PROGRESS IN BEAM FOCUSING AND COMPRESSION FOR TARGET HEATING AND WARM DENSE MATTER EXPERIMENTS

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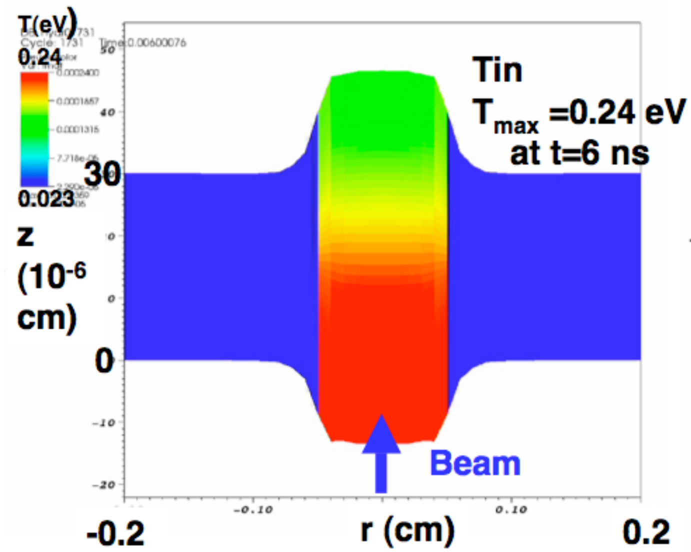
Outline

- 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

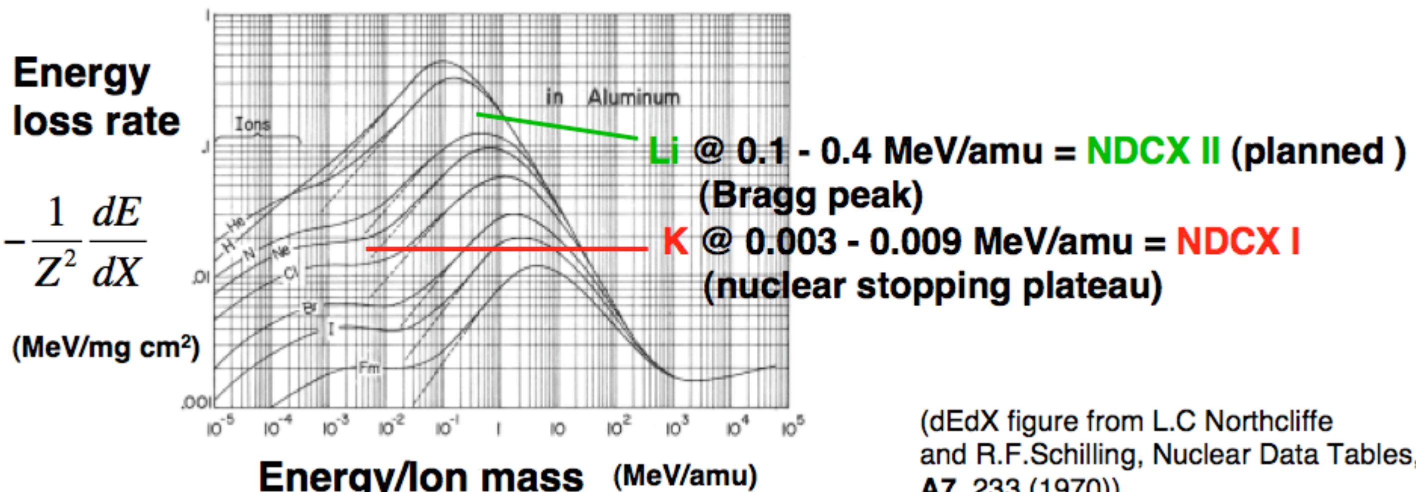
Explore warm dense matter (high energy density) physics by heating targets uniformly with heavy ion beams

Near term, NDCX-1: 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/cm^2
E_{total} = 0.8 mJ, Q_{beam} = 2.3 nC



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



(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

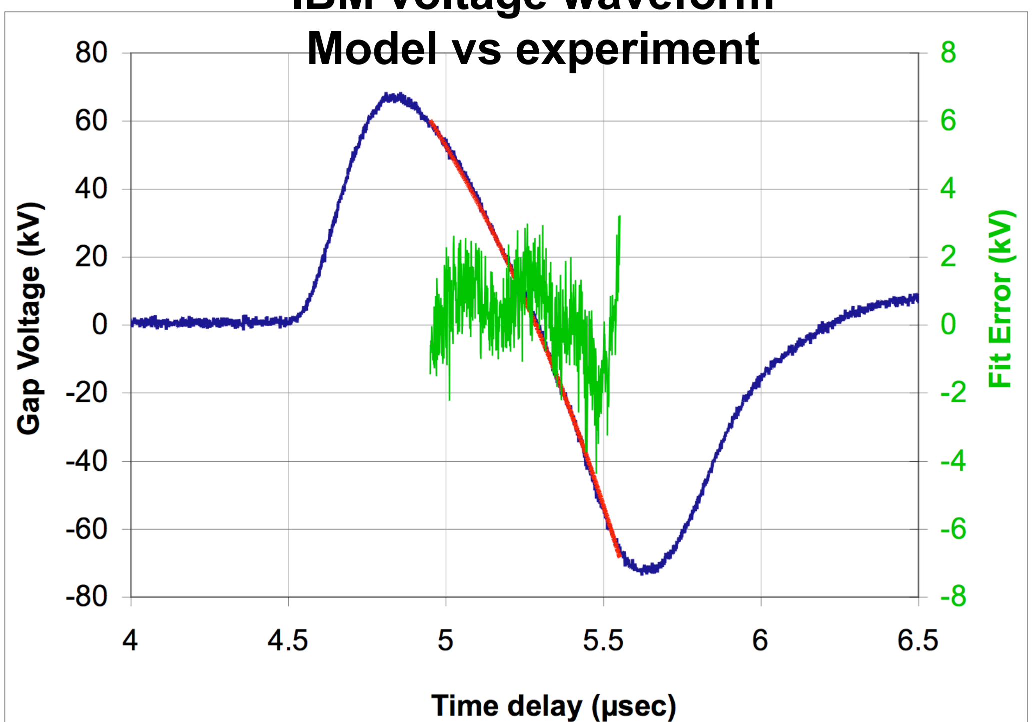
The time-dependent velocity ramp, v(t), that compresses the beam at a downstream distance L.

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

Induction bunching module (IBM) voltage waveform:

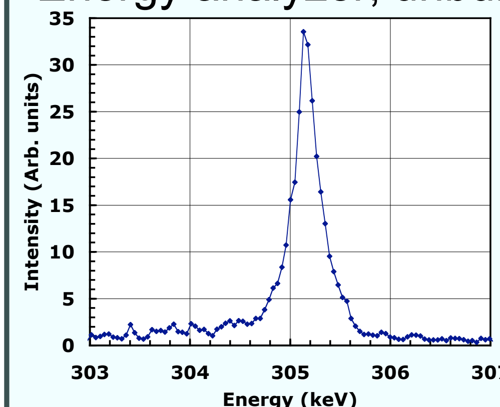
$$V(t) = \frac{1}{2}mv^2(t) - \phi_o$$, ($e\phi_o$ = ion kinetic energy.)

IBM voltage waveform
Model vs experiment



Measured ΔE of injected beam: adequate for ~ns bunches.

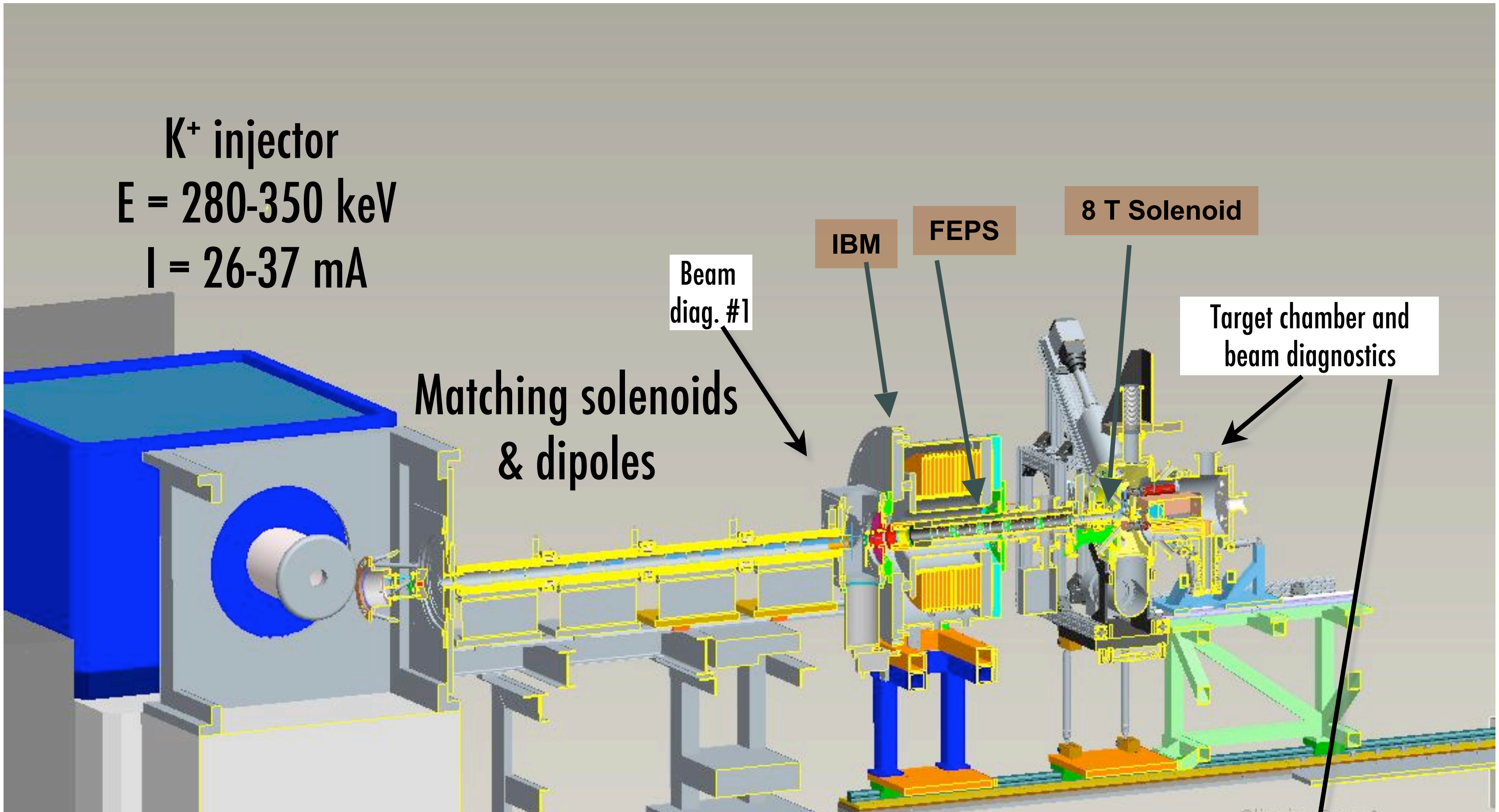
Energy analyzer, unbunched beam



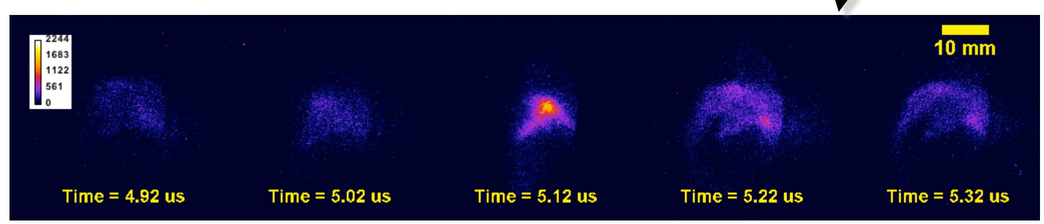
$$t_p = \frac{L}{v_L^2}\sqrt{\frac{2kT_L}{M}}$$

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

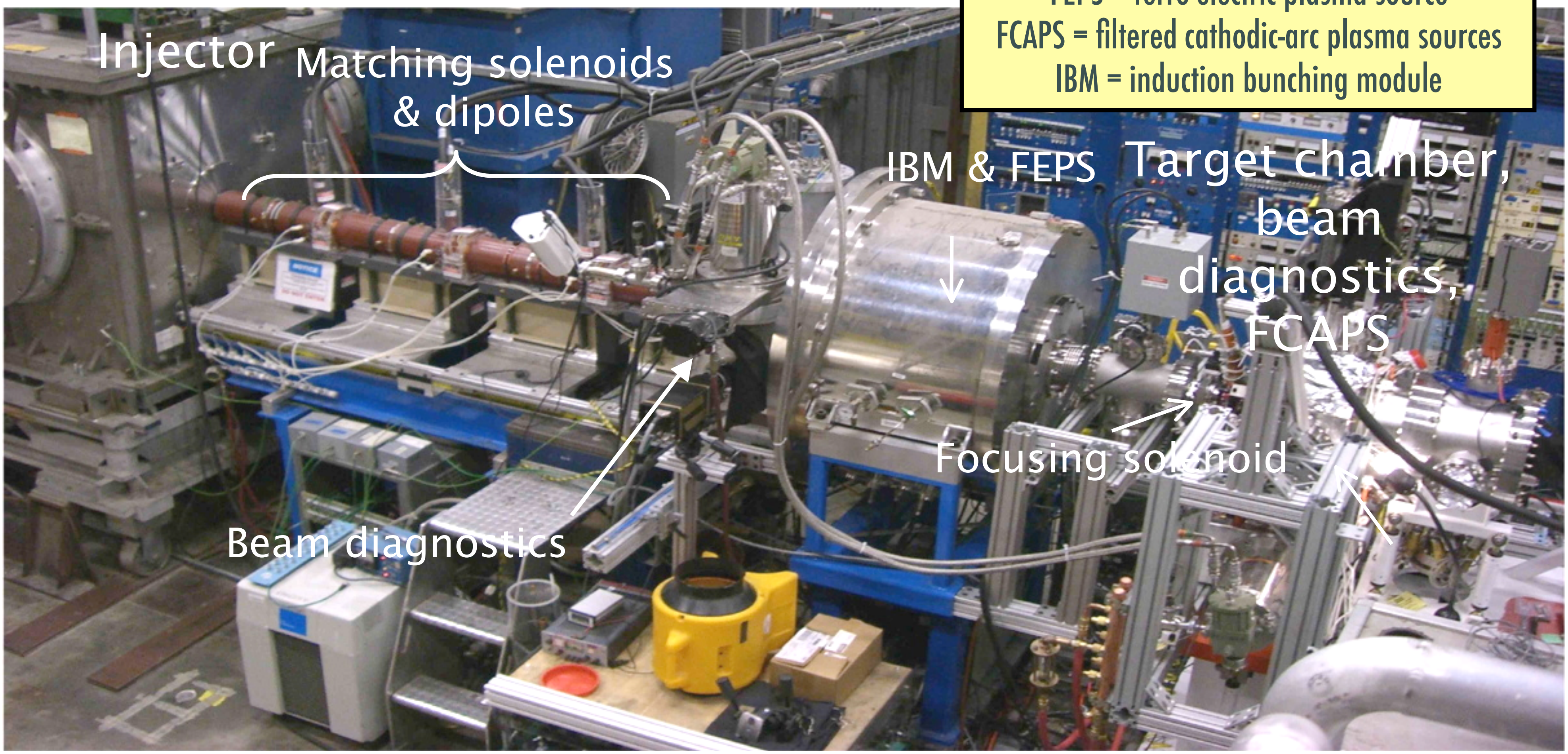
NDCX-1 has demonstrated simultaneous transverse focusing and longitudinal compression



Objectives: **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)**



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

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

Requirements:

Fast time response (~1 ns)

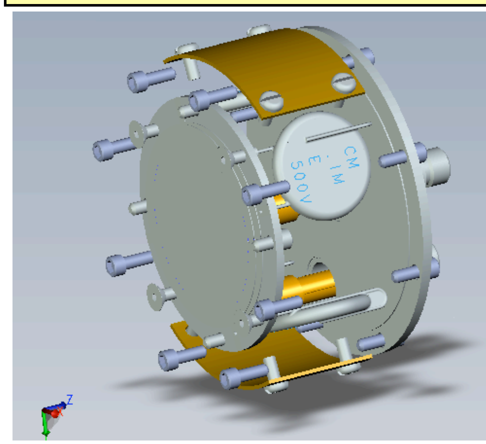
Immunity from background neutralizing plasma

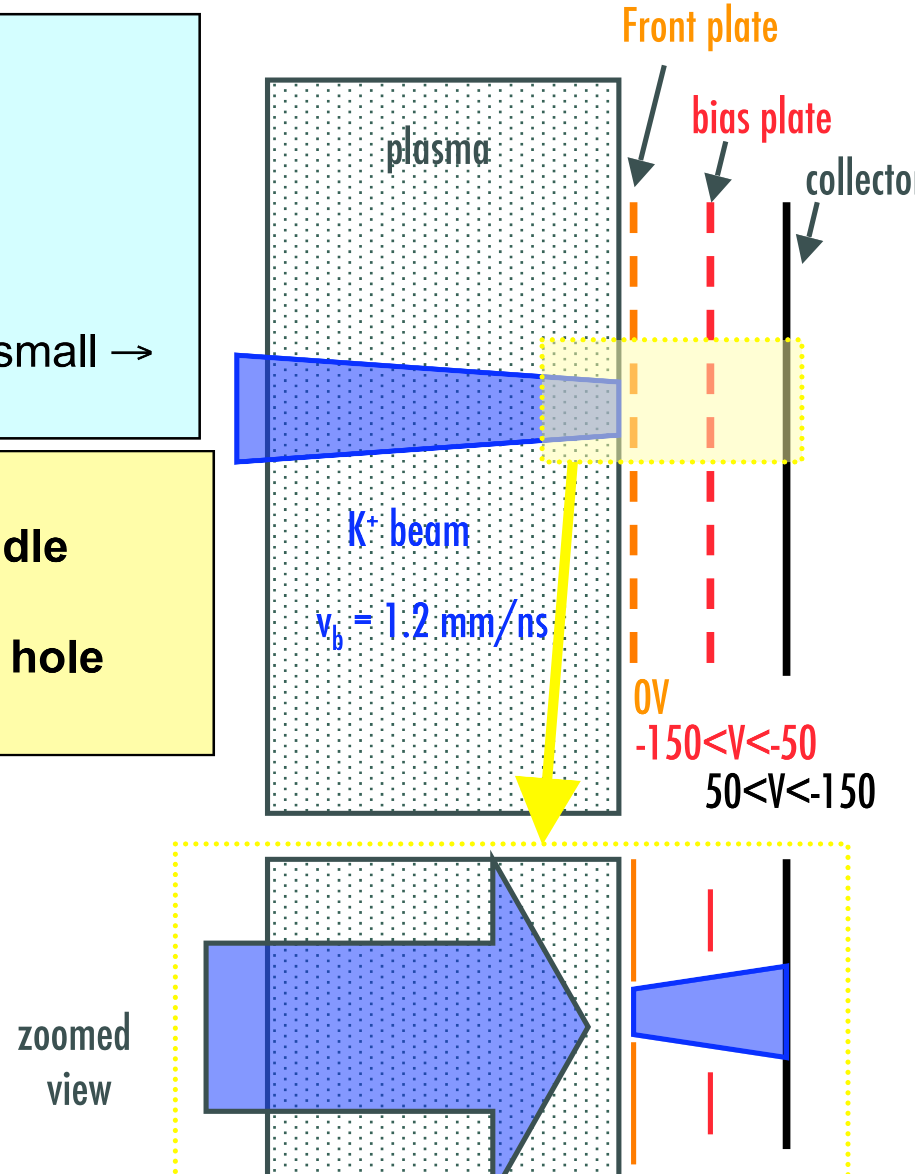
Design:

2 hole plates, closely spaced for fast response.

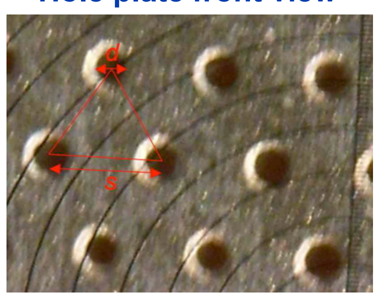
Hole pitch (1 mm) & diameter (0.23, 0.46 mm) small → blocks most of the plasma

- **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.**

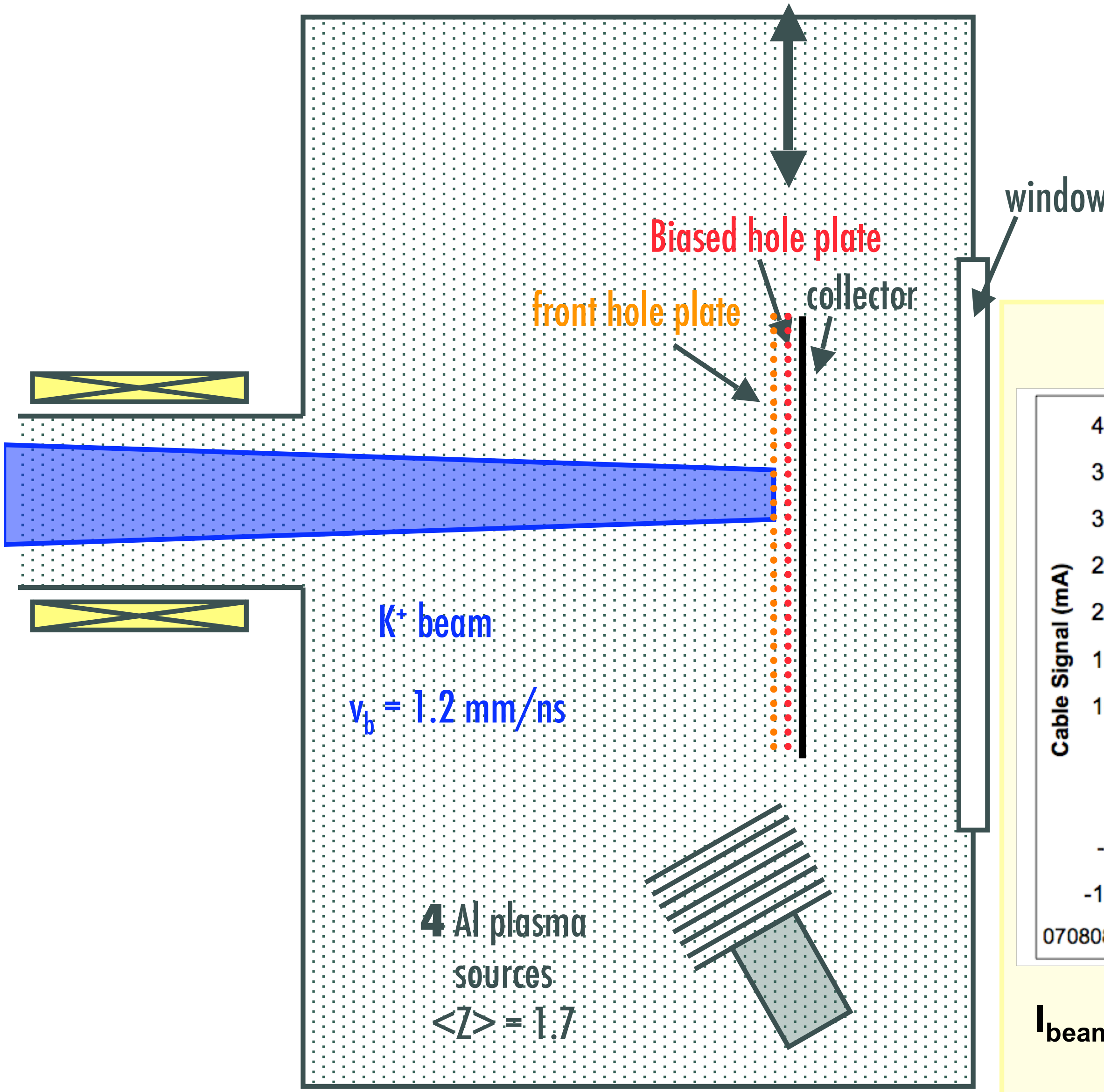




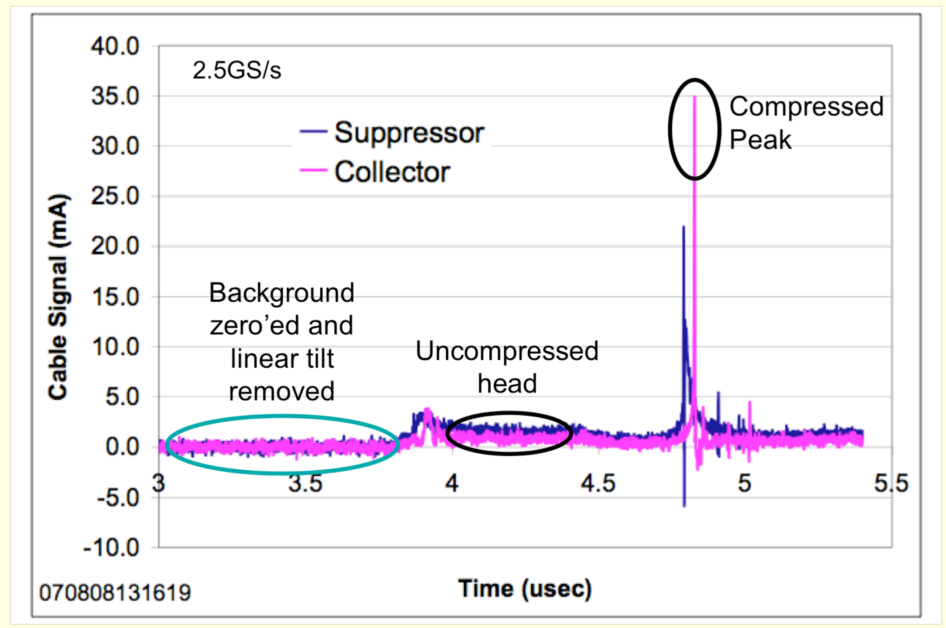
Hole plate front view



Beam diagnostics in the target chamber: Fast faraday cup



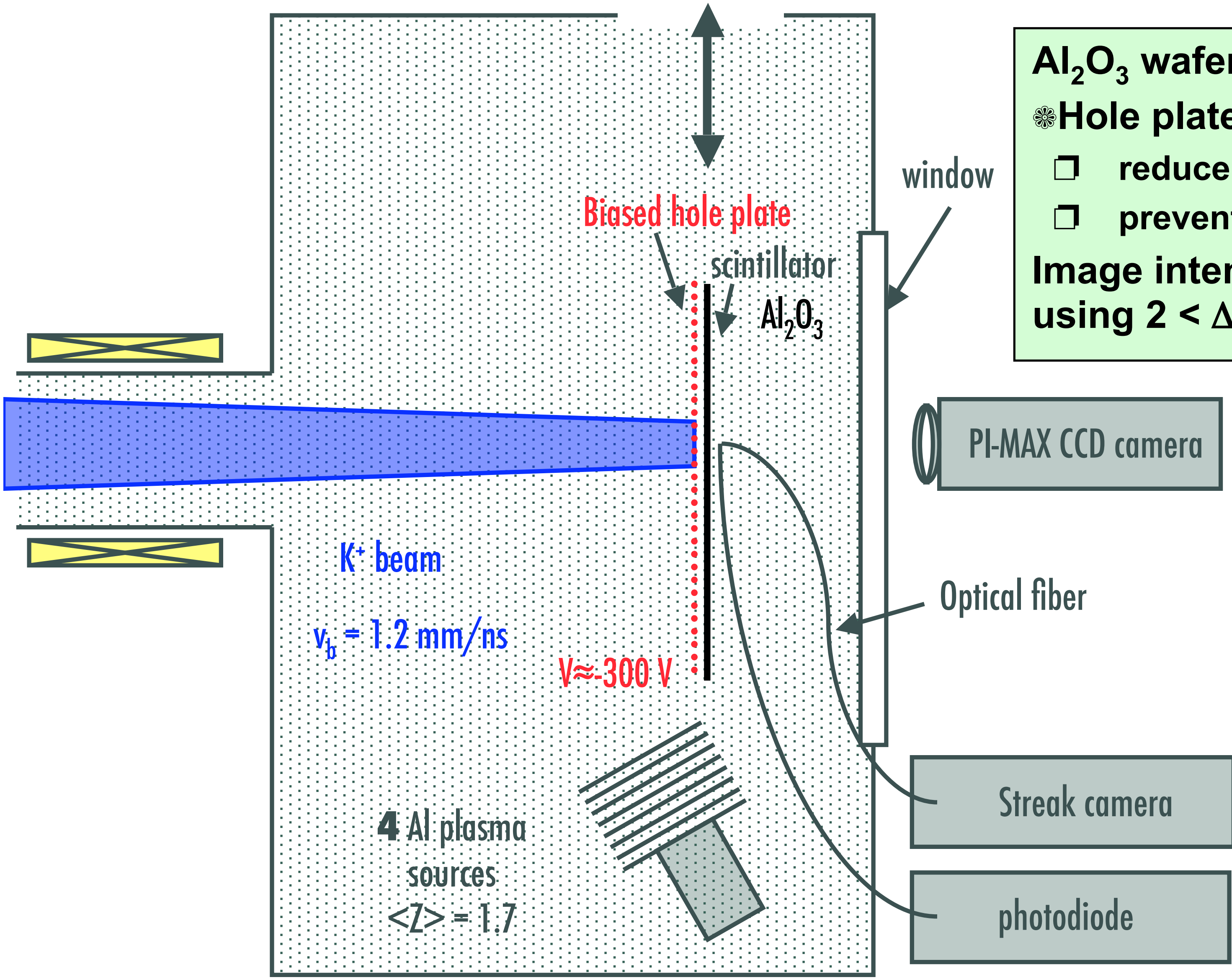
Example waveform



$I_{beam} = I_{collector}$ x (transparency)$^{-1}$

= 35 mA x 44 = 1.5 A peak.

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

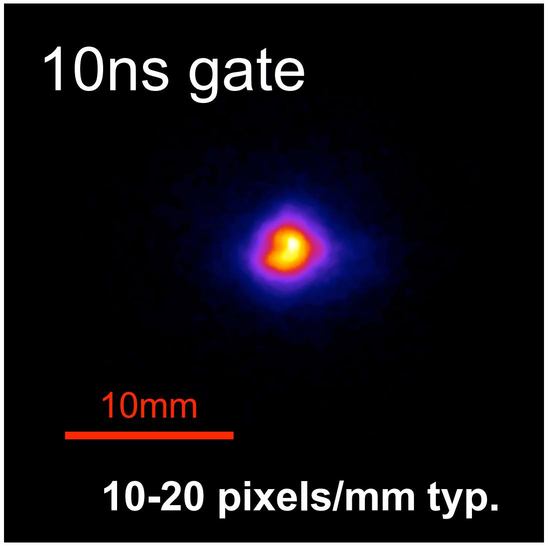


Al_2O_3 wafer with hole plate:

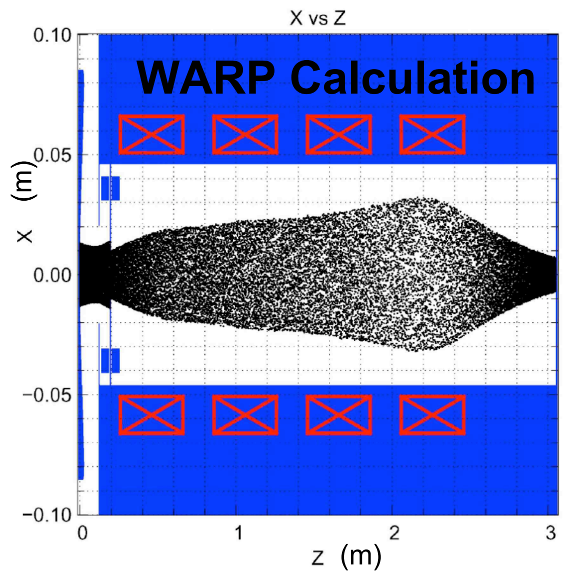
❁Hole plate to

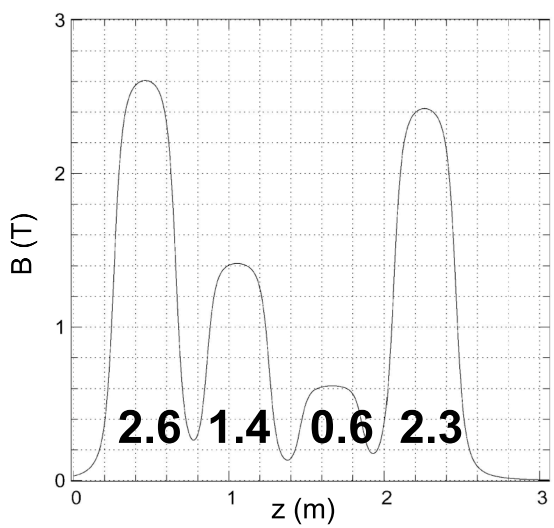
- ❒ **reduce beam flux: less damage**
- ❒ **prevent charge buildup.**

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



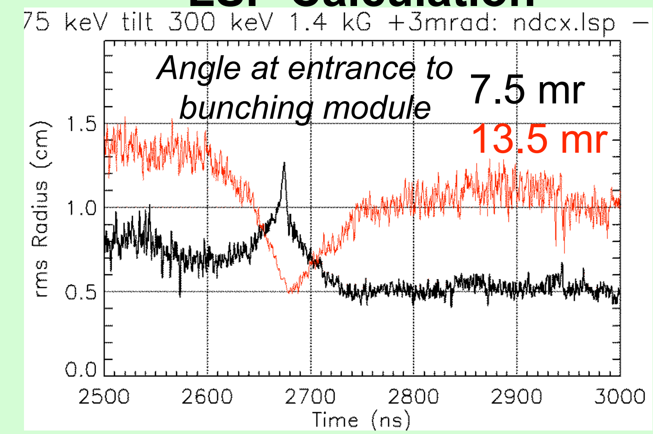
Simultaneous longitudinal compression and transverse focusing, compared to simulation.

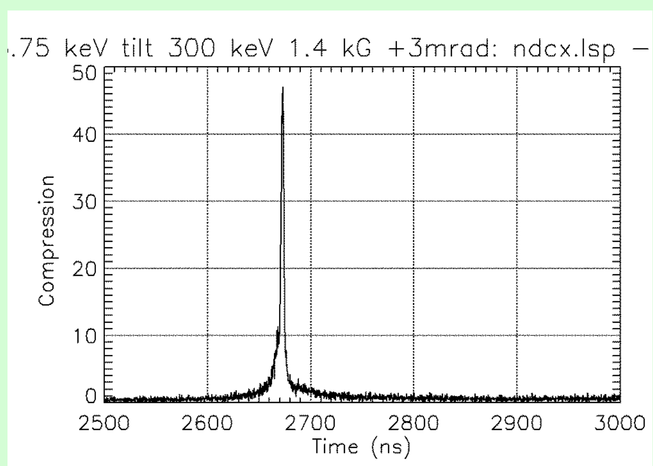




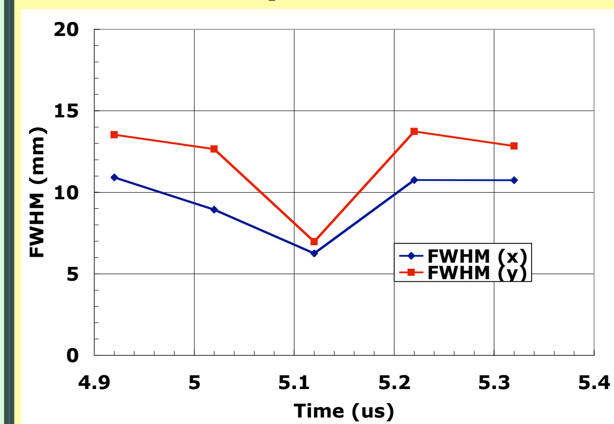
Net defocusing in gap due to energy change, E_r

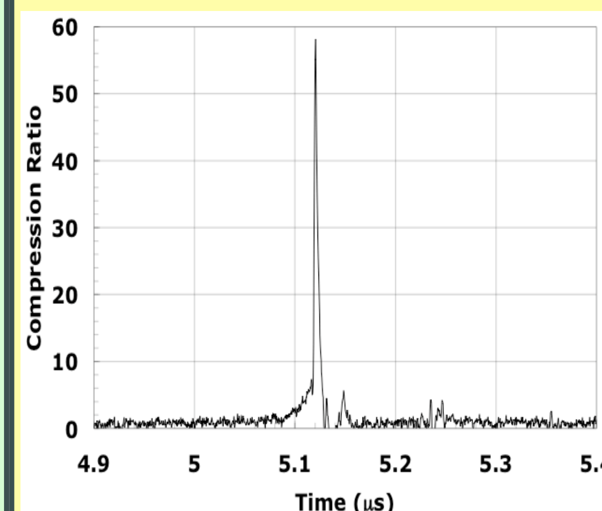
LSP Calculation

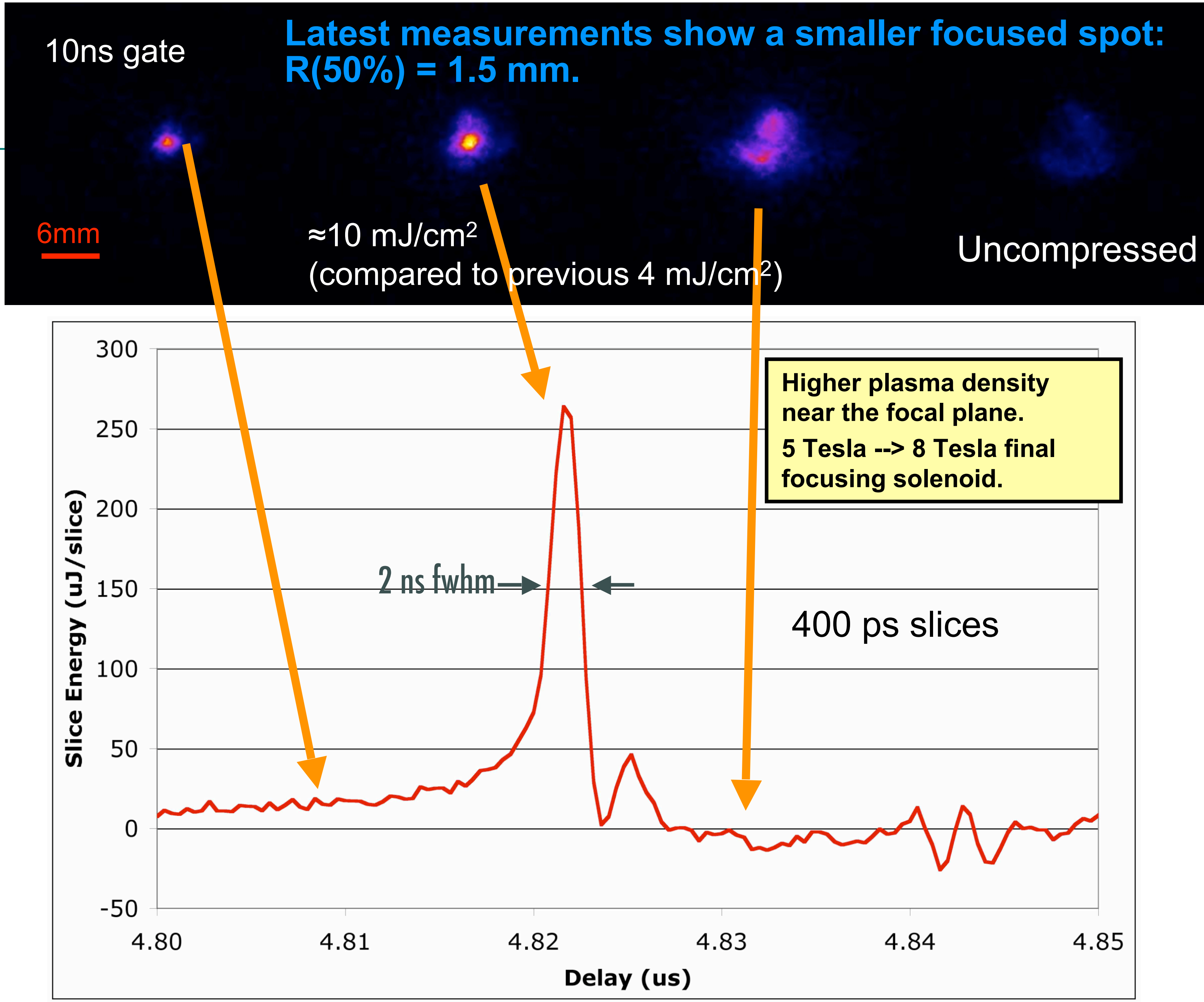




Experiment

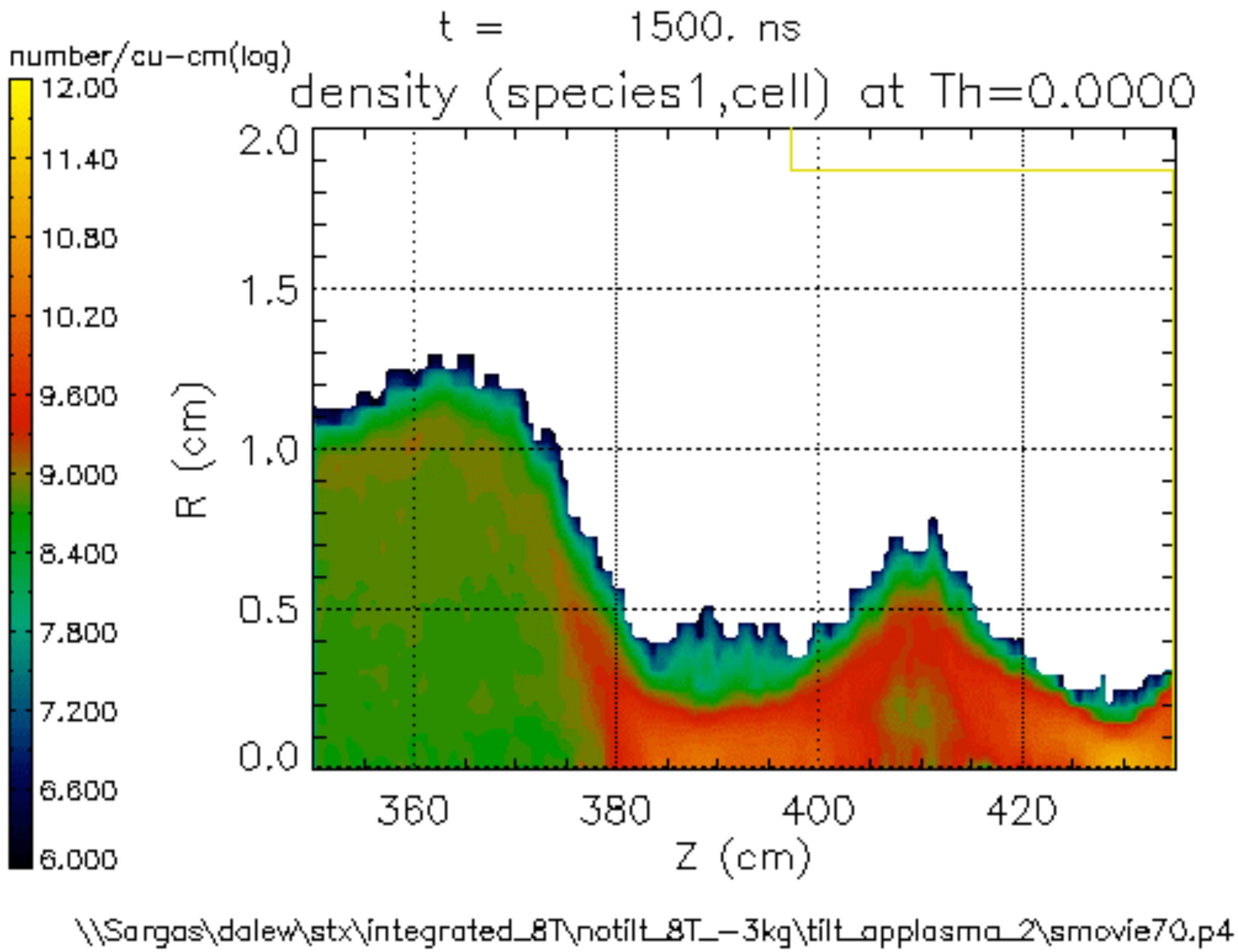






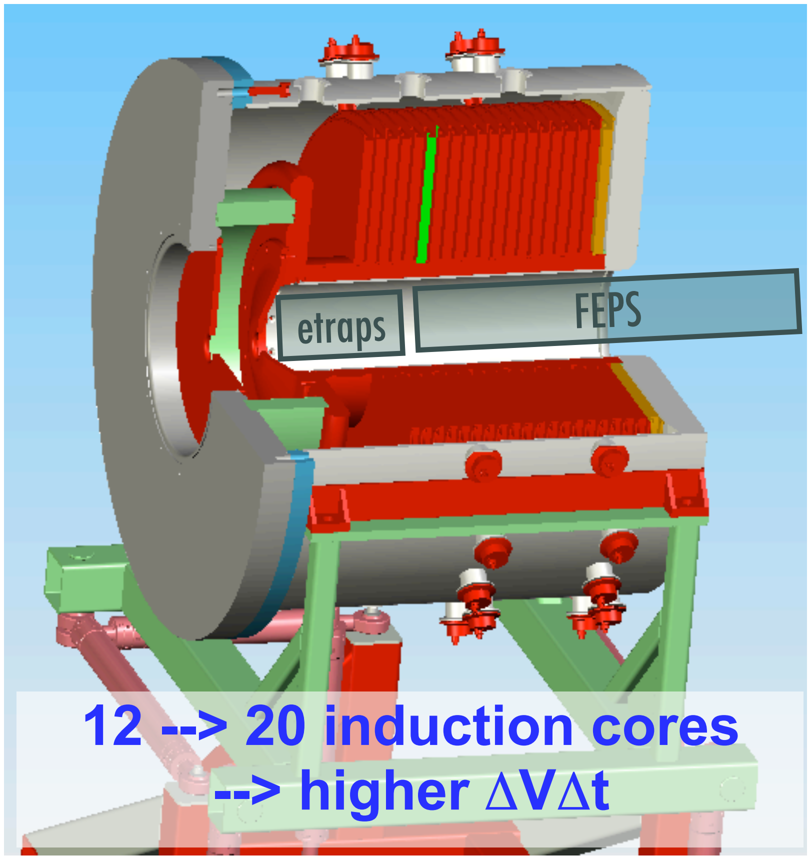
10ns gate
Latest measurements show a smaller focused spot: R(50%) = 1.5 mm.
6mm
≈10 mJ/cm2
(compared to previous 4 mJ/cm2)
Uncompressed
Higher plasma density near the focal plane.
5 Tesla --> 8 Tesla final focusing solenoid.
2 ns fwhm
400 ps slices
Slice Energy (uJ/slice)
Delay (us)
300
250
200
150
100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

LSP simulation of drift compression

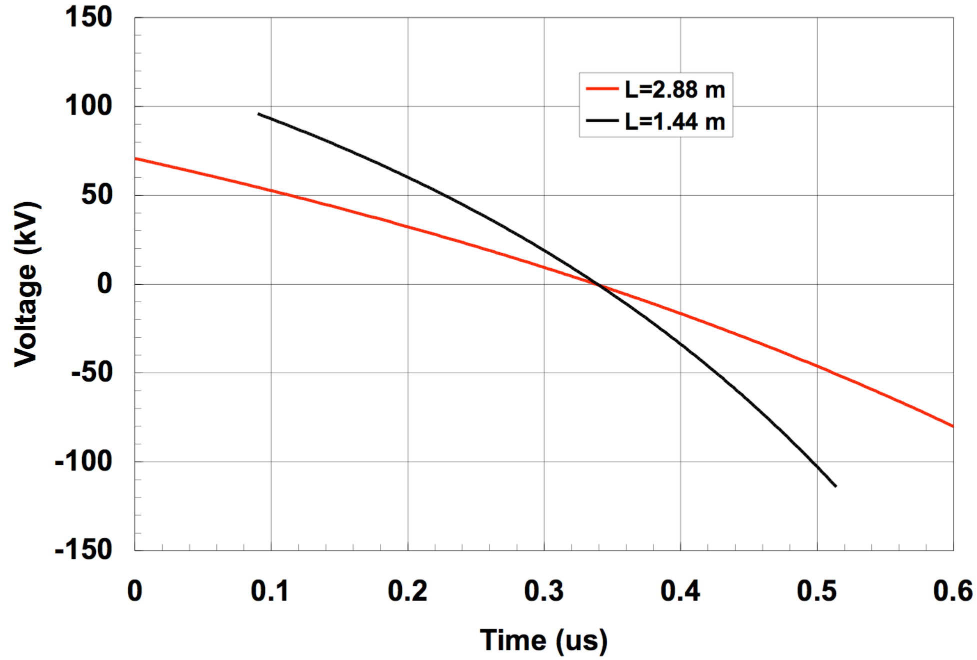


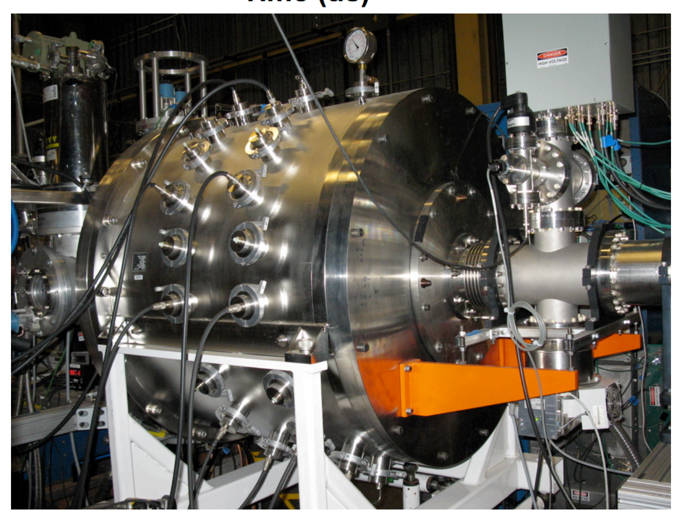
R≈ 15 mm

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

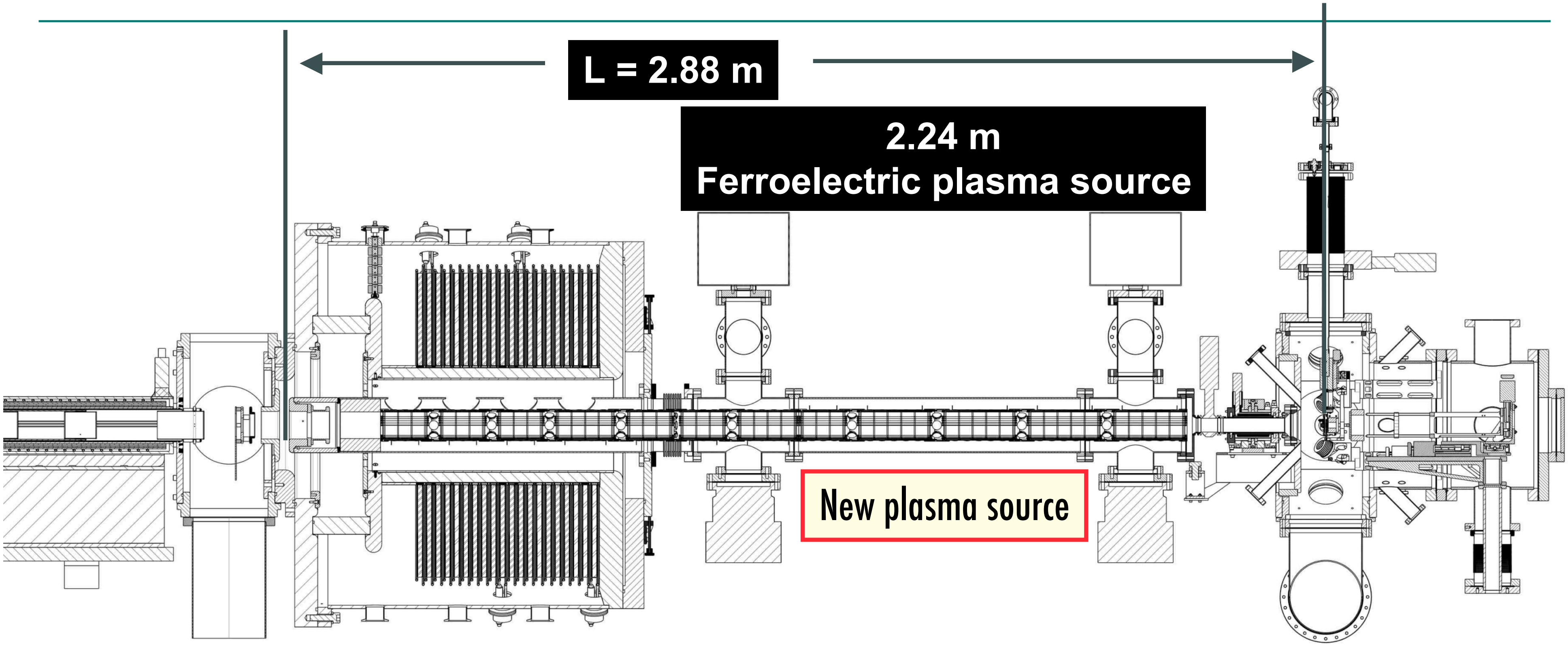


FEPS = ferro-electric plasma source





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

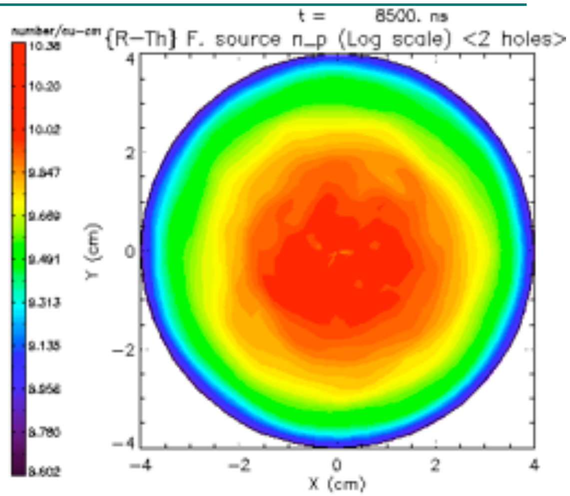


~2x longer drift compression section (L=2.88 m), Uses additional volt-seconds for a longer ramp and to limit ΔV_{peak} & chromatic effects

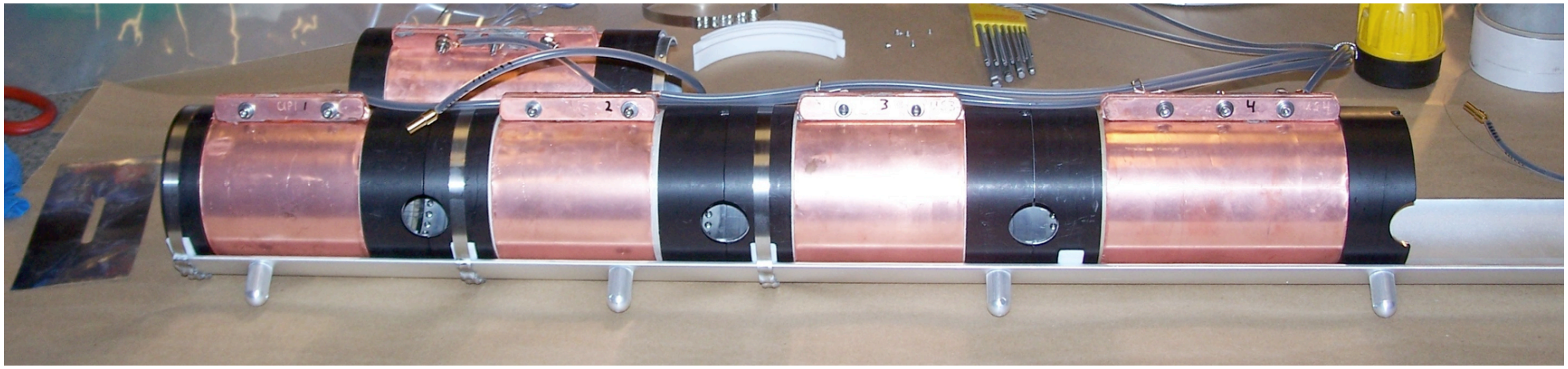
Ferro-electric plasma sources for neutralized drift compression (PPPL).

Ferro-electric plasma source (FEPS)

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



LSP simulation



New FEPS module prior to installation.

Commissioned new IBM and extended FEPS plasma source.

IBM 20 independent 50%-Ni, 50%-Fe (Astron) cores.

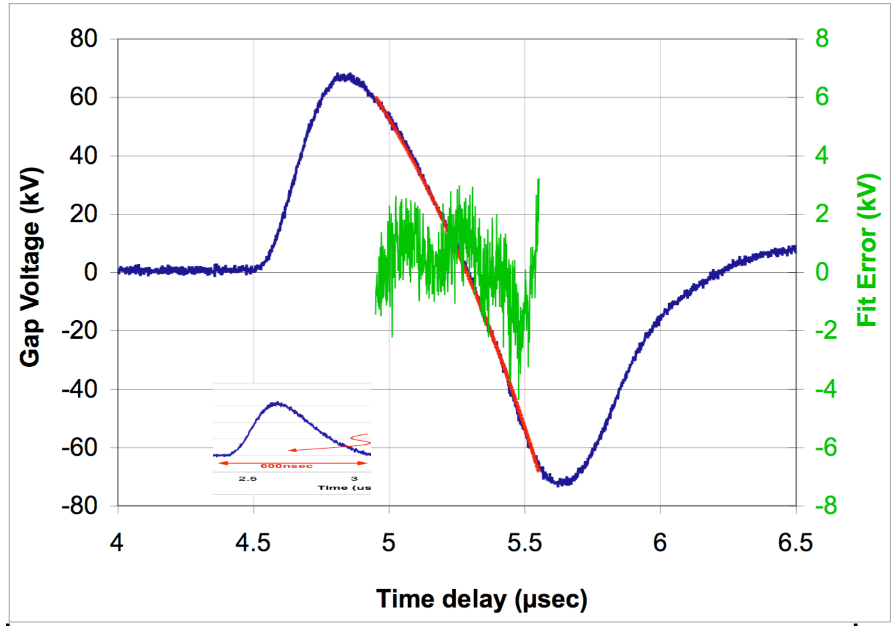
Waveform stacking efficiency

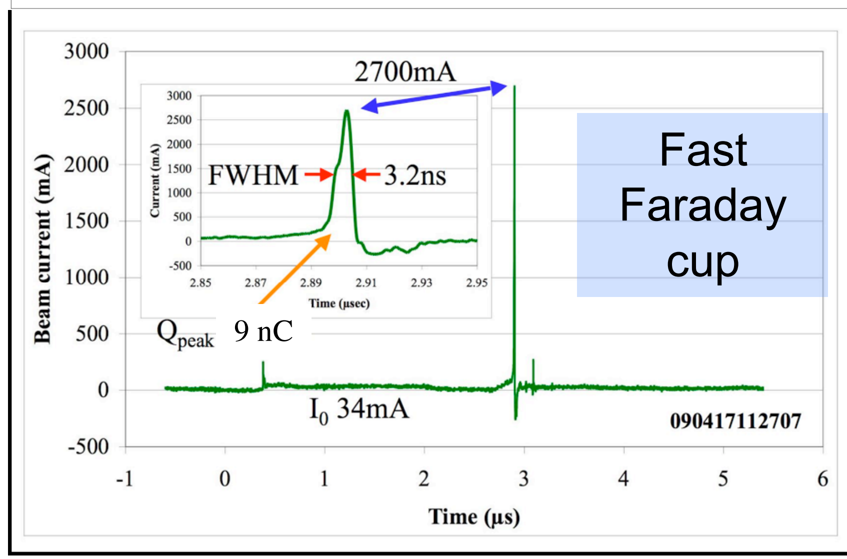
$$\eta_{net} = \frac{|V \bullet s \text{ in full range}|}{|V \bullet s \text{ in single core}| \times N_{cores}} = 56\%$$

due to partial cancellation from cores driven with opposite polarity

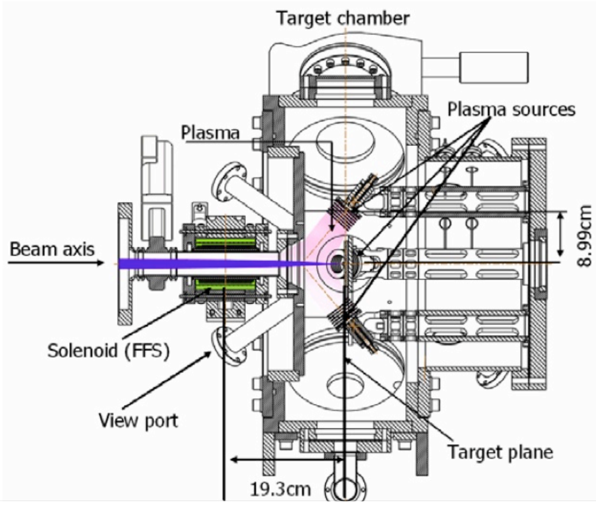
In the target chamber: With the **new IBM/FEPS: ~2 x more ion beam charge in a compressed pulse** than the previous IBM/FEPS.

Still tuning up the system.

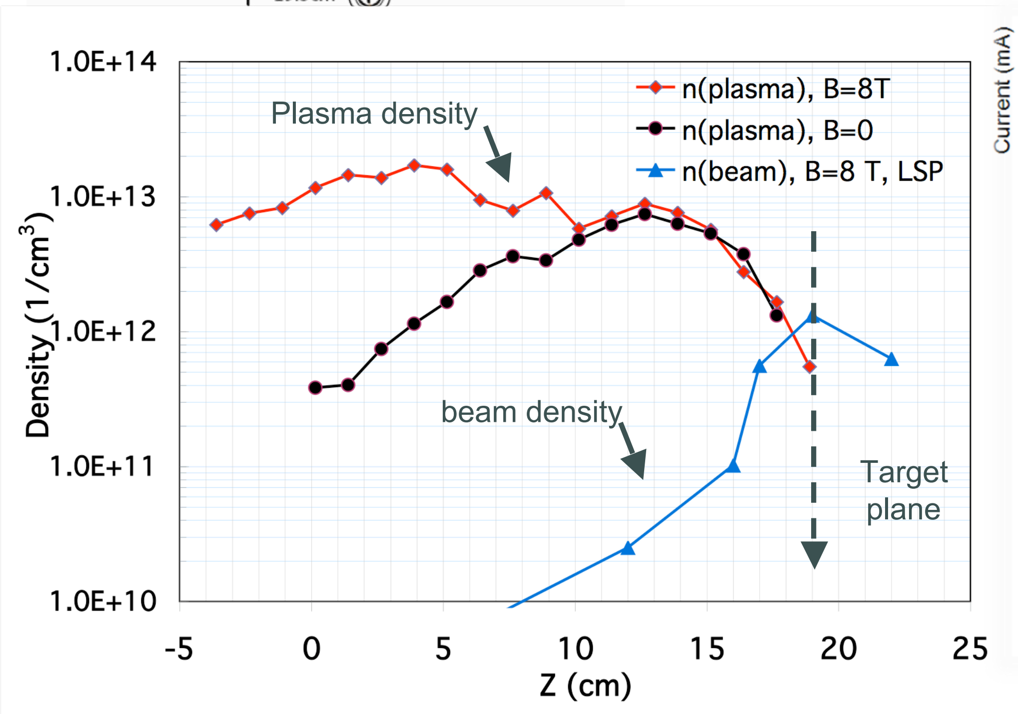


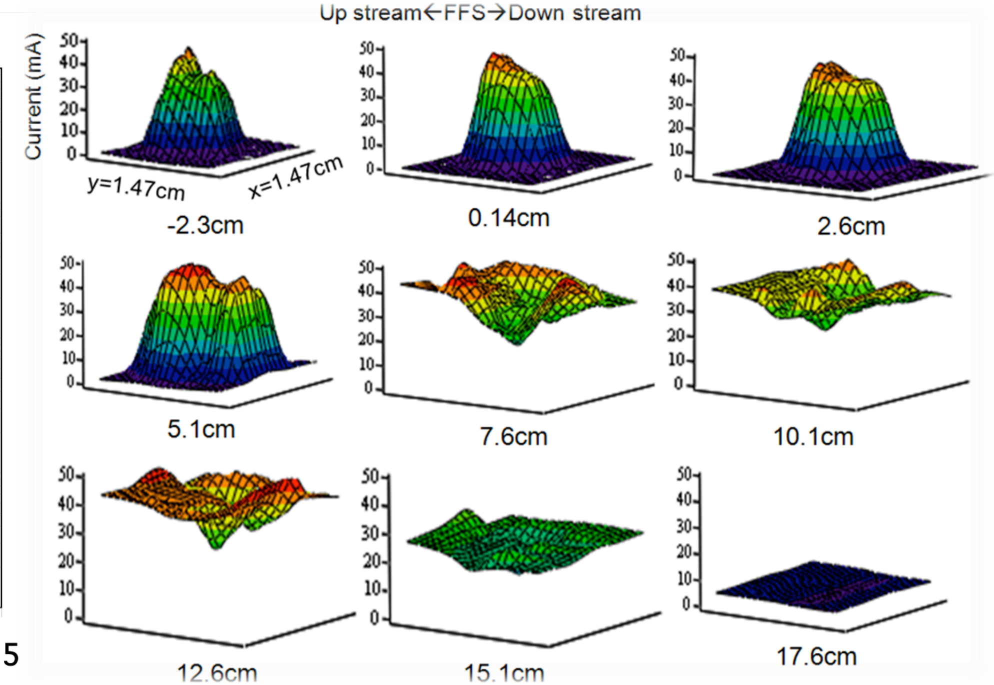


The improved filtered cathodic arc plasma source (FCAPS) injection has led to a higher plasma density near the target



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

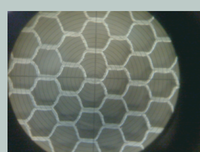




PIC simulation of injection from Cathodic-Arc Plasma Sources confirm experiment measurements

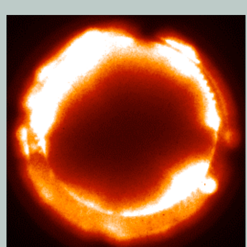
To provide more electrons at larger R in the solenoid:

Hexcel grid, self supporting

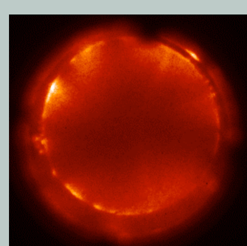


Compact FEPS

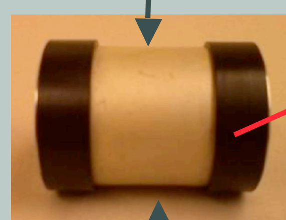
4 cm dia.

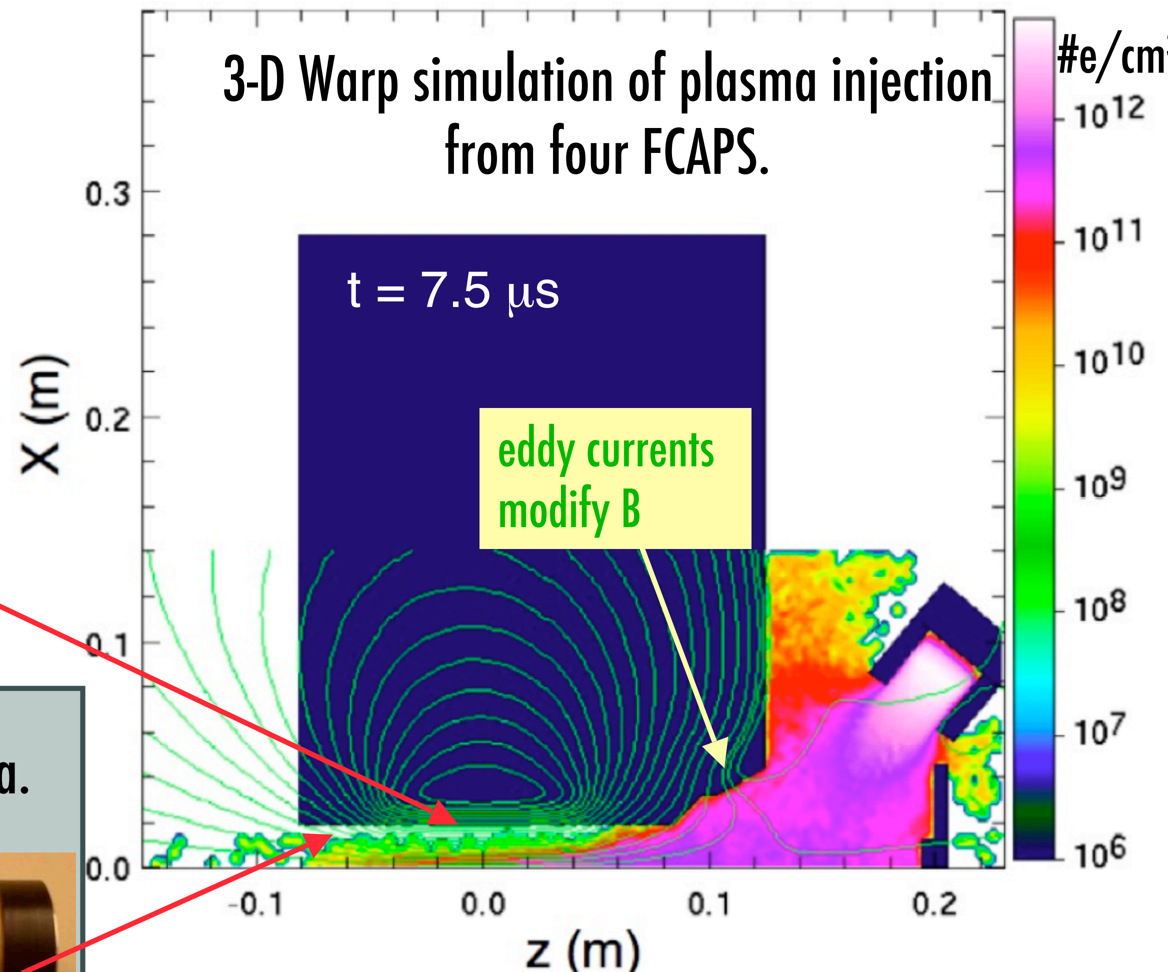


t = 1.0μs

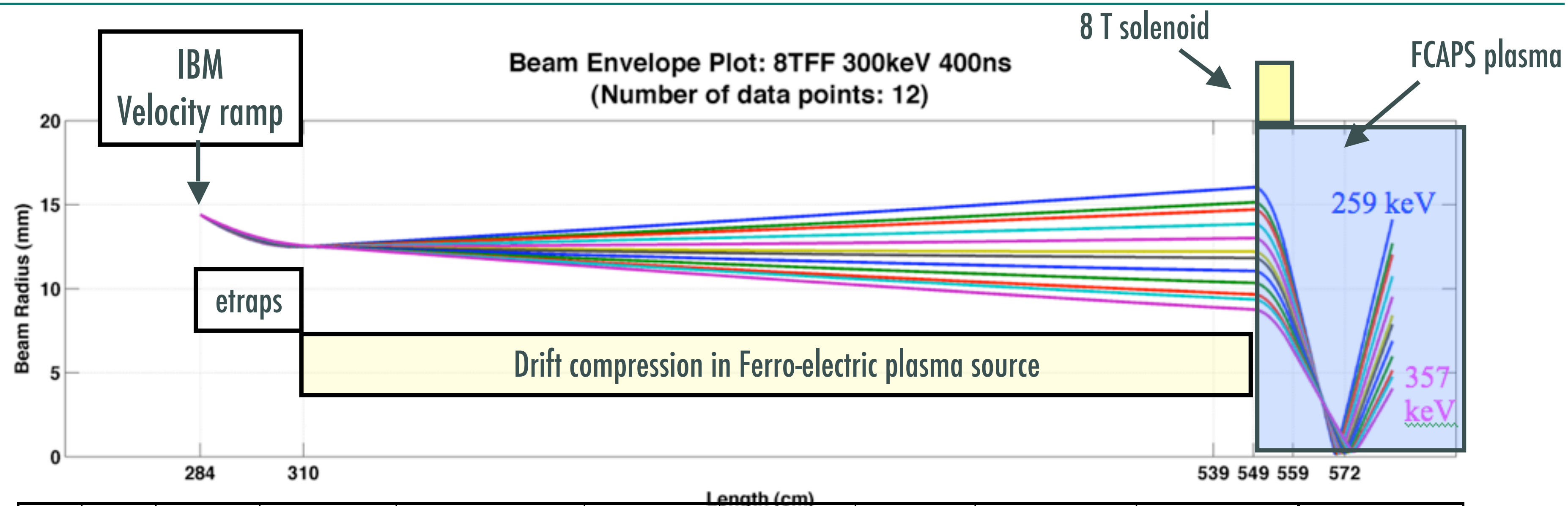


t = 2.0μs





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

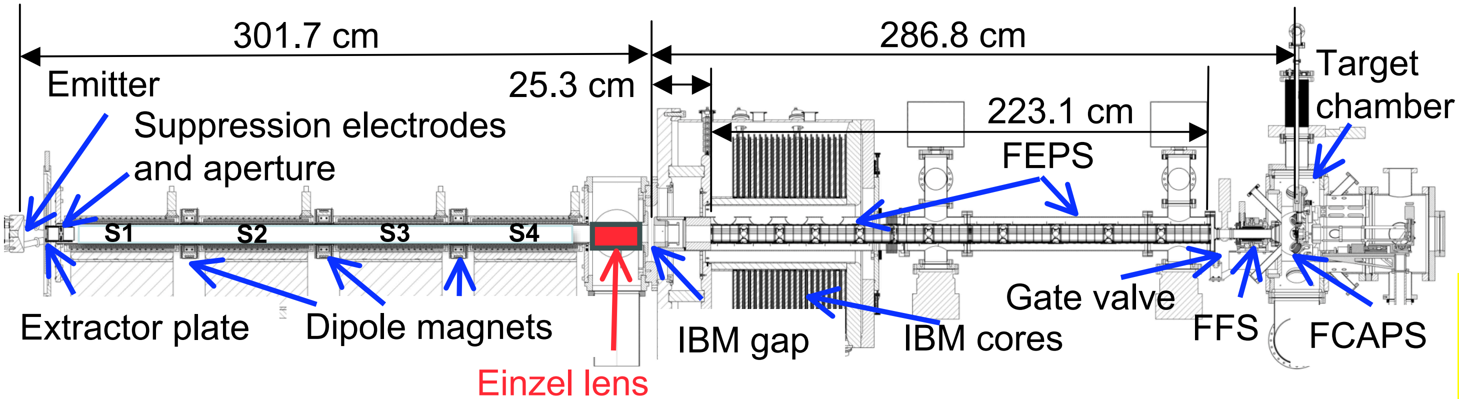
Comparison of LSP, the envelope-slice model, and the simple analytic model.

(a) no final focusing solenoid.

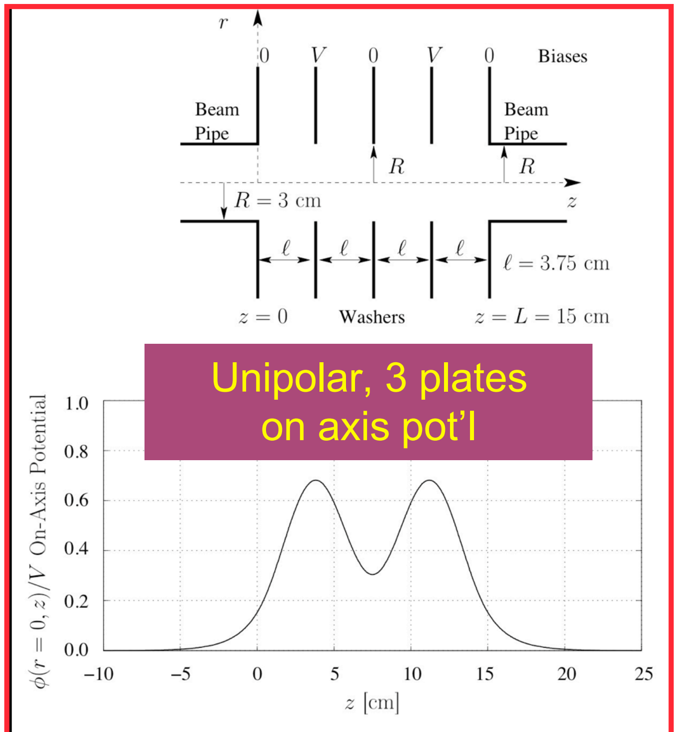
(b) New IBM, the final focusing solenoid (B_{max} = 8 Tesla) L_{drift} =144 cm, **initial setup**

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

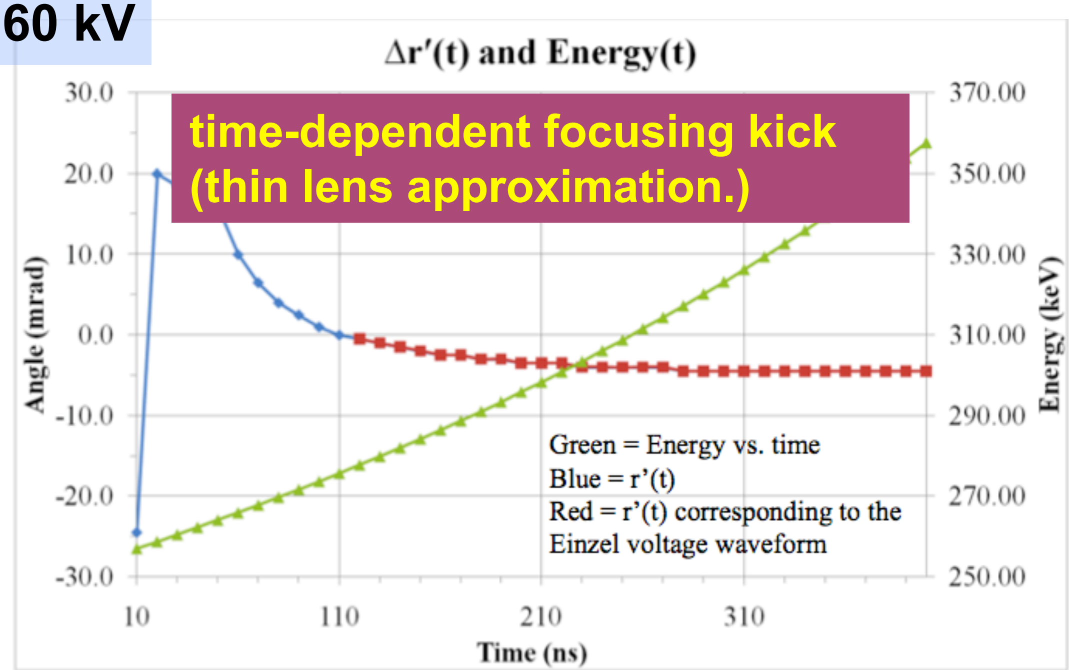
A time dependent Einzel lens to correct the chromatic aberrations



$$\Delta v_r \approx -\frac{qr}{2mv_{zo}^2}\frac{dV(t)}{dt}$$

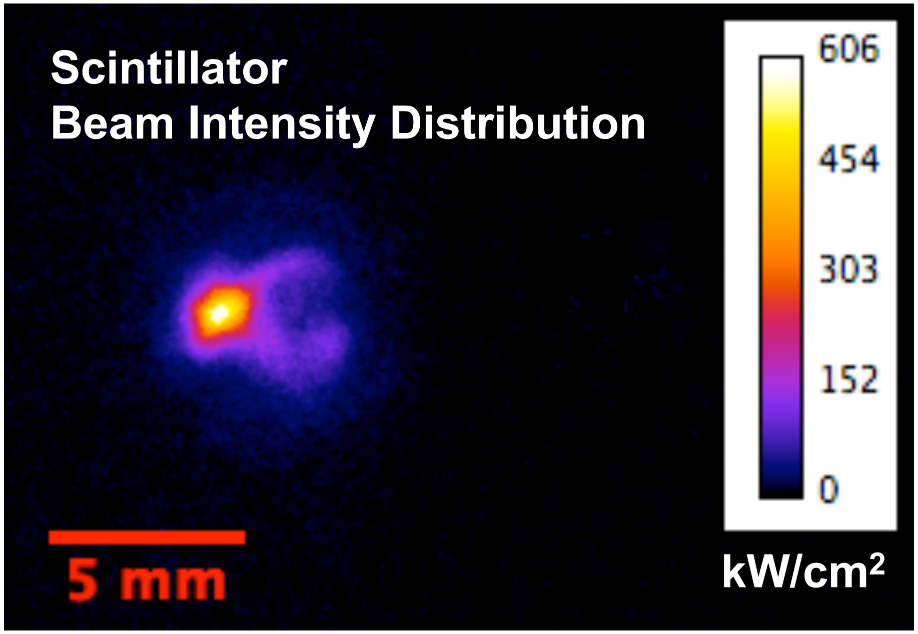


ΔV ≈ 60 kV

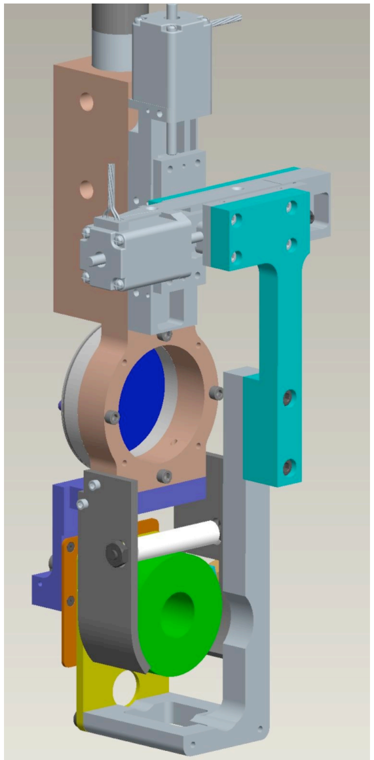


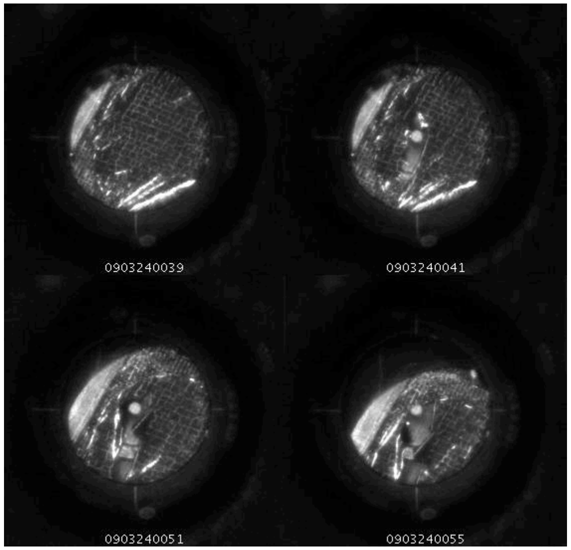
next: PIC modeling, pulser design, fab.

First target experiments: Prepulse heats thin foils to 3000-4000 K, additional heating by bunched beam.



New target manipulator: target shot rep rate increased:
1/day --> several/h





carbon foil target

From fast optical pyrometer data: thin gold and carbon **foil targets are heated to 3000-4000 K** by the portion of **the uncompressed beam (1 μs)** that precedes the bunched beam. **Additional heating from the bunched beam has been detected.**

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

Greater axial compression via a longer velocity ramp while keeping $\Delta v/v$ fixed.

Next steps: time-dependent focusing elements to correct considerable chromatic aberrations

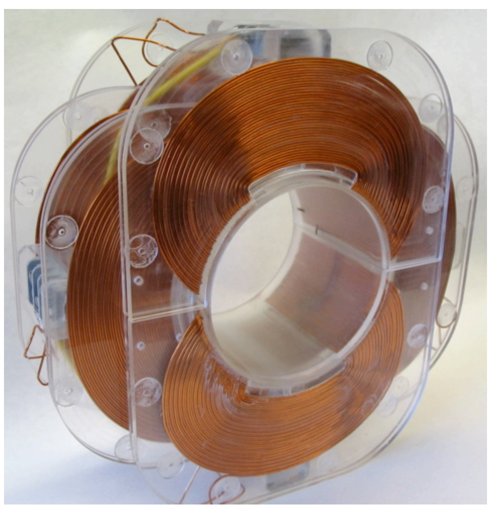
backup slides

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

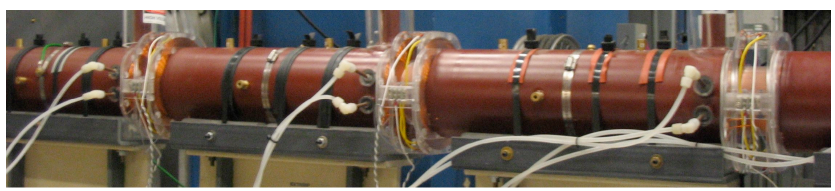
Alignment survey: mechanical structure aligned within 1 mm.
Manufacturing imperfections (coil w.r.t support structure) not included.

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

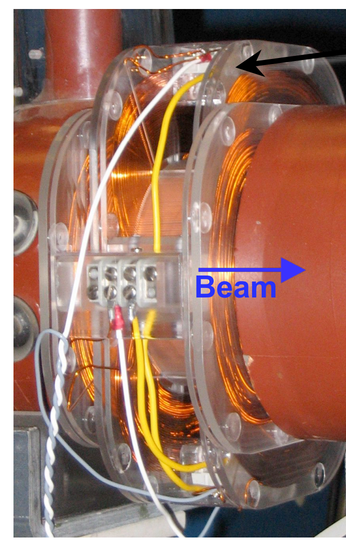
We can correct the centroid empirically with steering dipoles at the exit of the solenoid matching section.



3 dipole pairs between solenoids

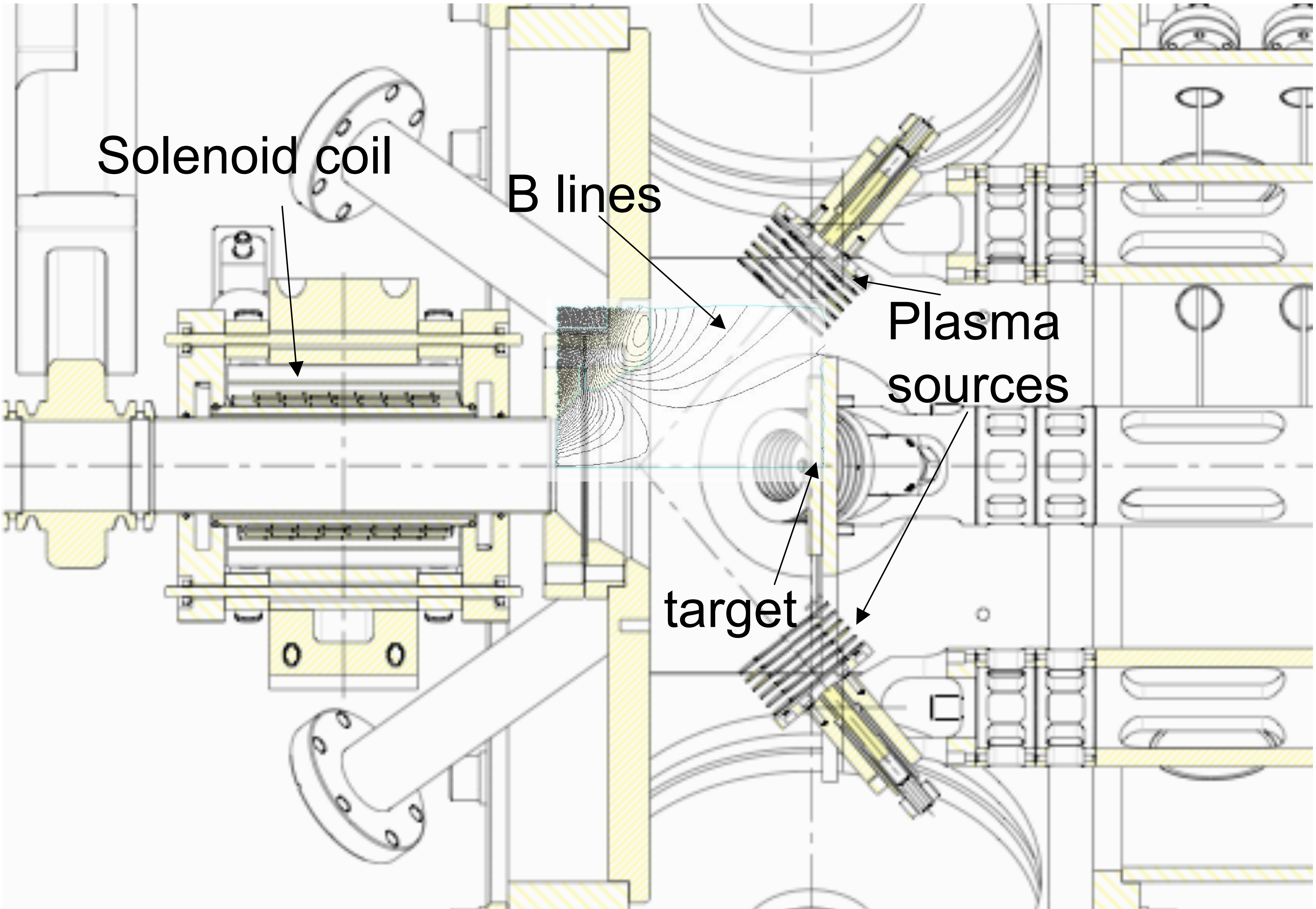


$I_{max} \sim 200$ A
$B_{max} \sim 0.5$ kG



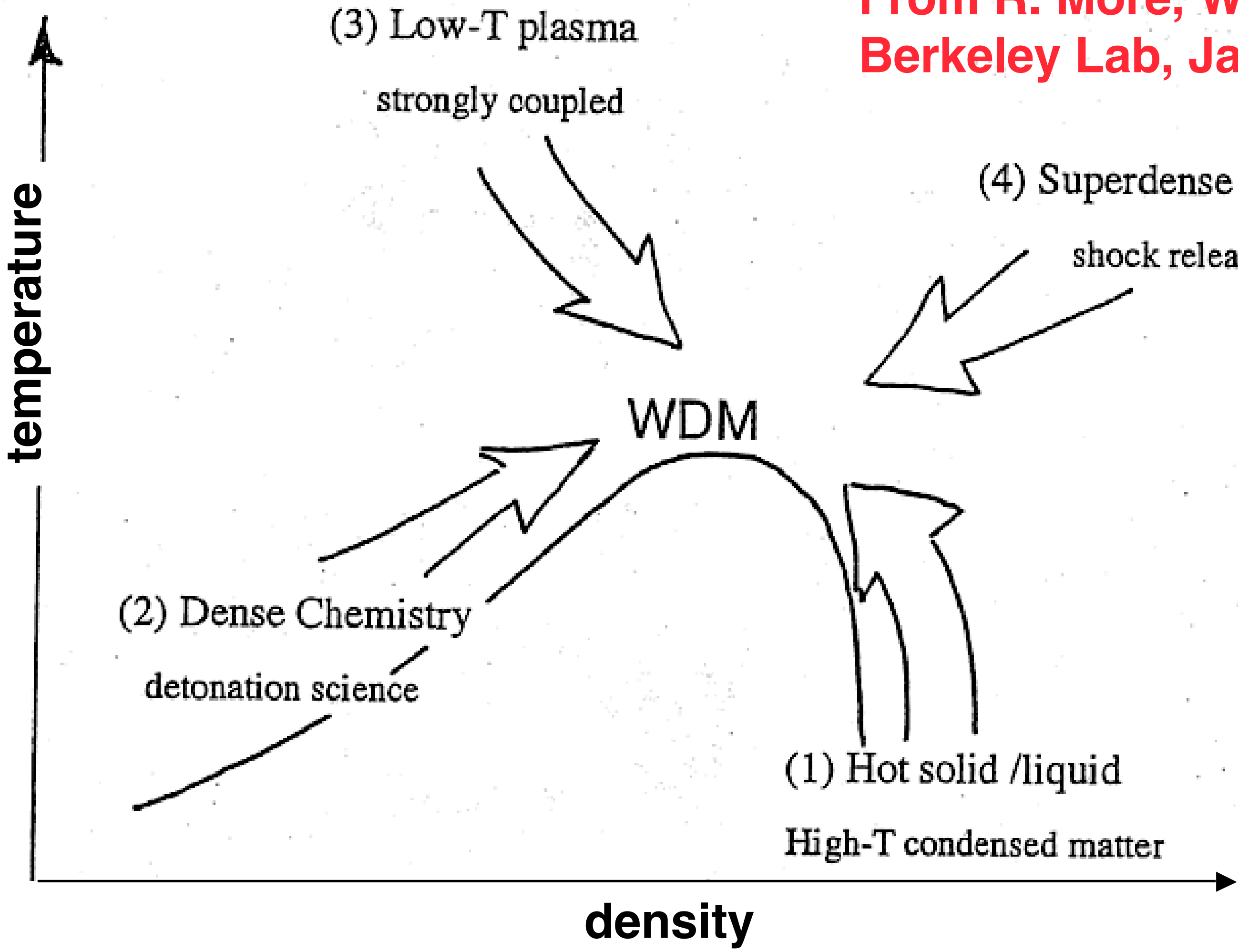
Y dipole
(inside)

45 degree view -- zoomed field lines only



The WDM regime is at the meeting point of several distinct physical regimes -- a scientifically rich area of HEDP

From R. More, Warm Dense Matter School, Berkeley Lab, January 2008.



Unknown properties:
EOS (p(ρ,T), E(ρ,T))
Liquid-vapor boundary
Latent heat of evap.
Evaporation rate
Surface tension
Work function
Electrical conductivity
dE/dX for hot targets

Phenomena:
Metal-insulator transition
Phase transitions?
Plasma composition?

Interesting phenomena at: $0.01\ \rho_{solid} < \rho < 1.0\ \rho_{solid}$
and $0.1\ eV < T < 10\ eV$

Accelerators have several advantages for generating warm dense matter

Precise control of energy deposition and ability to measure ion beam after exit

Sample size large compared to diagnostic resolution volumes (~ 1's to 10's μ thick by ~ 1 mm diameter)

Uniform energy deposition (<~ 5%)

Able to heat **any target material** (conductors, insulators, foams, powders, ...)

A **benign environment** for diagnostics

High repetition rates (10/hour to 1/second)