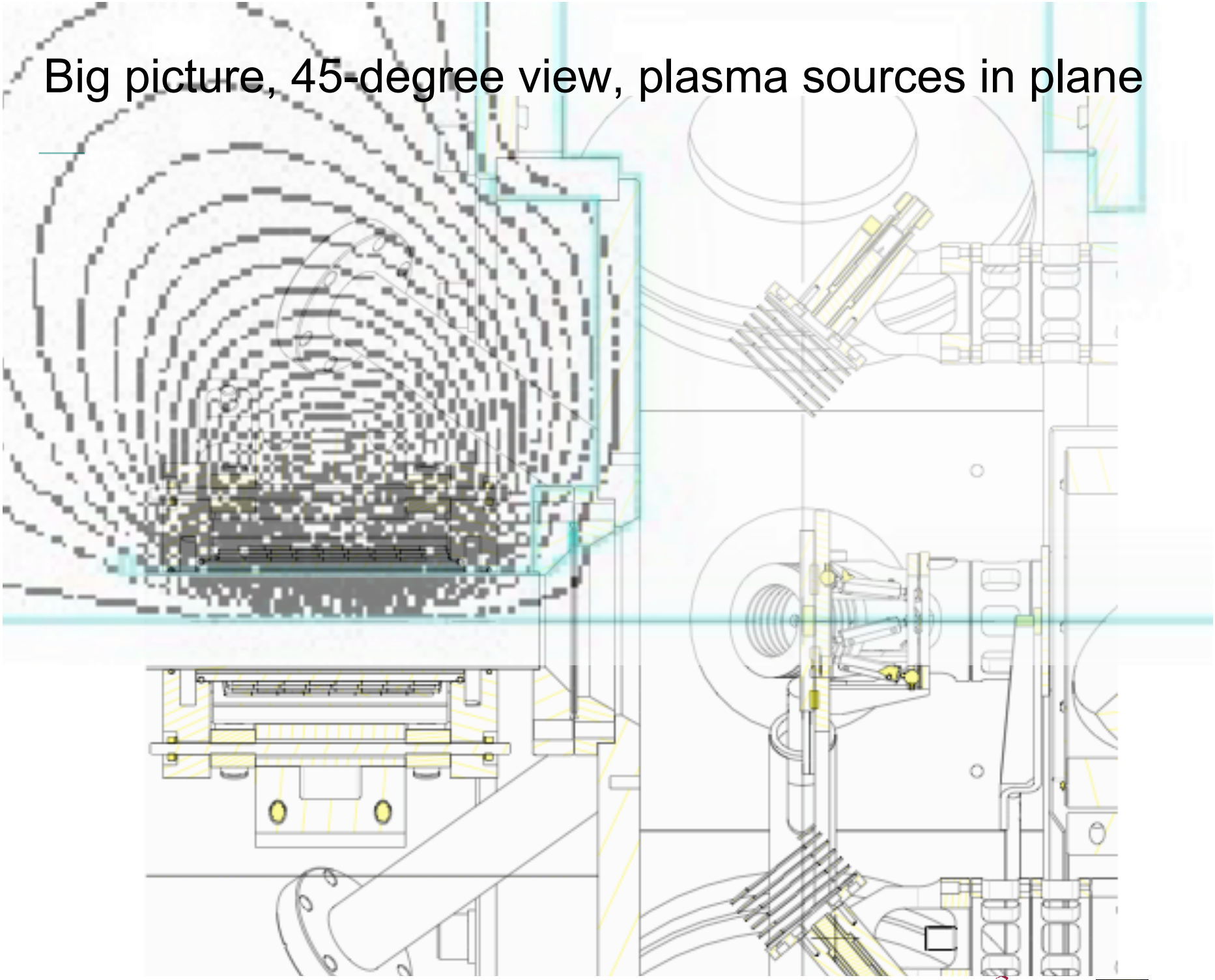
Next :

-comparison of runs with Eddy fields calculated from transient calculation in Ansys.

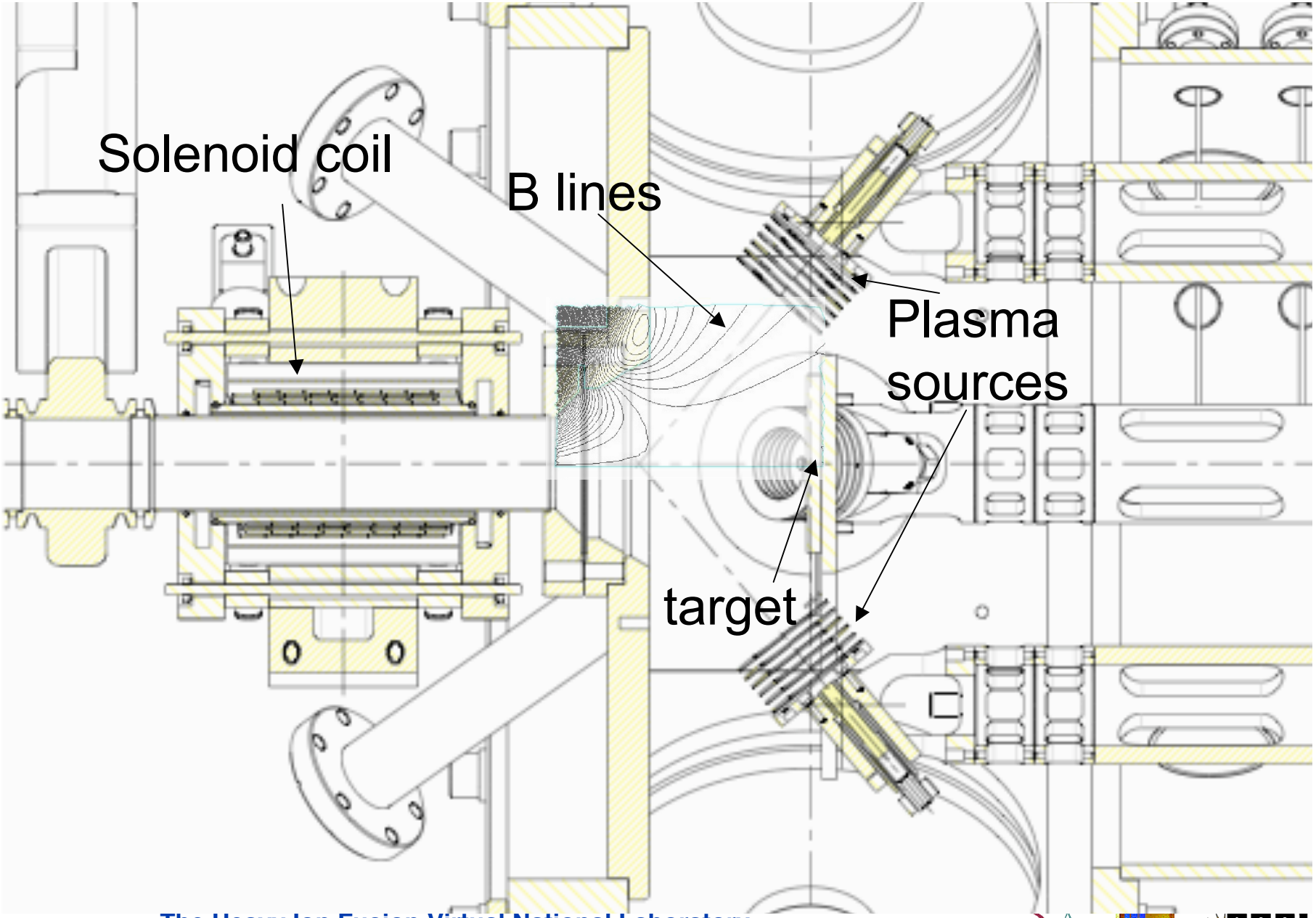
-Implicit model: hope for at least 10x speed-up in computation time.

-Fields from filters

Big picture, 45-degree view, plasma sources in plane

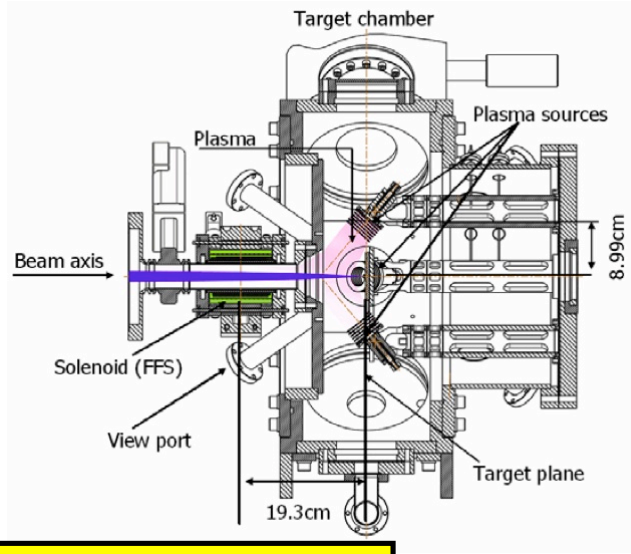


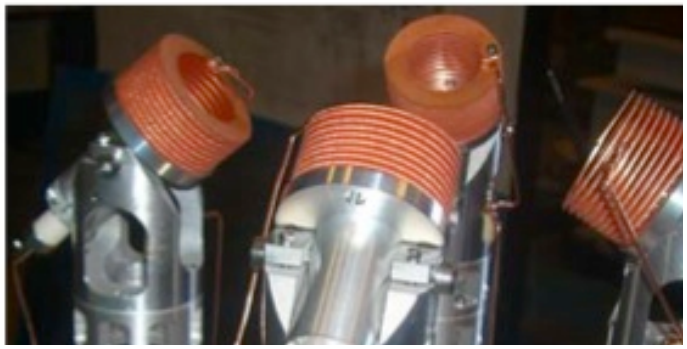
45 degree view -- zoomed field lines only



Improved plasma source orientation

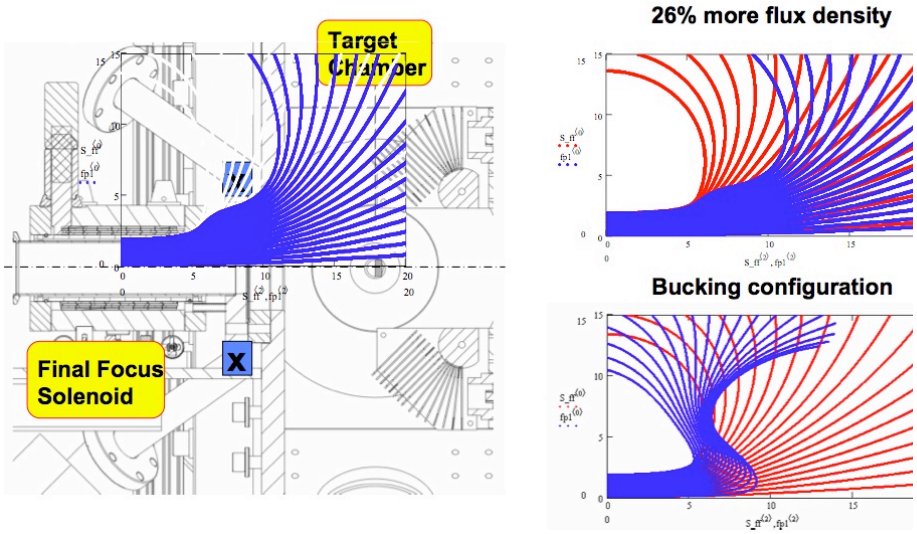
Plasma density > 10^{13} / cm^3 after modifications to FCAPS: straight filters, 2 --> 4 sources, increased $I_{discharge}$
(Roy, Mo-9)





Final focus solenoid (8 Tesla, 10-cm coil) to reduce focal spot size.

Field geometry modifications under consideration to increase plasma density in region just upstream of the target plane.

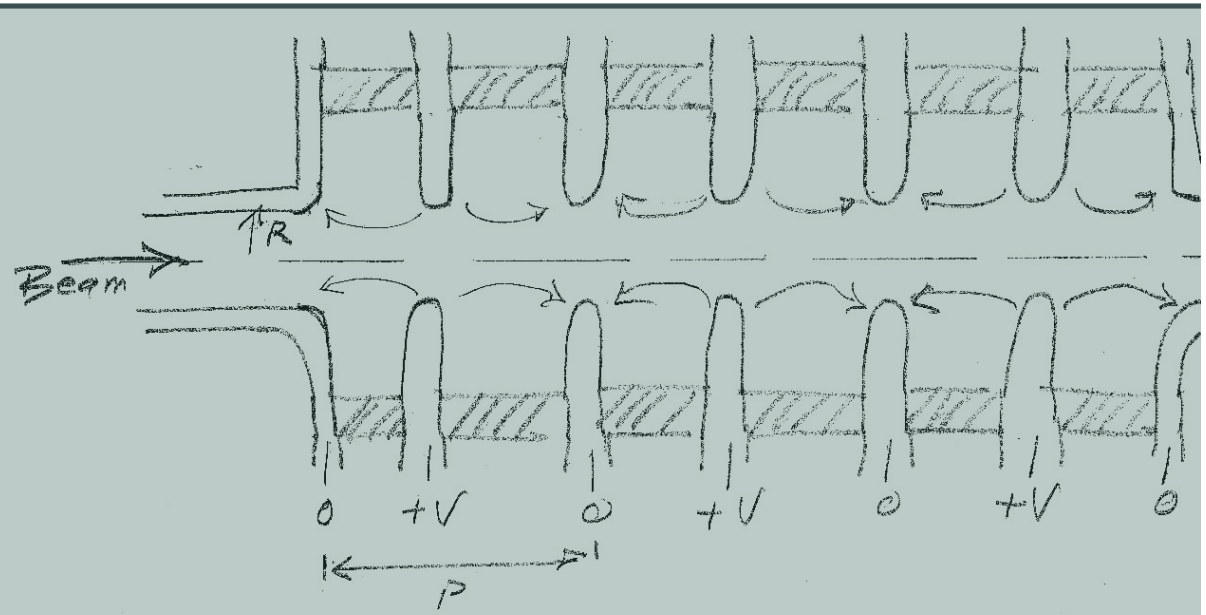


Correction of chromatic aberrations

Time dependent defocusing in bunching module, chromatic effects.

Ramped electric quadrupole or Einzel lens correction, close to the IBM. Example:

$V(t) = [100\ \text{kV}](t/1\mu\text{s})^{1/2}$
4 periods, P = 6 cm,
R = 2 cm
300 kV K^+
Modulates envelope by ≈20 mr in 1μs.



Will also explore lattice modifications static elements.

Summary

next steps toward higher focused beam intensity

- **greater axial compression via a higher $\Delta v/v$ velocity ramp**
- **improved centroid control via beam steering dipoles;**
- **time-dependent focusing elements to correct considerable chromatic aberrations**
- **enhanced plasma density in the path of the beam**