Emission Modeling for PITZ

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Introduction

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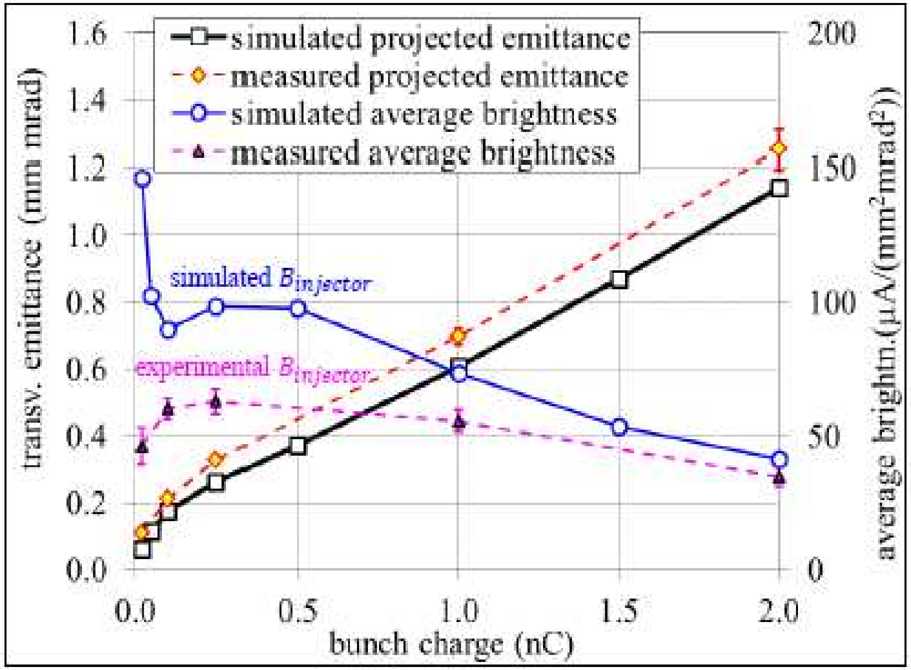
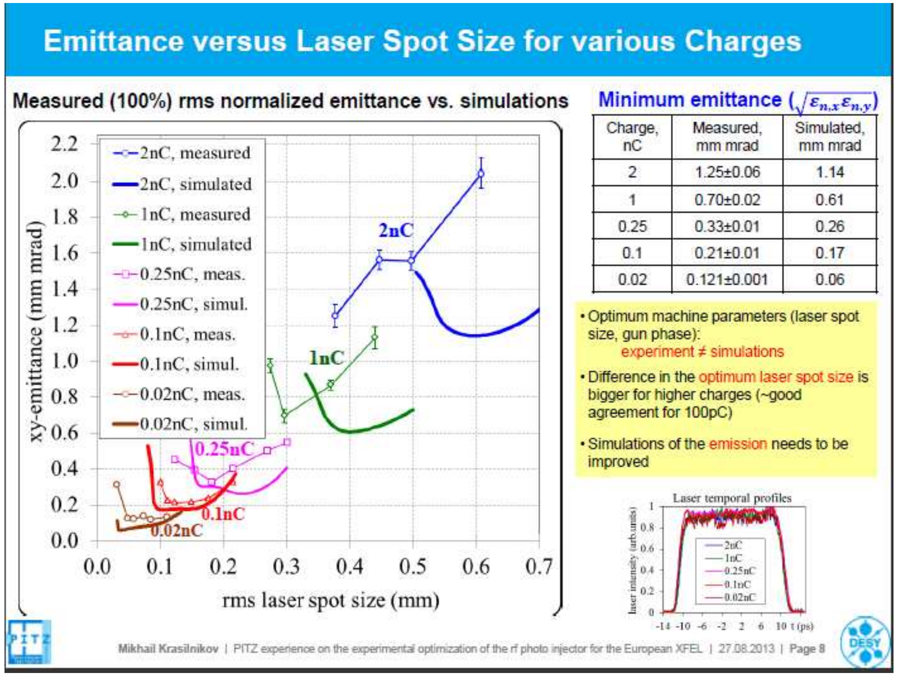
- Large differences are found between measurement and simulation - optimum emittance vs. spot size, spch limit, …
- Find source of discrepancy on simulation side

M. Krasilnikov, FEL 2013




Emittance versus Laser Spot Size for various Charges

Measured (100%) rms normalized emittance vs. simulations

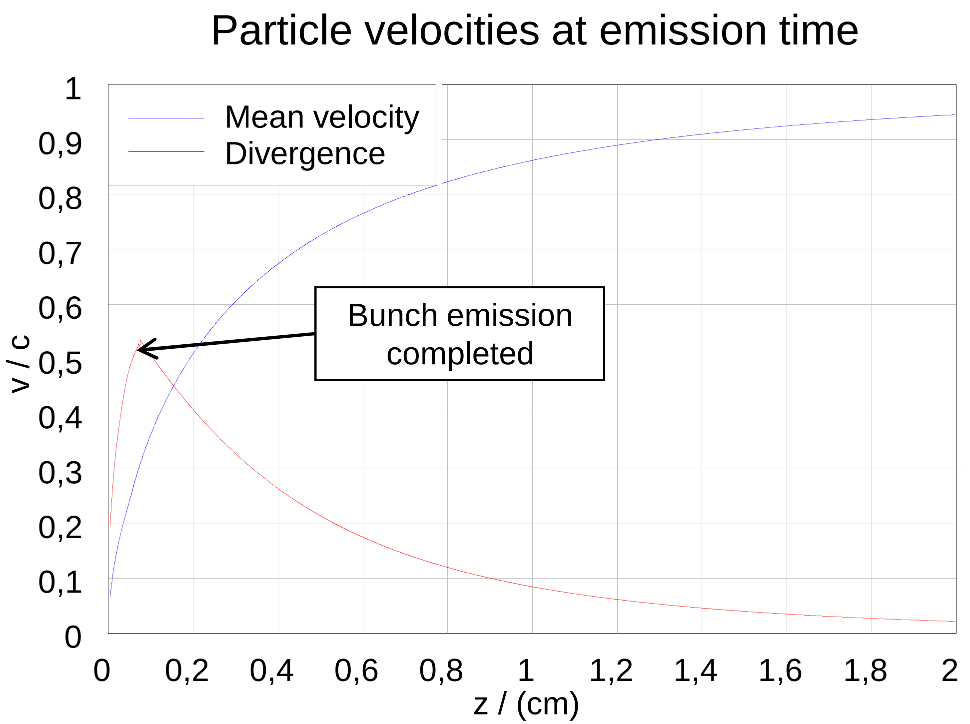
Minimum emittance ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$)

Charge, nC	Measured, mm mrad	Simulated, mm mrad
2	1.25±0.06	1.14
1	0.70±0.02	0.61
0.25	0.33±0.01	0.26
0.1	0.21±0.01	0.17
0.02	0.121±0.001	0.06

- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission needs to be improved

Introduction

- Hypothesis 1: problems originate at the cathode / gun
- Hypothesis 2: beam dynamics at emission time not properly modeled



Inertial frame codes (Astra, Parmela, …)

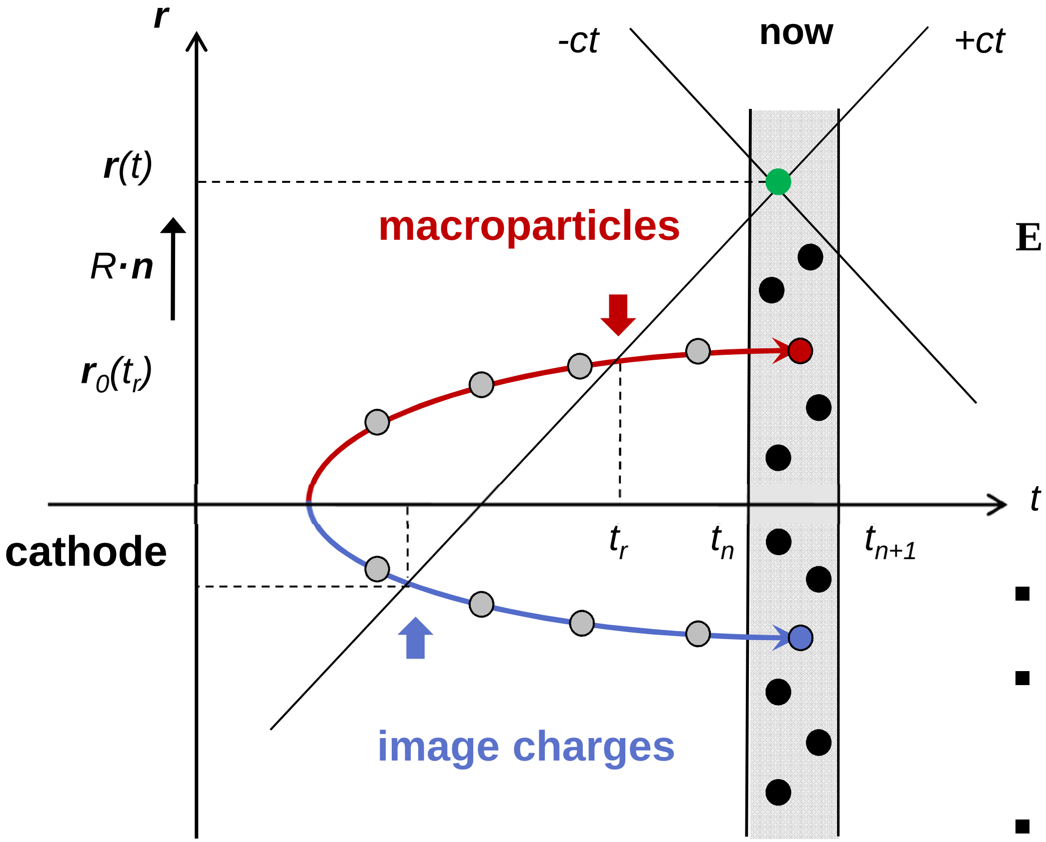
- Relative particle motion neglected
- Retardation effects (partially) omitted
- No acceleration radiation

Full EM simulations

- Particle-Particle (PP) codes
- Particle-In-Cell (PIC) codes

Introduction

- Lienard-Wiechert PP



acceleration radiation

$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0}\left[\frac{(\mathbf{n}-\boldsymbol{\beta})\left(1-|\boldsymbol{\beta}|^2\right)}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2} + \frac{\mathbf{n}\times(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{t=t_r}$$

Lorentz contraction

retardation

- Store full history of trajectories
- Search retarded interaction point for every particle-particle pair
- Scaling: $N^2 \, x \, \Delta t^2$

Introduction

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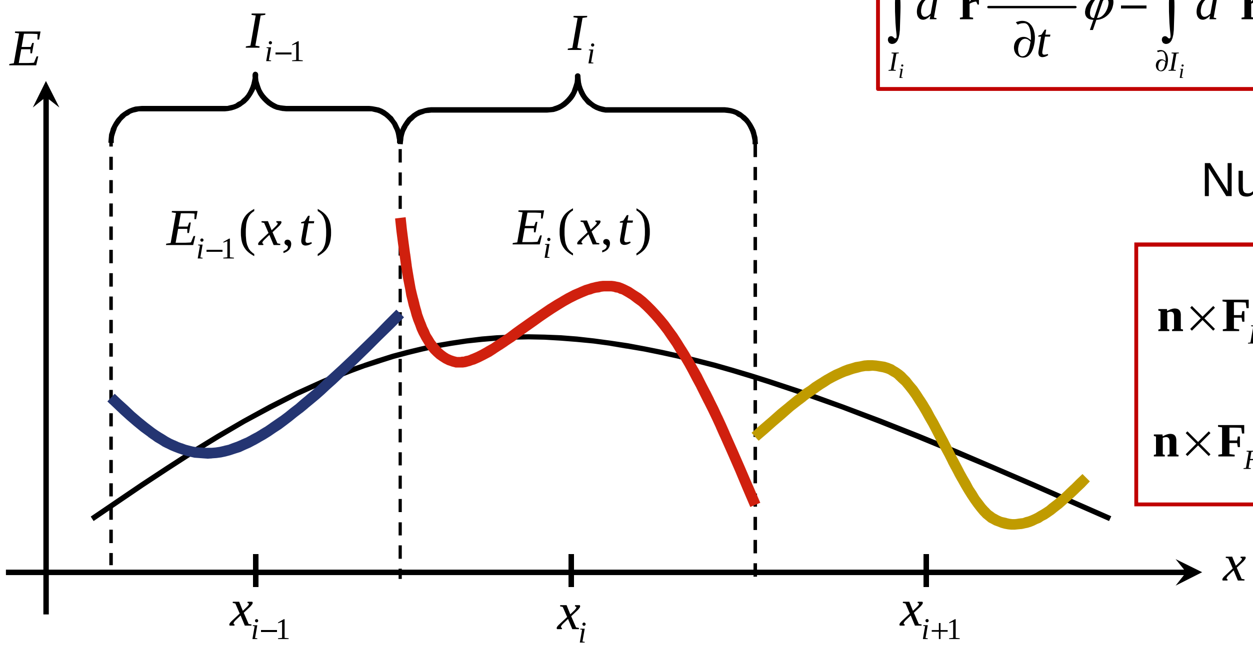
- Dicontinuous Galerkin (DG) PIC

FEM-like field approximation on grid with high order basis functions



Weak form of Ampere's law

$$\int_{I_i} d^3\mathbf{r}\,\frac{\partial \varepsilon \overline{\mathbf{E}}}{\partial t}\varphi - \int_{\partial I_i} d^2\mathbf{r}\,(\mathbf{n}\times\mathbf{F}_H)\,\varphi + \int_{I_i} d^3\mathbf{r}\,(\nabla\varphi)\times\overline{\mathbf{H}} = 0$$

Numerical interface fluxes

$$\mathbf{n}\times\mathbf{F}_E = \frac{1}{2}\mathbf{n}\times\left[\overline{\mathbf{E}}(\mathbf{r}^-,t)+\overline{\mathbf{E}}(\mathbf{r}^+,t)\right],$$

$$\mathbf{n}\times\mathbf{F}_H = \frac{1}{2}\mathbf{n}\times\left[\overline{\mathbf{H}}(\mathbf{r}^-,t)+\overline{\mathbf{H}}(\mathbf{r}^+,t)\right]$$

Introduction

- Dicontinuous Galerkin (DG) PIC

Current density approximation

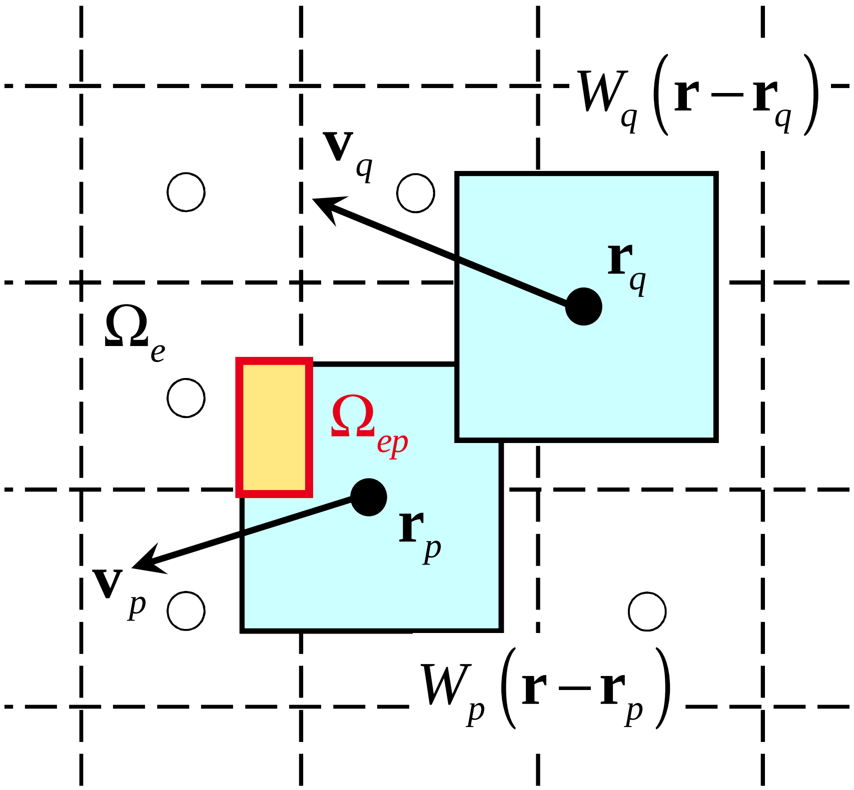
$$\mathbf{j}(\mathbf{r},t) = \sum_p Q_p \mathbf{v}_p(t) W_p\left[\mathbf{r} - \mathbf{r}_p(t)\right]$$

Grid projection

$$\mathbf{j}_i^e(t) = \sum_p Q_p \mathbf{v}_p(t) \int_{\Omega_{ep}(t)} d^3\mathbf{r}\, W_p(\mathbf{r},t)\varphi_i^e(\mathbf{r})$$

Total grid current / time step

$$\mathbf{J}_i^e(t^n, t^{n+1}) = \int_{t^n}^{t^{n+1}} dt\, \mathbf{j}_i^e(t)$$



SPCH Simulations in the Gun

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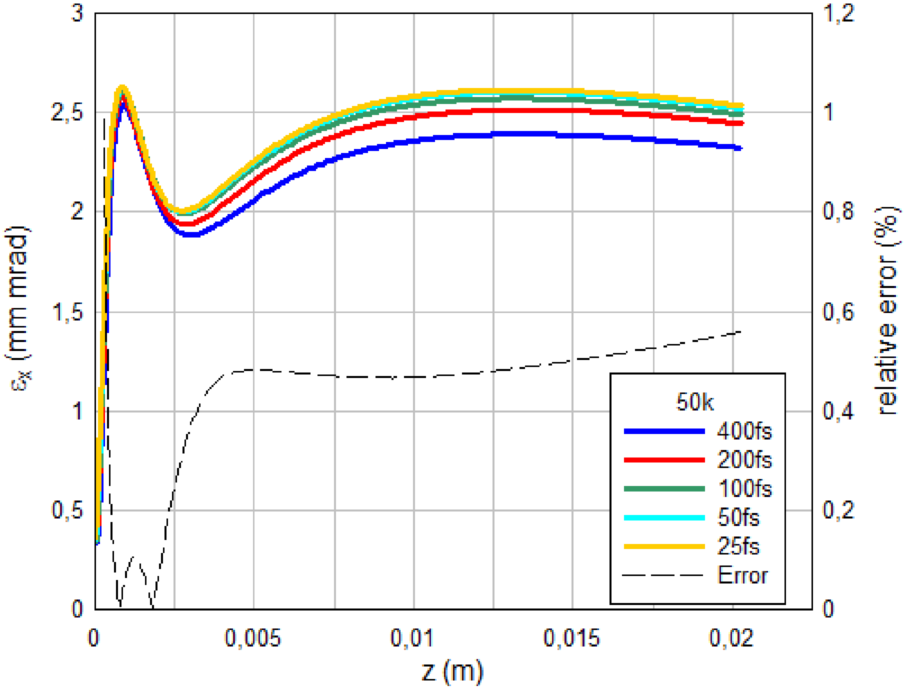
- Beam dynamics over short distance (up to 2cm behind cathode)
  - Sufficient to observe possible issues at emission time
  - Analyze numerical convergence
  - Identify numerical parameters for full-scale simulations
  - Perform comparison between different approaches
  - Estimate space charge limits

  - 3D-simulations throughout the following (except for Astra)
  - Nom. parameters/ PITZ-1.8: Q = 1nC, FWHM: 20/2 ps, XY_rms = 0.4mm, …

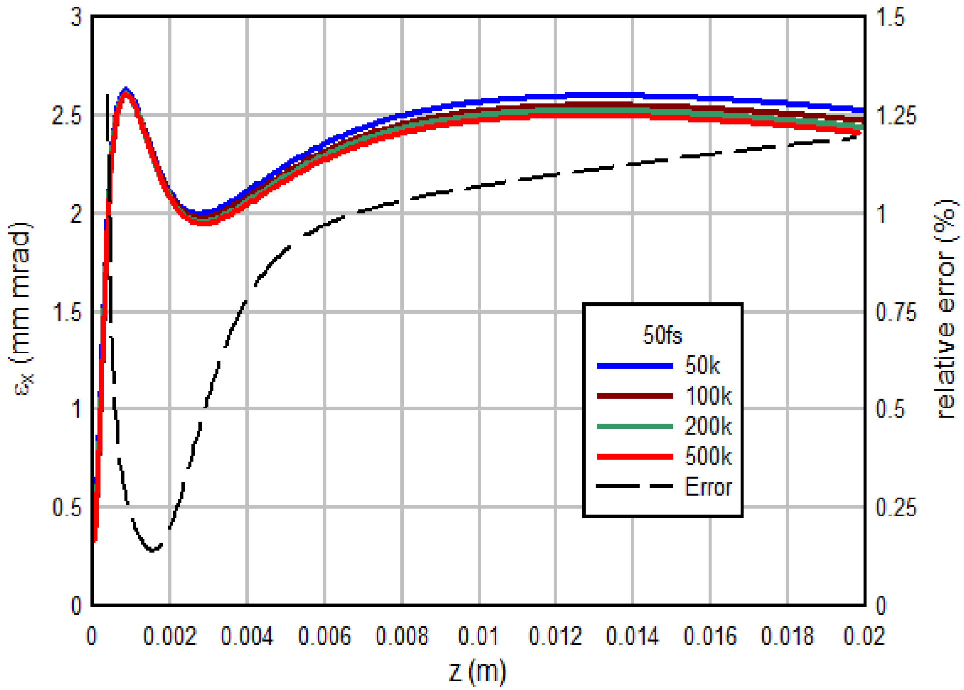
SPCH Simulations in the Gun

- LW-PP convergence

wrt. time step



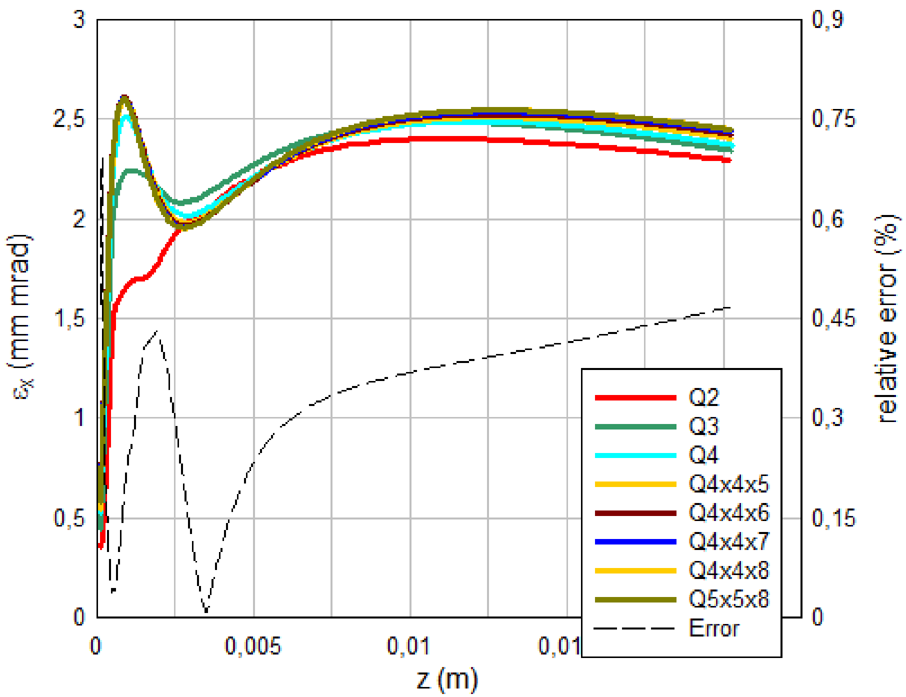
wrt. number of particles



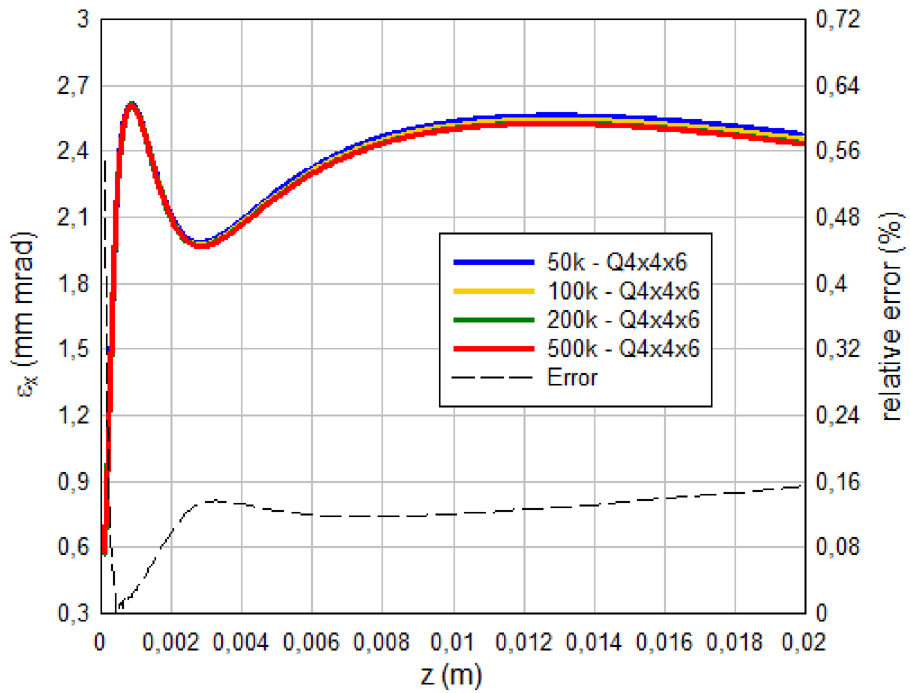
SPCH Simulations in the Gun

- DG-PIC convergence

wrt. approximation order

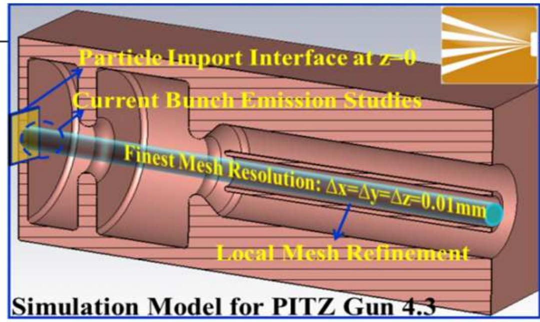


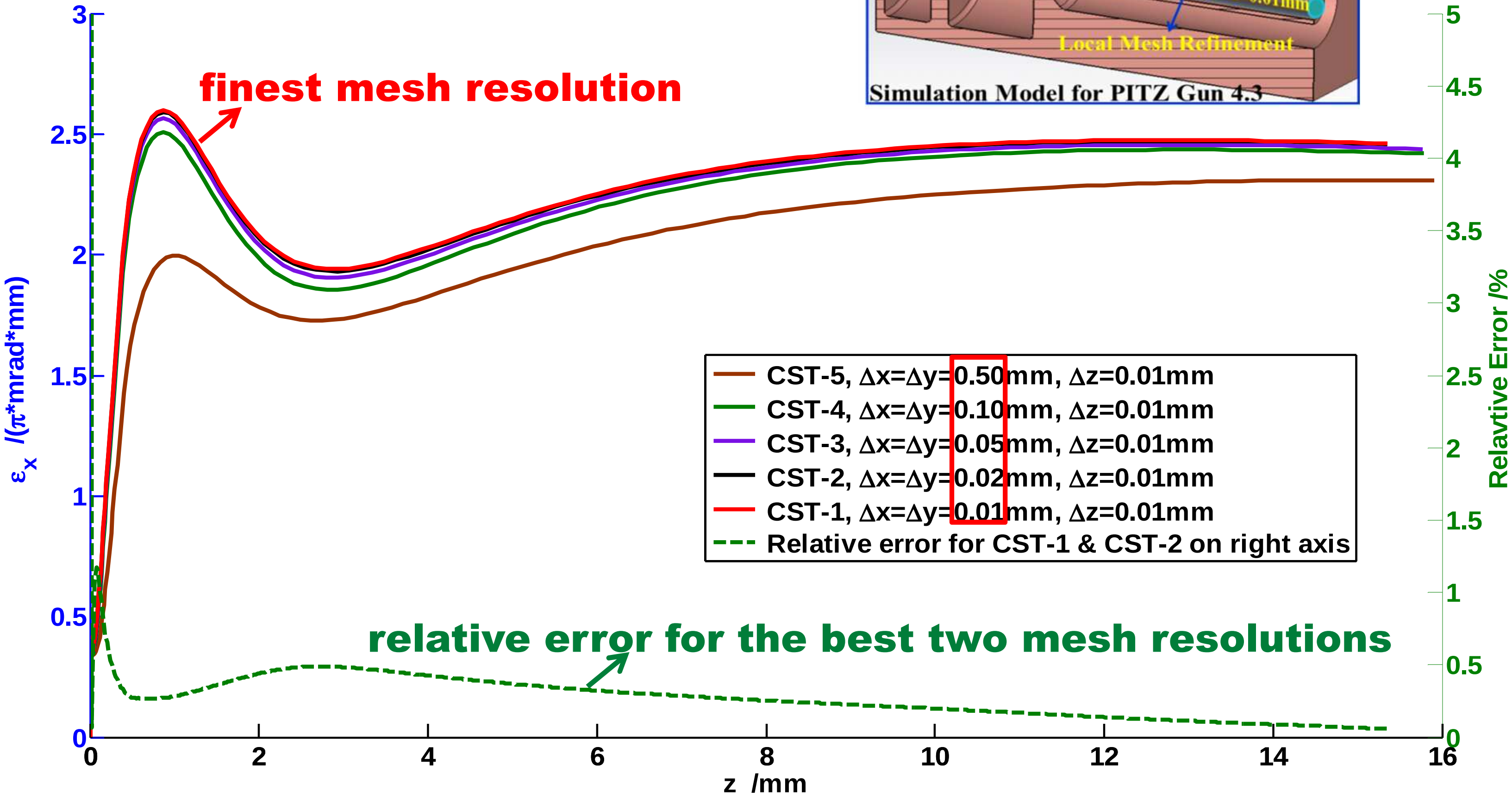
wrt. number of particles



SPCH Simulations in the Gun

- CST PS (PIC) convergence

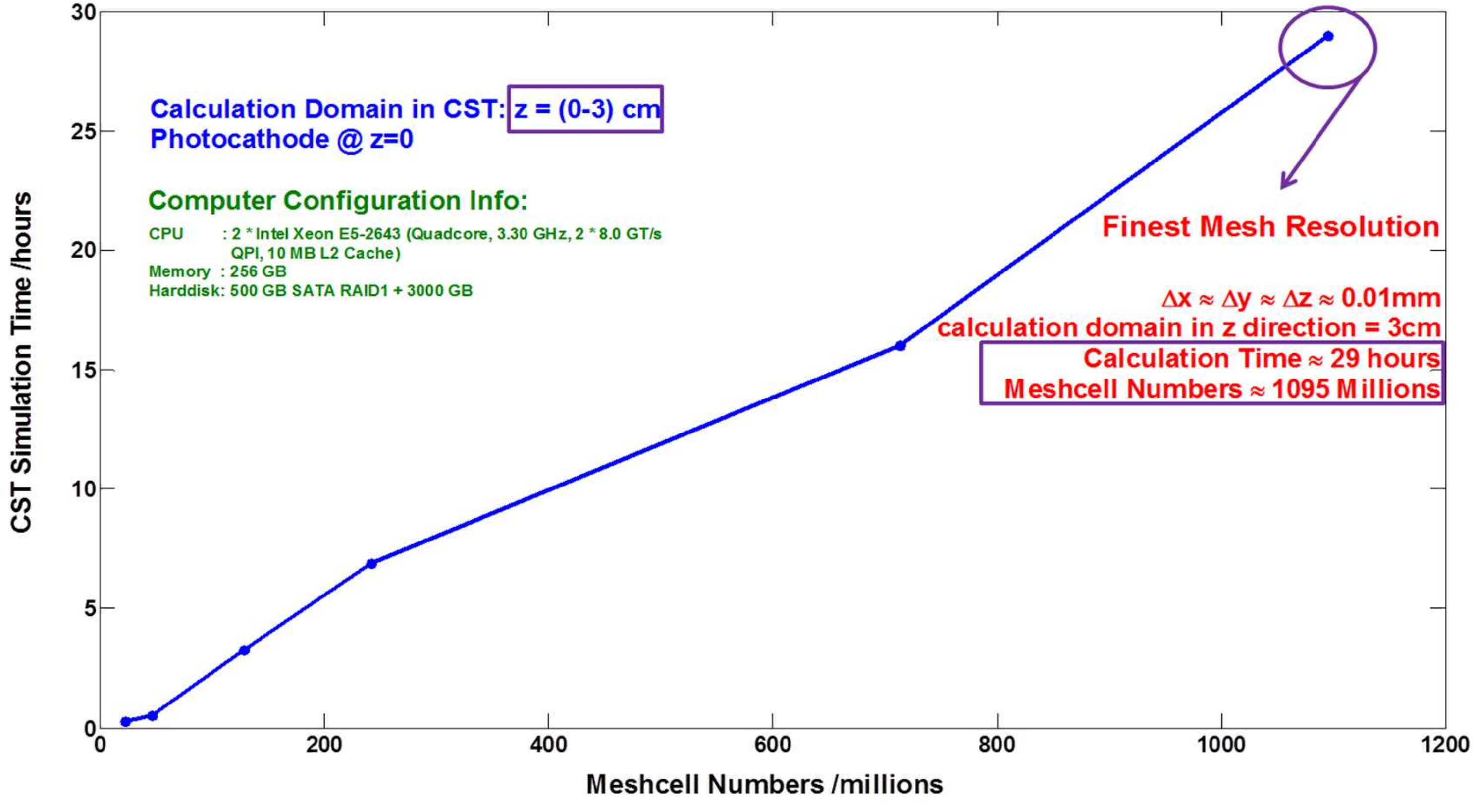




SPCH Simulations in the Gun

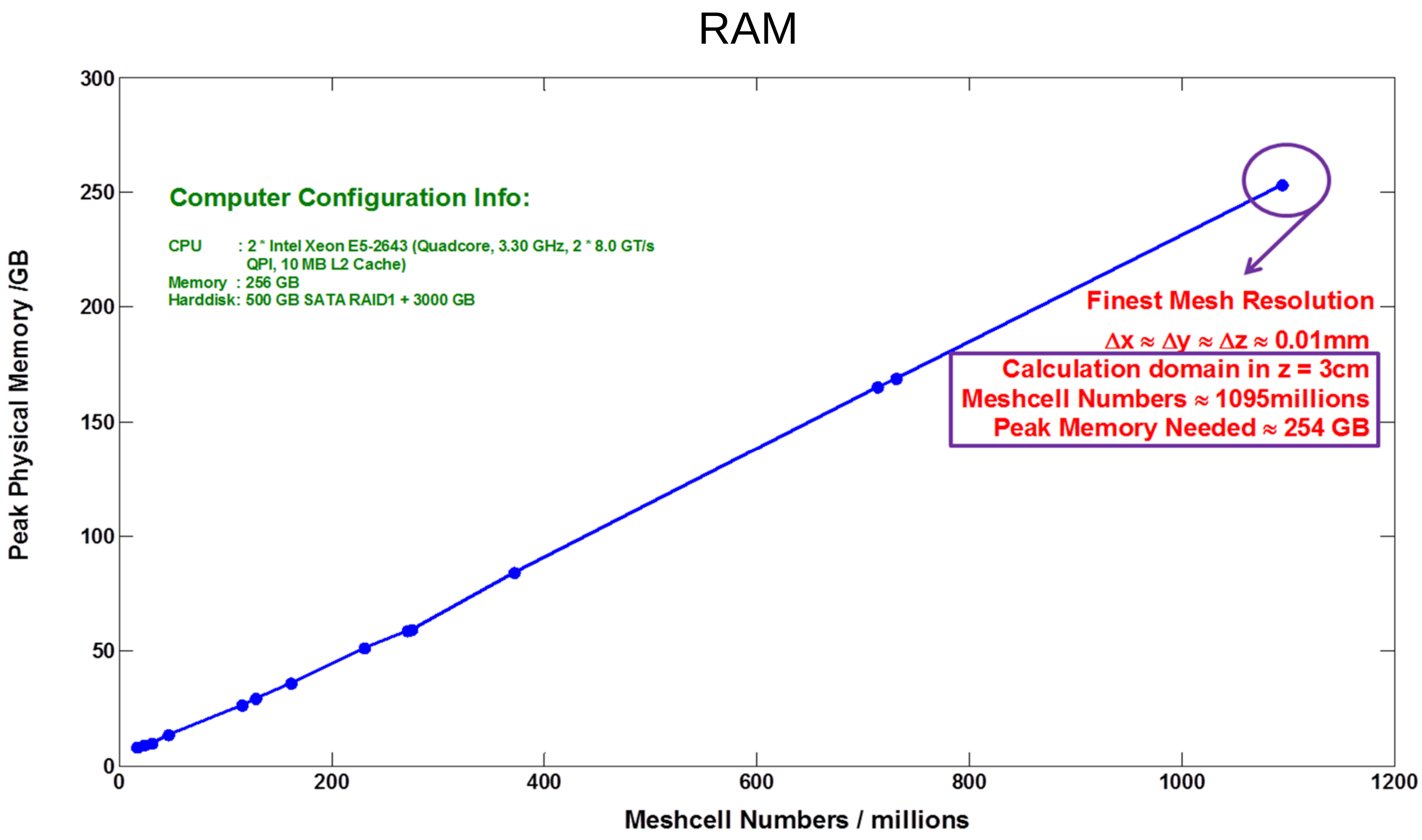
▪ CST PS (PIC) performance

CPU time



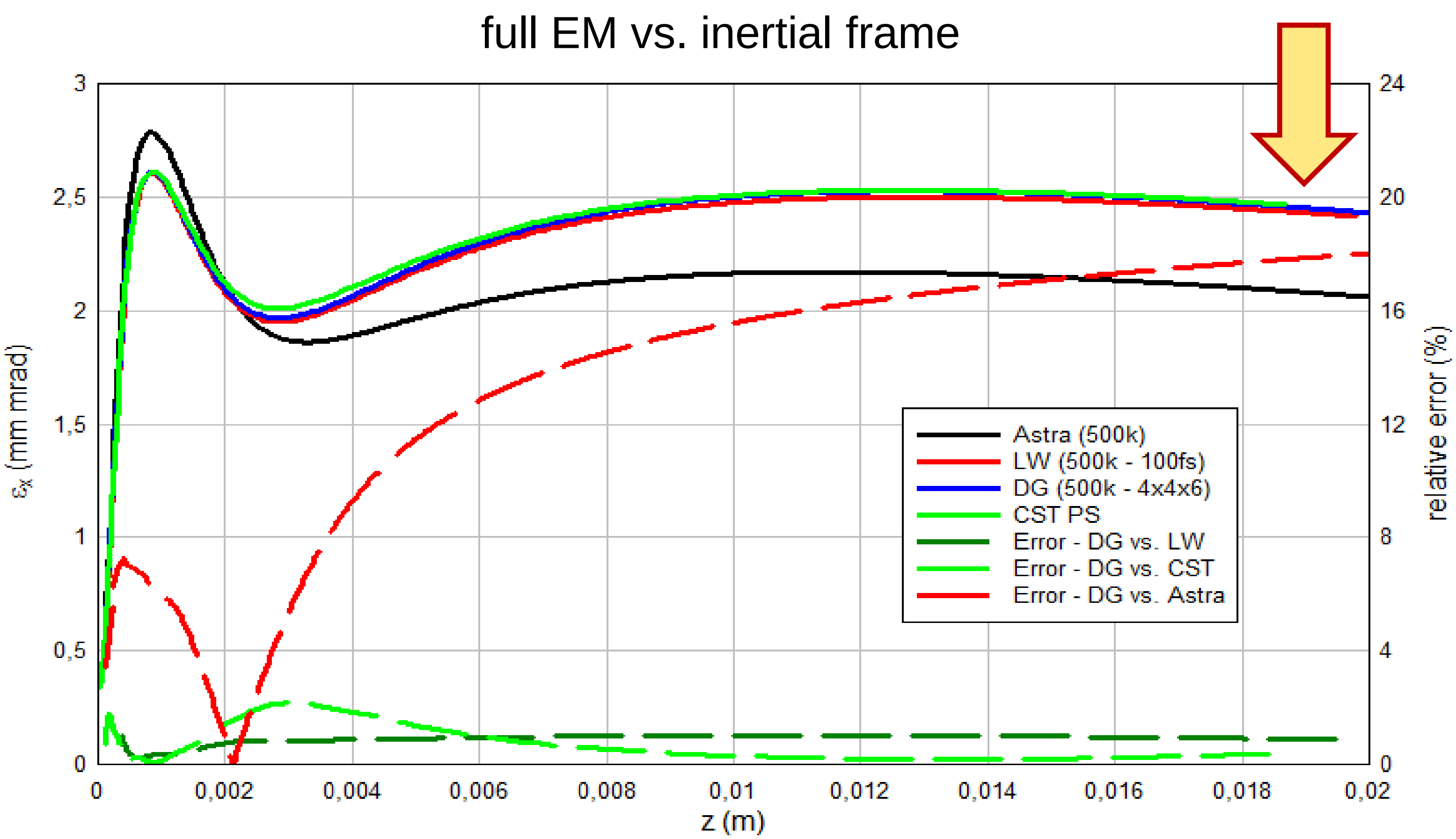
SPCH Simulations in the Gun

- CST PS (PIC) performance



SPCH Simulations in the Gun

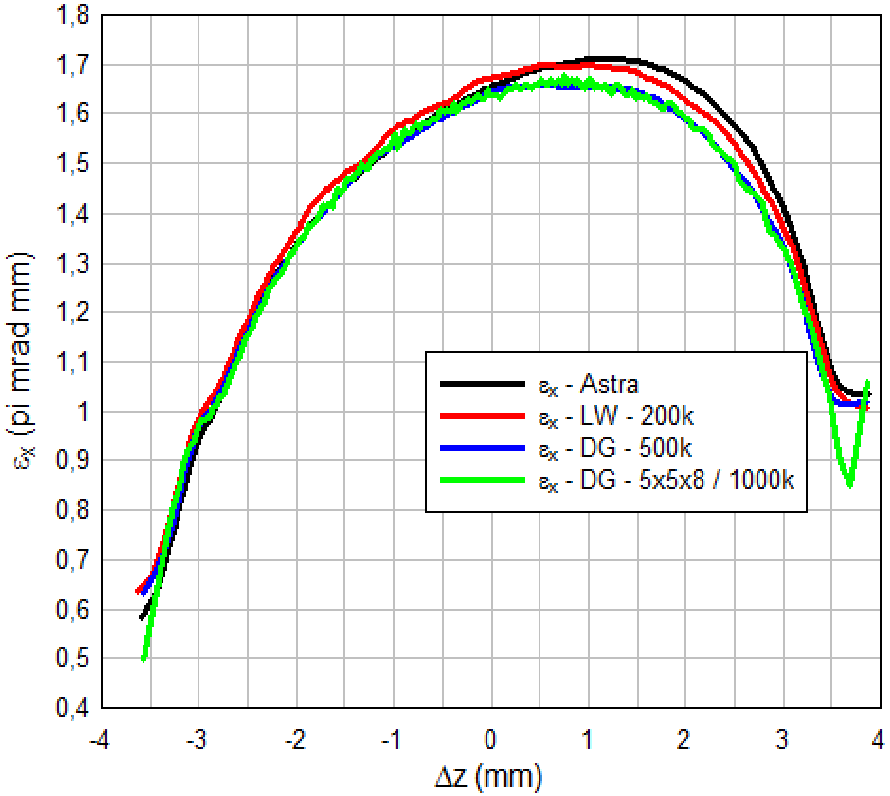
- Comparison



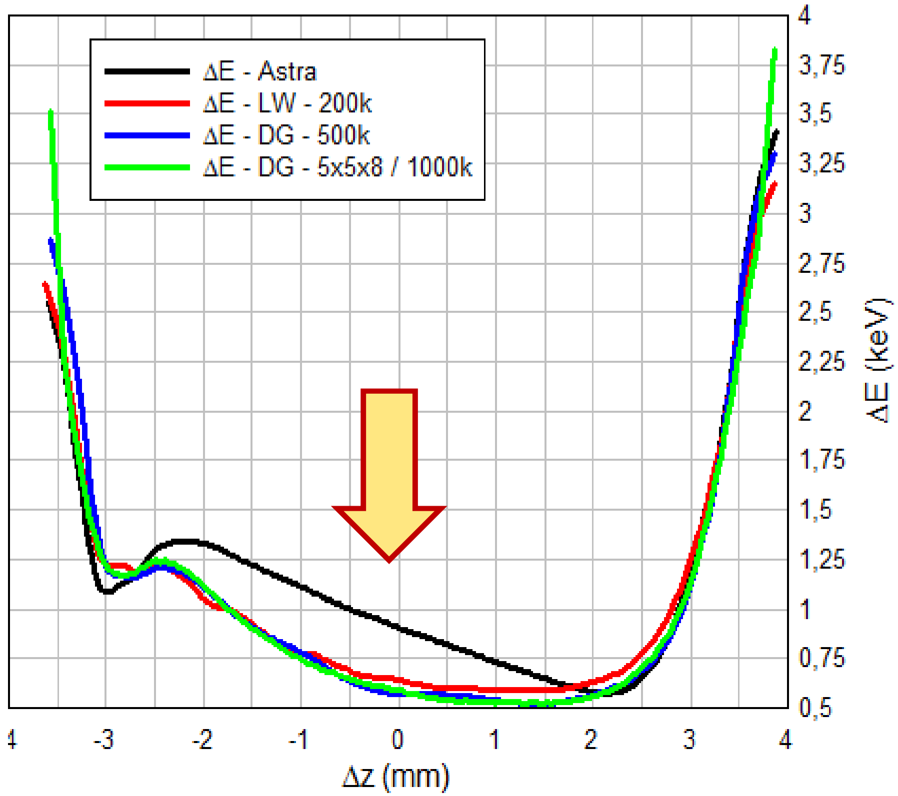
SPCH Simulations in the Gun

- Comparison

slice emittance (@ 2cm)



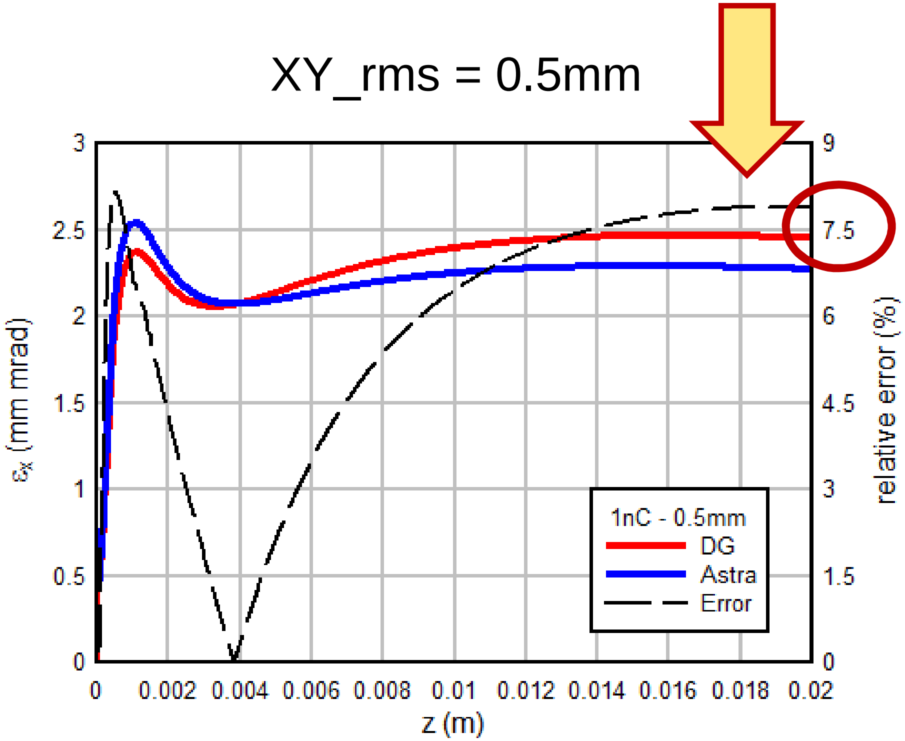
slice energy spread (@ 2cm)



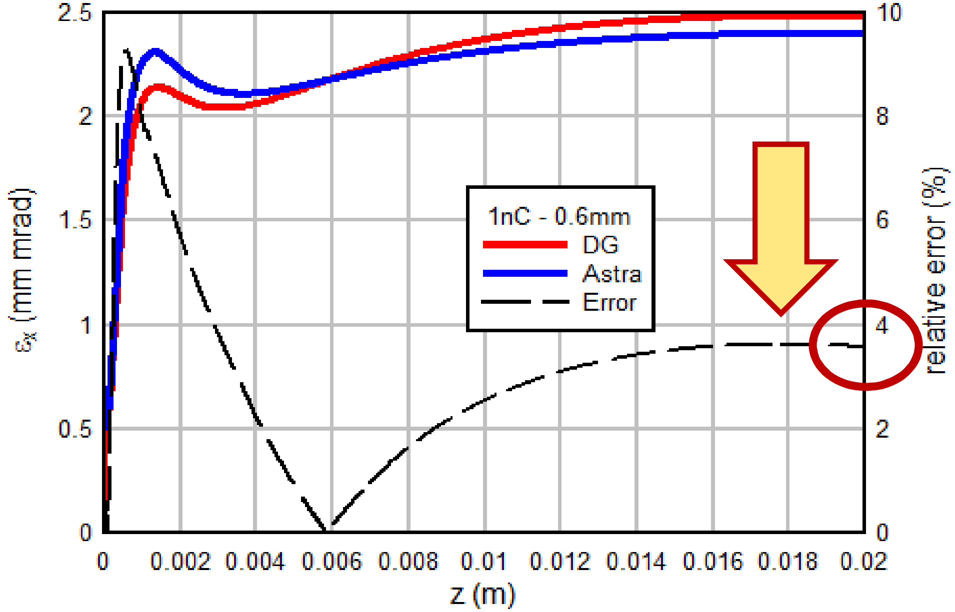
SPCH Simulations in the Gun

- Comparison for other bunches (Q = 1nC)

XY_rms = 0.5mm



XY_rms = 0.6mm



SPCH Simulations in the Gun

- Origin of discrepancy

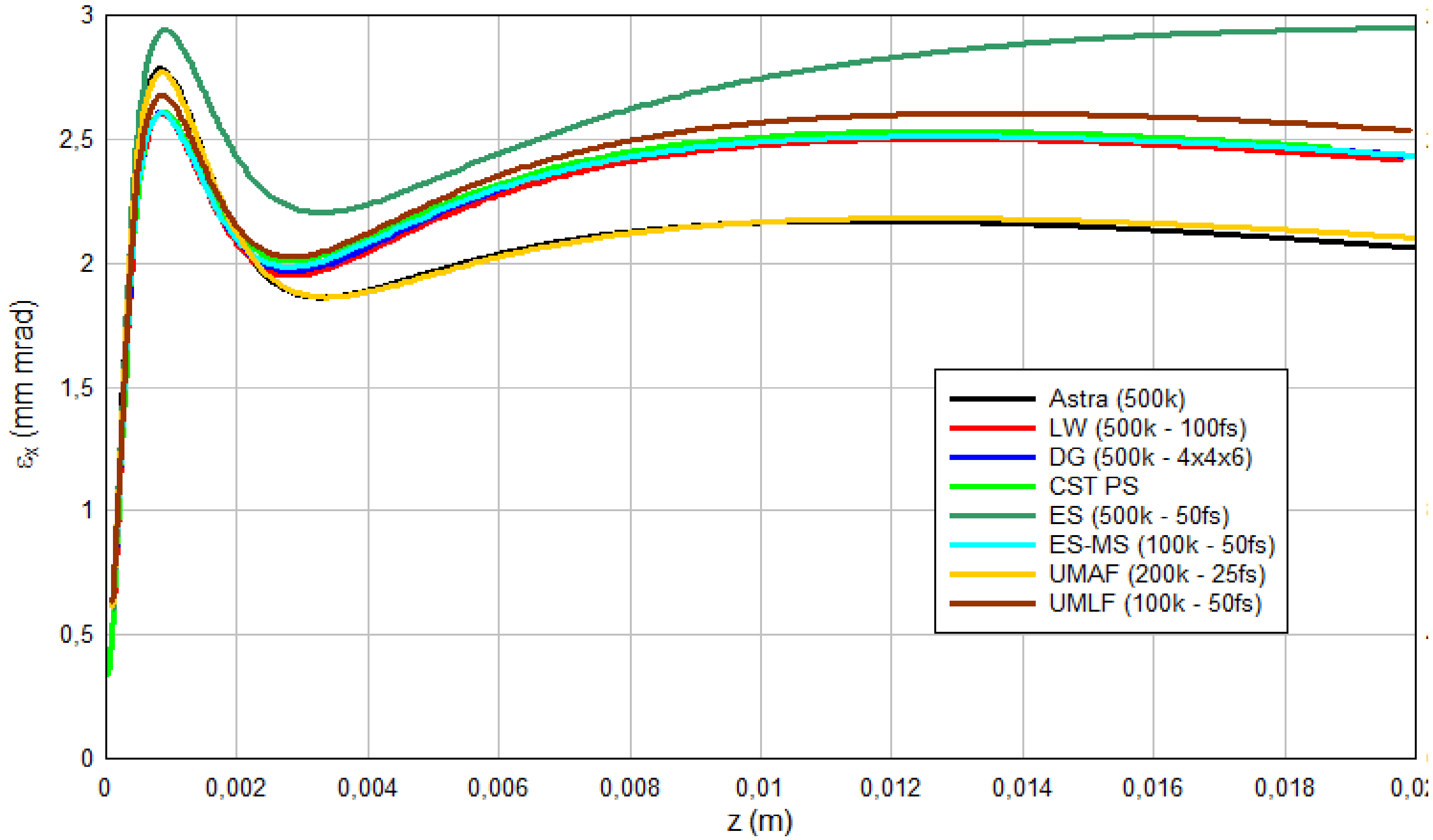
$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0}\left[\frac{(\mathbf{n}-\boldsymbol{\beta})\left(1-|\boldsymbol{\beta}|^2\right)}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2} + \frac{\mathbf{n}\times(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]\Bigg|_{t=t_r} , \quad \mathbf{B} = \frac{1}{c}\mathbf{n}\times\mathbf{E}\Big|_{t=t_r}$$

single particle fields

Hierarchy of approximations		retardation	contraction	radiation	relative motion
$\beta = 0$	E-statics (ES)	$-$	$-$	$-$	$-$
$\beta^2 \ll 1$	E-statics / B-statics (ES-MS)	$-$	$-$	$-$	$+$
$\beta = \text{const.}$	bunch in uniform motion / average frame (UMAF)	$\mp$	$\mp$	$-$	$-$
$\frac{\partial \beta}{\partial t} = 0$	individual particles in uniform motion / local frame (UMLF)	$\mp$	$\mp$	$-$	$+$

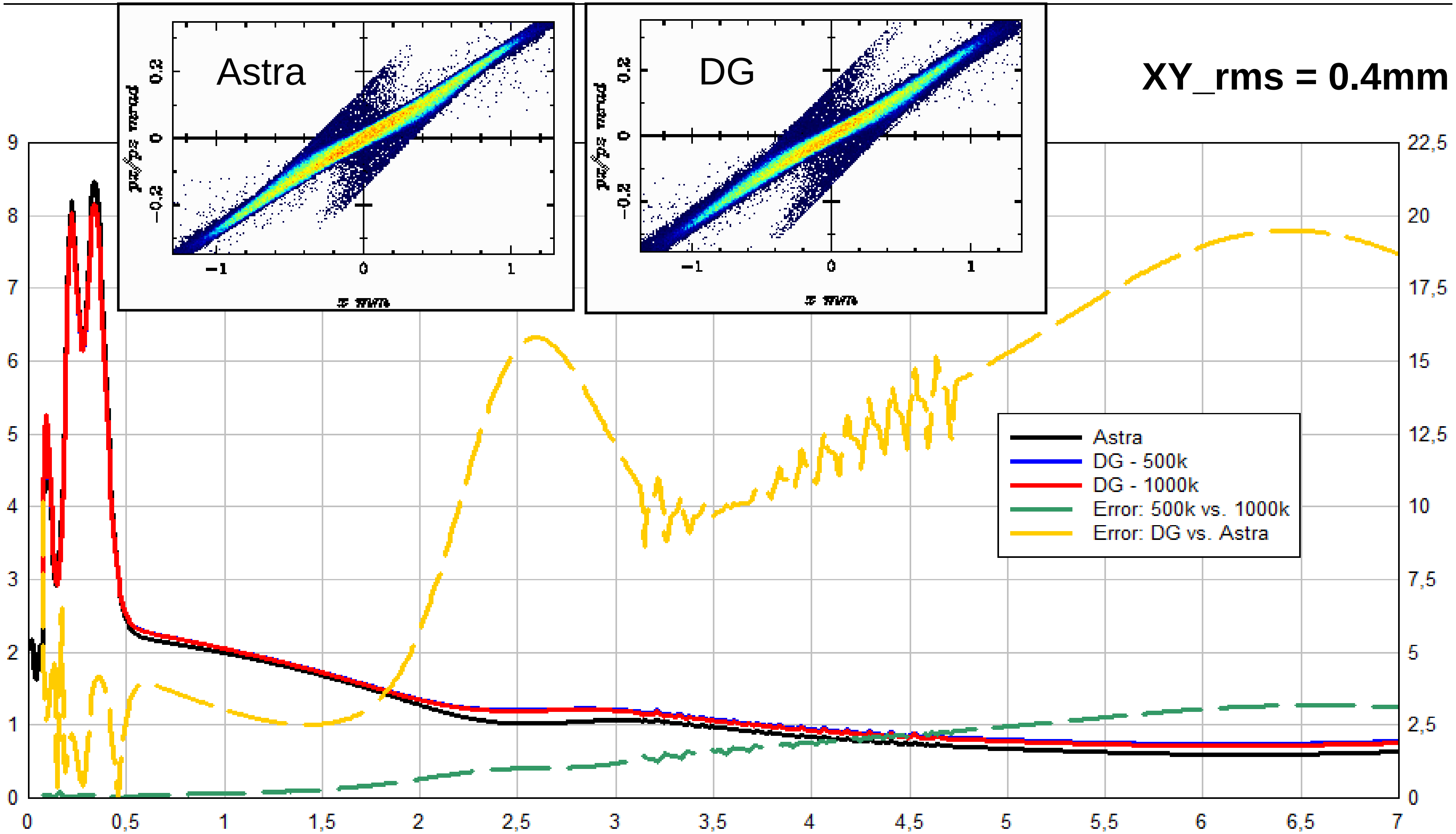
SPCH Simulations in the Gun

- Origin of discrepancy

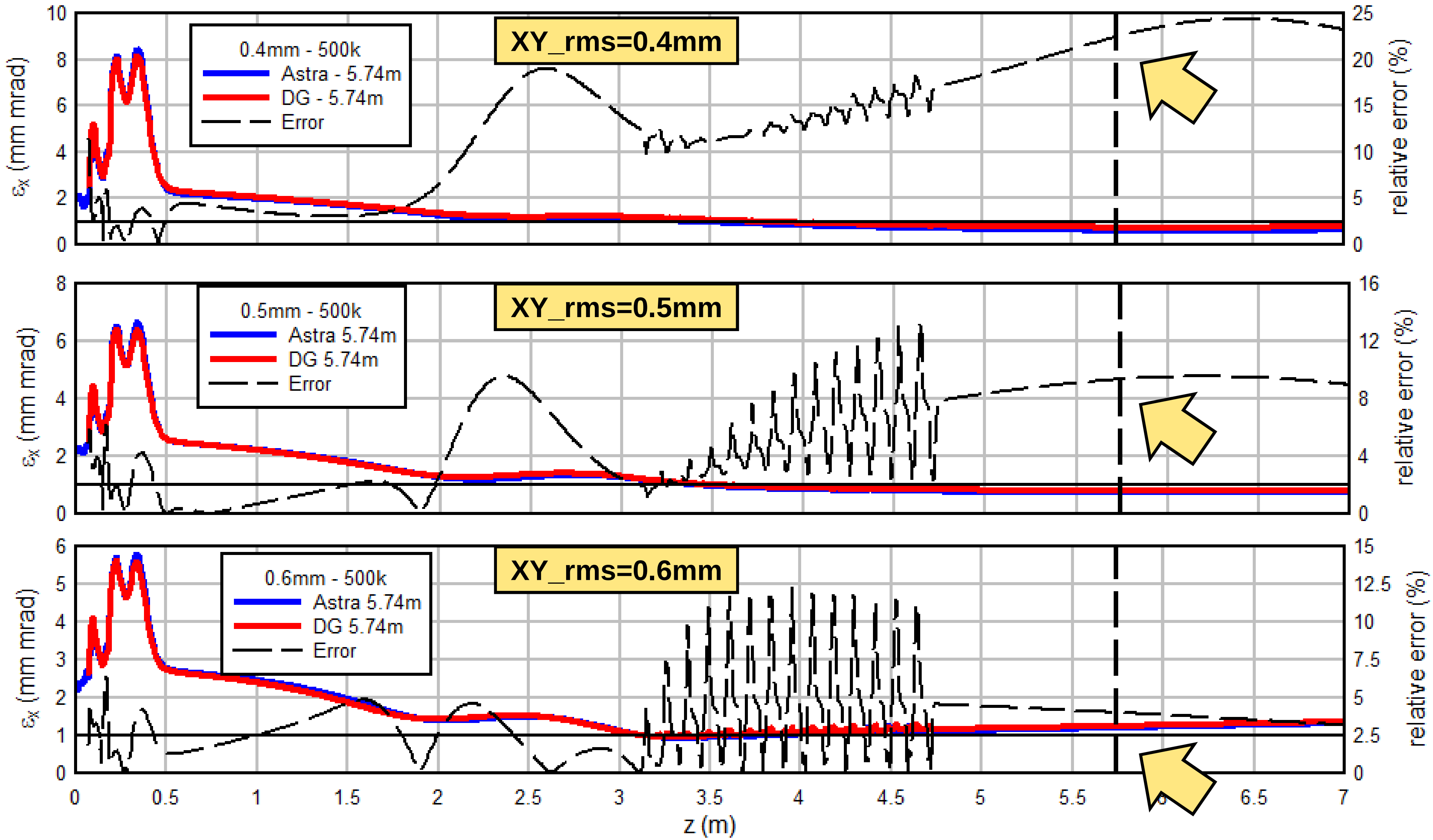


Emittance at EMSY1

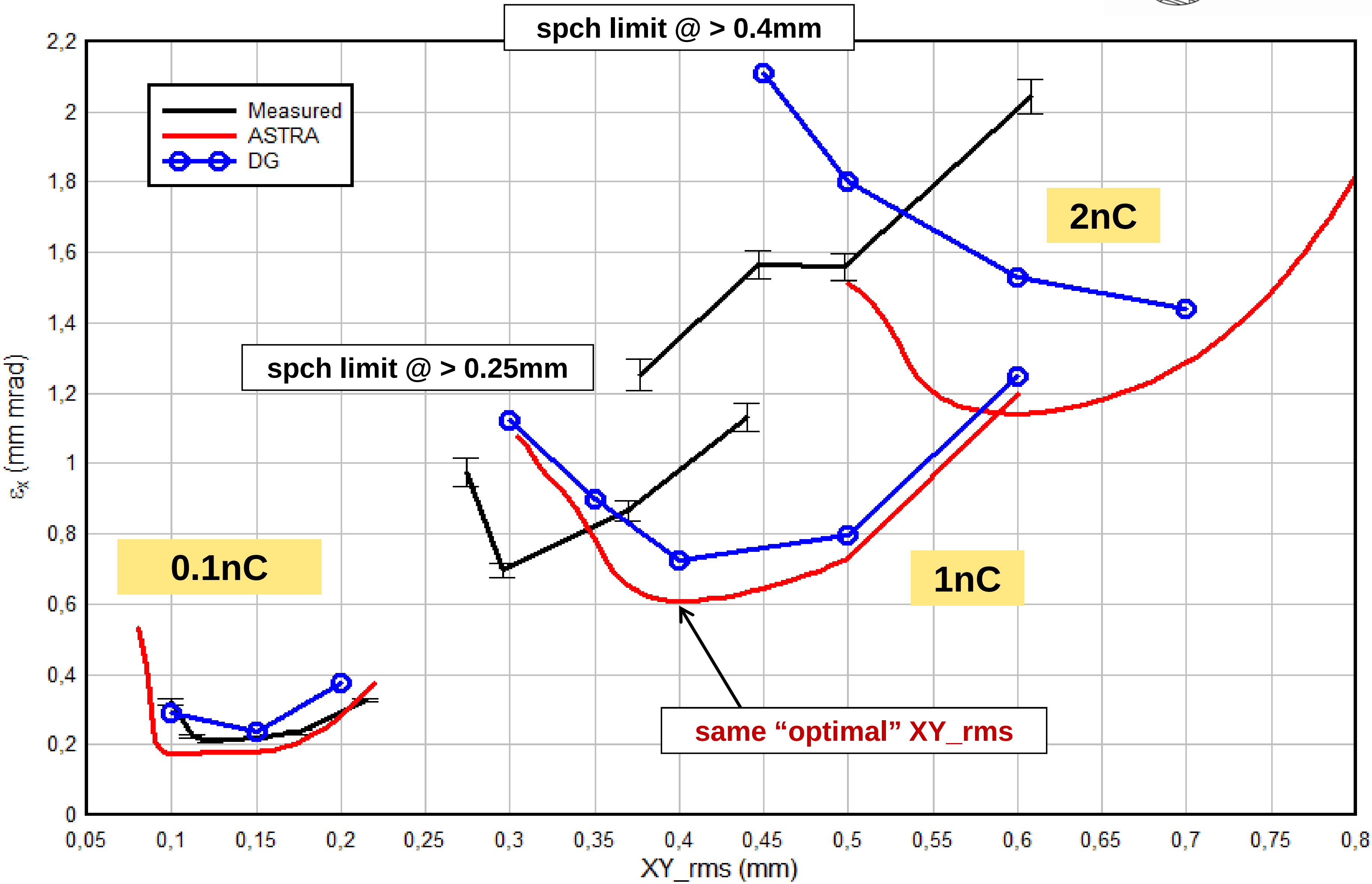
XY_rms = 0.4mm



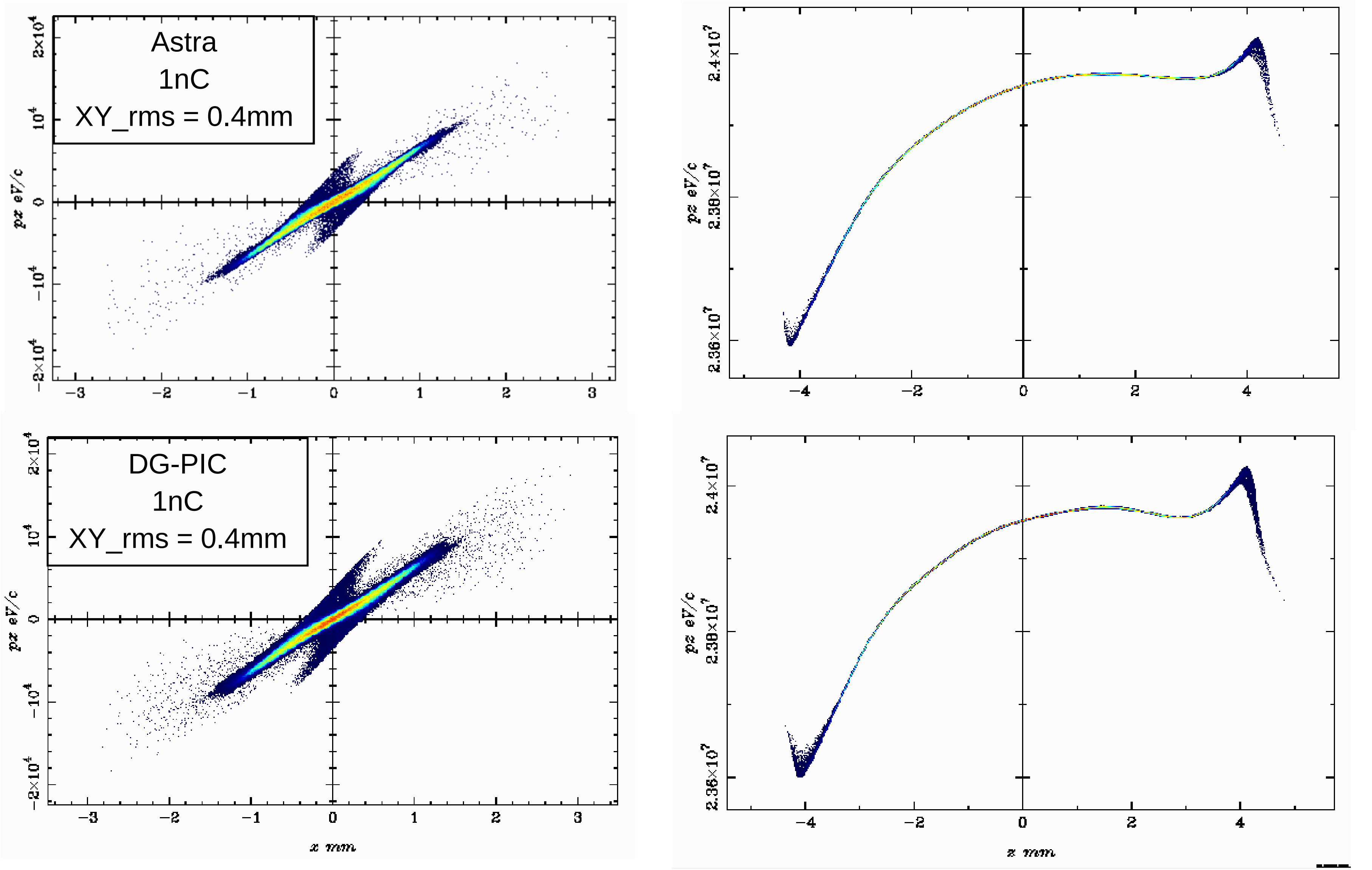
Emittance at EMSY1



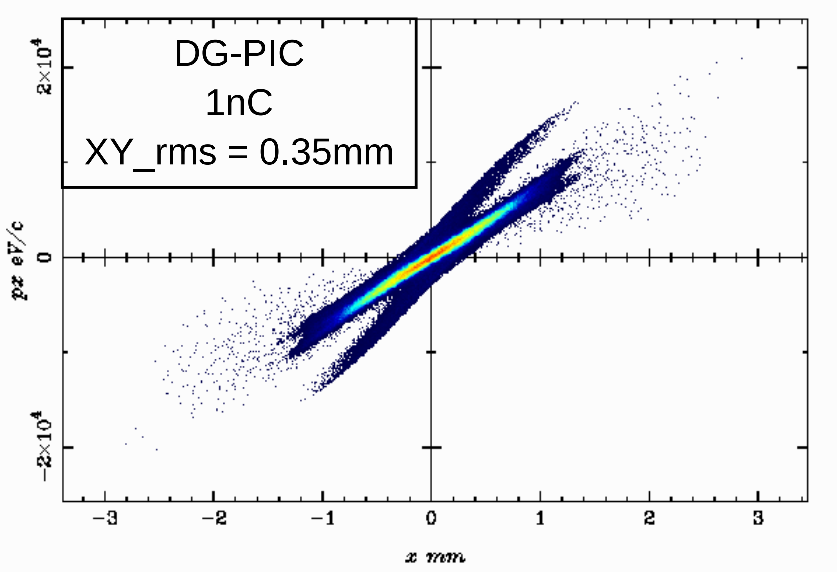
Emittance at EMSY1

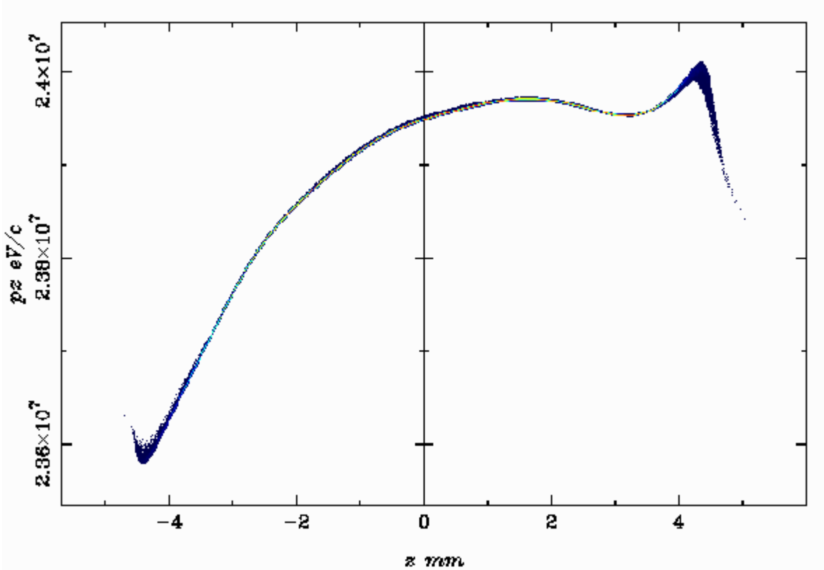


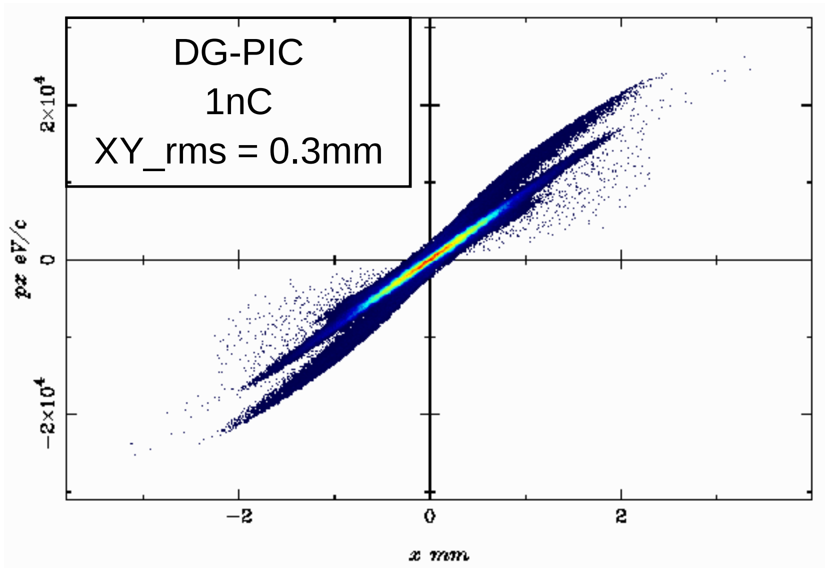
Emittance at EMSY1

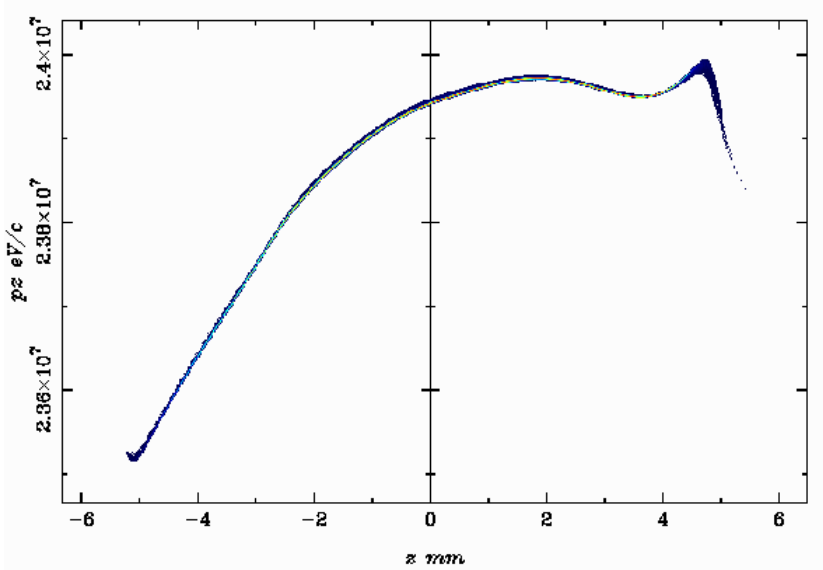


Emittance at EMSY1



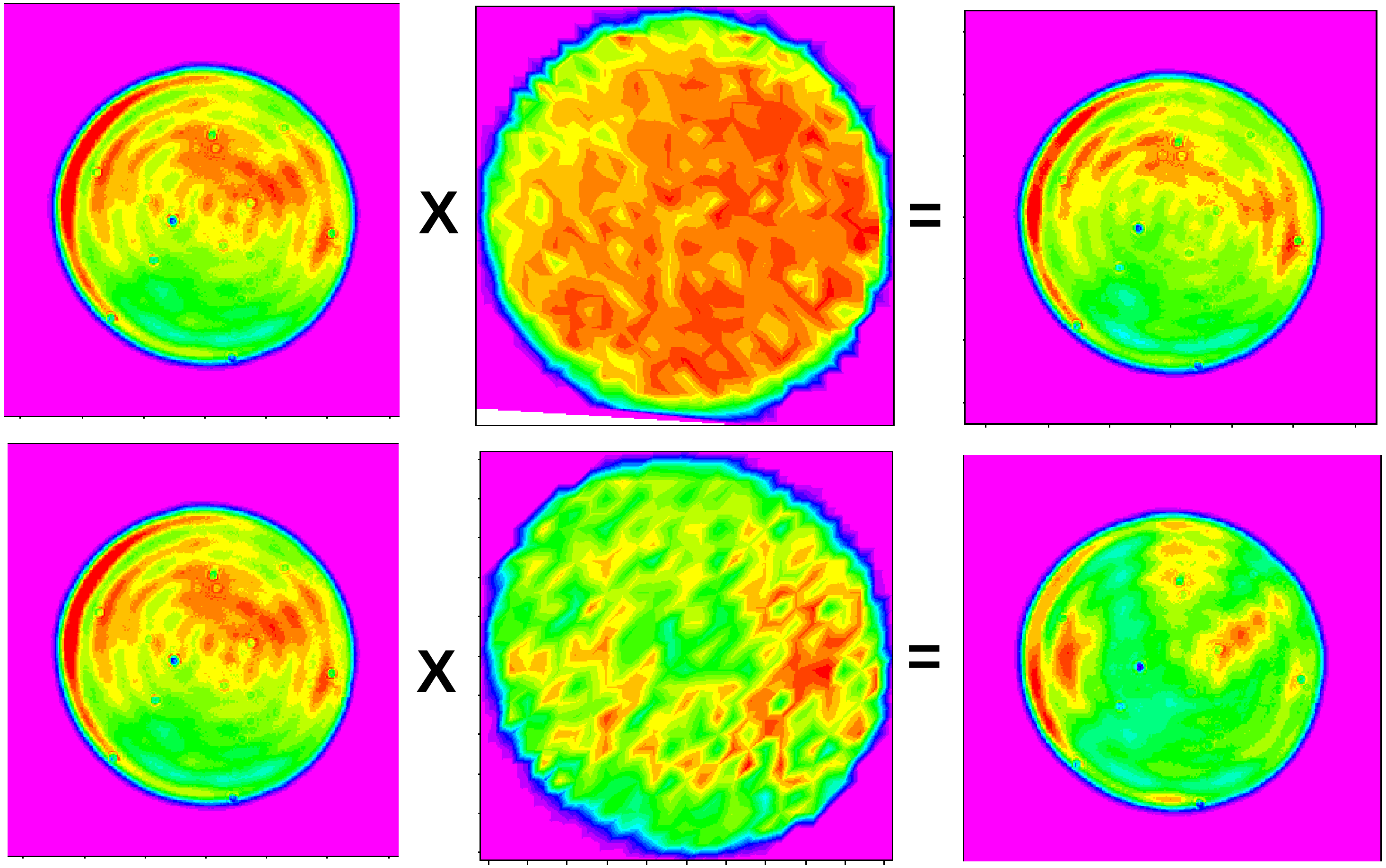






Transverse Spot Inhomogeneities

Laser | QE map | Charge density

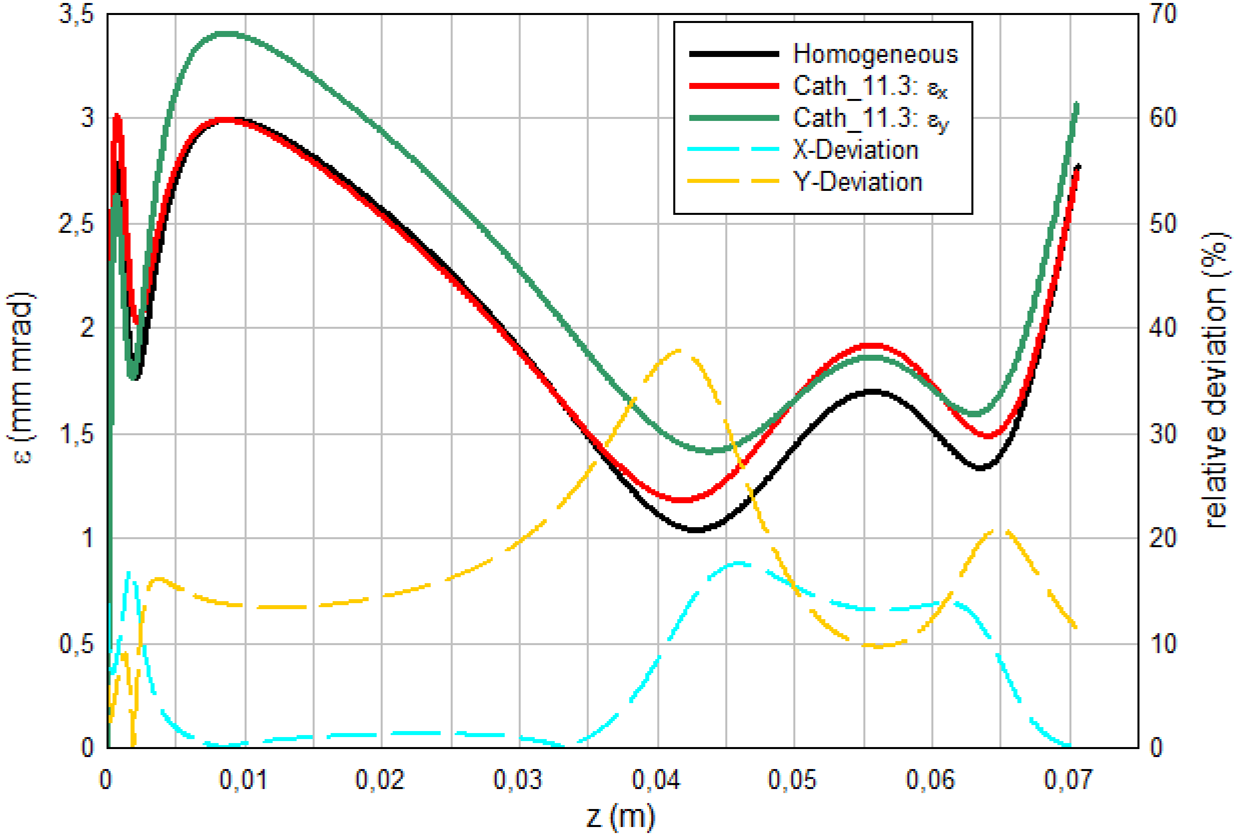


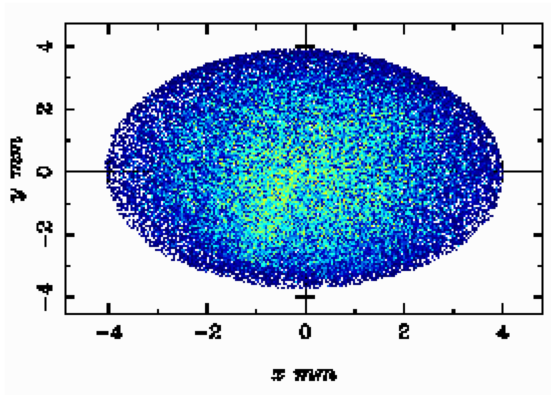
Cath_11.3
XY_rms = 0.3mm

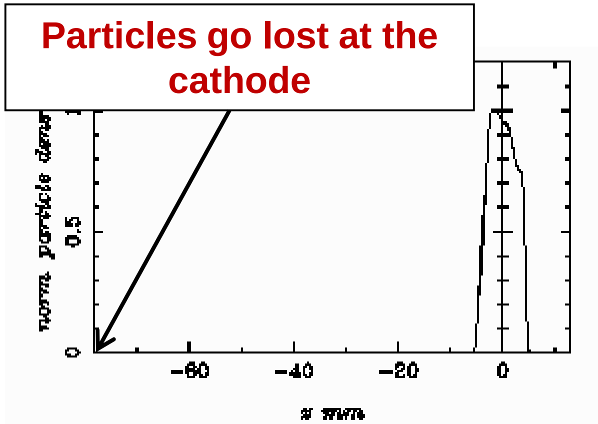
Cath_110.2
XY_rms = 0.3mm

Transverse Spot Inhomogeneities

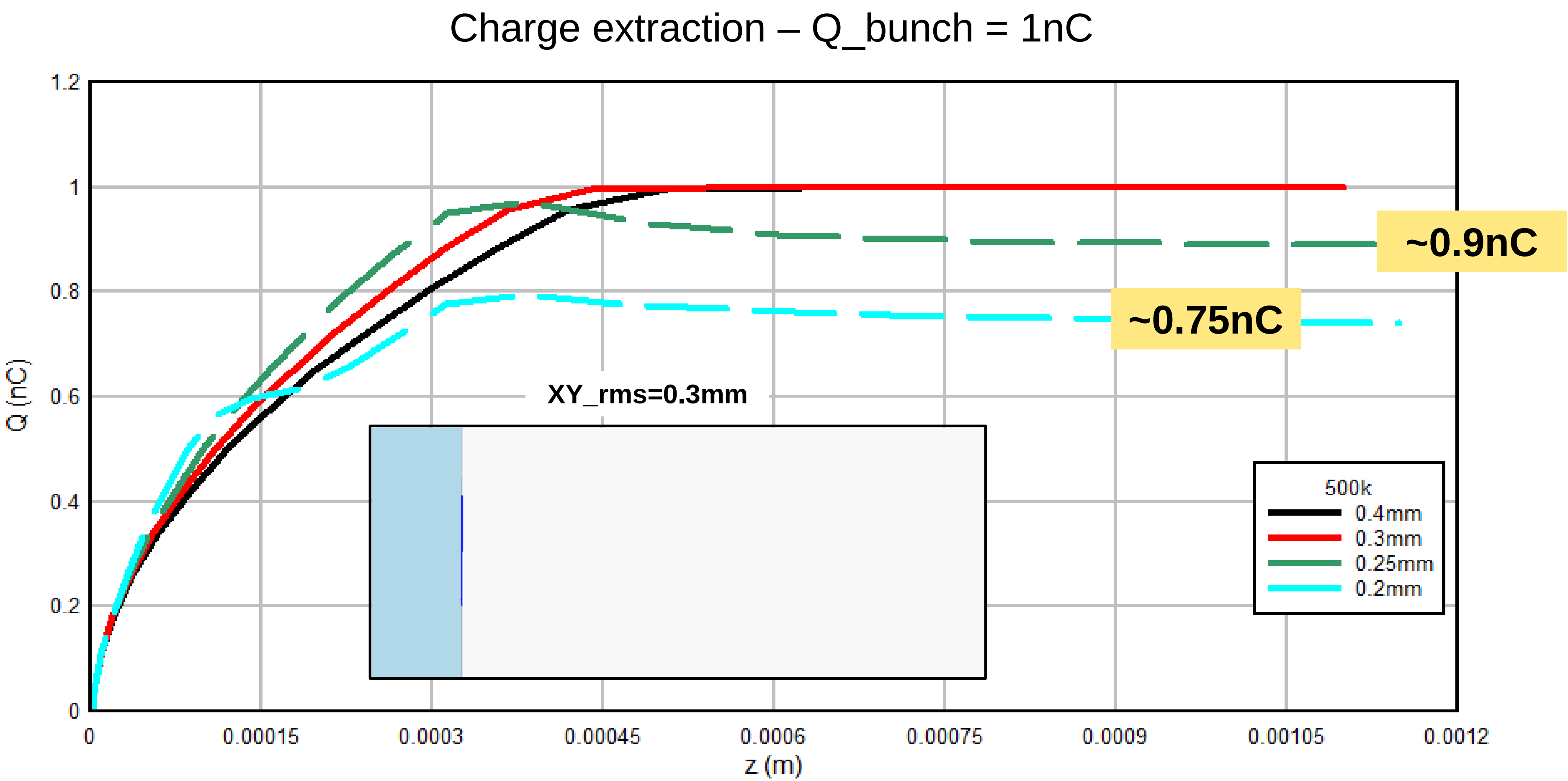
- Emittances up to 7cm



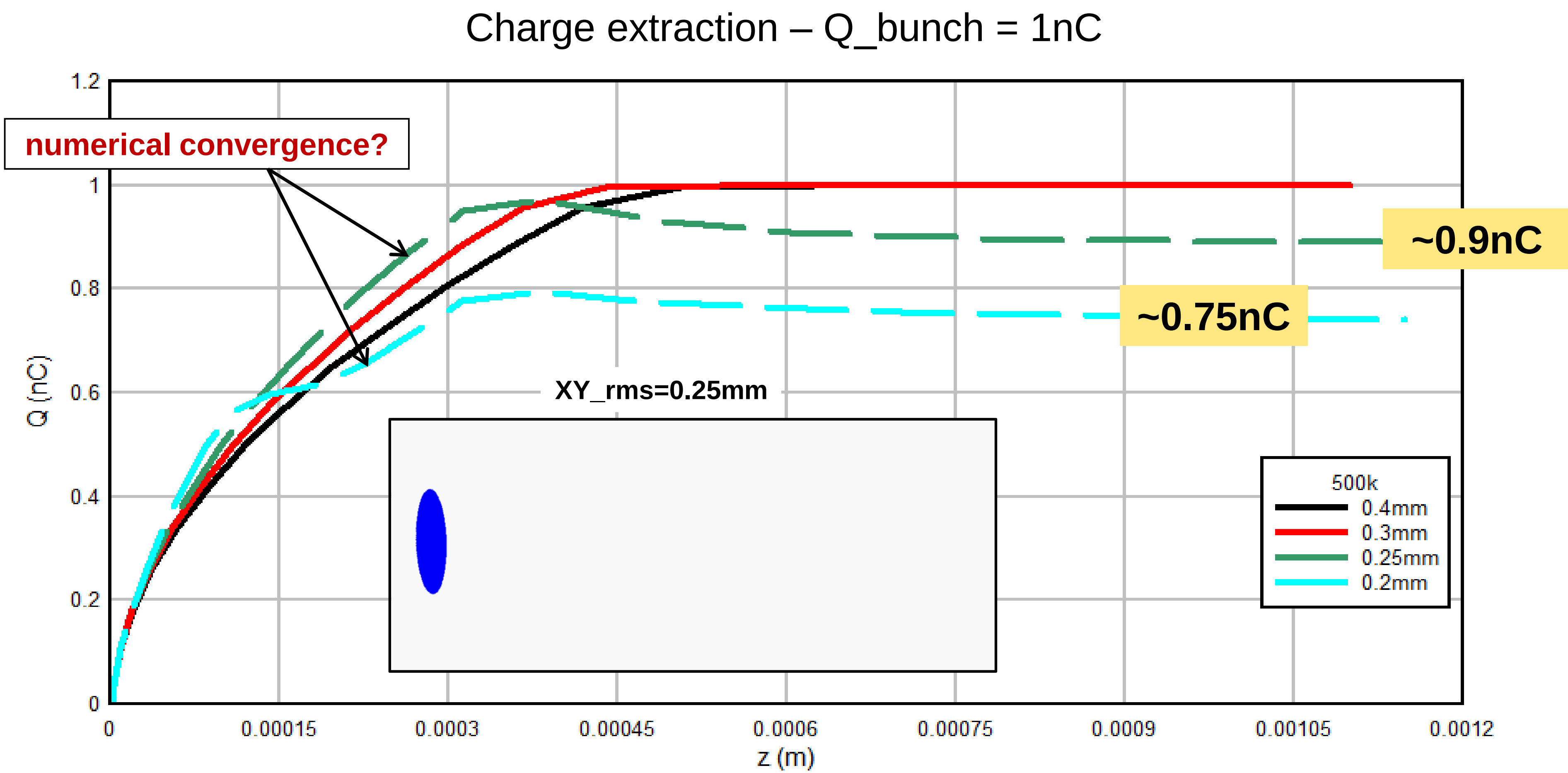




Space Charge Limits

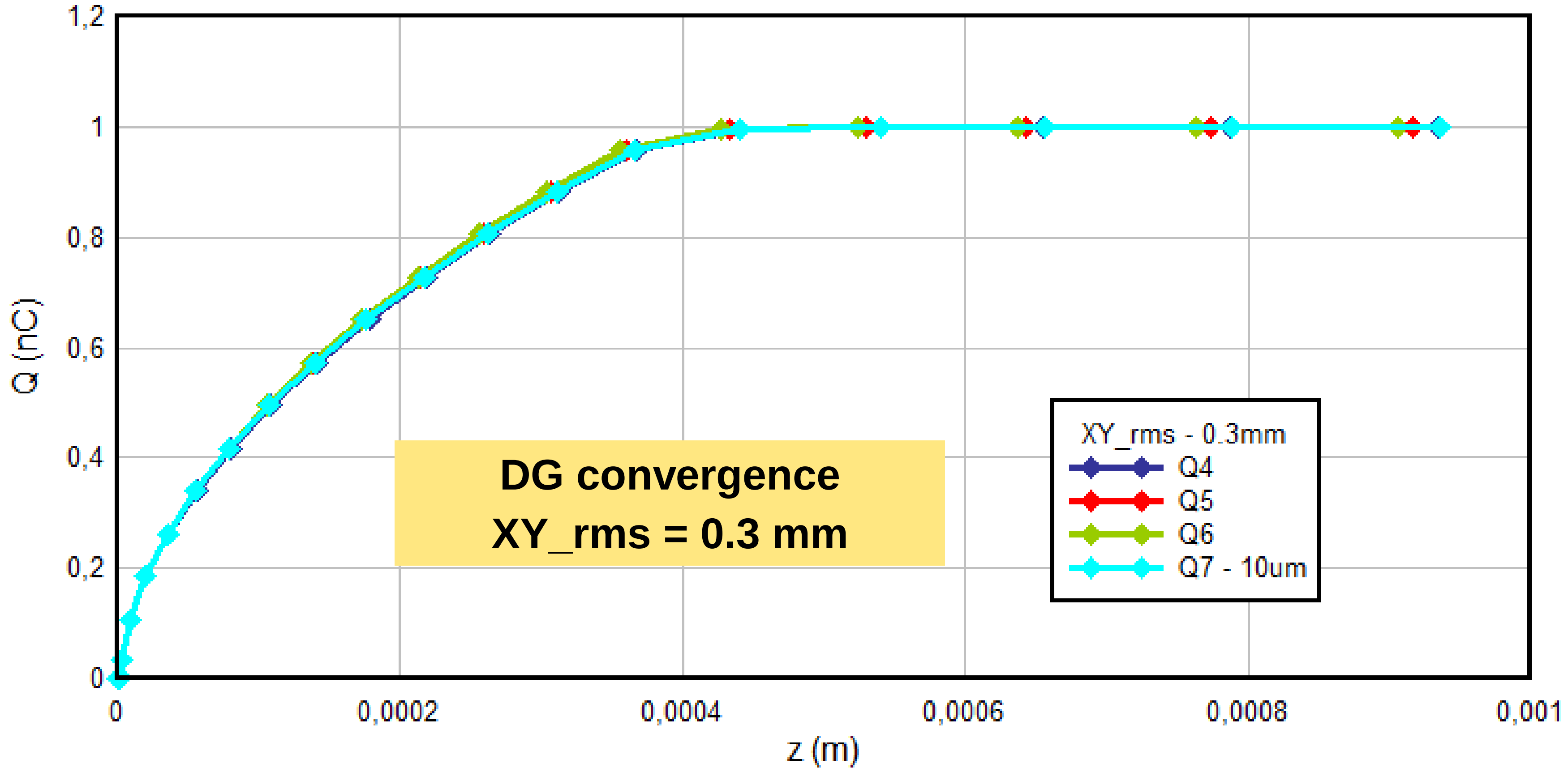


Space Charge Limits



Space Charge Limits

Charge extraction – Q_bunch = 1nC



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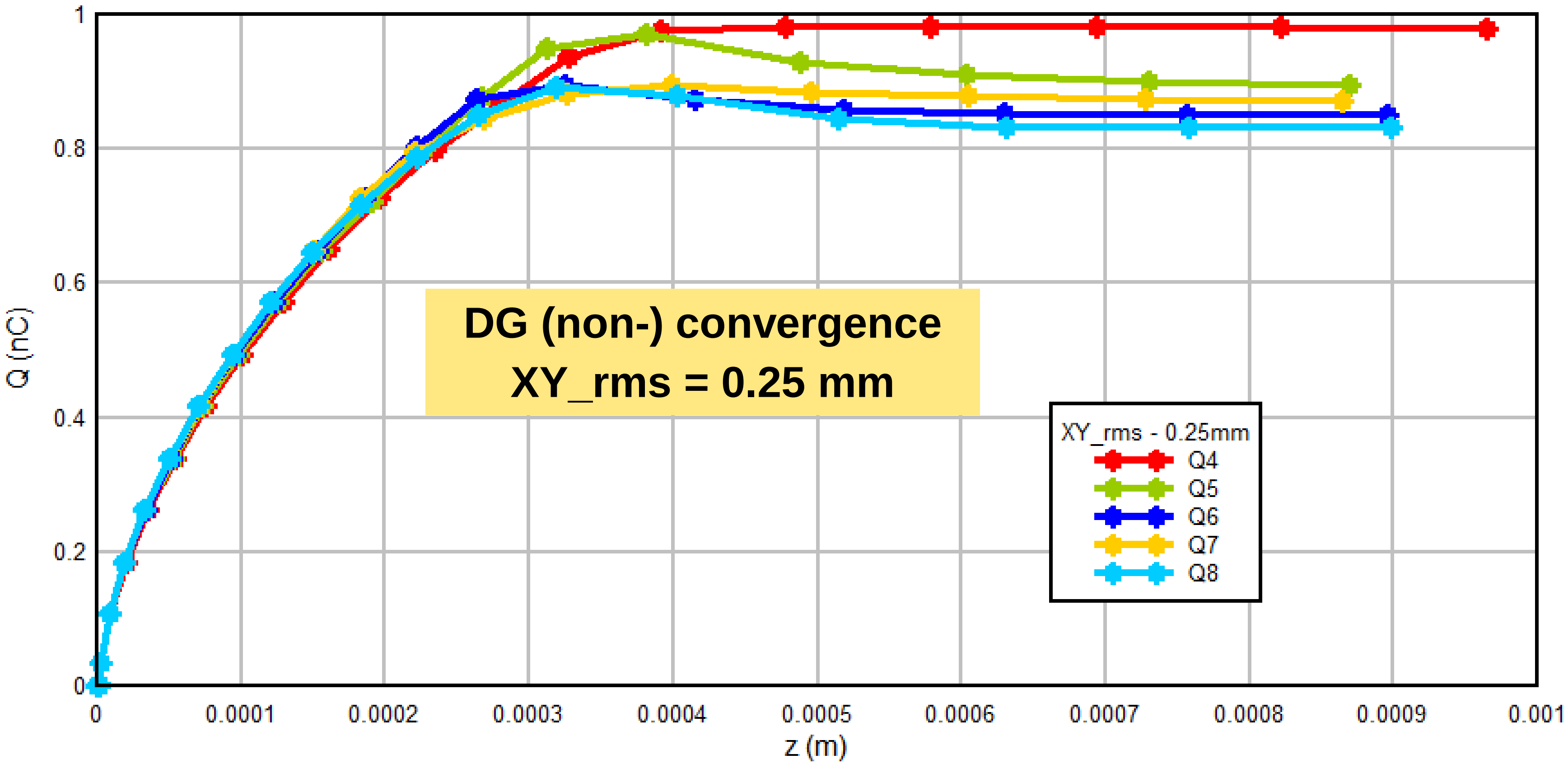

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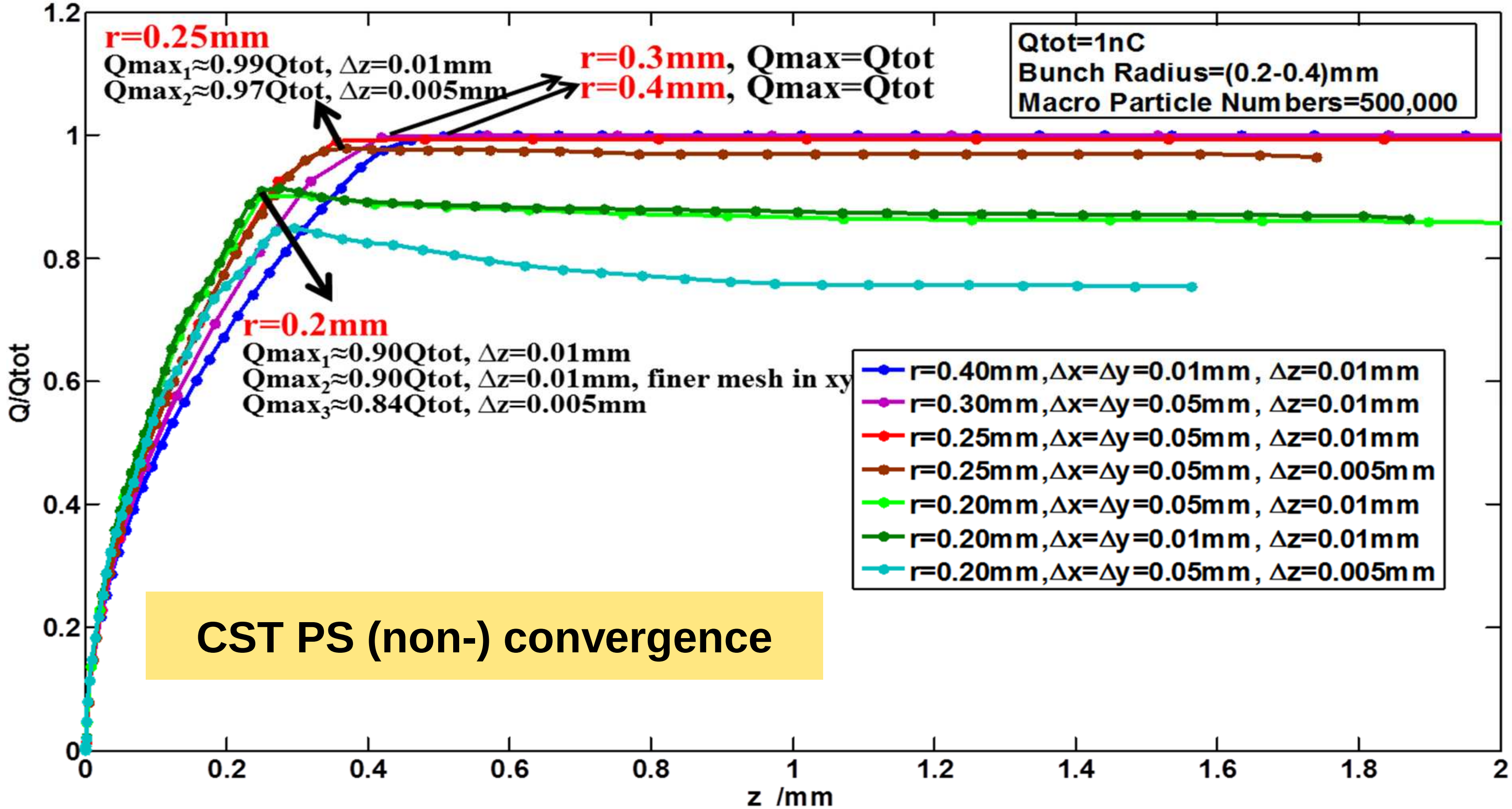
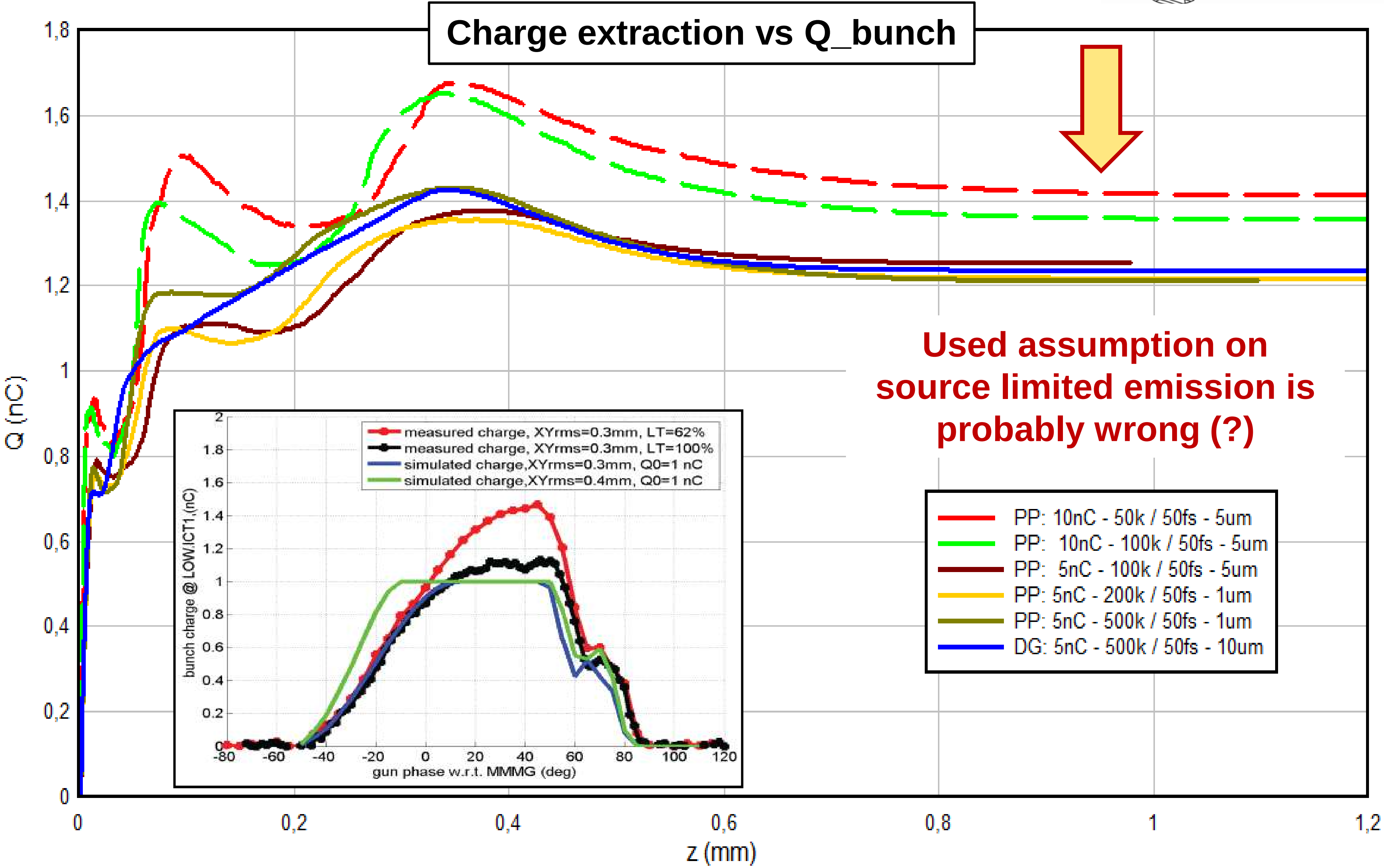


Space Charge Limits

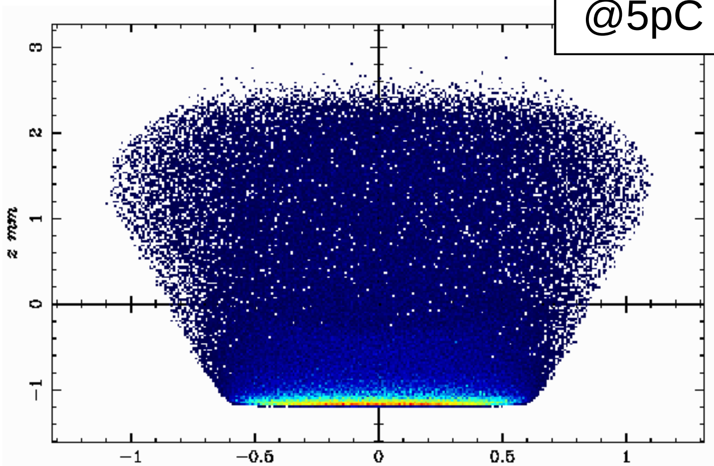


Used assumption on source limited emission is probably wrong (?)

Conclusions

- Modeling errors exist in Astra simulations
  - charge expansion effects at the cathode are neglected
  - projected emittance is overestimated: ~20% off at 1nC / 0.4mm
  - Predicted SPCH limits are lower than should be if source limited emission is assumed
- But, systematic shift in the optimal parameters (spot size) cannot be explained by these "numerical problems"
- The emission regime is yet unclear
  - If spch limitation occurs (partially) completely different beam dynamics is to be expected

@5pC



Thank you for your attention