Design and Modeling of the Multibeamlet Injector

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Outline

- HIF overview - injector requirements
- Single source injectors
- Multibeamlet injectors
  - Motivation
  - Design
  - Examples
- Experimental validation
  - High gradient experiment
  - Merging experiment

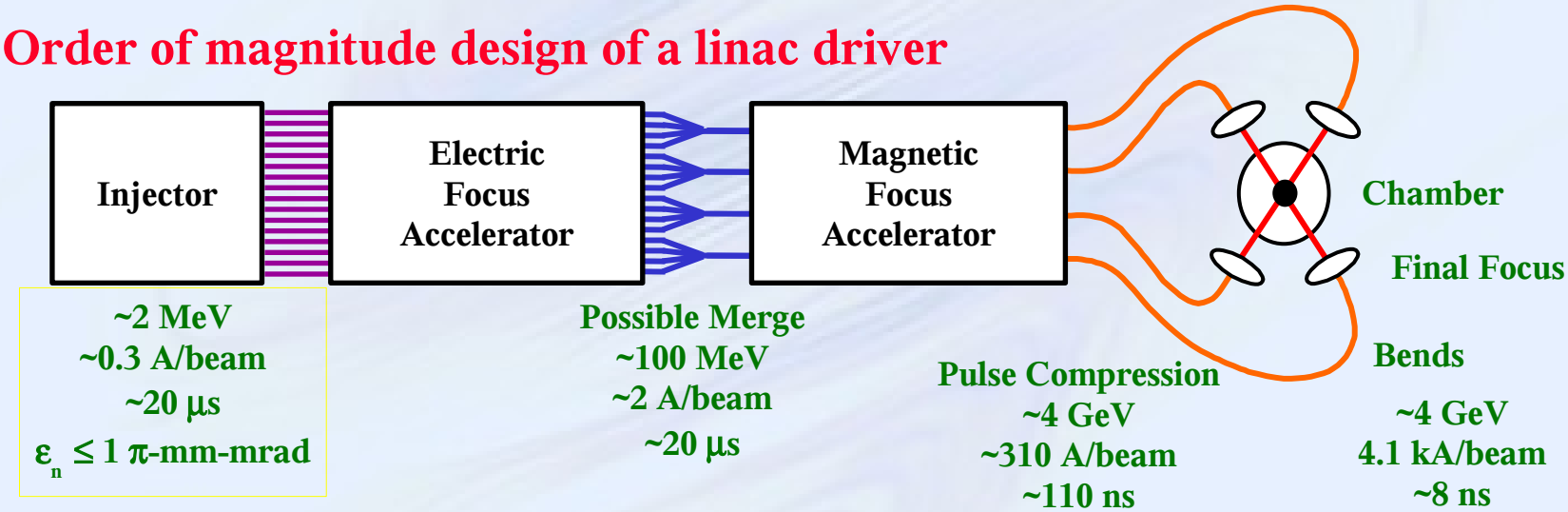
Heavy-ion fusion overview

Typical target requirements:

7 MJ x ~ 10 ns ⇒ *~ 500 Terawatts*

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1- 10 GeV*

Order of magnitude design of a linac driver



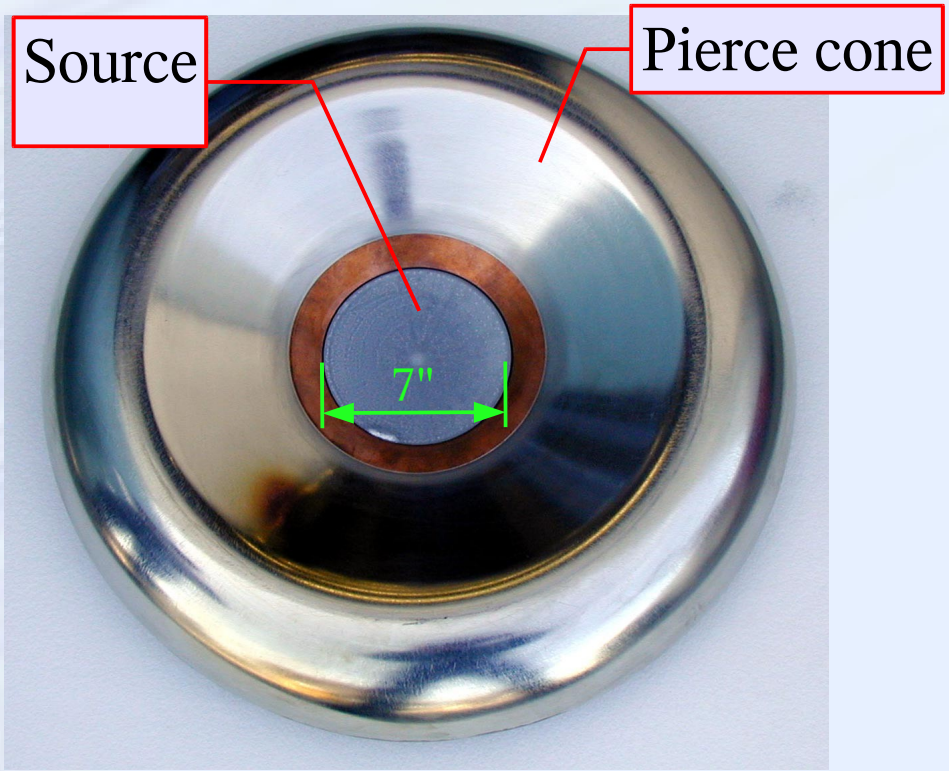
Induction acceleration

- Beams are very long: length >> width
- Significant current amplification ~ factors of 100

Very different regime than R-F accelerator

Single source injector

- Traditional approach is monolithic hot plate source with a large Pierce cone.
- It has proved successful so far
  - Produces pure beam, rapid pulse rise
- However, it has limitations.
  - Limited ion supply
  - Poor scaling to higher currents
  - Require operation at high temperatures



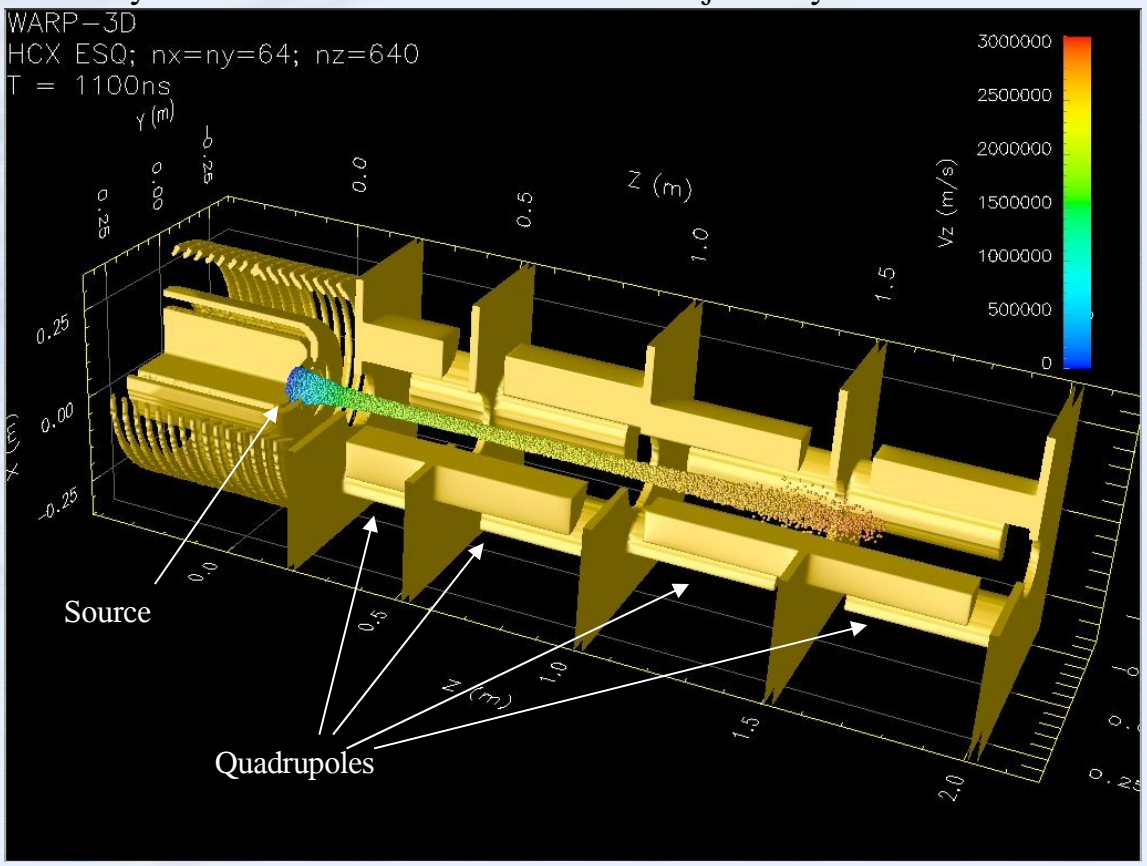
Typically 100's of mA of K^+ or Cs^+ at 100's of kV
with normalized emit < 1 π-mm-mrad

Example injector with single source

For High Current Experiment
0.5 A of K^+ at 1.6 MeV
$\varepsilon_n \sim 0.5\ \pi$-mm-mrad

- ESQ's provide strong focusing of large space-chage
- Arranged to also provide further acceleration
- In matching round beam from source to elliptical beam transport, large excursions unavoidable
- For multiple beams, injector system can become very large

Cut away view from WARP3d simulation of injector system of HCX



Single source exhibits poor scaling for high current

Constraints limit diode design

- Child-Langmuir for 1-D diode $J \propto \frac{V^{3/2}}{d^2}$ $I = AJ$
- Breakdown limits $V \propto \sqrt{d}$
- Minimizing geometric aberrations limits (A/d^2)

- Emitter area then a high power of the total current $A \propto I^{8/3}$
- And current density inversely proportional to the current $J \propto I^{-5/3}$

Multibeamlets circumvent the poor scaling

- Many small beamlets can have each have large current density.
- Assuming fixed total emitter area, proportionality of current and current density restored

$$I_{Total} = N\ I = NAJ$$
$$NA = constant$$

N is the number of beamlets.

Estimates of emittance growth

Assuming properly directed matched beam in uniform focusing:

From conservation of energy, can estimate emittance growth

- 'Excess' self field energy over uniform beam goes into emittance
- With occupancy factor
  $\eta = 2a/\delta_r, \quad a = \textit{Beamlet radius}, \quad \delta_r = \textit{center-to-center distance}$
- Perveance $Q = 2\lambda q / 4\pi\epsilon_0 m v_z^2$
- The normalized free space-charge energy is approximately

$$U_n \approx \frac{4}{N}\left(\frac{3}{4} - \ln 3 - \ln\eta + \frac{3}{8}\eta^2\right)$$

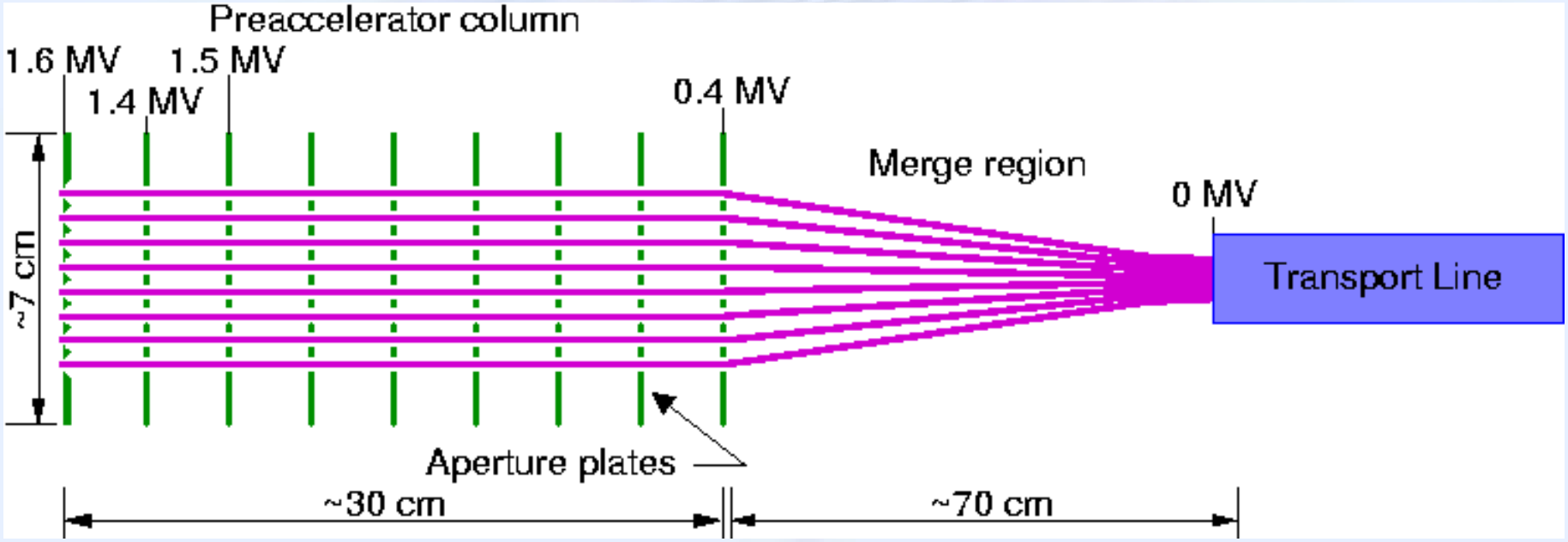
- Giving a change in emittance

$$\frac{\epsilon_{final}^2}{\epsilon_{initial}^2} \approx \frac{\langle X^2\rangle + \langle Y^2\rangle}{2\langle X^2\rangle}\left(1 + \frac{QU_n}{8\langle X'^2\rangle}\right)$$

- Maximize N, minimize η, minimize Q

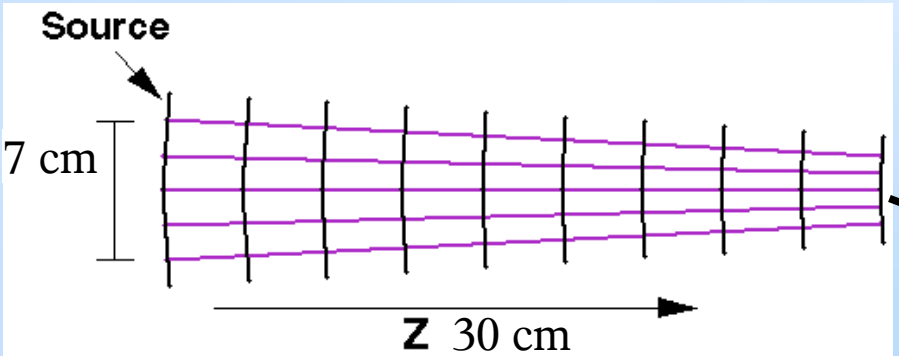
Injector layout

- Pre-accelerator column -- Einzel lenses + acceleration
- Merging region – with addition acceleration

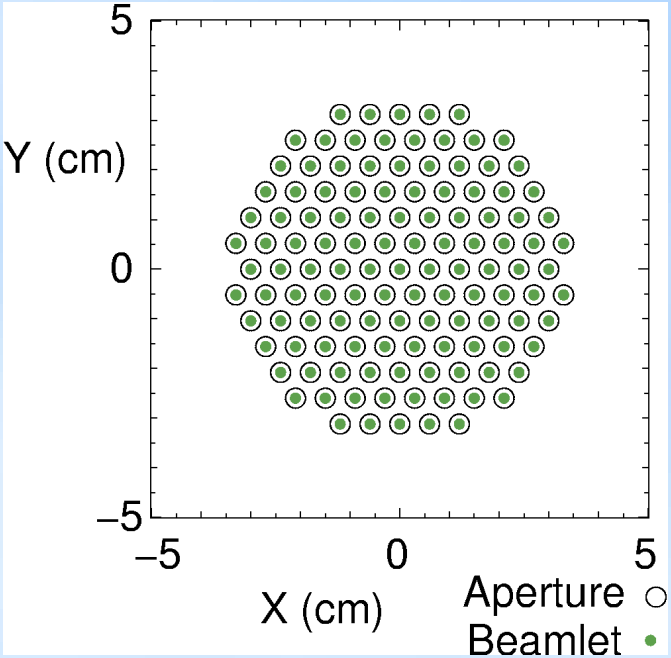


Layout cont.

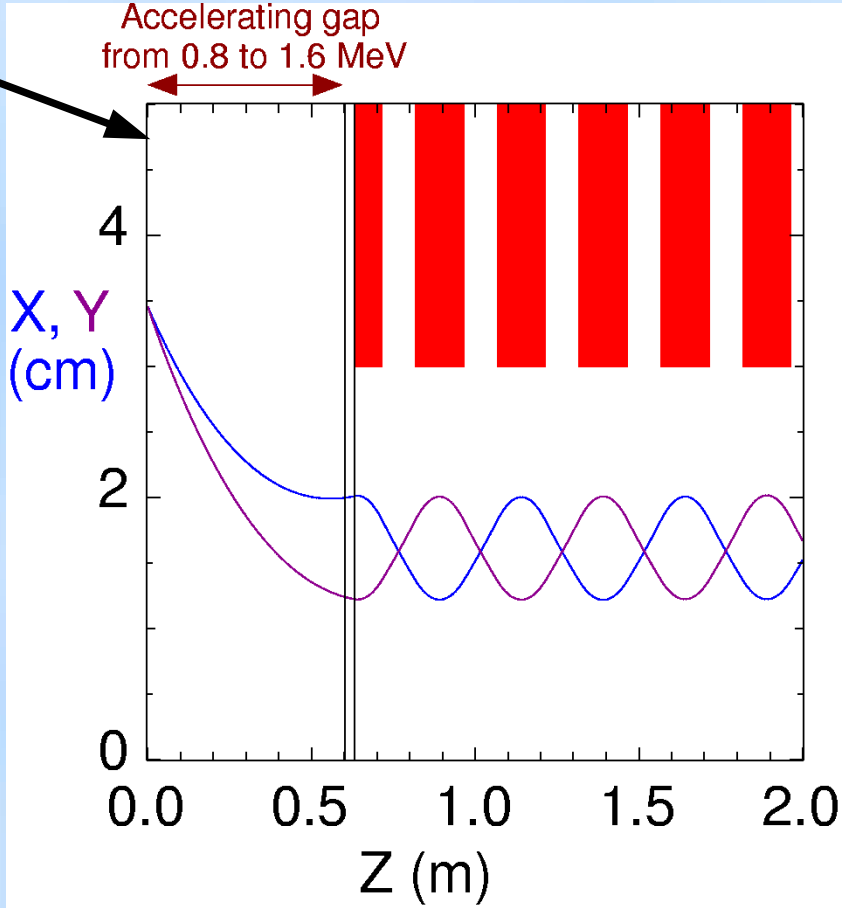
Beamlets converge



Hexagonal dense pack arrangement

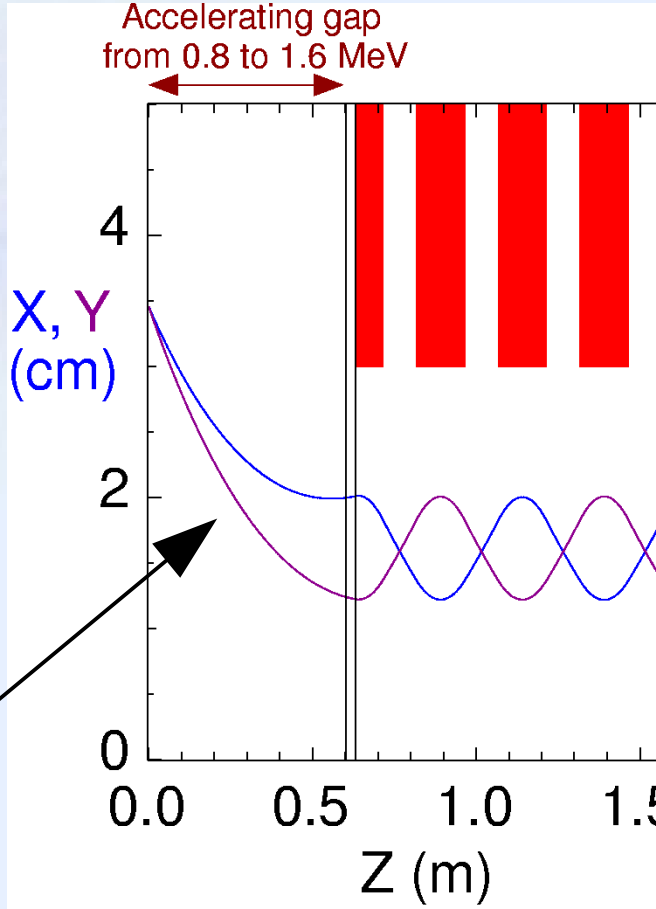


Beamlets aimed to be exactly matched to transport lattice. Note first quad is partial length



Injector designed starting with only two parameters

- Number of beamlets
- Energy at which beamlets merge
- The transport lattice is assumed known
- Constraints and minimization of the emittance determine the rest of the design
- The number of beamlets fixes the beam size at the last aperture plate.
  - A unique envelope solution matches into the transport lattice, which starts with a partial length quadrupole



Constraints on beamlet spacing

Space required between beamlet and aperture to avoid scraping

- Various errors can lead to beamlet offsets
- 100 micron errors lead to approximately 0.5 mm offset

Material needed between beamlets for rigidity of plate

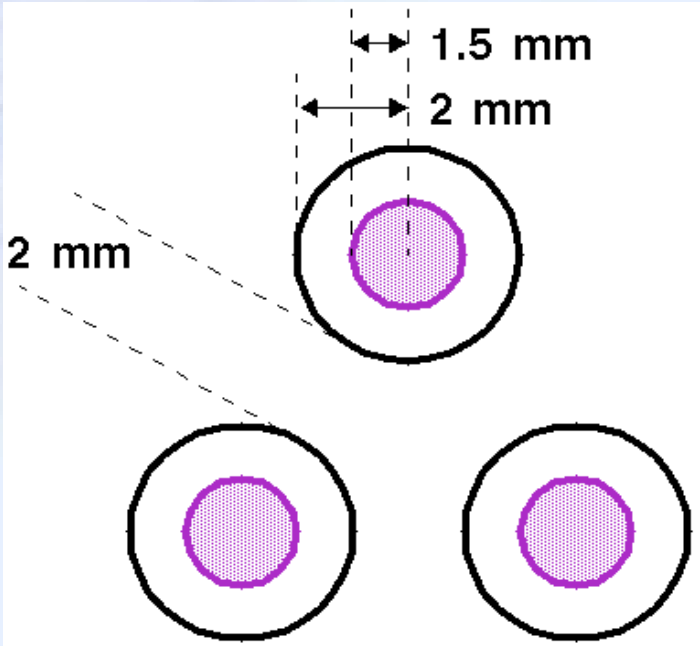
- 2 mm should be sufficient

Sufficient shielding between beamlets is required

- 2 mm should be sufficient

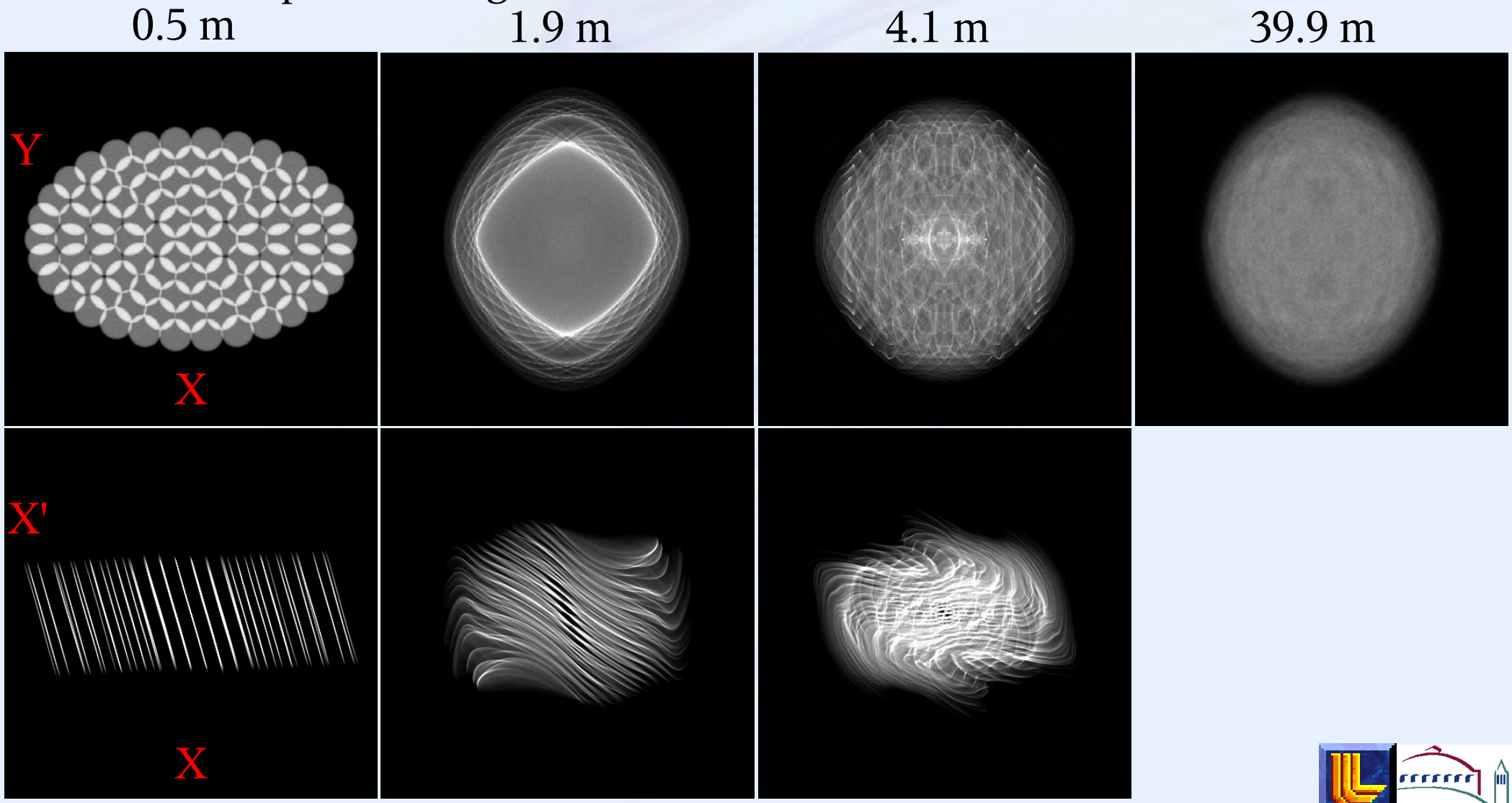
Achievable current density must also be taken into account

- $J_{max} \sim 100$ mA/cm^2
- ~1 mm source radius gives 3.1 mA



Slice simulations of merging region and transport

2-D grid 512x512 -> 20 grid cells across beamlet diameter
20,000 particles per beamlet, 91 beamlets
Elliptical arrangement of beamlets



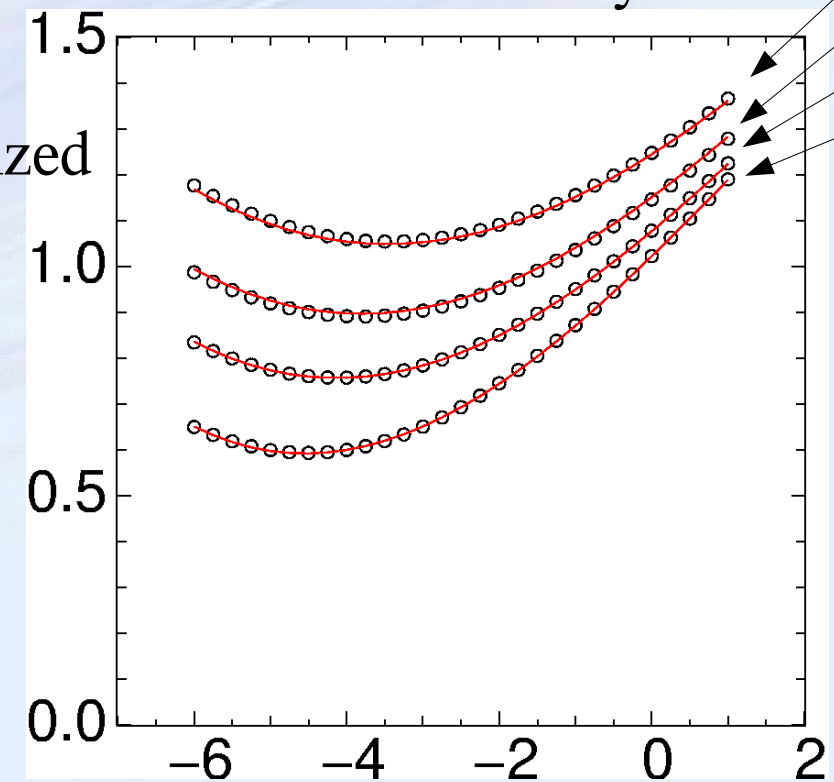
Characterization of merging

- Slice simulations of merging
- This example: 121 beamlets, hexagonal packing, merging at 0.8 MeV

Red curves are analytic fit

Initial beamlet radii
- 0.8 mm
- 1.0 mm
- 1.2 mm
- 1.5 mm

Merged normalized emittance (π-mm-mrad)



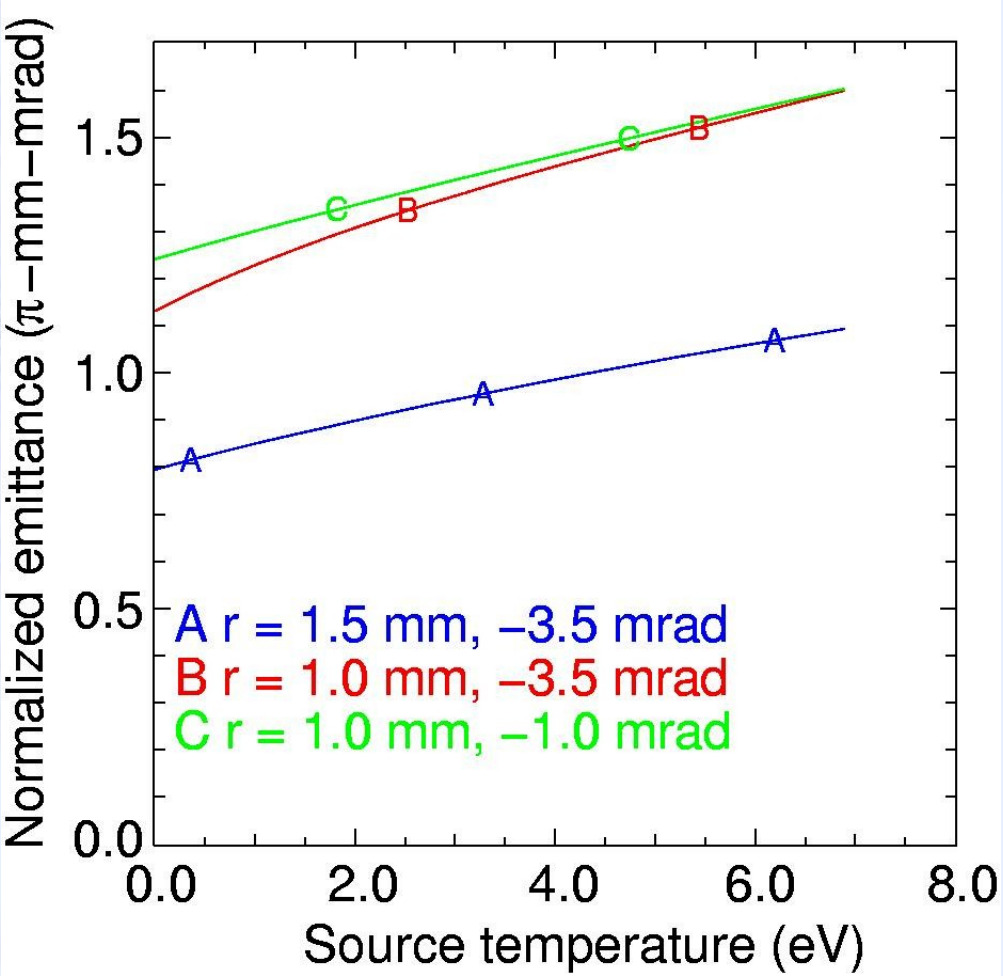
Beamlet convergence angle

Merged emittance insensitive to source temperature

Merged emittance weakly dependent on source temperature

- Solid surface source T < 1 eV
- Plasma source T ~ 2 eV

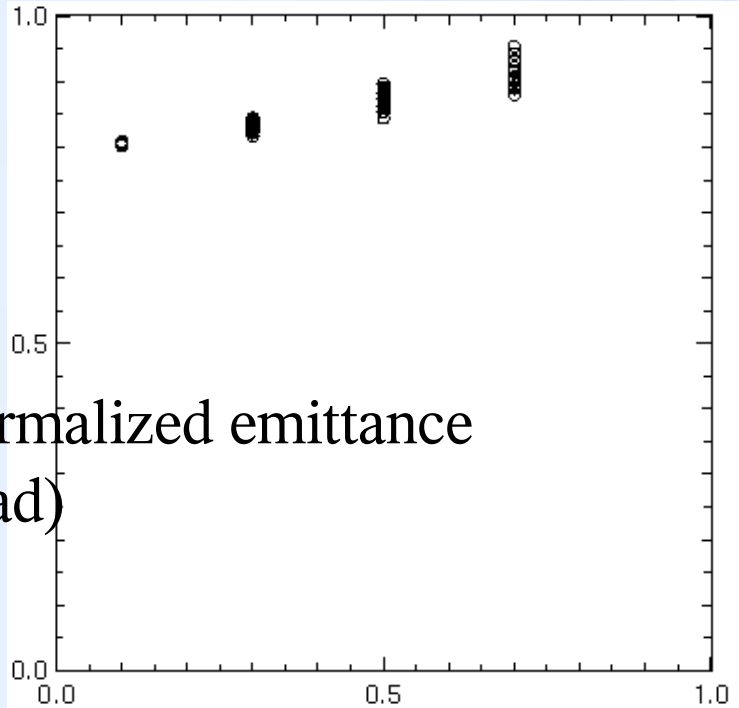
91 beamlets
Merging at 1.2 MeV



Robustness to errors

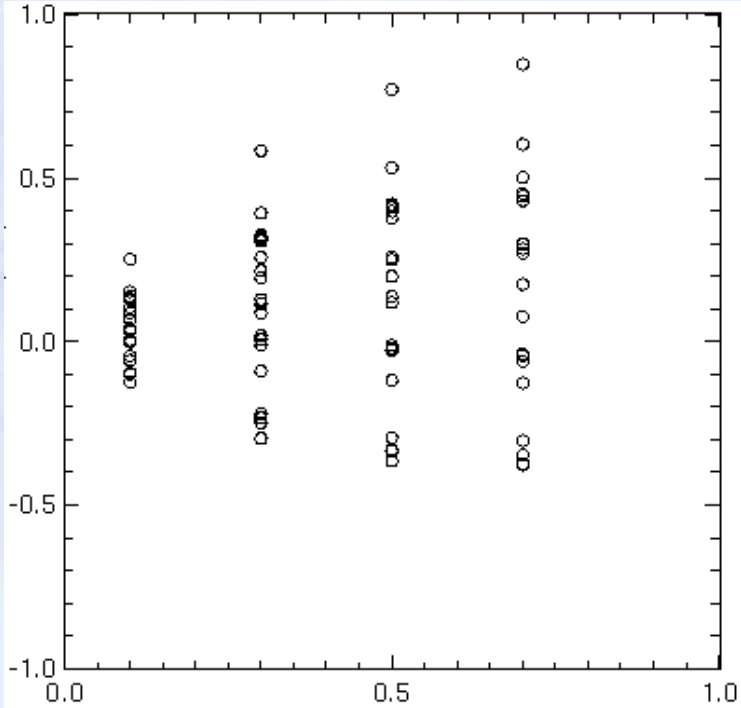
- Merged emittance insensitive to errors in beamlets
- Ensemble of 80 slice simulations of merging with differing random seeds and varying error amplitudes

Merged normalized emittance (π-mm-mrad)



Beamlet errors (mm, 0.5mrad)

X bar (mm)



Beamlet errors (mm, 0.5mrad)

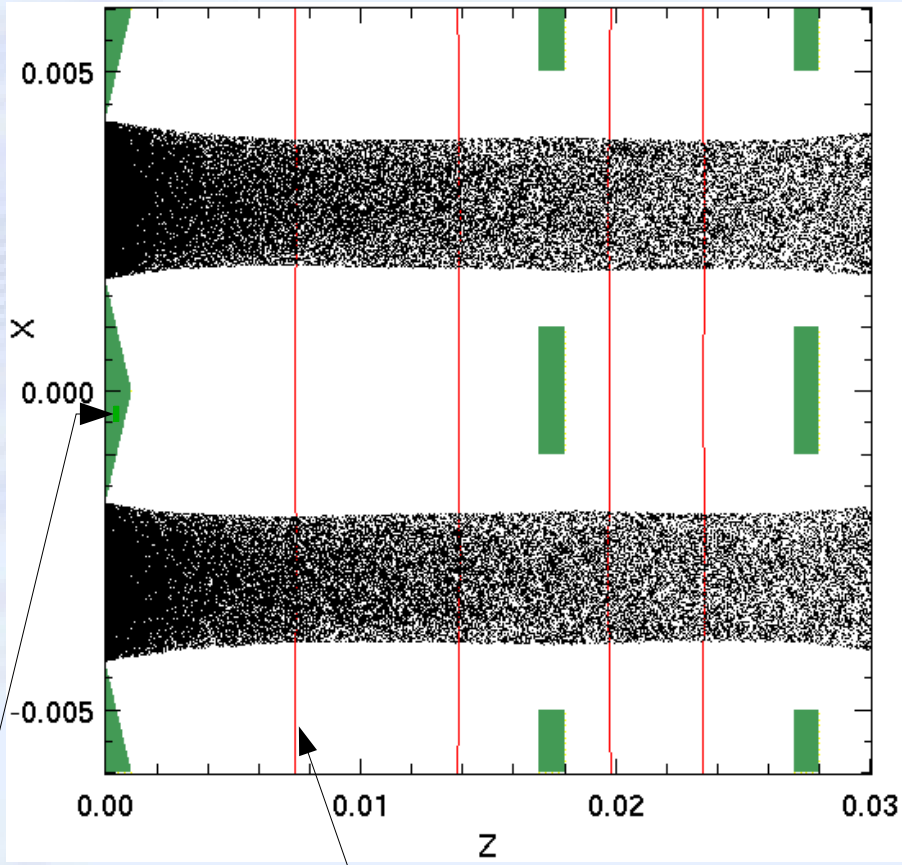
91 beamlets, merging at 1.2 MeV

Diode design

Source radius adjusted to give desired current.

Requires full 3-D simulation since neighboring Pierce cones intersect

6.4 mA per beamlet
Pierce angle of 60°
Source radius of 1.233 mm
Current density 133 mA/cm^2
64x64x200 grid
150k particles per beamlet

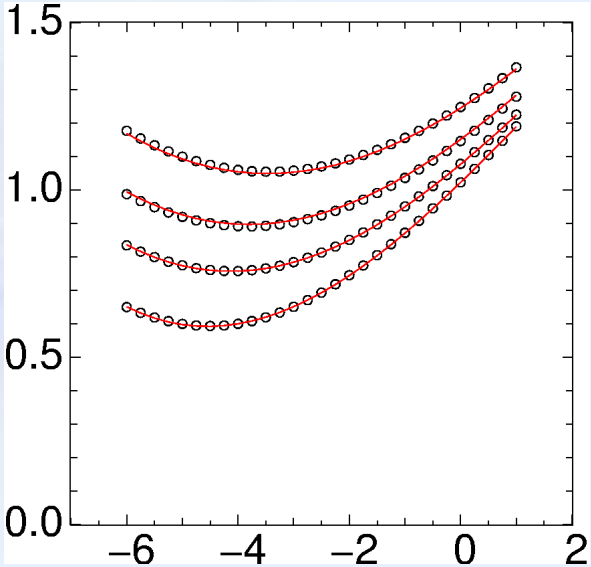


Contours of constant potential

Note that because of the intersection, the Pierce cones are very shallow.

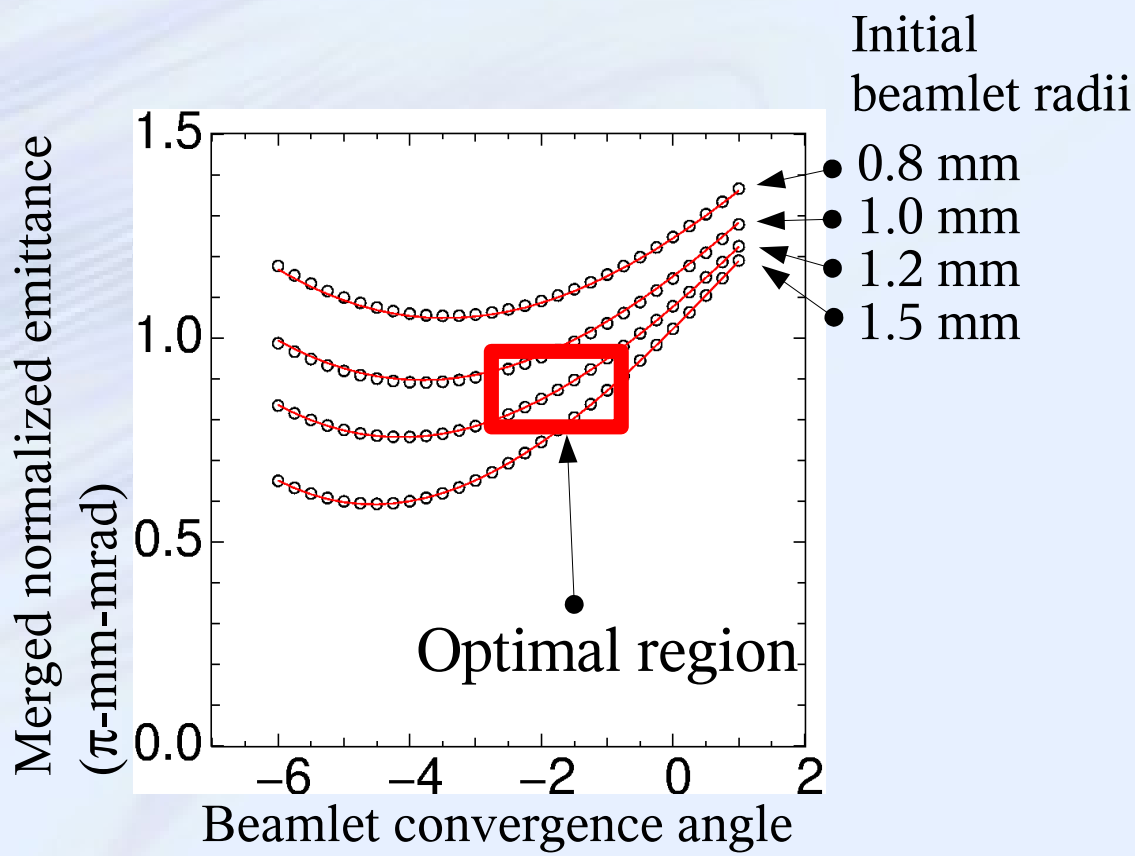
Optimizing preaccelerator column

- Vary plate location and voltage to find final beamlet parameters which minimize emittance
- Additional constraints:
  - Minimum transverse clearance of 0.5 mm (given 100 micron errors)
  - Plate separation within 5 mm to 5 cm (to minimize beamlet interaction)
  - Voltage on last plate is fixed (set by transport lattice)
  - Maximum voltage gradient below breakdown
  - Plate uniformly spaced (for cost reduction)
- Used SPSA multidimensional minimization algorithm with envelope calculations



Minimum emittance not reachable

- Balance between beamlet size and convergence angle
- The larger the beam size, the smaller the achievable size of the convergence
  - The decreasing focusing strength of the Einzel lenses at higher energy only hurts



Example column design

Final beamlet parameters
a = 1.14 mm
a' = -2.34 mrad

Resulting normalized emittance from fit
ε = 0.86 π-mm-mrad

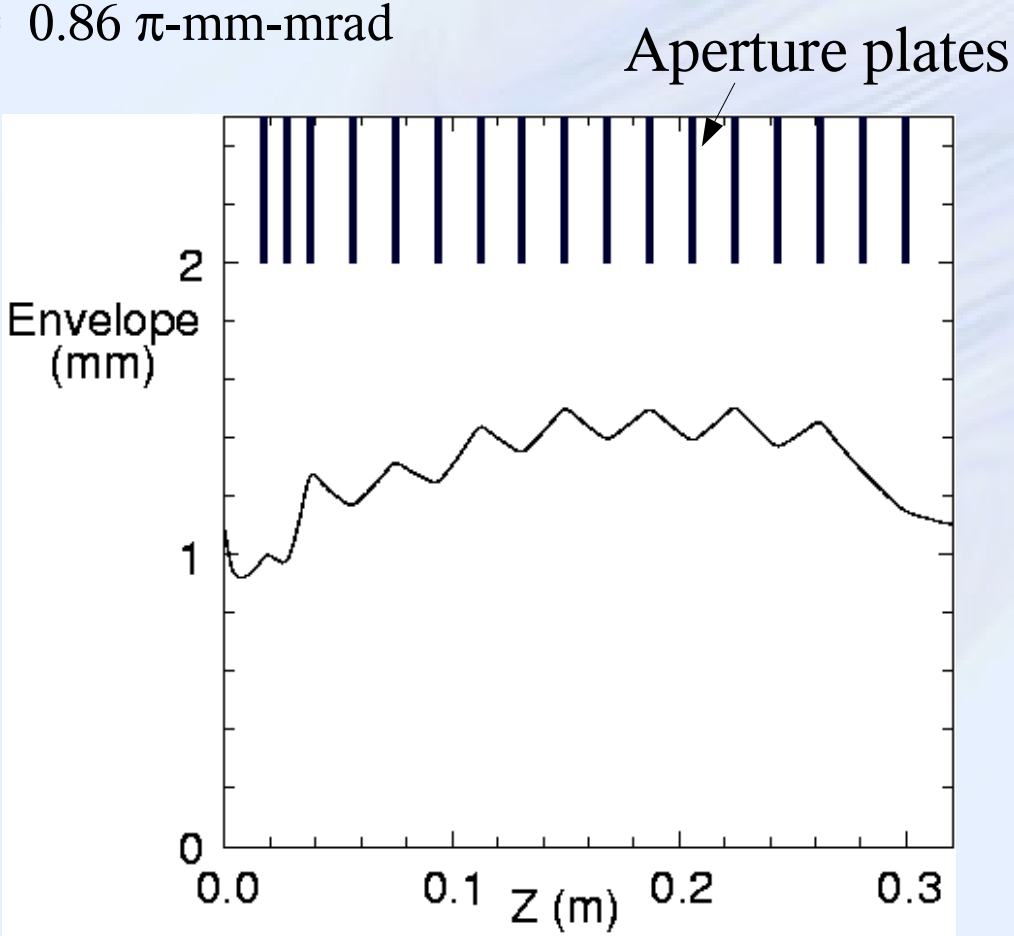


Plate locations (m)	Plate voltages (kV)
0.0175	700
0.0275	600
0.0375	700
0.0562	549
0.0749	572
0.0936	385
0.1123	504
0.1310	317
0.1497	444
0.1684	258
0.1871	376
0.2058	190
0.2245	368
0.2432	186
0.2619	373
0.2808	186
0.2993	0

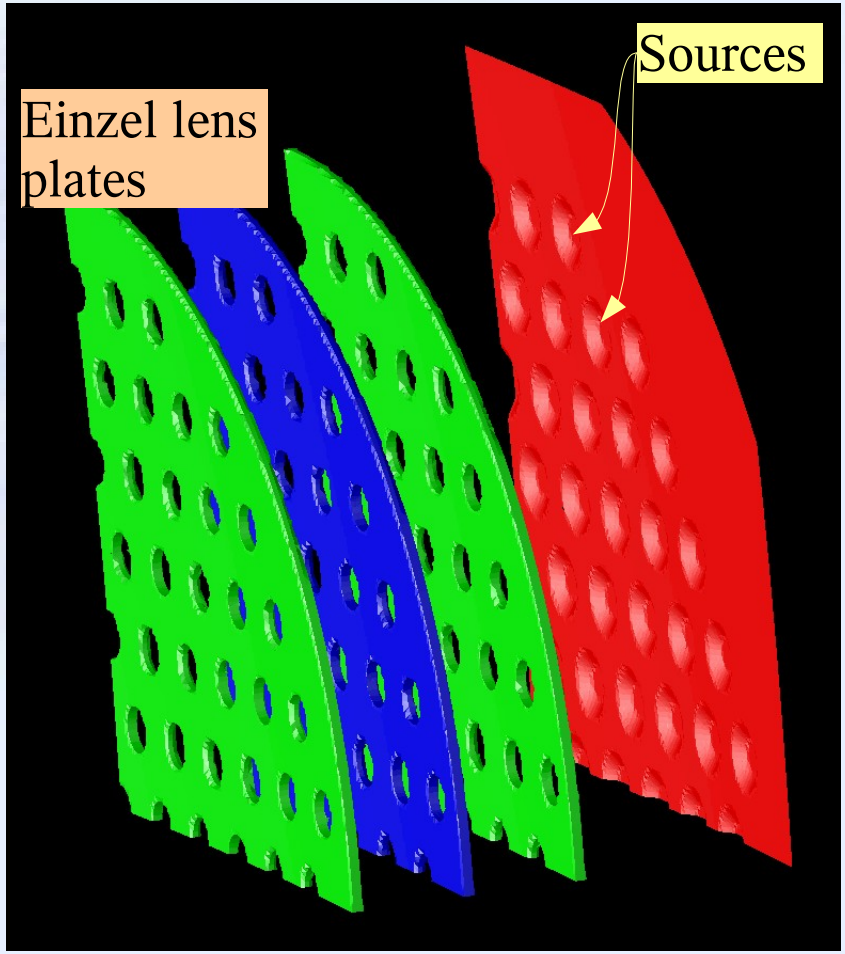
Aperture plate design – circular arrangement of beamlets

- Convergence angle is different in vertical and horizontal - it is astigmatic
- Plate surface normal to beamlets
- With x'=xa'/a, y'=yb/b', no surface exists
- Plates are nearly flat - sagitta ~few mm
  - Surface can be approximated
  - Error on order of several microns
- Two approximate surfaces defined by

$$(z-z_b)^2=[z_a-z_b-\sqrt{(z_0-z_a)^2-x^2}]^2-y^2$$

$$(z-z_a)^2=[z_b-z_a-\sqrt{(z_0-z_b)^2-y^2}]^2-x^2$$

Where z_a and z_b are x and y focal points, and z_0 is location of surface at x=y=0.



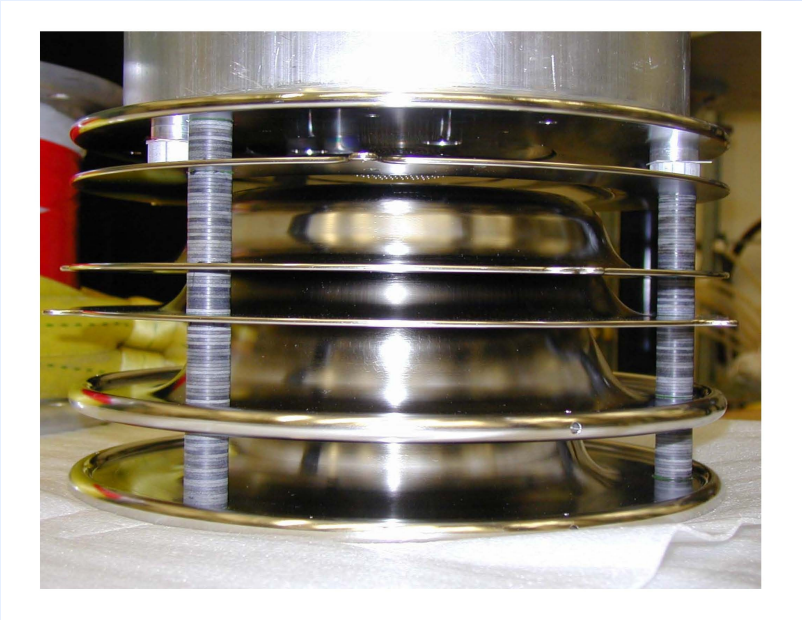
Global optimization

- Only small advantage to merging at higher energy
  - Lower emittance minimum at higher energy
  - But with weaker focusing - can't get as close to minimum
- Large advantage for smaller beam spacing – giving a more compact arrangement

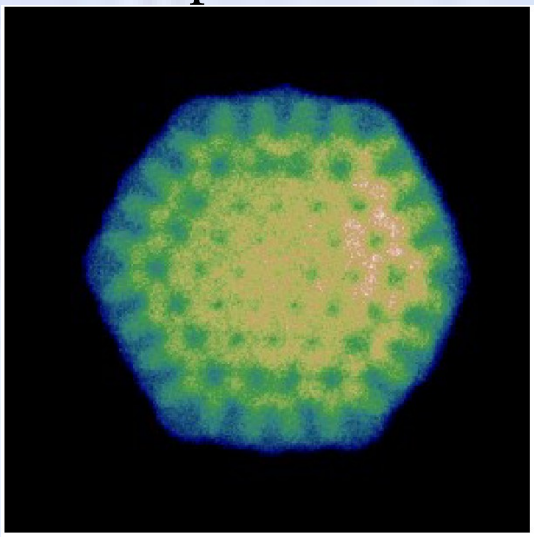
Beamlet Spacing (mm)	# Beamlets	Merge Energy (MeV)	Beamlet Size (mm)	Beamlet Convergence (mrad)	Normalized Emittance (π-mm-mrad)
6	121	1.2	1.21	-1.42	0.80
		0.8	1.34	-2.34	0.86
	199	1.2	1.21	-1.86	0.70
		0.8	1.15	-2.74	0.76
5	121	1.2	1.22	-1.35	0.60
		0.8	1.15	-2.50	0.62
	199	1.2	1.21	-1.87	0.51
		0.8	1.17	-2.74	0.55

High gradient experiment - STS500

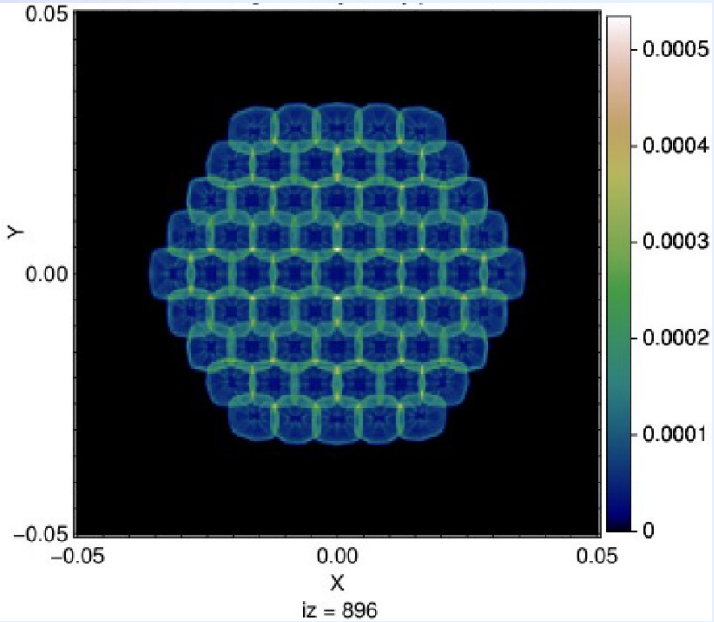
- Used to test voltage holding of closely space aperture plates in the presence of beamlets
- First 4 plates of injector at full voltage with 61 parallel beamlets
- Successfully held voltage > 100 kV/m



Experiment



Simulation

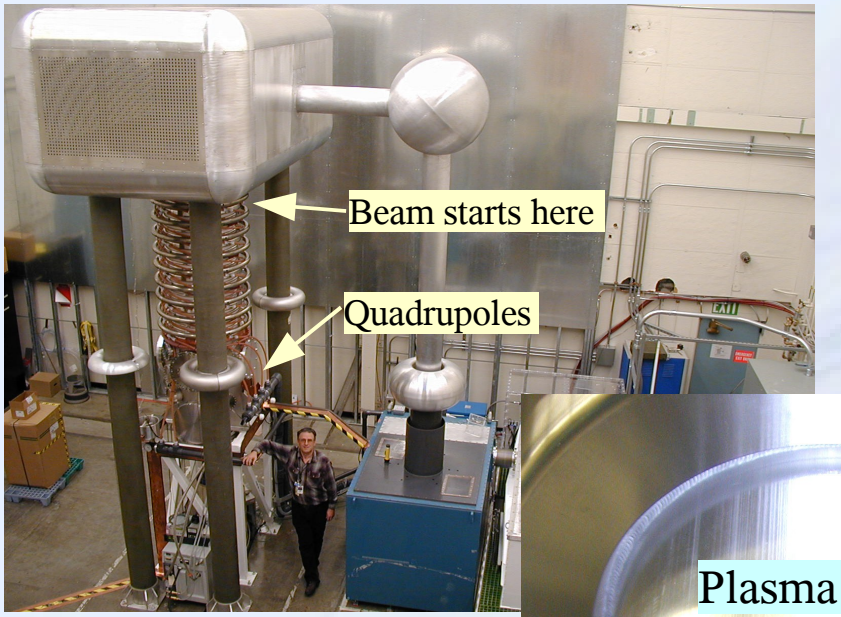


Beam density down stream

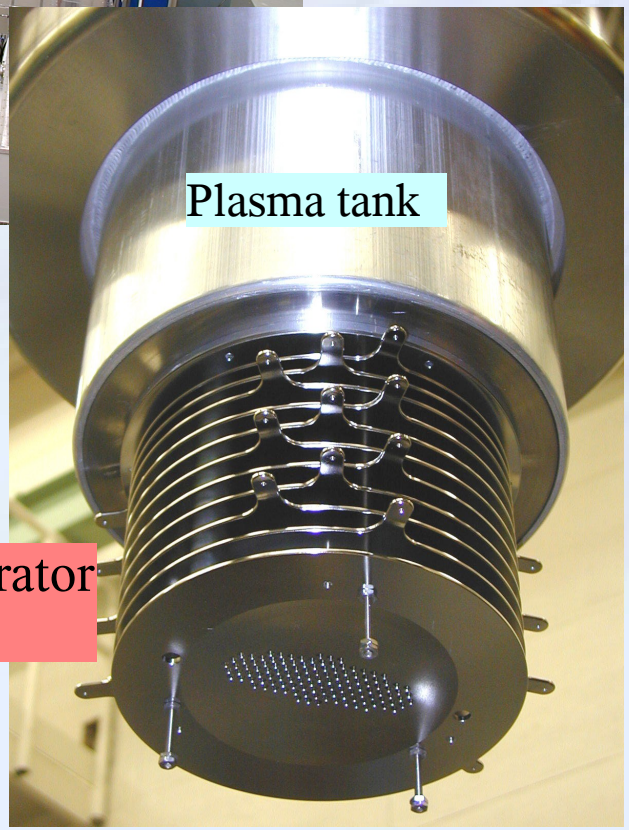
Merging experiment - STS500

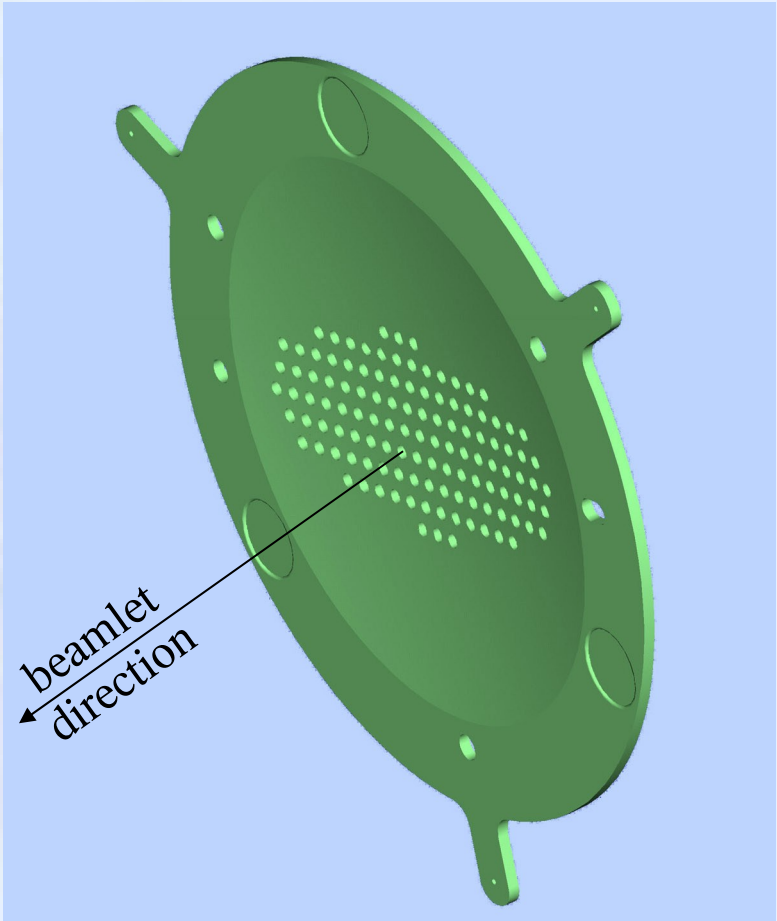
- Used to test beam physics
- Limited to 400 kV so used quarter voltage scale to model 1.6 MeV injector – only voltage scaled, beam size the same
- Due to cost limitations:
  - Used spherical plates
    - Beamlet arrangement becomes highly elliptical
    - Ellipticity causes large difference in x and y emittances
  - Use evenly spaced aperture plates (insulators all the same size)
  - Limited number of plate voltages available – only at evenly spaced voltages of the divider rings in the insulator column
    - Still enough flexibility though to reach optimal emittance

Merging experiment photos



Full STS500 system



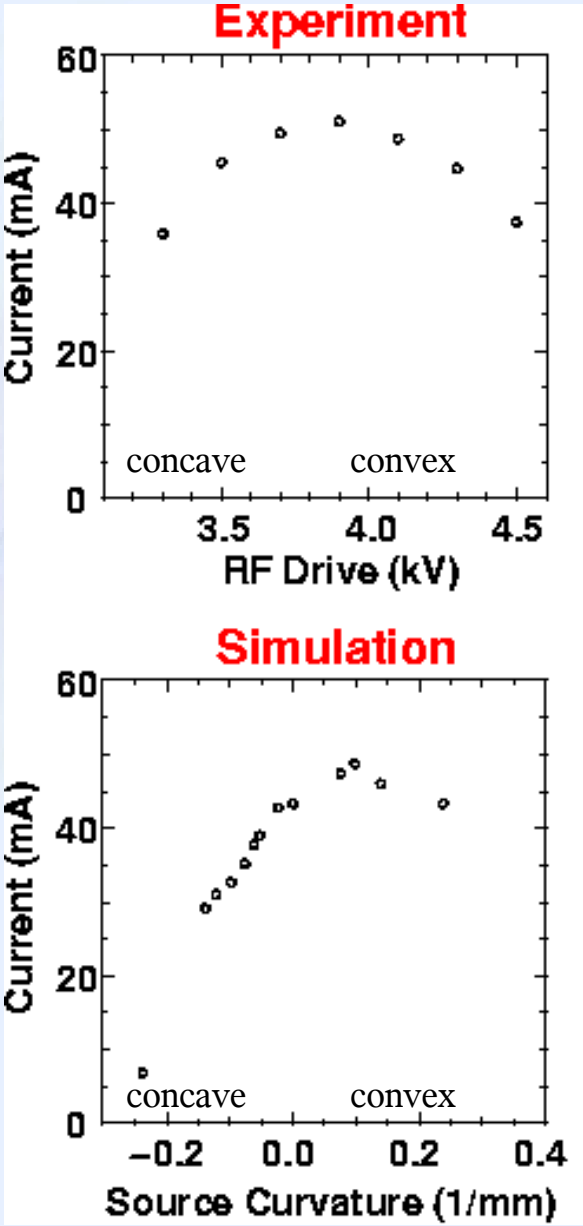


CAD drawing of single aperture plate
Note the elliptical hole pattern

Merging experiment results

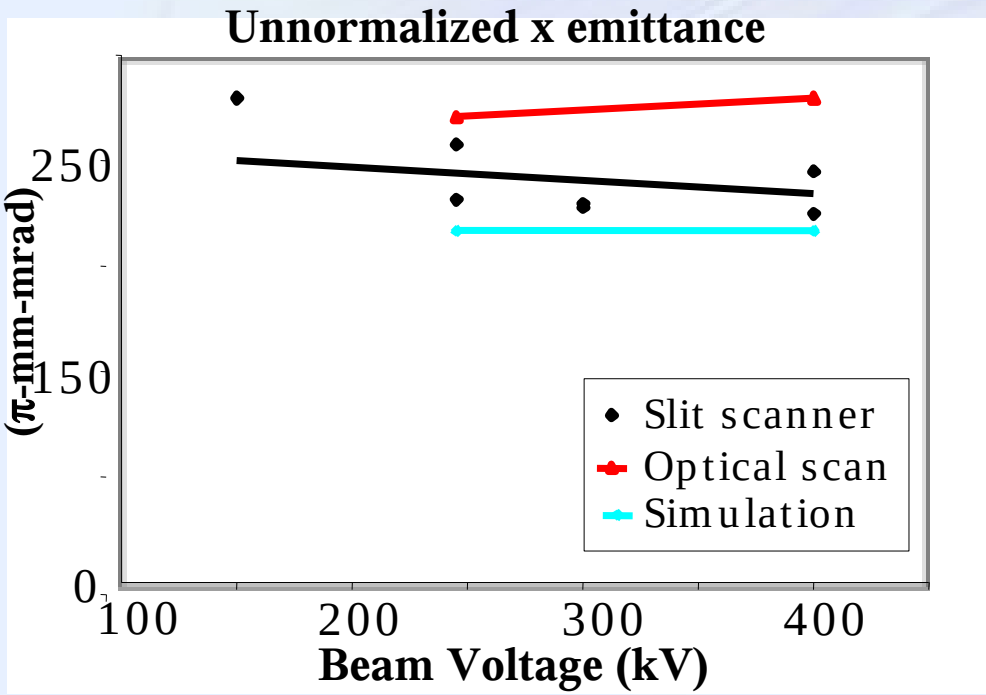
Scan varying plasma RF Drive

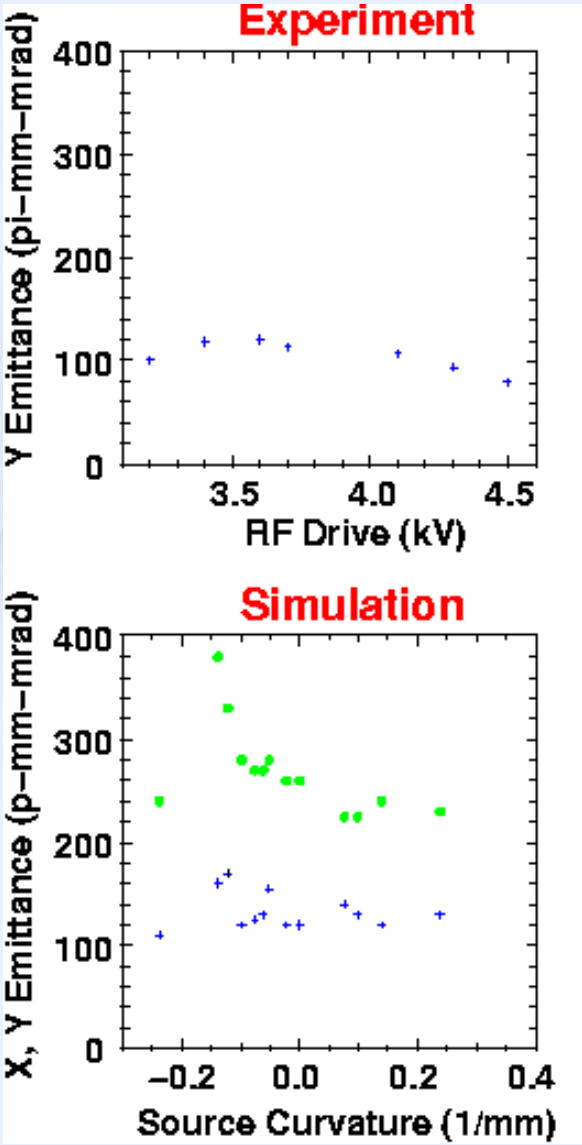
- Lower drive gives lower plasma density
  - Less current from each plasma source
  - Emitter surface becomes concave
  - Beamlets overfocused
- Higher drive gives higher plasma density
  - Emitting surface becomes convex
  - Beamlets defocused
- At the current maximum, beamlets start scraping on aperture plates
- Experiment and simulation agree on max current



Merging experiment emittances

- Good agreement between the simulation and experiment
- Scans with RF drive show agreement in y emittance (measured with double slit)
- Scans with beam voltage show agreement in X emittance

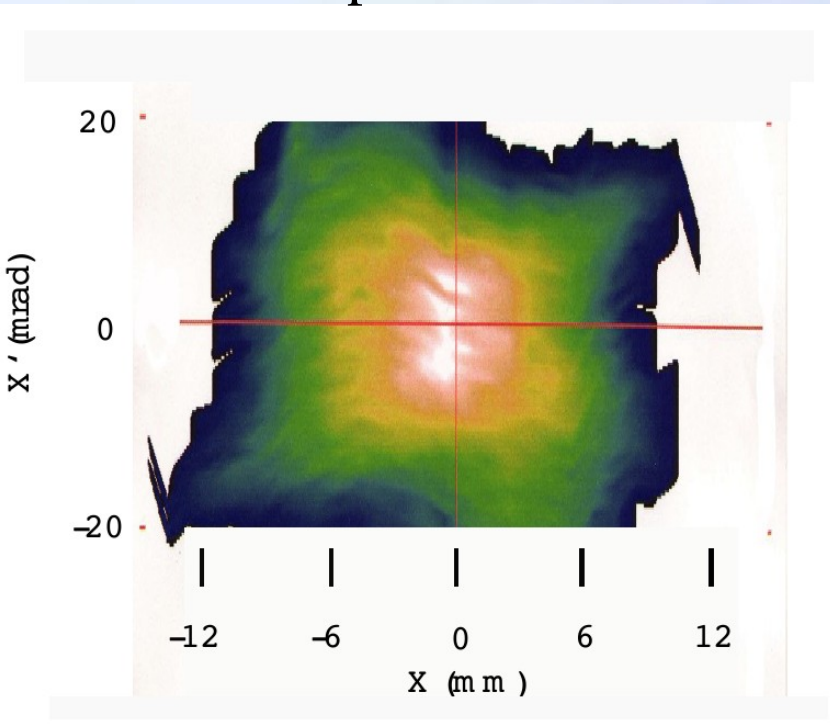




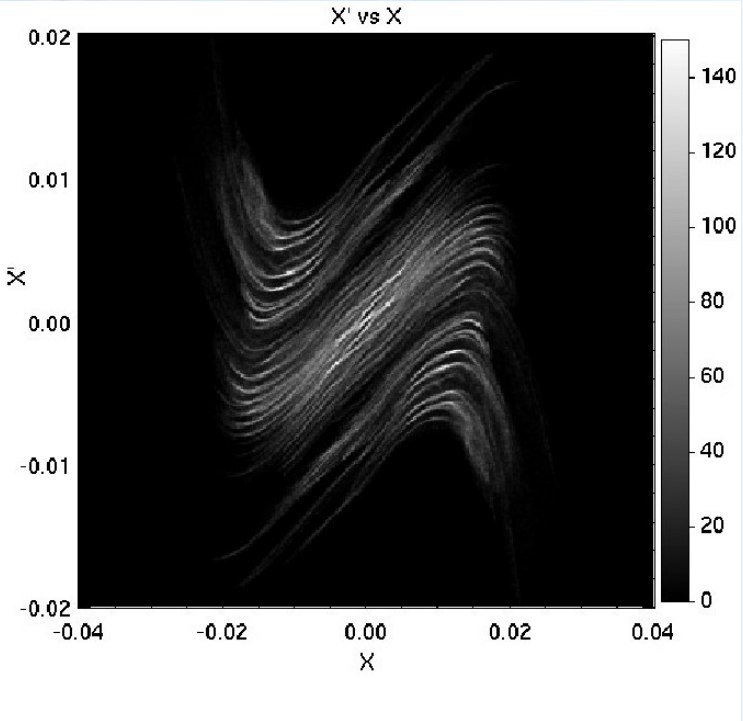
Merging experiment phase spaces

- Only qualitative agreement was found in the phase space images
- This can be due to many reasons
  - Nonuniform plasma source, uncertainties in emitter surface shape, errors in column and elsewhere...

Experiment



Simulation

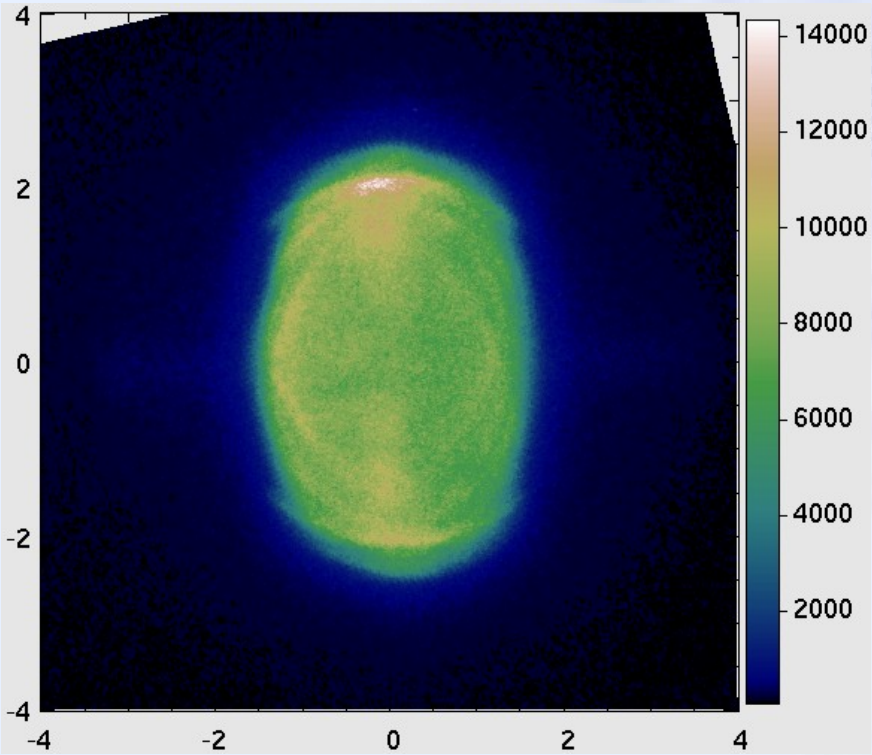


Both show remnants of the individual beamlets

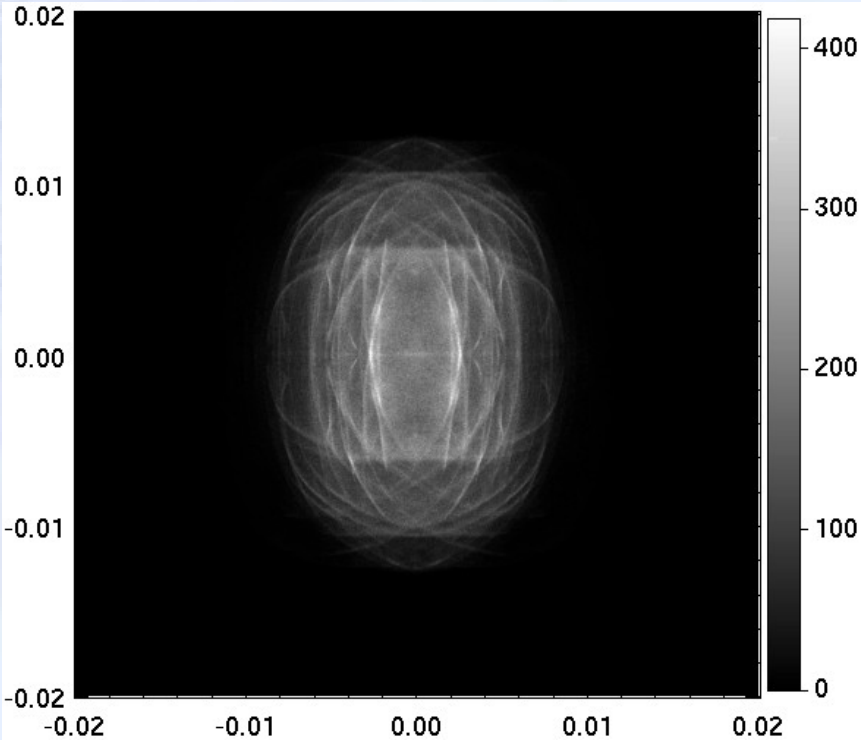
Configuration space

- Similarly to the phase spaces, only qualitative agreement was seen
- Both show fine structures, but the details differ greatly

Experiment



Simulation



Conclusion

- Single beam injector successful for HIF program to date, but potentially limited
- A multi-beamlet injector potentially provides a more robust injector solution for a high brightness beam, usable in HIF and any application requiring a compact, high brightness source
- However, requires careful, integrated design to produce optimizal beam quality
- Experimental validation was successful, showing both engineering feasibility and good agreement with the simulations