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DESY/TEMF Meeting - Status 2011

DESY, Hamburg, 16.12.2011

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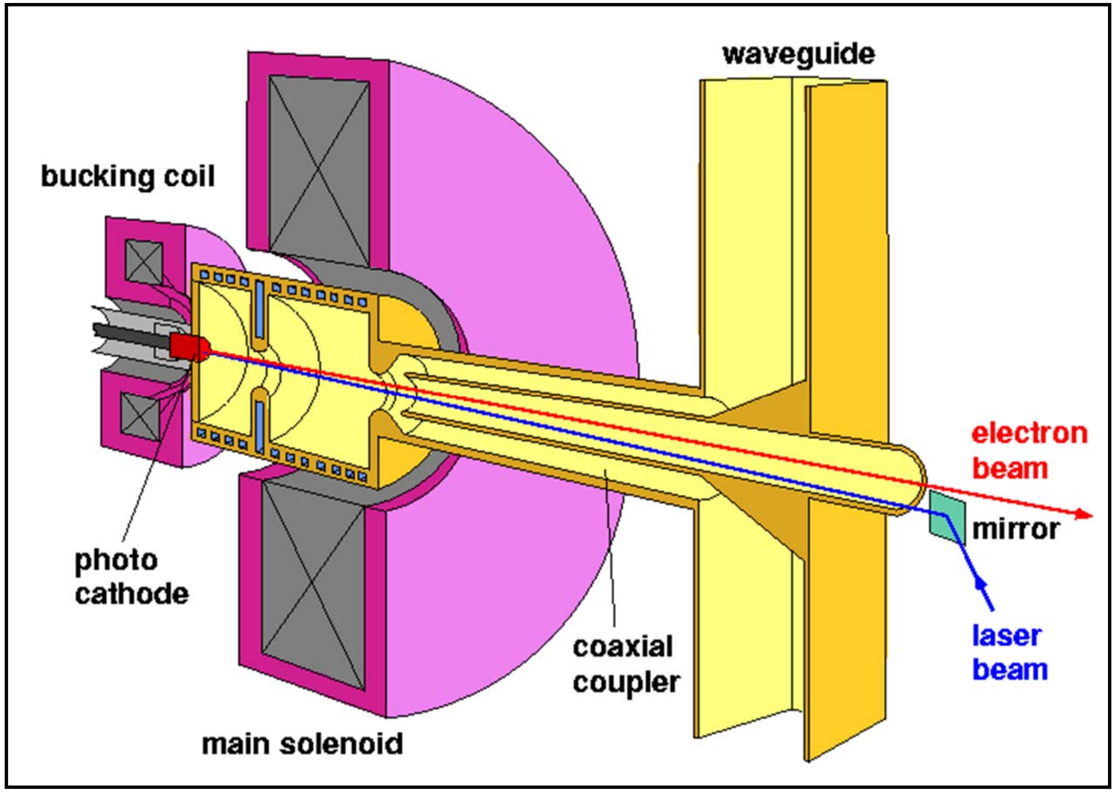
Emittance studies for the PITZ injector

Problem description



talk from M. Krasilnikov, Zeuthen, 2011

Optimized machine parameters for Q = 1nC (simulations)

	parameter	unit	value
cathode laser	temporal	profile	flat-top
	transverse	distribution	rad.homogen
	rt/FWHM\ft	ps	2/22\2
	XYrms	mm	0,401
	Ek	eV	0,55
	th.emit.	mm mrad	0,34
RF-gun	Ecath	MV/m	60,58
	phase	deg	-1,116
	maxBz	T	-0,22808
CDS boost	maxE	MV/m	20,6
	phase	deg	0
e-beam @EMSY1	charge	nC	1
	momentum	MeV/c	24,64
	proj.emit.	mm mrad	0,60
	th./proj.em.	%	57%
	<sl.emit.>	mm mrad	0,53

Emittance studies for the PITZ injector

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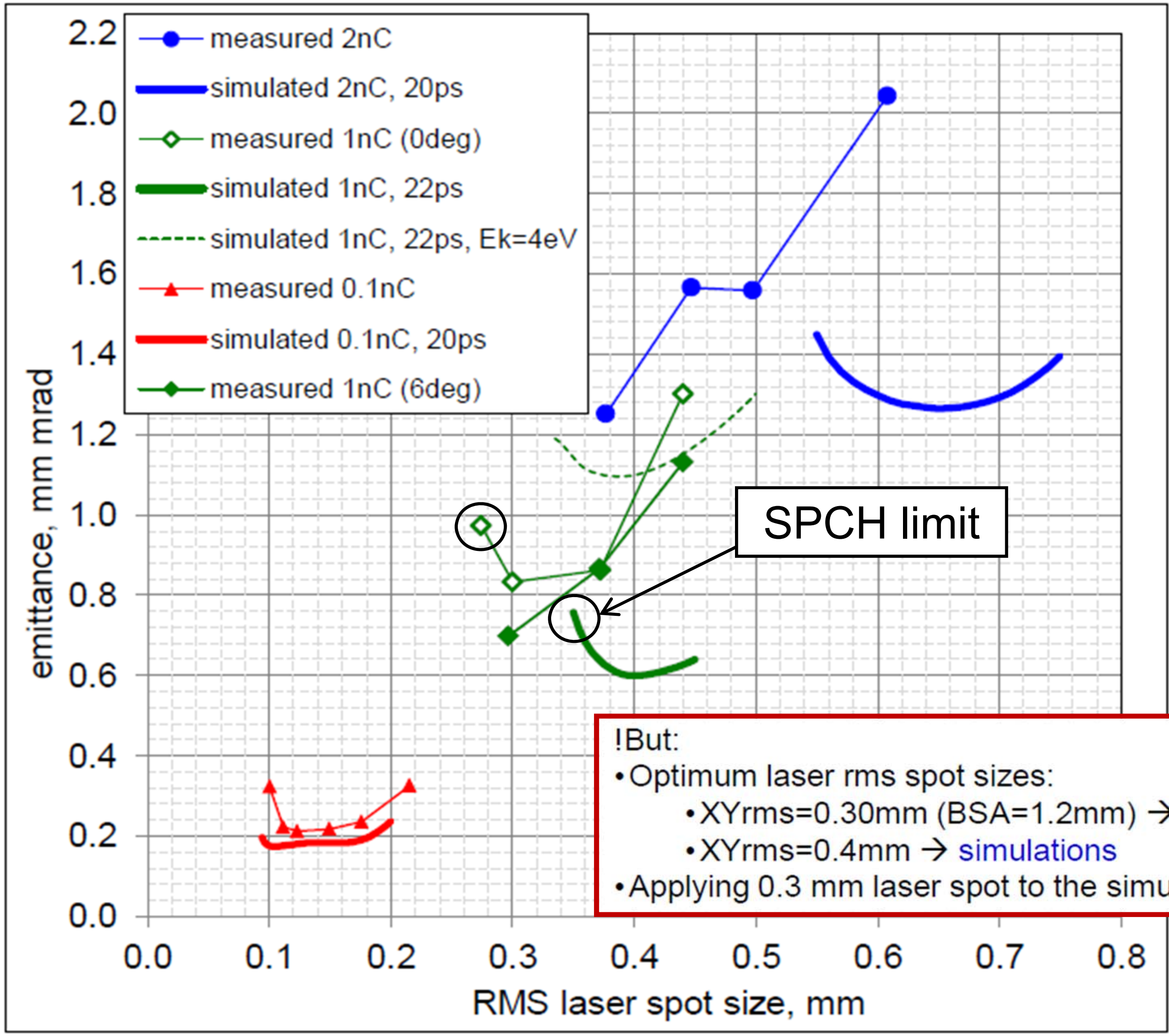

- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (good agreement for 100pC)
- Artificial increase of the thermal kinetic energy at the cathode (from 0.55eV to 4eV) did not improve the situation

talk from M. Krasilnikov, Zeuthen, 2011

!But:
- Optimum laser rms spot sizes:
  - XYrms=0.30mm (BSA=1.2mm) → experimentally
  - XYrms=0.4mm → simulations
- Applying 0.3 mm laser spot to the simulation – it is impossible to produce 1nC!

Emittance studies for the PITZ injector

Problem description

- Sources of discrepancy:
  - Thermal energy spread at cathode
  - Oxide layer effects and cathode impurities
  - Limited knowledge of machine conditions during measurement
  - Emittance measurement – slit scan technique
  - Wakefields
  - …
  - Improper modeling of radiation fields?
  - Inaccurate simulation of the emission process?

Emittance studies for the PITZ injector

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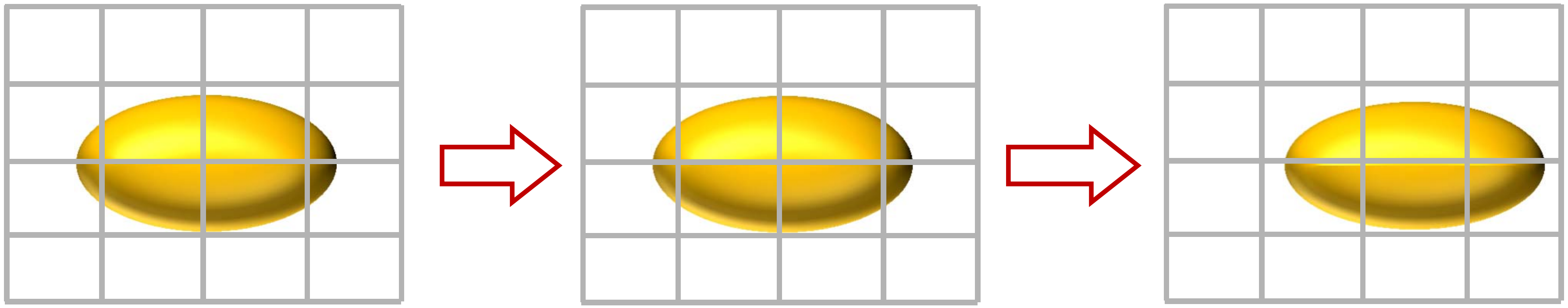
Problem description

Bring particles to computational grid | Solve for electrostatic field on the grid (DFT) | Push particle positions and momenta



Transform to average rest frame | **Transform (fields) back to lab frame**

- Boosted frame approach (ASTRA):
  - Retardation effects due to relative motion within bunch?
  - Acceleration radiation?
  - Relativistic correction for mirror charge fields?

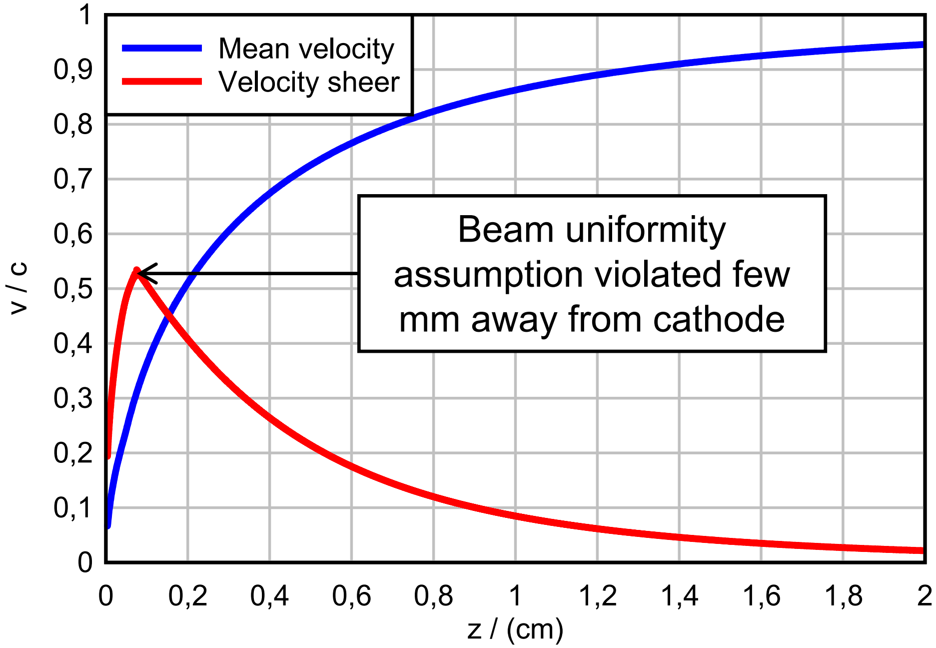
Beam dynamics in the boosted frame

Problem description

- Field of accelerated point charge:

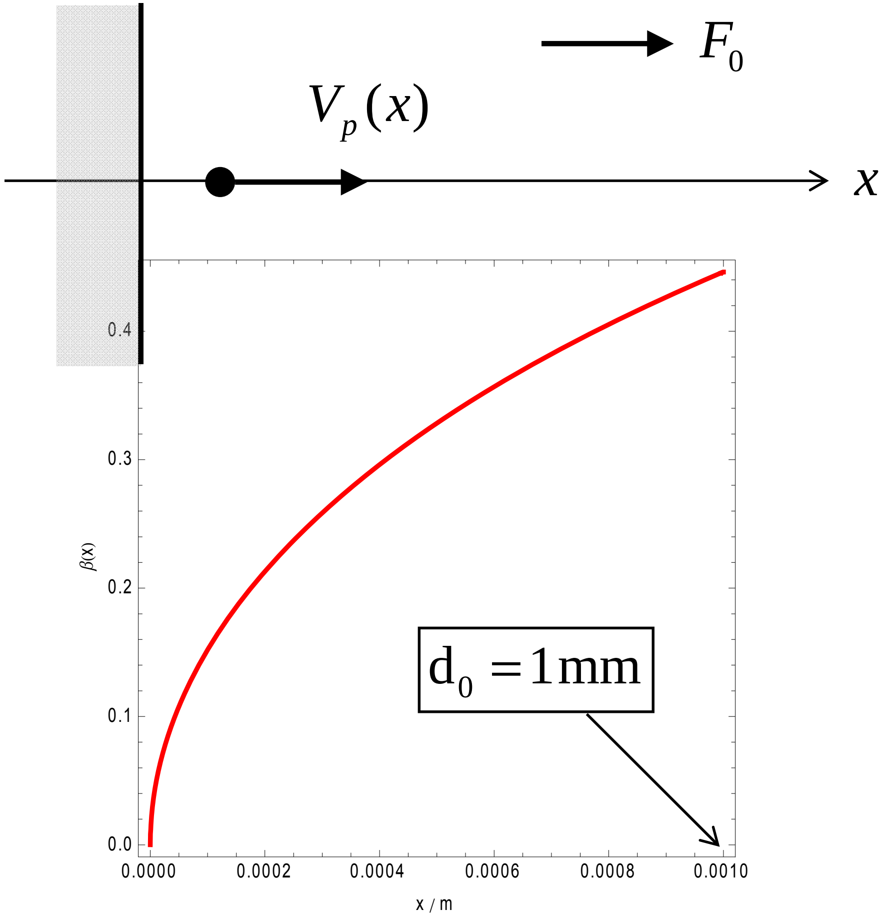
$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0}\left[\underbrace{\frac{(\mathbf{n}-\boldsymbol{\beta})\left(1-|\boldsymbol{\beta}|^2\right)}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2}}_{\text{retardation}} + \underbrace{\frac{\mathbf{n}\times(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3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

Velocity sheer
(space charge free simulation)



- Retardation only wrt. mean bunch motion
- Effect is stronger when space charge is included
- Effect is stronger when mirror charges are considered

Effect of retardation for single electron fields

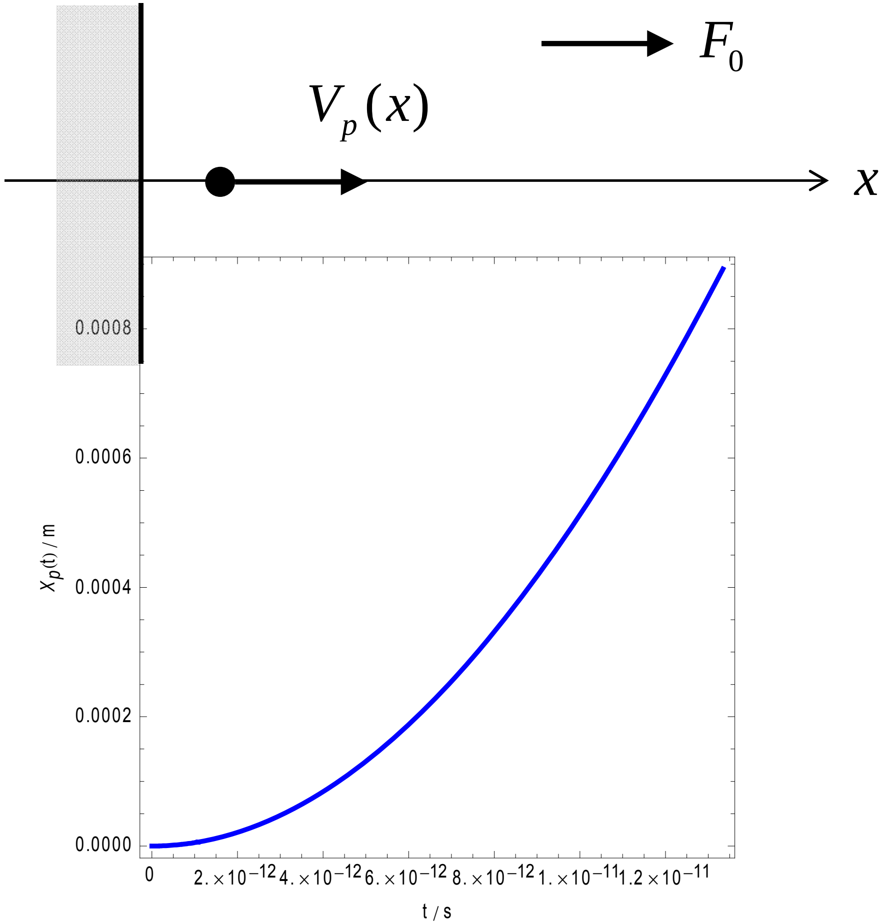


$$m = m_0$$
$$q = -e_0$$
$$F_0 = e_0 E_0$$
$$E_0 = 60\ \mathrm{MV/m}$$

$$\frac{m\, v(x)\, v'(x)}{\left(1 - \frac{v(x)^2}{c^2}\right)^{3/2}} = F_0, \quad v(0) = 0$$

$$\Rightarrow V_p(x) = \frac{c\sqrt{F_0 x (2c^2 m + F_0 x)}}{c^2 m + F_0 x}$$

Effect of retardation for single electron fields

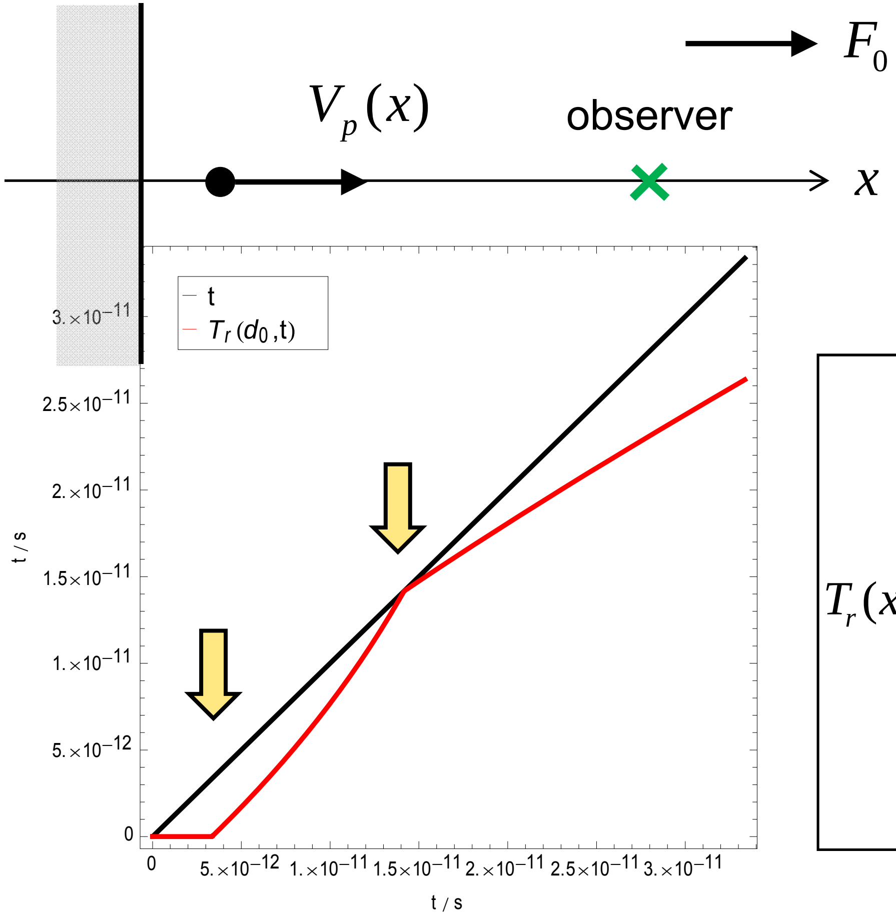


$$m = m_0$$
$$q = -e_0$$
$$F_0 = e_0 E_0$$
$$E_0 = 60 \text{ MV/m}$$

$$\frac{m\, v(x)\, v'(x)}{\left(1 - \frac{v(x)^2}{c^2}\right)^{3/2}} = F_0, \quad v(0) = 0$$

$$\Rightarrow X_p(t) = \frac{c\left(\sqrt{c^2 m^2 + F_0^2 t^2} - cm\right)}{F_0}$$

Effect of retardation for single electron fields



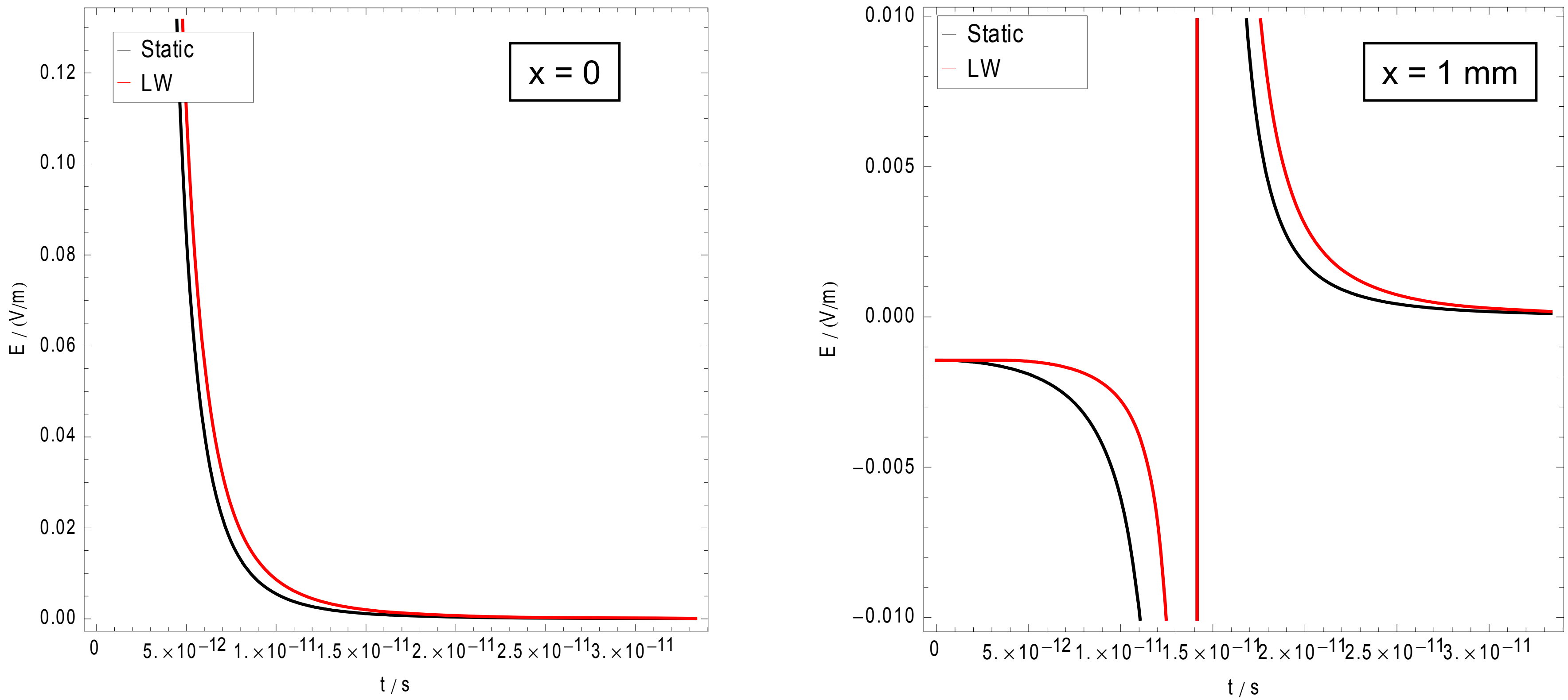
Retardation time at arbitrary observer position as a function of time:

$$T_r(x,t) = t - \frac{|x - X_p[T_r(x,t)]|}{c}$$

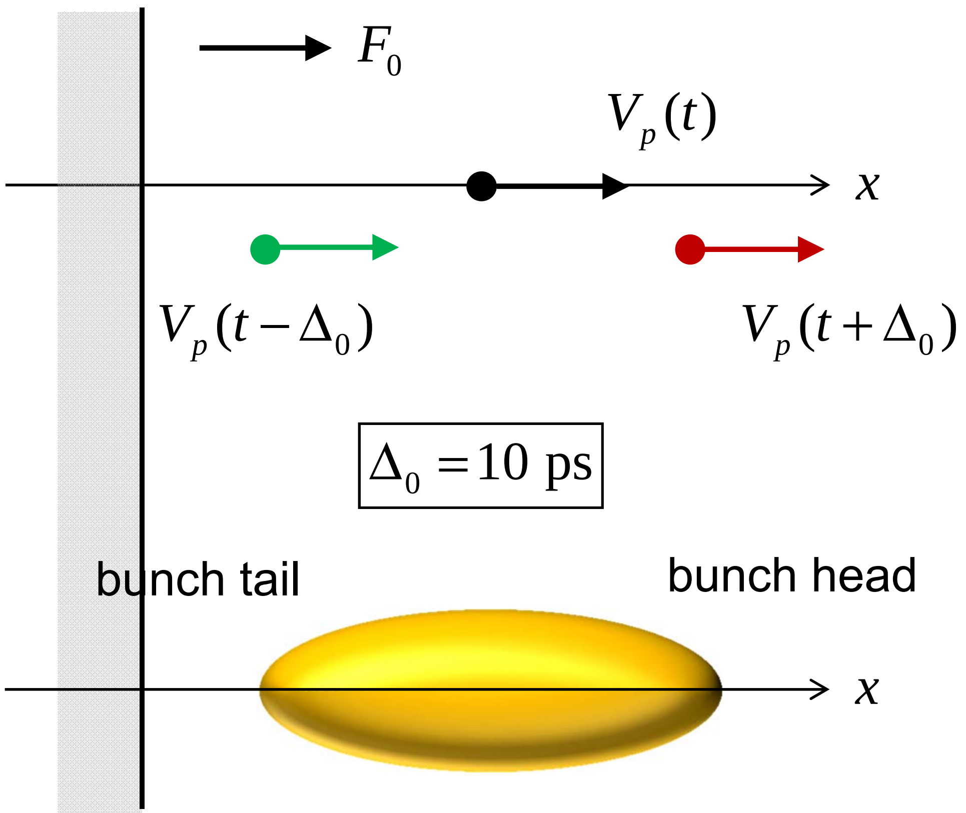
$$T_r(x,t) = \begin{cases} \dfrac{(ct-x)\left[2c^2m + F_0(x-ct)\right]}{2c[c^2m + F_0(x-ct)]}, & ct > x > X_p(t) \\ \dfrac{(ct+x)\left[2c^2m + F_0(x+ct)\right]}{2c^3m + 2cF_0(ct+x)}, & x < X_p(t) \\ 0, & x > ct \end{cases}$$

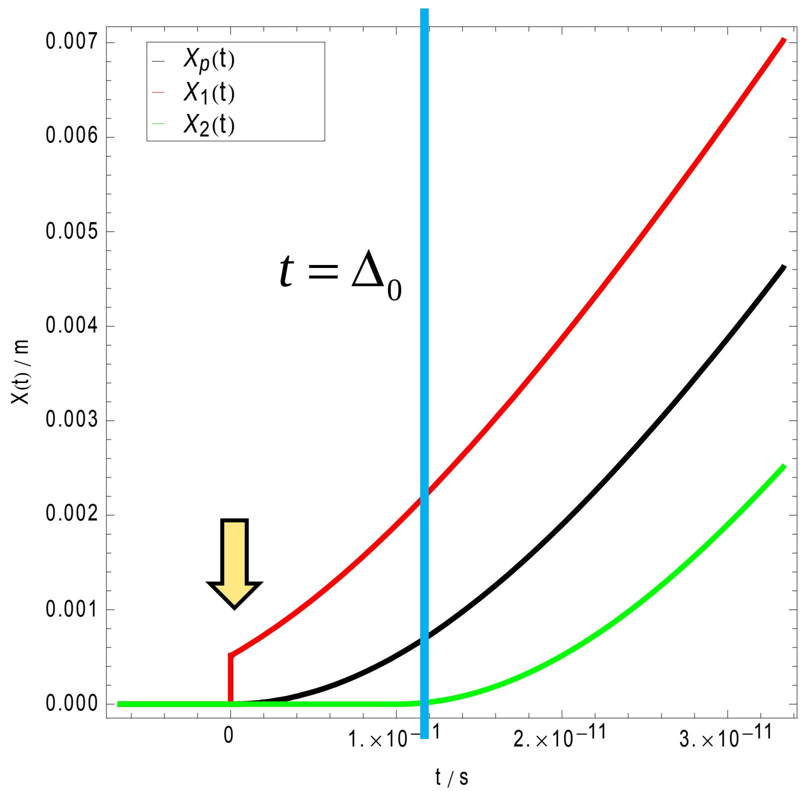
Effect of retardation for single electron fields

Electron fields at fixed positions



Effect of retardation for single electron fields





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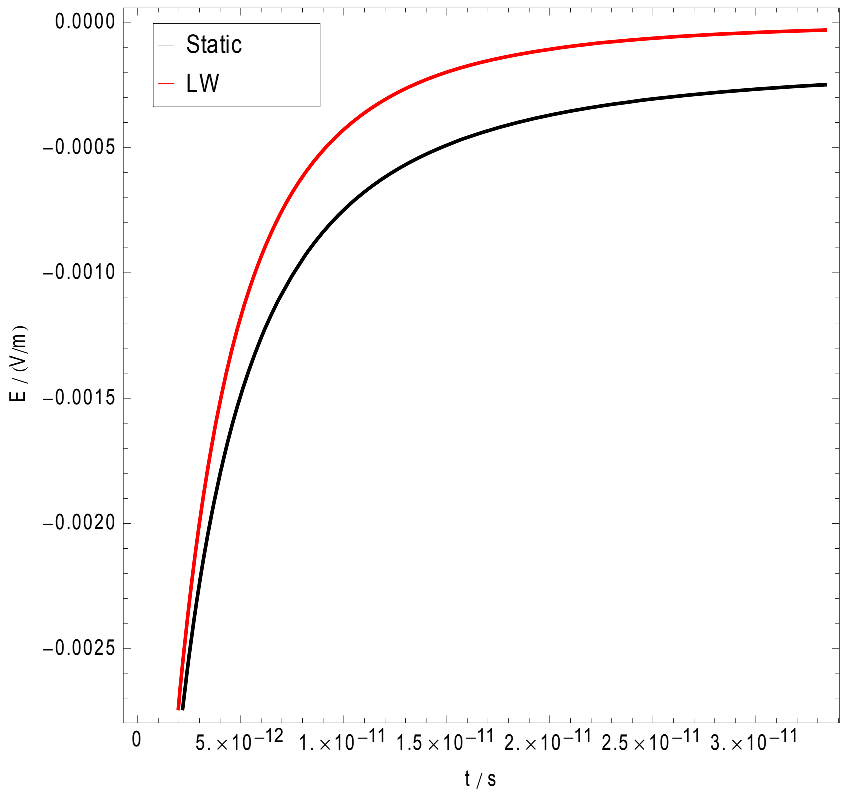
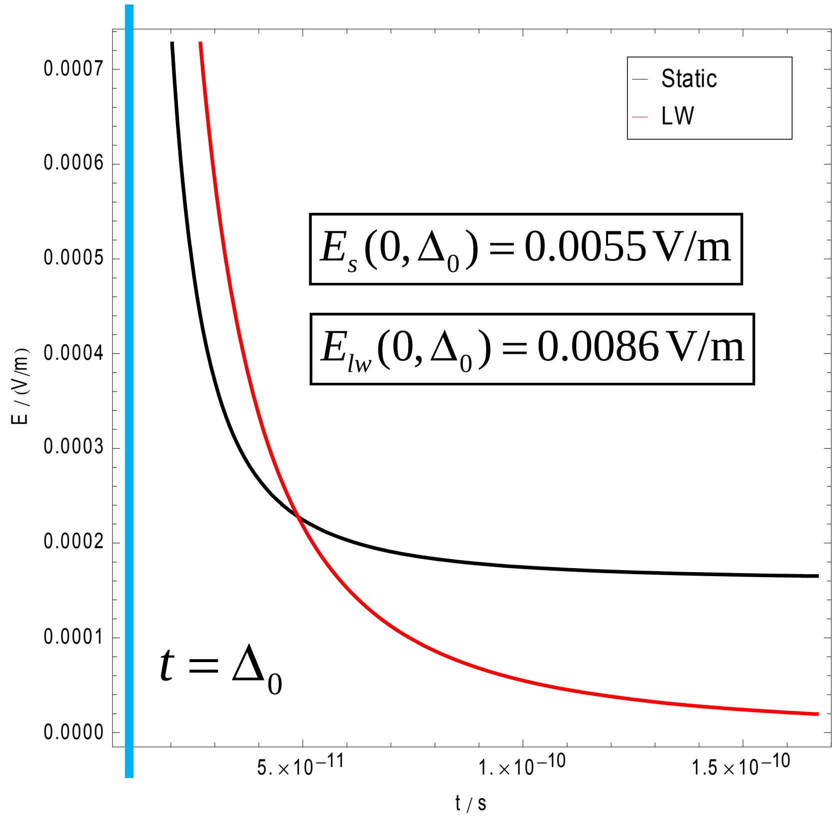
Effect of retardation for single electron fields

Fields at head particle



Fields at tail particle



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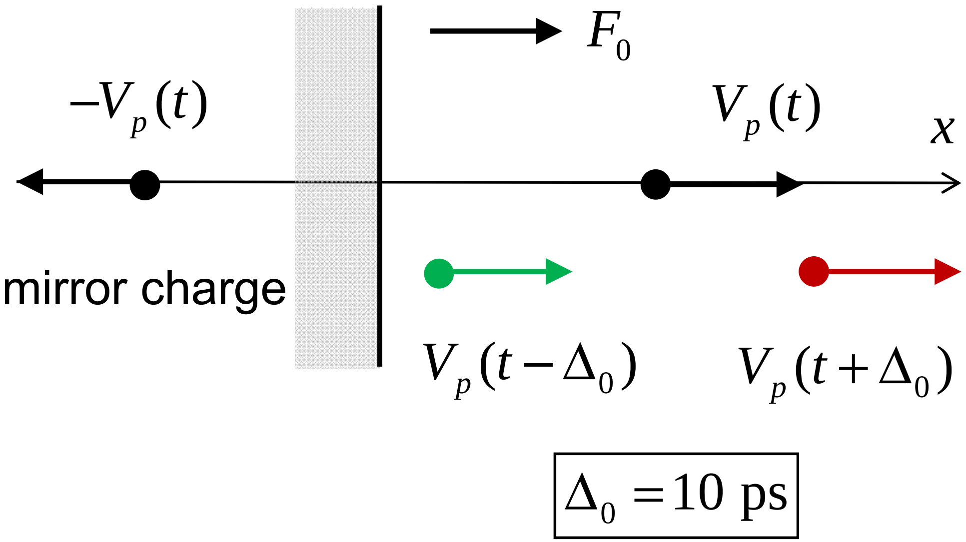
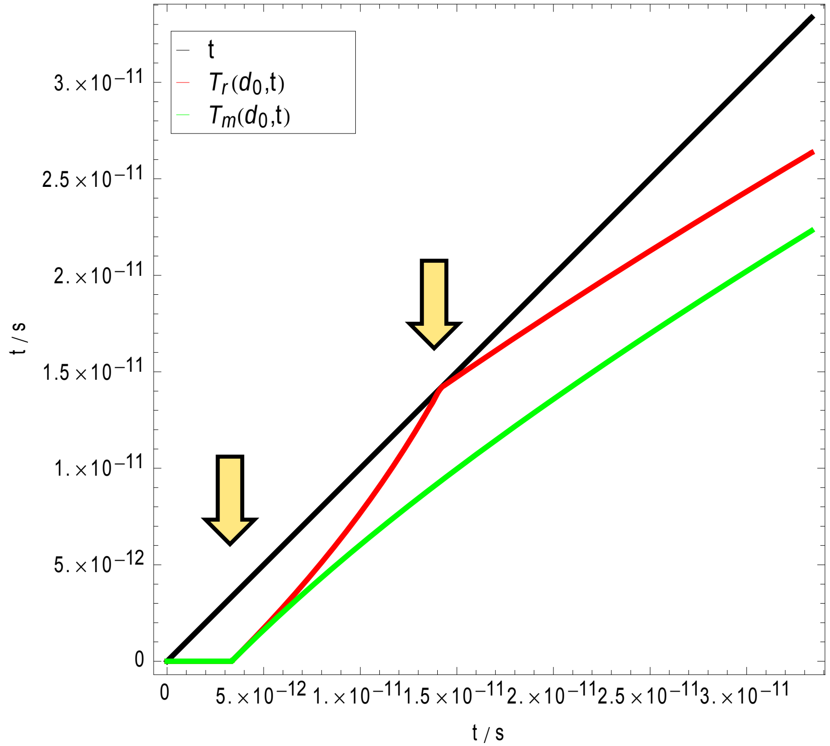
Effect of retardation for single electron fields

- Add mirror charge at conducting surface

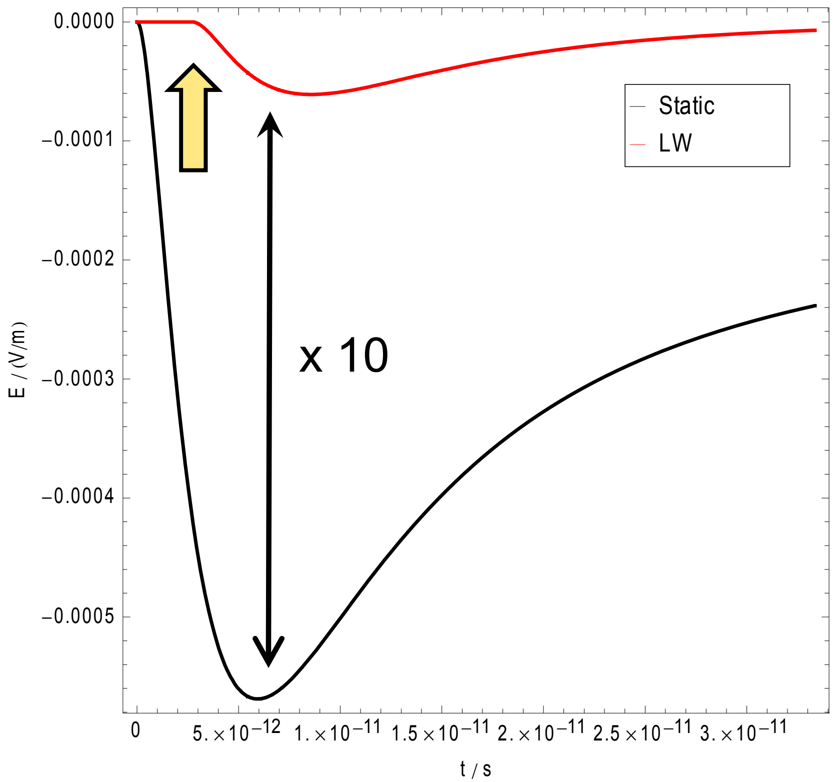


Retardation times of particle and its mirror

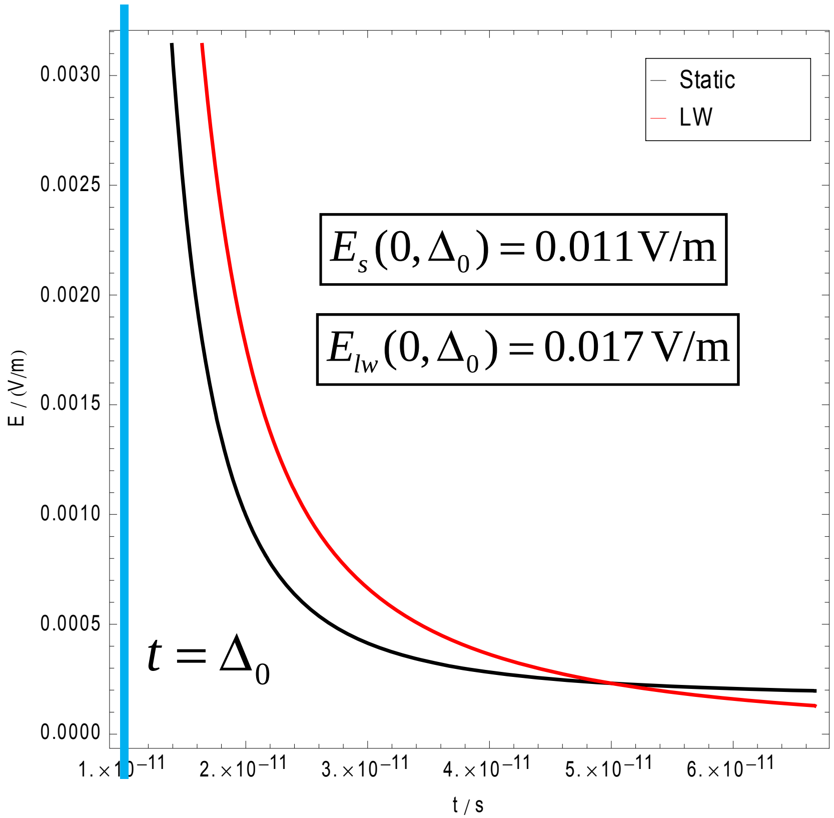


Effect of retardation on single electron dynamics

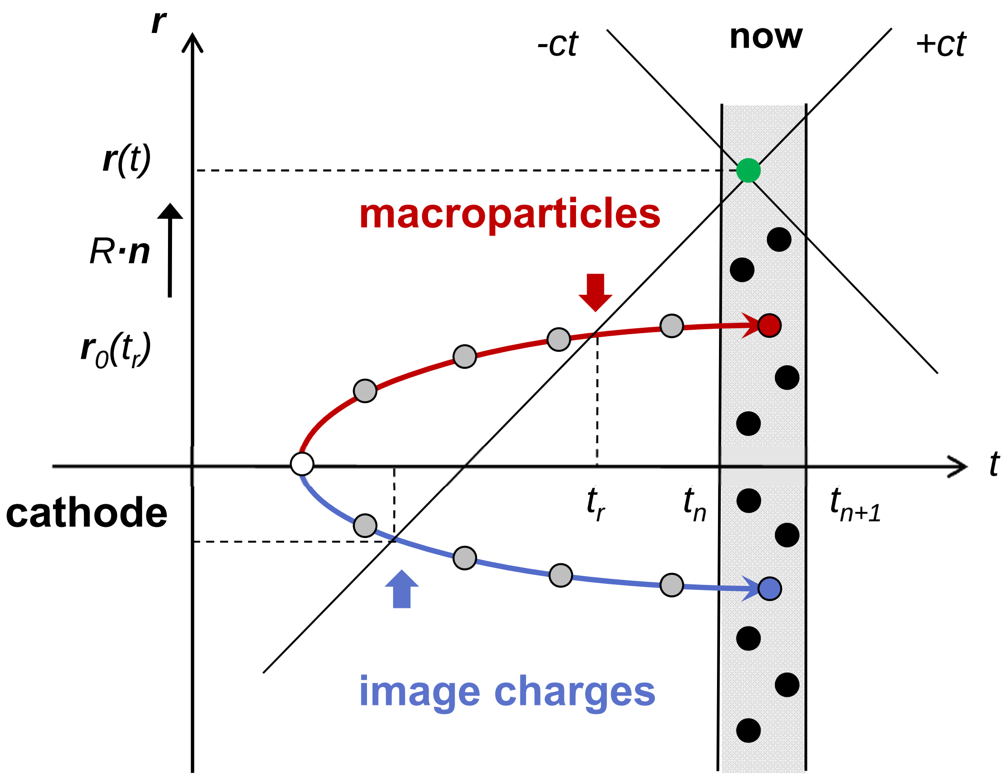
Total fields at head particle



Total fields at tail particle



Lienard-Wiechert particle-particle approach



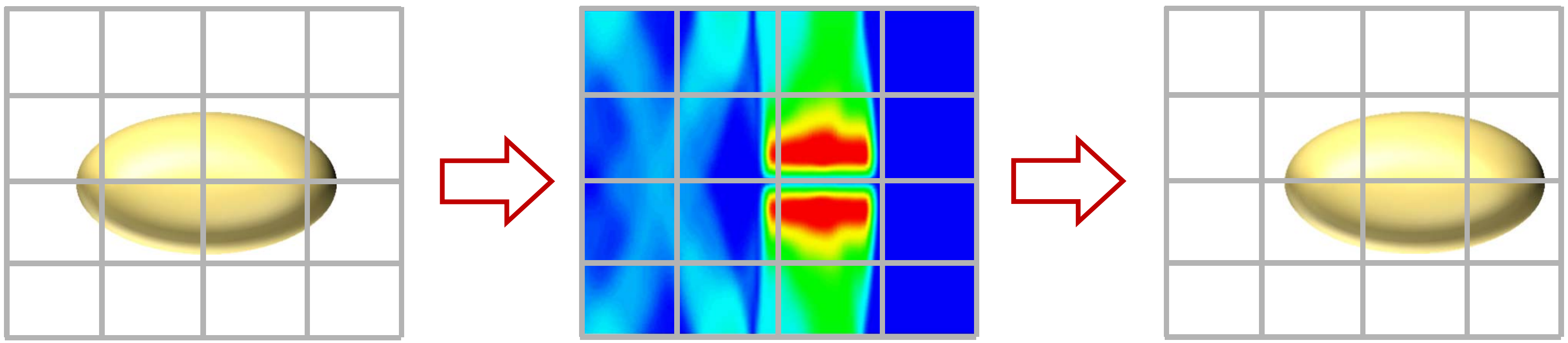
- Store full particle history – huge memory
- Search at every time step retarded times and positions for all particle positions - $N_p^2 \cdot N_t$ operations
- Full physics
- Accuracy depends only on
  - Time step
  - Number of particles

The PIC approach

Bring particles to computational grid

Solve full set of Maxwell equations on the grid

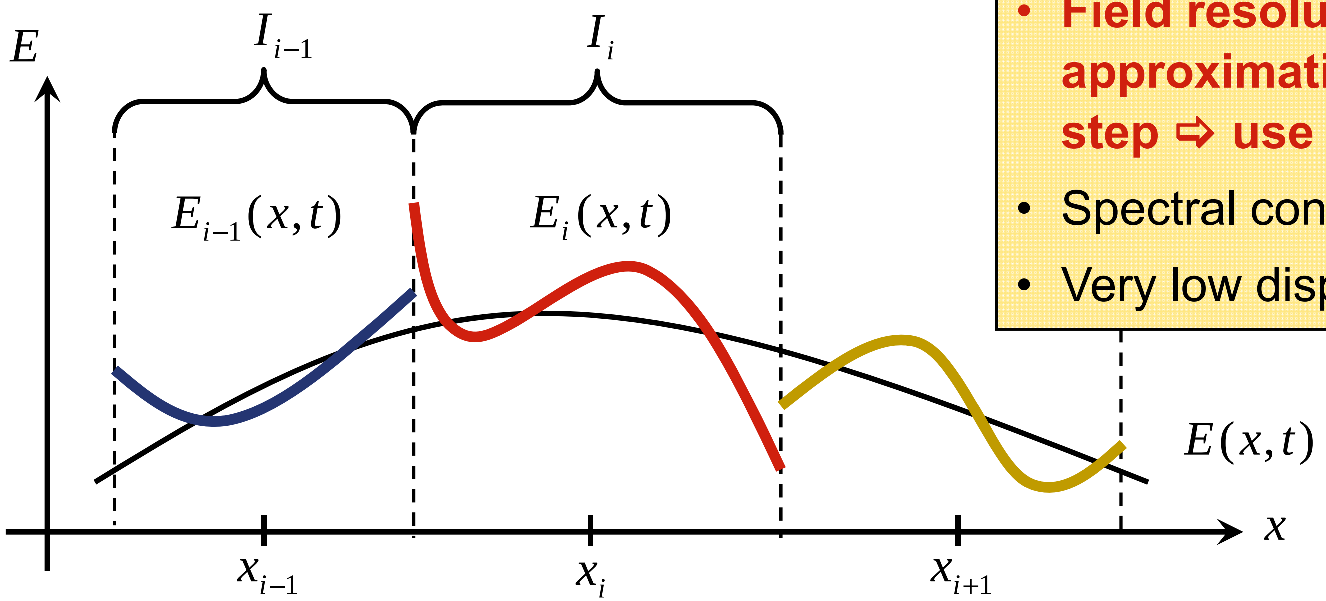
Push particle positions and momenta



- Includes all effects; can handle arbitrary geometry
- Numerically more efficient then LW approach
- Accuracy depends on: accuracy of field solution, number of particles, current smoothing, time step,…

High order DG-FEM method

- Very accurate field solutions using piecewise high order polynomial approximation with grid cells (DG-FEM)*



- **Field resolution is given by approximation order not by grid step ⇨ use sparse grids**
- Spectral convergence (wrt. order)
- Very low dispersion errors

* *E. Gjonaj at al., New J. of Phys., Vol. 8, (2006), pp. 1-21*

Charge conserving current interpolation

- Macroparticle current density:

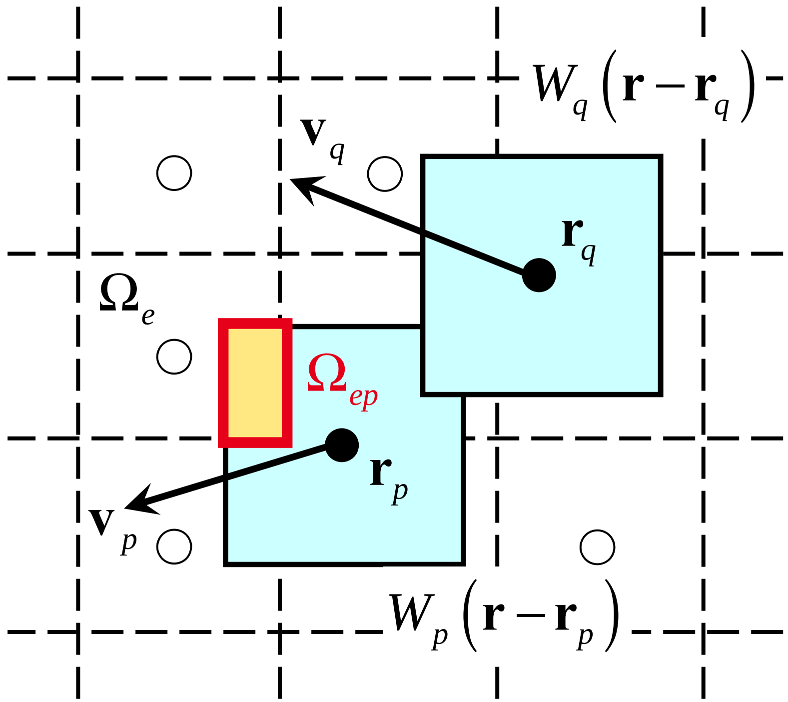
$$\mathbf{j}(\mathbf{r},t) = \sum_p Q_p \mathbf{v}_p(t) W_p\left[\mathbf{r} - \mathbf{r}_p(t)\right]$$

- DG-FEM current projection:

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

- Discrete current / time step / cell:

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



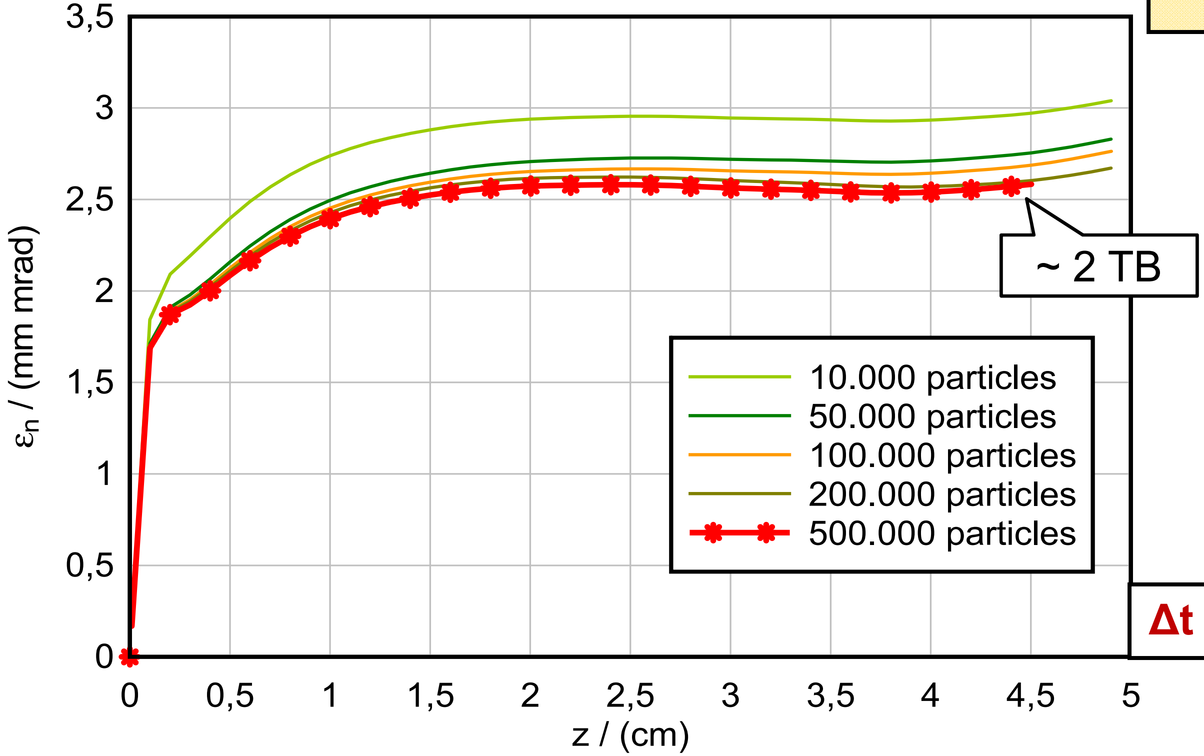
- **Choice of particle size most critical parameter for simulation accuracy**

Emittance studies for the PITZ injector

Beam dynamics in the gun: LW simulations

Q = 1 nC
XY_rms = 0.75 mm
non-optimized setup
(data from 2010)

Projected transverse emittance for different particle numbers



Δt = 0.1 ps

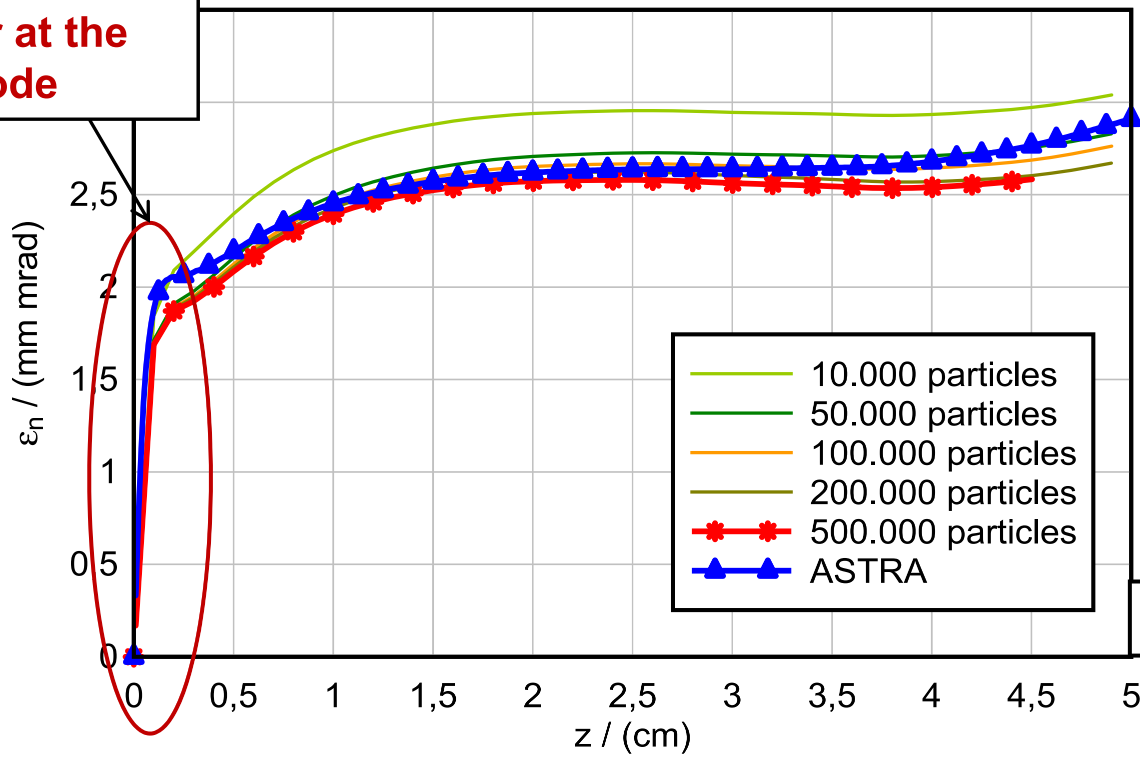
Emittance studies for the PITZ injector

Beam dynamics in the gun: LW simulations

Q = 1 nC
XY_rms = 0.75 mm
non-optimized setup
(data from 2010)

systematic different behavior at the cathode

Projected transverse emittance: comparison with ASTRA



Δt = 0.1 ps

Emittance studies for the PITZ injector

Beam dynamics in the gun: PIC simulations

Q = 1 nC
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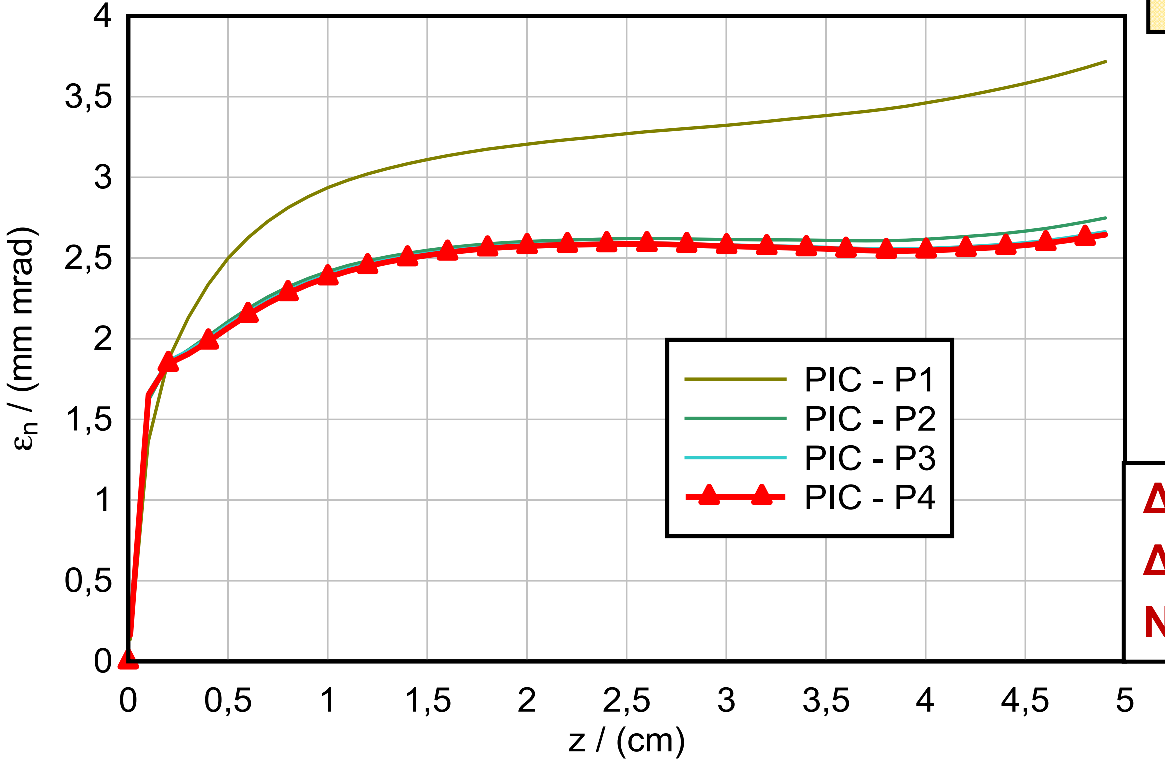
non-optimized setup
(data from 2010)

Projected transverse emittance for different approximation orders



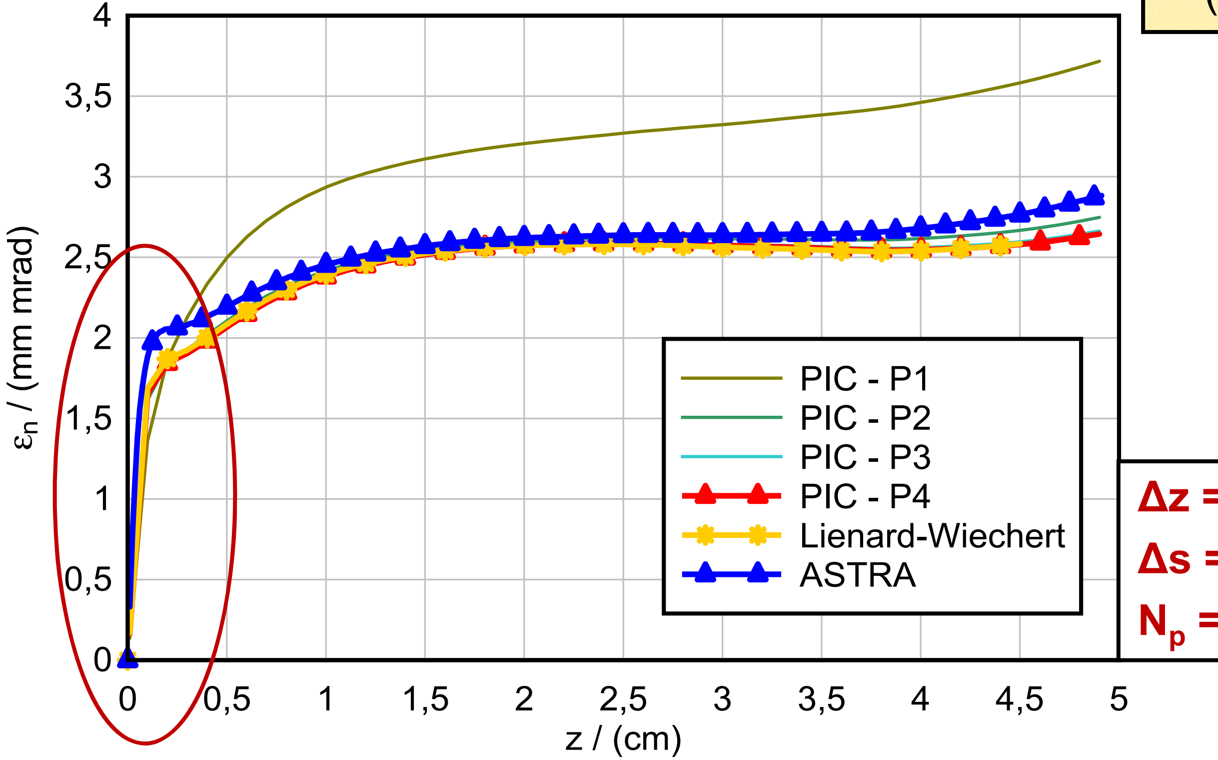
Δz = 1 mm
Δs = 10 μm
N_p = 50.000

Emittance studies for the PITZ injector

Beam dynamics in the gun: PIC simulations

Q = 1 nC
XY_rms = 0.75 mm
non-optimized setup
(data from 2010)

Projected transverse emittance for different approximation orders



Δz = 1 mm
Δs = 20 μm
N_p = 50.000

Emittance studies for the PITZ injector

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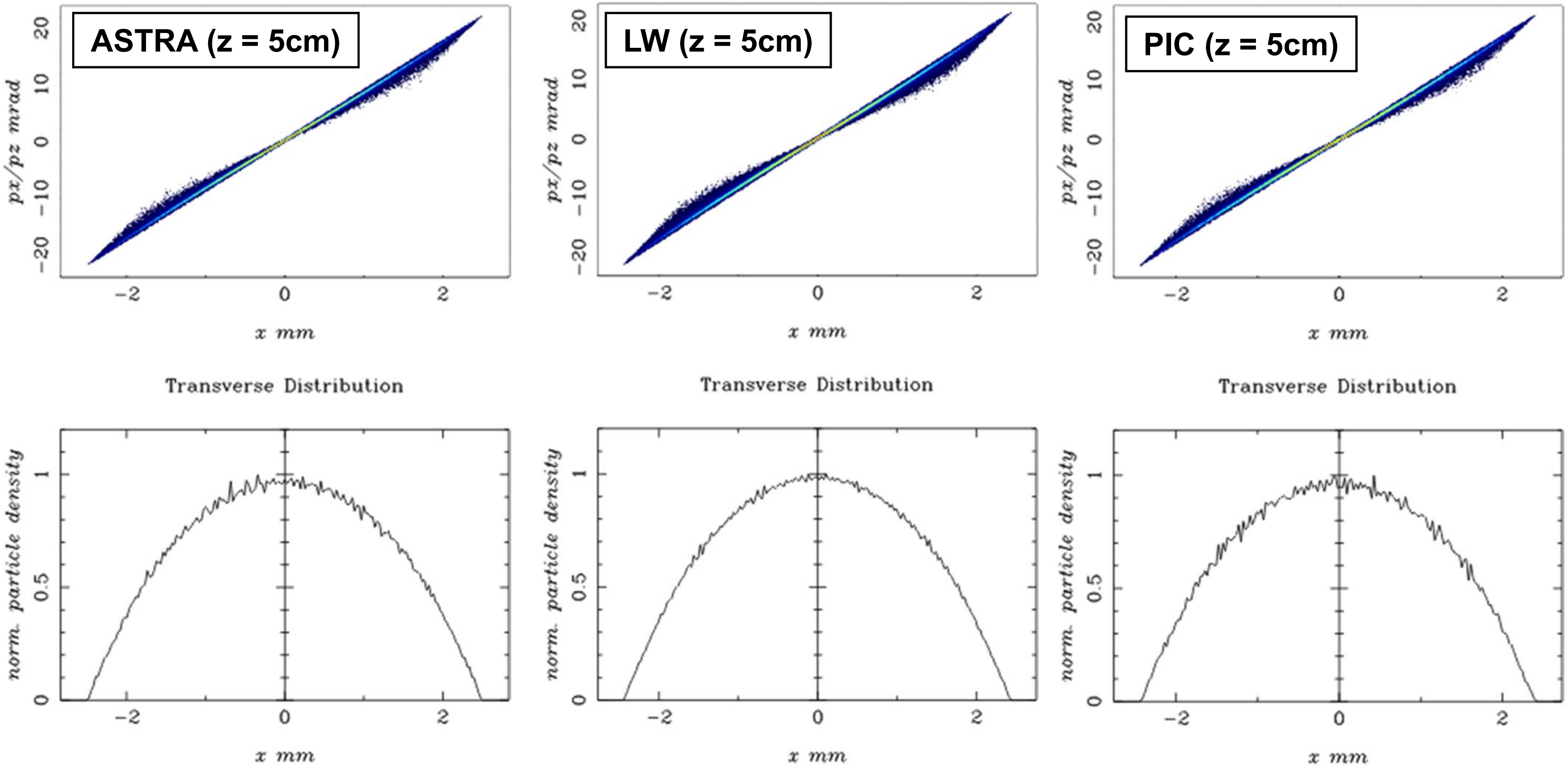
Beam dynamics in the gun

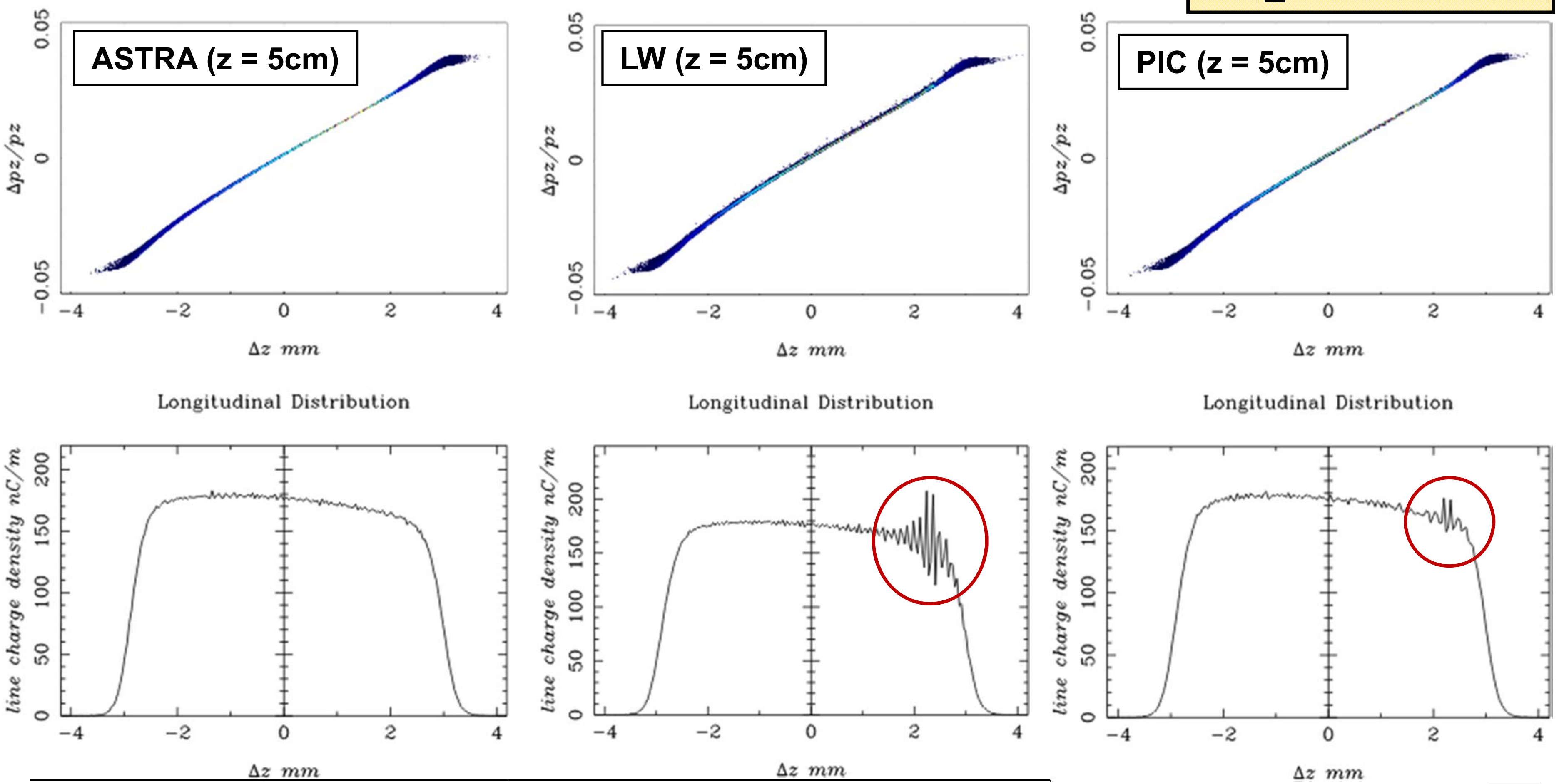
Q = 1 nC
XY_rms = 0.75 mm



Emittance studies for the PITZ injector

Beam dynamics in the gun

Q = 1 nC
XY_rms = 0.75 mm



Emittance studies for the PITZ injector

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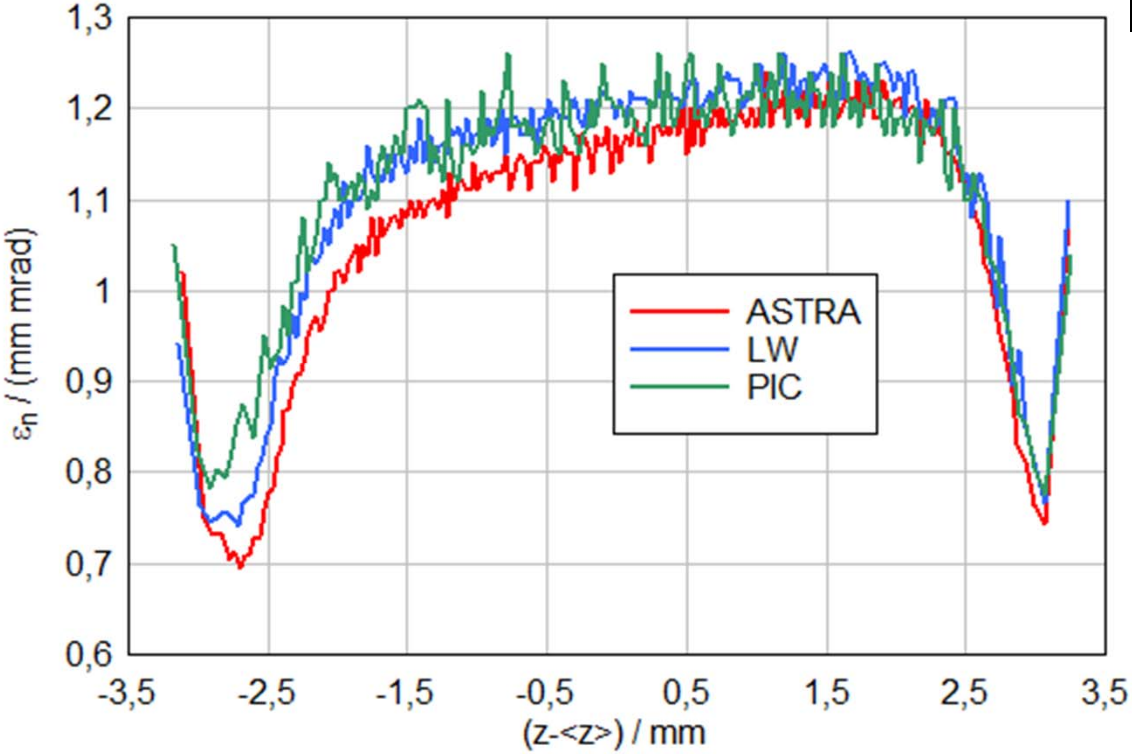
Beam dynamics in the gun

Q = 1 nC
XY_rms = 0.75 mm
non-optimized setup
(data from 2010)

Slice emittances for the different codes (z = 5 cm)



Emittance studies for the PITZ injector

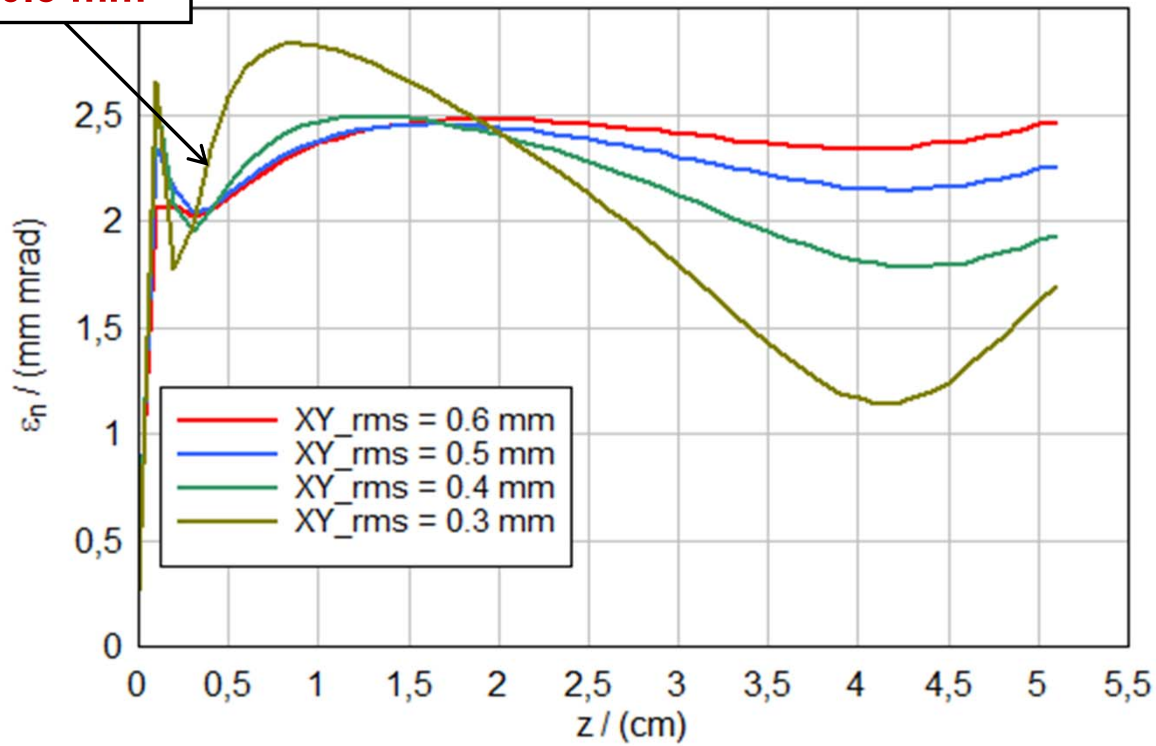
Beam dynamics for PITZ-1.8 setup

Q = 1 nC

PITZ-1.8 setup
(M. Krasilnikov, 2011)

no SPCH limiting at
XY_rms = 0.3 mm

Projected transverse emittance for
different XY_rms sizes



Emittance studies for the PITZ injector

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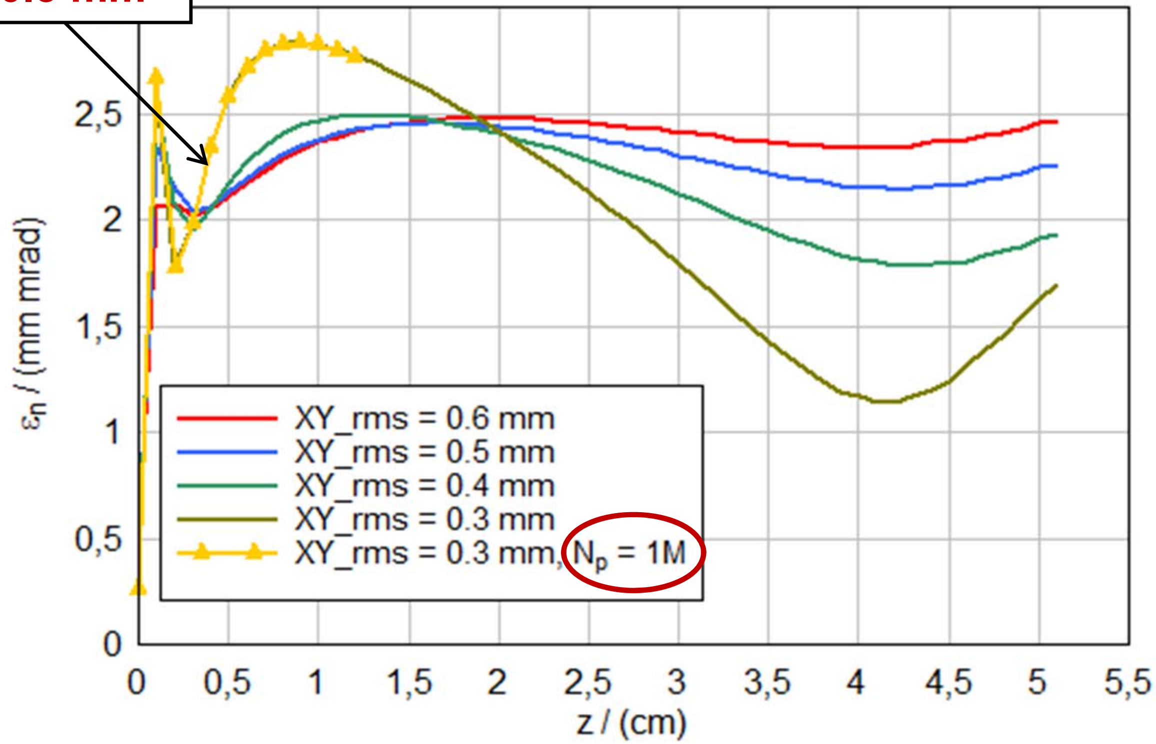
Beam dynamics for PITZ-1.8 setup

Q = 1 nC

PITZ-1.8 setup
(M. Krasilnikov, 2011)

no SPCH limiting at XY_rms = 0.3 mm

Projected transverse emittance for different XY_rms sizes



Emittance studies for the PITZ injector

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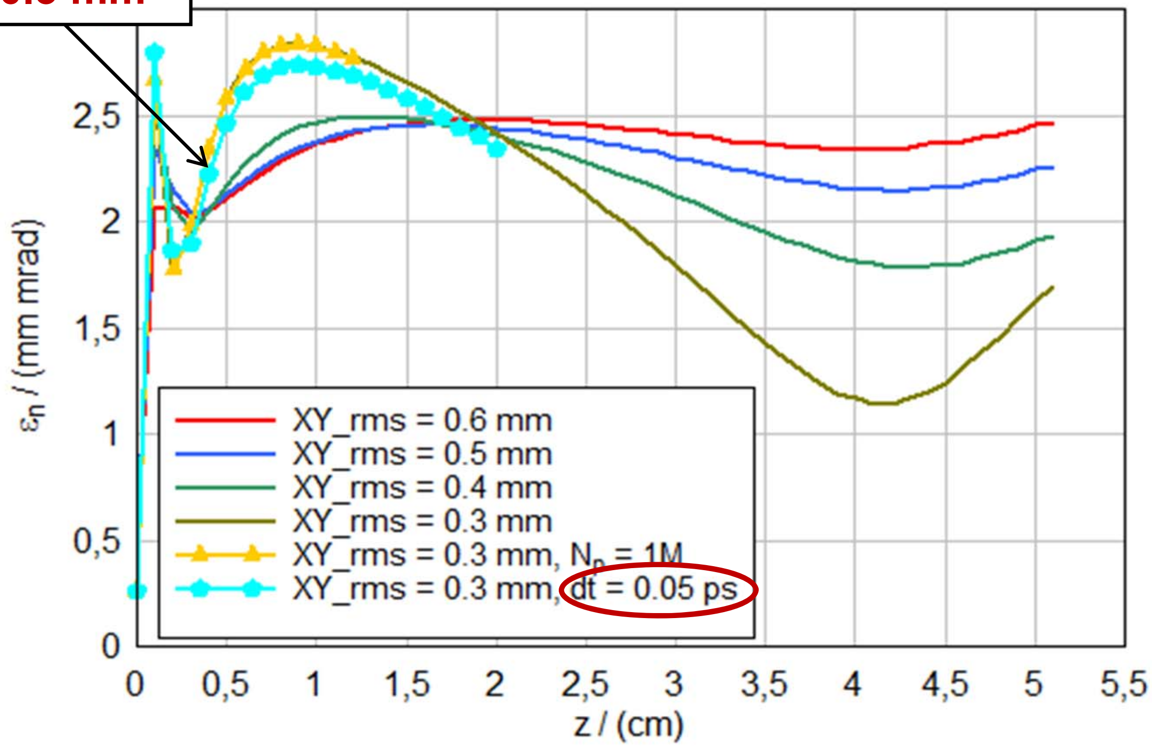
Beam dynamics for PITZ-1.8 setup

Q = 1 nC

PITZ-1.8 setup
(M. Krasilnikov, 2011)

no SPCH limiting at XY_rms = 0.3 mm

Projected transverse emittance for different XY_rms sizes



Emittance studies for the PITZ injector

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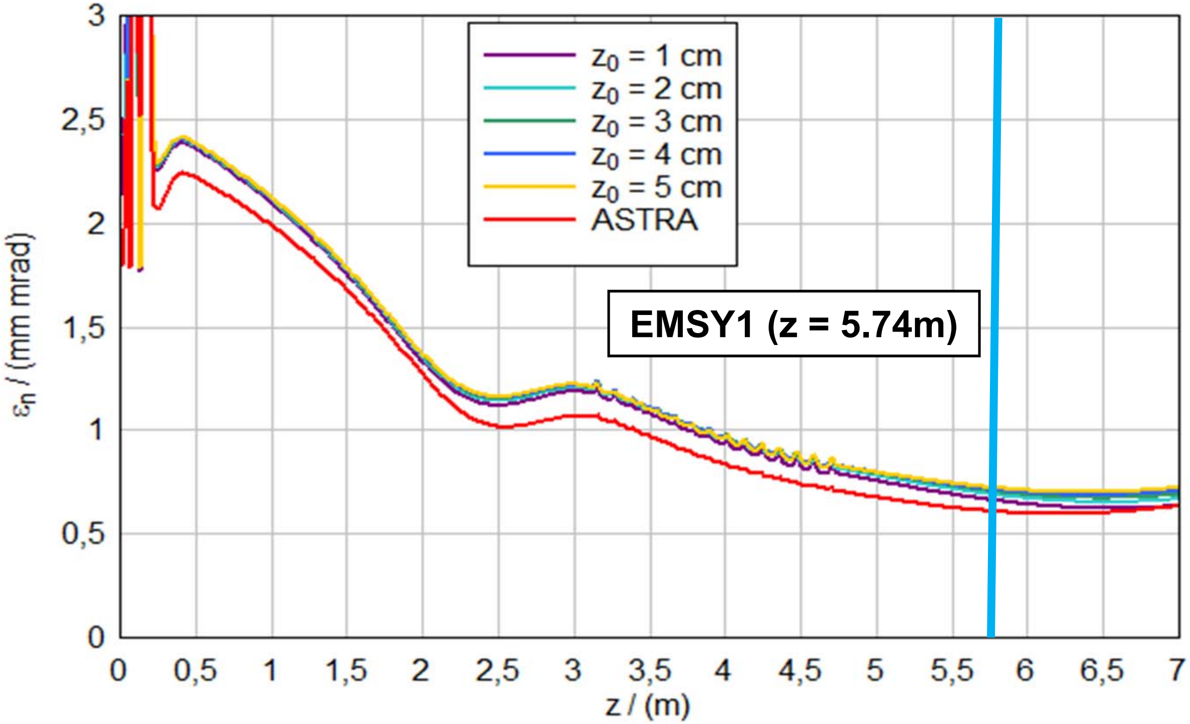
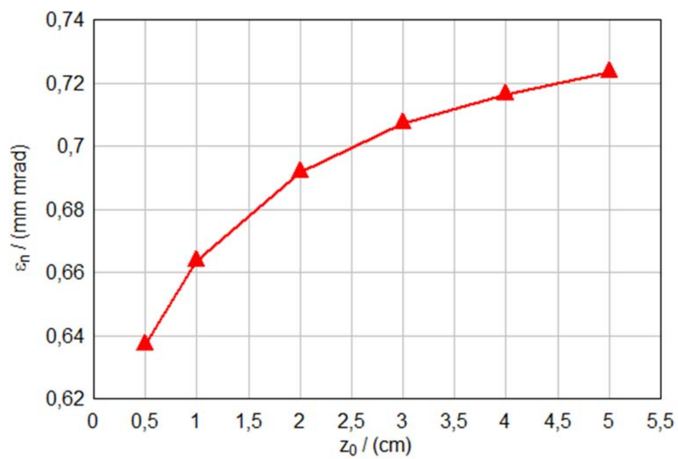
Beam dynamics for PITZ-1.8 setup

- Restarted ASTRA simulations with LW bunch as initial distribution

Q = 1 nC
XY_rms = 0.4 mm
PITZ-1.8 setup
(M. Krasilnikov, 2011)



Emittance at EMSY1 vs. z_0



Emittance studies for the PITZ injector

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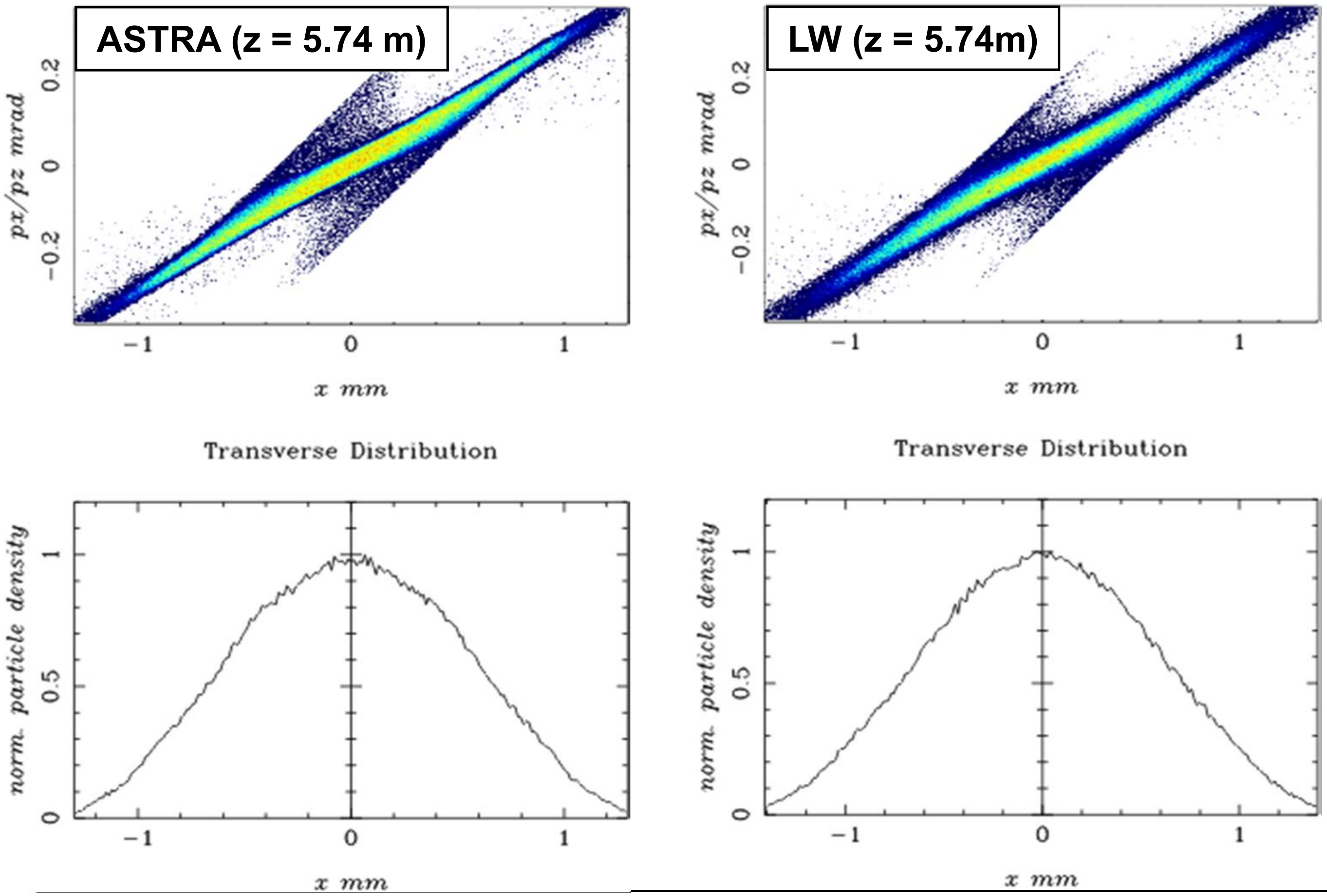
Beam dynamics for PITZ-1.8 setup



Q = 1 nC

XY_rms = 0.4 mm

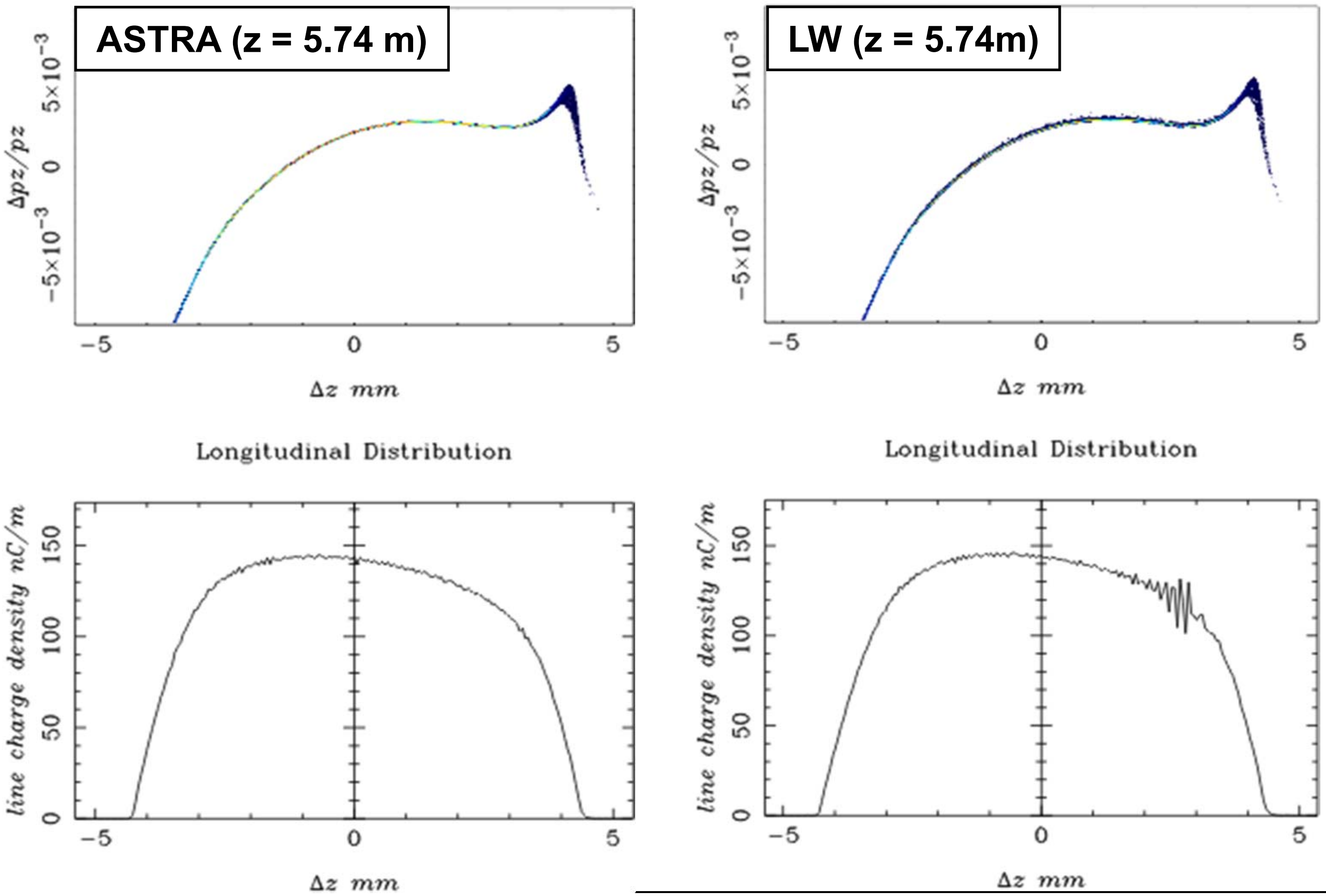
PITZ-1.8 setup

(M. Krasilnikov, 2011)

Emittance studies for the PITZ injector

Beam dynamics for PITZ-1.8 setup

Q = 1 nC
XY_rms = 0.4 mm
PITZ-1.8 setup
(M. Krasilnikov, 2011)



Emittance studies for the PITZ injector

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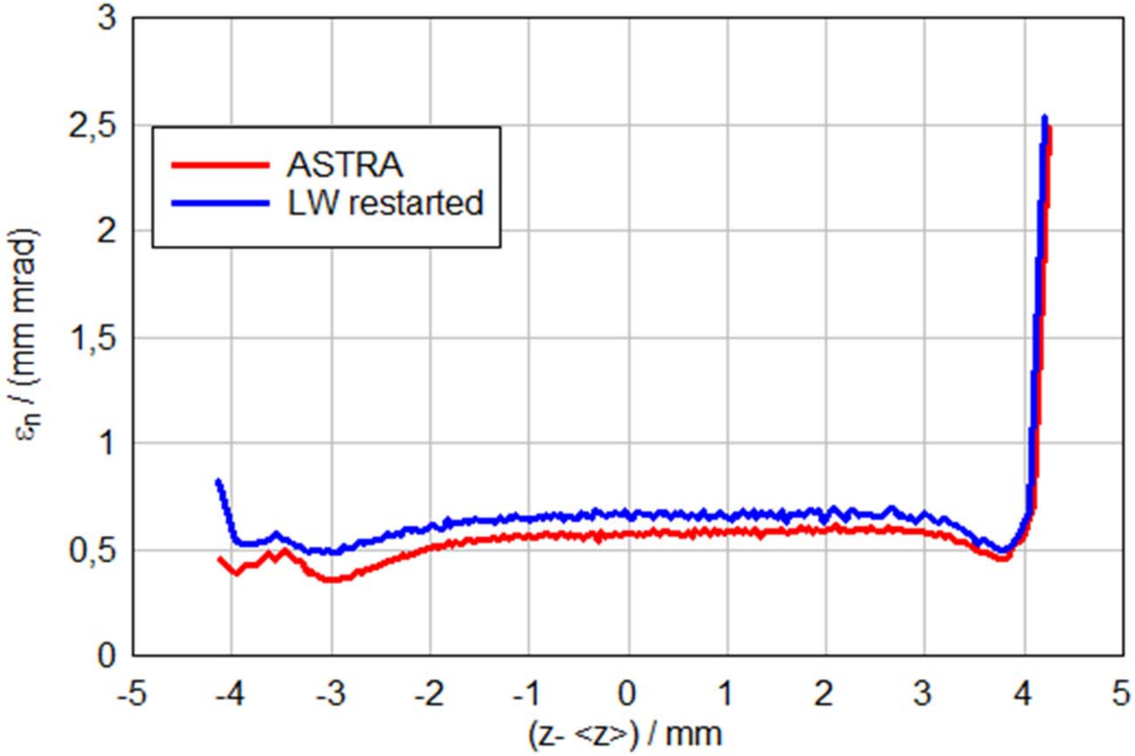
Beam dynamics for PITZ-1.8 setup

Q = 1 nC
XY_rms = 0.4 mm
PITZ-1.8 setup
(M. Krasilnikov, 2011)

Slice emittances for the different codes (z = 5.74 m)



Emittance studies for the PITZ injector

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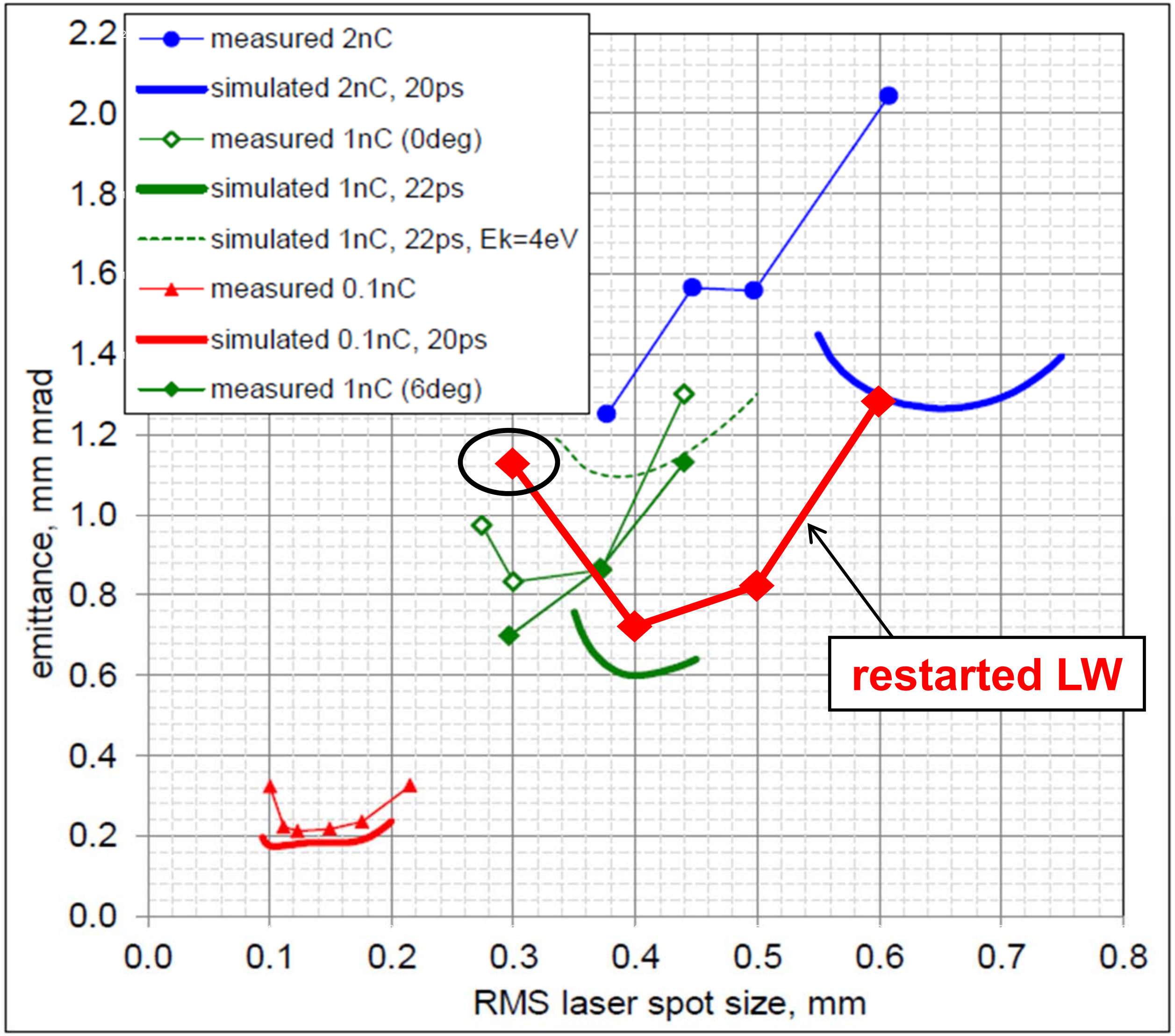

Q = 1 nC

PITZ-1.8 setup
(M. Krasilnikov, 2011)

Beam dynamics for PITZ-1.8 setup

- Still no good agreement with experiment
- Could extract full bunch charge at XY_rms = 0.3 mm
- Slightly larger emittance than ASTRA
- Emittance minimum and curve pattern same as ASTRA
- Are other effects responsible for the discrepancy (wakefields?)

- Restart positions too close to cathode backplane
- Longitudinal density oscillations not fully understood
- Convergence of LW vs. time step is unclear

Emittance studies for the PITZ injector

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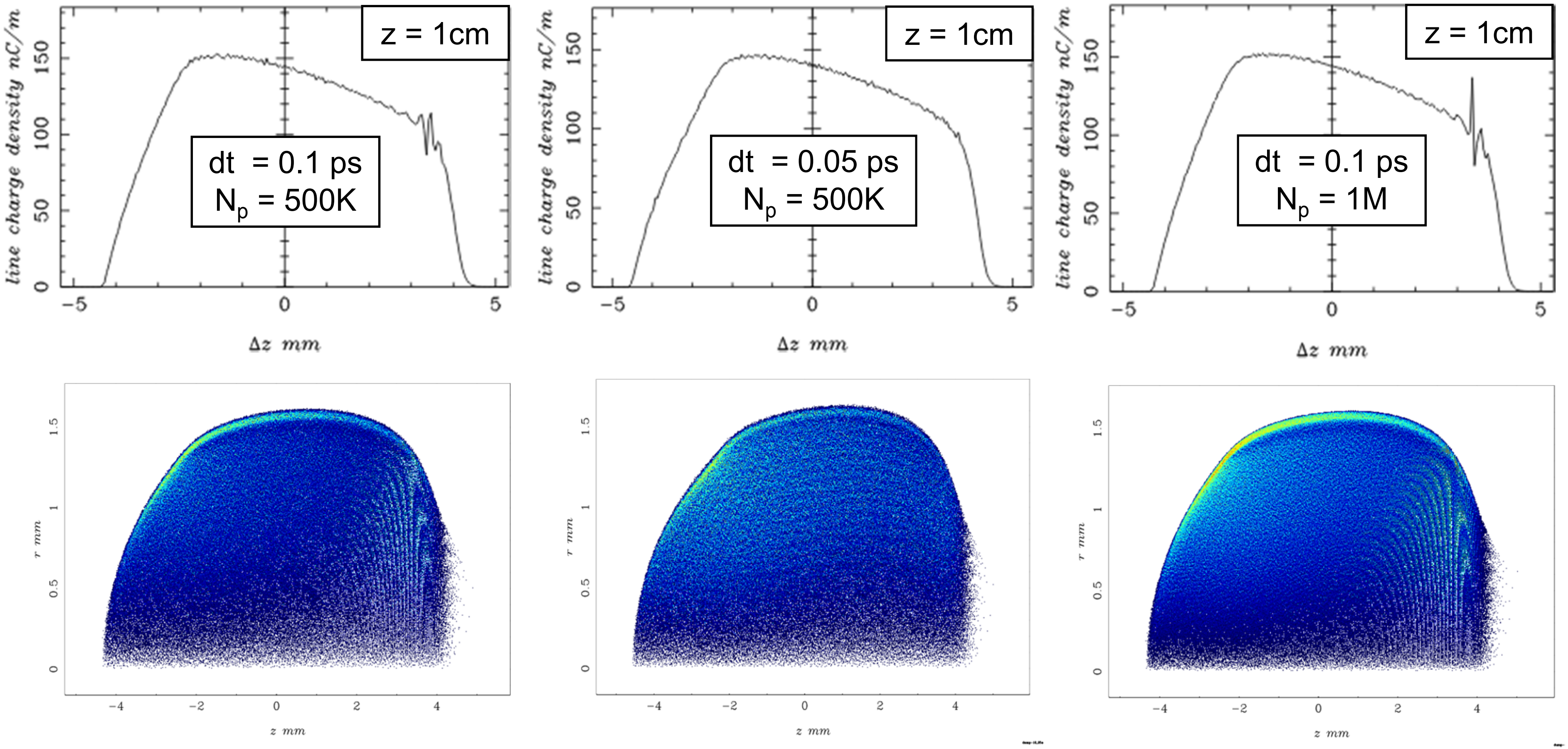
Discussion on space charge at the cathode

Q = 1 nC
XY_rms = 0.3 mm



Emittance studies for the PITZ injector

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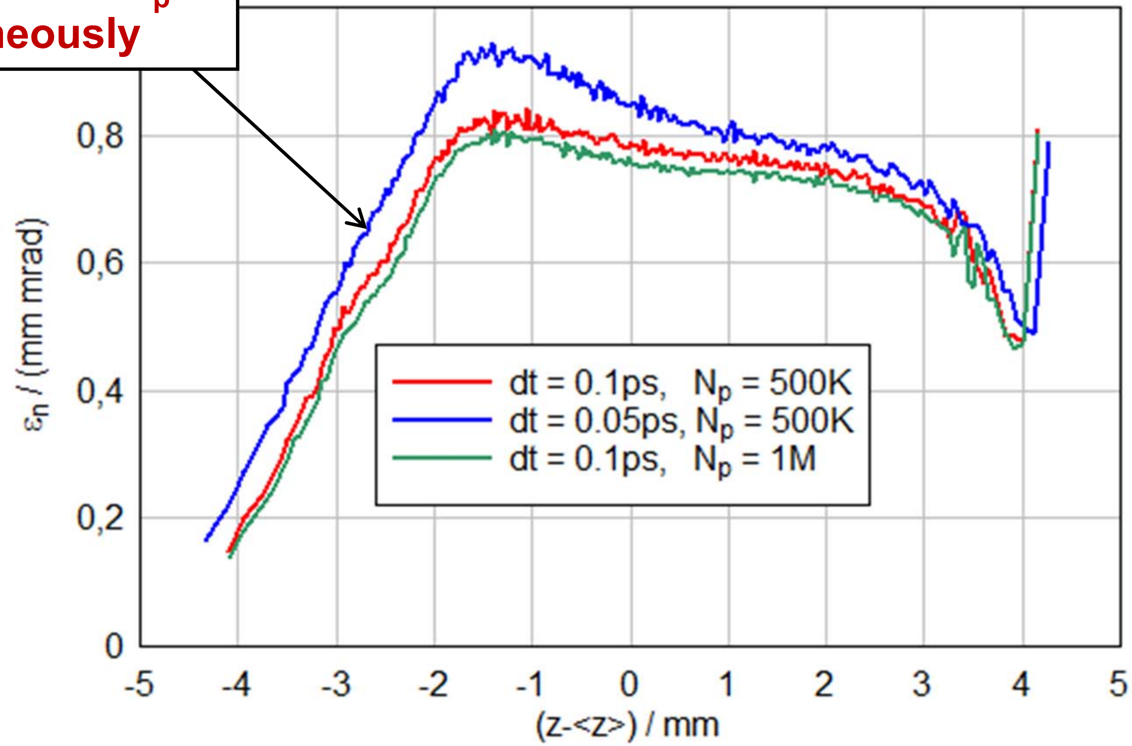
Discussion on space charge at the cathode

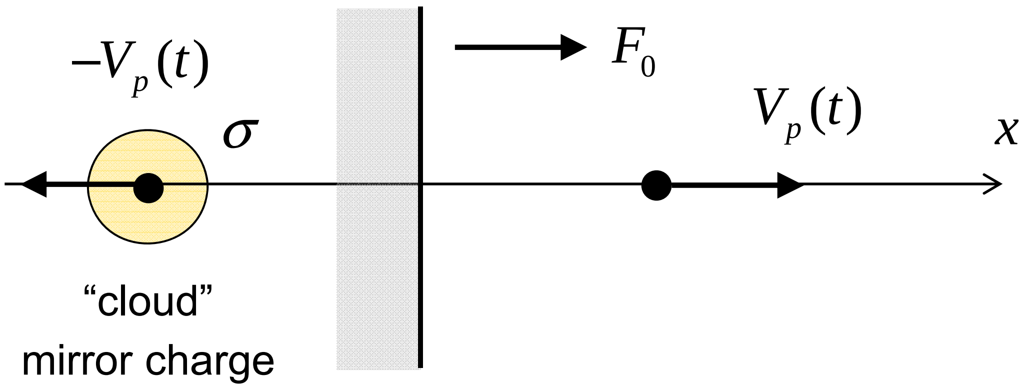
Q = 1 nC
XY_rms = 0.3 mm
PITZ-1.8 setup
(M. Krasilnikov, 2011)

No convergence: need to refine dt and N_p simultaneously

LW slice emittances for different parameters (z = 1cm)



Discussion on space charge at the cathode



$$\frac{m\,v(x)\,v'(x)}{(1-\frac{v(x)^2}{c^2})^{3/2}} = F_0 + F_m(x), \quad v(0)=0$$

$$F_m(x) = \frac{k e^{-\frac{2x^2}{\sigma^2}}}{\sqrt{2\pi}\,x\sigma} - \frac{k\,\mathrm{Erf}(\frac{\sqrt{2}x}{\sigma})}{4x^2}$$

Point charge emission from ideal surface not possible:

- Need a cloud mirror charge distribution

Main branch solution

$$v(x) = \sqrt{1 - \frac{16\pi^2 c^4 m^2 x^2 \sigma^2}{\left(\pi\sigma\left(4c^2 m x + k\,\mathrm{Erf}(\frac{\sqrt{2}x}{\sigma}) + 4F_0 x^2\right) - 2\sqrt{2\pi}\,k x\right)^2}}$$

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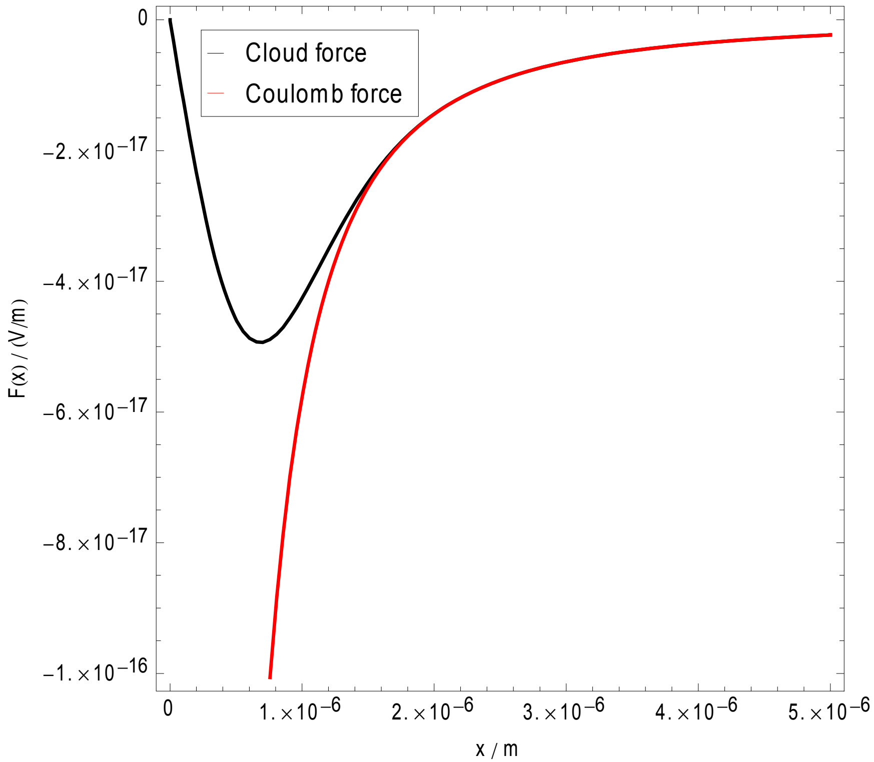
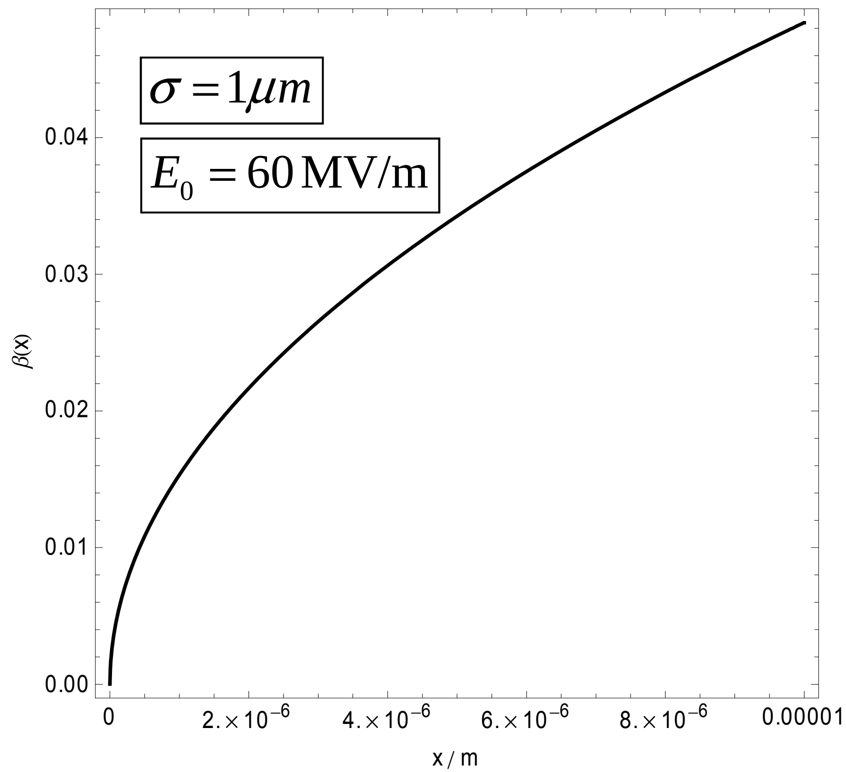
Discussion on space charge at the cathode

Wall force modified by cloud charge



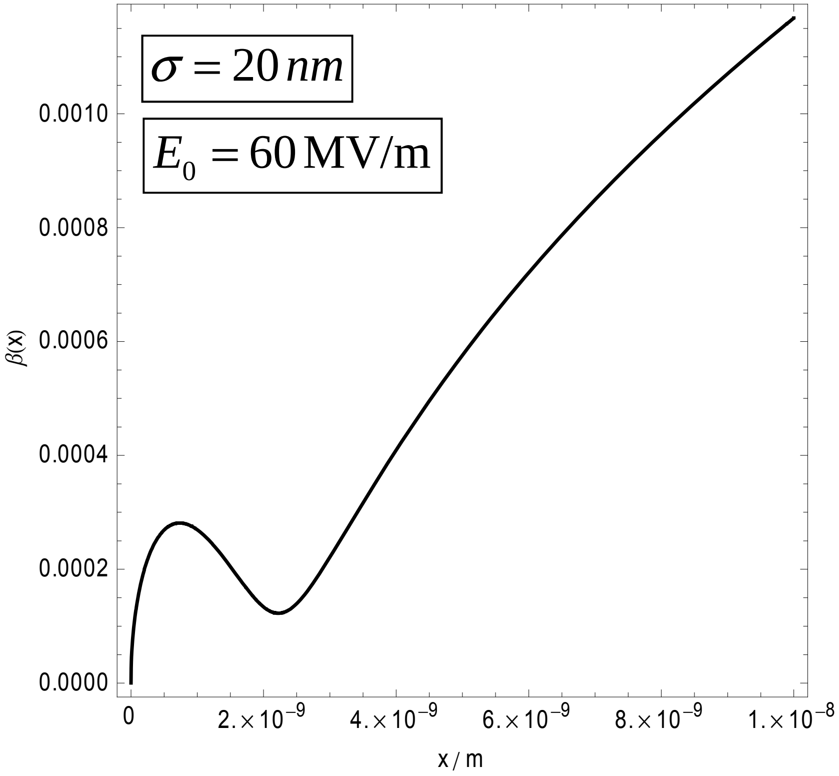
“Usual” trajectory: small wall interaction



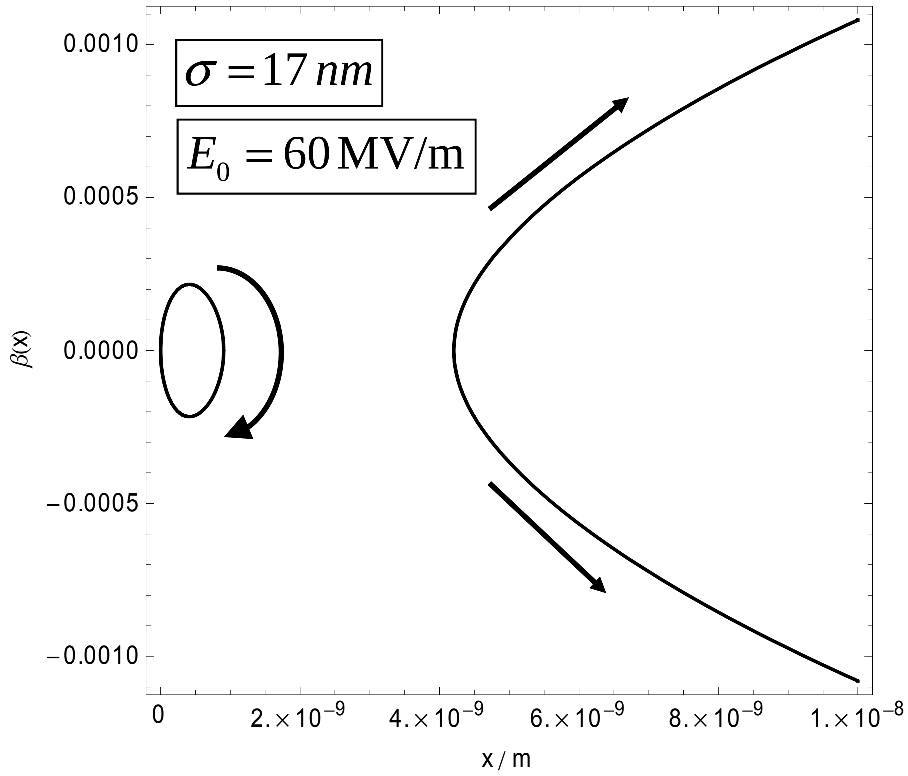
Emittance studies for the PITZ injector

Discussion on space charge at the cathode

Small size particle trajectory

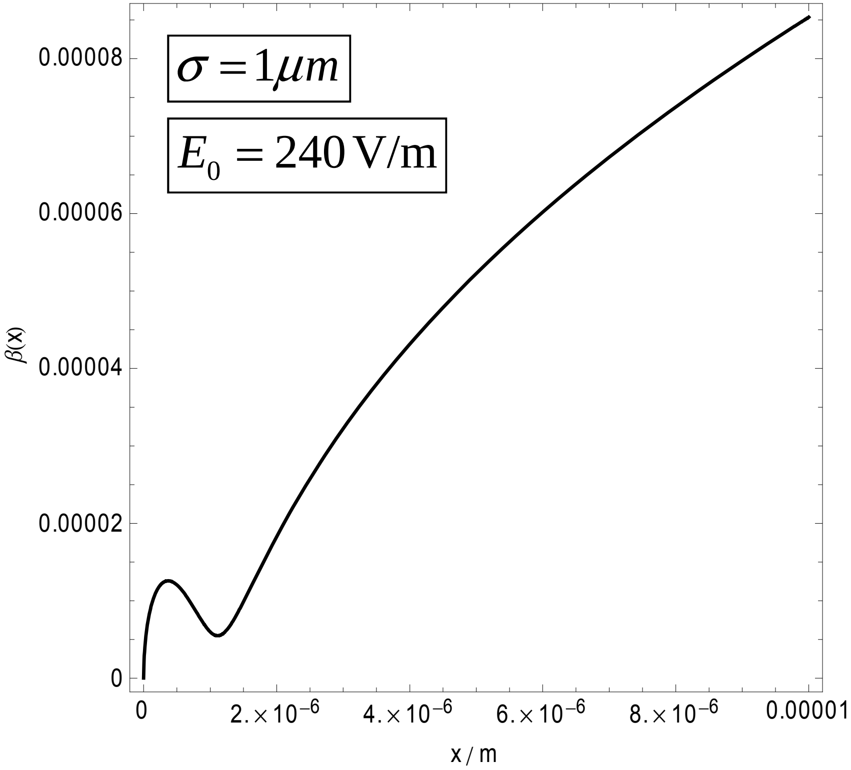


SPCH limited trajectory

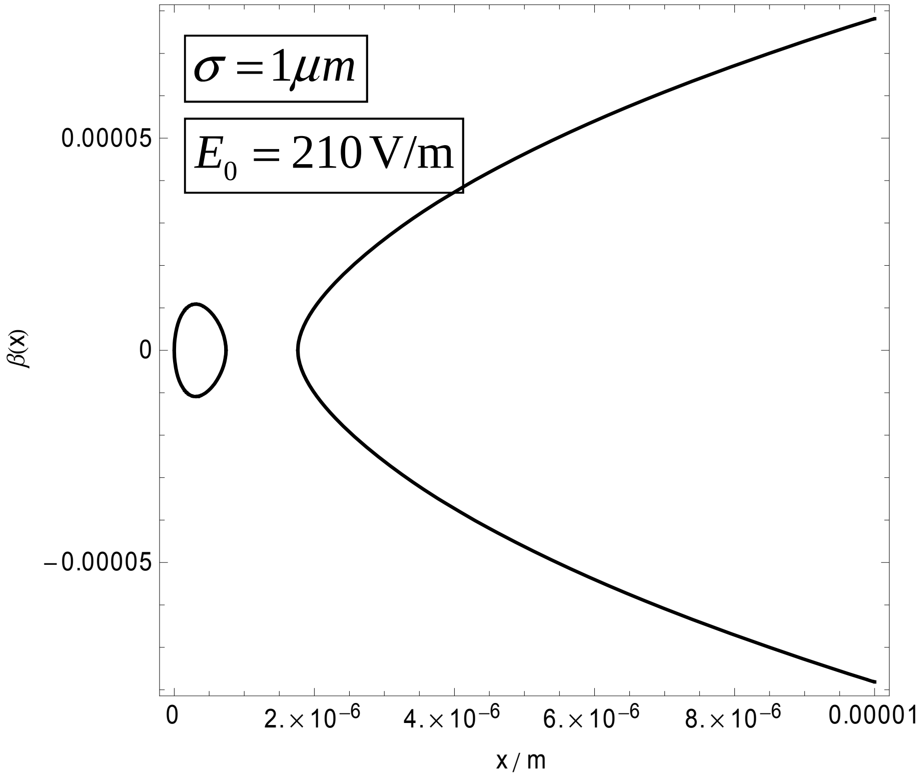


Discussion on space charge at the cathode

Low field / large size particle trajectory



SPCH limited trajectory



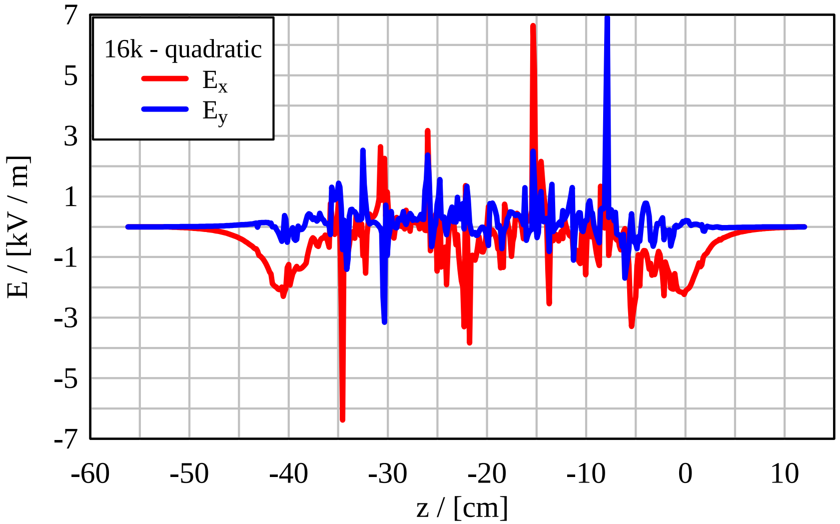
Discussion on space charge at the cathode

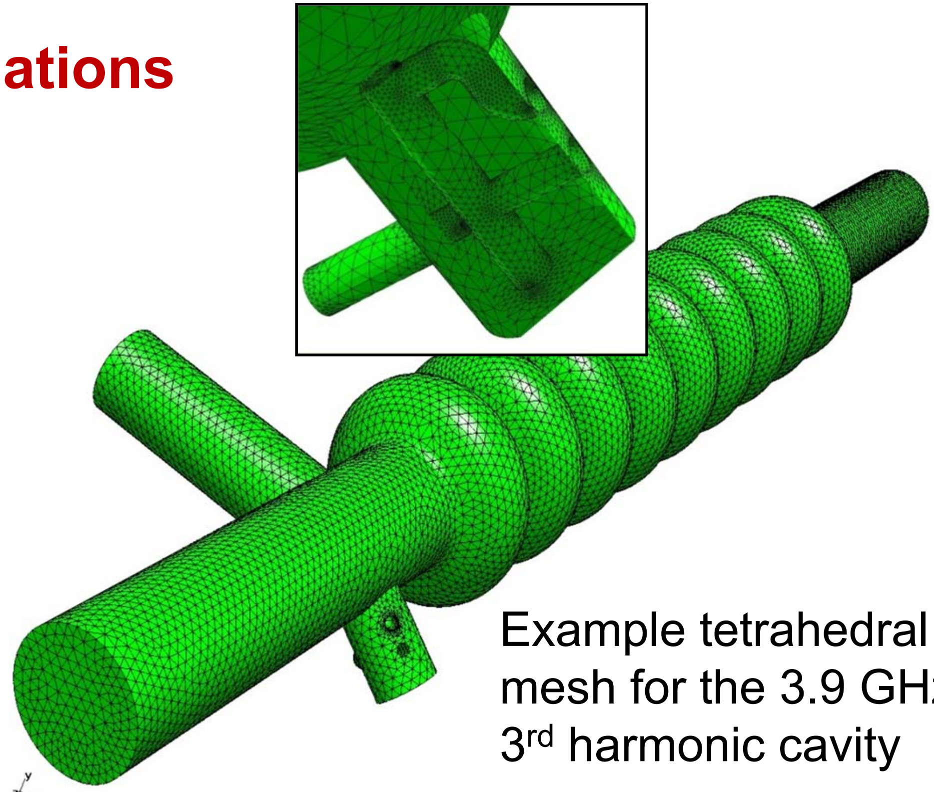
- Minimum separation distance between particle and its mirror:
  - LW: ~time step
  - PIC: macroparticle shape
  - ASTRA: longitudinal grid step (?)
- Needs to be reduced at high charge densities: $\sigma < \lambda_D$
- but end up with individual particle interactions
  - No numerical convergence
- **Only cure, increase number of particles in the simulation**
  - Full charge extraction at 0.3 mm possible with ASTRA (?)

Field map calculations

Field noise in eigenmode simulations

Typical field noise on-axis for computations with unstructured grids

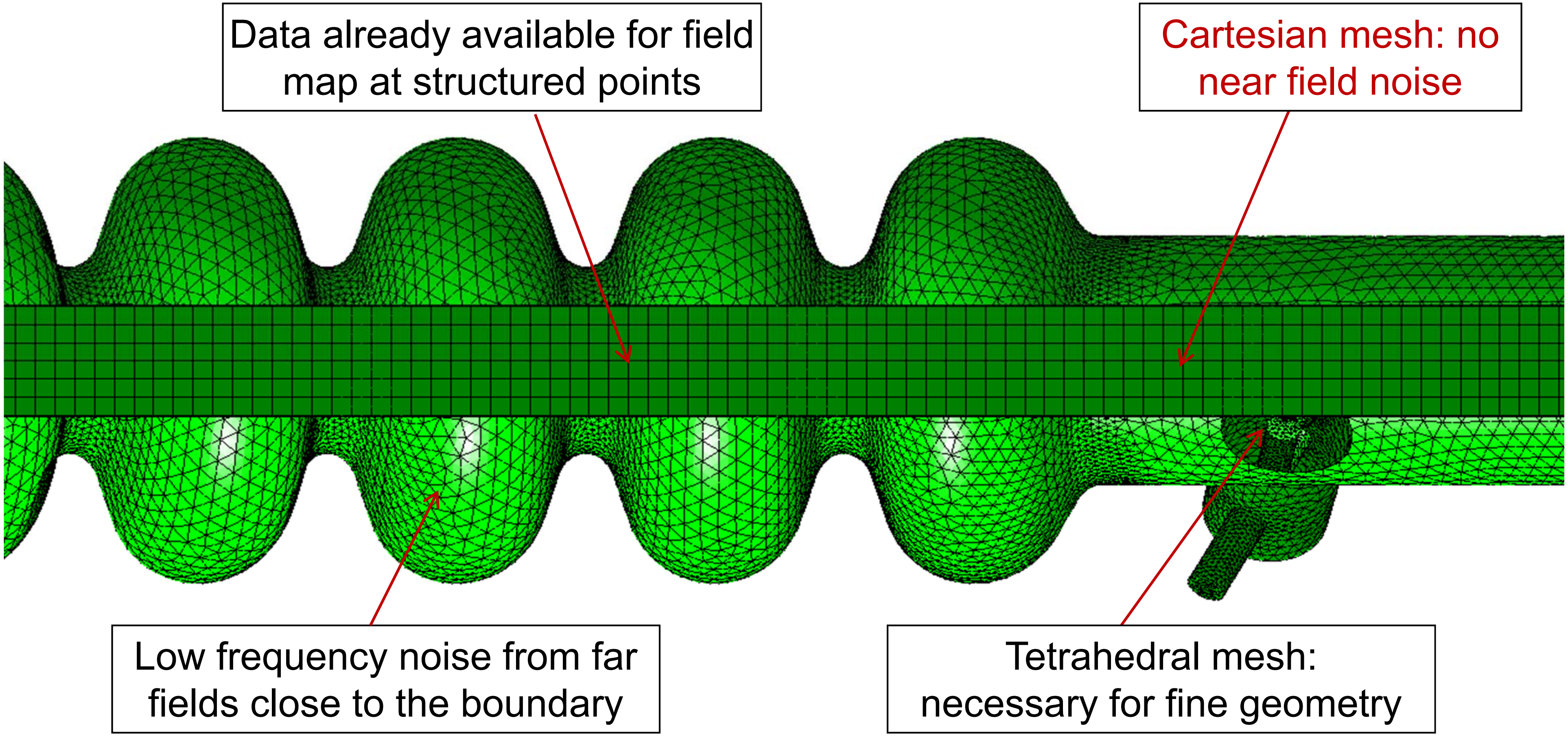




Example tetrahedral mesh for the 3.9 GHz 3[rd] harmonic cavity

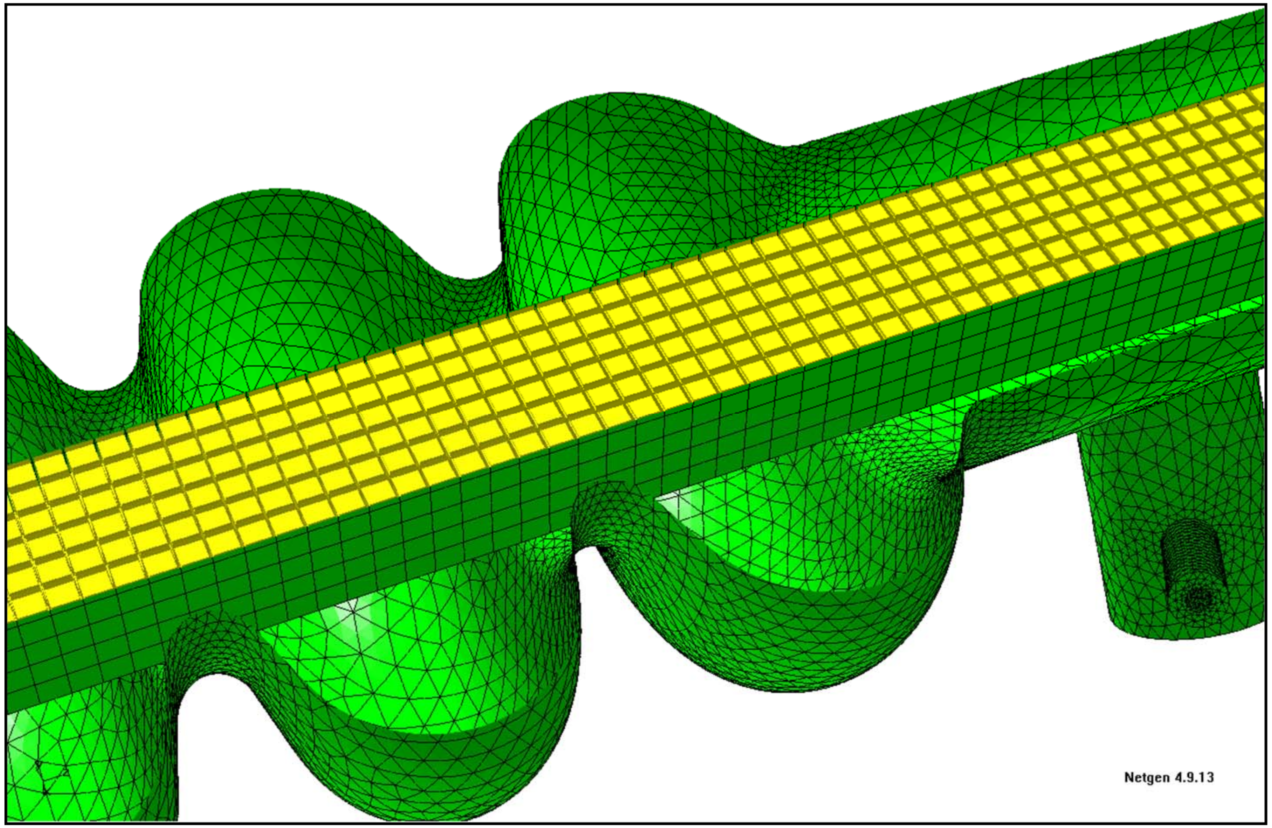
- Need huge amount of DoFs to compensate for mesh asymmetry
- Special treatment for the coupler kicks (PAC 2009, DESY / TEMF 2010)
- **So far completely noise-free field maps only possible with Cartesian grids**

Mixed mesh – high order FEM approach



Field map calculations

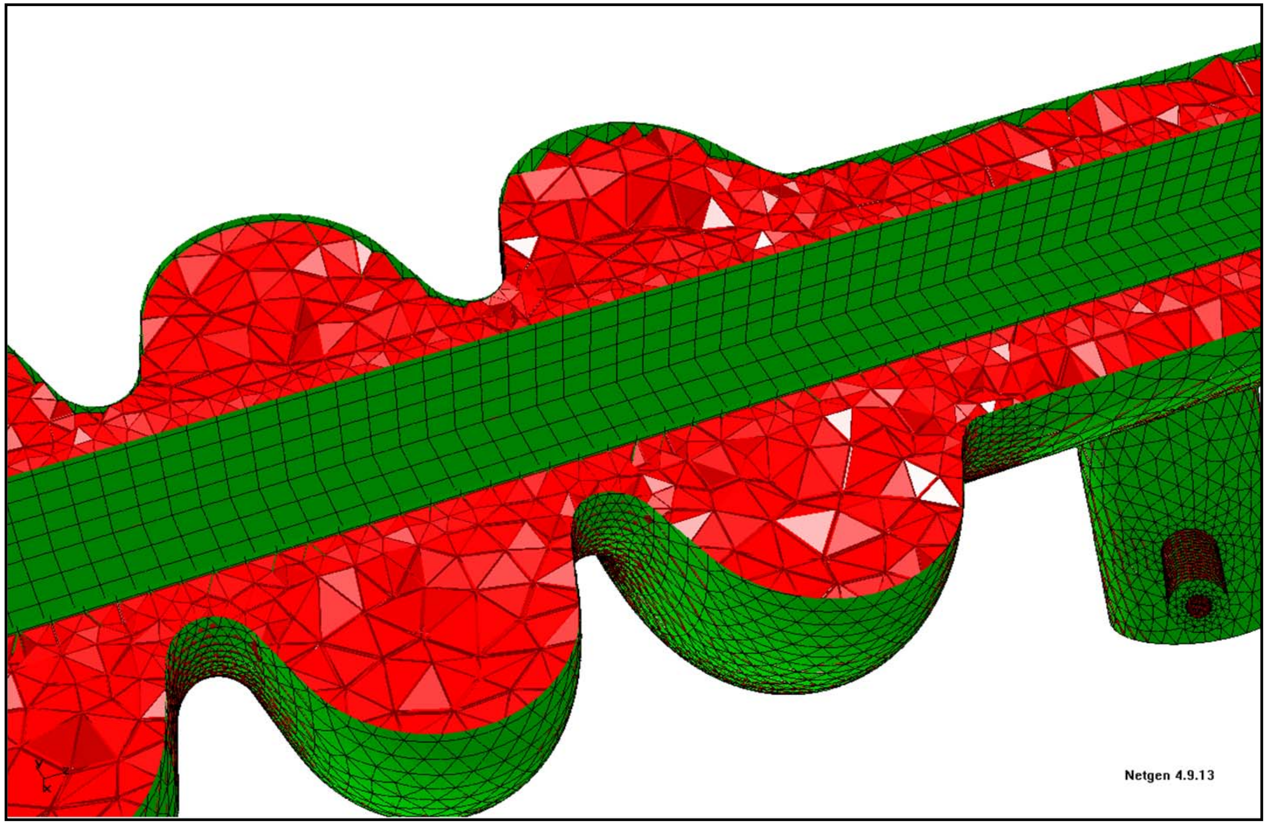
Mixed mesh – high order FEM approach



Field map calculations

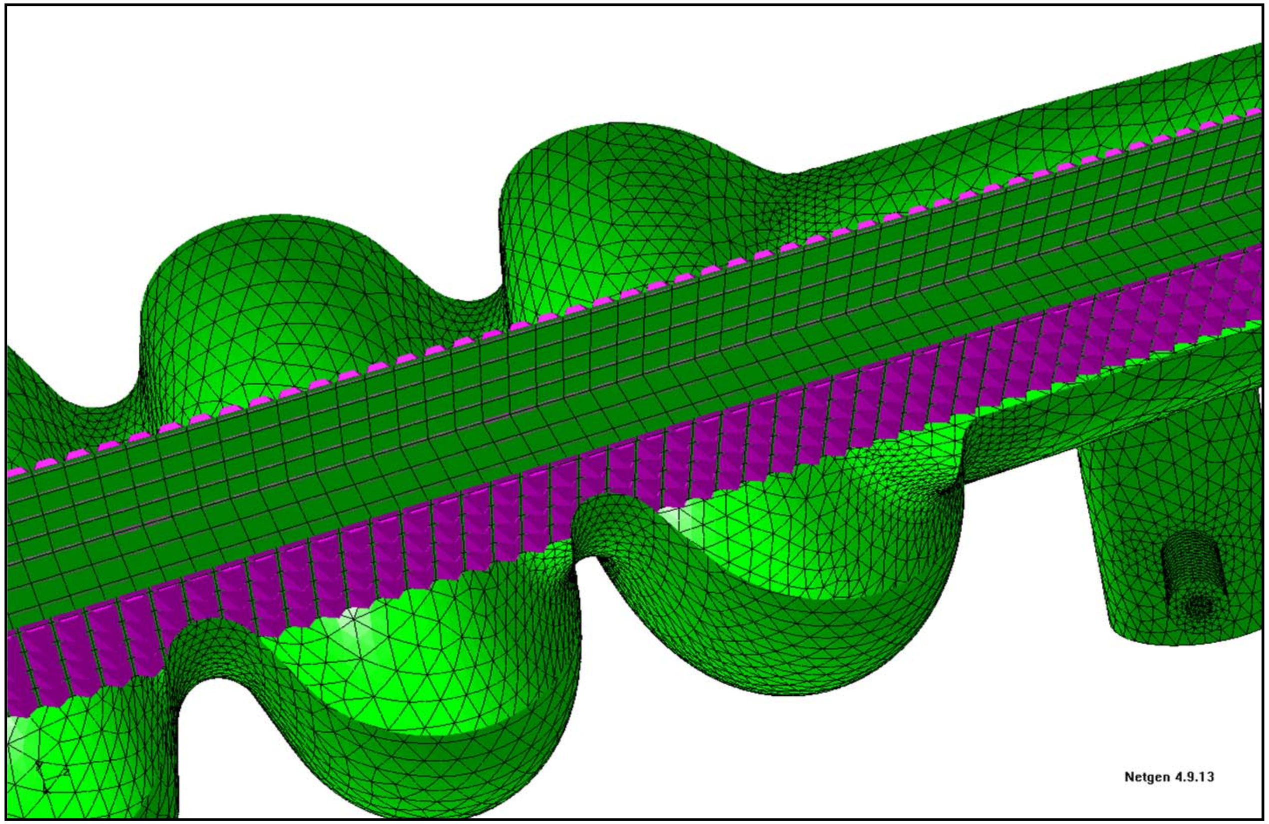
TECHNISCHE UNIVERSITÄT DARMSTADT

Mixed mesh – high order FEM approach



Field map calculations

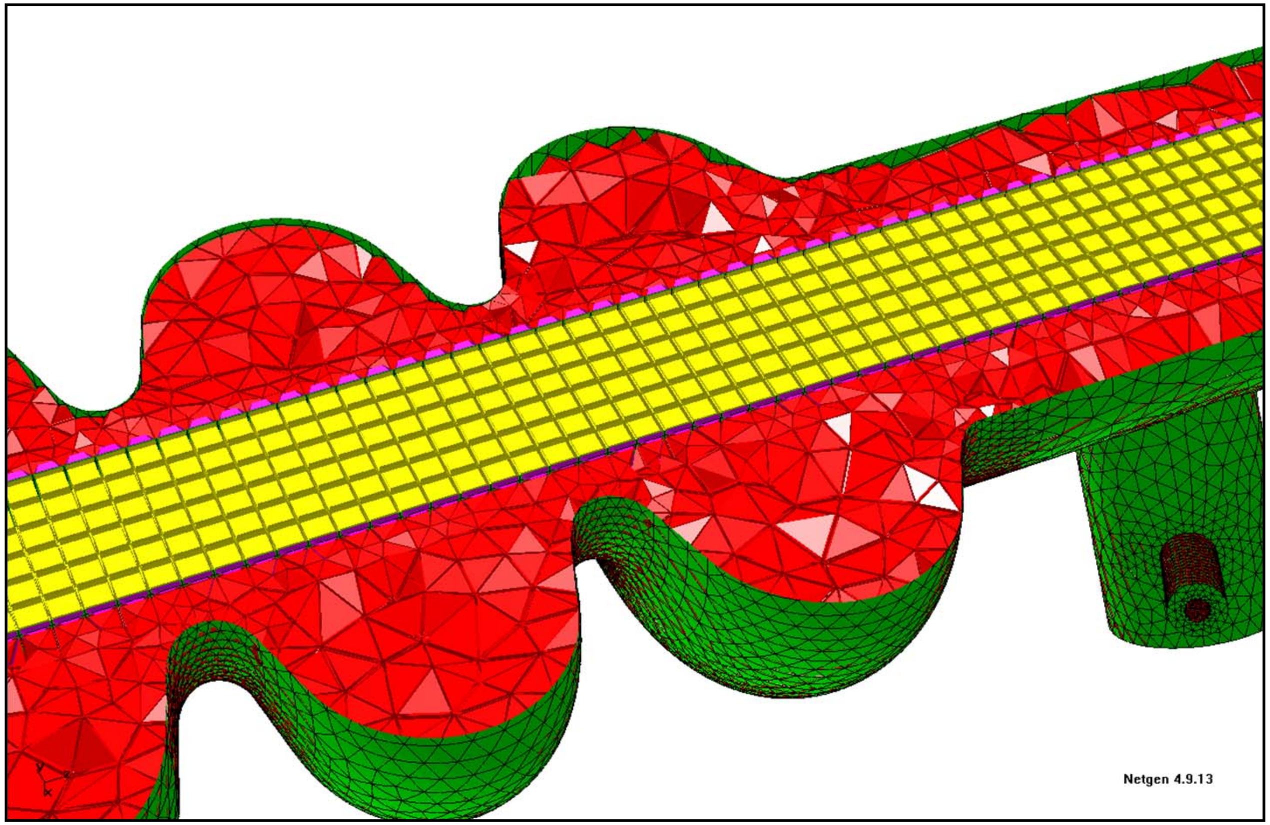
Mixed mesh – high order FEM approach



Field map calculations

TECHNISCHE UNIVERSITÄT DARMSTADT

Mixed mesh – high order FEM approach

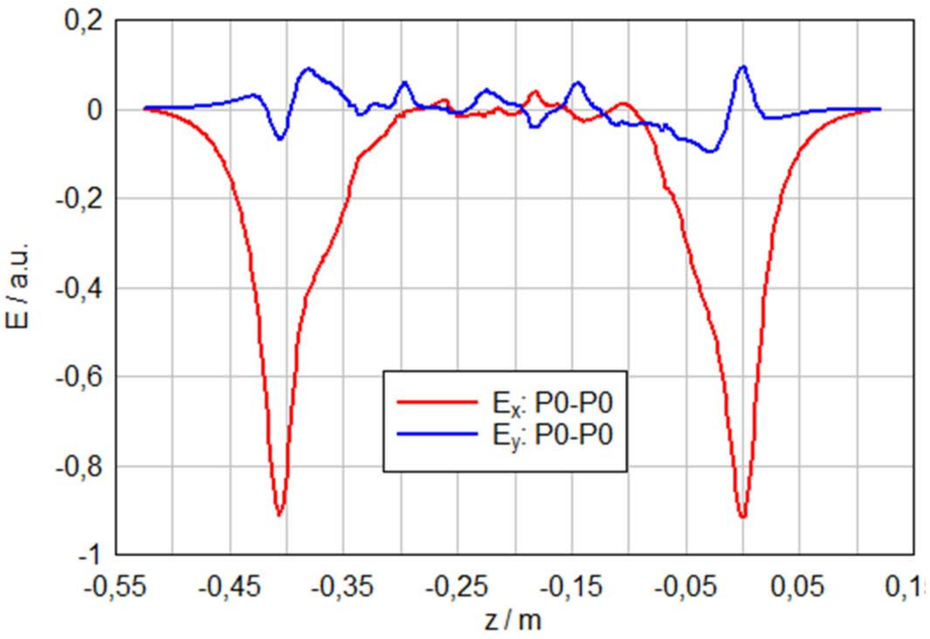


Field map calculations

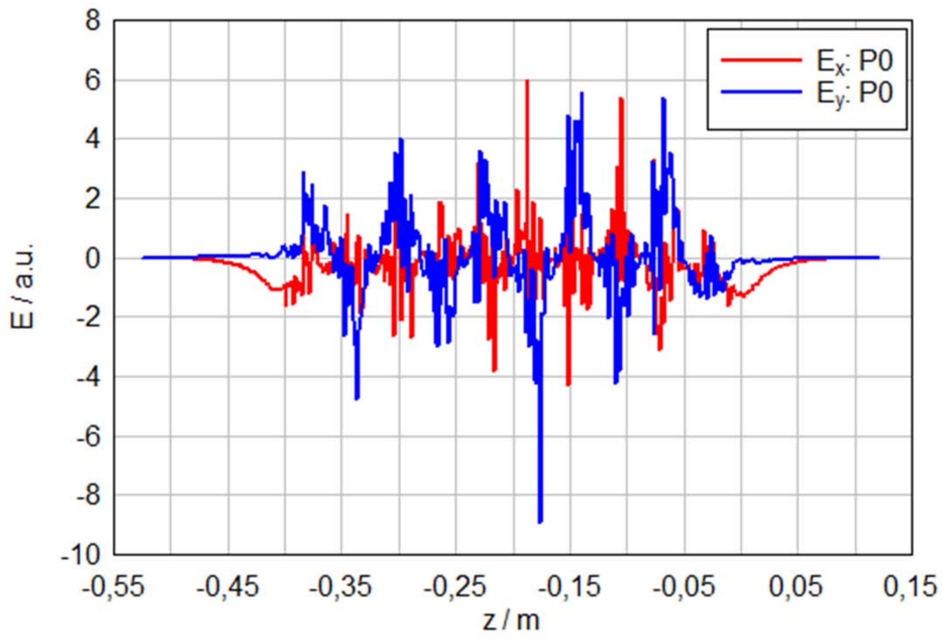
TECHNISCHE UNIVERSITÄT DARMSTADT

Field quality study for the 3.9 GHz cavity

Fields on axis:
Mixed mesh with 350K elements



Fields on axis:
Tetrahedral mesh with 450K elements



Field map calculations

TECHNISCHE UNIVERSITÄT DARMSTADT

Field quality study for the 3.9 GHz cavity

Fields on axis:
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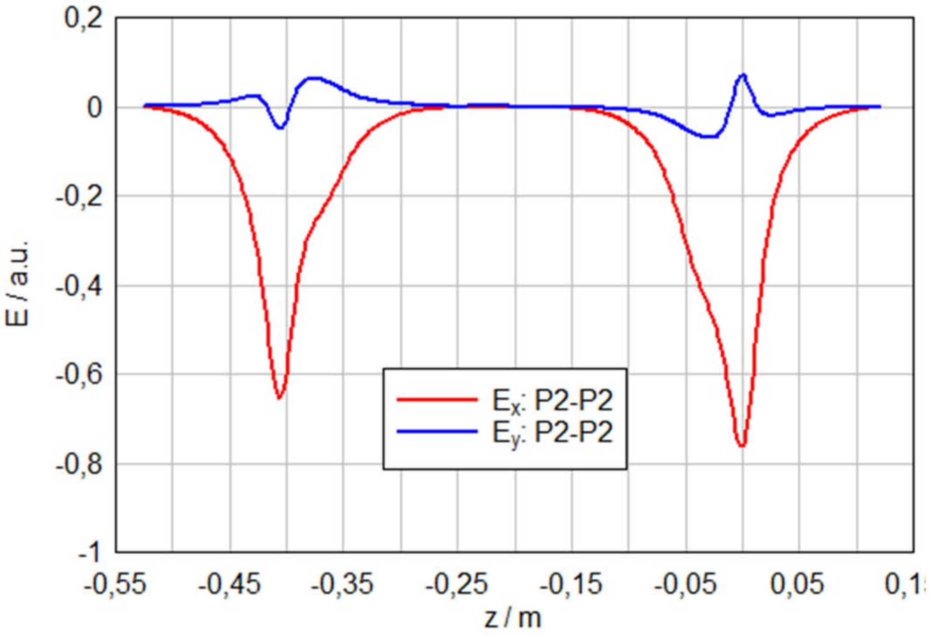
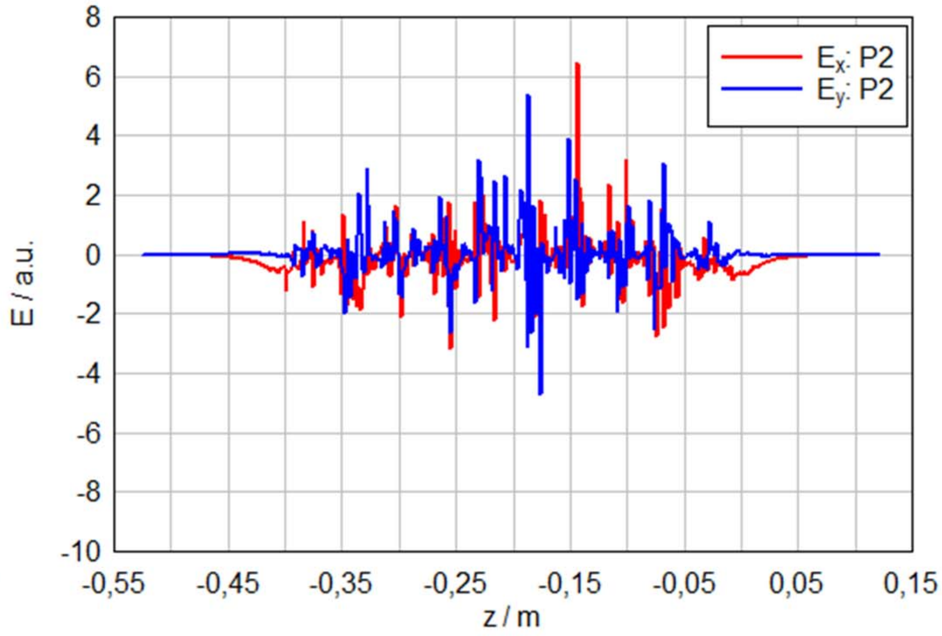


Fields on axis:
Tetrahedral mesh with 450K elements



Field map calculations

Field quality study for the 3.9 GHz cavity

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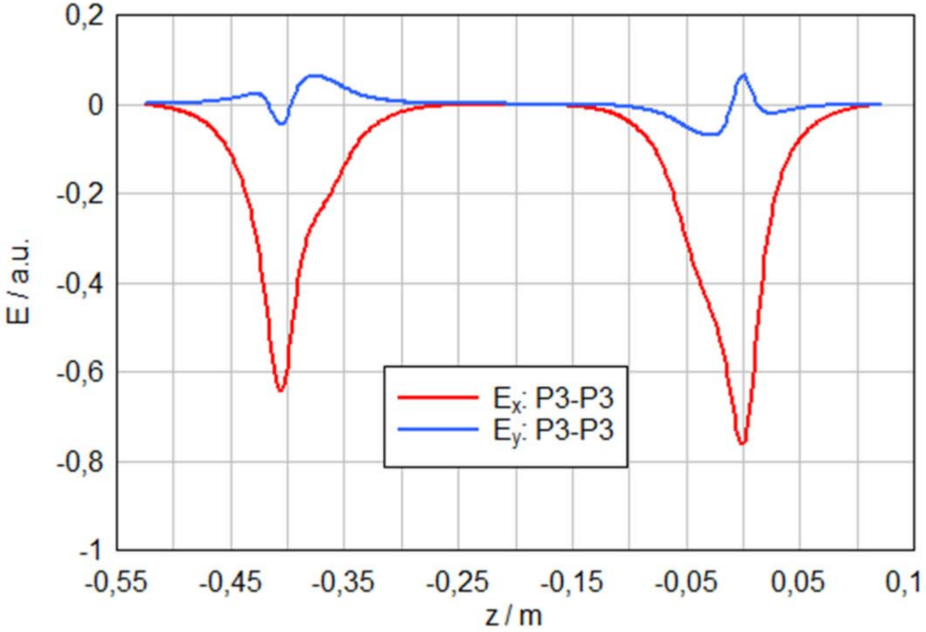

Fields on axis:
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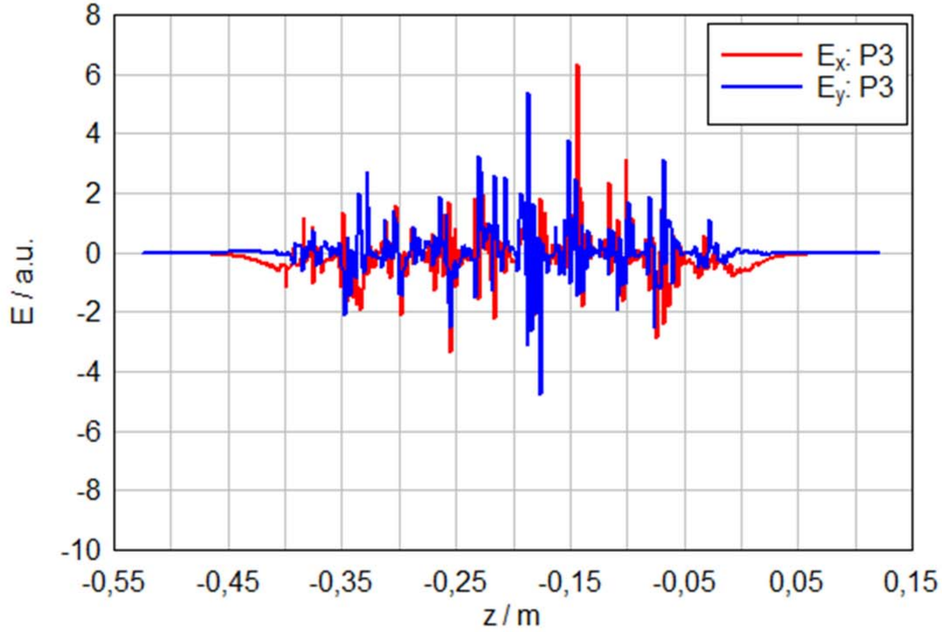
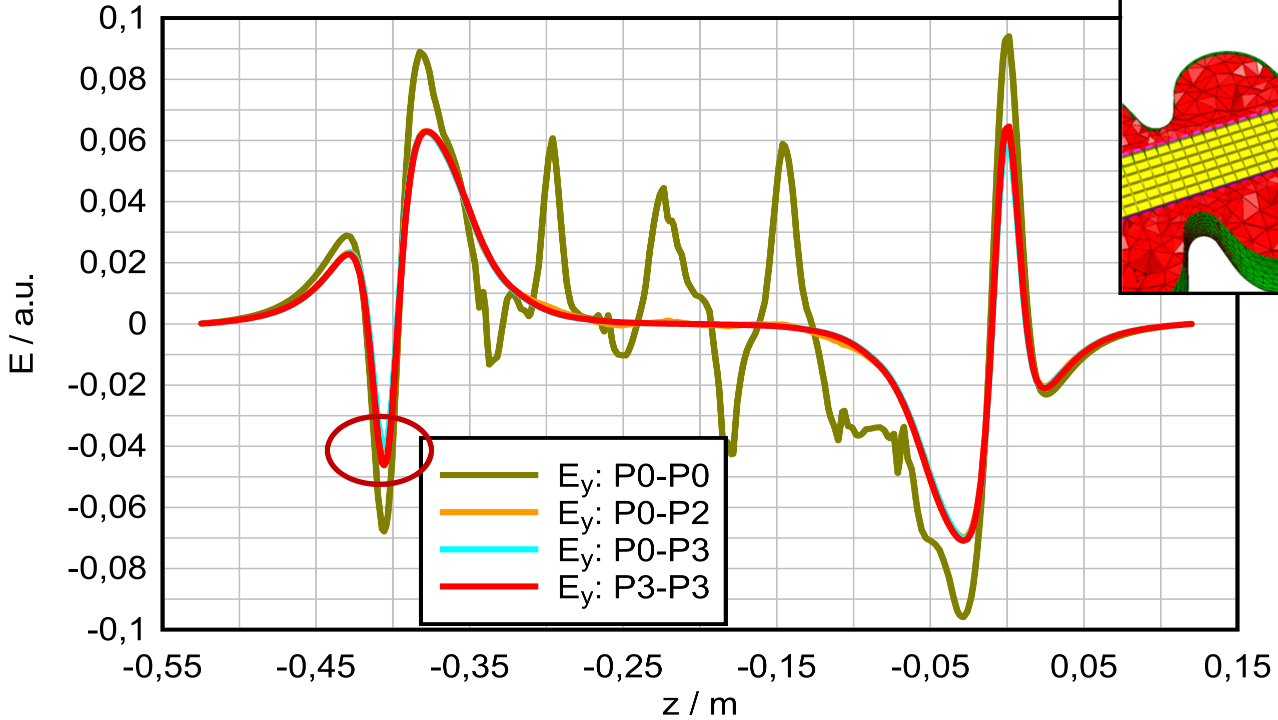
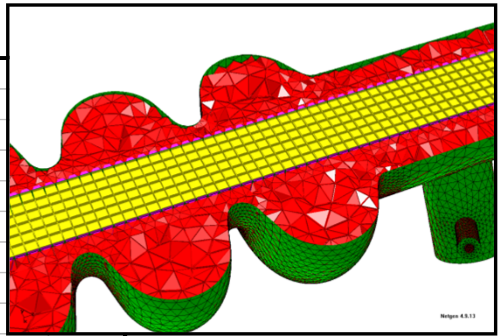


Field map calculations

Field quality study for the 3.9 GHz cavity

Use of different orders in different parts of the mesh to
increase smoothness (not accuracy)

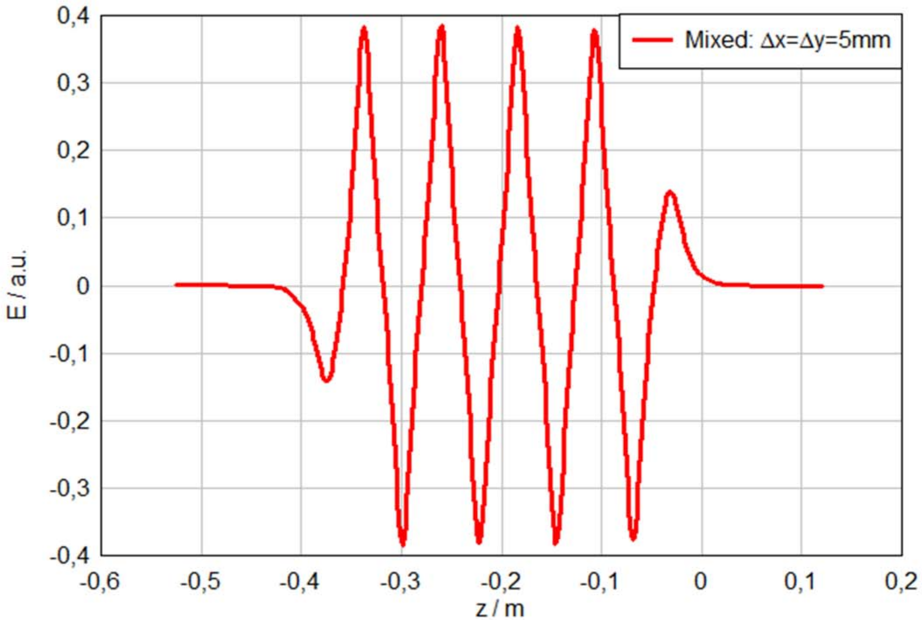




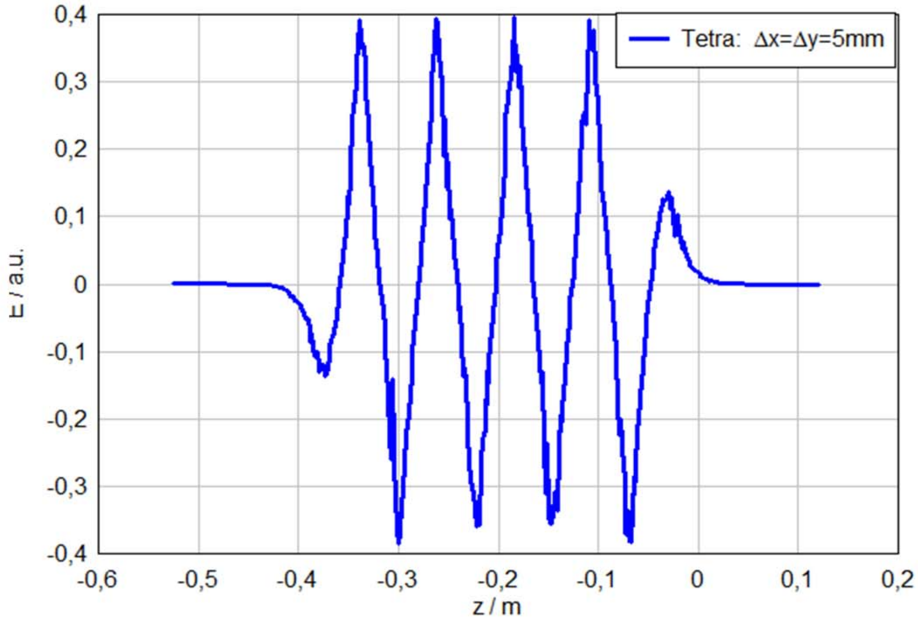
Field map calculations

Field quality study for the 3.9 GHz cavity

Transversal fields off axis:
Mixed mesh with 350K elements



Transversal fields off axis:
Tetrahedral mesh with 450K elements



Thank you for your attention