Emission modelling and injector simulations

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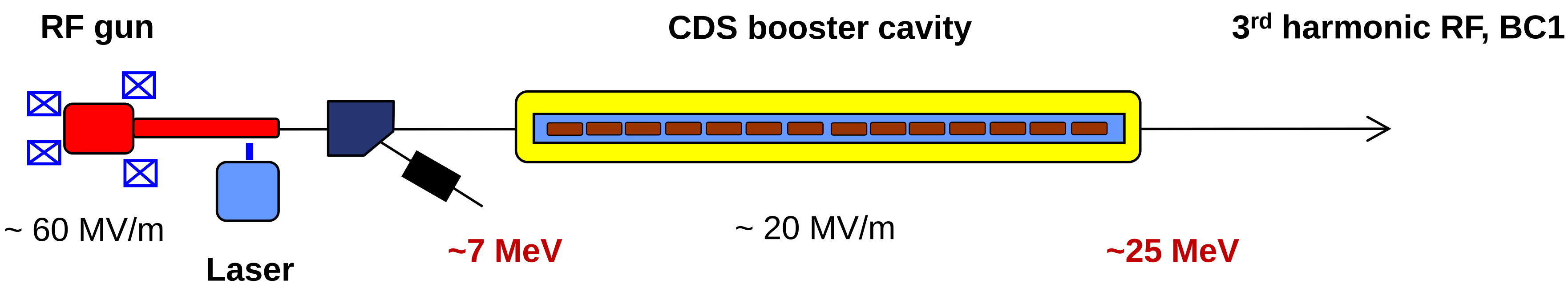
Layout of the E-XFEL injector (DESY, Hamburg)



RF gun – generate low emittance bunch ⇒ booster – matched acceleration to preserve emittance ⇒ measurement station, phase-space linearization, main linac,…

- 1999: project begin at PITZ facility in Zeuthen
- 2003: first operating device – 1.7 mm mrad for 1nC bunch
- 2010: PITZ-1.6 – 1.2 mm mrad
- since 2012: PITZ-1.8 – 0.9 mm mrad

The PITZ RF gun of the E-XFEL

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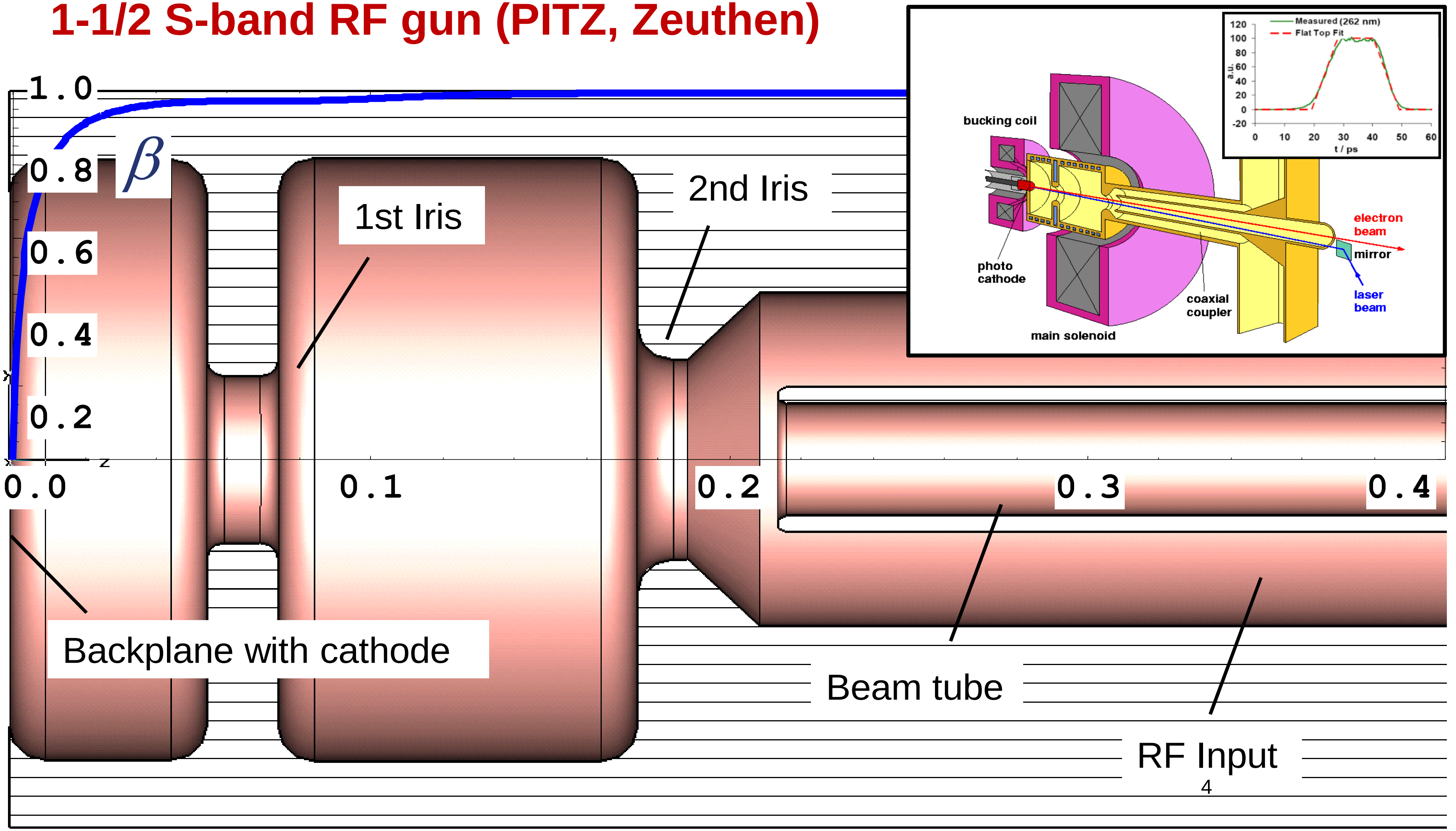
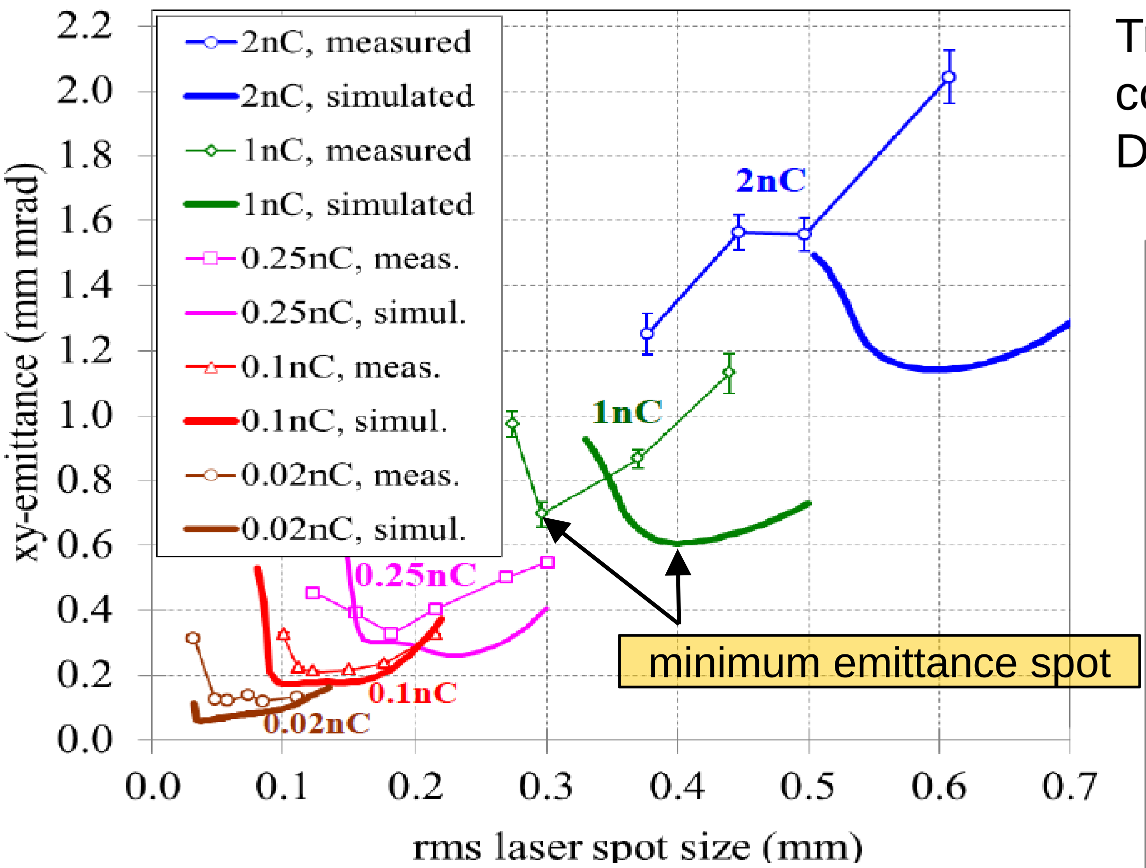
1-1/2 S-band RF gun (PITZ, Zeuthen)

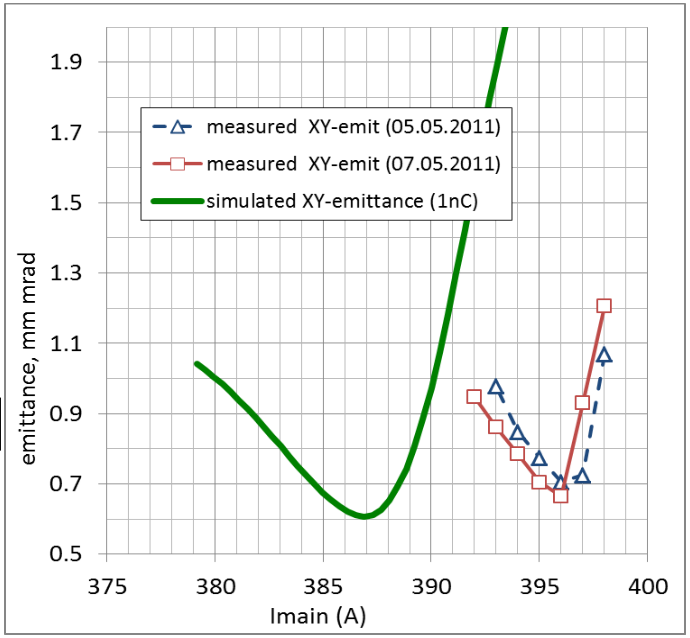


The PITZ RF gun of the E-XFEL

Discrepancies between experiment and simulation

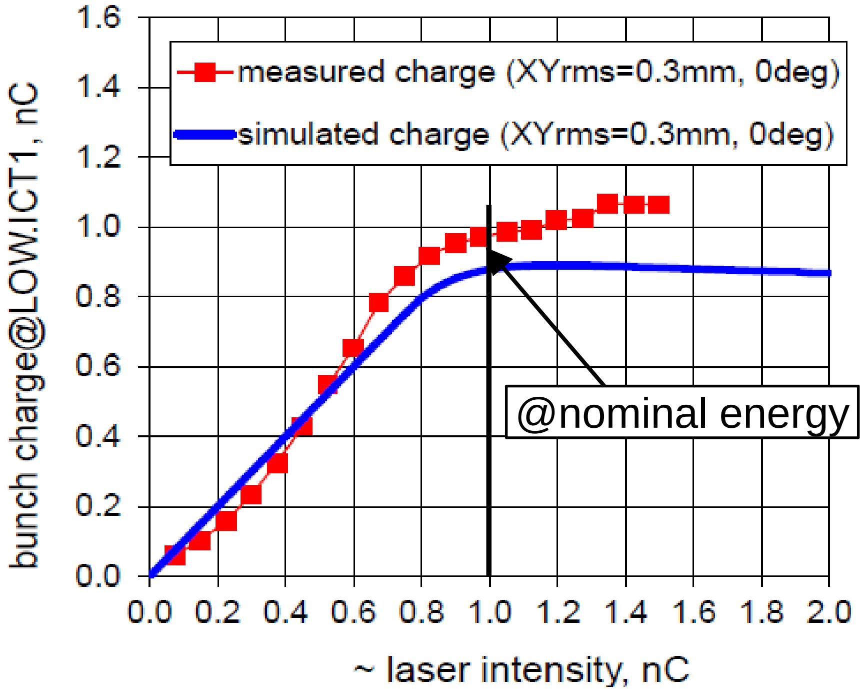


Transverse emittance comparisons (M. Krasilnikov, DESY)

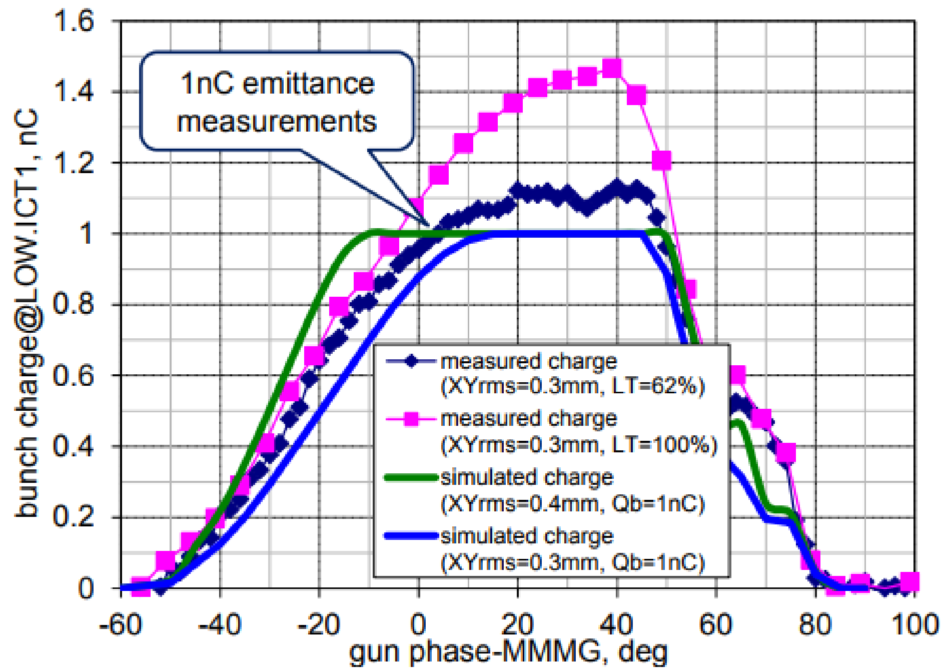


Discrepancies between experiment and simulation

Emitted bunch charge vs. laser energy



Emitted bunch charge vs. gun phase



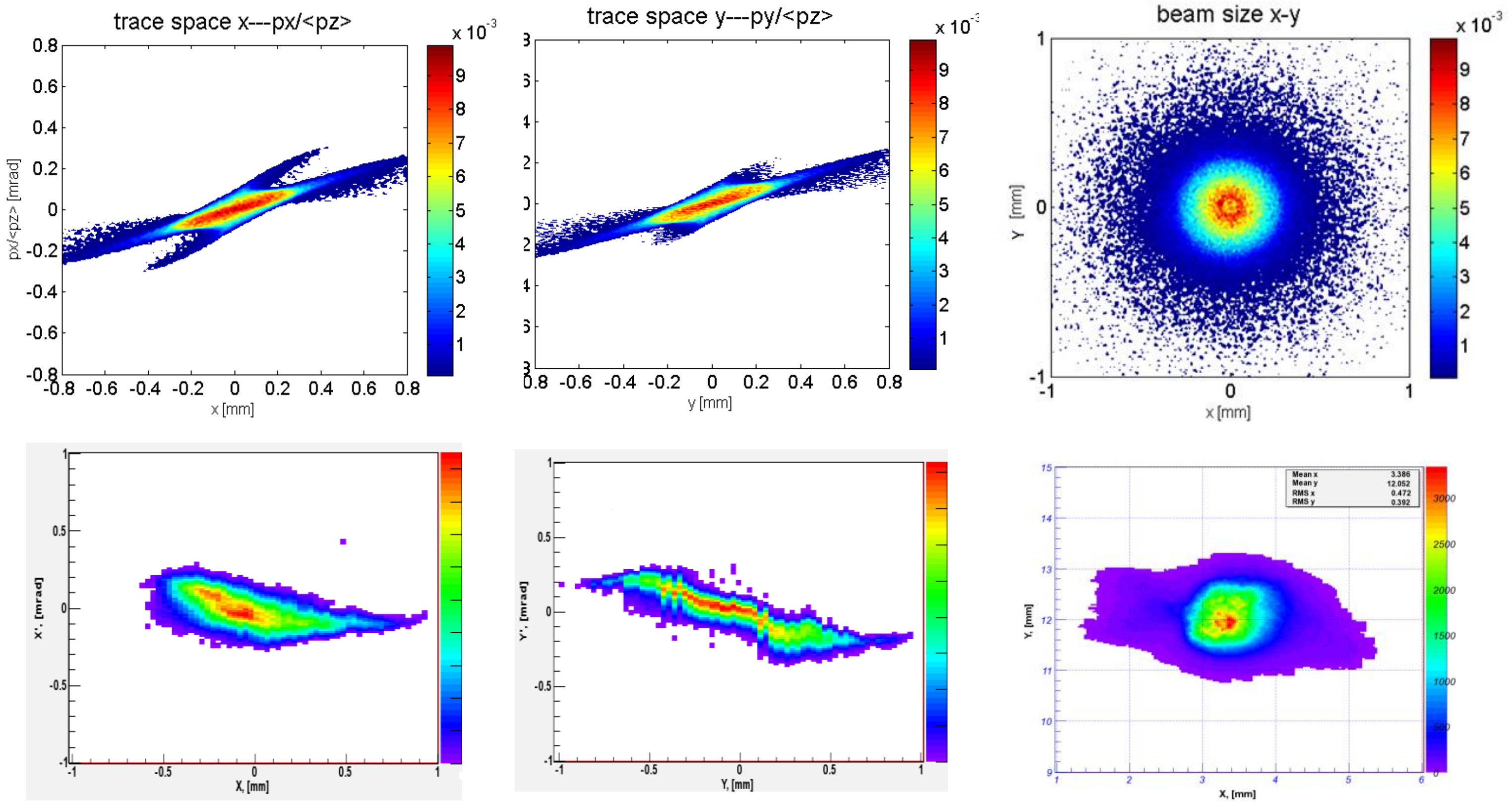
The PITZ RF gun of the E-XFEL

Discrepancies between experiment and simulation

Phase-space comparisons at EMSY1

Simulation

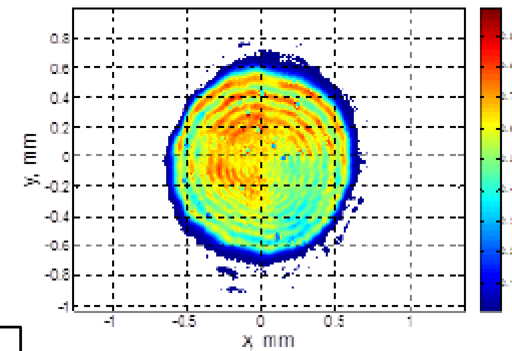
Experiment

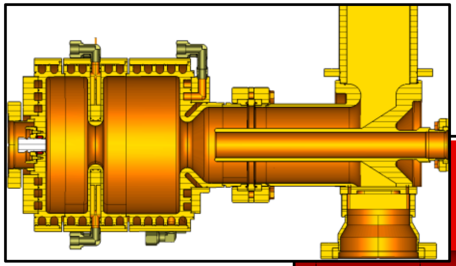


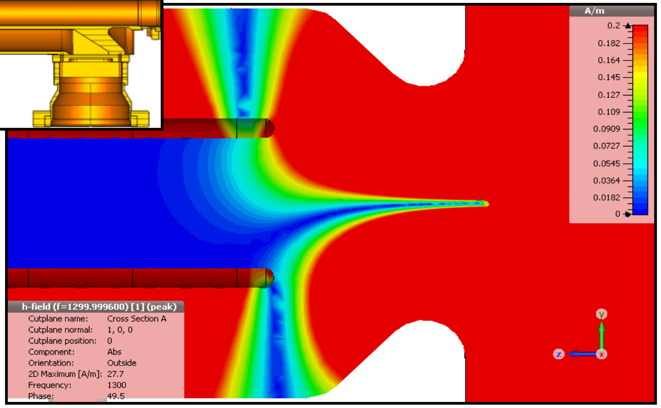
The PITZ RF gun of the E-XFEL

Discrepancies between experiment and simulation

- Experiment:
    - Laser profile and/or QE distribution at the cathode
    - Asymmetries of RF-field in the gun
    - Phase-space measurement scheme
- Simulation
    - Space charge calculation model
    - Emission model







Discrepancies between experiment and simulation

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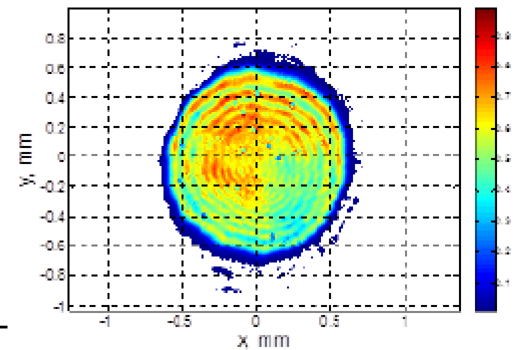
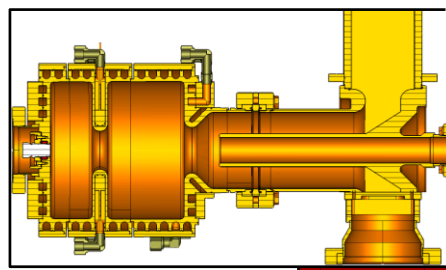
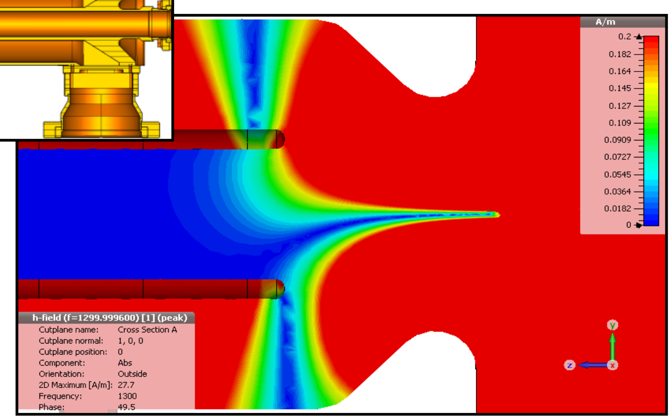
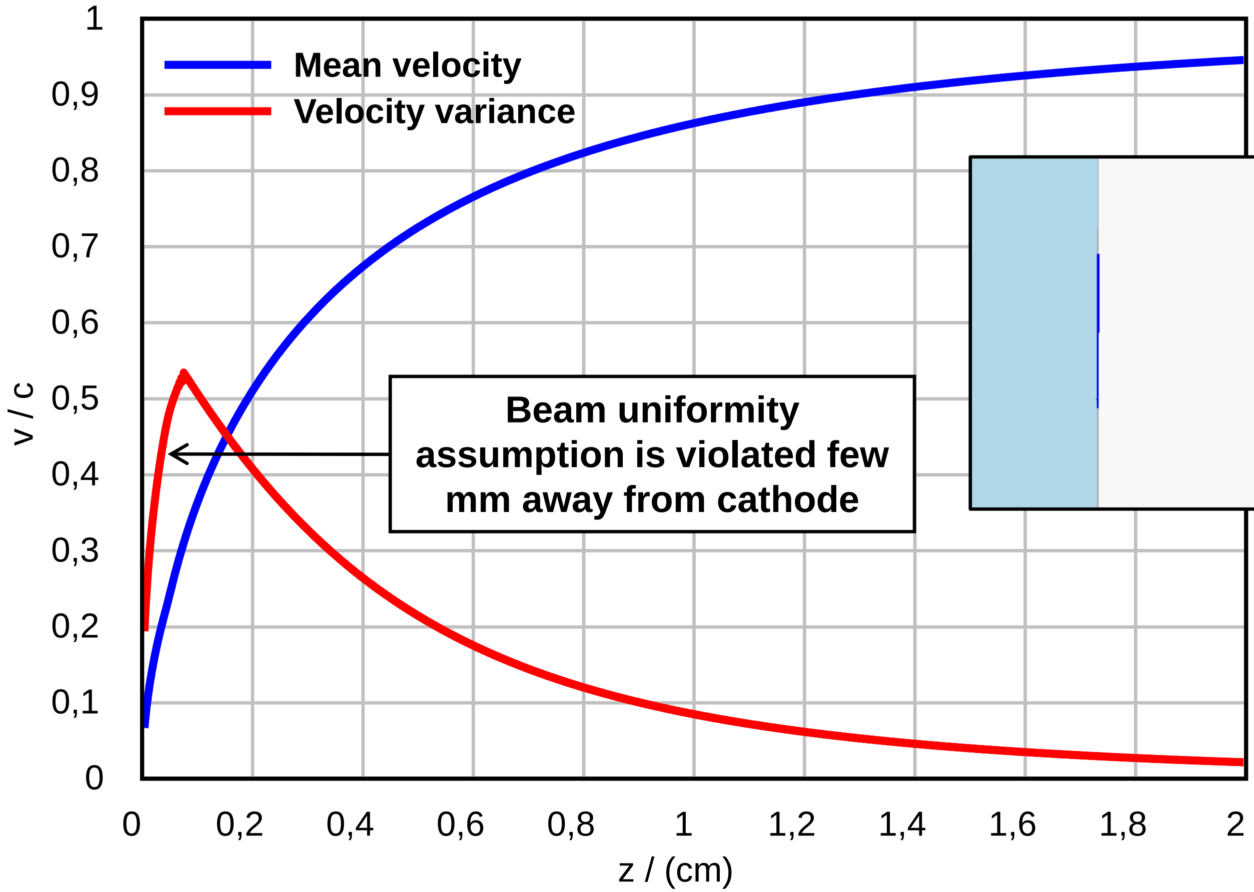






Relativistic field effects

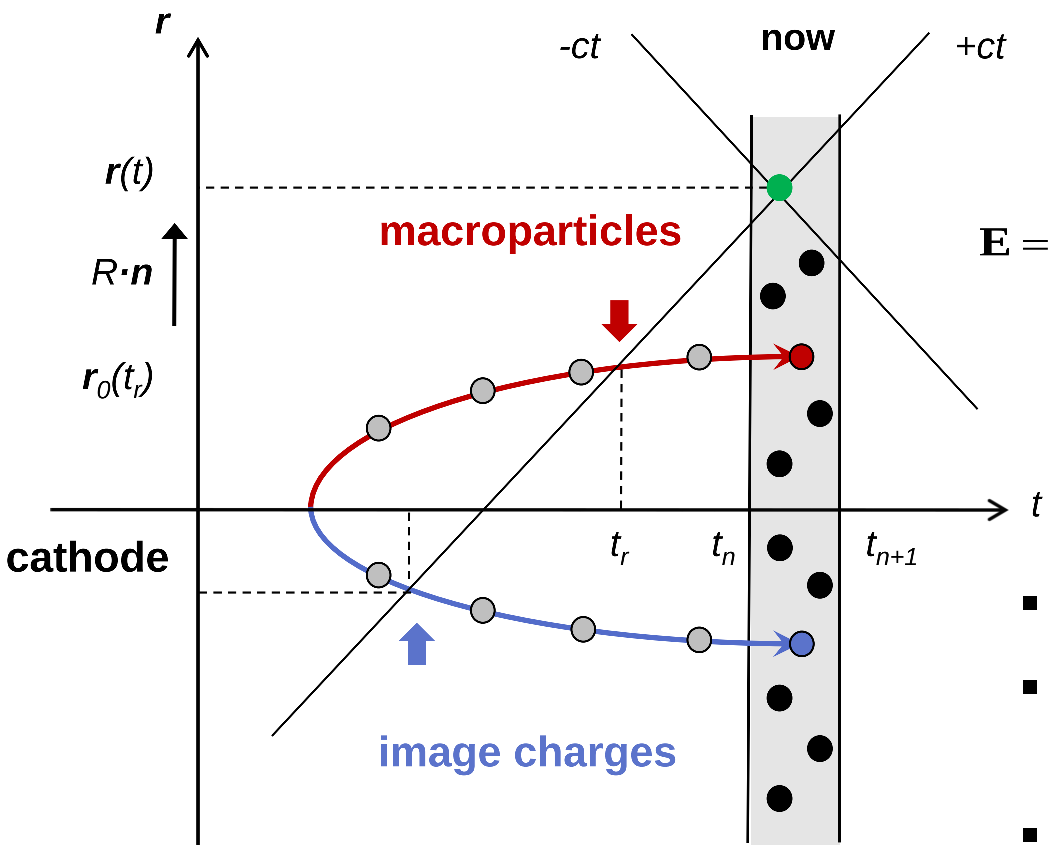
Variance of particle velocity during bunch emission



Need full electromagnetic space-charge model

Relativistic field effects

Lienard-Wiechert particle-particle approach



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

retardation

- Need to store full trajectory history
- Search retarded interaction point for every particle-particle pair
- Scaling: $N_p^2 \times N_t^2$

Relativistic field effects

Lienard-Wiechert particle-particle approach

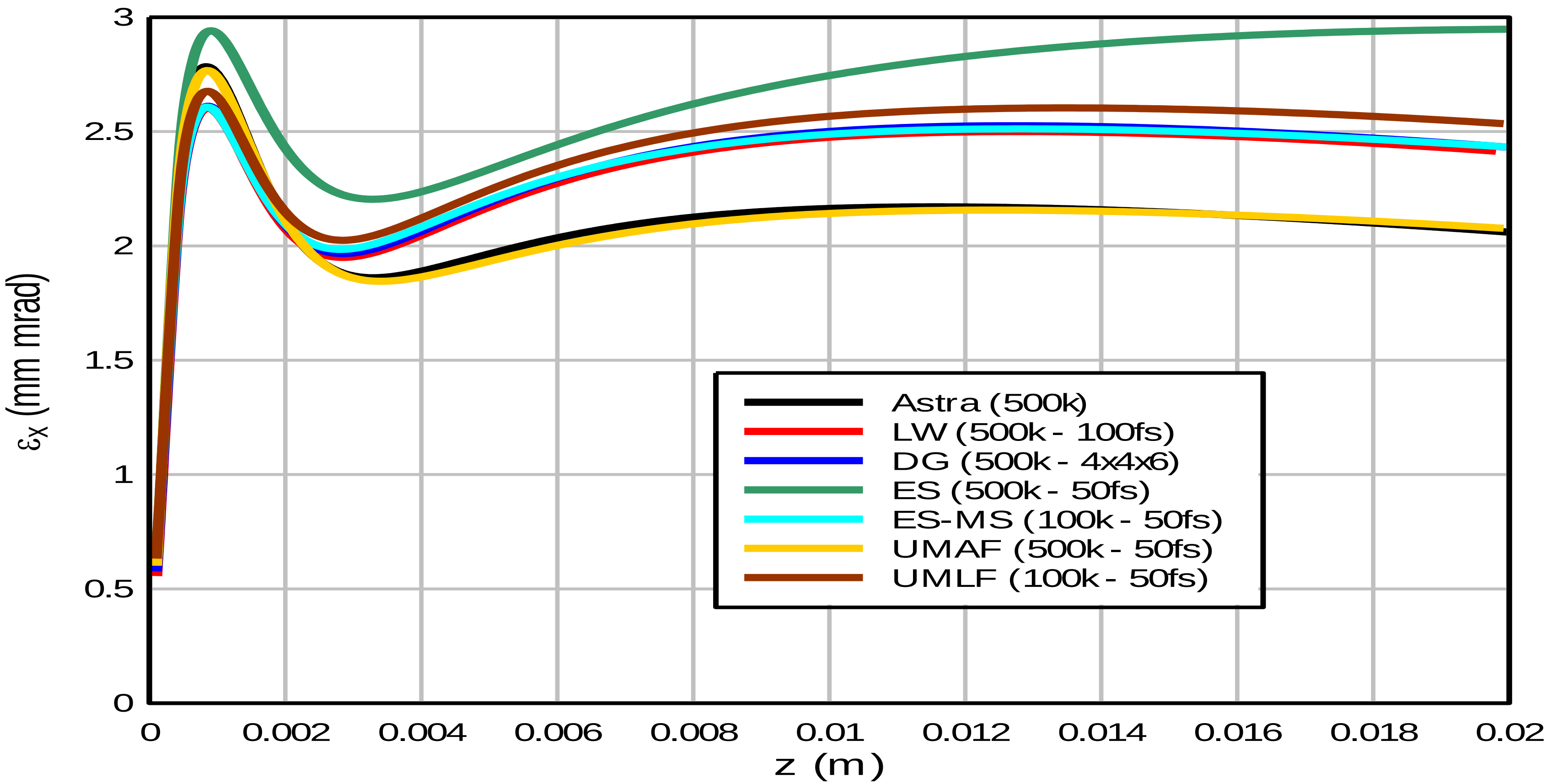
$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0}\left[\frac{(\mathbf{n}-\boldsymbol{\beta})\left(1-|\boldsymbol{\beta}|^2\right)}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2} + \frac{\mathbf{n}\times(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]\Bigg|_{t=t_r},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

LW single particle field

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

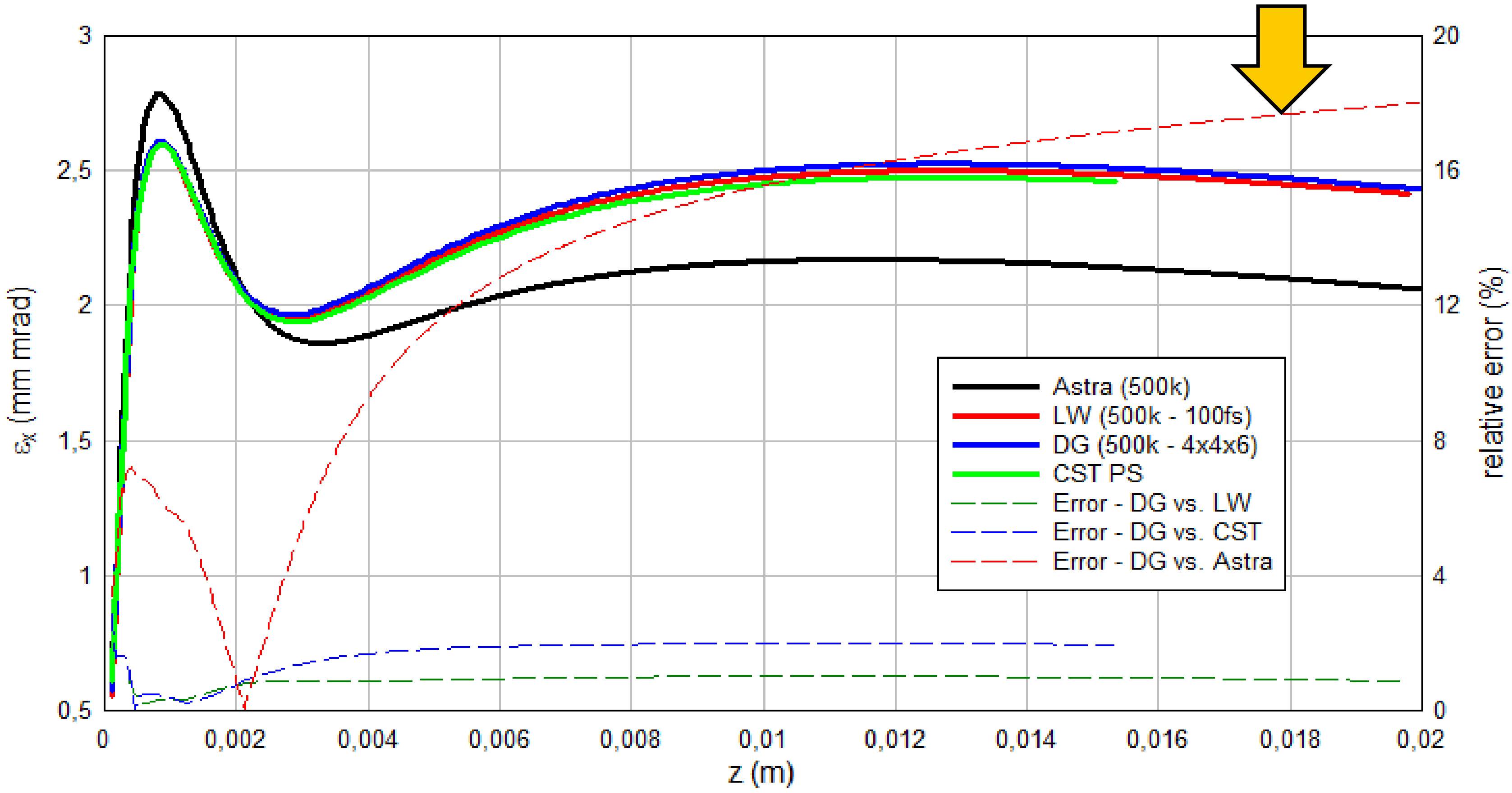
Relativistic field effects

Full EM vs. static/quasistatic approximations

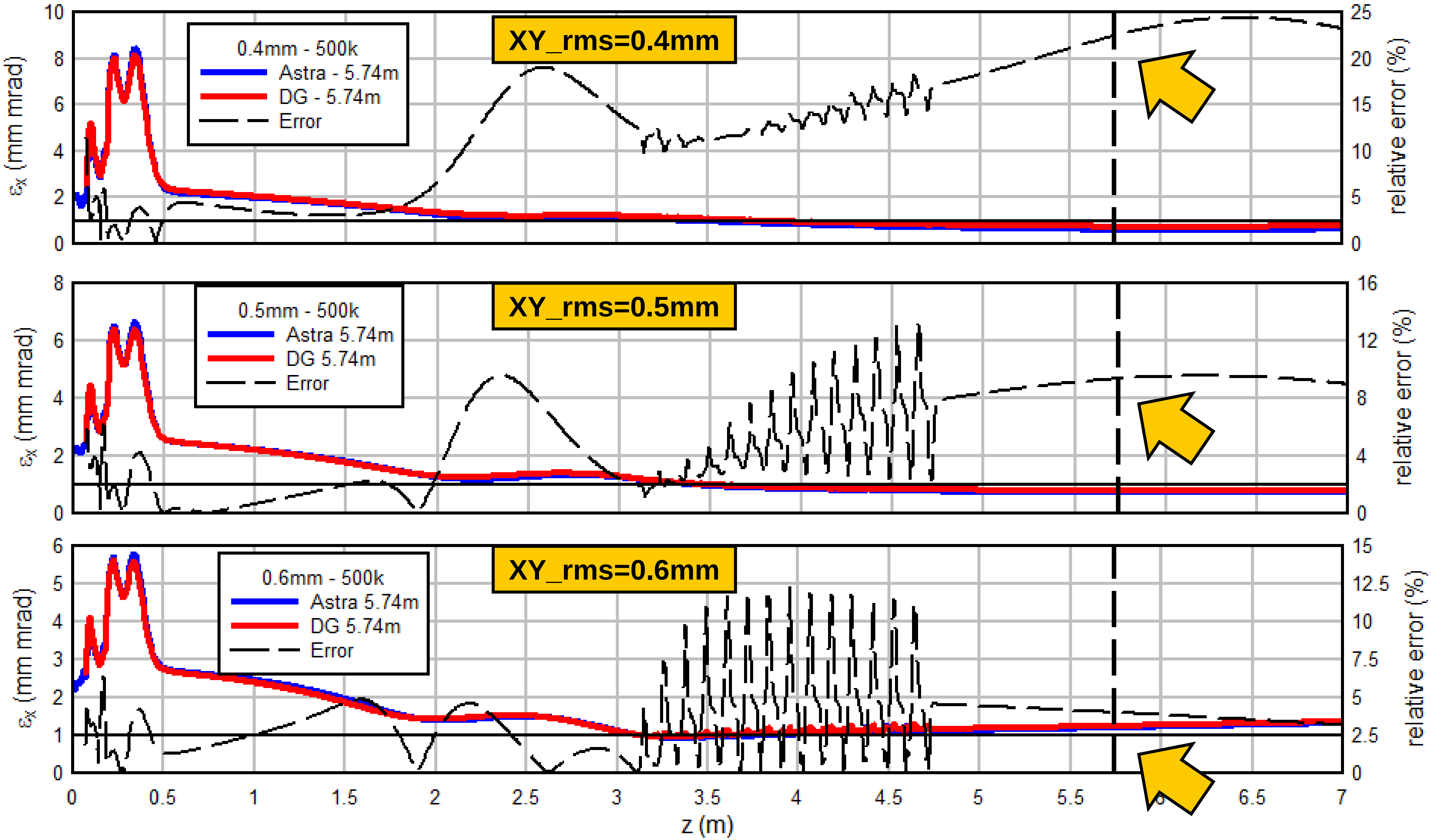


Relativistic field effects

Lienard-Wiechert vs. grid based solvers



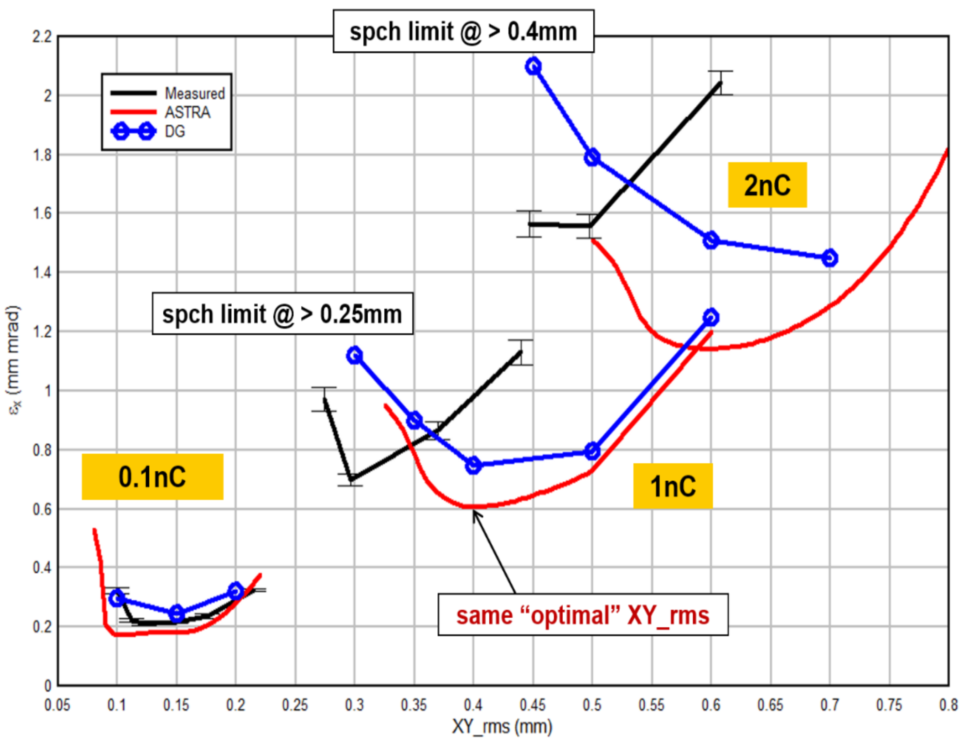
Relativistic field effects



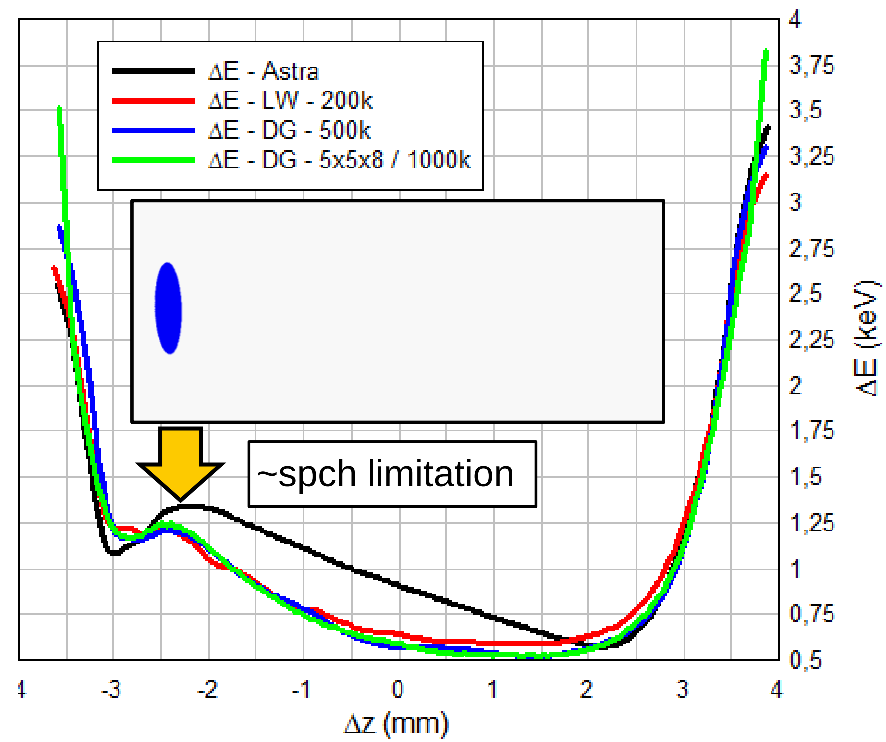
Relativistic field effects

Full EM vs. quasistatic approximation

Effect on transverse emittance



Effect on slice energy spread



Relativistic field effects

Effect on charge emission

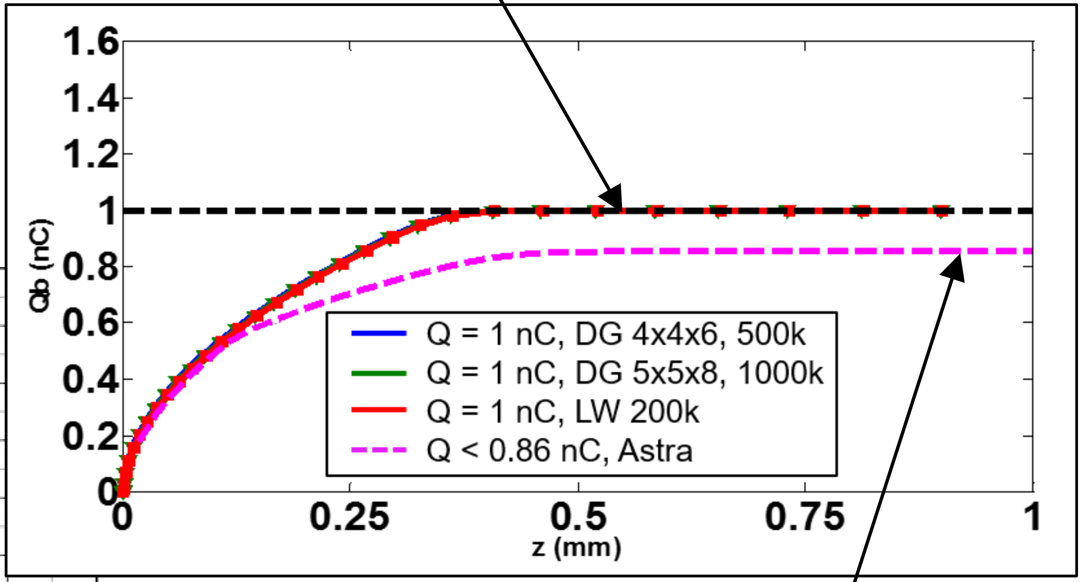
Nominal bunch:

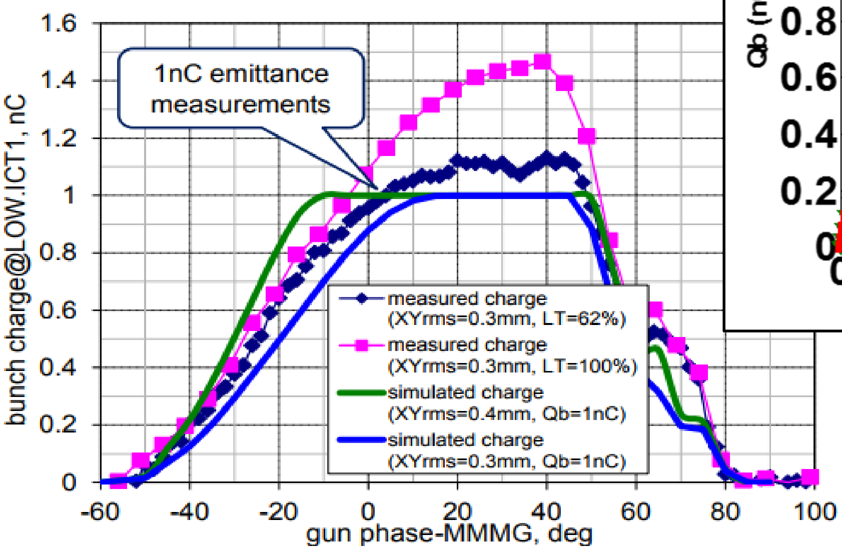
Flat-top: 2.2-21.46-2.2 ps

Acc. field: 60MV/m

Measured charge: 1nC

Full charge emission
with electromagnetic approach

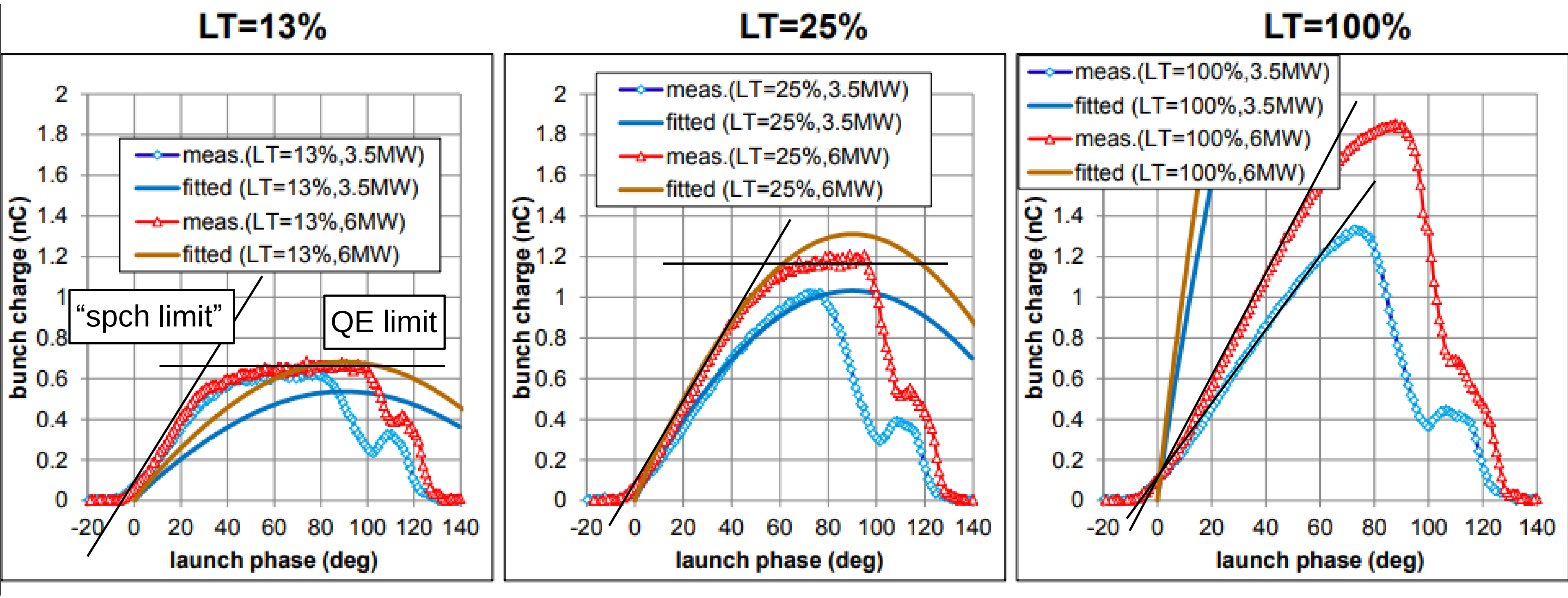




space charge limited emission
with Astra

Modelling emission with space charge

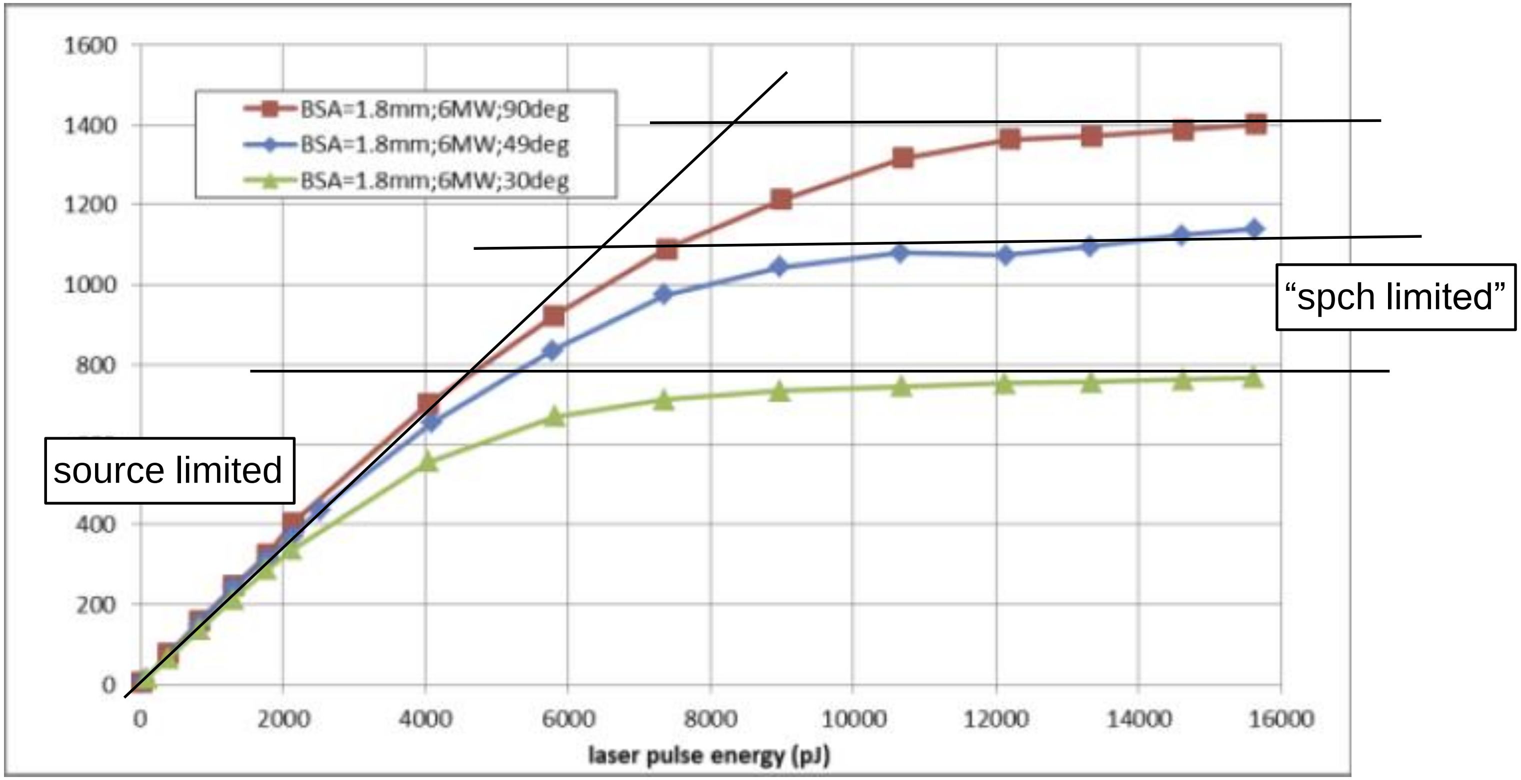
Space charge vs. source (QE) limited emission



(from M. Krasilnikov, DESY)

Modelling emission with space charge

Space charge vs. source (QE) limited emission

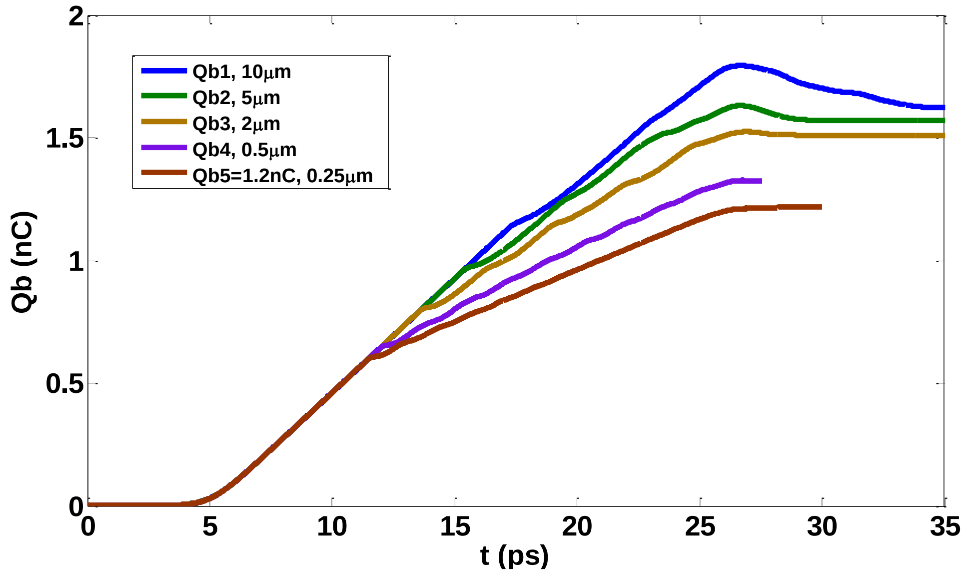


(from M. Krasilnikov, DESY)

Modelling emission with space charge

“Space charge limit” for transient emission

- Total emitted charge always depends on laser pulse intensity
- Very difficult to simulate for very high charge densities at the cathode



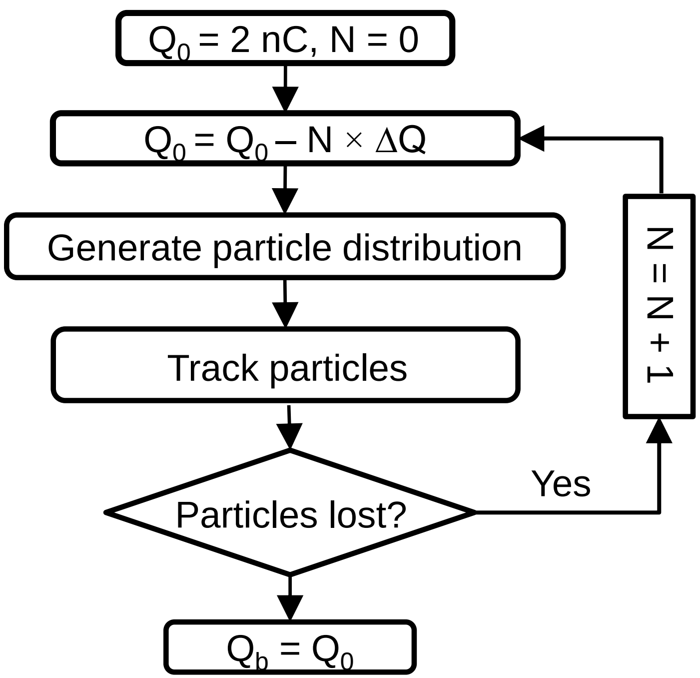
CST PS simulation for an input bunch with 2nC and different mesh resolutions

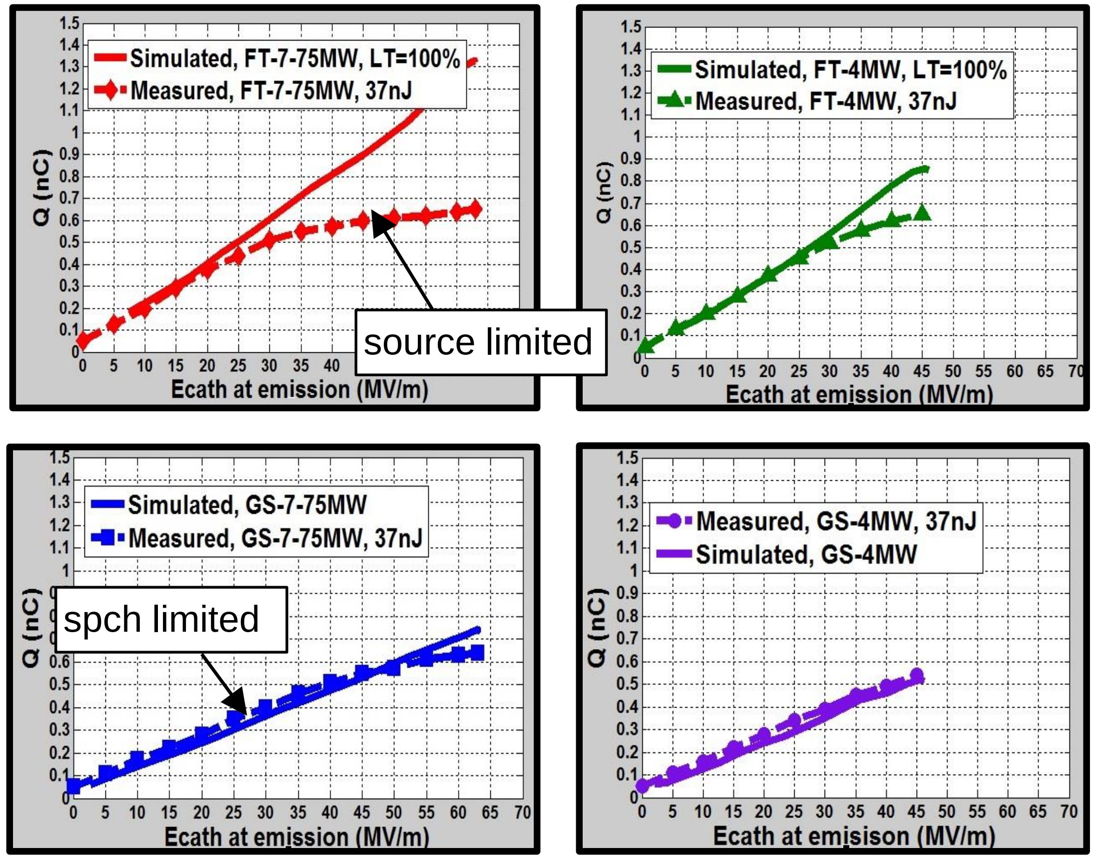
- Emission with strong space charge limitation not interesting.
  Define: highest bunch charge produced without back-moving particles

Modelling emission with space charge

“Space charge limit” for transient emission

Iterative calculation of space charge emission saturation:





Modelling emission with space charge

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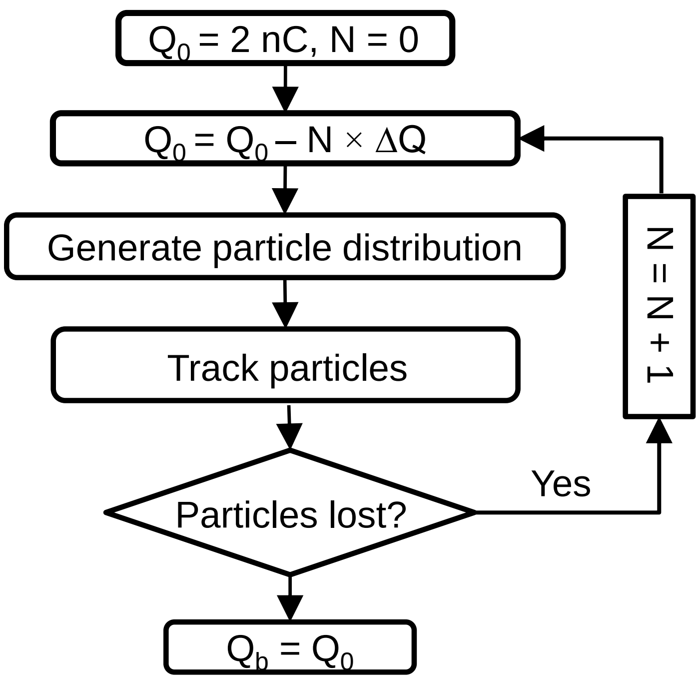
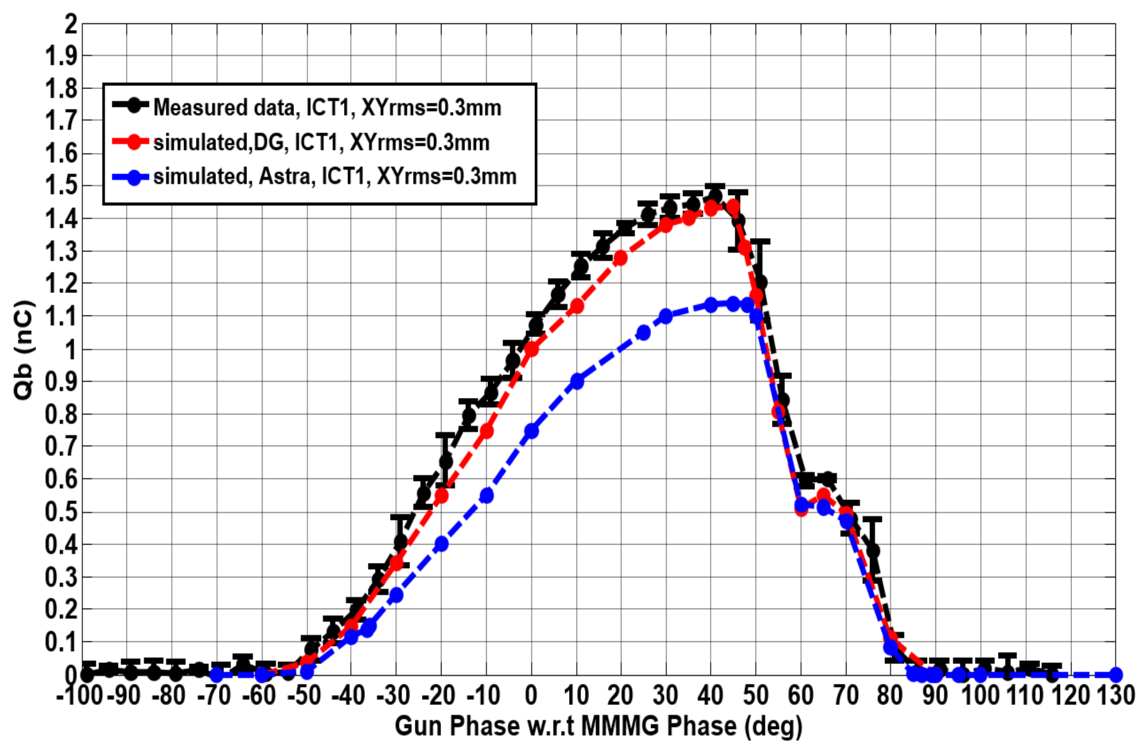
“Space charge limit” for transient emission

Iterative calculation of space charge emission saturation:





Modelling emission with space charge

Emission models for the cathode

$$\boxed{Q(t) = \int_{-\infty}^{t} e \frac{I_{laser}(\tau)}{h\nu} QE(\tau) d\tau}$$

Charge produced at the cathode by photoemission

Fowler-Dubridge model (metals): $QE_F(t) = \boldsymbol{\eta}[h\nu - \Phi_w]^2$

Spicer model (semiconductors): $QE_S = \frac{[h\nu - \Phi_w]^{3/2}}{[h\nu - \Phi_w]^{3/2} + \boldsymbol{\gamma}}$

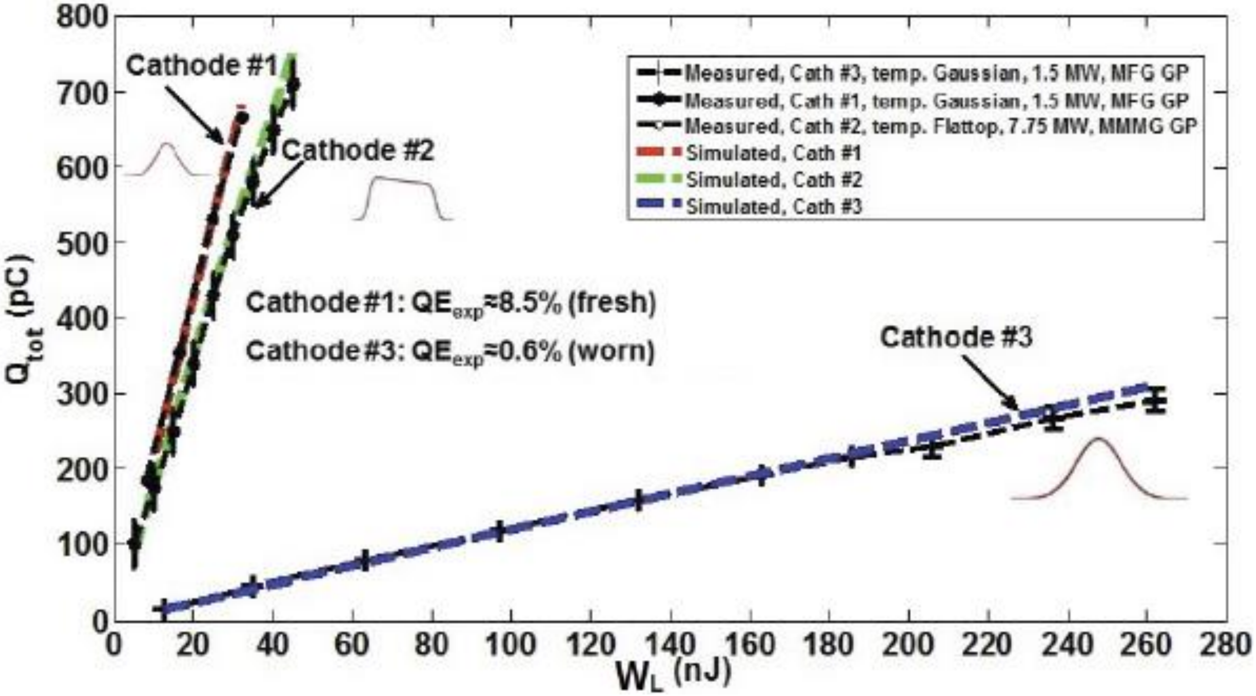
Jensen model (semiconductors): $QE_J = \frac{(1 - R_w)\sqrt{1 + (h\nu - \Phi_w)/E_a}}{2(\boldsymbol{p_0} + 1)(1 + (h\nu - \Phi_w)/E_a)^2}$

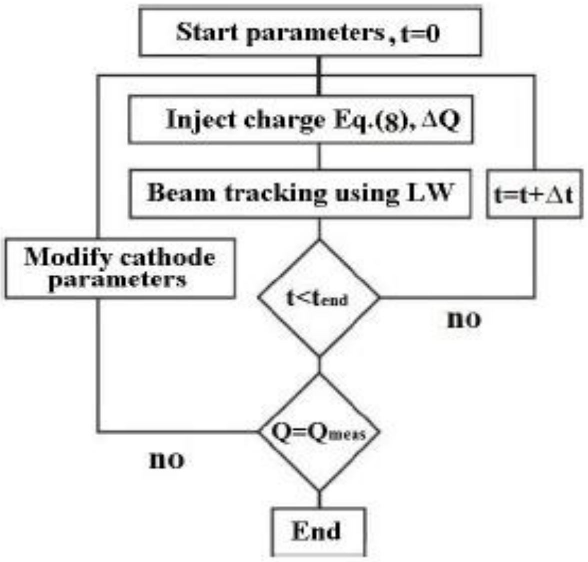
$$\Phi_w(t) = \Phi_{w0} - \overbrace{\sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{tot}(z=0,t)}}^{\text{Schottky effect}} + \overbrace{\boldsymbol{k}[I(z=0,t]^{\boldsymbol{n}}}^{\text{surface charge limit effect}}$$

Modelling emission with space charge

Cathode characterization

Find best match to a given measurement point in the cathode parameter space



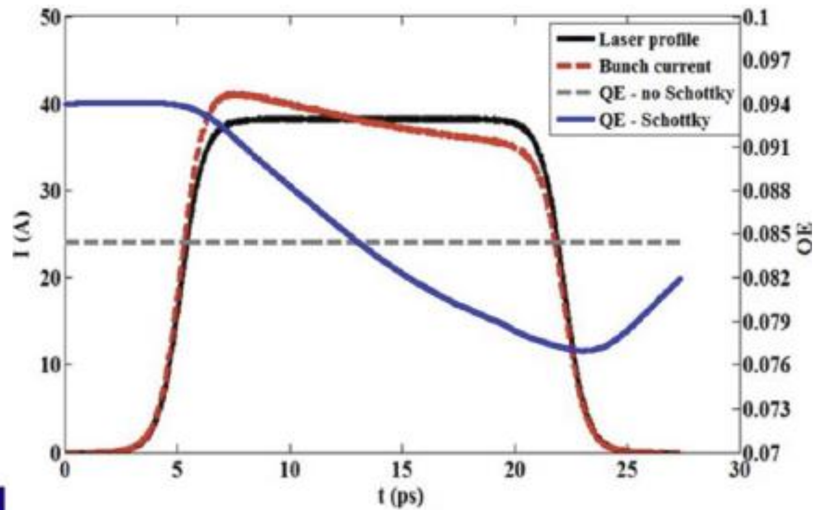


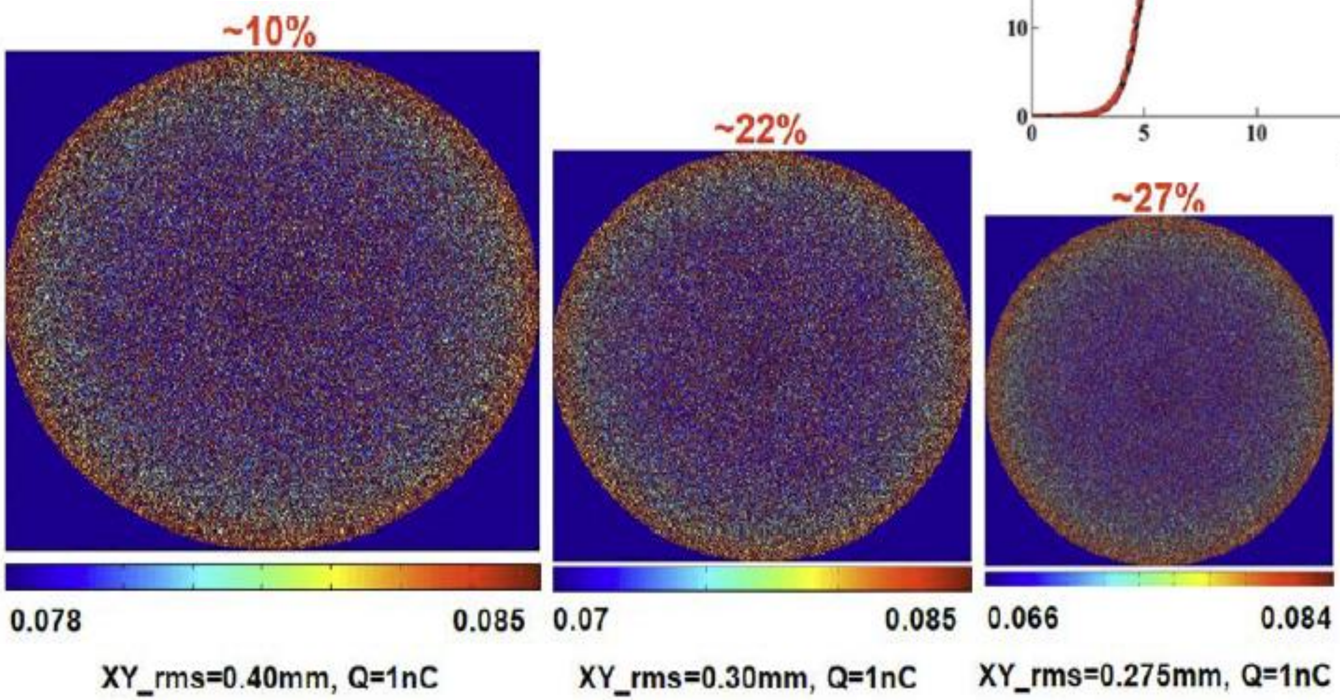
Example cathode characterization for 3 different cathodes, different RF powers, gun phases and bunch types.

Modelling emission with space charge

Schottky effect

Local modifications of cathode QE-map as well as of the temporal emission current profile





FT: 2.2-21.46-2.2ps

P_{rf} = 4.4MW

W_{laser} = 37nJ

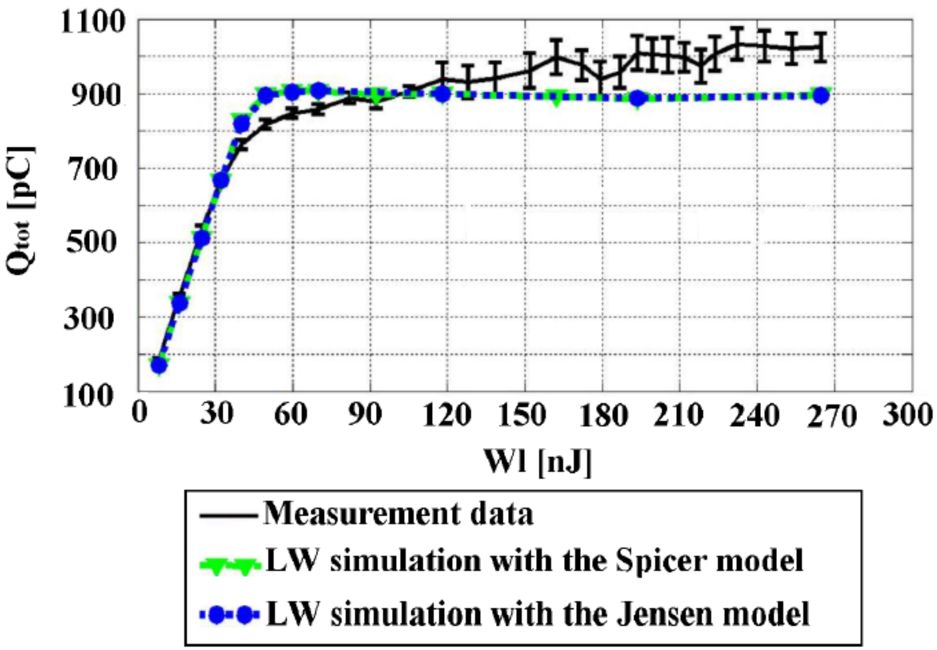
QE_{mean} = 8.8%

Q_{bunch}=1nC

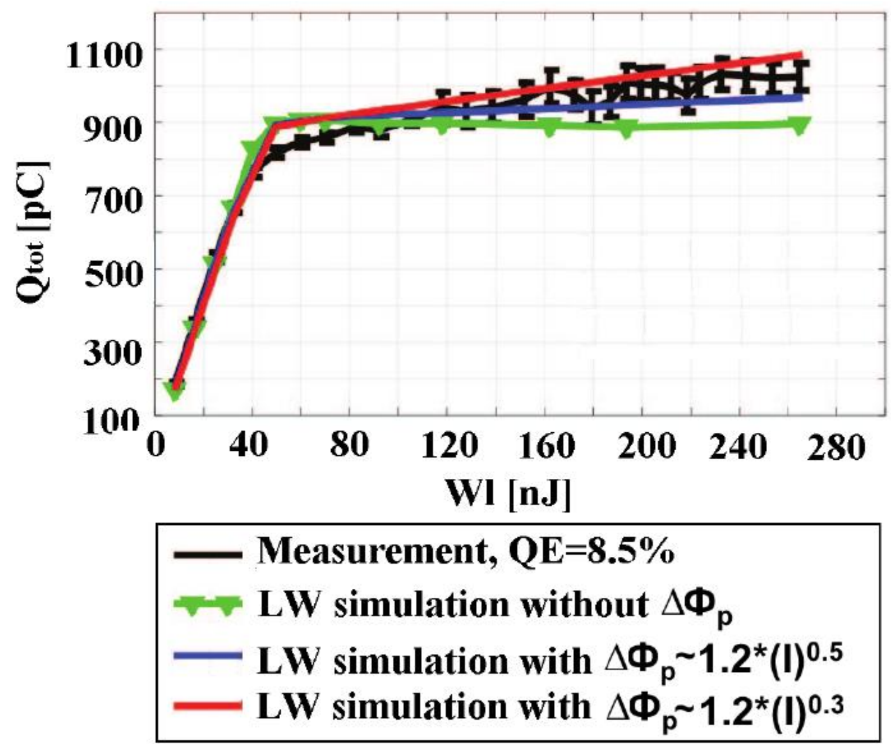
Modelling emission with space charge

Comparisons with experiment

Simulated bunch charge with Schottky effect only



Simulated bunch charge with Schottky and surface charge effect



Summary

- Space charge effects in RF photoinjectors
  - Relativistic effects in the gun
    - Fast charge expansion in the gun is important for beam emittance simulations as well as for the space charge limit of the injector
    - Relativistic corrections in space charge tracking codes are needed
  - Emission modelling with space charge
    - Calculation method for the space charge limits at different machine operation points; good agreement with measurements
    - Incorporate photoemission models into tracking codes in the source limited regime; cathode characterization
    - Modification of the longitudinal and transverse bunch profiles due to Schottky effect
    - Modification cathode QE due to surface charge limit effect at high laser pulse energies

Thank You for your attention