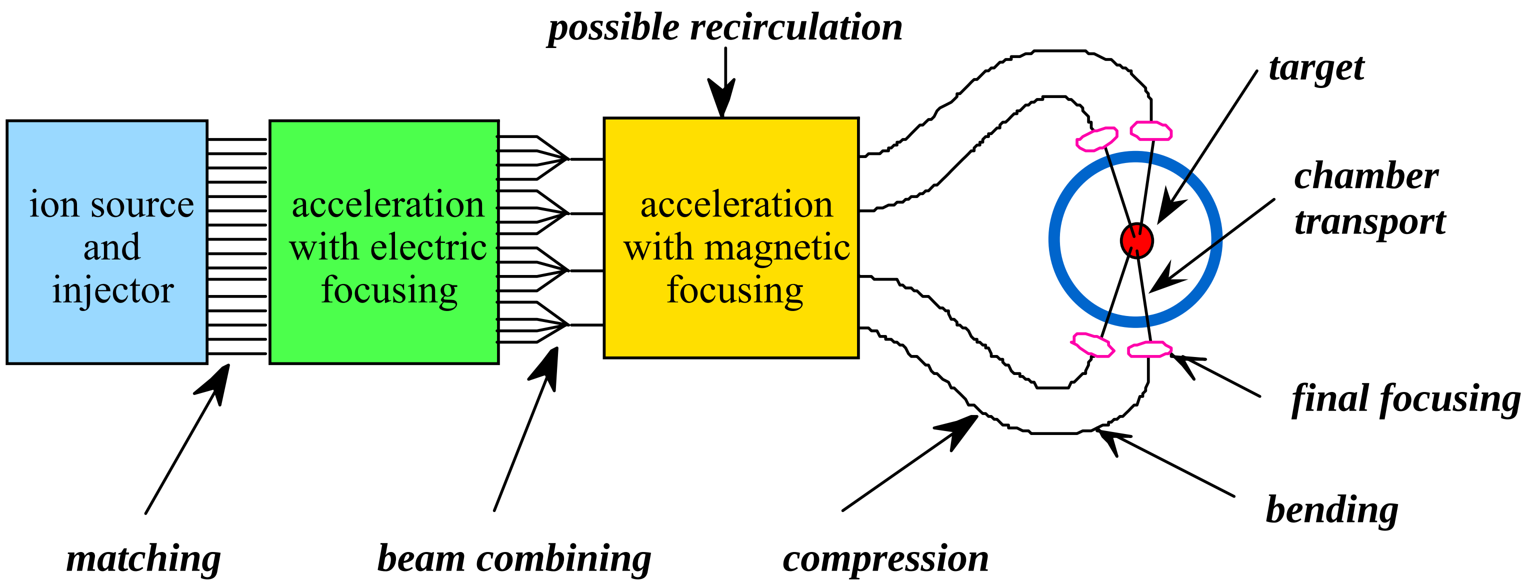
Merging Beamlet Experiment Review

May 10, 2004

Injector Group:

- Joe Kwan (experiment)
- Glen Westenskow (experiment)
- Dave Grote (theory)
- Irv Haber (theory)
- Erni Halaxa (designer)
- Gary Freeze (Mech. Tech)
- Bob Hall (Elec. Tech)

Ion Beams for Heavy Ion Inertial Fusion



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.**

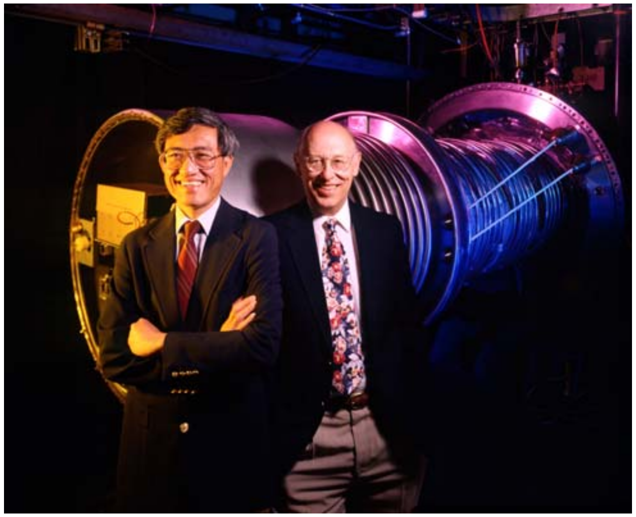
HIF Drivers require Injectors of Bright Beams

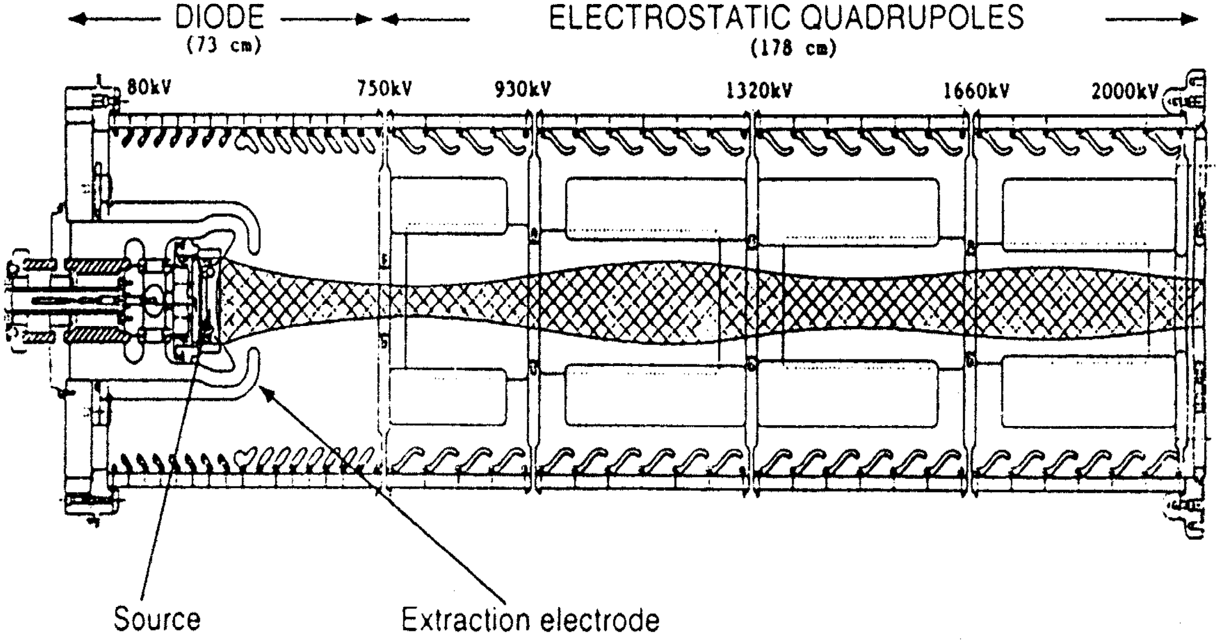
Ion mass	> 100 amu for driver, 39 amu for HCX
Total charge delivered	~ 1 mC
Beam current per beam	~ 0.5 ampere (transport limit)
Delta I/ I	± 0.2 %
Total beam current	≥ 50 ampere
Number of beams	≈ 100
Injector voltage	~ 1.5 - 2.0 MV
(Delta V)/ V	± 0.1%
Line charge density per beam	≥ 0.2 μC/m
Pulse length	≈ 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

Traditional HIF Injectors use large surface sources

- Surface ionization source diameter $\geq$ 10 cm, solid emitter boundary.
- Current density < 10 mA/cm^2 of K^+.
- 750 kV pre-accelerator before ESQ.

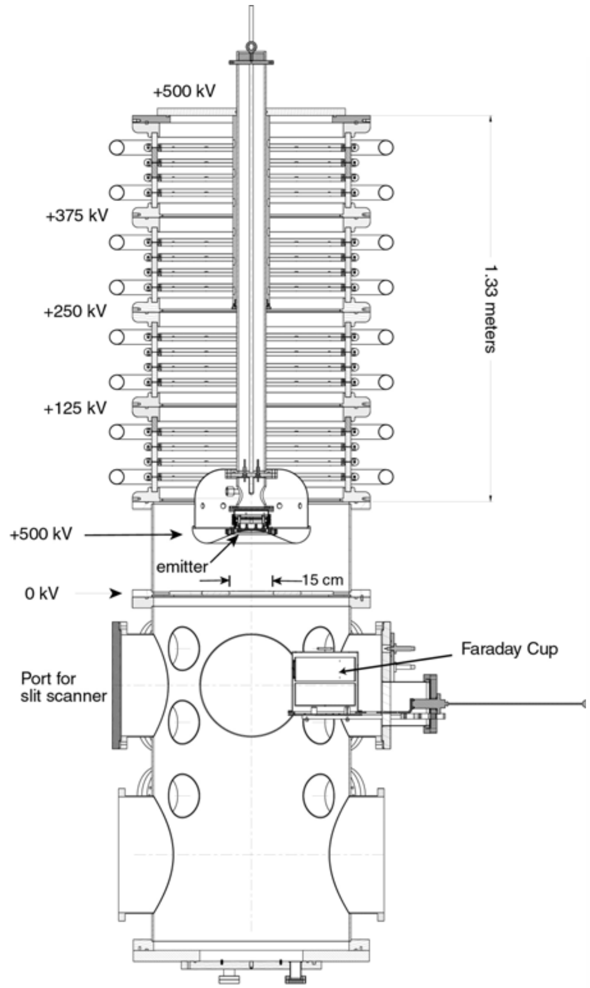




Specifications:

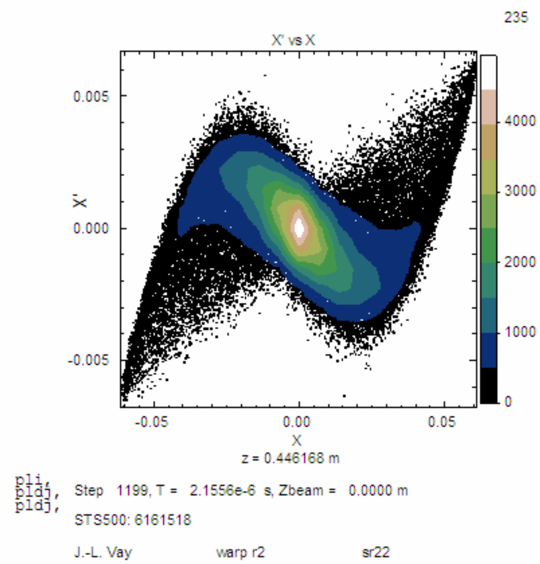
1.8 MV
0.6 A K^+
1 π-mm-mrad

Good agreement between experimental results and simulation predictions

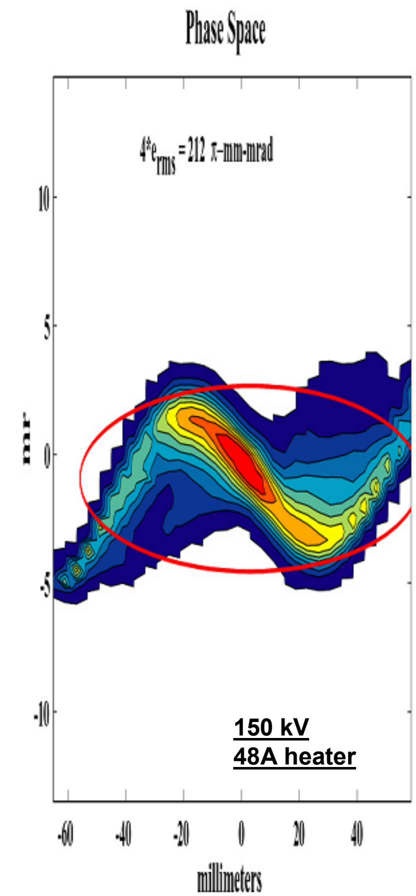


10-cm diameter K+
Alumino-silicate source

Warp simulations

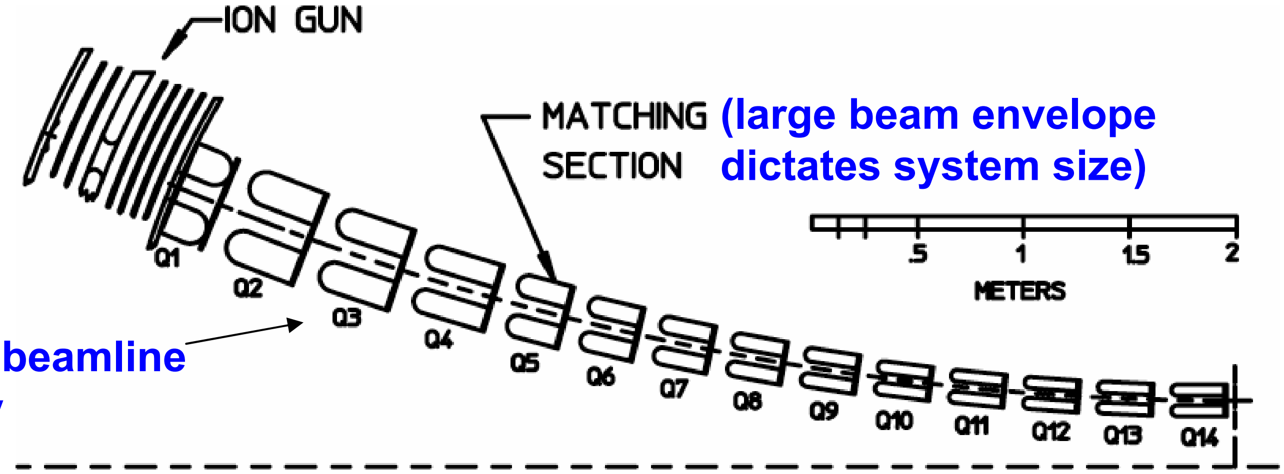


Experimental results



A 84-beam array injector is very large (and costly)

Present surface ionization sources operates at <u>low current density</u>



(large beam envelope dictates system size)

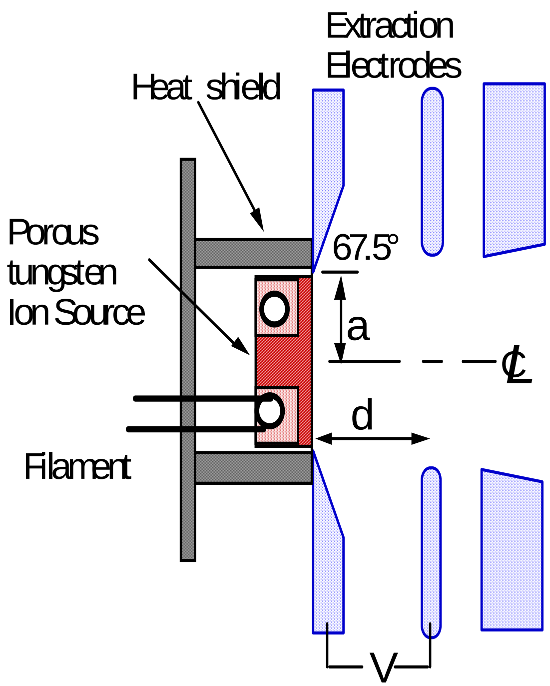
Outermost beamline in the array

Induction Linac

Is there a better way for HIF injector system?

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.

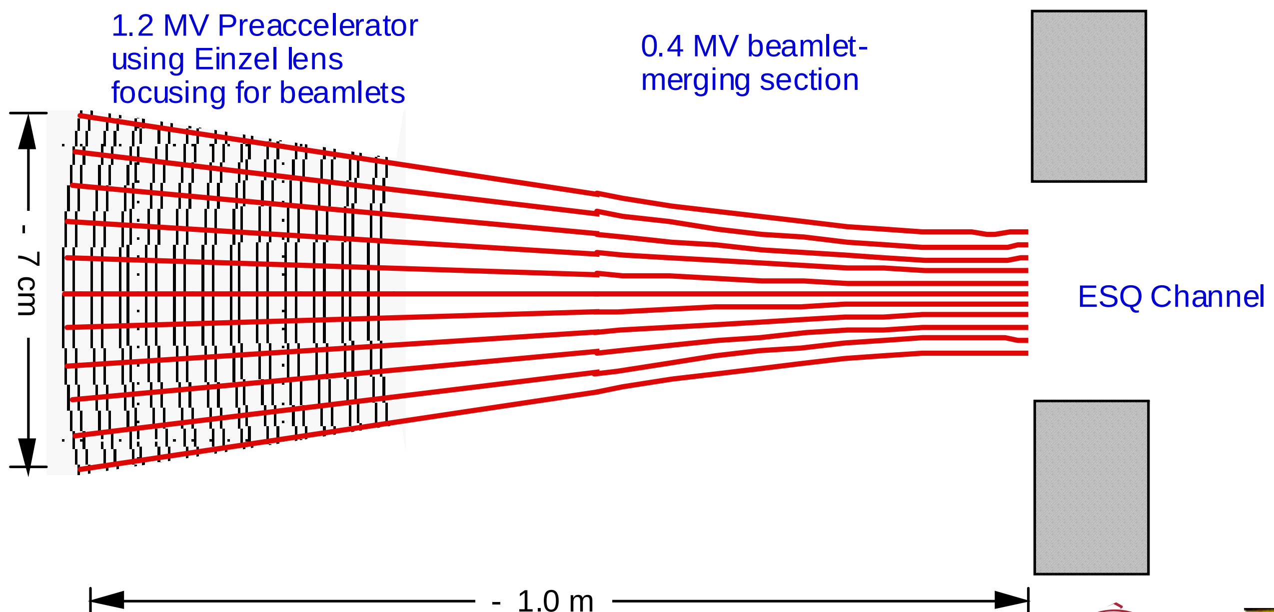
- **V is limited by breakdown**
  V ~ d for d < 1 cm
  V ~ $d^{0.5}$ for d > 1 cm
  so large ion diode needs high V but produces low J.

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

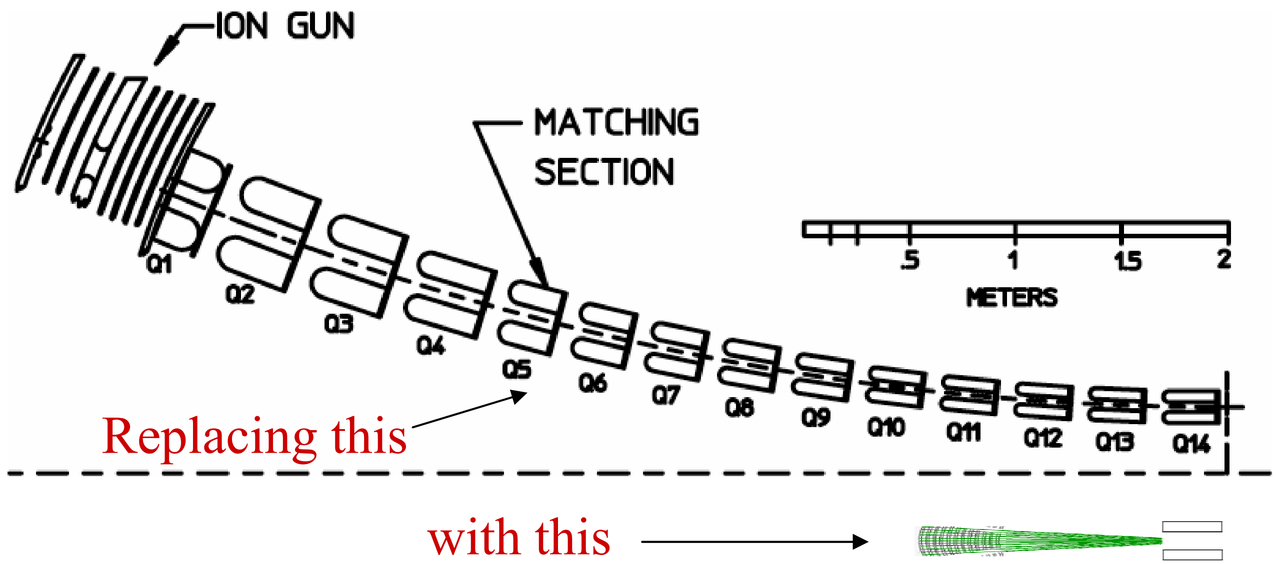
- **Conclusion: high current needs large V and d but results in low J, so the brightness is limited.**

High Current Density Option

- For effective LEBT, high brightness miniature beamlets (≈5 mA ea) can be accelerated to ≈ 1.2 MeV before they are merged into a single beam (≈ 1 ampere).
- Beamlets can be aimed and steered to rapidly match into an ESQ channel.
- Beamlet merging will introduce emittance growth, thus the miniature beamlets must be very bright.



The mini-beamlet approach can drastically reduce the size of a multiple beam injector



- **The merging beamlet approach requires a high current density ion source. It can tolerate a higher intrinsic ion temperature, so there are more ion source options.**
- **Merging beamlets produces emittance growth.**

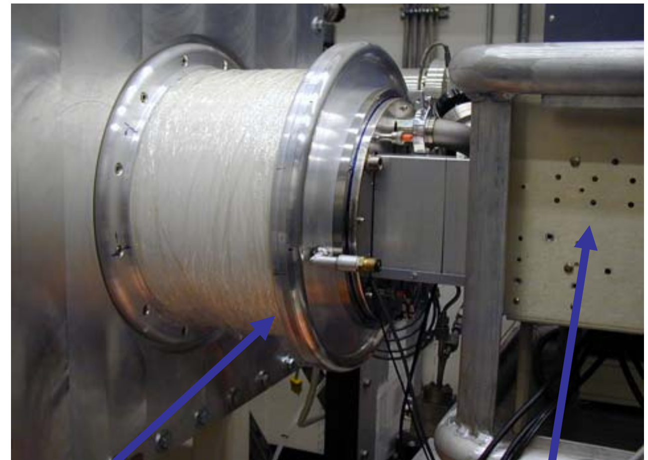
The purpose of the Merging Beamlets Experiment <u>was</u> to develop a prototype injector for IRE

- With the recent improvements in alumino-silicate sources, the single aperture source is probably still the optimum choice for single beam experiments
- Merging beamlets type injector is preferred for drivers with multiple beams
- We want to demonstrate that we have solutions to all the critical issues—high J, high gradient, tolerance etc.
- Study the physics of emittance growth from merging beamlets
- Benchmarking the simulation code will enable us to control beam profiles and halos.

The Merging Beamlets Experimental Plan

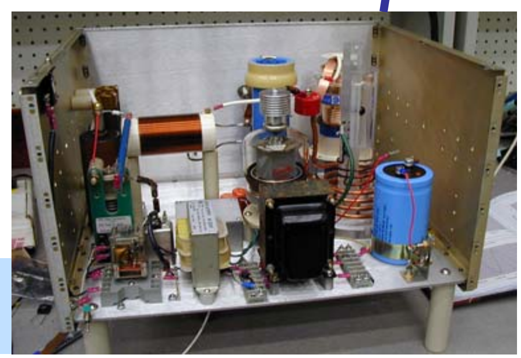
- Built an RF-driven argon plasma source that can deliver the current density over a large extraction area
- Built a high voltage test stand—a 500 kV column is just about the maximum voltage that can run in air. Higher voltage will require a compressed-air enclosure and cost more.
- Develop and test high gradient insulators and vacuum gaps: aim at 35 kV/cm and 100 kV/cm respectively.
- Do the experiment in three phases—(1) test the source, extraction and Einzel lens on STS-100, (2) experiment with full gradient beamlets up to the first 400 kV of a full size injector, (3) experiment with a ¼ scaled voltage (but full size) merging beamlets at 400 kV.

Testing a multi-beamlet Ar^+ RF-plasma source



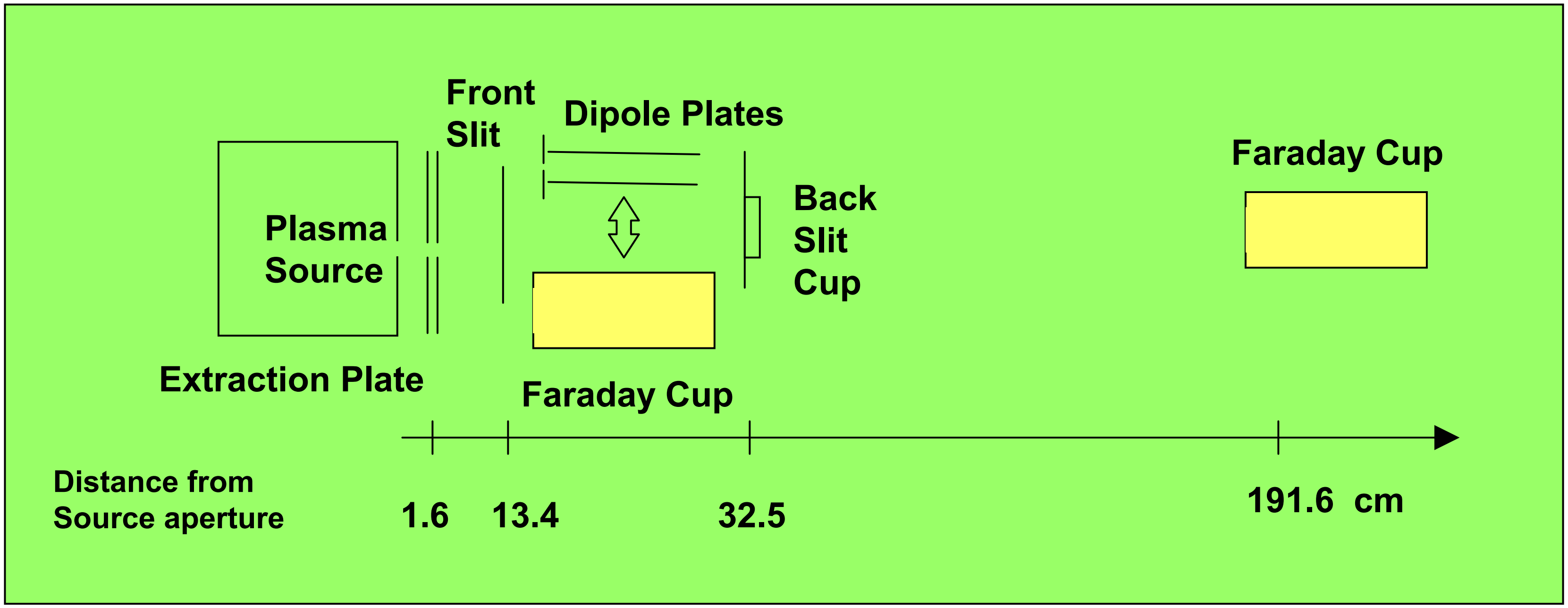
RF-driven multi-cusp source inside ceramic insulator

500μs, 20kW, ~ 10 MHz
Compact RF oscillator



Schematic Diagram of the RF-Source Experiment on STS-100

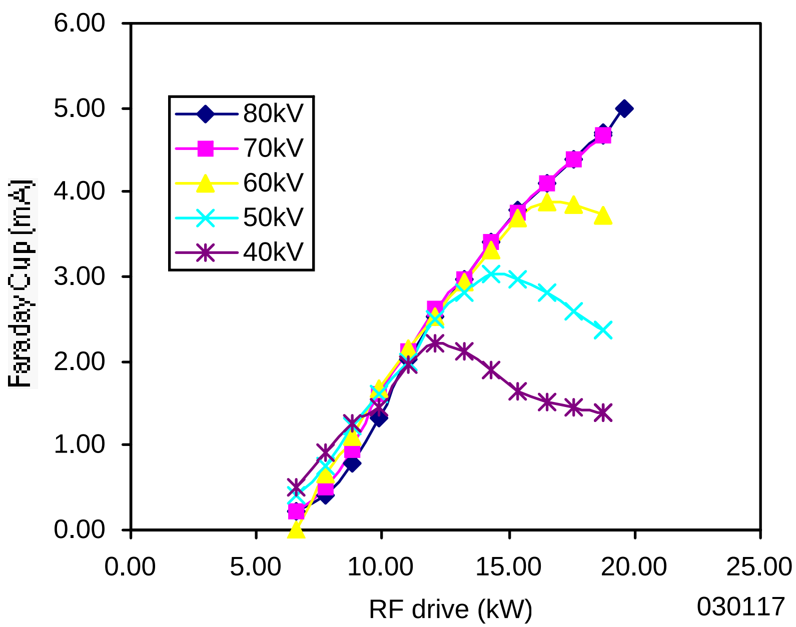
- Faraday cup to measure total beam current
- 2nd Faraday cup to measure Time of Flight (TOF)
- Doube-slit scanner to measure projectional emittance
- Dipole plates to measure energy dispersion

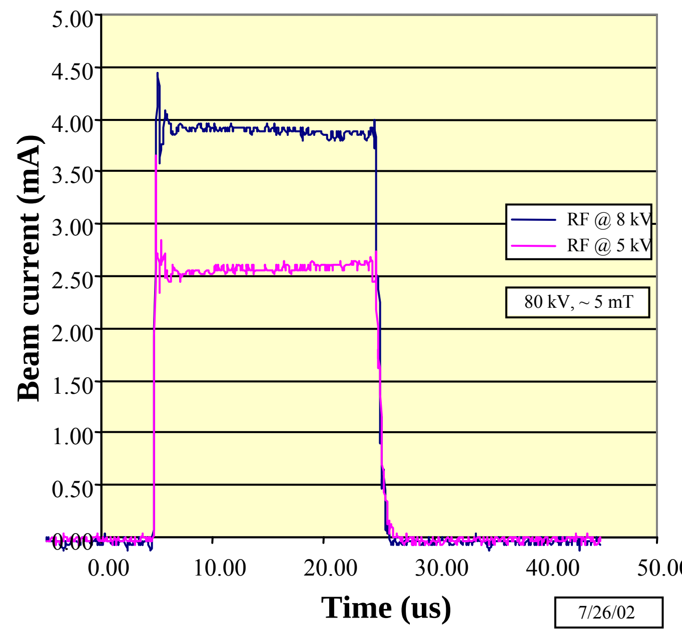


Argon plasma source has produced beamlets near the required current density

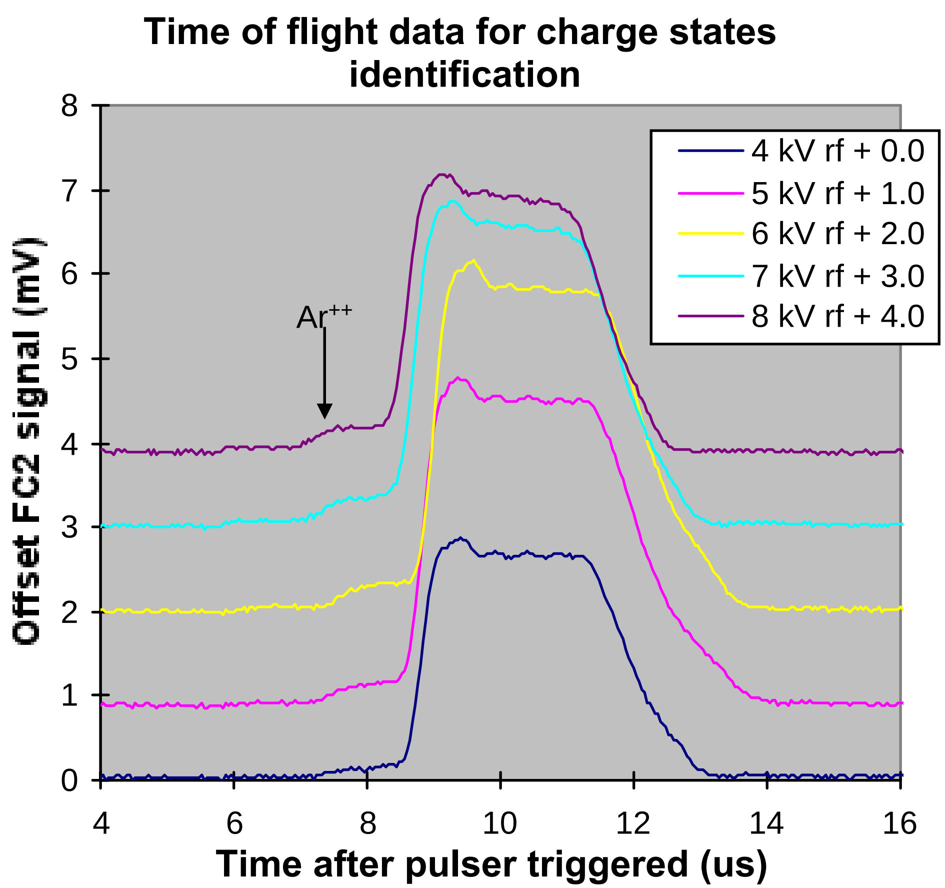
- Current peaks when a beam fills the exit aperture.
- Optimum optics at perveance = 5.3 mA / 80 kV$^{(3/2)}$

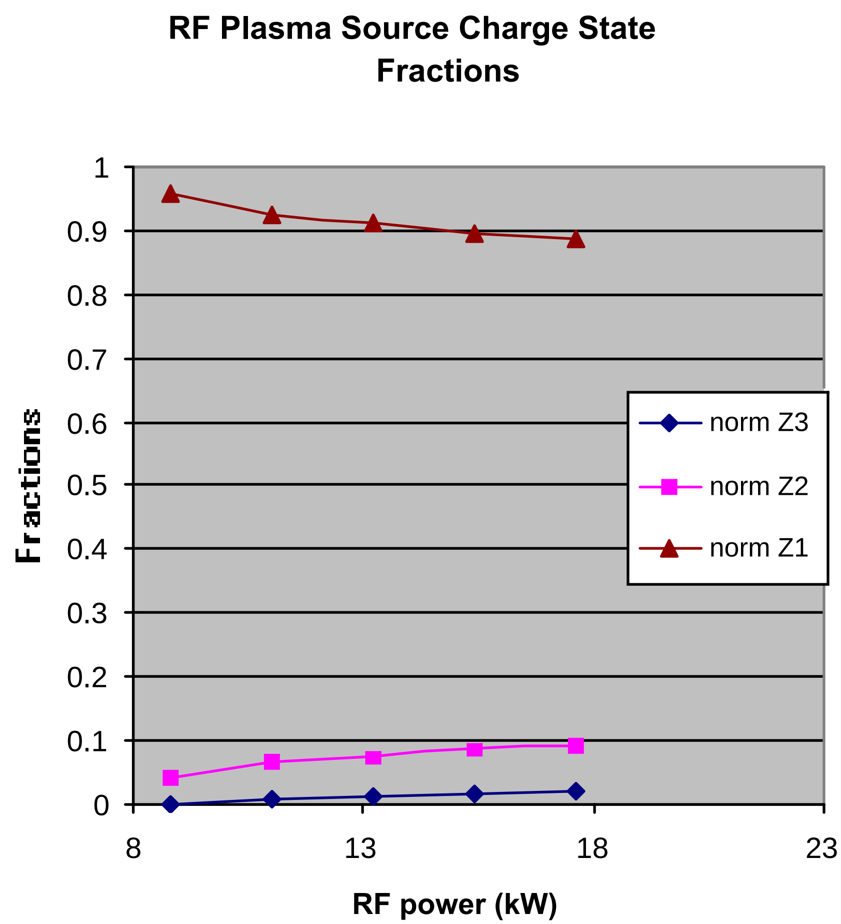
Obtained 3.9 mA from d=0.25 cm aperture
$\Rightarrow$ 80 mA/cm^2.
(compare to 8.3 mA/cm^2 for hot-plate source)





Charge states measurements





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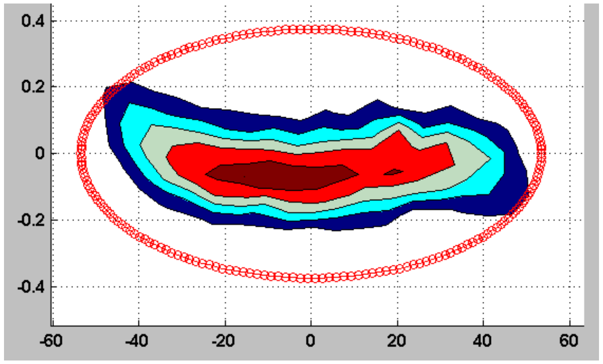
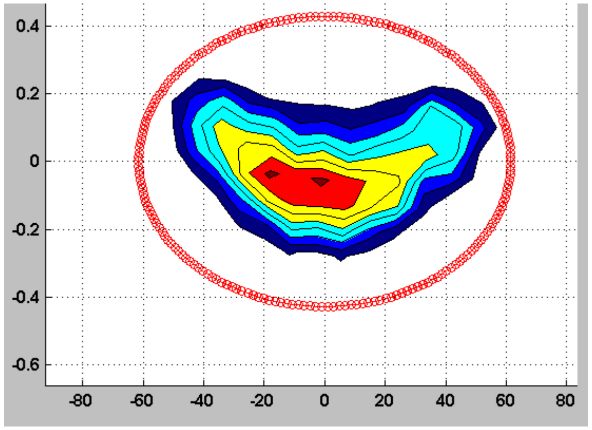
Emittance measurements

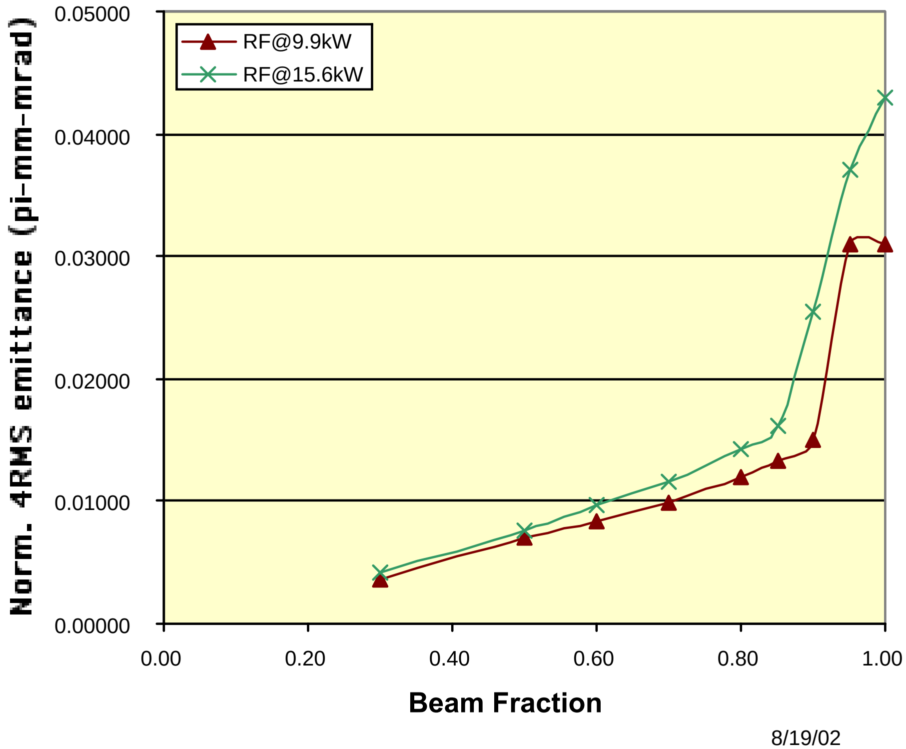
- **Measured emittance showed $T_{eff} \approx 2$ eV, which is adequate for use in merging beamlets.**
- **Possible emittance reduction by improving beam optics.**



matched optics

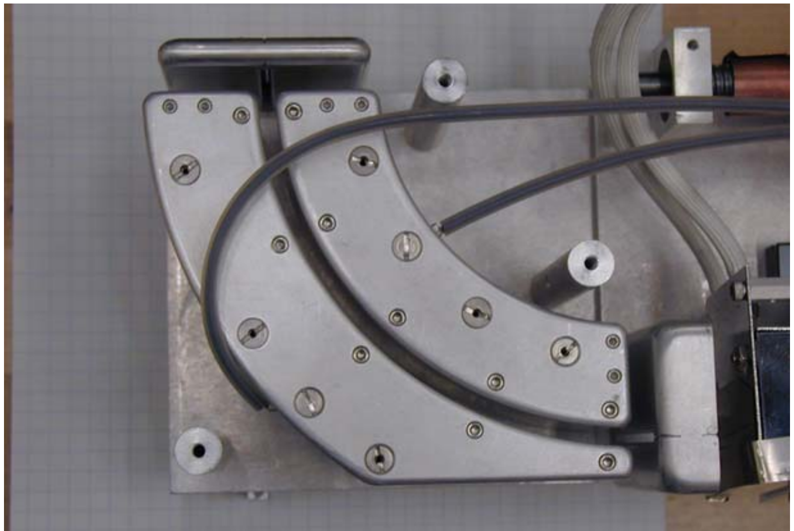


Overdense optics

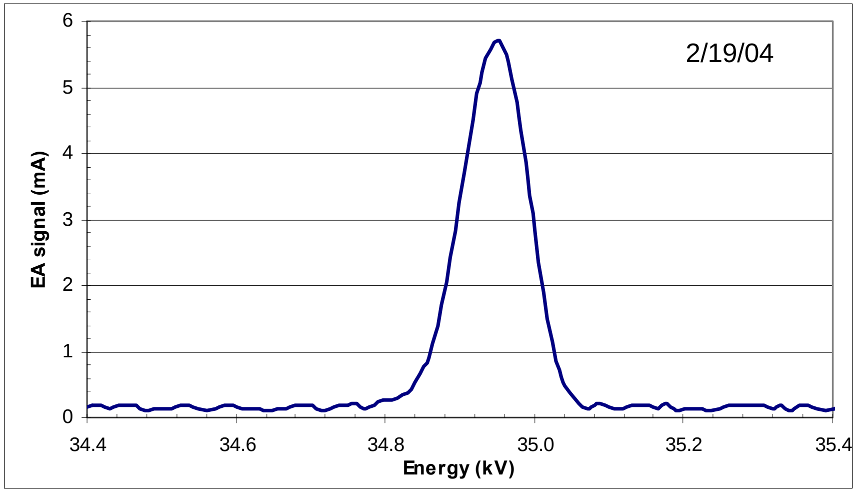


Energy dispersion can result from charge exchange loss during acceleration

- Use an energy analyser to measure the beam energy spread
- Compare results as a function of gas pressure in the source chamber

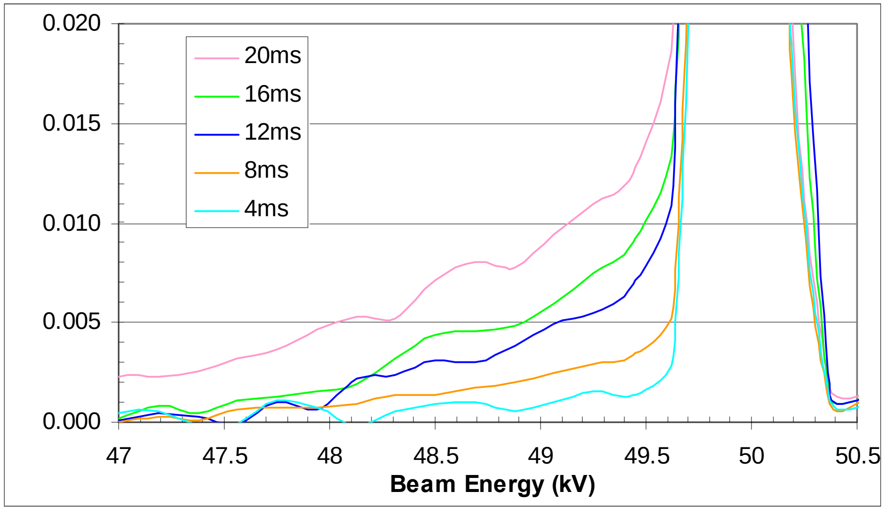


radius of curvature = 4 inches



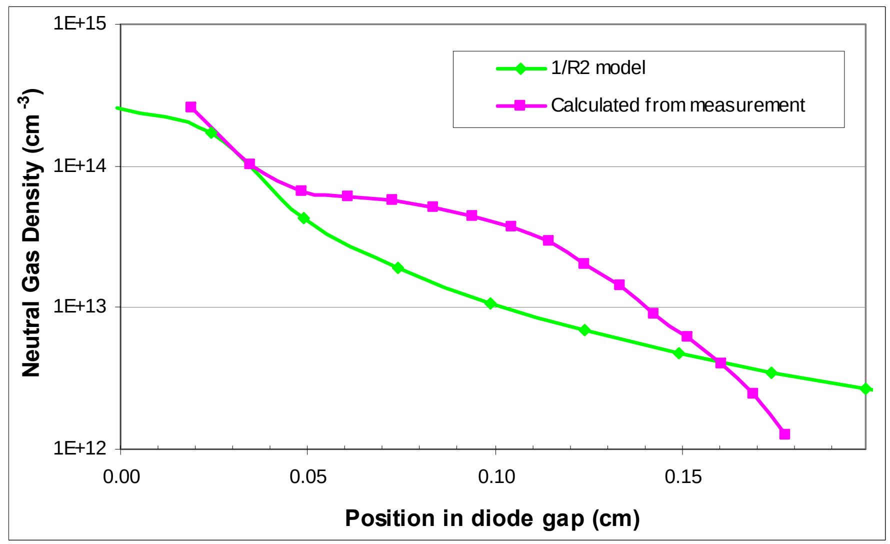
4ms on gas valve ~ 2 mTorr chamber pressure

Charge Exchange Loss



CX effect was proportional to gas pressure

Gas density profile in the extraction gap, calculated using known CX cross-section. Compares to 1/R^2 model.

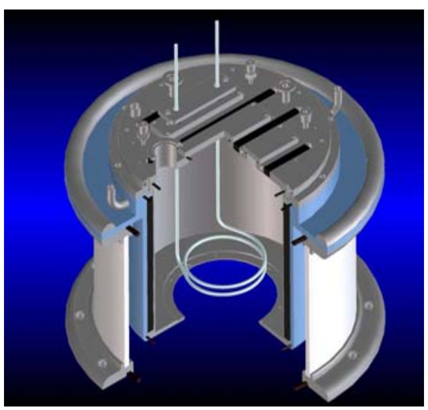


Recent Results from Argon RF Plasma Source

Single Beamlet:

Parameters	Results	Status
Current density	100 mA/cm^2 (5 mA)	met goal
Emittance	T_{eff} < 2 eV	met goal
Charge states	> 90% in Ar^+	met goal
Energy spread	< a few % beam suffers CX	met goal?

RF Source:



Multiple Beamlet:

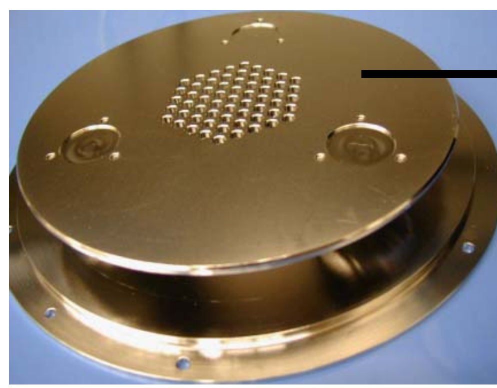
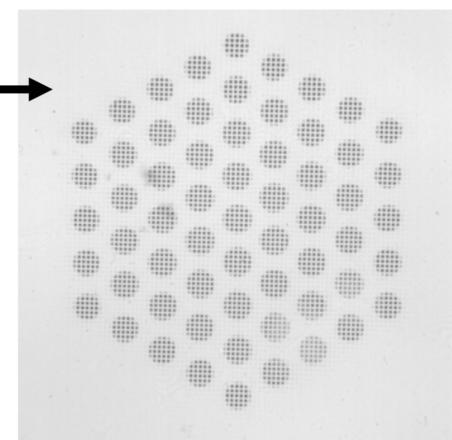
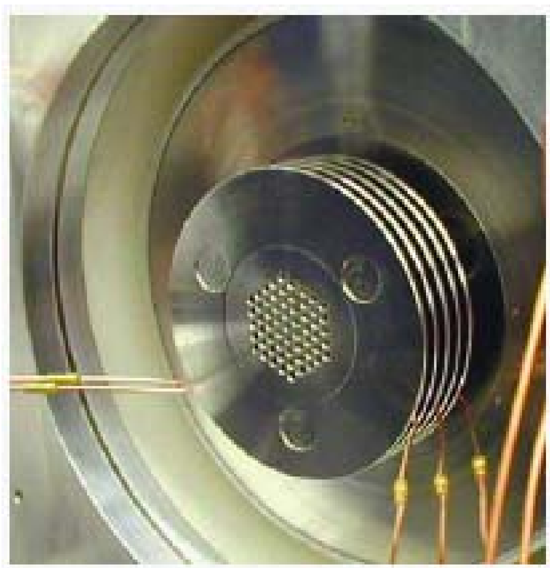


Image on Kapton:



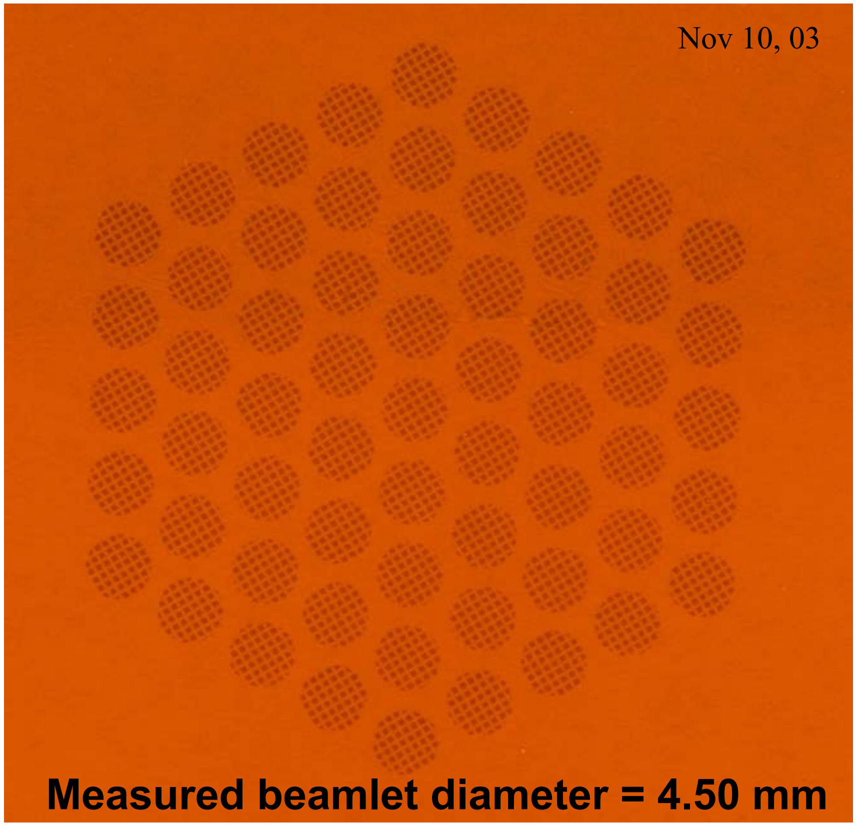
Results of the Einzel lens multi-beamlet experiment

Einzel lens using flat electrodes
HGI held 35kV/cm

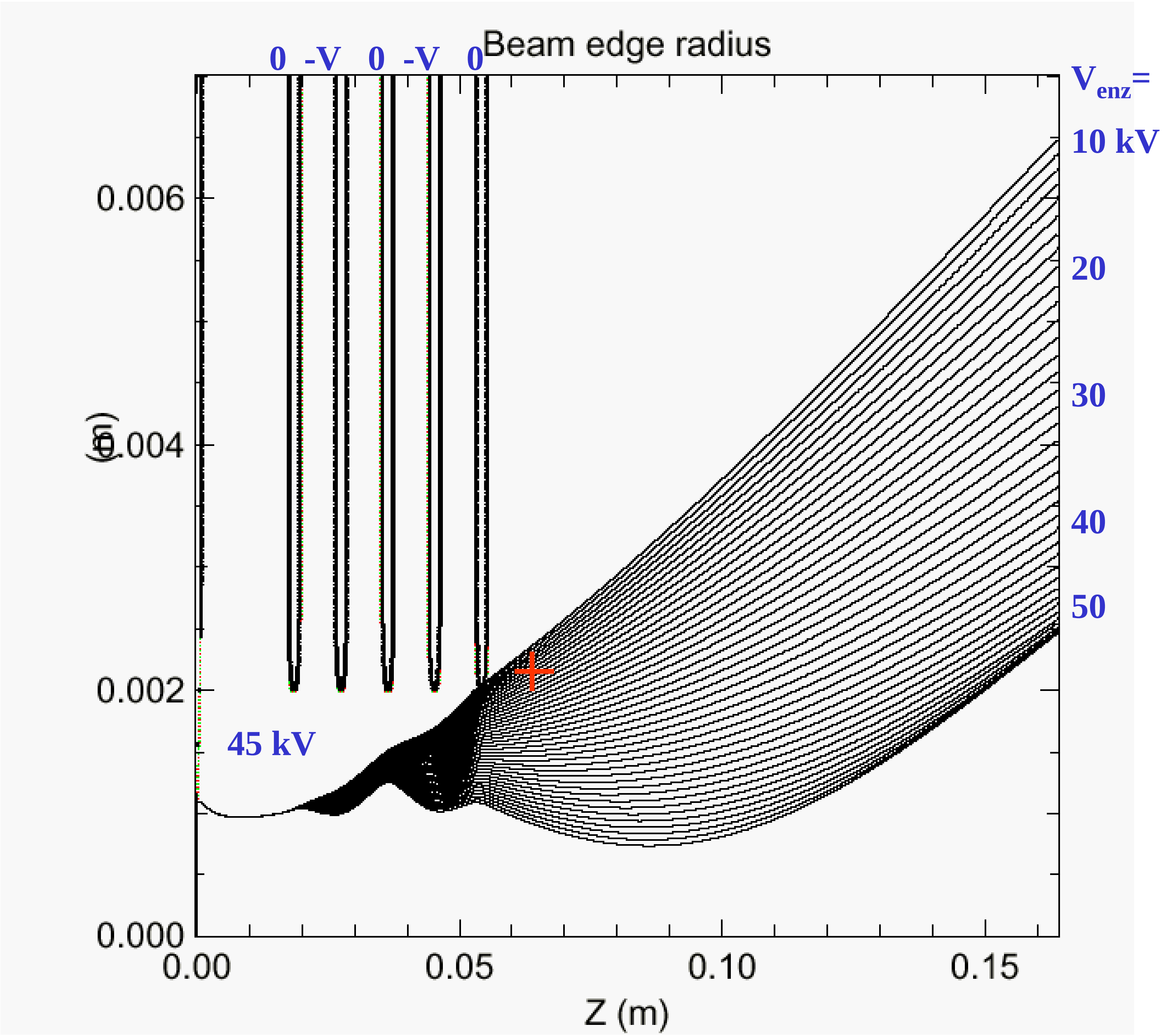


Grid parameters: 61 beamlets,
Pierce aperture diam. 2.21 mm
lens aperture diam. 4.0 mm
Spacing is 6.0 mm

Image on Kapton film



45 kV, 5.5 kV RF
-20 kV Einzel lens



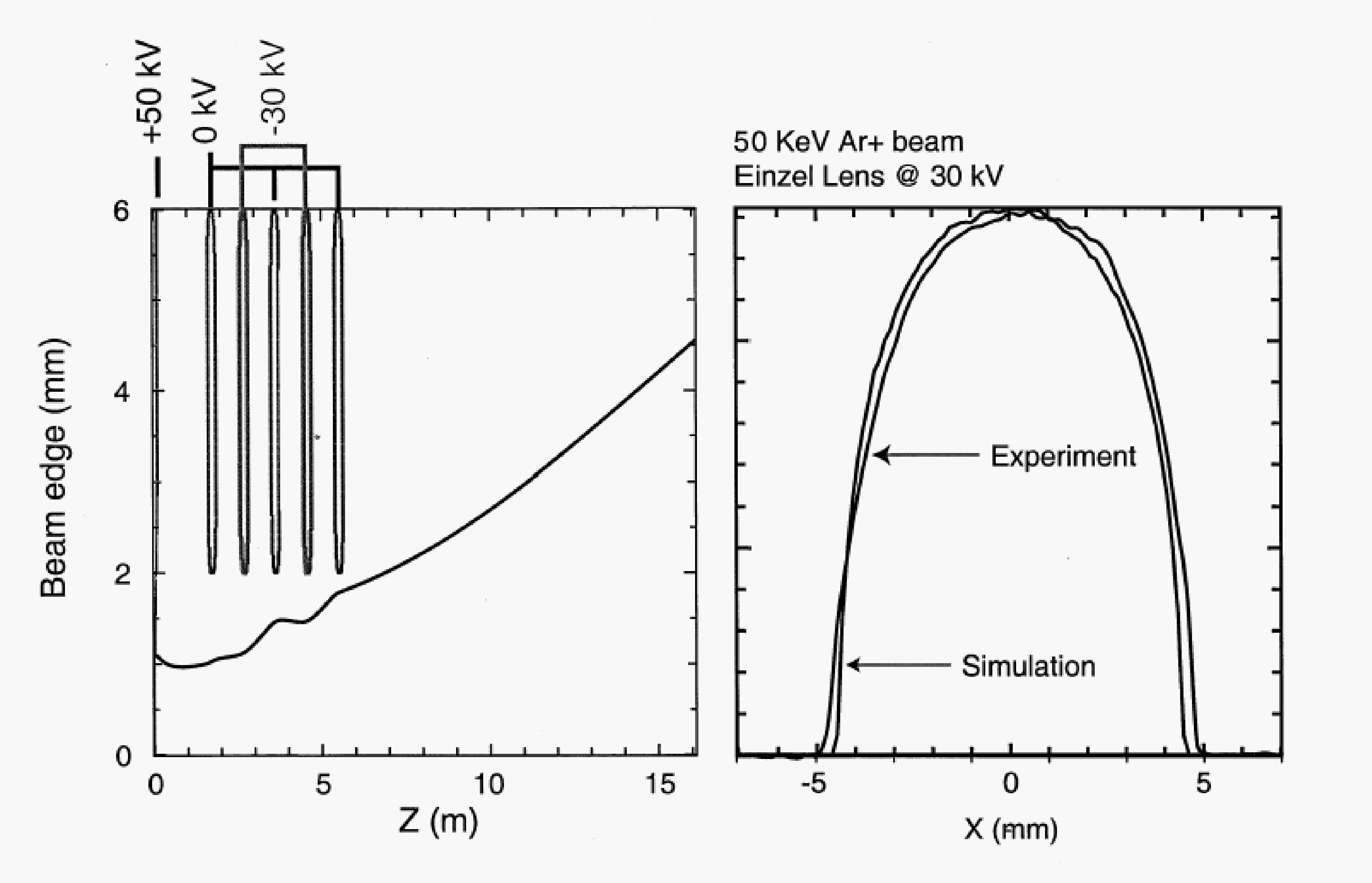
Kapton data:

Measured radius = 2.25 mm at 10 mm downstream.

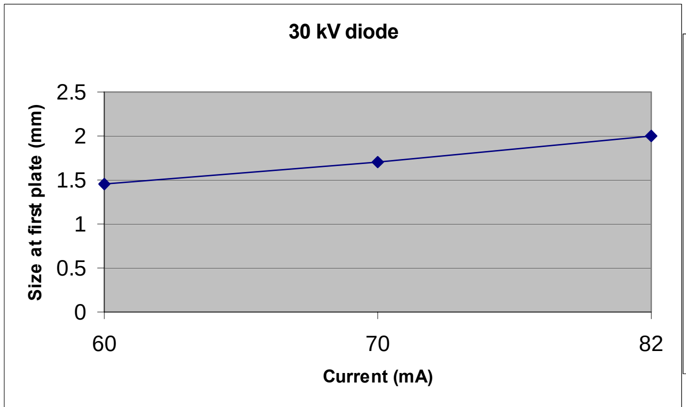
Actual Einzel lens voltage: 10 < V < 20 due to <u>lens drawing current from the power supply</u>

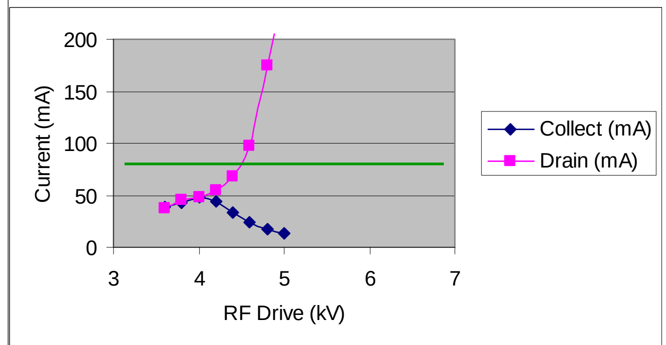
See 031117 presentation

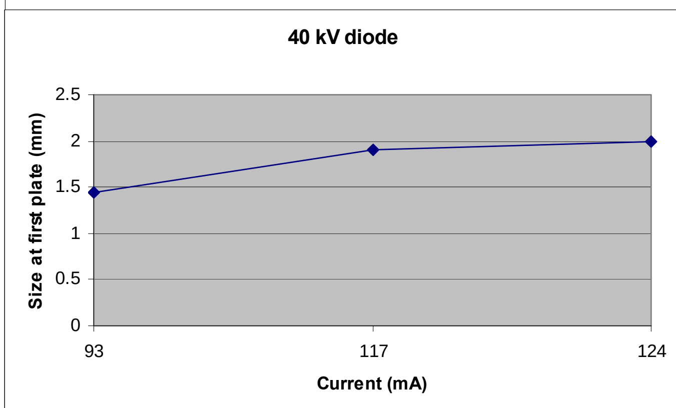
Beamlet profile measured from a slit scanner

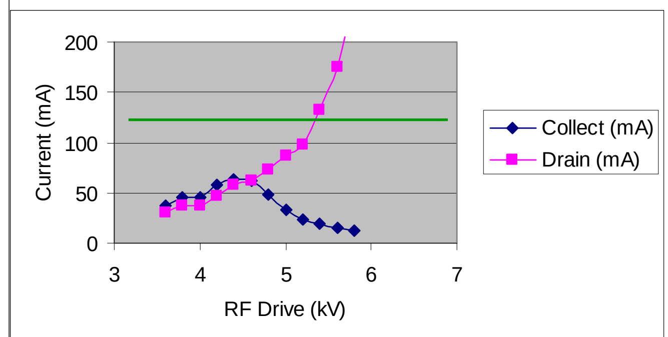


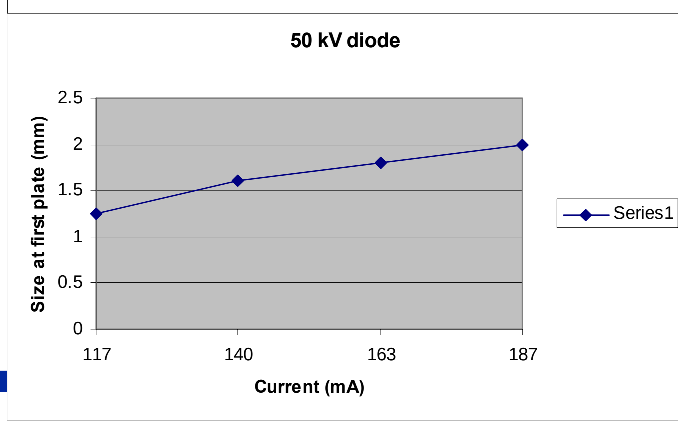
PBGUNs simulation was consistent with data

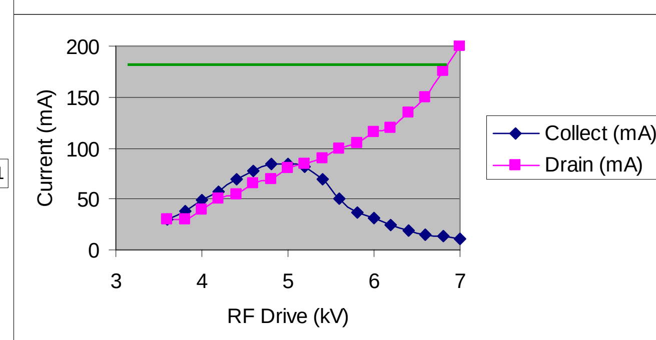






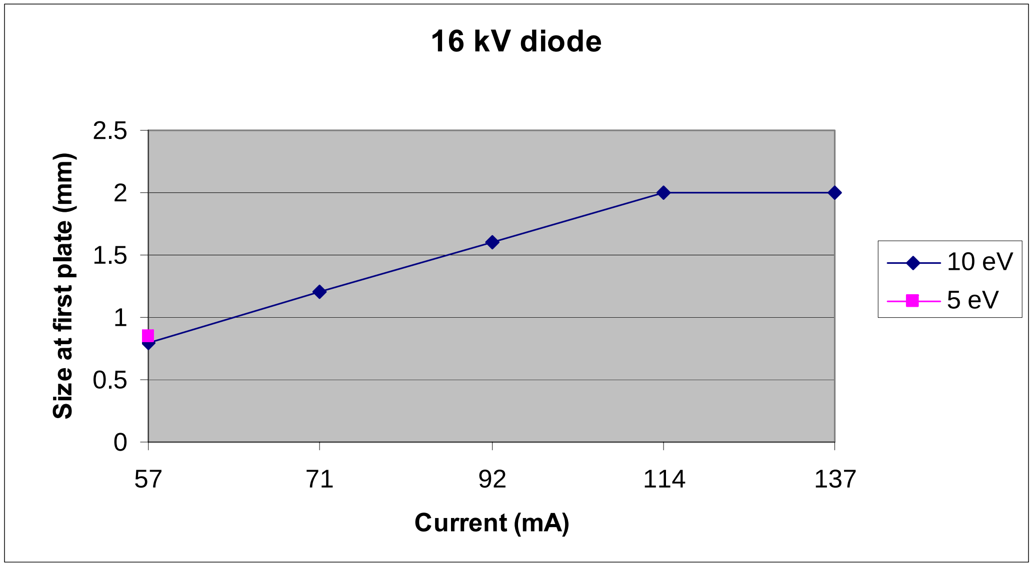






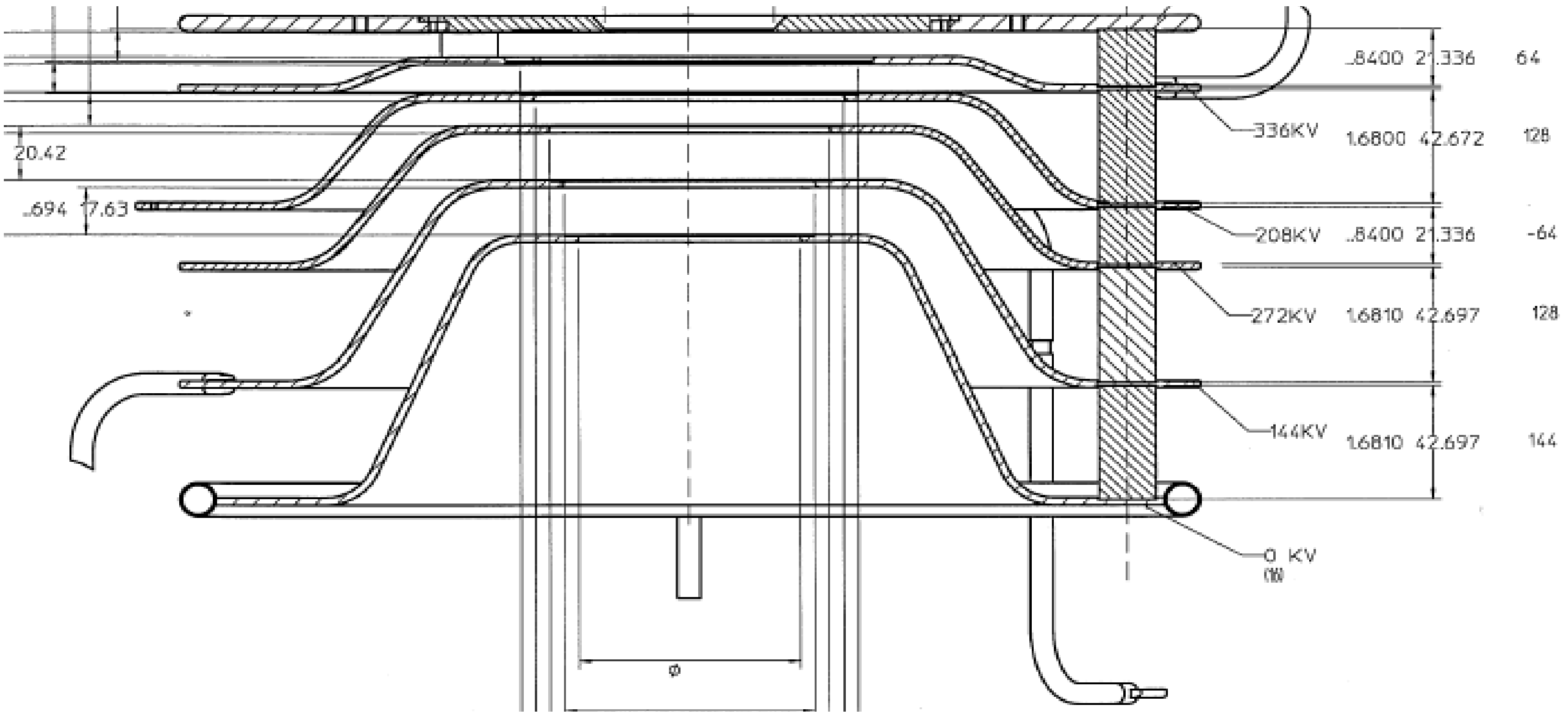
The Merging Beamlet Experiment has a conservative extractor design

Designed operating point for the merging beamlet experiment is ~ 58 mA



The Full-Gradient test will be installed this month

To demonstrate a full current density array, the vacuum gap voltage gradient (> 100 kV/cm) and check for interaction between beamlets.



We will use Faraday cup, and take images of the beamlets

The Final Phase will merge beamlets into an ESQ Channel