LCLS Drive Laser Shaping Experiments

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- *Description of the LCLS Injector and the Experiment*
- *Experimental Results*
- *Heuristic Model of the Emittance Growth*
- *Summary & Conclusions*

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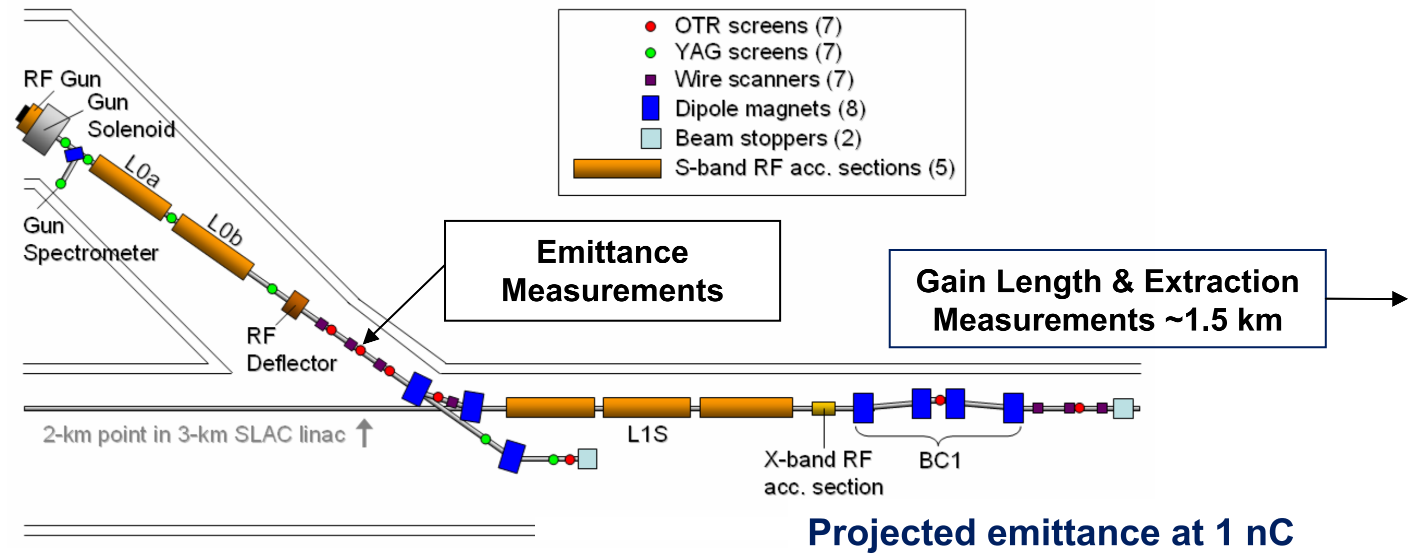
The LCLS Injector with Diagnostics

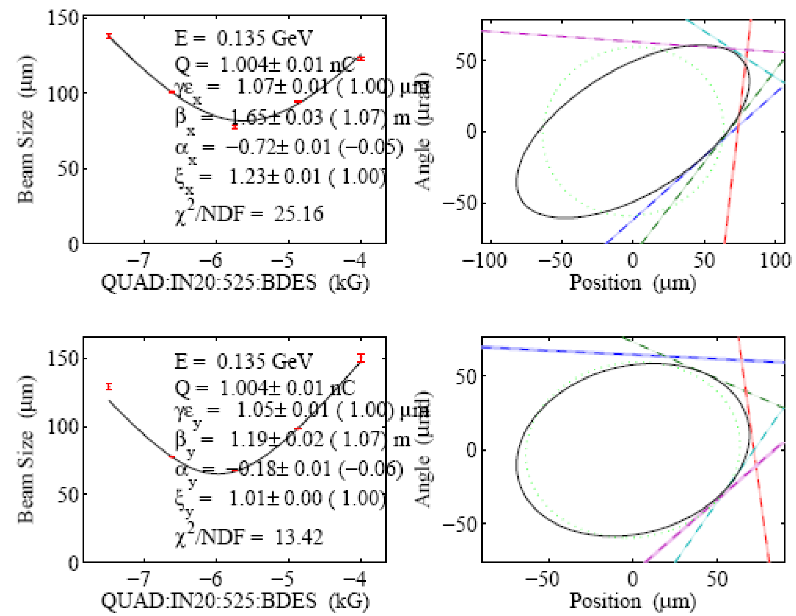
Location of Injector Diagnostics



Nominal Operating Parameters

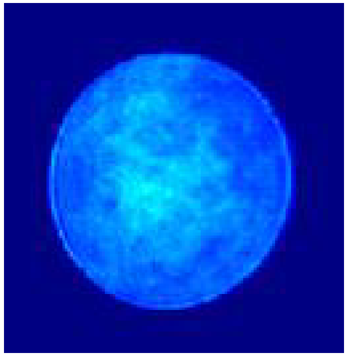
Parameter	Measured Value
Bunch Charge	250 pC
Projected Emittance (x-plane)	0.44 microns (rms)
Projected Emittance (y-plane)	0.46 microns (rms)
Slice Emittance (x-plane)	0.39 microns (rms)
Bunch Length	697.6 microns (rms)
Gain Length	3.7 meters
Electron Energy Loss	6.4 MeV

Projected emittance at 1 nC

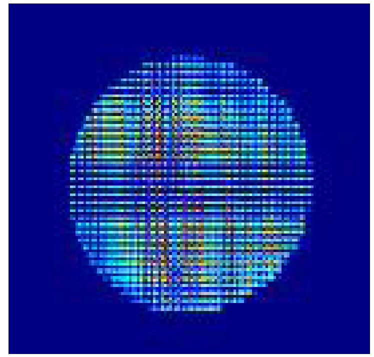


The Seven Laser Shapes

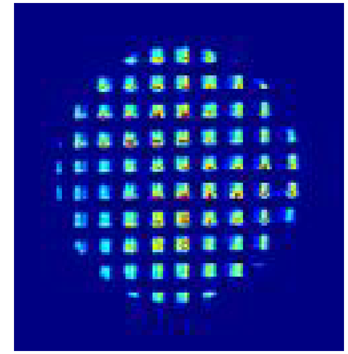
Nominal
1.2 mm dia.



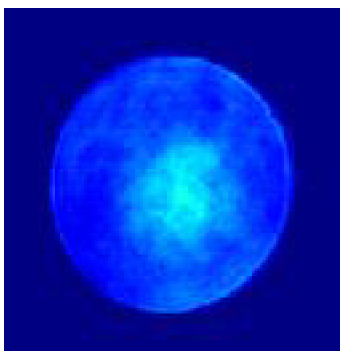
180 mesh
32 cycles per 1.2 mm
38 micron line spacing



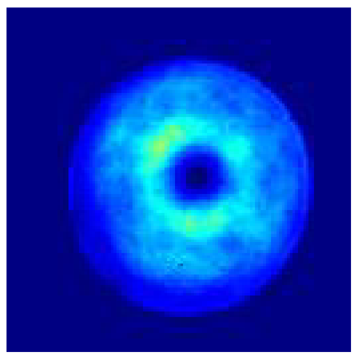
50 mesh
9 cycles per 1.2 mm dia.
133 micron line spacing



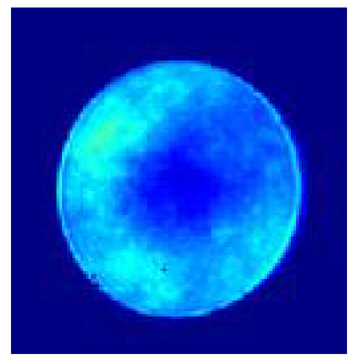
Gaussian



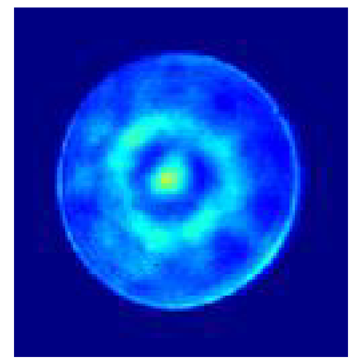
Bagel



Donut



Airy Diffraction

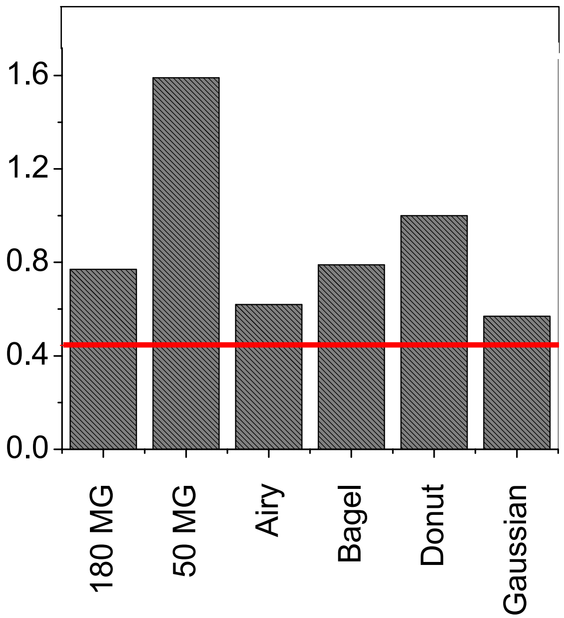


Measure for Each Shape:

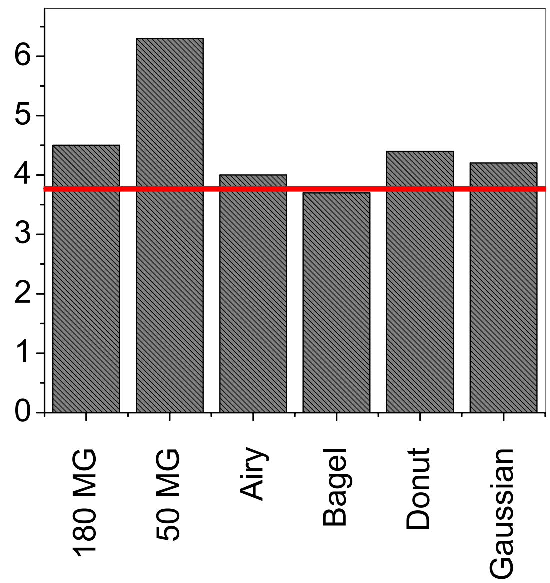
- Projected & Slice Emittance
- Gain Length
- FEL Extraction

Summary of Experimental Results

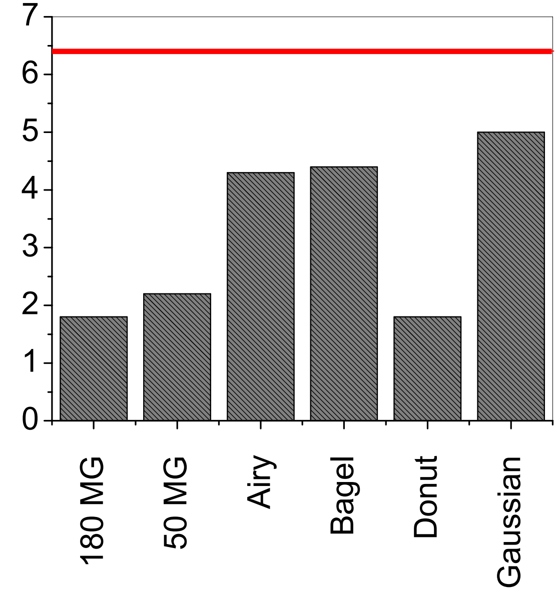
Projected Emittance at 135 MeV



Gain Length (m) at FEL wavelength 1.5 A



Energy Loss (MeV) of e-Beam After Lasing



Red lines indicate the nominal values

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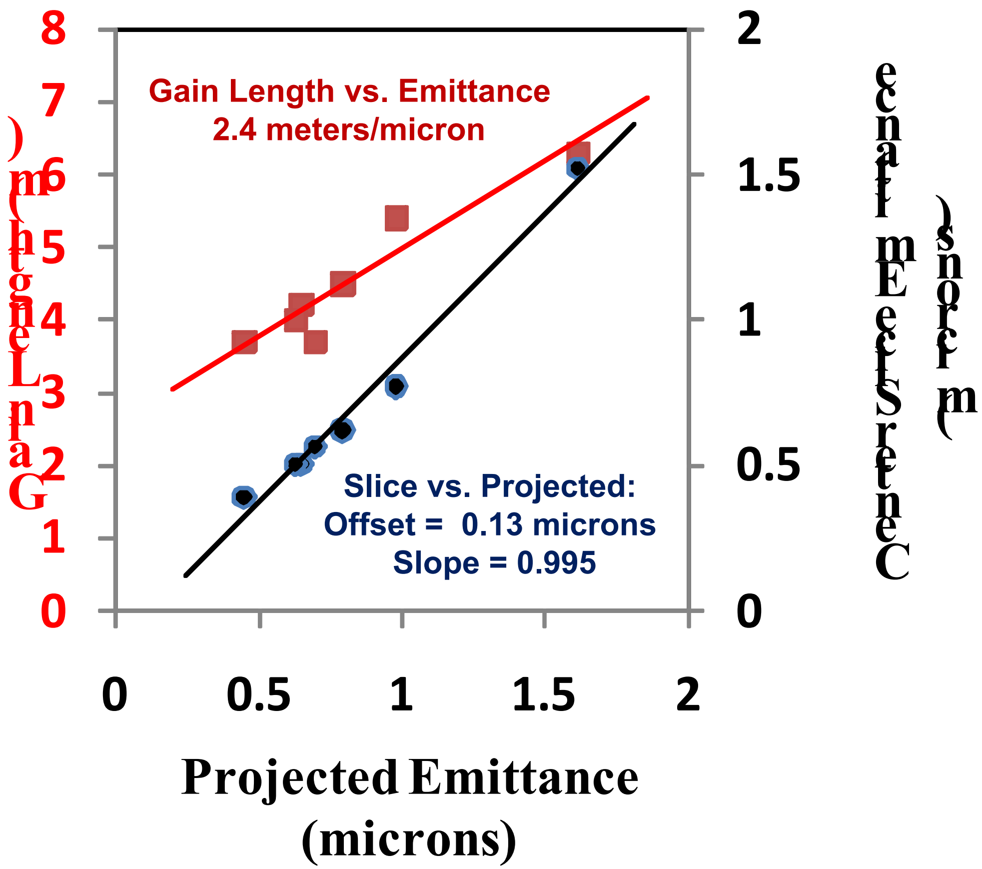
The Gain Length vs. Emittance

The emittances were measured at 250 pC and 135 MeV. The FEL gain lengths are for lasing at 1.5 Angstroms with an electron beam energy of 13.63 GeV.



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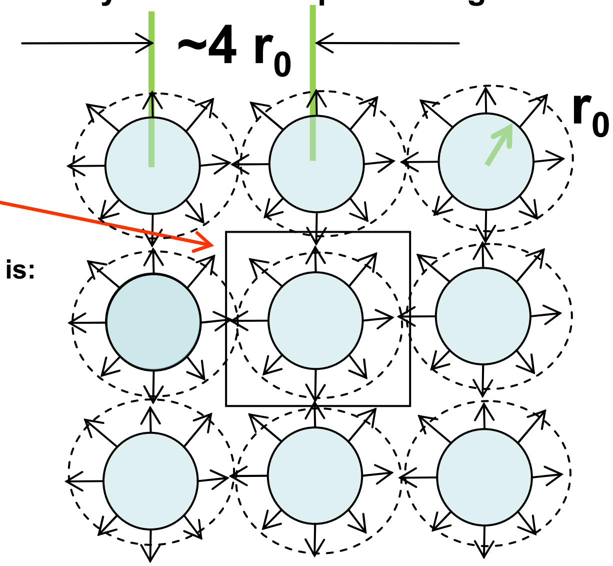
A Simple Model for the Emittance Growth

Basic Assumptions of Model

1. Charge is distributed in a regular array of tubes, beamlets.
2. Beamlets see radial space charge force until they overlap.
3. After overlapping the sc-force becomes small, the electrons are left with radial velocity which becomes emittance.

Beam consists of a rectangular array of beamlets, each driven outward by their radial space charge force



Area (cell) occupied by each beamlet is: $(4r_0)^2$

∴ Number of beamlets is:

$$N_b = \frac{\pi R^2}{16 r_0^2}$$

Radial electric field outside the tube/beamlet of charge:

$$E_r = \frac{\rho_l}{2\pi\varepsilon_0 r} \qquad \rho_l = \frac{Q}{N_b l_b} = \frac{16 r_0^2 Q}{\pi R^2 l_b}$$

$$E_r = \frac{8}{\pi^2}\frac{Q}{\varepsilon_0}\frac{r_0^2}{R^2 l_b r}$$

Integrate to get energy gain of electron at radial edge of beamlet:

$$\frac{p_r^2}{2m} = \frac{8Qr_0^2}{\pi^2\varepsilon_0 R^2 l_b}\int_{r_0}^{ar_0}\frac{dr}{r} = \frac{8Qr_0^2}{\pi^2\varepsilon_0 R^2 l_b}\ln a$$

Leap of faith: Assume $\langle p_x^2\rangle \approx \frac{p_r^2}{4}$

Then the emittance definition:

$$\varepsilon_n = \sigma_x \frac{\sqrt{\langle p_x^2\rangle}}{mc}$$

Gives the emittance due to the rectangular array of beamlets:

$$\Delta\varepsilon_n \propto \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{Q\ln a}{\varepsilon_0 m c^2 l_b}}$$

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Simple Model Compared to the Expt.

General parameters:

Laser Radius : $R = 0.6mm \Rightarrow \sigma_x = 0.3mm$

Bunch Charge : $Q = 250\,pC$

Bunch Length : $l_b = 6.6\,ps = 2mm$

Nominal Emittance : $\varepsilon_{nominal} = 0.45 microns$

$$\Delta\varepsilon_n \approx \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{Q\ln a}{\varepsilon_0 mc^2 l_b}}$$

$$\varepsilon_n = \sqrt{\Delta\varepsilon_n^2 + \varepsilon_{nominal}^2}$$

For 50 mesh pattern: $r_0 = 33\mu m$

$$\left.\frac{\Delta\varepsilon_n}{\sigma_x}\right|_{50mesh} = 5.8 microns/mm(rms)$$

$$\Delta\varepsilon_n\big|_{50mesh} = 1.7 microns$$

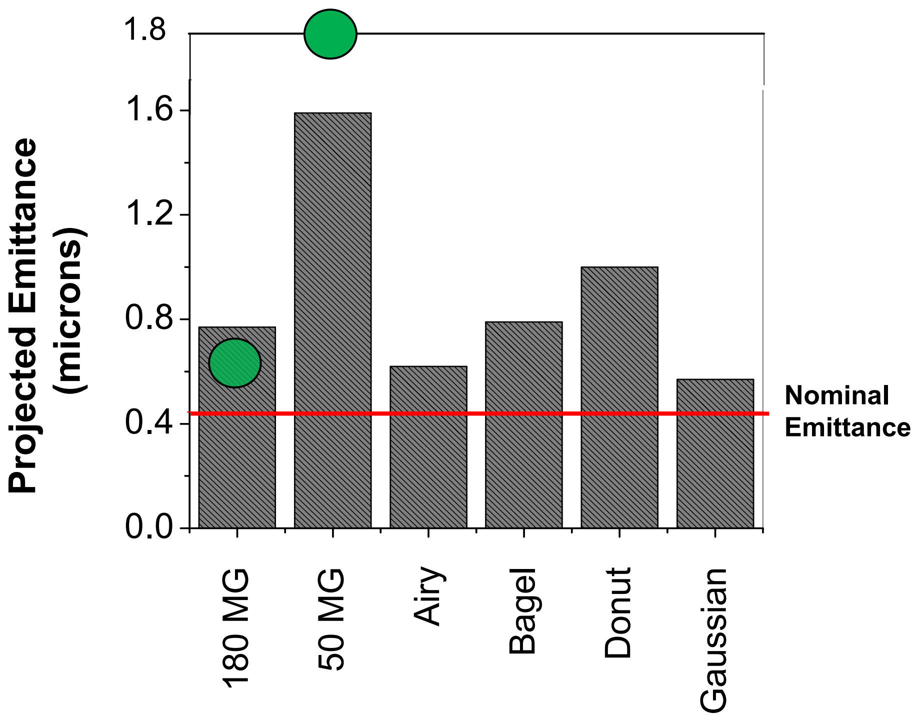
$$\varepsilon_n\big|_{50mesh} = \sqrt{1.7^2 + 0.45^2} = 1.8 microns$$

For 180 mesh, the emittance will be 180/50= 3.6 times smaller: $r_0 = 9\mu m$

$$\left.\frac{\Delta\varepsilon_n}{\sigma_x}\right|_{180mesh} = 1.6 microns/mm(rms)$$

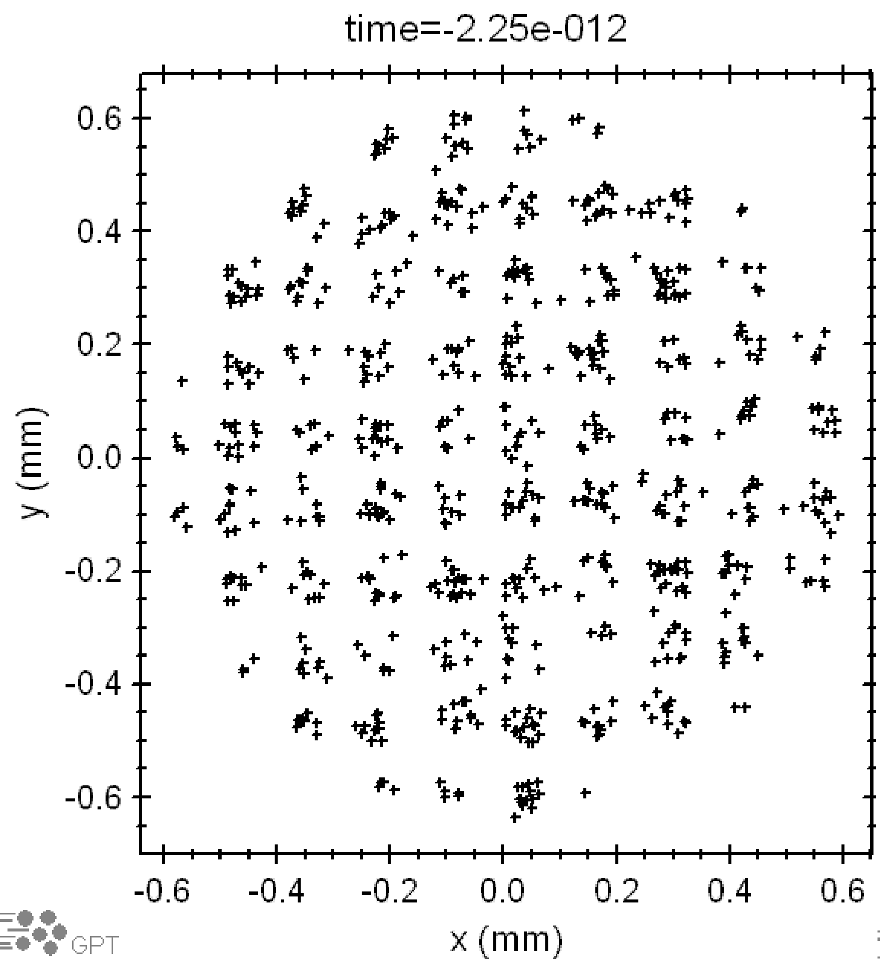
$$\Delta\varepsilon_n\big|_{180mesh} = 0.48 microns$$

$$\varepsilon\big|_{180mesh} = \sqrt{0.48^2 + 0.45^2} = 0.65 microns$$

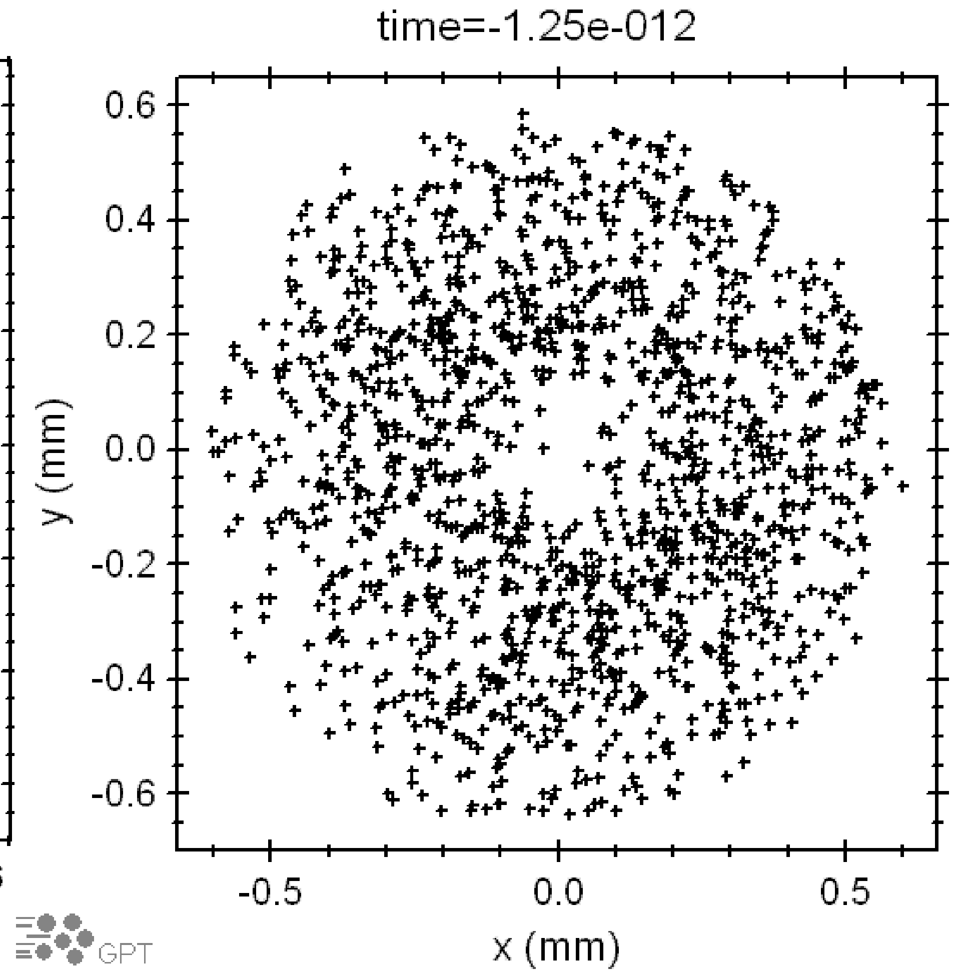


GPT Simulation Shows Beamlet Expansion in Early Life of the Beam

50 Mesh Laser Shape



Bagel Laser Shape



GPT: General Particle Tracer, Pulsar Physics, www.pulsar.nl

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Summary and Conclusions

- *Measured Emittance and FEL Performance at 1.5 A for rectangular grid and radial symmetric laser transverse shapes.*
- *Found most uniform shape gives the lowest emittance and shortest gain length.*
- *Derived model for emittance growth based on radial expansion of beamlets driven by space charge force.*
- *Using this model, derived relation for emittance due to regular rectangular pattern. Reasonable agreement with measurements.*
- *Model can be extended to other radial shapes.*
- *Comparison with GPT simulation indicates most growth occurs during expansion during ~10s of ps.*
- *Particle tracking simulations using GPT are in progress.*