Summary of the Workshop on Accelerators for Heavy Ion Fusion

and

Beam experiments at LBNL

Peter Seidl

October 14, 2011

Japan – US Workshop on Heavy Ion Fusion

Osaka University, Japan

Outline

1. Workshop on Accelerators for Heavy Ion Fusion, May 23-26, 2011 Berkeley Lab
    a. Objectives and motivation
    b. Participation from many labs
    c. Results, what is next
        i. IFE targets
        ii. Ion sources and injectors
        iii. RF accelerators
        iv. Induction accelerators
        v. Chamber and chamber-driver interface.
2. Beam experiments at LBNL
    a. Neutralized Drift Compression Experiments – I (NDCX-I)
    b. Prompt gas desorption from heavy ions (NDCX-I)
    c. Experiment on un-neutralized drift compression (NDCX-II)
    d. Driver-scale injection and transport at ~10 Hz (HCX)

Workshop on Accelerators for Heavy Ion Fusion
Objectives and motivation

The purpose of the Workshop was to review the status of heavy ion fusion (HIF) research, and to identify the most promising areas of research.

The National Ignition Facility has commenced its campaign of ignition experiments. These are stimulating interest in inertial fusion energy systems, including Heavy Ion Fusion (HIF).

The U.S. National Academies of Sciences and Engineering are sponsoring a review of the prospects for inertial confinement fusion energy systems. This will include various driver systems, including heavy-ion accelerators. Presentations commenced early in 2011. http://sites.nationalacademies.org/BPA/BPA_058425

Workshop website: http://ahif.lbl.gov

The principal challenges for further research

Heavy ions of mass ~100 amu and T ≥ 1 GeV → suitable stopping range for yield >100 MJ and gain >50.

A heavy-ion driver must deliver 1–10 MJ of energy, properly shaped, at a peak power ≥100 TW at ~10 Hz.

Near the ion sources and near the target multiple beams are desired for physics reasons. For the induction linac approach, multiple beams are desired for economic reasons. High charge per bunch → accelerate a longer bunch and then compress it to the short length required at the target.

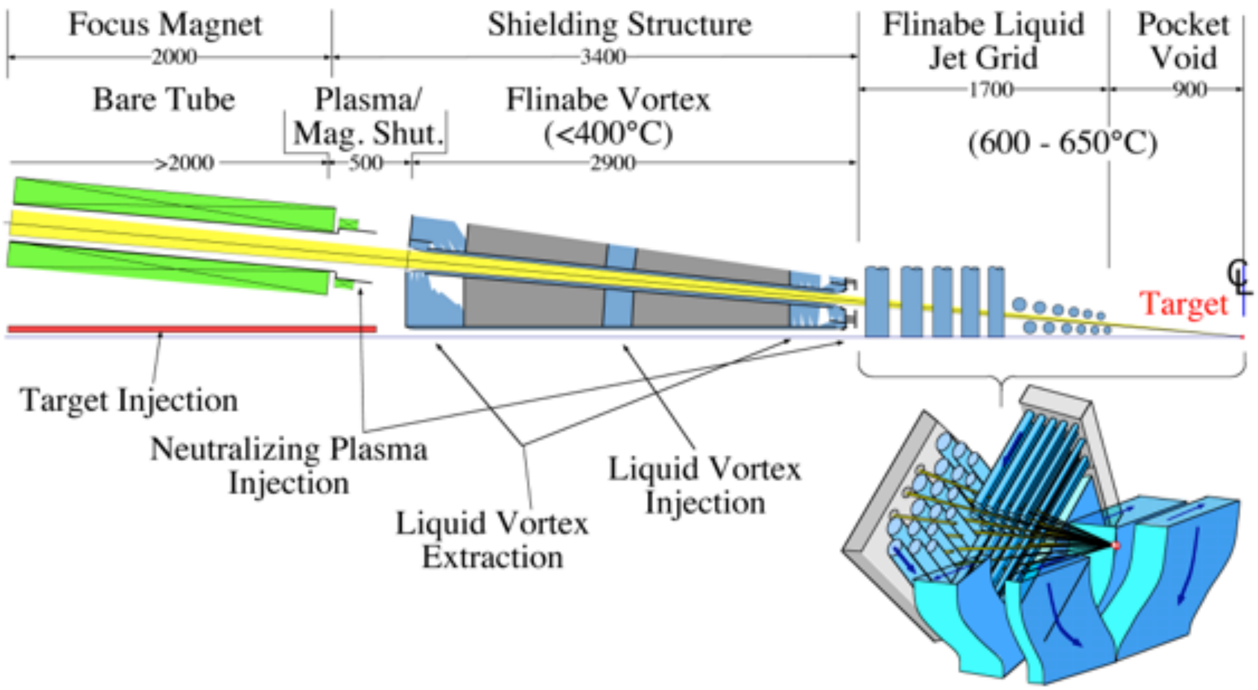
The beams' quality and alignment: focused onto the target to a radius of a few millimeters from a distance of several meters.

Limitations due to space charge, emittance growth, beam-gas, and beam-plasma interactions must be sufficiently controlled throughout the driver.

Advantages of HIF

Nuclear and high energy physics accelerators, with total beam energy of ≥ 1 MJ have separately exhibited intrinsic efficiencies, pulse repetition rates (>100 Hz), power levels (TW), and durability required for HIF.

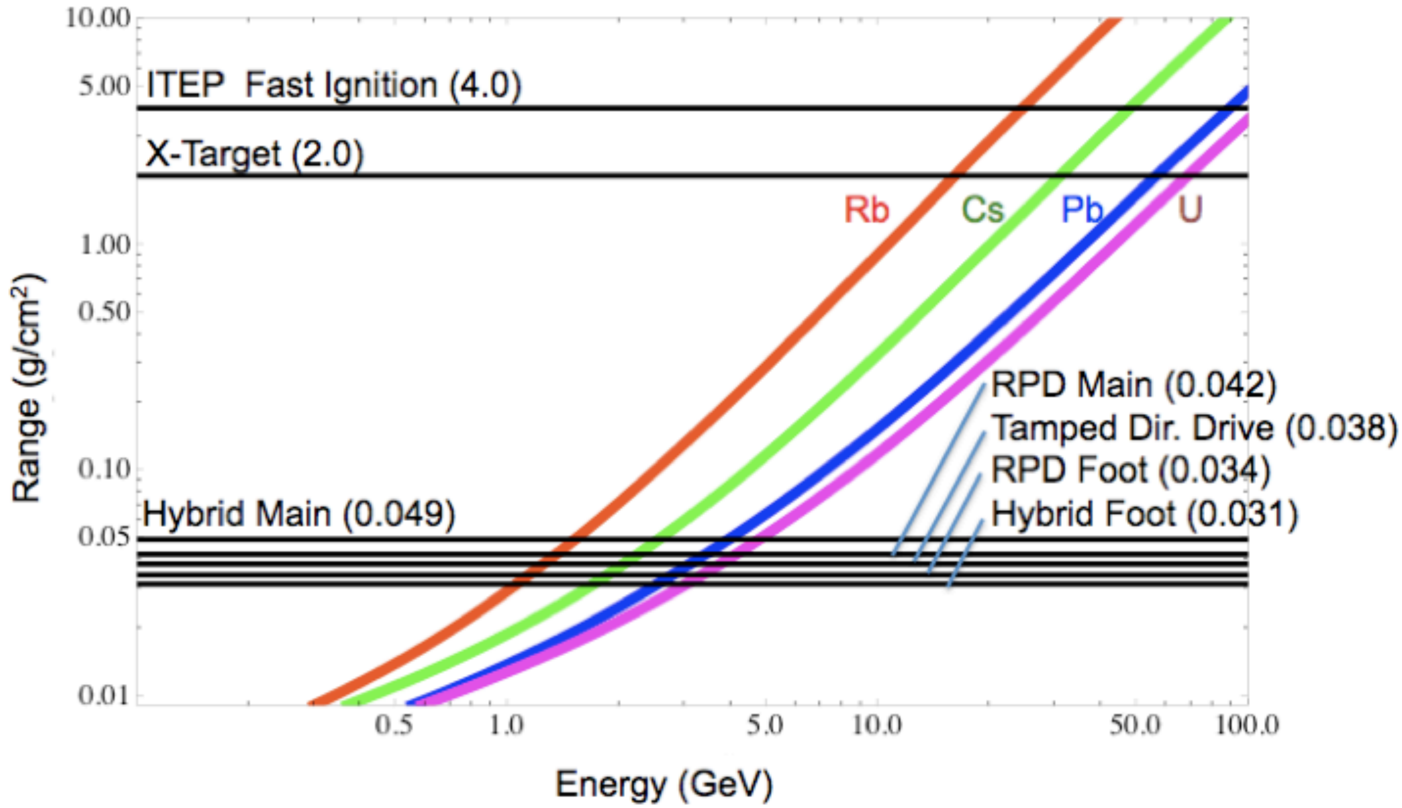
Final focus elements can be protected from the energetic particles and X-rays produced by the fusion target.



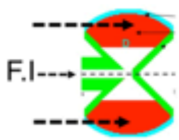
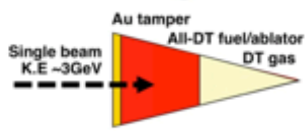
Schematic Liquid Jet Geometry

There is a continuum of target design possibilities

Eg: resembling NIF targets, to shock- and fast-ignition. Here are some specific examples, showing the ion energy and corresponding ion range in Al.



The range of HIF target design simulations has broadened

	Features	Issues
Indirect drive – *HS ign.* 	• Integrated 2D designs exist • Ablation/burn physics on NIF • Natural two-sided geometry	• Lower drive efficiency • Lower gains, high driver energies
Direct drive X-target – *Fast ign.* 	• Inherent one-sided drive • High coupling efficiencies • Reduced stability issues • Potential for high yields (~GJ) and gains	• High gains require high densities under quasi-3D compression • Higher ion kinetic energies • High power, small focal spot beams needed for fast ignition • Driver concepts immature
Direct (+indirect) drive, tamped – *Shock ign.* 	• High coupling efficiencies (tamped ablation) • Simple targets • High gains consistent with low ion-kinetic-energies (~2-10GeV)	• Optimum ion species and energy • Two-sided (polar) geometry to be established** • High power beams needed for shock ignition • Stability to be confirmed
Direct drive, cylindrical compression – *Fast ign.* 	• Inherent one-sided drive • High coupling efficiencies • Simple targets	• Low gains, high driver energies • High ion kinetic energies • High power. small focal spot beams needed for fast ignition • Driver concepts immature • No U.S target design interest

**Will leverage present NIF PDD studies

The target work requires iteration among other elements of the power plant (e.g. chamber and accelerator).

Ion sources and injectors

(total charge ~ 1 mC) and several GeVs at the target. This charge can be generated by combining 0.5 -1 Ampere beams from ~100 sources and longitudinally injecting 10 to 20 μs pulses (at the sources), and later compressing the bunch after some acceleration.

RF accelerator approach: I~ 10-100 mA each, pulse length > 100 *μ*s.

Normalized transverse emitttance requirement is determined by the need to focus the beam down to mm-size target. $\varepsilon_{inj} < \varepsilon_{acc} < \varepsilon_{target}$.

Usually single ionized ions because of the ease of production and the low space charge.

Future work:

- Demonstrate that at least one design for the injector for a multiple beam accelerator driver will work. Gas load @ 10 Hz, beam control, quality, matching. Single beam experimental results suggest no show-stoppers.
- Higher charge state ions could reduce the cost of acceleration. Beam quality? Charge state purity?

First exploration of the RF accelerator approach to HIF ~1976.

1998: Most detailed RF design – European Heavy Ion Driven Inertial Fusion (HIDIF) collaboration
indirectly driven target,
ballistic (un-neutralized) focusing.

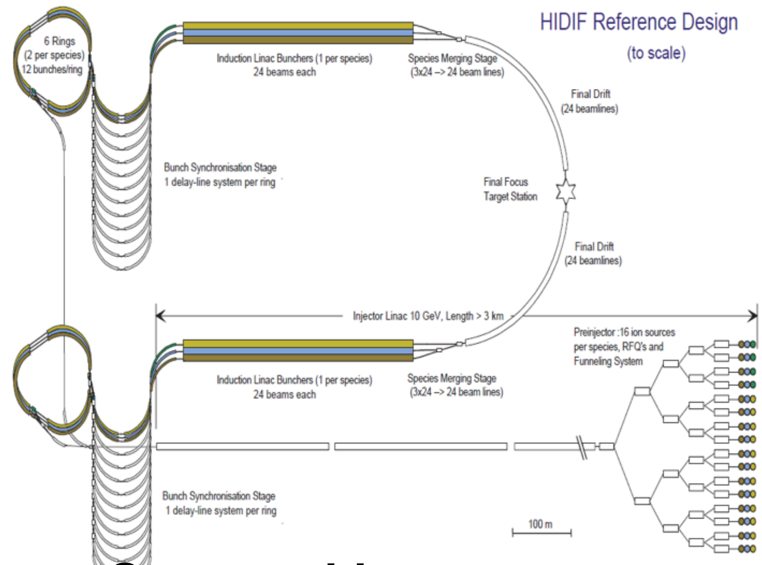
Recently a single-pass RF-accelerator concept eliminating the use of storage rings has been proposed by Fusion Power Corporation.

FAIR Project at GSI

Facility for Rare Isotope Beams (FRIB), MSU

SNS, 1 MW

Superconducting cavity technology (¼-wave/ ½-wave structures, IH/CH structures, spoke resonator cavities, elliptical cavities) has been applied to high-power proton linacs.



Opportunities:

- Experimental programs at existing heavy-ion facilities: accumulation, compression, space-charge neutralization and beam-target interactions.
- Quantify economies of scale for specific conceptual designs.

Induction linac approach to HIF

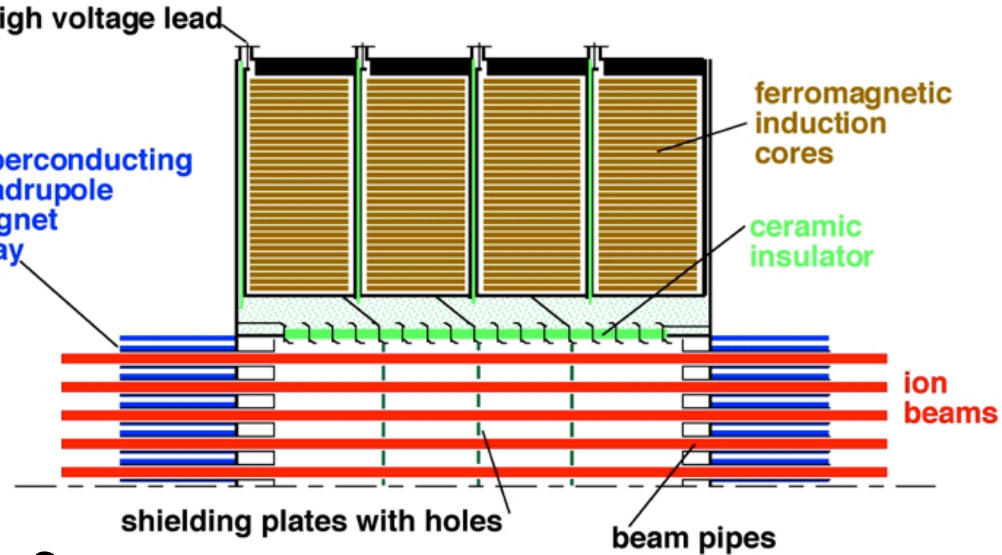
a few to 10 kA (most of accelerator)

Many beams transported in parallel channels through a common set of induction modules.

→ Efficiency 20-40%.

→ A linac, several km long.

- controlling beam-gas and electron clouds
- Emittance growth?
- Beam-beam, beam-core interactions?
- Alignment, steering.

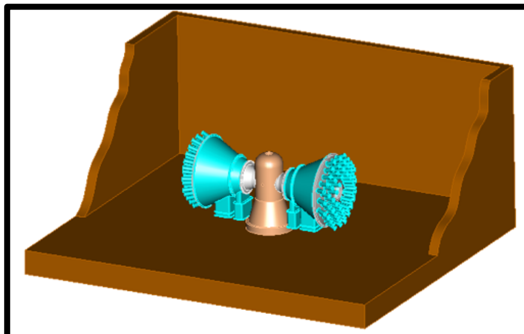


$$\mathbf{a}'' = -\mathbf{ka} + \frac{\varepsilon^2}{\mathbf{a}^3} + \frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}}$$

R&D mix of scaled (relevant **K**, **K**a^2/ε^2, and full scale:

- Scaled experiments with Paul traps (PPPL, Univ. Hiroshima), low E electron rings (UMER).
- High current electron induction accelerators (DARHT, 1 kA).
- Full scale experiments with heavy ions (HCX)
- R&D on components to reduce risk and answer basic questions. Eg: Build a prototype module, including quadrupoles for a demonstration driver. (E_{acc})

Chamber and Chamber Driver Interface Research agenda:



shown in the ITER building
approximately 75 m long

Comprehensive survey of status, knowledge
on liquid wall designs,
neutralization sources,
beam neutralization requirements,
and a tolerable momentum spread
of the beam for focusing.

Explore combinations of electrostatic and magnetic quadrupoles for achromatic focusing.

Develop designs with thick liquid walls, including a liquid vortex with no moving parts with 50-year lifetime and reduced pumping power, and conduct fluid dynamic experiments to validate designs.

Design rotating shutters to keep debris out.

Study plasma sources for neutralization capable of working in a neutron radiation environment.

Include dipoles to steer the beams to the target.

Comprehensive optimization

68 participants from many laboratories, universities and companies:

BNL,
FNAL,
GSI (Germany),
LANL,
LBNL,
LLNL,
ORNL,
PSFC/MIT,
MSU,
PPPL,

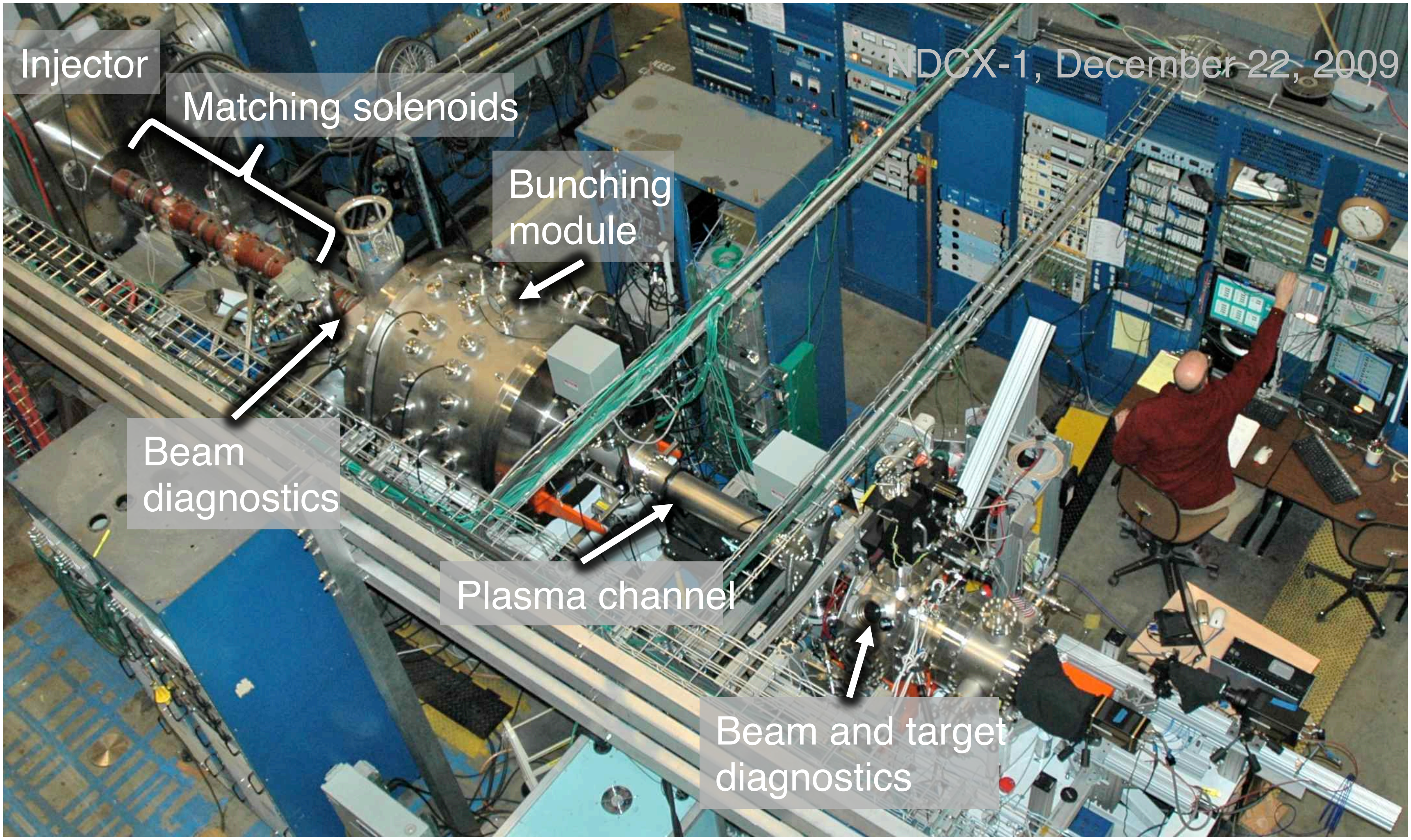
Univ. of Maryland,
Technischen Universität Darmstadt (Germany),
Utsunomiya Univ., (Japan),
Fusion Power Corp.,
Vallecitos Molten Salt Research,
Voss Scientific.

The participants see opportunities for collaboration, and expressed interest in a follow-up workshop to address key issues in greater detail.

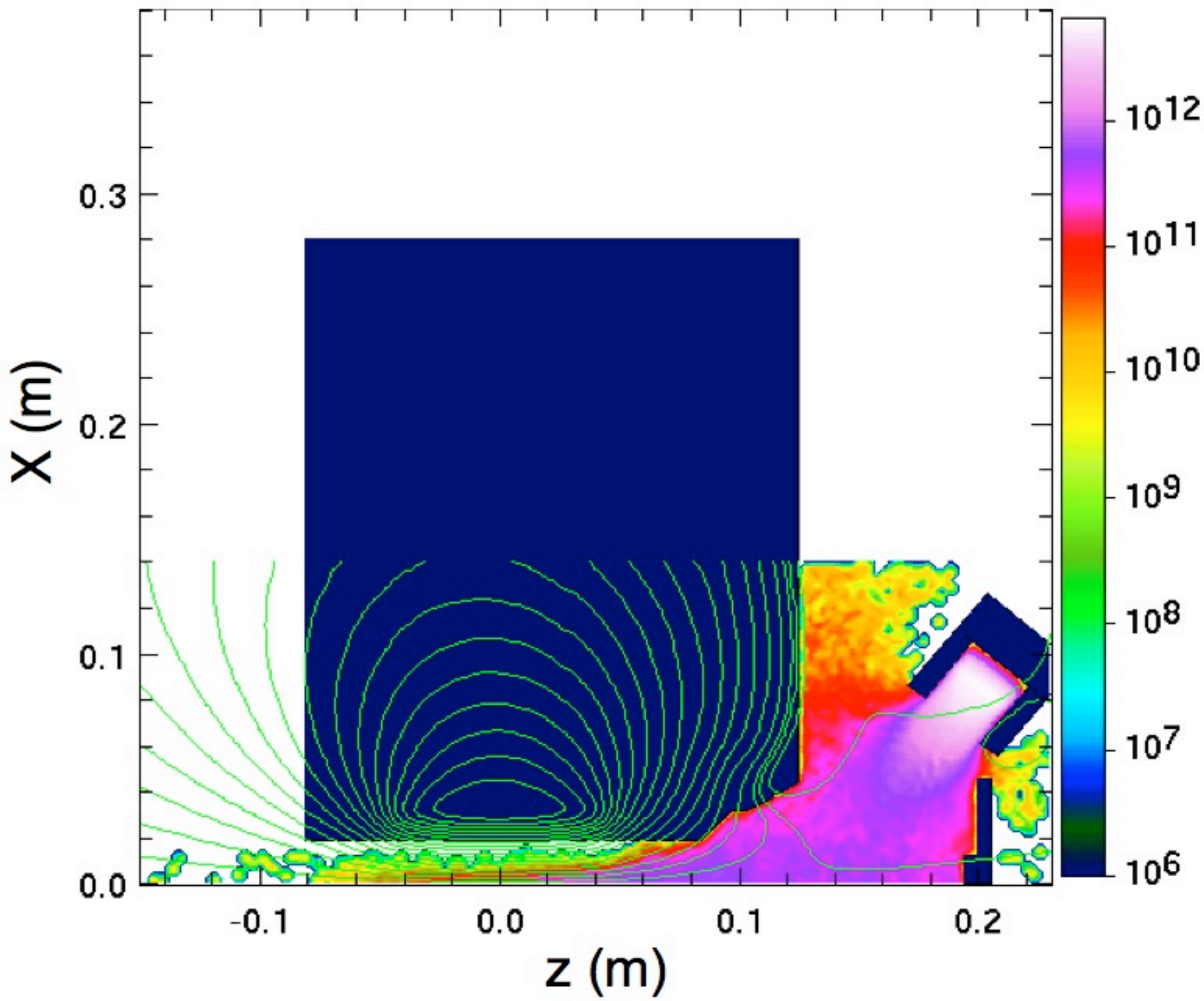
http://ahif.lbl.gov/workshop-reports/A-Summary-report.pdf

Beam experiments at LBNL

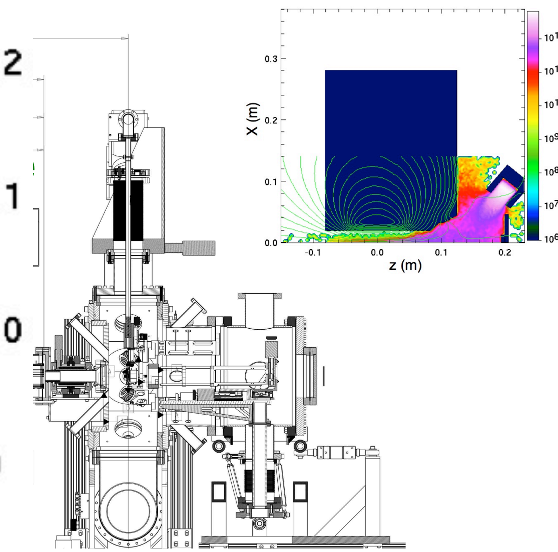
Beam experiments at LBNL



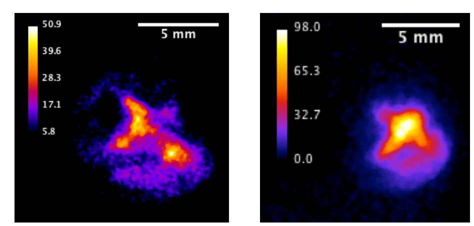
Experiments and modeling to understand the focused beam in the Neutralized Drift Compression eXperiment



.1 mm·mrad



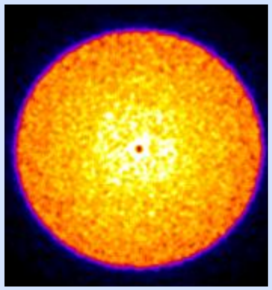
asma in the FEPS.



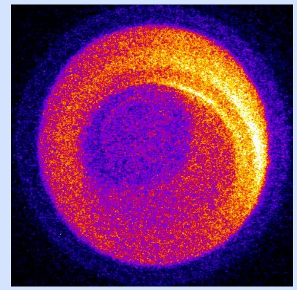
er fluence,

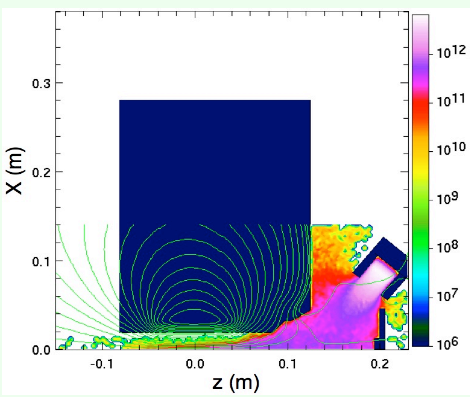
Improving the model: Partial neutralization, and non-ideal initial distribution:

Warp distribution, initialized at z=0 (ion emitter)



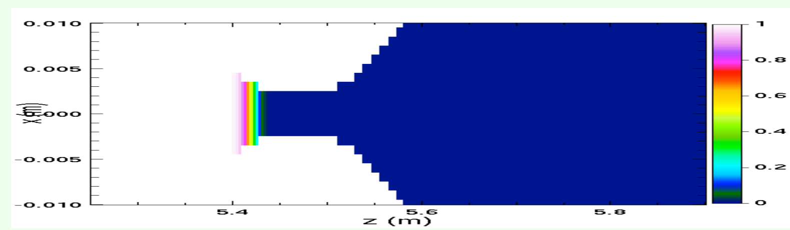
Initialized at z = 2.7 m, constrained by scintillator measurements of the beam profile





$$\frac{1}{r}\frac{d}{dr}\left(rA_\theta\right) = B_z(r)$$

Coil radius R= 3 cm



r > R: $A_\theta = \dfrac{B_z R^2}{2r}$

r < R: $A_\theta = \dfrac{B_z r}{2}$

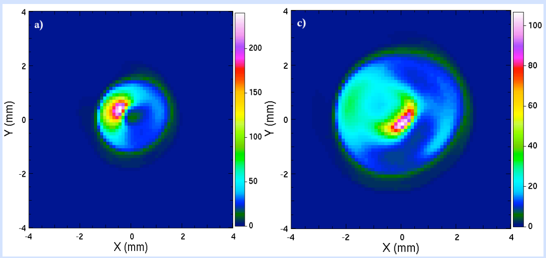
Threshold plasma surface parameter: $\sqrt{rA_\theta} = \sqrt{\dfrac{B_z}{2} r}$

$\sqrt{rA_\theta}$	**Minimum radius**
2.0	1 cm (full plasma)
0.011	5.5 mm
0.005	2.5 mm
0	0 mm (no plasma)

Resulting model fluence in better agreement with previous estimates, distribution details still differ

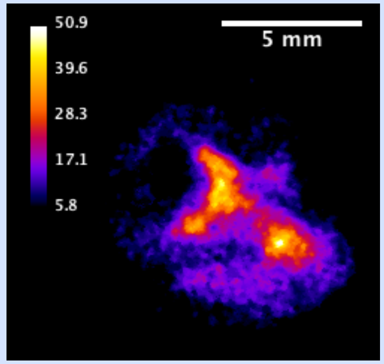
Warp

240 mJ/cm2 107 mJ/cm2

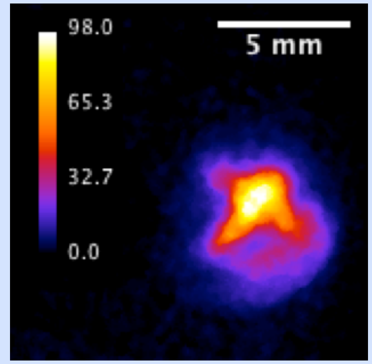


Full plasma, Rmin = 2.5mm

(assumes no beam line misalignments)

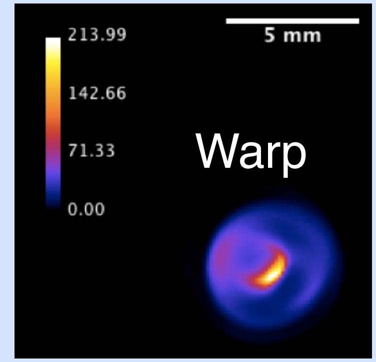


25 mJ/cm^2



49 mJ/cm^2

Experiment



107 mJ/cm^2

Impact on NDCX-II: Will need a new magnet with a larger bore (≈2x).

Perhaps internal plasma sources or electron producing grids…

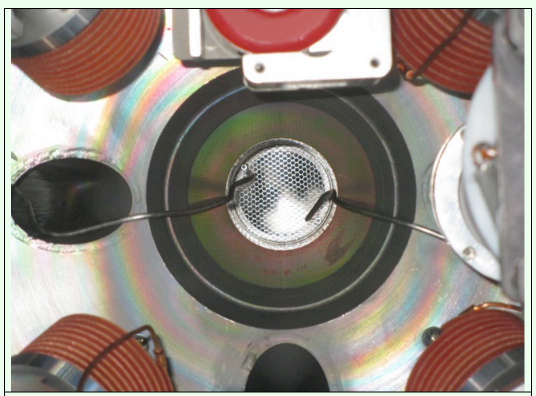


Fig. 4: Installed hexagonal cell grid. The view is looking upstream in the target chamber past the FCAPS.

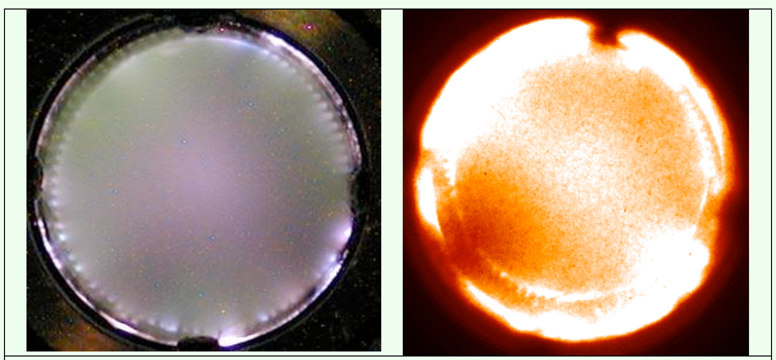
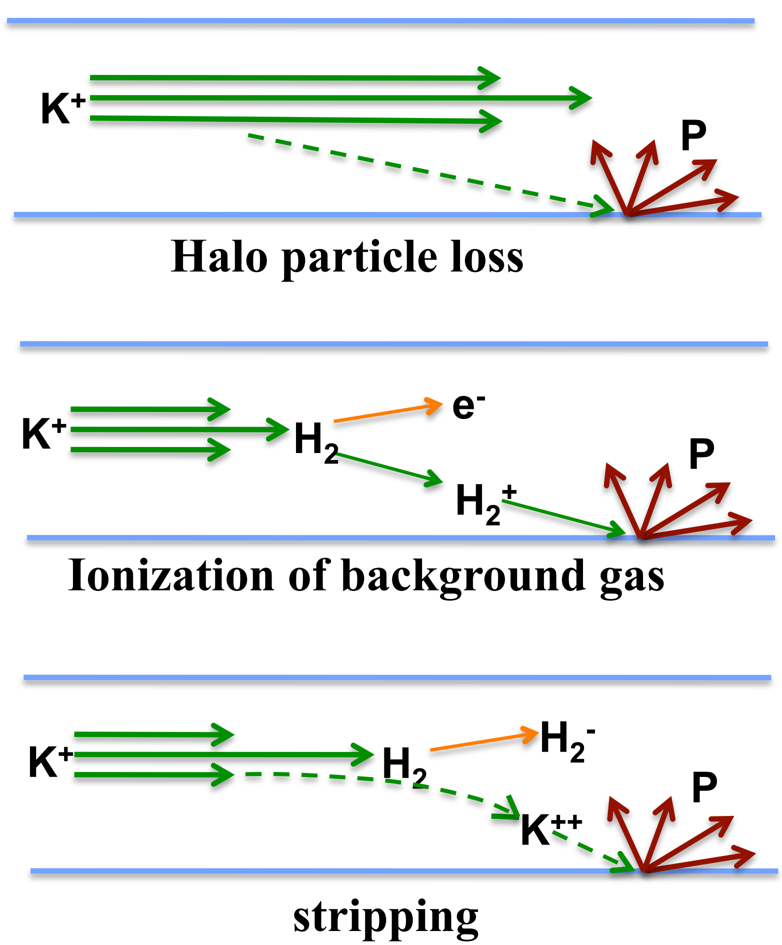


Fig. 12: An optical image with a commercial digital camera (left) clearly shows the plasma being emitted from the holes in the perforated steel sheet inner electrode. A false-color image from a scientific-grade intensified CCD camera system (right) allows for quantitative analysis of the emitted light.

Prompt gas desorption from heavy ions (NDCX-I)

Beam loss mechanisms

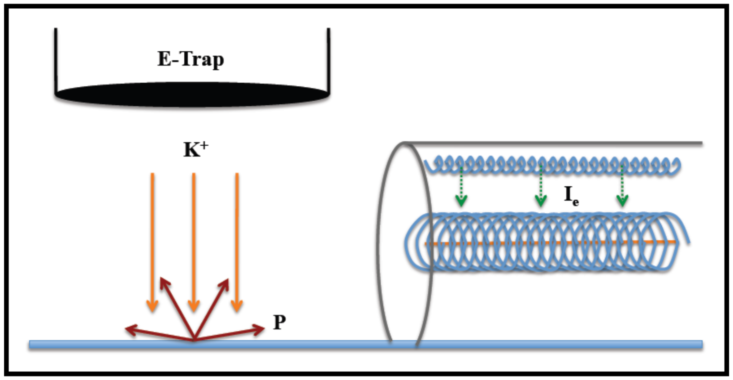


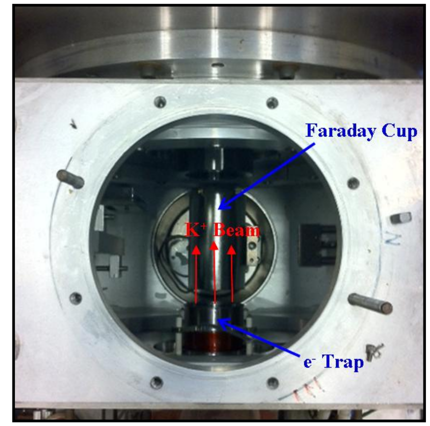
<u>Goals:</u>

- **develop a fast-response pressure-measuring diagnostic using a Bayard-Alpert ionization gauge,**
- **preliminary diffusion model for desorbed particle evolution;**
- **understand desorption on microsecond time-scales**
- **obtain desorption and sticking coefficients**
- **This follows on Gas-Electron Source Diagnostic (GESD) to characterize <u>slow</u> pressure response – Molvik et al., 2005**

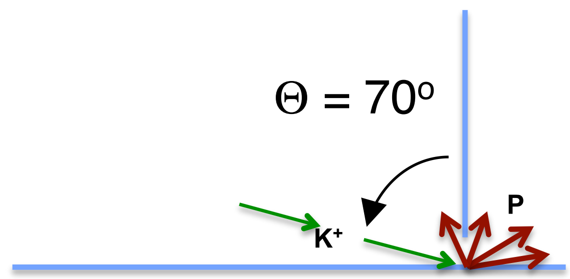
A 320 keV K+ ion beam impacting the target plate centimeters away from the ion gauge. Mu-metal is used to shield against fringe solenoid fields

…





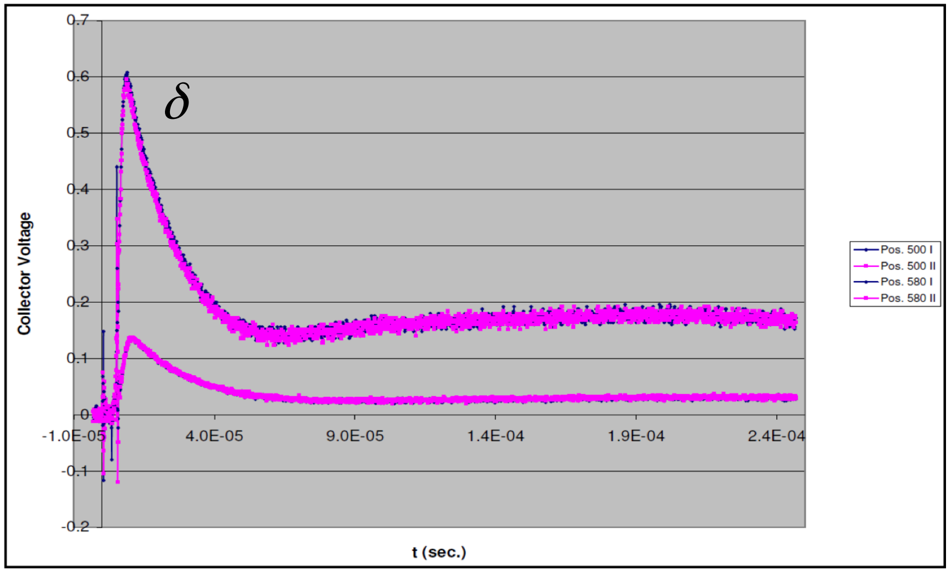
$$I_{ion} = \sigma_i L \left(\frac{P}{k_B T} \right) Ne$$



Electron oscillations about the anode generate ionizing collisions with a known cross-section

Desorption yield $\gamma \approx 1400$, at $\theta = 70^o$, $\approx$150-300 at $\theta = 0^o$ (normal incidence)

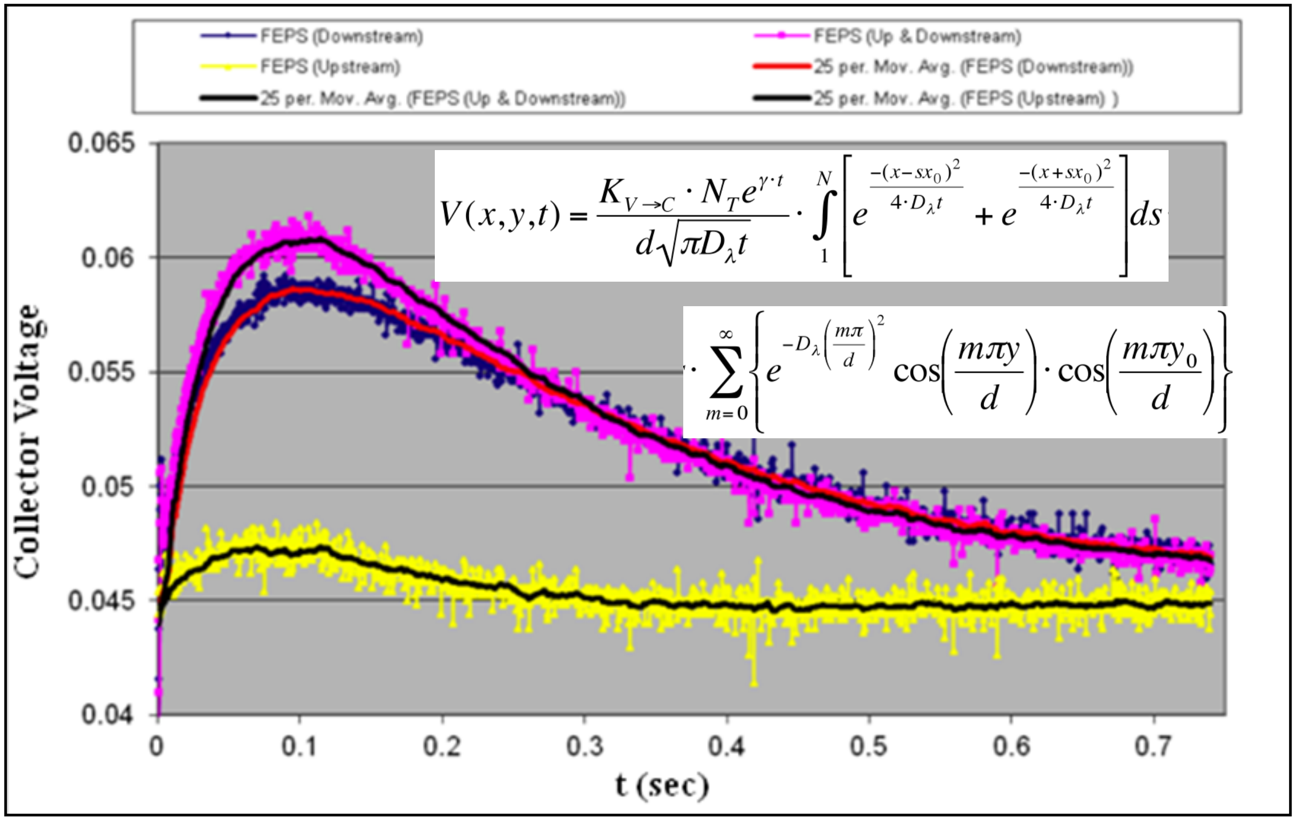
Prompt signal at a 10-40 μs-timescale and at varying distances to the particle source



5 μs pulse, 8.4×10^{11} ions strike the stainless-steel plate.

Prompt signal confirms presence of a fast pressure spike, before many bounces and sticking.

Measurement of pressure rise and sticking coefficient in long ferro-electric plasma source



$$V(x,y,t)=\frac{K_{V\to C}\cdot N_T e^{\gamma\cdot t}}{d\sqrt{\pi D_\lambda t}}\cdot\int_1^N\left[e^{\frac{-(x-sx_0)^2}{4\cdot D_\lambda t}}+e^{\frac{-(x+sx_0)^2}{4\cdot D_\lambda t}}\right]ds$$

$$\cdot\sum_{m=0}^{\infty}\left\{e^{-D_\lambda\left(\frac{m\pi}{d}\right)^2}\cos\left(\frac{m\pi y}{d}\right)\cdot\cos\left(\frac{m\pi y_0}{d}\right)\right\}$$

Upstream FEPS burst vs downstream FEPS burst vs both on at the same time.

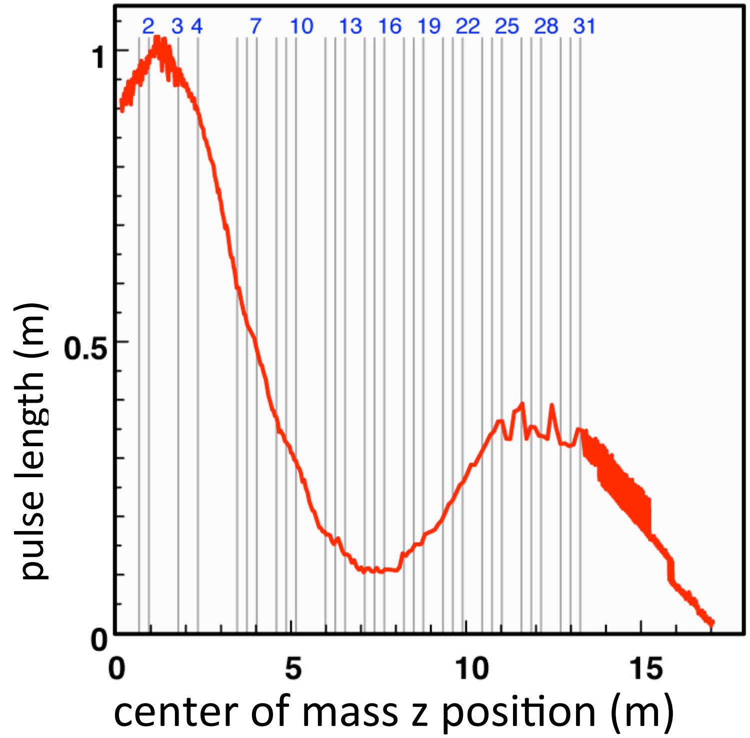
(sections of FEPS, ≈1 m each)

$$\eta=1-\left[\frac{\int_0^\infty V_{u+d}(t)\cdot dt}{\int_0^\infty V_d(t)\cdot dt}\right]^{\frac{1}{\left\langle n/l\right\rangle\cdot(L_u-L_d)}}\approx 0.00269$$

- Estimated pressure rise $\Delta P=3.2\times10^{-6}$ Torr

Experiment on un-neutralized drift compression (NDCX-II)

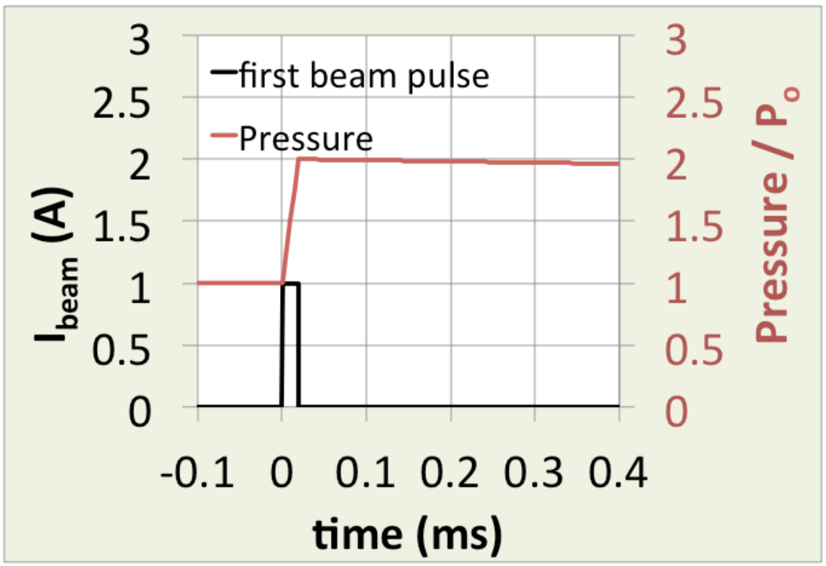
- Compression of non-neutral, (high-perveance) and neutralized beams.
- Employs space charge to remove velocity tilt.
- Longitudinal beam control.
- Chromatic aberration in final focus and methods to compensate or correct.
- Beam diagnostic development.
- Beam loss, halo characterization and mitigation
- Beam - plasma instabilities.



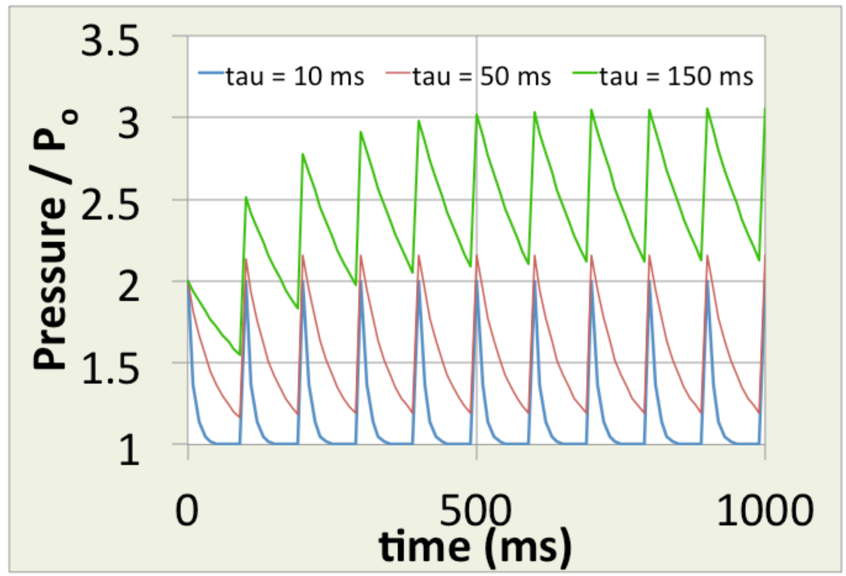
Driver-scale injection and transport at ~10 Hz (HCX)

Dynamic pressure control: The first pulse enters high vacuum (~10^{-8} Torr). How much is the tail of the bunch affected? How are succeeding bunches affected?

Sources and sinks determine the steady state pressure:
Gas desorption from ionized gas, beam ions (halo) striking wall



The beam pulse will create a burst of pressure, which may affect the tail of the same pulse



The decay time of the pressure burst will determine the effect on the steady state vacuum pressure

Eg:, Turner, 2006, J. Vac. Sci. Technol. A 14(4).

Relevant atomic cross sections are greatest at low energy. Key experiments are possible with modest enhancements to existing equipment.

σ_s, **stripping**, eg: $Cs^+ + A^o \rightarrow Cs^{2+} + A^o + e^-$

σ_{RCX}, **resonant charge exchange**, eg: $Cs^+ + Cs^o \rightarrow Cs^o + Cs^+$

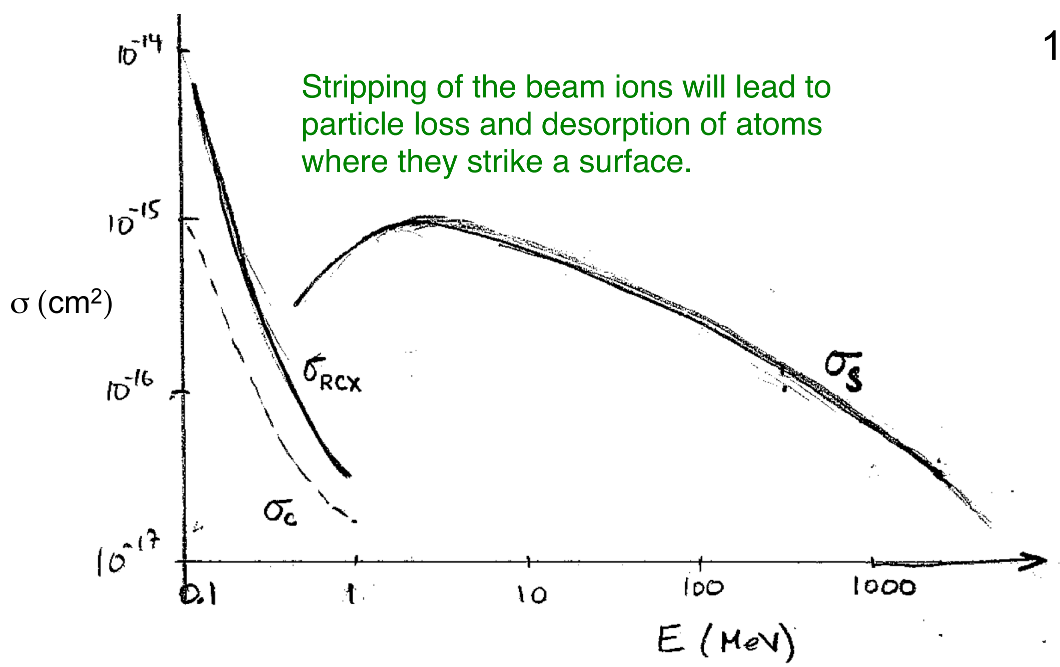
σ_c, **capture**, eg: $Cs^+ + A^o \rightarrow Cs^o + A^+$

σ_I, **ionization**, eg: $Cs^+ + A^o \rightarrow Cs^+ + A^+ + e^-$

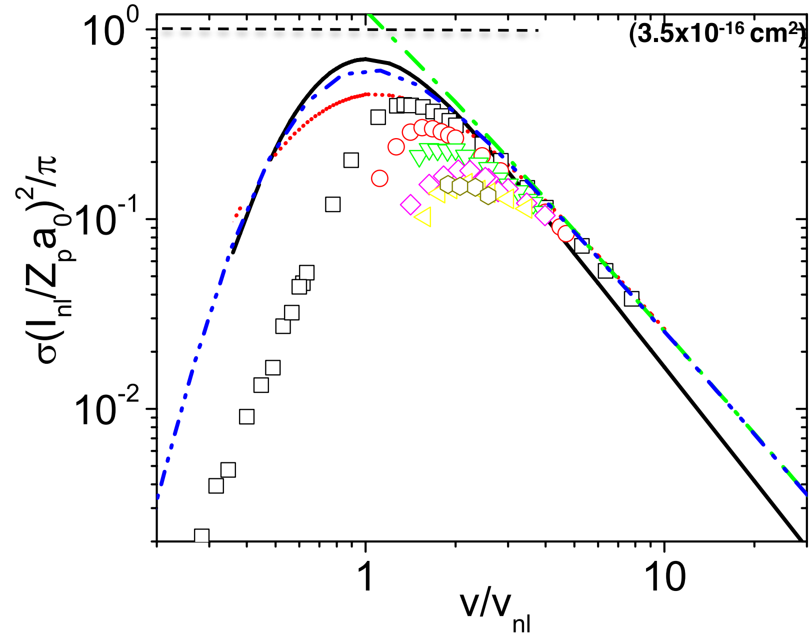
σ_{IS}, **intra-beam scattering**, eg: $Cs^+ + Cs^+ \rightarrow Cs^{2+} + Cs^o$
$Cs^+ + Cs^+ \rightarrow Cs^{2+} + Cs^+ + e^-$

(Dunn, 1979, ≈ 2 x 10^{-16} cm^2)

A^o, a neutral gas atom (or molecule)



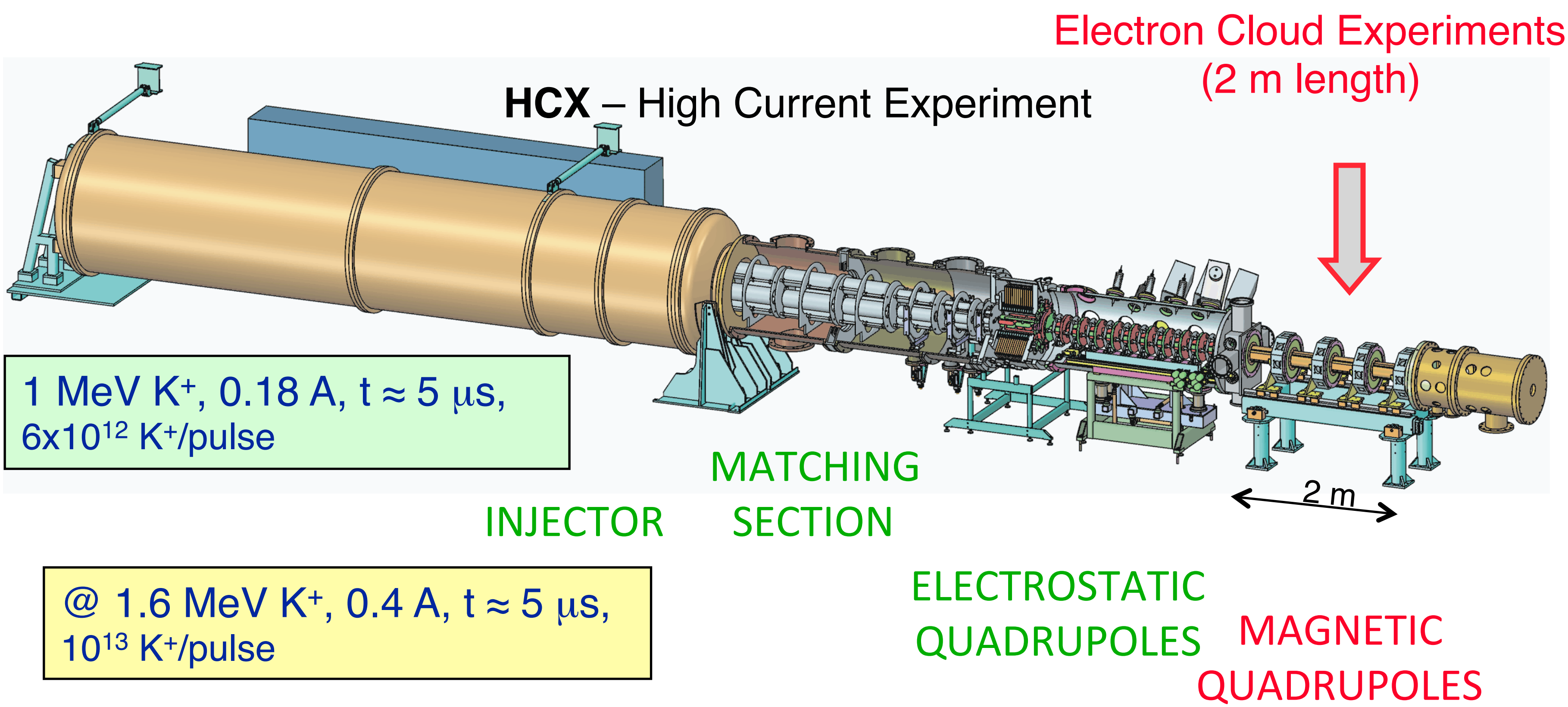
Ionization (of background gas)



Kaganovich et al., New J. Phys. 8 (2006) 278

Injection, matching, low-energy transport at driver scale

- Most accelerators operate at a repetition rate exceeding HIF requirements, but at much lower current.
- With modifications to HV Marx, **HCX** is capable of doing ~10 Hz experiments.



1 MeV K^+, 0.18 A, $t \approx 5$ μs,
6×10^{12} K^+/pulse

@ 1.6 MeV K^+, 0.4 A, $t \approx 5$ μs,
10^{13} K^+/pulse

F.M. Bieniosek et al., Phys. Rev. PRST-AB **8, 010101 (2005)**

L.R. Prost et al., Phys. Rev. PRST-AB **8, 020101 (2005).**