Multi-Beamlet Injector Background and STS500 Design

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Merging Beamlet Physics Design Review
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Outline

- Basic physics of merging
- Characterization of merging injector
- STS500 experiment design

Emittance growth from merging

Oscar Anderson had looked at emittance growth from various beam configurations, including multiple beamlets.

From conservation of energy, can estimate emittance growth

- Calculate 'excess' energy in self field compared to uniform beam
- Assume all excess goes into emittance and small increase in size
- Define normalized free space-charge energy

$$U_n = \frac{U_f - U_0}{U_0}$$

- Here U_f is the field energy of the beamlet arrangement, and U_0 is the field energy of a uniform beam with the same radius

Estimates of emittance growth

For matched beam in uniform focusing, beamlets in concentric circles

- With occupancy factor

$$\eta = 2a/\delta, a = \text{Beamlet radius}, \delta = \text{center-to-center distance}$$

- Perveance $Q = 2\lambda q / 4\pi\varepsilon_0 m v_z{}^2$
- The normalized free space-charge energy is approximately

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

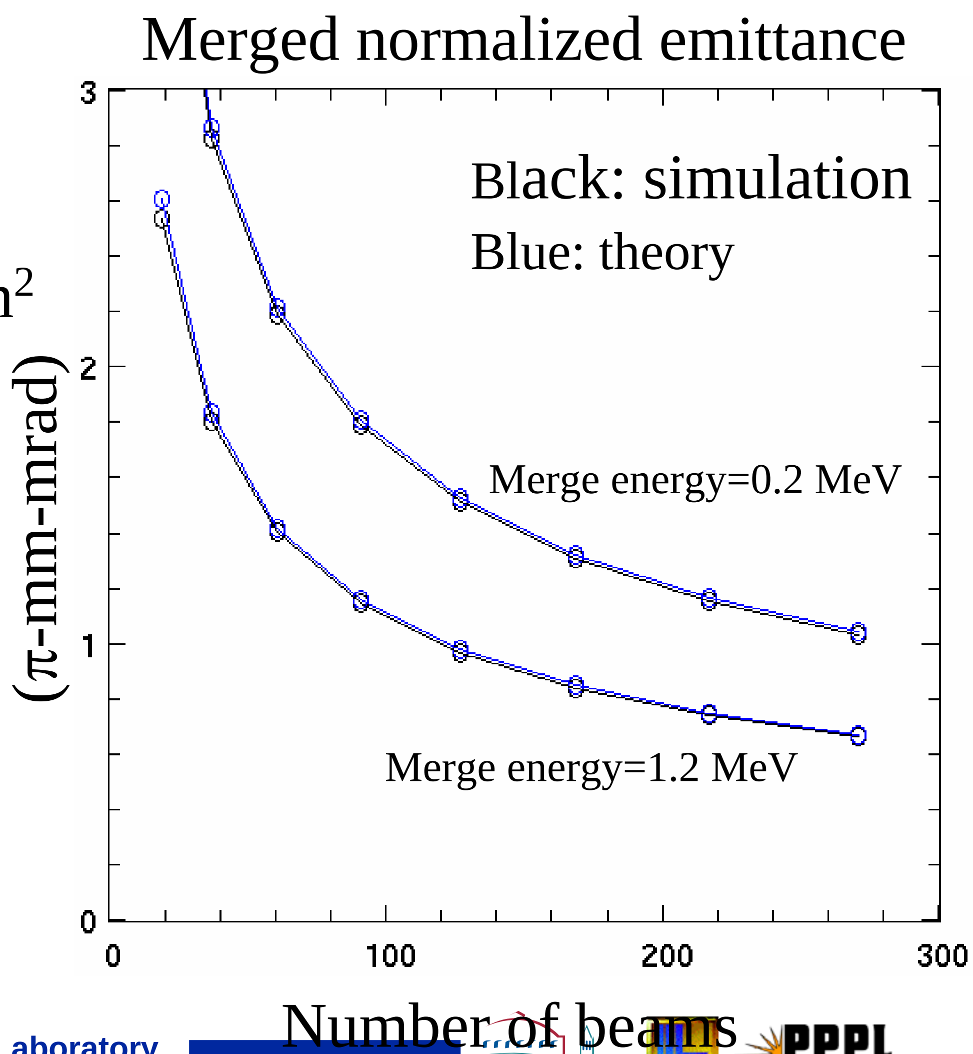
- Giving a change in emittance

$$\frac{\varepsilon^2{}_{\text{final}}}{\varepsilon_{\text{initial}}{}^2} = \frac{\langle X^2\rangle + \langle Y^2\rangle}{2\langle X^2\rangle}\left(1 + \frac{QU_n}{8\langle X'^2\rangle}\right)$$

Comparison to particle simulation

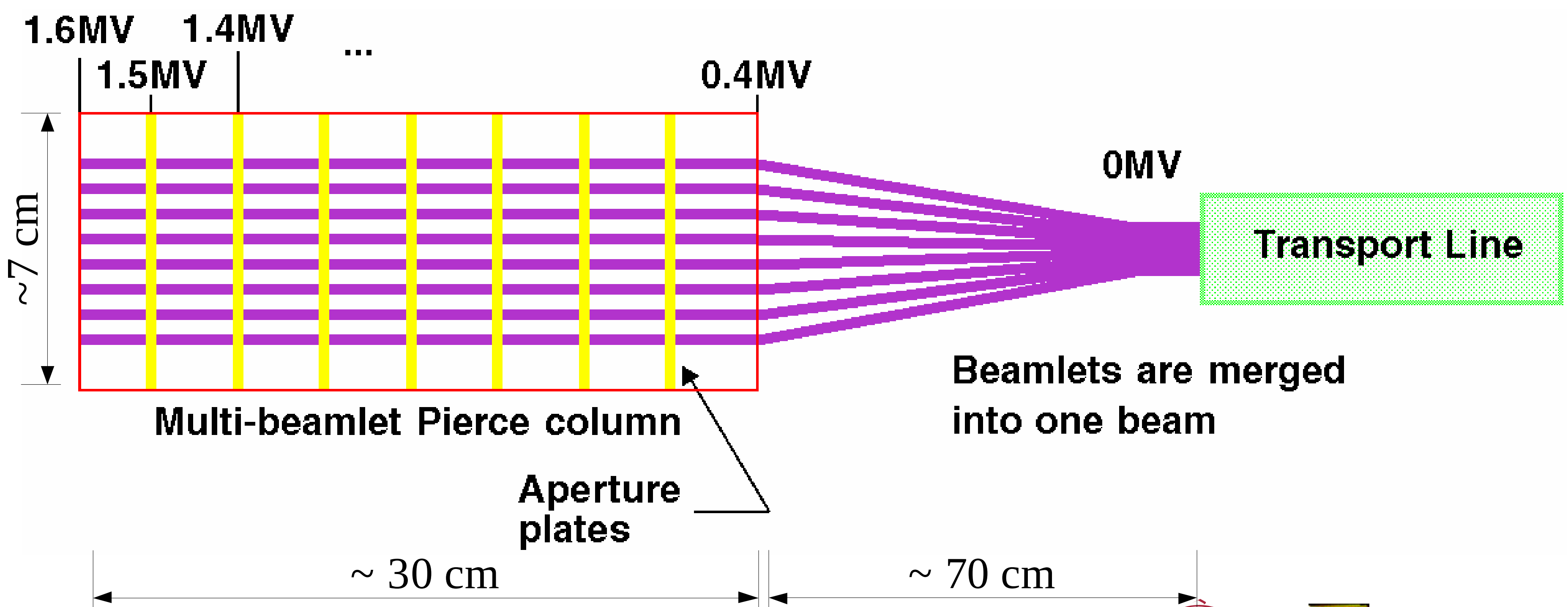
Concentric rings of beams
Uniform transverse focusing
Fixed parameters:
- Total current = 0.57 A
- Beamlet current density = 100 mA/cm^2
- Total RMS beam size = 1.63 cm

512x512 grid
2000 particles per beamlet



Injector layout

- Pre-accelerator column -- Einzel lenses
- Merging region

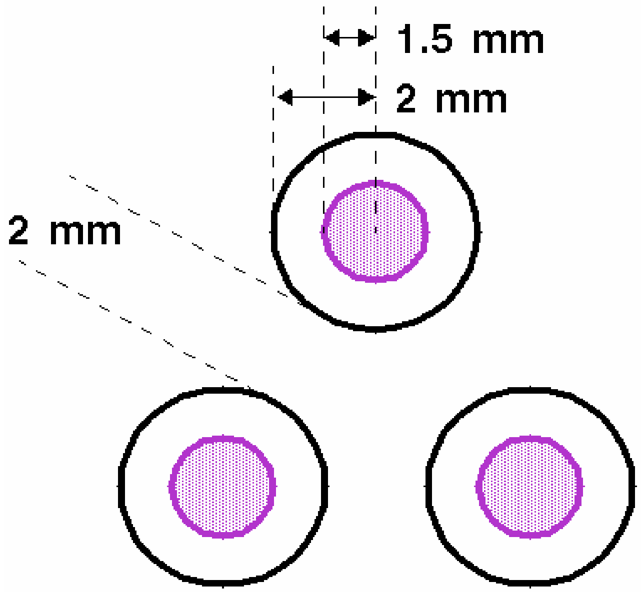


Trade offs

- Merging energy
  - Higher is better for merged emittance
  - But Einzel lenses become weaker, and more plates
- Number of beamlets
  - The more the better for emittance
  - But becomes larger transversely
- Aperture plate shape
  - Aspherical allows compact beamlet arrangement and x and y emittance to be the same
  - Spherical plates easier to build

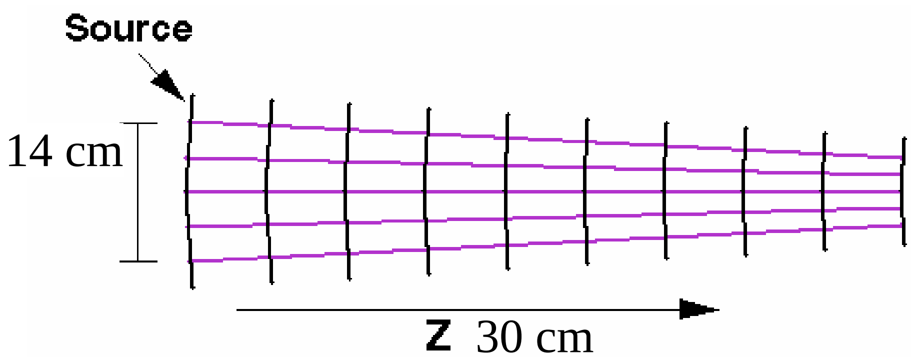
Trade offs (continued)

- Einzel lens plate transparency
  - The higher the transparency (more closely packed beamlets) the lower the merged emittance
  - Space needed for
    - Rigidity of the plate (~ 2 mm material minimum)
    - Clearance for beamlets (100 μ errors → 0.5 mm offset)
    - Shielding between beamlets
  - Enough area to transport current
    - $J_{max} \sim 100$ mA/cm^2
    - ~1 mm source radius gives 3.1 mA

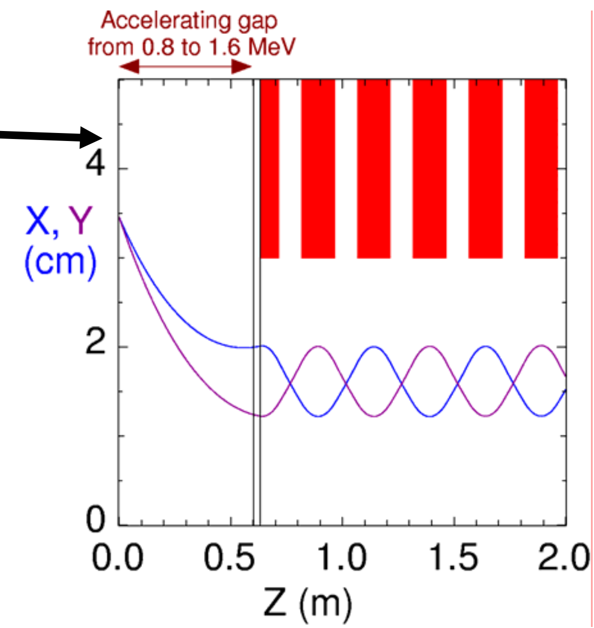


Optimized layout

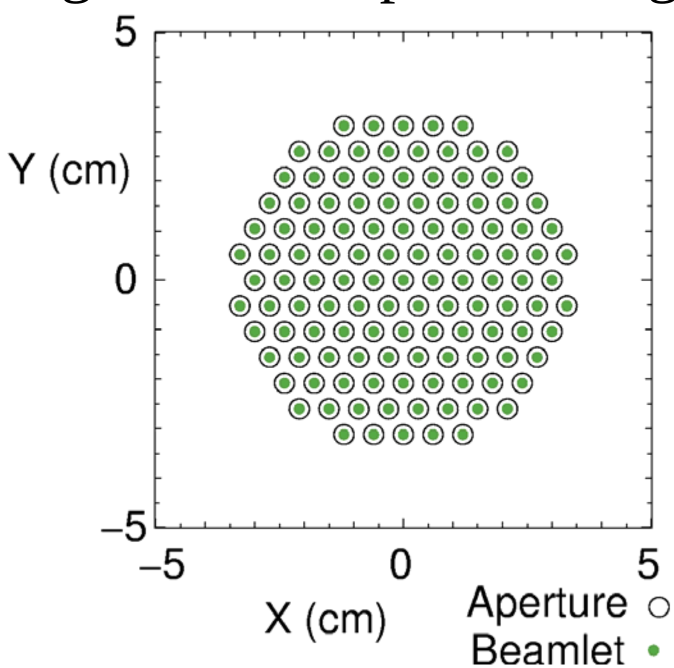
Beamlets converge

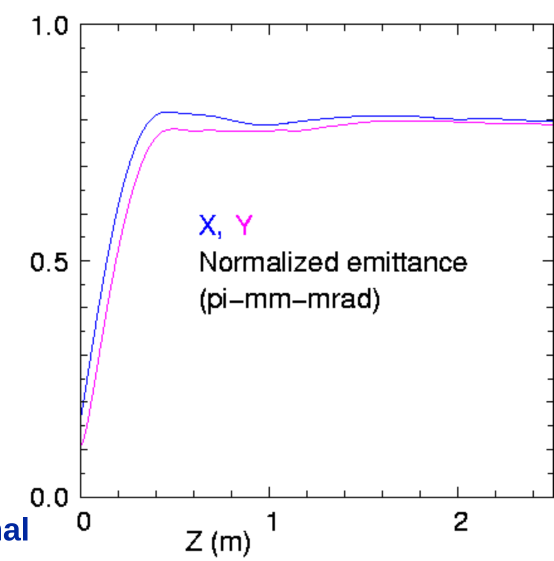


Beamlets aimed to be exactly matched to transport lattice.



Hexagonal dense pack arrangement





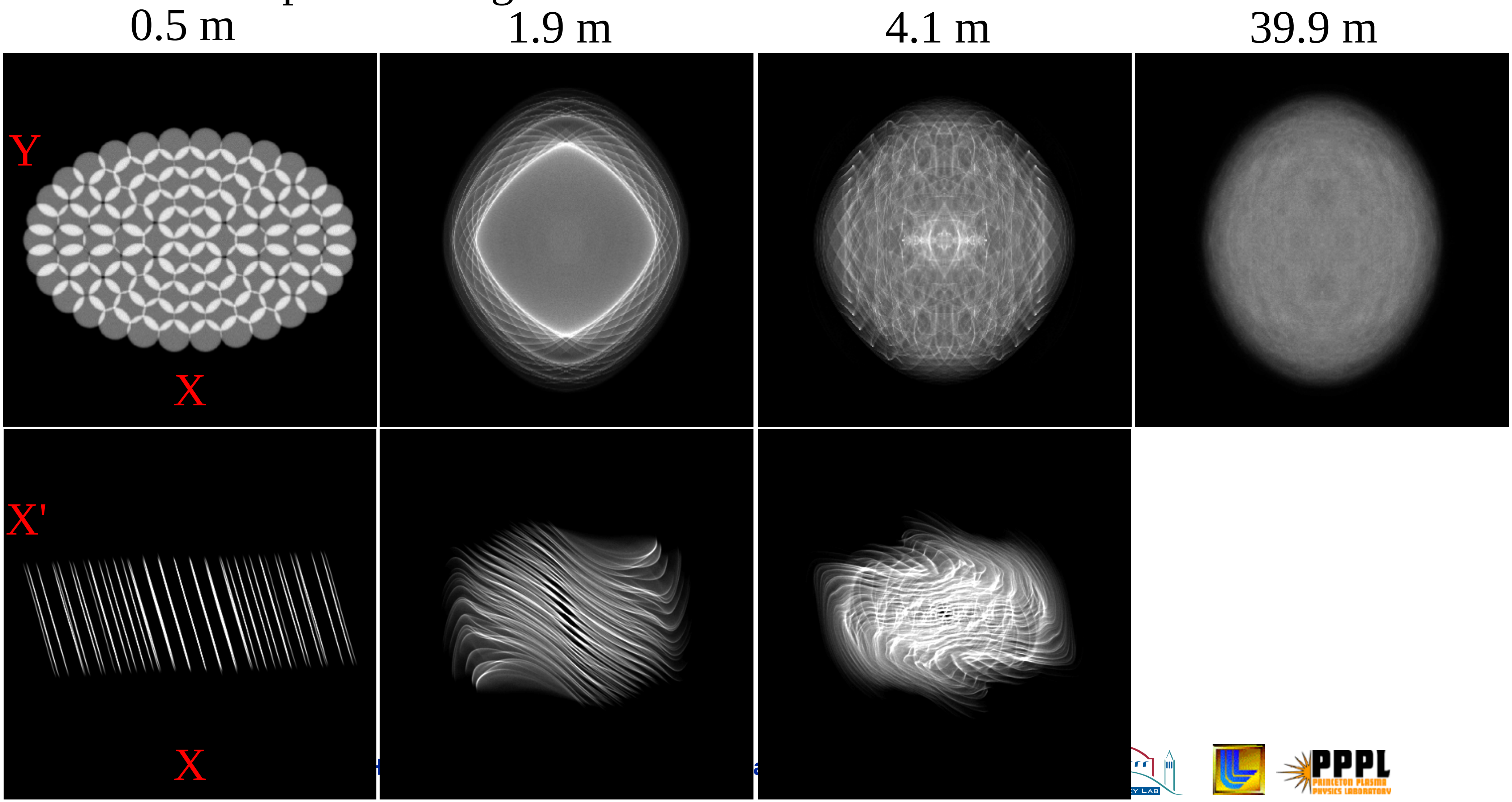
X and Y emittances are about equal

Slice simulations

2-D grid 512x512 -> 20 grid cells across beamlet diameter

20,000 particles per beamlet, 91 beamlets

Elliptical arrangement of beamlets



Optimized designs

For 0.5 Amps, 1.6 MeV, K^+

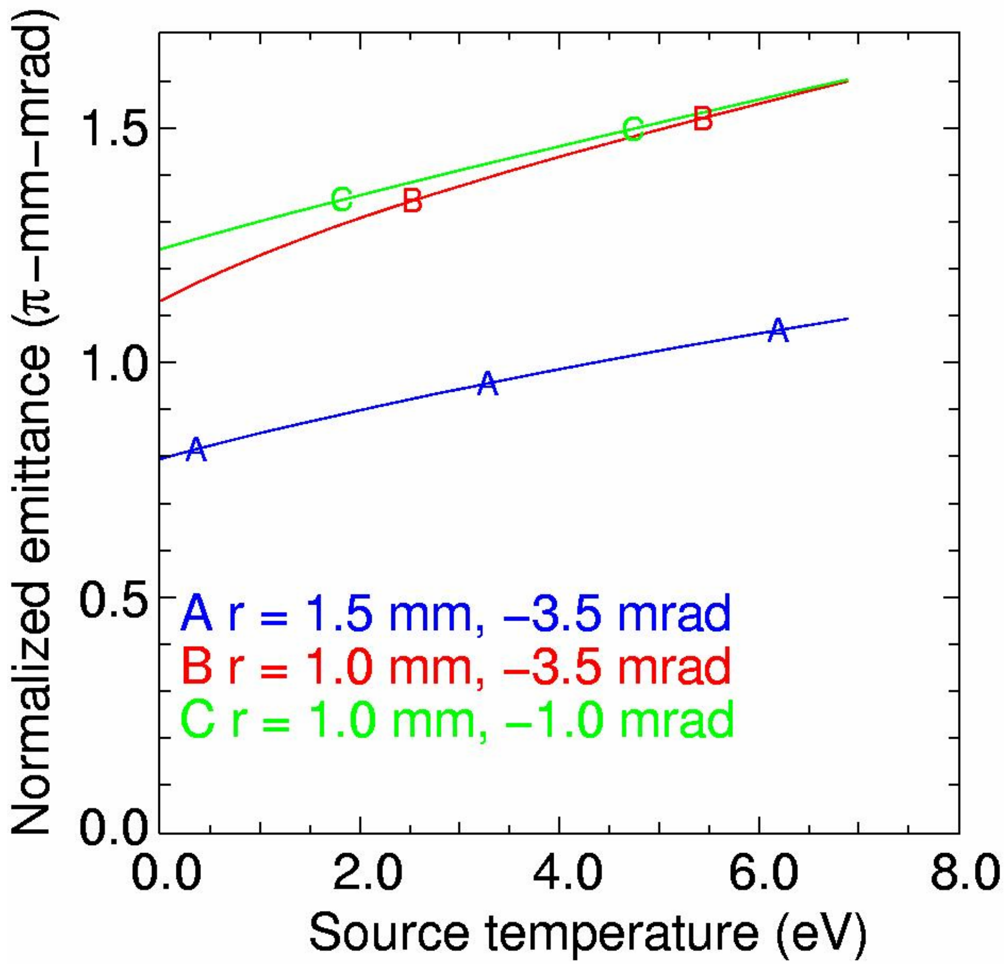
- Aspherical plates, nearly round arrangement
  - Lower emittance minimum at higher energy
  - But with weaker focusing - can't get as close to minimum

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

Source temperature

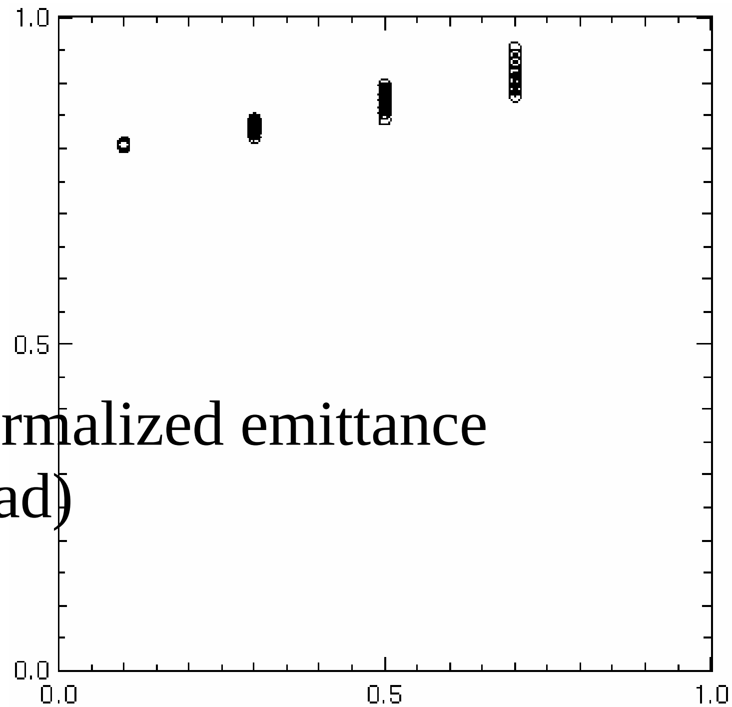
Merged emittance weakly dependent on source temperature
•Solid surface source T < 1 eV
•Plasma source T ~ 2 eV

91 beamlets
Merging at 1.2 MeV



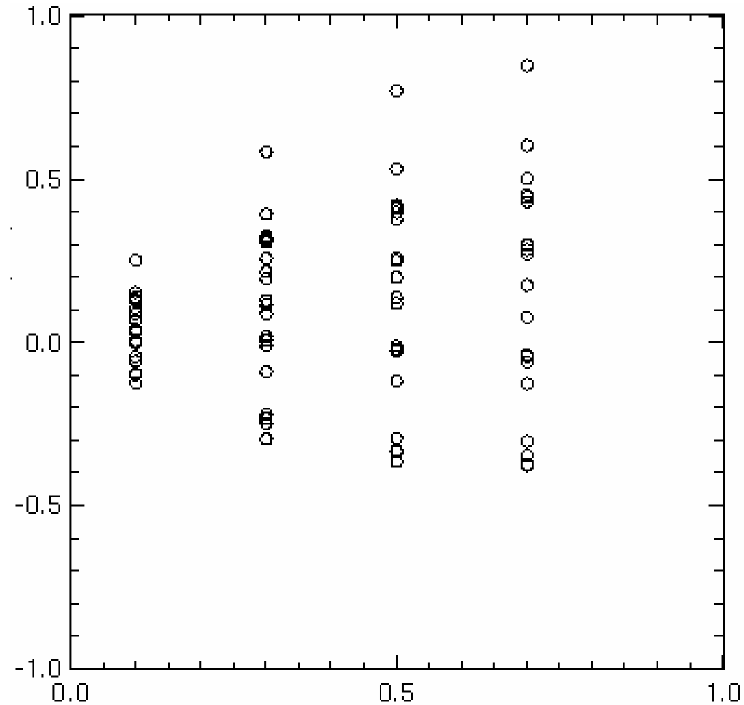
Robustness to errors

- Merged emittance insensitive to errors in beamlets
- Ensemble of 80 simulations 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

Trade offs for STS500

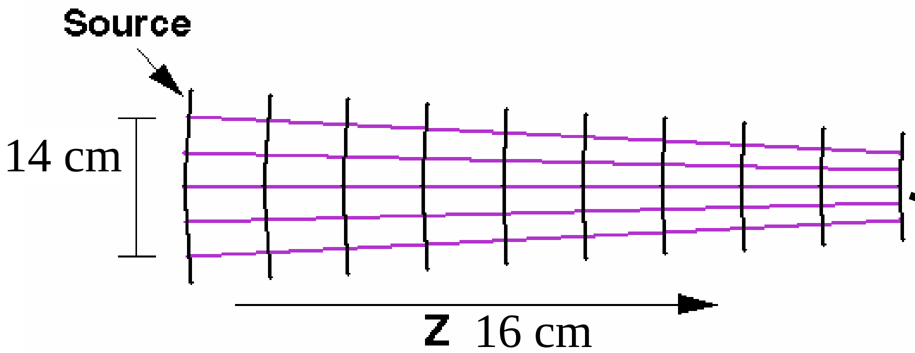
- Voltage is ¼ scale, size is full scale
- Merge at 160 kV (640 kV at full scale)
  - Requires only 12 plates (cheaper to build)
- Number of beamlets
  - ~100 (actual number determined by arrangement)
- Choose spherical (cheaper to build)

➢ Though design not optimal (for emittance)…

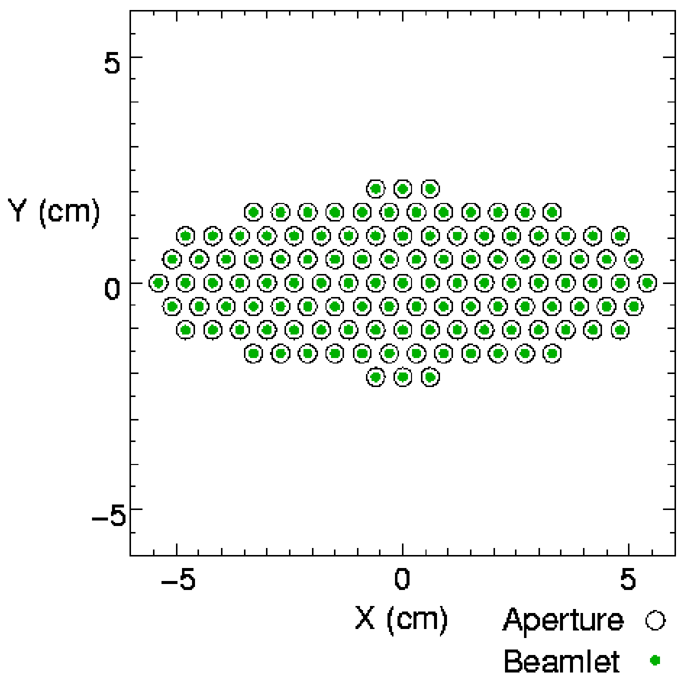
- Will still test all relevant physics of the merging process
- Provides validation of the simulation

Layout for STS500

Beamlets converge



Hexagonal dense pack arrangement



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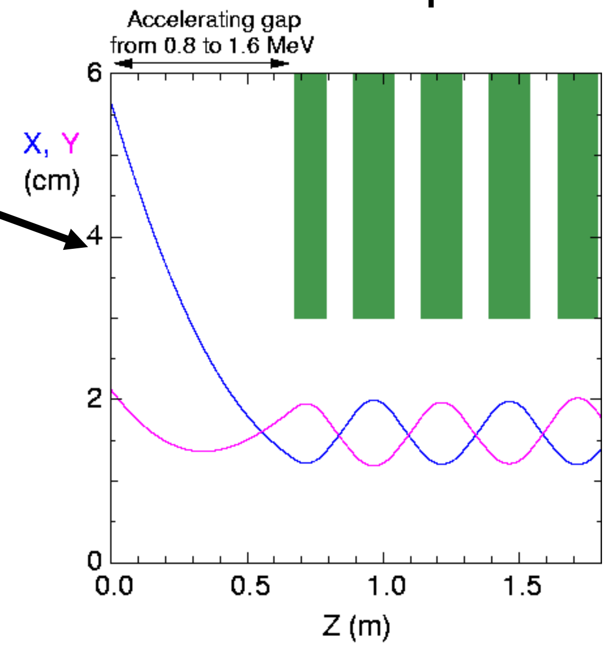
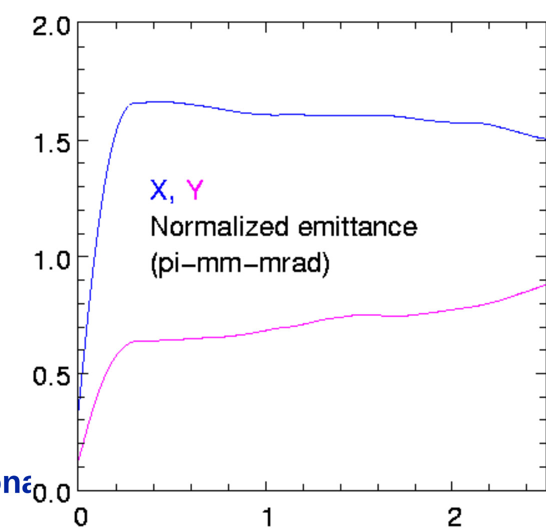




X and Y emittances very different

Basic design procedure

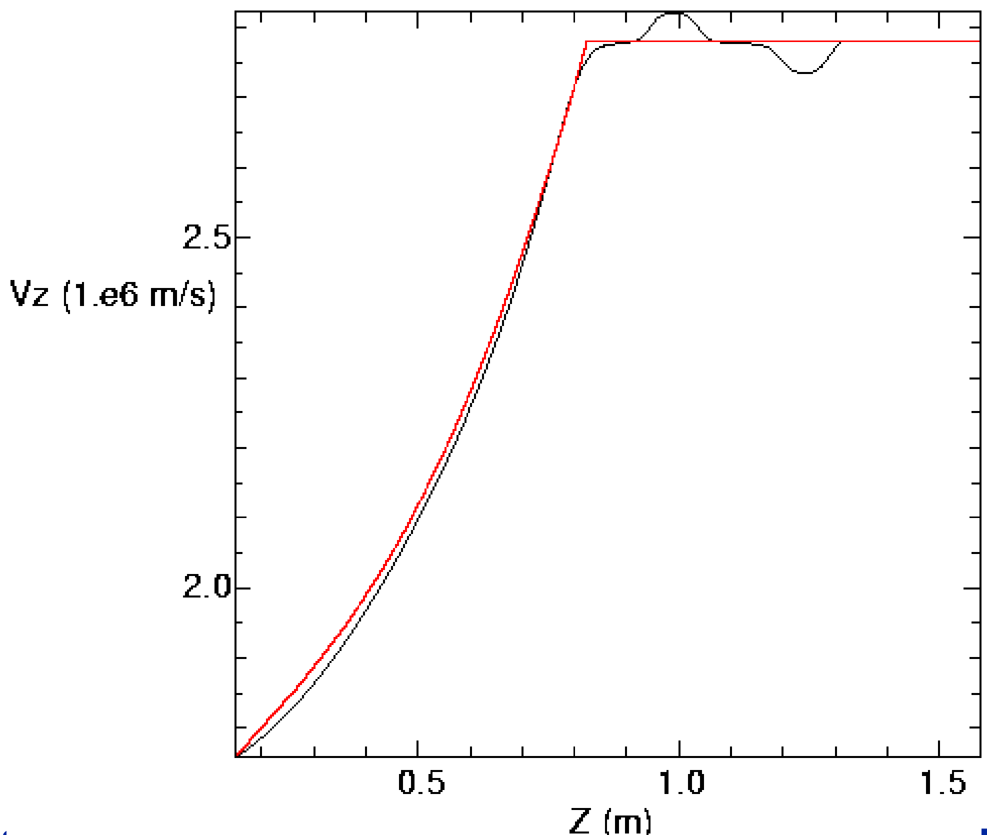
- Design merging region
  - Choose merging energy, spherical
  - Gives beamlet arrangement
- Characterize merged emittance
  - 2-d transverse slice simulations
- Optimize pre-accelerator column
  - To produce beamlet parameters minimizing emittance

Merging region design

- Find envelope solution, going upstream.
  - Initial conditions from matched solution.
  - Final conditions meets two conditions:
    - Contain ~120 beamlets
    - Spherical convergence
- Include shield – Ez varies approximately quadratically
  - $Ez \sim E_0 + E_1 z^2$
  - E_0 obtained from Laplace solve with estimate of merge length, ~ 70 cm.
  - E_1 then fixed by integration to give correct voltage change

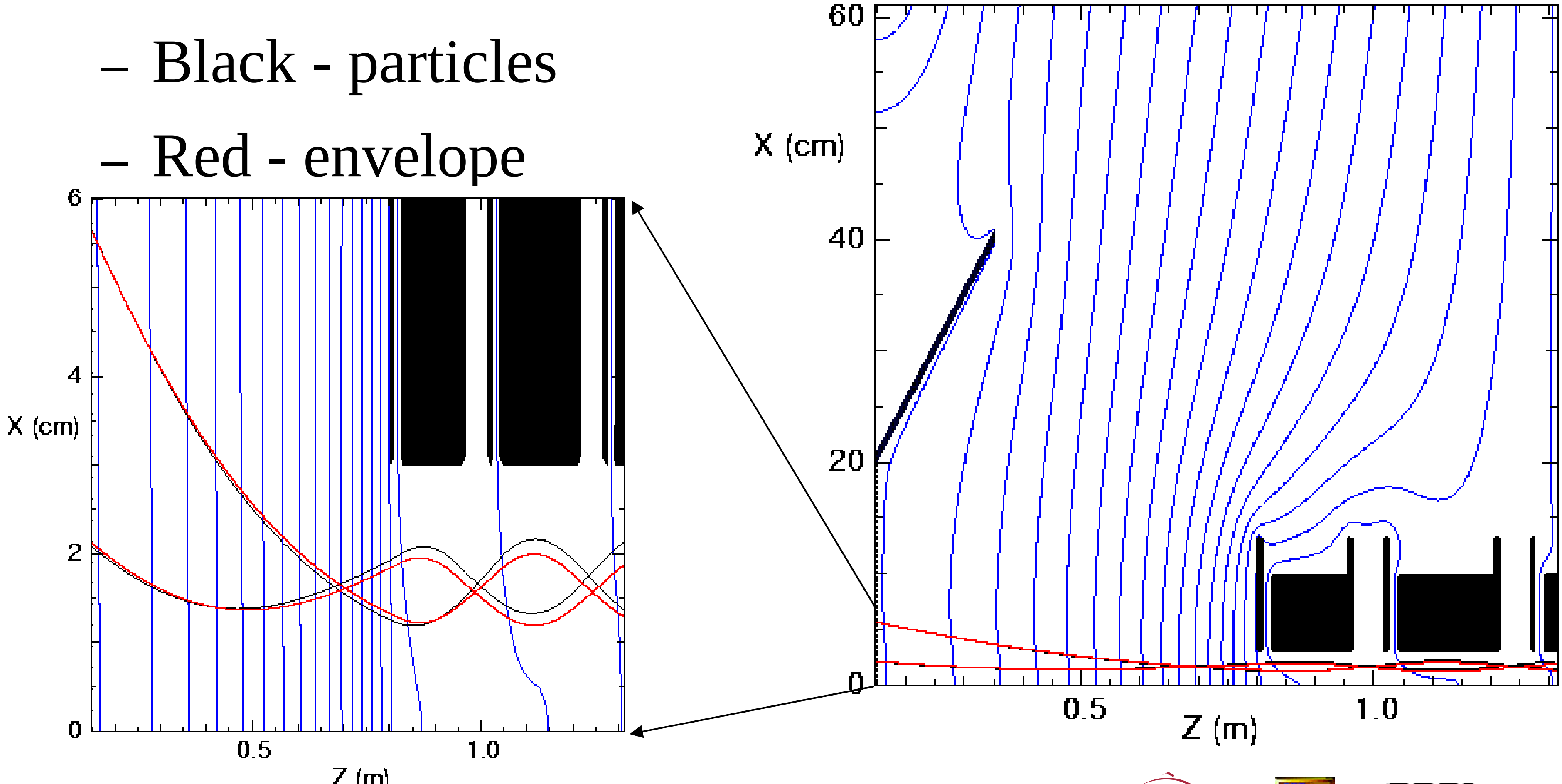
Quadratic Ez is a good approximation

- Black is particle simulation, including shield
- Red envelope with quadratic Ez



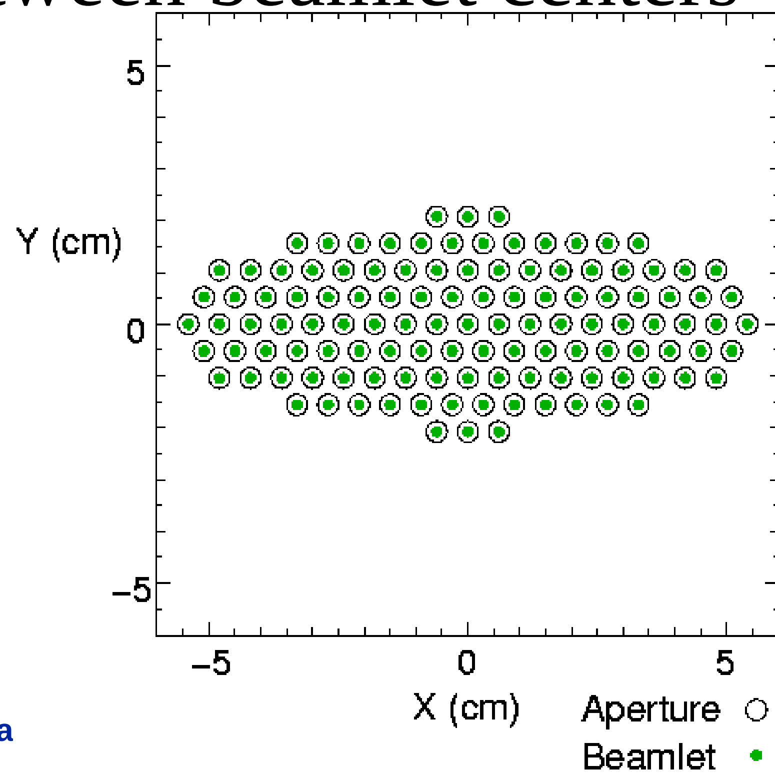
Merge region continued

- Compare particle simulation and envelope
  - Black - particles
  - Red - envelope



Resulting elliptical arrangement

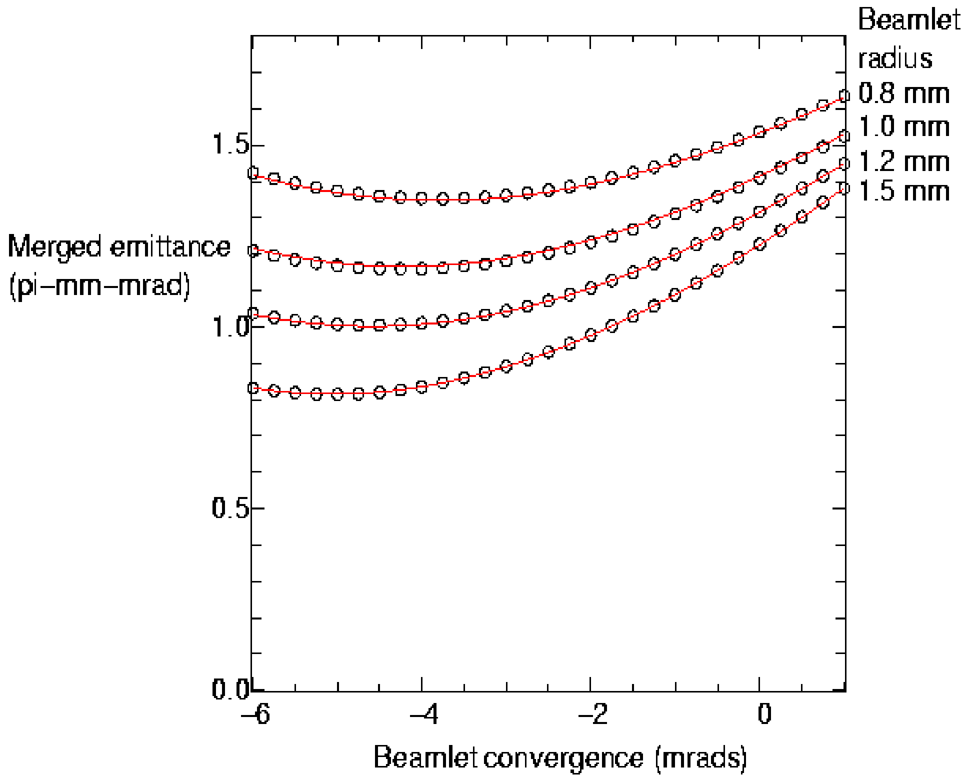
- Pattern on last plate of accelerating column
- Hexagonal dense pack
- 6 mm between beamlet centers



Emittance from slice simulation

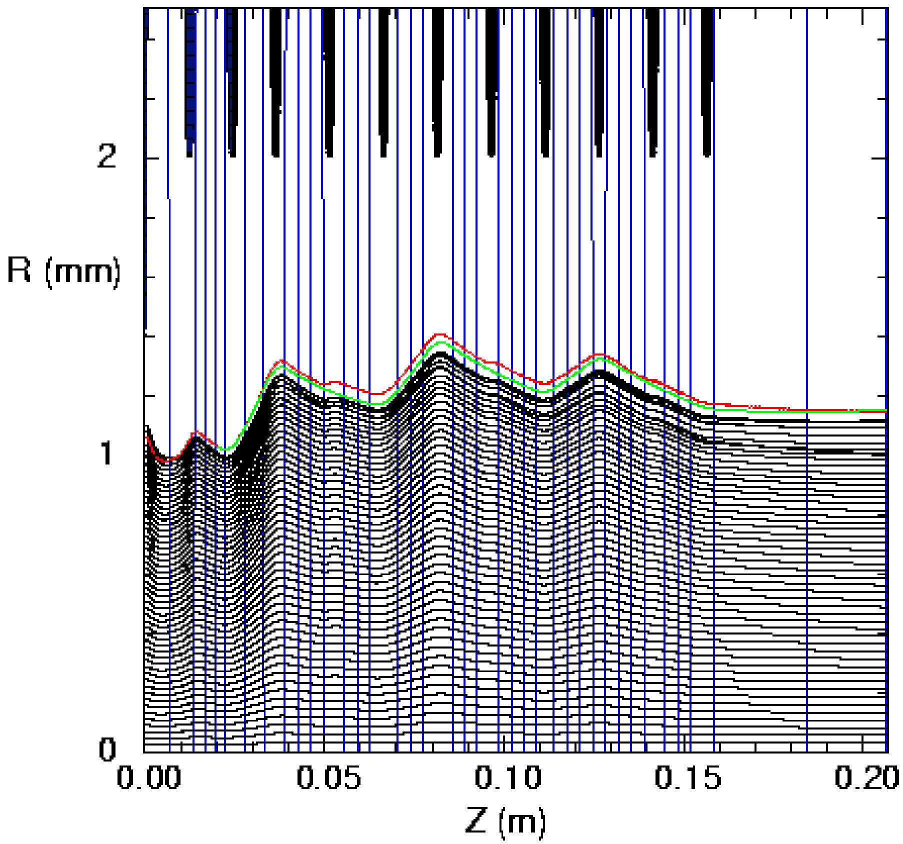
- Varied beamlet convergence and radius at list plate
- Quadratic variation in Ez

Emittance is geometric mean of X and Y after 7 half lattice periods

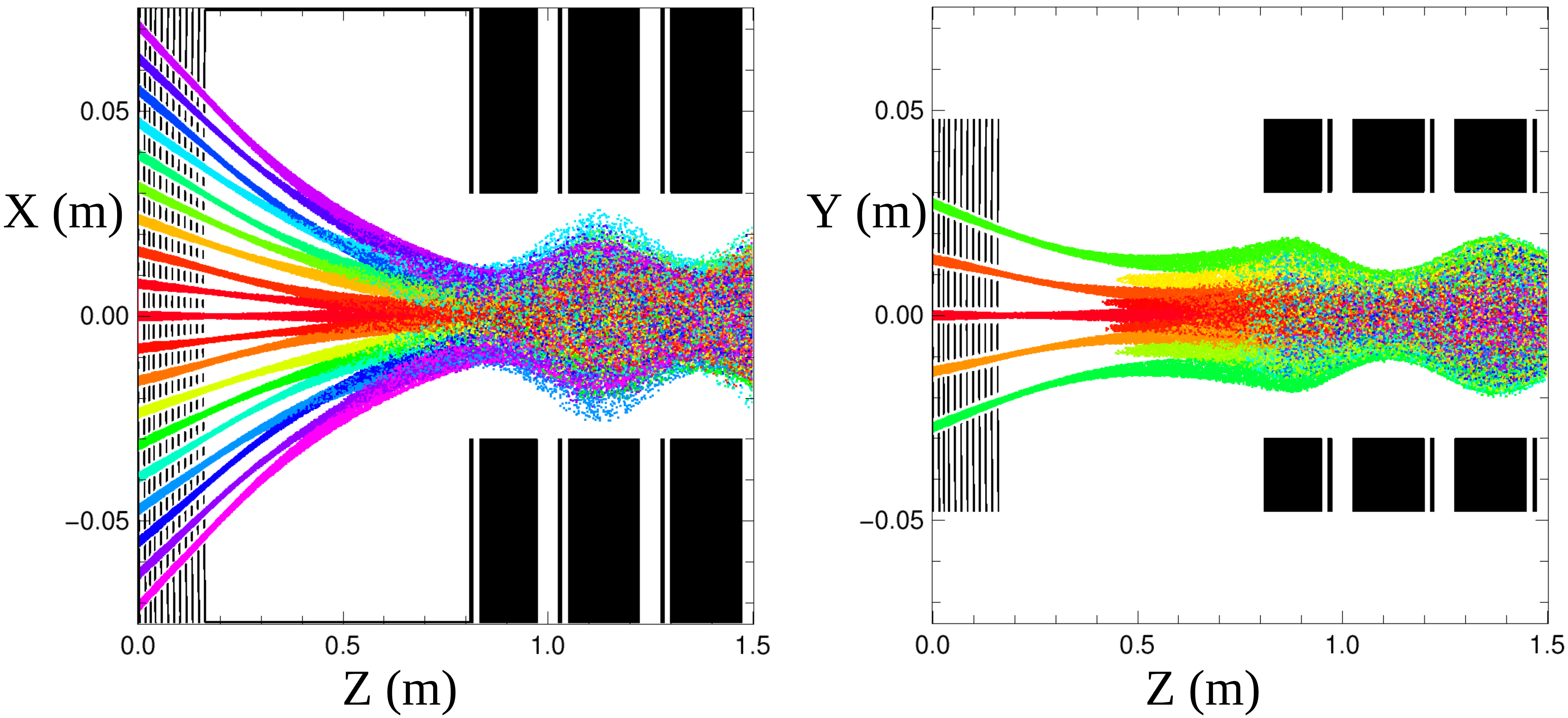


Accelerating column

- Envelope somewhat optimized to reduce emittance.
  - a = 1.152
  - a' = -0.733
  - ε_n = 1.25
- Plates evenly spaced
- Voltages at tie off points of insulator



3-D simulation



Possible experiments

- Main design – compare to simulation
  - Total current, beamlet current
  - Emittance after quads
  - Images of merging process
- Mask off holes – different hole patterns
- Change Einzel lens voltages
  - Examine beam emittance with changing beamlets

Changing Einzel lens voltage

- Effect of emittance should be measurable
- Table shows estimated emittances

Plate voltages (kV)				Beamlet	Beamlet	Estimated
Plate number				size	divergence	emittance
8	9	10	11	(mm)	(mrad)	(π-mm-mrad)
272	304	240	240	1.02	-2.63	1.19
272	304	272	240	1.08	-0.63	1.30
272	288	256	240	1.13	0.99	1.47
272	256	240	240	1.96	1.80	1.57