Overview of Heavy Ion Fusion Accelerator Research in the U.S. Virtual National Laboratory

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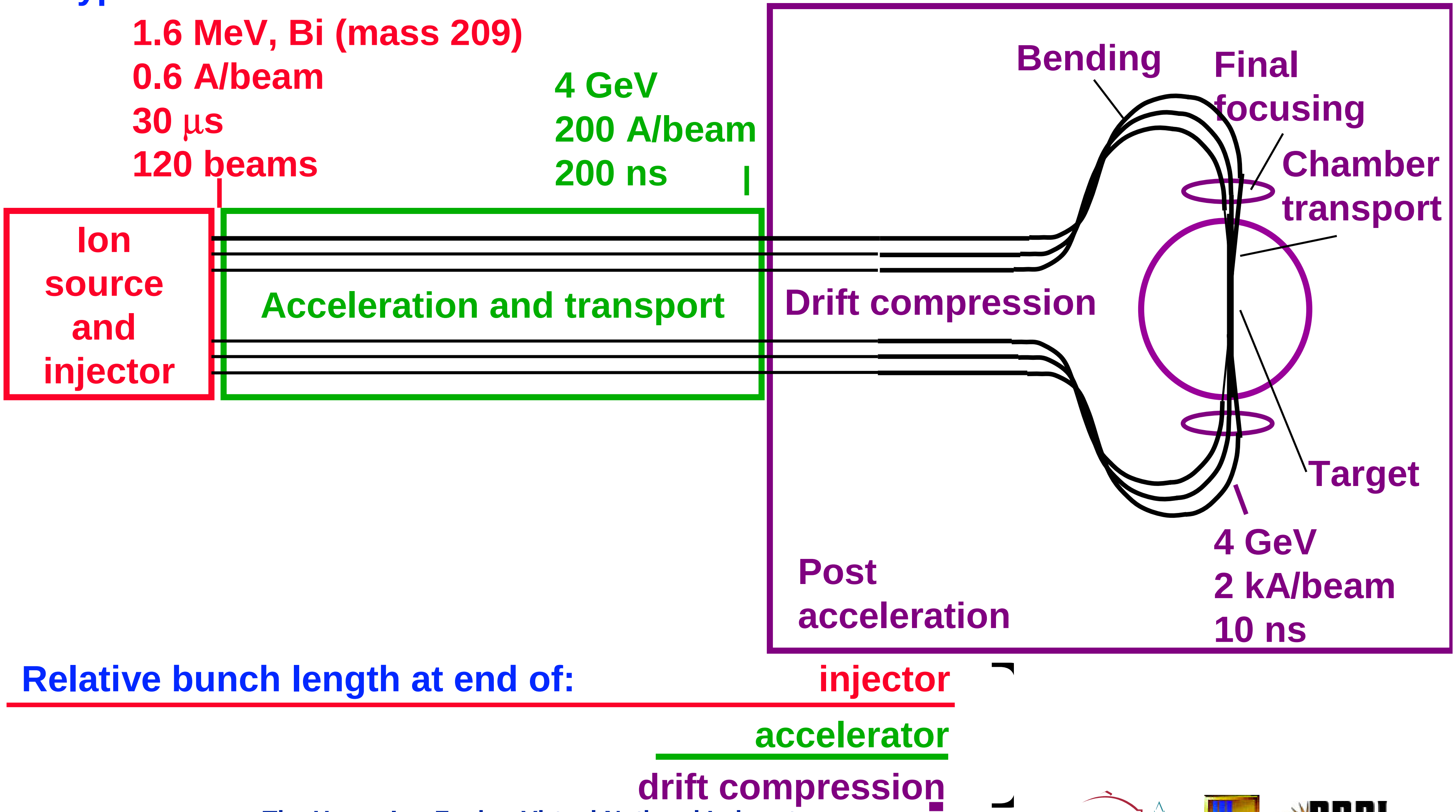
Workshop on Recent Progress in Induction Accelerators

October 29-31, 2002

KEK,Tsukuba, Japan

Induction acceleration for HIF requires several beam manipulations from source-to-target

Typical Driver Parameters:



Accelerator research in the HIF VNL (at LBNL/ LLNL/ PPPL) focuses on three new experiments

1. Ion source/injector:

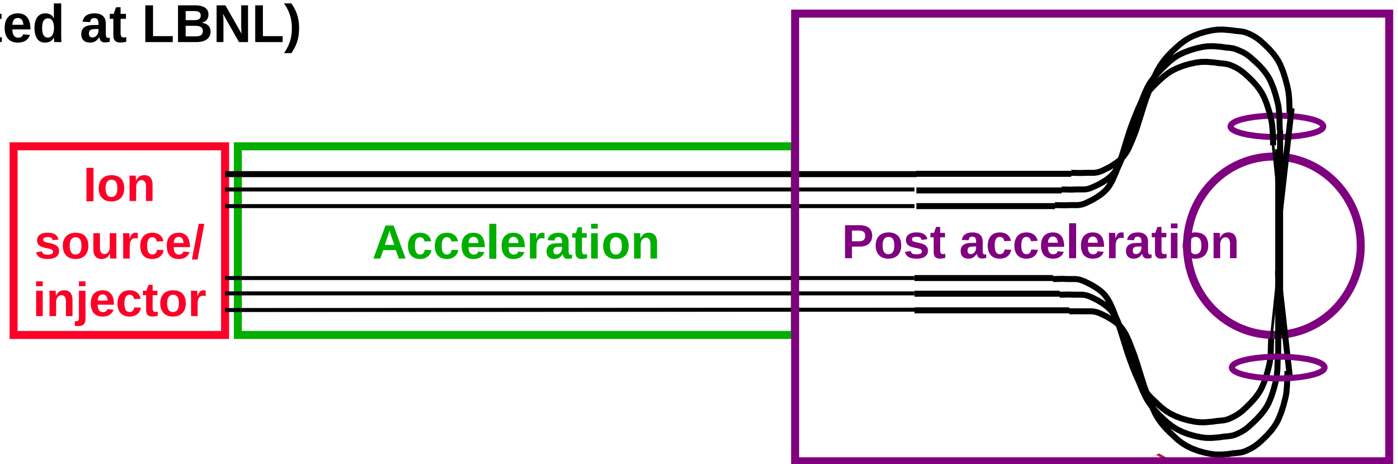
High Voltage Injector Test Stand (STS-500) (commissioned in December 2001, sited at LLNL)

2. Acceleration and transport:

High Current Experiment (HCX) (commissioned in January 2002, sited at LBNL)

3. Post acceleration (final focus/chamber transport/drift compression):

Neutralized Transport Experiment (NTX) (commissioned in August 2002, sited at LBNL)



1. Injector/Source Research: High Voltage Test Stands (STS 500 and STS100)

Parameters:

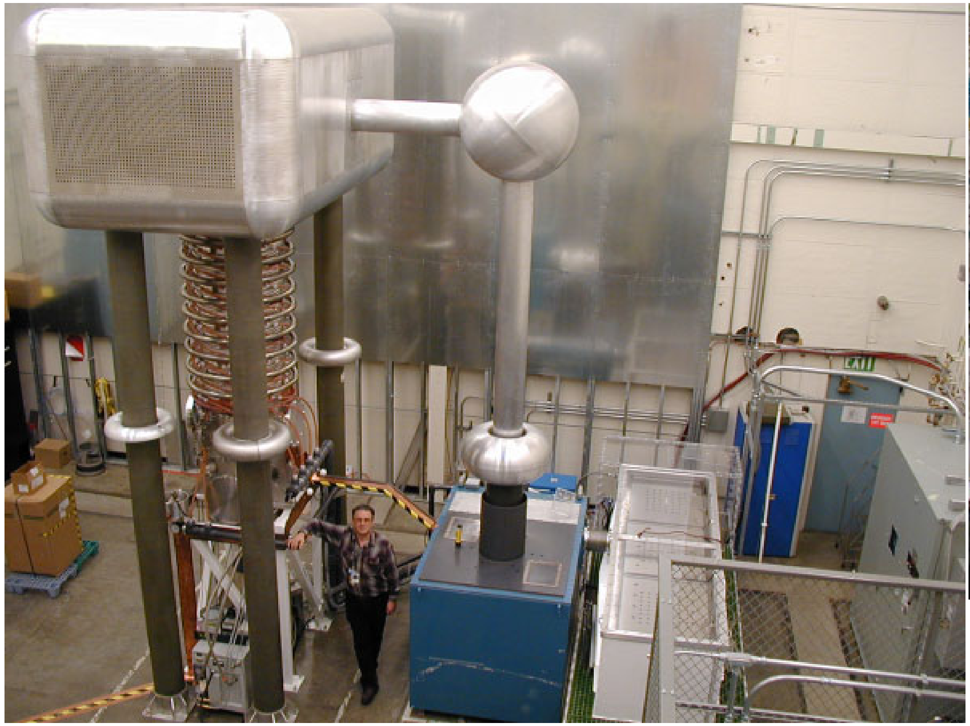
STS500: 500 kV, up to ~1 A, up to 20 μs
STS100: 100 kV, ~100 mA, ~10 μs

Mission:

1. **To test the multi-beamlet option for injector**
2. **To evaluate and down-select between solid surface sources vs. gas/plasma sources**
3. **To evaluate injector designs for near- and mid-term experiments**

Two test stands are being used to study source/injector physics

STS-500



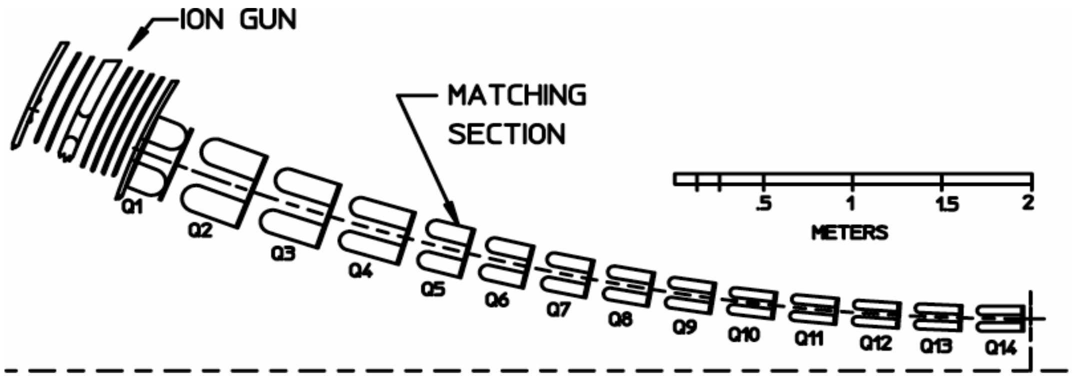
500 kV, up to ~1 A, up to 20 μs
Current research: large aperture sources; aperturing experiments; high gradient insulators

STS-100

100 kV, ~100 mA, ~10 μs
Ion: variable, currently Ar^+
Current research:
Plasma sources;
Multiple beamlet sources;

Injector/source experiments will lead to down selection between single source or multibeamlet injector

traditional design using single large diameter source



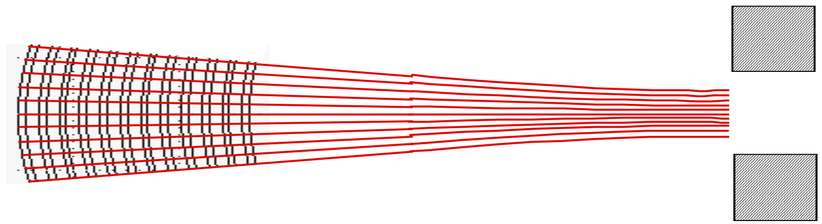
advanced design using multiple beamlets

Each beamlet carries higher current density; But merging beamlets increases thermal spread.

Child-Langmuir $J_{CL} \propto \frac{V^{3/2}}{d^2}$

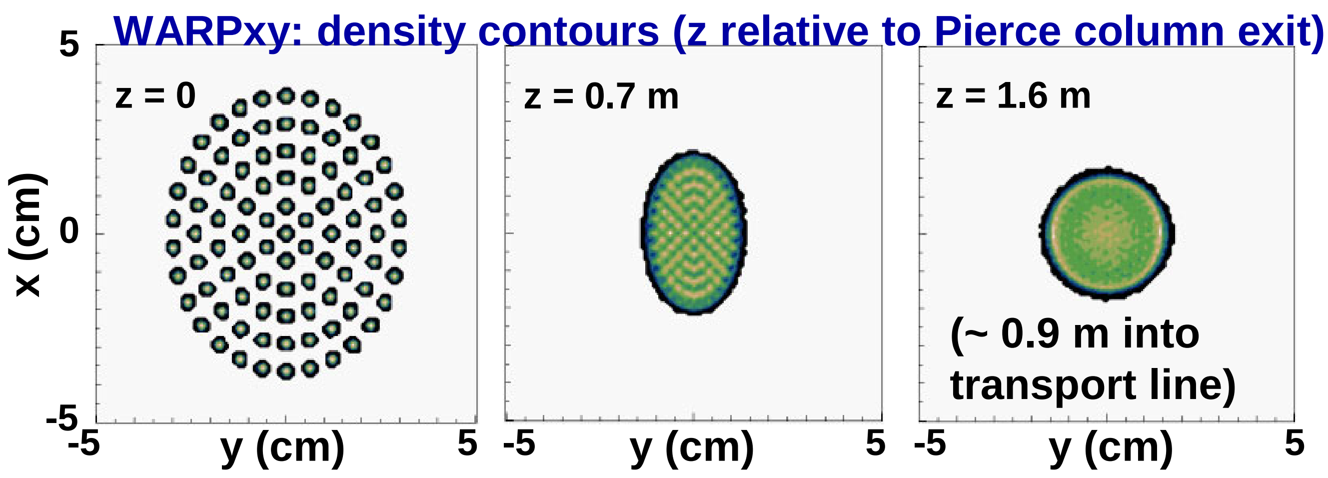
Breakdown limit $V \propto d^{1.0 \; to \; 0.5}$

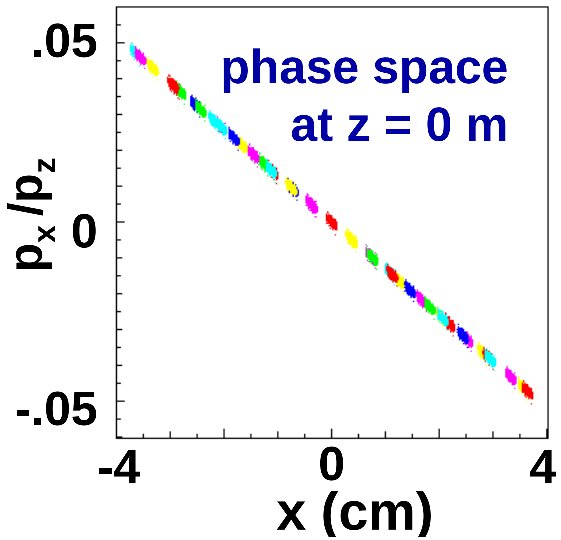
$$J \propto V^{-1/2 \; to \; -5/2} \propto d^{-1/2 \; to \; -5/4}$$

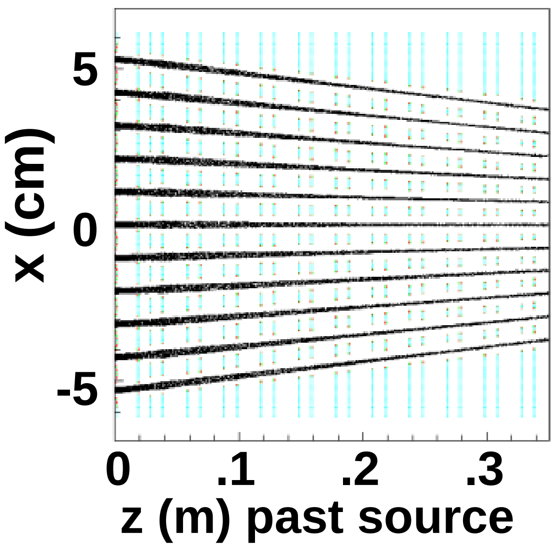


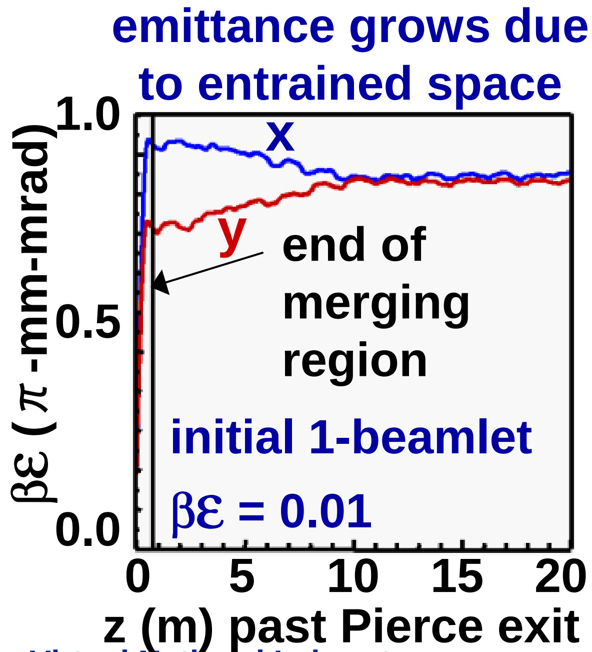
Merge and match beamlets into an ESQ channel

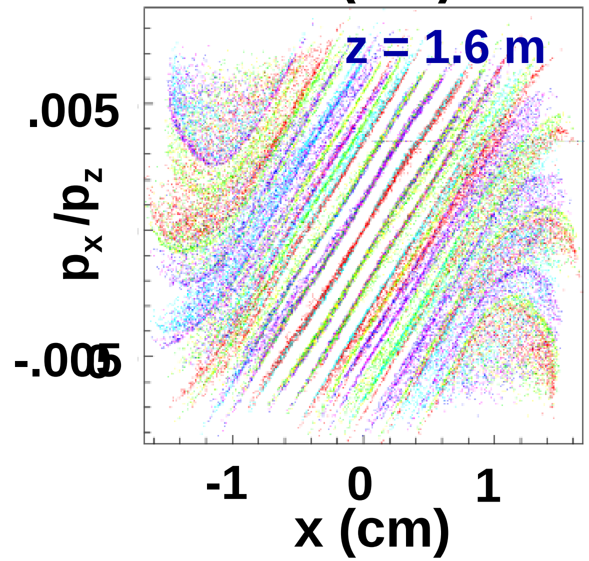
Simulations of merging-beamlet injector



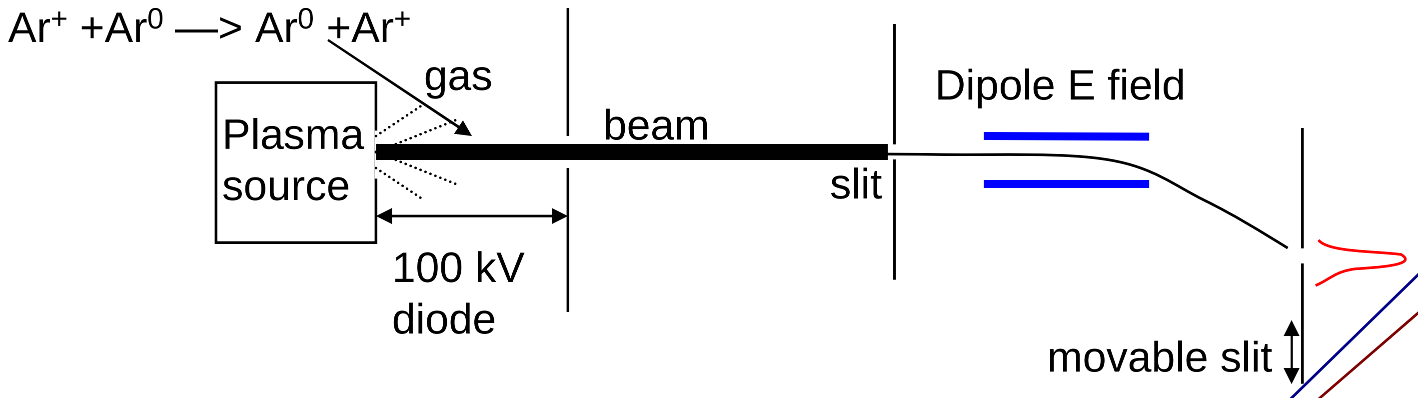




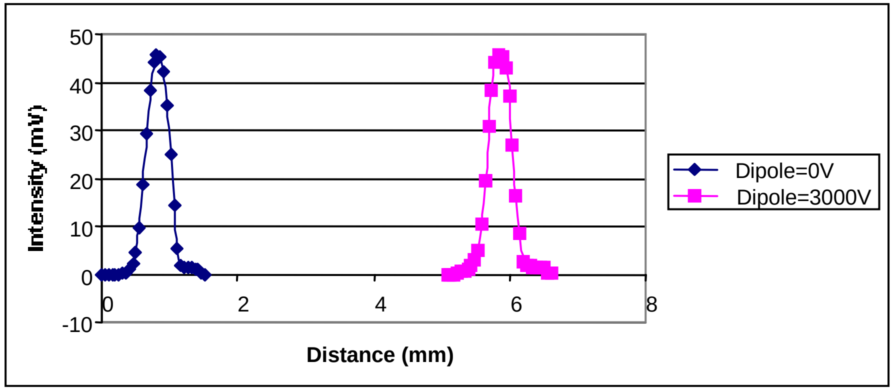


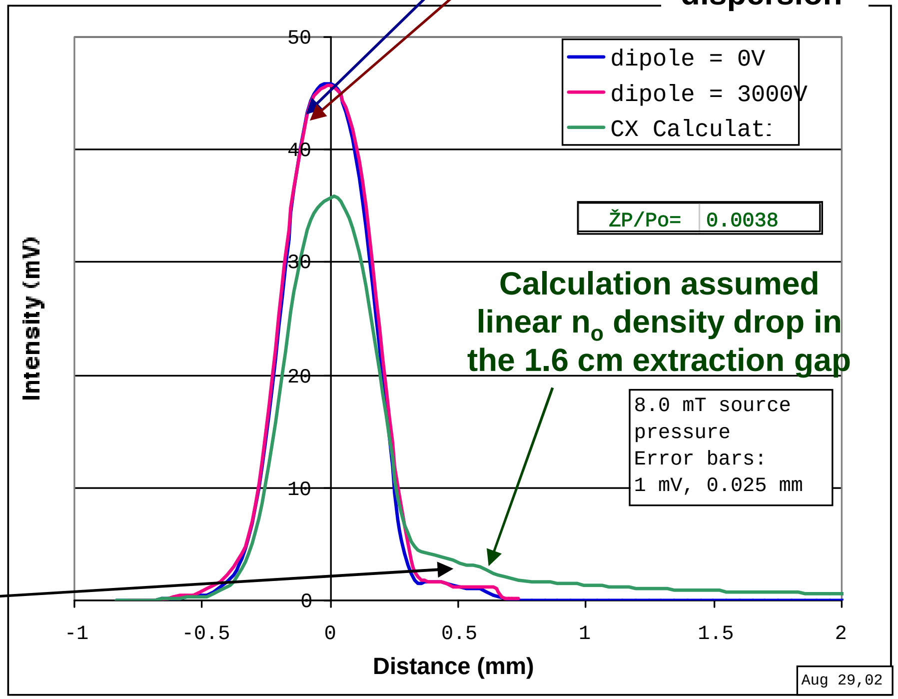


Energy dispersion is a consequence of charge exchange loss inside the diode



Overlay of **blue** and **red** curves do not indicate energy dispersion





Low energy tail was not observed at up to 8.5 mT of source pressure.

Ion source research for merging beamlet injector

- **Current experiments on RF plasma source will address if this technology can be used to build merging beamlets:**

Parameters	Goal	Status
Current density	5 mA at 100 mA/cm^2	80%
Emittance	T_{eff} < a few eV	met goal
Charge states	Minimization of Ar^{++}	~6%
Energy spread	$\Delta p/p_o < 0.1\%$ for a 1.6 MeV injector	refining analysis

- **Additional fast rise time requirement for future experiments:**

  -Small beamlet transit time is inherently short.

  -Formation of a stable plasma meniscus sets a time limit.

2. Acceleration and Transport Research: High Current Experiment (HCX)

Parameters:

1 - 2 MeV, 0.2 - 0.8 A, 2 - 6 μs, K^+

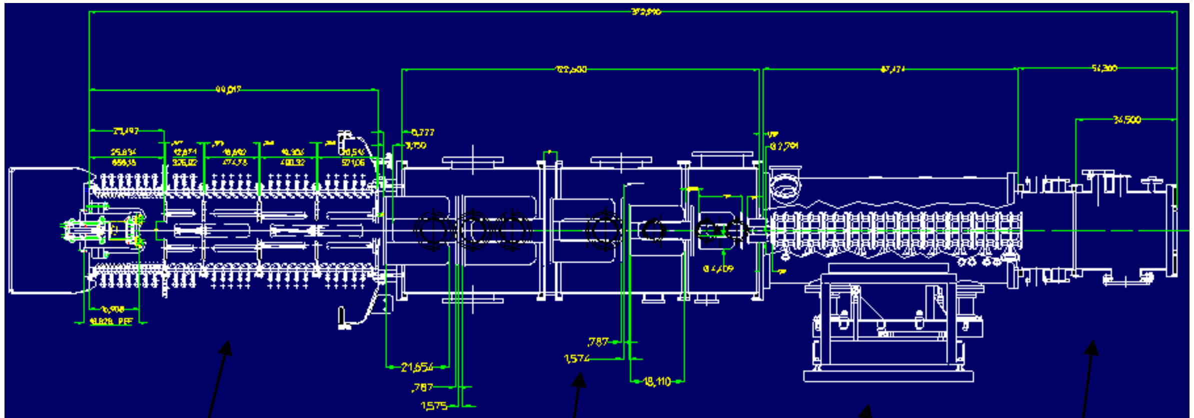
Mission:

1. **To demonstrate beam transport at line charge density comparable to a driver**
2. **To investigate the effects of electrons, residual gas atoms, and beam/wall interactions on beam emittance and beam halo**
3. **To establish the "fill factor," i.e. the maximum ratio of beam radius to aperture radius that would allow economical beam transport with acceptable emittance growth and beam loss**

High-Current Experiment (HCX): first transport experiment using a driver-scale heavy-ion beam

Presently: 1 MeV, 0.2 A, 4 μs through 10 ES quads

First beam was achieved on January 11, 2002



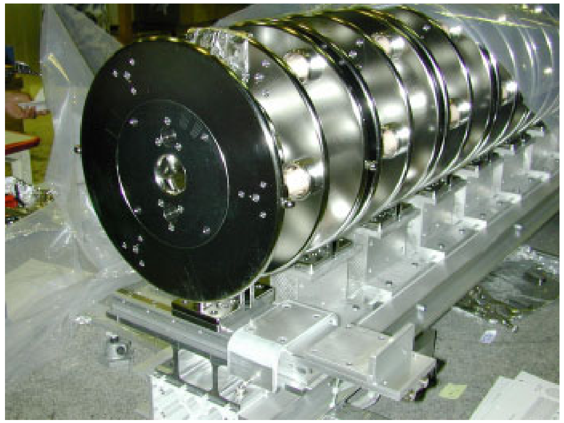
ESQ Injector

Matching section

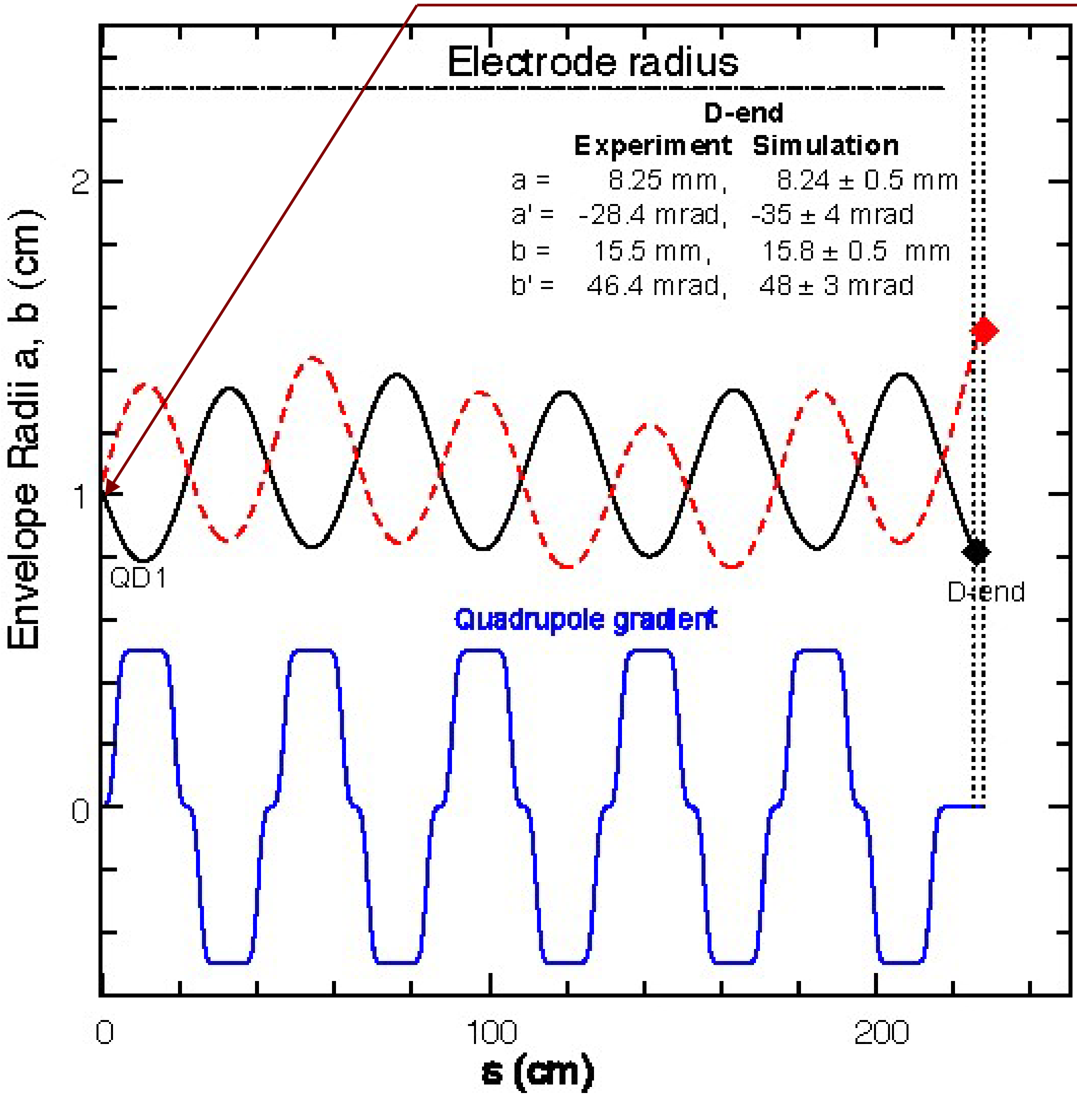
ESQ transport

Diagnostic tank

Electrostatic Quadrupole Transport section

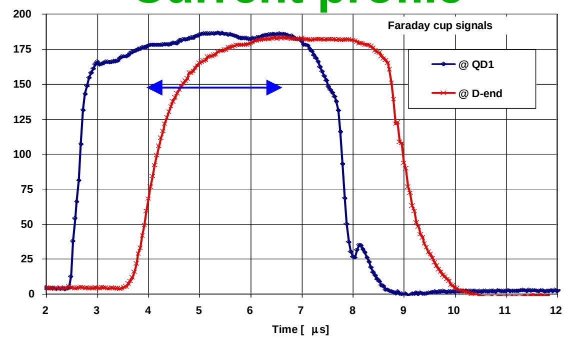


Measured HCX envelope at the end of 10-quad transport is close to predictions



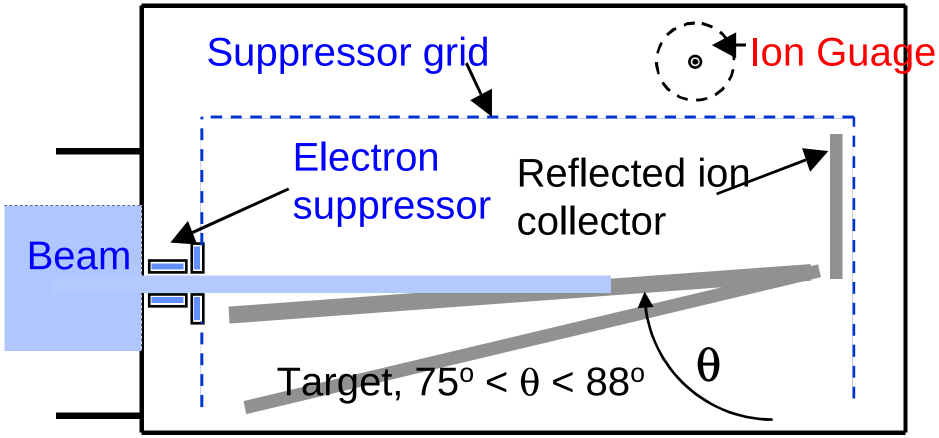
Predicted envelope initialized with I, ε, a a', b, b' measured at QD1

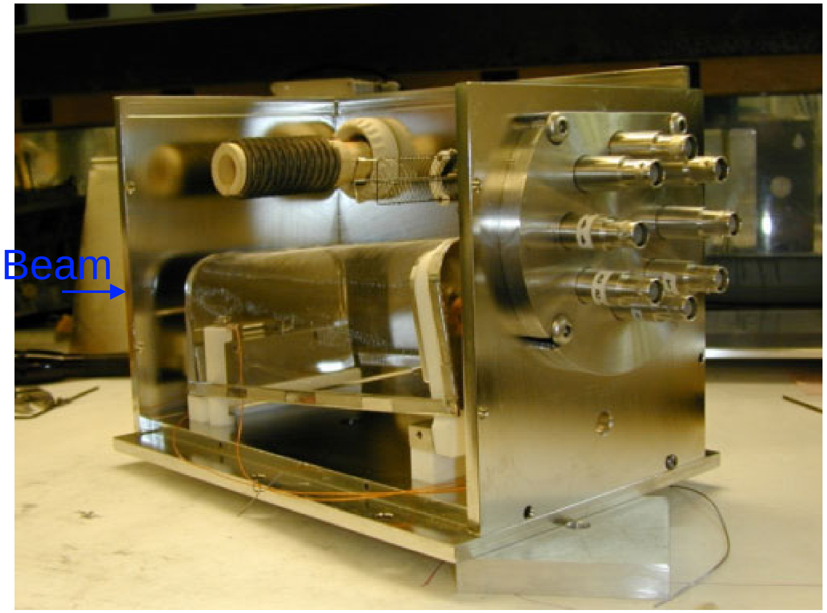
Current profile



First results: No measurable emittance growth (±10%) and < 2% beam loss through 10-quad section with beam filling factor of 0.60.

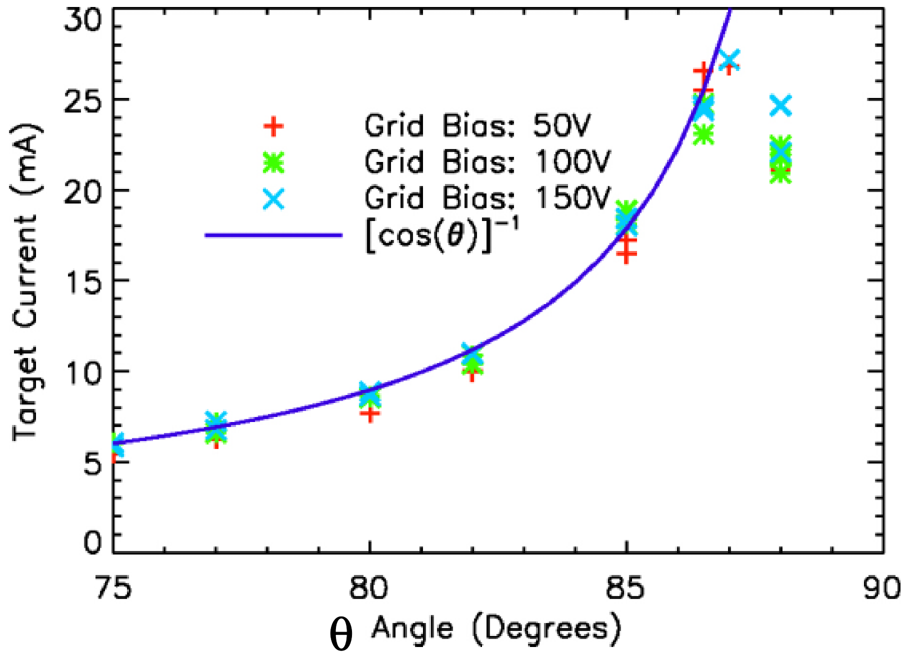
Gas and Electron Source Diagnostic (GESD) measures gas desorption and secondary electron and ion emission





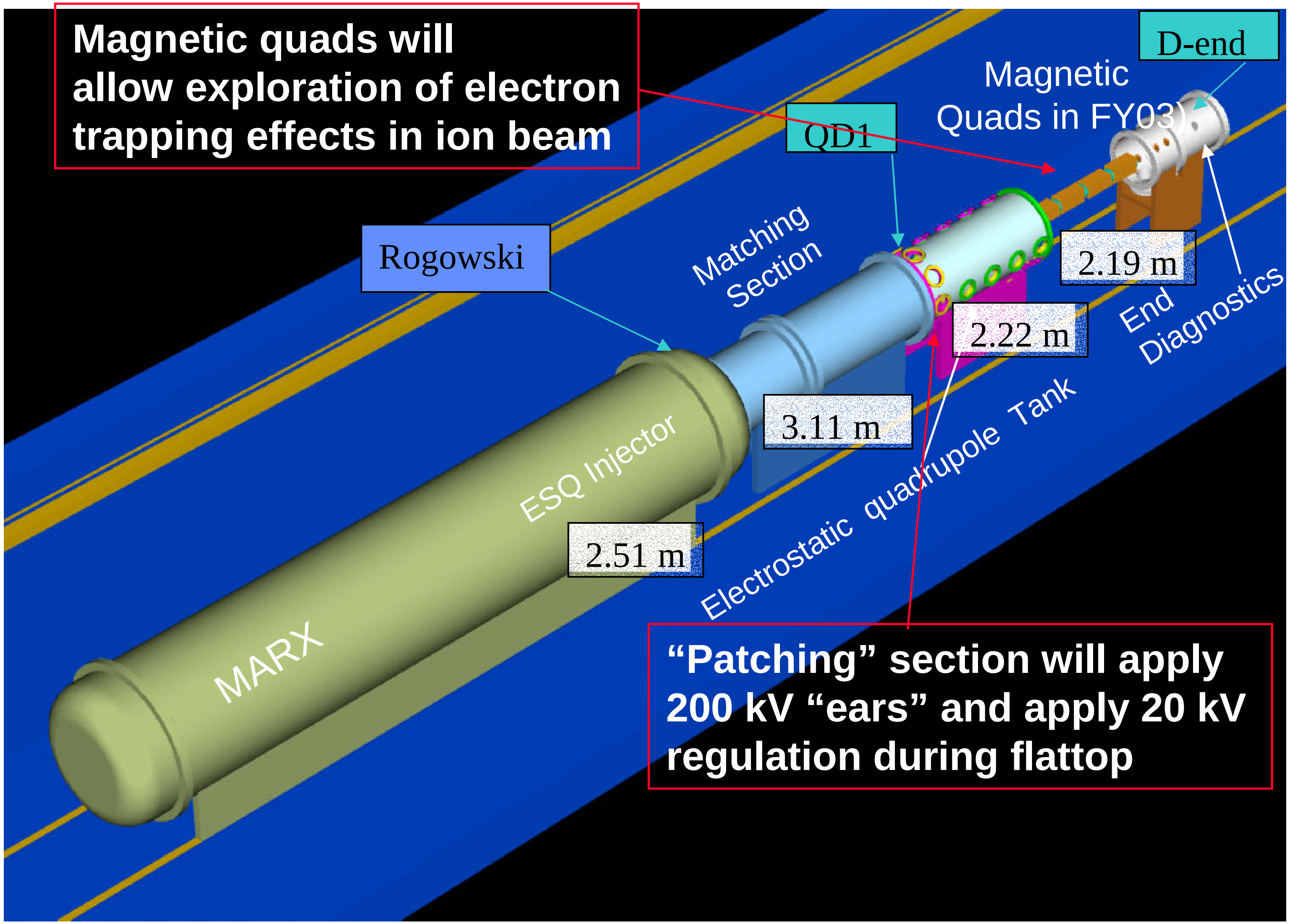
The secondary emission coefficient η has been measured:

η~ 40 at 75° from normal
~185 at 88° (grazing incidence= 90°).
~ [cos θ] $^{-1}$ as theory* predicts.



*Theory: H. Seiler, J. Appl. Phys. 54 (11), Nov 1983

Next on HCX: 4 pulsed magnetic quads and "ear" modulator in current fiscal year



3. Post Acceleration: Neutralized Transport Experiment (NTX)

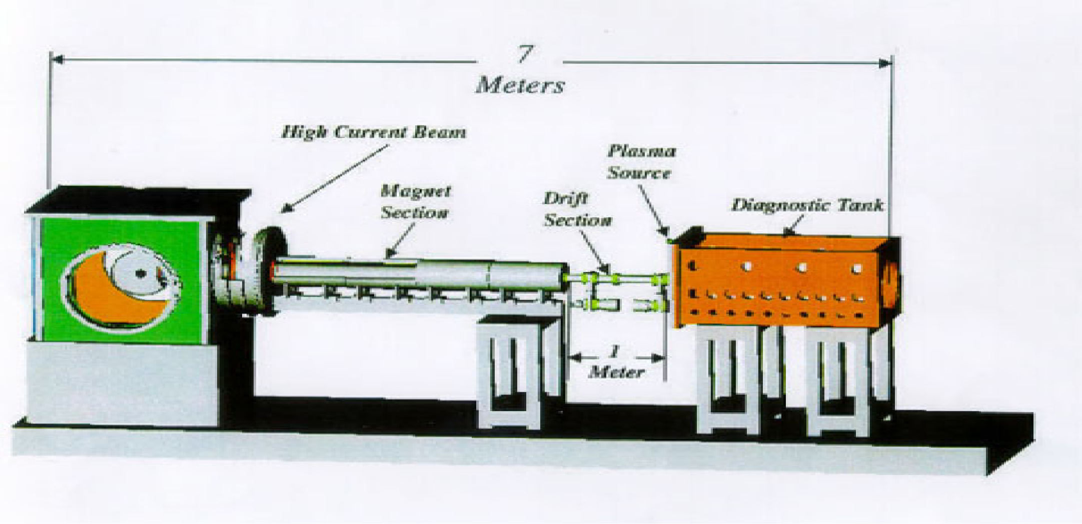
Parameters: 400 kV, 75 mA, 4 μs, K^+

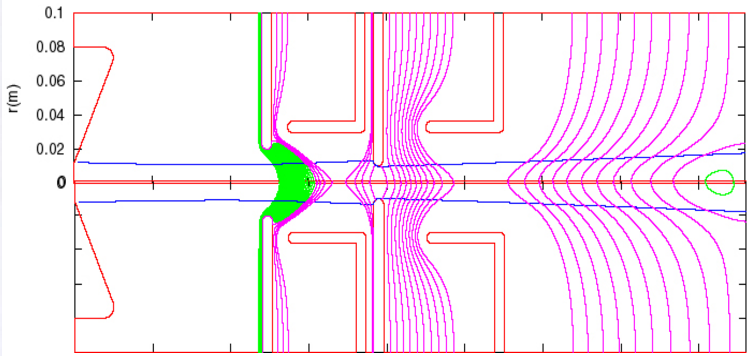
Mission:

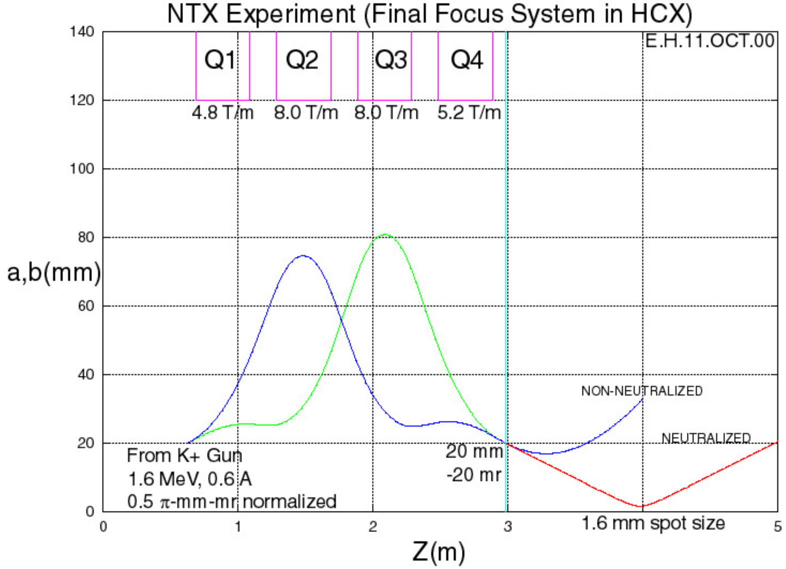
To study neutralized final transport in the chamber, from a "plasma plug," a "volumetric plasma source" and from beam-generated ionization

To investigate geometric aberrations of the beam from magnet fringe fields (B_z and pseudo-octupole), non-paraxial effects and correction schemes (octupoles)

Neutralized Transport Experiment (NTX) will test beam neutralization in chamber

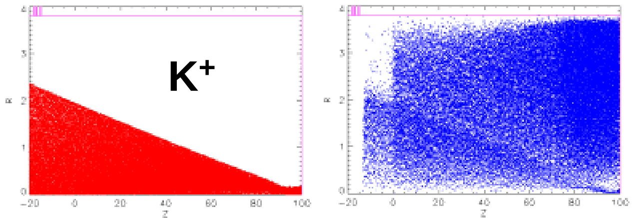




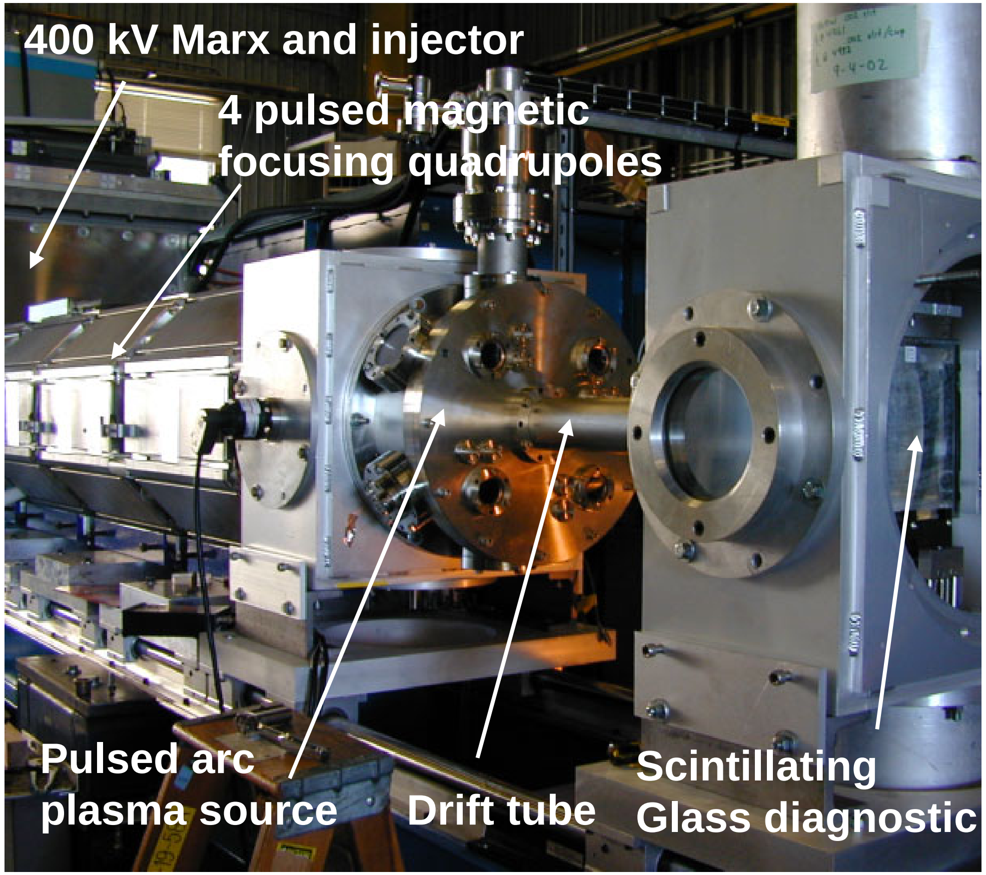


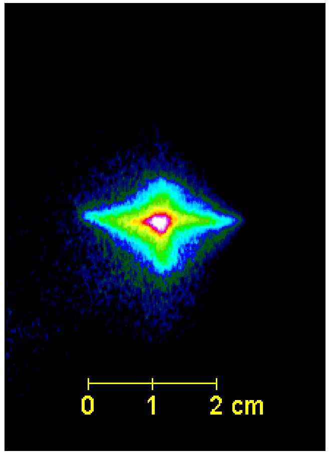
NTX will conduct a scaled experiment with perveance (10^{-4} to 10^{-3}) similar to a driver (Perveance ~ Current/Energy$^{3/2}$)

Simulations predict 99% neutralization

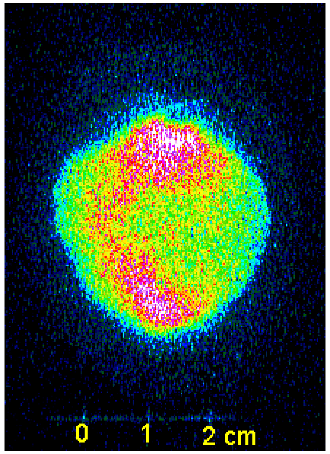


First beam through neutralized drift section with plasma plug (September 6, 2002)



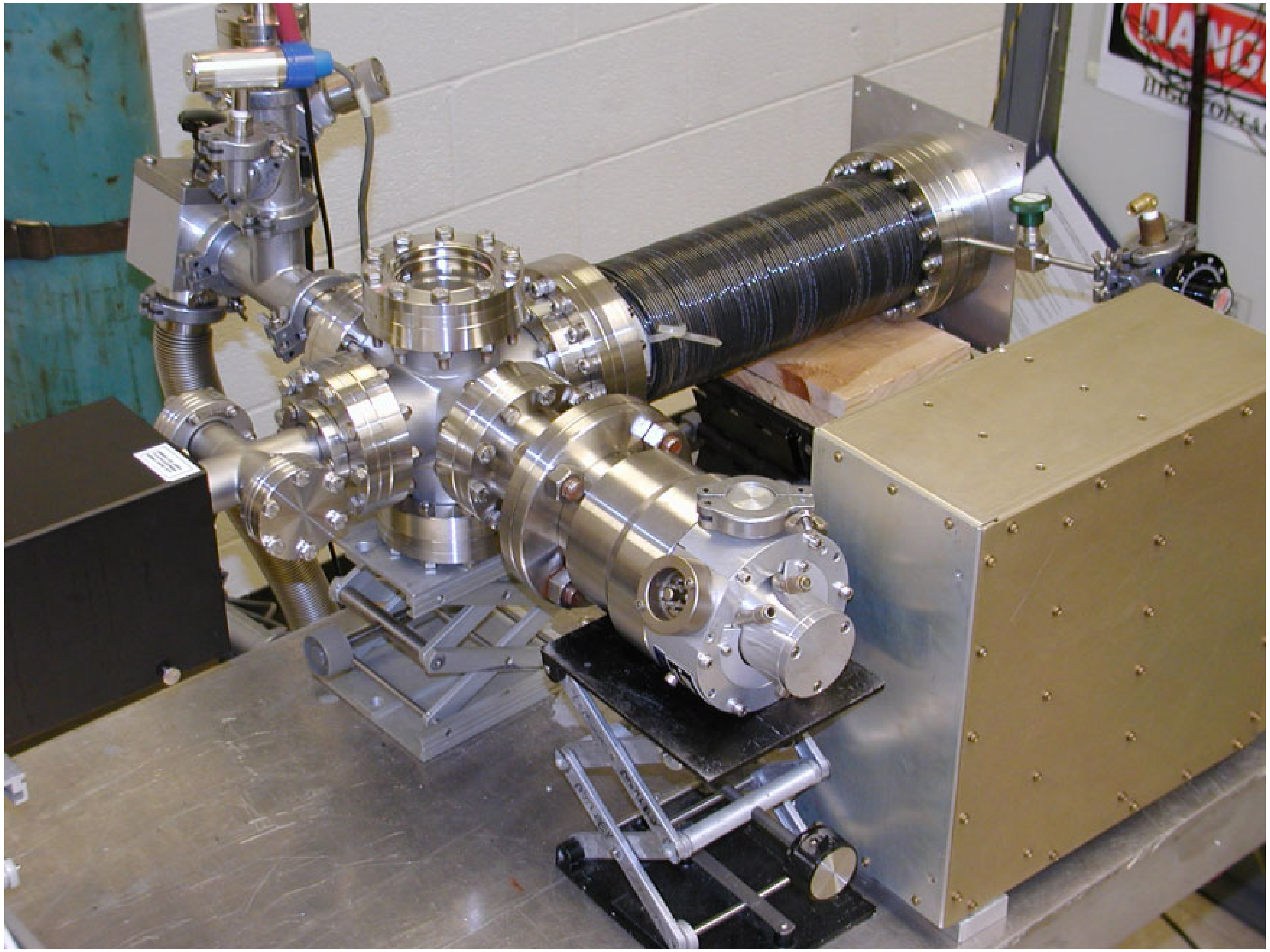


Focal spot with plasma plug

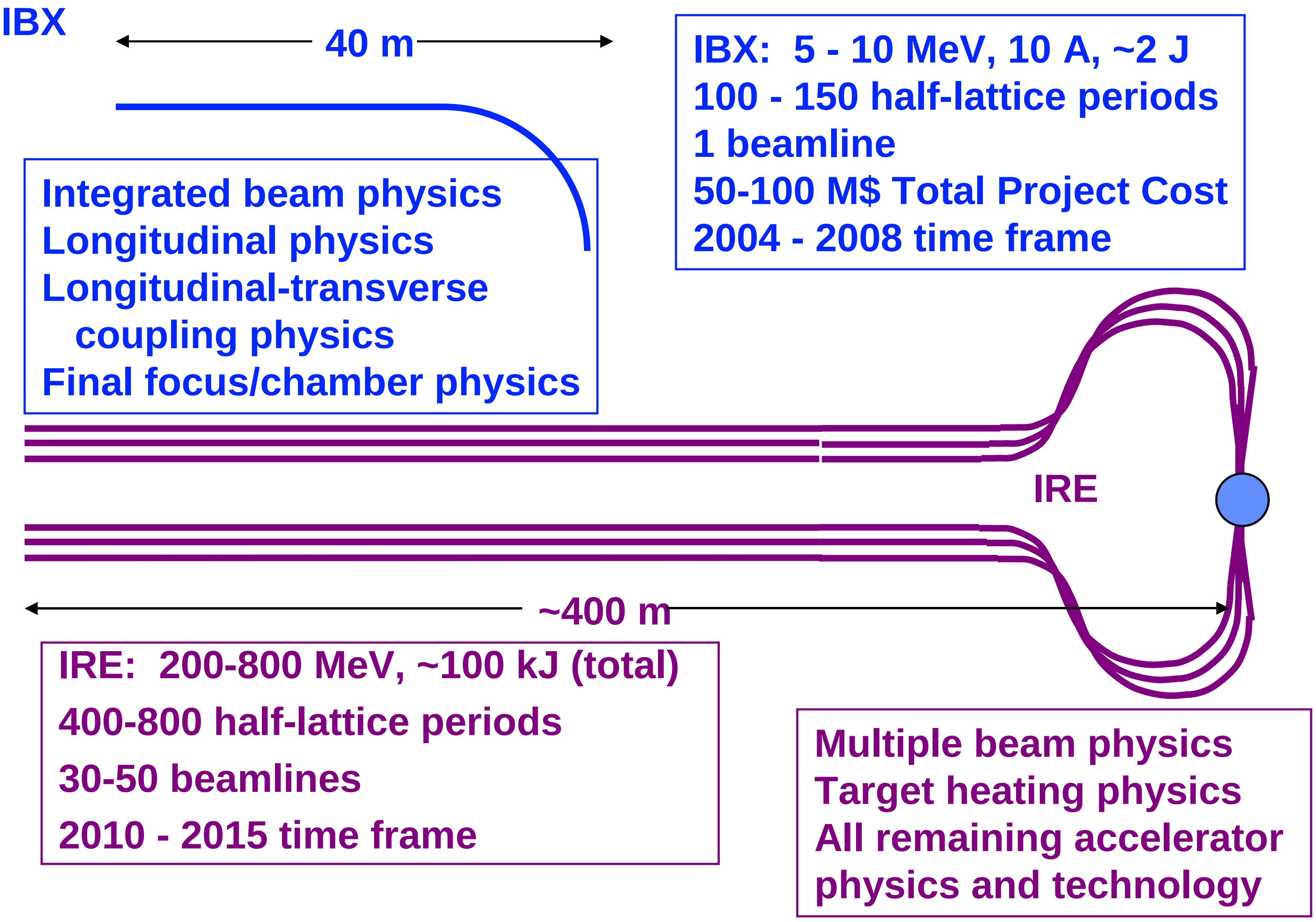


Focal spot without plasma plug

PPPL ECR Plasma Source will be installed on NTX this fiscal year (for volumetric plasma and gas effects)



Future plans: the Integrated Beam Experiment (IBX) and the Integrated Research Experiment (IRE)



IBX: 5 - 10 MeV, 10 A, ~2 J
100 - 150 half-lattice periods
1 beamline
50-100 M$ Total Project Cost
2004 - 2008 time frame

Integrated beam physics
Longitudinal physics
Longitudinal-transverse coupling physics
Final focus/chamber physics

IRE: 200-800 MeV, ~100 kJ (total)
400-800 half-lattice periods
30-50 beamlines
2010 - 2015 time frame

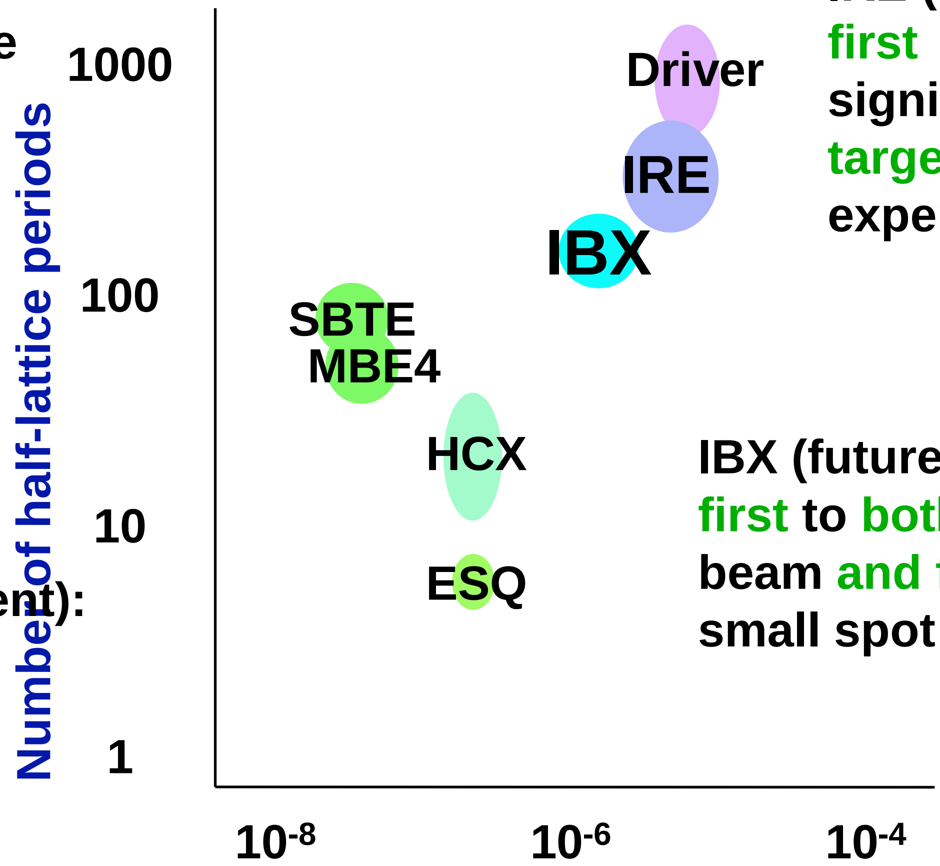
Multiple beam physics
Target heating physics
All remaining accelerator physics and technology

HIF research in the US is evolving from scaled beam science, to driver-scale, integrated experiments

SBTE (1980's):
stability of space-charge dominated beams

MBE-4 (80's and 90's):
multiple beams and simple pulse compression

HCX and ESQ (present):
line charge comparable to initial line charge in driver; electron effects



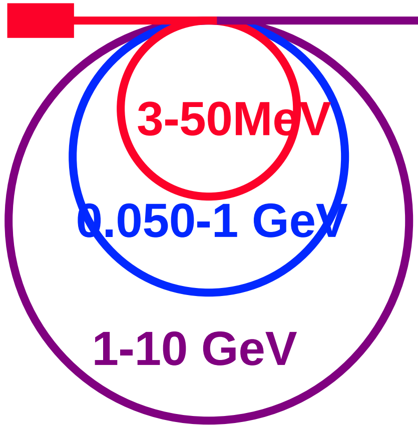
Final line charge density of a single beam (C/m)

IRE (future):
first significant target heating experiments

IBX (future):
first to both compress beam and focus to a small spot

In 1991 LLNL/LBNL/FMT published study of recirculating induction accelerators as drivers for HIF

Linac is currently main focus of US HIF VNL program, however, in order to focus on one approach and minimize dilution of resources



2 km circumference of High Energy Ring

4 beams throughout;

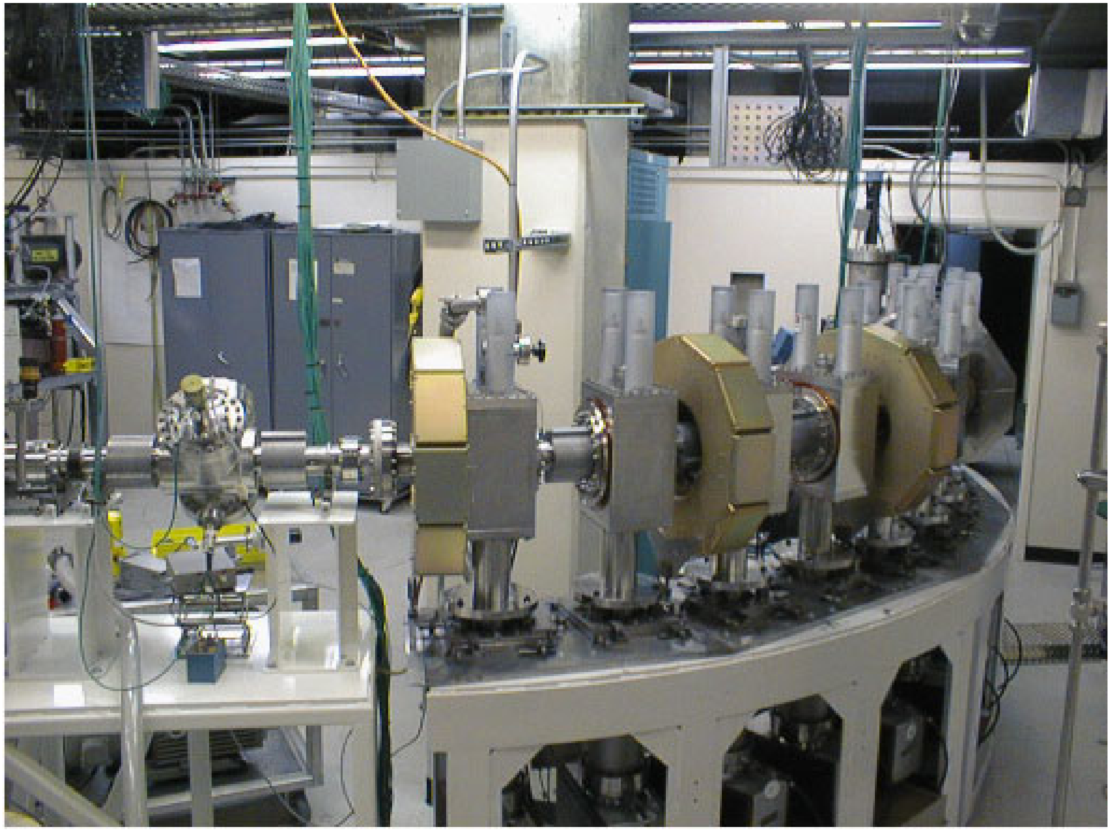
Ion mass = 200; ion charge=+1; 4 MJ total;

Each beam: 10 kA, 10 ns at target;

Main physics issues:
1. **Resonance crossing/ beam steering and control**
2. **Vacuum instabilities (residence time 3-16 ms in each ring)**
3. **Energy loss in magnetic dipoles**

Solid state FET's chosen for pulse power:
- **Repetition rate 2-50 kHz**
- **Pulse duration 200 μs (Low Energy Ring) - 250 ns (High Energy Ring)**

In mid-90's LLNL/LBNL constructed 1/4 of "small recirculator" testing beam physics and technology

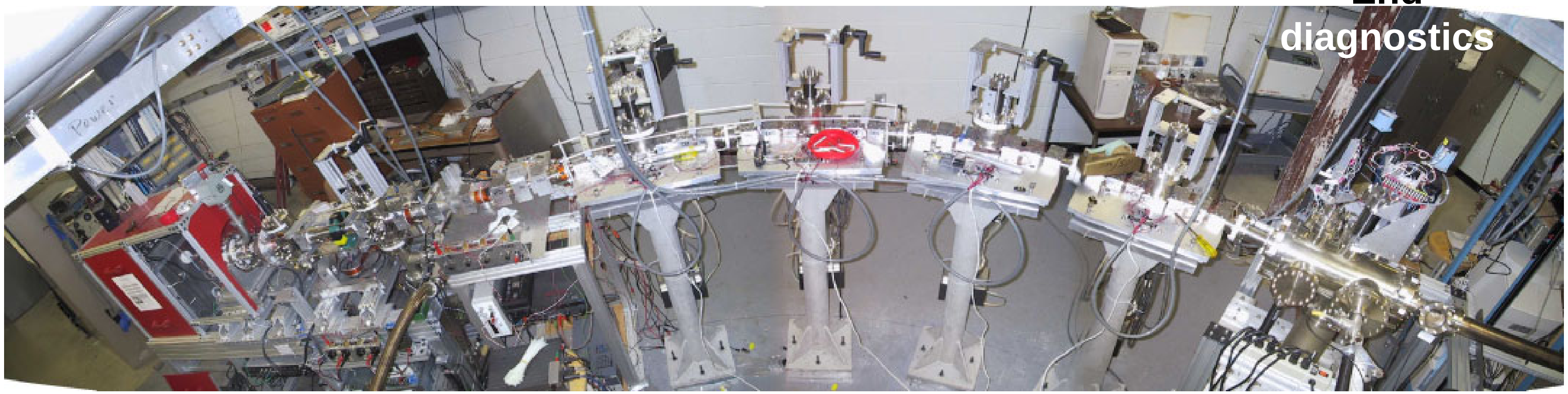


Bending and recirculation experiments:
2 mA, 80 kV, K^+

Studied coordinated bending and acceleration of space charge dominated beam in induction accelerator; beam sensing and steering.

Ring not completed to consolidate research program onto linacs

Last few years: University of Maryland Electron Ring (UMER) (currently at 90 degrees)



10 keV, 100 mA electron gun

Matching section

90 deg segment of ring dipoles and quadrupoles (18 hlps)

Topics to be addressed by UMER:

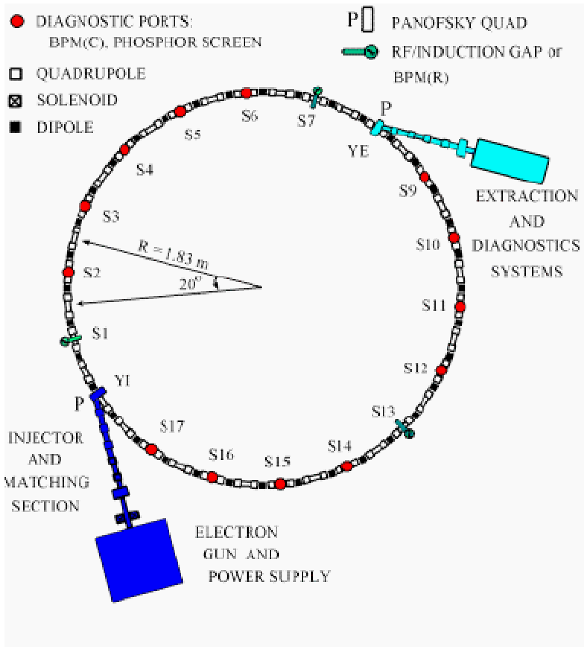
Induction gap confinement and bunch-end effects (with three ± 1.5 keV induction cells, by next summer)

Space-charge waves – longitudinal/transverse coupling

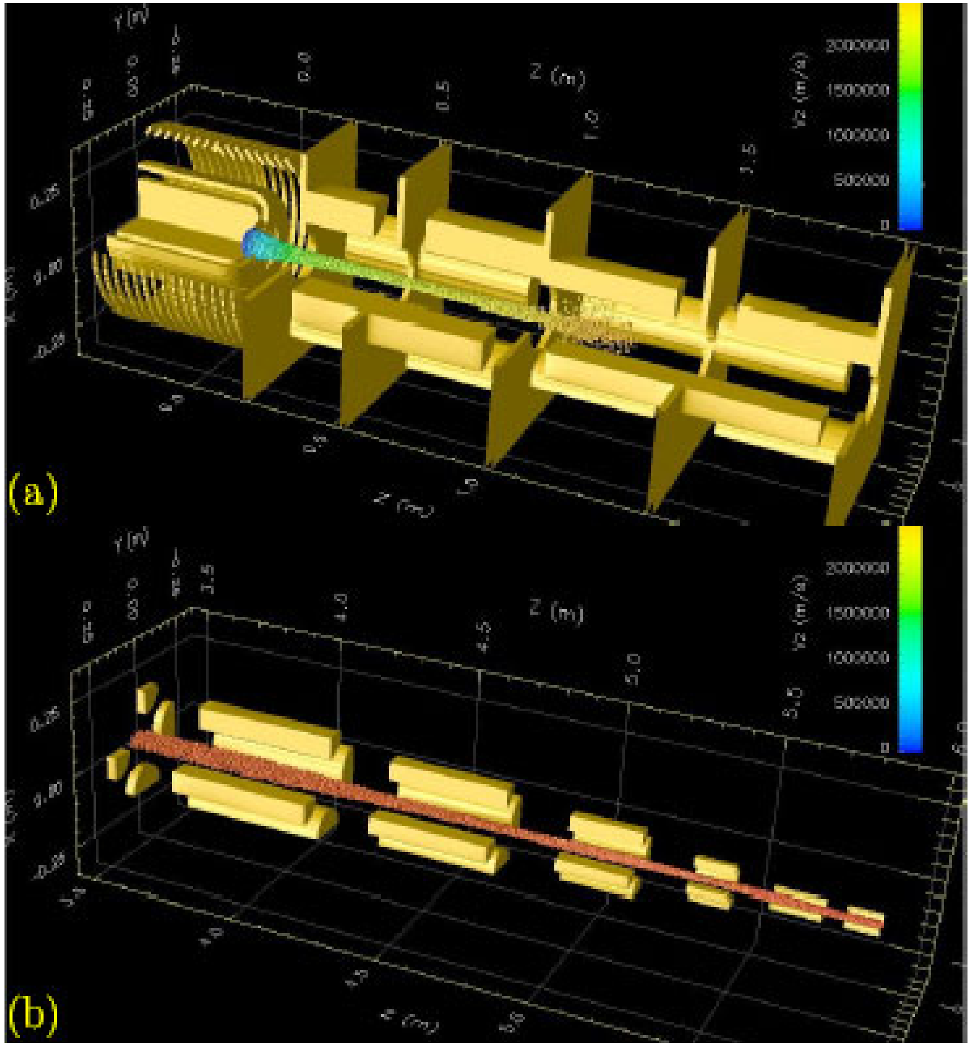
Equilibrium distributions, mixing, & stability

Halo formation

Induction acceleration and resonance traversal



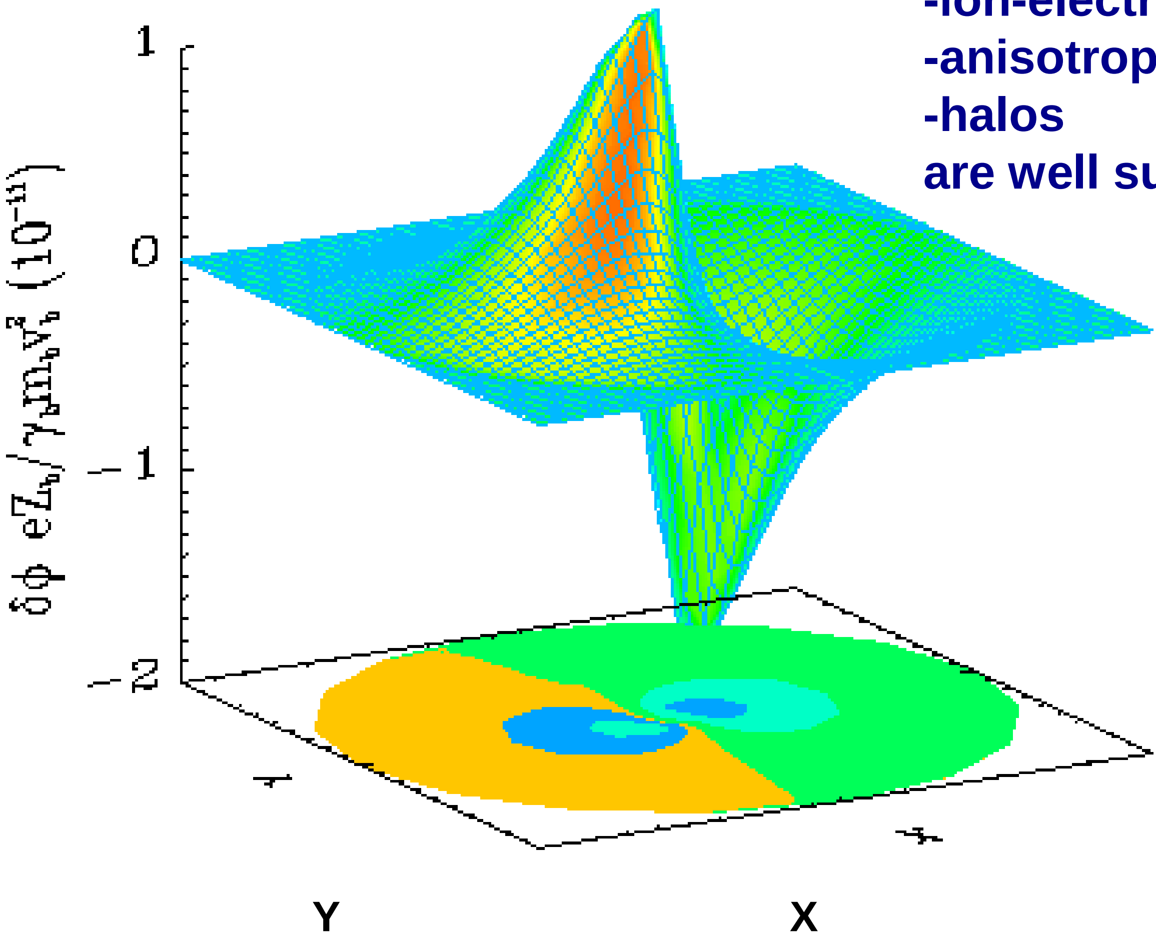
WARP (2-D or 3-D, time-dependent) particle-in-cell code models all of the experiments



(a) Time dependent 3-D WARP simulation of the MeV HCX beam accelerating through the Electrostatic-Quad Injector. Note the radial spread of mismatched particles in the head of the beam.

b) Mapping a midpulse-slice (2-D) of the HCX beam passing from region (a) into the matching section and through the transport line.

BEST code (a 3-D nonlinear perturbative (δf) particle code) for “beam equilibria, stability, and transport”



Stability studies such as:

-ion-electron instabilities

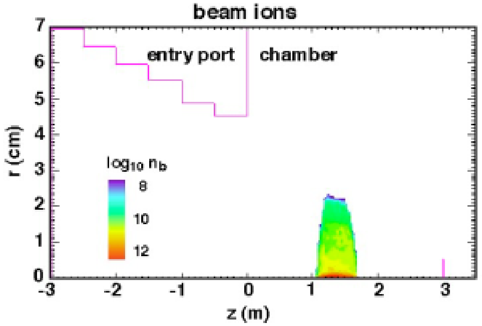
-anisotropy instabilities

-halos

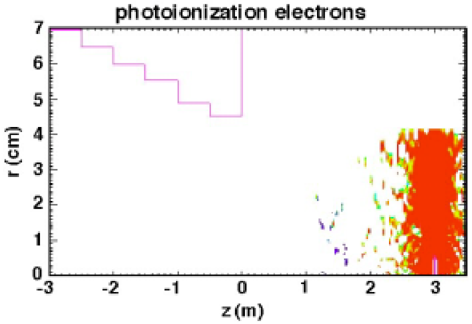
are well suited for BEST

BEST simulation of two-steam instability with electron density 10% that of the beam, showing perturbed potential over the X-Y beam cross section.

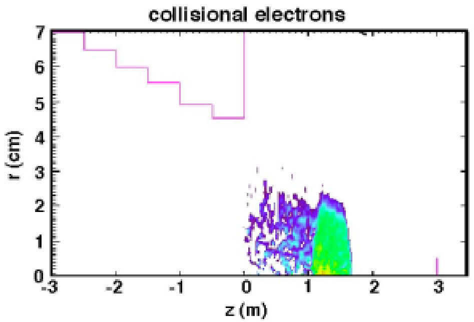
LSP (large scale plasma) is a 3-D particle/fluid hybrid code (by MRC) used for chamber propagation studies



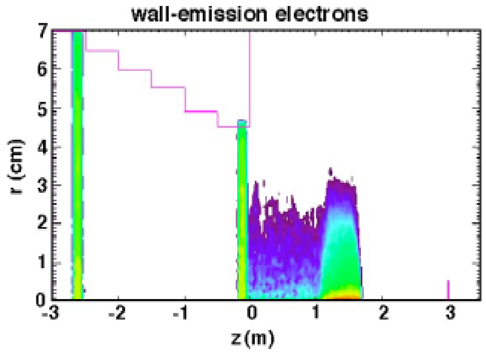
Snapshot of beam ions about halfway into chamber



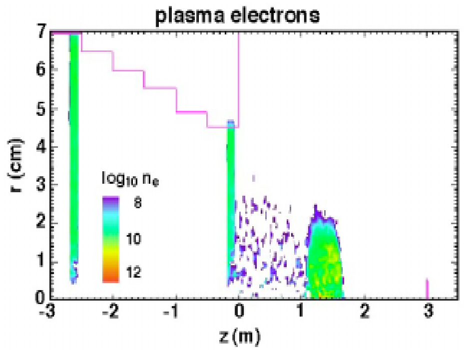
UV photons emitted by target photo-ionize chamber gas



Chamber gas ionized by beam ion impact

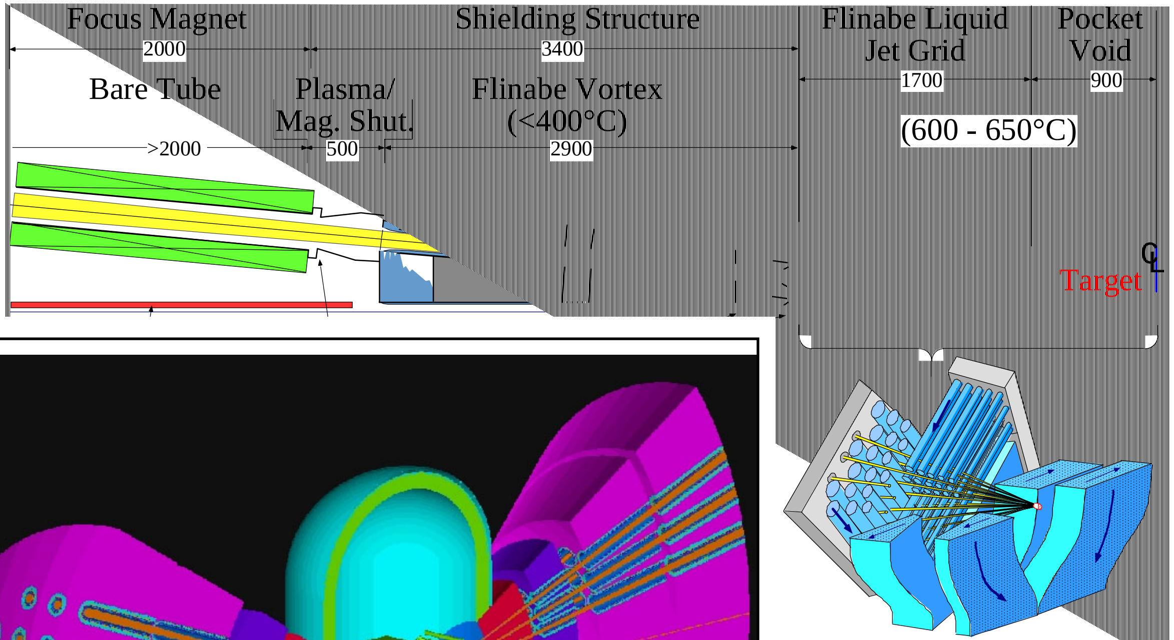


Beam space charge pulls in wall-emitted electrons



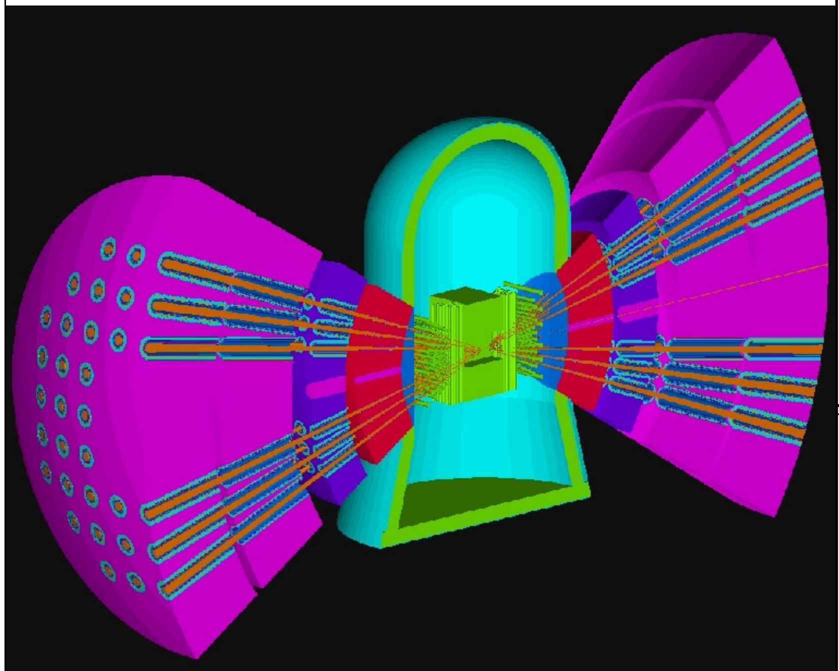
Beam passing through pre-formed plasma “plug” layers can pull in electrons

A study to create a “Robust Point Design” of a self-consistent HIF power plant is nearing completion

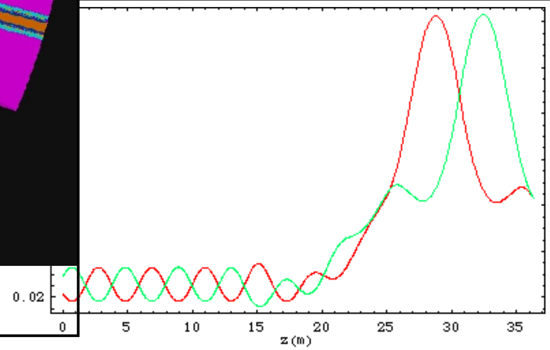


Schematic Liquid Jet Geometry

Chamber dynamics

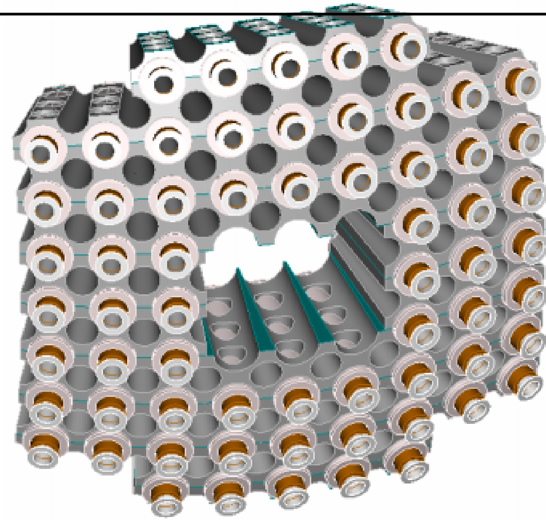


3 D neutronics calculations



Final beam optics

- Ion: Bi^{+} (A=209)
- Main pulse: 4 GeV
- Foot pulse: 3.3 GeV
- 120 beams total (72 main, 48 foot)
- Pulse energy: 7 MJ
- Final spot radius: 2.2 mm



Mechanical engineering

+ target physics + chamber propagation

Conclusion

US Heavy Ion Fusion accelerator program is addressing 3 critical areas in the development of a driver:

1. **Source/injector development (STS100 and STS500)**
2. **Low energy transport (at high line charge density) (HCX)**
3. **Neutralized Ballistic Focusing (NTX)**

Induction recirculator research is not currently pursued in the VNL but UMER research goes forward

Theory and simulation program goal is source-to-target modeling

Future experimental program focused on IBX, (and later on IRE)