A Multi-beamlet Injector for Heavy Ion Fusion: Experiments and Modeling

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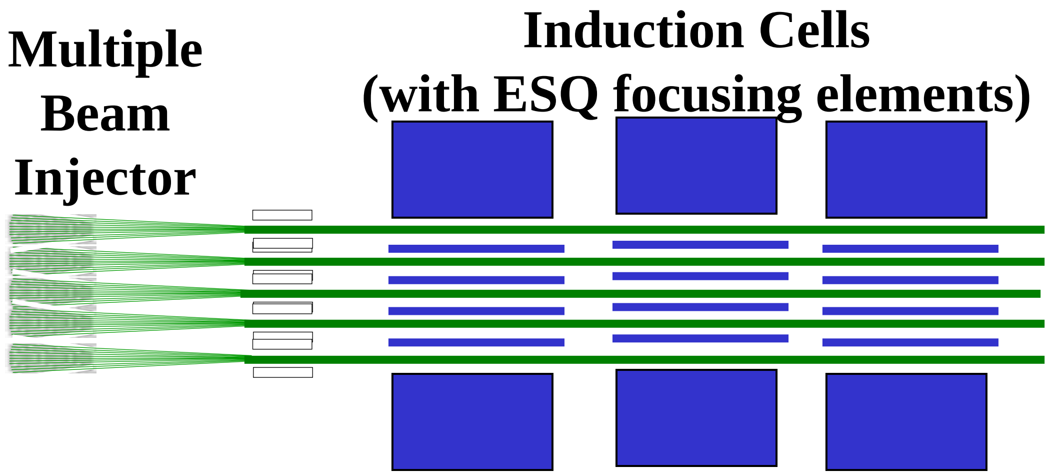
In our proposed Heavy Ion Fusion driver we accelerate ~ 100 heavy ion beams to ~ 8 GeV. All beam pass through each induction cell.

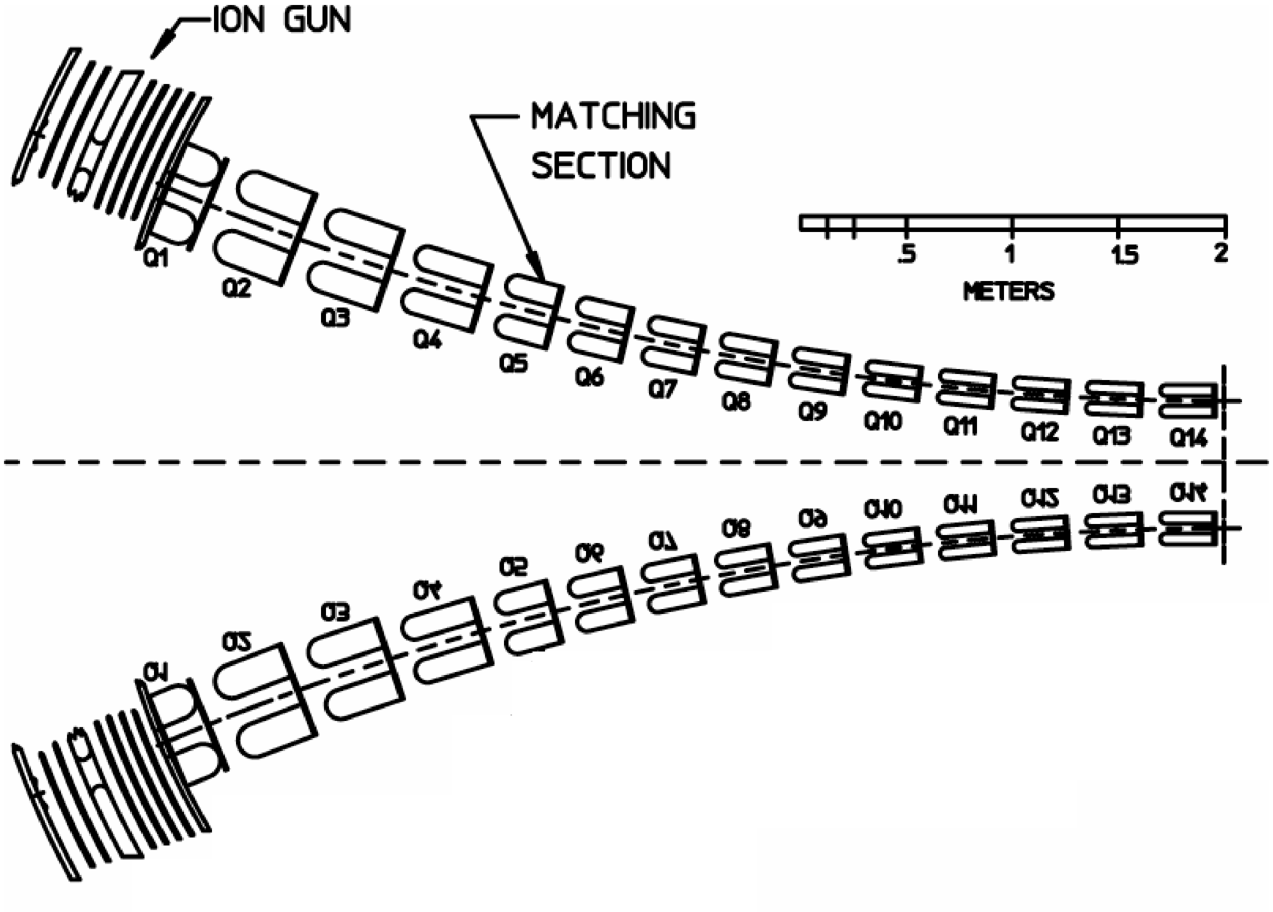


At the injector, each beam has ~ 1 A of current, and is ~ 20 μs in duration. Heavy ions are chosen to couple energy to the target without having large space charge fields in the final focus.

Our challenge is to provide a suitable compact ion source.

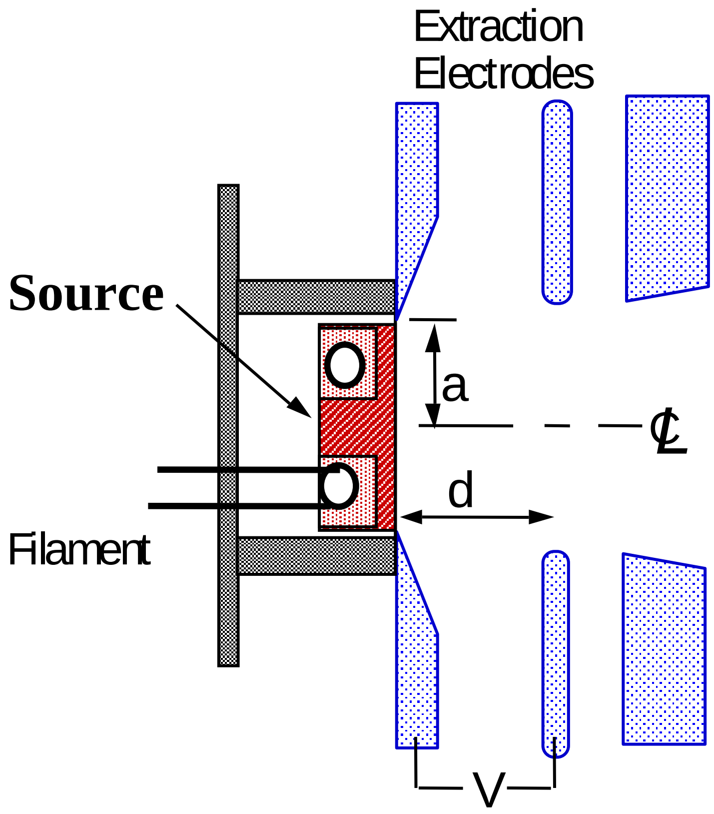
“Funneling” 100 large sources does not work well.

A surface-ionization source produces alkali metal Ions, $J \leq 20$ mA/cm^2.



Beam extraction scaling law

$$J_{CL} = \chi \frac{V^{\frac{3}{2}}}{d^2} \qquad I_{CL} = \pi\chi\left(\frac{a}{d}\right)^2 V^{\frac{3}{2}}$$



- Space-charge-limited flow in the extraction diode is governed by Child-Langmuir equation.
  where **$\chi = (4\varepsilon_o/9)(2q/M)^{1/2}$** with q and M being the charge and mass of the ions respectively, a is the aperture radius, d the diode length, and V is the extraction voltage.

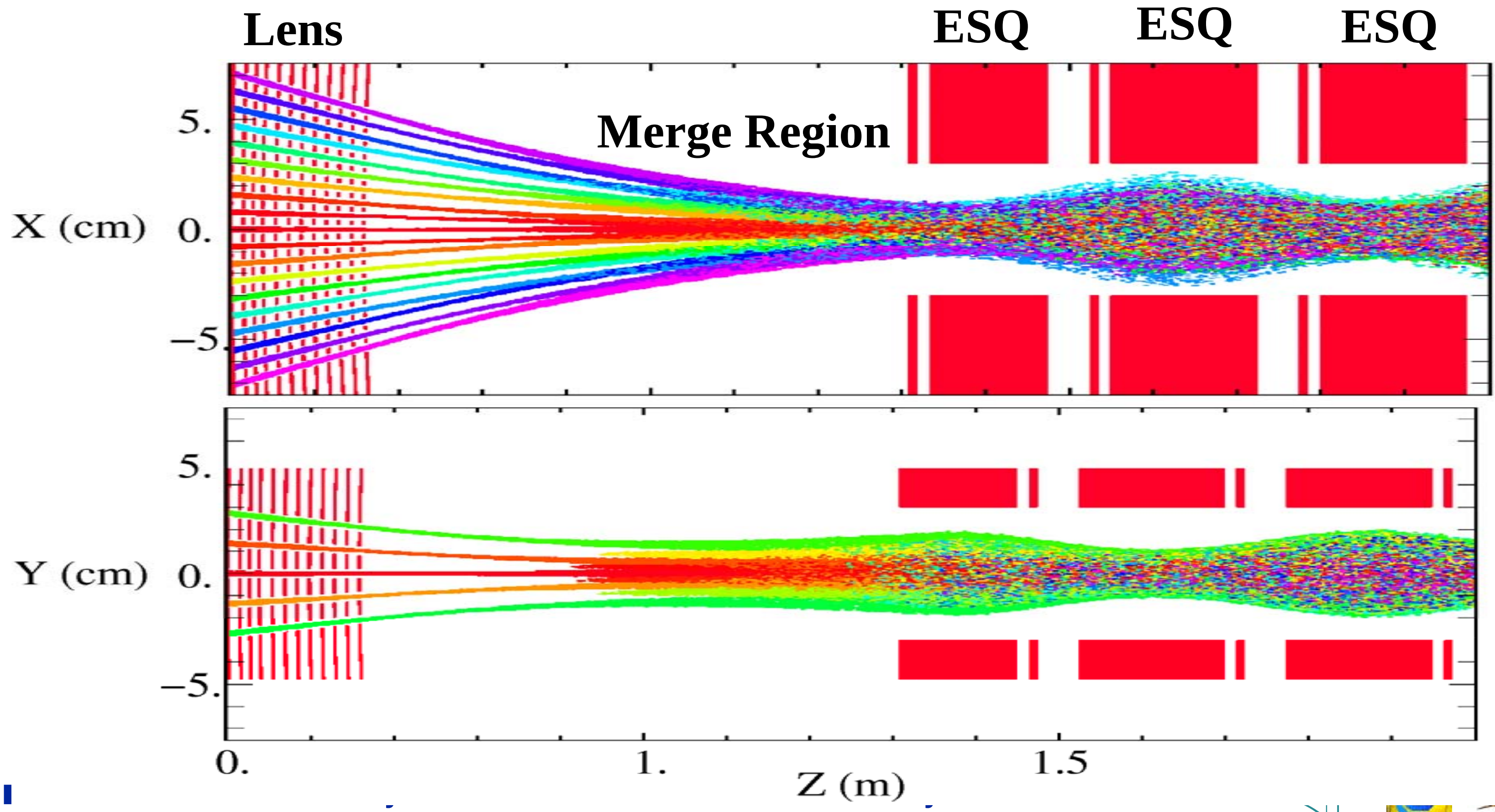
- V is limited by breakdown
  $V \sim d$ for $d < 1$ cm
  $V \sim d^{0.5}$ for $d > 1$ cm
  so large ion diode needs high V but produces low J.

- Spherical aberration depends on the aspect ratio a/d (typically < 0.5)
  thus $I_{max} \sim V^{3/2}$

- Conclusion: high current needs large V and d but results in low J, so the brightness is limited.

We propose forming each beam from ~200 beamlets.

- Beamlets are accelerated to ~ 1.6 MeV before entering the ESQs
- 200 beamlets are merged to form a 1-A beam
- Beamlets are aimed and steered to rapidly match into an ESQ channel.



We first needed to demonstrated that we could produce suitable beamlets.

- The merging beamlet approach requires a high current density ion source.

  A surface-ionization source produces alkali metal ions (with low ionization potential) from a solid surface with high work function (e.g. tungsten) at high temperature. Ion temperature $\leq$ 0.3 eV and J $\leq$ 20 mA/cm^2.

  RF plasma sources can source high current density.

- This approach can tolerate a higher intrinsic ion temperature, so there are more ion source options.

  RF plasma sources can provide many different ion species. We have measured the temperature for our source.

Issues of using an RF Plasma Source were investigated.

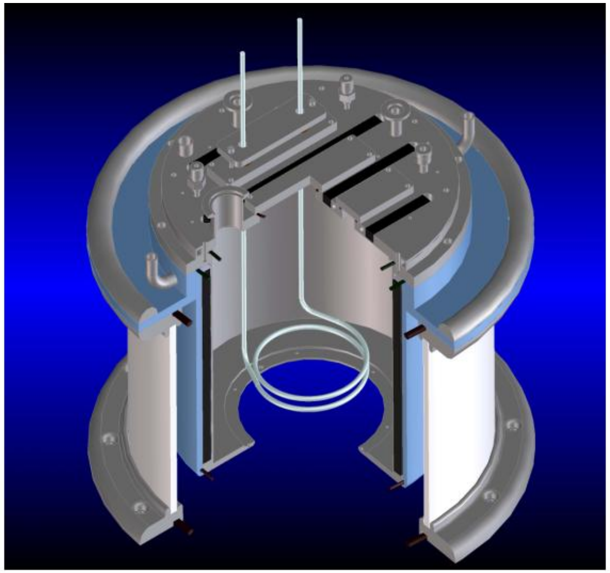
Issues	Results
Reaching high enough current density	100 mA/cm^2 (5 mA)
Obtaining a low emittance beamlet	T_{eff} < 2 eV
Charge state purity	> 90% in Ar^+
Energy spread from charge exchange	< 0.5% beam spread over 2kV (50 kV beam)

STS100

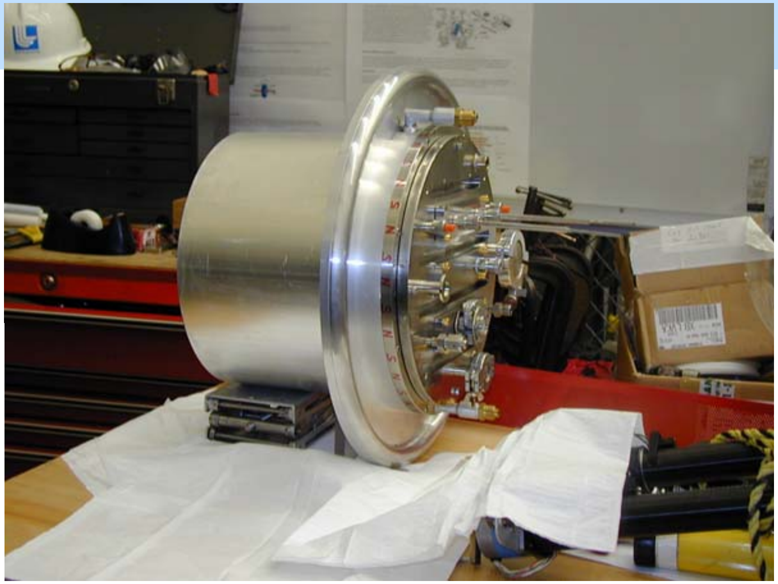
Diagnostics

Plasma chamber

Pressure: ~ 1 to 20 mTorr Argon
RF power: 4-20 kW
RF Frequency: 13.6 MHz



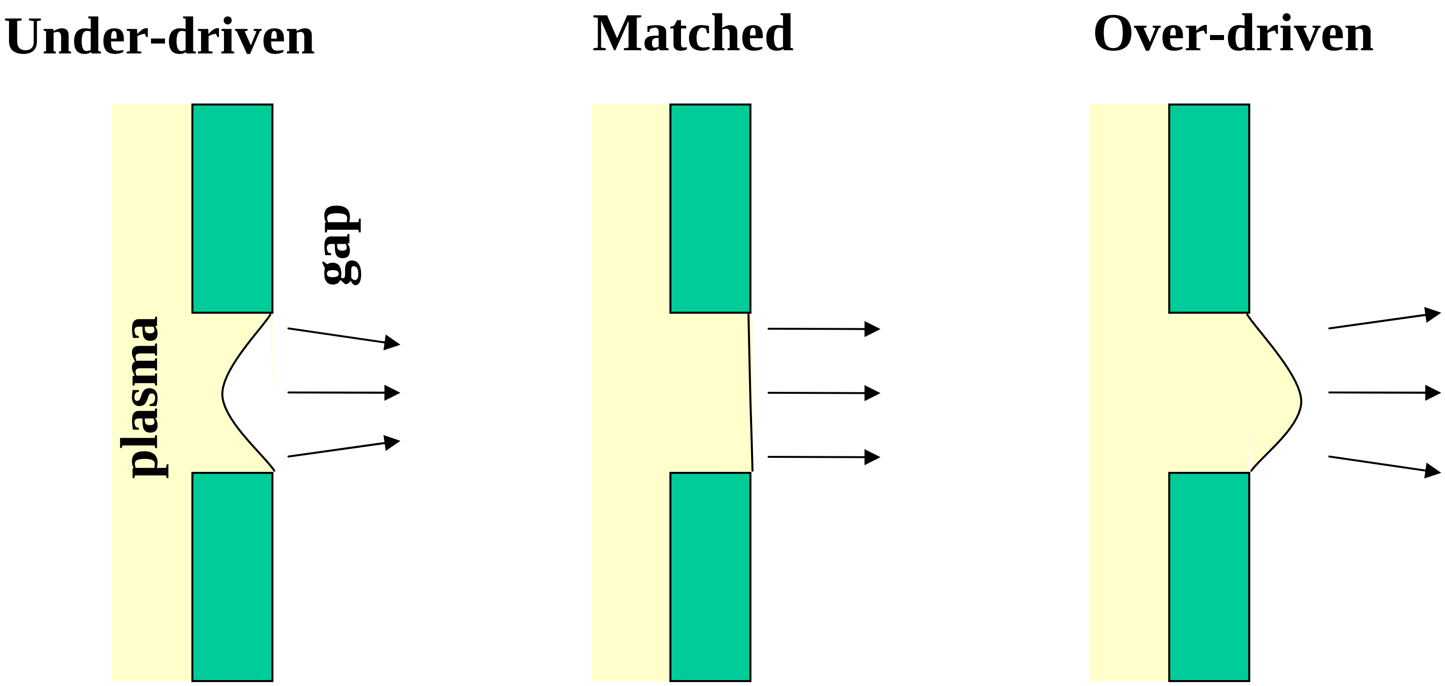
→| 14 cm |←



100 mA/cm^2

Multiple extraction holes each ~ 2.5 mm diameter

We obtained the best beamlet optics when the plasma was slightly underdriven.



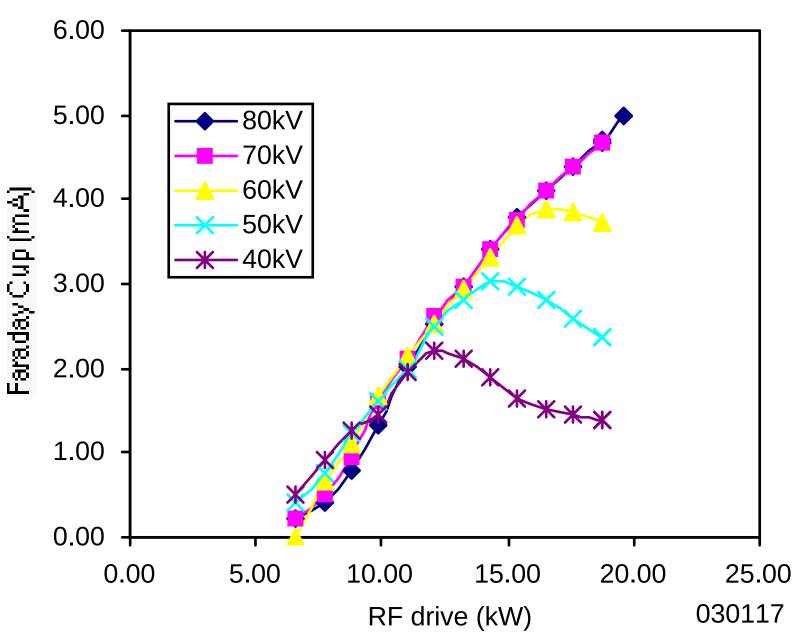
Lower current

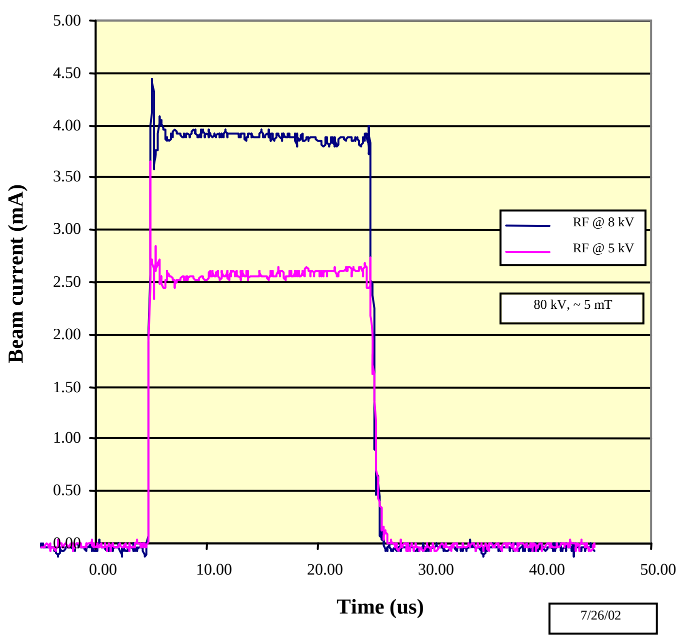
Higher emission current, but may not transport

Our Argon Plasma Source has produced beamlets at the required current density

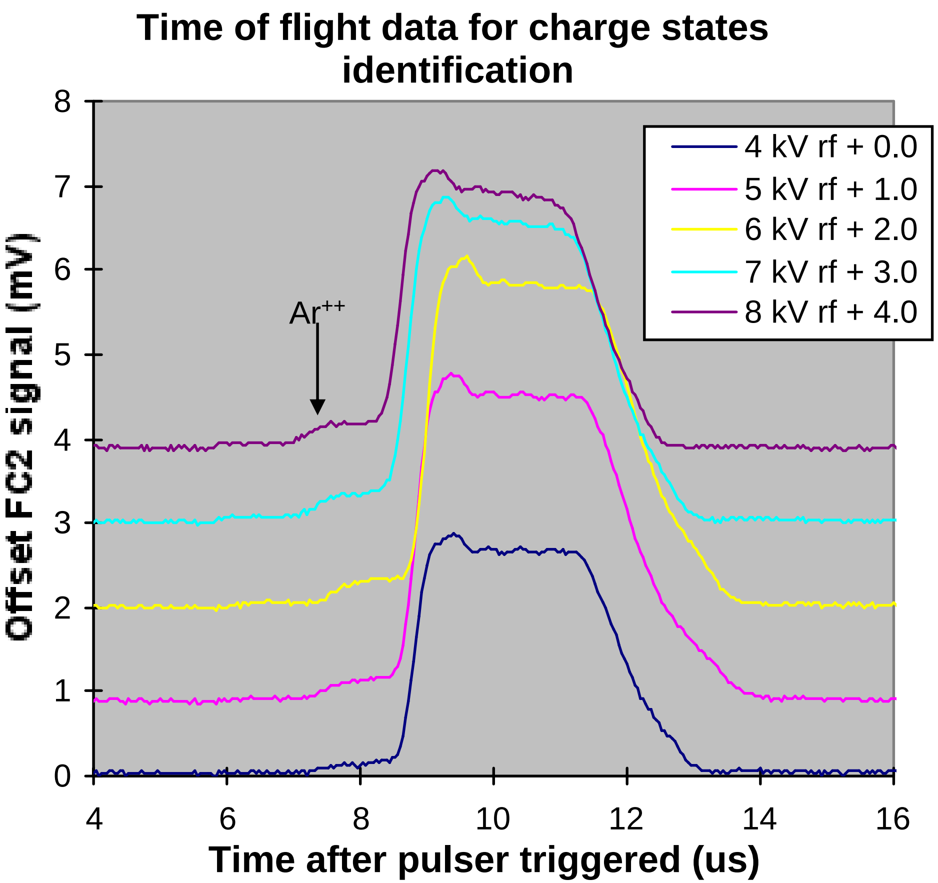
- Current peaks when the beam fills the exit aperture.
- Optimum optics at perveance = 5.3 mA / 80 kV$^{(3/2)}$

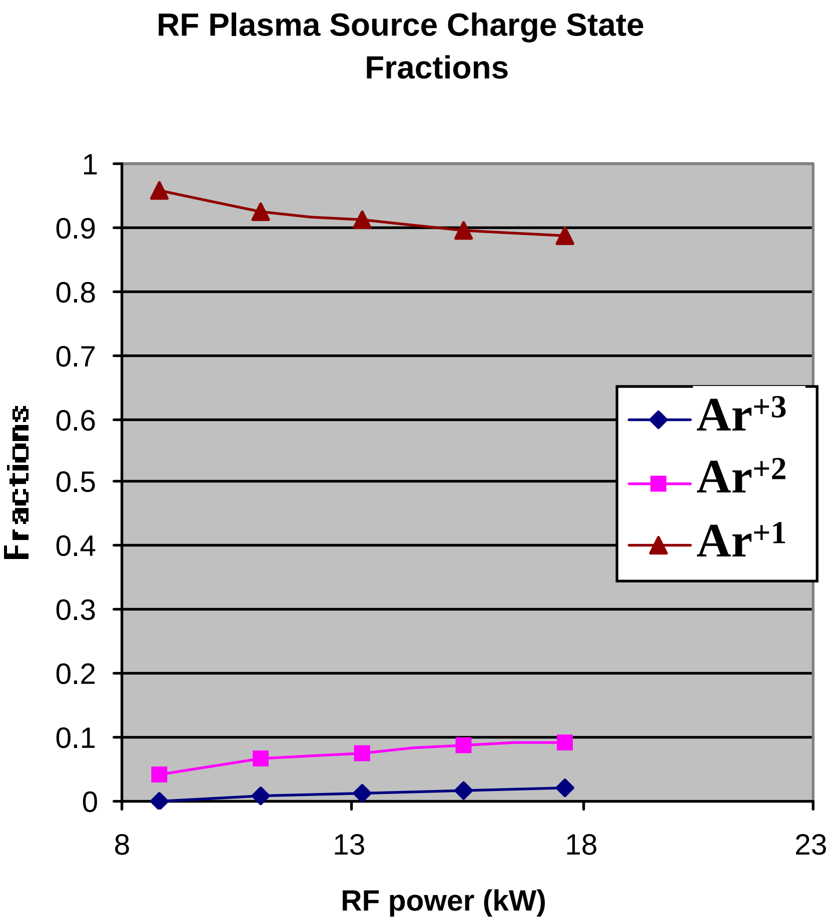
Obtained 5 mA from a ¼ cm hole
$\Rightarrow$ 100 mA/cm^2.
(compare to ~10 mA/cm^2 for a typical hot-plate source)





Used time-of-flight technique to measure charge state purity



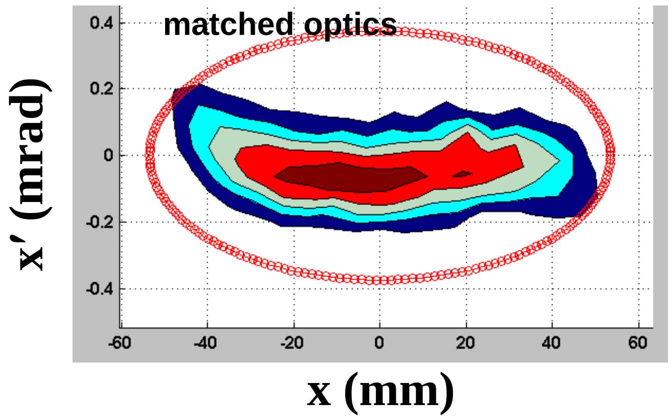


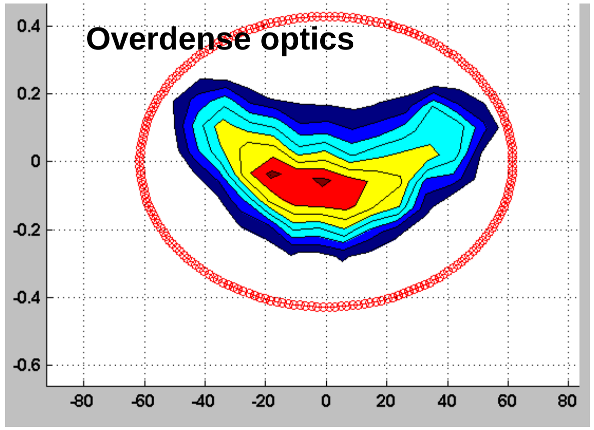
020924Zi.xls

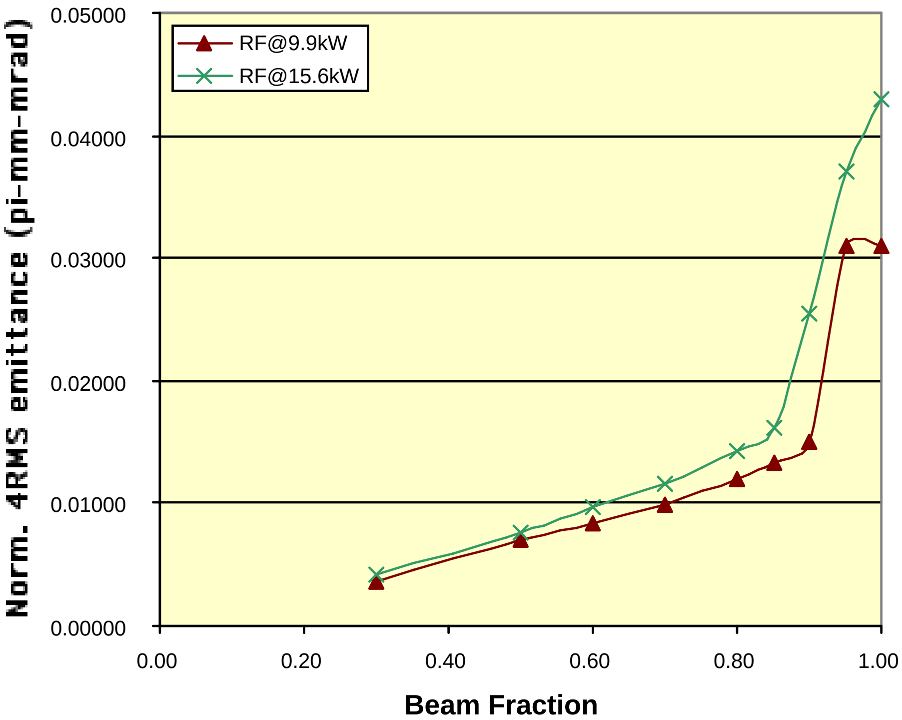
Drift ~ 1.7 m

Used to a 2-slit emittance measurement technique

- Measured emittance showed $T_{eff} \approx 2$ eV, which is adequate for use in merging beamlets.
- Possible emittance reduction by improving beam optics.





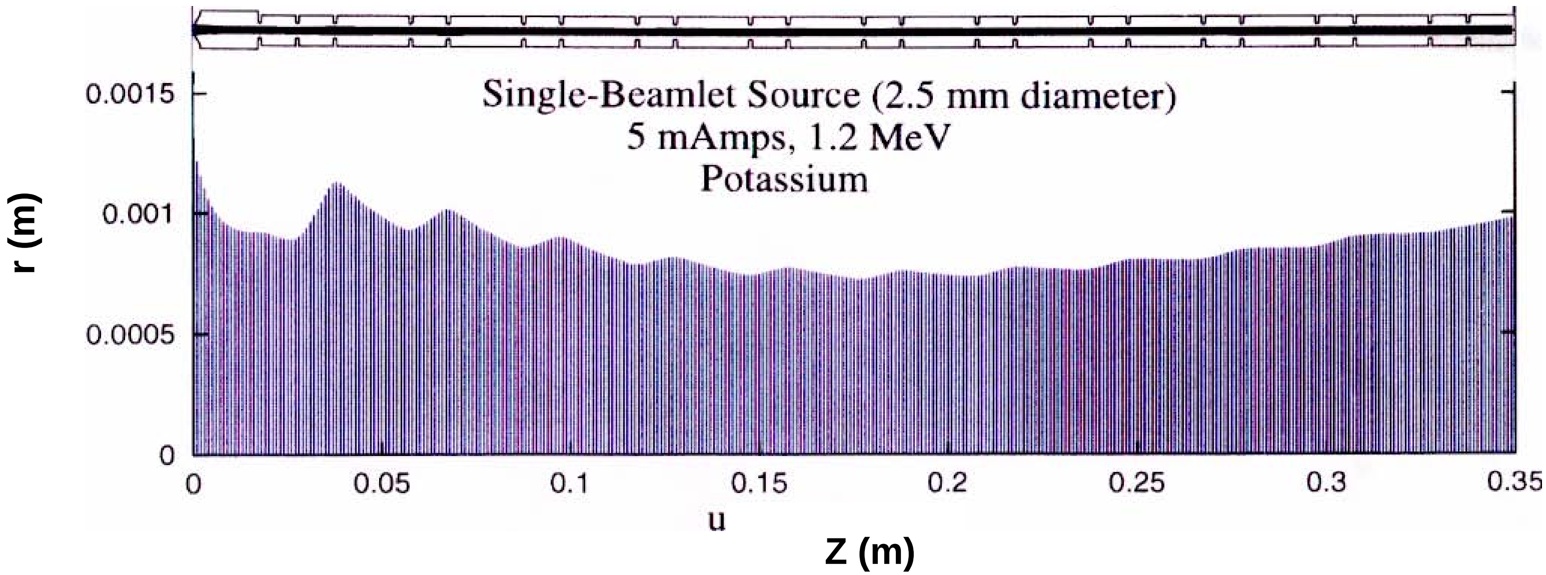


of a simulated flat source

Extraction and Acceleration of Beamlets Using Einzel Lenses

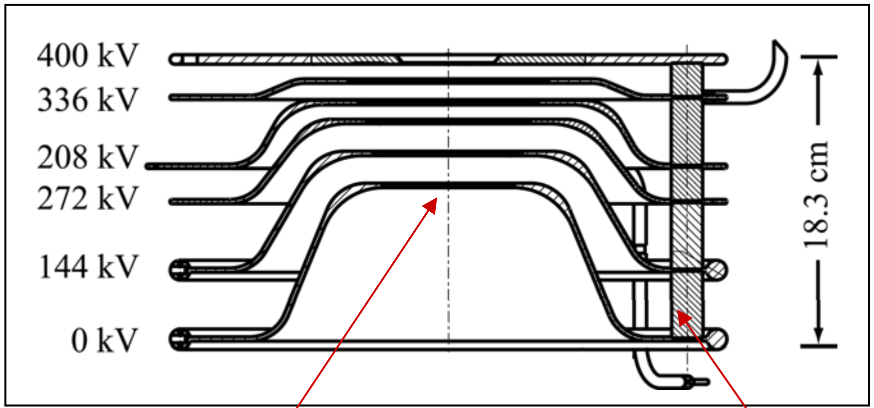
- **To minimize emittance growth, we want more than 100 beamlets, thus 5 mA (of K^+) per beamlet.**
- **The maximum current density that can be focussed by the Einzel lenses has 100 mA/cm^2 at the source aperture.**

1100 1100 1000 900 800 700 600 500 400 300 200 0kV
1000 900 800 700 600 500 400 300 200 100 0 kV



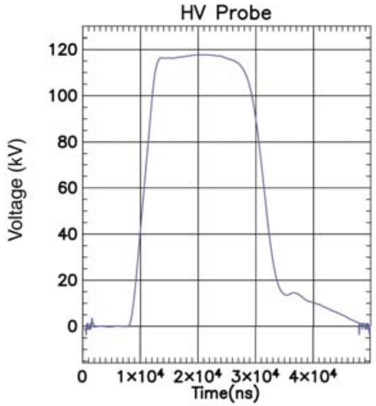
We tested the first four gaps of an Einzel Lens array at full gradient.

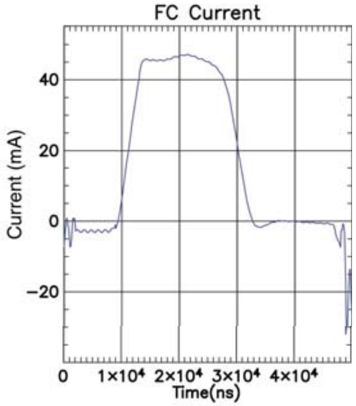
Designed for high vacuum gap voltage gradient >100kV/cm to reach >100 mA/cm^2



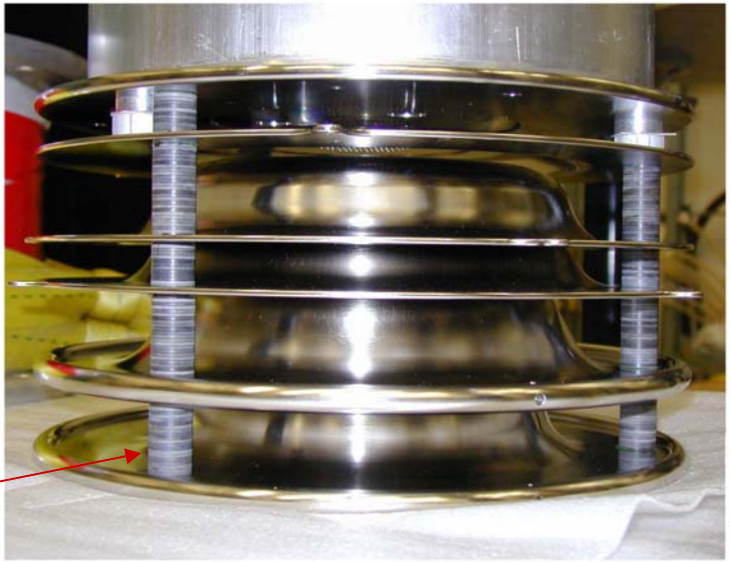
Thin stainless steel flat electrodes.

High Gradient Insulators



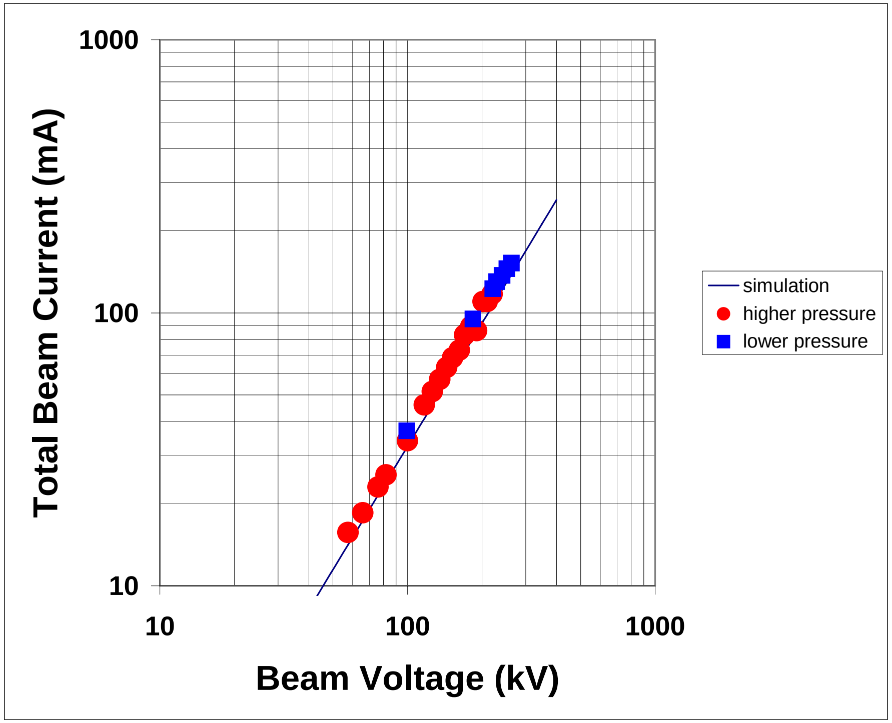


All but the last gap operated at design voltages.



Top view

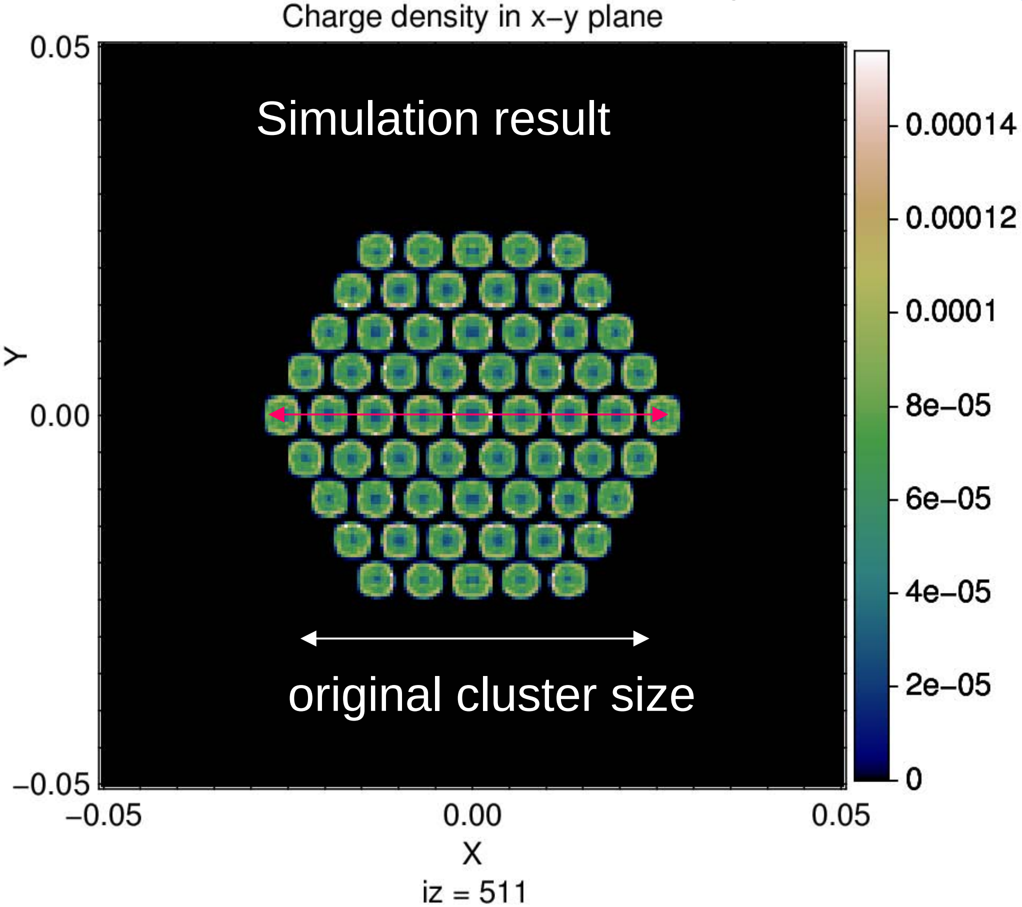
The measured beam current from the 61 beamlets scaled with extraction voltage.

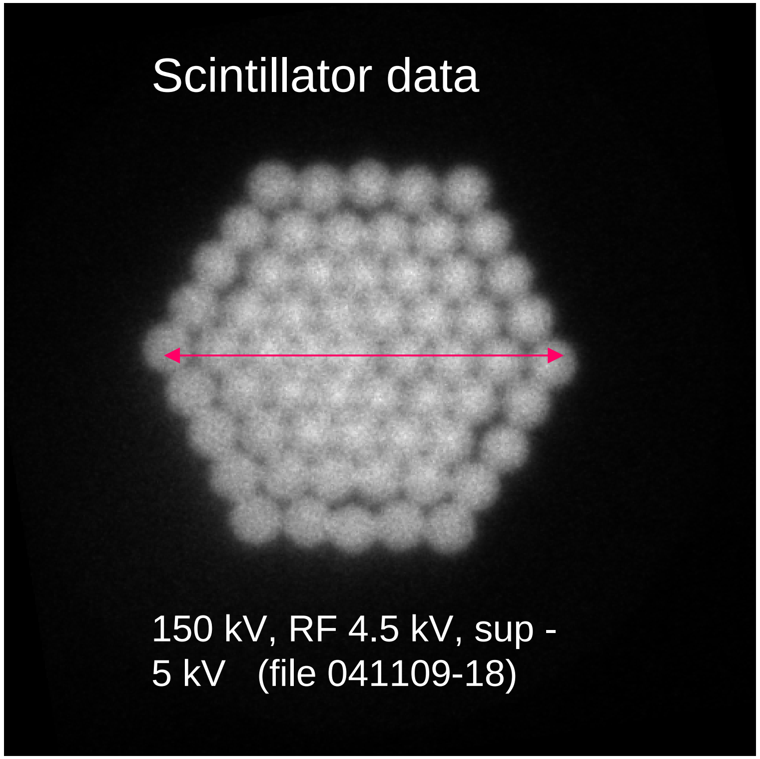


Current density projects to >100 mA/cm^2 (or 3.835 mA per beamlet) when at full voltage.

By shorting out the fields in the last gap we achieved full gradient on the other gaps and reached a current density of 100 mA/cm^2.

Comparison of the beam's profile with a simulation (at the exit of the lens assembly).





The overall cluster size and beamlet positions at z=15 cm agree with simulation prediction but the individual beamlet profile is less sharp leading to slight overlapping at the central region.

Why did we perform the full-gradient test?

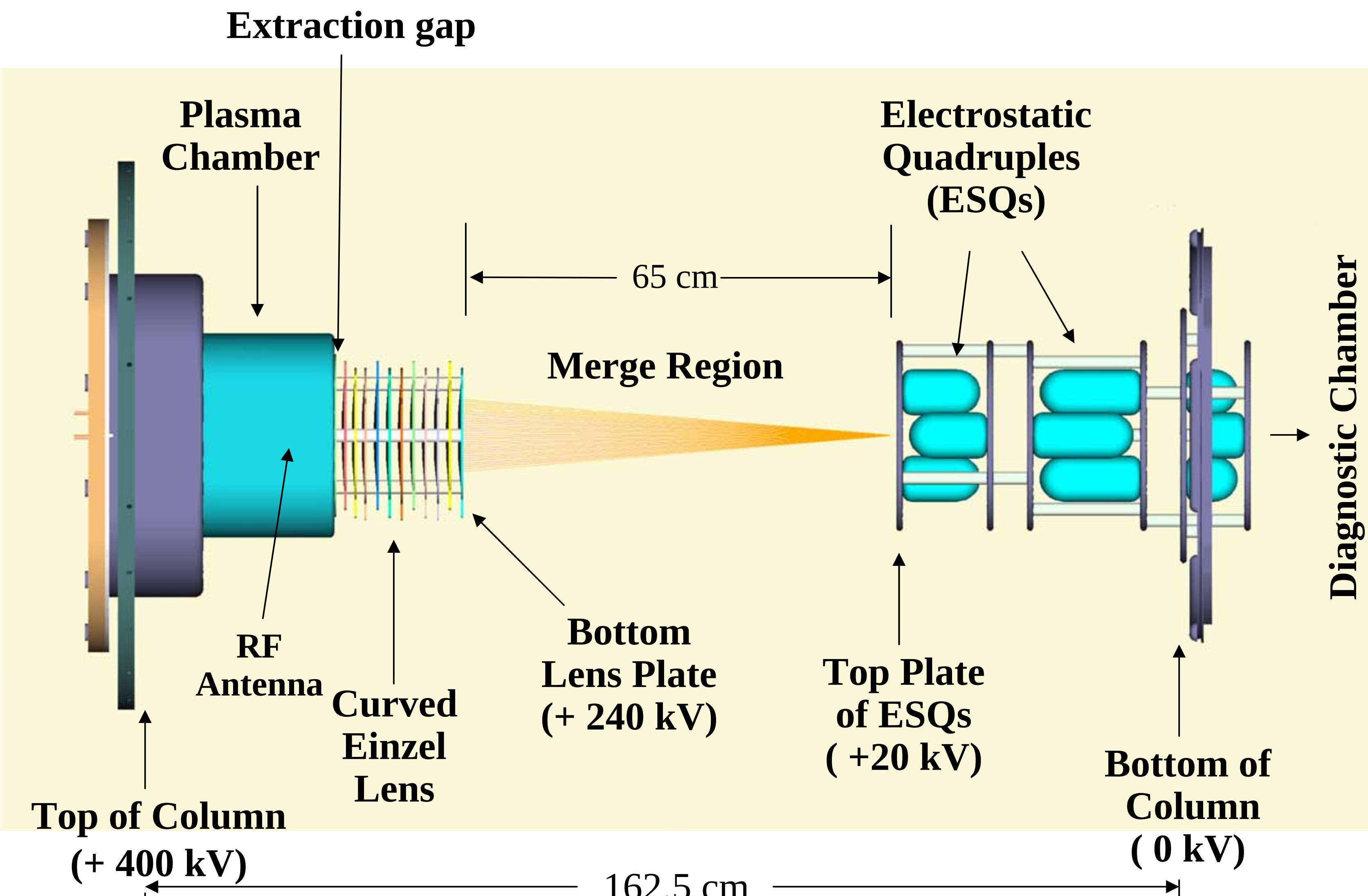
Do learn how high of an operating gradient can be used.

- **Want to operate at high-as-possible gradient to produce high-current low-emittance beams.**
- **Operation in a harsh environment:**
  - **During the switch-on time most of the ions are loss to the walls, where they produce secondary particles.**
  - **Plasma source is operated at about 2 mTorr. Gas flows through the first few gaps before it can be removed from the beam path.**
  - **Working with 20 μs pulses.**

Can we operate at ~100 kV/cm ?

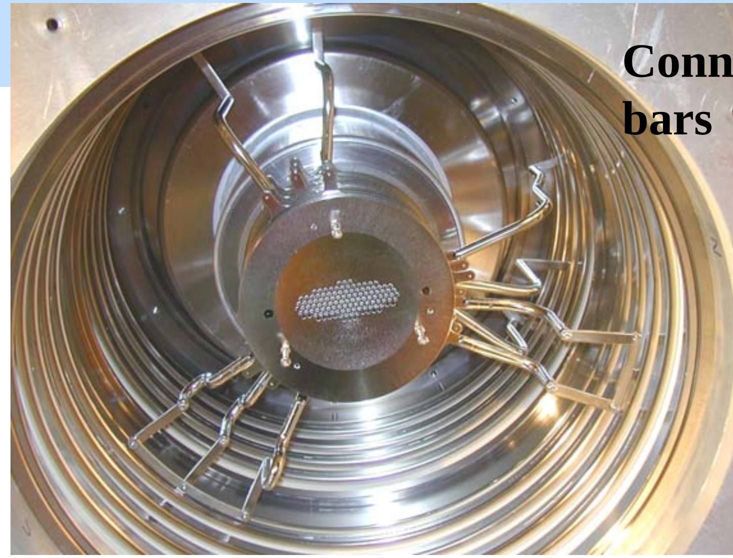
Yes, but we were near the threshold with present mode of operation.

Elements of the Merging Experiment (¼ voltage)



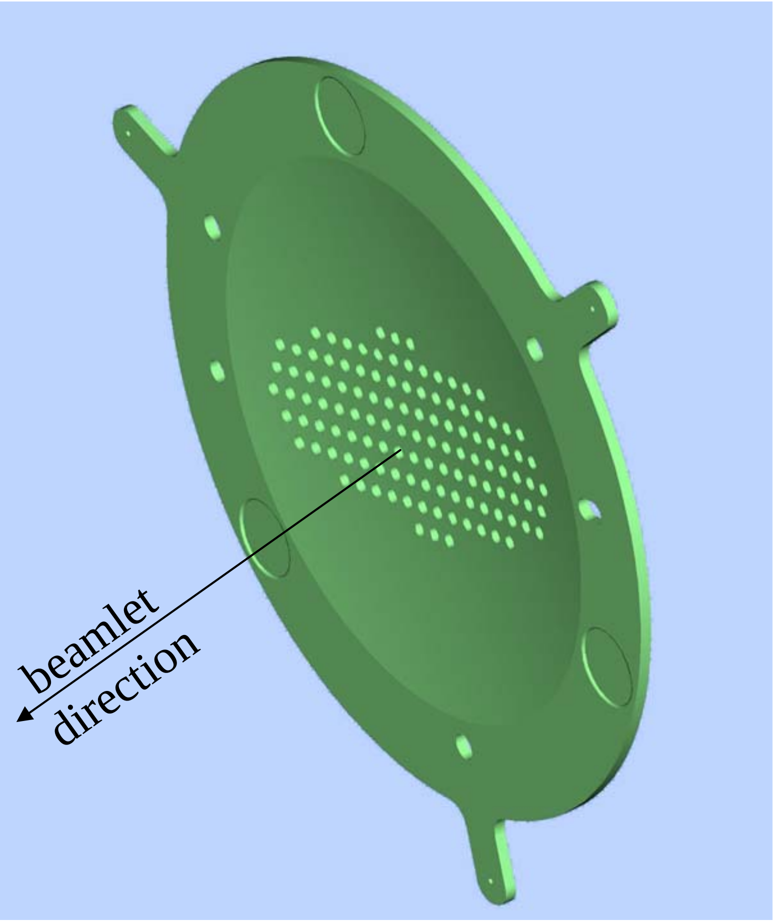
Einzel Lens Assembly

Lens

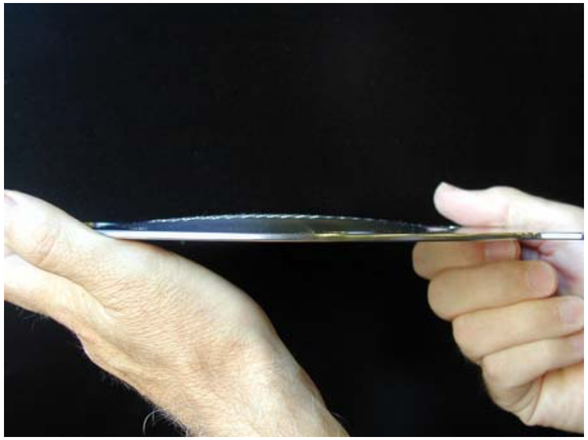


Lens provides transverse focusing as the beamlets are accelerated.

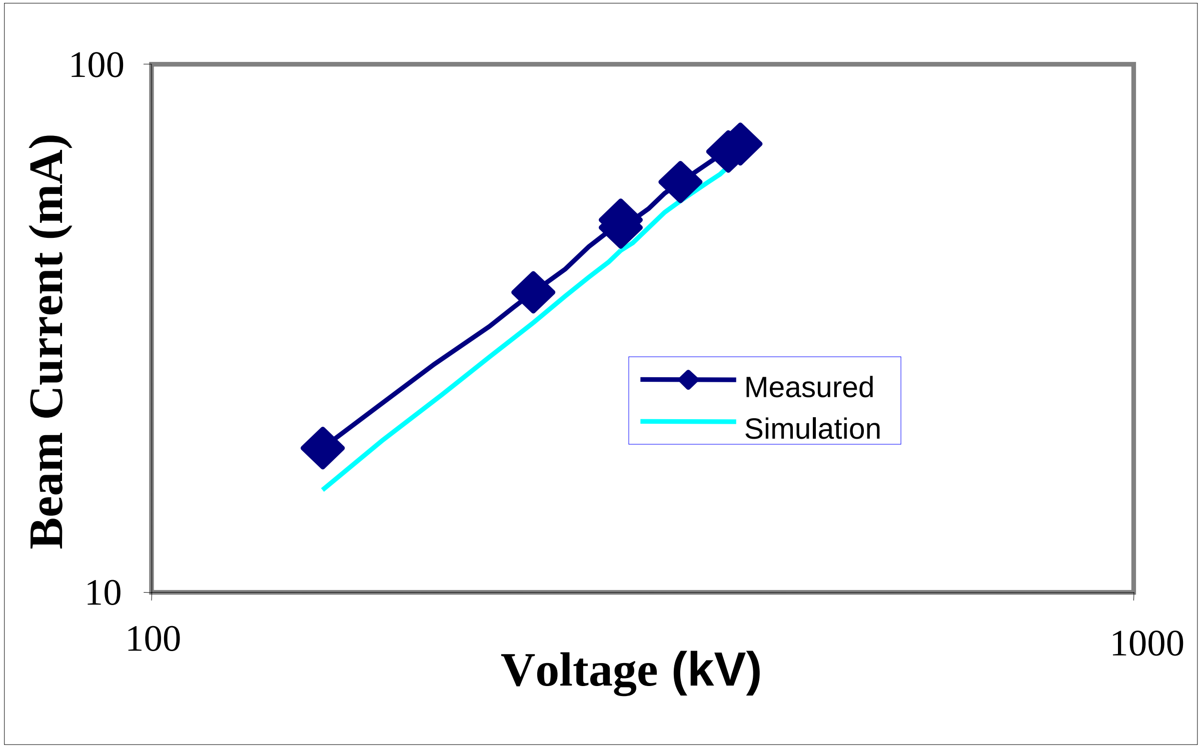
Example of a plate in the Einzel Lens Assembly



- 20 cm OD plates
- 3.2 mm thick
- SS material
- ~ 60 cm curvature
- 119 beamlets

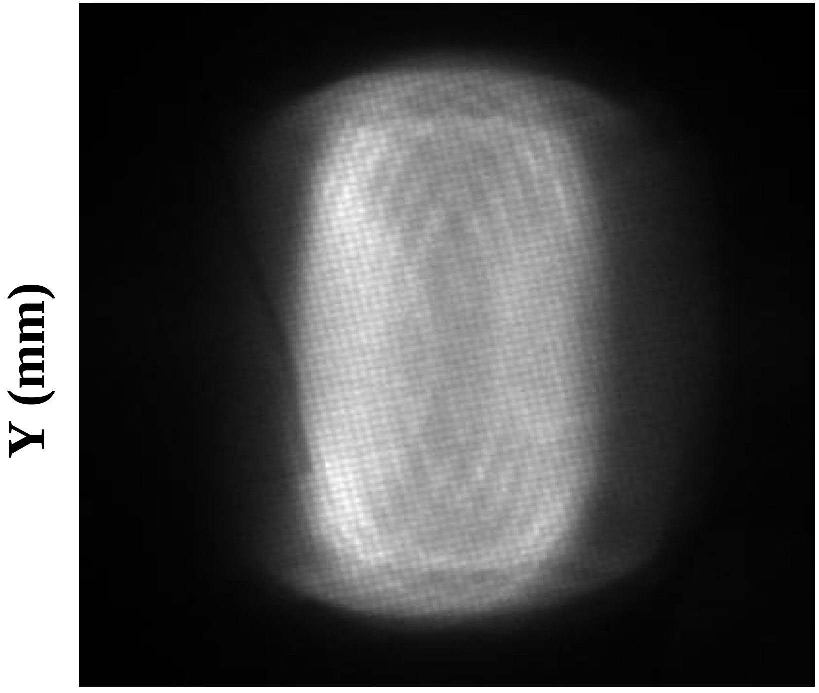


Beam current scaled according to space charge limit.



Images show that merged beam has substructure.

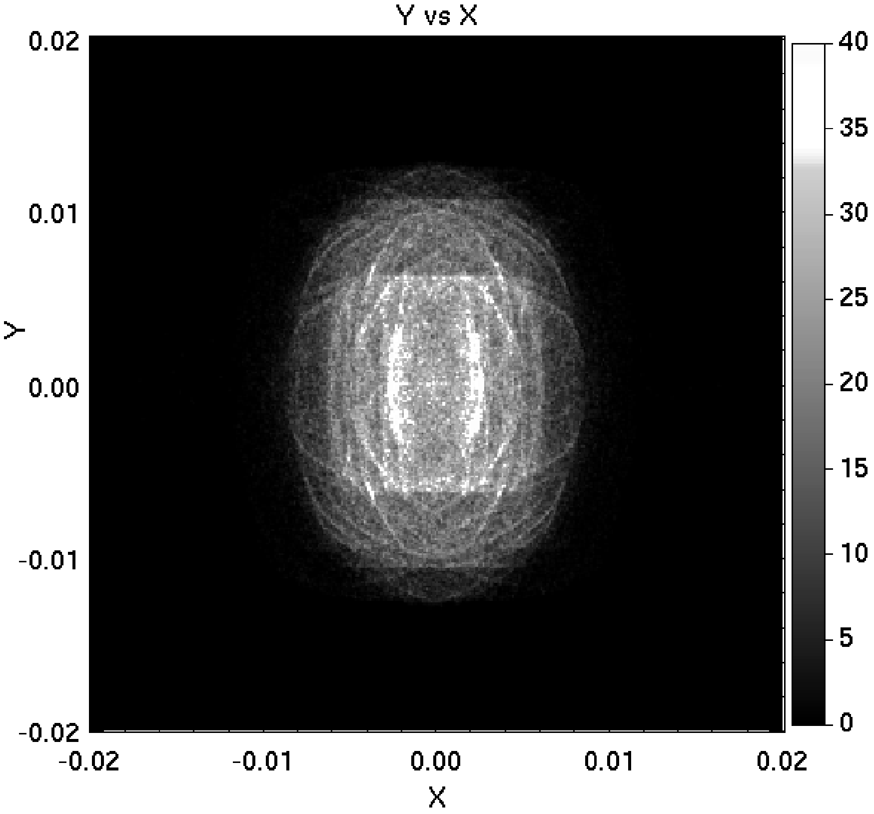
Experiment



X (mm)

(taken about 20 cm below the slit)

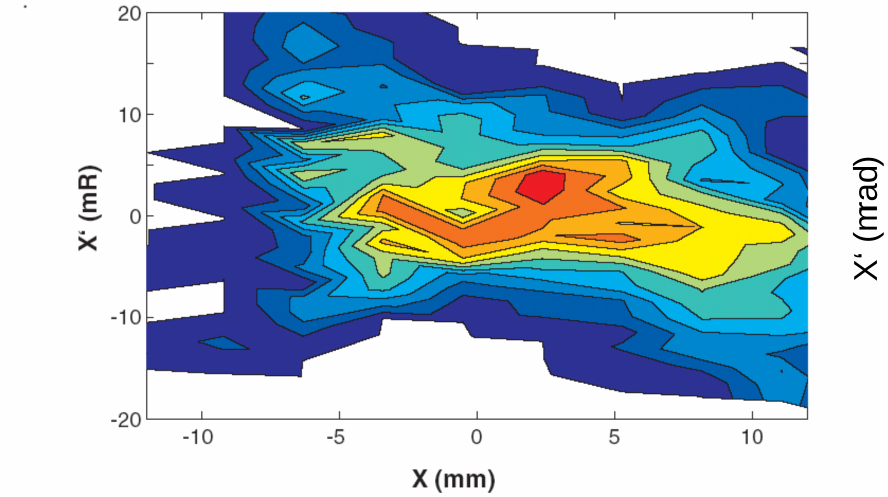
Simulation



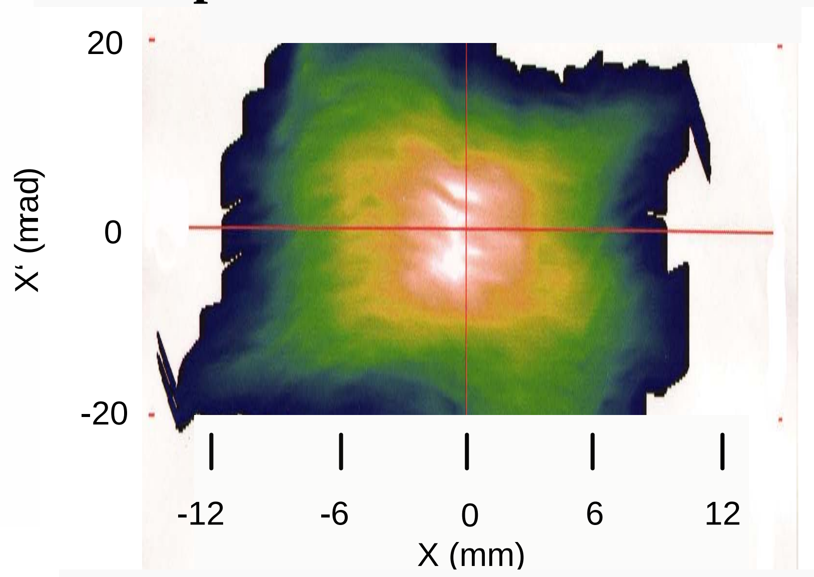
(at the slit)

Measurement of the X-X′ phase space after the ESQs

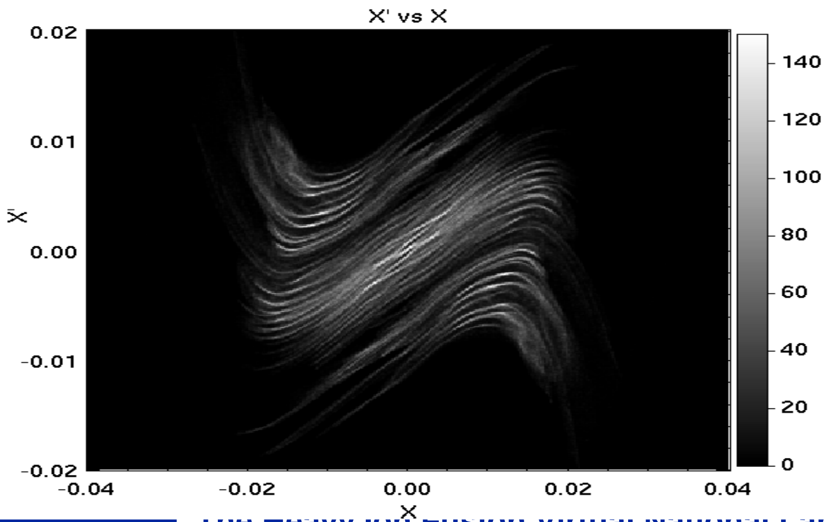
Slit scanner



Optical scan

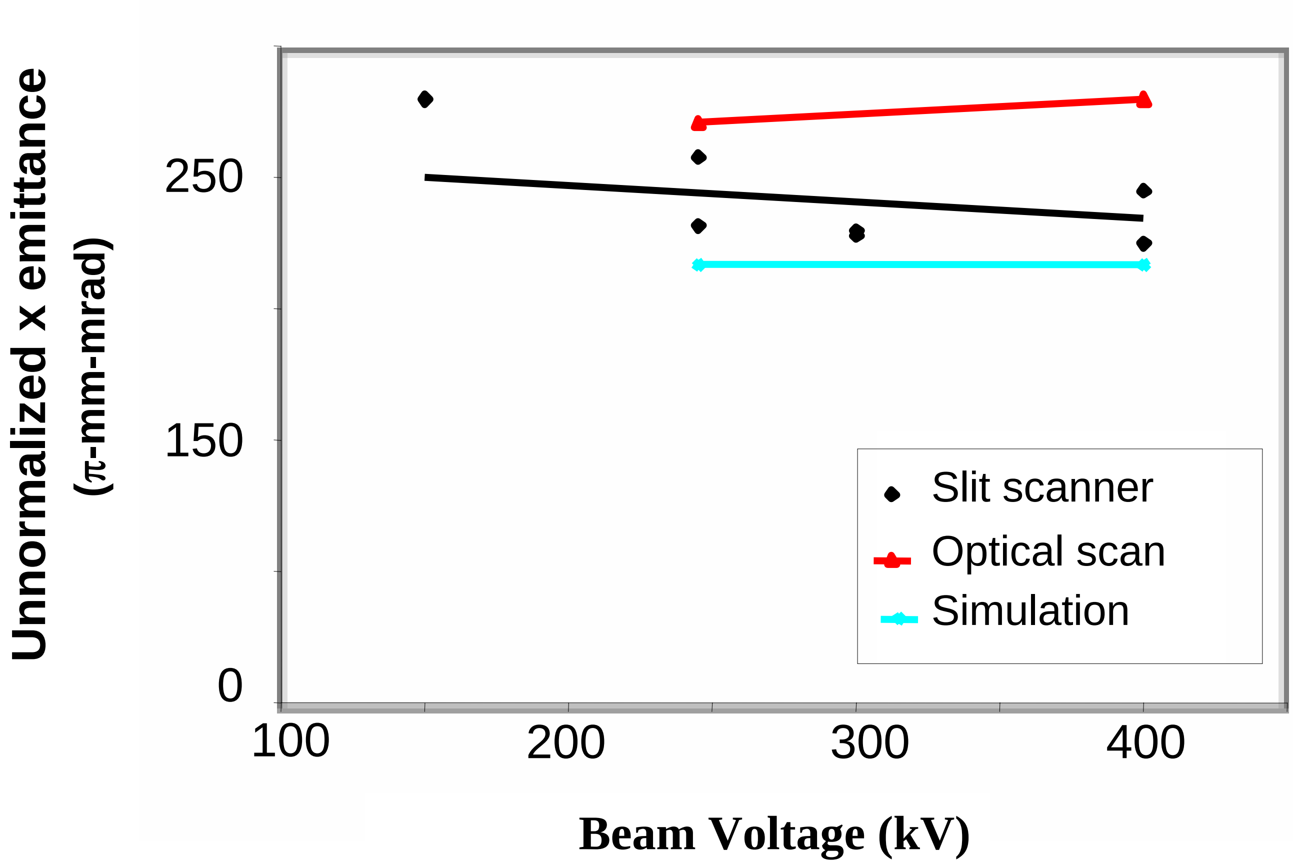


Code prediction



Unnormalized emittance is constant

ESQ fields were adjusted for each beam energy measured.



Summary for the Merging Beamlet Experiments

- The merging experiments were in support of a compact, high-current high-brightness injector for use in a HIF Fusion Driver.

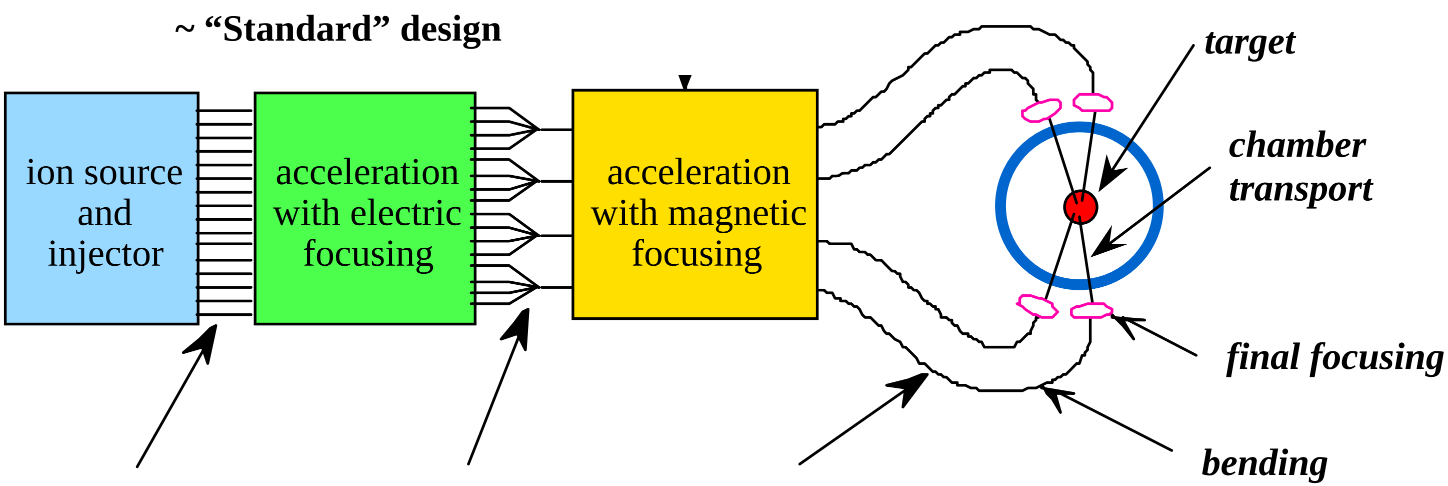
- The experiments have added to our knowledge base, so that we could now build a multi-beam source.

- An RF-driven multi-cusp plasma source produced satisfactory high-current-density beamlets.

- Good agreement with simulations.

Backup Slides

Ion Beams for Heavy Ion Inertial Fusion



matching	beam combining	compression	
2-3 MeV	~100 MeV	~10 GeV	~10 GeV
~1 A/beam	~10 A/beam	~400 A/beam	~4000 A/beam
~10 µs	~ 4 µs	~100 ns	~10 ns

Power amplification to the required 10^{14}-10^{15} W is achieved by beam combining, acceleration and longitudinal bunching.

- Heavy ion beams have significant space-charge effects
- Multiple beams provide better target illumination symmetry and a better match to the beam transport limits.

Why Ion beams ? Why heavy Ions?

- Ion accelerators can operate at > 10 Hz, 30% efficient, and with radiation-hardened final focusing.

- Desirable ion range for fusion target is ~ 0.1 g/cm^2 so want ~ 80 MeV light ions (e.g. ^{7}Li) or ~ 8 GeV heavy ions (e.g. ^{207}Pb).

- For a given power on target, light ions would need ~ 100 times more current.

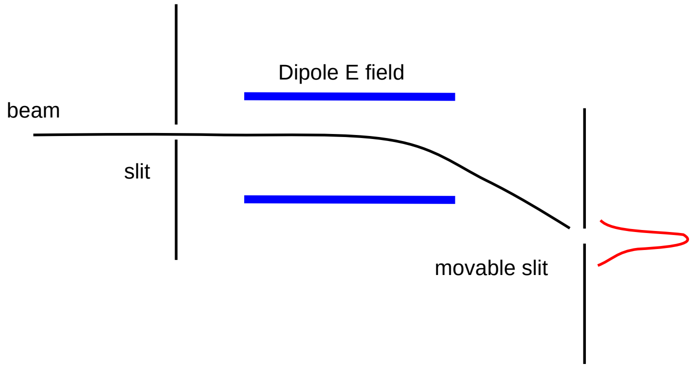
- Total required heavy ion charge on target is ~ 1 mC.

Typical HIF Driver Injector Requirements

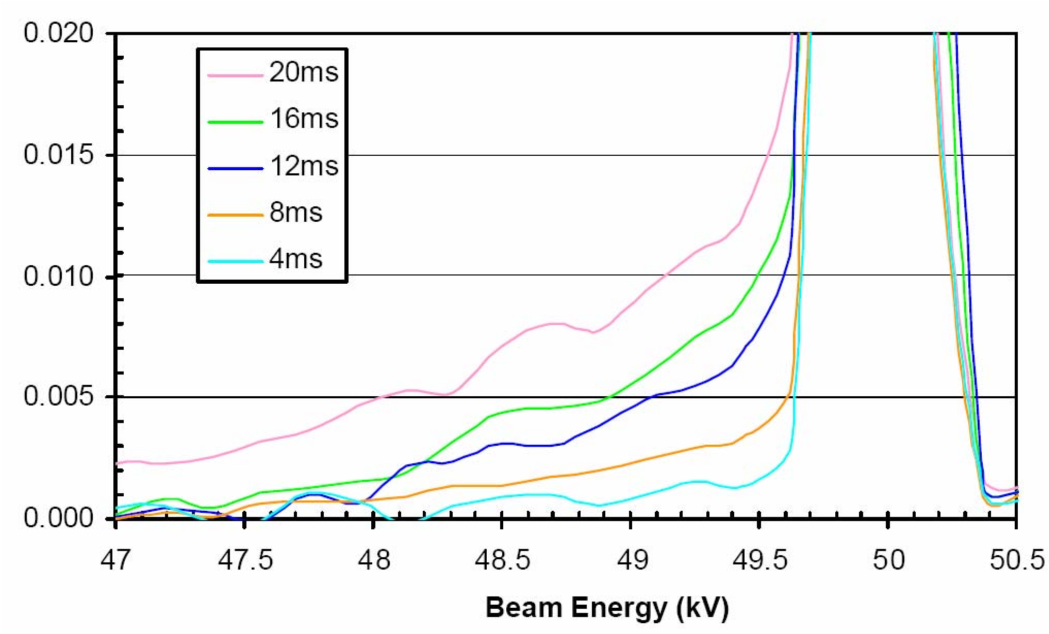
Ion mass	**> 100 amu for driver, 39 amu for HCX**
Total charge delivered	**~ 1 mC**
Beam current per beam	**~ 0.5 ampere (transport limit)**
Delta I/ I	**± 0.2 %**
Total beam current	**≥ 50 ampere**
Number of beams	**≈ 100**
Injector voltage	**~ 1.5 - 2.0 MV**
(Delta V)/ V	**± 0.1%**
Line charge density per beam	**≥ 0.2 μC/m**
Pulse length	**≈ 10 - 20 μs**
Rise time	**< 1 μs**
Current density uniformity	**± 10%**
Emittance (each 0.5 A beam)	**< 1 π-mm-mrad (adequate, but smaller is better)**
Life time	**~ 5 Hz x 3.15×10^{7} sec/yr = 1.6×10^{8} pulses**

Achieved parameters are in red fonts

Energy dispersion is a consequence of charge exchange loss inside the pre-accelerator



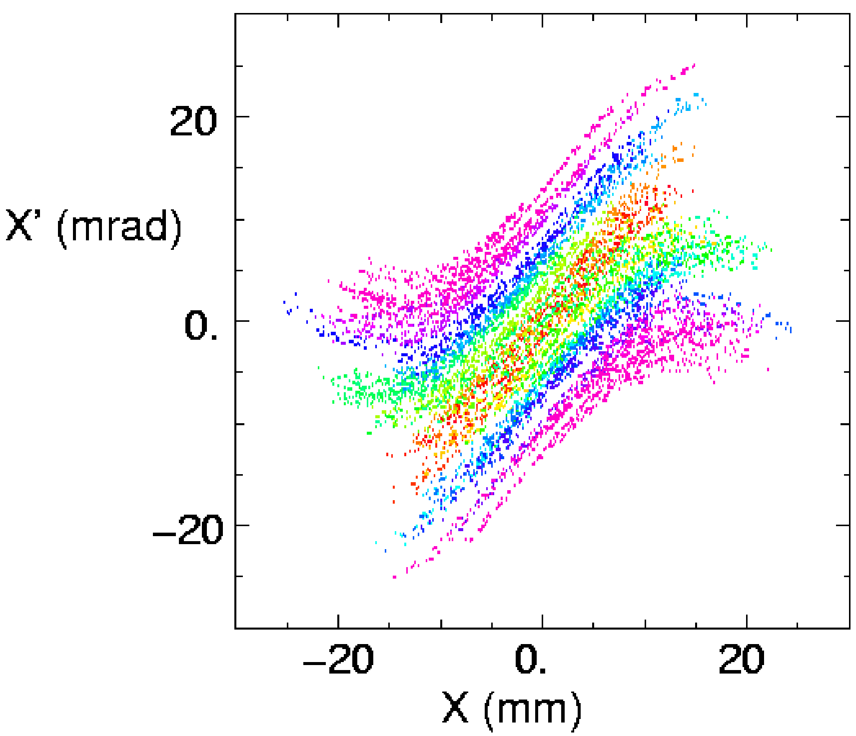
0.5% beam spread over 2kV
(50kV beam energy)

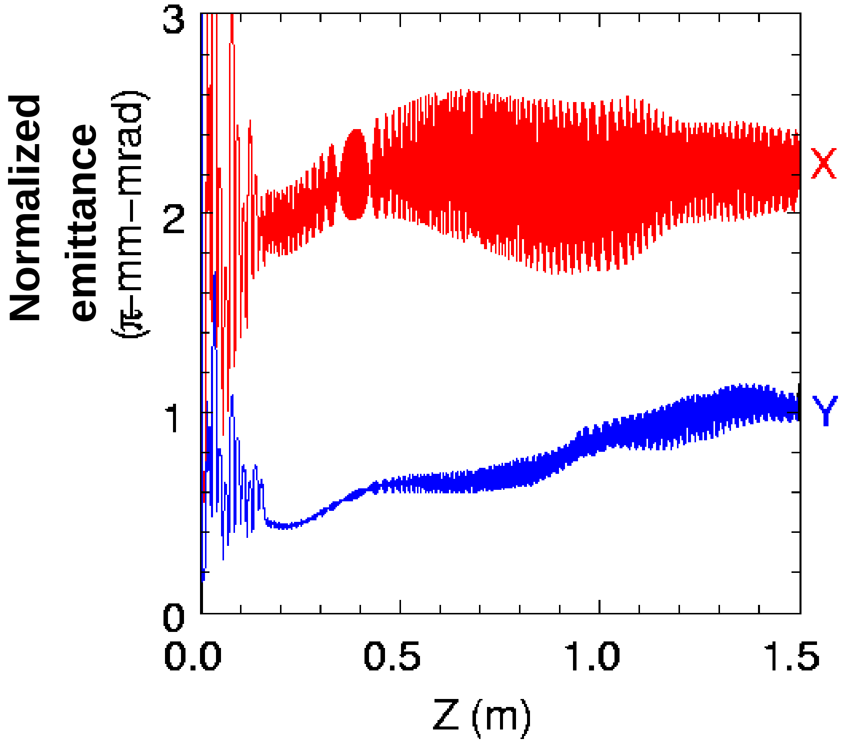


4 ms gas puff equals 2 mTorr.

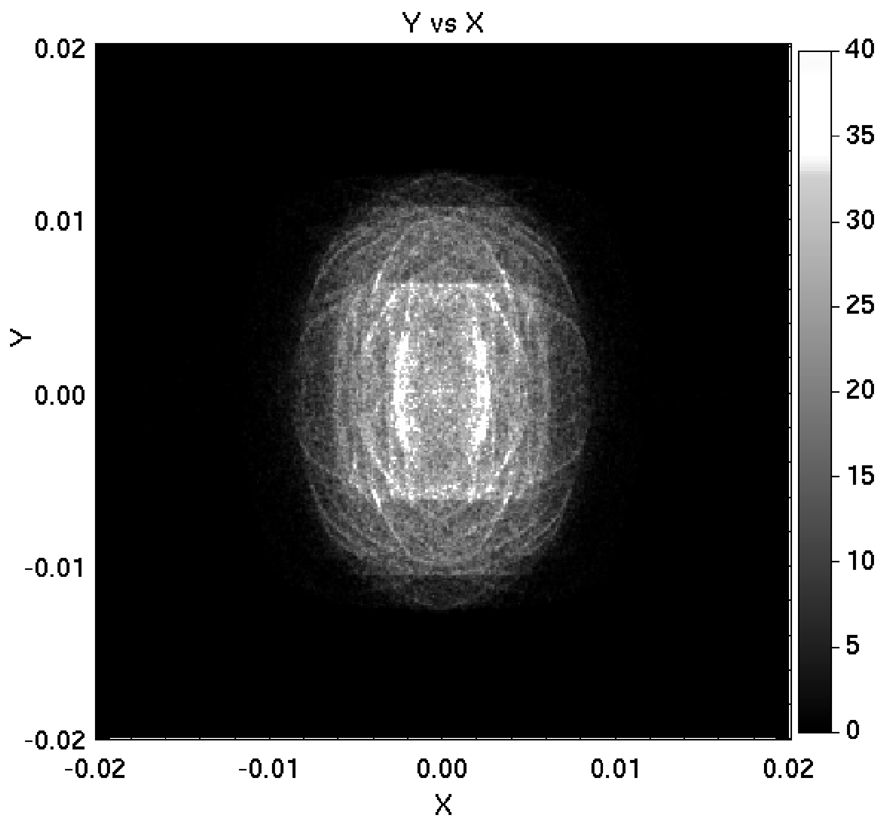
Phase space of the 119-beamlet merged beam

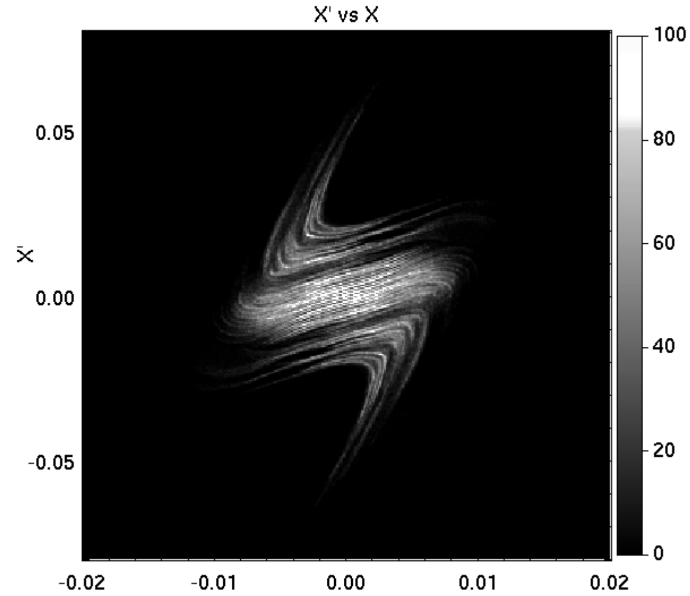
Current = 70 mA, Final energy = 400 KeV

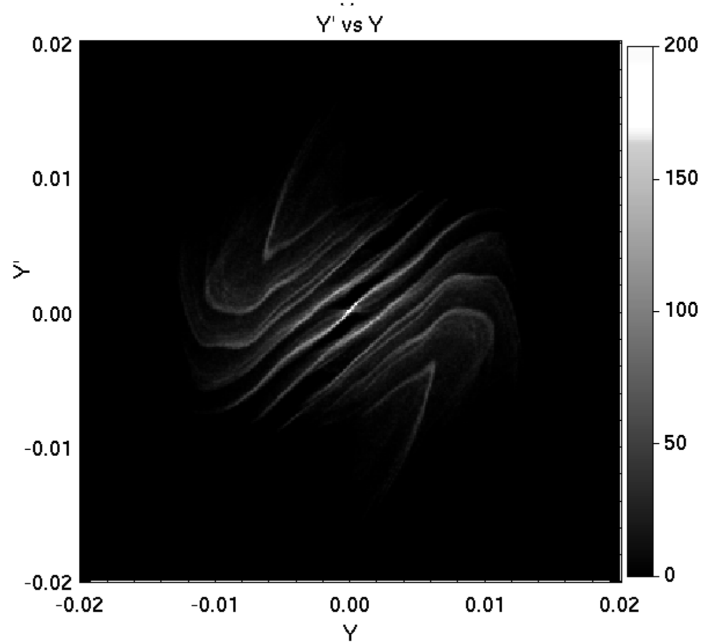




WARP's prediction at the emittance slit.







Other types of ion sources for HIF

	Large Ionizer	Mini-ionizer	ECR/ EBIS	MEVVA	Laser	Gas arc	Discharge	Converter
Packing factor	O	¦	O	X	X	?	¦	¦
Life-time	X	X	X	X	O	?	¦	?
Reproducibility	¦	¦	?	X	X	?	¦	¦
Current density	O	X	¦	¦	¦	¦	¦	?
Transparancy	--	¦	¦	¦	¦	¦	¦	X
Ion Temp	¦	¦	O	O	O	?	X	O
Uniformity	¦	¦	X	X	X	?	¦	¦
Gas load	¦	¦	?	¦	¦	?	O	O
Low noise	¦	¦	?	X	X	?	¦	¦
Purity (A & Z)	¦	¦	O	X	X	?	¦	¦
Rise-time	¦	¦	O	¦	¦	?	X	¦
Power Efficiency	O	X	O	¦	¦	?	¦	¦
Contamination	O	OO	¦	O	O	?	¦	¦
Simplicity	¦	X	O	¦	X	?	¦	¦
Reliability	X	X	?	X	X	?	¦	?

Innovation should make use of HIF's short pulse nature.

Key: -- not applicable, ¦ = good, X=improvement needed, O=bad