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Benchmarking of 3D space charge codes using a DC gun

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LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

Talk outline

- Motivation
- Boundary conditions (ebeam optics)
- Diagnostics
- Initial conditions (laser & cathode)
- Simulations: Parmela3D and GPT
- Data analysis & comparison

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Motivation for the study

- ERL X-ray source is electron-source limited, needs $\varepsilon_{\perp n} \leq \mu m$ at high avg. current (0.1A)
- Optimizations using space charge codes show ~0.3 μm should be achievable
- Code vs. measurement benchmarking data that withstand serious scrutiny are sparse
- Important physics missing in mainstream codes? E.g. wakes, space charge force too grainy/smooth
- How credible are these predictions?

Timeline

Feb, 2006 the NSF funds the ERL prototype

Jan, 2007 DC gun is built with diagnostics line

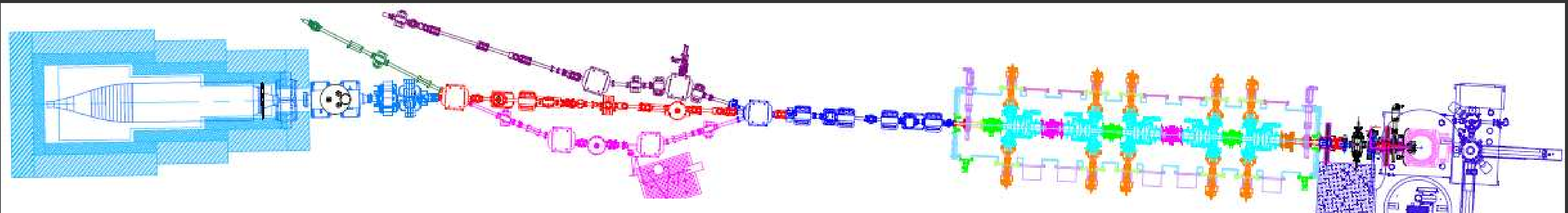
Mar, 2008 the DC gun beamline operation stops

Apr, 2008 100 mA SRF module installed; the DC gun is moved and rebuilt for the 3rd time

Jun, 2008 first beam (~5 MeV)

Jul, 2008 ~15 MeV

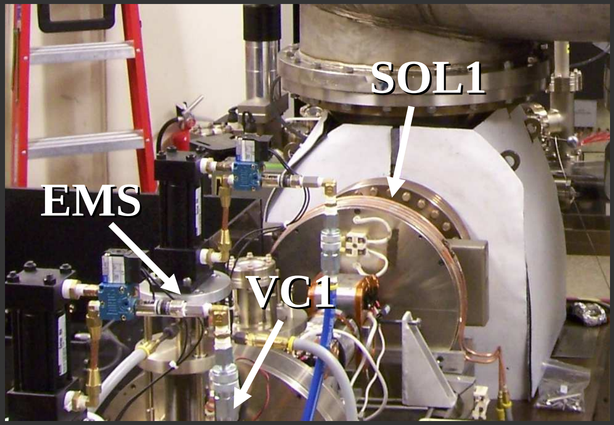
Aug, 2008 the full injector beam experiments begin

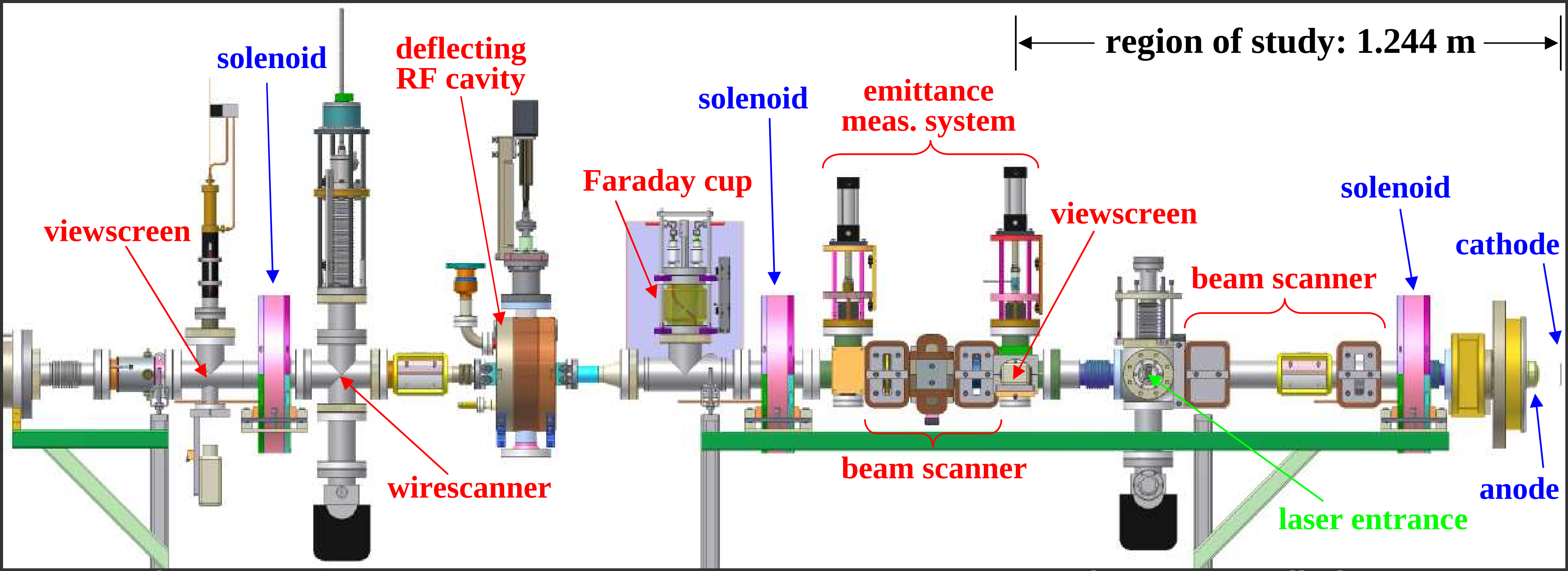


100 mA, 5-15 MeV injector (95% complete)

Simple beamline

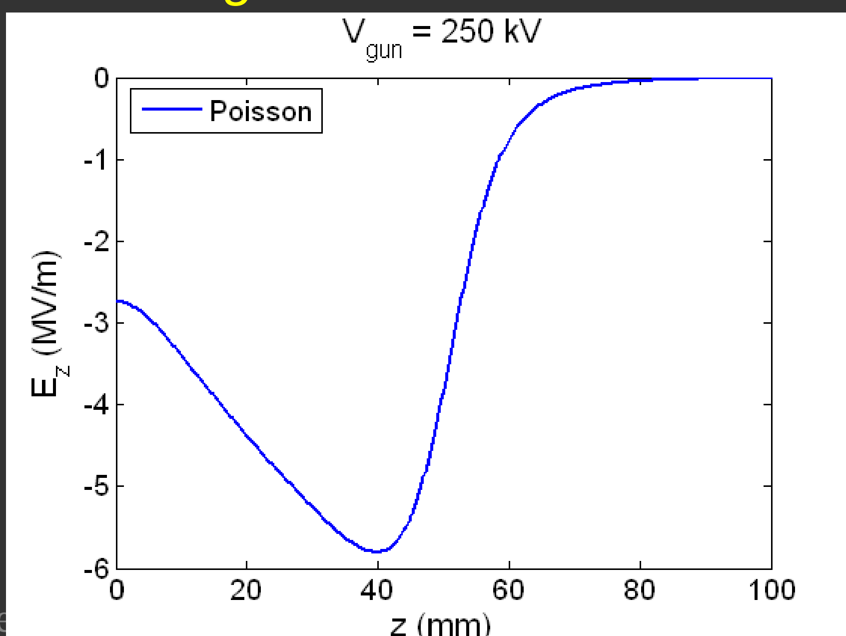
- *1.244 m* from the photocathode to Emittance Measurement System
- DC gun followed by a solenoid
- Diagnostics!

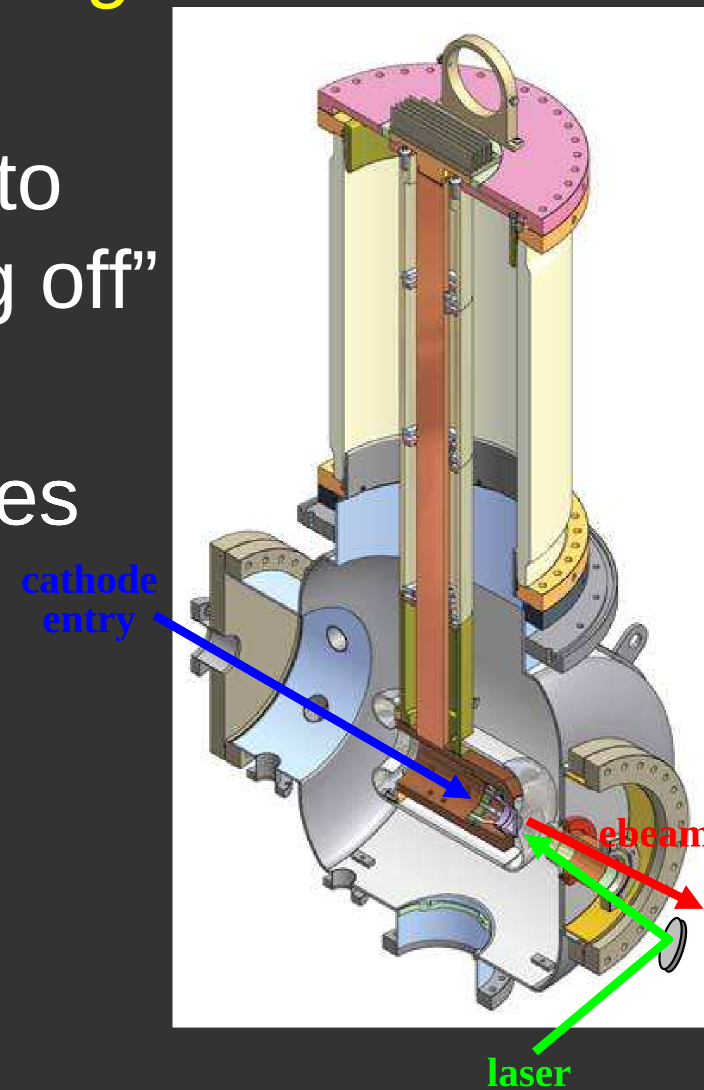




HV DC gun

- Highest voltage *during HV processing ~400 kV*
- Plagued by *field emission* (traced to dust from ceramic coating "peeling off" during HV processing)
- Thus, *V_{gun} = 250 kV* in these studies





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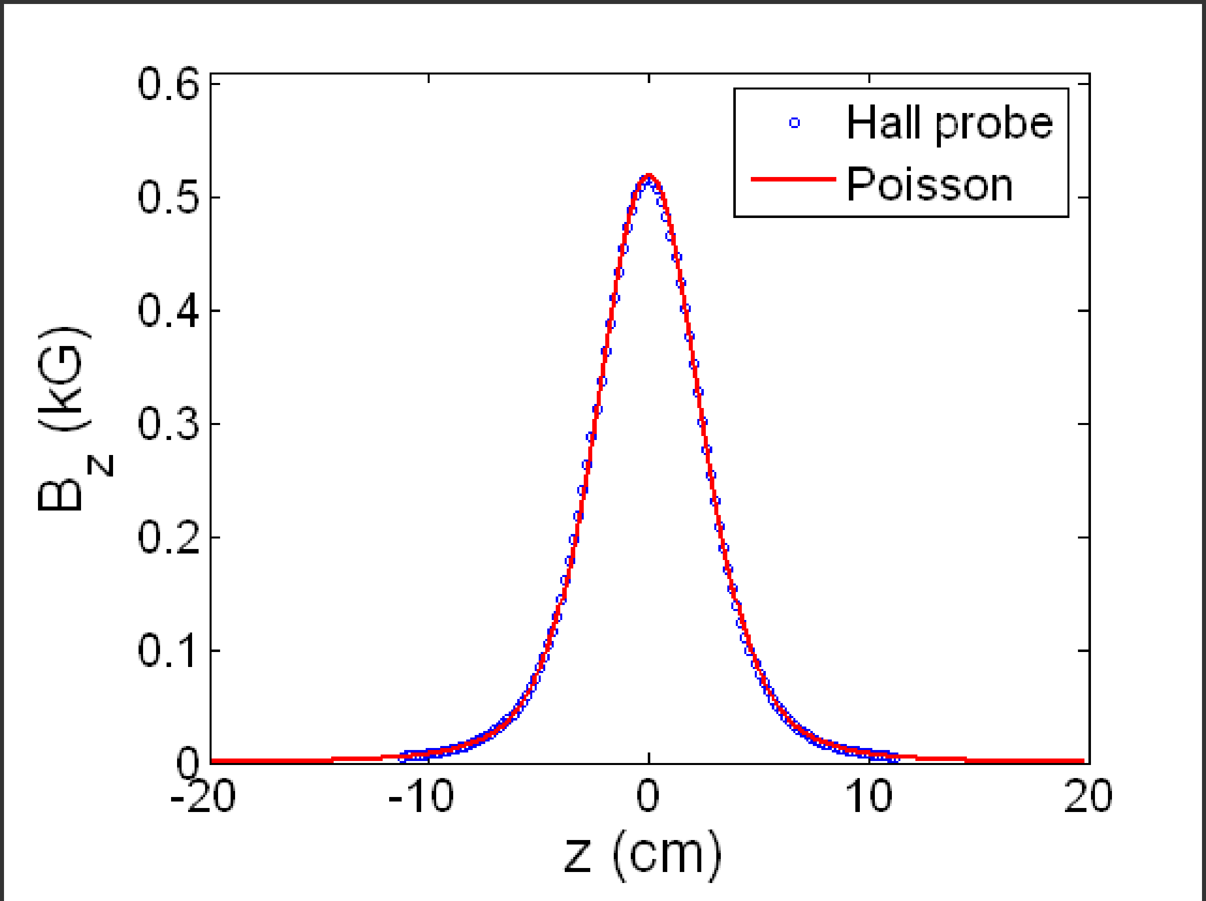
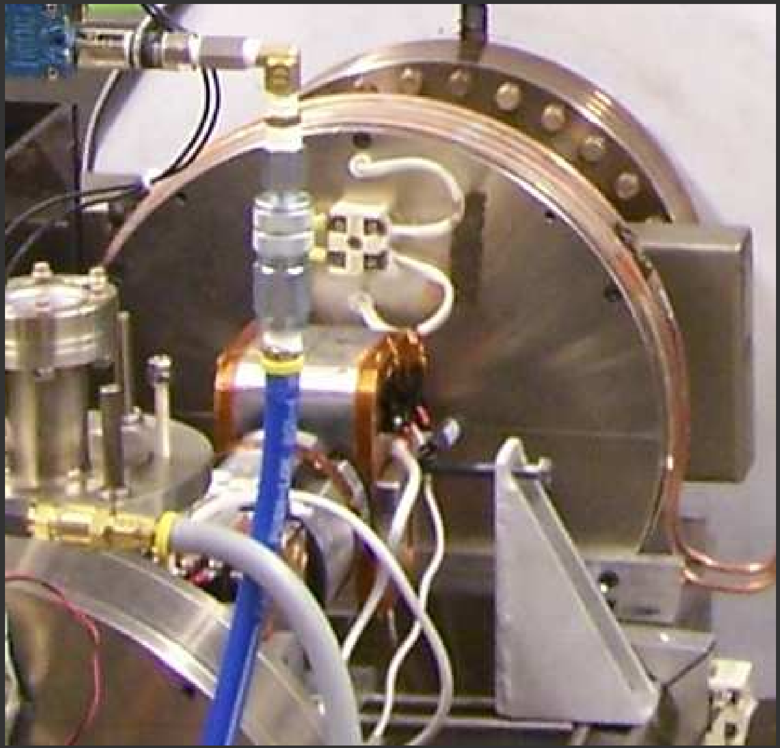
Solenoid

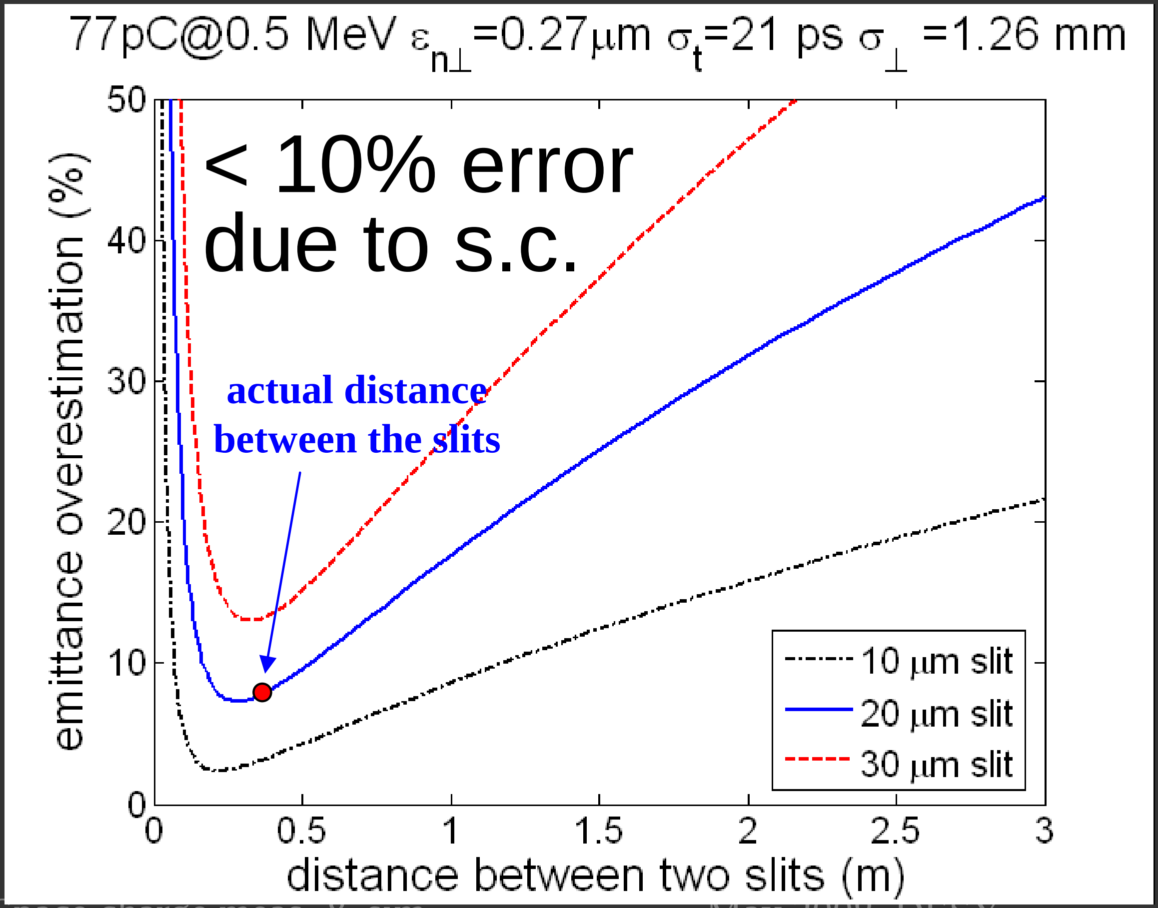
- Cathode to solenoid center distance is *0.335 m*
- Solenoid center to the viewscreen/EMS is *0.909 m*

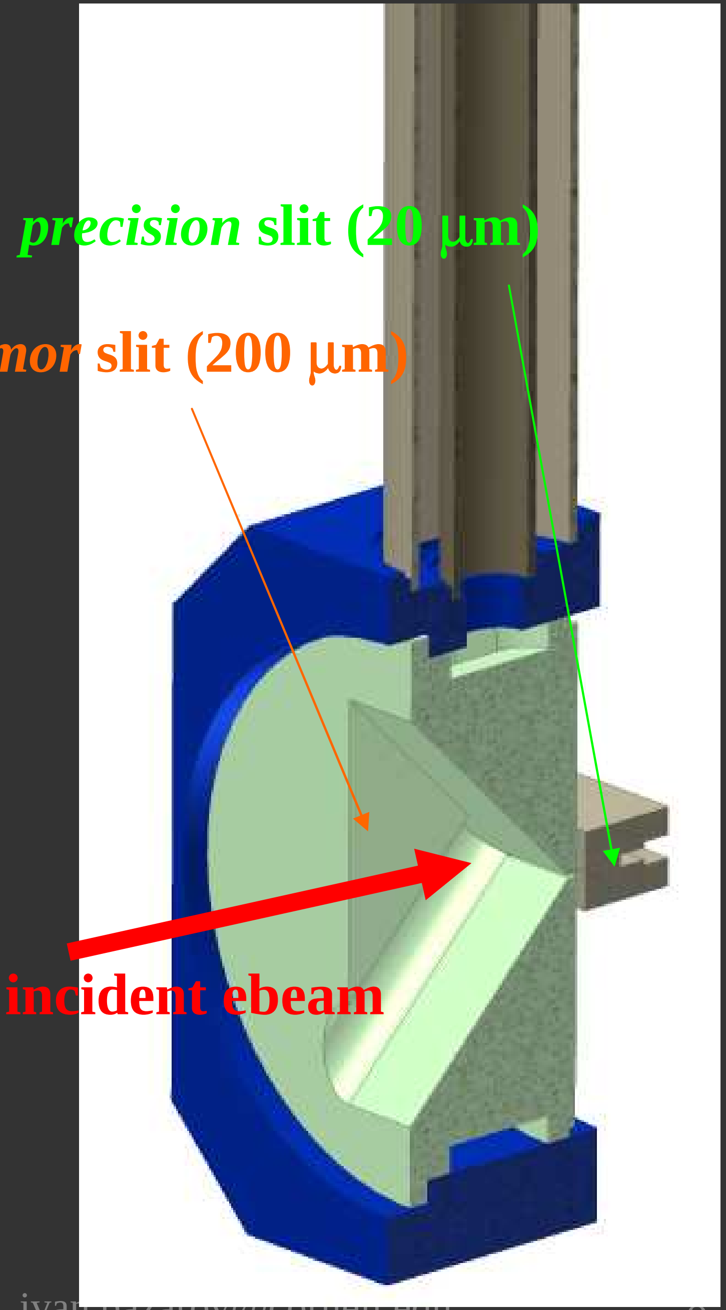




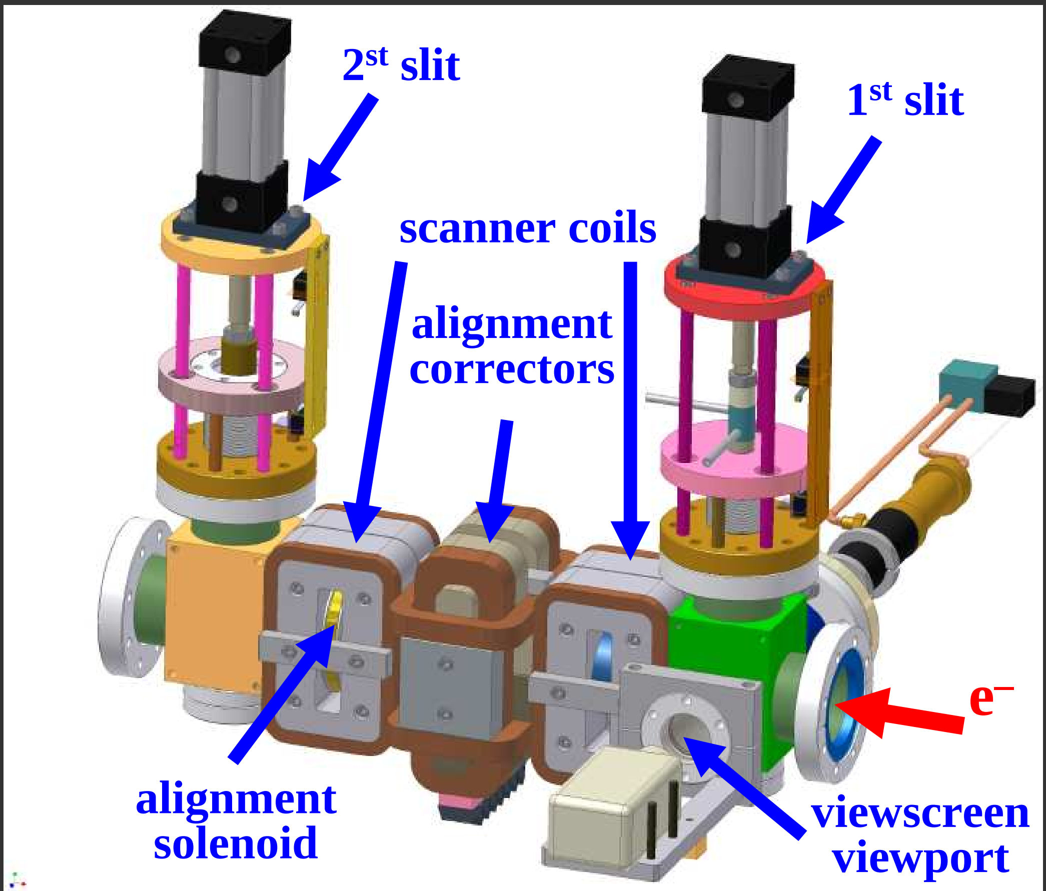
Emittance Meas. System

- 20 μm precision double slits
- No moving parts; fast DAQ
- ~1 kW beam power handling



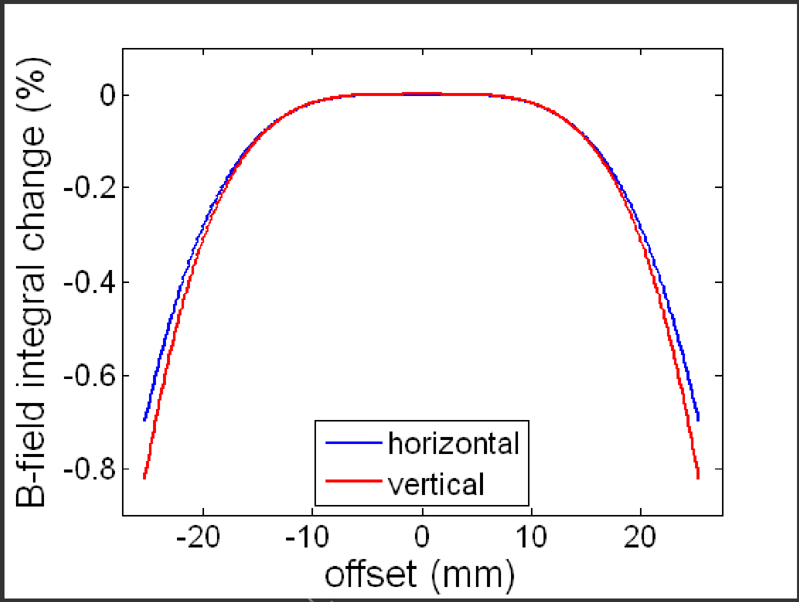


EMS (2)



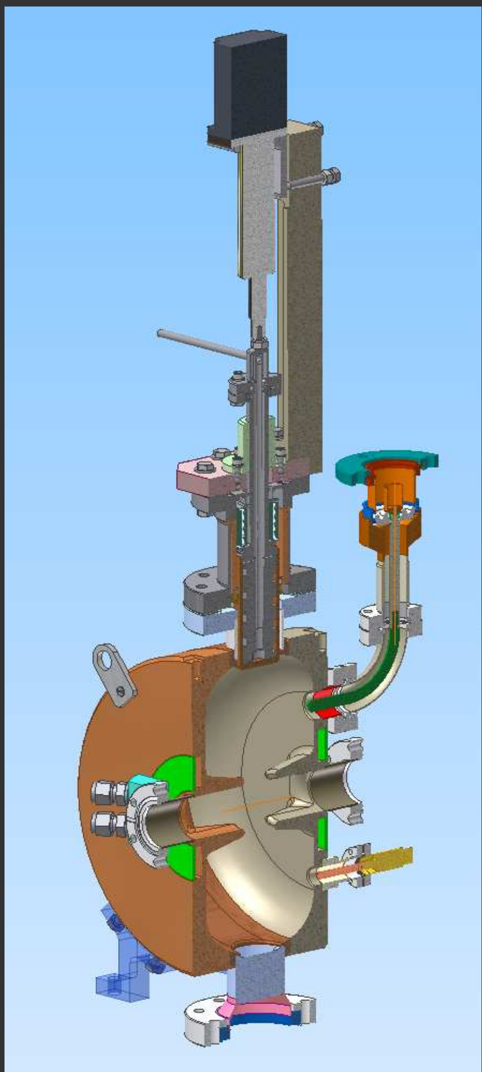
- roll compensation by small solenoid (~1° max)
- pitch/yaw compensation by correctors
- ⇒ relaxed tolerances

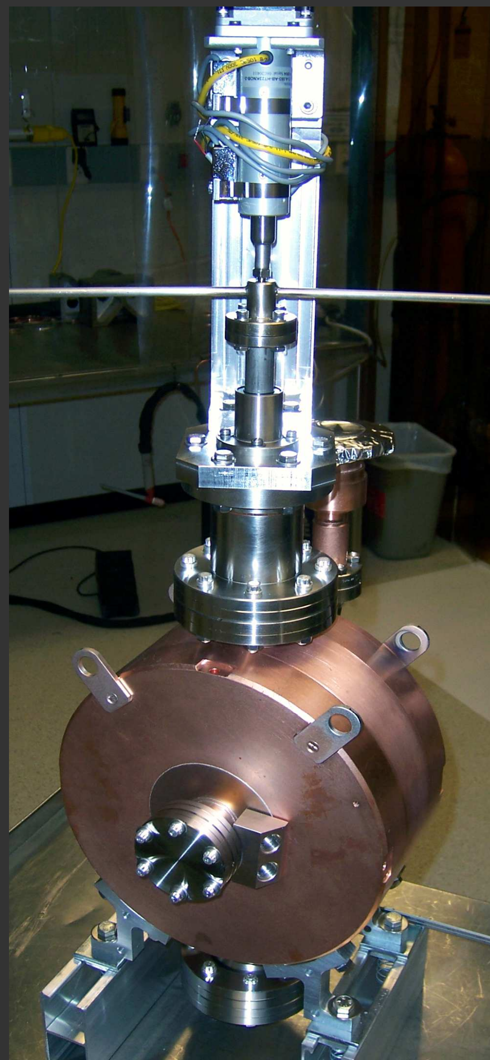
scanner uniformity



- scanner coils cancel to ≤ 1%
- sextupole-component free
- max scan rate ~200 Hz

RF deflecting cavity

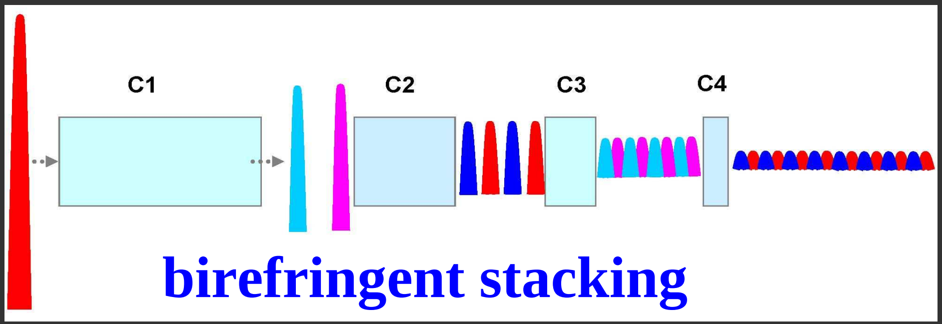




- Essential diagnostics tool for temporal profile measurements; cathode response time
- ~1 ps rms resolution (100 fs with collimation)

Laser

- Frequency-doubled Yb-fiber soliton laser
- 2.5 ps pulses at 50 MHz, avg. power ~1W in green
- Shaped temporally using birefringent crystals
- Transversely spot is blown up and clipped with 2.6 mm diameter aperture; then 1:1 imaged onto the photocathode (Newport shaper was tried as well)



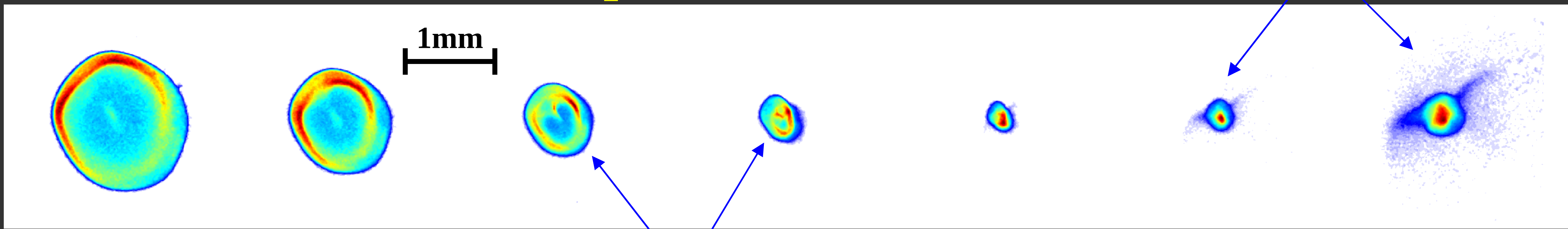
Experimental procedure

- Setup 1:1 imaging on laser CCD camera
- Record laser transverse profile for each data set
- Run << pC charge/bunch, obtain temporal profile
- Obtain viewscreen images of ebeam transverse profile vs. solenoid current
- Obtain phase space scans vs. solenoid current
- Repeat for 80pC, 20pC and 0.5pC

Some surprises

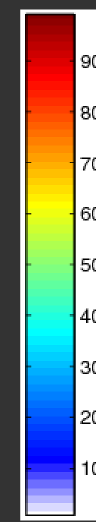
“structure”

80 pC viewscreen XY data



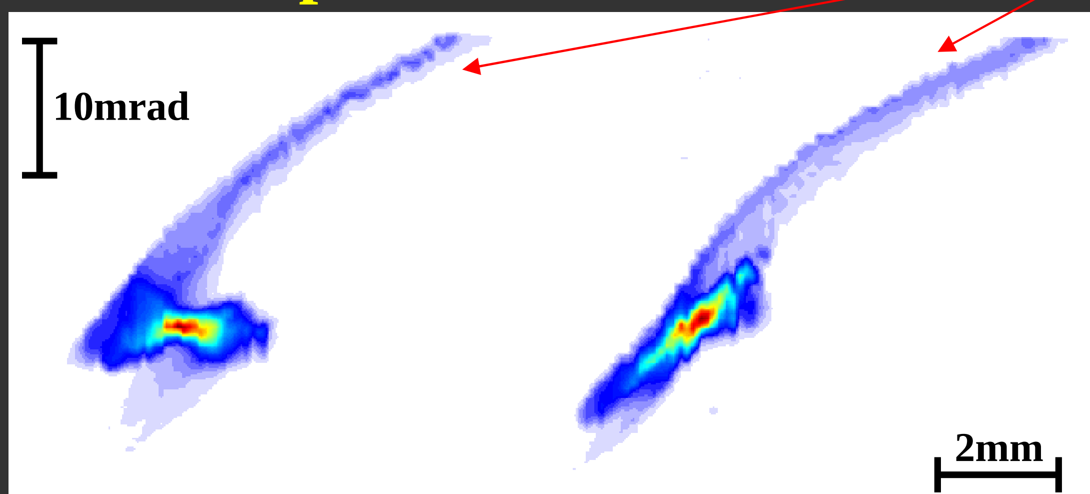
SOL1=3.3A 3.4A 3.5A 3.6A 3.7A 3.8A 3.9A

“structure”



nasty “tails”

80 pC EMS YY’ data



SOL1=3.7A 3.8A

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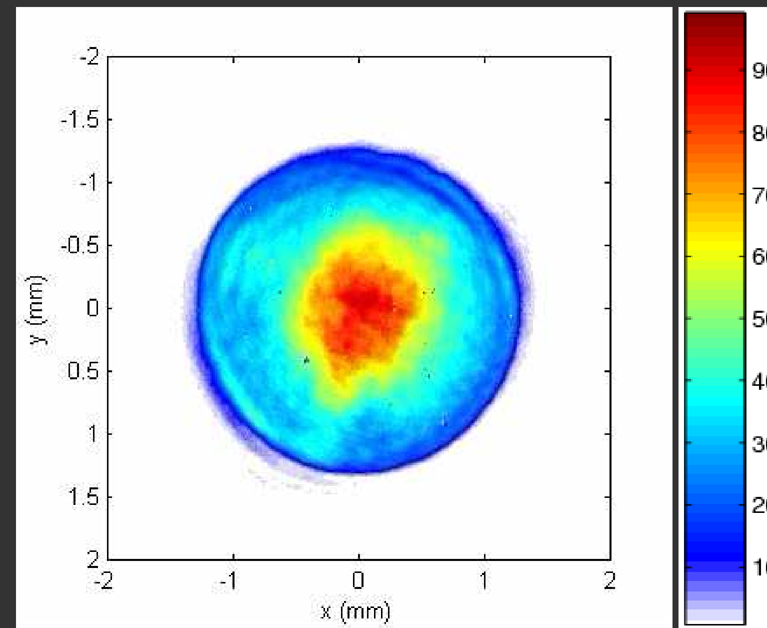
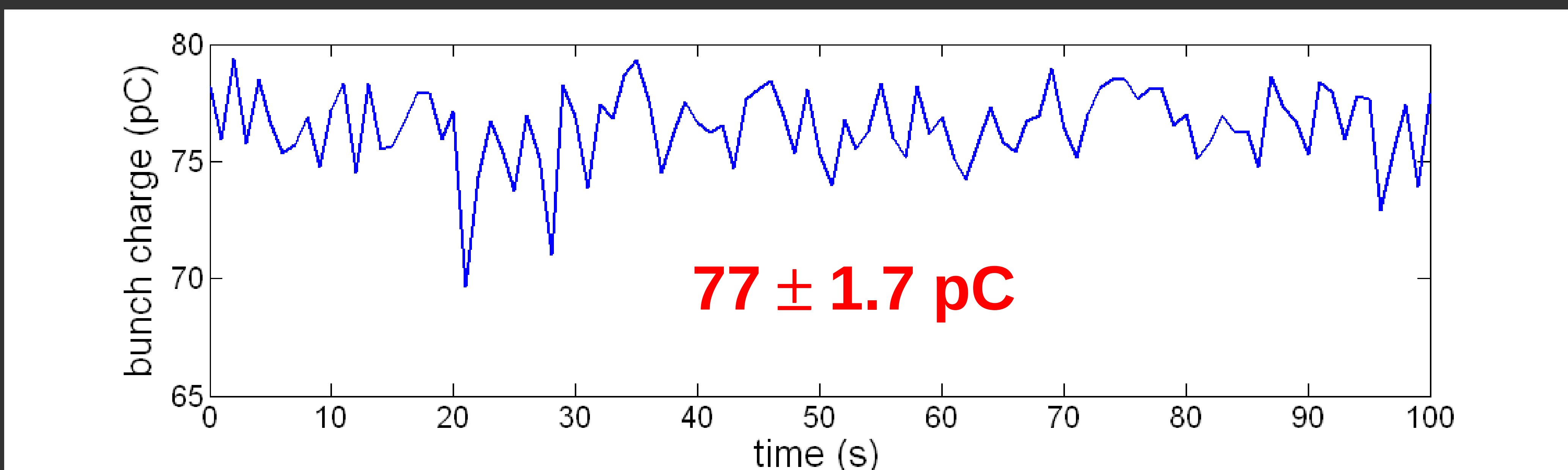
Laser stability

- Pointing stability of the laser spot 50-80 μm rms (needs much improvement)
- Laser intensity stability 2% rms (OK)



laser profile on the cathode



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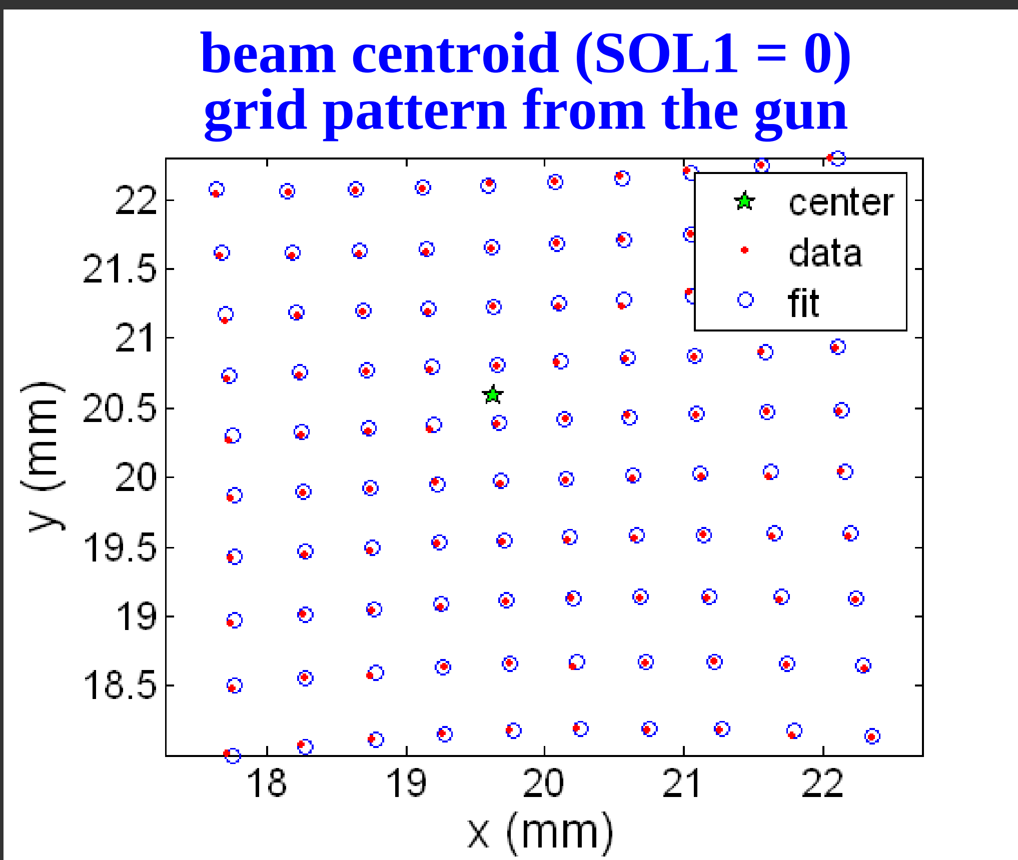
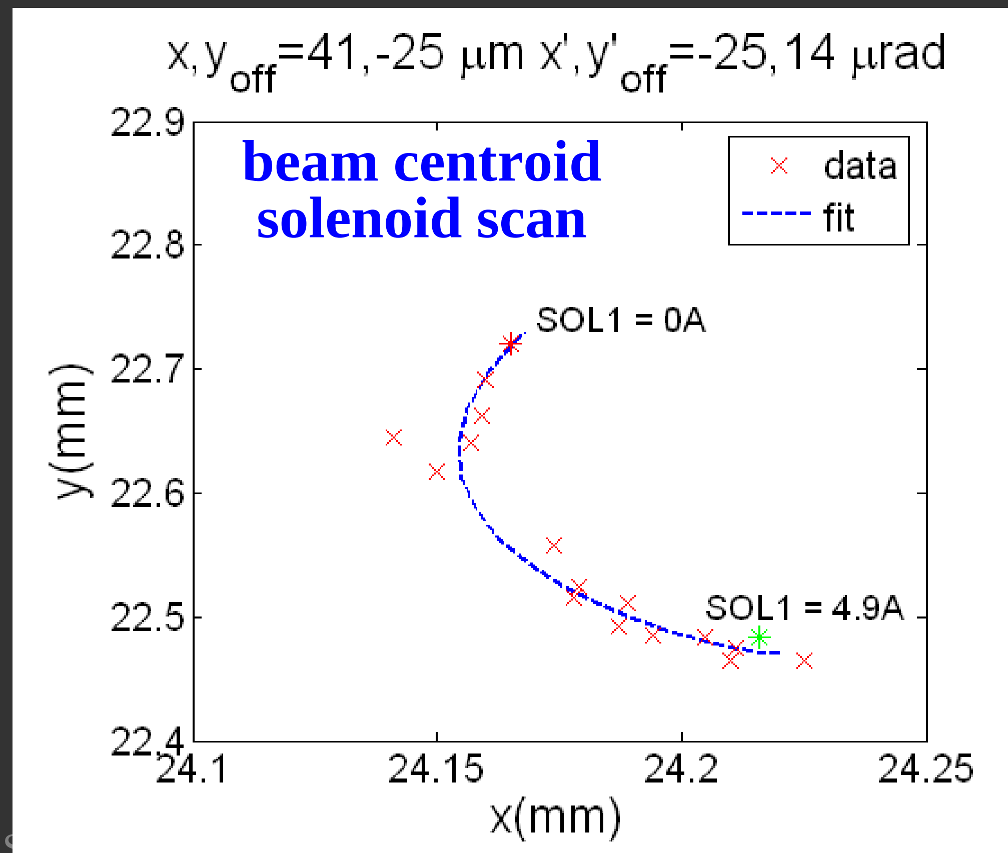
Beam based alignment

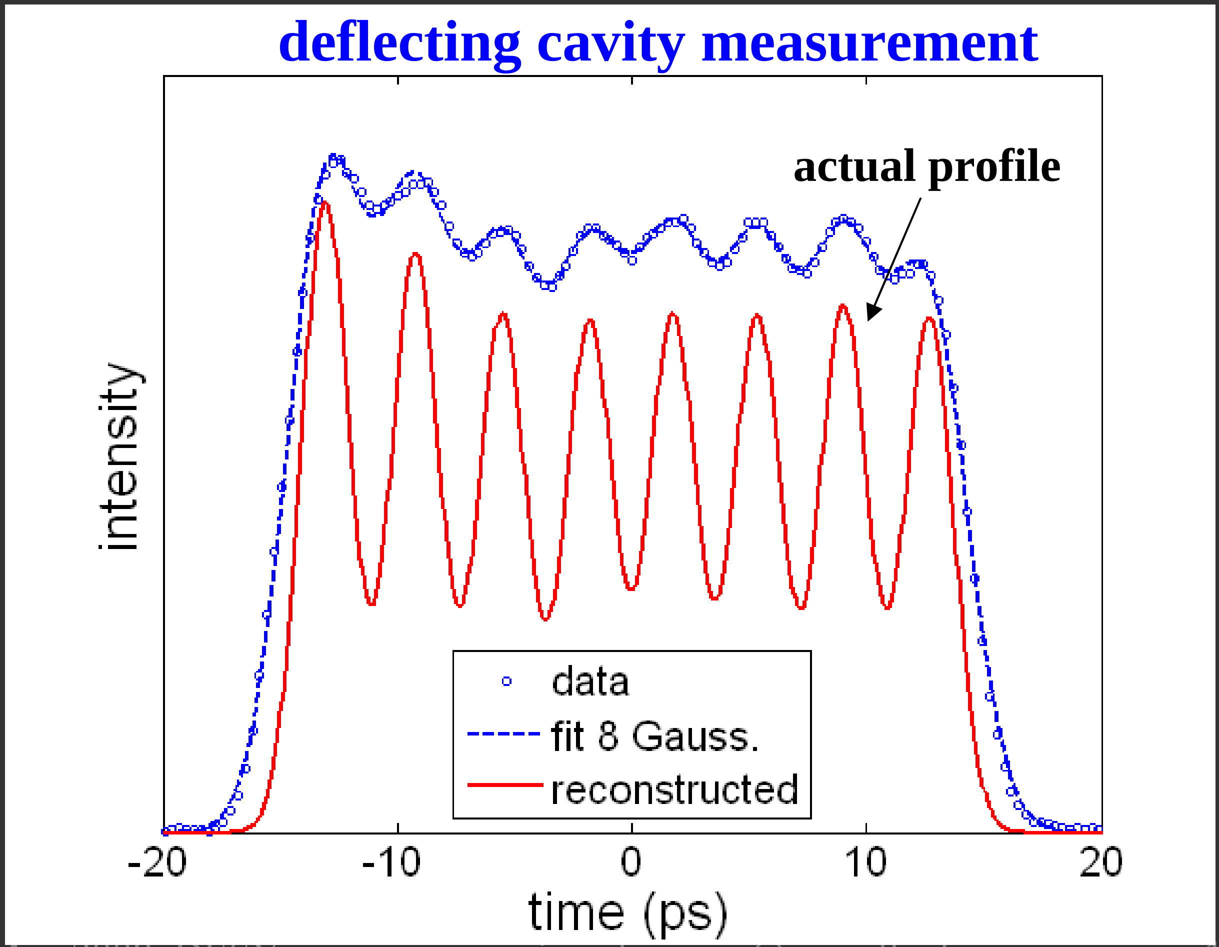
- Use ebeam based alignment of solenoid / gun to reduce potential causes of phase space asymmetry
- Solenoid (physically adjusted) / gun aligned to few 10 μm; solenoid / beam axes parallel to few 10 μrad





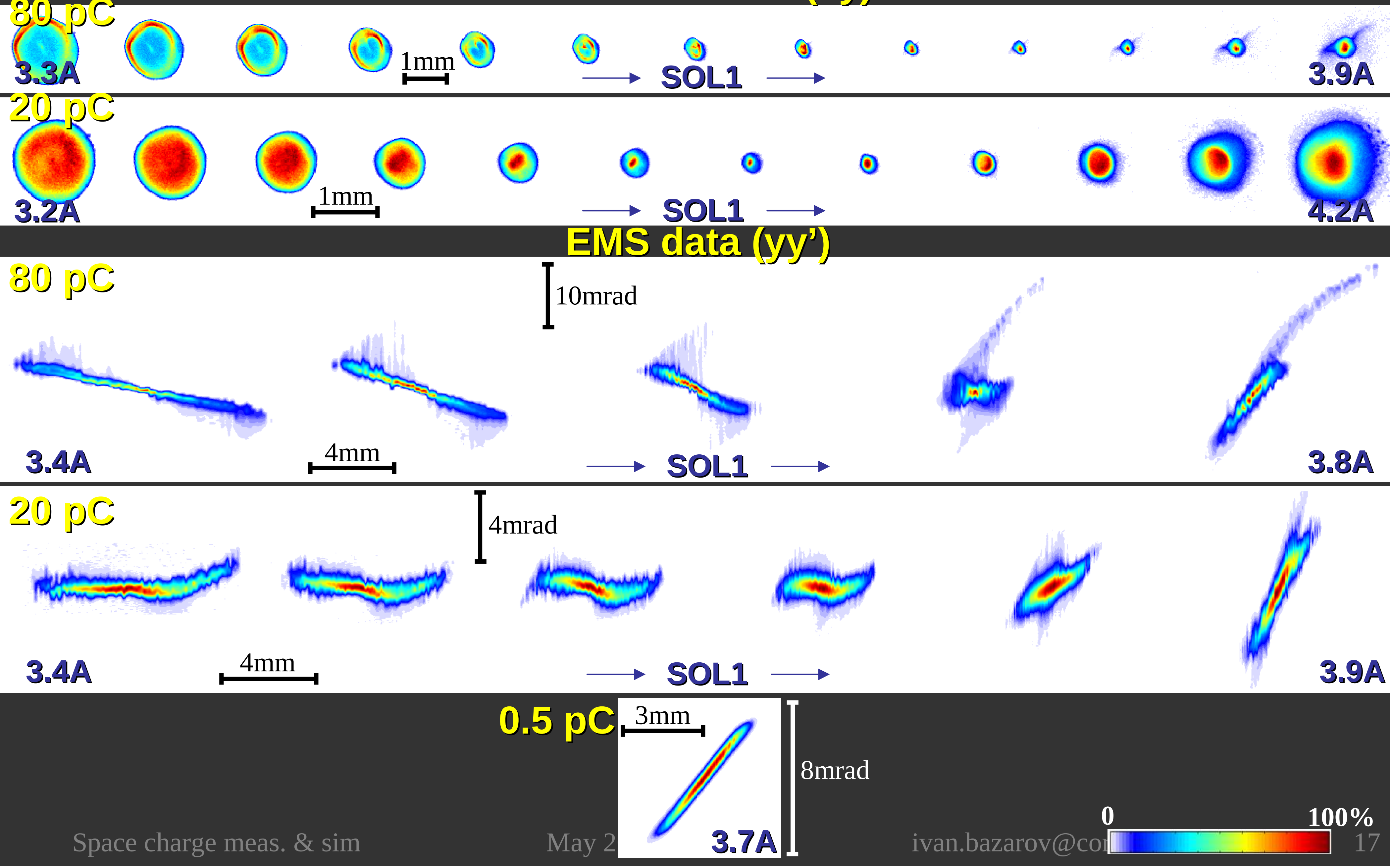
Initial temporal profile

- 3 stacking crystals were used
- Deflecting cavity data was fitted with 8 Gaussians to account for finite resolution of the setup
- Each Gaussian assigned σ = 1 ps (as measured by optical auto-correlation)



Data

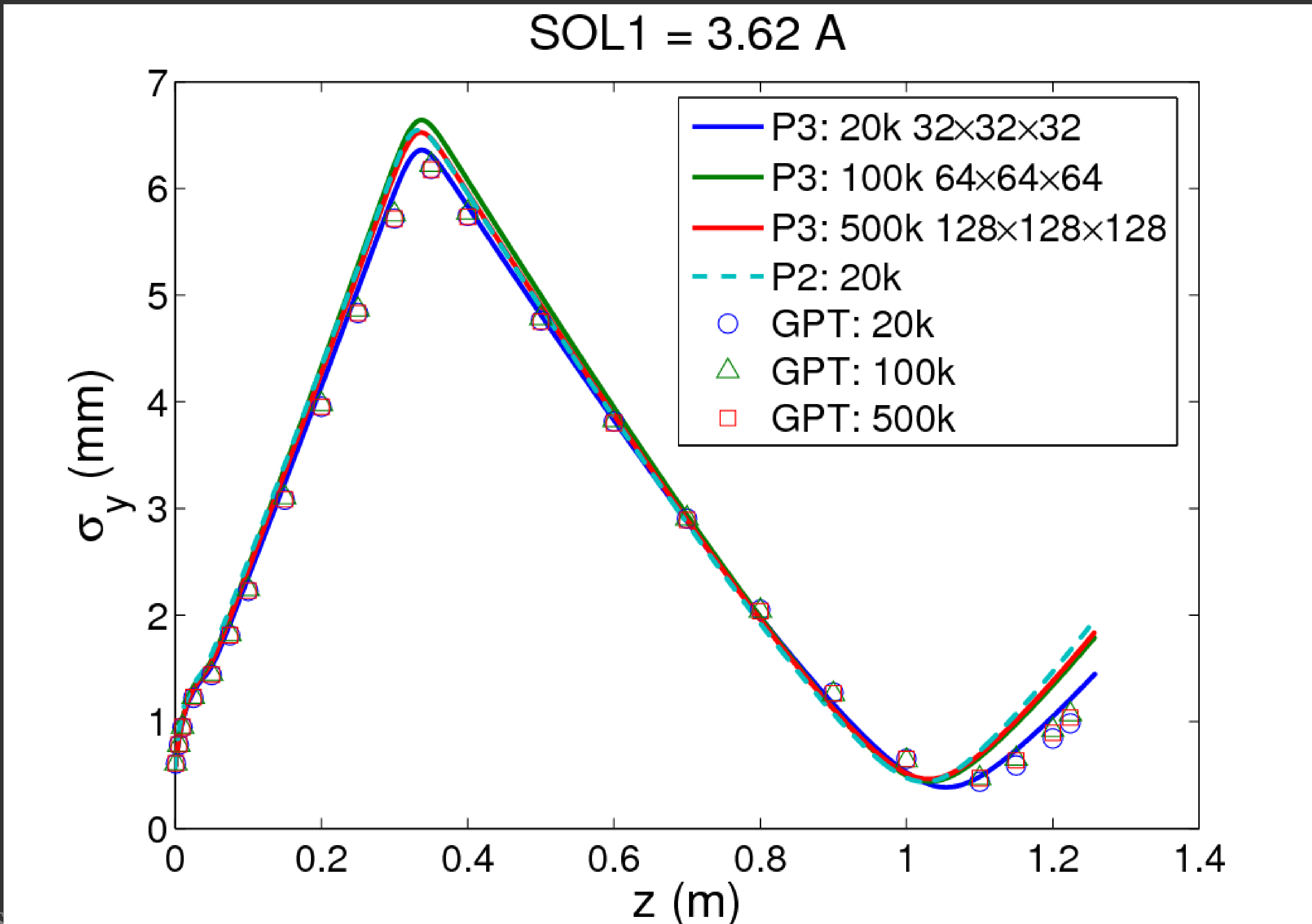
viescreen data (xy)



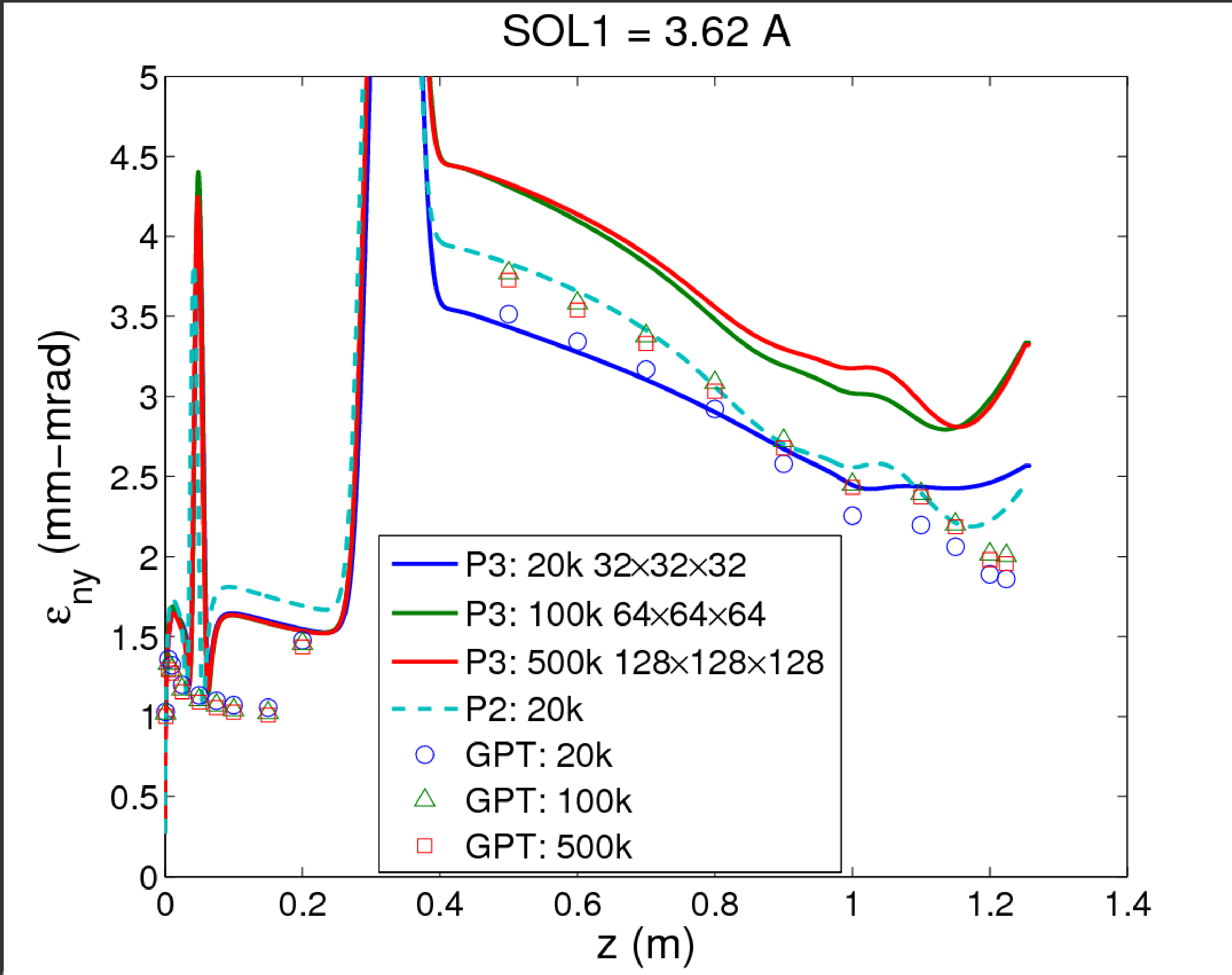
Simulations

- Use measured laser transverse and temporal profiles to create 3D particle distributions
- Thermal emittance for GaAs at 520 nm is known from previous measurements to be 0.48 mm-mrad per 1 mm rms spot
- Adequate convergence in GPT with 100k macro-particles and 50x50x50 non-equidistant mesh
- Parmela3D runs had 100k with 64x64x64 mesh

Parmela3D/GPT σ_y



Parmela3D/GPT ε_{ny}



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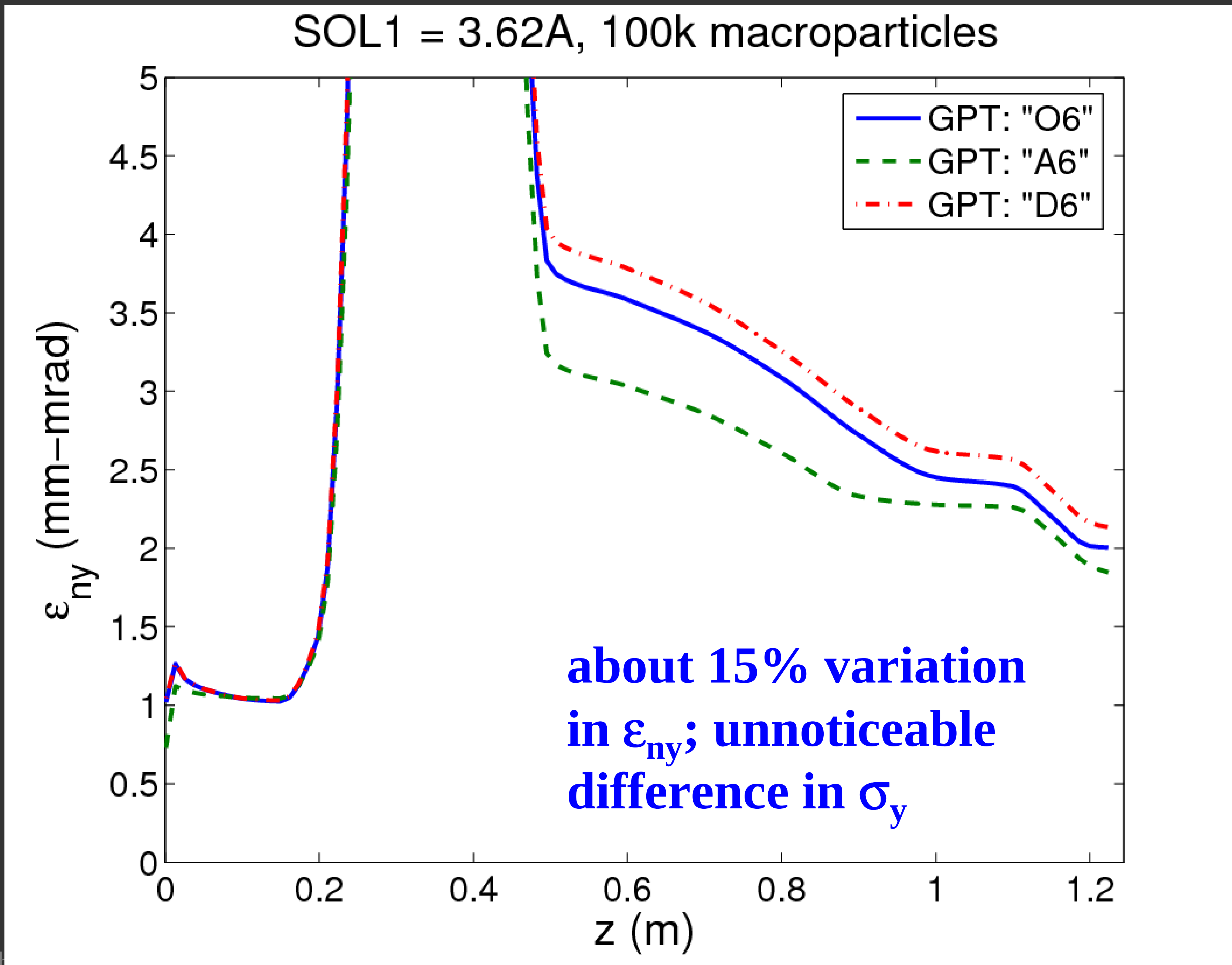
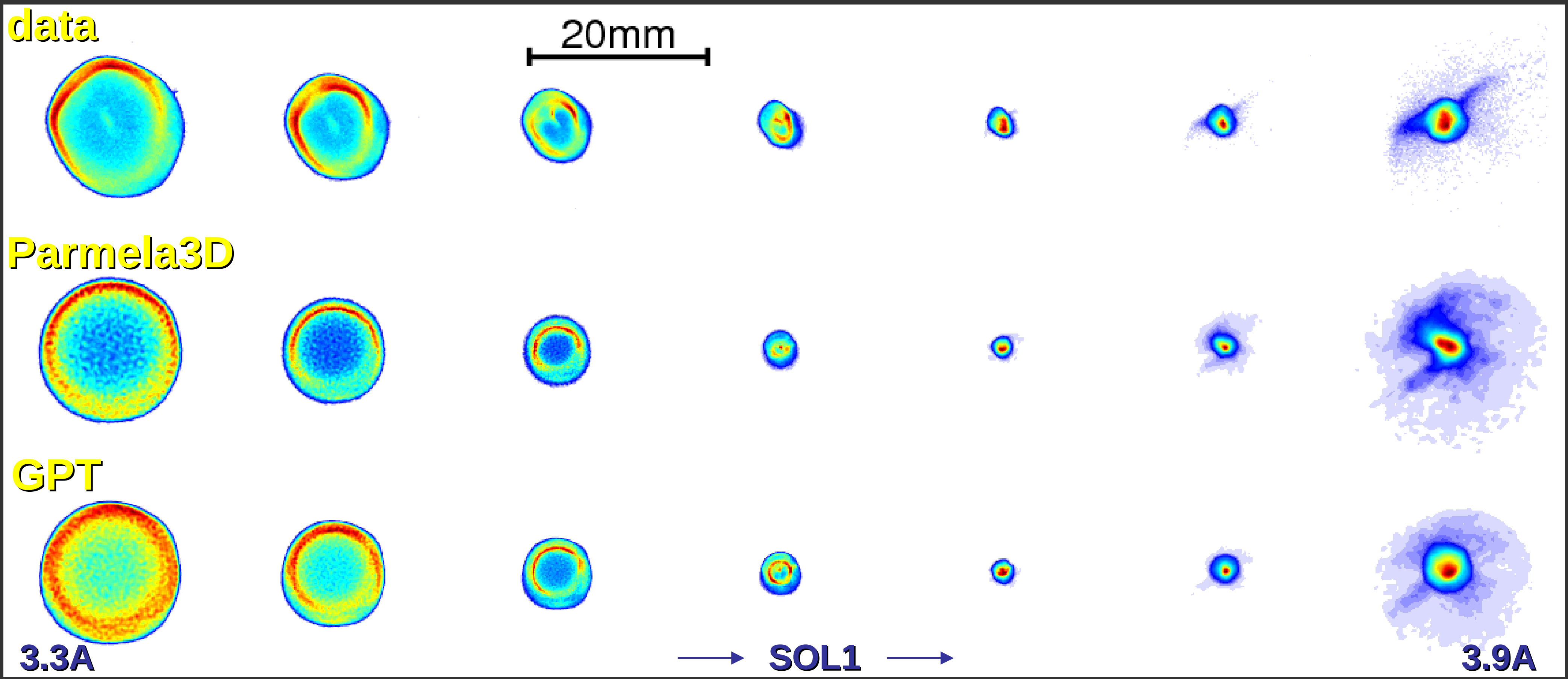
GPT boundary cond.



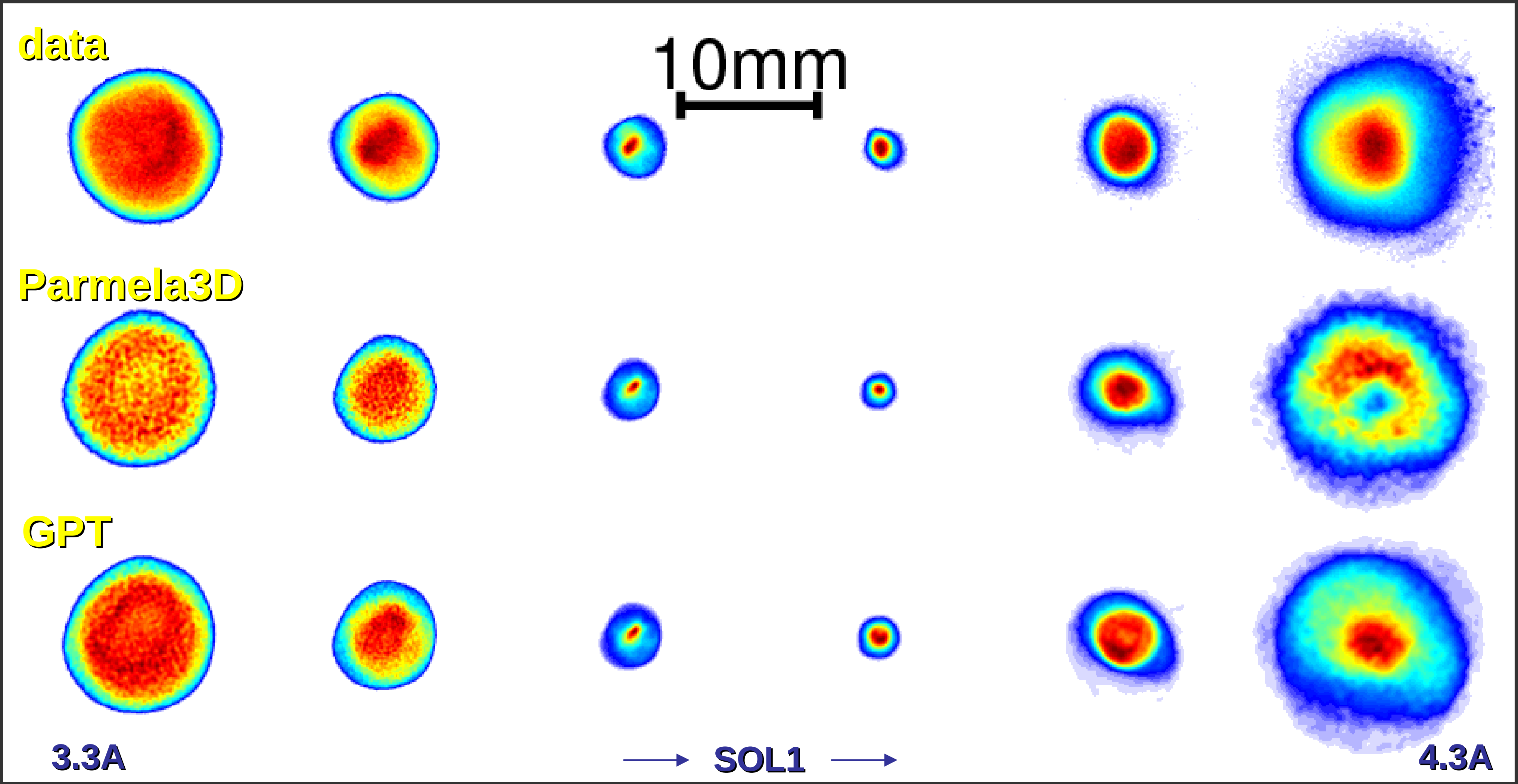
Data vs. sim (80 pC, scr.)

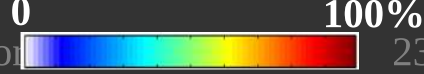
z = 1.244m



Data vs. sim (20 pC, scr.)

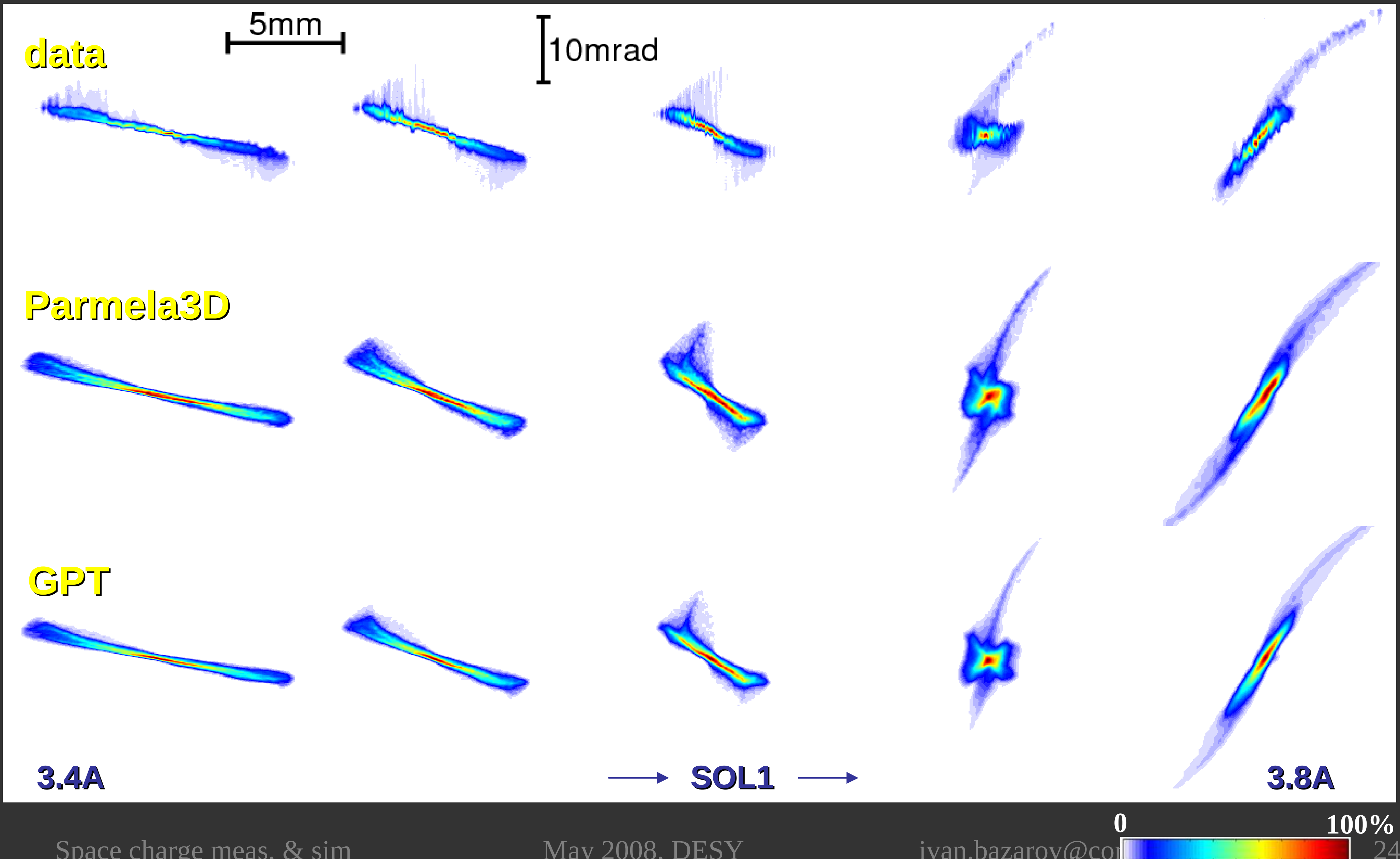
z = 1.244m



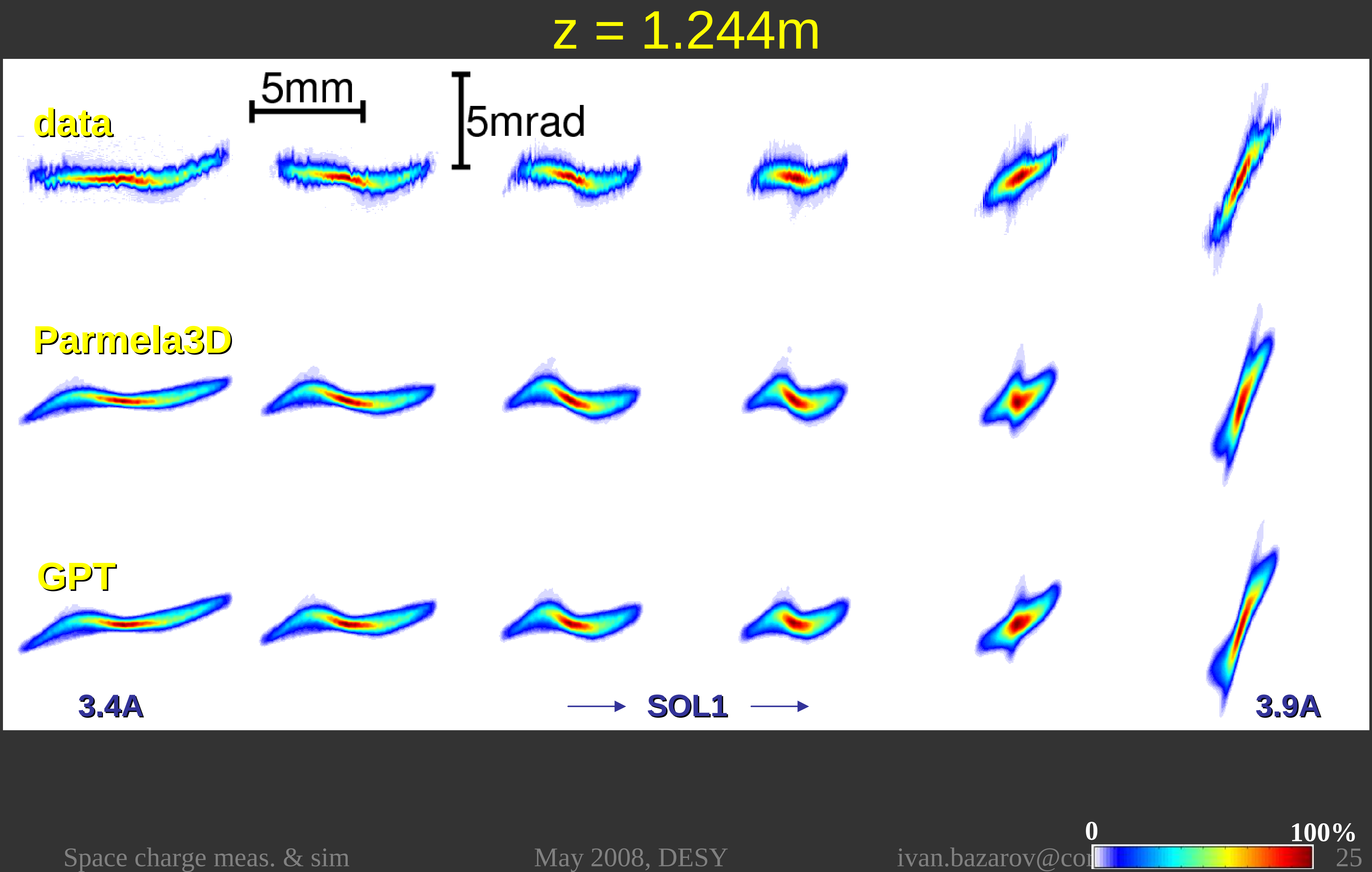


Data vs. sim (80 pC, ems)

z = 1.244m

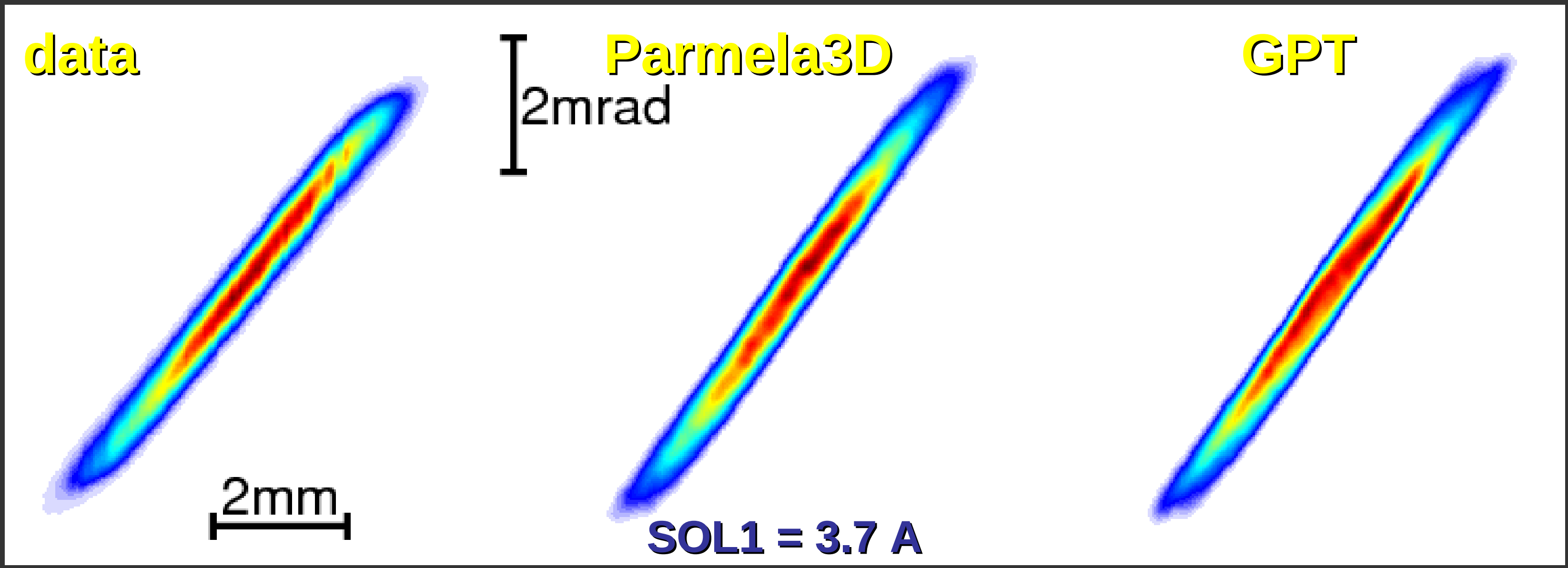


Data vs. sim (20 pC, ems)



Data vs. sim (0.5 pC, ems)

z = 1.244m

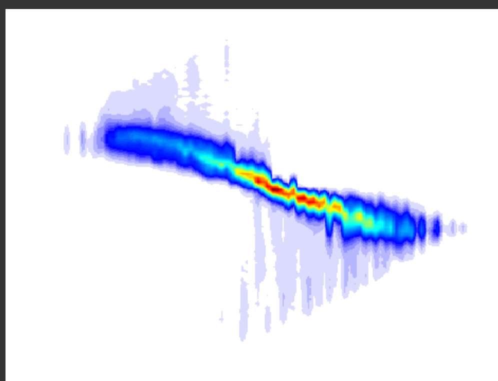


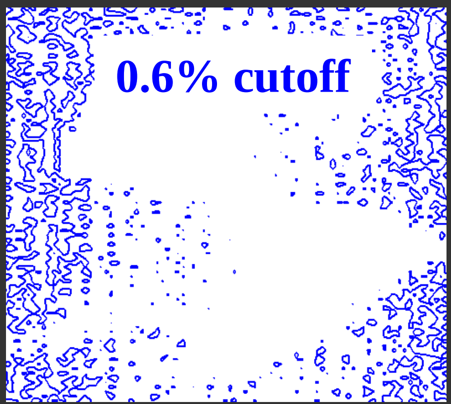
Data processing

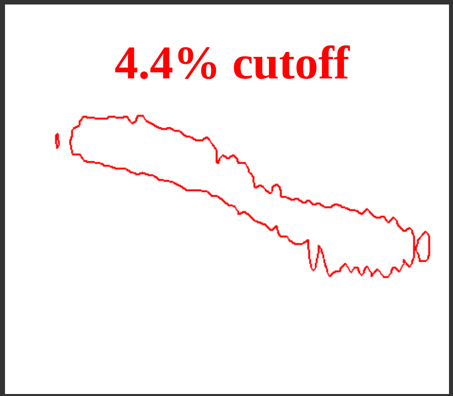
- Extraction of second moments from profiles requires noise subtraction
- General approach:
  - a contour delineates data region from noise region
  - average intensity I_n outside the contour represents noise
  - subtract noise I_n from data, assign 0 to the outside region
  - "grow" the contour; the parameter of interest should be "stable" vs. included area when all data is accounted for
- Circular contours used for viewscreen profiles
- Boundary detection employed for phase-space scans

Data processing (2)

- Boundary detection: based on observation that thresholded data region forms a continuous island, whereas noise – many individual islands







- a) blur (convolve) image with n×n square; b) find smallest threshold that generates a single island; c) grow n and repeat – stop when the island starts including chunks of noise (clearly visible)

Verify subtraction

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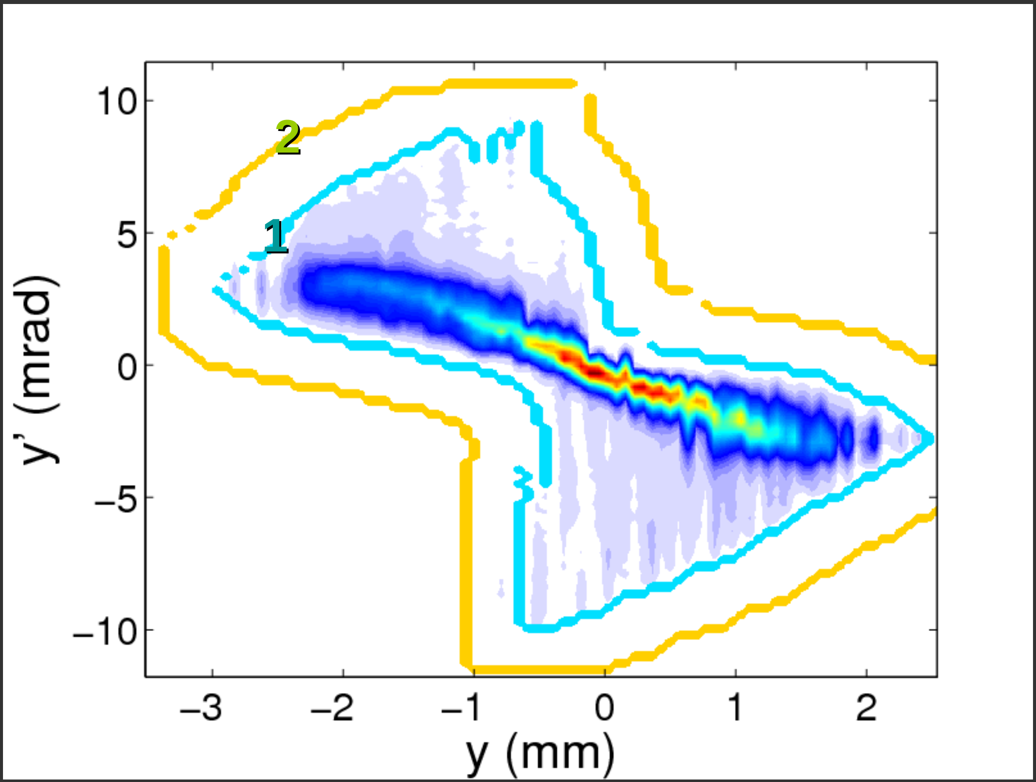
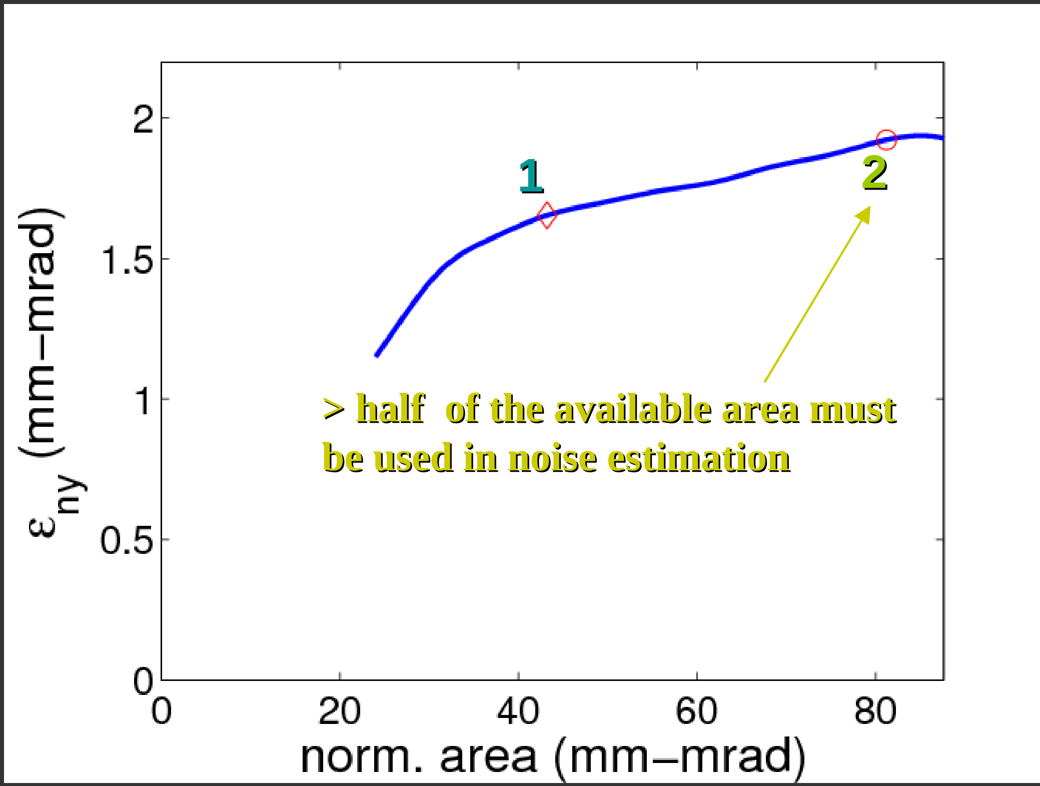
- Verify noise subtract. by growing/shrinking contour

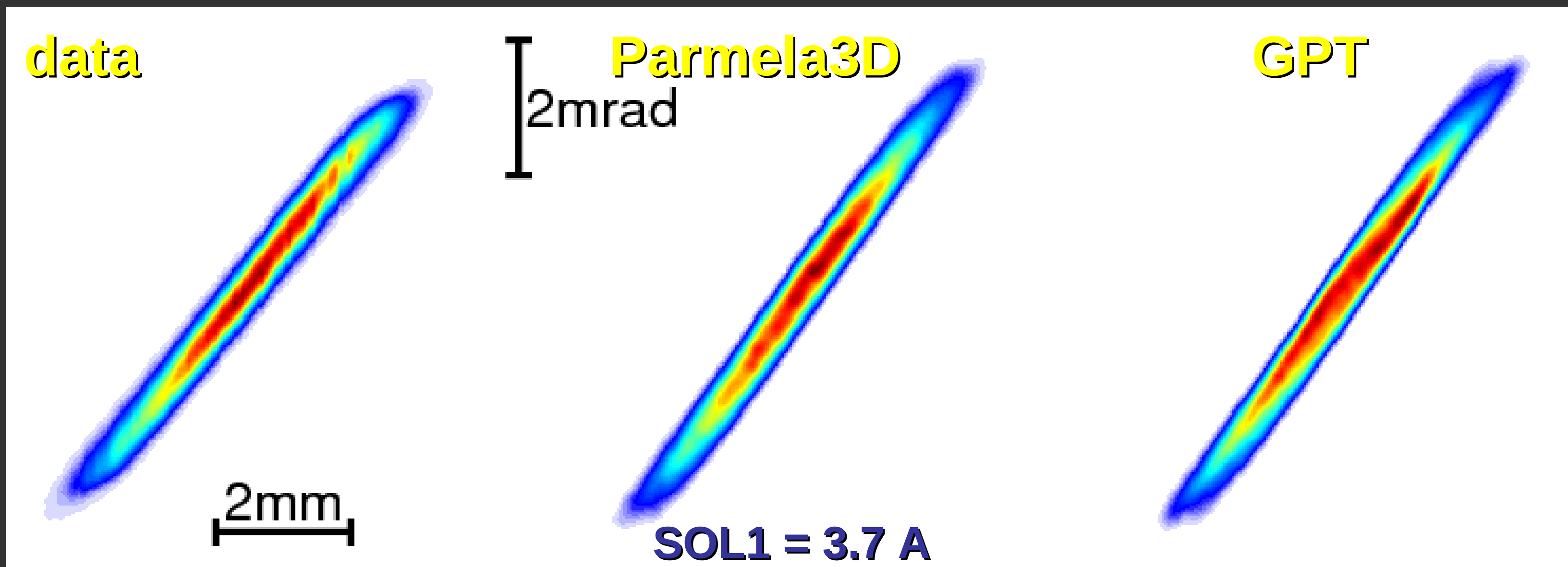




- Error budget:
  - rms emittance ±12%
  - rms spot size from viewscreen ±5%
  - rms spot size from slits ±4%

Data vs. sim (0.5 pC, ems)

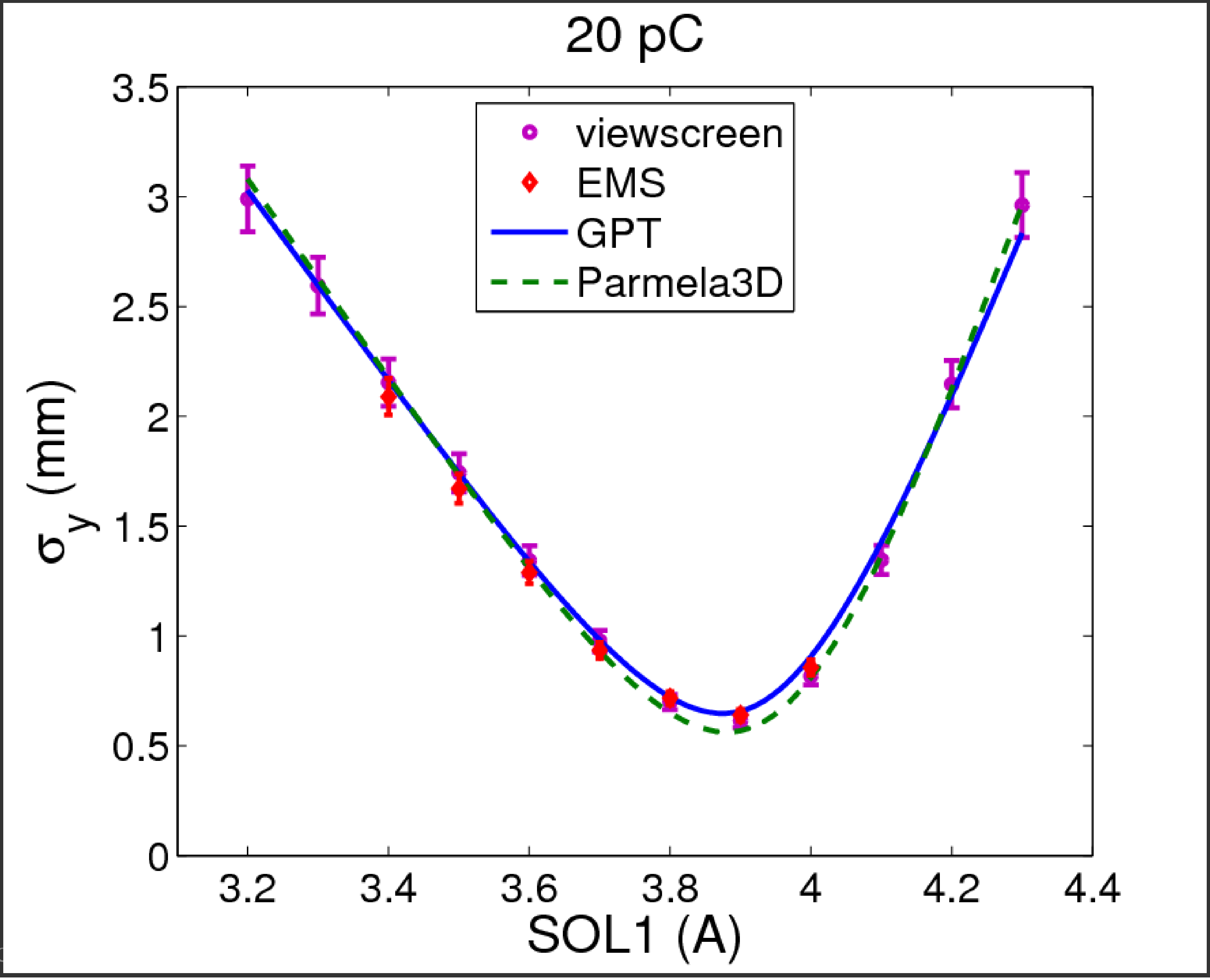
z = 1.244m



ε_{ny} = 0.31±0.04 μm 0.29 μm 0.28 μm

σ_y = 1.15±0.05 mm 1.14 mm 1.14 mm

Data vs. sim (20 pC, scr.)



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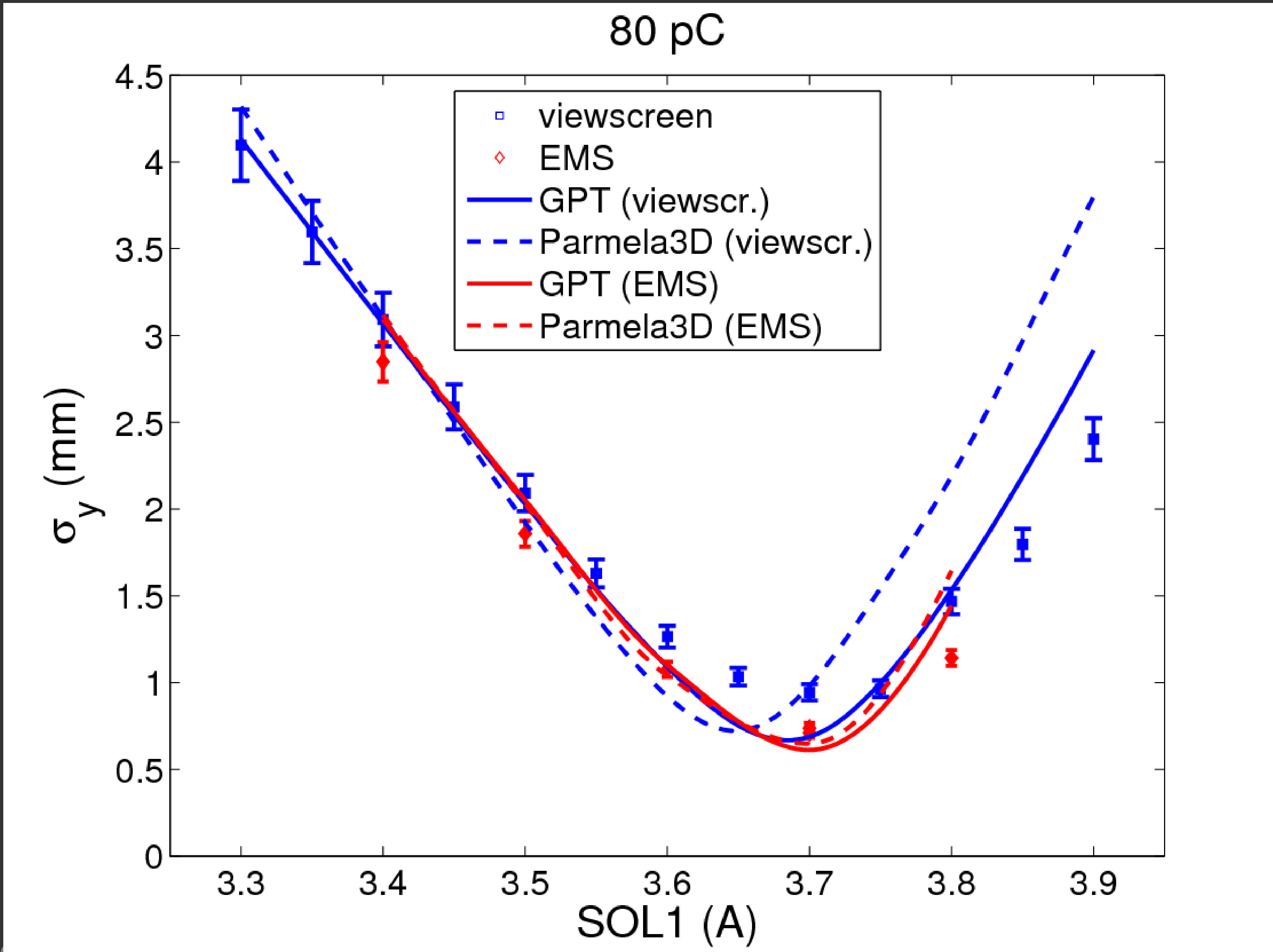
Data vs. sim (80 pC, scr.)



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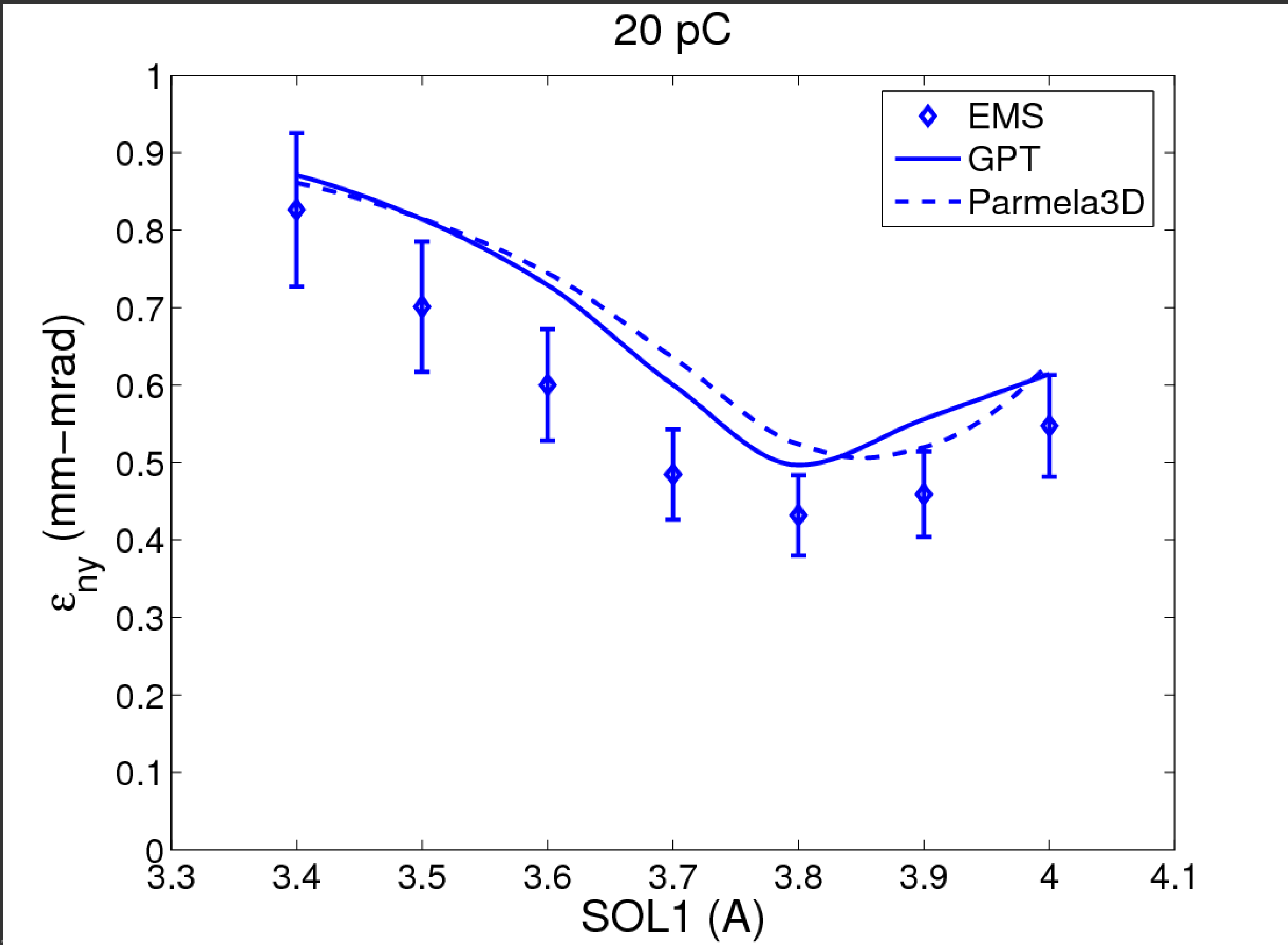
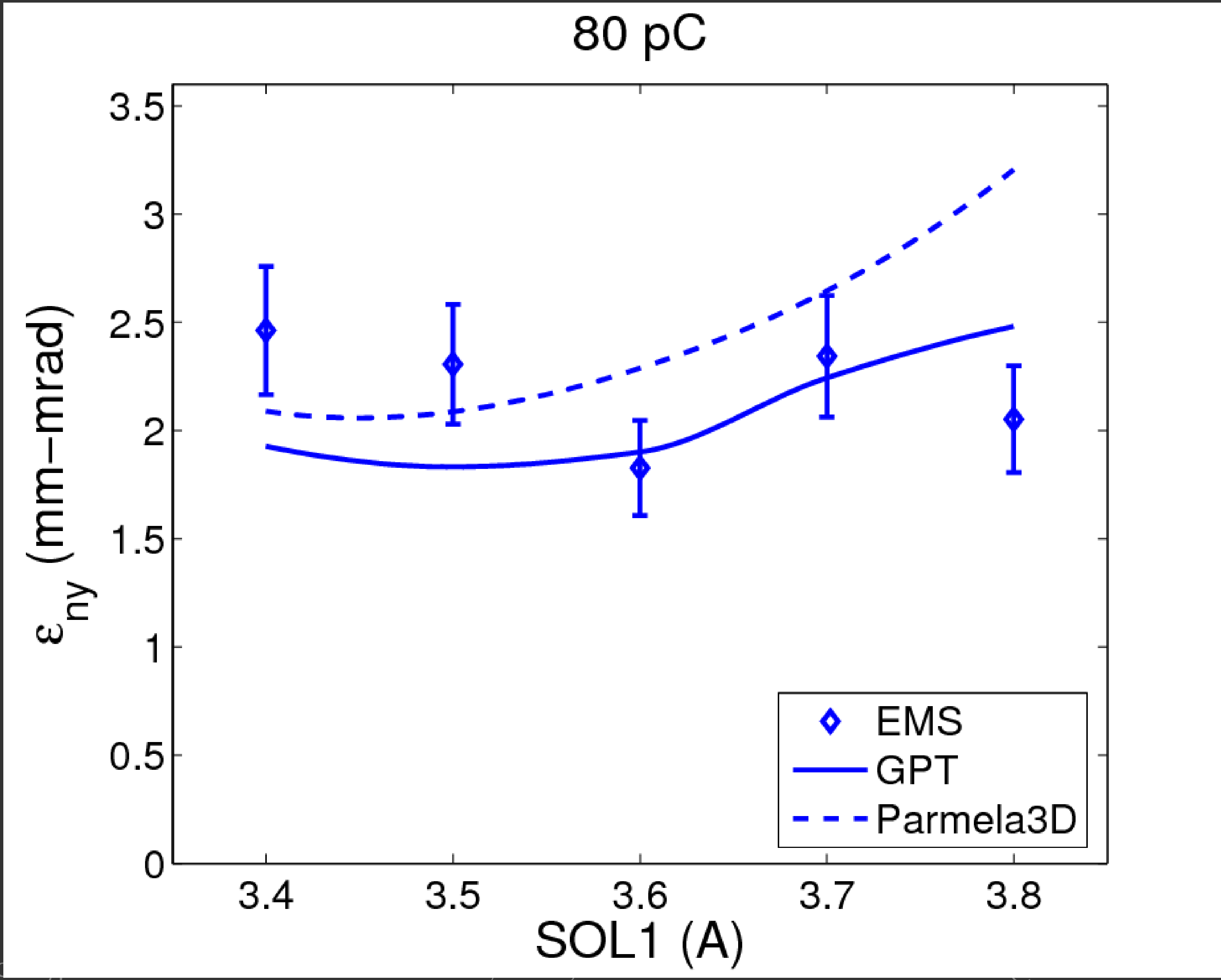
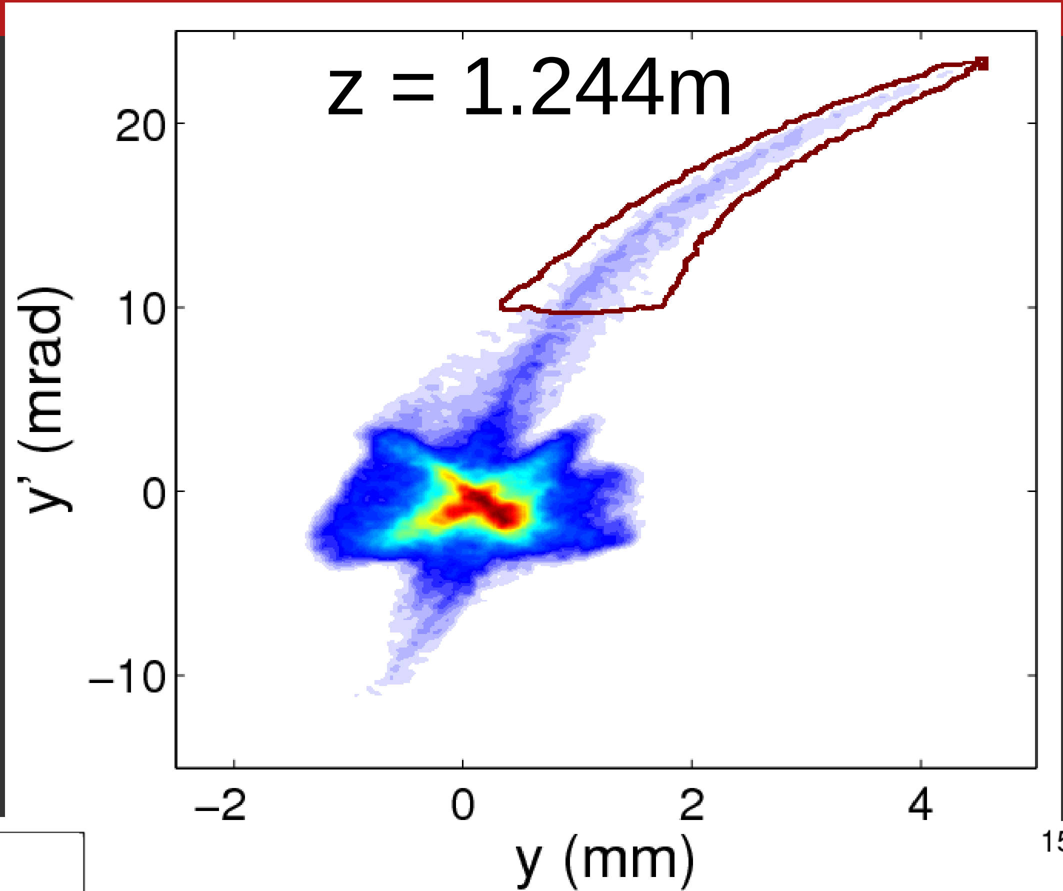
Data vs. sim (20 pC, ems)



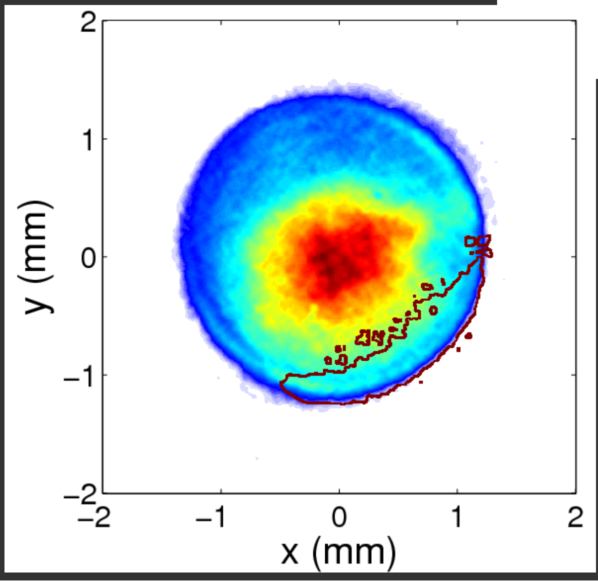
Data vs. sim (80 pC, ems)



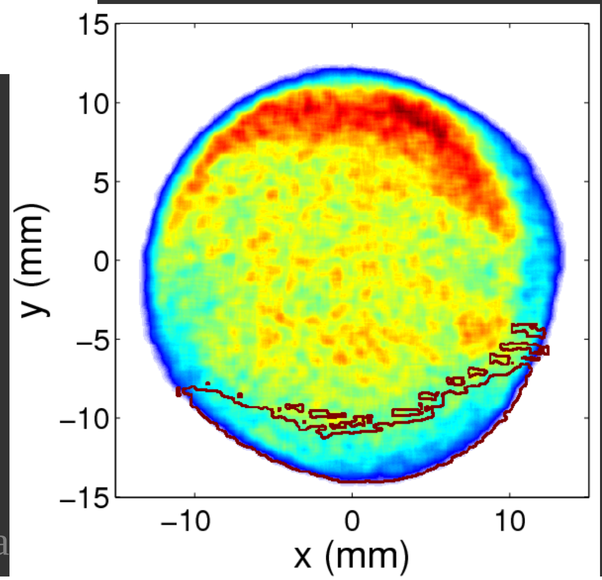
Tail explained



at cathode
z = 0m

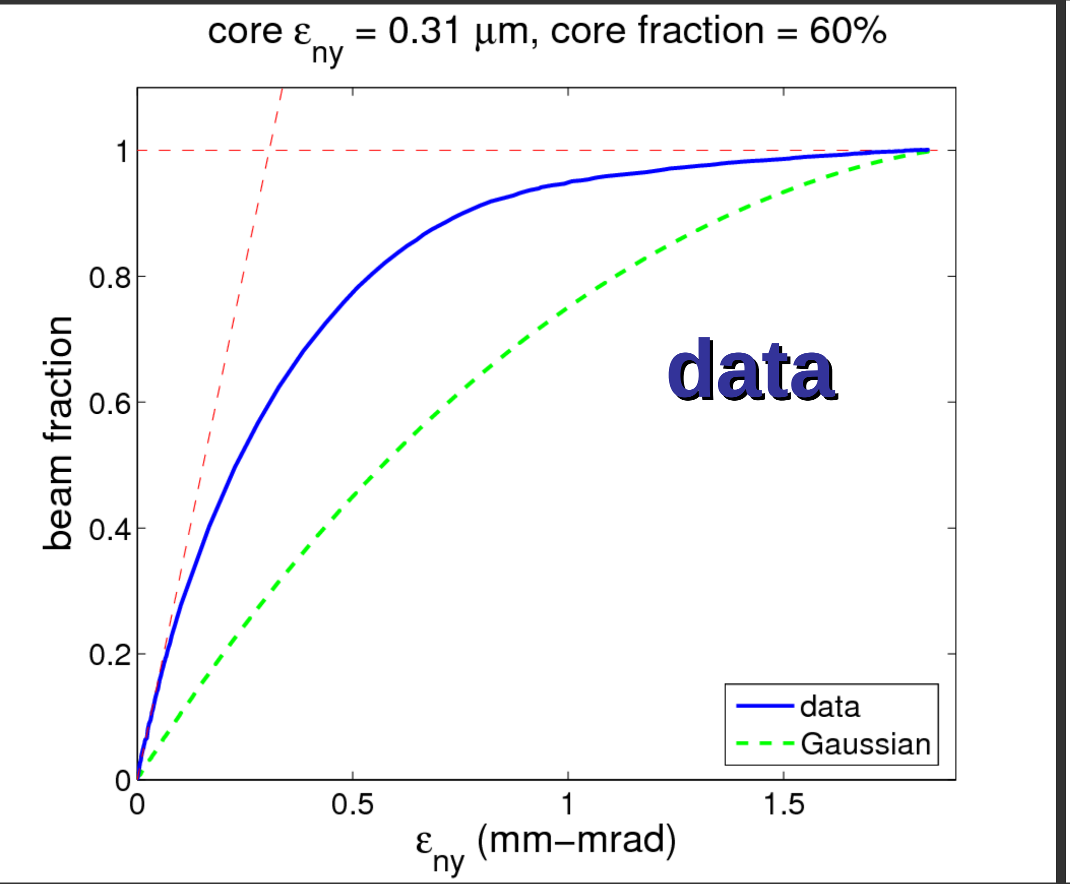


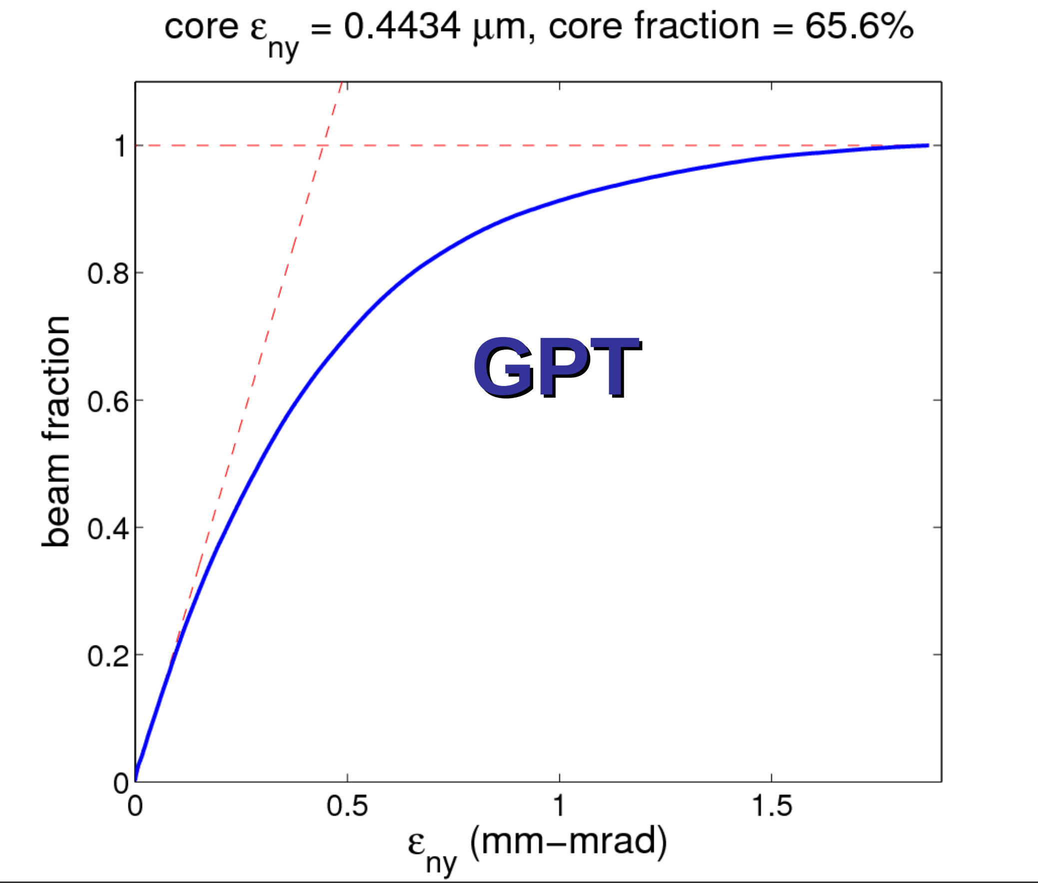
inside solenoid
z = 0.35m



Emittance curve: 80pC

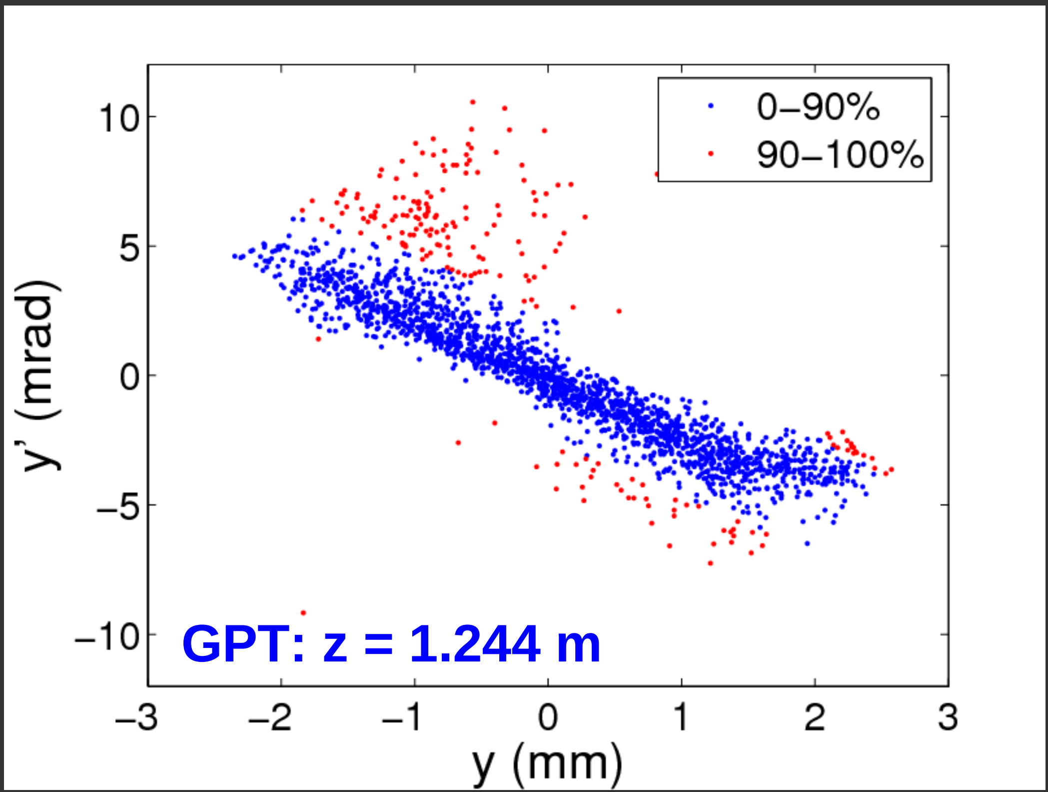
ε_{ny} (100%) = 1.8 mm-mrad

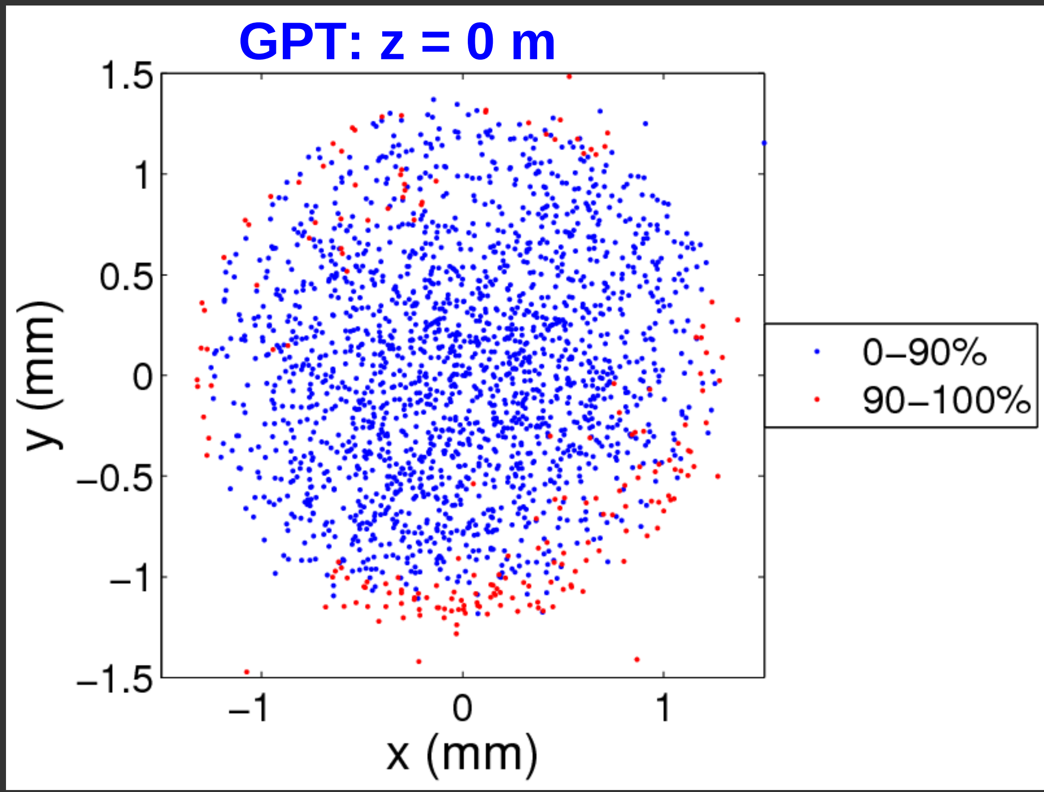




Worst 10%

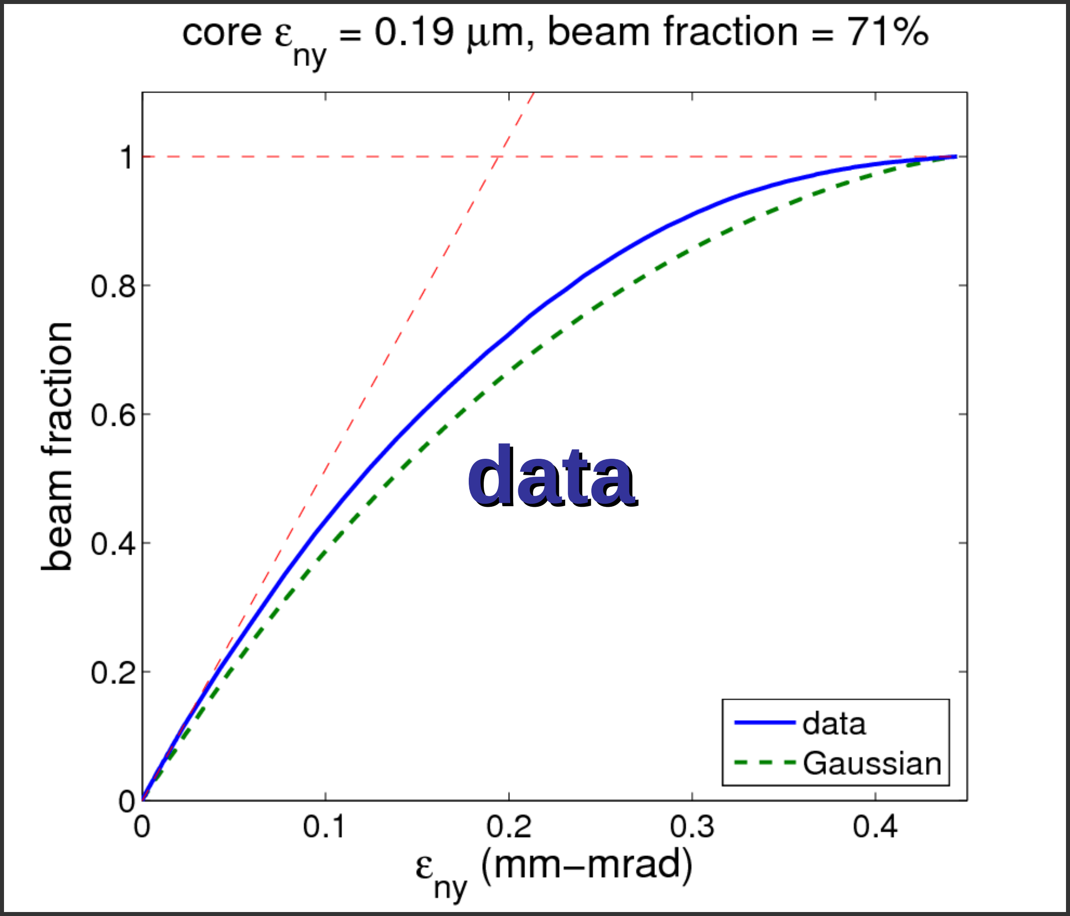
80 pC





Emittance curve: 20pC

ε_{ny} (100%) = 0.43 mm-mrad



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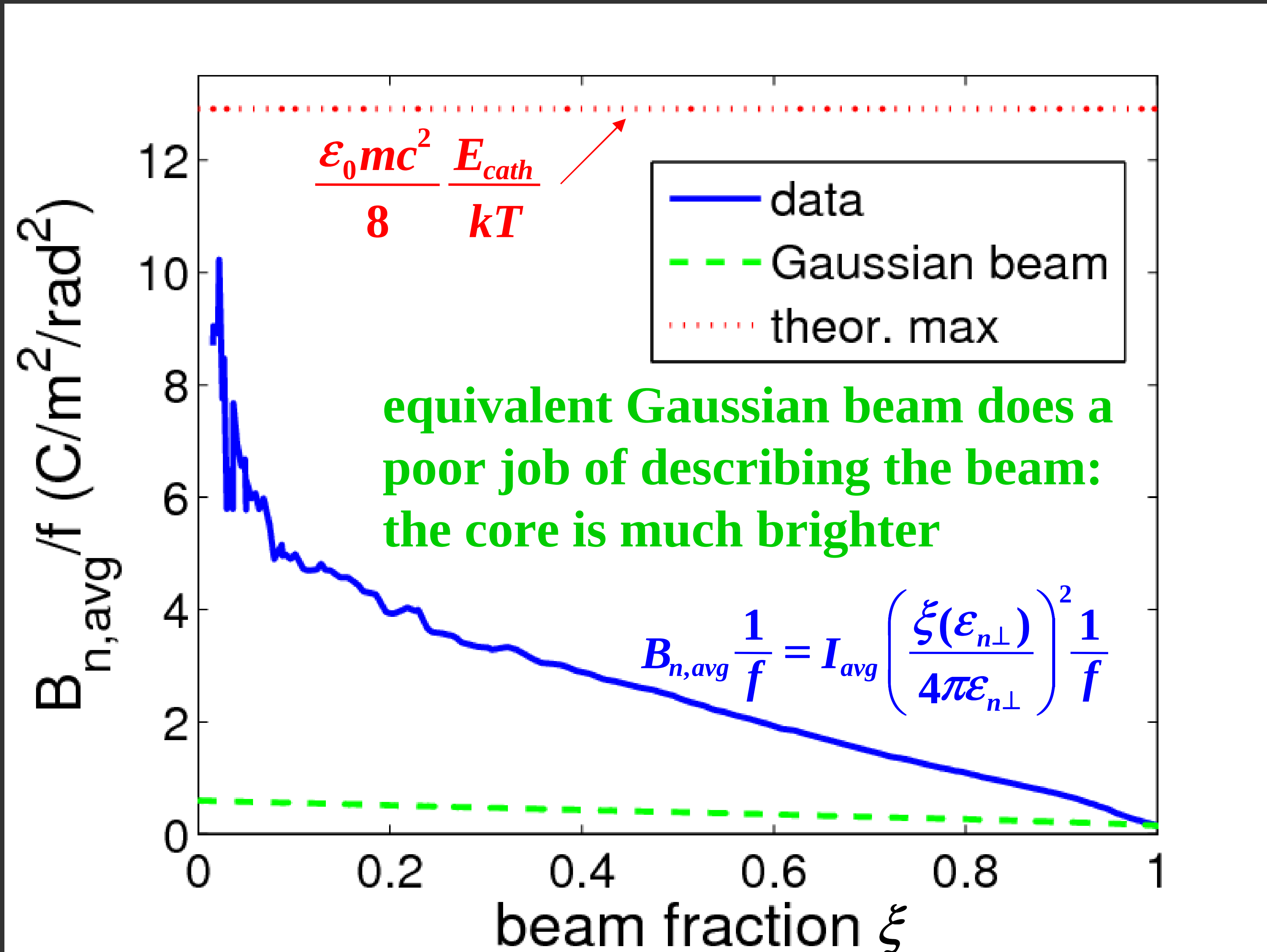
Beam brightness (80 pC)



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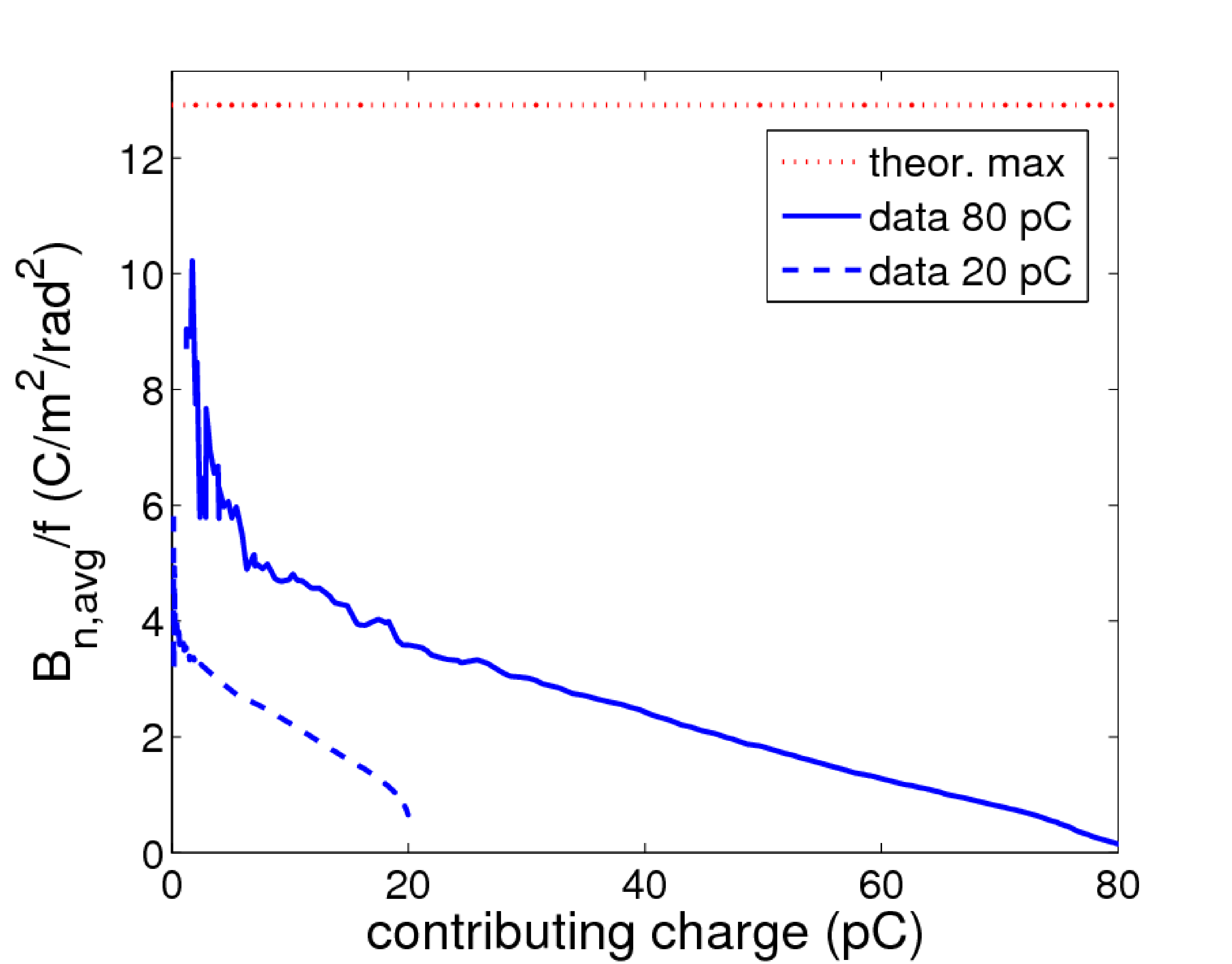
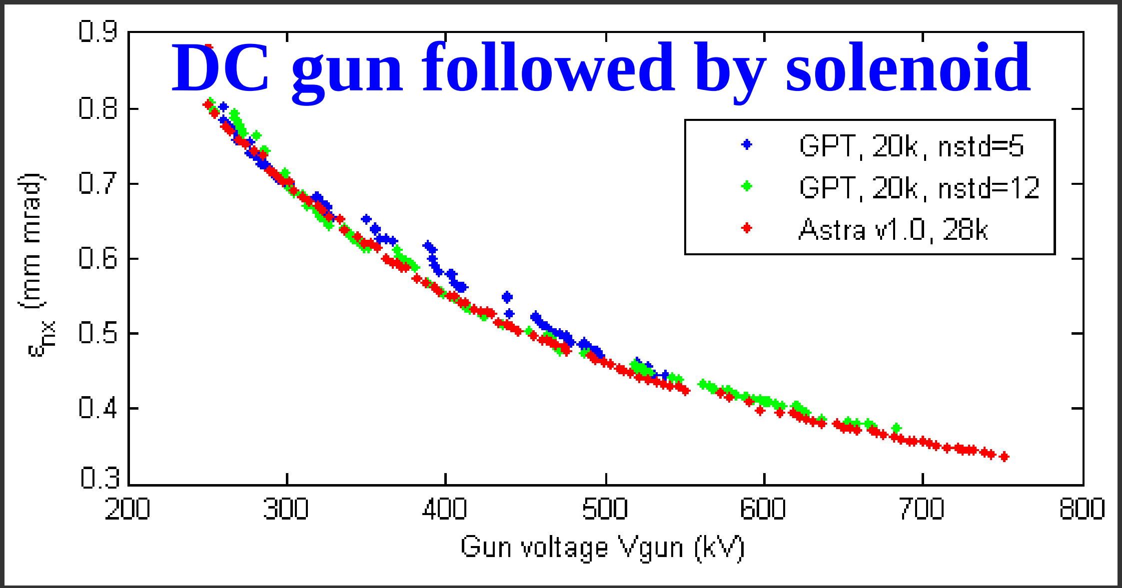
Beam brightness



Things to do…

- Substantially lower $\varepsilon_{n\perp}$ (100%) after the DC gun possible:
  - higher gun voltage
  - improved laser trans. profile
  - longer laser pulse (optimum 50% longer than what's used)



- It is a matter of time (& money) before this performance is reached

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Summary

- Overall, good agreement (quantitative and qualitative) has been experimentally established between simulations and space charge measurements from a DC gun
- 100% rms emittance substantially underestimates max beam brightness for 80 pC case
- Despite a modest gun voltage, good beam brightness for the beam core has been shown
- We understand which parameters & direction to push for better performance

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Acknowledgements

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