Manipulating Ion Beams for High Energy Density Physics Studies

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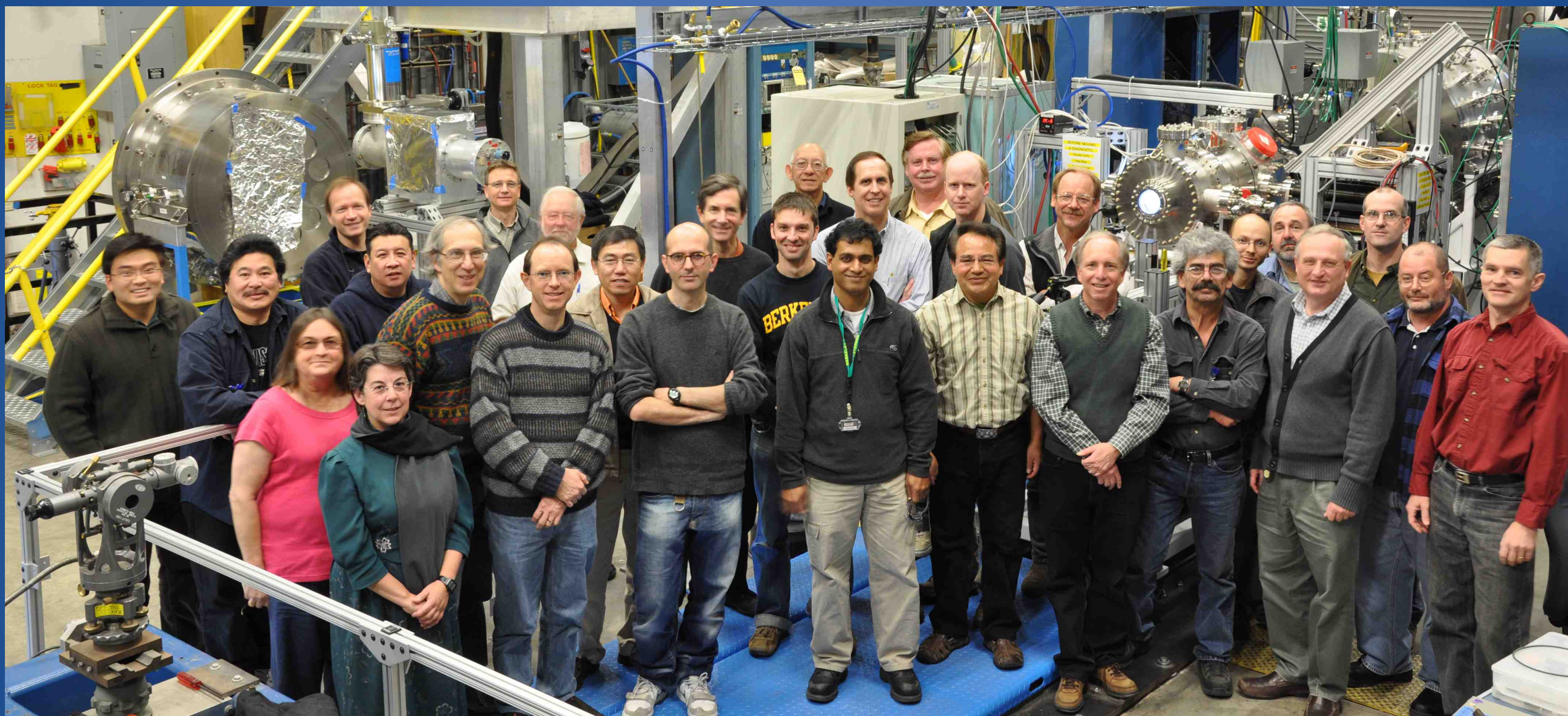
Center for Beam Physics Seminar
29 January 2010

HIFS-VNL Team



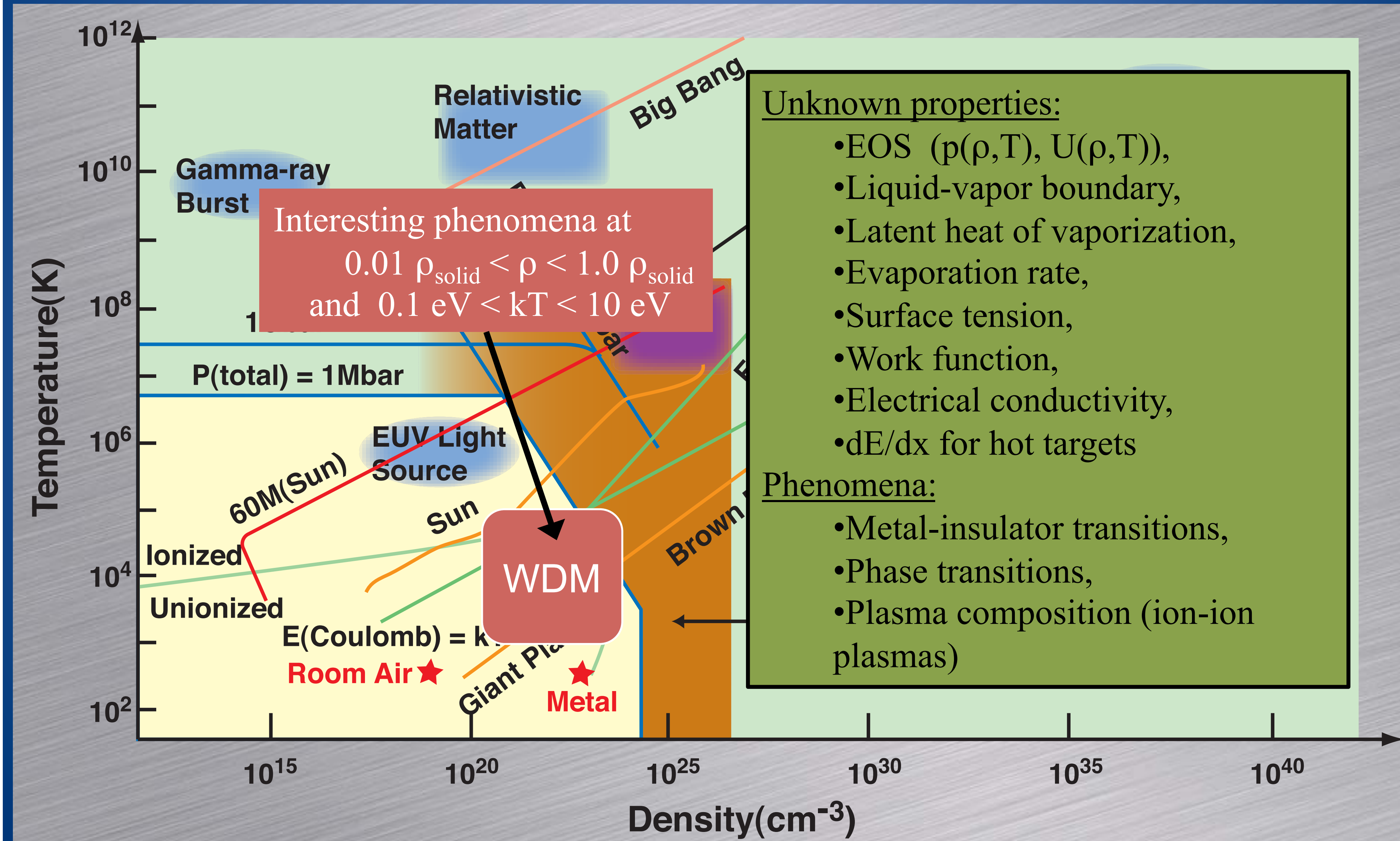
Not pictured:

G. Bazouin, F. Becker, J. Coleman, R. Davidson, M. Dorf, E. Gilson, I. Kaganovich, M. Kauffeldt, D. Ogata, A. Sefkow, K. Van den Bogert, J-L Vay, D. Welch, C. Wootton, S. Yu

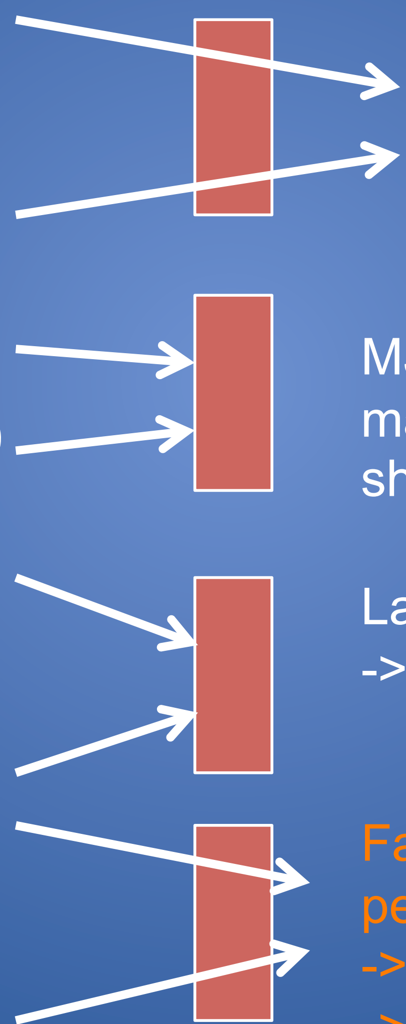
Introduction

- High Energy Density (HED) and Warm Dense Matter (WDM)
- Why Ion Beams?
- Manipulating Ion Beams for HEDP
  - Stage 1: Neutralized transport and focus (NTX)
  - Stage 2: Neutralized drift compression (NDCX-I)
  - Stage 3: Add acceleration schedule (NDCX-II)
  - Stage 4: Pulse shaping and shock timing (IB-HEDPX)

HEDP Space


Temperature(K)
Density(cm-3)
10^12
10^10
10^8
10^6
10^4
10^2
10^15
10^20
10^25
10^30
10^35
10^40
Relativistic Matter
Big Bang
Gamma-ray Burst
P(total) = 1Mbar
EUV Light Source
60M(Sun)
Sun
Ionized
Unionized
E(Coulomb) = k
Room Air
Giant Pla
Metal
Brown
WDM
Interesting phenomena at
0.01 ρsolid < ρ < 1.0 ρsolid
and 0.1 eV < kT < 10 eV
Unknown properties:
•EOS (p(ρ,T), U(ρ,T)),
•Liquid-vapor boundary,
•Latent heat of vaporization,
•Evaporation rate,
•Surface tension,
•Work function,
•Electrical conductivity,
•dE/dx for hot targets
Phenomena:
•Metal-insulator transitions,
•Phase transitions,
•Plasma composition (ion-ion plasmas)

What's so interesting about ions?



Foils heated by hard x-rays

XFEL heating -> small energy/volumes (~1μm radius, ~0.1μm thickness)
May limit diagnostic accuracy.
Poor coupling to lower Z.

Supersonically heated foams or low Z material (thermal x-rays)

MJ of soft x-rays available on Z machine but limited number of shots.

Shock compressed and heated thin foils

Lasers absorb at $\rho_{critical} << \rho_{solid}$
-> large density/pressure gradients

Tailored Bragg-peak ion beams heating thin foils

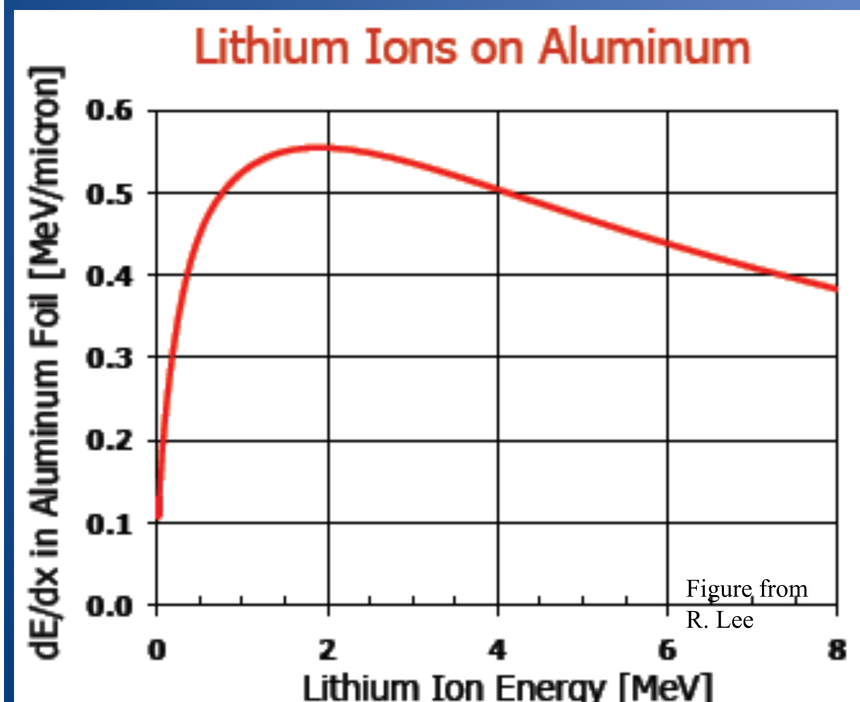
Fast heating of a solid with penetrating ions
-> more volume/lower gradients
-> more accurate EOS

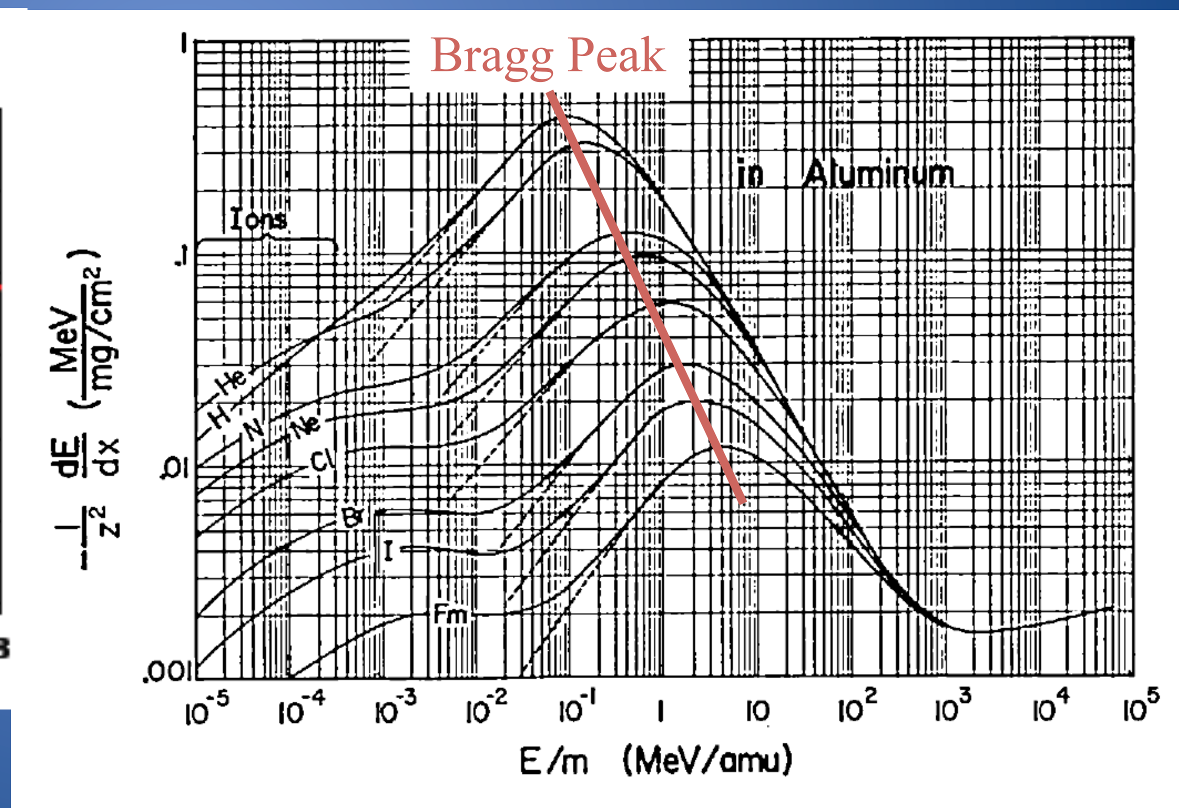
Ion Beams on Solids

Range matched to energy and species,

For < 1 MeV, can use lighter ions, e.g. He+,

For > 10 MeV, can use heavier ions, e.g. C+





Ion beam source limitations

- Multicusp Plasma, Pulsed ECR
  - High residual gas pressure – results in resonance charge exchange processes that increase energy spread
  - High ion temp (~2eV), high current density (100 mA/cm^2)

- Contact Ionization/Aluminosilicate
  - Produces alkali metal ions (with low ionization potential) from a solid surface with high work function (e.g. tungsten) at high temperature.
  - Ion temperature ≤ 0.3 eV; $J \leq 20$ mA/cm^2.
  - It had been used widely for ion thrusters in the early space-rocket program.

- Metal Vapor Vacuum Arc (MEVVA) sources
  - $J \sim$ 10's mA/cm^2
  - Low pressure, no residual gas
  - Mixed ion charge states

High current / High brightness beams

$$B \equiv \left(\frac{2}{\pi^2}\right)\frac{I}{\varepsilon^2}$$

At the ion source:

$$\varepsilon \equiv 2r\sqrt{\frac{kT_i}{mc^2}}$$

thus

$$B \propto \frac{J}{T}$$

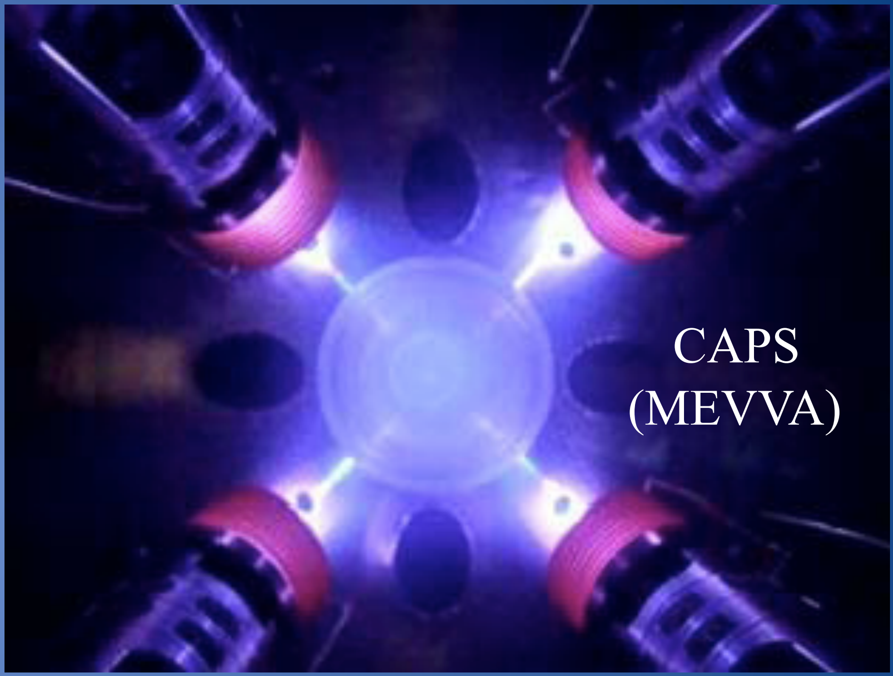
- High brightness means either low emittance, or high current, or both.
- At the ion source, high brightness is obtained by either high current density, or low ion temperature, or both.
- Achieving both high current and high brightness together is difficult at the ion source.
- Typical ions are (K, Li, Na,) Bi, Pb, Hg, Cs, Xe, Rb, K, Ar, and Ne.

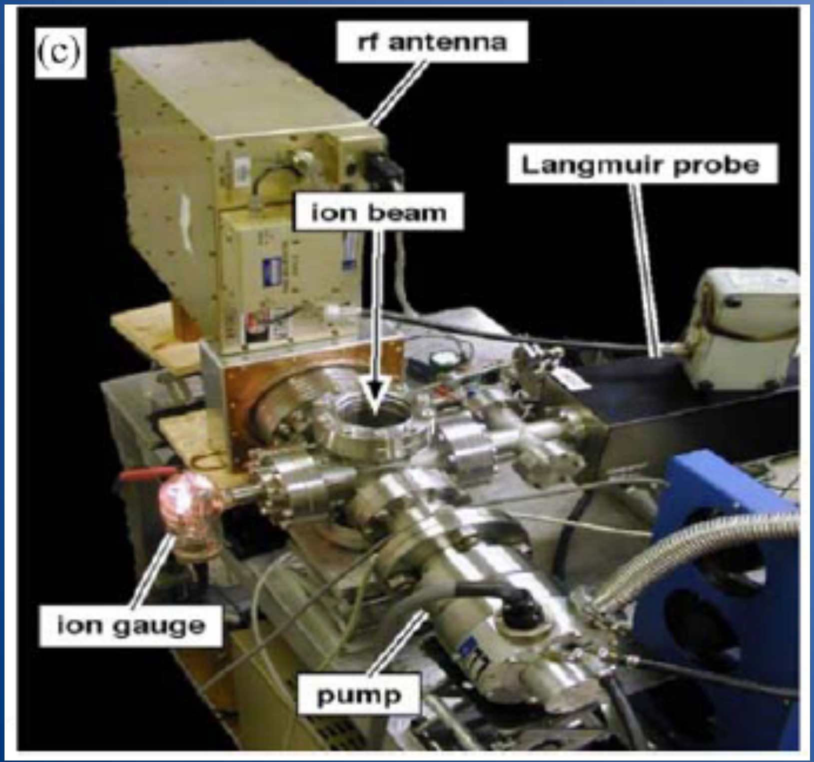
Neutralization boosts final intensity

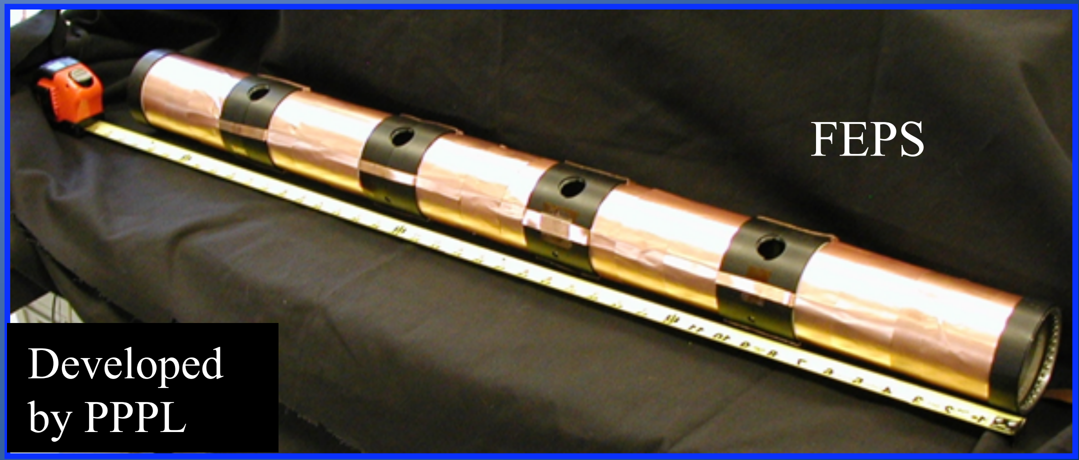
- Achieving mm to sub-mm spot sizes with high perveance, high brightness beams requires
  - Excessively large stored energy in final focus solenoids, or
  - Removing repulsive space charge forces and using reasonably sized focusing magnets
- Neutralized plasma requirements
  - $Z_b N_e > N_b$
  - Denser electron plasma densities closer to target plane

Plasma Technology

- Ferroelectric plasma source (FEPS)
  - ($N_e \sim 10^{10}$ /cm^3)
- RF sources
  - ($N_e \sim 10^{11}$ /cm^3)
- Cathodic Arc plasma source (CAPS)
  - ($N_e \sim 10^{14}$ /cm^3)







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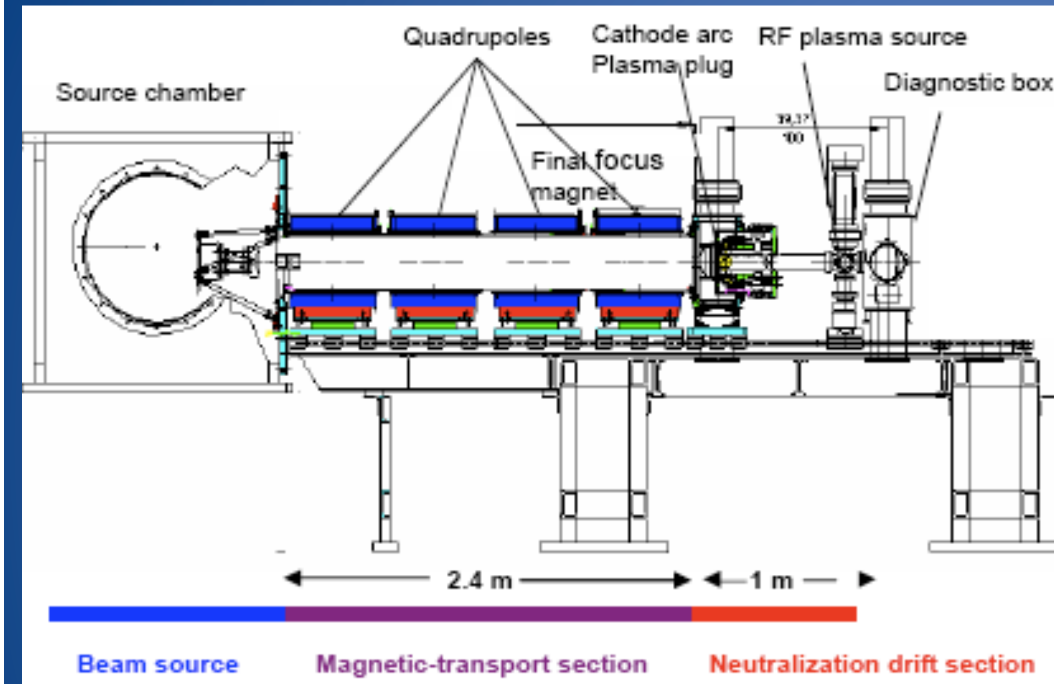
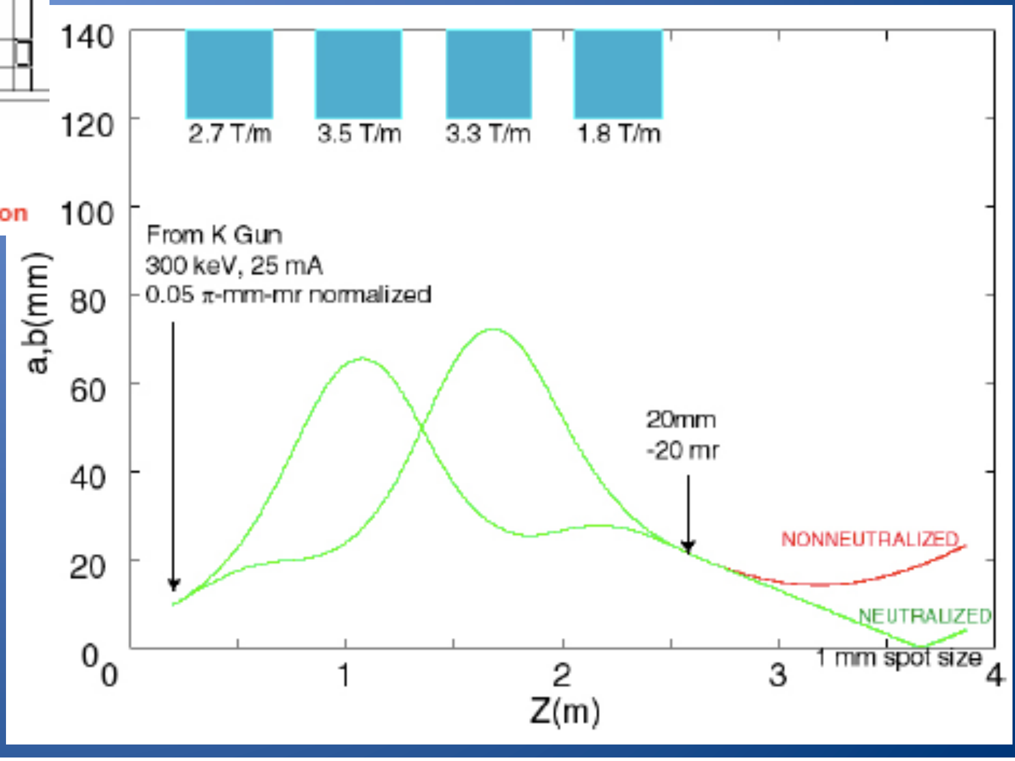
NTX: Neutralized Transport Experiment



Introduce neutralizing plasmas in final focus beamline

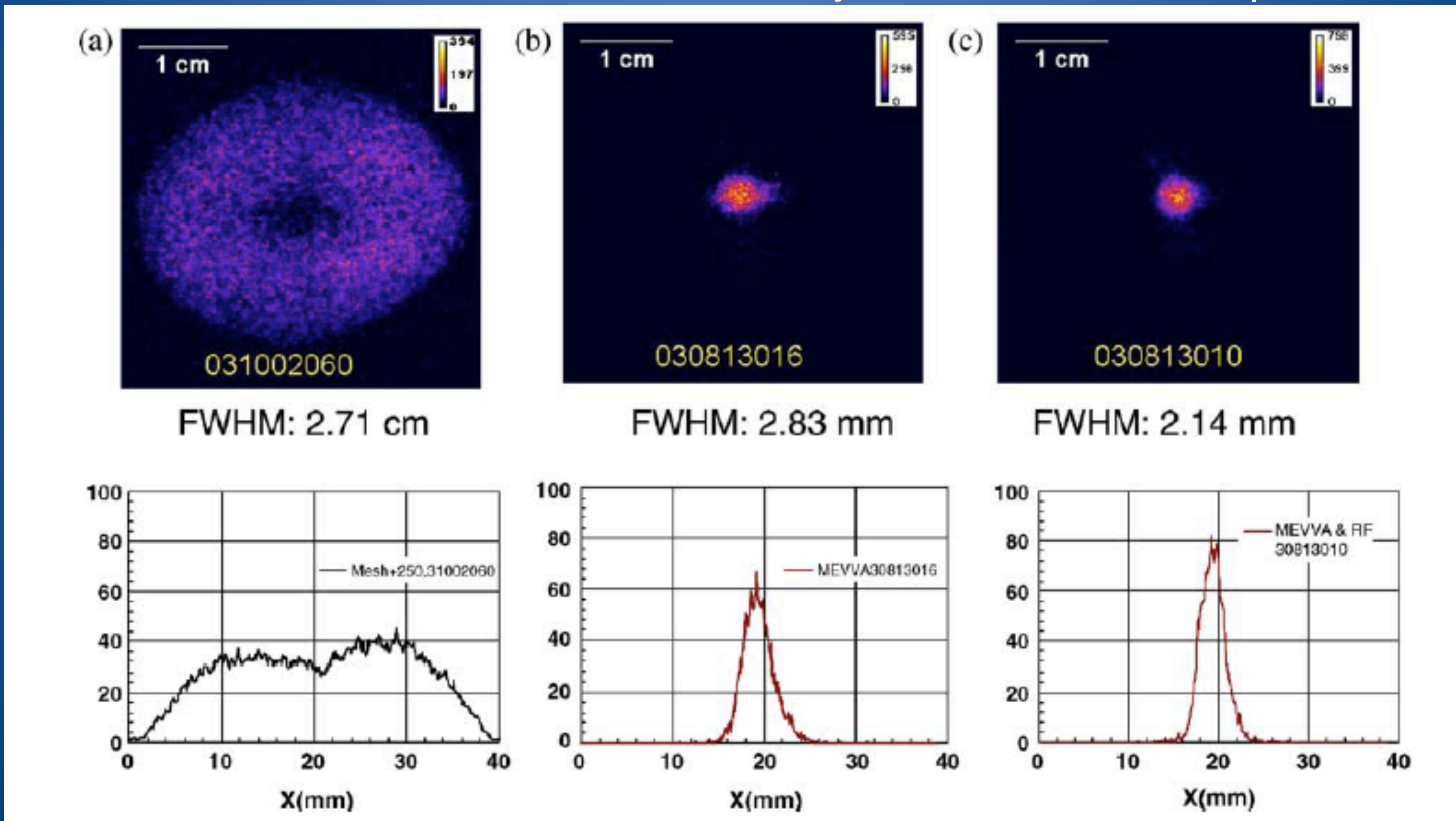


NTX Parameters:

- 300kV, 25mA, 10μsec K+ beam
- 4 transport magnetic quadrupoles
- 2 MEVVA density ~10^{10}-10^{11} cm^{-3}
- RF plasma density ~10^{11}-10^{12} cm^{-3}

Neutralized Transport Results

No neutralization | MEVVA only | MEVVA + RF plasma



P.K. Roy, *et. al.*, NIM **A544** (2005), 225-235.

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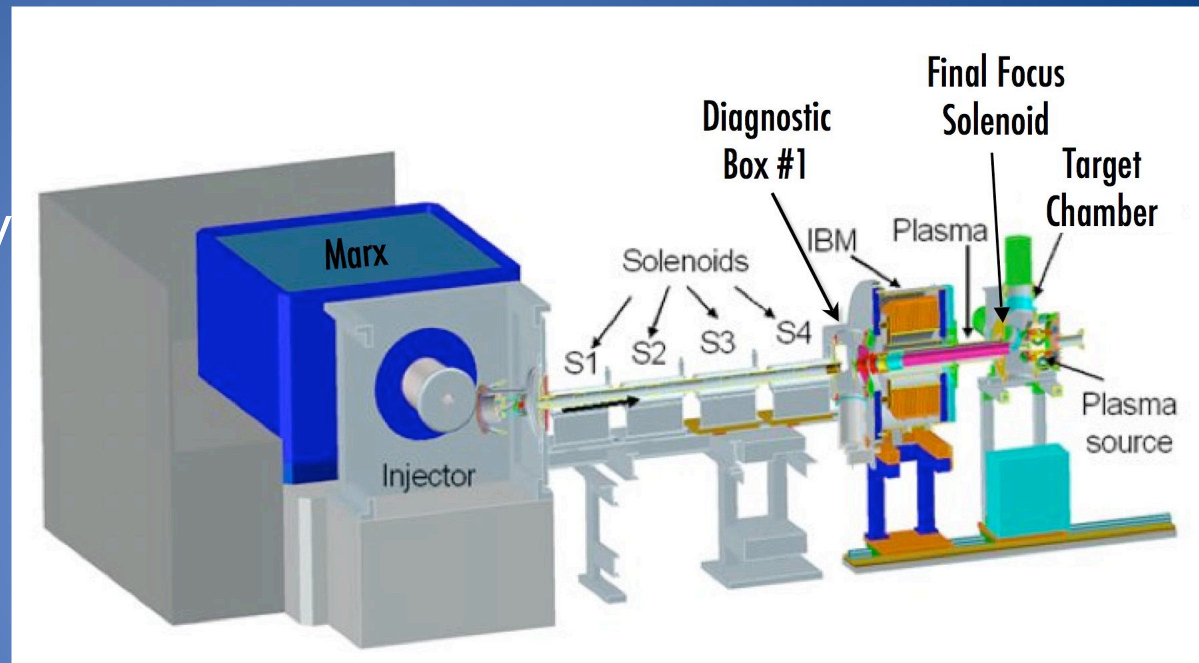
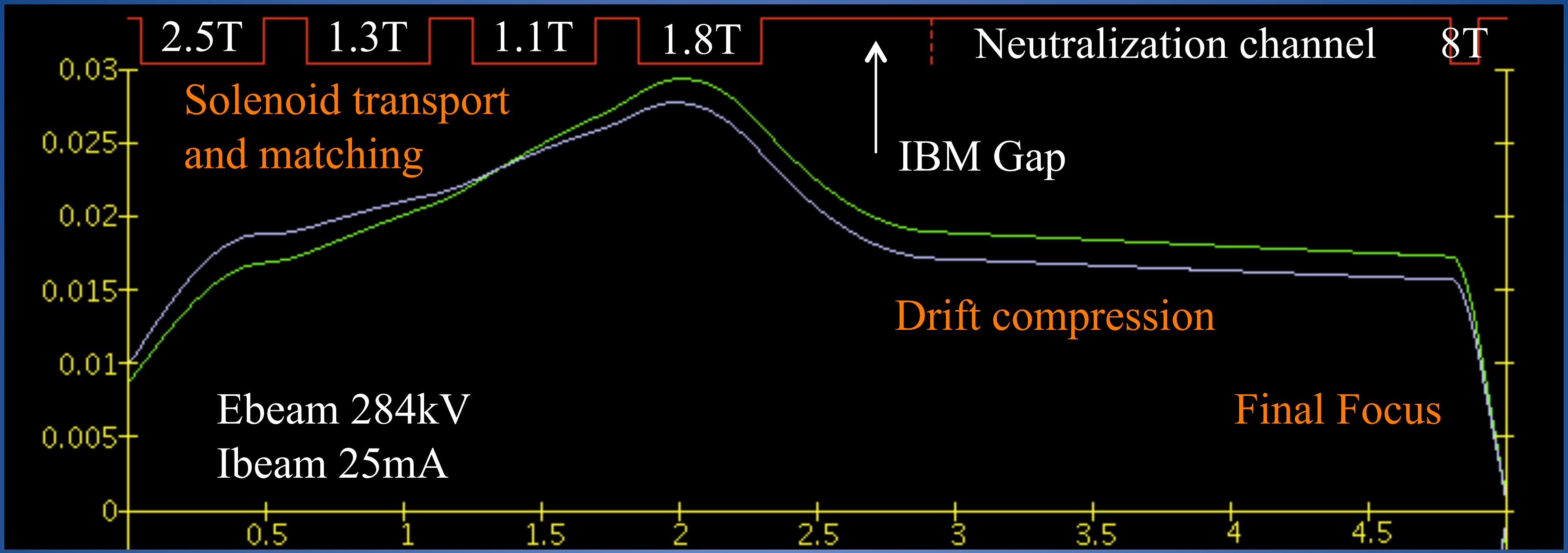
NDCX-I

Beam species	K^+
Beam current	25 - 40 mA
Beam energy	270 - 350 kV
Beam power	~7-14 kW
Energy spread	~0.2 keV
Pulse length	~3-20 μsec



Injector solenoids	~3T peak field
Final focus solenoid	8T peak field
Neutralizing plasmas	
FEPS	$2 – 8\ 10^{10}\ /cm^3$
4 MEVVA/FCAPS	$0.9 - 6\ 10^{13}\ /cm^3$
Compressing Voltage Swing	~150 keV / 500 nsec

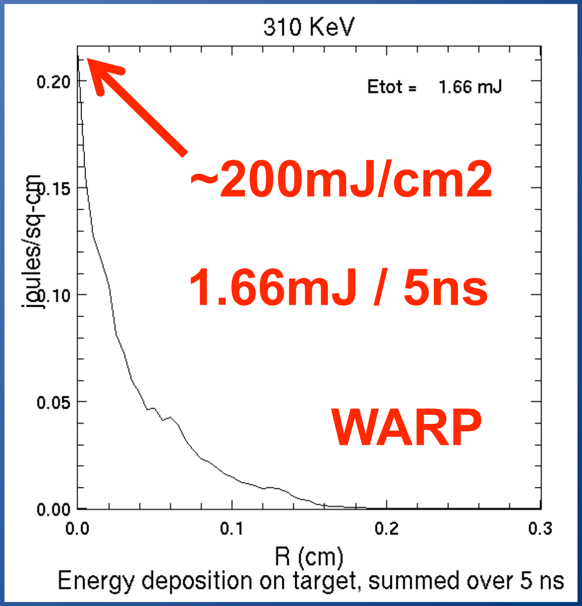
Envelope Dynamics



Uncompressed Beam

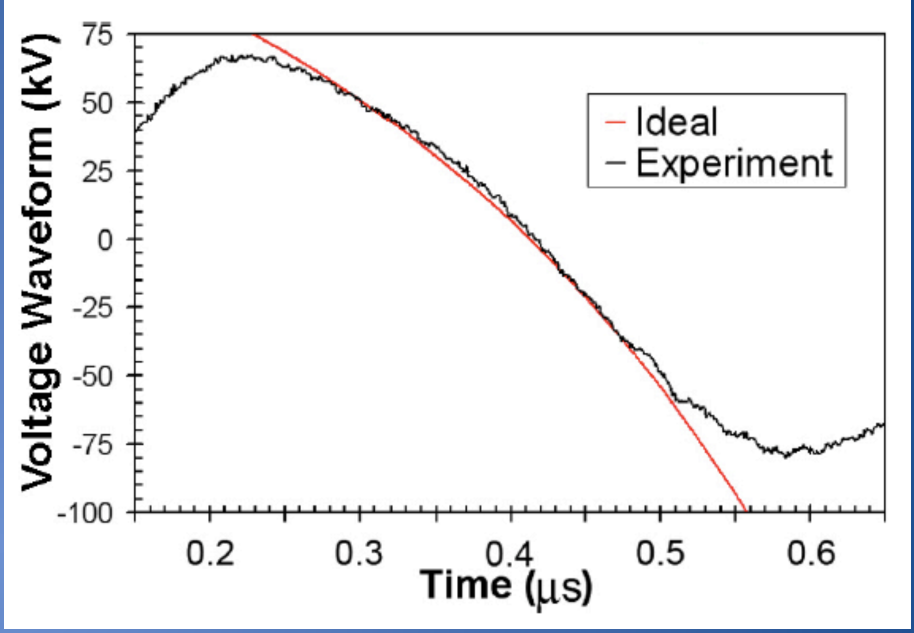
Beam compresses ballistically in the drift compression stage.

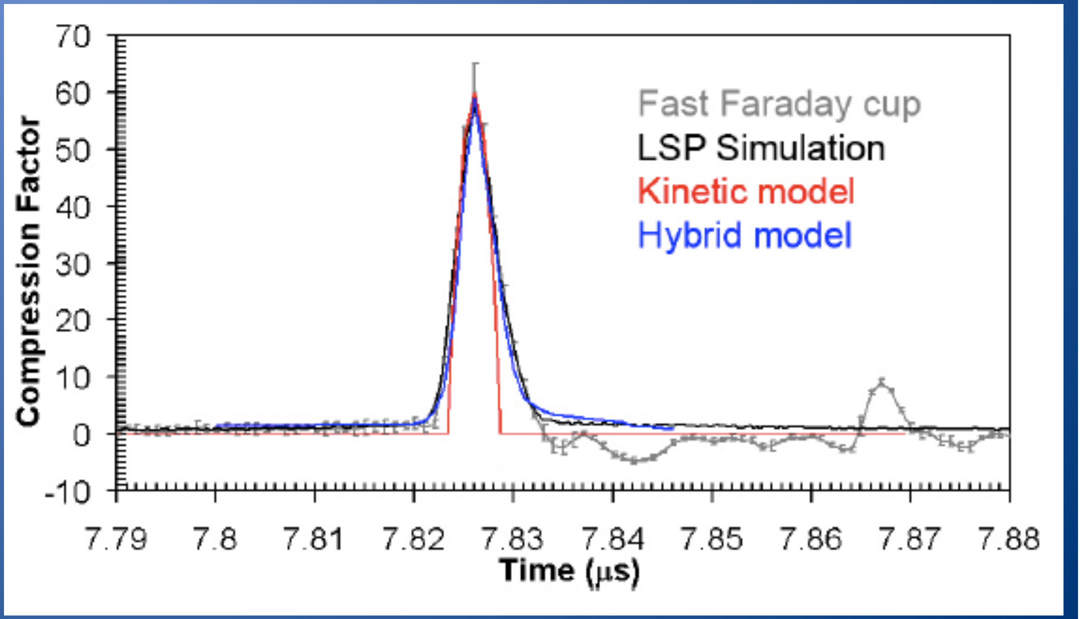
Compressed pulse fluence at target plane



Drift Compression

- Simple ballistic compression of non-relativistic beams.
- Use a programmable pulser to impart time-dependent velocity ramp.
- Neutralize beam space charge to improve compression factor.
- Trade some volt-seconds to add acceleration.





NDCX-I Emittance limits

- Transverse ($\beta_z \sim 0.004$)
  - Gun exit: $4\varepsilon_{nrms} = 0.088\ \pi$ mm mrad $\sim 2\ (2\pi\ r_{emitter}\ v_{Tx})$
  - IBM entrance: $4\varepsilon_{nrms} = 0.088\ \pi$ mm mrad
- Longitudinal
  - $T_z = (2.4 \pm 1.6)\ 10^{-2}$ eV K+ beam itself
  - $T_z = (4.7 \pm 2.8)\ 10^{-2}$ eV K+ beam after neutralization
- Final Focus Optics

$$r_{spot} \cong \frac{\varepsilon}{r'_{conv}}$$

~25mrad convergence angle – $r_{spot} \sim 0.9$mm

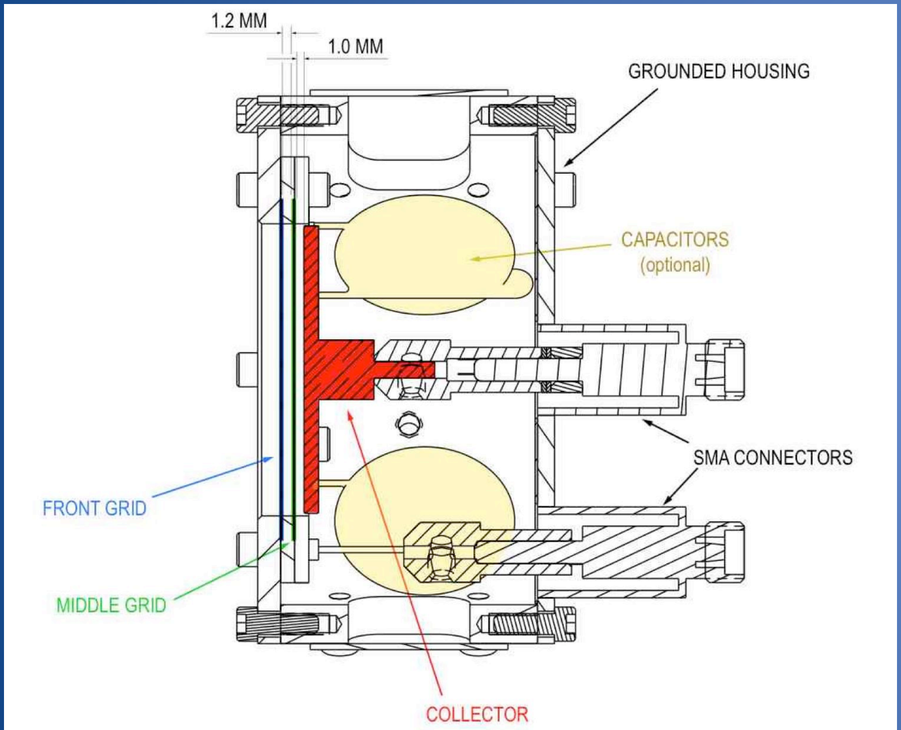
- Longitudinal Compression

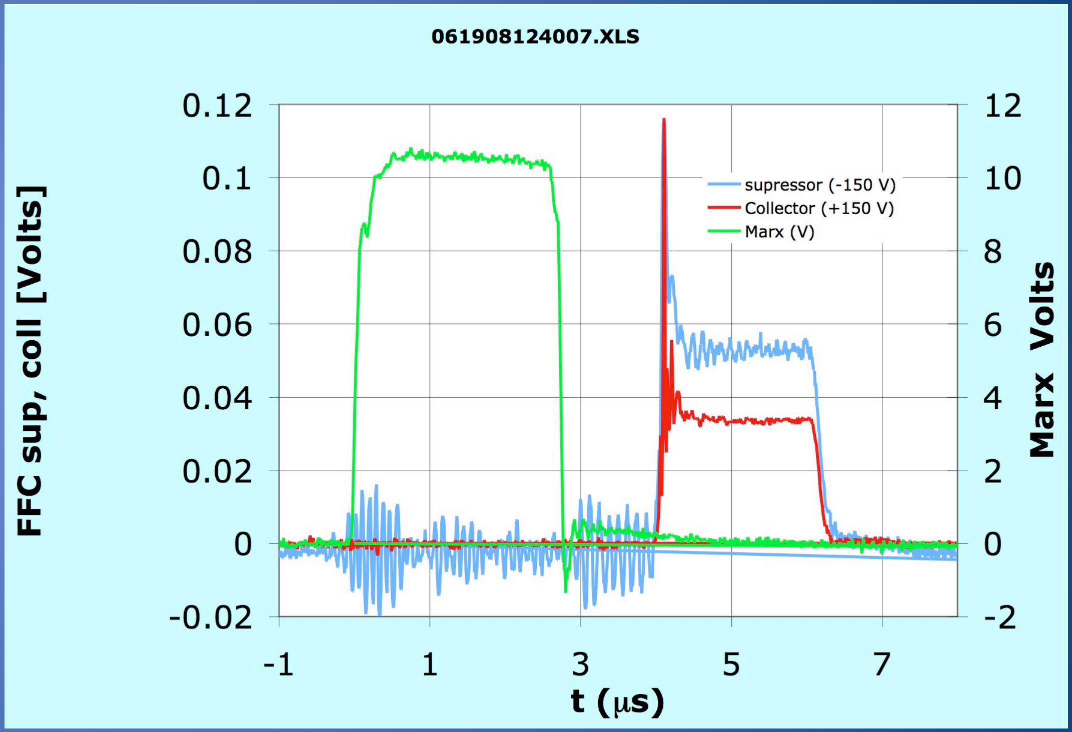
$$t_{\min} = \frac{L_{drift}}{2c}\left[\frac{m_i c^2}{E_i}\right]\sqrt{\frac{T_i}{m_i c^2}}$$

~100-200ps for NDCX-I (L_{drift} ~1.5 – 3 m)

Target Chamber Beam Diagnostics

- Fast Faraday Cup ~1ns response time (ion transit time)

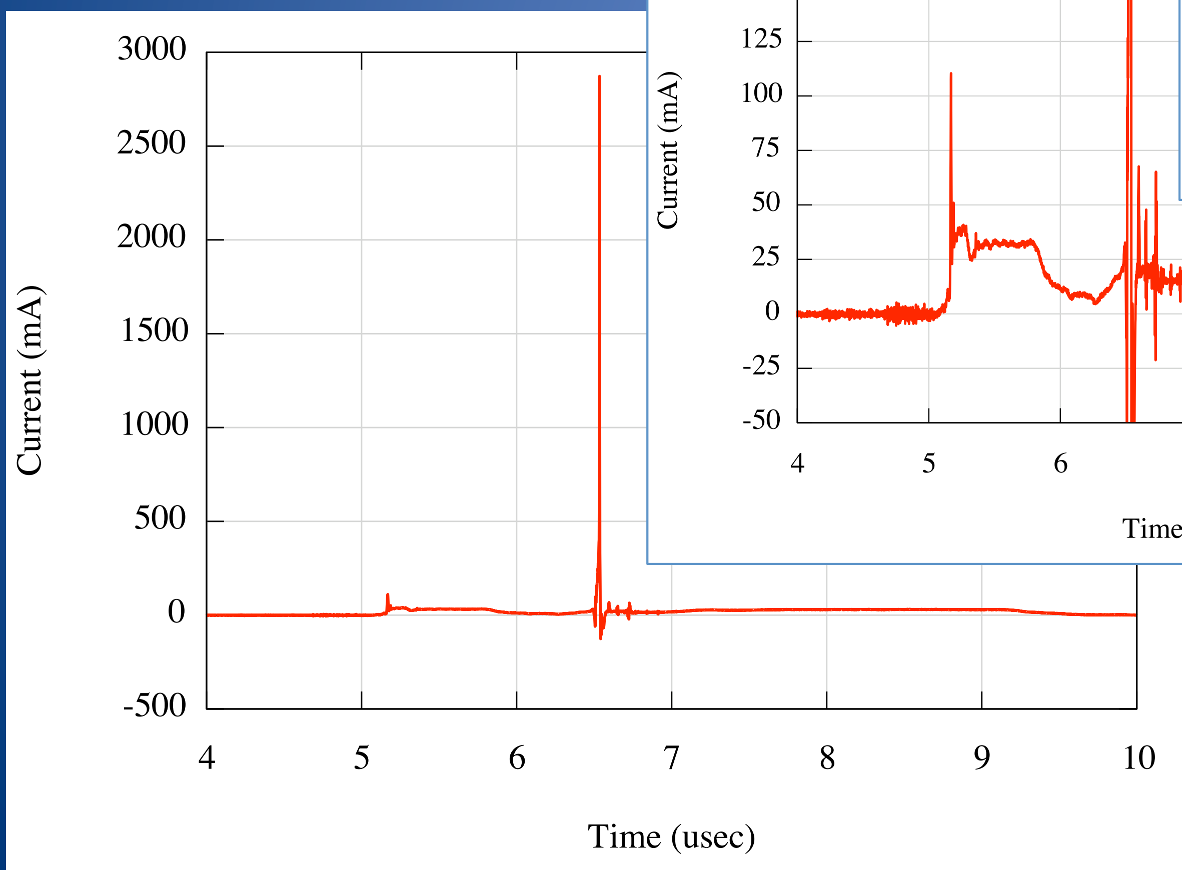


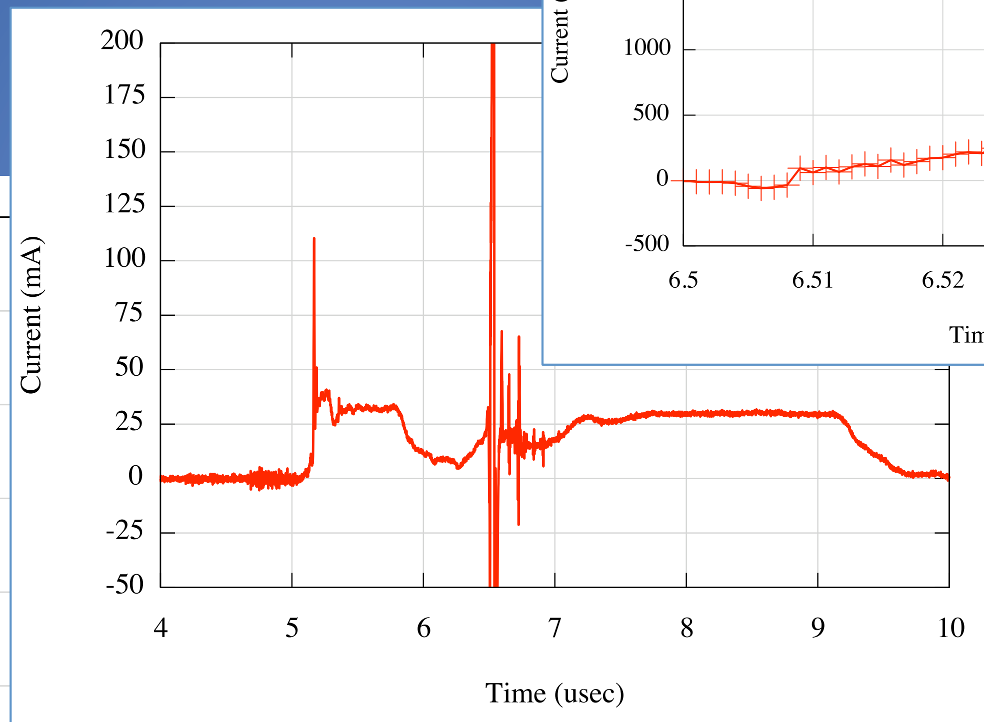


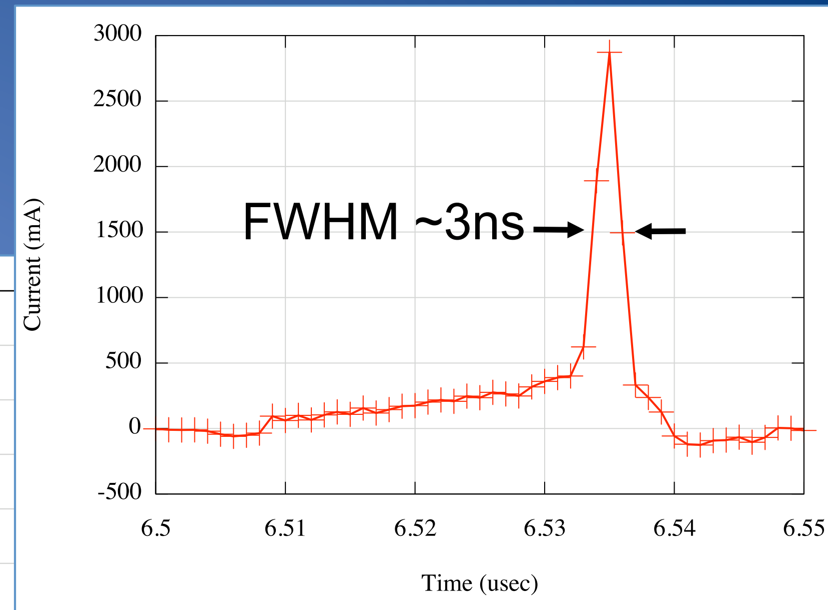
- Alumina scintillator with intensified, gated MCP camera – 10ns resolution, ~30ns minimum gate

Compressed Current

Peak current ~2.8A
Uncompressed ~30mA



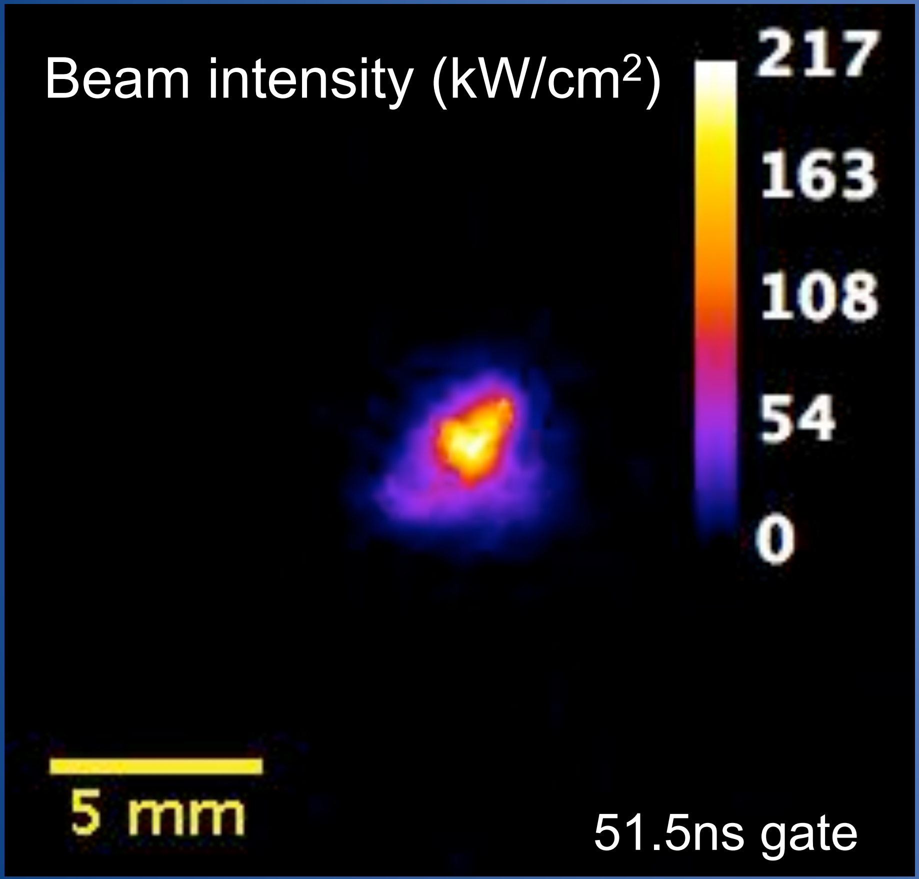


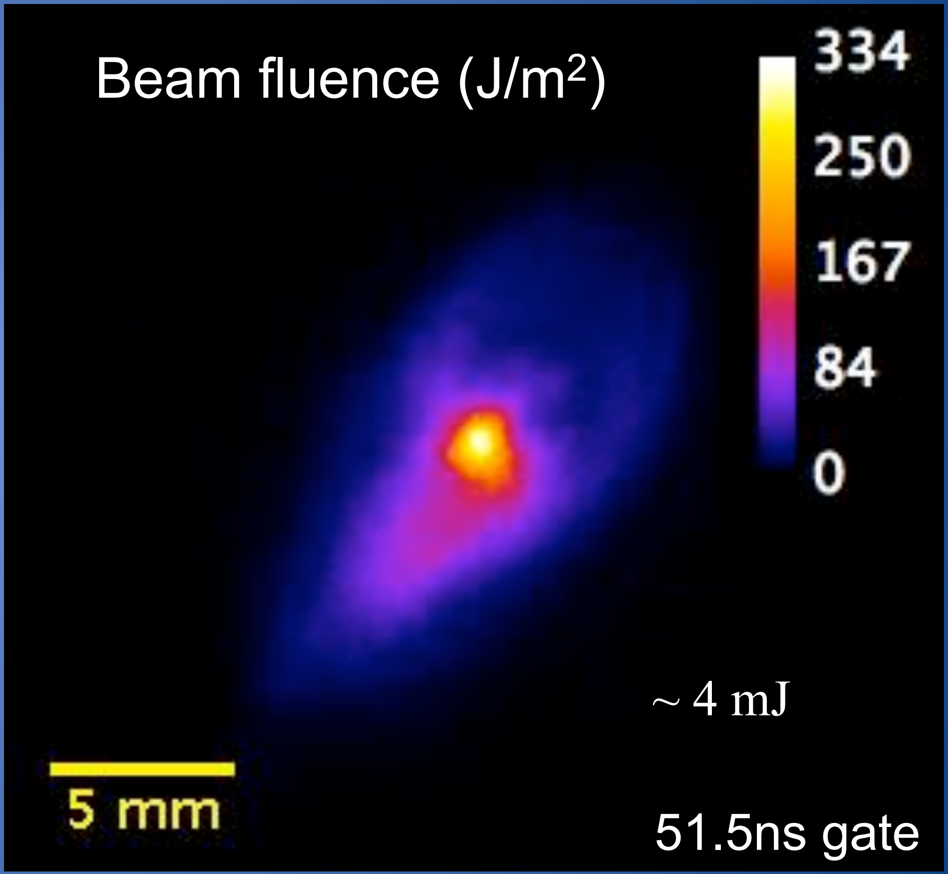


Compression
Ratio >90

Beam Intensity and Fluence

284kV beam energy, 25mA current, ~7kW beam power





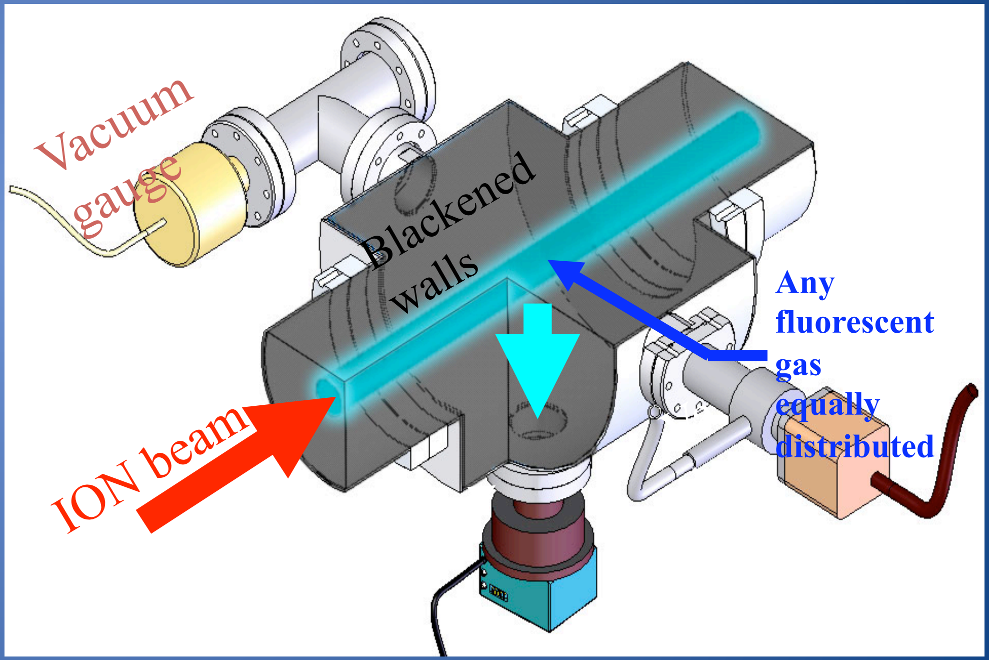
Uncompressed

Compressed

High Intensity Beam Profiling

Solid state scintillators incur damage and lose sensitivity with every shot – nonlinear in intensity

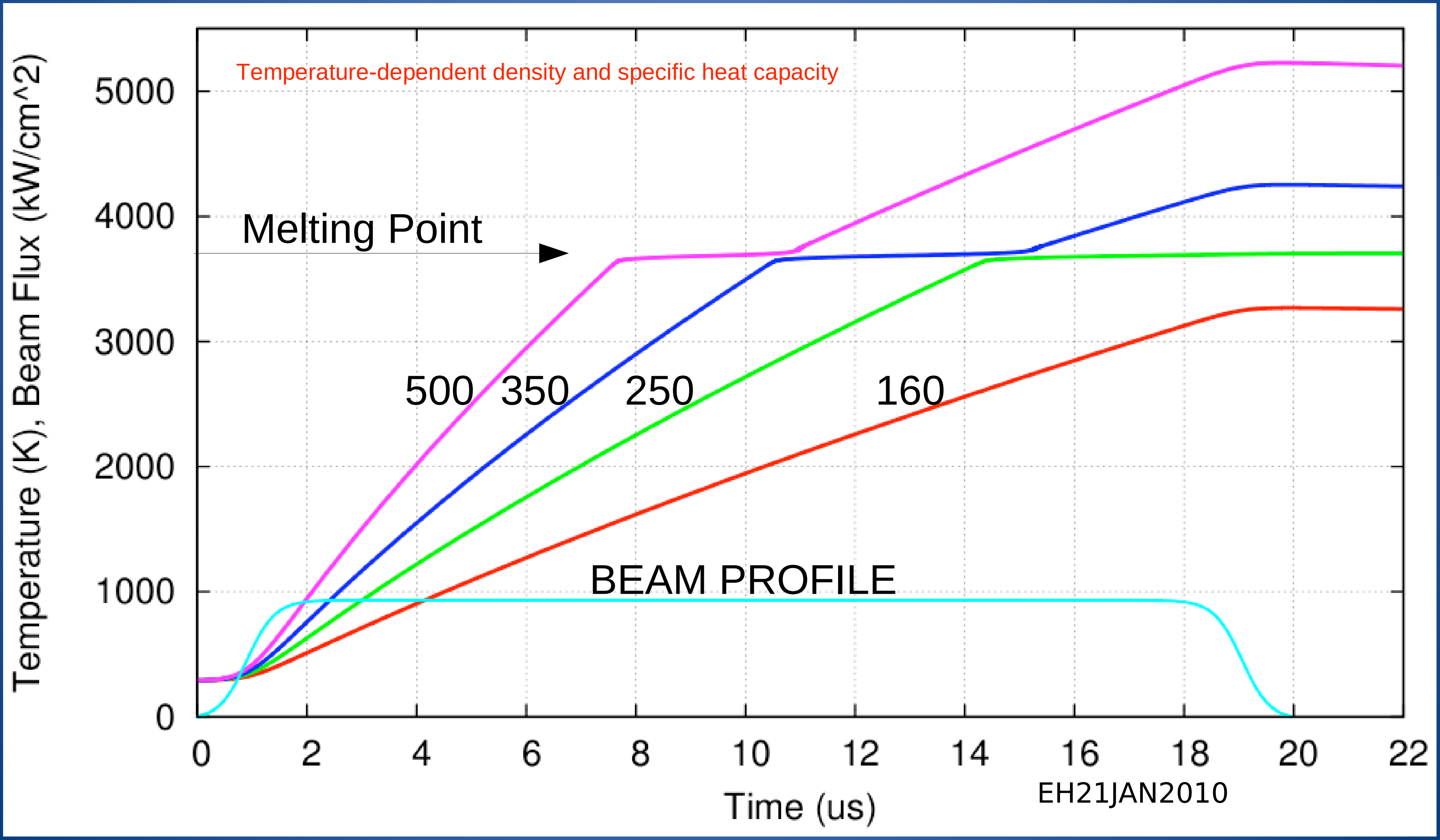
Gas phase Beam Intensity Monitor
Observe beam excited gas lines,
correlate to beam distribution



Tungsten foil calorimeter –
3μm thick foil responds to beam peak intensity –
radiated intensity ~ σT^{4+}

Calibrating the calorimeter

Merging of beam and target diagnostics

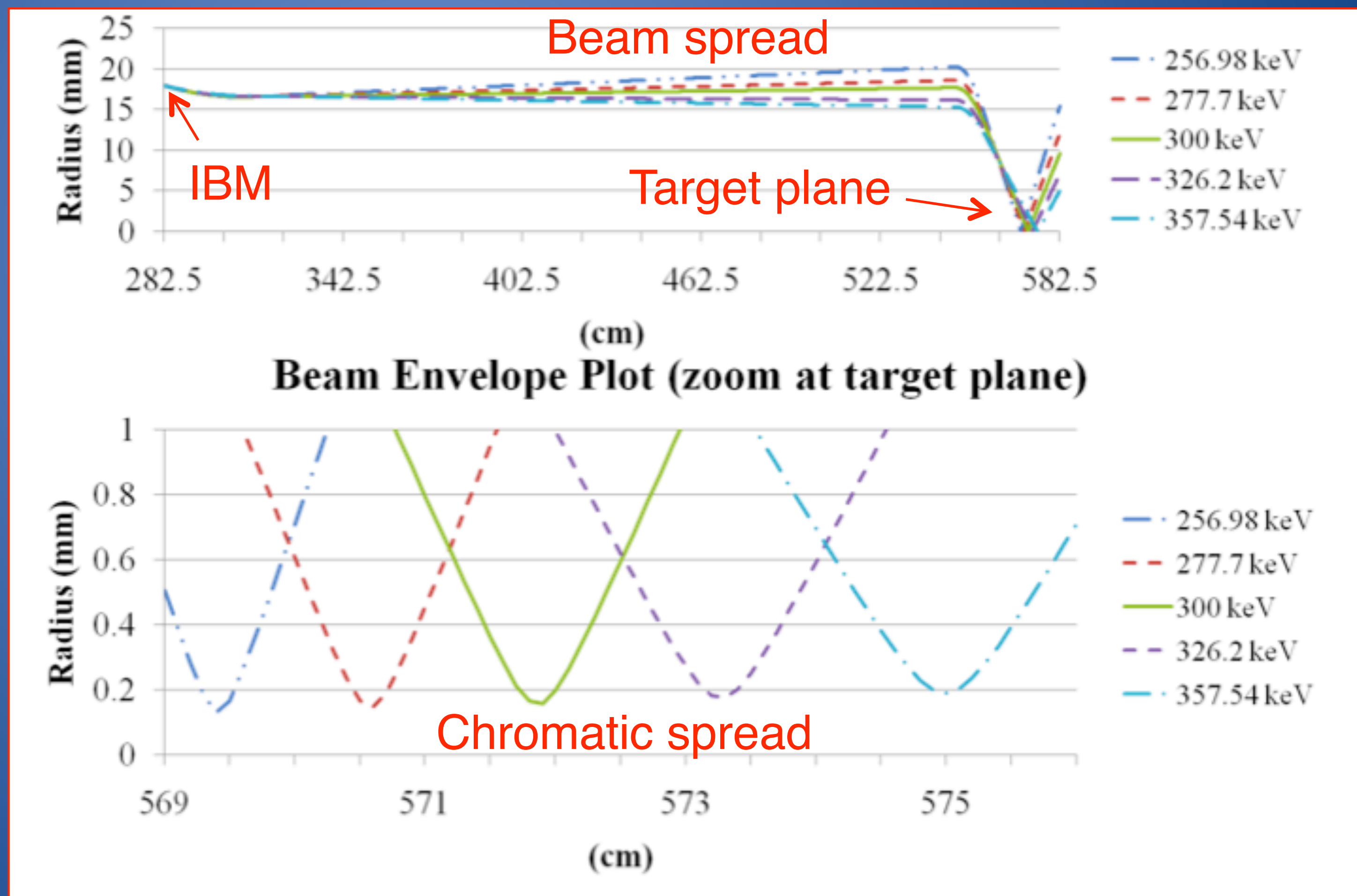


Time-Dependent Aberrations

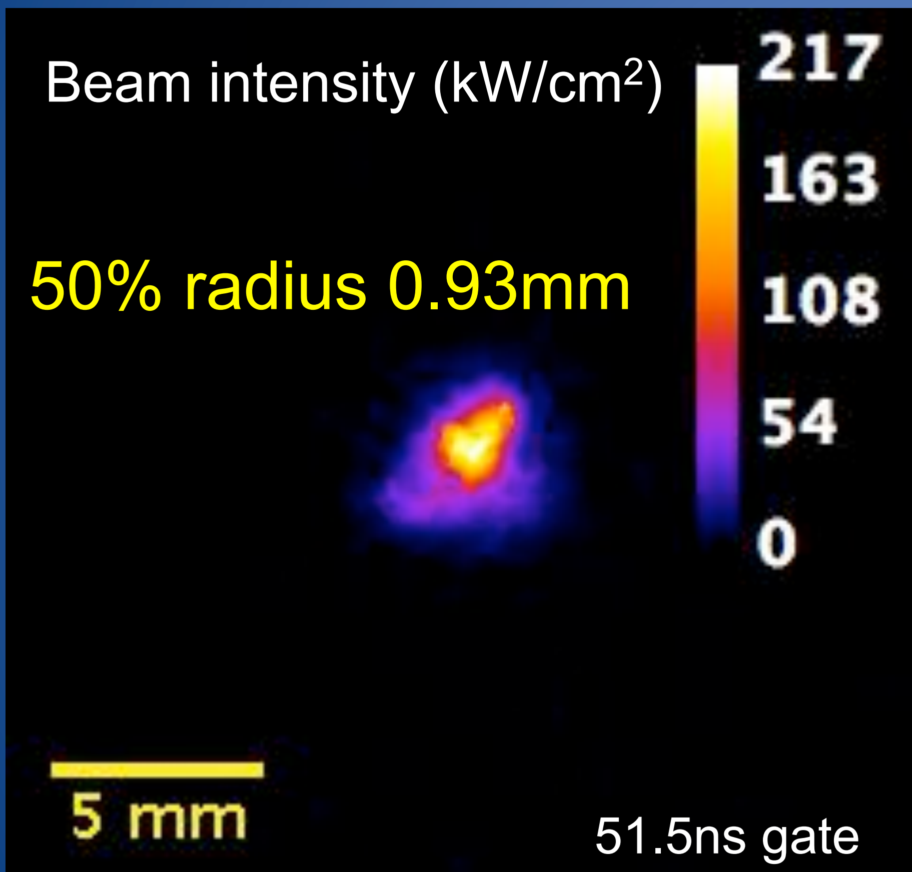
$$\Delta v_r \approx -\frac{qr}{2mv_{z0}^2}\frac{dV_{gap}(t)}{dt}$$

Time-dependent gap defocusing is correlated to slice energy through the impressed IBM energy modulation.

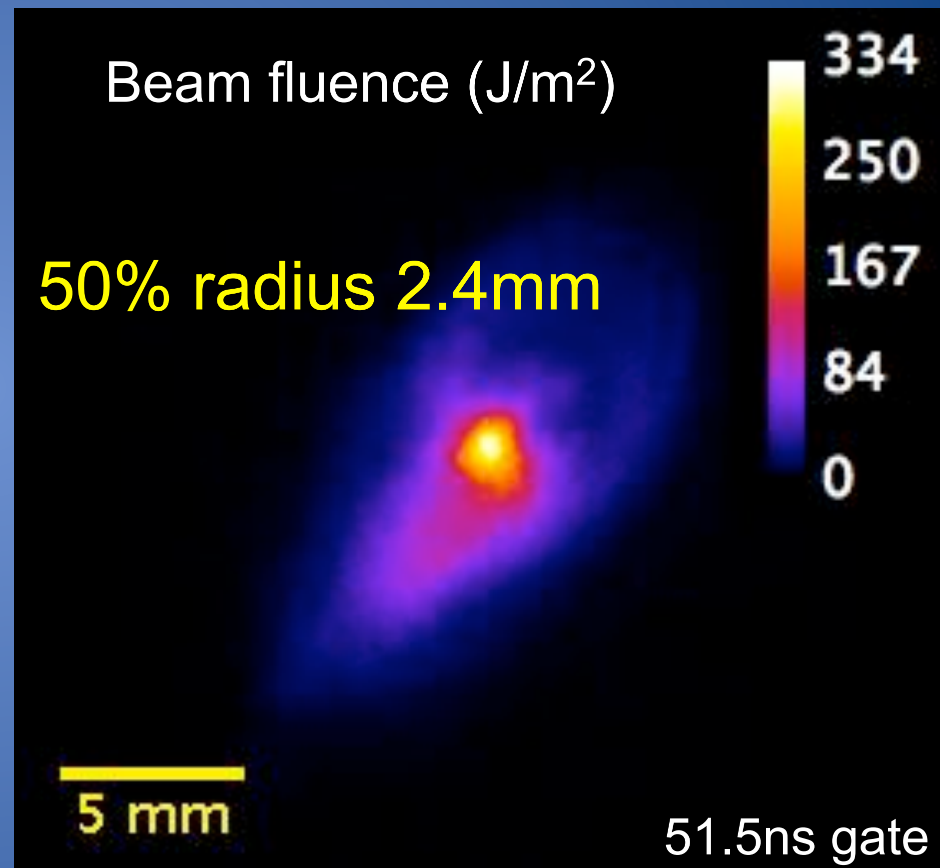
This effect compounds chromatic aberrations in the final focus section.



Measurement of chromatic variations



Uncompressed

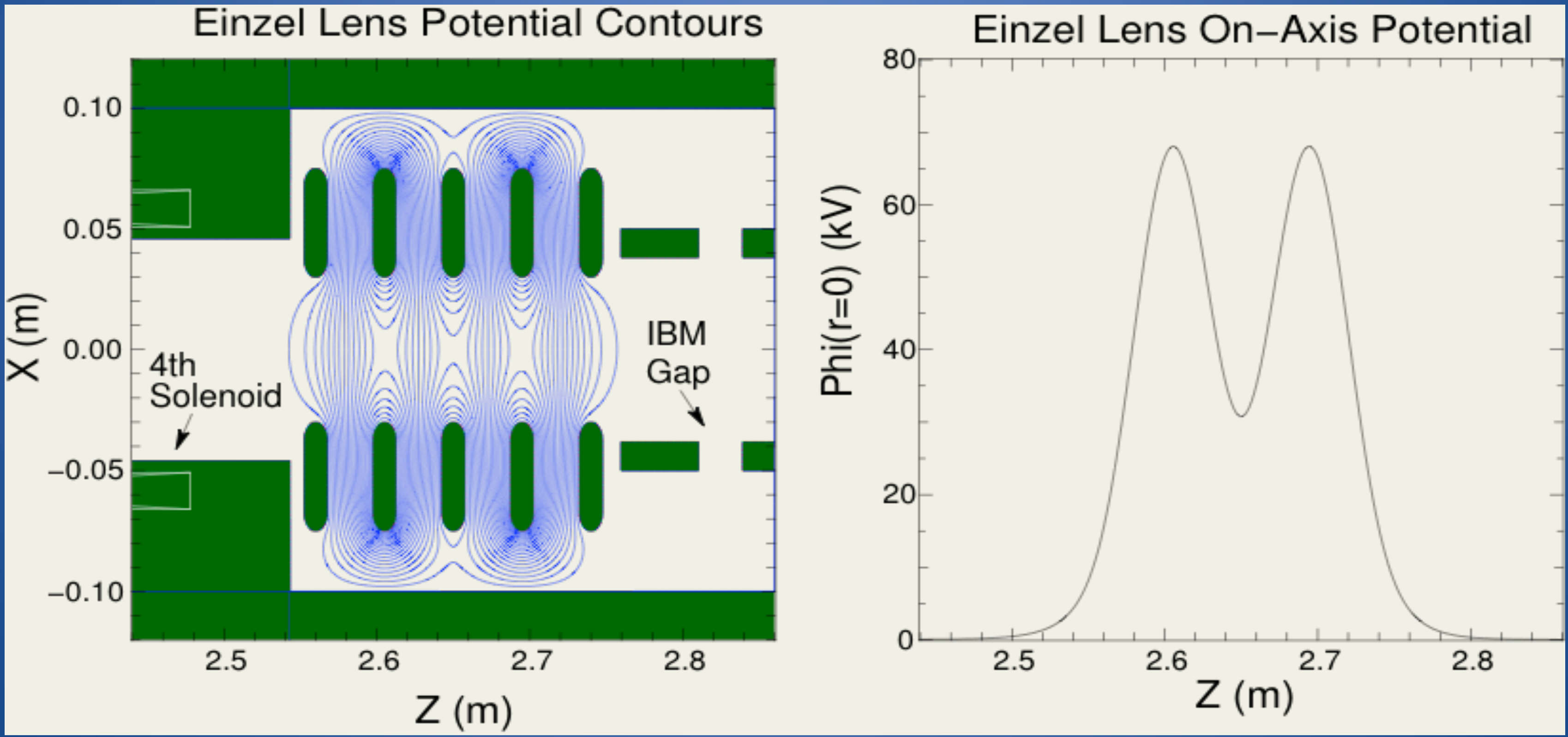


Compressed

~33mJ/cm^2 compared with ~200mJ/cm^2

Fast Corrector

Time-dependent geometric and chromatic aberrations can in principal be corrected.

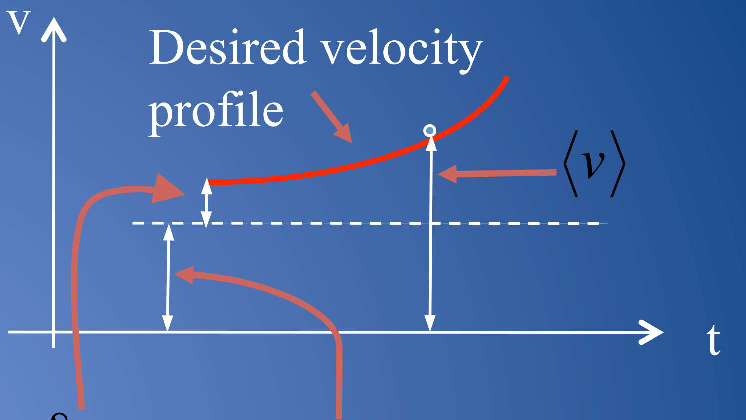


Transit-time effects complicate matters.

Longitudinal slippage with unipolar IBM waveform

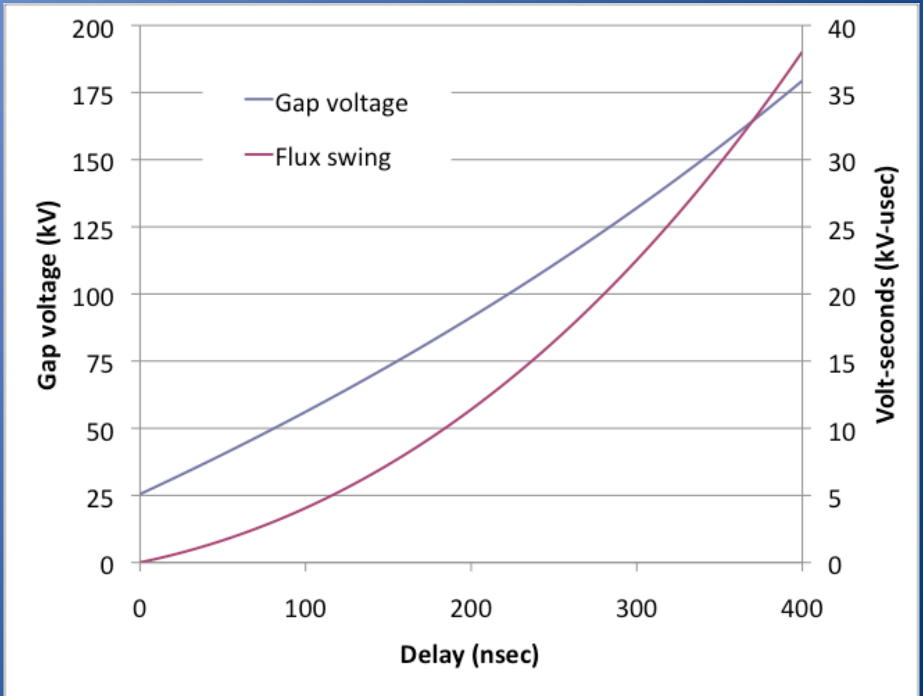
$$\Delta t_{slip}(\Delta z) = \left(\frac{1}{\langle v \rangle} - \frac{1}{v_0} \right) \Delta z$$

$$\langle v \rangle = \frac{L_{Drift}}{\tau_p} \ln \left(\left[1 - (v_0 + \delta v) \frac{\tau_p}{L_{Drift}} \right]^{-1} \right)$$

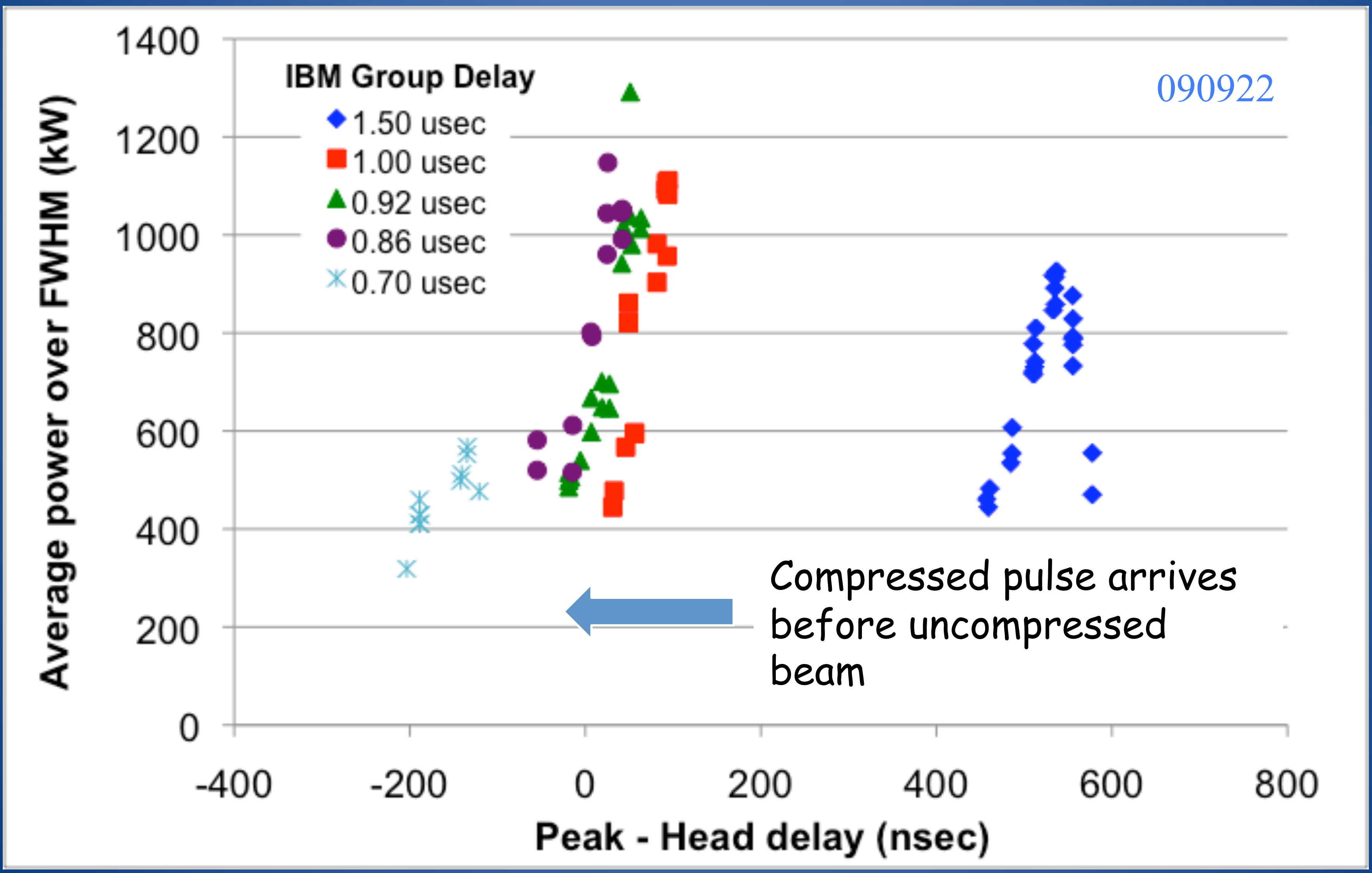


$$\delta v = v_{head} - v_0$$

IBM and Drift Design			
Ion Energy	E (eV)	300000	
Initial Axial Velocity	v0 (m/s)	1216819	
Initial Pulse duration	tau (s)	4.00E-07	
Pulse length	v0*tau (cm)	48.7	
Drift length	Ld (m)	2.88	
Avg. Voltage gain	Vbar (eV)	95000	
Average beam voltage	Vbeam (eV)	395000	
Beam head velocity	vh (m/s)	1267417	
Beam tail velocity	vt (m/s)	1538184	
Average pulse velocity	<v> (m/s)	1396252	
Slippage rate, 1/<v> - 1/v0	(ns/m)	-106	
Pulse slippage, Ld(1/<v> - 1/v0)	(nsec)	-304	(-) earlier, (+) later
Volt-seconds in pulse	Dphi (kV-usec)	37.97	400ns
Average voltage across gap	kV	94.9	



Longitudinal compression vs. group delay

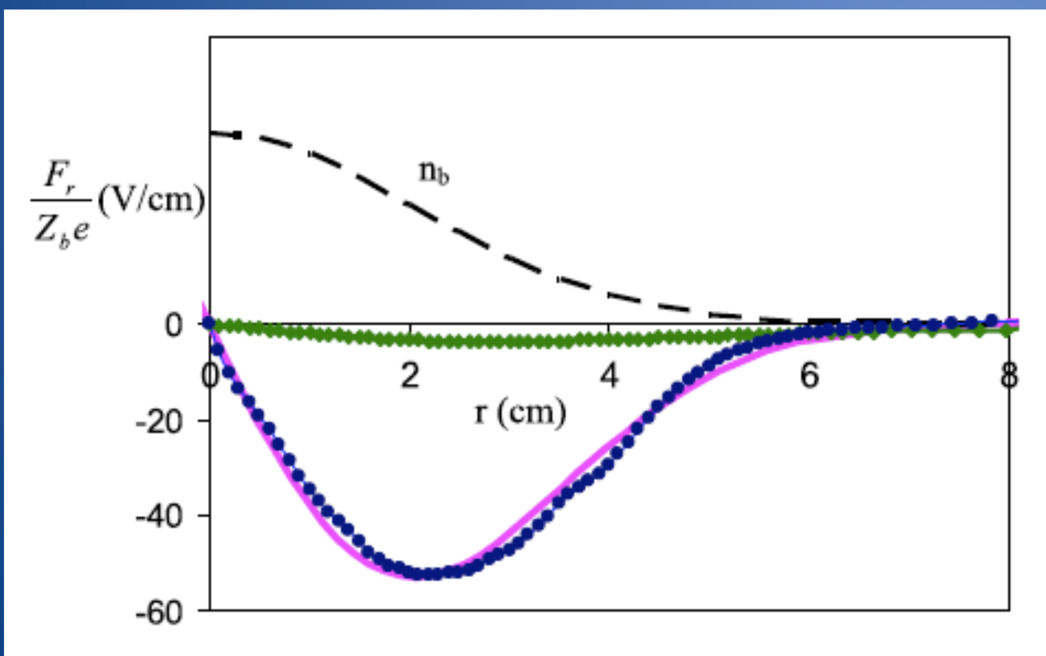


Collective focusing

PRL 103, 075003 (2009) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2009

Enhanced Self-Focusing of an Ion Beam Pulse Propagating through a Background Plasma along a Solenoidal Magnetic Field

Mikhail A. Dorf, Igor D. Kaganovich, Edward A. Startsev, and Ronald C. Davidson
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA
(Received 17 February 2009; published 13 August 2009)



A collective focusing scheme has been suggested by colleagues at PPPL.

Requires a final focus magnet field of ~100-300G rather than 8T!

Electrostatic focusing by trapped electron population.

The moving ion beam polarizes the magnetized plasma background, creating a strong radial self-electric field, which provides the enhanced self-focusing.

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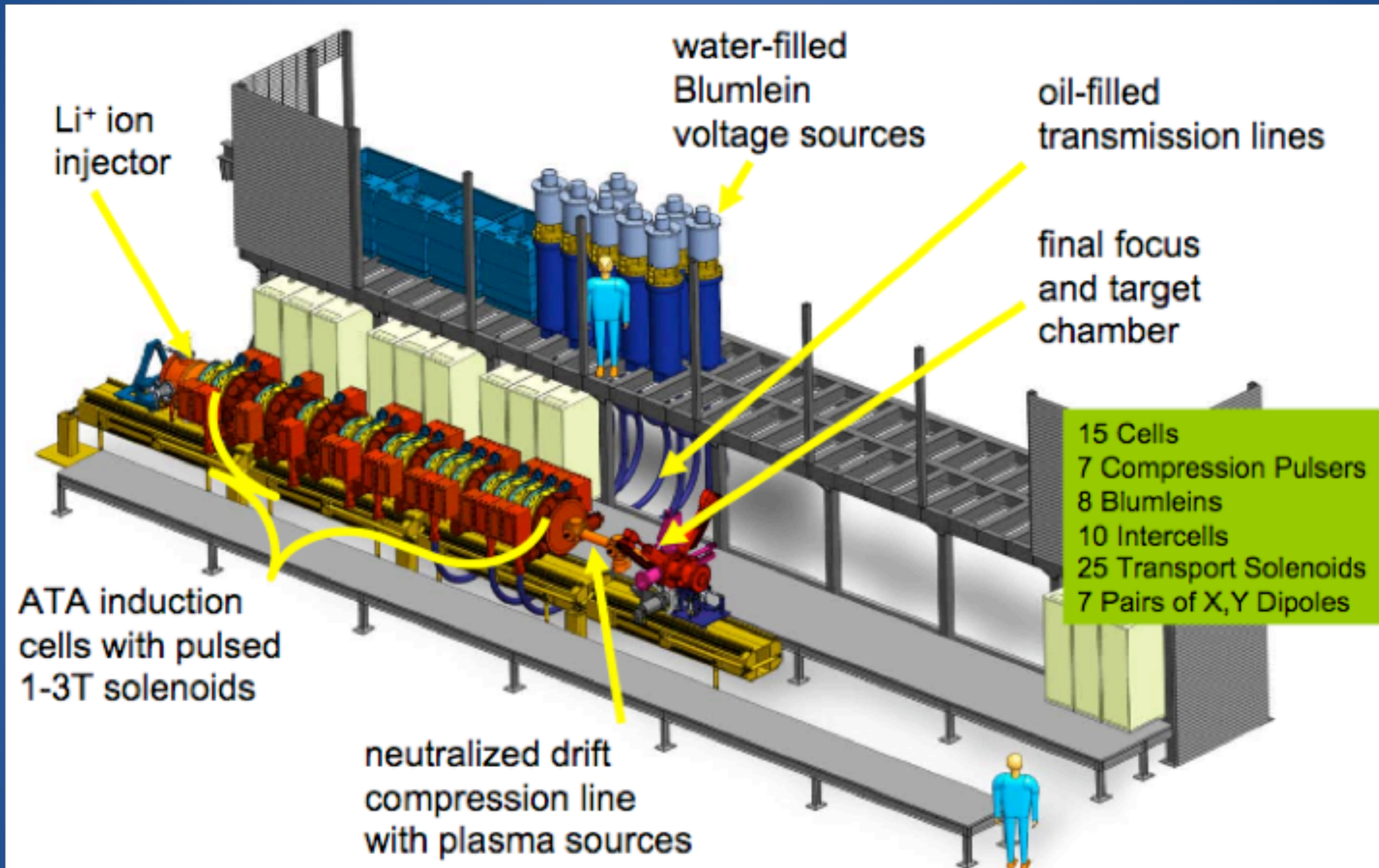
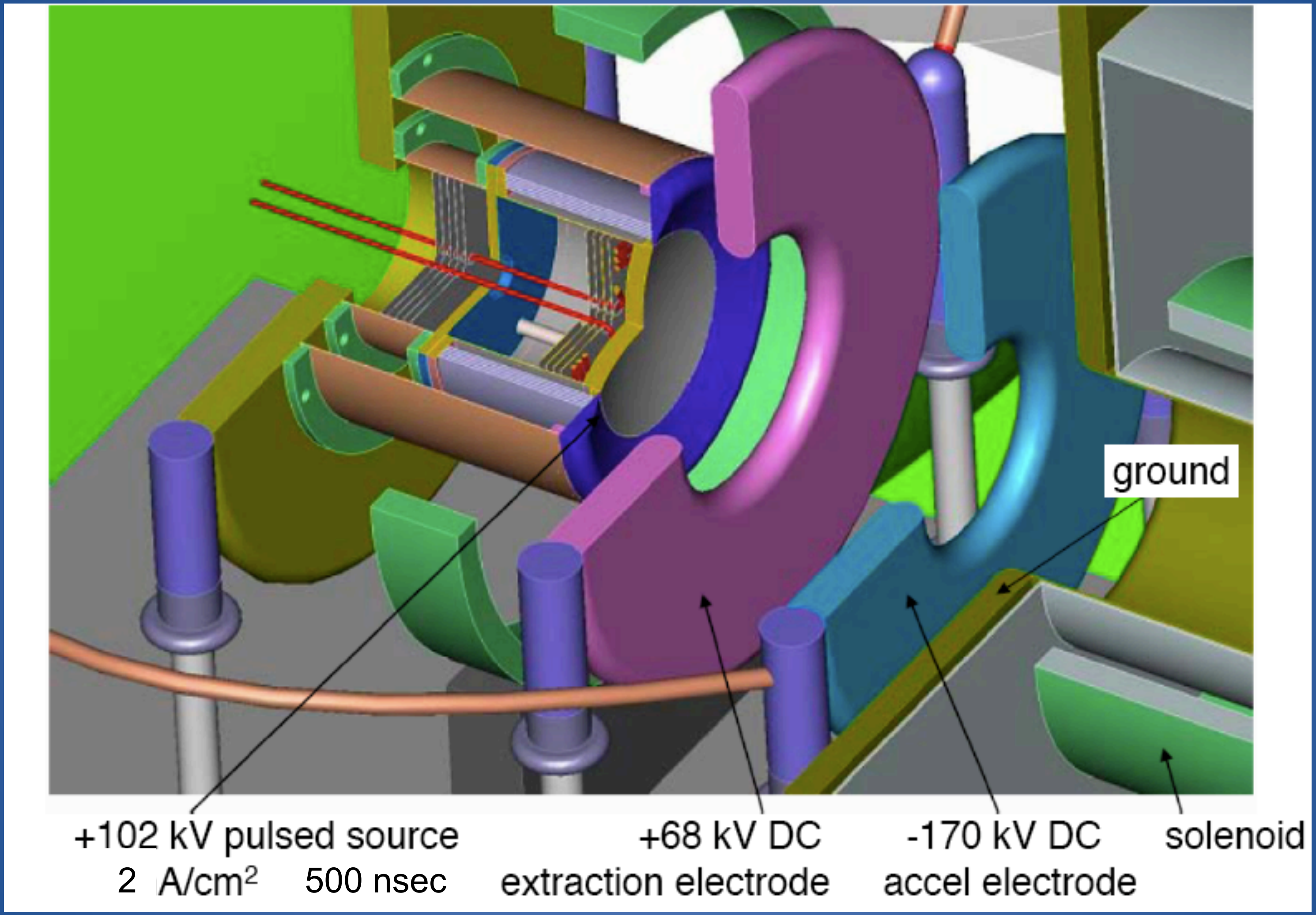
NDCX-II (15 cells, 2.0MeV)

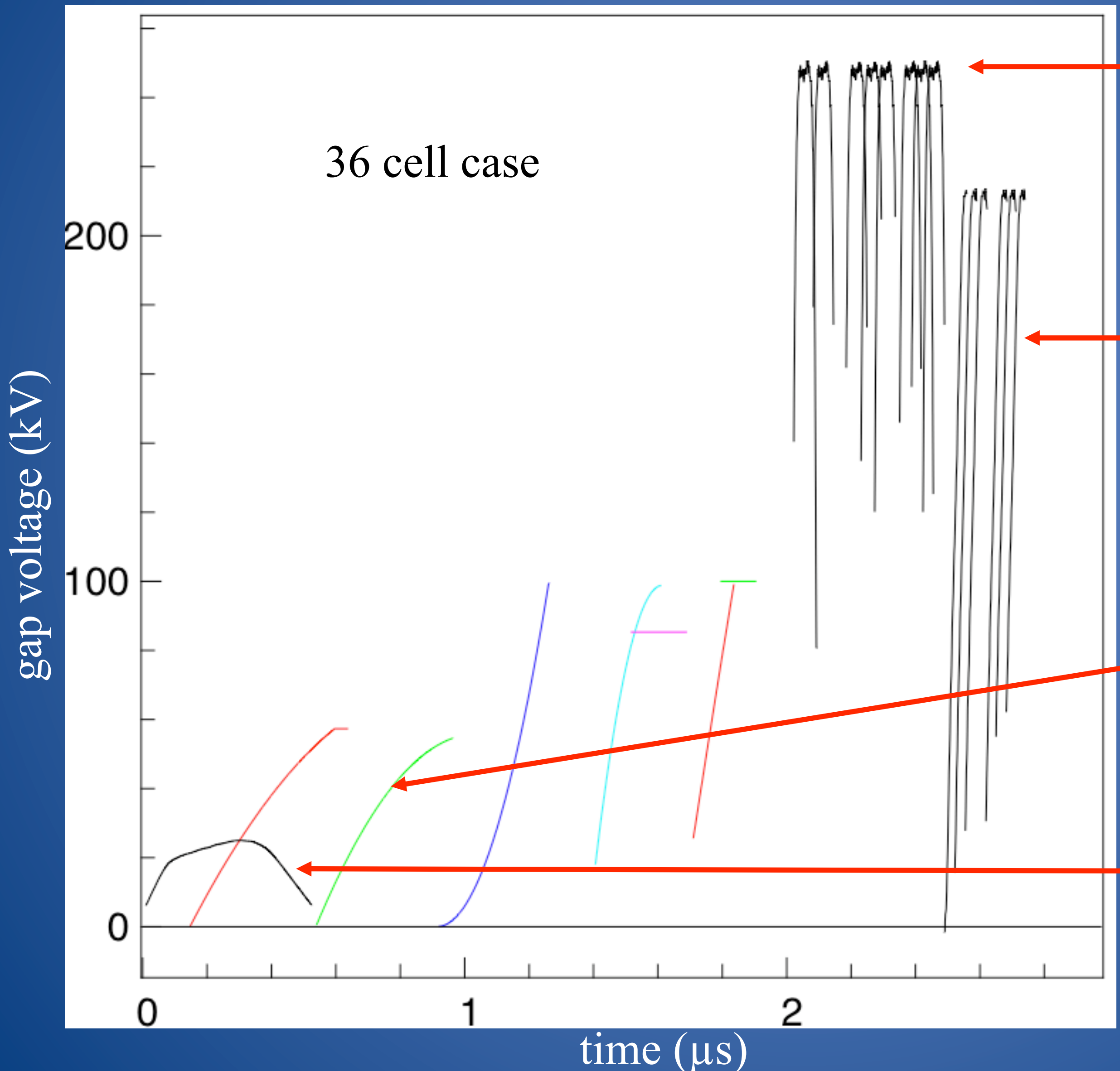


Accel/Decel Injector



Perveance 'multiplier':
Shortens pulse length to economize on induction module volt-seconds.

Compression and Acceleration



250 kV “flat-top” (measured waveform from test stand)

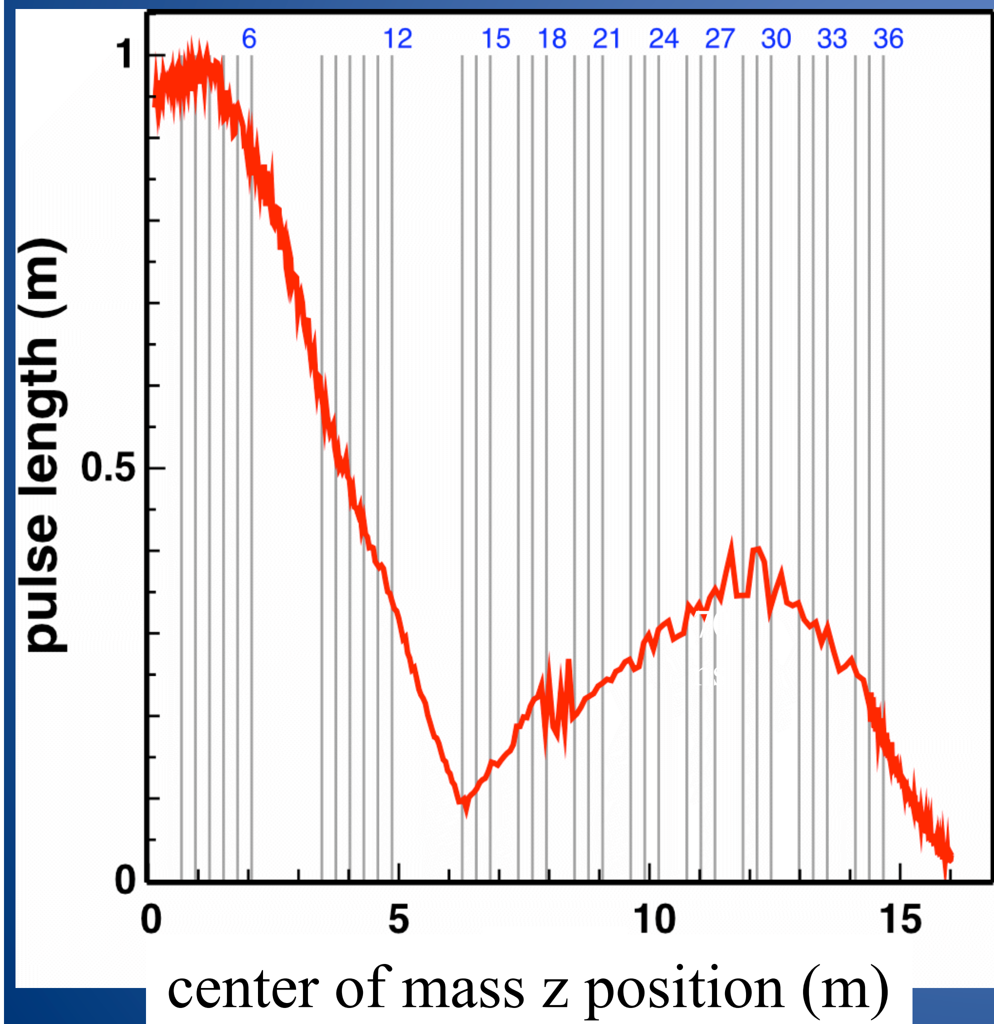
200 kV “ramp” (measured waveform from test stand)

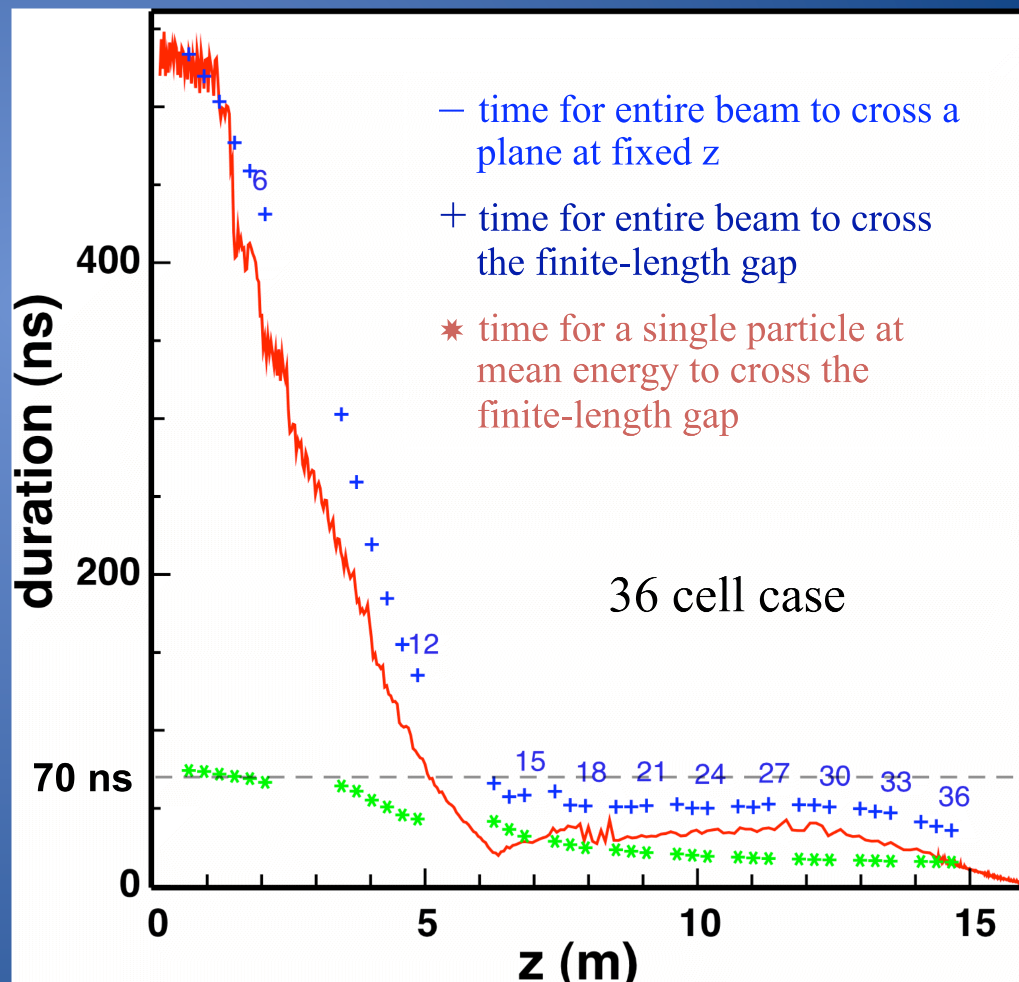
“shaped” (to impose velocity tilt for initial compression)

“shaped” (to equalize beam energy after injection)

"Let It Bounce" ™

Final bunch lengths can be obtained with minimum emittance growth by allowing the longitudinal phase space to evolve, with guidance.



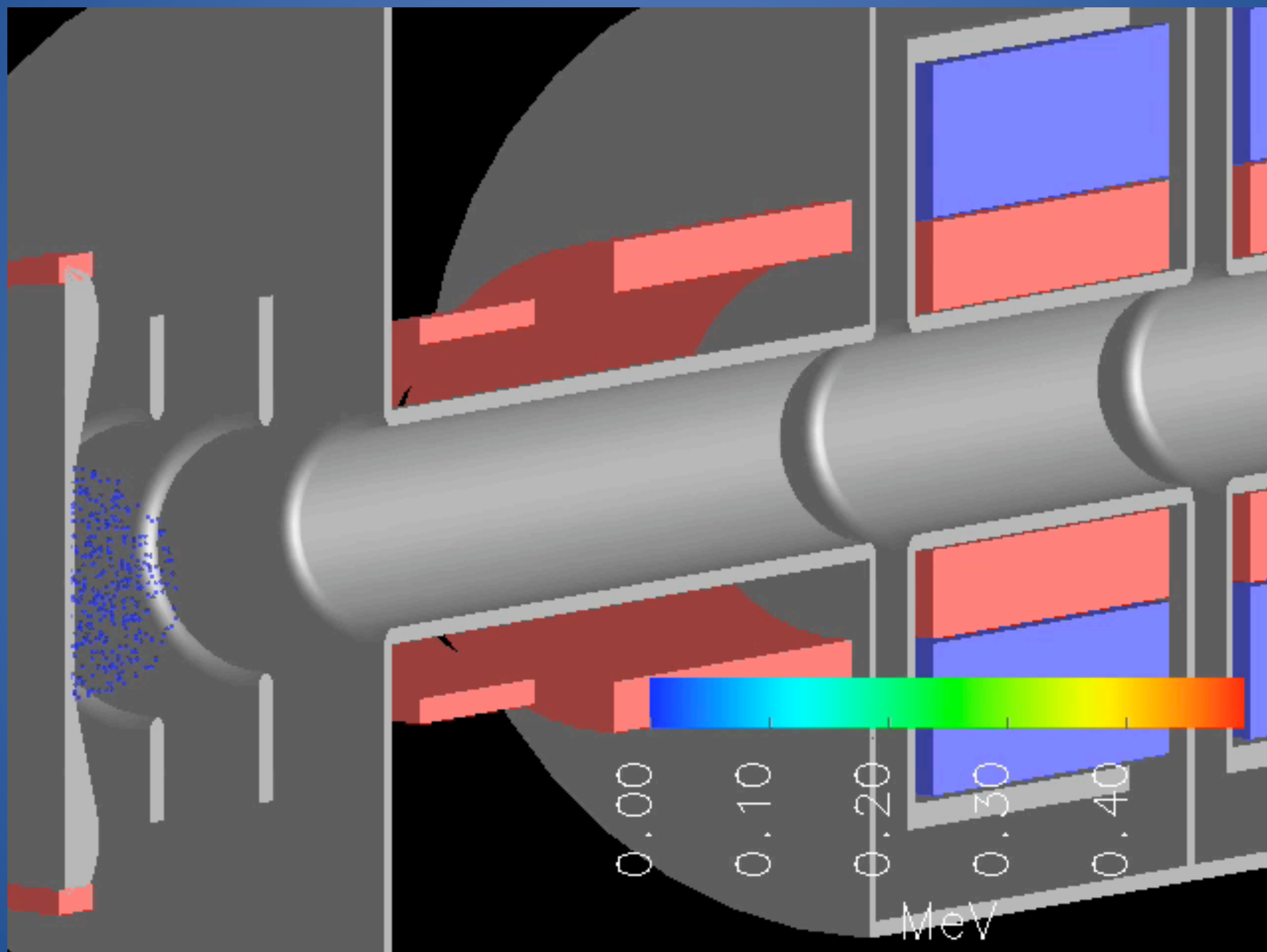


NDCX-II vs. NDCX-I

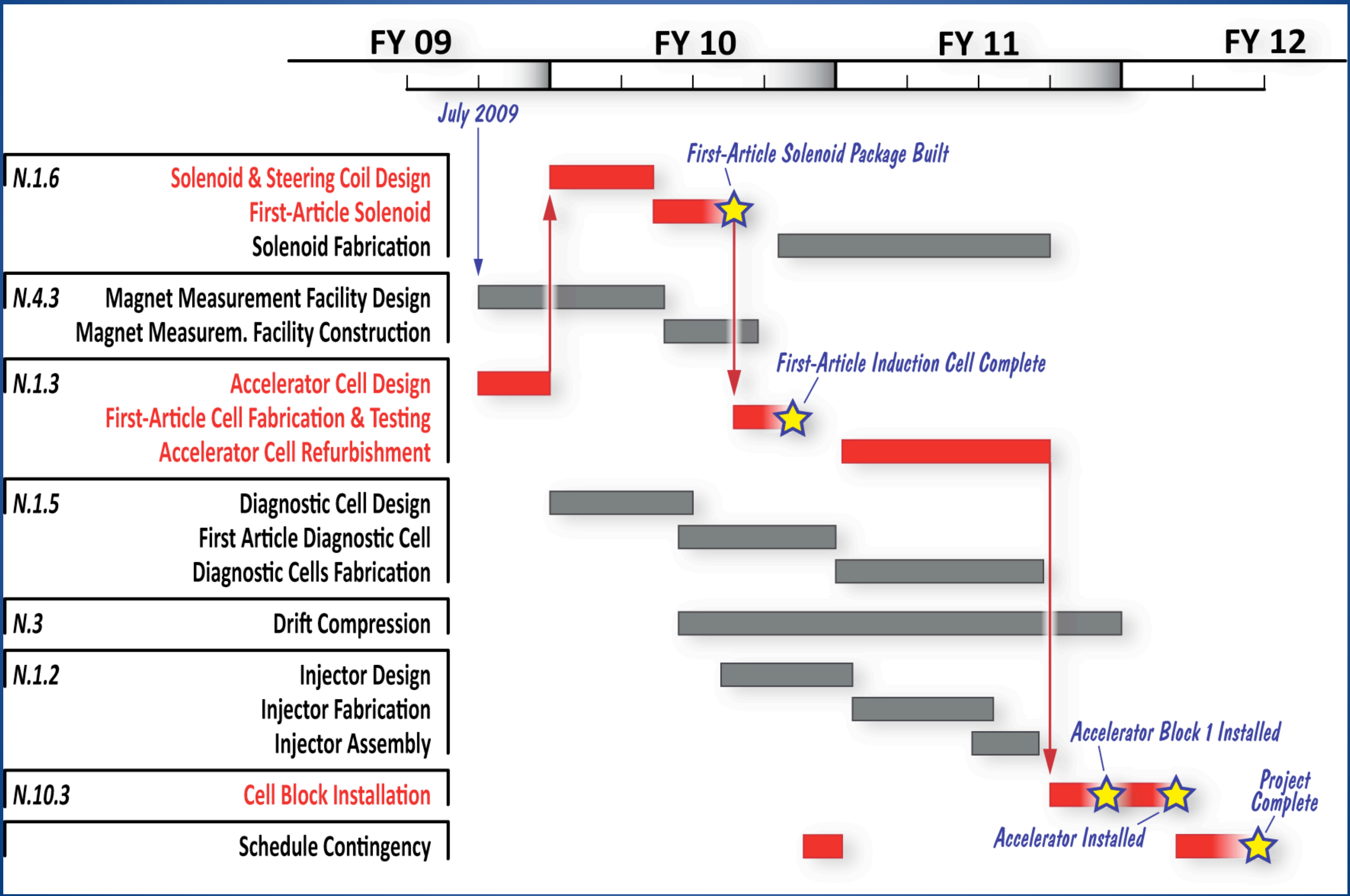
	NDCX-I (typical bunched beam)	NDCX-II 15-cell (r,z simulation)
Ion species	K^+ (A=39)	Li^+ (A=7)
Total charge	15 nC	55 nC
Ion kinetic energy	0.3 MeV	2.0 MeV
Focal radius (containing 50% of beam)	1 mm	0.7 mm
Bunch duration (FWHM)	2 ns	0.45 ns
Peak current	3 A	17 A
Peak fluence (time integrated)	0.03 J/cm^2	17 J/cm^2
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	9.5 J/cm^2 (1 ns window)
Fluence within 50% focal radius and FWHM duration (k.e. x I x t / area)	0.014 J/cm^2	1.0 J/cm^2

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

NDCX-II, The Movie



Project Path



Prototype hardware components are tested for QA

IB-HEDPX

- Conceptual device to attain ~10eV/1Mbar conditions in planar heated targets.
- Extend NDCX-II to 50 ATA cells, ~10 MeV acceleration
- Short pulses (100-200ps)
- Pulse shaping and shock timing
  – Can study hydrodynamic coupling and shock physics.

Summary

- Beam manipulations are crucial elements in ion beam drivers for HEDP studies.
- These manipulations are only possible due to access to high density, large volume, cool (T_e~eV's) plasma sources.
- NDCX-II will significantly expand our reach into WDM and HEDP studies.
- Complex beam dynamics will play an ever increasing role in providing usable beam fluence.

Back up slides

Beam intensity requirements

- Source brightness (space charge limited)
  - Aluminasilicate sources,

    K^+, Na^+ ~ 0.5A/(mm mrad)^2 (J ~ 10 mA/cm^2)

    Li^+ ~ 0.005 A/(mm mrad)^2 (J ~ 2 mA/cm^2)
  - Normalized emittance ~ <1 to few π mm mrad

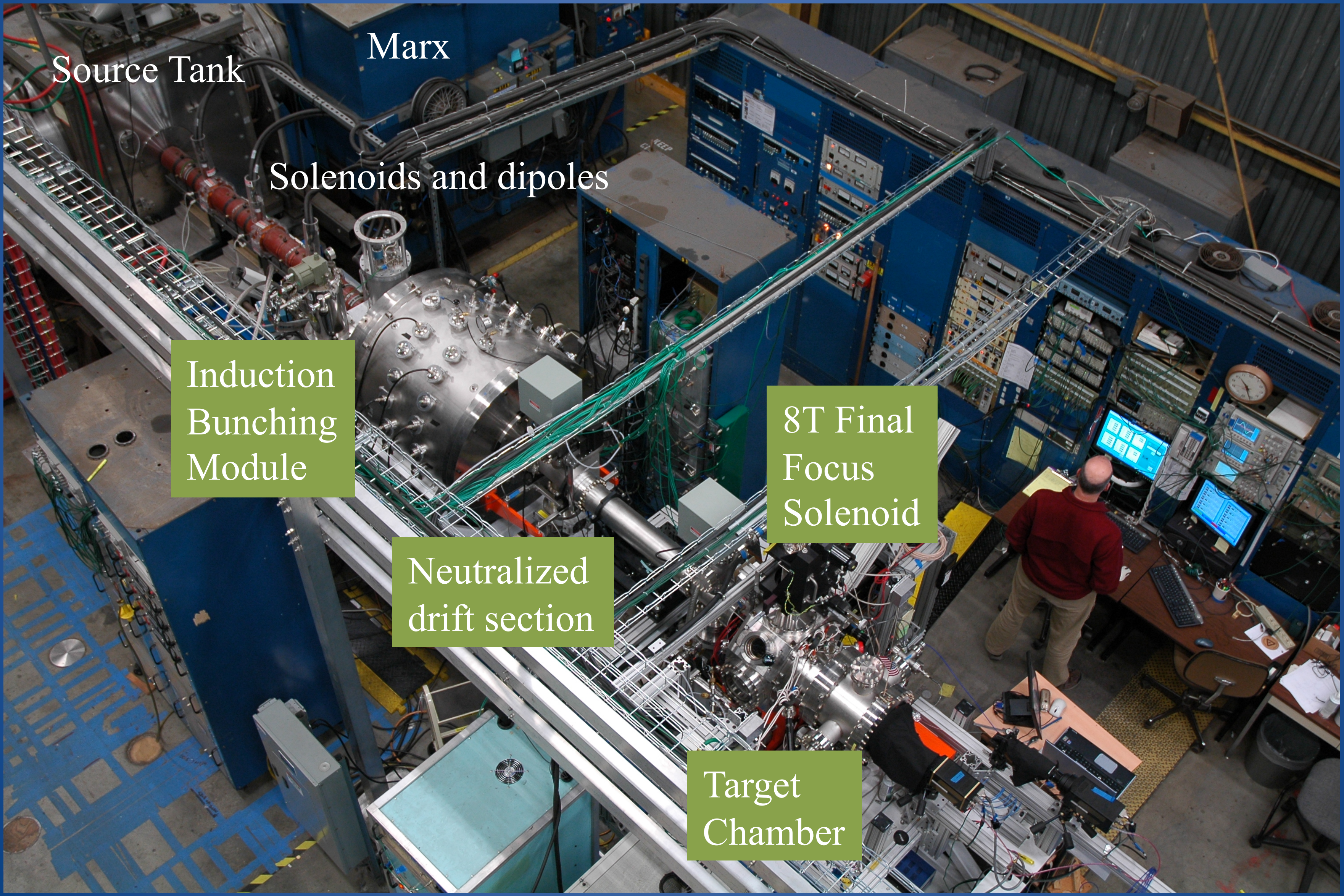
- Required target plane peak intensity

  T ~ 0.5eV (15nC K^+, 300keV) 0.2J/cm^2 , ~200A/cm^2

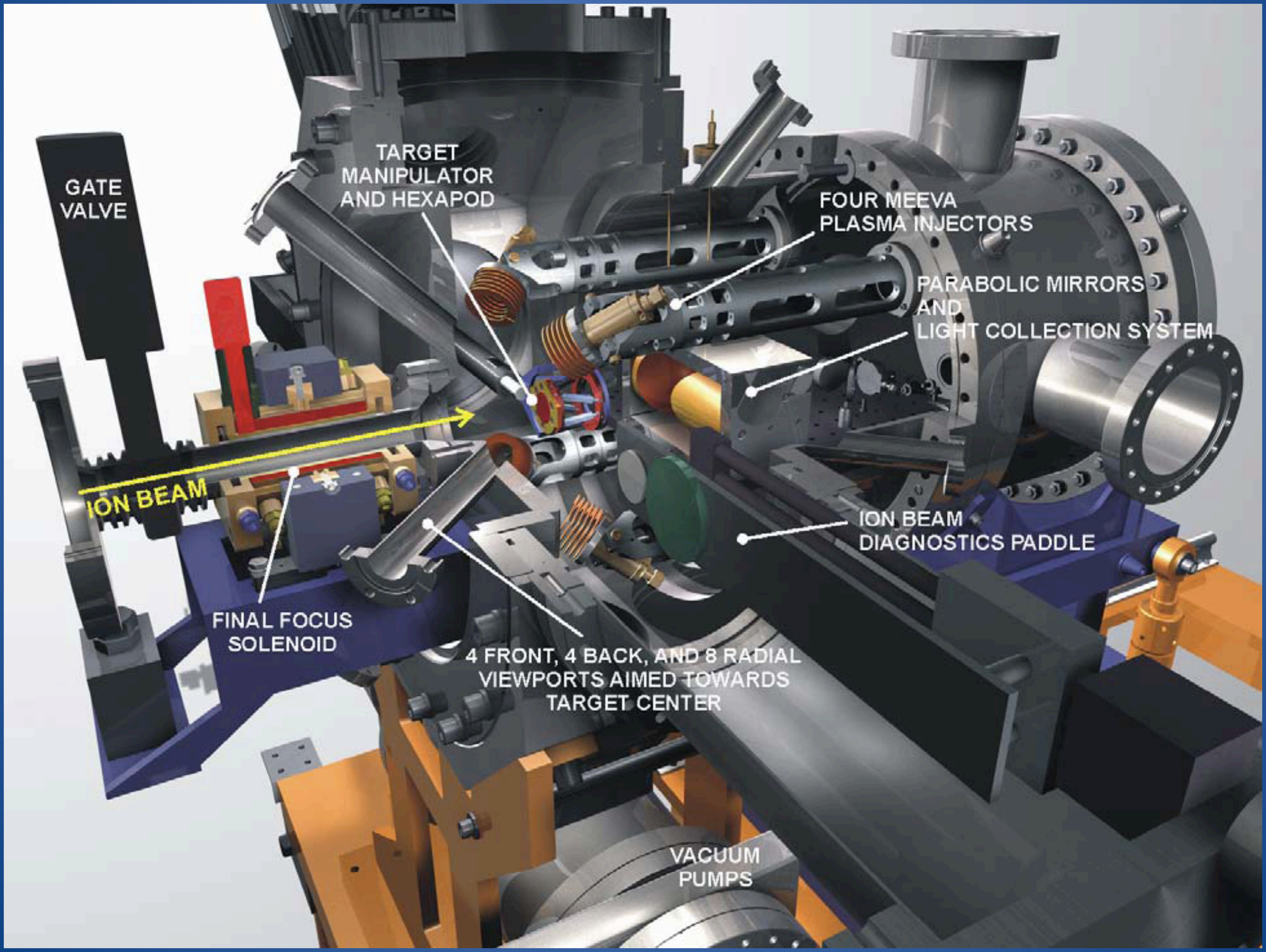
  T ~ 1-2 eV (30nC Li^+, 3MeV) 30J/cm^2 , ~ 8kA/cm^2

  T ~ 10 eV (30nC Na^+, 10MeV) 200J/cm^2 , ~1MA/cm^2

NDCX-I in Bldg 58

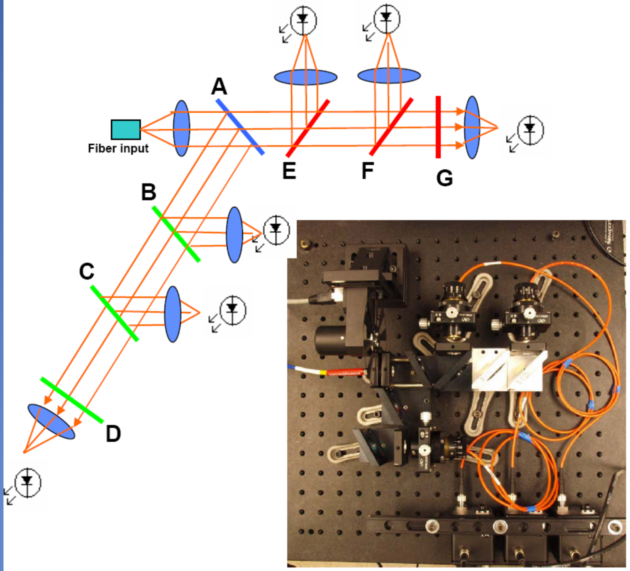


Target Chamber



Target Diagnostics

Fast Optical Pyrometer



Challenges and requirements:

Being able to detect at least ~1 mW of light from 400 nm to 2000 nm in a sub-ns time scale:

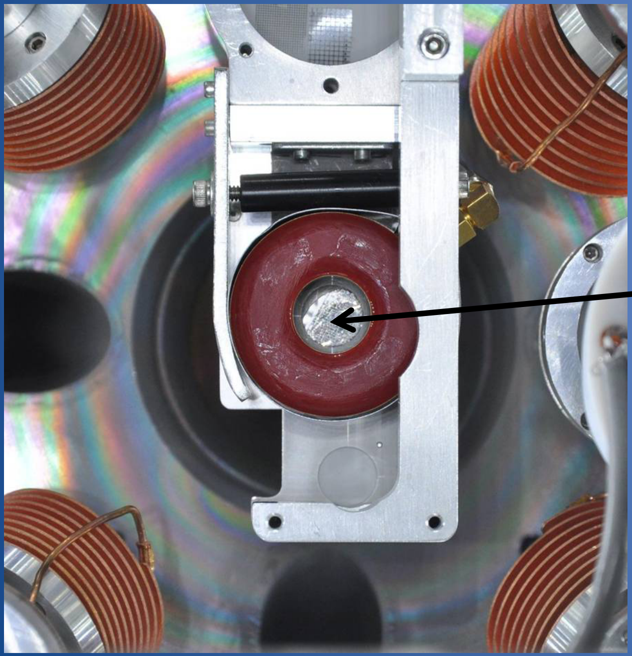
- Ultra fast response (sub-ns)
- Higher sensitivity (>=1500 K)
- Different, more efficient beam splitting mechanism
- No published paper

Technical issues:

- Need low noise amplified photo receiver with flat gain from DC to 4GHz and big active surface.
- Fiber coupling limits the efficiency
- Picoseconds time scale means: Modal (temporal) dispersion in MM fiber, careful cabling, impedance match and termination of detectors

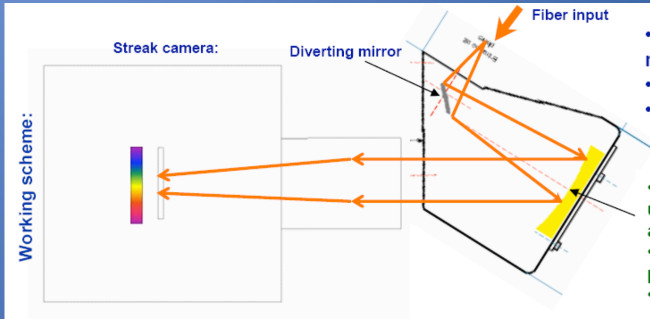
Channel #1: 750 nm+-75 nm, 76 ps rise/fall time detect[illegible] level ~2500 K (blackbody)
Channel #2: 1000 nm+-75 nm, 72 ps rise/fall time detectable level ~1500 K (blackbody)
Channel #3: 1400 nm+-75 nm, 70 ps rise/fall time detectable level ~2000 K (blackbody)

Fast Current Transformer



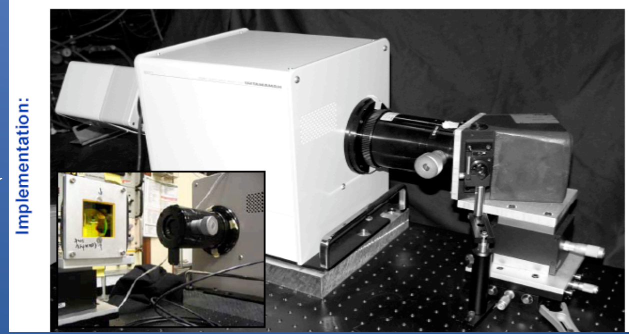
Target Foil

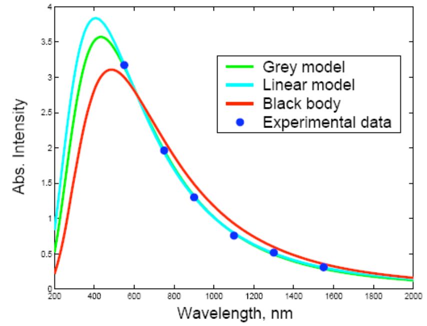
Absolutely-calibrated streak-spectrometer



- Records continuous spectrum from 500 nm to 850 nm
- Temporal resolution down to 5 ps
- Linear response

- When calibrated with tungsten lamp, can be used for true temperature determination and spectral emissivity
- Can discriminate useful signal from NDCX plasma radiation
- No published paper





NDCX-II Induction Cell Detailed Design

A module is one or more induction cells plus an "Intercell" for beam steering and diagnostics