Photoemission Modeling of the High Brightness Electron Bunch for E-XFEL Applications

Ye Chen, Erion Gjonaj
TEMF, TU Darmstadt

DESY-TEMF Collaboration Meeting
Lecture Room S2|17-103, TEMF, TU Darmstadt
February 12th 2015

Contents

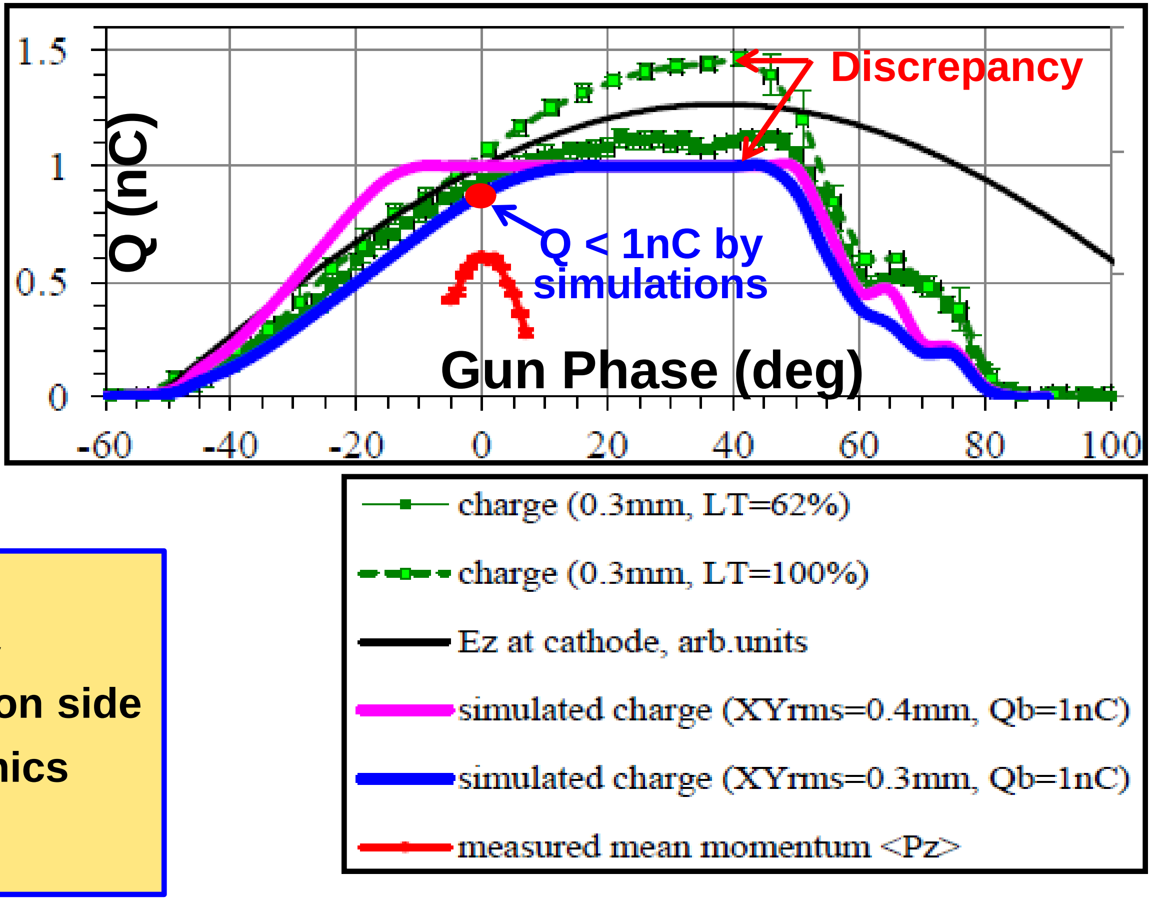
Introduction: motivation

- **Discrepancy of the total extracted bunch charge** in between experiments and simulations.
- **Space charge limit** predicted by previous simulations at less than 1 nC for XY_rms = 0.3 mm, whereas 1 nC and even higher bunch charges were detected experimentally.

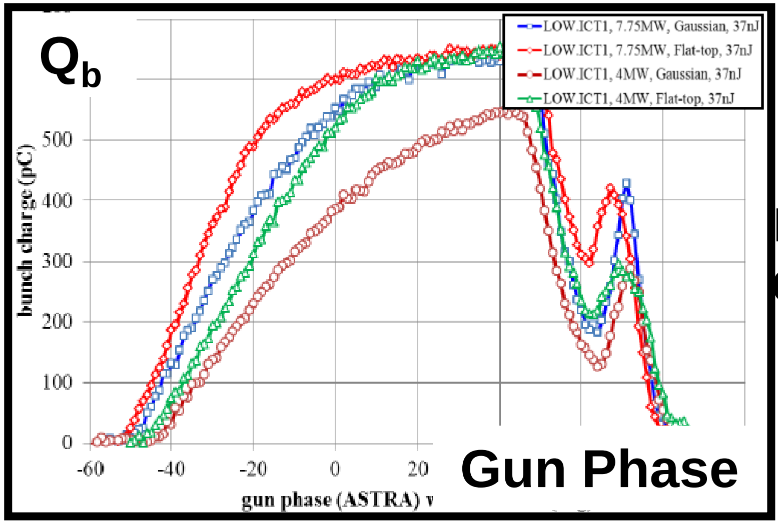
Objectives:

1. **Find out the discrepancy source from the simulation side**
2. **Improve the beam dynamics modeling of the bunch emission process**

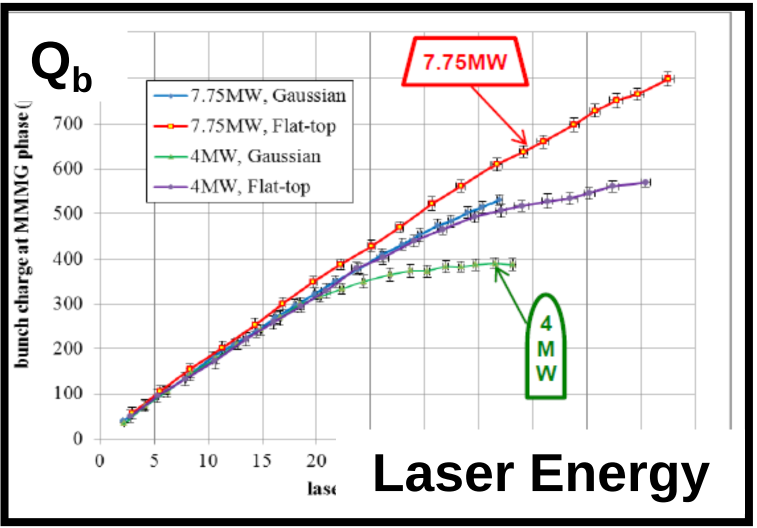
Total Emitted Bunch Charge vs. Launch Phase

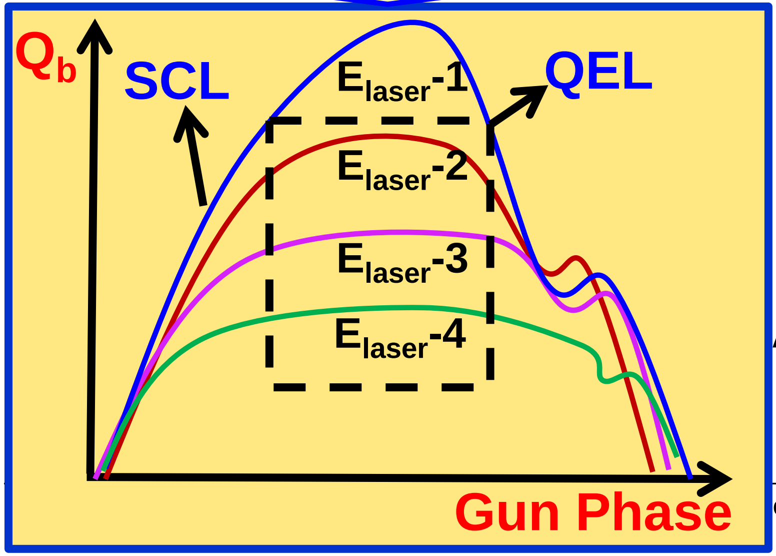


Introduction: from observations to assumptions

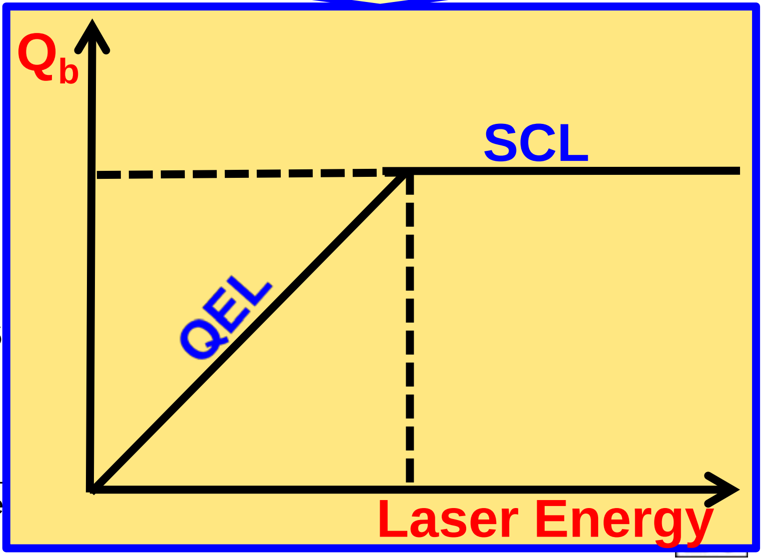


Experimental Observations





Simulation Assumptions



Introduction: from observations to assumptions

- **Space Charge Limited (SCL) Regime:**
  - **Main Idea:** assuming that the emission source just provides the maximum number of particles that allows the beam to propagate without reflected particles (space charge limit calculation)
  - **Simulation Method: “Bunch Charge Iteration Algorithm"**
- **Quantum Efficiency Limited (QEL) Regime:**
  - **Main Idea:** assuming a time-dependent emission where the initial charge distribution needs to be modified due to the transient effects during emission (time-dependent QE)
  - **Simulation Method: "Temporal Profile Iteration Algorithm"**

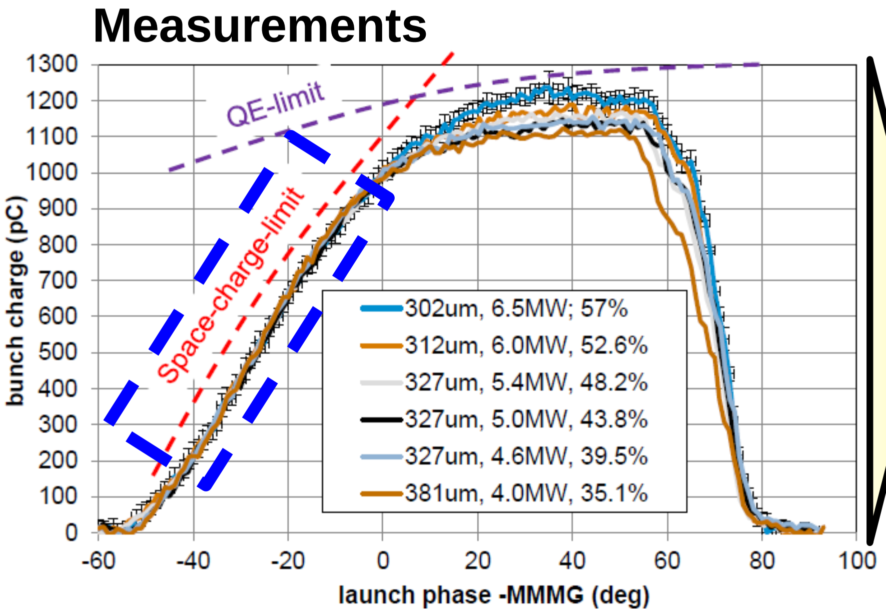
Bunch Charge Extractions in the SCL Regime

(see the simulation algorithm from YC´s talk at DESY Hamburg, 09.07.2014)

- **Algorithm validation**: considering different laser spot sizes (σ_{xy}), accelerating field gradients (Ecath), laser transmissions (LT) and temporal laser profiles (FT/GS) for SCL simulations

Simulations vs. Measurements

Measurements



Simultaneous variations of multiple parameters

Experiment 1 to 6

#	σ_{xy} /mm	LT	$P_{rf,\,gun}$/MW	$\sqrt{P_{rf,\,gun}} \times \sigma_{xy}$
1	0.302	57%	6.49	0.769
2	0.312	52.6%	5.99	0.764
3	0.327	48.2%	5.45	0.763
4	0.341	43.8%	5.00	0.762
5	0.361	39.5%	4.55	0.770
6	0.382	35.1%	3.99	0.762

laser spot size σ_{xy}

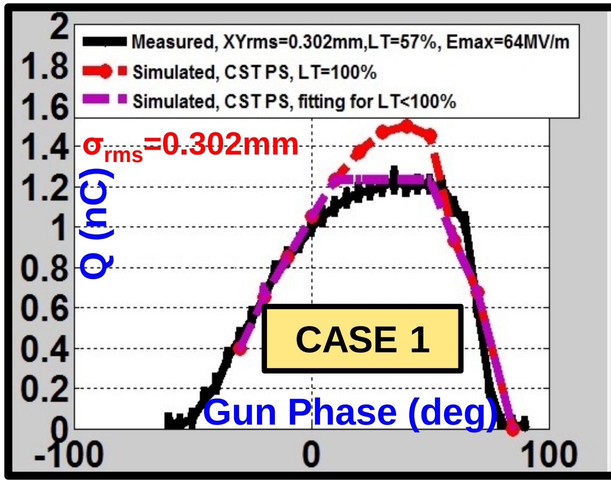
RF power $P_{rf,\,gun}$

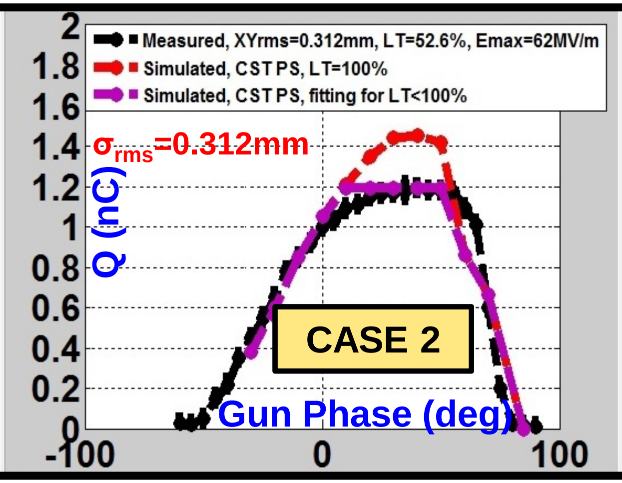
Laser transmission LT

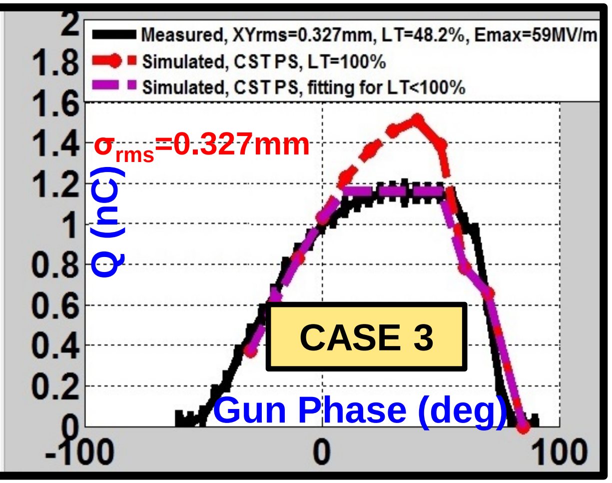
1. **Reproduce the six measurements in simulations**
2. **Compare the total bunch charge with measurements in the SCL regime**

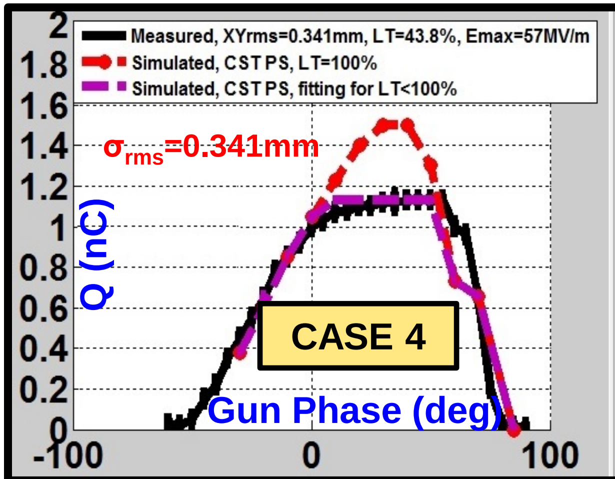
Simulations vs. Measurements

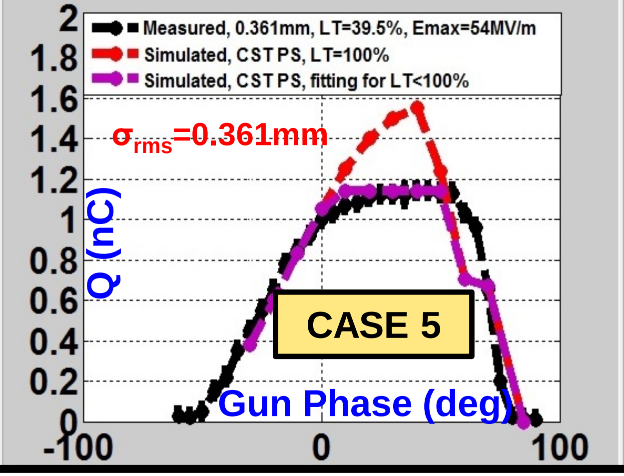
▪▪▪▪▪ Measurement; ▪▪▪▪▪ Simulation (100% LTs); ▪▪▪▪▪ Simulation (lower LTs)

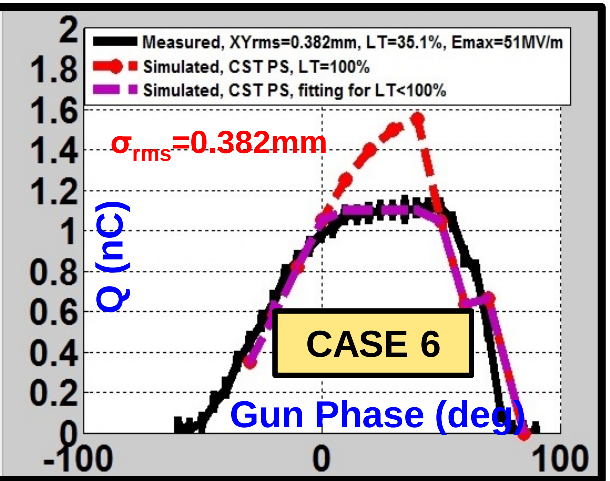






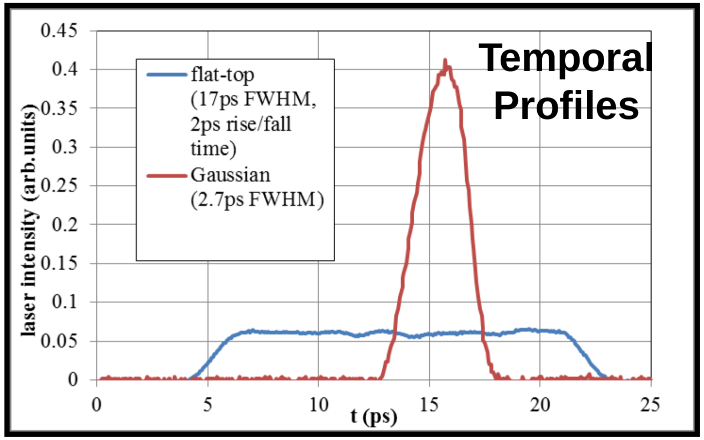


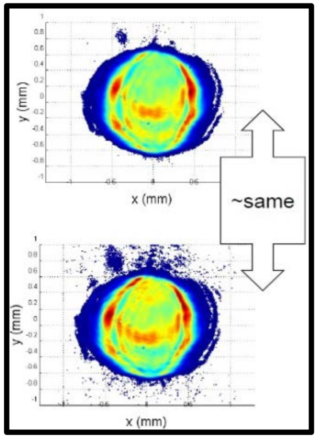


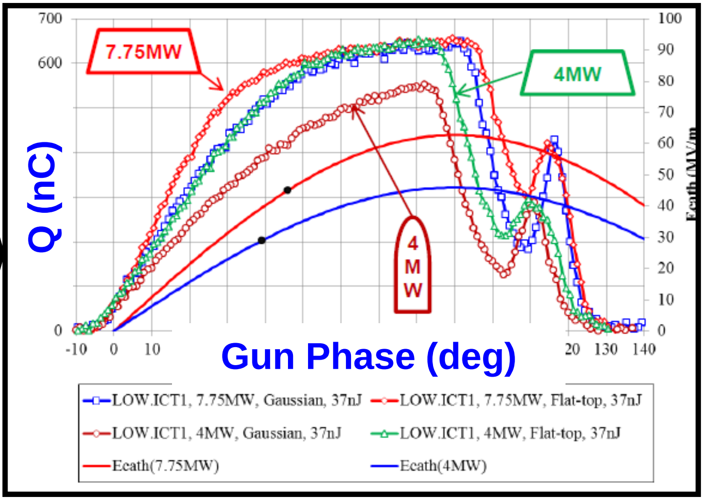


Simulations vs. Measurements

Further validation by considering different temporal laser profiles





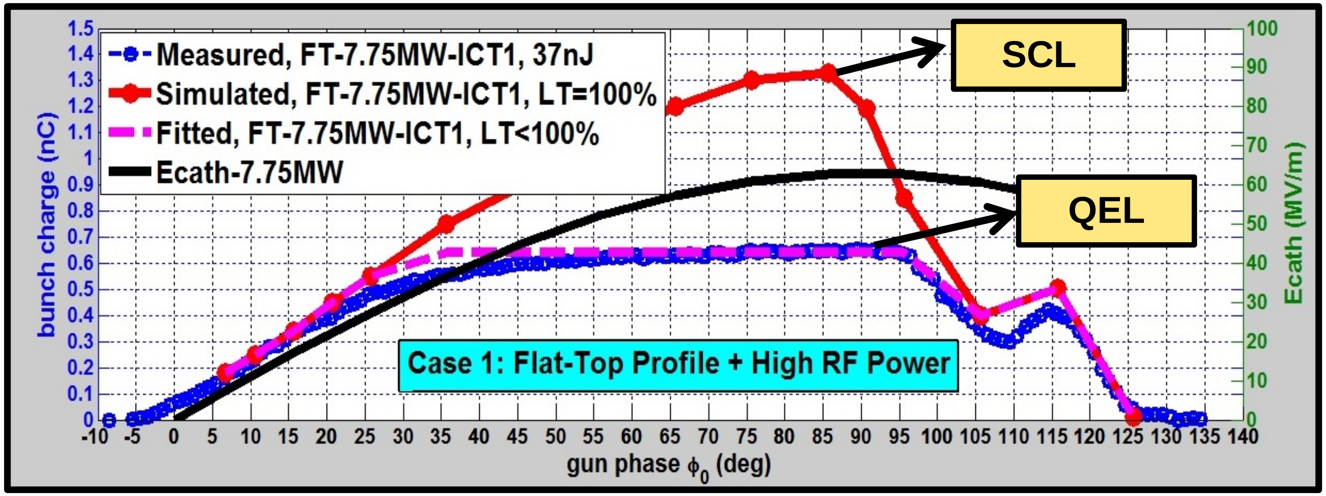


	7.75MW	4MW
Flat-top (17ps)	case 1	case 3
Short Gaussian (2.7ps)	case 2	case 4

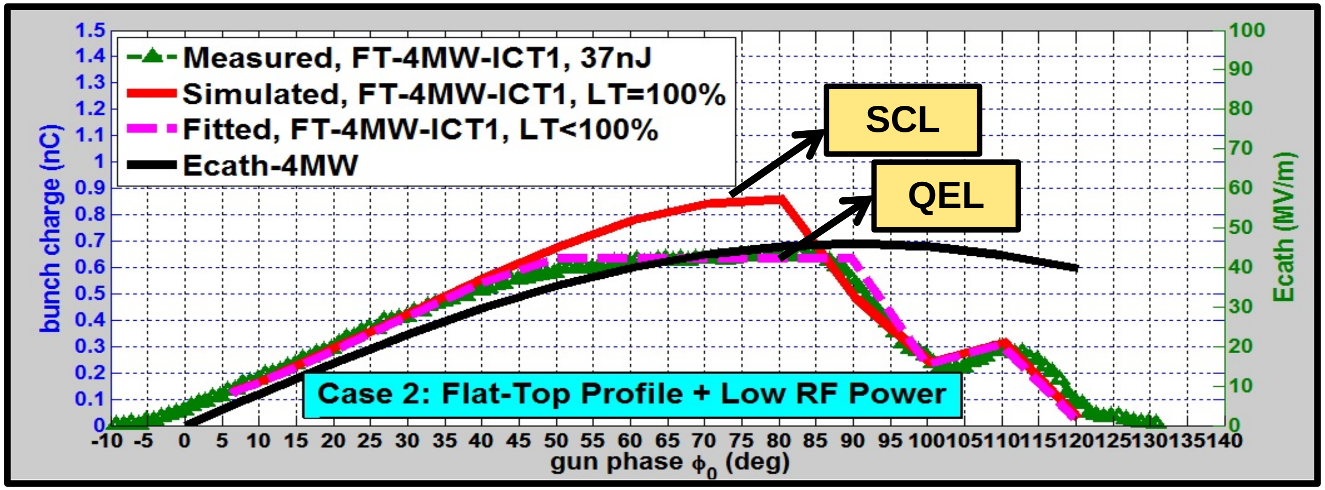
1. **Reproduce the four measurements in simulations**
2. **Compare the total bunch charge with measurements in the SCL regime**

Simulations vs. Measurements

1.



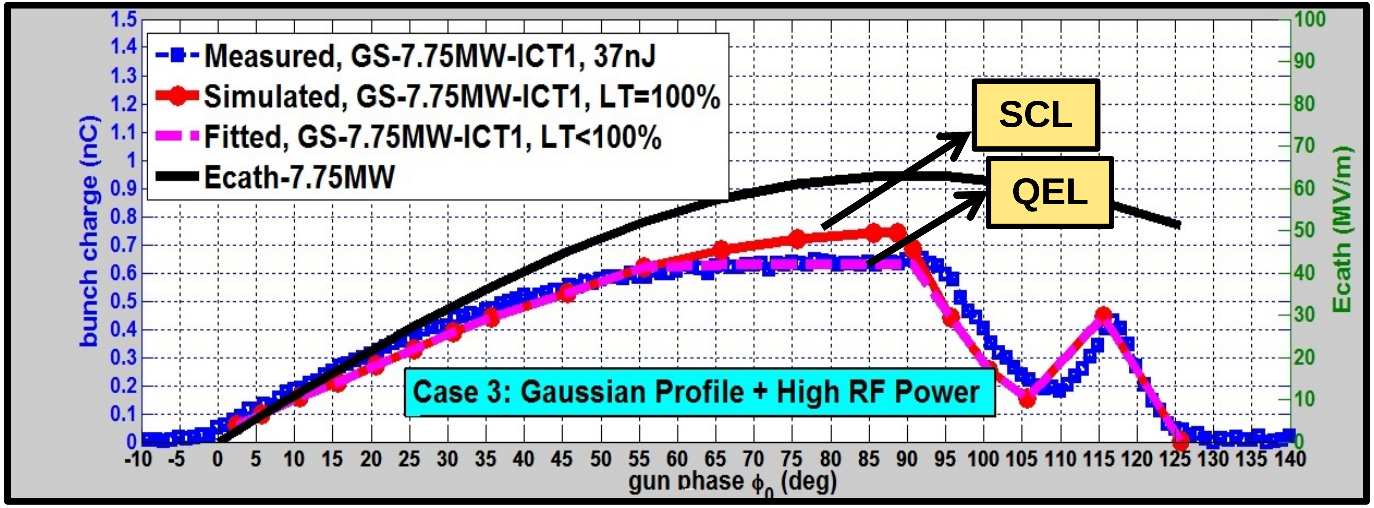
2.



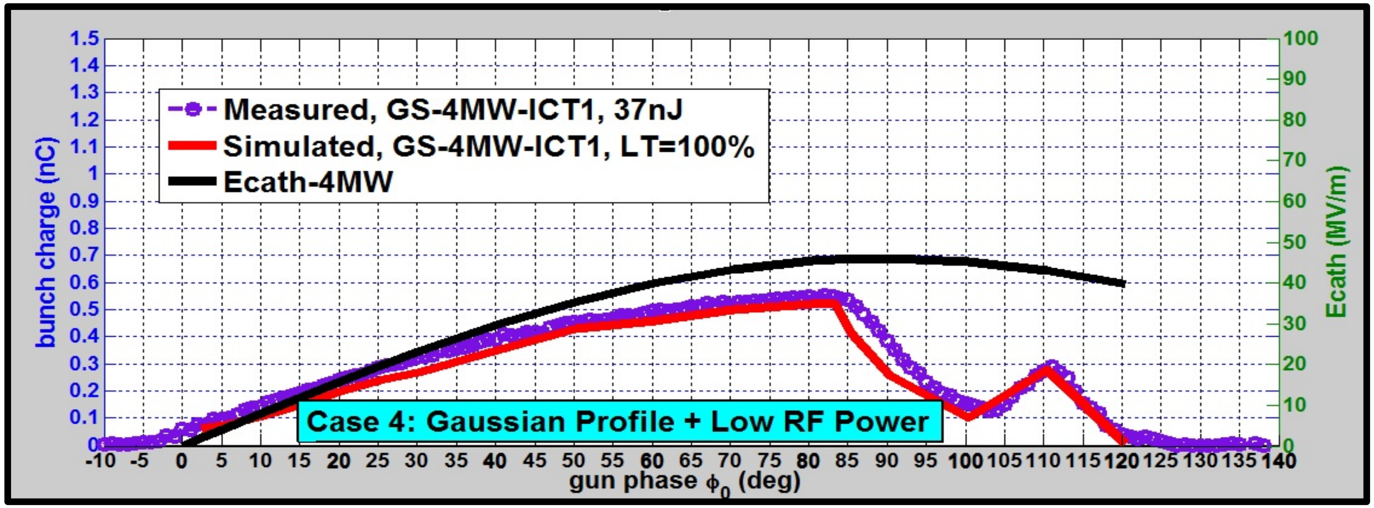
Flat-top Profile (FWHM: 17ps)

Simulations vs. Measurements

3.

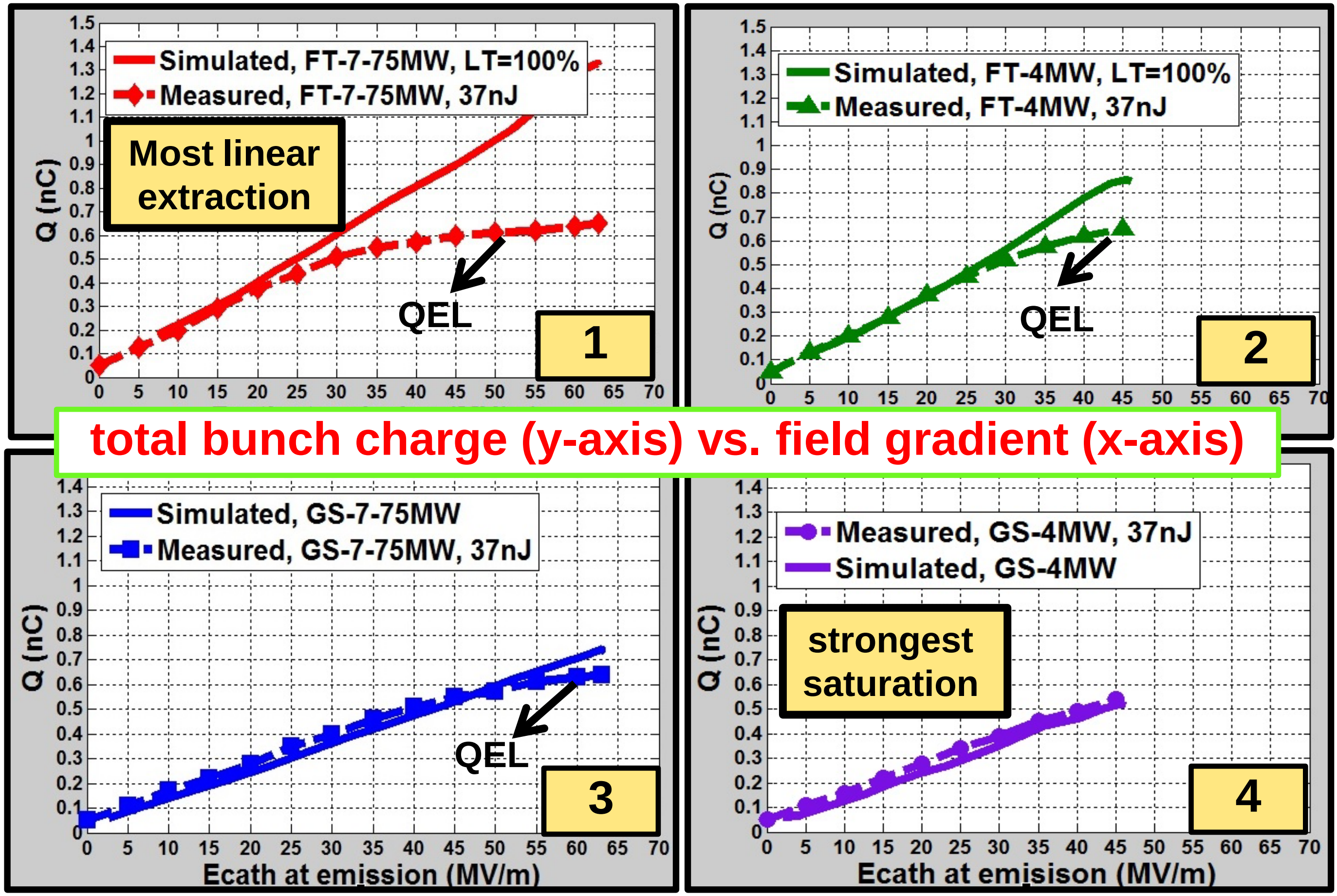


4.



Short Gaussian Profile (FWHM: 2.7ps)

Simulations vs. Measurements



total bunch charge (y-axis) vs. field gradient (x-axis)

- **SCL to QEL transition:**

  1: FT + 7.75 MW

  2: FT + 4 MW

  3: GS + 7.75 MW
- **Strongest saturation :**

  4: GS + 4MW

  closest to SCL
- **Most linear extraction:**

  1: FT + 7.75MW

Intermediate Summary

1. Measurements at the space charge limits with all machine parameters can be reproduced correctly by full-wave PIC simulations, but not by Astra.
2. "Bunch Charge Iteration Algorithm" has been proposed and verified based on the self-consistent emission model of CST-PS.
3. Comparison results have shown, that the transverse profile of the bunch does not play a critical role in the bunch charge studies.

Analysis of Effective Bunch Size at Emission by SCL Emission Models (new)

(Investigations on **the shift of the laser spot size**
for the optimum emittance at EMSY1)

- Model A: 1-D Parallel Plate Capacitor (PPC)
- Model B: 2-D C-L Scaling Law Based on PIC Simulations
- Model C: 2-D Analytical C-L Scaling Law

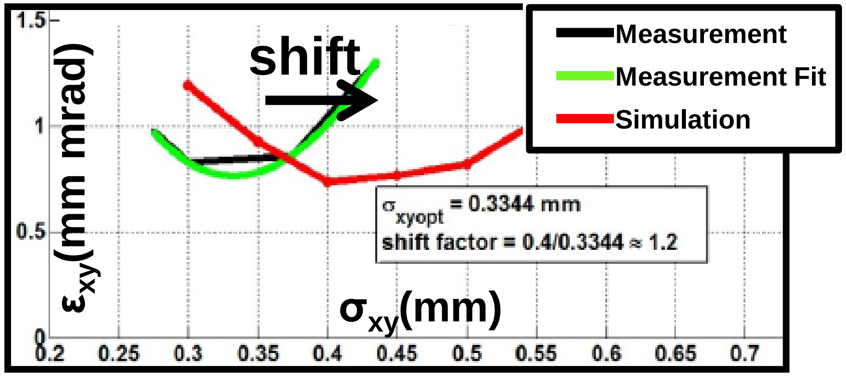
Motivation

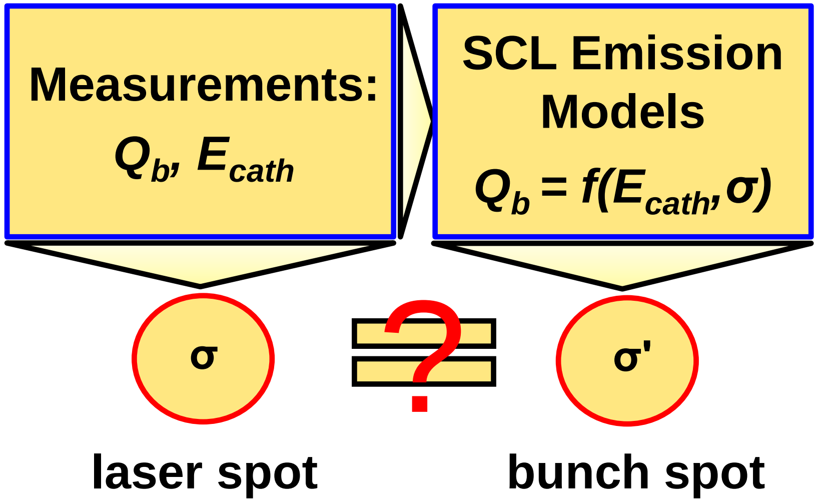
- The optimum laser spot size for minimum emittance at EMSY1 was found at ~0.3 mm rms, however, all simulations predict an optimum spot size of 0.4 mm rms for 1 nC case.
- Q = 1 nC, XY_rms = 0.3 mm, close to the space charge limit
- New charge simulations by CST-PS have shown good agreements with measurements at the space charge limits.

$$\text{shift factor}(SF) = \frac{\text{effective bunch size}}{\text{laser spot size}}$$

Observation: SF ≈ 1.2

Emittance vs. Laser Spot Size




Measurements: Q_b, E_{cath}

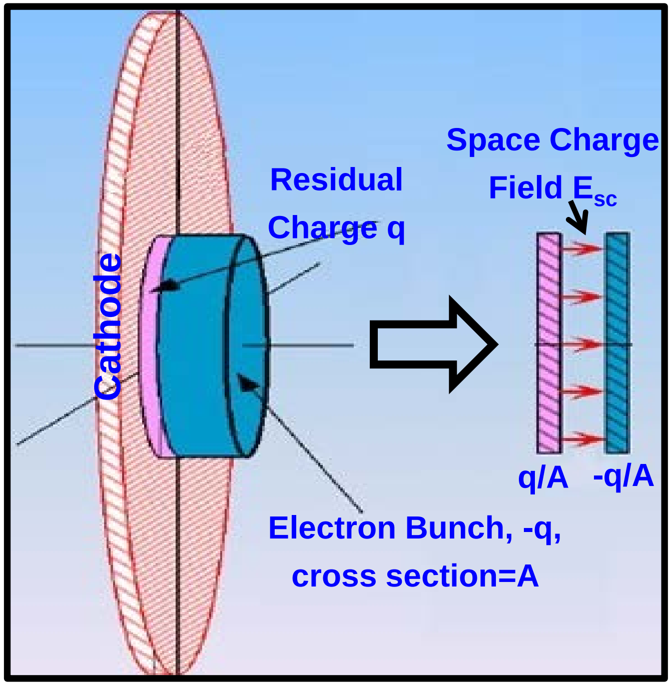
SCL Emission Models $Q_b = f(E_{cath},\sigma)$

σ ≠? σ'

laser spot

bunch spot

Model A: 1D Parallel Plate Capacitor (PPC)



SC field: $E_{sc} = \sigma/\varepsilon_0$

SCL occurs when $E_{sc} = E_{rf}$

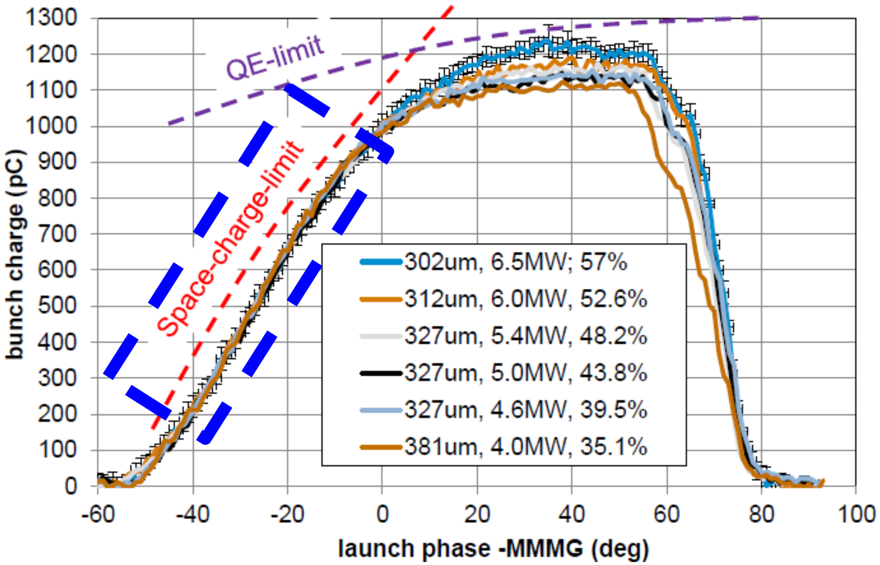
Limiting charge density: $\sigma_{scl} = \varepsilon_0 E_{rf}$

Emitted charge: $Q = \pi R^2 \varepsilon_0 E_{rf} \sin\phi_{rf}$

R: effective bunch size, should be found by measurements

Model A: 1D Parallel Plate Capacitor (PPC)

TECHNISCHE
UNIVERSITÄT
DARMSTADT



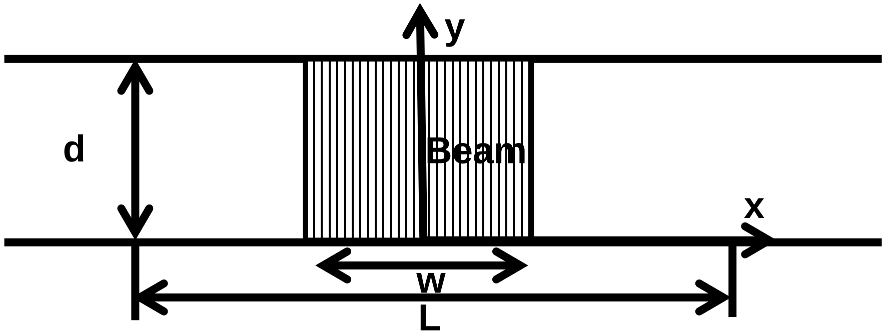
#	Laser Spot Size σ_{xy} (mm in rms)	Effective Radius R_{eff} (mm in rms)	Shift Factor $= R_{eff} / \sigma_{xy}$
1	0.302	0.4478	1.483
2	0.312	0.4603	1.475
3	0.327	0.4775	1.460
4	0.341	0.4908	1.439
5	0.361	0.5060	1.402
6	0.382	0.5322	1.393

Experiment 1 to 6

#	σ_{xy} /mm	LT**	$P_{rf,\,gun}$/MW	$\sqrt{P_{rf,\,gun}} \times \sigma_{xy}$
1	0.302	57%	6.49	0.769
2	0.312	52.6%	5.99	0.764
3	0.327	48.2%	5.45	0.763
4	0.341	43.8%	5.00	0.762
5	0.361	39.5%	4.55	0.770
6	0.382	35.1%	3.99	0.762

- **PPC model fits the measurement data with a prediction of larger effective bunch size than laser spot size**
- **The shift factor is ~1.45 > 1.2**
- **PPC model is only in 1D, apparently not accurate enough!** ⇨ **2D Models**

Model B: 2D C-L Scaling Law based on PIC Simulations



$$Q_{SCL-2D} = \frac{8}{9}\pi\varepsilon_0 E_0 \times \left(R^2 + 0.15725Rd + 0.0001d^2\right)$$

C-L Law: $$J_{SCL-1D} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\,\frac{V_0^{3/2}}{d^2}$$

Scaling Law for finite transverse dimension:

$$\frac{J_{SCL\_2D}}{J_{SCL\_1D}} = 1 + \frac{0.3145}{w/d} + \frac{0.0004}{(w/d)^2}$$

$$V_0 = E_0 d,\ d = \frac{eE_0}{2m}\Delta t^2$$

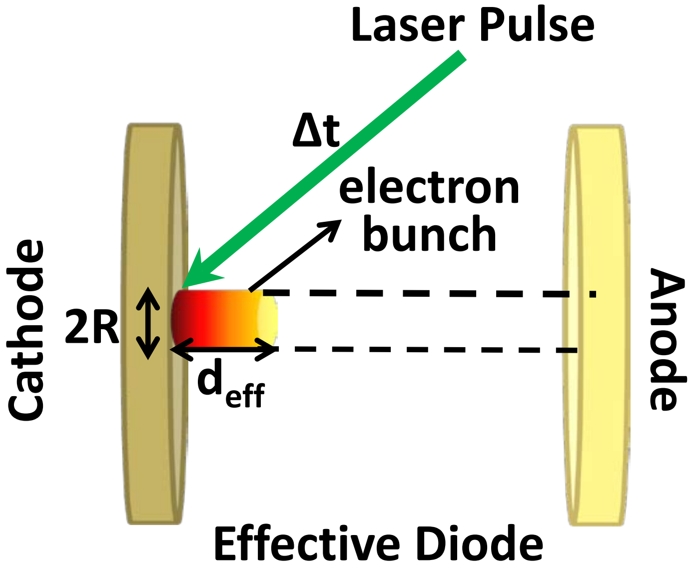
d:bunch extension length to effective diode

w: width of emission, 2*R

#	Laser Spot Size σ_{xy} (mm, rms)	Effective Radius R_{eff} (mm, rms)	Shift Factor $= R_{eff}/\sigma_{xy}$	R-square of Fitting
1	0.302	0.332	1.099	0.970
2	0.312	0.346	1.109	0.969
3	0.327	0.368	1.125	0.966
4	0.341	0.385	1.129	0.963
5	0.361	0.404	1.119	0.959
6	0.382	0.436	1.141	0.949

- Predicted spot size > laser spot size
- Shift factor **~ 1.1 < 1.2**
- **Model B is in 2D, but the length of the effective diode is fixed for all the cases, which results in inaccuracies.** ⇨ **2D Model with unfixed d_{eff}**

Model C: 2D C-L Scaling Law



Define an effective diode of length d_{eff}, and apply the C-L law to the new diode geometry.

C-L law: $J \sim V_0^{1.5}$
$\sim d^{-2}$

Finite Transverse Dimensions

$$Q_{SCL-2D} = I_{SCL-2D}\,\Delta t$$

$$= \frac{\sqrt{2}}{9}\frac{I_0 R^2}{\sqrt{d_{eff}}}\left(\frac{eE_0}{mc^2}\right)^{1.5}\Delta t$$

$d = d_{eff}$

$V_0 = E_0 d_{eff}$

R: beam radius

Δt: length of laser pulse

c: speed of light

I_0: constant, 17kA

#	Laser Spot Size (mm in rms)	Fitted Radius (mm in rms)	Shift Factor	d_{eff} (mm)	R-square of Fitting
1	0.302	0.372	1.232	1.63	0.9441
2	0.312	0.382	1.224	1.55	0.9333
3	0.327	0.392	1.199	1.39	0.9168
4	0.341	0.406	1.191	1.37	0.9023
5	0.361	0.419	1.159	1.26	0.8831
6	0.382	0.432	1.131	1.10	0.8459

Analysis of Effective Bunch Size at Emission

- Estimations of Emission Spot Size with Different Analytical Models at SCL

#	Laser Spot Size (mm in rms)	Shift Factor = Fitted Spot Size / Laser Spot Size		
		1-D PPC	2-D C-L (PIC)	2-D C-L (Analytical)
1	**0.302**	1.483	1.099	1.232
2	**0.312**	1.475	1.109	1.224
3	**0.327**	1.460	1.125	1.199
4	**0.341**	1.439	1.129	1.191
5	**0.361**	1.402	1.119	1.159
6	**0.382**	1.393	1.141	1.131

Length of the Effective Diode

d_{eff} (mm)
1.63
1.55
1.39
1.37
1.26
1.10

- Predicted spot size > laser spot size
- Shift factor **1.232 ≈ 1.2**
- **Model C predicts a most comparable shift factor as observation at EMSY1**

Intermediate Summary

1. **The shift of the laser spot size for minimum emittance at EMSY1 can be explained by the 2D C-L Law analytically.**
2. **Simulation prediction fits the theory of SCL emission which indicates the shifting is unlikely physical but seems coming from measurement issues.**
3. **For that reason, relevant experimental issues in terms of the laser spot size measurement need to be checked.**

Quantum Efficiency Limited (QEL) Emission (new)

Descriptions

In QE-Limited Regime,

1. QE strongly depends on the fields at the cathode surface and becomes time-dependent due to the field effects
2. Production of the electron bunch will then, not only depend on the cathode drive laser, but also the QE of the cathode
3. Normally the electron bunch at the cathode reproduce the cathode drive laser profile. But now, the cathode laser pulse profile ≠ the emitted electron bunch profile because of a time-dependent QE

- Transient effects modeling
- Field effects on QE can be determined by the Schottky effect
- Time-Dependent emission model will lead to a modified "asymmetric temporal profile" of the drive laser pulse

Longitudinal Beam Dynamics Modeling

Mathematical Model

Time-Dependent Emission Modeling

(1)
$$QE(t) = \boldsymbol{\eta}[h\nu - (\Phi_{cath} \mp \Delta\Phi(t))]^2$$
QE behavior

(2)
$$\Delta\Phi(t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(z=0,t)}$$
work function reduction due to field effects

(3)
$$Q(t) = \int_{-\infty}^{t} e \frac{P_{laser}(\tau)}{h\nu} QE(\tau) d\tau$$
total charge produced at the cathode

$\boldsymbol{\Phi_{cath}}: work\ function, 3.5\ eV, h\nu\ = 4.81\ eV$

$\boldsymbol{P_{laser}}: power\ profile\ of\ the\ laser\ pulse$

$\boldsymbol{\Delta\Phi(t)}: modification\ of\ the\ work\ function$

$\boldsymbol{\eta}: cathode\ property\ constant$

$\boldsymbol{E_{cath}}:\ total\ fields\ at\ the\ cathode\ surface$

$''\mp''\ characterizes\ the\ work\ function\ variation\ when\ the\ total\ field\ changes\ sign$

Mathematical Model

η,

describing cathode properties, which should be found from the specific emission measurement

In theory, η should be exactly identical for the same photocathode under same experimental conditions.

$$QE(t) = \overset{\text{Unknown}}{\eta}\left[h\nu - (\Phi_{cath} \mp \Delta\Phi(t))\right]^2 \quad \textbf{(1)}$$

$$\Delta\Phi(t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(z = 0, t)} \quad \textbf{(2)}$$

$$\overset{Q_{meas}}{Q(t)} = \int_{-\infty}^{t} e\frac{P_{laser}(\tau)}{h\nu} QE(\tau)d\tau \quad \textbf{(3)}$$

Determining η, by numerically integrating Equations (1) to (3) in the designed simulation loop, such that Q in Eq. (3) equals to the measured total charge, then Q(t) gives the modified temporal profile accordingly.

If η is found to be same everywhere, then the model is correct.

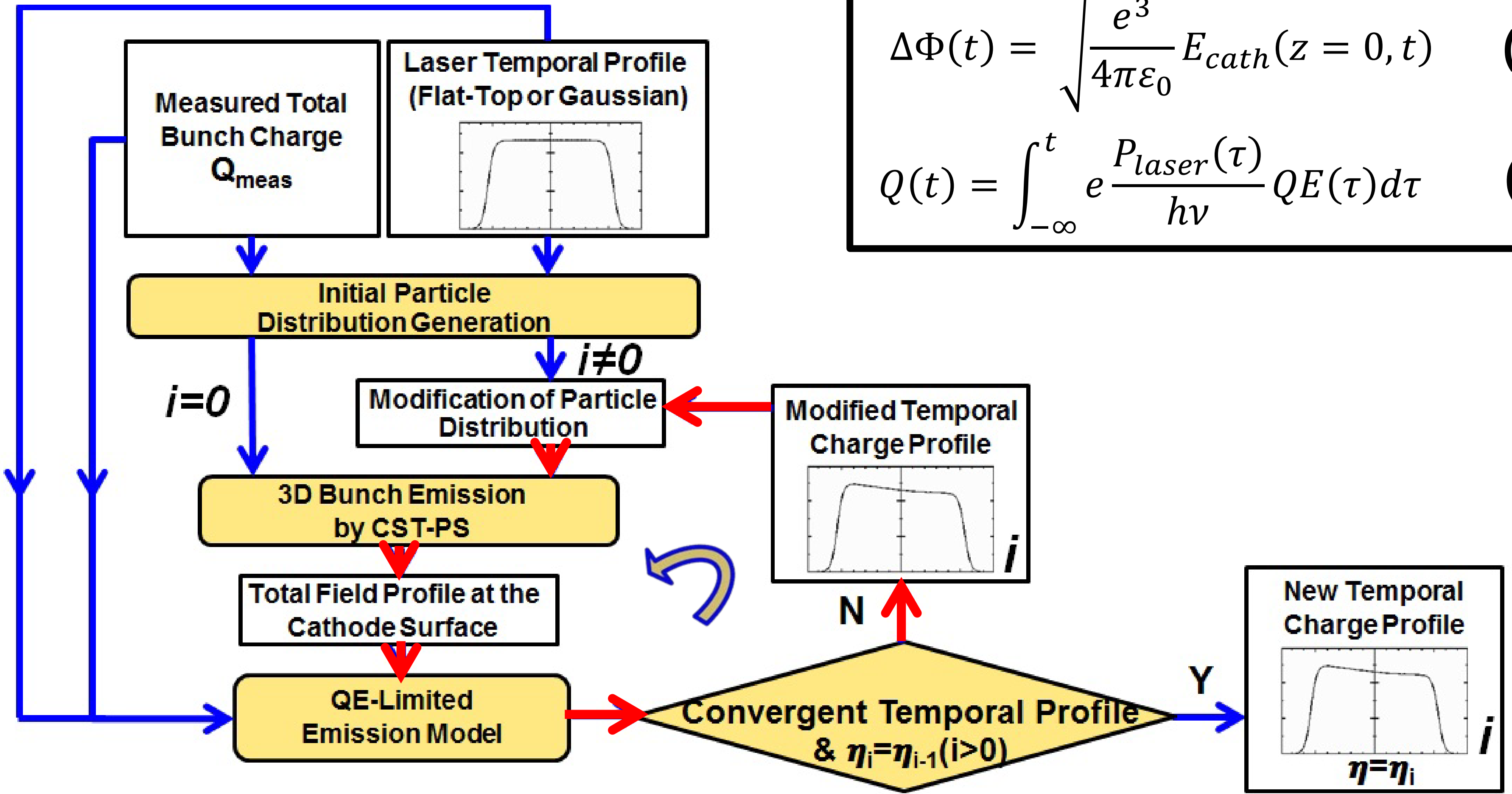
Simulation Algorithm

– Consistent Simulation Loop

$$QE(t) = \boldsymbol{\eta}[h\nu - (\Phi_{cath} \mp \Delta\Phi(t))]^2 \quad \textbf{(1)}$$

$$\Delta\Phi(t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(z=0,t)} \quad \textbf{(2)}$$

$$Q(t) = \int_{-\infty}^{t} e \frac{P_{laser}(\tau)}{h\nu} QE(\tau)\, d\tau \quad \textbf{(3)}$$



Measured Total Bunch Charge Q_{meas}

Laser Temporal Profile (Flat-Top or Gaussian)

Initial Particle Distribution Generation

i=0

i≠0

Modification of Particle Distribution

Modified Temporal Charge Profile

i

3D Bunch Emission by CST-PS

Total Field Profile at the Cathode Surface

QE-Limited Emission Model

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

N

Y

New Temporal Charge Profile

i

$\eta=\eta_i$

i: iteration times

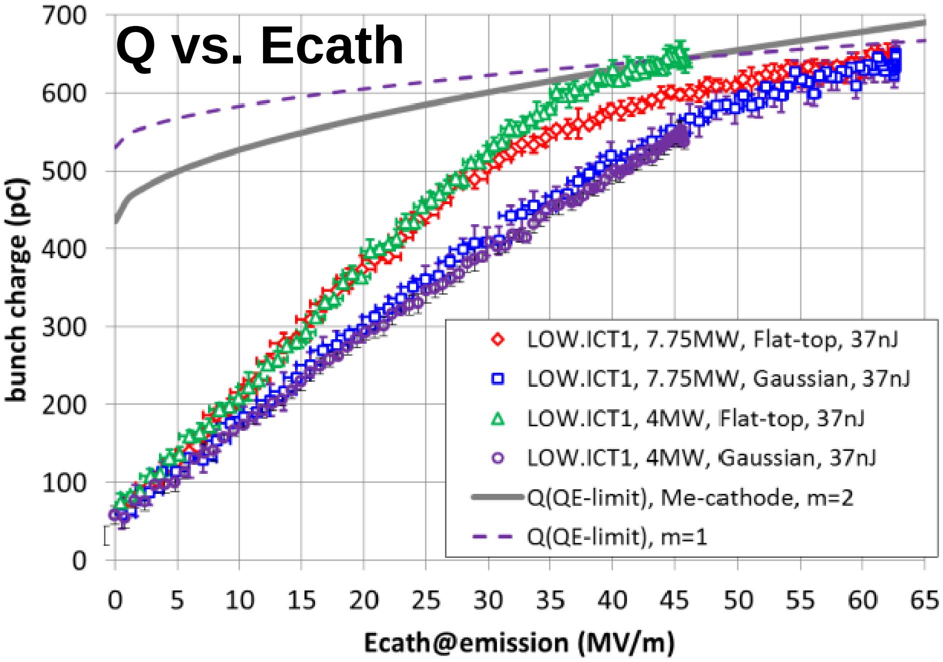
Comparisons to Measurements

two typical measurements for injector commissioning

TECHNISCHE
UNIVERSITÄT
DARMSTADT

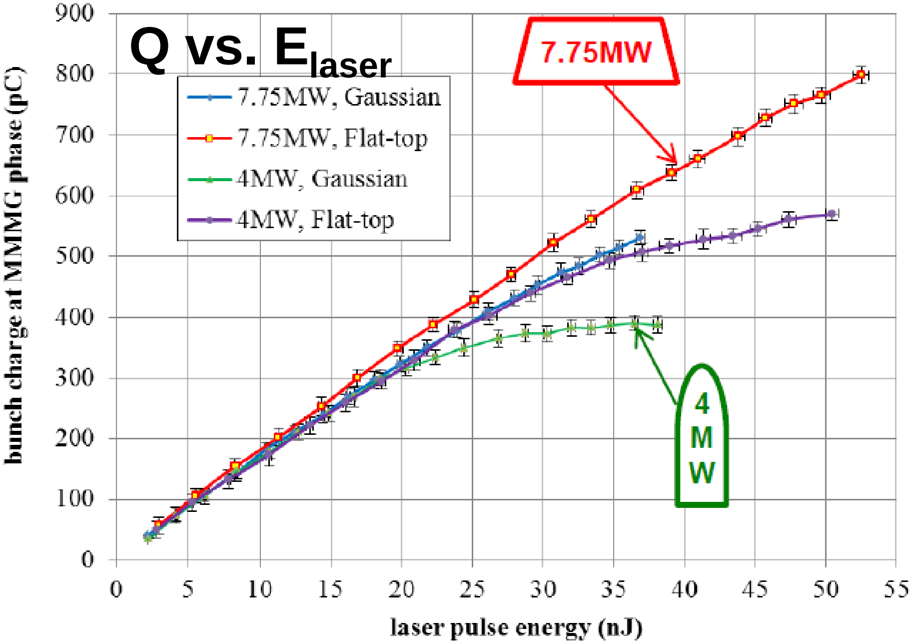
Measurement A:

Total Charge vs. Field Gradients at E_{laser}=37 nJ



Measurement B:

Total Charge vs. Laser Energies at MMMG phase



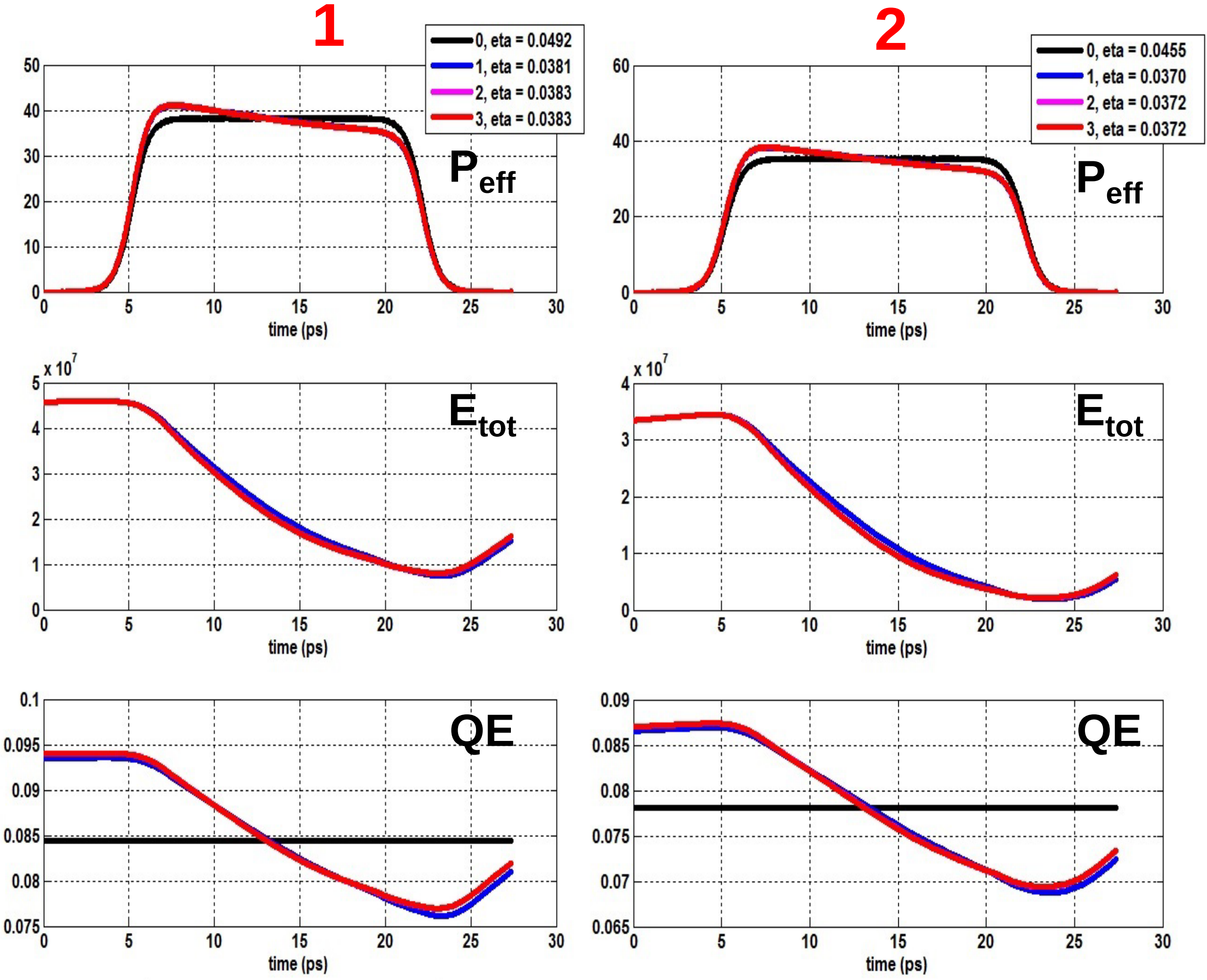
2 Temporal Profiles + 2 Gun Powers

	7.75MW	4MW
Flat-top (17ps)	case 1	case 3
Short Gaussian (2.7ps)	case 2	case 4

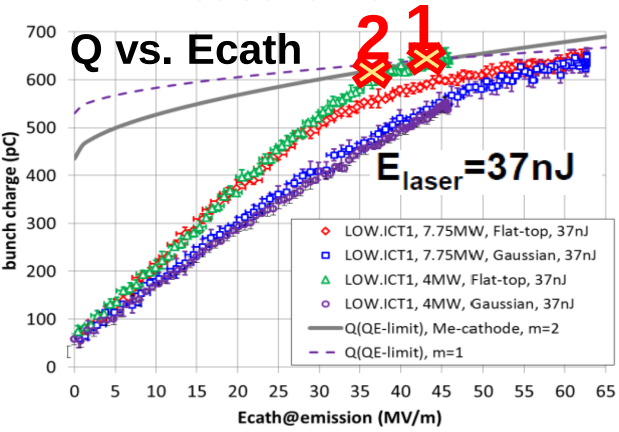
1. **Reproduce the four measurements in simulations**
2. **Compare the total bunch charge with measurements in QEL regime**

Simulation Results:
applying to different field gradients

iteration evolution of main parameters



Measurement A

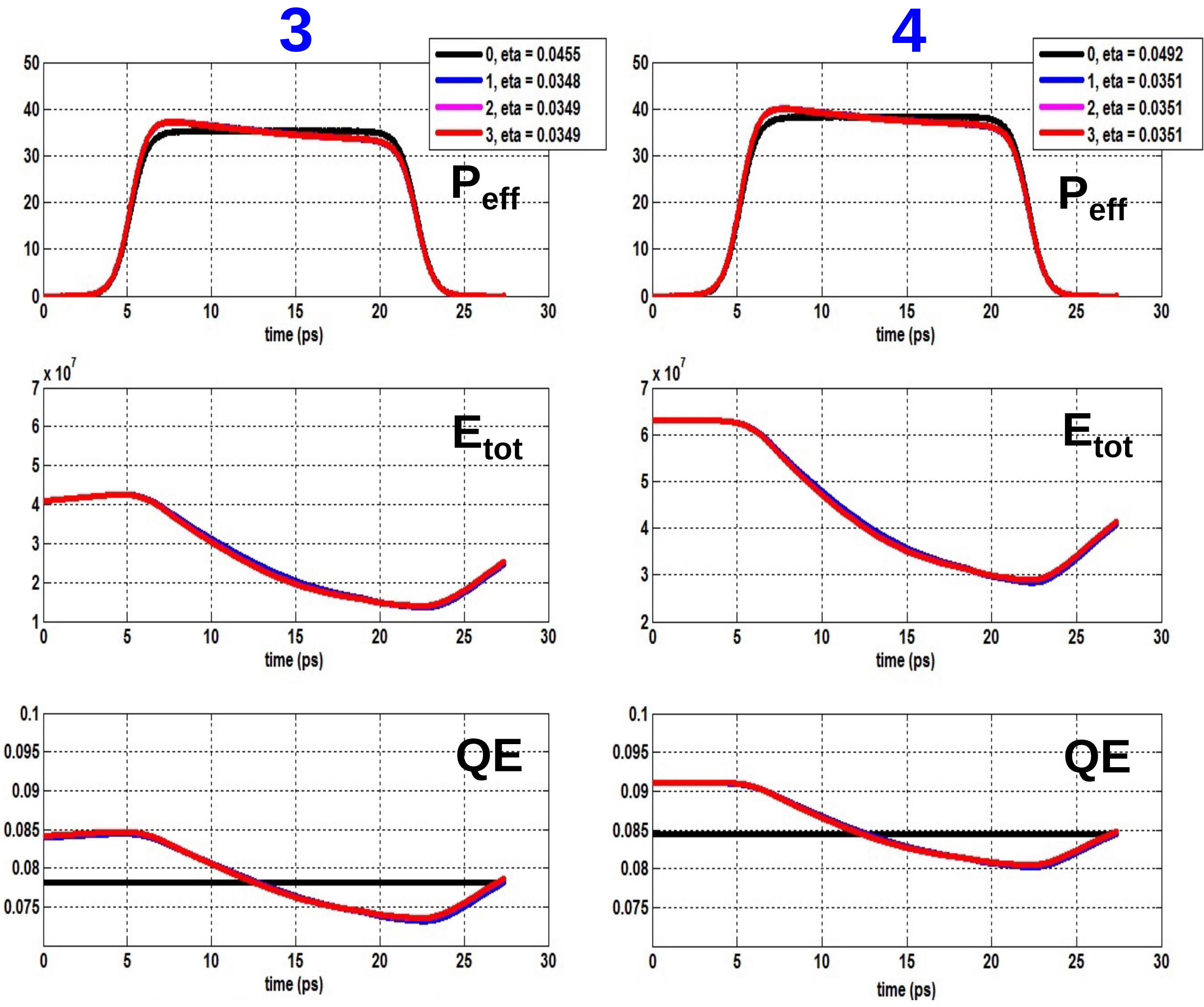


4 MW RF Power

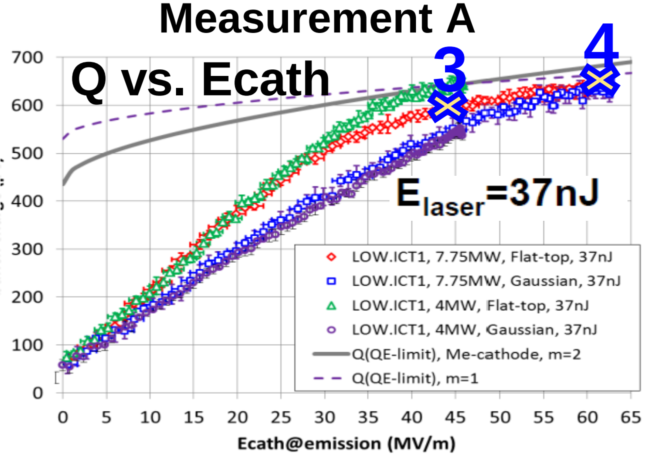
	E_{laser} (nJ)	E_{cath} (MV/m)	η
1	37	~36.7	0.0372
2		~46	0.0383

Simulation Results: applying to different field gradients

iteration evolution of main parameters



Measurement A

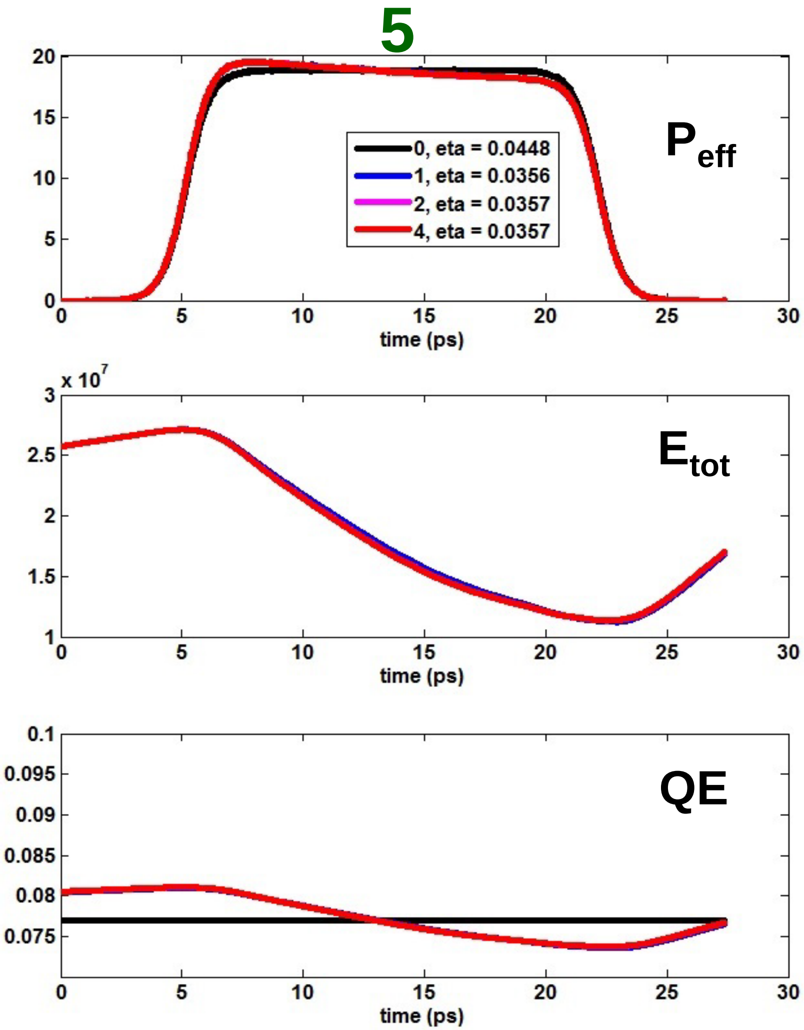


7 MW RF Power

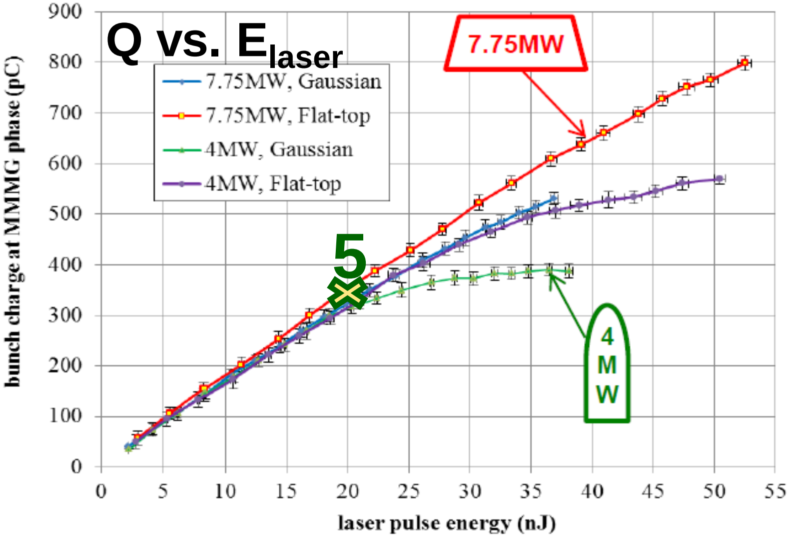
	E_{laser} (nJ)	E_{cath} (MV/m)	η
3	37	~46	0.0349
4		~63	0.0351

Simulation Results:
applying to different laser energies

iteration evolution of main parameters



Measurement B

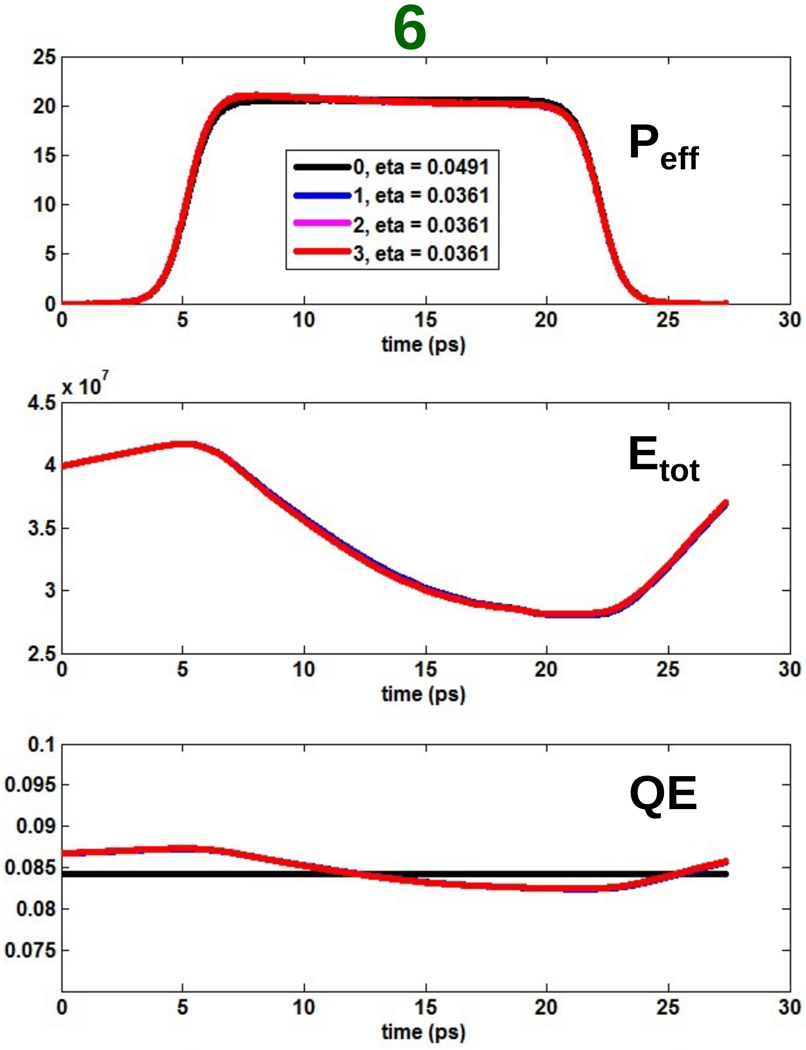


4 MW RF Power

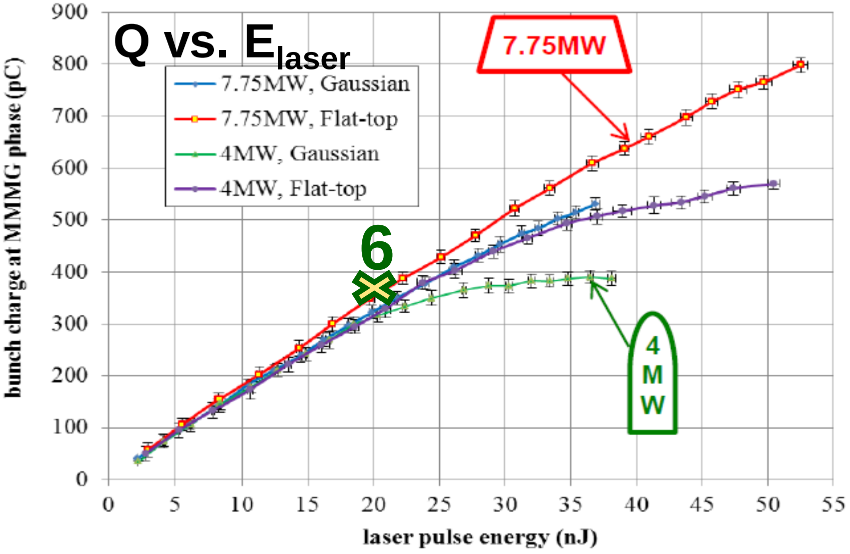
	E_{laser} (nJ)		η
5	20	FT + 4 MW	0.0357

Simulation Results: applying to different laser energies

iteration evolution of main parameters



Measurement B

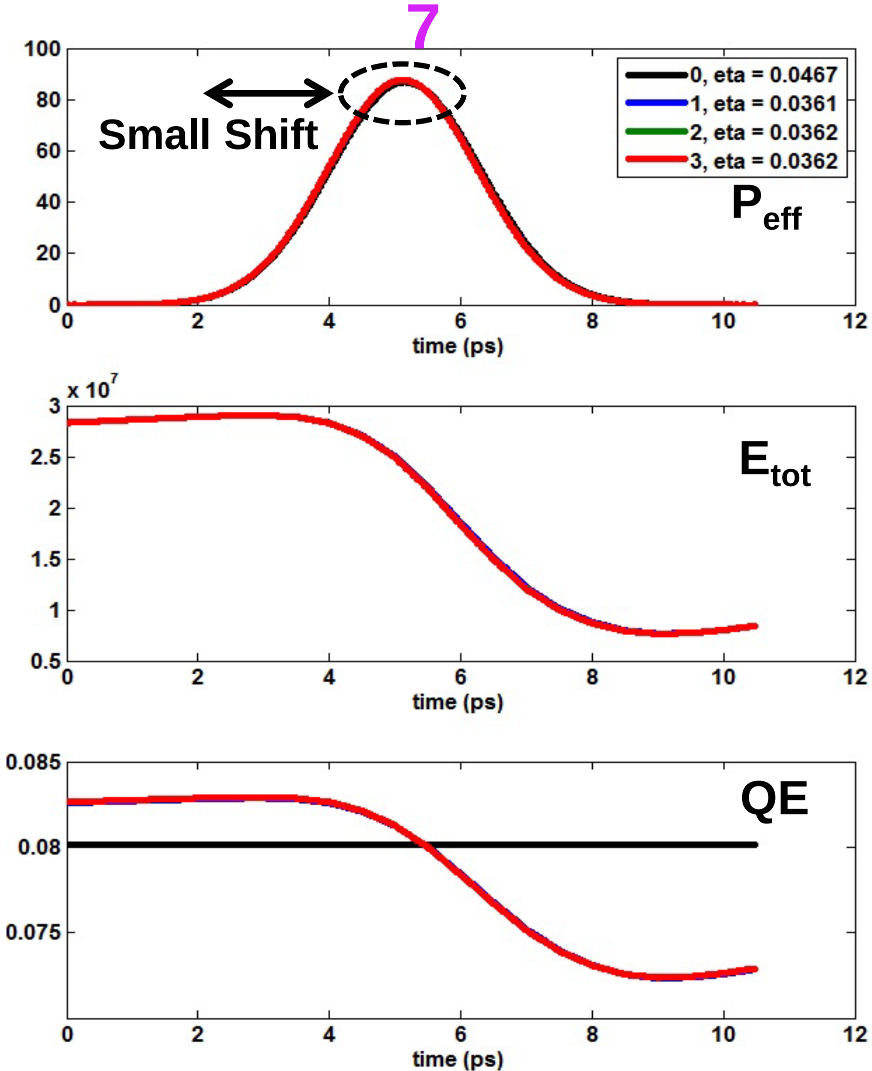


7 MW RF Power

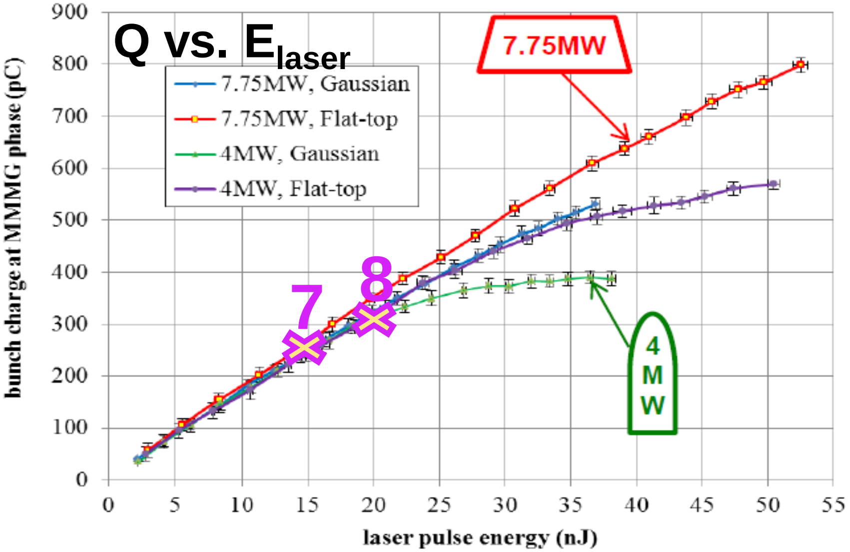
	E_{laser}(nJ)		η
6	20	FT + 7.75 MW	0.0361

Simulation Results:
applying to different laser profiles(Gaussian)

iteration evolution of main parameters



Measurement B

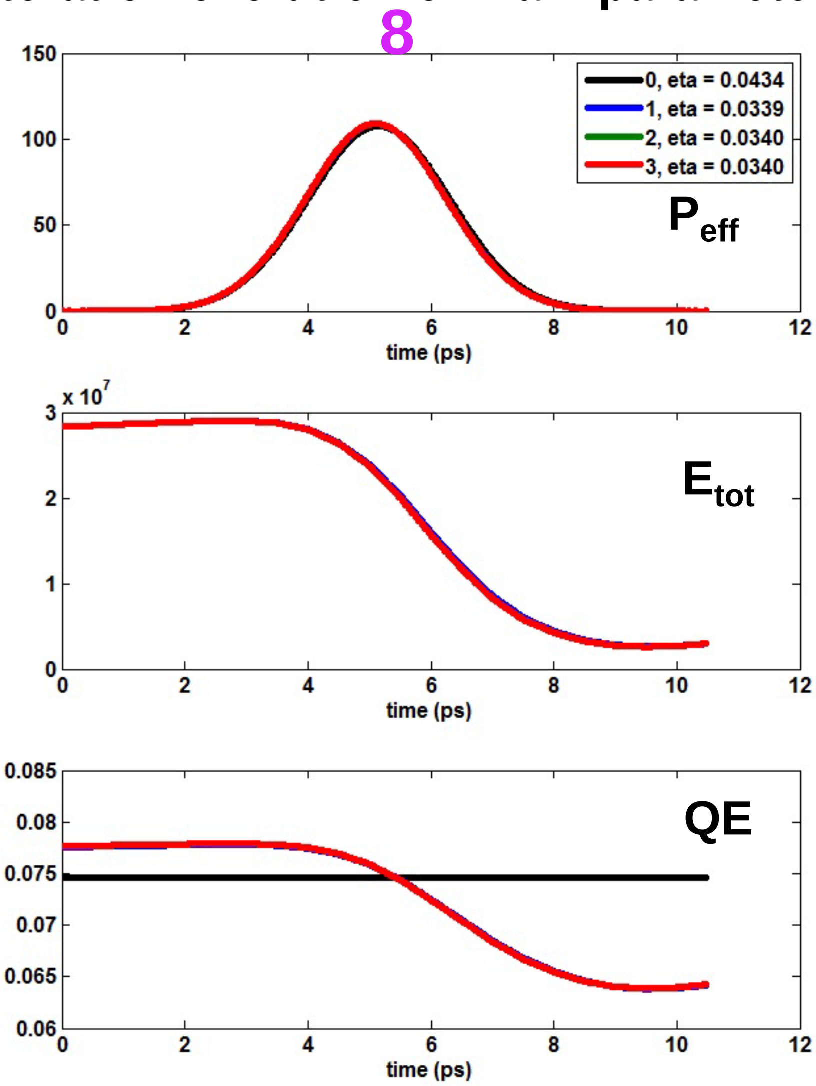


4 MW
RF Power

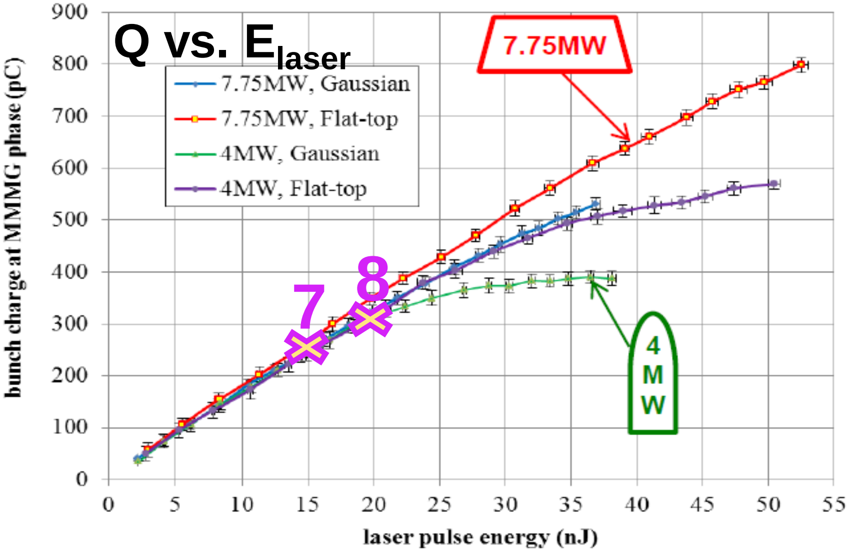
	E_{laser} (nJ)	η
7	15	0.0362

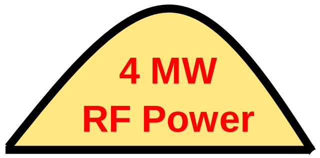
Simulation Results:
applying to different laser profiles

iteration evolution of main parameters



Measurement B





4 MW
RF Power

	E_{laser} (nJ)	η
8	20	0.0340

At QE-Limited Regime

	Profile	RF Power	E_{laser}	η
1	FT	4 MW	37 nJ	**0.0372**
2	FT	4 MW	37 nJ	**0.0383**
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	GS	4 MW	15 nJ	**0.0362**
8	GS	4 MW	20 nJ	**0.0340**

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

$$\frac{\eta_i - \bar{\eta}}{\eta_i} \times 100 < 6.3\%$$

- η **found by simulations for 2 temporal profiles, 2 gun powers, 3 laser engeries and several field gradients, are quite close to each other, which indicates the emission model works well in the QEL Regime!!**

Intermediate Summary

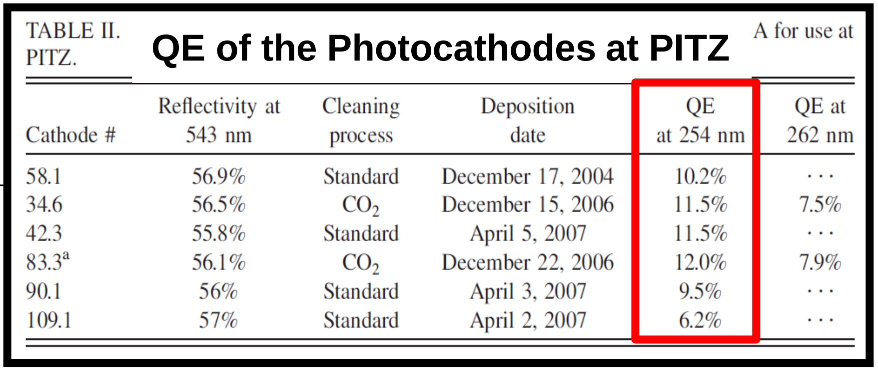


TABLE II. QE of the Photocathodes at PITZ A for use at
PITZ.

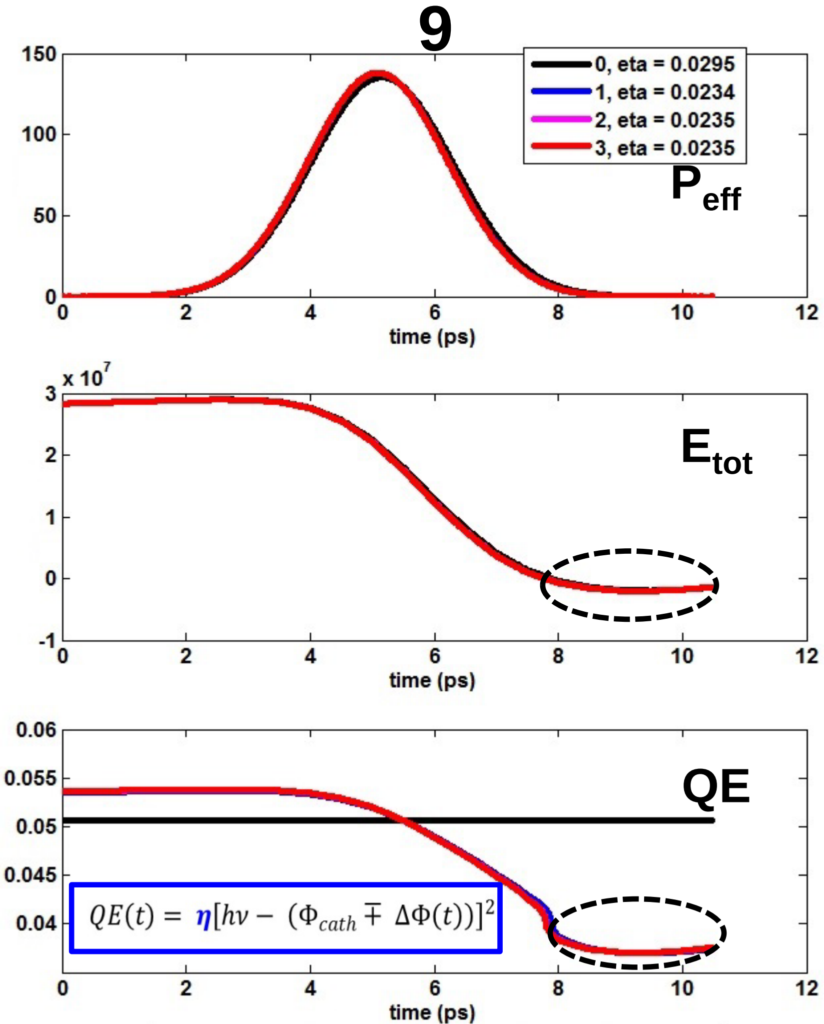
Cathode #	Reflectivity at 543 nm	Cleaning process	Deposition date	QE at 254 nm	QE at 262 nm
58.1	56.9%	Standard	December 17, 2004	10.2%	···
34.6	56.5%	CO_2	December 15, 2006	11.5%	7.5%
42.3	55.8%	Standard	April 5, 2007	11.5%	···
83.3[a]	56.1%	CO_2	December 22, 2006	12.0%	7.9%
90.1	56%	Standard	April 3, 2007	9.5%	···
109.1	57%	Standard	April 2, 2007	6.2%	···

1. **The time-dependent emission model well predicted the total bunch charge in the QEL regime for full range of machine parameters.**
2. **Self-consistent simulation loop has been designed and applied to study the longitudinal beam dynamics.**
3. **Predicted QE are comparable with the experimental findings.**

From QEL to SCL

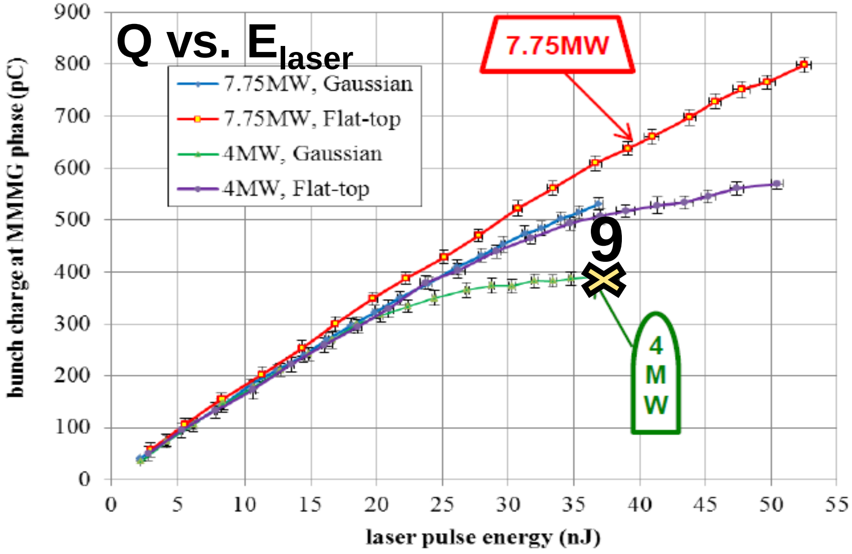
What happens if applying the model to the case close/at SCL?

iteration evolution of main parameters



$$QE(t) = \eta[h\nu - (\Phi_{cath} \mp \Delta\Phi(t))]^2$$

Measurement B



4 MW
RF Power

	E_{laser}(nJ)	η
9	37	0.0235

η is smaller than in the QEL regime!!

From QEL to SCL

$$QE(t) = \eta[h\nu - (\Phi_{cath} \mp \Delta\Phi(t))]^2 \tag{1}$$

$$\Delta\Phi(t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0} E_{cath}(z=0,t)} \tag{2}$$

$$Q(t) = \int_{-\infty}^{t} e \frac{P_{laser}(\tau)}{h\nu} QE(\tau)d\tau \tag{3}$$

	E_{laser}(nJ)		Ecath (MV/m)	η
9	37	GS + 4 MW RF Power	~29.8	**0.0235**
10		FT + 4 MW RF Power	~19.7	**0.0240**
11		FT + 7.75 MW RF Power	~17	**0.0230**

- **η smaller than in QEL regime, which means the QEL model predicts more charge at the space charge limit.→ Unphysical**
- **The reason is, that Eq. (3) should be normalized to the totally produced charge at the cathode, but at the space charge limit, $Q_{meas} = Q_{scl} < Q_{QEL}$!!!**
- **Even so, the QEL model gives the same η at space charge limits under different situations, which again indicates the model itself is correct !!!**

Intermediate Summary

1. **The bunch charge at the space charge limit predicted by the QEL emission model, should be normalized to the total produced charge at the cathode.**
2. **Same η is given by the QEL emission model even for different space charge limits, which indicates the model is correct.**
3. **Ongoing work to generalize the emission model which also works in the SCL regime. Until then, one can refer to our previous charge iteration algorithm for the SCL bunch charge.**

Summary and Perspective

- **SC-Limited Regime**
  - **Self-consistent emission model of CST-PS** can well predict the total bunch charge in the SCL regime for full range of machine parameters.
  - **Bunch Charge Iteration Algorithm has been proposed and applied to SCL charge simulations.**
  - **Simulation predictions of the bunch spot size** well fit the theory of SCL emission, which suggests the shifting problem at EMSY1 is likely from the experimental issues.
- **QE-Limited Regime**
  - **The time-dependent emission model** works well in the QEL regime for distinct experimental conditions.
  - **Temporal Profile Iteration Algorithm** was proposed and used to QEL charge simulations.
  - **Ongoing work** to generalize the emission model which works for SCL and QEL regime in the meantime.

Reference

1. **Mikhail Krasilnikov, PITZ: Simulations versus Experiment, Darmstadt, 19.12.2013**
2. **Rosenzweig et al., NIM A341(1994)**
3. **J. W. Luginsland et al., Physics of Plasmas Vol. 9, No.5 (2002)**
4. **D. Filippetto et al., PRST-AB 17, 024201 (2014)**
5. **David H. Dowell et al., PRST-AB 12, 074201 (2009)**
6. **Computer Simulation Technology AG, http://www.cst.com/**

Thank you for your attention!