Numerical modelling of photoemission for the PITZ photoinjector

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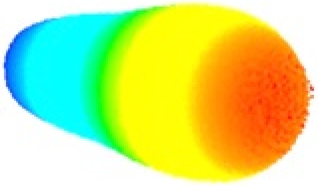
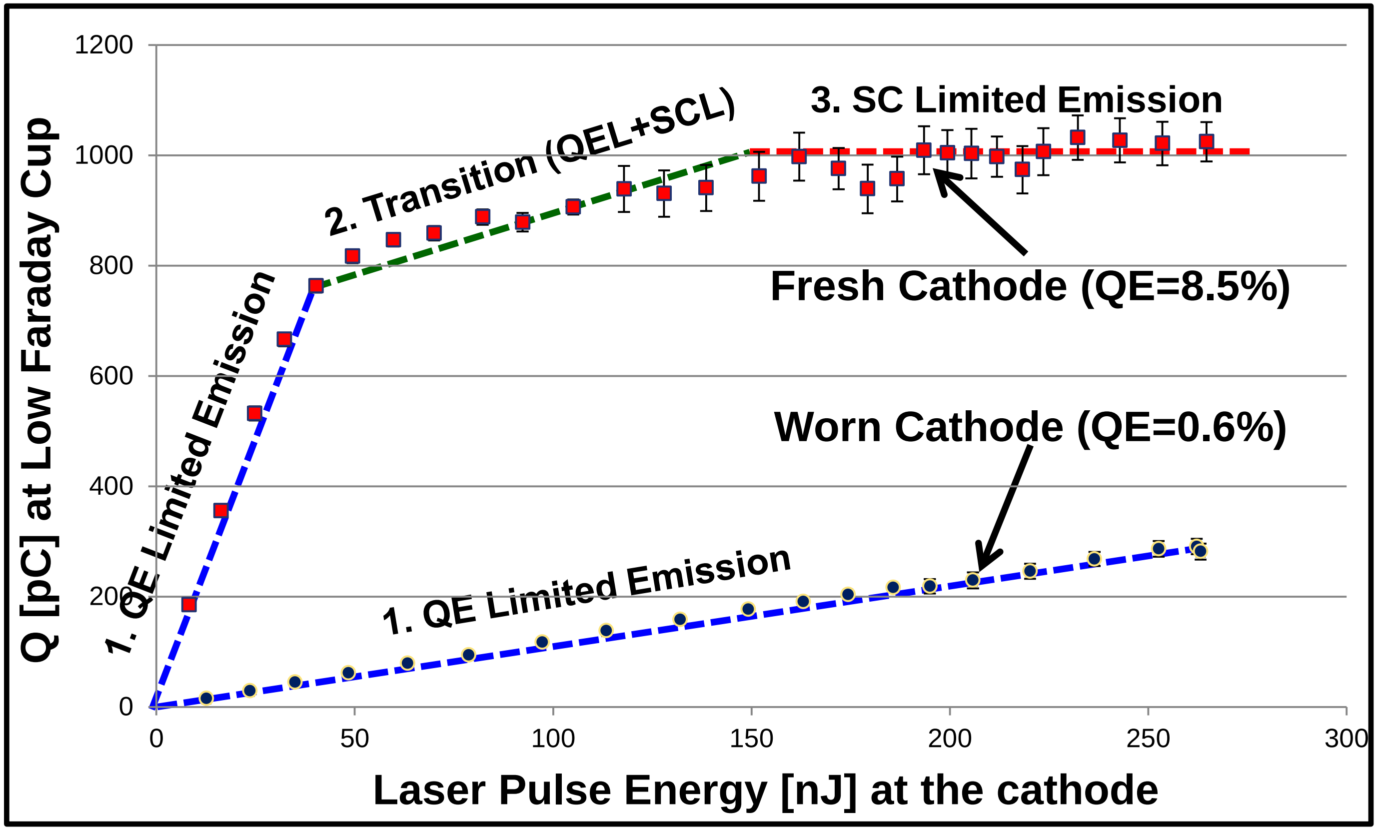


Introduction

Charge vs Laser Pulse Energy*
identified emission regimes for OLD and NEW cathodes



Motivation

1. **Identify source of discrepancies between measurement and simulation** in terms of photoemission parameters.
2. **Develop** a **numerical model** of photoemission.

***Measurement data sets provided by PITZ, 17.03.2015**

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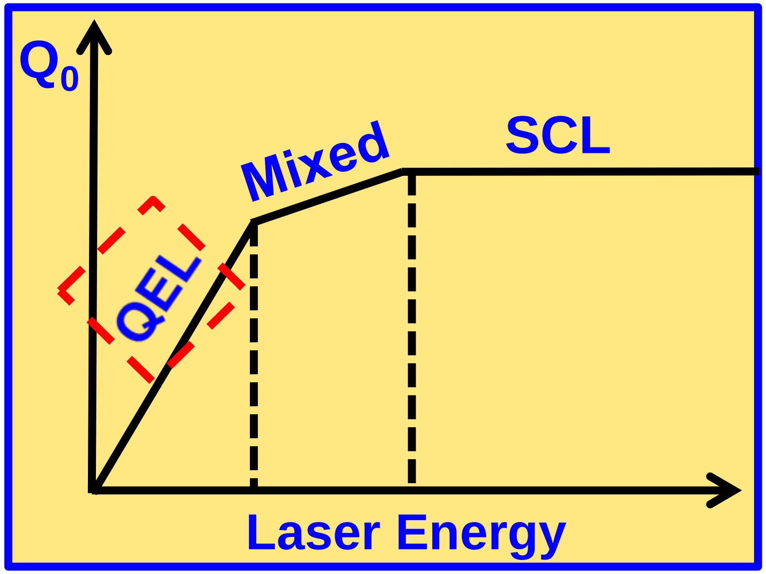
Self-consistent QE limited bunch emission (QEL)

QEL emission modelling

- Q_{tot}
  1. Total bunch charge produced by the laser pulse at cathode
  2. Input bunch charge for simulation
- $E_{tot} \longrightarrow$ QE
  1. Influences of Schottky effect on bunch temporal profile



Simulation assumption

QEL bunch emission: key factors

- **Two related but independent processes:**
  1. **Charge production:** the **laser pulse** illuminates the **photocathode** and produces electrons at the cathode for extraction.
  2. **Charge (electrons) emission:** decisions of emission are made by the **local total field** at the cathode at the moment of extraction.
- **Key factors**
  1. **Laser pulse:** temporal shape and energy
  2. **Local fields at cathode:** RF+SC, perpendicular to the PEC surface
  3. **Quantum efficiency (QE) of photocathode**

QEL bunch emission: relation between E_{cath}, QE and Q_{tot}

With no applied fields

$$QE^{*} = \eta[h\nu - \Phi_{cath0}]^2 \quad (1)$$

η: cathode factor that depends on material properties such as the absorption coefficient, density of states, transition probability, and the angle of incidence of the laser light.

hν: photon energy, 4.81 eV

Φ_{cath0}: work function with no applied field, 3.5 eV

$$Q_{tot} = e\frac{E_{laser}}{h\nu}QE \quad (2)$$

$$E_{cath}(x, y, z = 0, t)$$

work function correction due to field effects

$$\Delta\Phi(x, y, z = 0, t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0}E_{cath}(x, y, z = 0, t)} \quad (3)$$

$$\Phi_{cath} = \Phi_{cath0} \mp \Delta\Phi(x, y, z = 0, t) \quad (4)\ **$$

$$QE(\eta;\ x, y, z = 0, t) = \eta[h\nu - \Phi_{cath}]^2 \quad (5)$$

$$Q_{tot} = \int_{t_0}^{t}\iint_{xy} e\frac{P_{laser}(\tau)}{h\nu}QE(\eta; x, y, z = 0, \tau)\, dxdyd\tau \quad (6)$$

Local fields at cathode introduce space- and time- dependences to QE, while the latter corrects distributions of the emitted electron bunch accordingly.

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* **QE:** incident photon to converted electron (IPCE) ratio.

** **"∓"** characterizes the work function variation when the total field changes sign.

QEL bunch emission: modelling steps

- **Total bunch charge produced at the cathode by the laser pulse:**

$$Q_{tot} = \eta \int_{t_0}^{t} \iint_{xy} e \frac{P_{laser}(\tau)}{h\nu} \left[h\nu - \left[\Phi_{cath0} \mp \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(x, y, z = 0, t)} \right] \right]^2 dxdyd\tau \; \mathbf{(7)}$$

- **Modelling of $Q_{tot}\ (\eta; x, y, z = 0, t)$**
  - **1st step: photocathode characterization**
    - Determination of η
    - Verification of η for different operation parameters (i.e. E_{laser}, E_{cath}, temporal profiles)
    - Use determined η for Schottky effect investigations
  - **2nd step: use determined η and full information of the local total fields at cathode to emit particles dynamically from the cathode**
    - Dynamic corrections of transverse and longitudinal distributions of the emitted electron bunch within each time step

Numerical approach

- Integrate equation (8) in a simulation loop, by correcting the temporal profile (TP) of the emitted electron bunch iteratively according to the local fields at cathode, such that Q_{tot} is normalized to Q_{meas} from measurements.

$$Q_{tot} = \eta \int_{t_0}^{t} e \frac{P_{laser}(\tau)}{h\nu} \left[h\nu - \left[\Phi_{cath0} \mp \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(z=0,t)} \right] \right]^2 d\tau \qquad (\mathbf{8})$$

- Ecath is the total field (RF + SC) at the cathode, perpendicular to the surface.
- The transverse dependence of Ecath is not yet considered.
- Settings of initial particle distributions

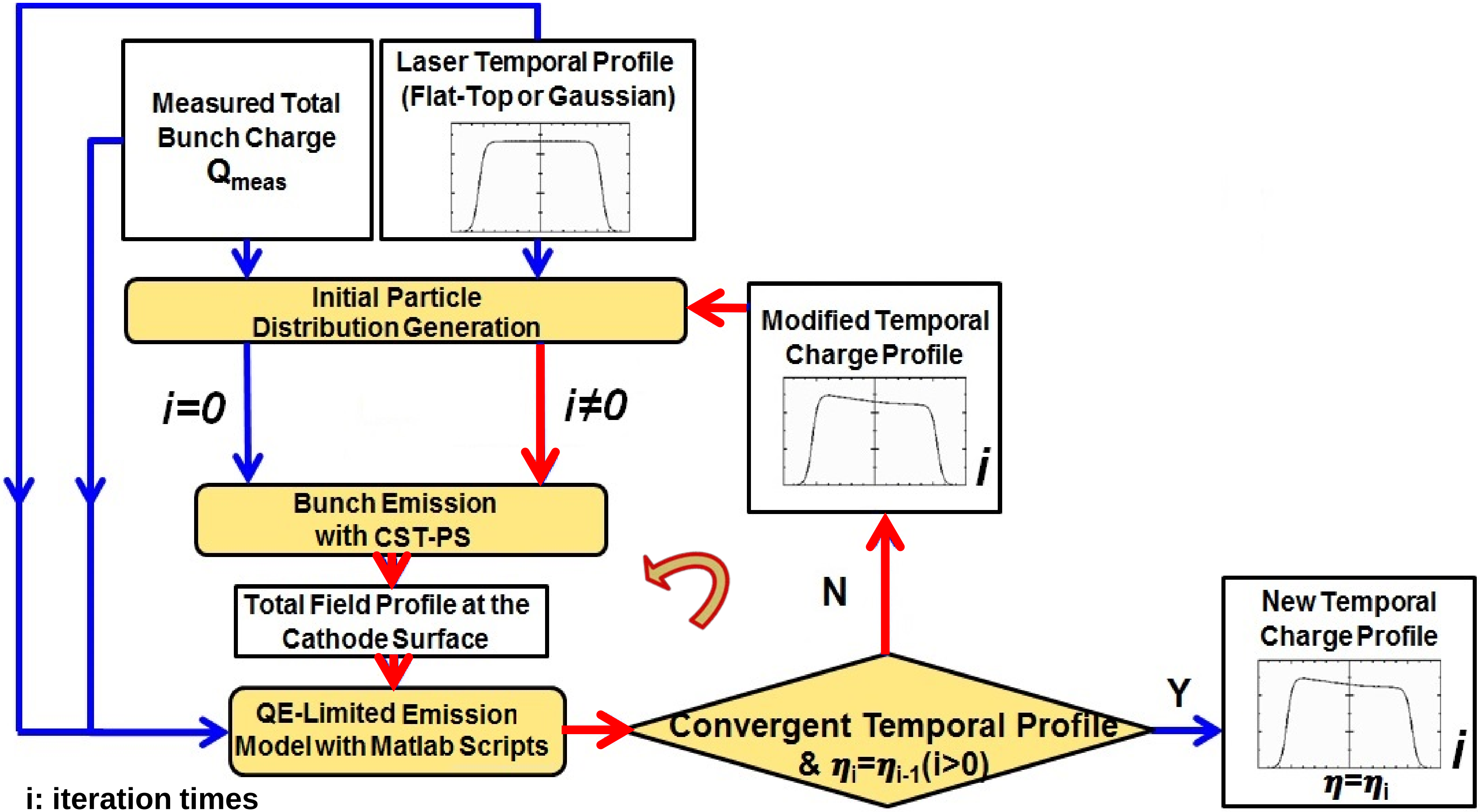
  i. Initial kinetic energy: 0.55 eV;

  ii. Transverse distribution (x, y, p_x, p_y): uniform;

  iii. Temporal profile: laser pulse profile;

  iv. Momentum (angle) distribution (p_z): isotropic;

Numerical approach



Measured Total Bunch Charge Q_{meas}

Laser Temporal Profile (Flat-Top or Gaussian)

Initial Particle Distribution Generation

Modified Temporal Charge Profile *i*

i=0

i≠0

Bunch Emission with CST-PS

Total Field Profile at the Cathode Surface

QE-Limited Emission Model with Matlab Scripts

N

Convergent Temporal Profile & $\eta_i=\eta_{i-1}(i>0)$

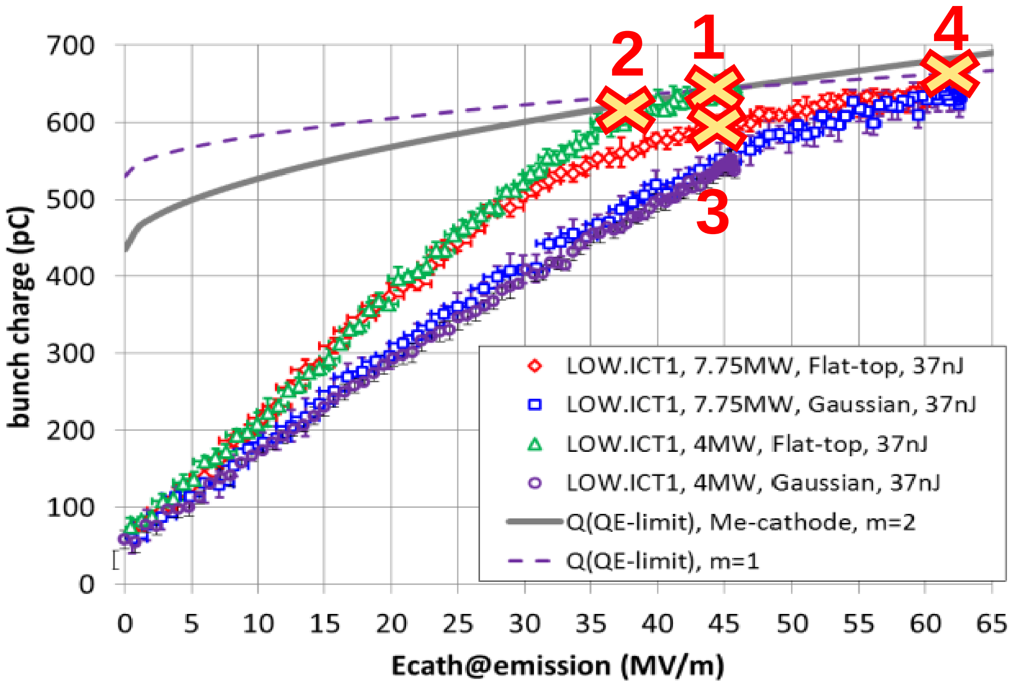
Y

New Temporal Charge Profile *i* $\eta=\eta_i$

i: iteration times

Cathode (2013) characterization (1): determination of η using different E_{cath}

***Total bunch charge vs. gun gradient at E_{laser} = 37 nJ**



* M. Krasilnikov, PITZ: Simulations versus Experiment, Darmstadt, 19.12.2013

(measurement data sets taken from 02.2013)

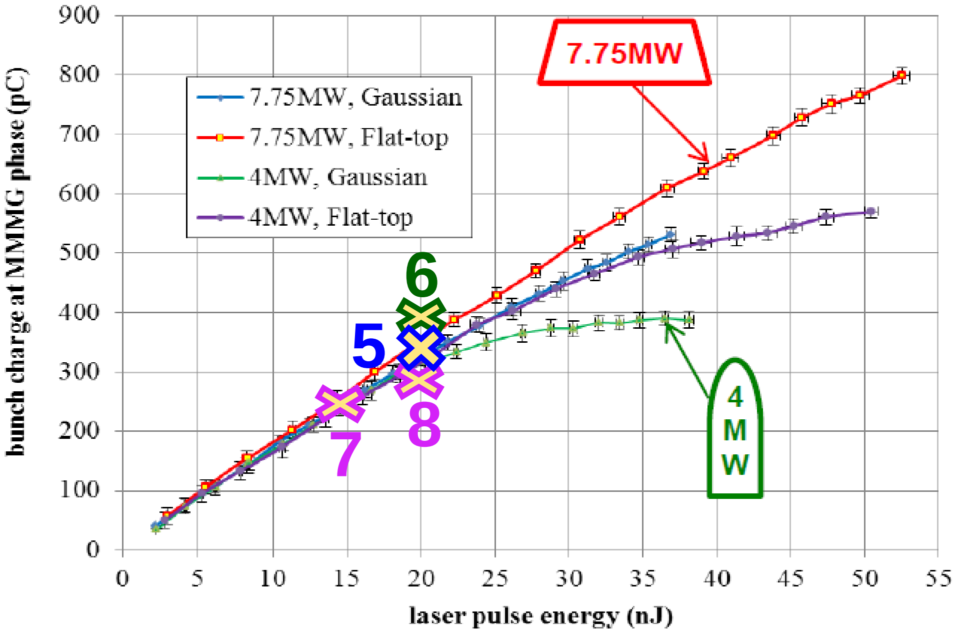
Results (1)

	E_{laser} (nJ)	E_{cath} (MV/m)	η	RF Power	TP
1	37	~46	0.0383	4 MW	FT
2		~36.7	0.0372	4 MW	FT
3		~46	0.0349	7 MW	FT
4		~63	0.0351	7 MW	FT

– Determined η is very close for the measurements using different cathode fields Ecath.

Cathode (2013) characterization (2): determination of η using combinations of E_{laser} / FT / GS / P_{rf}

*** Total bunch charge vs. laser pulse energy at MMMG phase**



* M. Krasilnikov, PITZ: Simulations versus Experiment, Darmstadt, 19.12.2013 (measurement data sets taken from 02.2013)

Results (2)

	E_{laser} (nJ)		η
5	20	FT + 4 MW	0.0357
6	20	FT + 7.75 MW	0.0361
7	15	Gaussian + 4 MW	0.0362
8	20	Gaussian + 4 MW	0.0340

- Determined η is also very close for the measurements using multiple combinations of machine parameters.

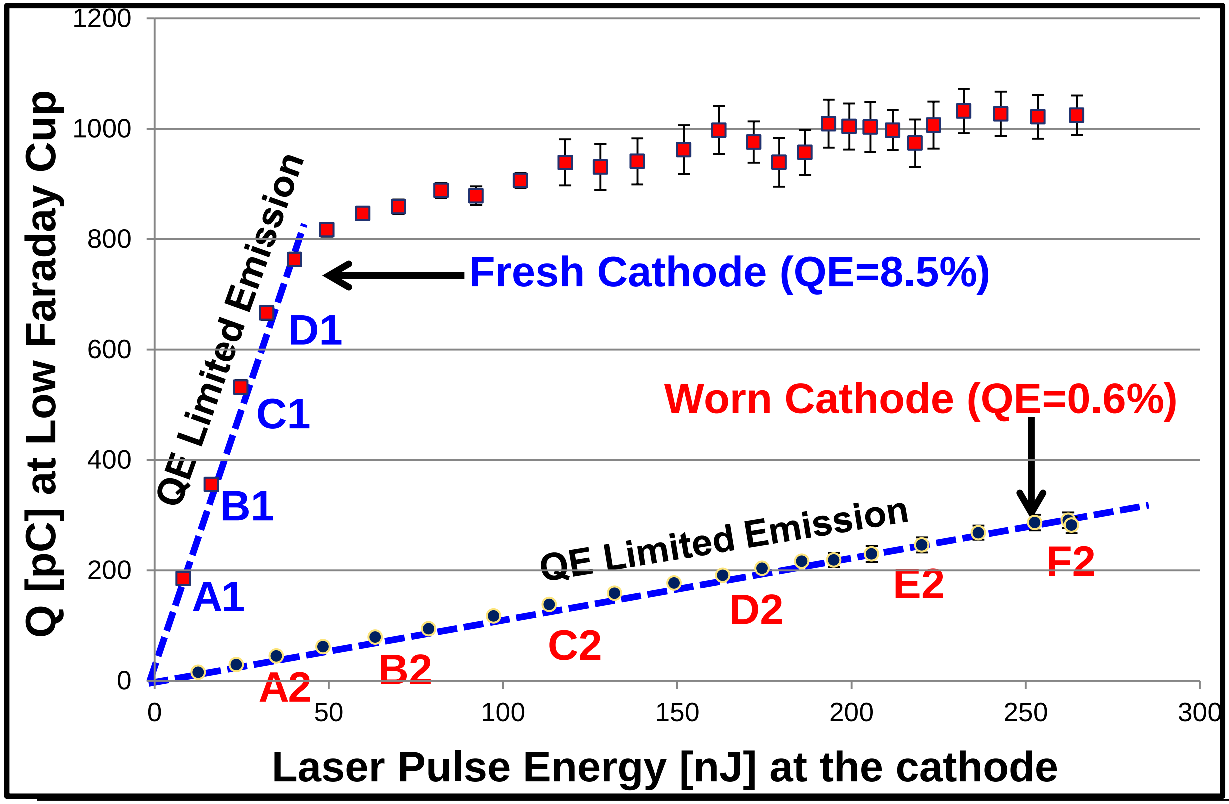
Cathode (2015) characterization (3): determination of η using different cathodes

New measurements* in 2015

Bunch charge vs Laser Pulse Energy

Pgun=1.5 MW at X0-90 phase and **BSA=1.8mm**.

With fresh cathode (QE=8.5%) and worn cathode (QE=0.6%)



Results (3)

Fresh Cathode

	E_{laser} (nJ)	η
A1	8.22	0.0477
B1	16.32	0.0456
C1	24.79	0.0448
D1	32.23	0.0432

Worn Cathode

	E_{laser} (nJ)	η
A2	34.96	0.002710
B2	63.35	0.002608
C2	113.34	0.002548
D2	163.08	0.002451
E2	205.81	0.002332
F2	252.65	0.002371

***Measurement data sets provided by PITZ, 17.03.2015**

Cathode characterization: verification of η

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No.	Laser Profile	RF Power	E_{laser}	η
1	Flat-Top (FT)	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 (GS)	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**

Cathode 1, 02. 2013

$$\bar{\eta} \approx 0.0359$$

$$\frac{\eta_i - \bar{\eta}}{\eta_i} \times 100 < 6\%$$

Cathode 2, 02. 2015

$$\bar{\eta} \approx 0.0453$$

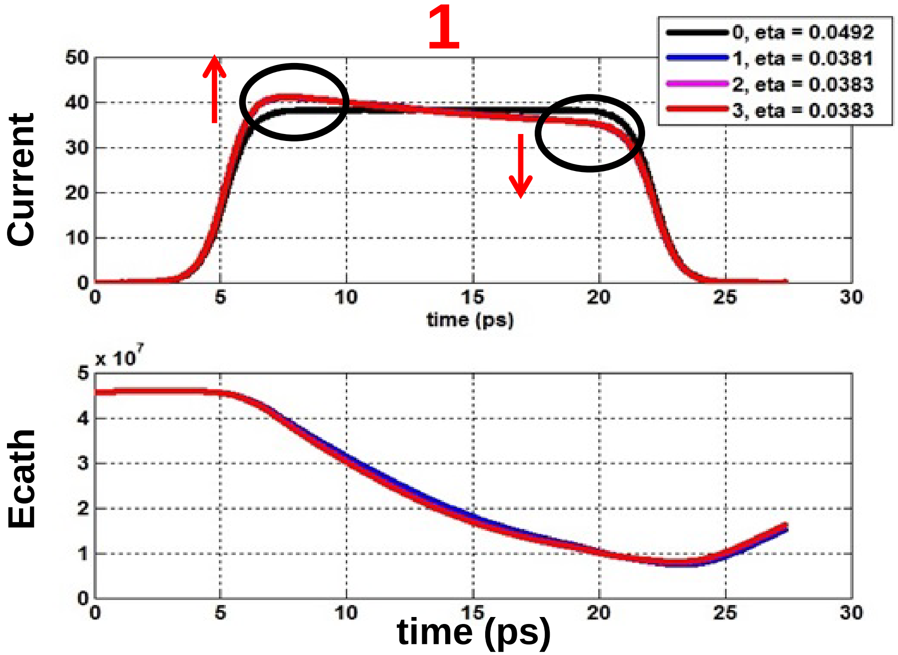
$$\frac{\eta_i - \bar{\eta}}{\eta_i} \times 100 < 5\%$$

Cathode 3, 02. 2015

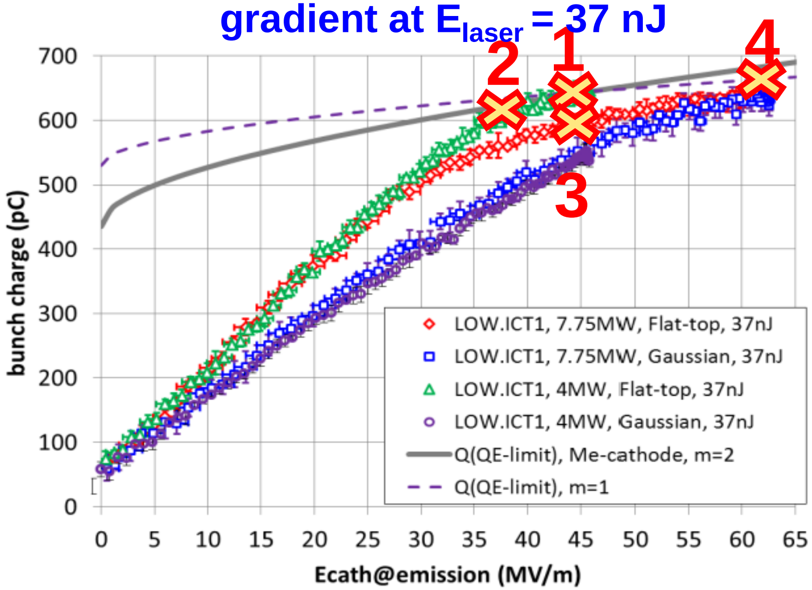
$$\bar{\eta} \approx 0.002503$$

$$\frac{\eta_i - \bar{\eta}}{\eta_i} \times 100 < 7\%$$

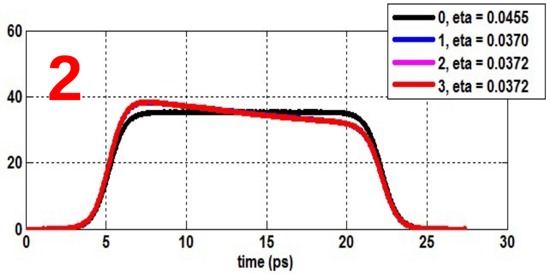
Influence of Schottky effect due to η (1)

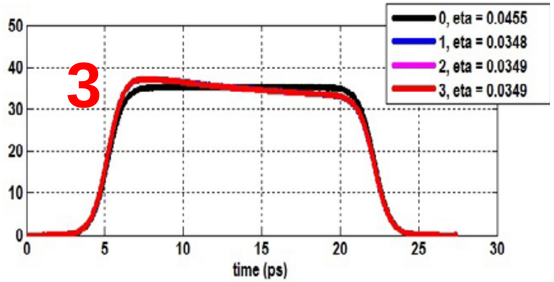


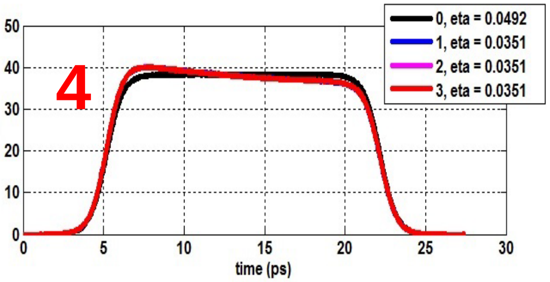
Total bunch charge vs. gun gradient at E_{laser} = 37 nJ



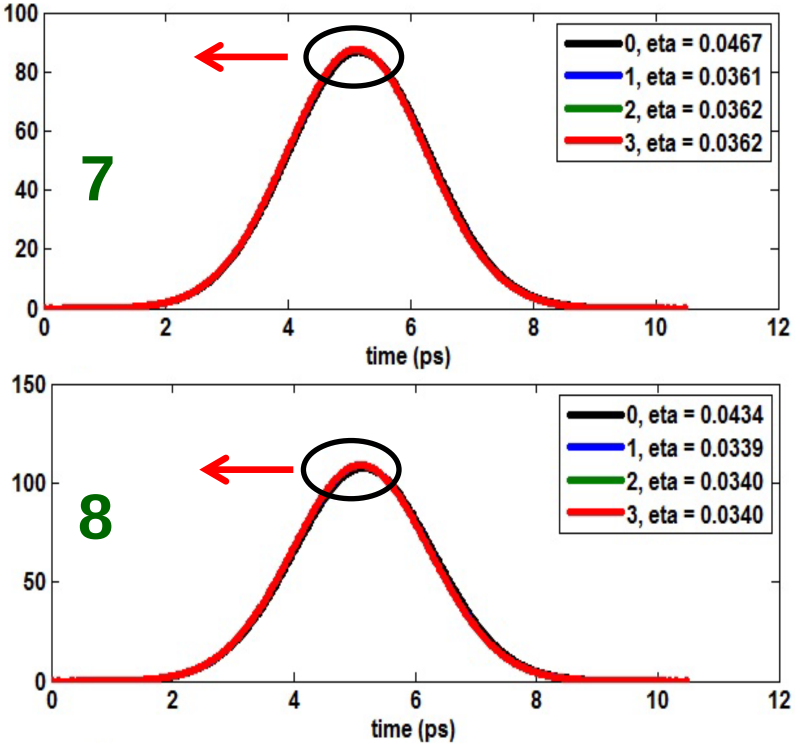
- Schottky effect brings asymmetry to bunch temporal profile.
- It modifies the work function and thus corrects QE of cathode.





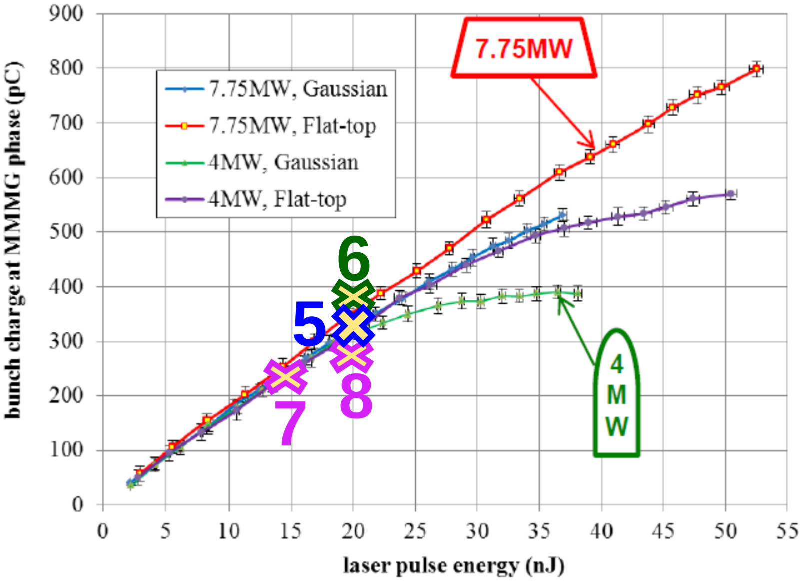


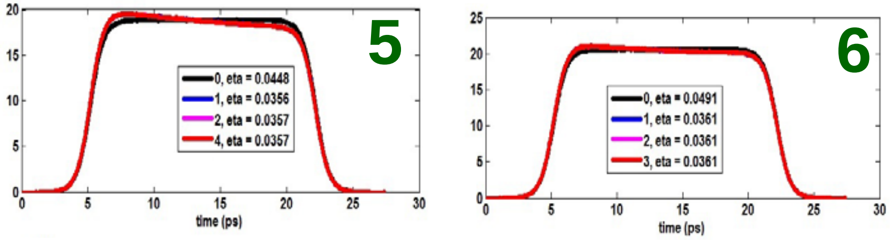
Influence of Schottky effect due to η (2)



- Temporal profile "peak" shifts to earlier times.
- Effect not prominent.

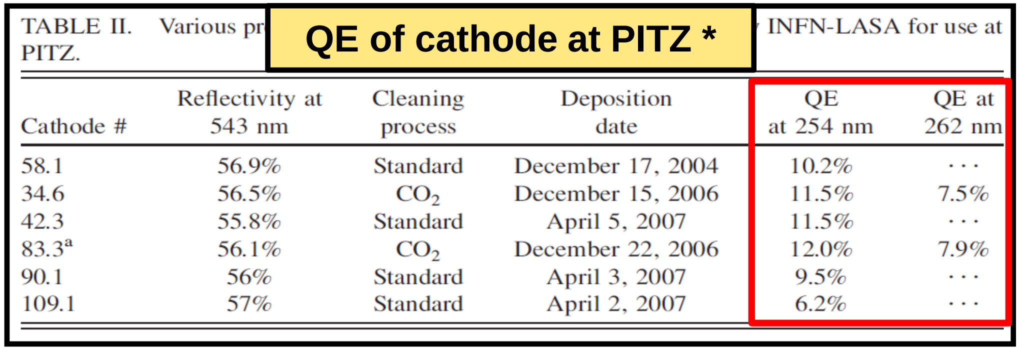
Total bunch charge vs. laser pulse energy at MMMG phase





Intermediate summary

1. **QEL emission model proposed and fits well the measurement data.**
2. **Cathode characterizations done** for 3 cathodes, cathode factor η **determined** using different machine operation parameters.
3. **Predicted QE is comparable with the measurement data.**
   - i. "Worn cathode" : 0.54%~0.62% ; Measurement: ~0.6%
   - ii. "Fresh cathode" : 9.91%~10.98%; Measurement: ~8.5%



QE of cathode at PITZ *

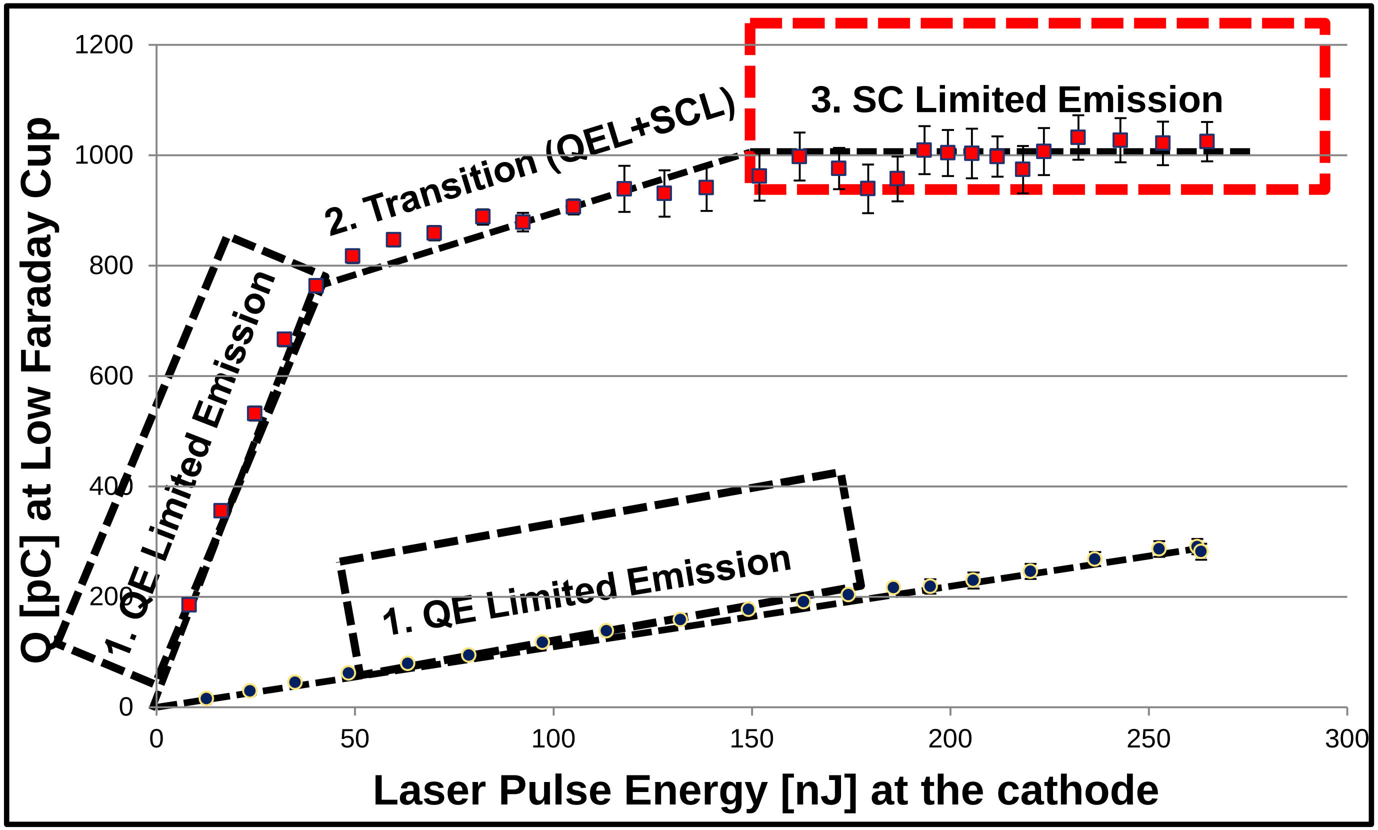
TABLE II. Various pr INFN-LASA for use at PITZ.

Cathode #	Reflectivity at 543 nm	Cleaning process	Deposition date	QE at 254 nm	QE at 262 nm
58.1	56.9%	Standard	December 17, 2004	10.2%	· · ·
34.6	56.5%	CO$_2$	December 15, 2006	11.5%	7.5%
42.3	55.8%	Standard	April 5, 2007	11.5%	· · ·
83.3[a]	56.1%	CO$_2$	December 22, 2006	12.0%	7.9%
90.1	56%	Standard	April 3, 2007	9.5%	· · ·
109.1	57%	Standard	April 2, 2007	6.2%	· · ·

* F. Stephan et al., PRST-AB 13, 020704 (2010)

4. **Influences of Schottky effect on emission using determined η**
   - i. Correcting bunch temporal profile: symmetry to asymmetry
   - ii. Emission peak shifts to earlier times; Effect not prominent.

Numerical modelling of space charge limitation (SCL)



Numerical modelling of SCL

- **Space charge limitation modelling method**
  - **"Brute-force"** (standard approach): very slow convergence, very expensive
  - **"Bunch charge iteration"*** (speed-up technique): good convergence
- **Modelling status**
  - Both methods converge to the same SCL for FT-shaped bunches (FT).
  - Both methods agree with measurements for different machine parameters (FT).
  - Not applicable for GS-shaped bunches (GS).
- **Numerical modelling issues**
  - Convergence of the emitted bunch charge at / above SCL*****
  - Deviation in bunch charge prediction between different solvers******

*** Y. Chen et al., Photoemission Studies for PITZ, DESY-Zeuthen site, 28.05.2014**

**** E. Gjonaj, Emission Modeling for PITZ, DESY-Zeuthen site,19.12.2013**

"Brute-force" method

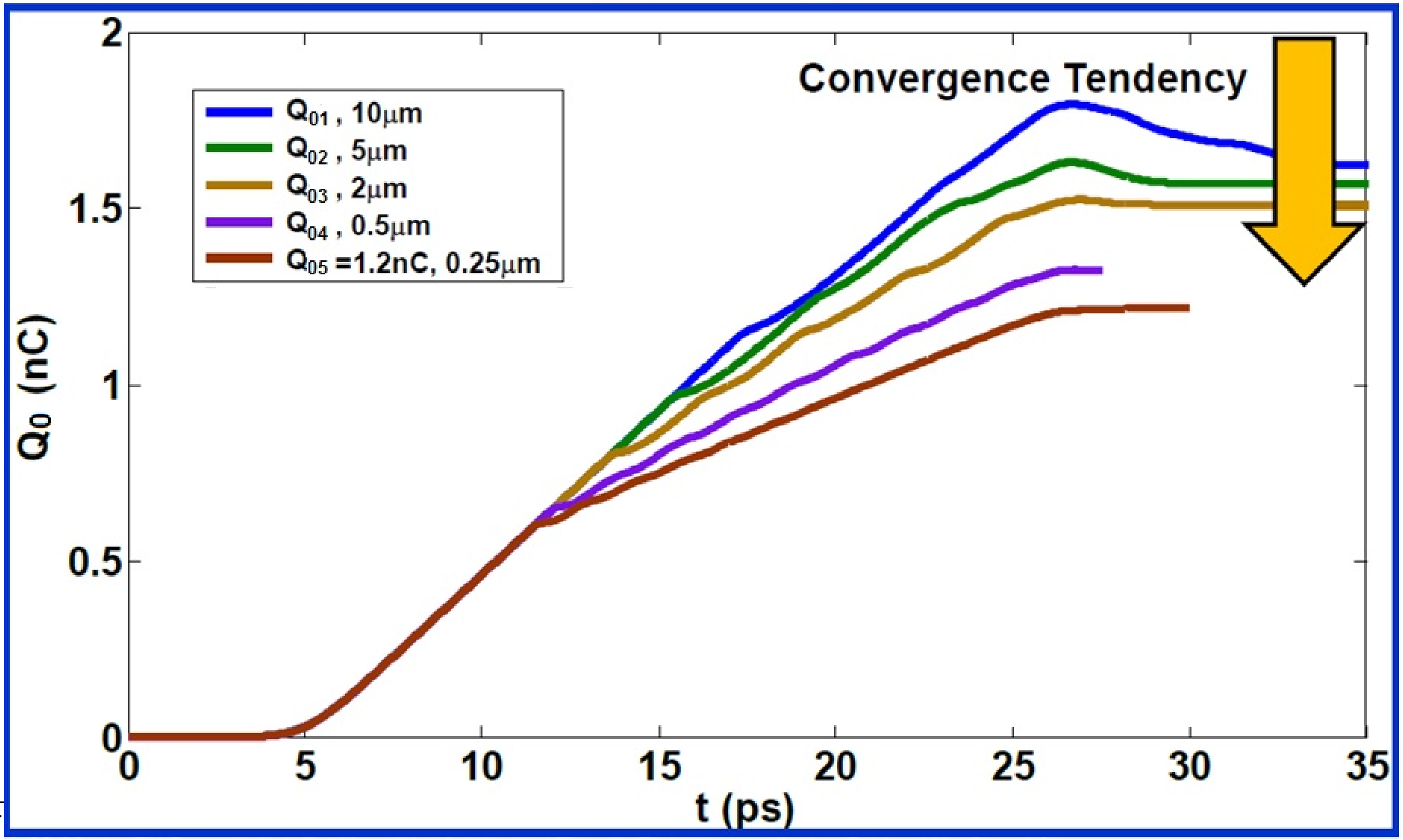
- **Definitions**
  - Q_b : input bunch charge
  - Q_0 : output bunch charge
- **"Brute-force" technique**
  - Inject particles at the cathode, and estimate from the local fields whether they can be emitted or not.
  - Convergence check needed.
- **Convergence of Q_0**
  - w.r.t. mesh resolution (Δx, Δy, Δz)
  - w.r.t. number of particles (Np)
  - w.r.t. time step (Δt)
  - w.r.t. Q_b

"Brute-force" method:
Q_0 w.r.t. mesh: flat-top-shaped bunch

(0) Space charge limit close to 1 nC for the nominal bunch (measurement).

(1) When $Q_b >> Q_0$, numerical convergence w.r.t. mesh is rather slow (simulation).

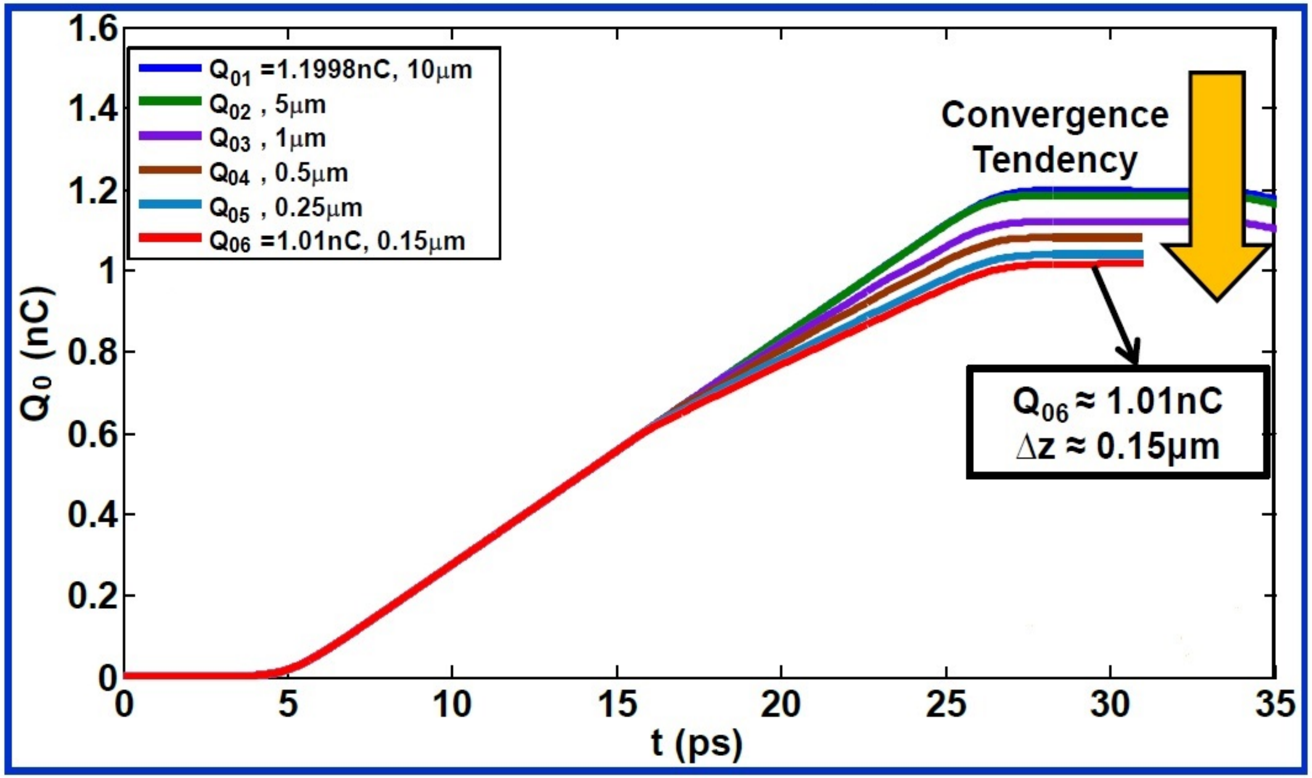
XY_{rms}=0.3mm, Q_b=2nC



"Brute-force" method: Q_0 w.r.t. mesh: flat-top-shaped bunch

(2) As Q_b is approaching Q_0, the convergence w.r.t. mesh is getting better.

XY_{rms}=0.3mm, Q_b=1.2nC

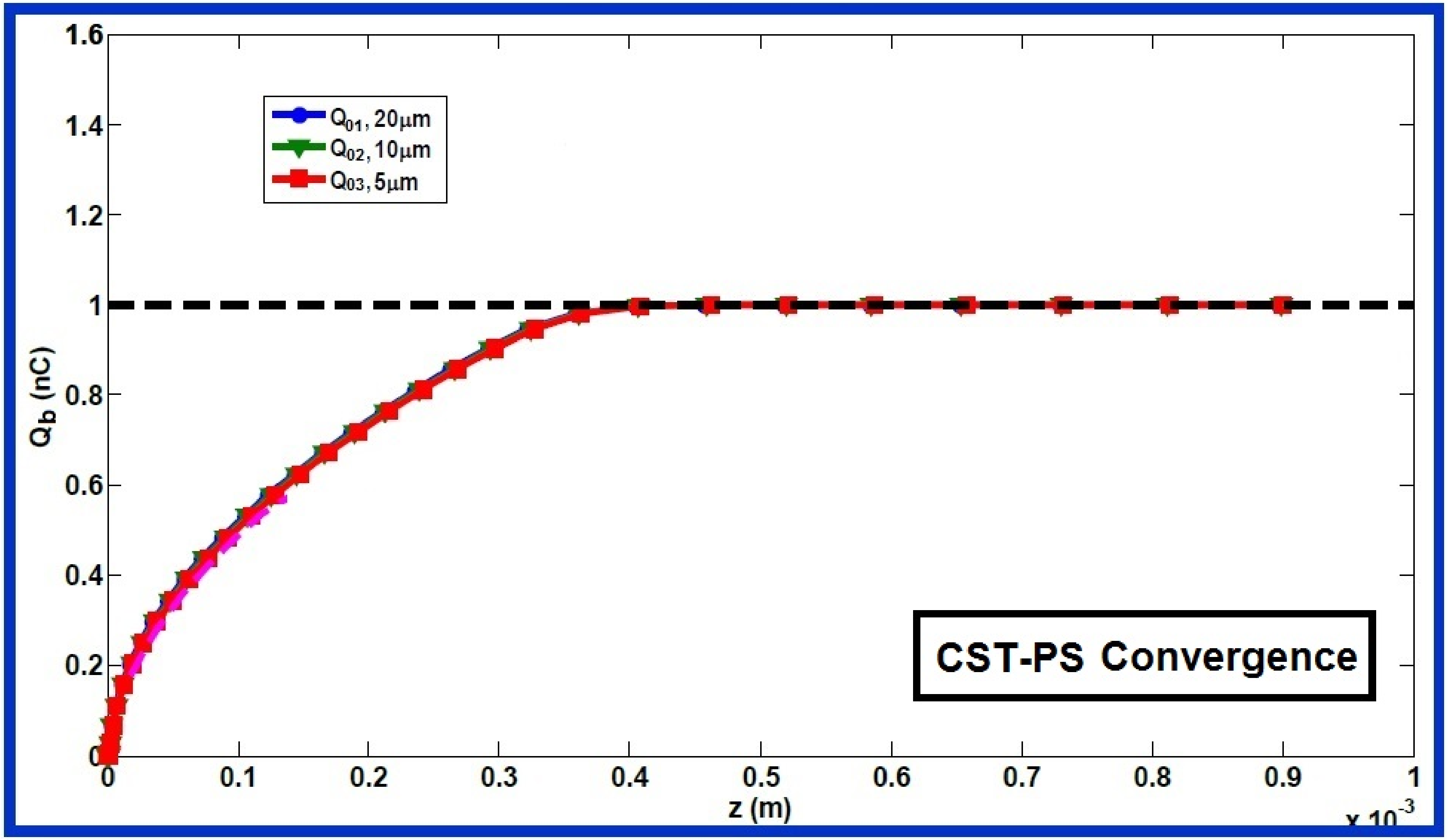


- The "brute-force" method can predict the space charge limit using a very fine mesh resolution, however, slow and expensive.

"Brute-force" method:
Q_0 w.r.t. mesh: flat-top-shaped bunch

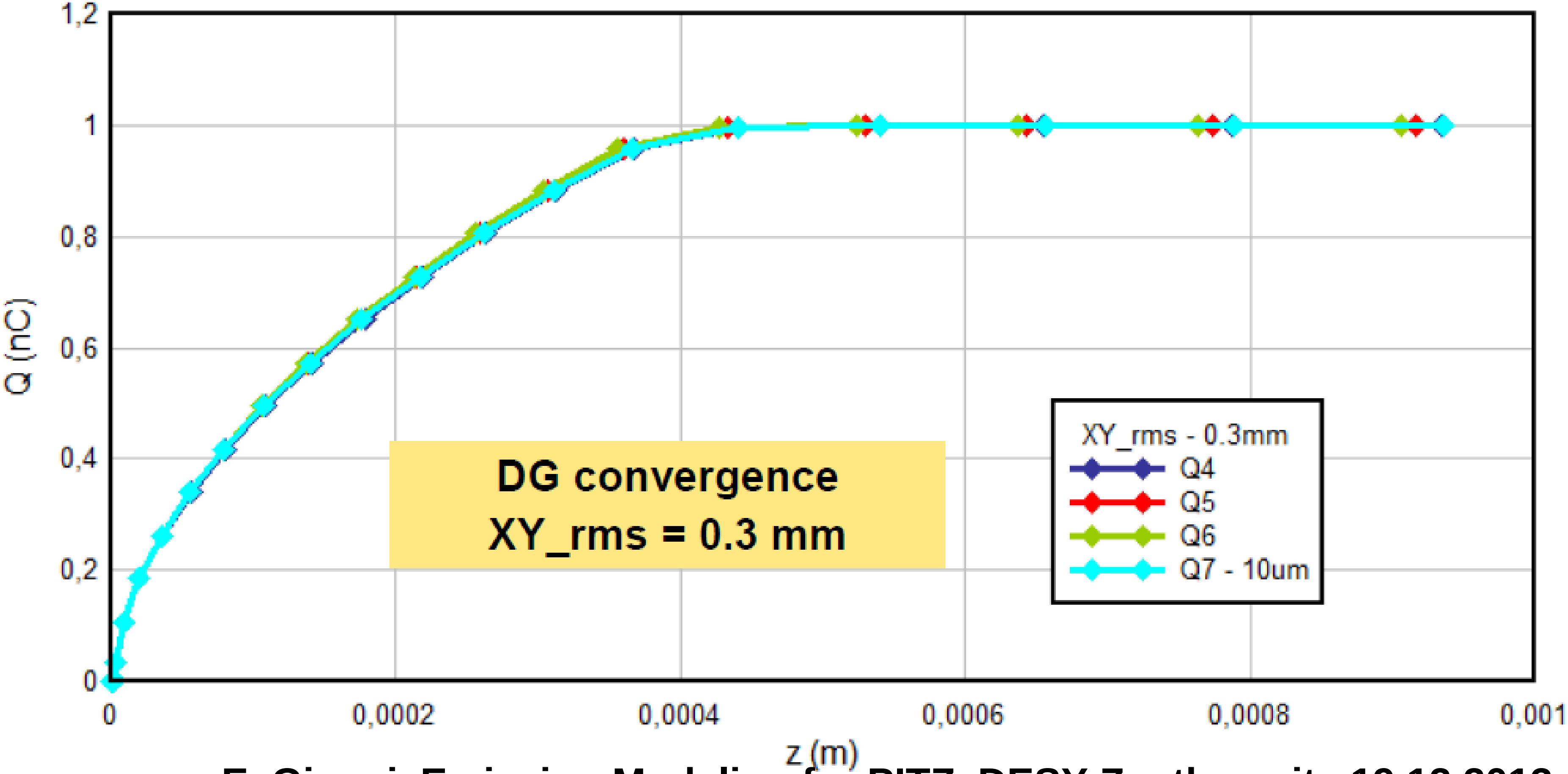
(3) When $Q_b \approx Q_0$, the convergence w.r.t. mesh is good.

XY_{rms}=0.3mm, Q_b=1nC



"Brute-force" method:
Q_0 w.r.t. approximation order: flat-top-shaped bunch

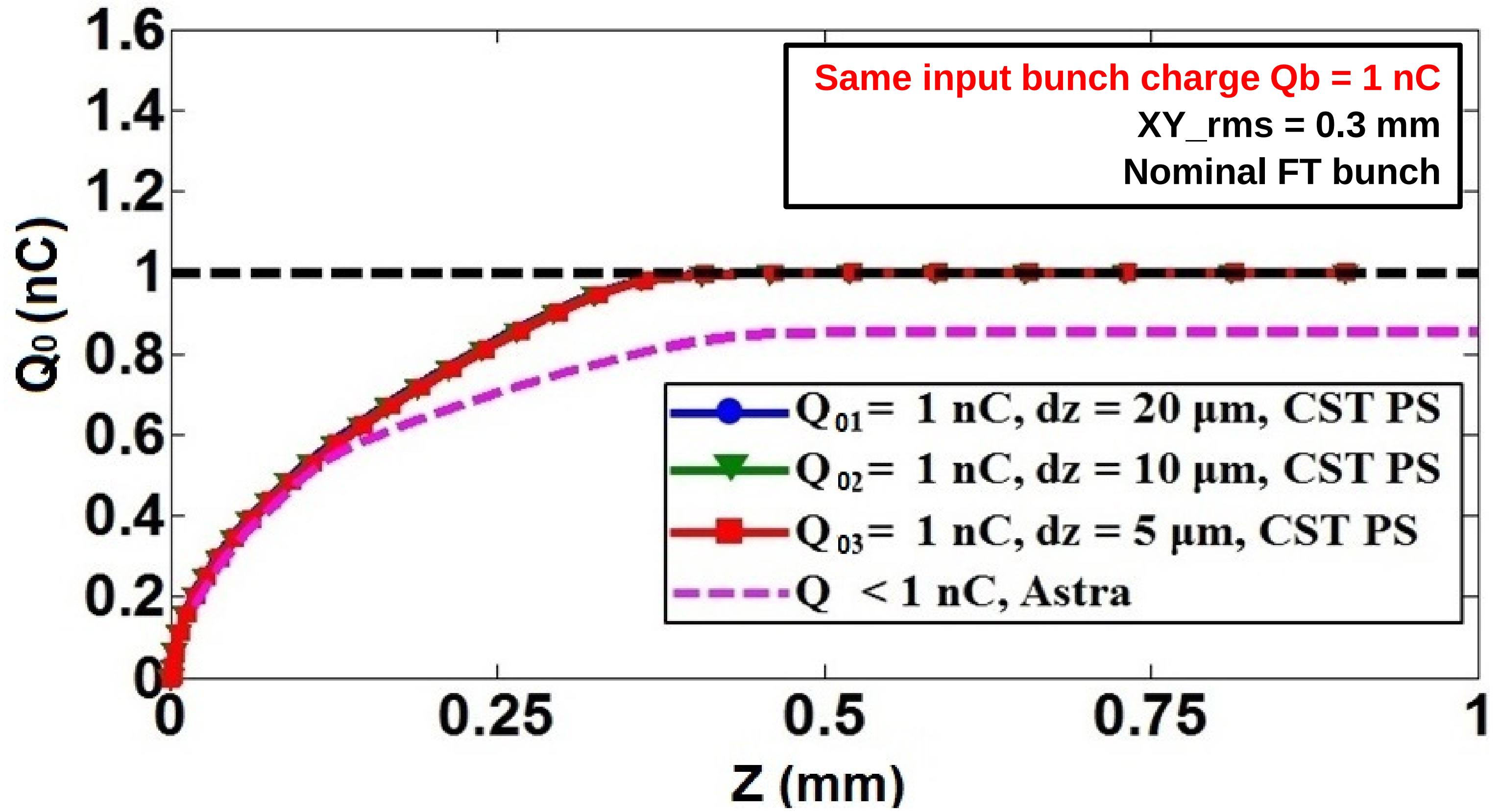
(4) When $Q_b \approx Q_0$, the convergence w.r.t. approximation order is good.



DG convergence
XY_rms = 0.3 mm

E. Gjonaj, Emission Modeling for PITZ, DESY-Zeuthen site,19.12.2013

Deviation of SCL between different solvers



Same input bunch charge Qb = 1 nC
XY_rms = 0.3 mm
Nominal FT bunch

- **Same input Q_b = 1nC for both algorithm.**
- **Calculations of SCL with standard approach (No Iteration)**
- **Different output Q_0**

Motivation of "charge iteration method"

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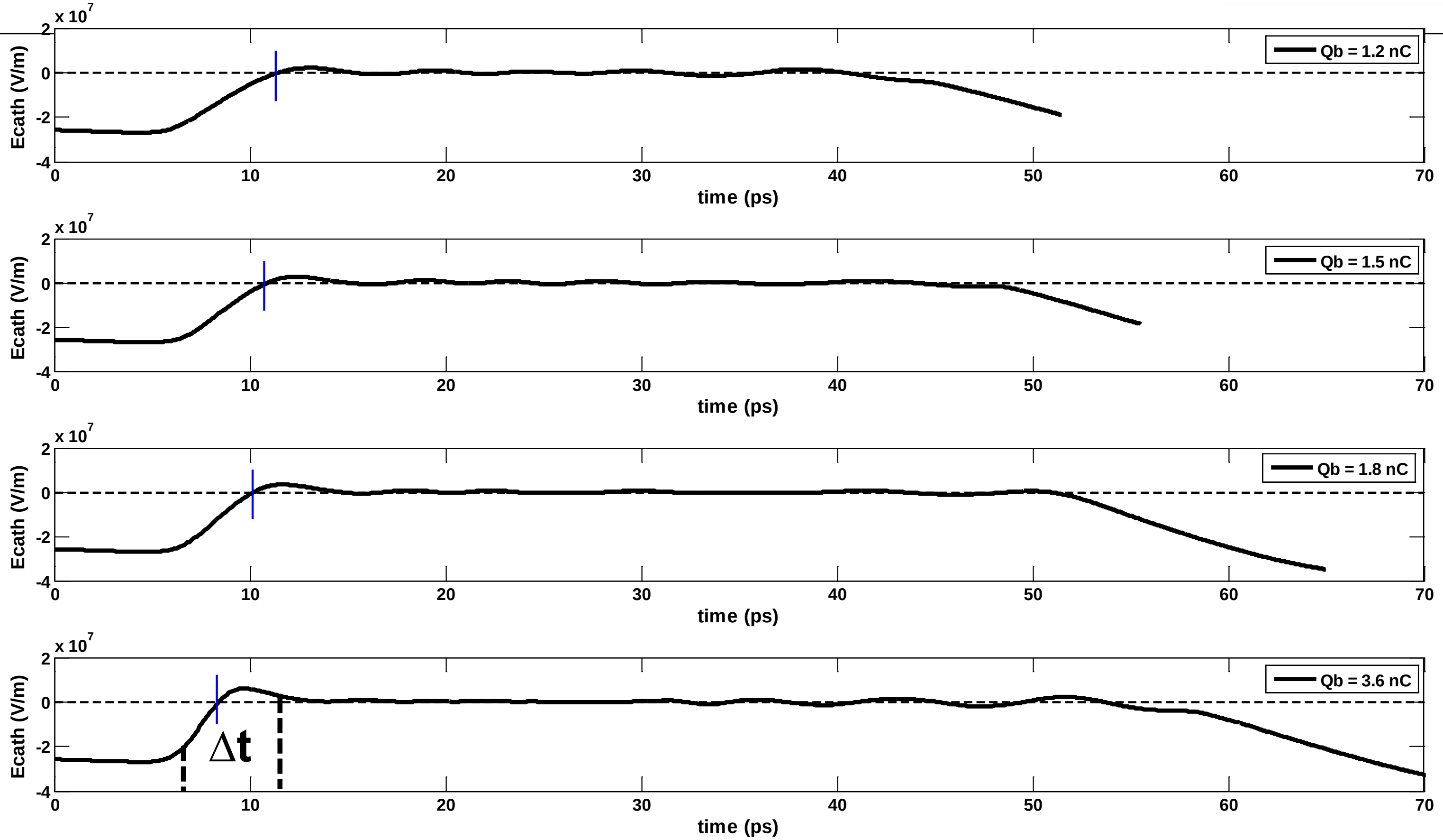
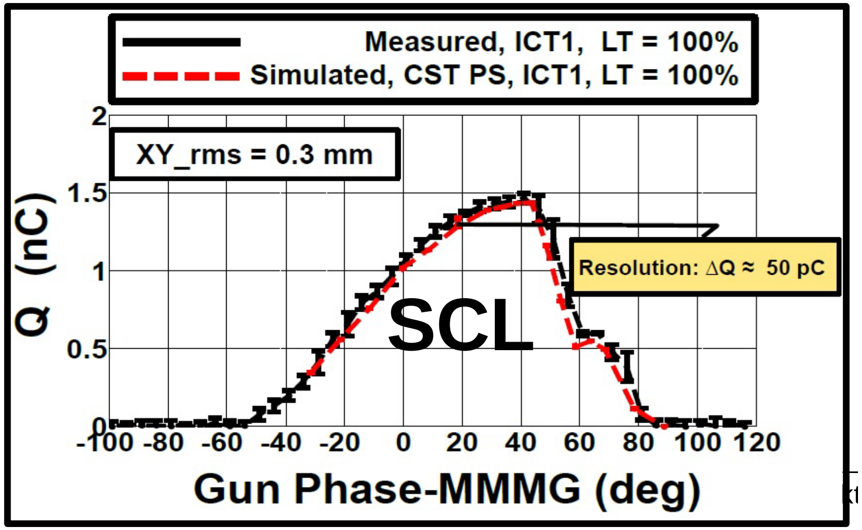


1. Space charge limit (SCL) occurs when the total field at the cathode changes sign.
2. Above SCL, this happens soon as the emission begins, meaning Δt << t.
3. During the beginning time of Δt, the steady state assumption is not valid, however, this method can still estimate from most of time in the emission process.

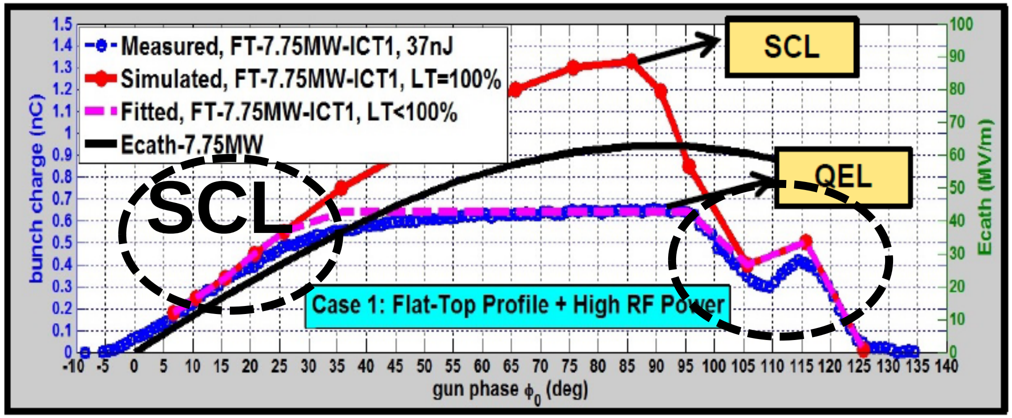
Comparisons with measurements

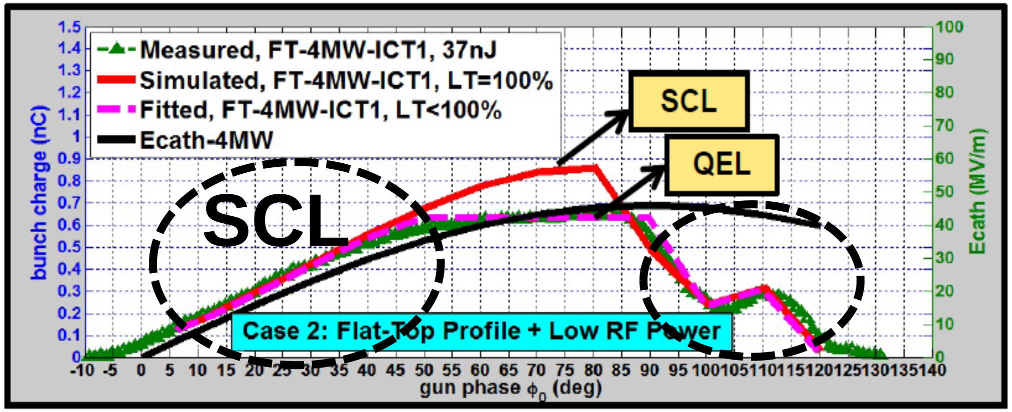
- Using the charge iteration method, the simulated total bunch charges can well fit the measurement data under different experimental conditions in the case of FT-shaped bunches.

XY_rms = 0.3 mm, Prf ≈ 6 MW
FT-shaped, 21.5 ps (FWHM)



XY_rms = 0.3 mm, Prf ≈ 7 MW and 4 MW
FT-shaped, 17 ps (FWHM)





Summary and Perspective

1. QE limited emission

- Model proposed
- Numerical approach used for three photocathode characterizations
- Determination of η verified under different experimental conditions
- Influences of Schottky effect investigated in terms of bunch temporal profiles

2. SCL modelling

- Numerical issues discussed w.r.t. convergence problem
- "Brute-force" agrees with "charge iteration" on SCL predictions
- Good agreements with measurements for FT-shaped bunches
- Method not valid for GS-shaped bunches

3. Perspective

- Implementation within each time step of corrections of the temporal and / or transverse distribution of the emitted bunch by using the full information of the local total fields at cathode
- New simulation tool preferable

Thank you for your attention!

非常感谢您的关注！