Beam Compression in Heavy-Ion Induction Linacs

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Outline

Beam requirements

Method: bunching and transverse focusing

Beam diagnostics

Recent progress:

- longitudinal phase space measured
- simultaneous transverse focusing and longitudinal compression
- enhanced plasma density in the path of the beam

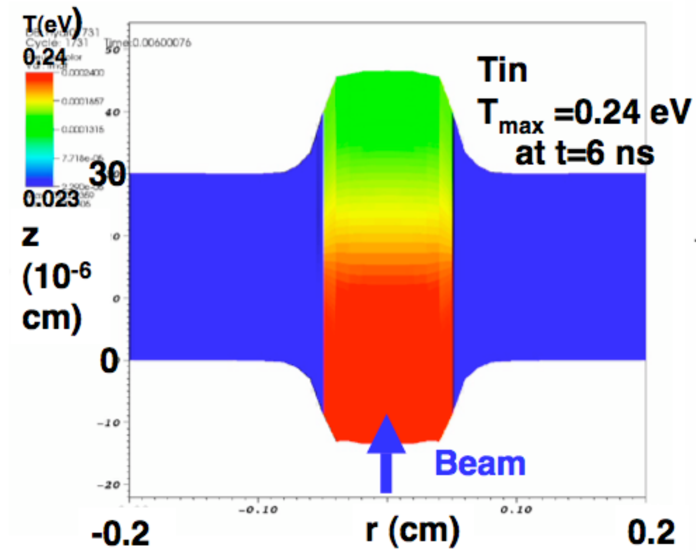
Next steps toward higher beam intensity & target experiments

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

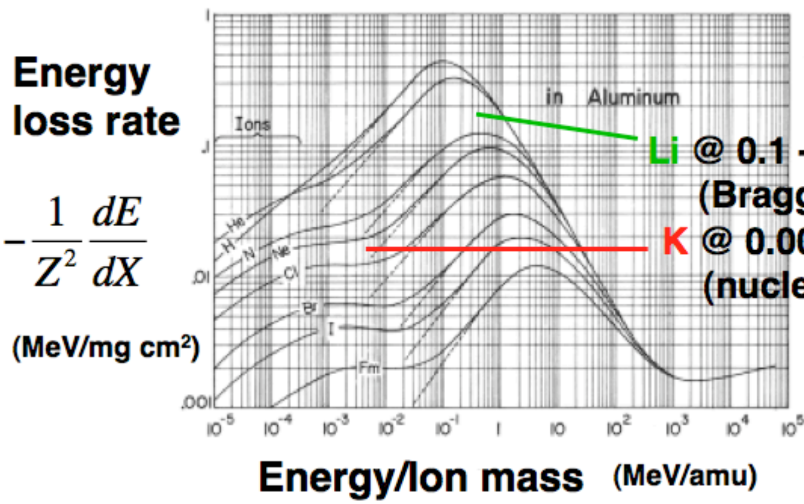
Explore warm dense matter (high energy density) physics by heating targets uniformly with heavy ion beams

Near term: planar targets predicted to reach T ≈ 0.2 eV for two-phase studies.

Assumptions for Hydra simulation:
E = 350 keV, K^+,
I_{beam} = 1 A (40X compression)
t_{beam} = 2ns FWHM
r_{beam} = 0.5 mm, $\mathcal{E}$ = 0.1 J/cm²
E_{total} = 0.8 mJ, Q_{beam} = 2.3 nC



Later, for uniformity, experiments at the Bragg peak using Lithium ions



Li @ 0.1 - 0.4 MeV/amu = NDCX II (planned)
(Bragg peak)
K @ 0.003 - 0.009 MeV/amu = NDCX I
(nuclear stopping plateau)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))

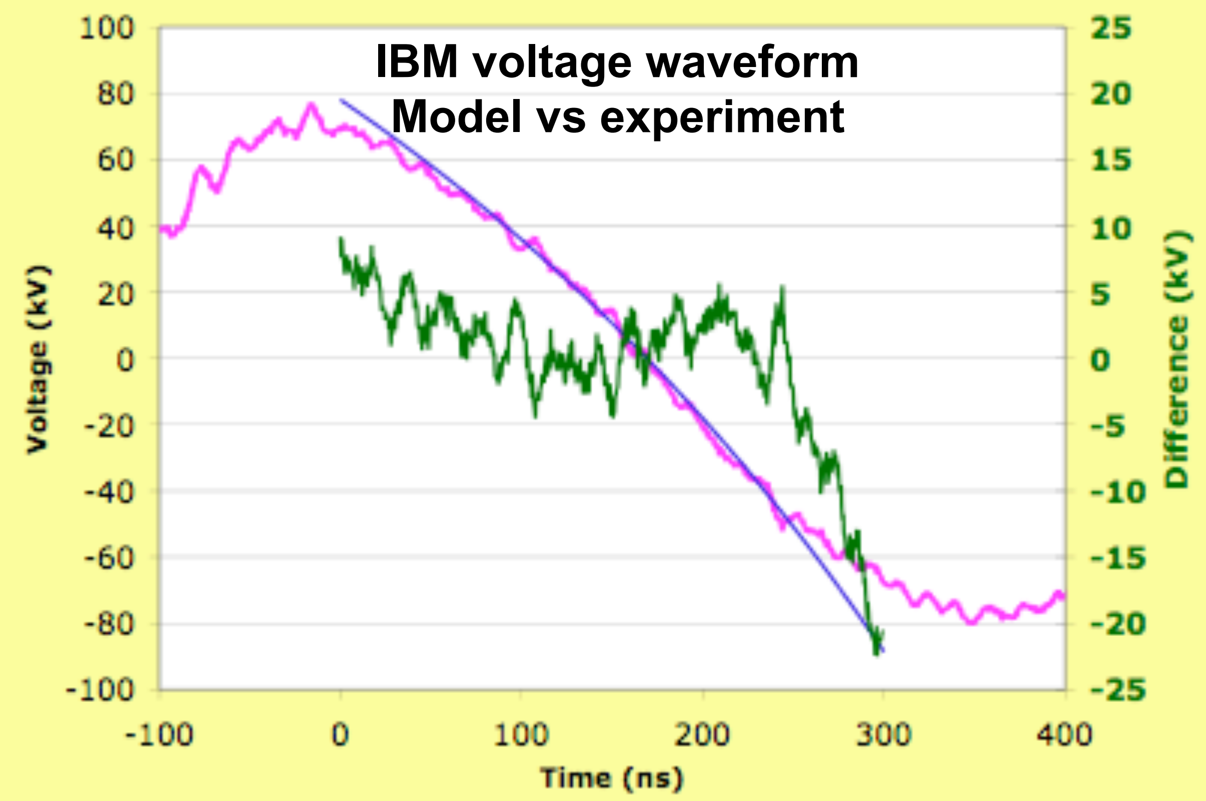
Approach: High-intensity in a short pulse via beam bunching and transverse focusing

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

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

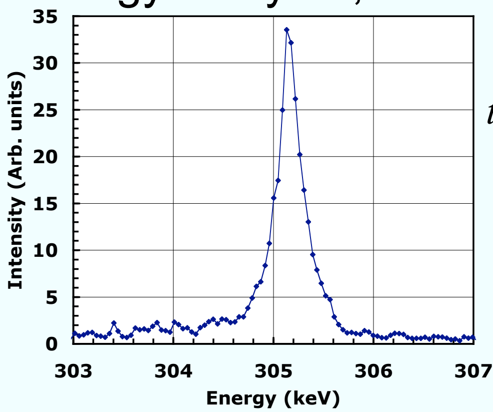
Induction bunching module (IBM) voltage waveform:

$V(t) = \frac{1}{2} m v^2(t) - \phi_o$, ($e\phi_o$ = ion kinetic energy.)



Measured energy spread is adequate for ~ns bunches.

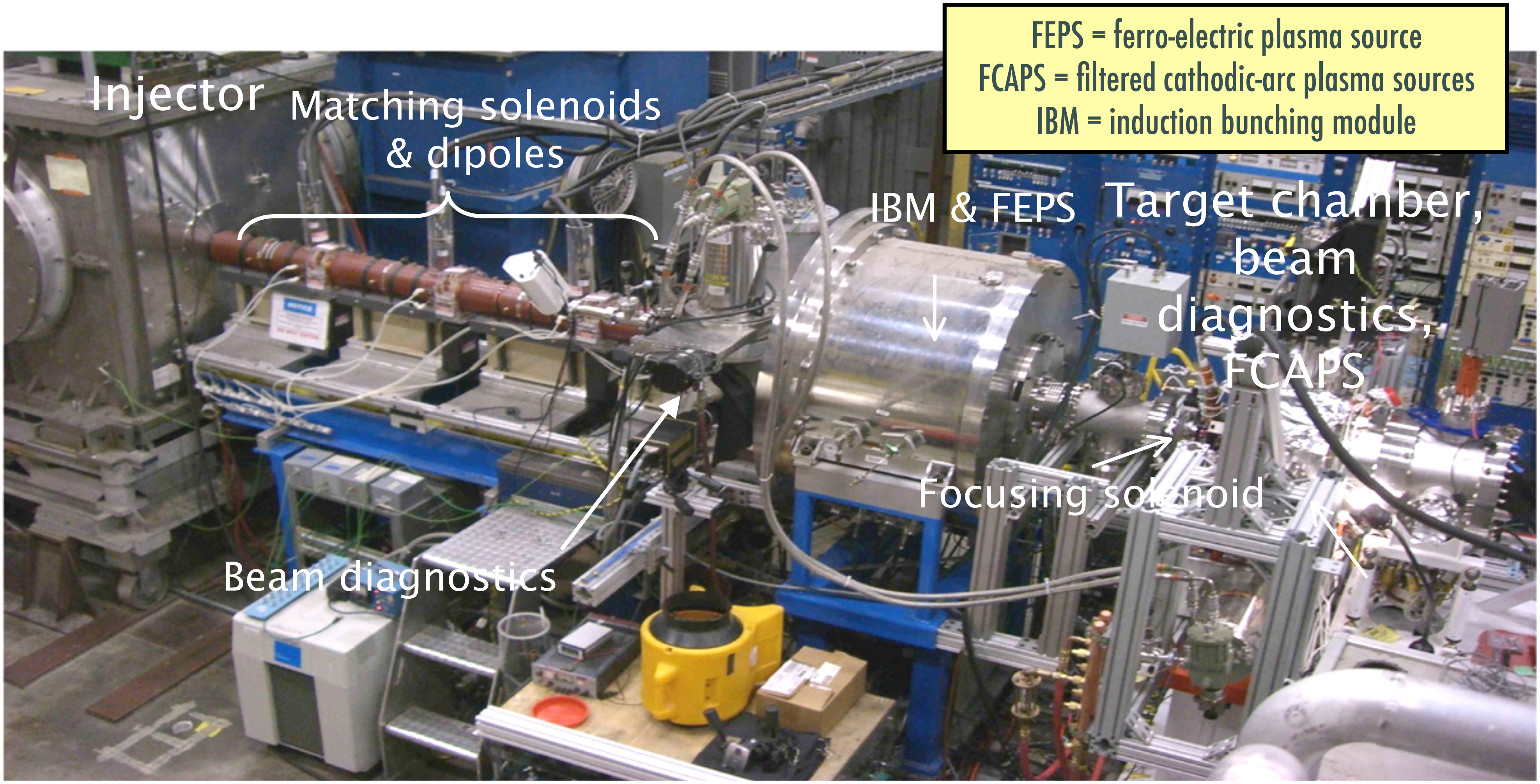
Energy analyzer, unbunched beam



$$t_p = \frac{L}{v_L^2}\sqrt{\frac{2kT_L}{M}}$$

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

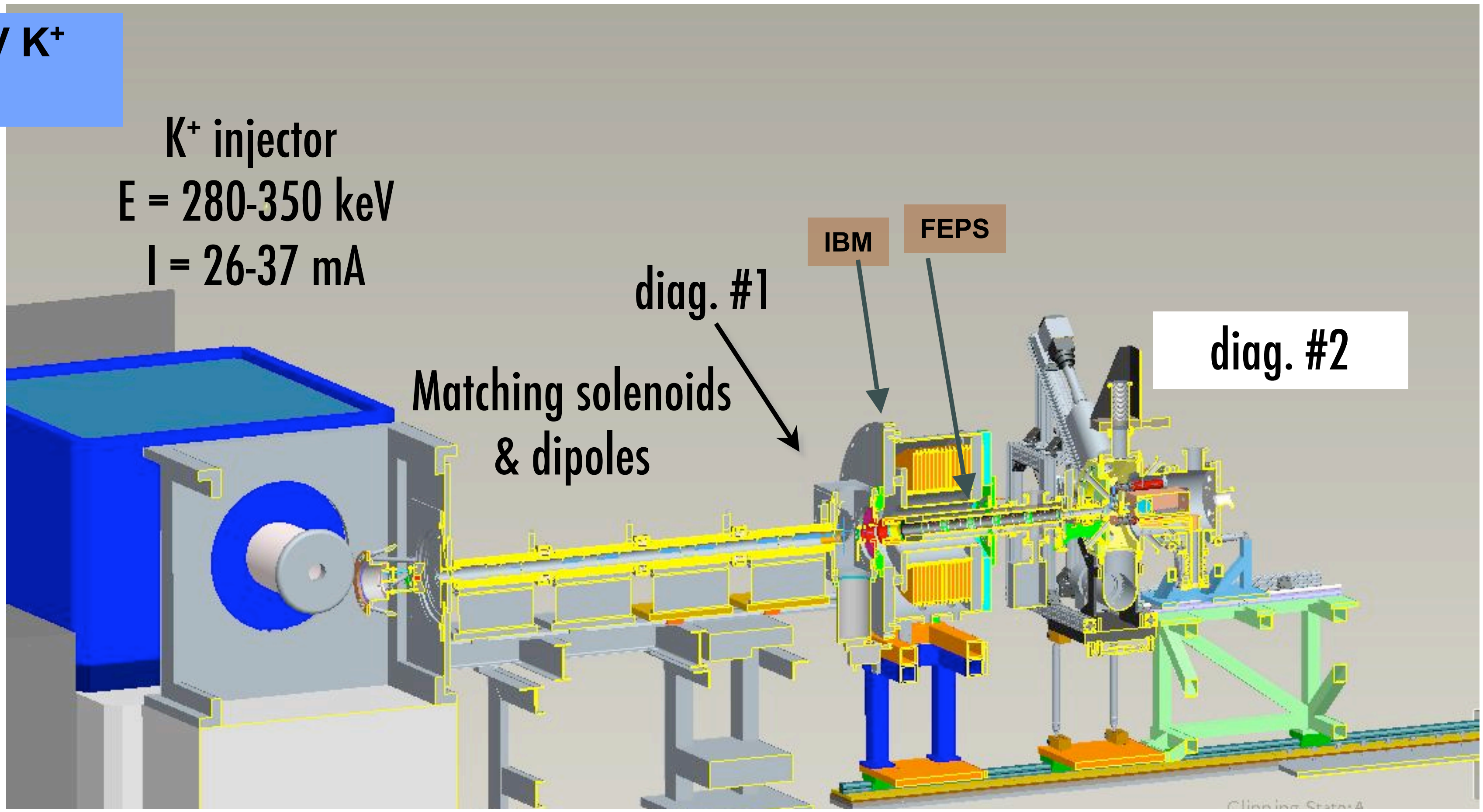
Neutralized Drift Compression Experiment (NDCX) with new steering dipoles, target chamber, more diagnostics and upgraded plasma sources



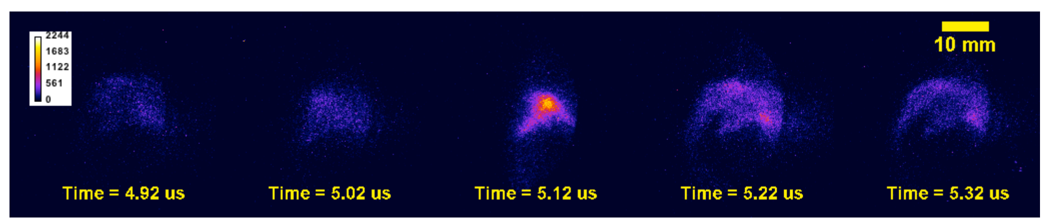
New: steering dipoles, focusing solenoid (8T), target chamber, more diagnostics, upgraded plasma sources

NDCX-1 has 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 $n_p > n_b$, (ε_{ni} = 0.07 mm-mrad, $n_{b\text{-init}} \approx 10^9$ /cm^3, $n_{bmax} \approx 10^{12}$ /cm^3 now, later, $\approx 10^{13}$ /cm^3)



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

Requirements:

Fast time response (~1 ns)

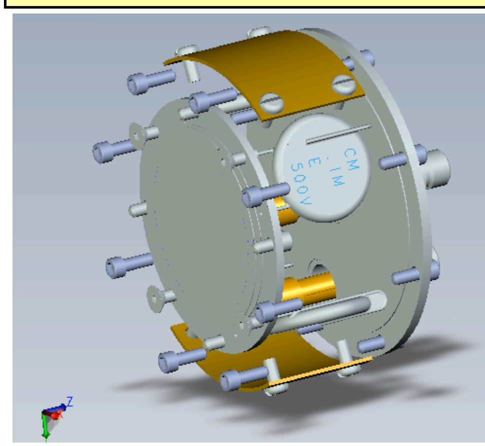
Immunity from background neutralizing plasma

Design:

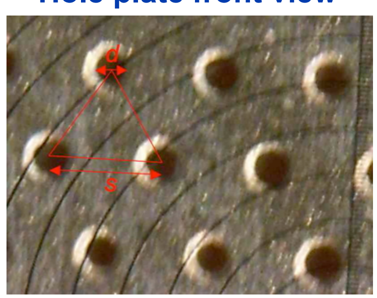
2 hole plates, closely spaced for fast response.

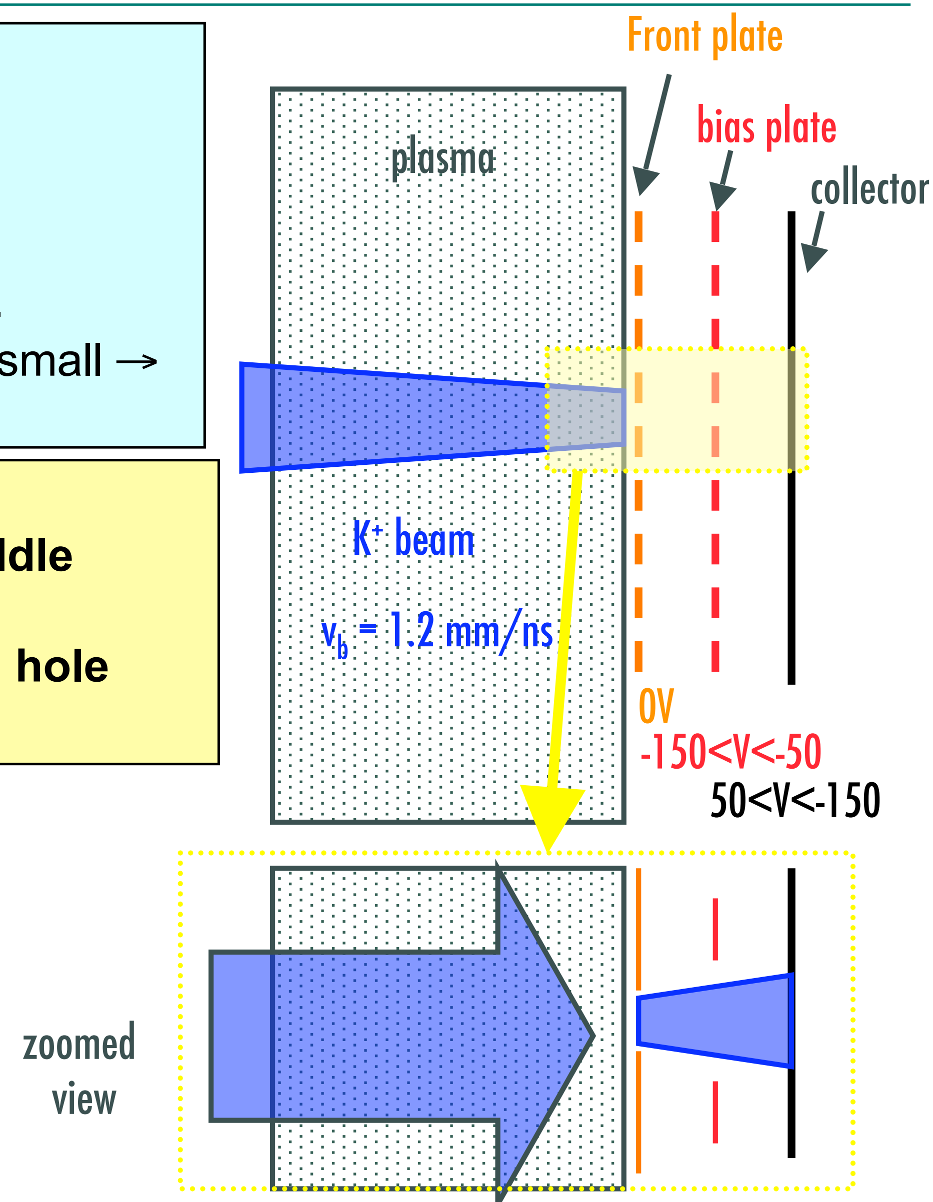
Hole pitch (1 mm) & diameter (0.23, 0.46 mm) small → blocks most of the plasma

- **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.**

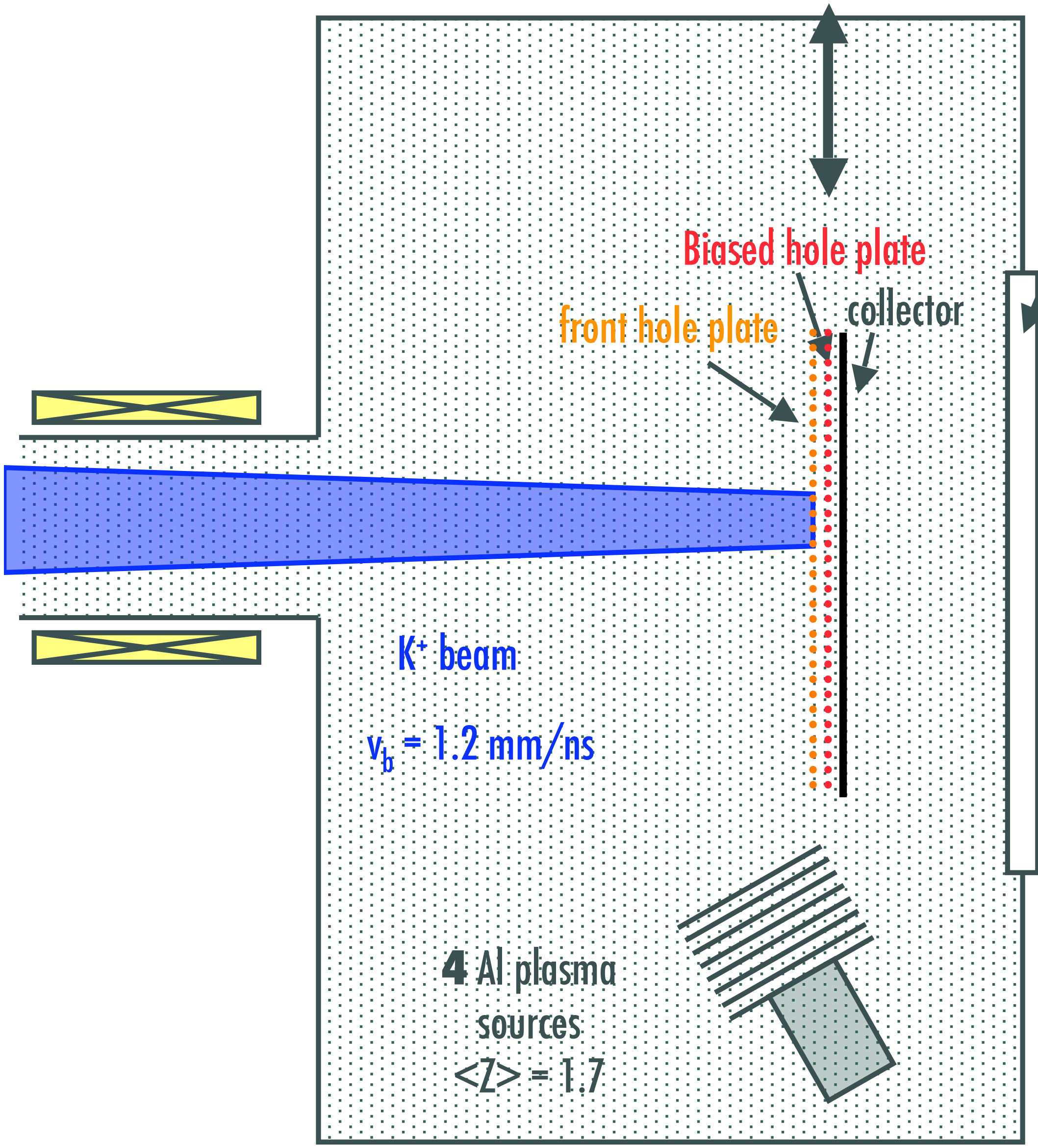


Hole plate front view

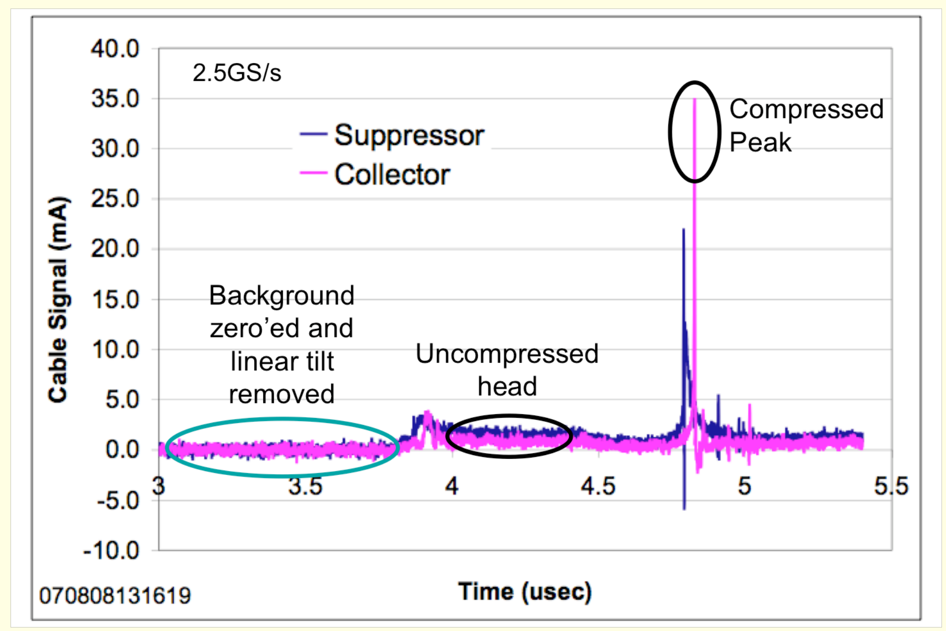




Beam diagnostics in the target chamber: Fast faraday cup



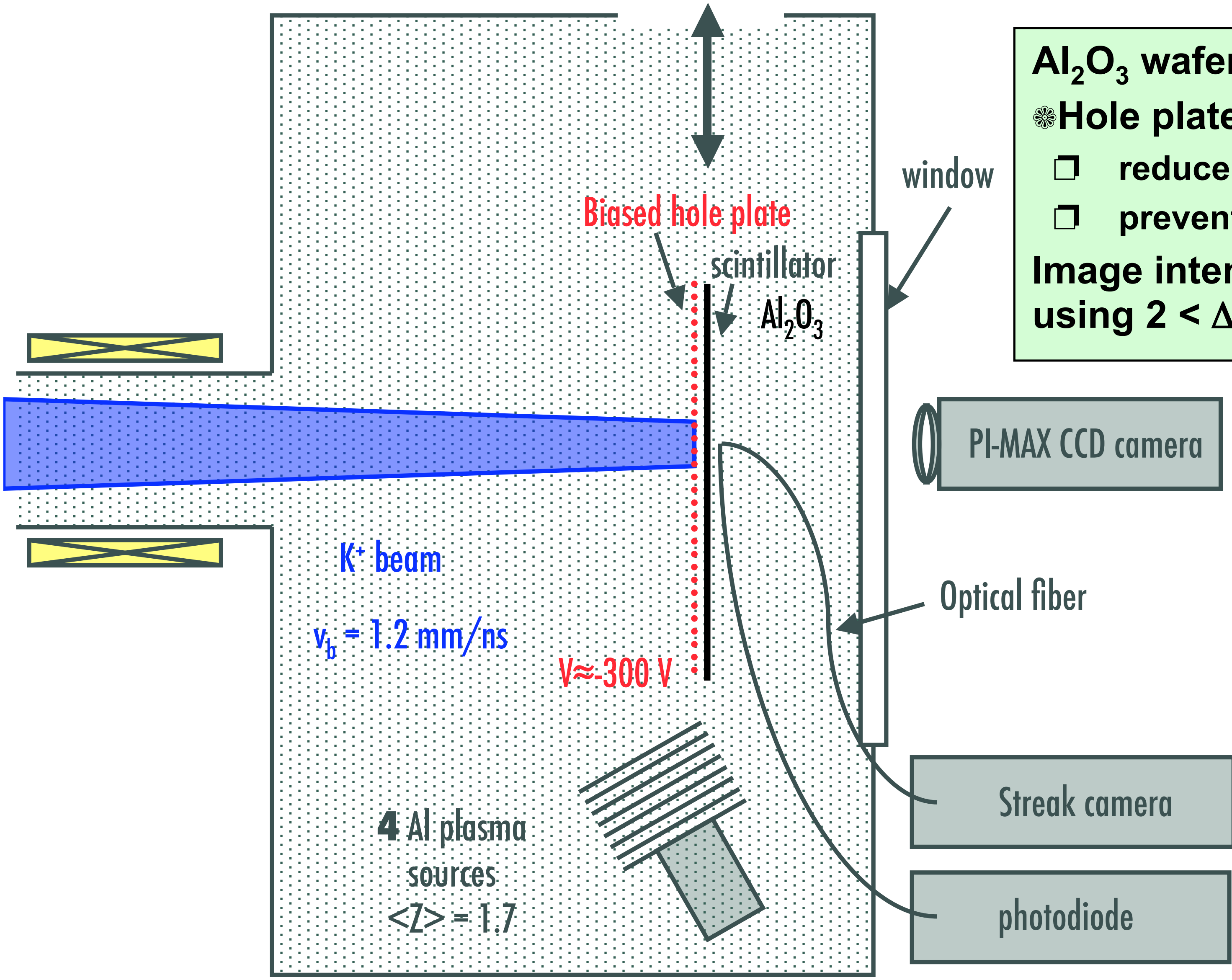
Example waveform



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

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

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

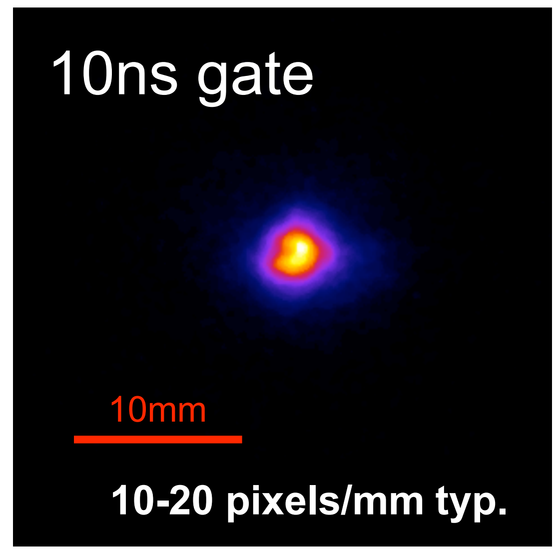


Al_2O_3 wafer with hole plate:

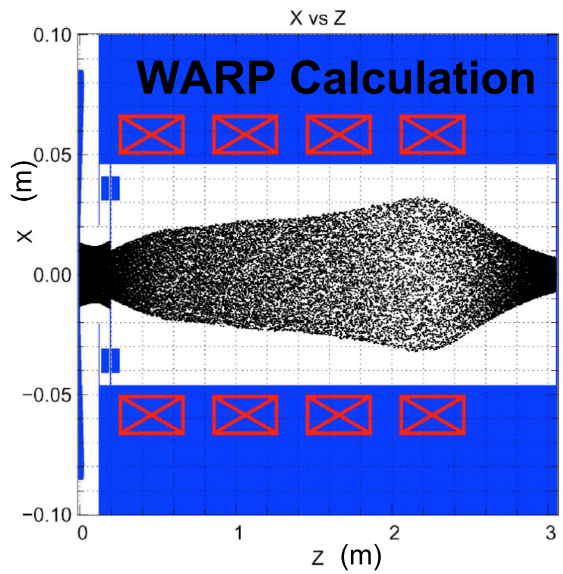
❁**Hole plate to**

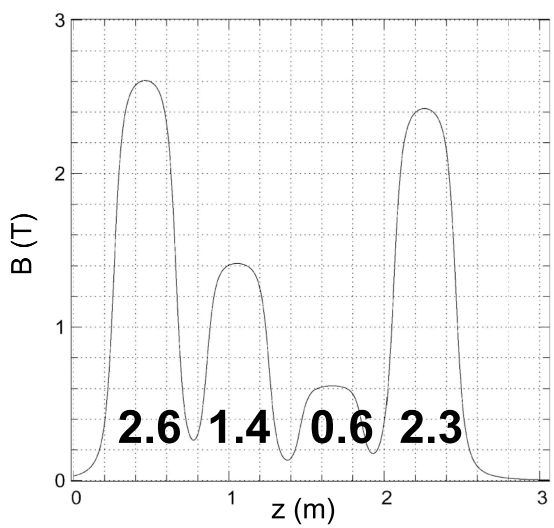
- ❒ **reduce beam flux: less damage**
- ❒ **prevent charge buildup.**

Image intensified CCD camera using 2 < Δt <500 ns gate.



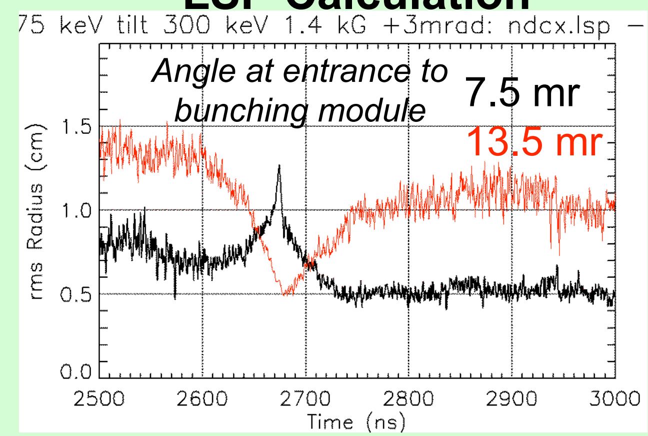
Simultaneous longitudinal compression and transverse focusing, compared to simulation.

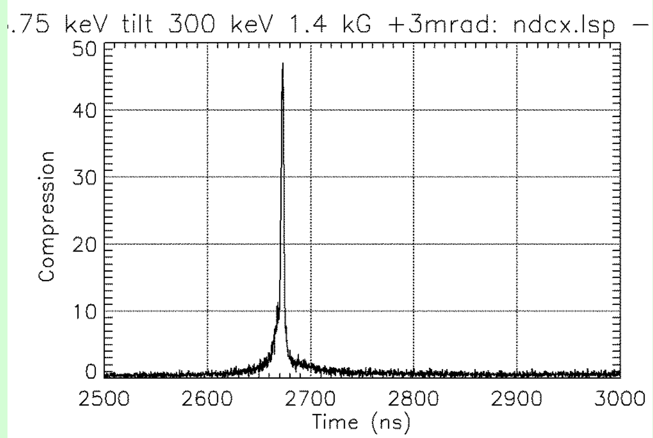




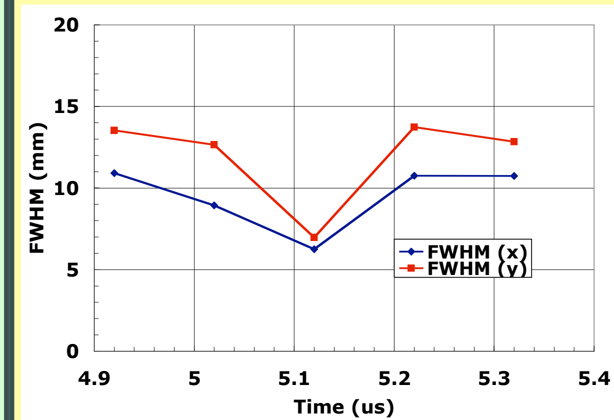
Net defocusing in gap due to energy change, E_r

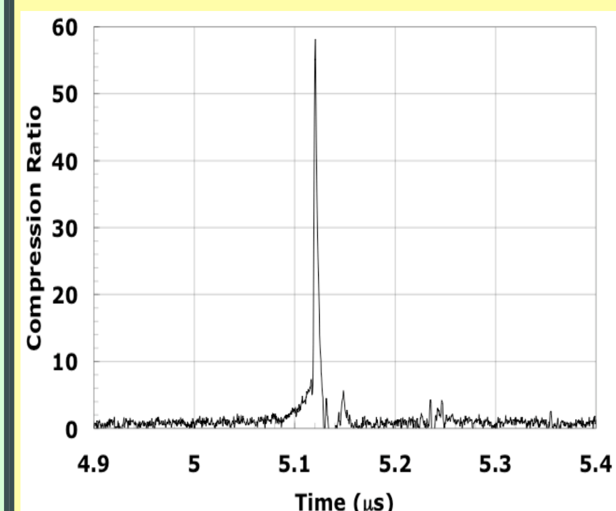
LSP Calculation

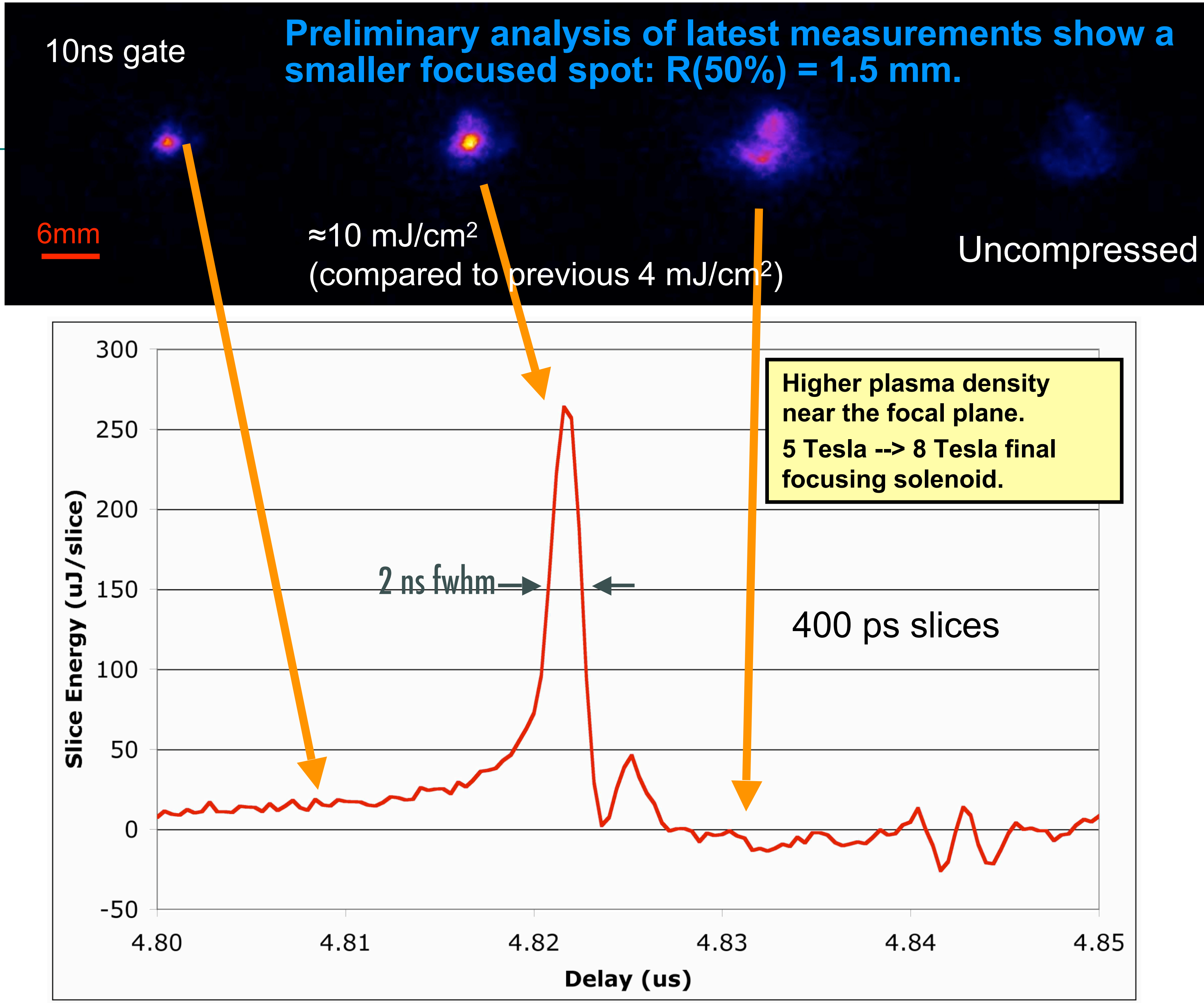




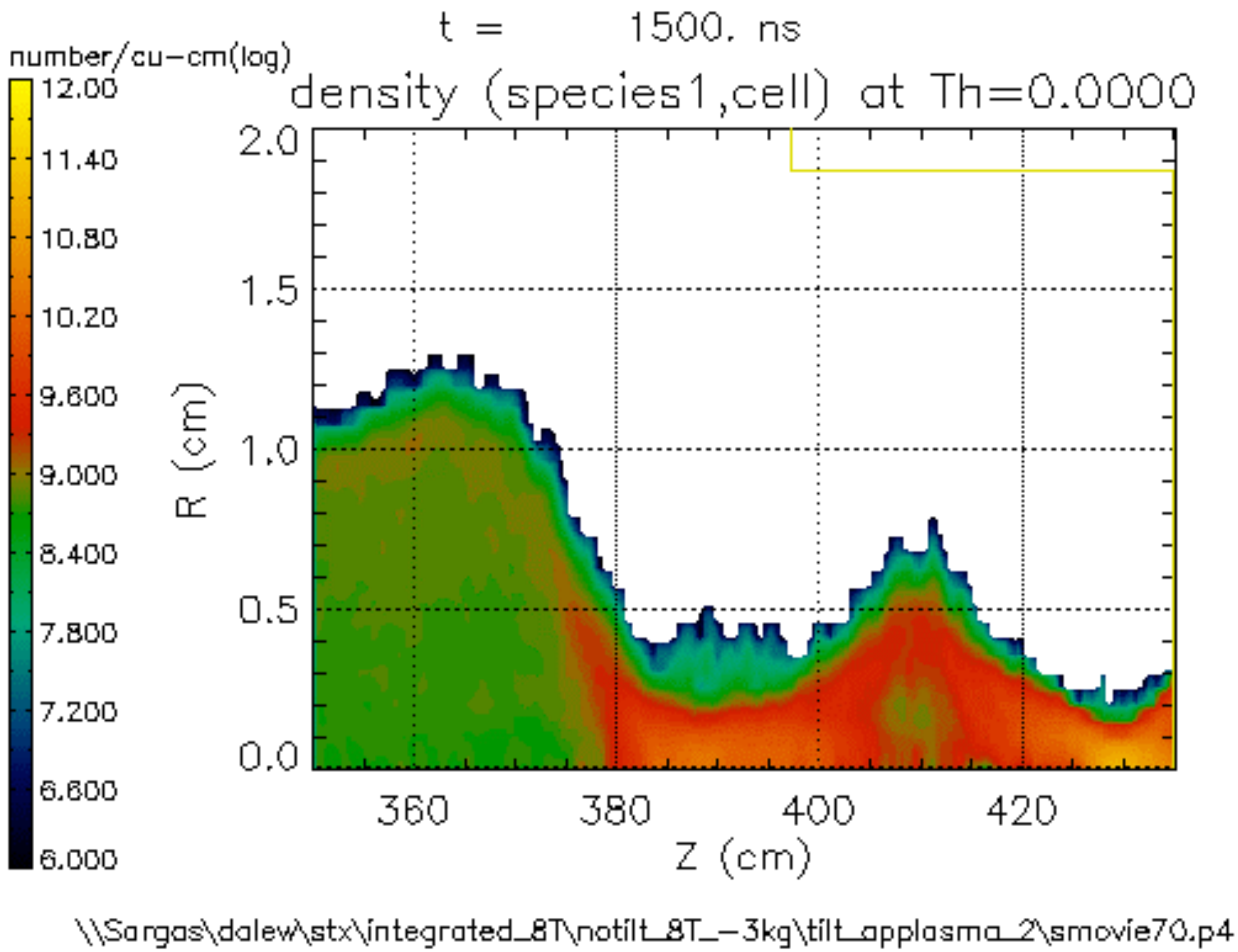
Experiment



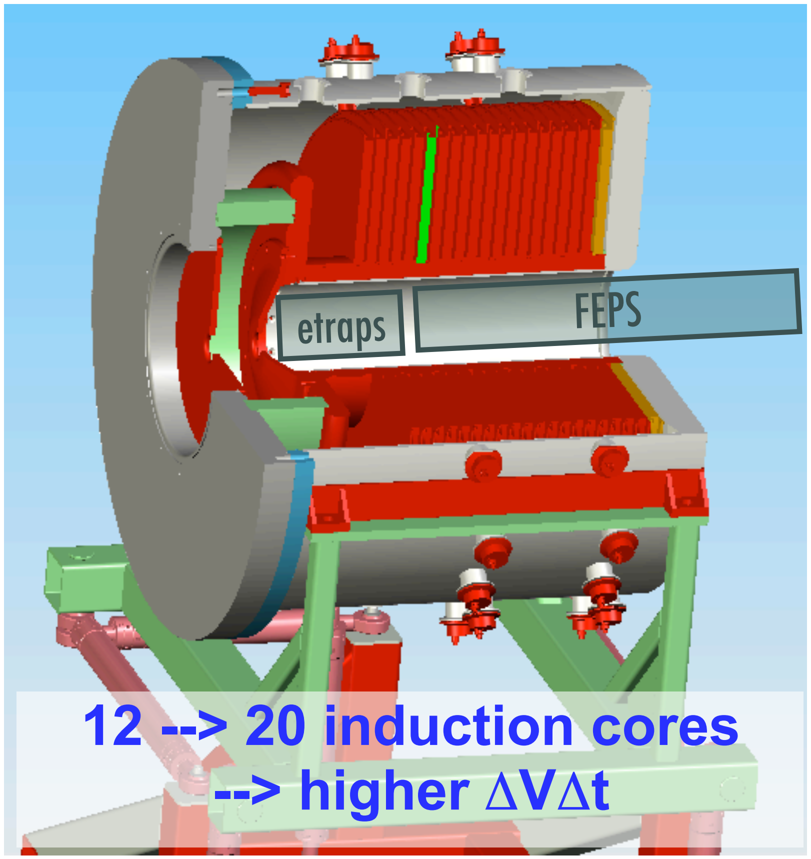


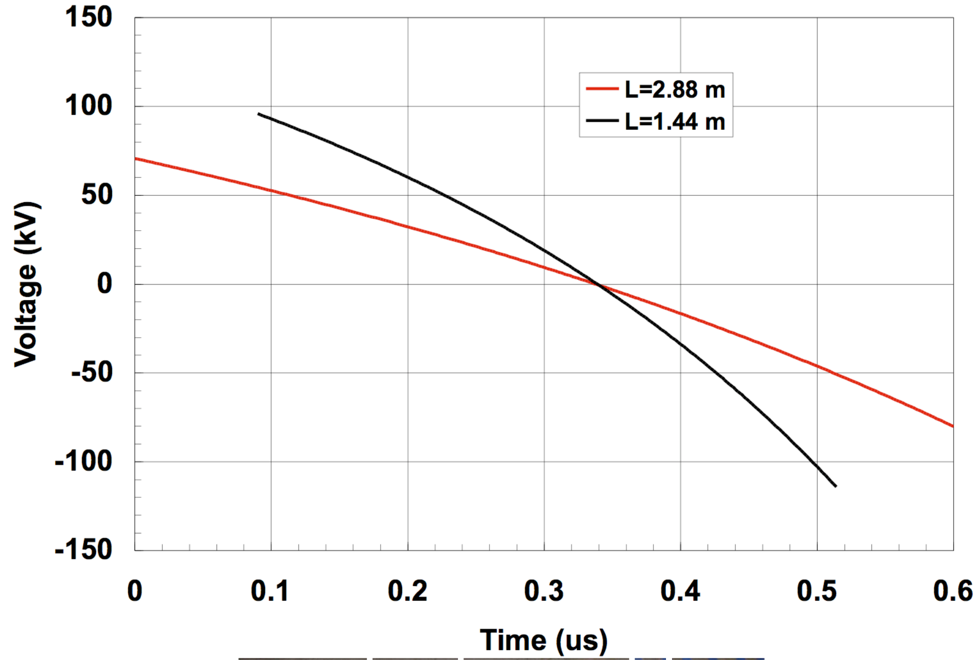

10ns gate
Preliminary analysis of latest measurements show a smaller focused spot: R(50%) = 1.5 mm.
6mm
≈10 mJ/cm2
(compared to previous 4 mJ/cm2)
Uncompressed
Higher plasma density near the focal plane.
5 Tesla --> 8 Tesla final focusing solenoid.
2 ns fwhm
400 ps slices
Slice Energy (uJ/slice)
300
250
200
150
100
50
0
-50
4.80
4.81
4.82
4.83
4.84
4.85
Delay (us)

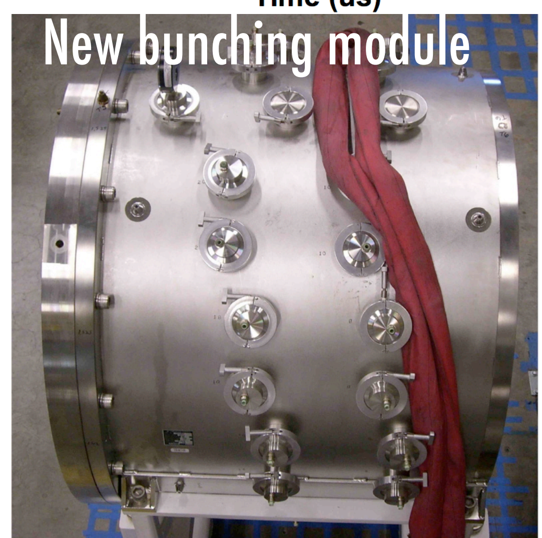
LSP simulation of drift compression



With the new bunching module, the voltage amplitude and voltage ramp duration can be increased.



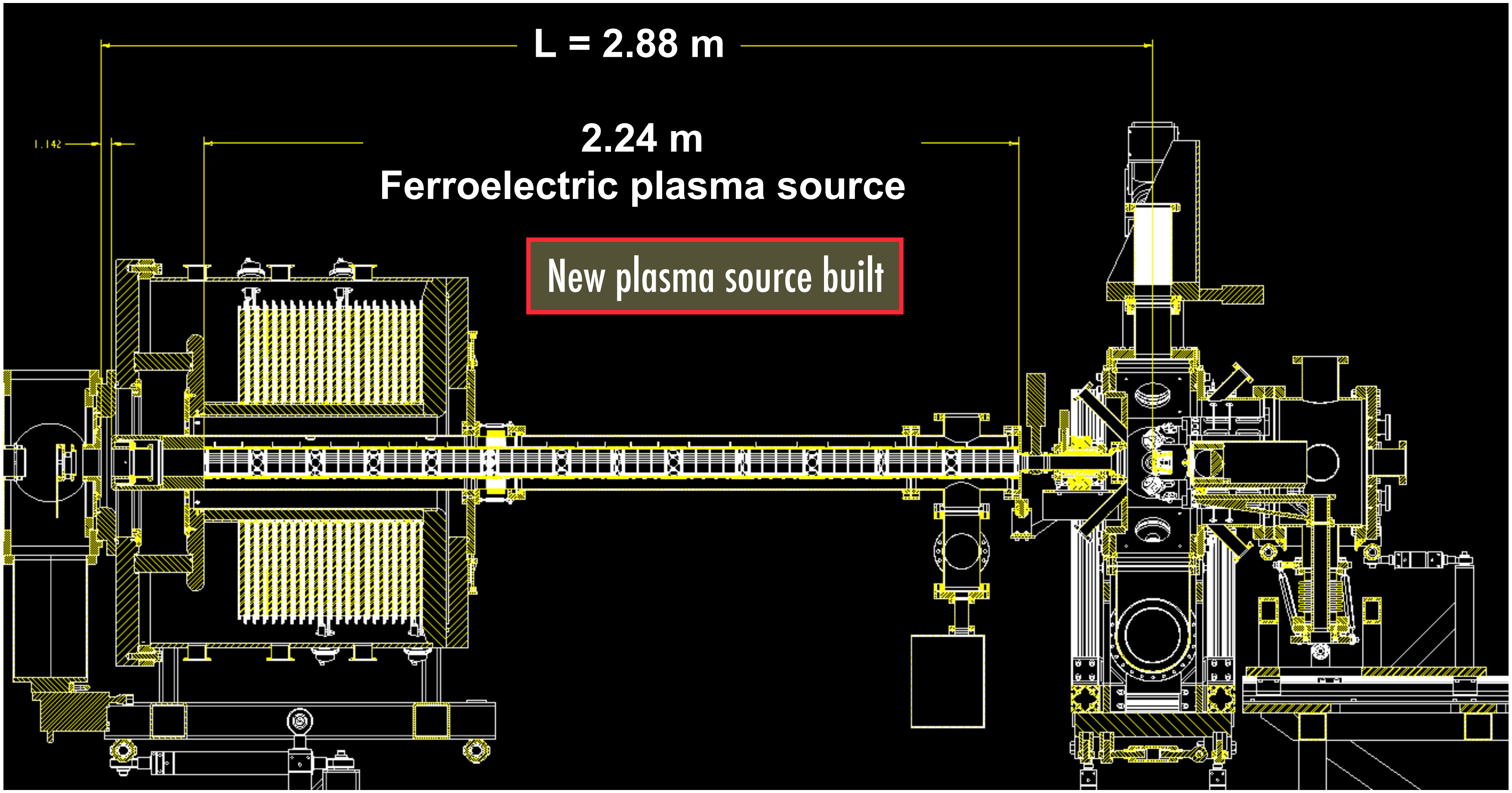




FEPS = ferro-electric plasma source

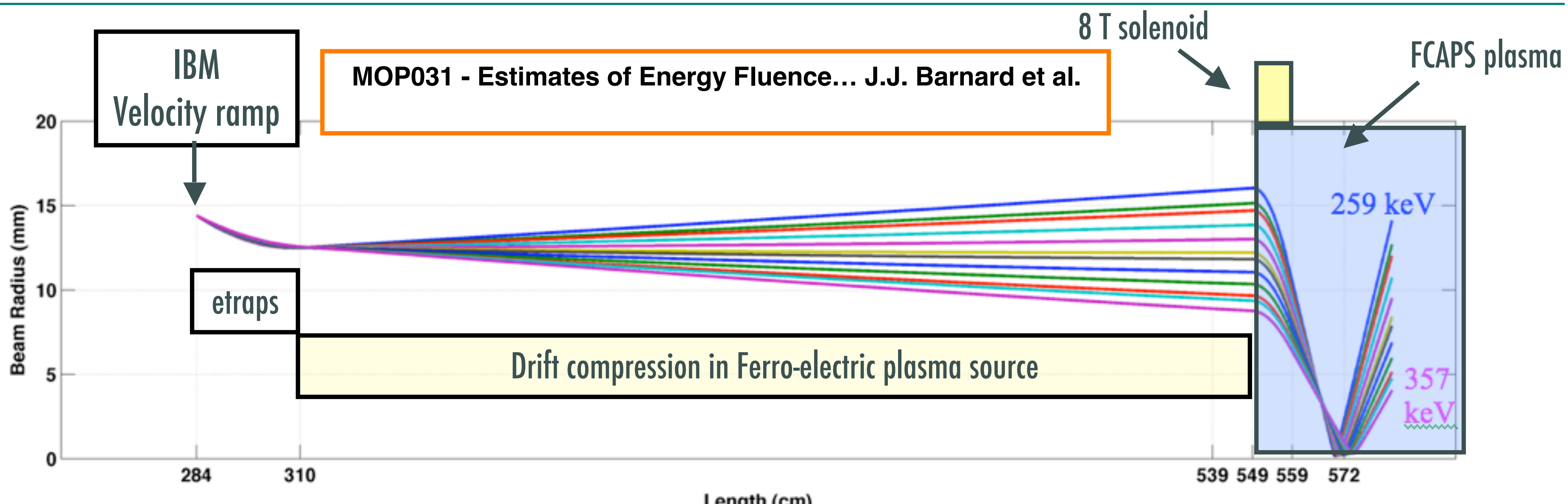
Beam experiments in 2008.

It is advantageous to lengthen the drift compression section by 1.44 m via extension of the ferro-electric plasma source



~2x longer drift compression section (L=2.88 m), Uses additional volt-seconds for a longer ramp and to limit ΔV_{peak} & chromatic effects

Calculations support a longer IBM waveform with twice the drift compression length



	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

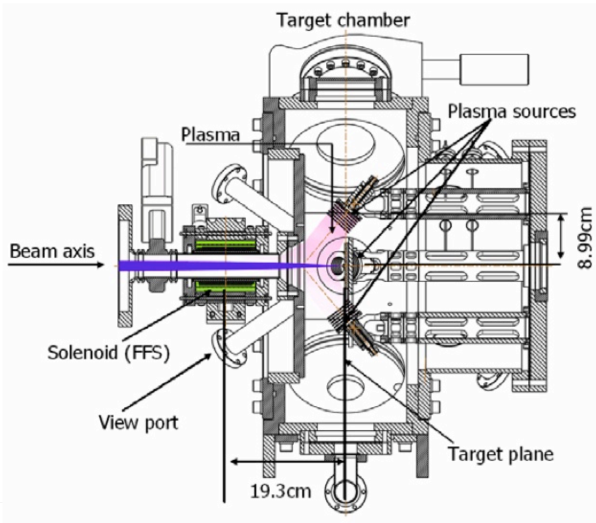
Comparison of LSP, the envelope-slice model, and the simple analytic model.

(a) no final focusing solenoid.

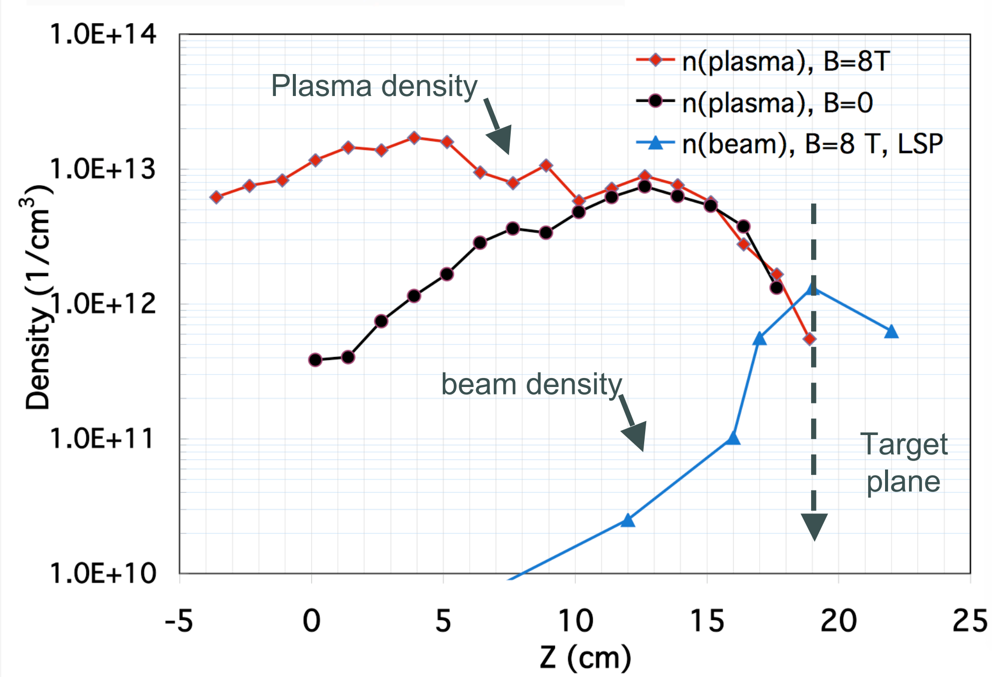
(b) New IBM, the final focusing solenoid (B_{max} = 8 Tesla) L_{drift} =144 cm, **present setup**

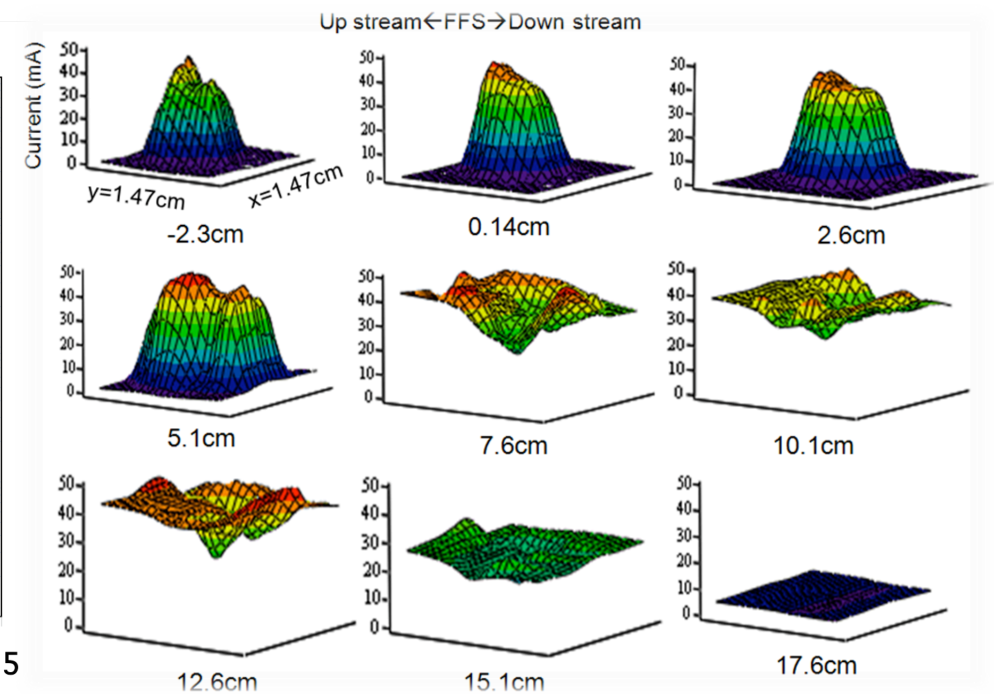
(c) with twice the drift compression length (L=288 cm) as the present setup.

The improved filtered cathodic arc plasma source (FCAPS) injection has led to a higher plasma density near the target

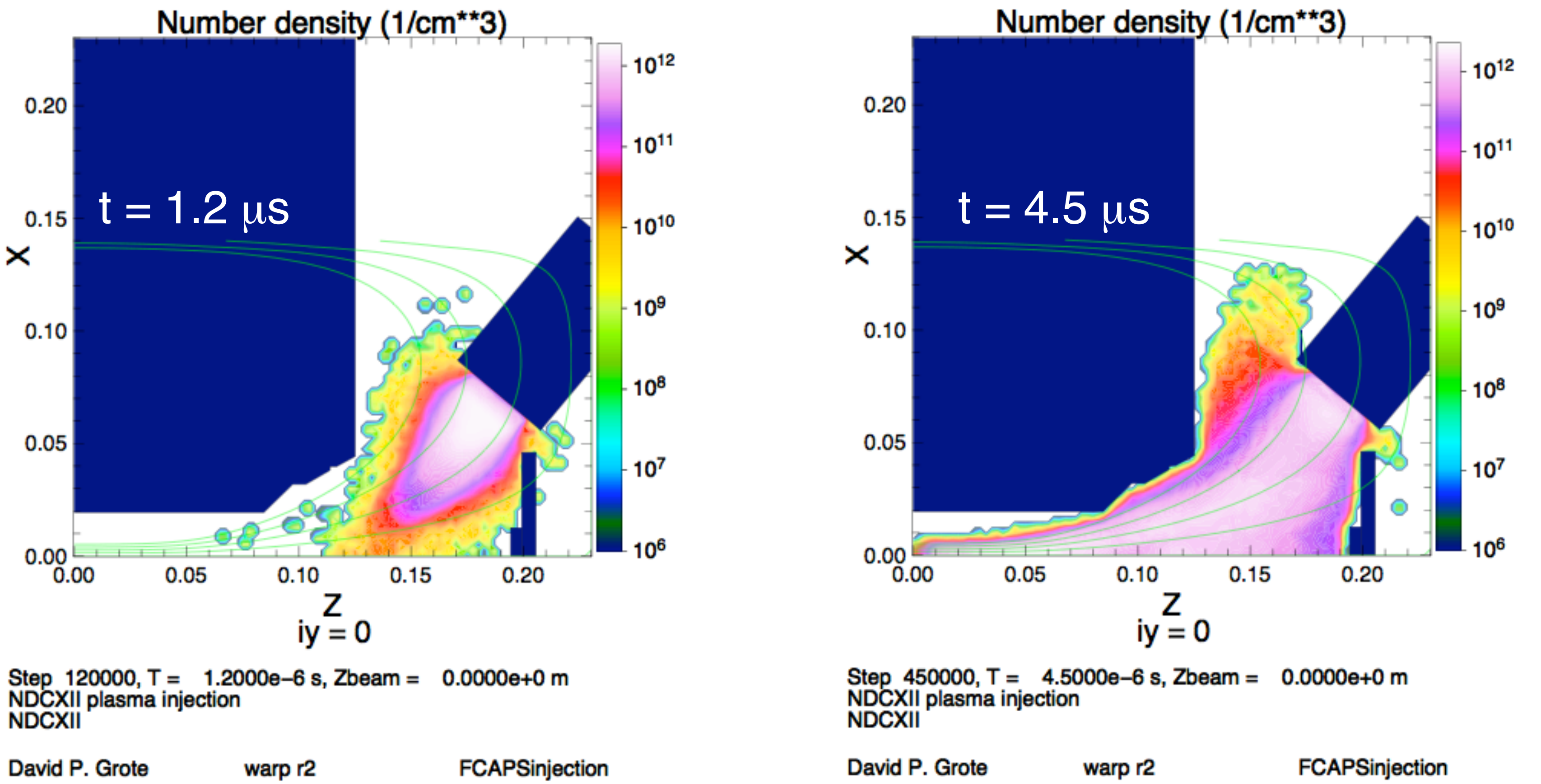


Plasma density > 10^{13} / cm^3 after modifications to FCAPS: straight filters, 2 --> 4 sources, increased $I_{discharge}$





Warp can now simulate injection from Cathodic-Arc Plasma Sources



Next :

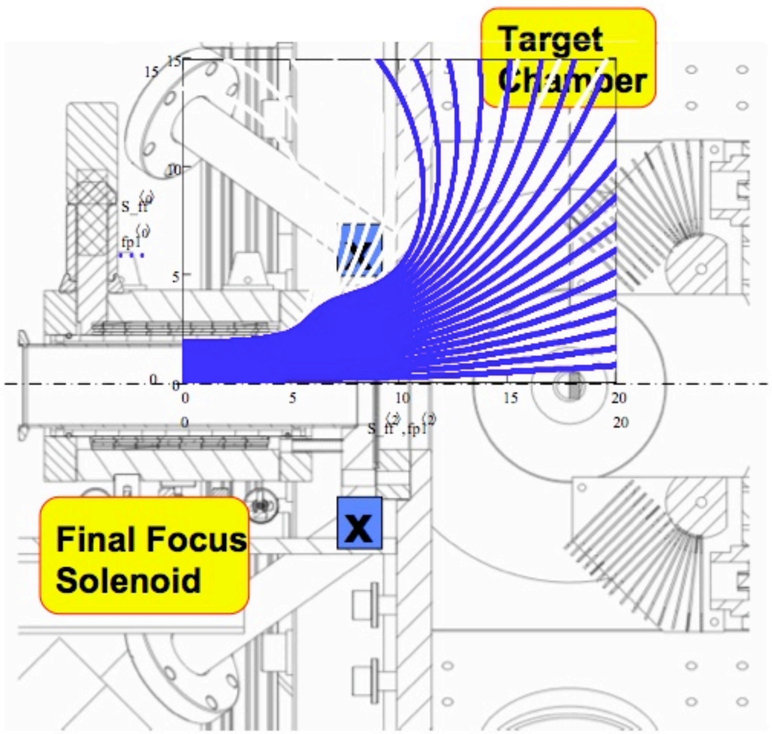
-comparison of runs with Eddy fields calculated from transient calculation in Ansys.

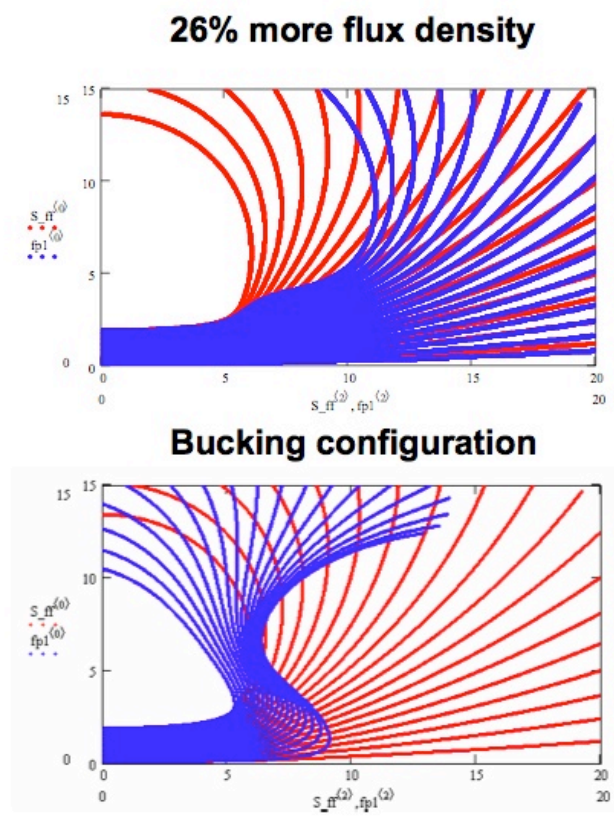
-Implicit model: hope for at least 10x speed-up in computation time.

-Fields from filters

Example field modifications under consideration to increase plasma transport to the beam path near the target

An additional coil near target
might increase plasma density just upstream of the target plane.

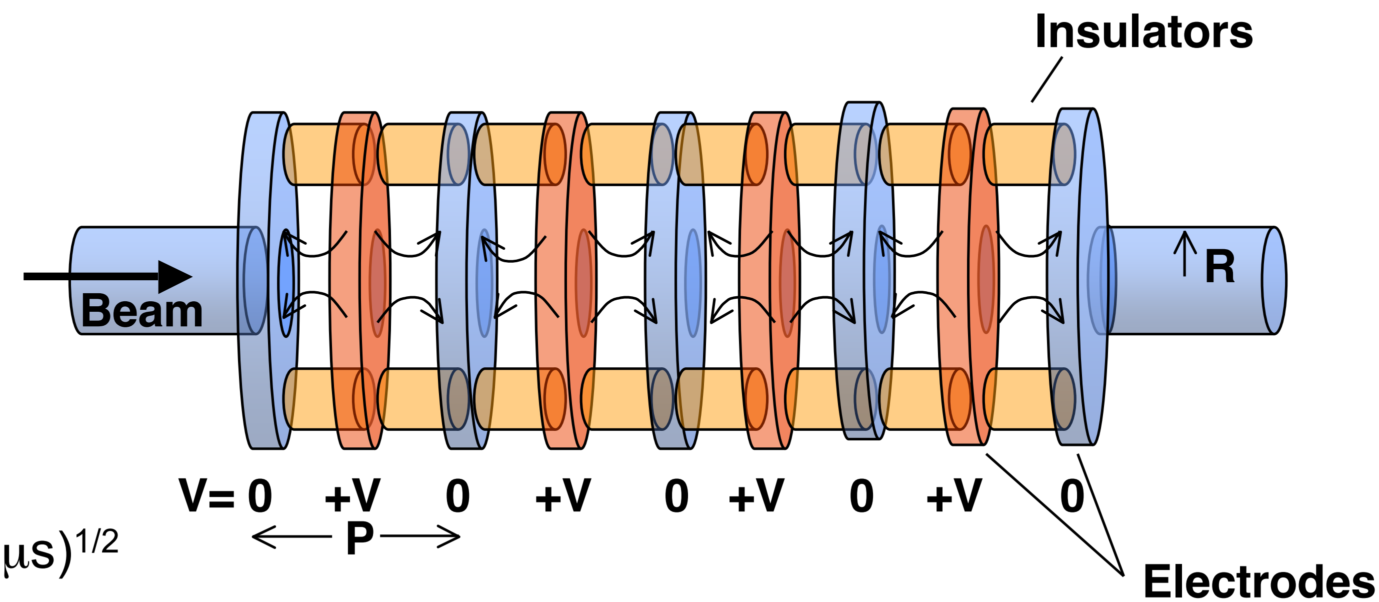




We are studying time dependent lenses to compensate the chromatic aberrations

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

Example:



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

The beam characteristics are now satisfactory for target diagnostic commissioning and first target experiments

Energy spread of initial beam is low (130 eV / 0.3 MeV = 4 x 10^{-4})
--> good for sub ns bunches.

Simultaneous axial compression (≈50x) to 1.5 A and 2.5 ns

Beam diagnostics

enhanced plasma density in the path of the beam

PIC simulations of plasma and beam dynamics

next steps: greater axial compression via a longer velocity ramp while keeping $\Delta v/v$ fixed.

time-dependent focusing elements to correct considerable chromatic aberrations