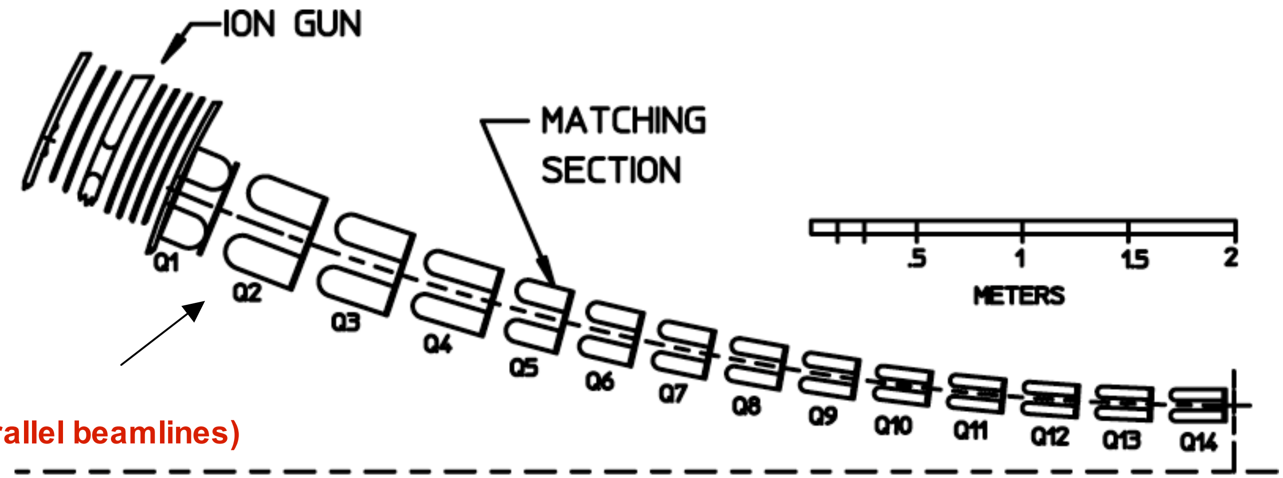
Advances in Intense Ion Beam Experiments in the U.S.

Outline
1. Source and injector development
2. High brightness ion beams and electron cloud effects
3. Neutralized drift compression

P.A. Seidl
for the
Heavy Ion Fusion Virtual National Laboratory

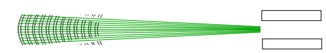
U.S.-Japan Workshop on Heavy Ion Fusion
and High Energy Density Physics
Utsunomiya University, Japan
September 29, 2005

1. Simplification, cost reduction of heavy-ion fusion driver front end



Low J design
(one of many ≈parallel beamlines)

High J multi-beamlet design
(one of many ≈parallel beamlines)

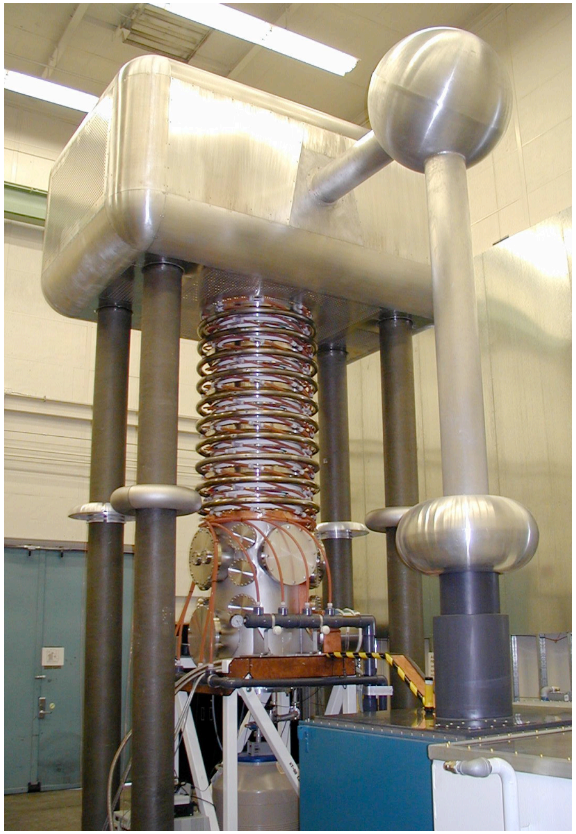


⇒ Compact <u>multi-beamlet</u> injector:

- ***high current density / beamlet***
- ***low emittance growth in merging process***
- ***Injection of elliptical distribution to match AG transport.***

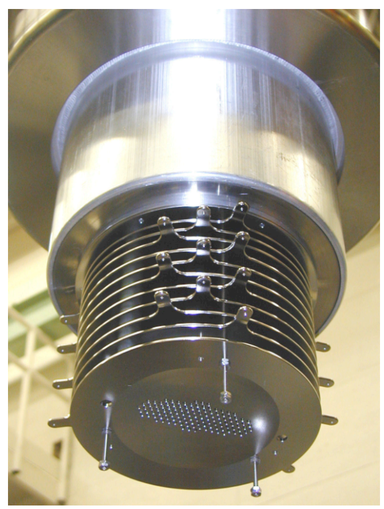
2005 goal: Complete the converging beamlets experiments on STS-500 [Source Test Stand 500 kV]

Completed experiments on merging multi-beamlets in a high current compact injector for HIF drivers

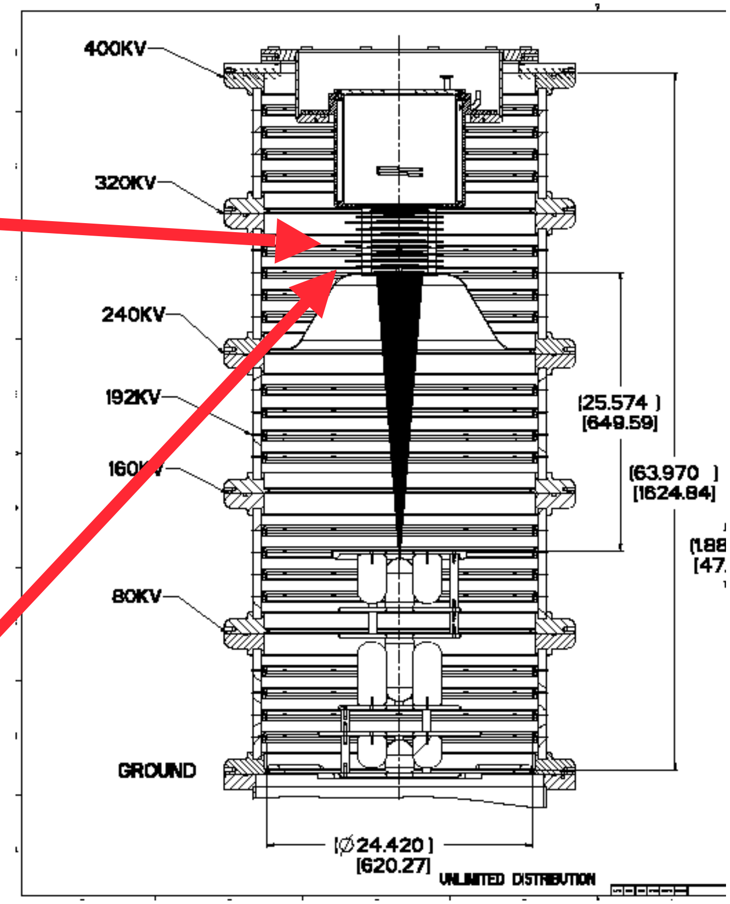


“STS-500” Injector Test Stand at LLNL (500 kV 20μs)

(1) Full-gradient test

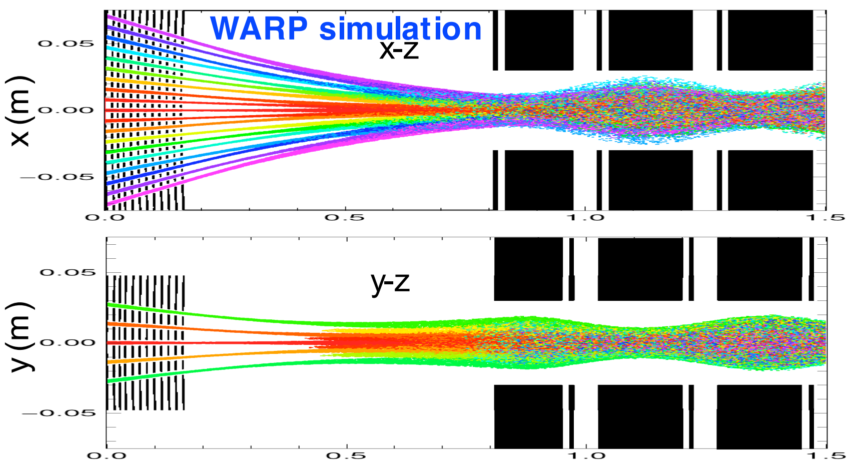


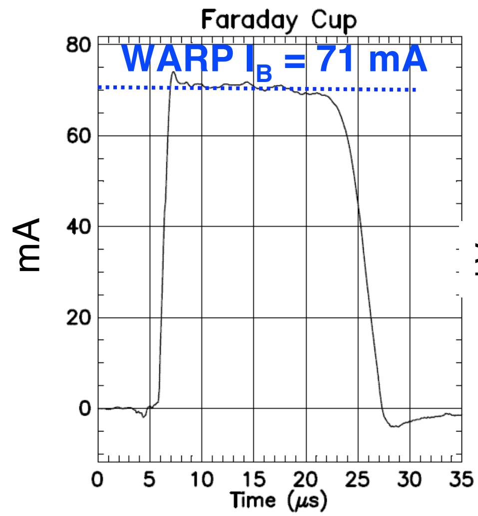
(2) Converging-beamlets test

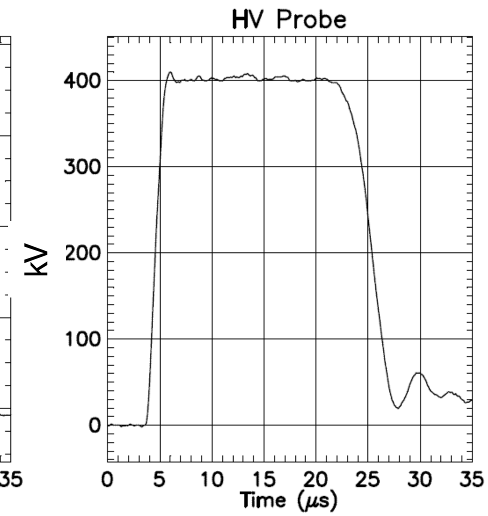


Merging Beamlets into an ESQ channel

Merging Results (STS-500): Beamlets merge with little beam loss. Data analysis is underway.







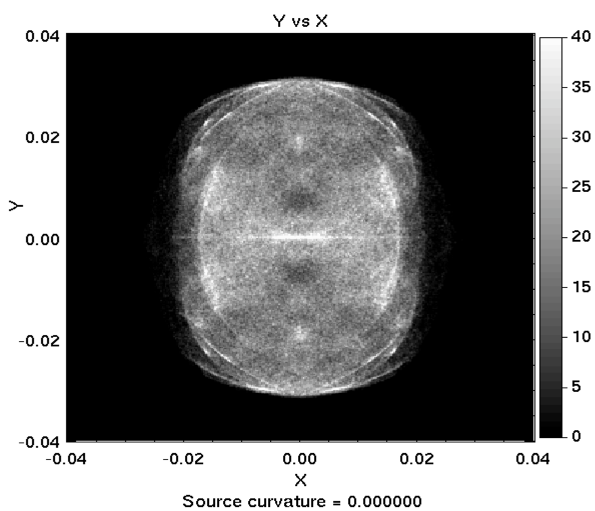
0.4 MeV 71 mA

1.6 MeV 568 mA

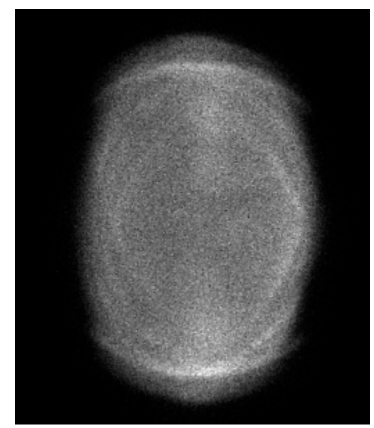
Qualitative features in simulated distribution are seen in the measured beam image.

Emittance similar to simulation.

Prelim. analysis shows qualitative agreement with simulations.



Simulation result



Experimental data

50317027drotate79

Injector Development Summary

We have completed the merging-beamlets injector experiment—learned how to build a compact injector for HIF drivers.

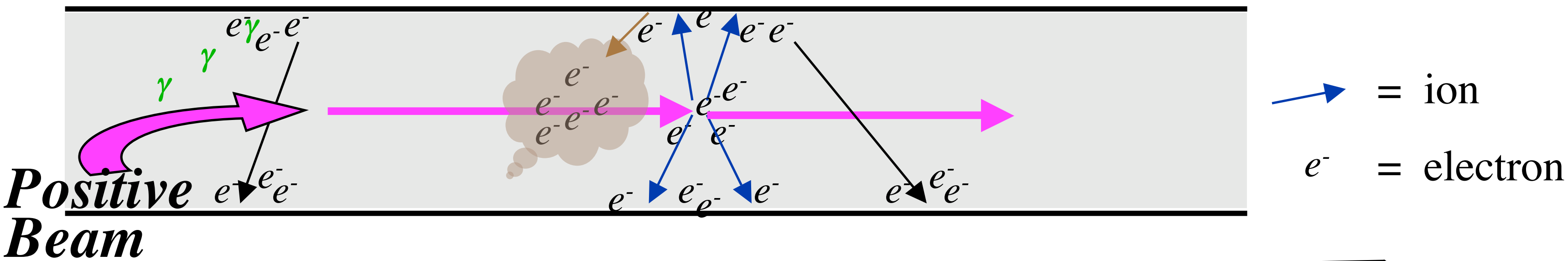
The experimental facility at LLNL is decommissioned:

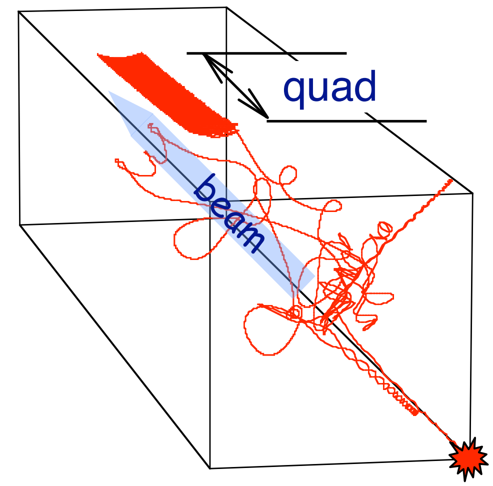
STS-100 will be relocated to LBNL,

STS-500 may be relocated to LBNL for use by another group (IBT).

Our next injector development task is to develop a Na^+ alumino-silicate source for NDCX. Also testing Li^+.

2. High Brightness Beam Transport - electron effects on intense ion beams





e^- motion in a quad

Electron cloud caused by:

- Beam halo scraping $\Rightarrow$ e^- emission
- Ionization of background gas
- Expelled ions hitting vacuum wall
- Ionization of desorbed gas

} esp. for HIF, HEDP

- Synchrotron radiation
- Secondary emission from e^- accelerated by beam

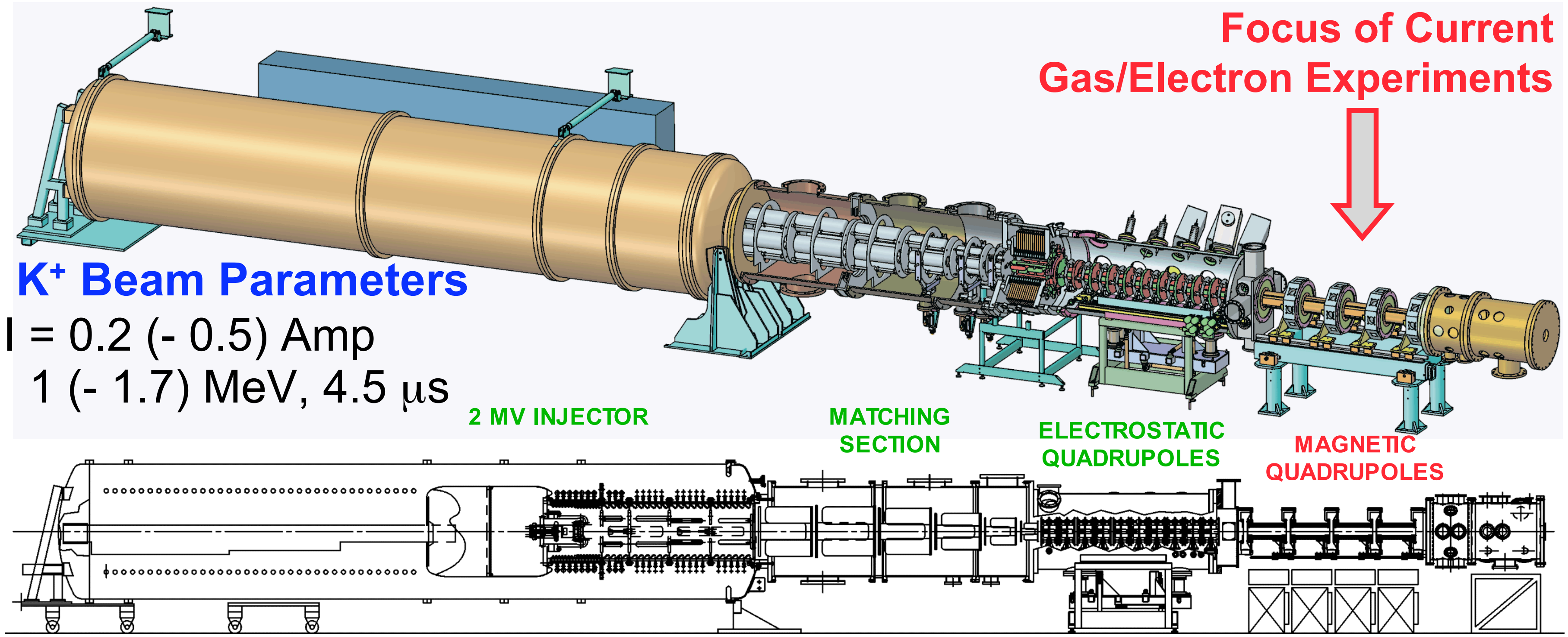
2005 Goal: Advance our understanding of the physical processes leading to the accumulation of electrons in magnetic quadrupoles in the HCX

The High Current Experiment (HCX) is exploring beam transport limits

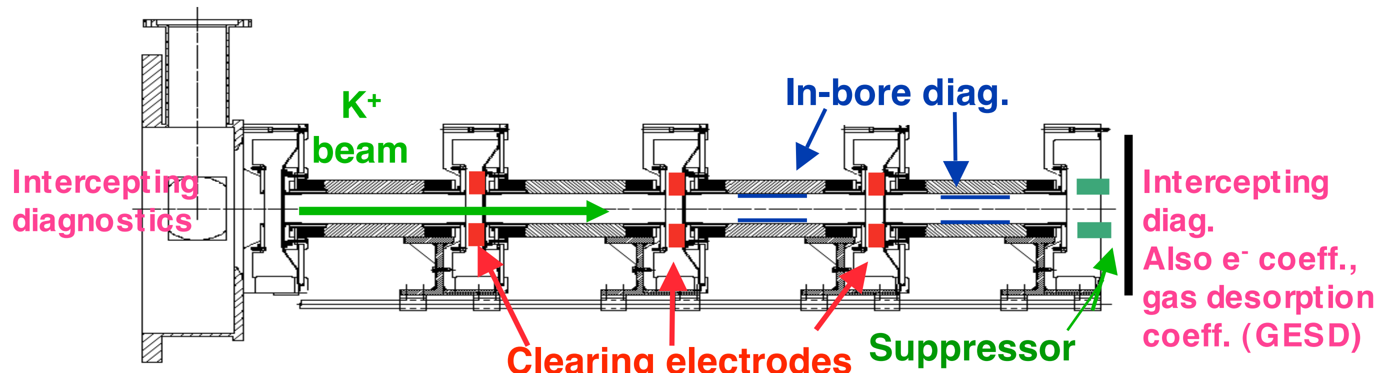
K⁺ Beam Parameters

I = 0.2 (- 0.5) Amp

1 (- 1.7) MeV, 4.5 μs



4 magnetic quadrupoles, many diagnostics



We are looking at fundamental questions in our e-cloud work

Primary electron emission

- ❒ yield & velocity distribution

Secondary emission

- ❒ yield & velocity distribution (comparison with codes)

Desorbed gas

- ❒ mechanism, yield & velocity distribution

Accumulation & retention in quads

- ❒ loss mechanisms, sources

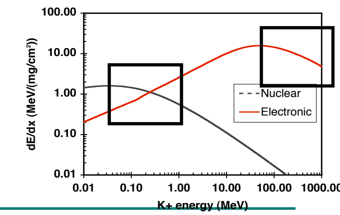
Effects of electrons on beam

- ❒ harder - must exaggerate sources because of short experiment

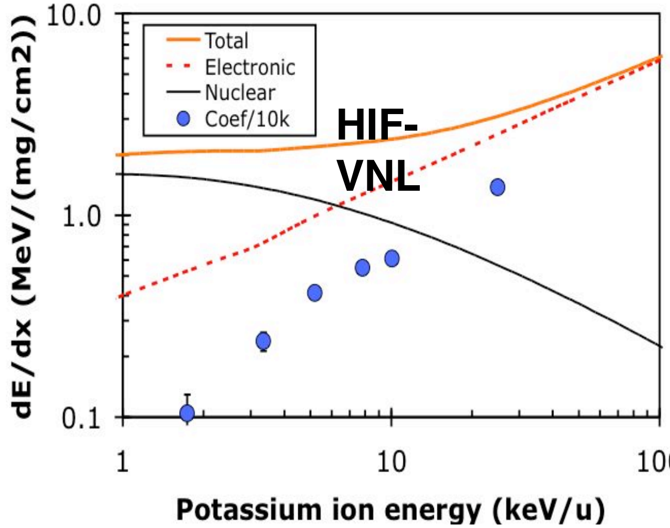
Efficacy of mitigation methods

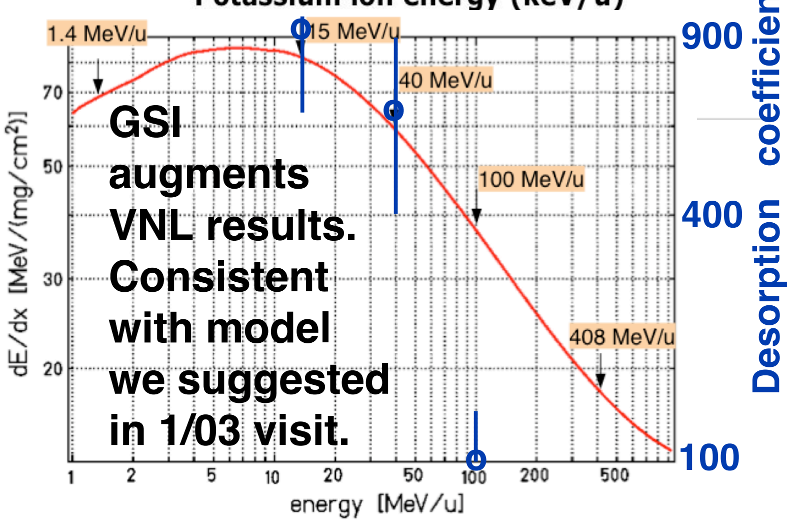
Results are expected to scale to other accelerator regimes

Discovered that copious gas desorption in accelerators is due to electronic sputtering



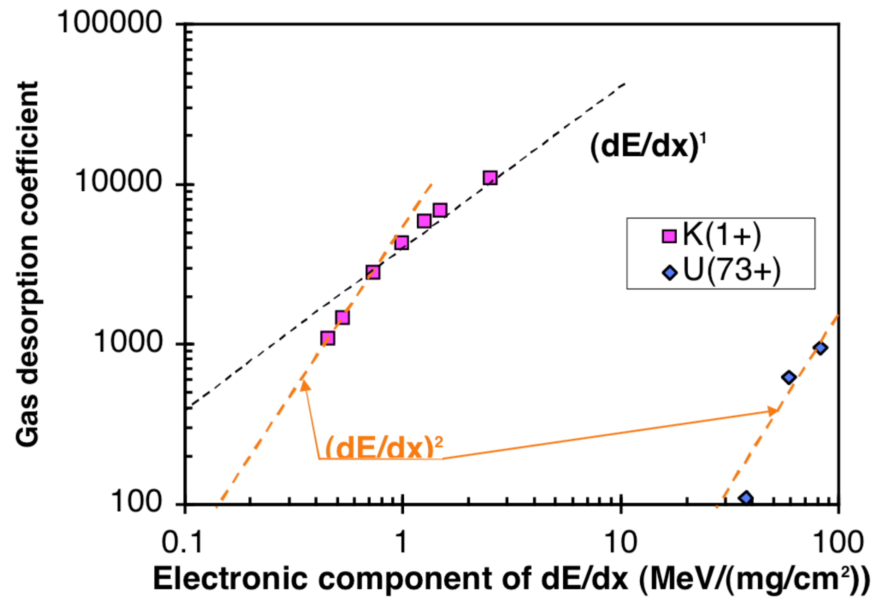
- Gas desorption measured below (HIF-VNL) and above Bragg peak (GSI).





Gas desorption scales with electronic component of dE/dx to the first to second power, similar to electronic sputtering from ions incident on frozen gas.*

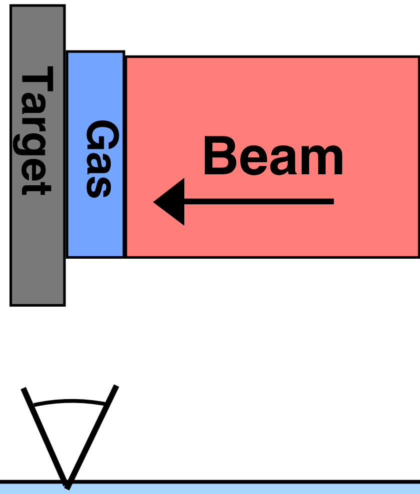
*** R. E. Johnson, Rev. Mod. Phys. 68, 305 (1996).**



HIF-VNL facilities ideal: energy range from nuclear dominating to electronic slowing dominating.

Intense beam excitation of gas – enables measuring velocity distribution of desorbed gas

<u>Observation: desorbed gas in beam emits light</u>



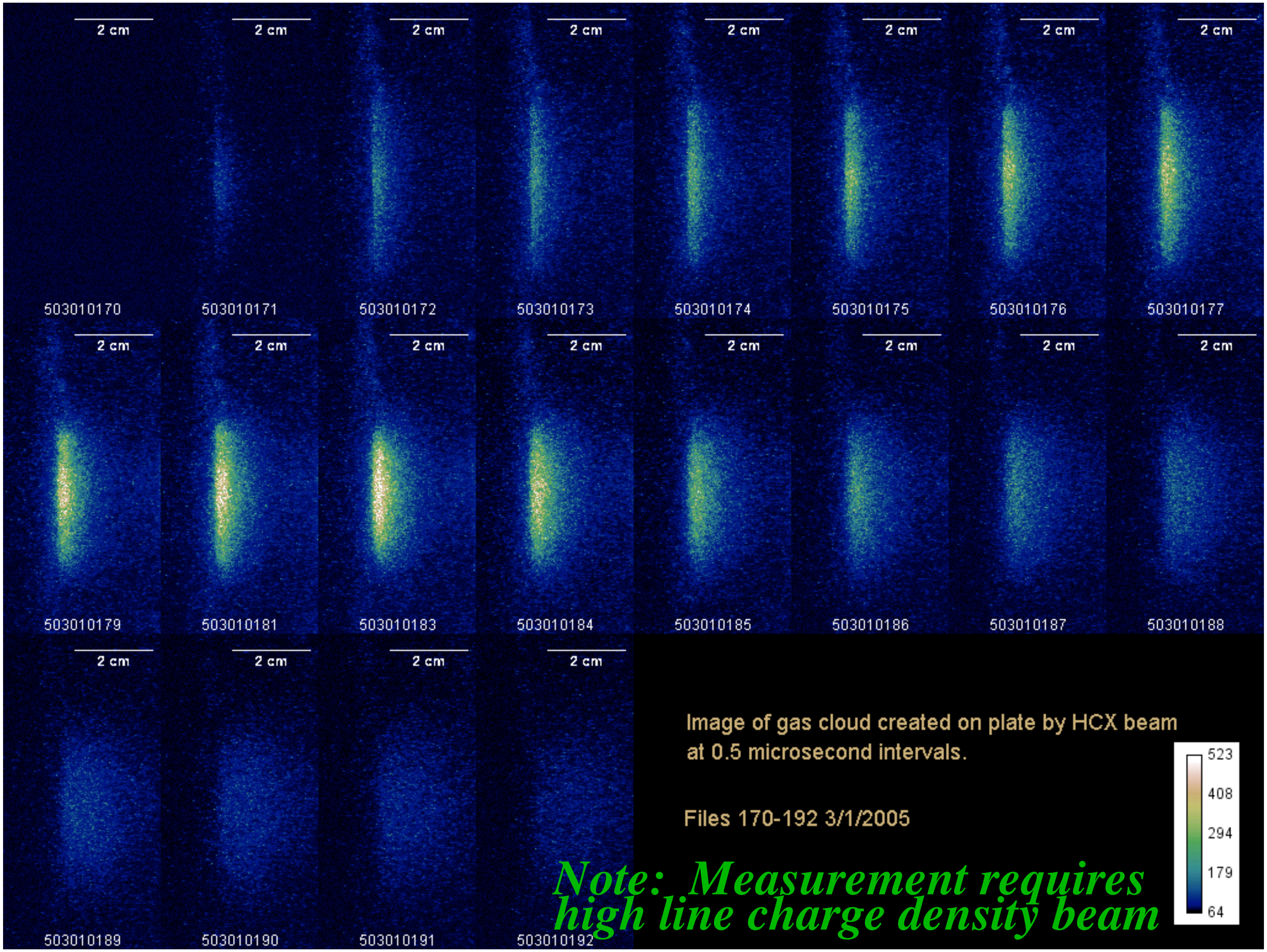
View expanding gas cloud from side – $f(v_0)$ normal to hole plate [with gated camera or streak camera]

Follow-on Options:

- **Tilt target – $f(v_0)$ near grazing incidence**
- **Narrow ribbon target – $f(v_0,\theta)$ with gated camera**
- **Absolute calibration to obtain desorption coef.**
- **Other targets: NEG, …**

Benefits – needed to model time for gas to reach beam
info on physical mechanisms of gas desorption

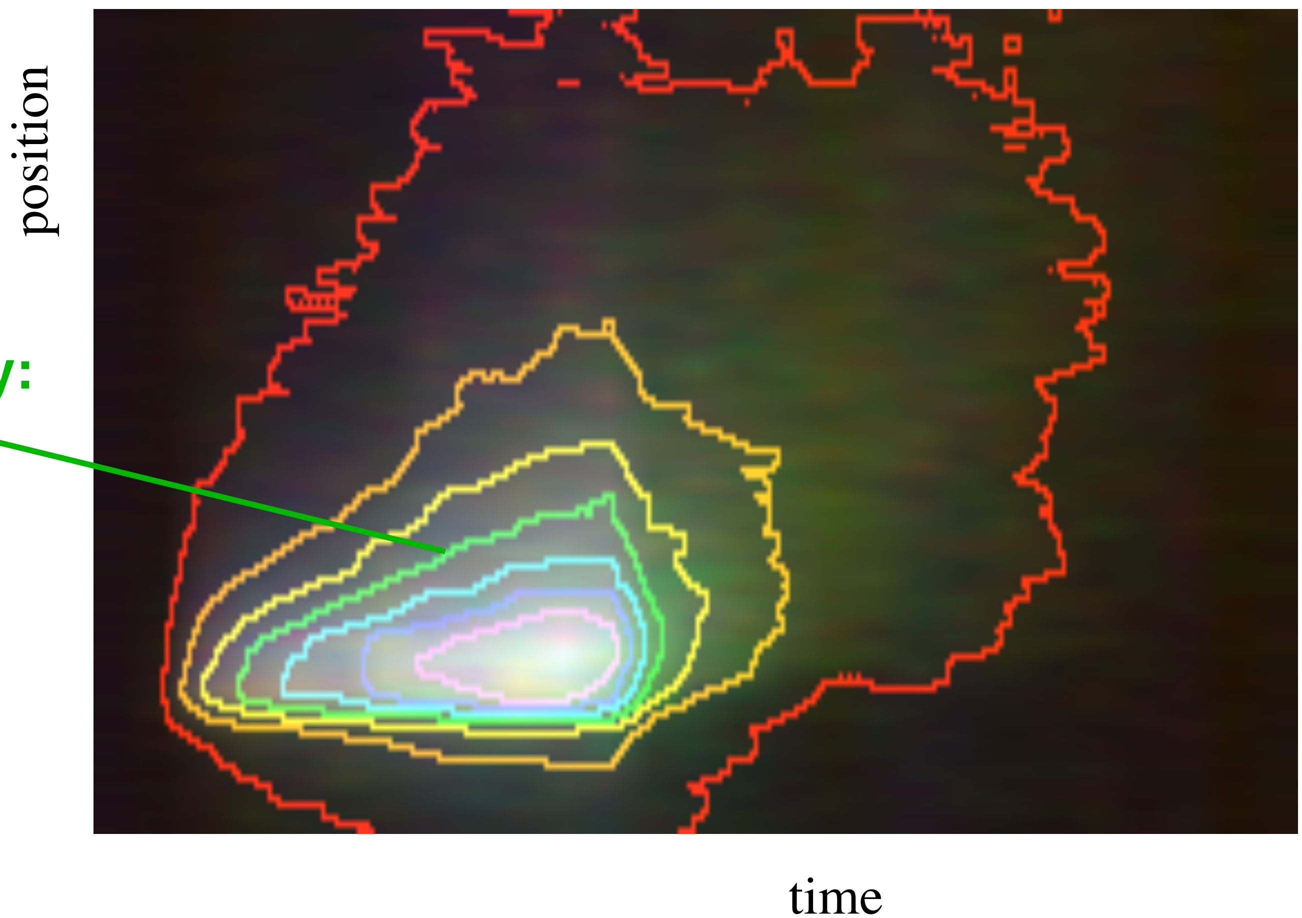
Images of the gas cloud show growth and decay as a function of time.



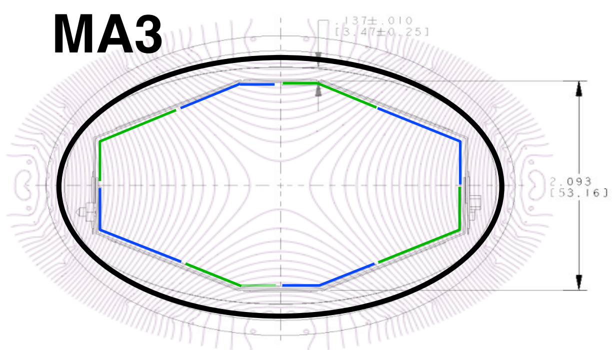
Note: Measurement requires high line charge density beam

Line integral of images indicates an expansion velocity of up to a few mm/μs

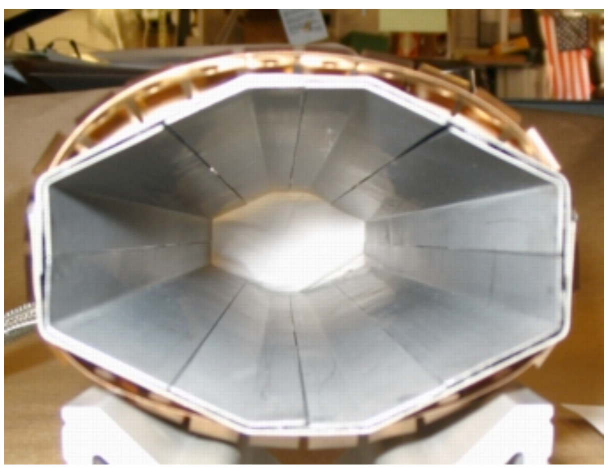
Estimated velocity:
Slope ~1 mm/μs

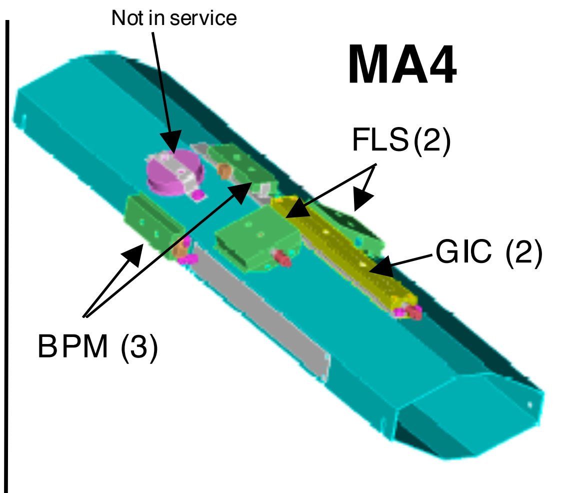


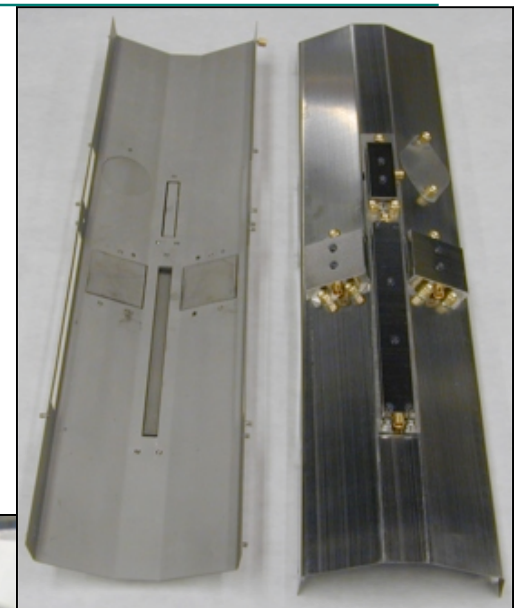
Diagnostics in two magnetic quadrupole bores, & what they measure

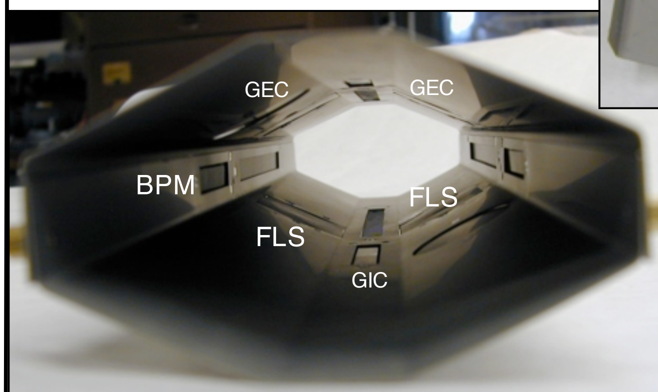


8 “paired” Long flush collectors (FLL): measures capacitive signal + collected or emitted electrons from halo scraping in each quadrant.









3 capacitive probes (BPM); beam capacitive pickup $((n_b - n_e)/ n_b)$.

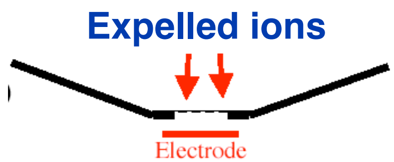
2 Short flush collector (FLS); similar to FLL, electrons from wall.

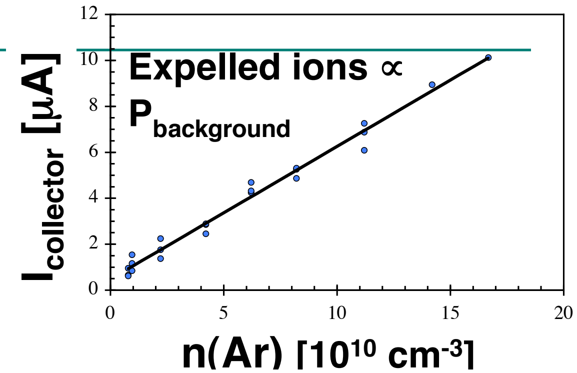
2 Gridded e^- collector (GEC); expelled e^- after passage of beam

2 Gridded ion collector (GIC): ionized gas expelled from beam

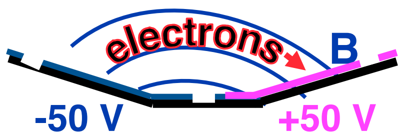
Sources of electrons and expelled or secondary ions can be measured

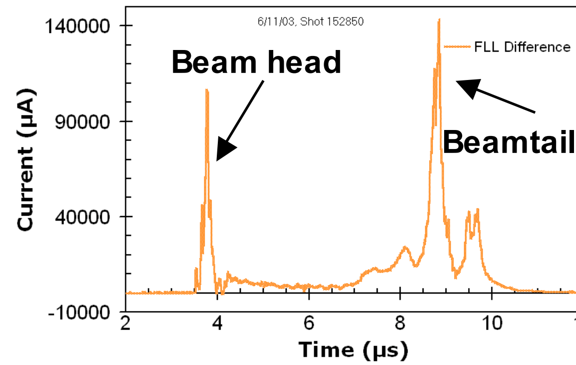
1. **Ionization of gas by beam**



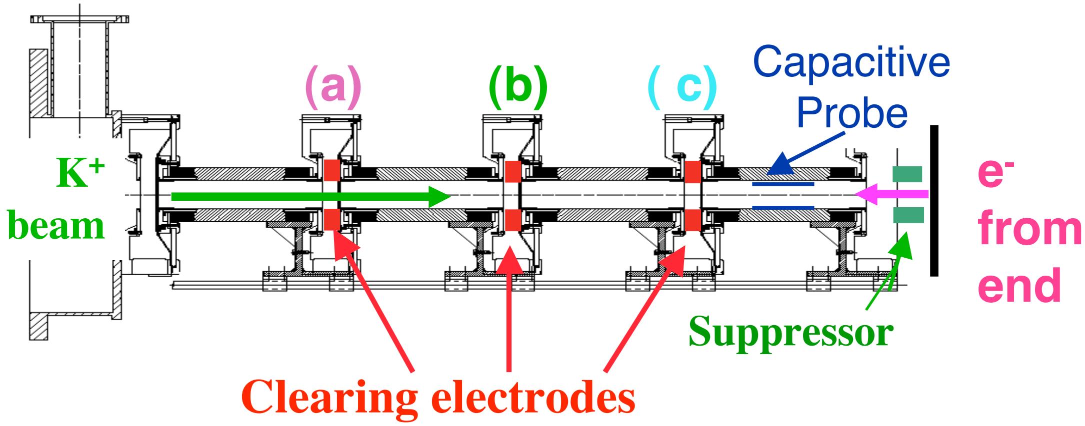


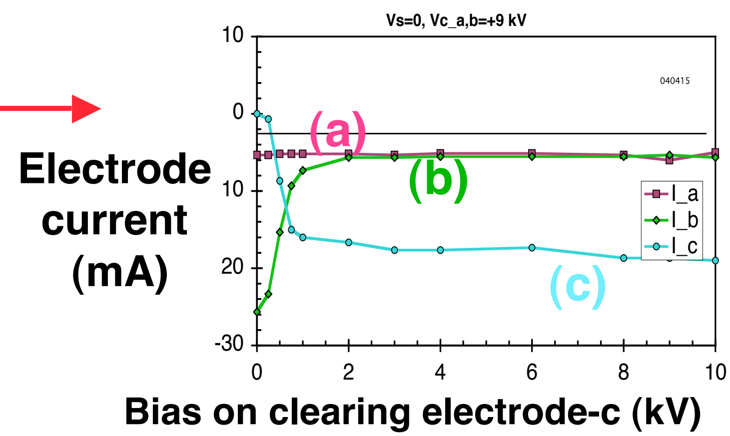
2. **Electron emission from wall**





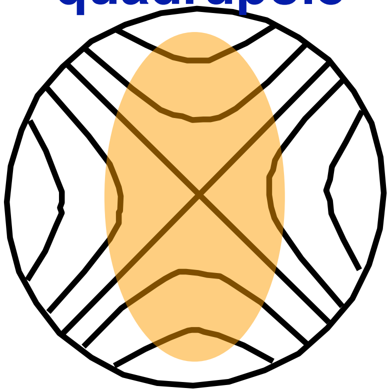
3. **Axial current of electrons from end**





A new computational “mover” relaxes the problem of short e$^-$ timescales in magnetic field

Magnetic quadrupole

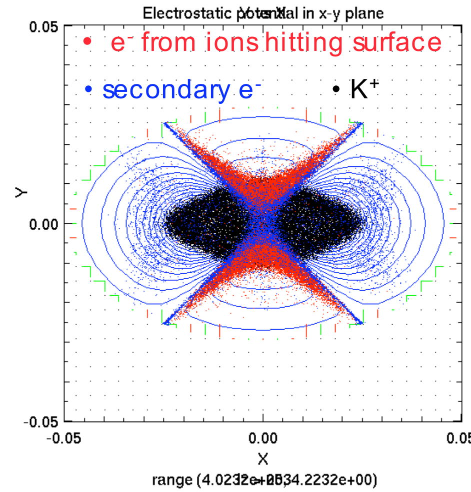


Problem: Electron gyro timescale

<< other timescales of interest

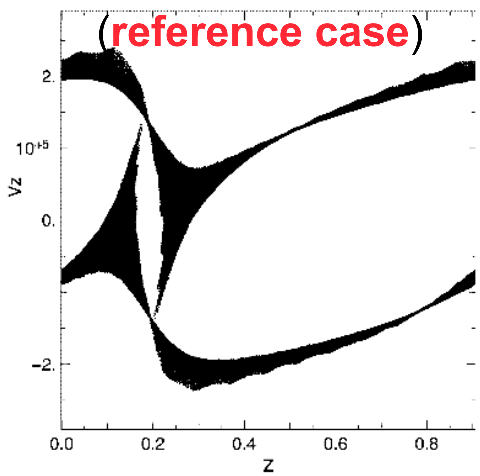
$\Rightarrow$ brute-force integration very slow due to small Δt

Solution*: Interpolation between full-particle dynamics (“Boris mover”) and drift kinetics (motion along B plus drifts)

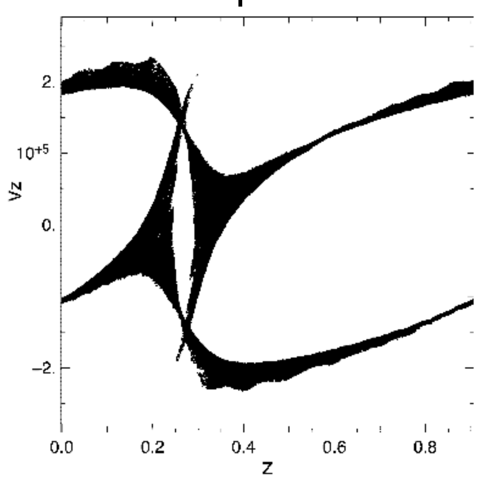


Test:
Magnetized two-stream instability

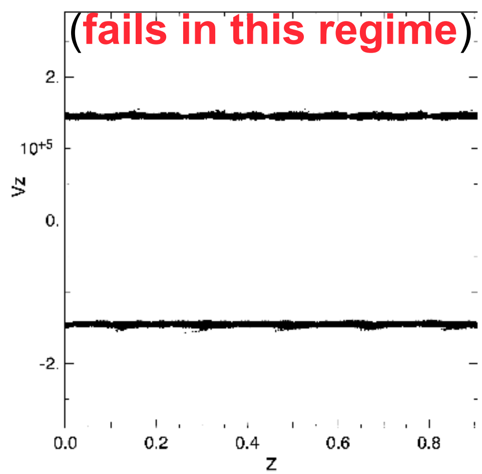
small $\delta t=0.25/\omega_c$
Standard Boris mover
(**reference case**)



large $\delta t=5./\omega_c$
New interpolated mover

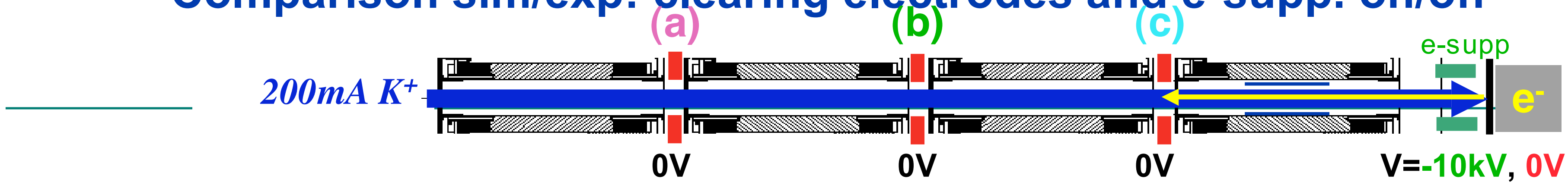


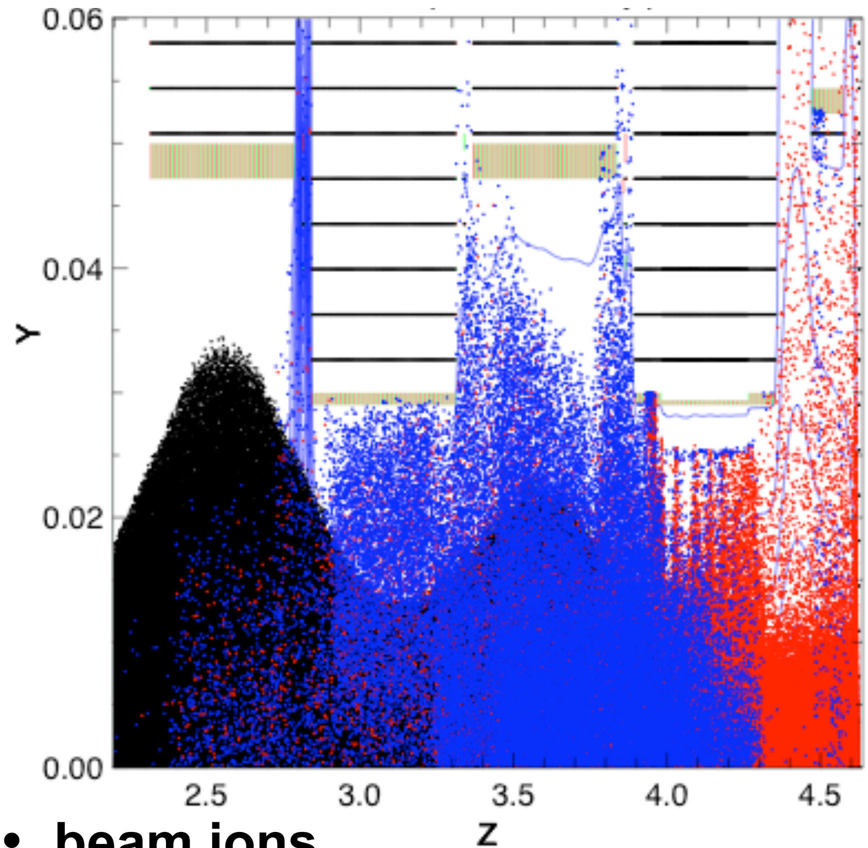
large $\delta t=5./\omega_c$
Standard Boris mover
(**fails in this regime**)

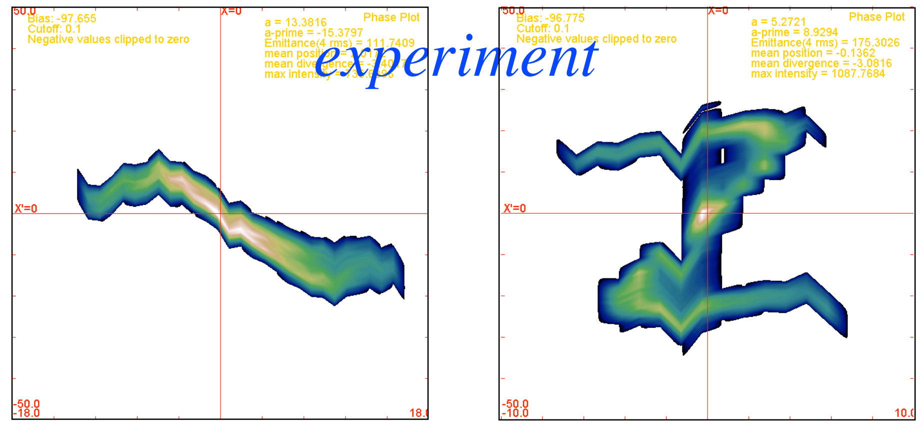


***R. Cohen et. al., Phys. Plasmas, May 2005**

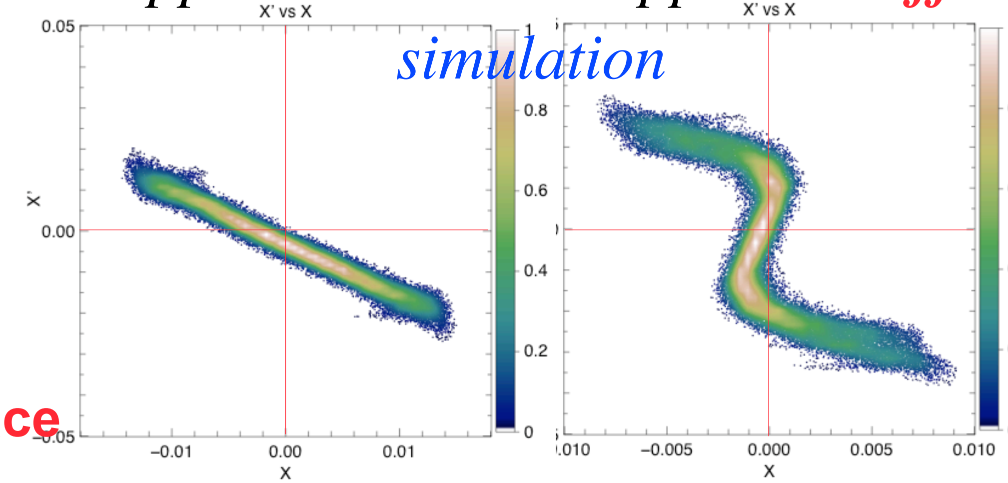
Comparison sim/exp: clearing electrodes and e-supp. on/off







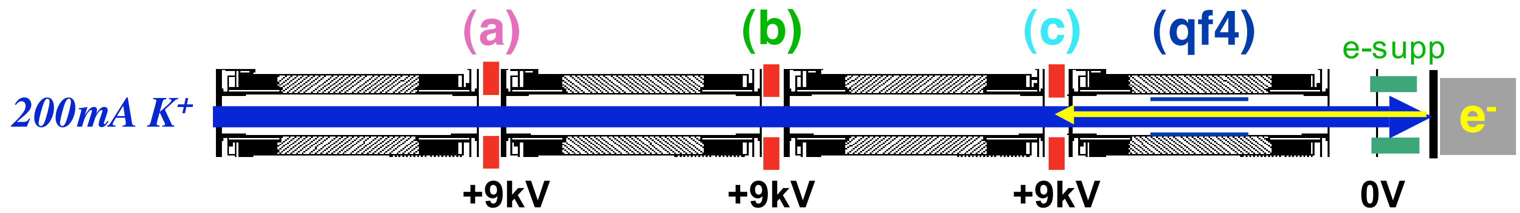
Suppressor on *Suppressor off*

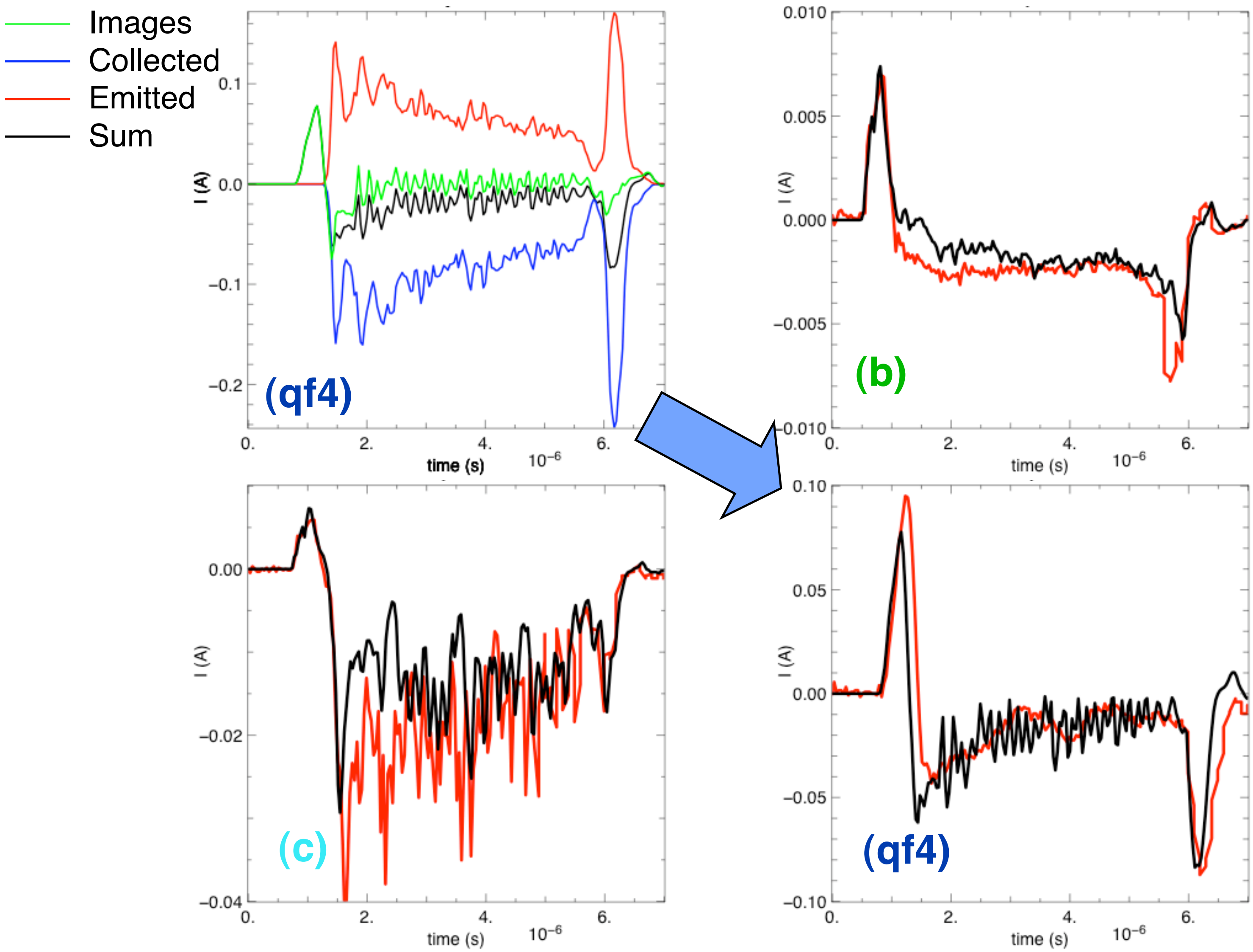


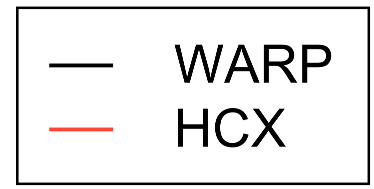
- beam ions
- electrons from ions hitting surface
- secondary electrons

Exp / Sim Comparison suggest semi-quantitative agreement.

Signal from simulation is sum of three components





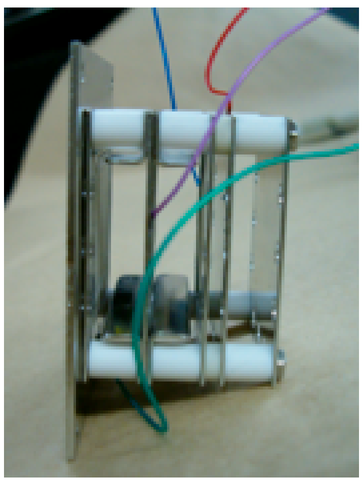


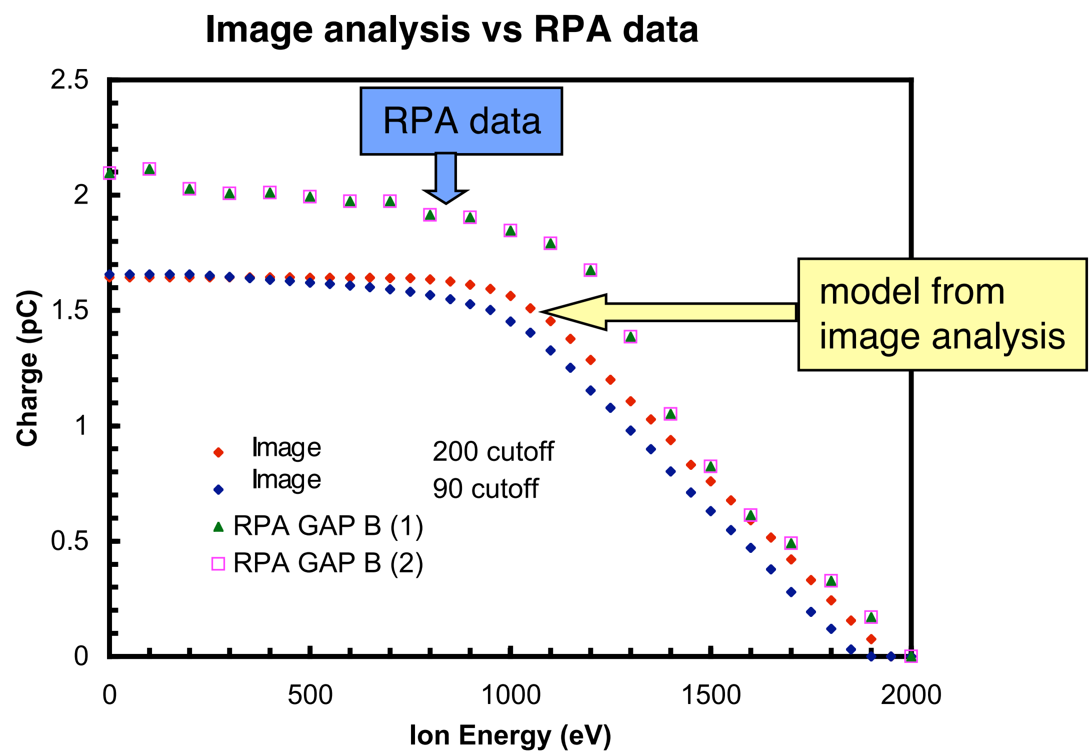
Self-consistent model of ion beam with e⁻ built around WARP (HIF) and POSINST (HEP).

Collaboration with M. Furman, M. Pivi

Retarding potential analyzer (RPA) measures energy distribution of expelled ions

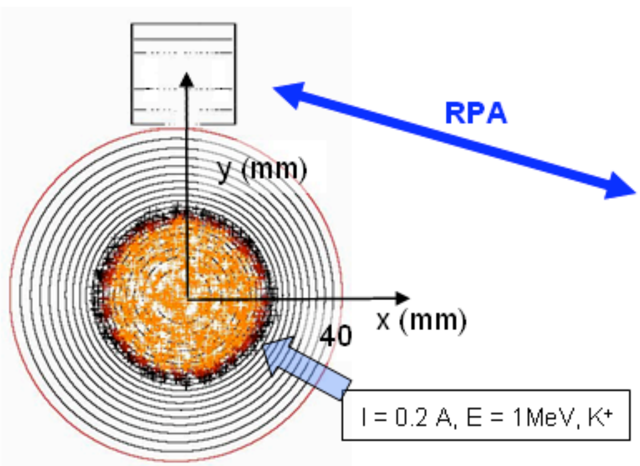
- RPA an extension of ANL design (Rosenberg and Harkay)
- Can measure either ion (shown) or electron distributions
- Potential of beam edge ~1000 V, beam axis ~ 2000 V



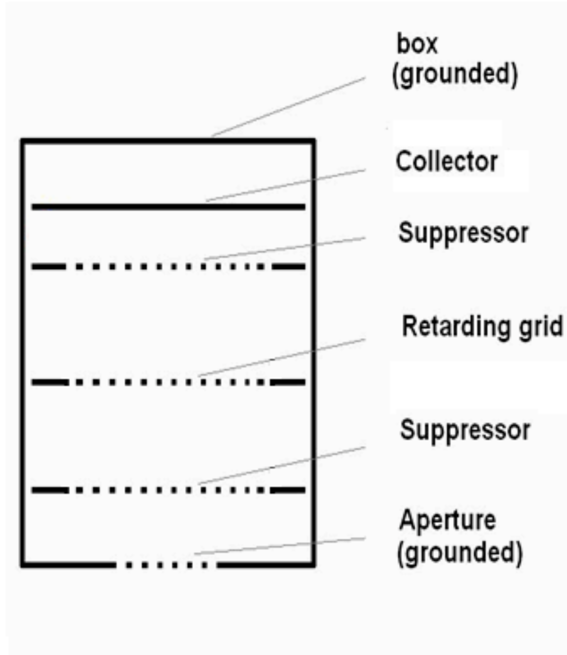


Ref: Michel Kireeff Covo, to be published (UCB & LLNL SEGRF fellow working with A. Molvik)

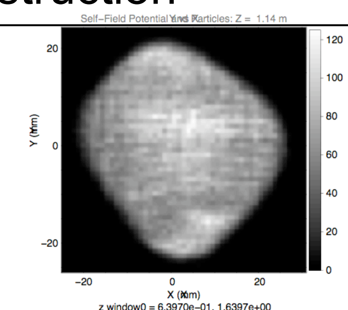
Retarding Potential Analyzer for e⁻ and ion energy scans

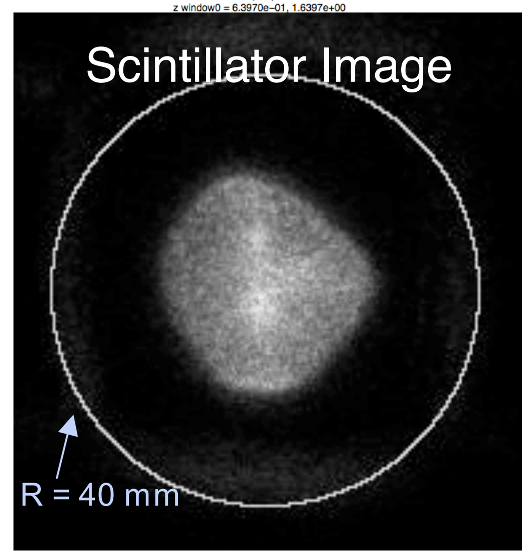


PIC simulation, contours showing electric potential



WARP (initialized with upstream (D2) data reconstruction





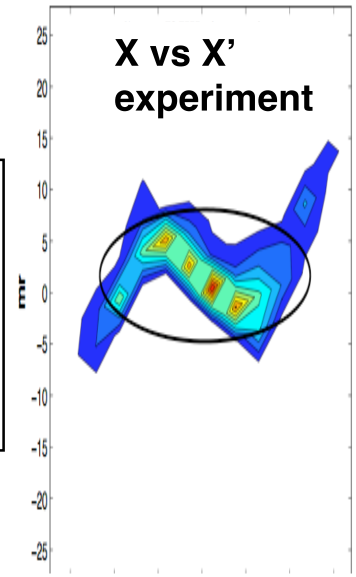
The particles measured are those resulting from the ionization of the background gas, which are then expelled during (ions) or immediately after (e-) the beam pulse.

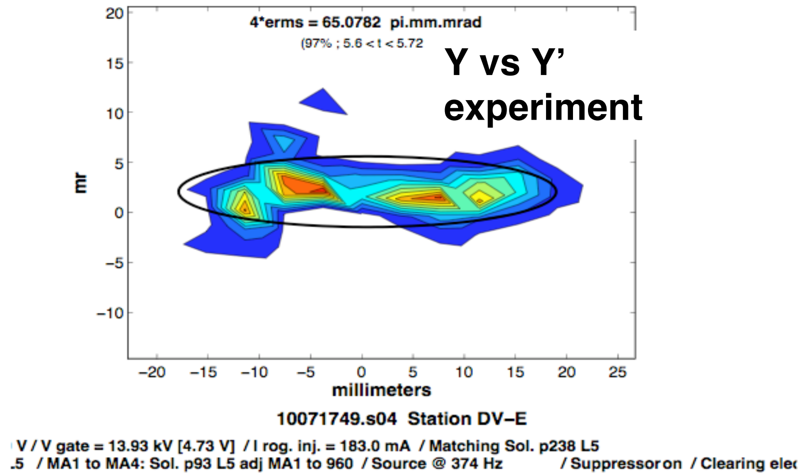
Reconstructed 4D phase space derived from upstream optical diagnostic $\Rightarrow$ Initialize PIC. **Simulated transport captures the observed distribution distortions downstream.**

x-x’, y-y’ @ end of magnet lattice (D-end) sheared [slope removed]

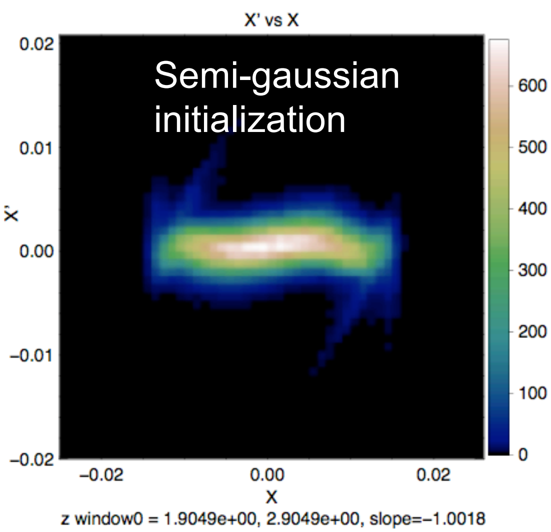
To do:

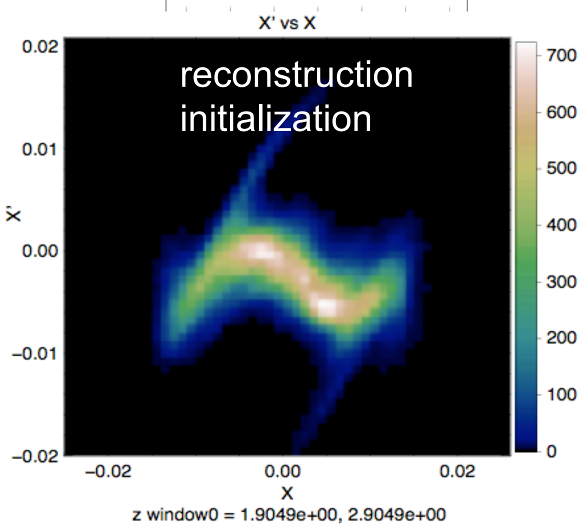
- Check effect of small differences (rms) between double-slit and optical upstream measurements.
- Incorporate into 3D runs with electron effects…

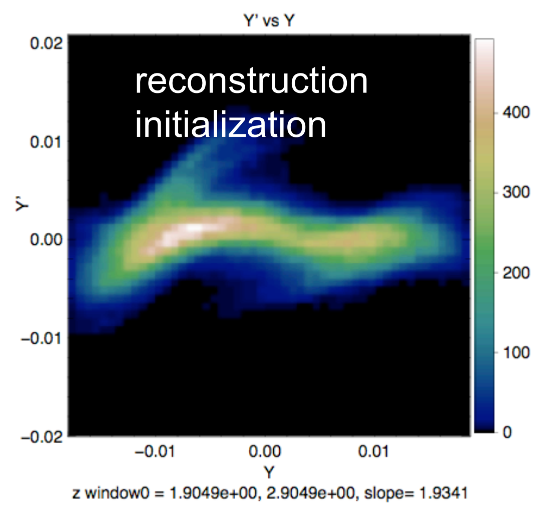




Warp 2D (no e$^-$)







3. Neutralized drift compression

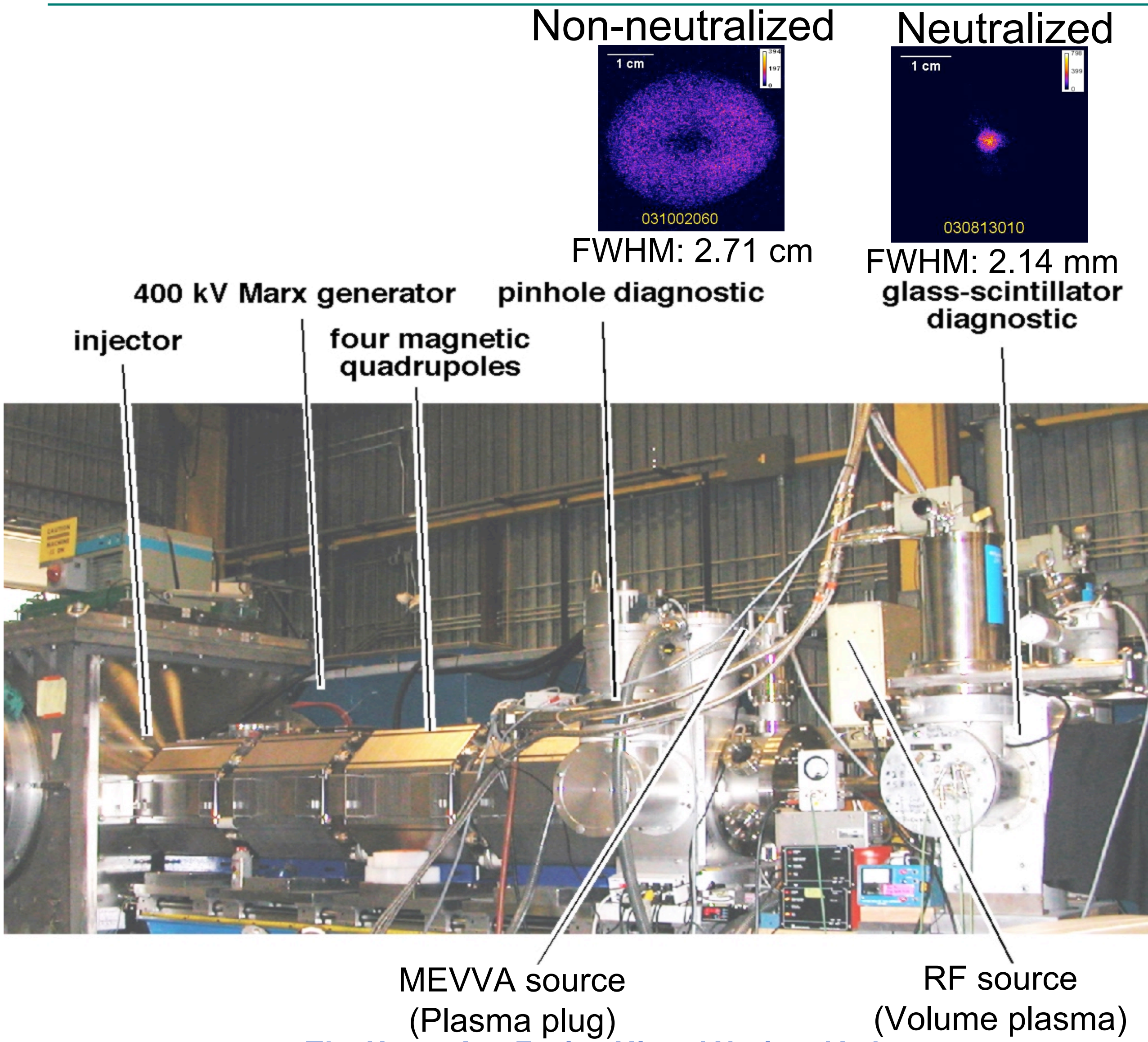
"How can **heavy ion beams** be **compressed to the high intensities required** for creating **high energy density matter and fusion ignition conditions**?"

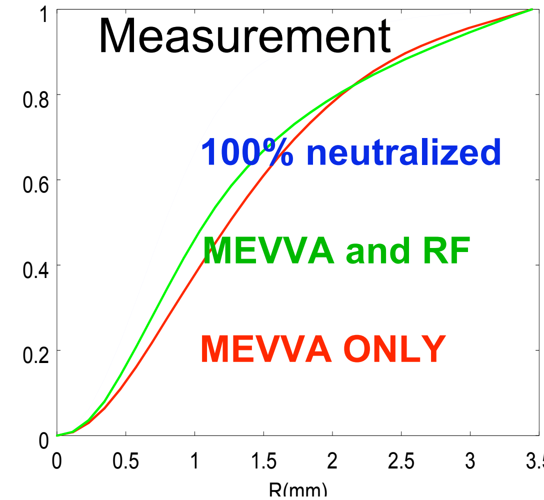
- *Frontiers For Discovery In High Energy Density Physics*

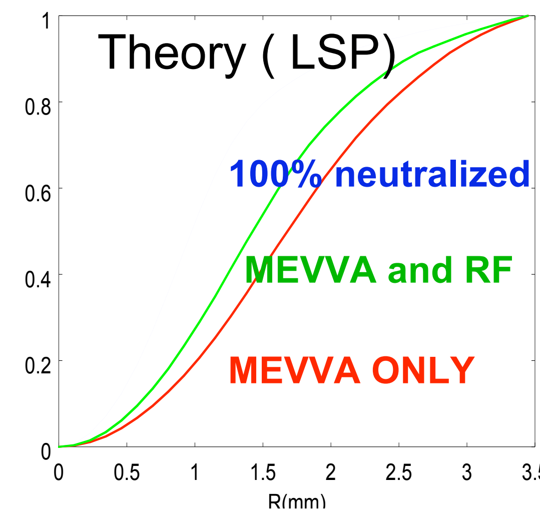
2005 Goal: Commission and conduct preliminary testing of the Neutralized Drift Compression Experiment

- Transverse compression of beam
  - ⇒ Completion of Neutralized Transport Experiment
- Longitudinal compression
  - ⇒ Neutralized drift compression

Neutralized Transport Experiment (NTX) completed with quantitative agreement between simulation and experiment

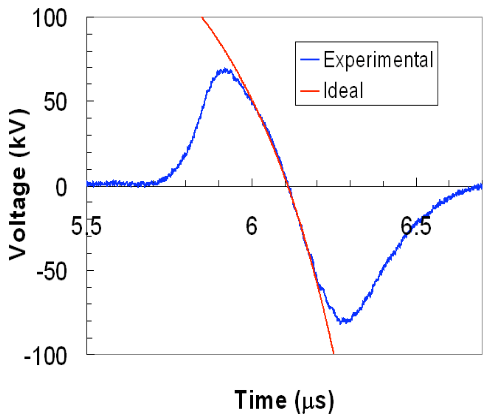




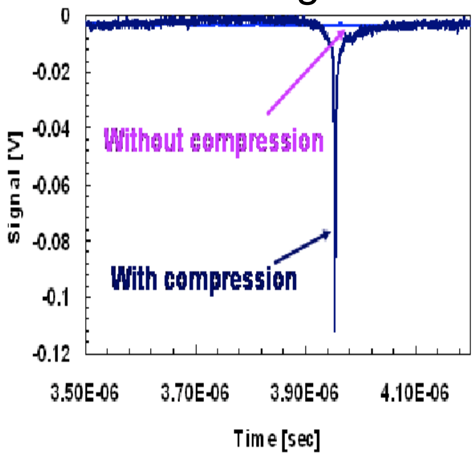


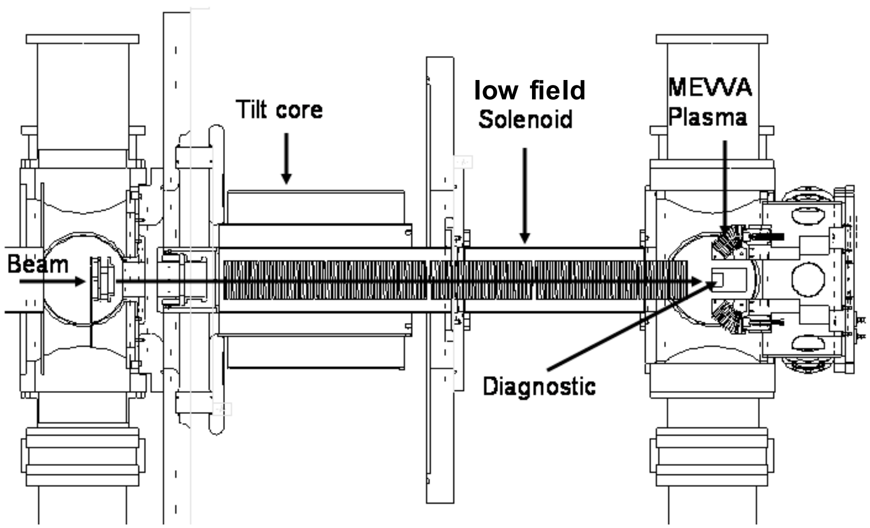
Neutralized drift compression experiment (NDCX)

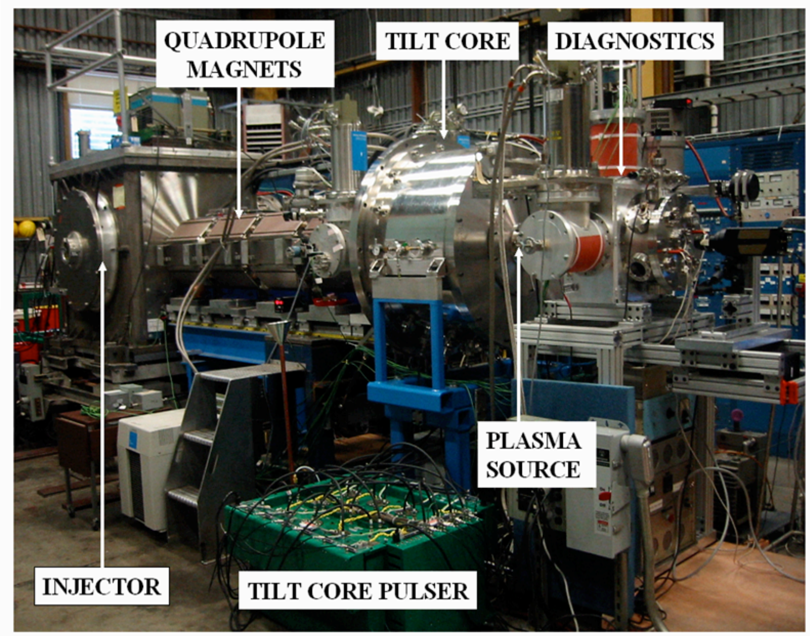
Tiltcore waveform



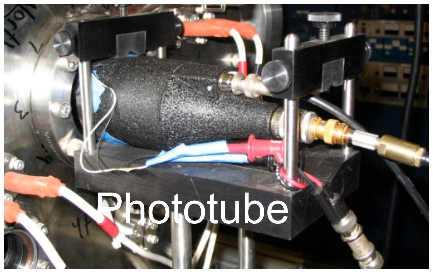
Beam current diagnostic

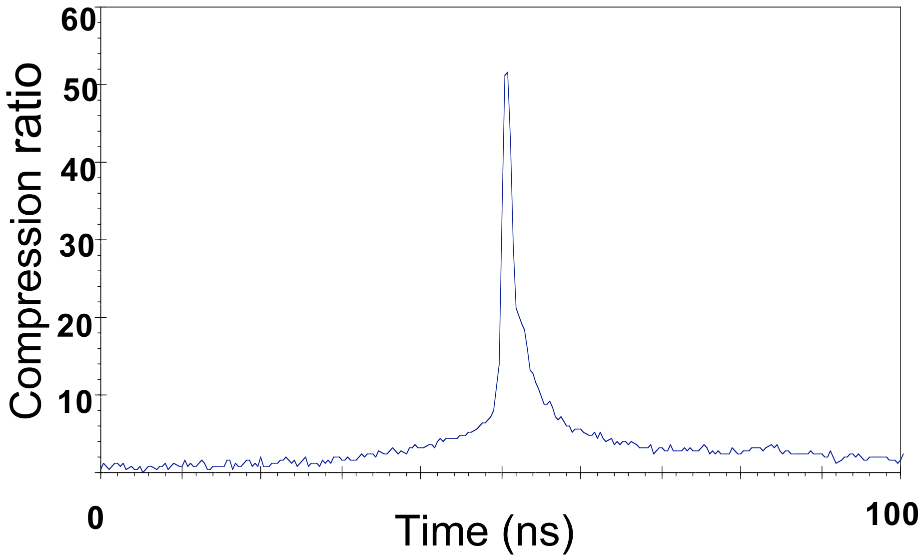


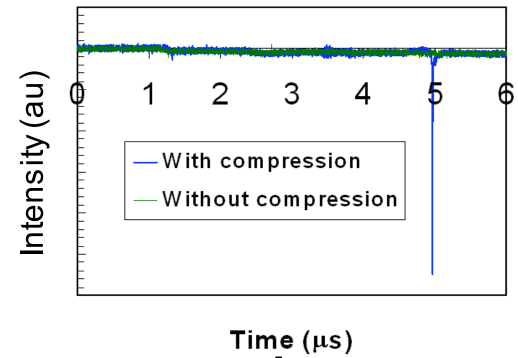




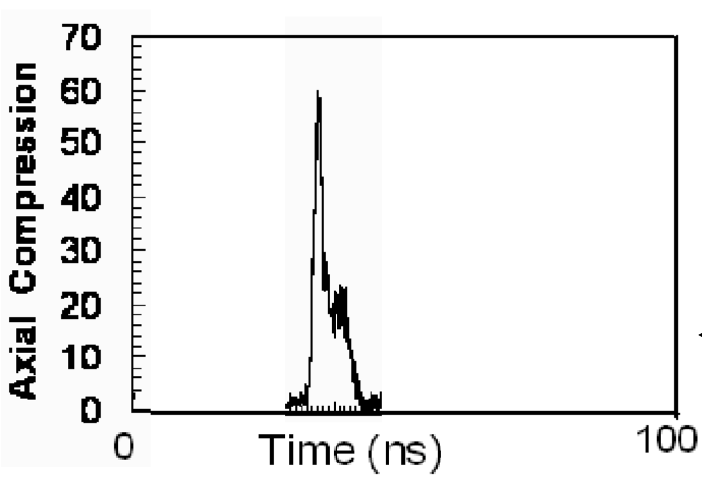
50 Fold Beam Compression achieved in neutralized drift compression experiment





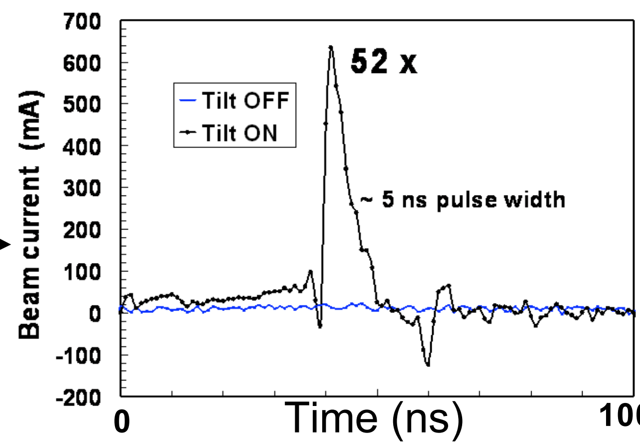


Optical data

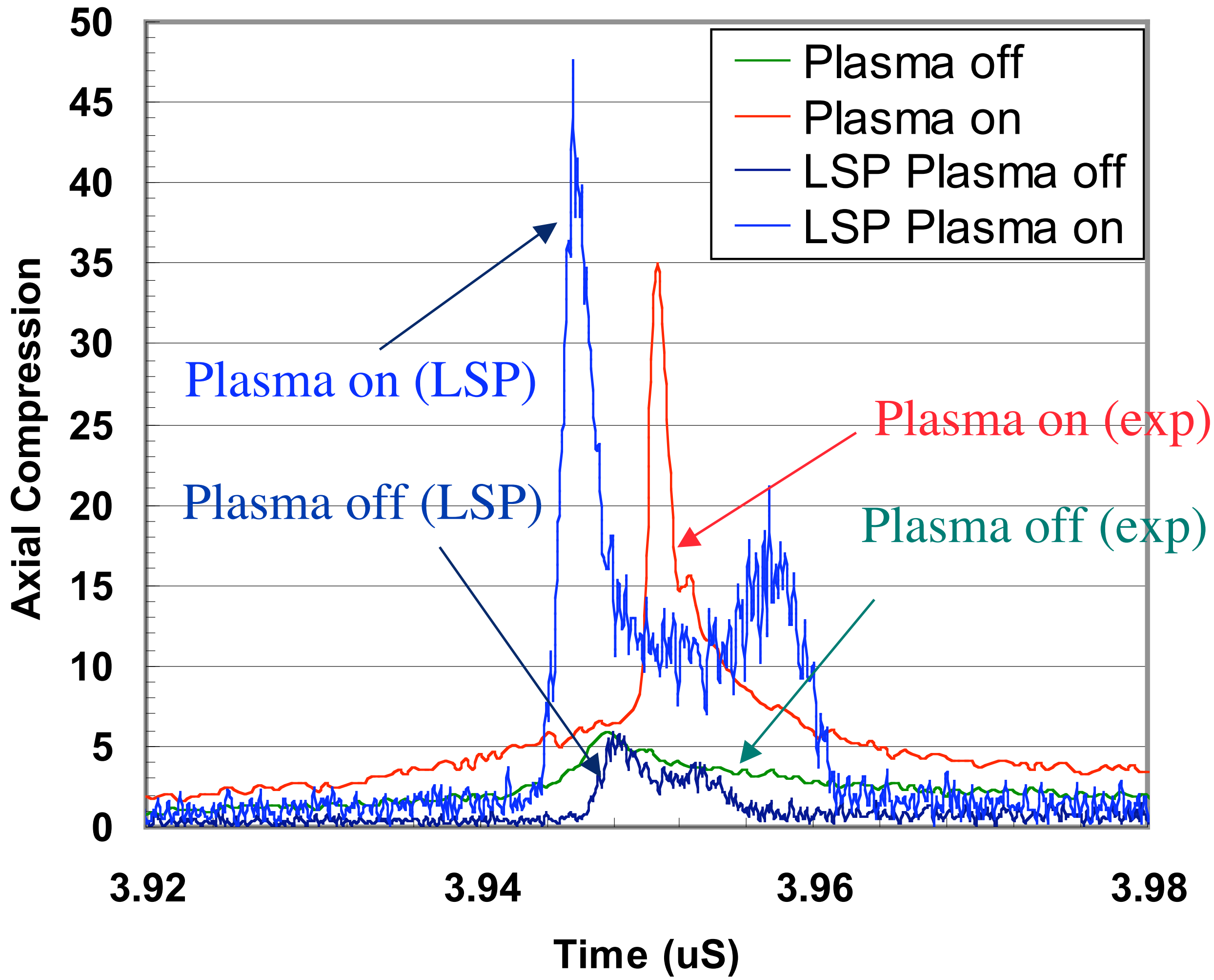


LSP simulation

Corroborating data from Faraday cup

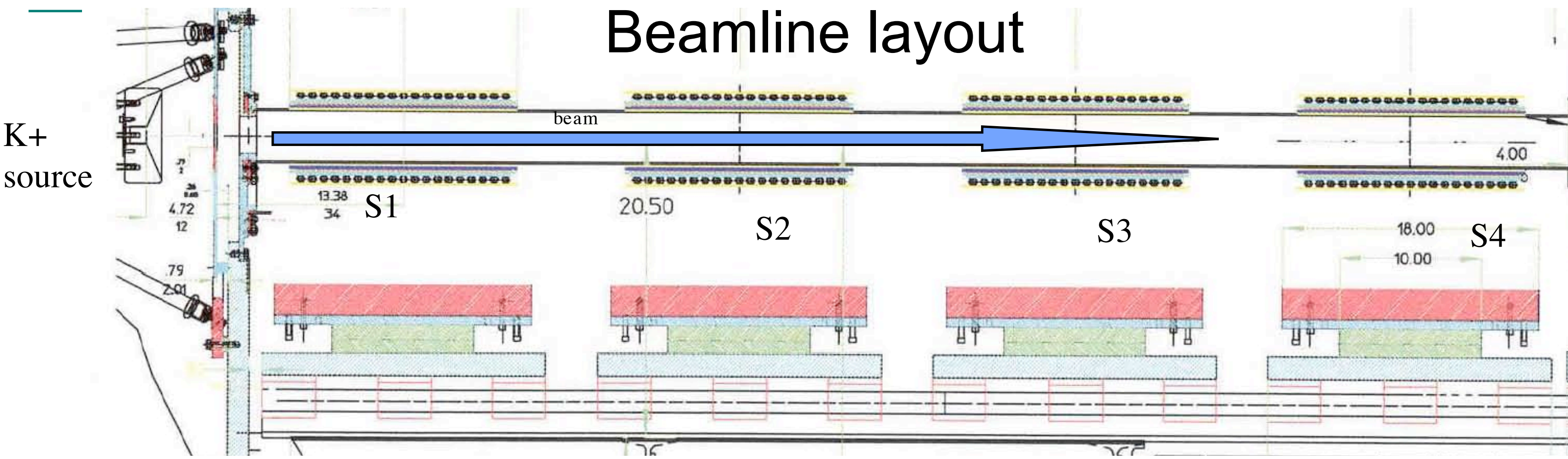


Experiment and theory (LSP) demonstrate importance of neutralization

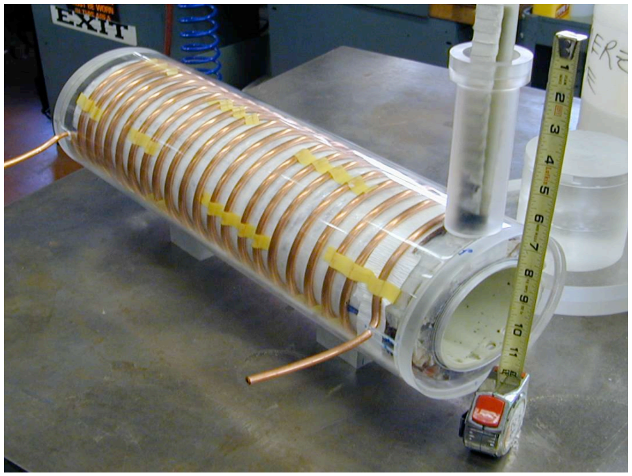


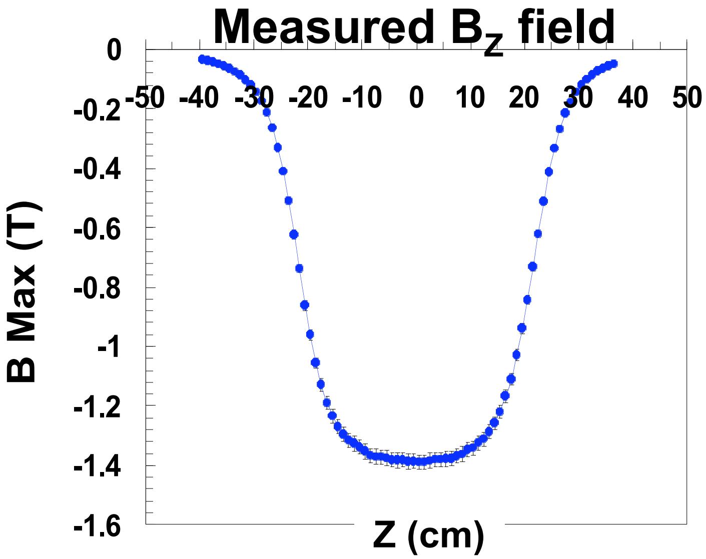
Solenoid transport experiment is ready for deployment in December 2005

Beamline layout

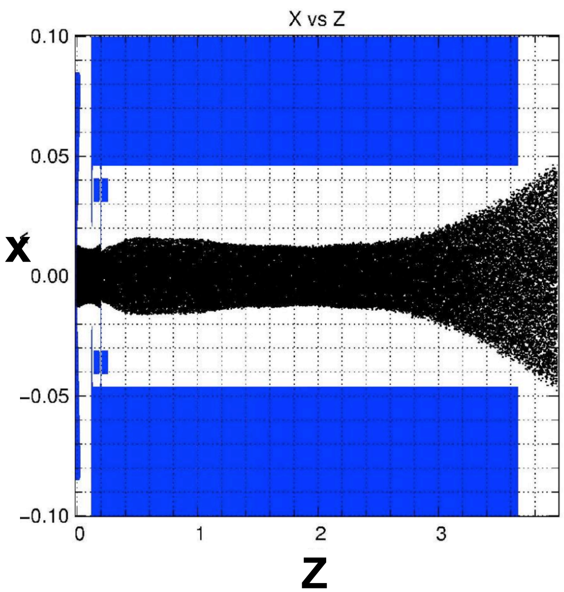


Pulsed solenoid tested at 3 T

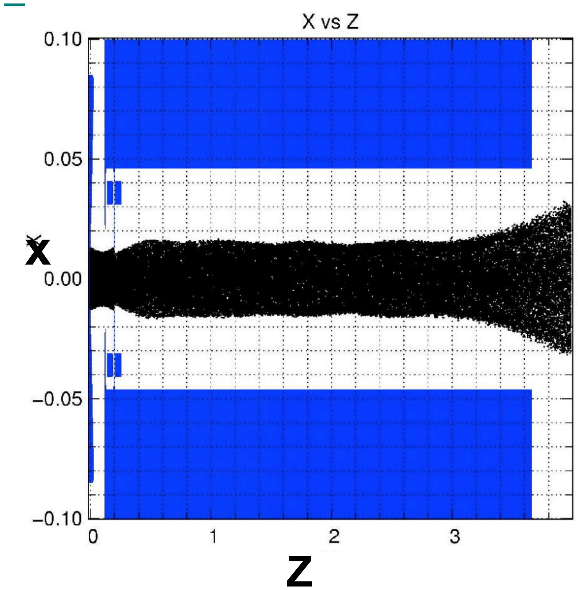




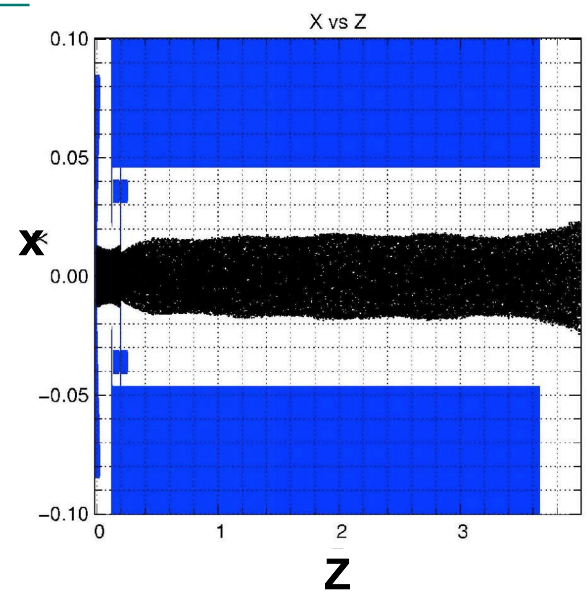
Secondary electron control to be assessed in solenoidal transport experiment



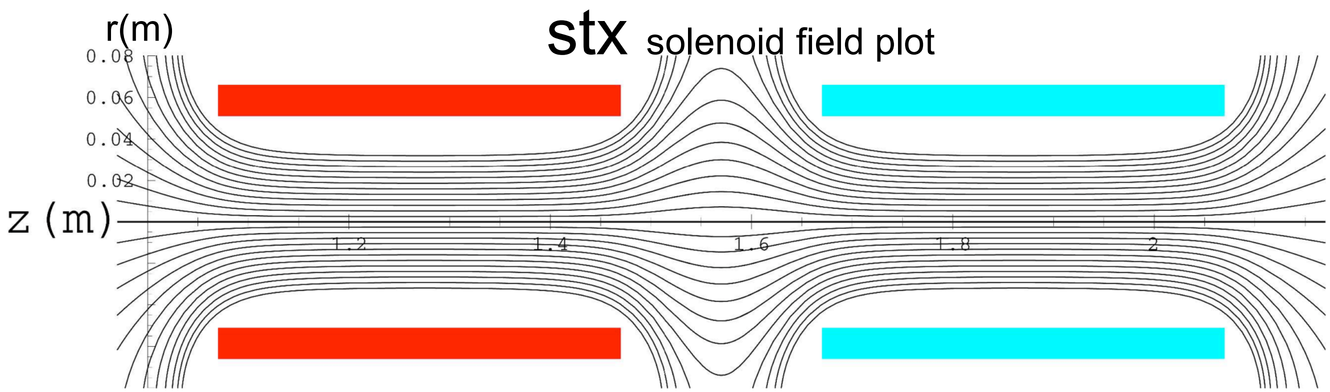
Solenoids at 60 cm center to center



Solenoids at 70 cm center to center

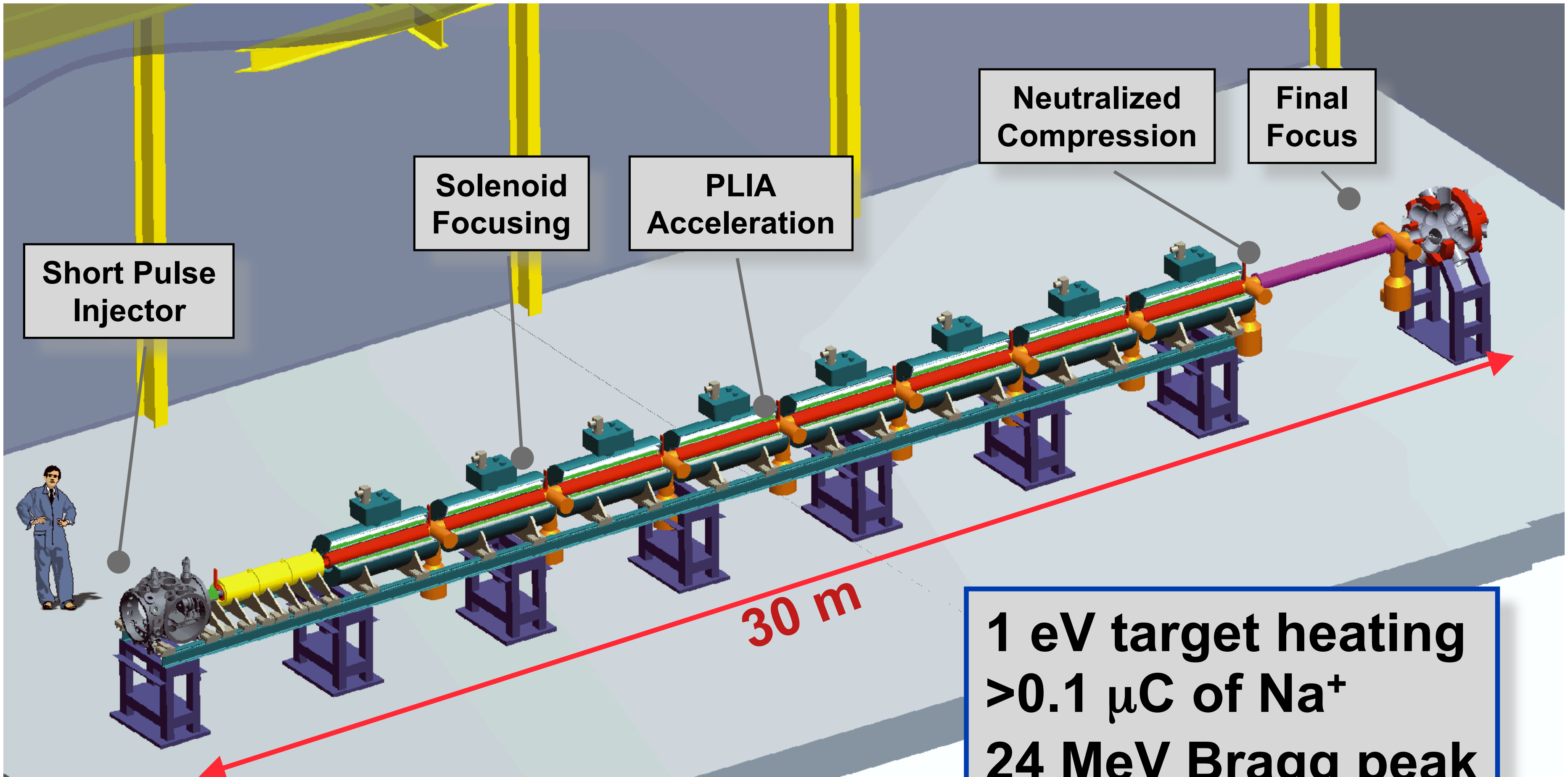


Solenoids at 80 cm center to center



stx solenoid field plot

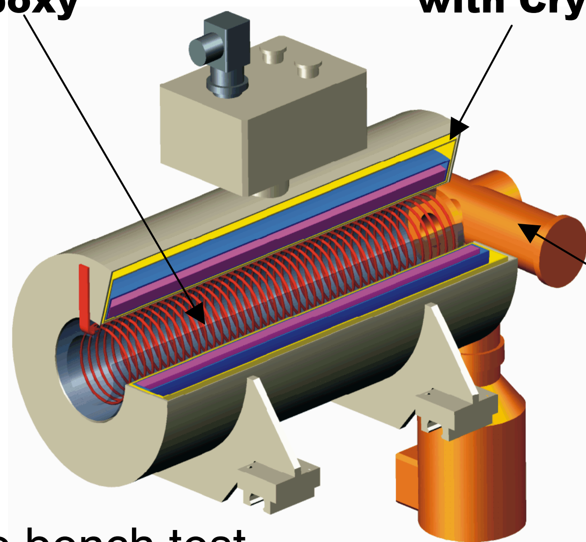
A new accelerator concept (PLIA) can lead to a near-term HED facility (NDCX-II) with 10x reduction in the $ / MeV



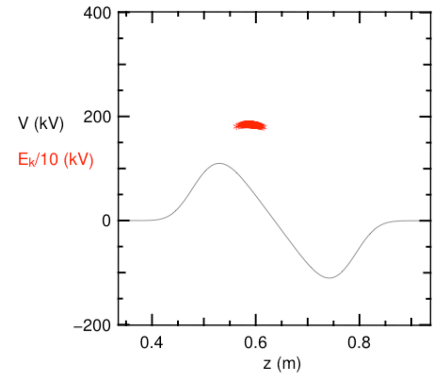
1 eV target heating
>0.1 μC of Na^+
24 MeV Bragg peak

Pulse Line Ion Accelerator (PLIA): a low frequency traveling wave accelerator based on simple distributed transmission lines*

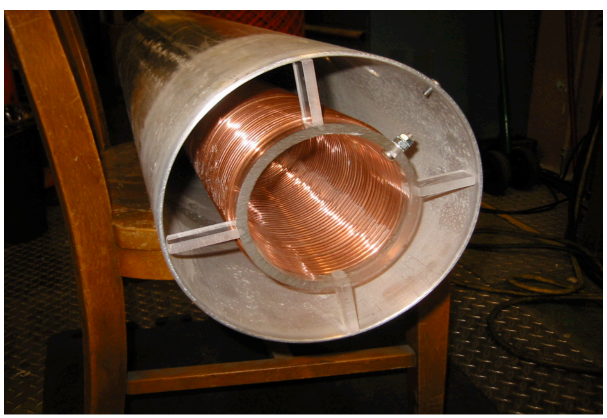
NDCX-II Accelerator Cell



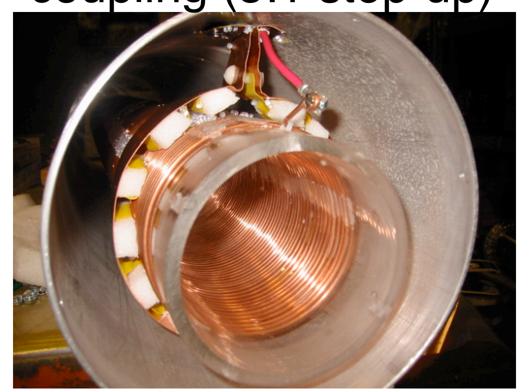
Particles synchronous with wave



First low voltage bench test

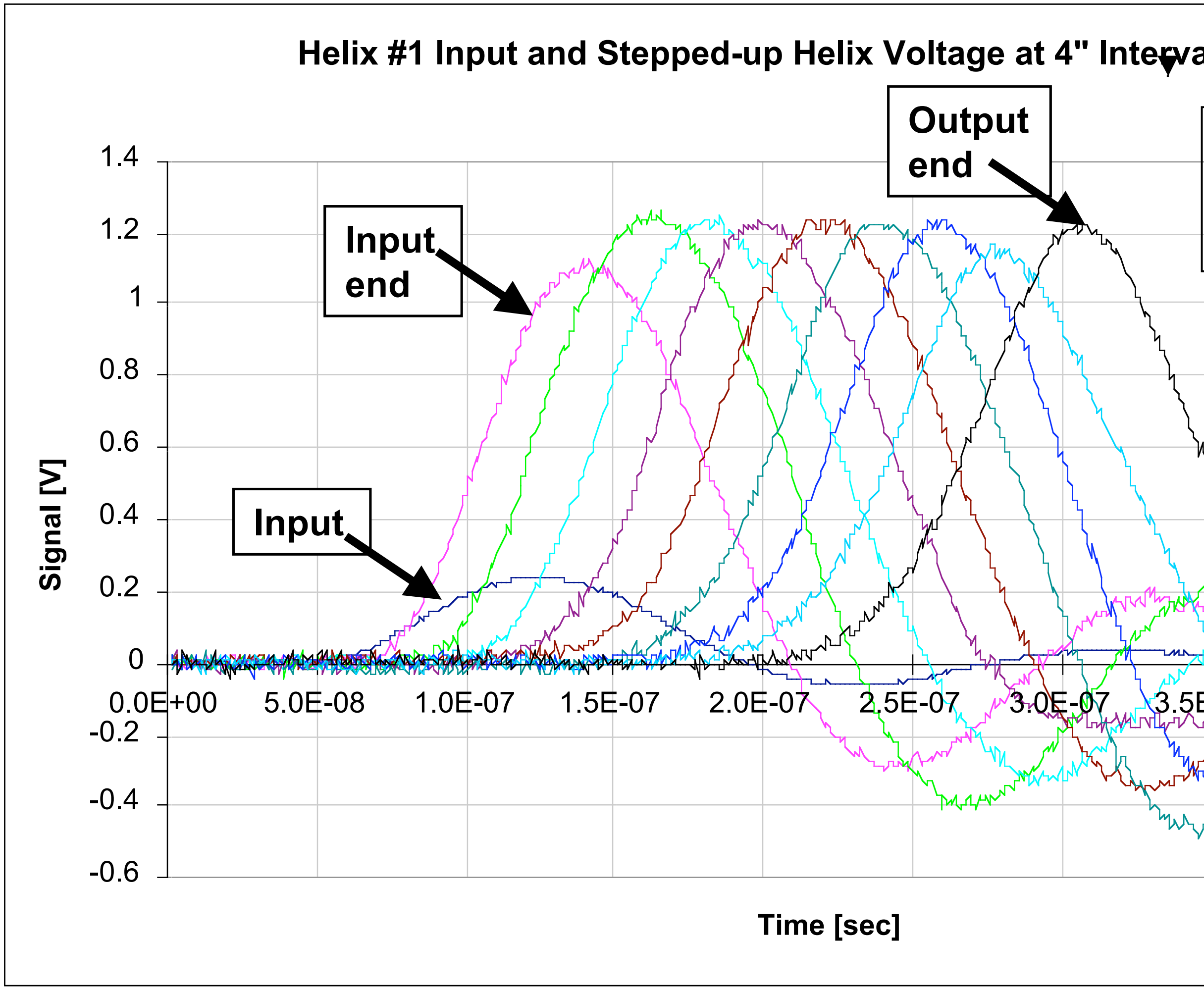


Compact transformer coupling (5:1 step-up)



***(R.J. Briggs, et al - LBNL Patent Aug 2004)**

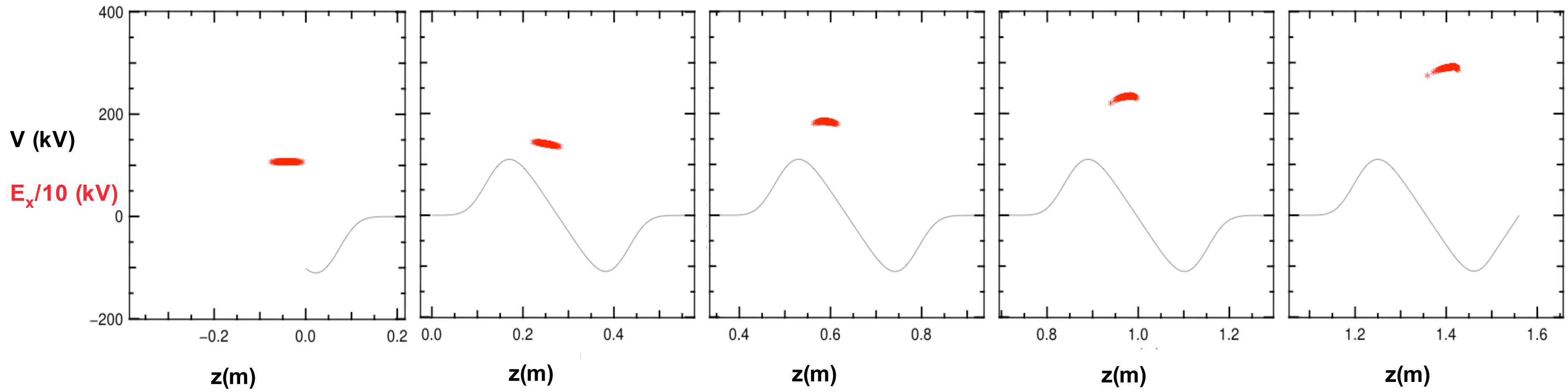
V(z) Along the (air) Dielectric Helix



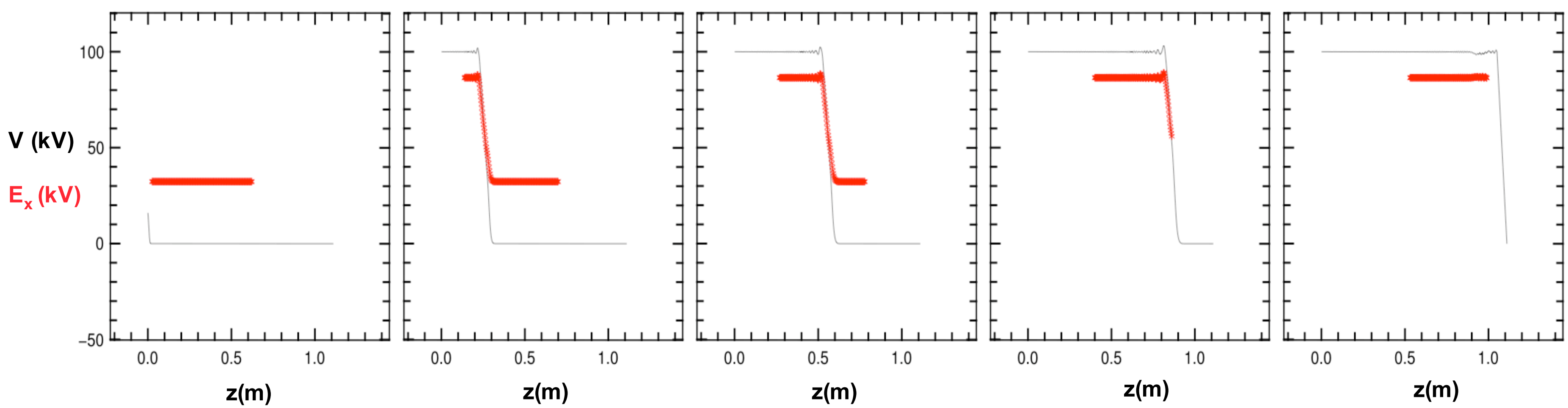
$$v_{ph} = \frac{1}{\sqrt{LC}}$$

PLIA can be operated in the short pulse ("surfing") mode or the long pulse ("snowplow") mode

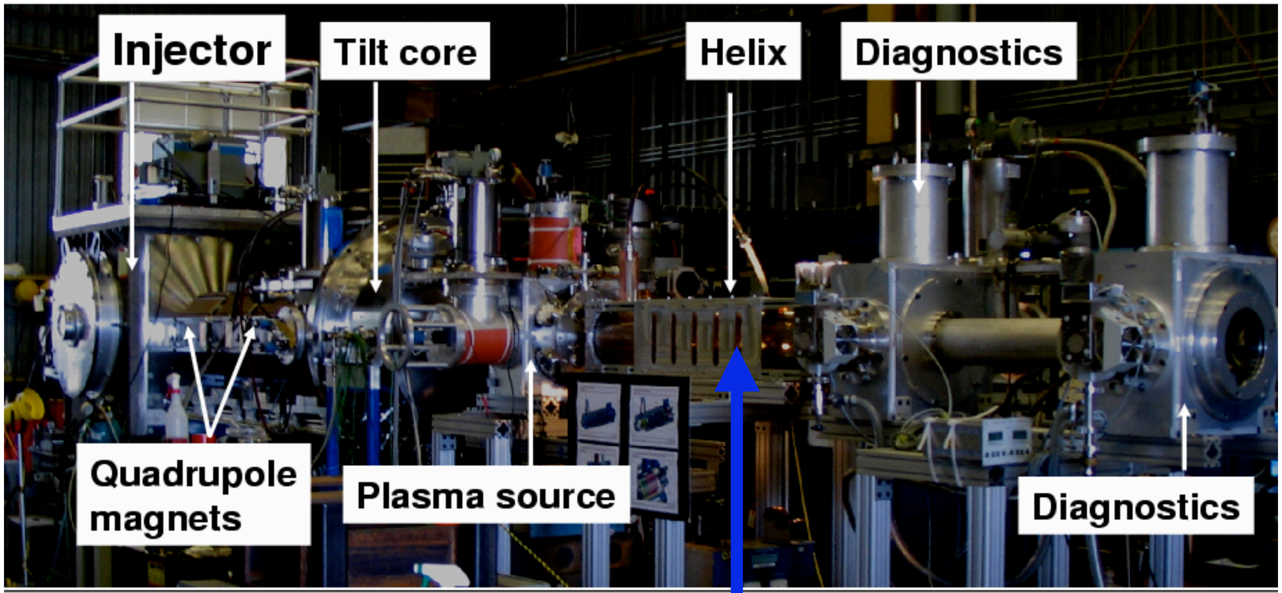
Short beam "surfs" on traveling voltage pulse (snapshots in wave frame)

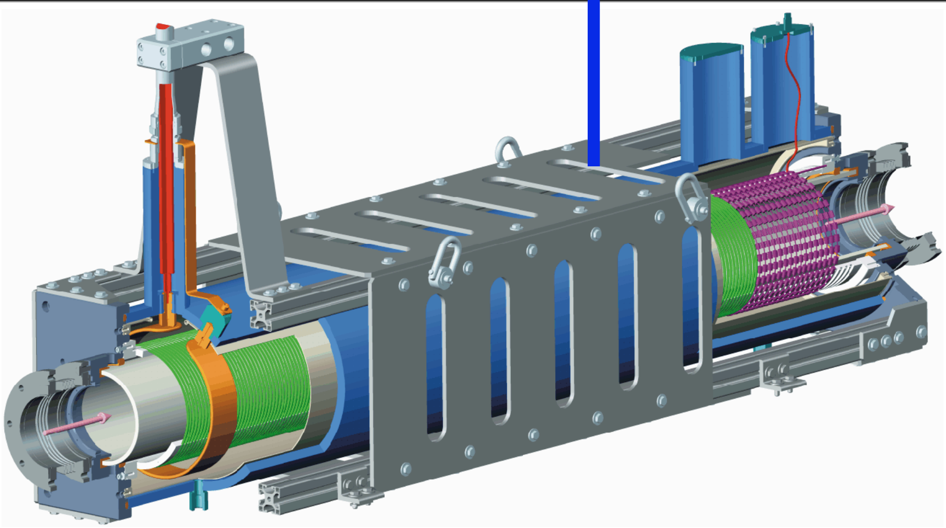


Longer beam is accelerated by "snowplow" (snapshots in lab frame)

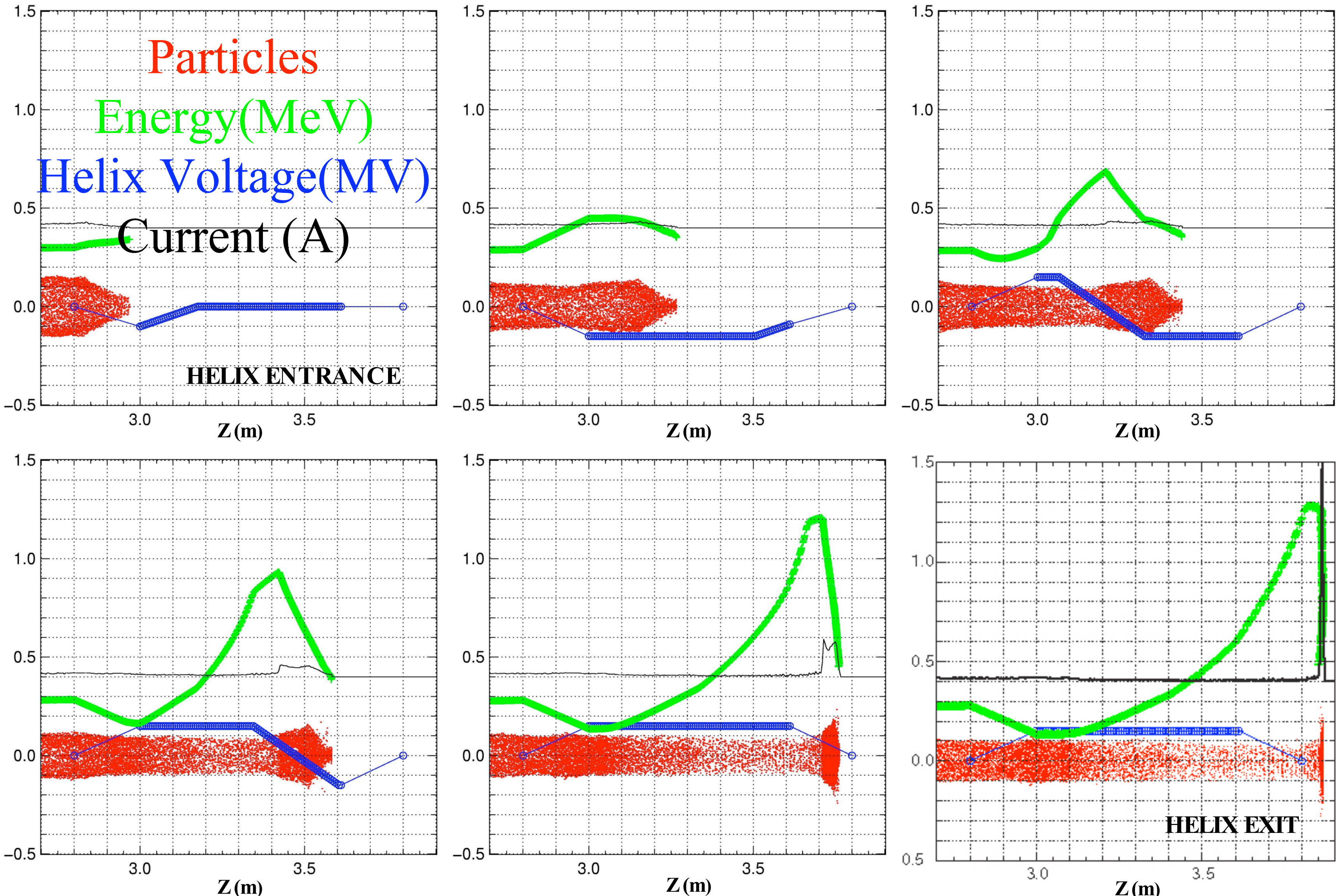


Pulse Line Ion Accelerator Experiment (PLIA)



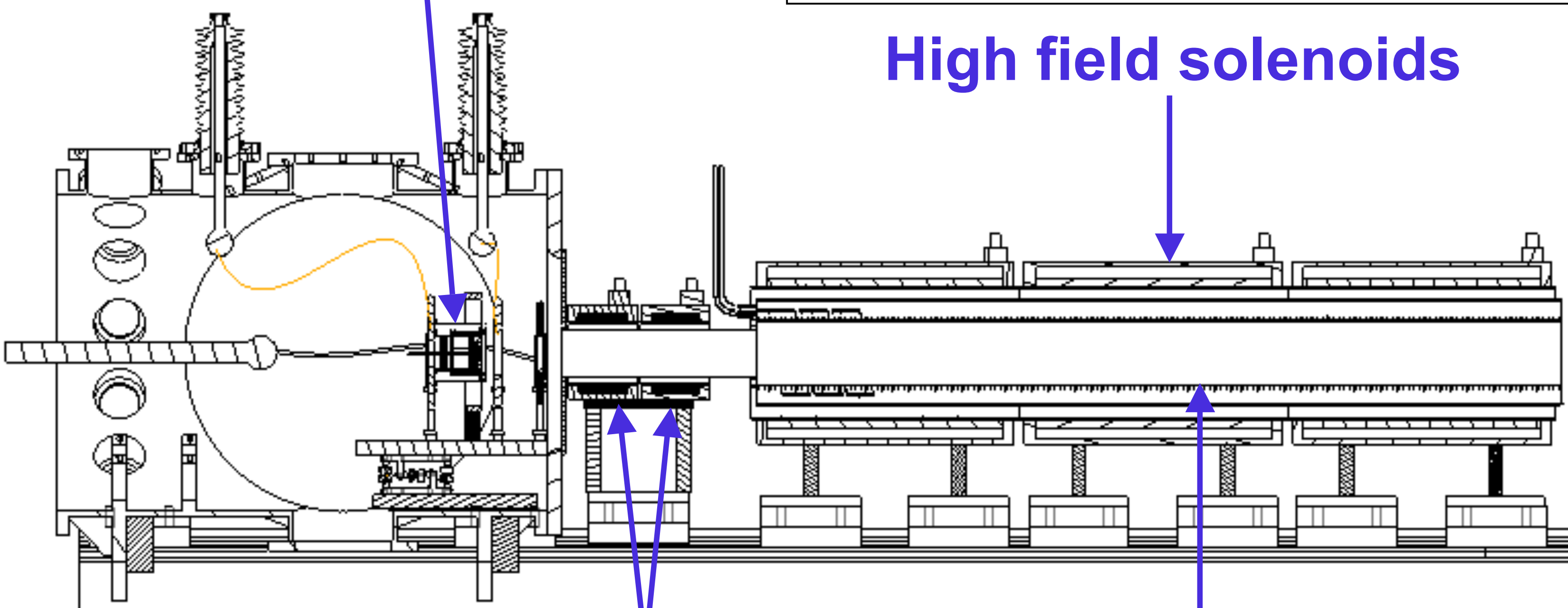


WARP-3D simulation of NDCX1d experiment -- Beam dynamics inside the helix



We have designed a short pulse injector (NDCX-IC) which can serve as the front-end of NDCX-II

Beam species K^+ $(\Rightarrow Na^+)$
Total charge 0.1μC
ε_{nx} ε_{nz}=(1mm-mrad) x (8mm-mrad)
[1/10 of NDCX-II design goal]



conclusion and summary

1. Source and injector development:

   Beamlet prototype experiments successfully completed.

   Good confidence for compact, lower cost HIF injector.

2. High brightness ion beams and electron cloud effects:

   Gas desorption mechanism: Energy dependence ⇒ electronic dE/dx

   Novel electron mover ⇒ speed up calculations 20x

   Encouraging comparisons between simulations and experiments

   Positioned to make significant contributions to IFE, HEP, NP

3. Neutralized drift compression

   NTX - neutralized transport beam profile reduced to mm from cm.

   Significantly increased confidence in a neutralized HIF final focused scenario.

   NDCX - ~50x longitudinal compression in preliminary experiments

   Encouraging for planned exploration of HEDP.

   We are developing components of an experimental HEDP / WDM experimental facility: solenoid transport, short pulse injector, PLIA