Beam dynamics studies of H- beam chopping in a LEBT for project X

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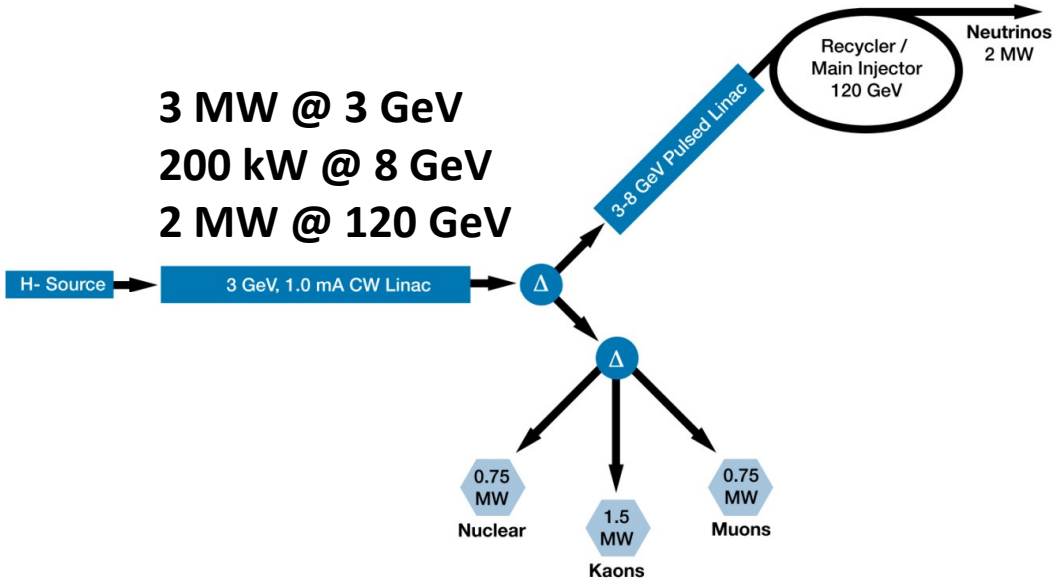
Project X Injector Experiment (PXIE)

- Project X is a high intensity proton facility being proposed by Fermilab to support a world-leading program in neutrino and flavor physics.
- PXIE is the centerpiece of the Project X R&D program
  - Validate the concept for the Project X front end, thereby minimizing the primary technical risk element within the Reference Design.
  - Ion Source
    - Demonstrate up to 10 mA CW H- production
  - Low Energy Beam Transport (LEBT)
    - Minimum emittance growth
    - Pre-chopping

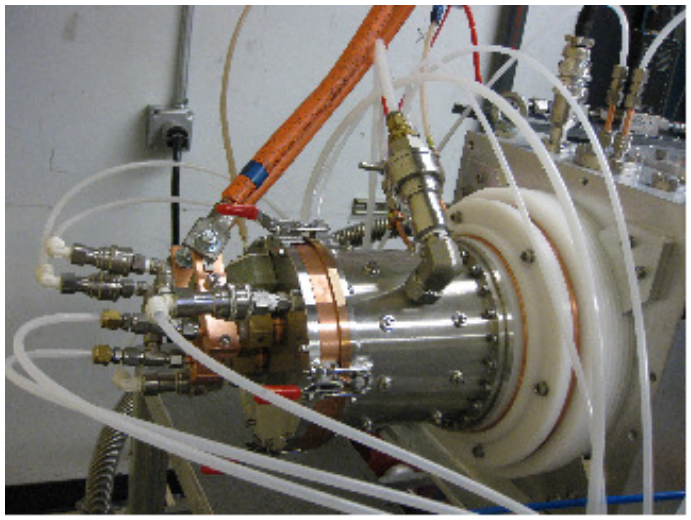


Filament Discharge H- Ion Source

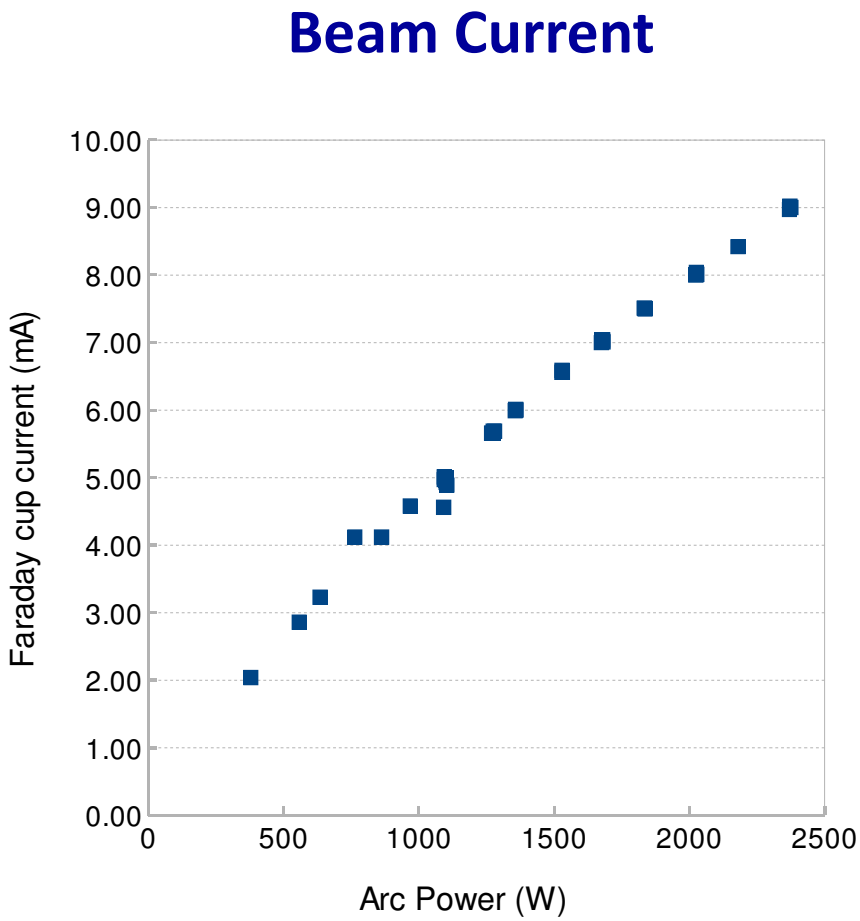
- PXIE baseline H^- ion source identified.
  - DC filament, Penning, and RF H^- ion source evaluated.

- Filament driven H^- source provides a rapid-entry, low risk solution
  - cw 10 mA, proven technology
  - No Cs
  - Emittance should meet specifications at 10mA of output beam current
    - normalized rms emittance < 0.2 π mm mrad
  - Limited lifetime of the filament (~ 500 hrs @ 5mA operation)
    - Two ion sources with a switching magnet shorten downtime significantly

Up to 10 mA of H- Ion Beam Demonstrated

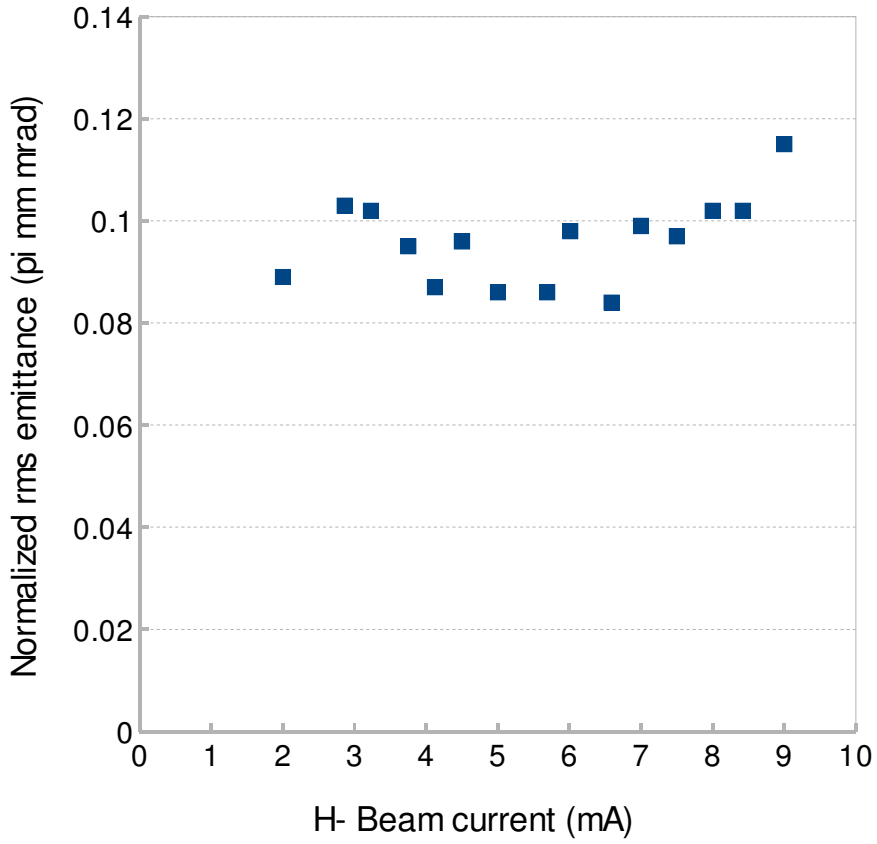


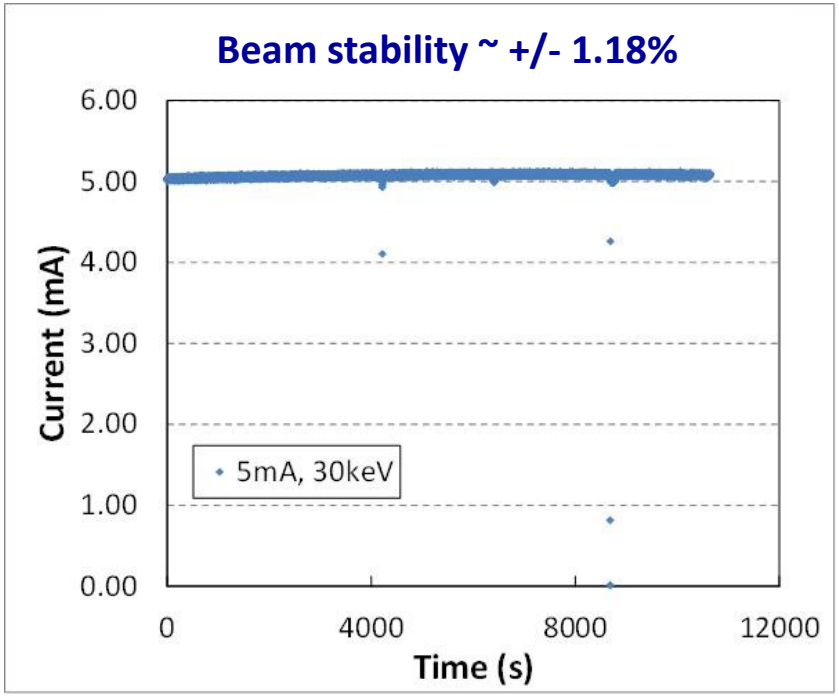
- Ion source assembly was purchased from D-Pace
  - Designed for 15 mA H^- beam production
  - Acceptance tests up to 10 mA
  - Ion source is now installed at LBNL
  - Performance was verified



Emittance and Stability Meet Specification

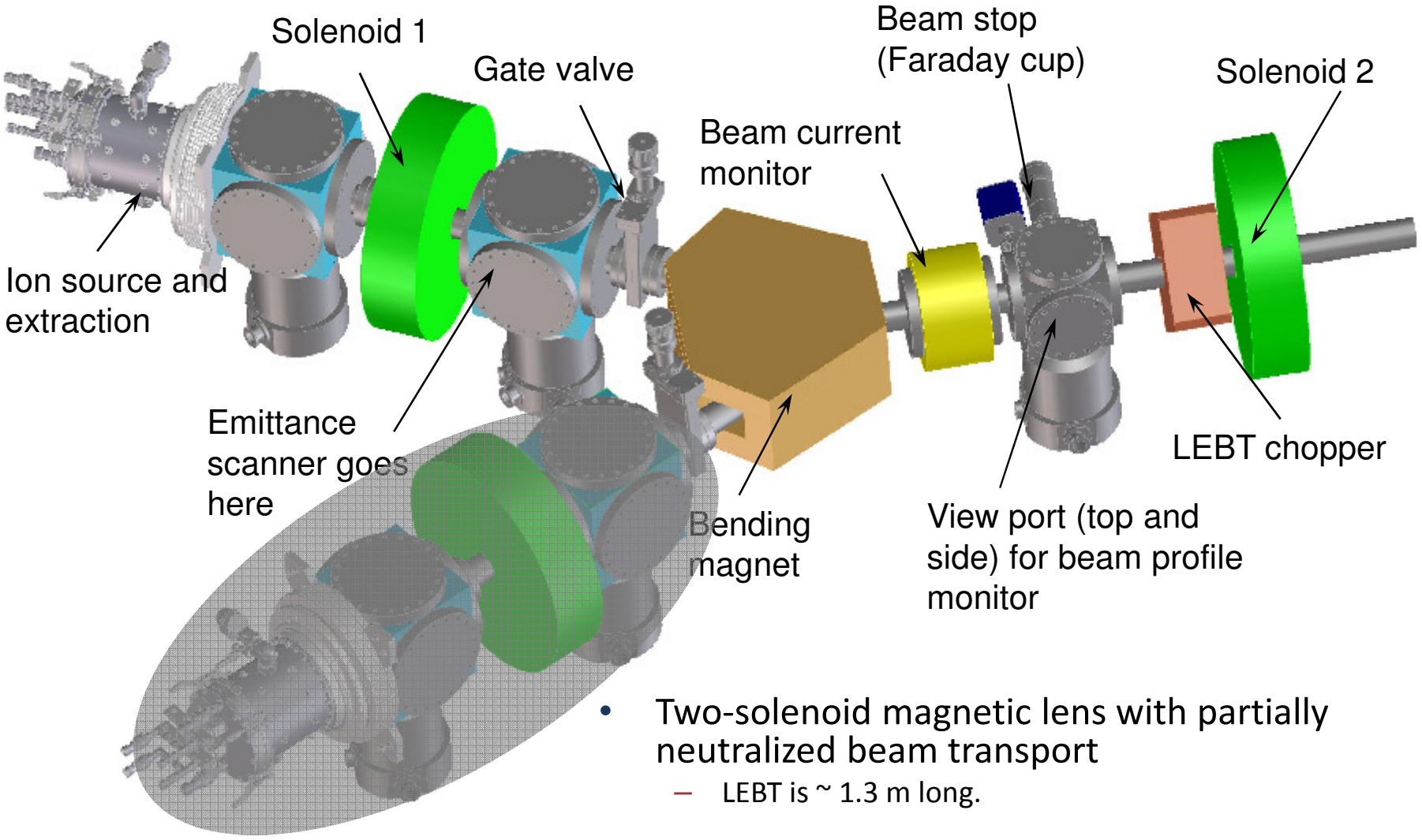
Emittance





- **No active feedback control loop,**
- **No adjustment of any parameters including source operation conditions, extraction electrode biases.**

PXIE LEBT Conceptual Design



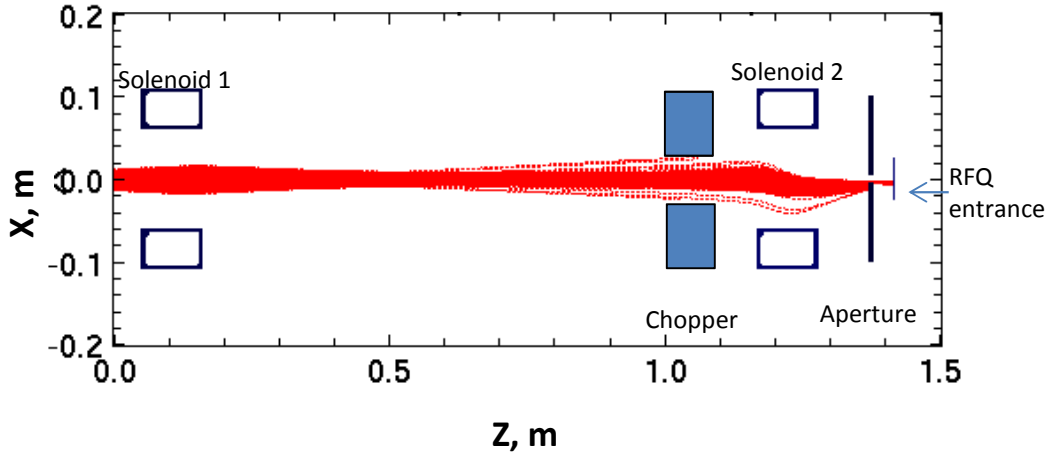
- Two-solenoid magnetic lens with partially neutralized beam transport
  - LEBT is ~ 1.3 m long.

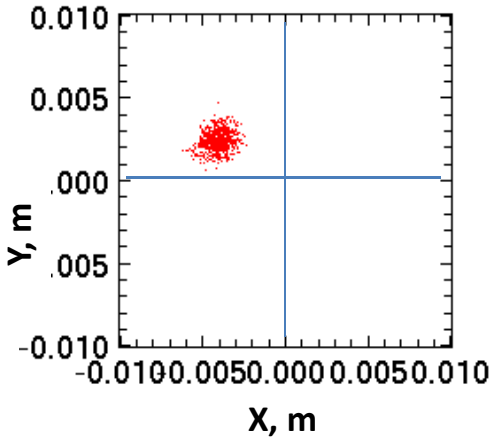
PXIE LEBT Optics

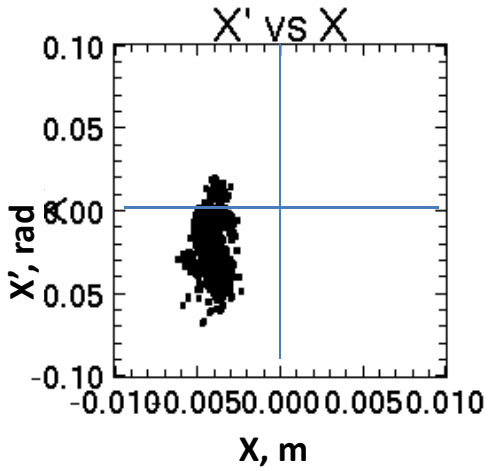
- LEBT beam dynamics has been simulated using various codes
  - Trace 3D
  - Astra
  - TLAT
  - WARP 3D
- All results have good agreement.

I = 10mA
E_k = 30keV
Deflecting voltage: ± 650 V
with *90% space charge* neutralization throughout the LEBT

WARP simulation:
snapshot of particle distribution at x-z

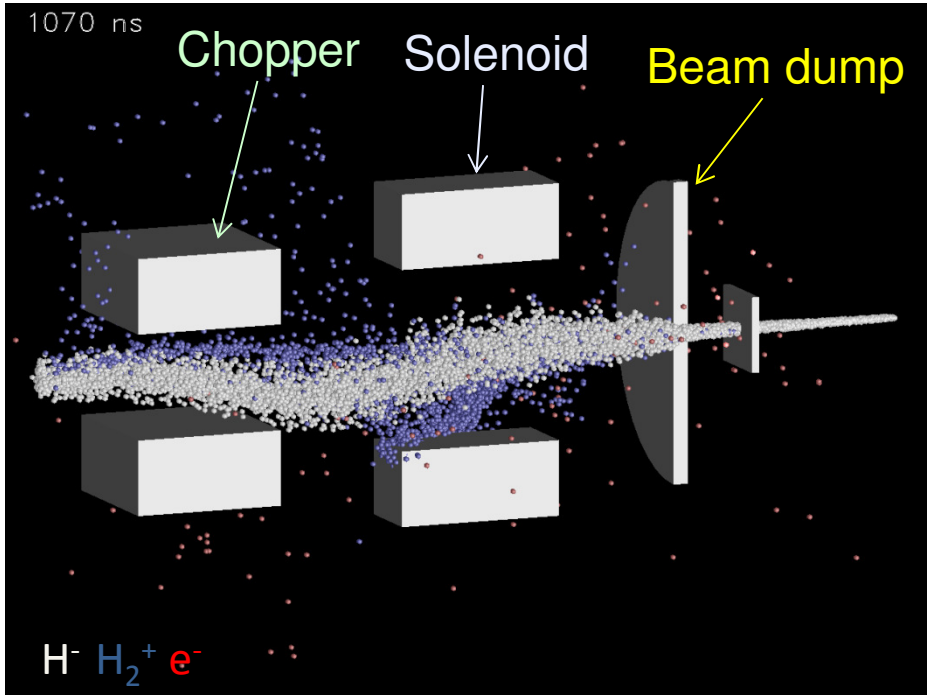






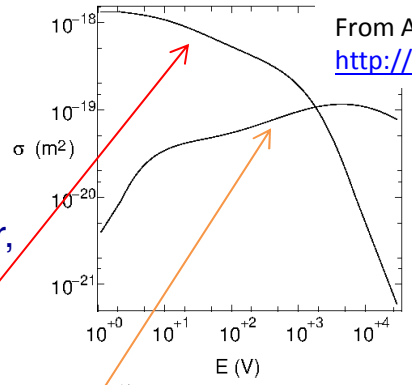
LEBT and Chopper Beam Dynamics Simulation

- Partial space charge neutralization will be lost along the beam in the chopper and maybe through the second solenoid.
  - Typical space charge neutralization time ~ 50 μsec at 10^{-6} Torr.
- Beam dynamics study is crucial to investigate the time-dependence of the space charge neutralization in the segment after the chopper
  - Beam stability
  - Emittance growth
- Time-dependent simulation of LEBT chopper using WARP 3D
  - Chopper + solenoids
  - Simulations performed with particle interactions

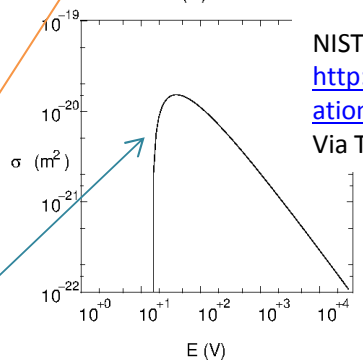


Simulation Including Particle Interactions with Background Gas

- **WARP 3D is a particle-in-cell code, developed to achieve end-to-end 3D self-consistent time-dependent simulations of beam.**
  - ✓ acceleration, focusing and compression along accelerator,
  - ✓ Particle loss at walls, interaction with desorbed gas and electrons, halo
  - ✓ neutralization from plasma in chamber.
- **WARP 3D being further developed to support PXIE**
- **Includes multiple interactions**
  - Charge exchange $H^- + H \rightarrow H + H^-$
  - Ionization $e^- + H \rightarrow H^+ + 2\,e^-$
  - Detachment $H^- + H \rightarrow 2\,H + e^-$
  - Detachment $H^- + H_2 \rightarrow H + H_2 + e^-$
  - Ionization $e^- + H_2 \rightarrow H_2^+ + 2e^-$
  - Ionization $H^- + H_2 \rightarrow H^- + H_2^+ + e^-$

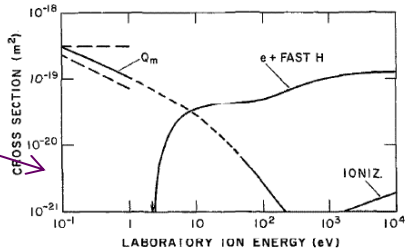


From Aladdin cross section database
http://www-cfadc.phy.ornl.gov/home.html

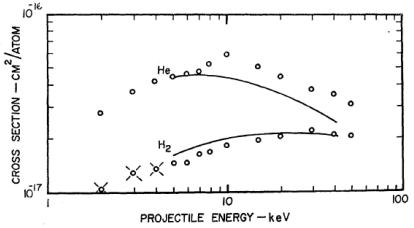


NIST Electron impact cross sections
http://physics.nist.gov/PhysRefData/Ionization/Xsection.html
Via TxPhysics library

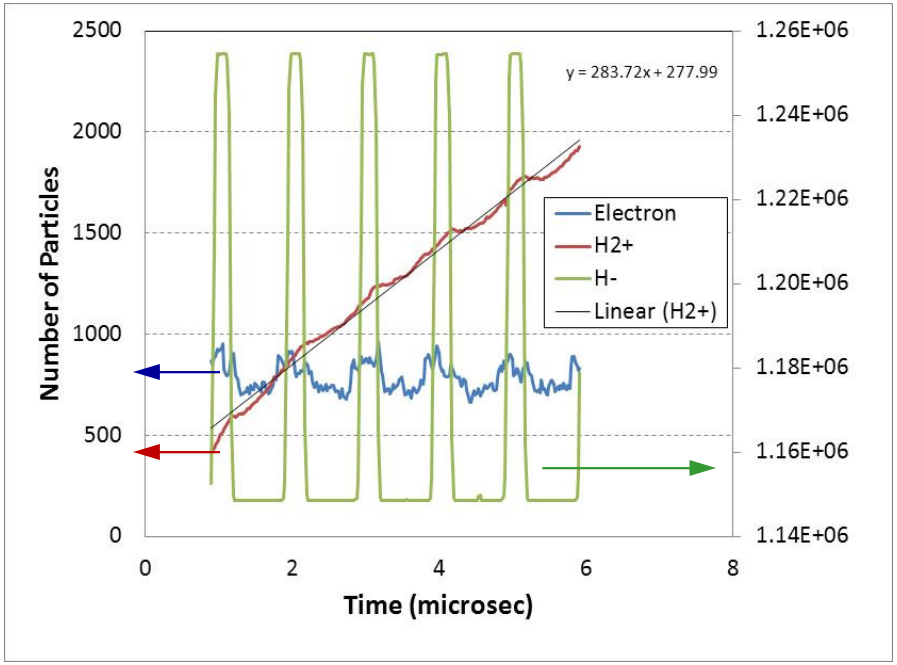
A. V. Phelps, J. Phys. Chem. Ref. Data, 19, 653(1990).



J. F. Williams, Phys. Rev., 154, 9(1967).



Simulation Results

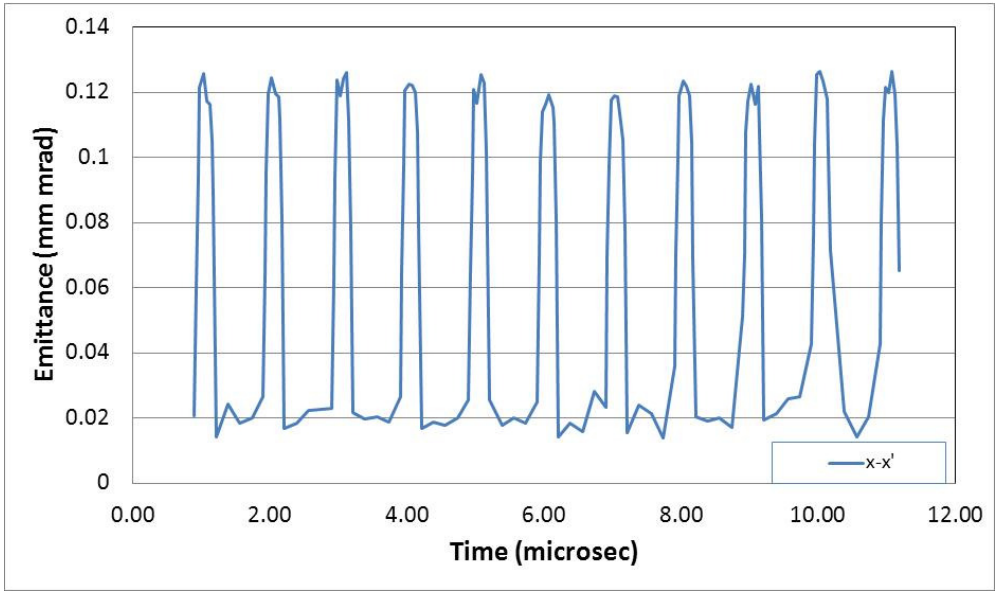


NERSC
1 Node
24 CPU
24 Hrs

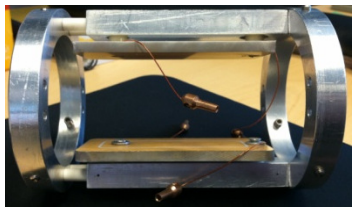
➡

6 μs
of particle
interactions

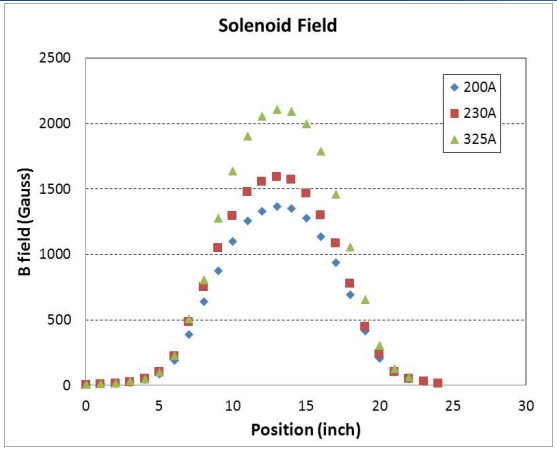
Preliminary results shows $\varepsilon_{xx'}$ increases ~ 20%



Chopper Simulation Benchmark Experiment Setup



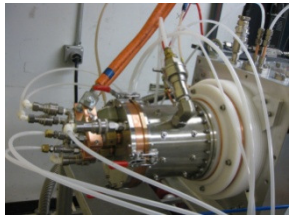
Chopper



Emittance scanner

Solenoid

Ion Source

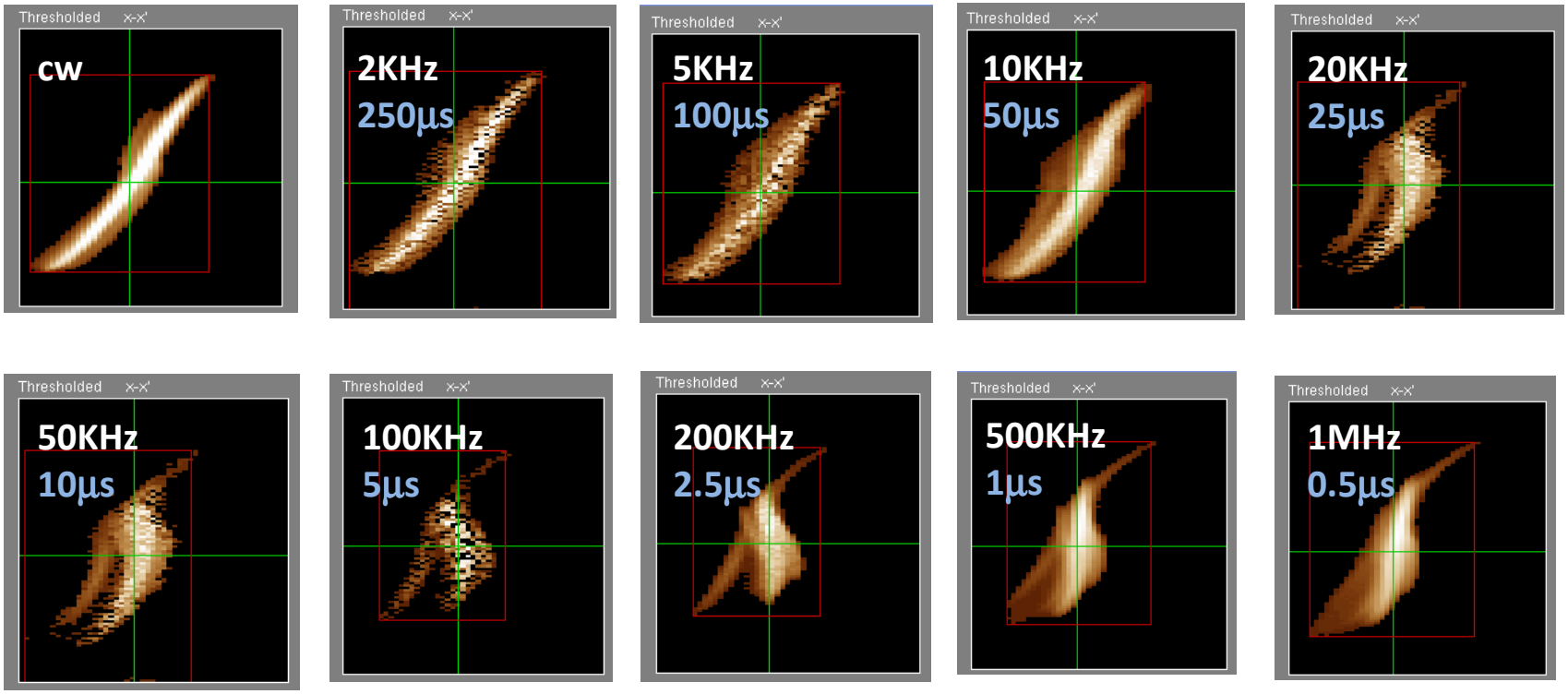


Faraday cup

Simulation shows that @ 16 KeV, there is a beam waist between the solenoid and emittance scanner.

16 KeV, 3.5mA H- Beam pulsed @ 50% duty factor

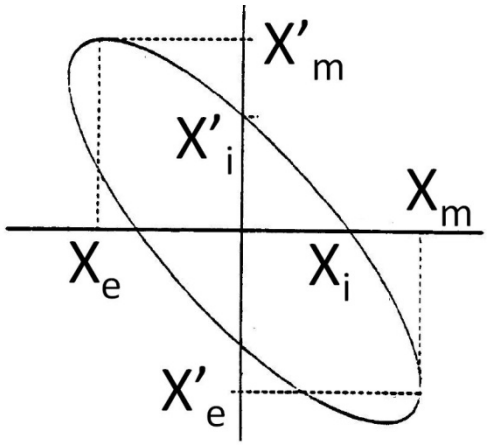
Pulse width → **shorter**



Higher repetition rate → Less space charge neutralization

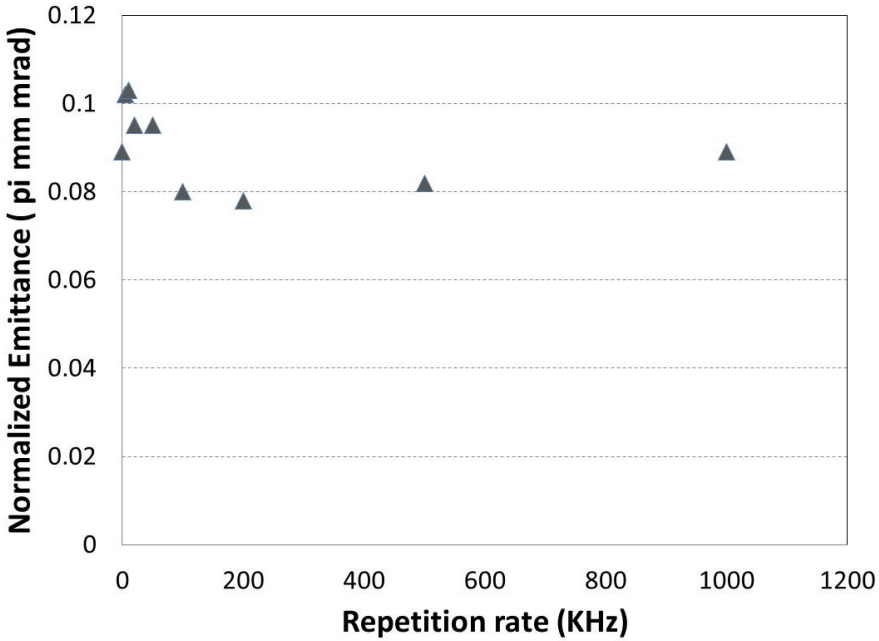
Beam waist moves downstream

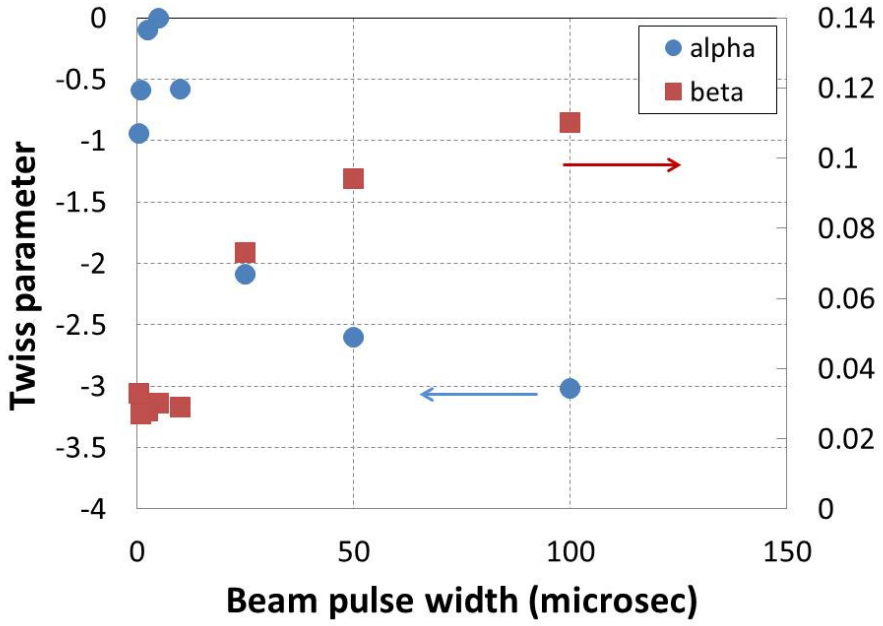
Emittance and Twiss parameters vs. Rep Rate



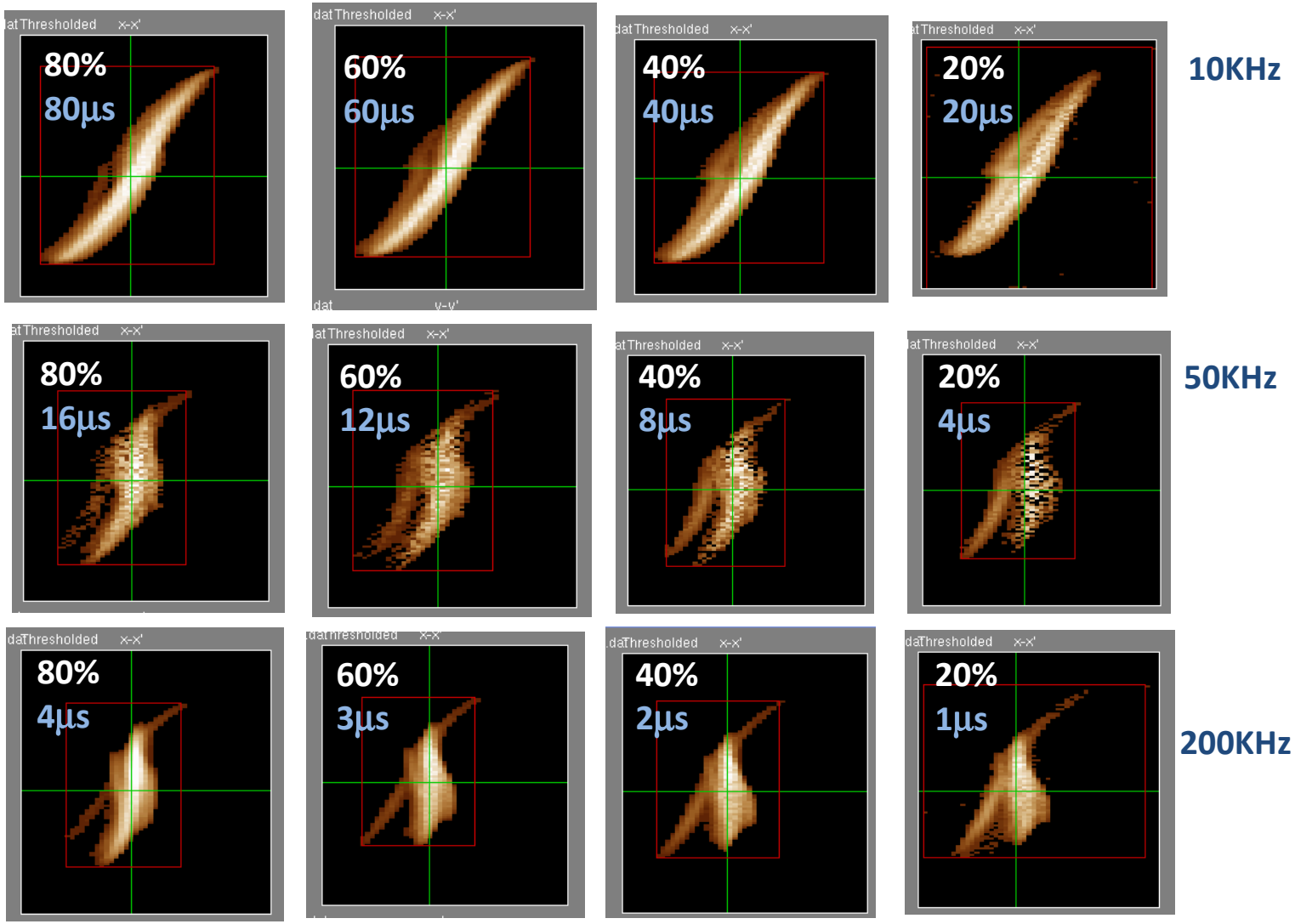
$$\alpha = -\frac{x_e}{x_i} = -\frac{x'_e}{x'_i}$$

$$x_m = \sqrt{\beta\varepsilon}$$

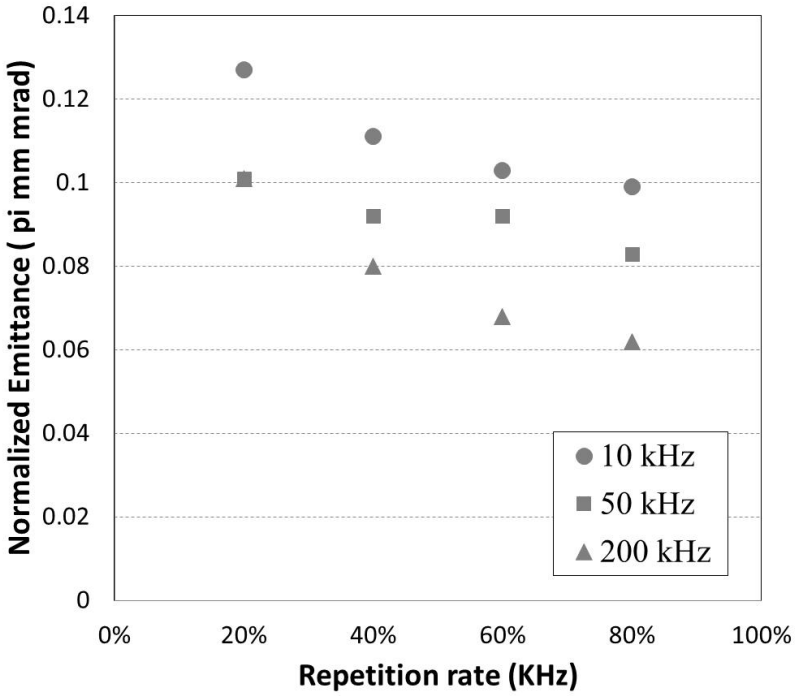


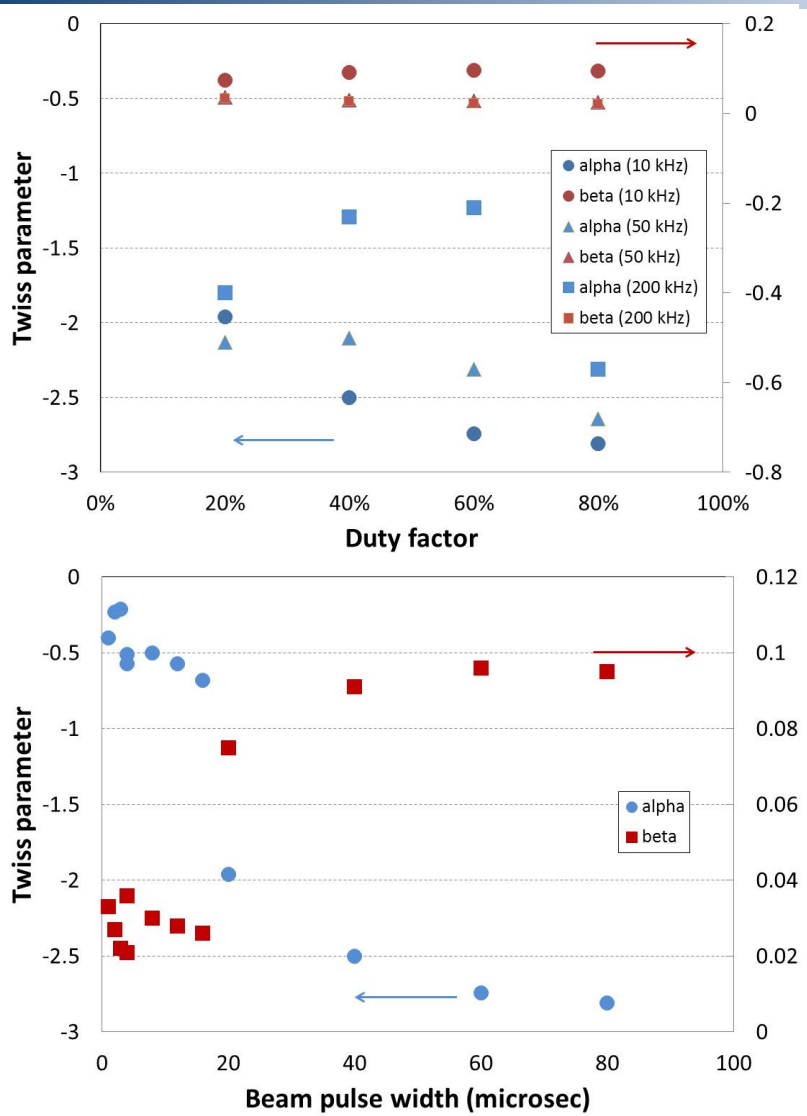


Effect of Pulse Duty factor

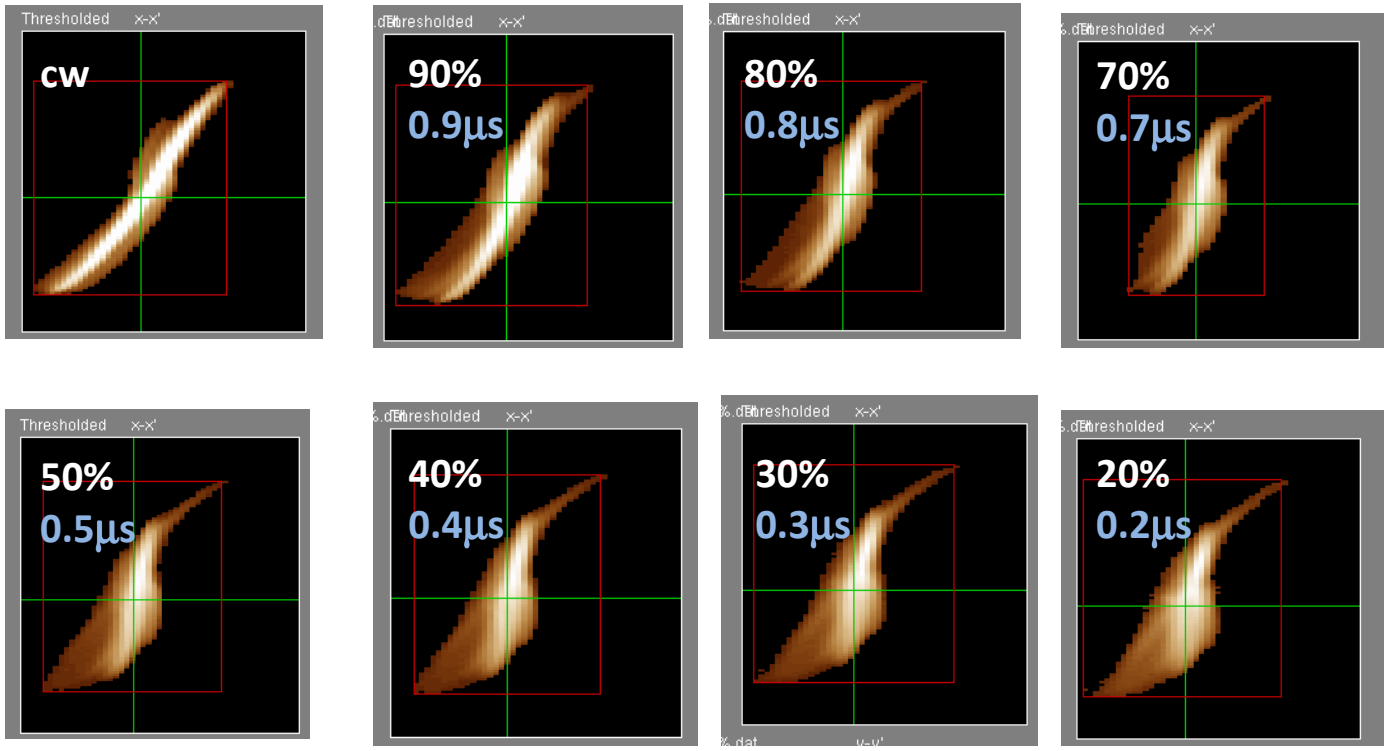


Emittance and Twiss parameters vs. Pulse Duty Factor

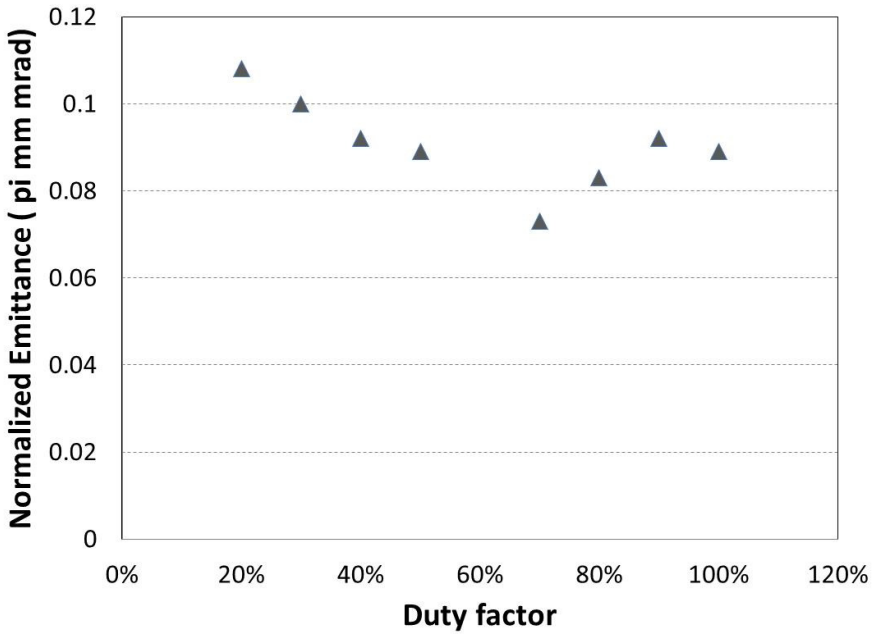


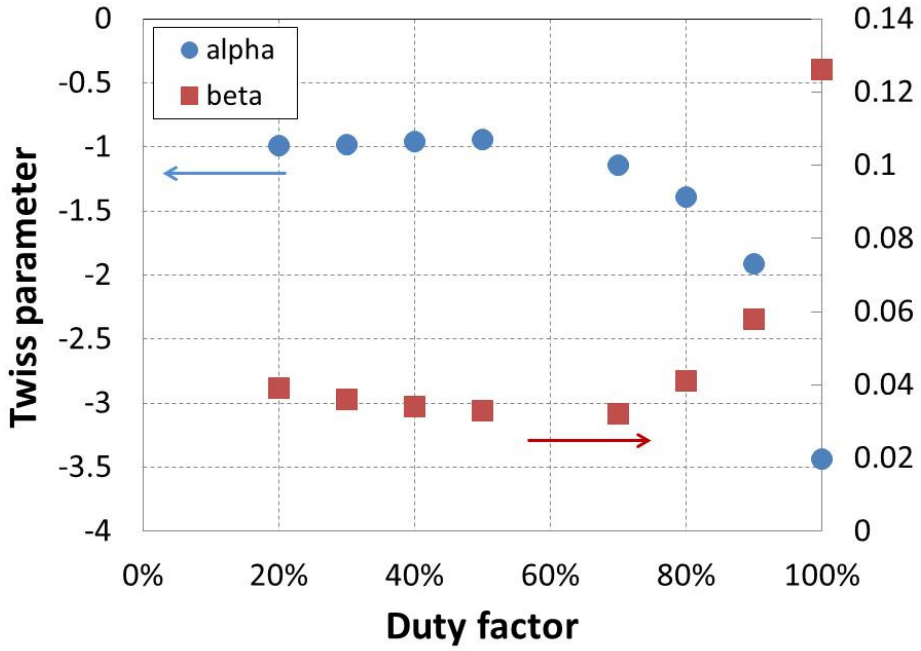


16 KeV, 3.5mA H- Beam pulsed @ 1 MHz



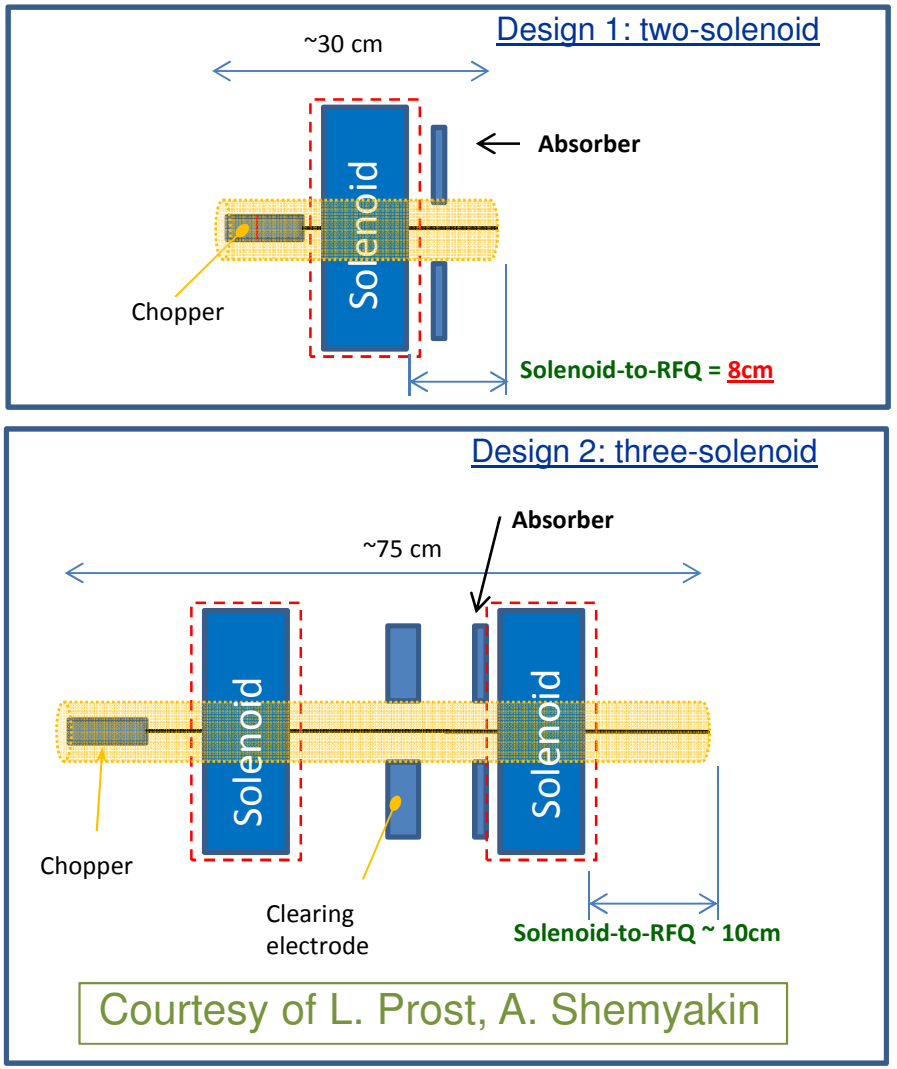
Emittance and Twiss parameters @1MHz





Future Plan

- WARP 3D simulation
  - Simulation of 3.5 mA, 16 keV H- beam dynamics in a chopper and solenoid as in the benchmark experiment
  - Emittance and twiss parameter vs. pulse repetition rate
  - Comparison between simulation and experimental results
- Time-dependent simulation of both two- and three-solenoid LEBTs including particle interactions with background gas.



Summary

- PXIE H- ion source has been tested at LBNL. Beam current, emittance, and stability all meet the functional specification requirements.
- A two-solenoid magnetic lens LEBT has been proposed.
- Time-dependent WARP 3D simulations of particle interactions, such as electron detachment, charge exchange, H- ionizations etc. in the LEBT are still ongoing. Preliminary results showed that, from the chopper to the entrance of RFQ, emittance increases ~ 20%.
- Chopper simulation benchmark experiment has been performed at various pulse duty factor and repetition rate. A collection of emittance and twiss parameter data have been taken, which are ready to be used in benchmarking WARP 3D simulations.