Beam dynamics studies for PITZ using a 3D full-wave Lienard-Wiechert PP code

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TECHNISCHE UNIVERSITÄT DARMSTADT

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DESY Hamburg Site, Germany

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Overview

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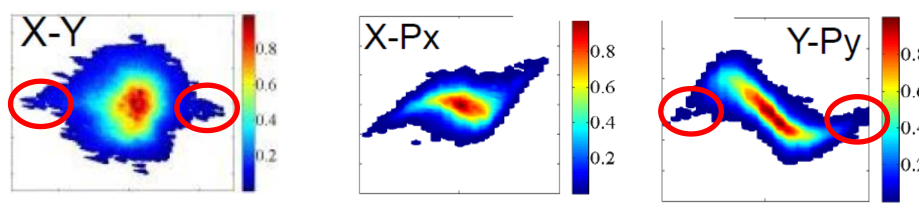
Effects possibly contributing to Q_{tot}, ε_{xy} and other beam quality parameters

- **Cathode effects** → **more precise photoemission modeling**
  - Relativistic field effect
  - Schottky effect
- **Beam line (components) effects** → **investigations on asymmetries / coupling in beam profile and phase space**

  → **machine parameter differences (e.g., ΔI_{main})**
  - RF kicks
  - Solenoid misalignment
  - Coaxial coupler (field) asymmetry
  - Vacuum mirror etc.



Asymmetries in beam profile and bunch transverse phase space

Contents

- **Introduction**
- **Dynamic emission model including Schottky-like effect**
  - Development, validation and implementation in Lienard-Wiechert code
- **Impacts of Schottky-like effect on beam dynamics**
  - At emission: transient charge profiles, QE maps
  - After emission: emittance, energy spread, etc.
  - Impacts on total bunch charge extraction
- **Investigation of asymmetries / coupling in beam profile and phase space**
  - Imperfections of main solenoid and / or RF fields
- **Summary and outlook**

Introduction
So far on photoemission studies

Topics	Contents	Codes	Important Findings
Full EM modeling of photo-emission	Relativistic field effect during bunch emission	<u>3D full EM codes:</u> Lienard-Wiechert (LW) PP Discontinuous Galerkin (DG) PIC CST Particle Studio (PS) PIC <u>+ Multiple dedicated numerical approaches</u> based on different hierarchies of approximations	– Relative particle motion within the bunch during emission – Magnetic SPCH fields needed – Differences in transverse emittance (~20%) and SC limits as well
Space-charge limited emission	Steady state solution (charge iteration method)	CST PS PIC	– Good prediction of maximum emitted charge (FT-bunch)
	Brute force method	DG PIC	
Quantum efficiency limited emission	Cathode characterization	CST PS PIC	– Consistent QE factors found for the same cathode [illegible] beam parameters
	Dynamic emission model including Schottky-like effect (Fowler-Dubridge model)	LW PP	– [illegible] LW code – Validation by measurements
	Contributions of Schottky-like effect on beam dynamics	LW PP	– [illegible] charge density profiles – [illegible] phase space parameters

❖ **Lienard-Wiechert (LW) tracking code**

– Store **full history** of particle trajectories

– Search **retarded interaction point** for each particle-particle pair

– Compute **LW fields** for particle tracking

– Parallel computation **with TEMF Cluster**

Dynamic emission model

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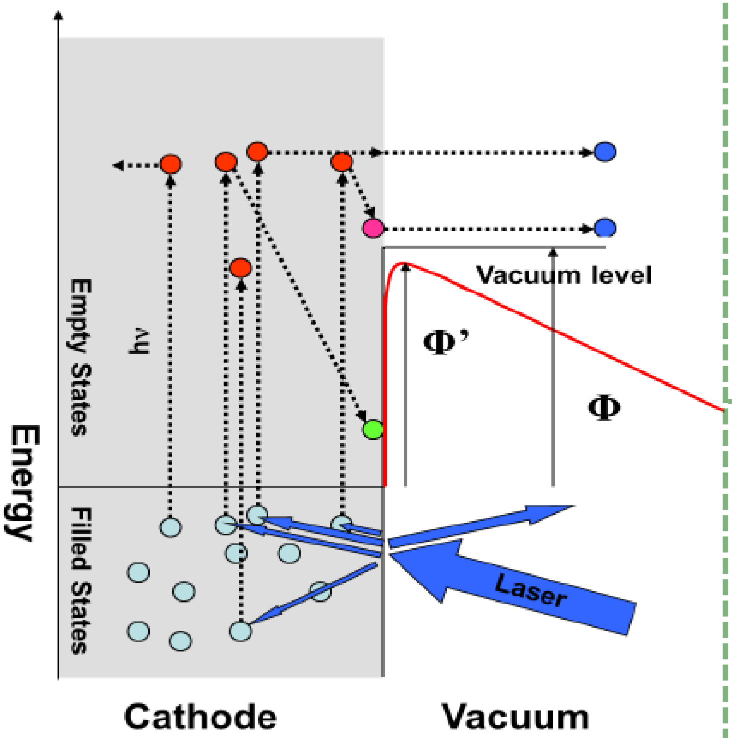
Photoemission model



1. *M. Cardona and L. Ley: Photoemission in Solids 1, Springer-Verlag, 1978*
2. *L.A. DuBridge, Physical Review 43, 0727 (1933).*

– **Simple Fowler-Dubridge model for planar cathode**

$$J_{FD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_\lambda(\omega)(\hbar\omega-\Phi)^2 I_\lambda$$

Absorption ($1-R$), Scattering losses ($F_\lambda(\omega)$), Transmission (I_λ)

⟶ $J_{FD}(\lambda) \propto (\hbar\omega-\Phi)^2$ **Currently**

⟶ $J_{FD}(\lambda) \propto (\hbar\omega-\Phi)^p$ **In testing**

– **Field dependent work function (Schottky-like)**

$$QE(\mathbf{r},t) = \boldsymbol{\eta}[h\nu - (\Phi_w \mp \Delta\Phi(\mathbf{r},t))]^2$$

$$\Delta\Phi(\mathbf{r},t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0}E_{cath}(\mathbf{r},t)}$$

$$Q(\mathbf{r},t) = \int_{-\infty}^{t}\iint_S e\,\frac{P_{laser}(\tau)}{h\nu}QE(\mathbf{r},\tau)d^2\mathbf{r}\,d\tau$$

Dynamic emission model

- **Local beam current depends on**

  (1) cathode properties; (2) dc / rf gun fields; (3) space charge fields

- **Total field at the cathode,** $E_{cath}(x,y,t) = E_{rf}(x,y,t) + E_{sc}(x,y,t)$

  (1) Emitted charge profile generally not identical with laser pulse shape

  (2) Transverse distribution of e- bunch no longer uniform over emission area

- **Calculation of total emitted bunch charge**

QE

$$Q(\boldsymbol{r},t) = \int_{-\infty}^{t} \iint_{S} e \frac{P_{laser}(\tau)}{h\nu} \boldsymbol{\eta}[h\nu - (\Phi_w \mp \Delta\Phi(\boldsymbol{r},t))]^2 d^2\boldsymbol{r}\, d\tau$$

Form factor is needed!

η: cathode form factor

(1) Depending on **material properties** such as the absorption coefficient, density of states, transition probability, and the angle of incidence of the laser light

(2) Independent of experimental conditions / machine parameters (assumption)

(3) Determined only once for one cathode, then can be used for simulations involving different sets of gun and beam parameters

Dynamic emission model

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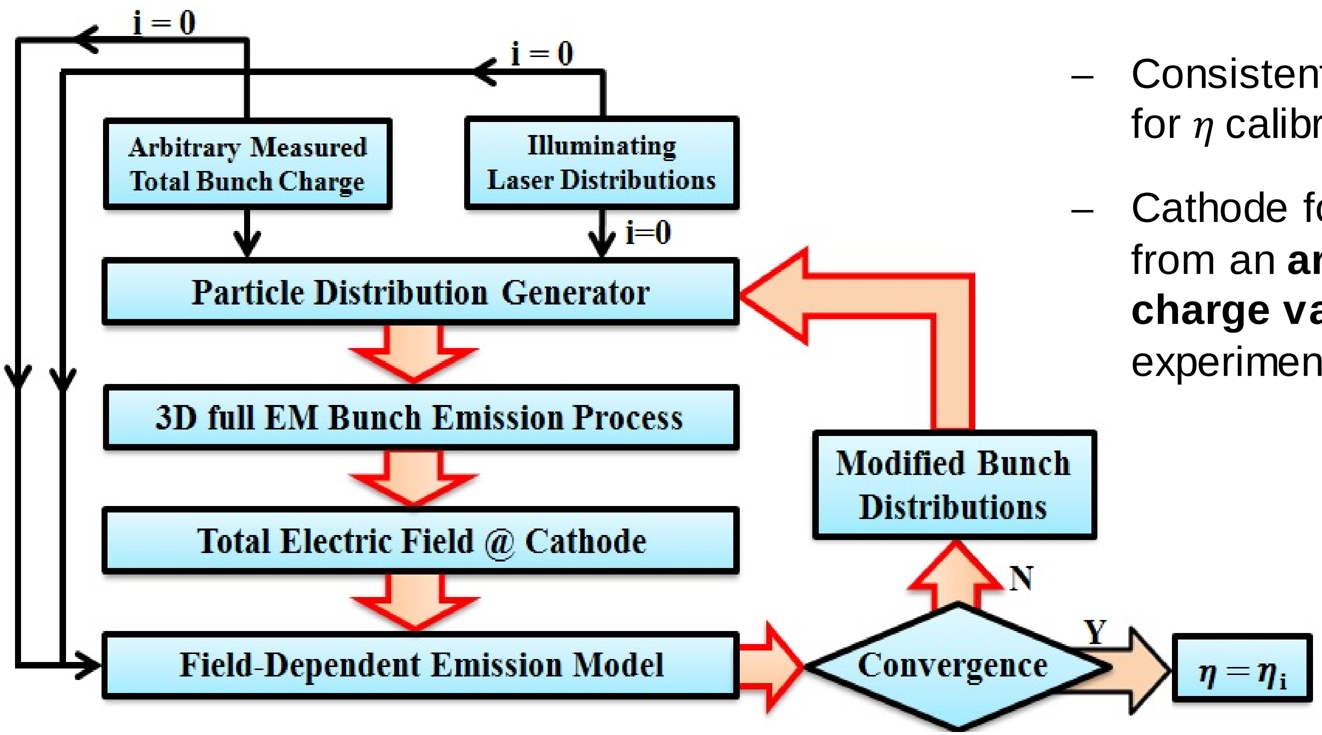
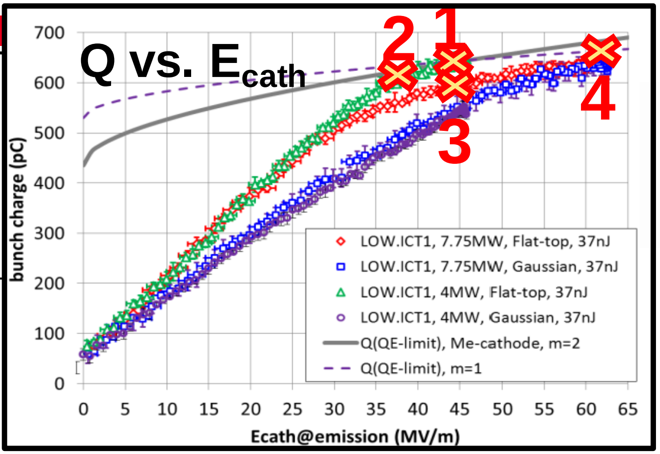
– **Determination of cathode form factor**



– Consistent iterative procedure for η calibration

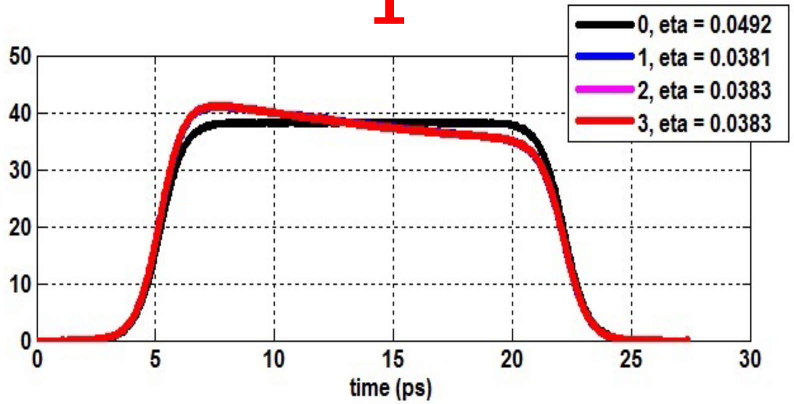
– Cathode form factor calibrated from an **arbitrary bunch charge value** obtained experimentally

Dynamic emission model



– **Convergence check of η**

1



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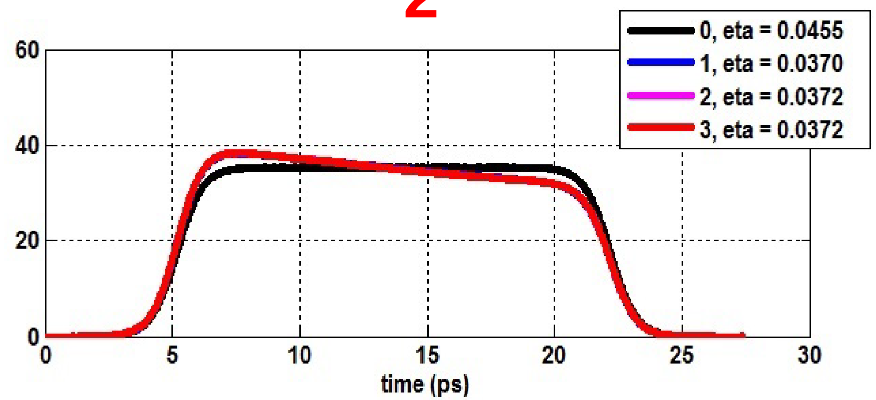

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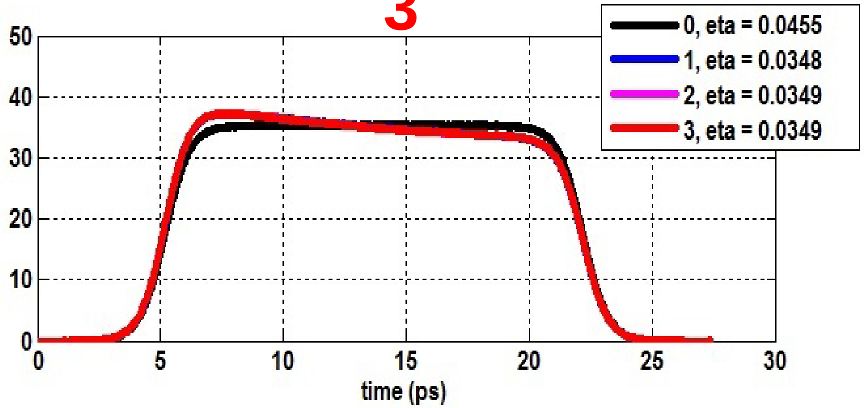

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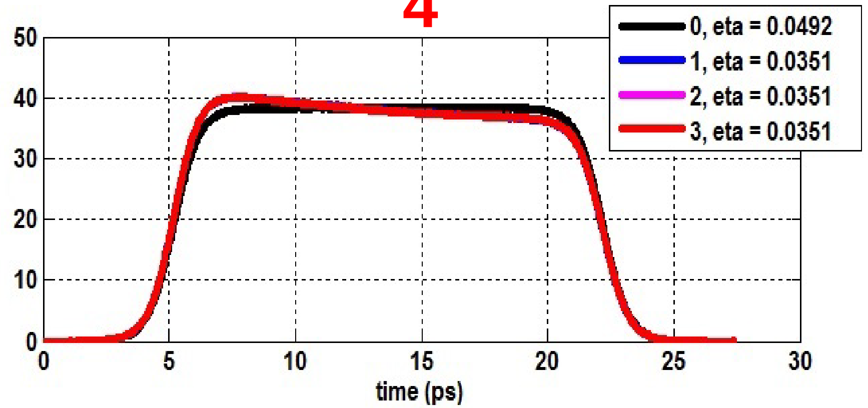
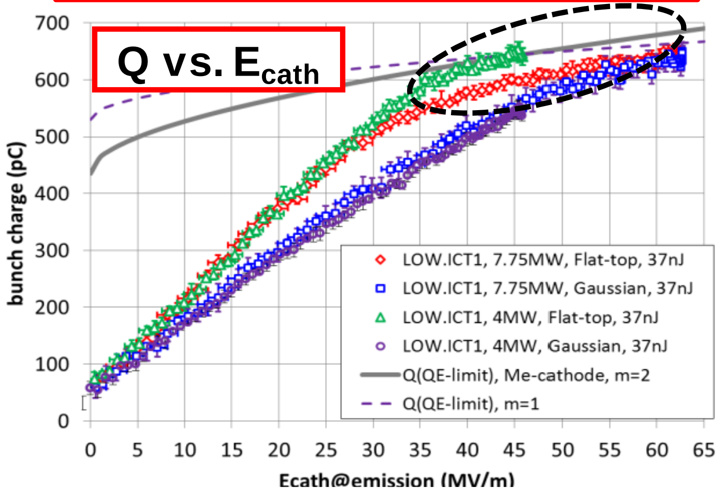
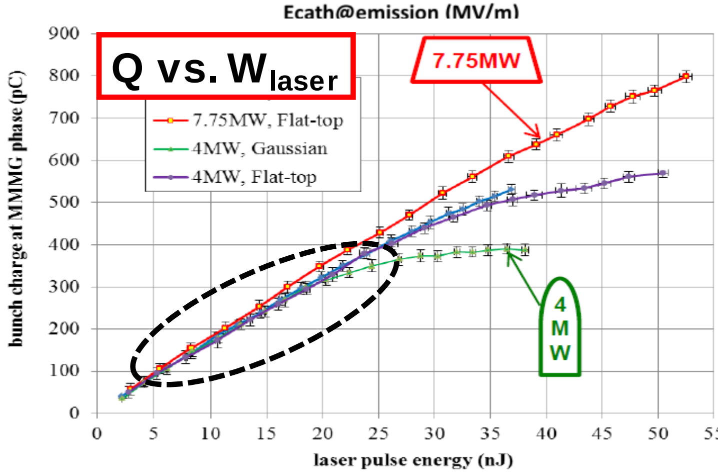


Model validation

If the cathode form factor independent of experimental conditions?

Measurements





Nr	Laser Profile	RF Power	E_{laser}	η
1	Flat-Top	4 MW	37 nJ	**0.0383**
2	FT	4 MW	37 nJ	**0.0372**
3	FT	7.75 MW	37 nJ	**0.0349**
4	FT	7.75 MW	37 nJ	**0.0351**
5	FT	4 MW	20 nJ	**0.0357**
6	FT	7.75 MW	20 nJ	**0.0361**
7	Gaussian	4 MW	15 nJ	**0.0362**
8	GS	4 MW	20 nJ	**0.0340**
9	GS	1.5 MW	8.22 nJ	**0.0477**
10			16.32 nJ	**0.0456**
11			24.79 nJ	**0.0448**
12			32.23 nJ	**0.0432**
13	GS	1.5 MW	34.96 nJ	**0.002710**
14			63.35 nJ	**0.002608**
15			113.34 nJ	**0.002548**
16			163.08 nJ	**0.002451**
17			205.81 nJ	**0.002332**
18			252.65 nJ	**0.002371**

Model validation

Example of cathode form factor determination using arbitrary measured bunch charge values from different cathodes

Cathode	Form factor	Relative deviation
# 1	0.0359	≤ 6%
# 2	0.0453	≤ 5%
# 3	0.002503	≤ 7%

→ resulting from using different sets of measurement data for cathode characterizations

1. **Same characteristic factor found for the same cathode, nearly independent of experimental conditions**
2. **Consistent emission model**
3. **Cathode factor used as one of the input parameters for simulations involving different sets of gun and beam parameters**

Model validation

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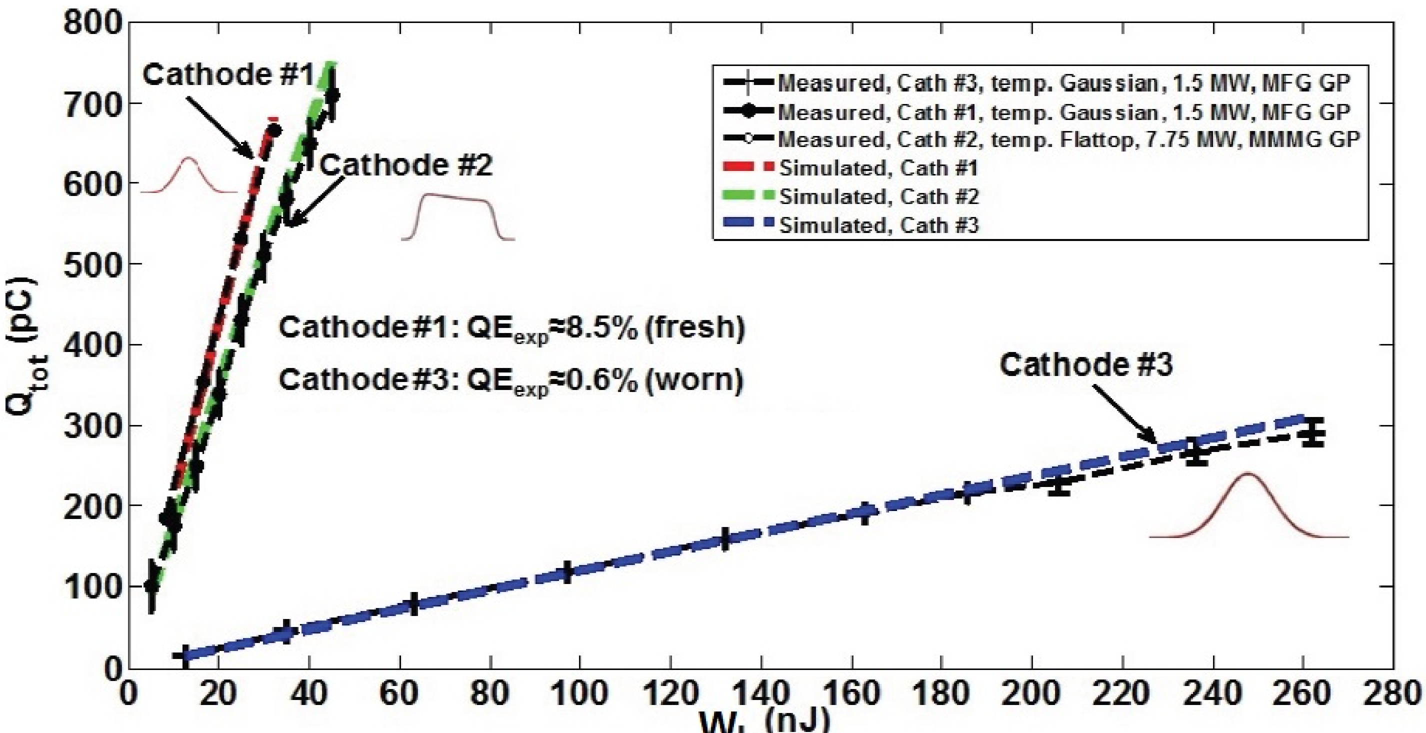
– **Good agreements between measurements and simulations in QE regime using the emission model in LW code**

Predictions with the LW code for QE-limited total extracted bunch charges from 3 different cathodes using different operation parameters



- **3 cathodes**
- **2 RF gun powers**
- **2 cathode laser profiles**
- **2 gun phases**

Influences of Schottky-like effect on transient charge profiles during emission

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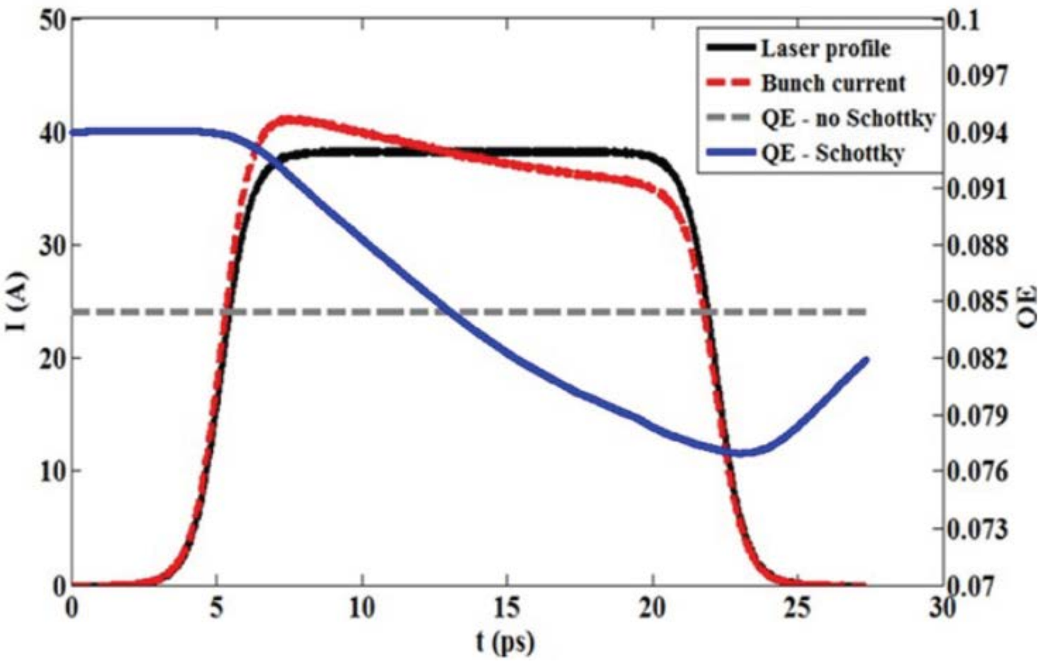
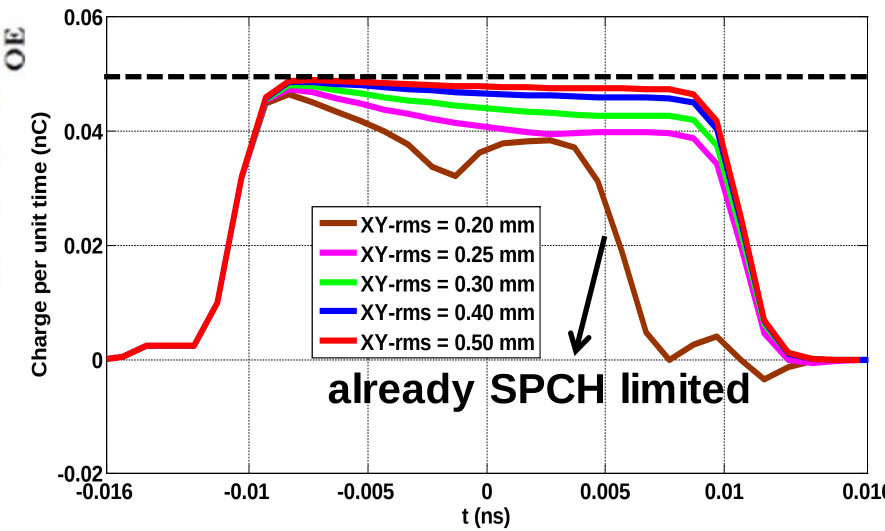
Modification of beam temporal profile due to Schottky-like effect



FT: ~21 ps, $W_{laser} \approx 37$ nJ,

$P_{rf} \approx 4$ MW, $QE_{mean} \approx 8.5\%$

For different laser spot sizes at the cathode



Effect is stronger as SPCH density increases

Influences of Schottky-like effect on transient charge profiles during emission

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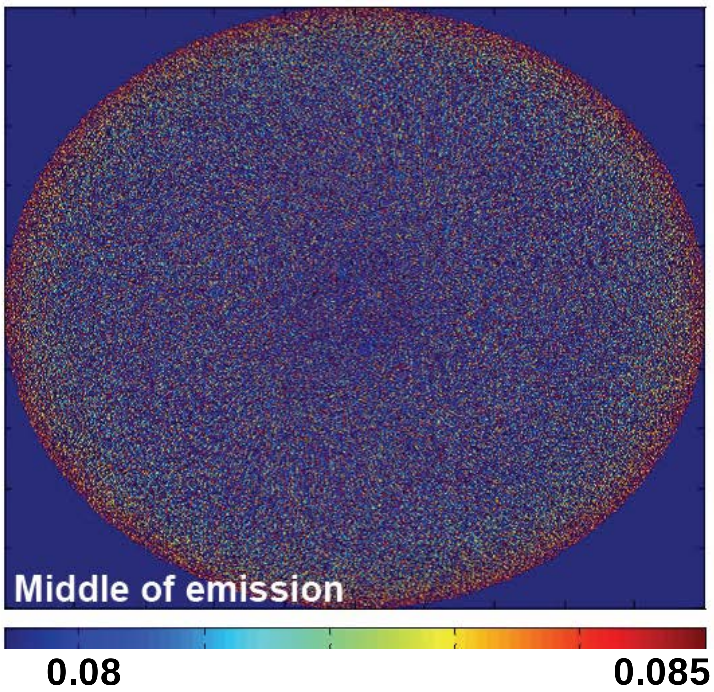
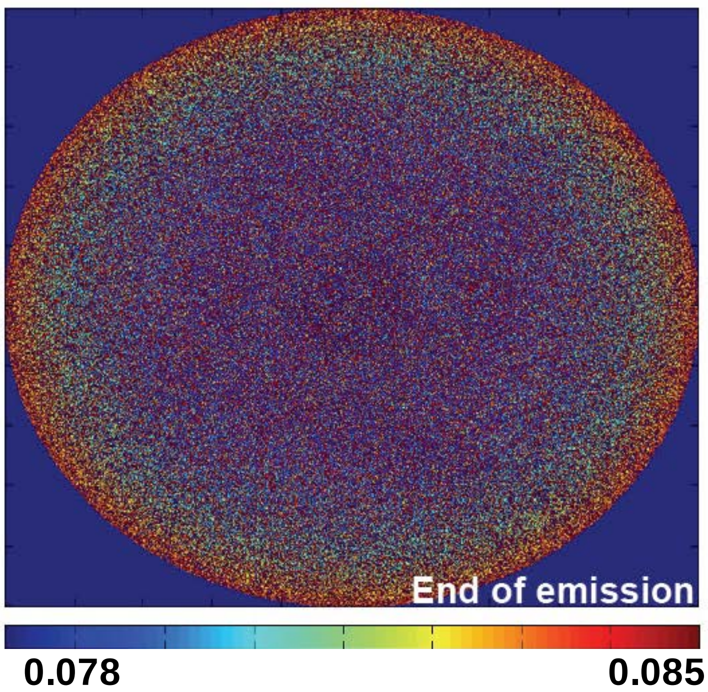
Modification of beam transverse profile due to Schottky-like effect

Computed local QE-map of the cathode

bunch center (t~16ps)



bunch end (t~30ps)



XY_rms = 0.4 mm, Q = 1 nC, ~ 30 ps flattop cathode laser, E_max ~ 60 MV/m

Influences of Schottky-like effect on transient charge profiles during emission

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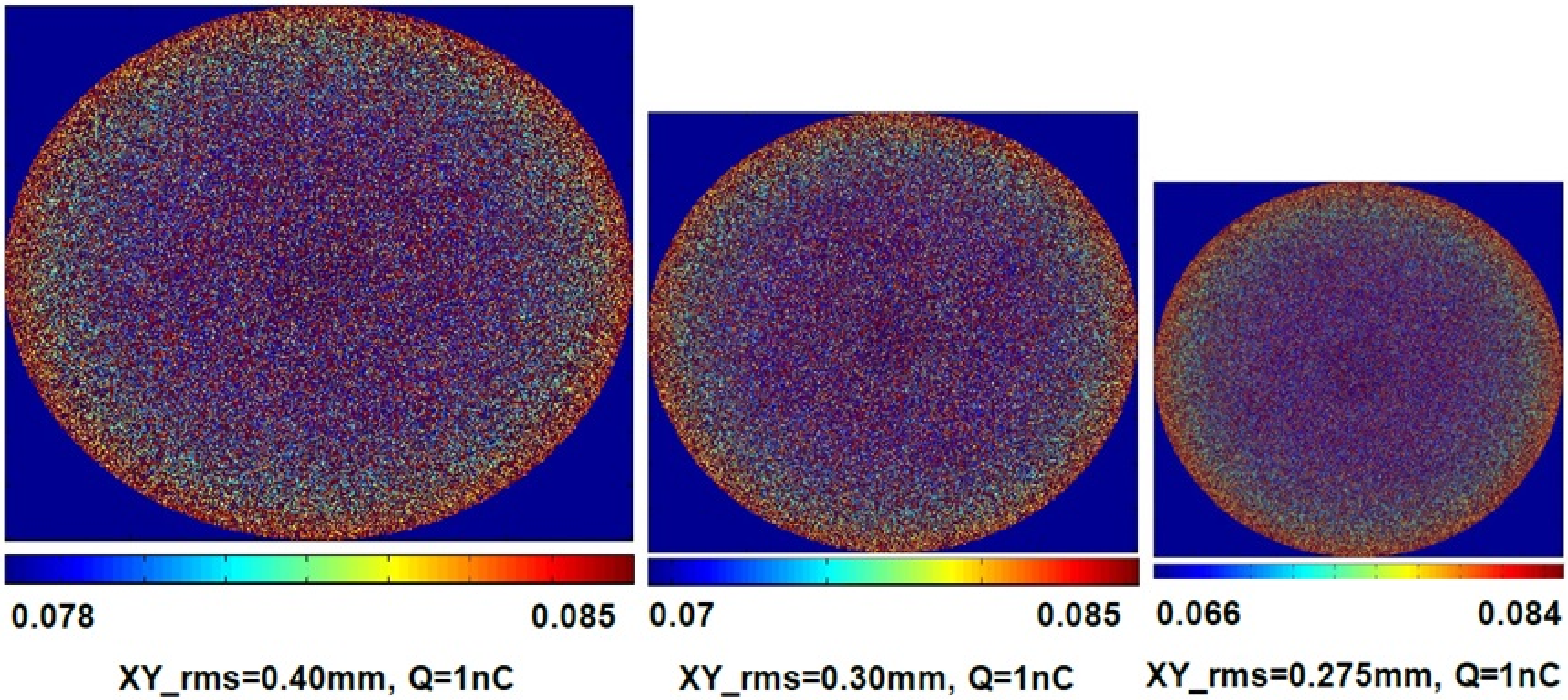
Maxi. Deviation of QE between center and edge over emission area



low **SPCH density** **high**

Influences of Schottky-like effect on beam dynamics downstream from cathode

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- **Comparisons on beam dynamics parameters between Schottky (dynamic extraction) and Schottky-free (uniform extraction)**
- **For extracting 1 nC bunch charge using different cathode laser spot sizes (laser pulse energies at cathode adjusted)**
  - Case 1: XY_rms = 0.4 mm, $Q_{out} \approx 1$ nC (Elaser ≈ 59.92 nJ) → **Low SPCH density**
  - Case 2: XY_rms = 0.3 mm, $Q_{out} \approx 1$ nC (Elaser ≈ 62.80 nJ) → **Medium SPCH density**
  - Case 3: XY_rms = 0.275 mm, $Q_{out} \approx 1$ nC (Elaser ≈ 64.50 nJ) → **High SPCH density**
- Other parameters: ~ 22 ps flattop laser (FWHM), E_max ~ 60 MV/m, B_max ~ 0.228 T

Influences of Schottky-like effect on bunch phase space

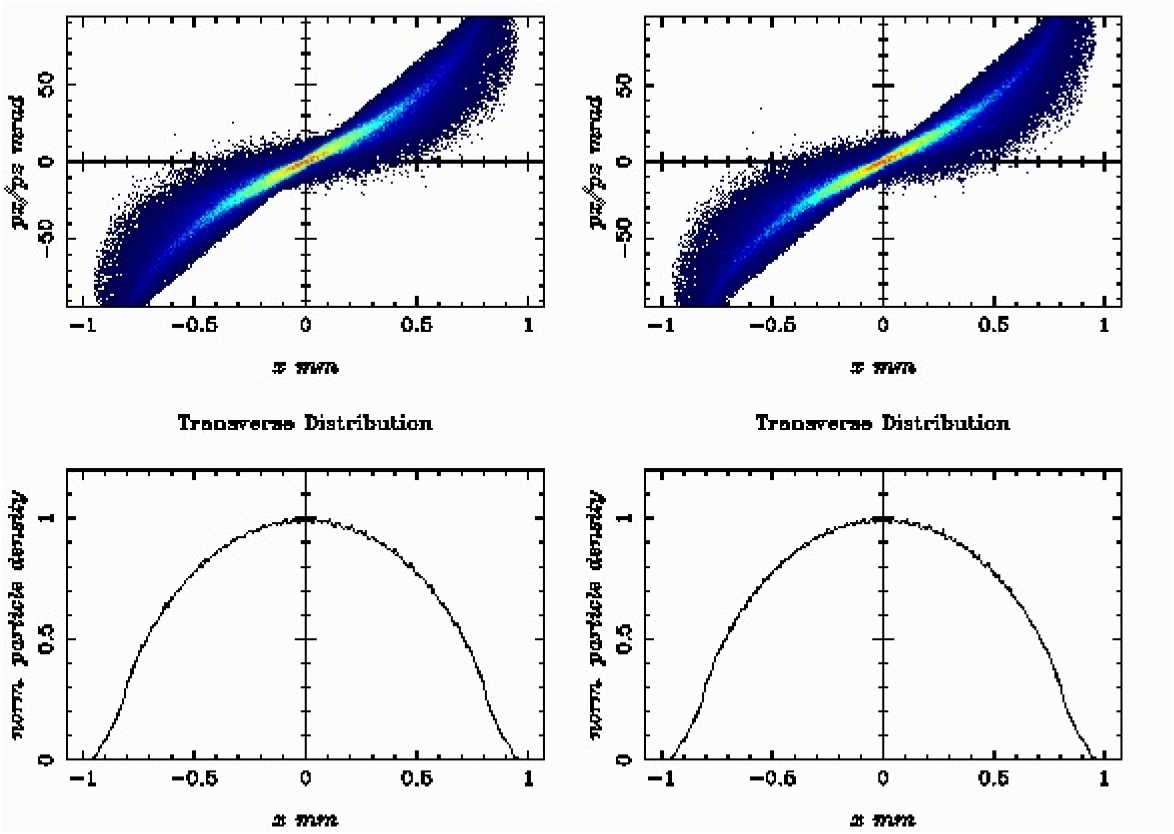
@ $z \approx 1$ mm, $\Delta\varepsilon_{xy} \approx 4\%$

Case 1

XY_rms = 0.4 mm

Q = 1 nC

w/o Schottky | **with Schottky**



Influences of Schottky-like effect on bunch phase space

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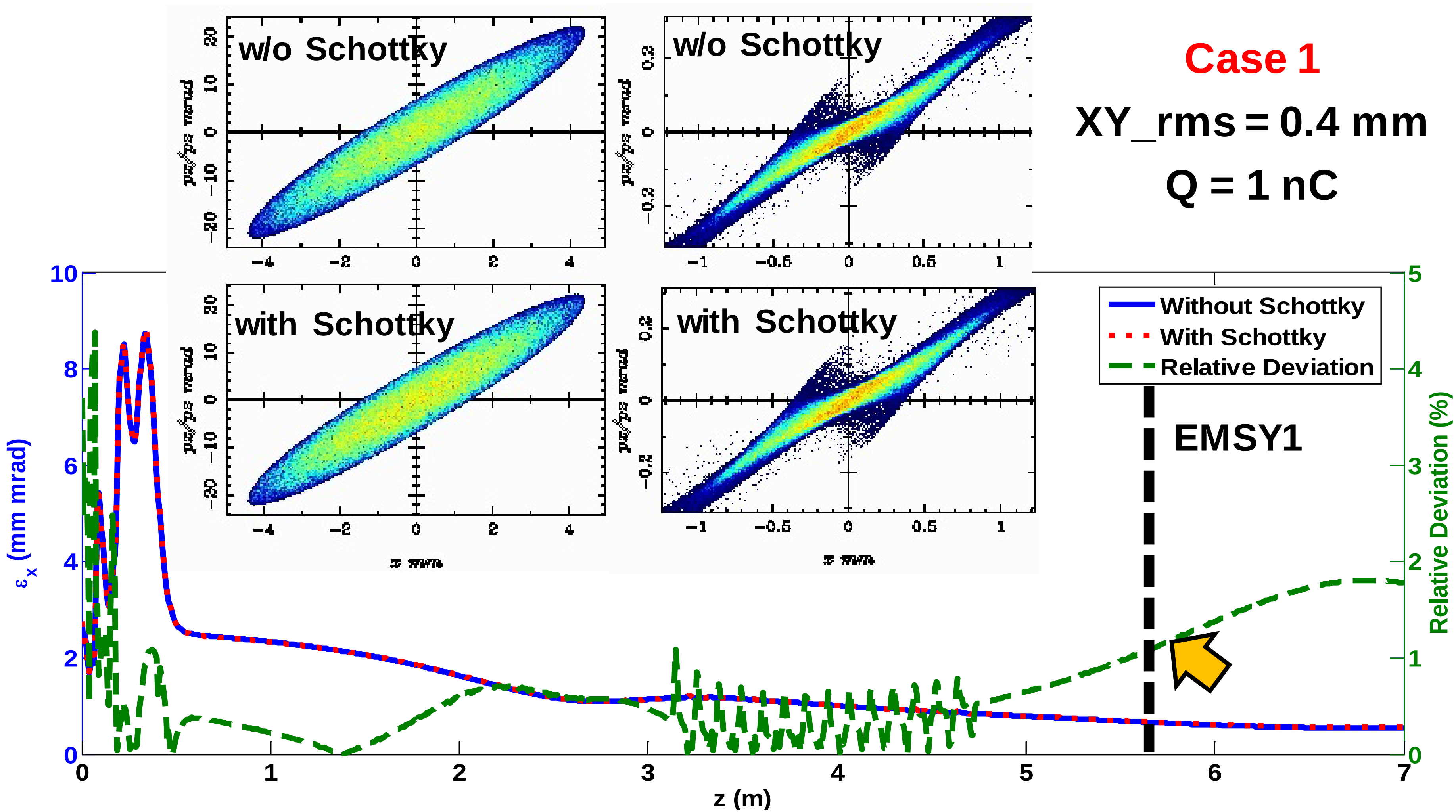
@ z ≈ 10 cm, $\Delta\varepsilon_{xy} \approx 1.5\%$ @ z ≈ 5.74 m, $\Delta\varepsilon_{xy} \approx 1\%$

Case 1

XY_rms = 0.4 mm

Q = 1 nC



Influences of Schottky-like effect on bunch energy spread

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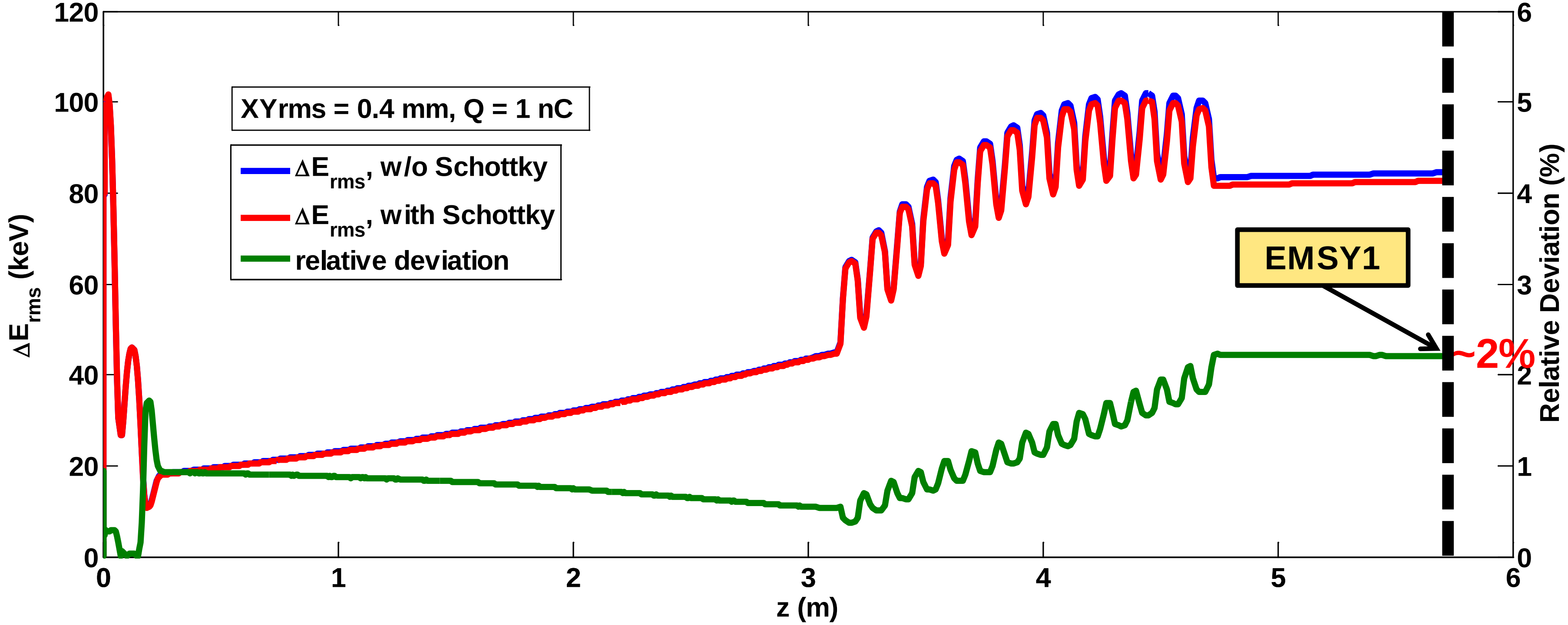
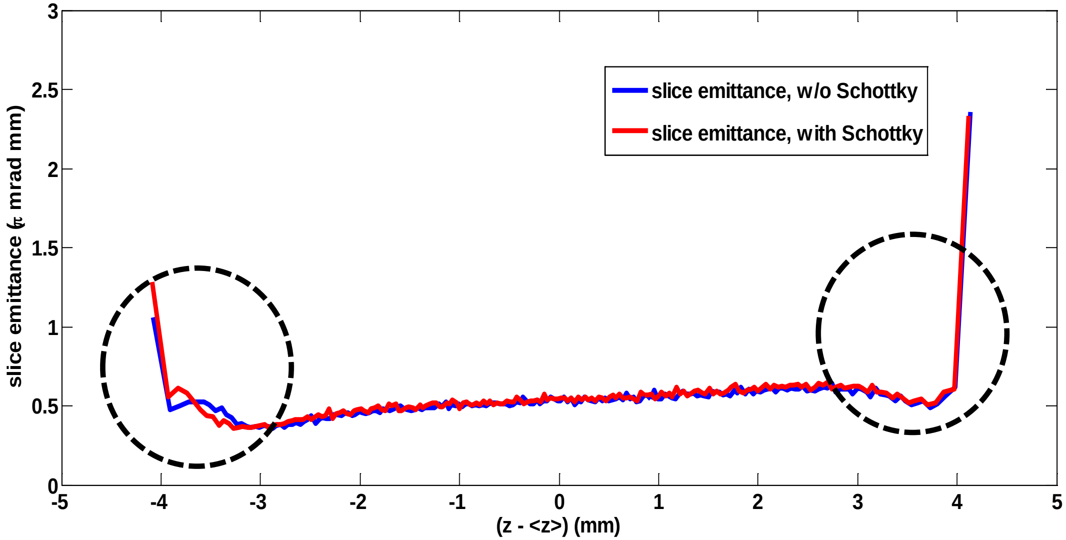
Case 1: XY_rms = 0.4 mm , Q = 1 nC



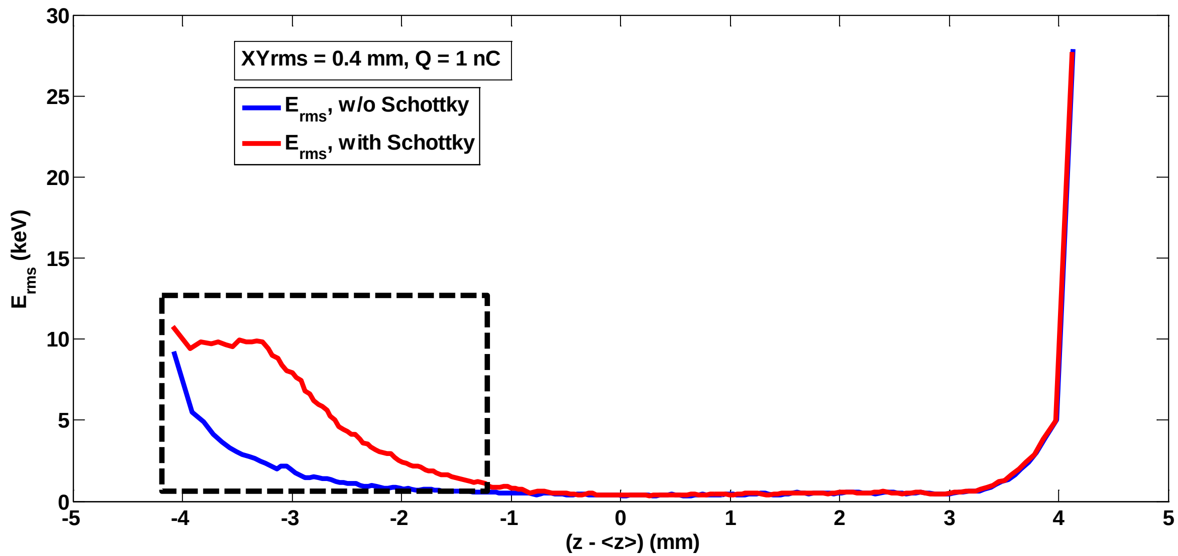
Influences of Schottky-like effect on slice emittance and slice energy spread



Case 1

XY_rms = 0.4 mm

Q = 1 nC



Influences of Schottky-like effect on bunch phase space

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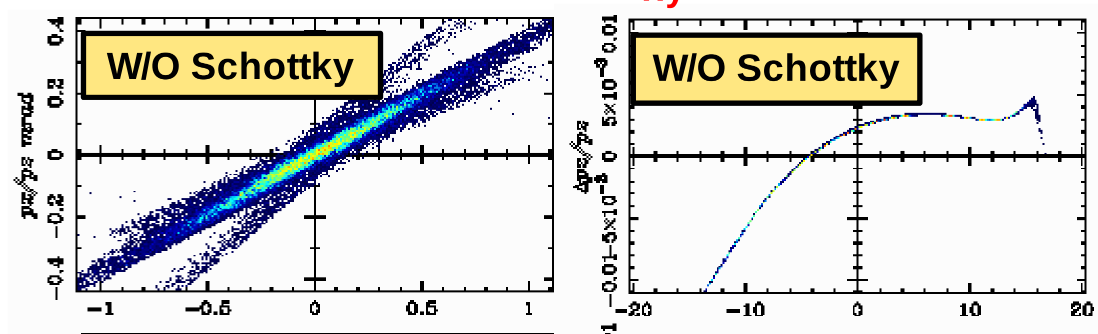
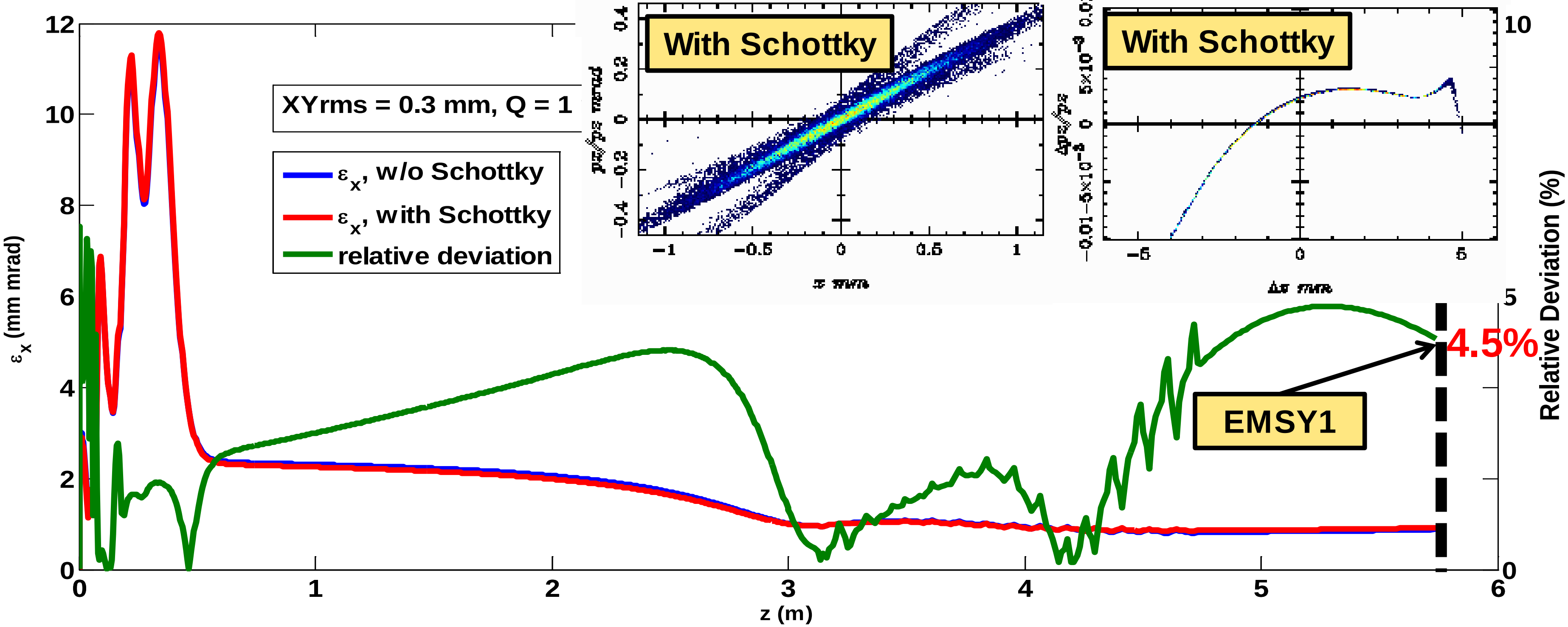
@ z ≈ 5.74 m, $\Delta\varepsilon_{xy}$ ≈ 4.5%

Case 2

XY_rms = 0.3 mm

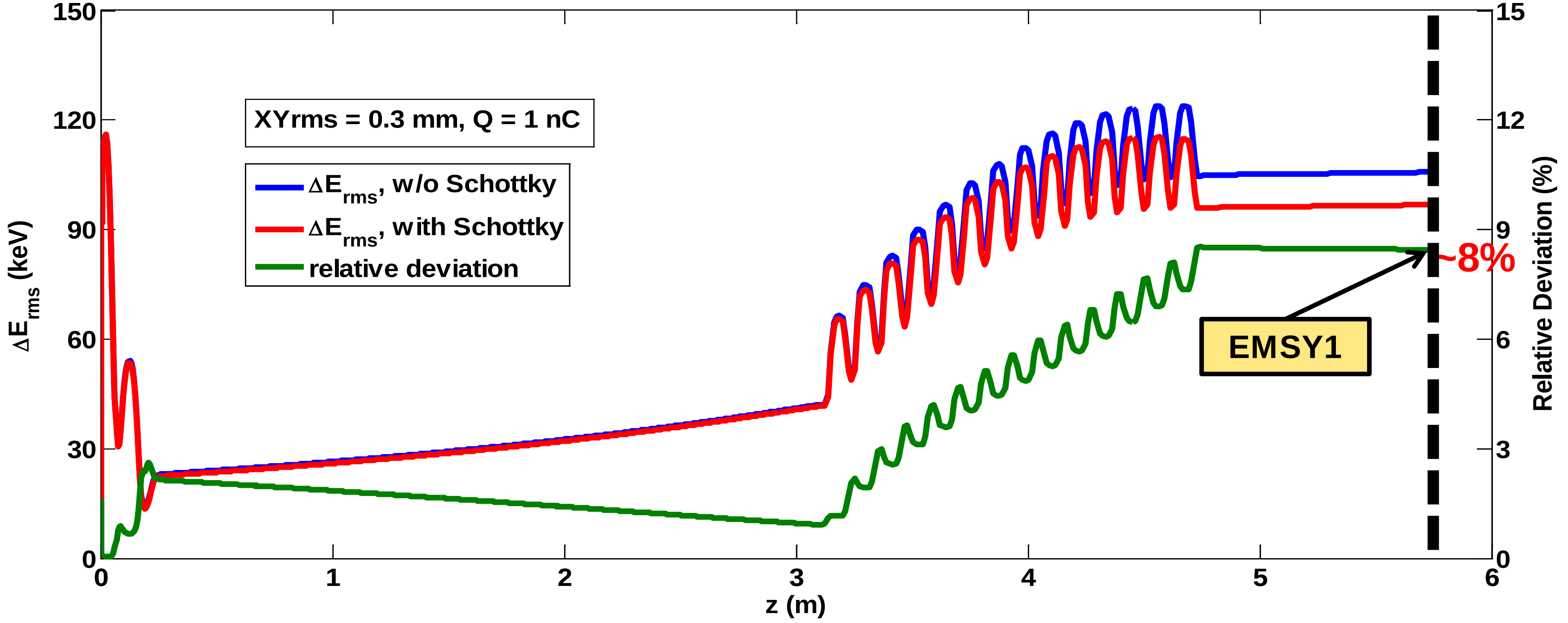
Q = 1 nC



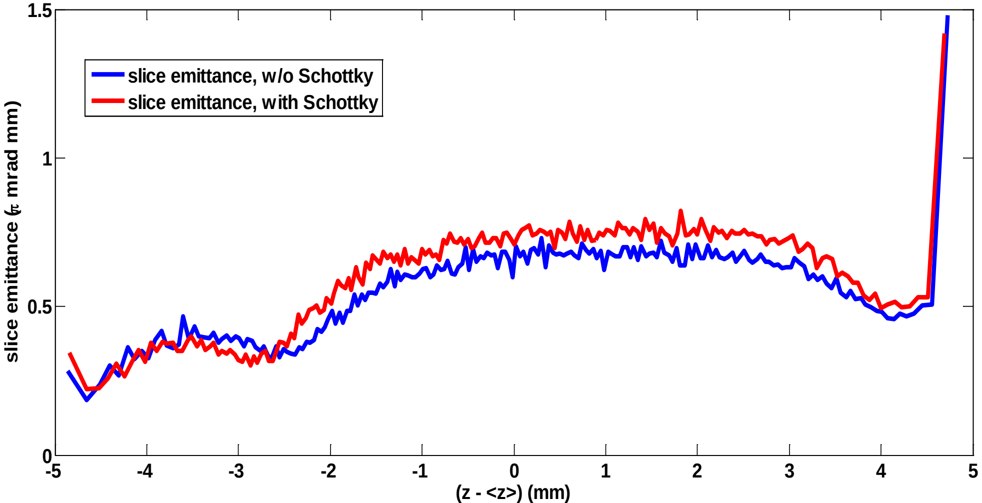


Influences of Schottky-like effect on bunch energy spread

Case 2: XY_rms = 0.3 mm , Q = 1 nC



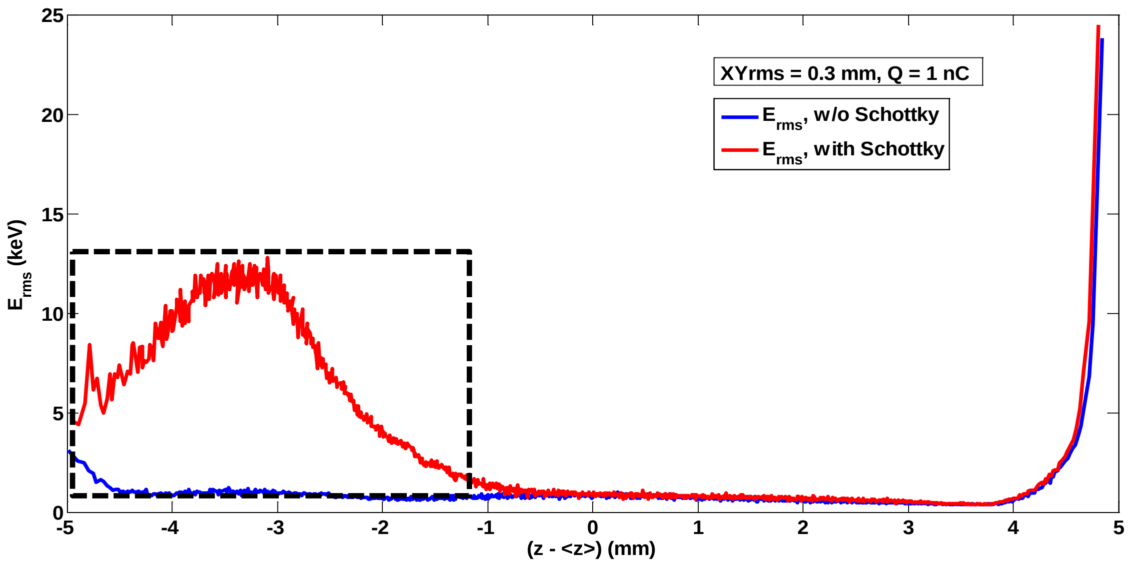
Influences of Schottky-like effect on slice emittance and slice energy spread



Case 2

XY_rms = 0.3 mm

Q = 1 nC



Influences of Schottky-like effect on bunch phase space and energy spread

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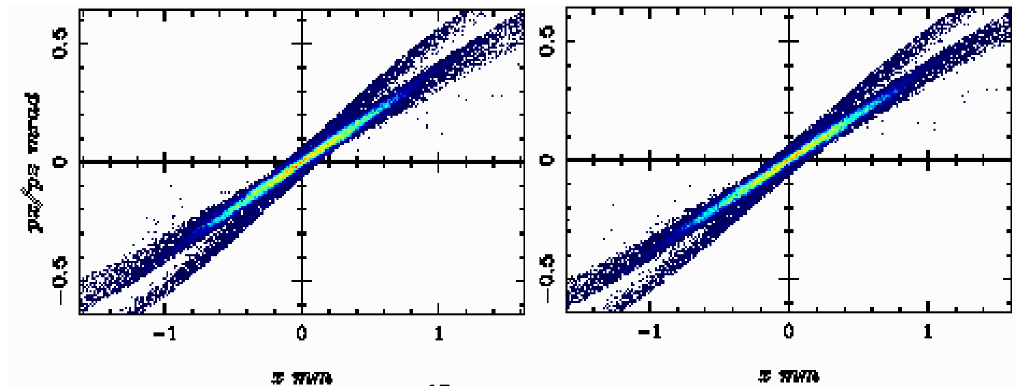
Case 3

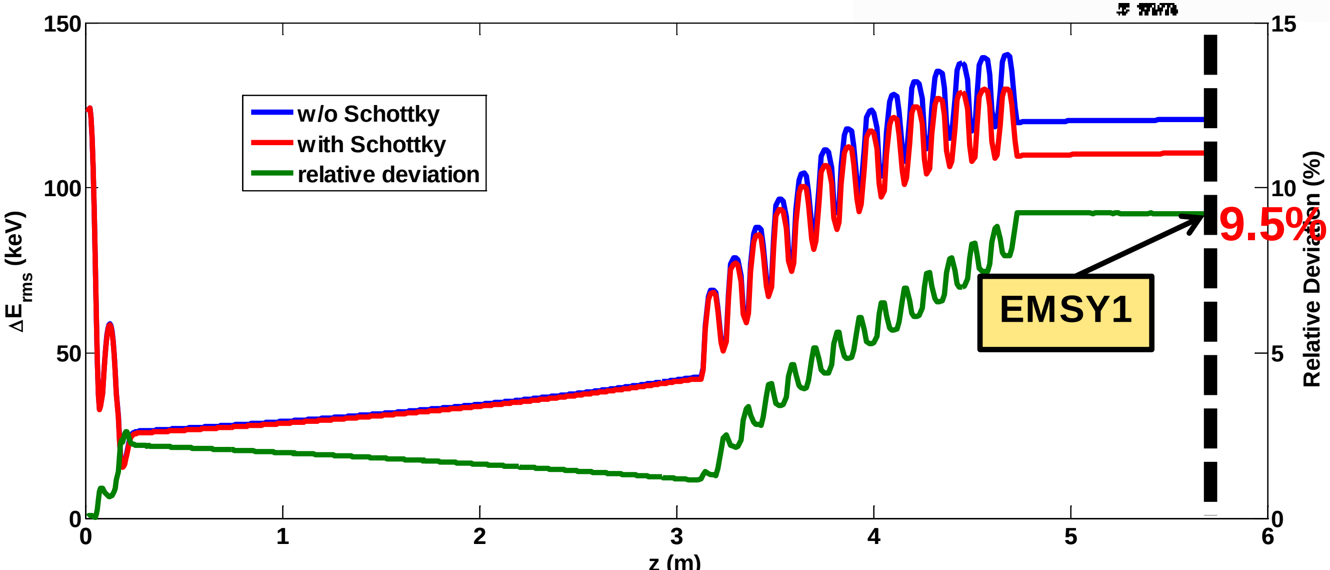
XY_rms = 0.275 mm

Q = 1 nC

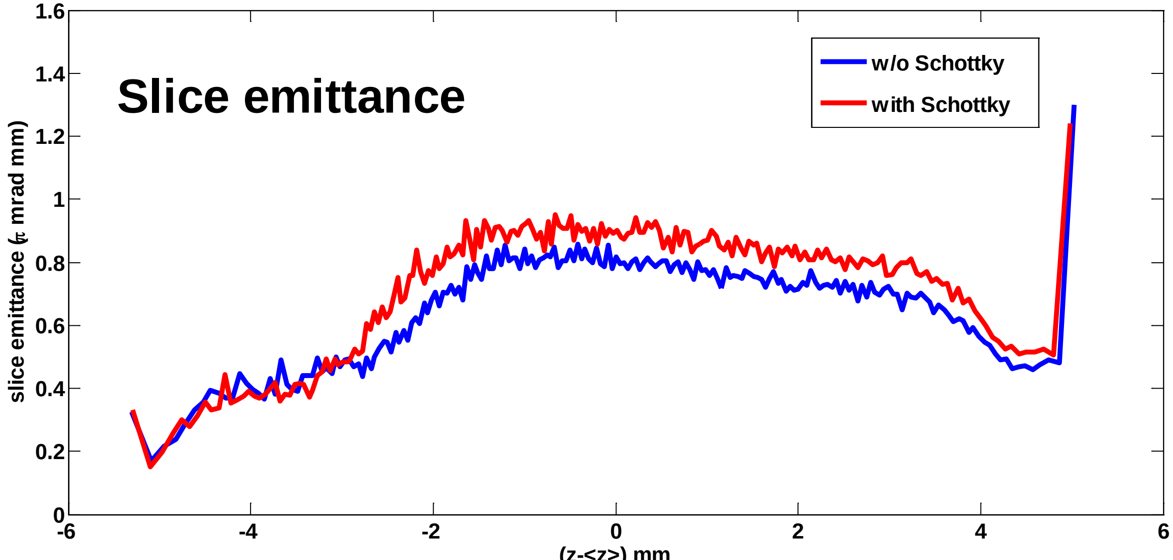
@ z ≈ 5.74 m, $\Delta\varepsilon_{xy}$ ≈ 7.1%

W/O Schottky | **With Schottky**





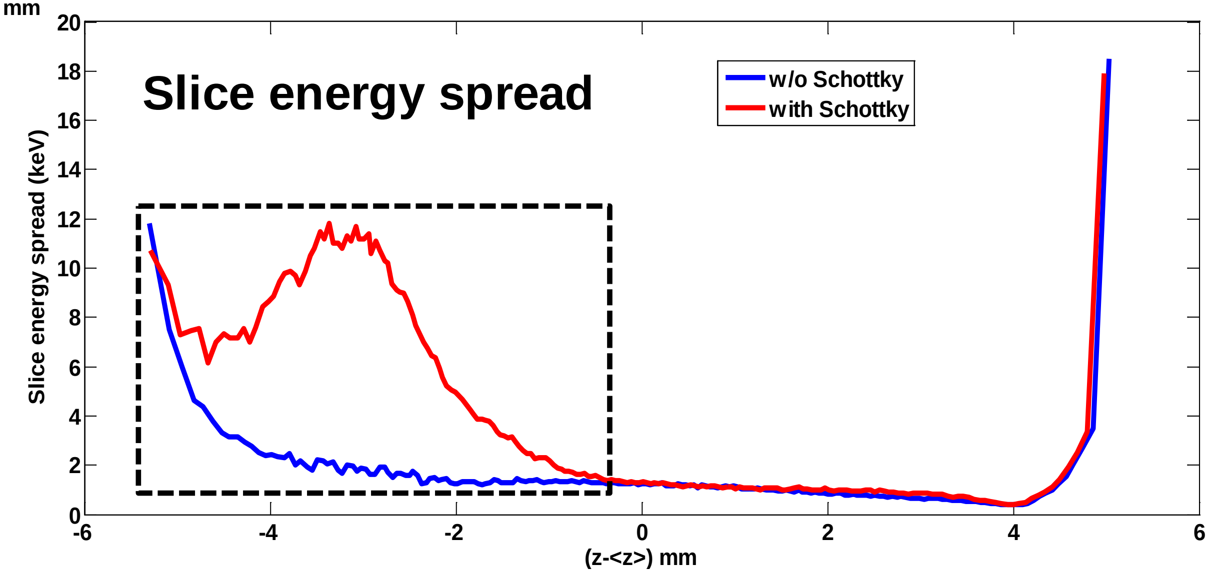
Influences of Schottky-like effect on slice parameters



Case 3

XY_rms = 0.275 mm

Q = 1 nC



Impact of Schottky effect on total bunch charge extraction

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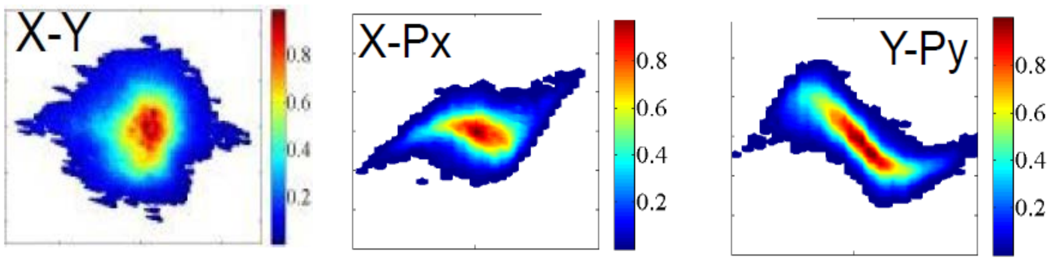
- Using same laser pulse energy, total extracted bunch charges different for Schottky and Schottky-free case
- Schottky effect enhances photoemission under high gradient accelerating fields providing more emitted bunch charge
- However, if switch off relativistic field effect, simulations not able to explain the total bunch charge obtained experimentally, even with Schottky effect

Example of bunch charge extraction using one characterized cathode

XY_rms (mm)	Elaser (nJ)	Schottky-like effect	Q_{tot} (nC)
0.3	~78.5	Excluded	1.0
		Included	~1.23
0.4	~78.5	Excluded	1.0
		Included	~1.30

Investigations on asymmetries / coupling in beam profile and transvers phase space

– **Motivation:**



Measured beam profile and transvese phase spaces at EMSY1

– **Possible sources of asymmetries**

- Cathode effect → Seems not
- Beam line effect?
  - ❖ Coaxial coupler (field asymmetries)
  - ❖ Main solenoid imperfections
  - ❖ Vacuum mirror etc.

Investigations on asymmetries / coupling in beam profile and phase space

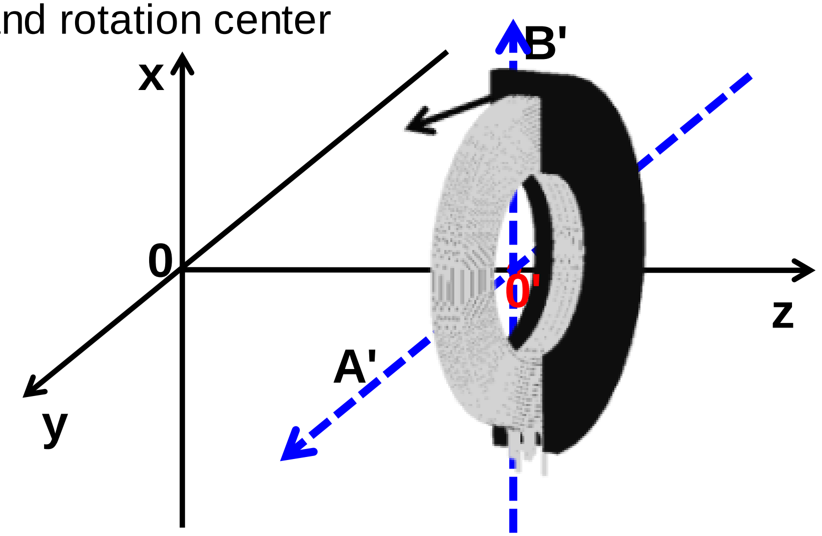
– **First attempts:** Using tilted main solenoid fields / RF cavity fields

– **Ideas**

  - Calculating a 3D field map ⟶ computationally expensive, can be done later
  - Simplification: translating particles to the local solenoid / cavity frame for paraxial field calculations

⟶ 3D rotation about arbitrary axis and rotation center

⟶ $\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \mathbf{M} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$



Preliminary tracking simulations

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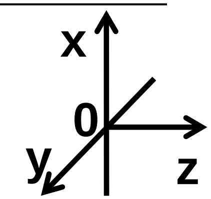


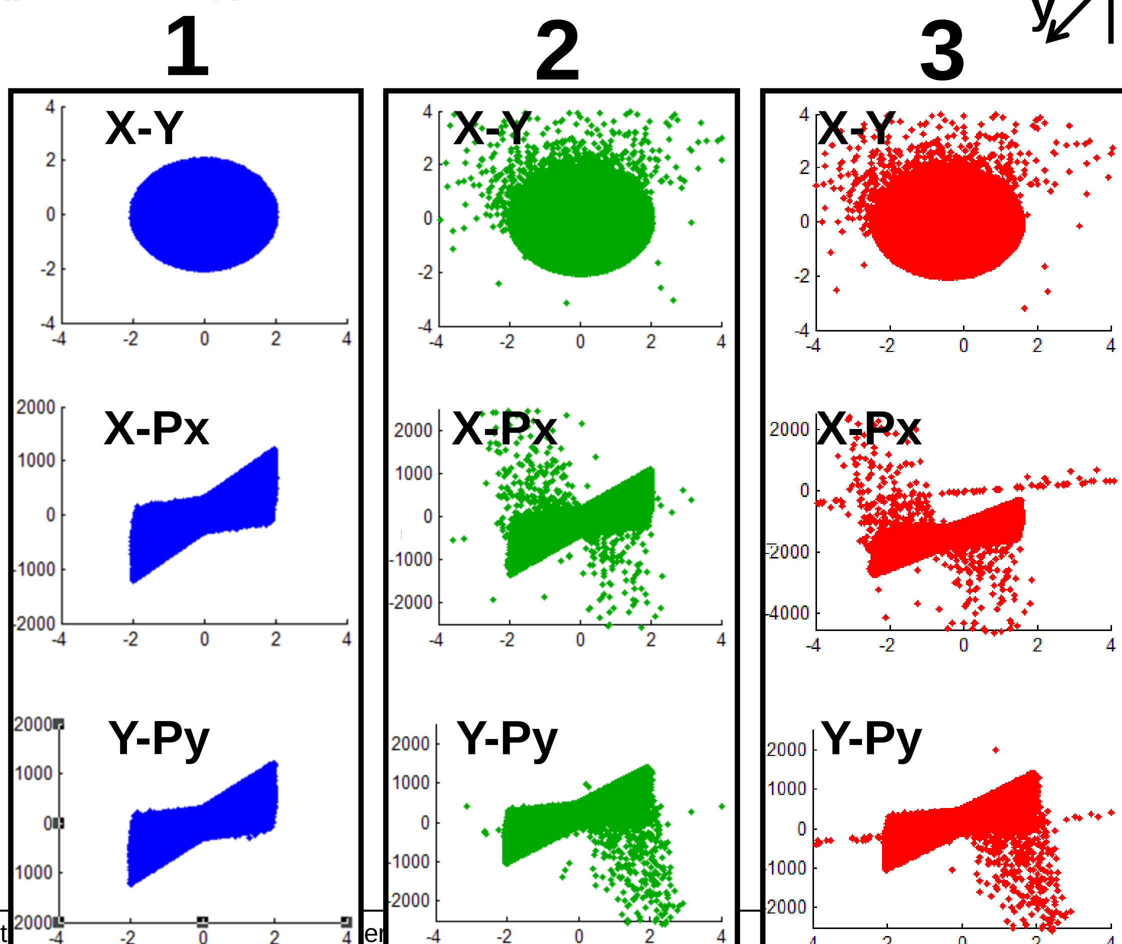
- RF rotation, parallel to y-axis by 0.01 deg, rotation center (0 0 0)
- Tracking simulation results (preliminary)

@ EMSY1, z = 5.74 m

1. No rotation
2. Rotating by ϴ = 0.01 deg
3. Rotating by ϴ = 0.01 deg, with tilted booster field

- ❖ **RF influences very strong**
- ❖ **Only a very small rotation can do the asymmetric coupling**

typical measured profiles



Preliminary tracking simulations

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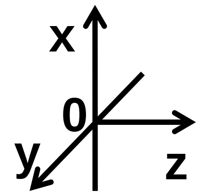
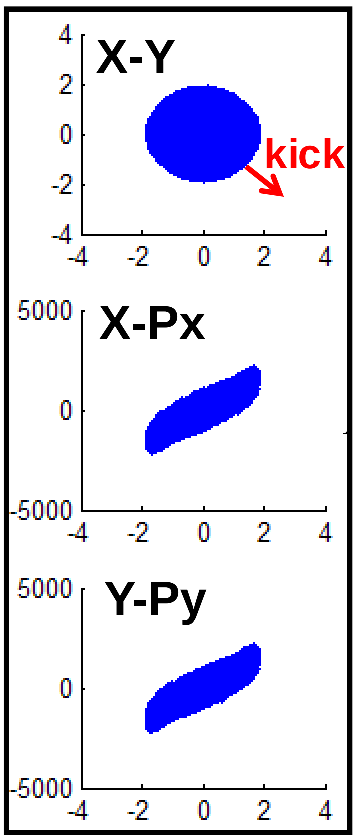
– **Main solenoid rotation, parallel to x-axis by 1 deg, rotation center (0 0 $z_{solenoid}$)**

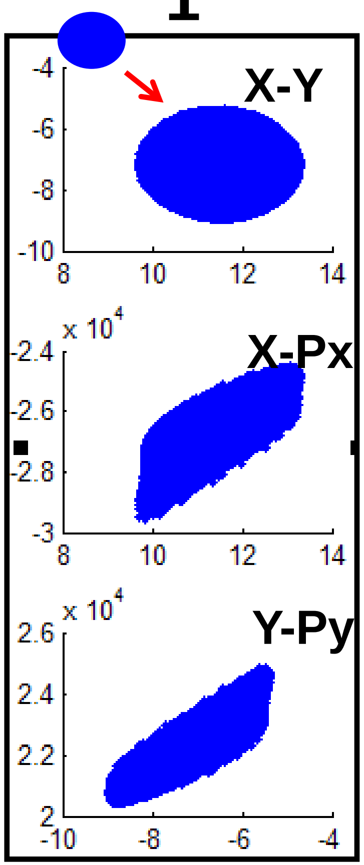


– **Main solenoid rotation, parallel to y-axis by 1 deg, rotation center (0 0 $z_{solenoid}$)**

No Rotation



1

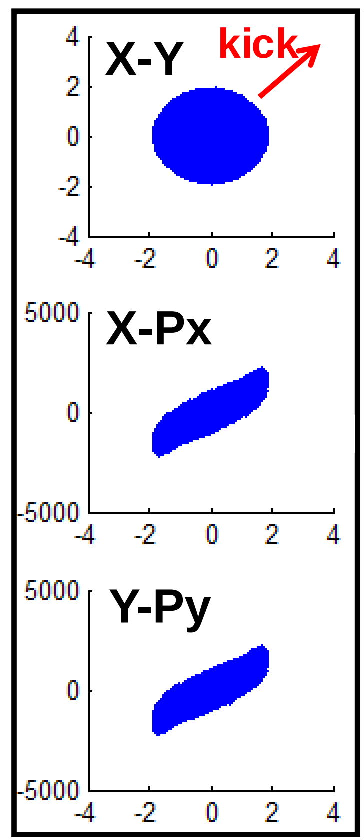


@ EMSY1, z = 5.74 m

1. **Rotating by Θ = 1 deg, x-axis**
2. **Rotating by Θ = 1 deg, y-axis**

- **Transverse kick observed**
- **Shapes not changed much**

No Rotation



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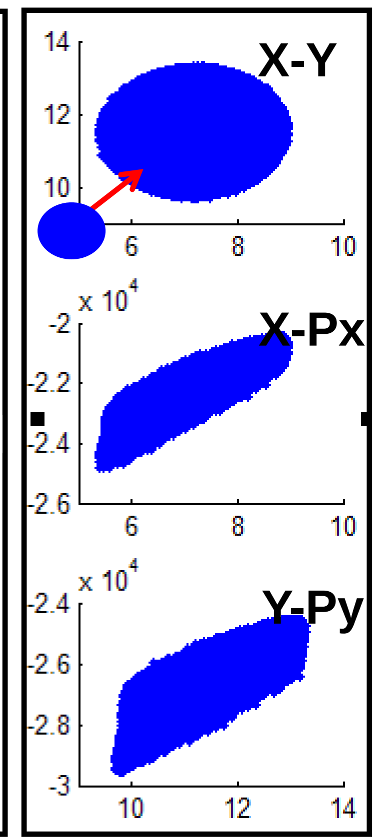

Summary & Outlook

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1. A **numerical photoemission model** including Schottky-like effect developed at TEMF using a Lienard-Wiechert approach
2. Model applied at PITZ for photoemission studies predicting **extracted bunch charges in good agreements with measurements** for different bunch / gun parameters
3. **Impacts of Schottky-like effect on beam dynamics** systematically investigated
4. Preliminary studies performed for **asymmetries / coupling observed in beam profiles / phase spaces showing strong RF influences even with a small tilted angle**

- ❖ Further photoemission modeling based on **novel quantum theory for semiconductor QE**
- ❖ Further studies of **distortions in transverse phase space**
- ❖ Intrinsic **emittance optimization**

Thank you for your attention!