Beam dynamics simulation with photoemission modeling in strong RF and beam-self fields

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Ye Chen
Deutsches Elektronen-Synchrotron DESY

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY talks from EWPAA 2017

HZB Helmholtz Zentrum Berlin

Talk: Challenges of the Cs_2Te photocathodes for FLASH and European XFEL by S. Lederer

→ **Performance of Cs_2Te photocathodes at DESY FEL facilities**

→ **Further requirements posed**

Talk: Space charge dominated photoemission at PITZ by M. Krasilnikov

→ **Experimental & numerical studies of photoemission in RF gun environment**

Goal: to show what a role photoemission can play in injector beam dynamics

Contents

- Budgeting injector emittance in a transition regime of photoemission*
- Observation of (strong) cathode field dependencies of measured QE in the gun
- Summary

slides partially available at FEL'19

Budgeting injector emittance in a transition regime of photoemission

FEL-based X-ray facilities require high-brightness electron injectors

- High peak current (I) & **low emittance** (ε_n) → **high beam brightness** (B_n)
  - → High I → high charge and short length → high FEL gain and efficiency
  - → Low ε_n → required beam energy at a given wavelength (λ)
- Fixed charge → **emittance minimization**
- **Emittance** can only be improved **in** the **injector**
- **Emittance budget** & **optimization strategy**
  - → Minimizing space charge contribution
  - → Improving cathode intrinsic emittance
  - → Making other items negligible
- **Intrinsic emittance** → **lower limit** of final emittance

$$B_n \propto \frac{I}{{\varepsilon_n}^2}$$

$$\frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

$$\varepsilon_n \propto \sqrt{{\varepsilon_{th}}^2 + {\varepsilon_{spch}}^2 + {\varepsilon_{rf}}^2 + {\varepsilon_{Bz}}^2 + \cdots}$$

+ coupling items

intrinsic emittance (ε_{th})
space charge emittance (ε_{spch})
rf emittance (ε_{rf})
cathode magnetic field caused emittance (ε_{Bz})

W. Decking, H. Weise, Commissioning of the European XFEL accelerator, Paper MOXAA1, IPAC 2017

F. Stephan, M. Krasilnikov, High Brightness Photo Injectors for Brilliant Light Sources, Chap. Of "Synchrotron Light Sources and Free-Electron Lasers", 2016

Ch.-X. Tang, Paper MO2A04, LINAC 2016

F. Sannibale, W.S. on High Repetition-rate XFEL Physics and Technology, 2017

European XFEL electron injector, Frank Brinker, 06.2017

Emittance optimization at PITZ for FLASH and European XFEL

RF Gun[1-2]

▪**L-band** (1.3 GHz) 1.6-cell copper cavity

▪Ecath **≥ 60 MV/m** → 7 MeV/c e-beams

▪650 μs ×10 Hz → up to **45 kW** av. RF power

▪**Cs_2Te** PC[3] (QE~5-20%) → up to 6 nC / bunch

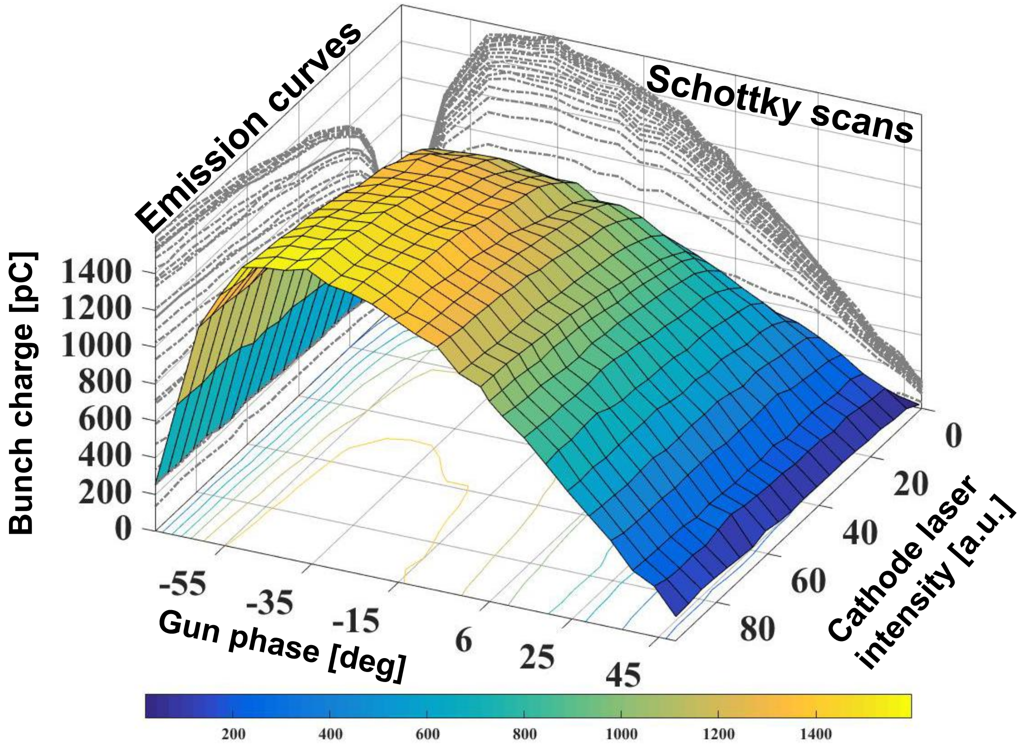
- Photo Injector Test facility at DESY in Zeuthen (PITZ)
- Typical **optimization scheme** at PITZ
  - **Slit-Scanning emittance vs. gun solenoid current at a given transverse cathode laser spot size**
  - **Optimize the spot size for smallest achievable emittance**

(fixed bunch charge, cathode laser pulse length and shape, gun and booster gradient and phase)

[1]*Phys. Rev. ST Accel. Beams 13, 020704 (2010)*
[2]*Phys. Rev. ST Accel. Beams 15, 100701 (2012)*
[3]*Cathode production: S. Lederer, L. Monaco, D. Sertore, P. Michelato*

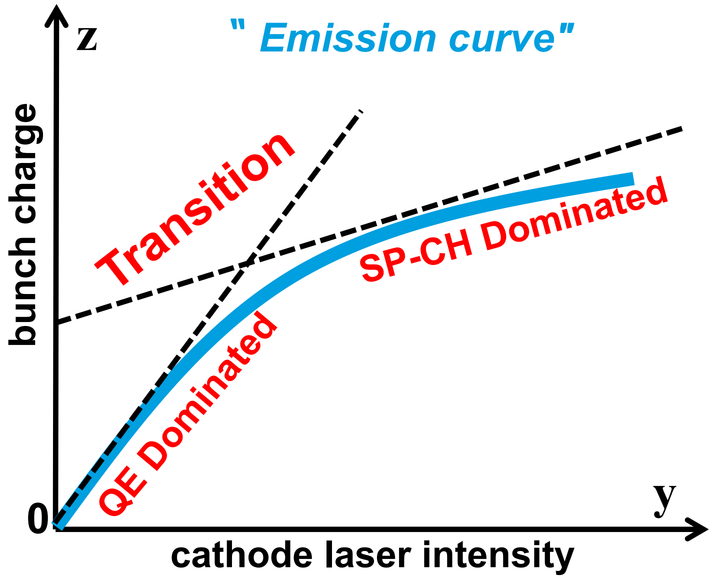
Transition regime of photoemission in RF gun environment

Emission characterization in the gun
Cs_2Te, 60 MV/m



LINAC'18 THPO116

Concept: transition regime



QE: Quantum Efficiency
SP-CH: Space-Charge

Transition regime of photoemission in RF gun environment

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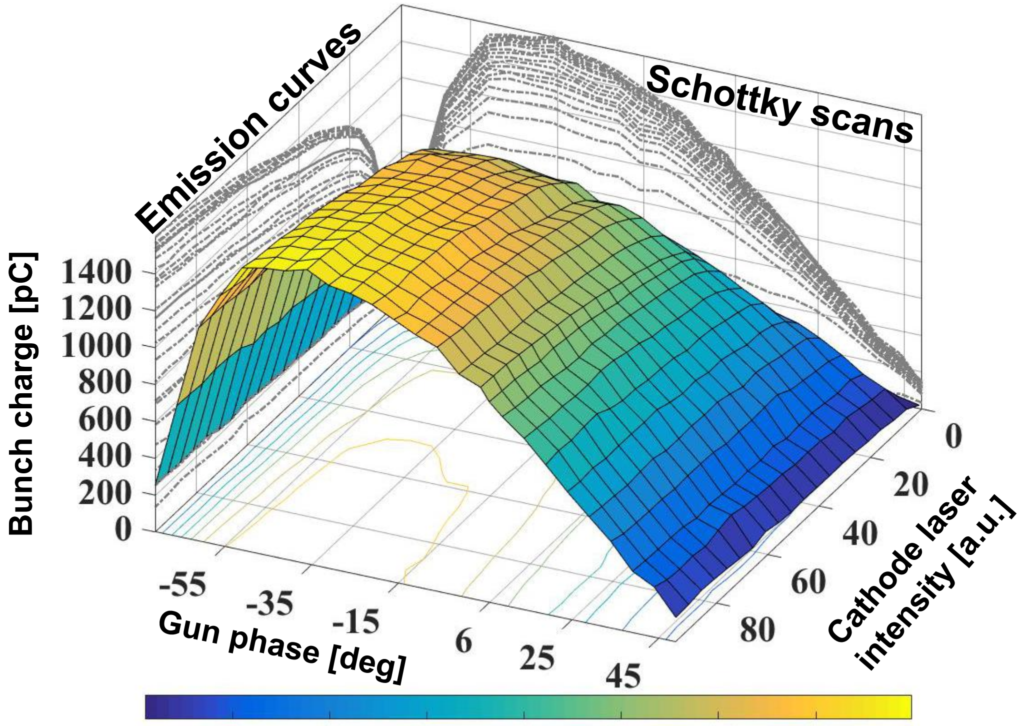
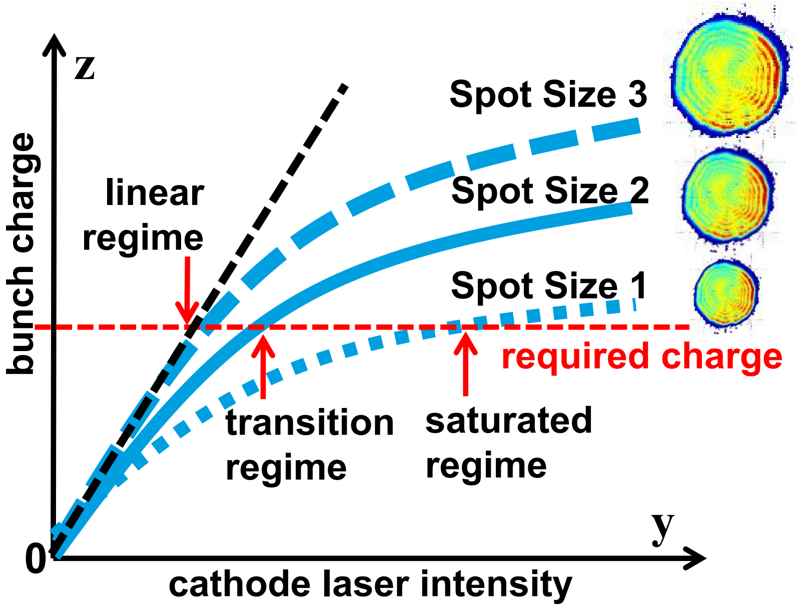


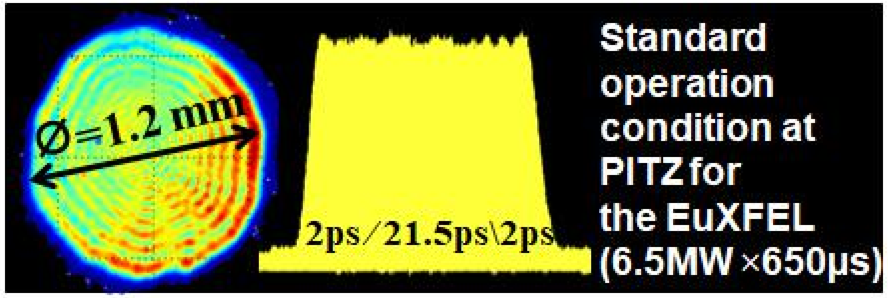
LINAC'18 THPO116

Concept: working point

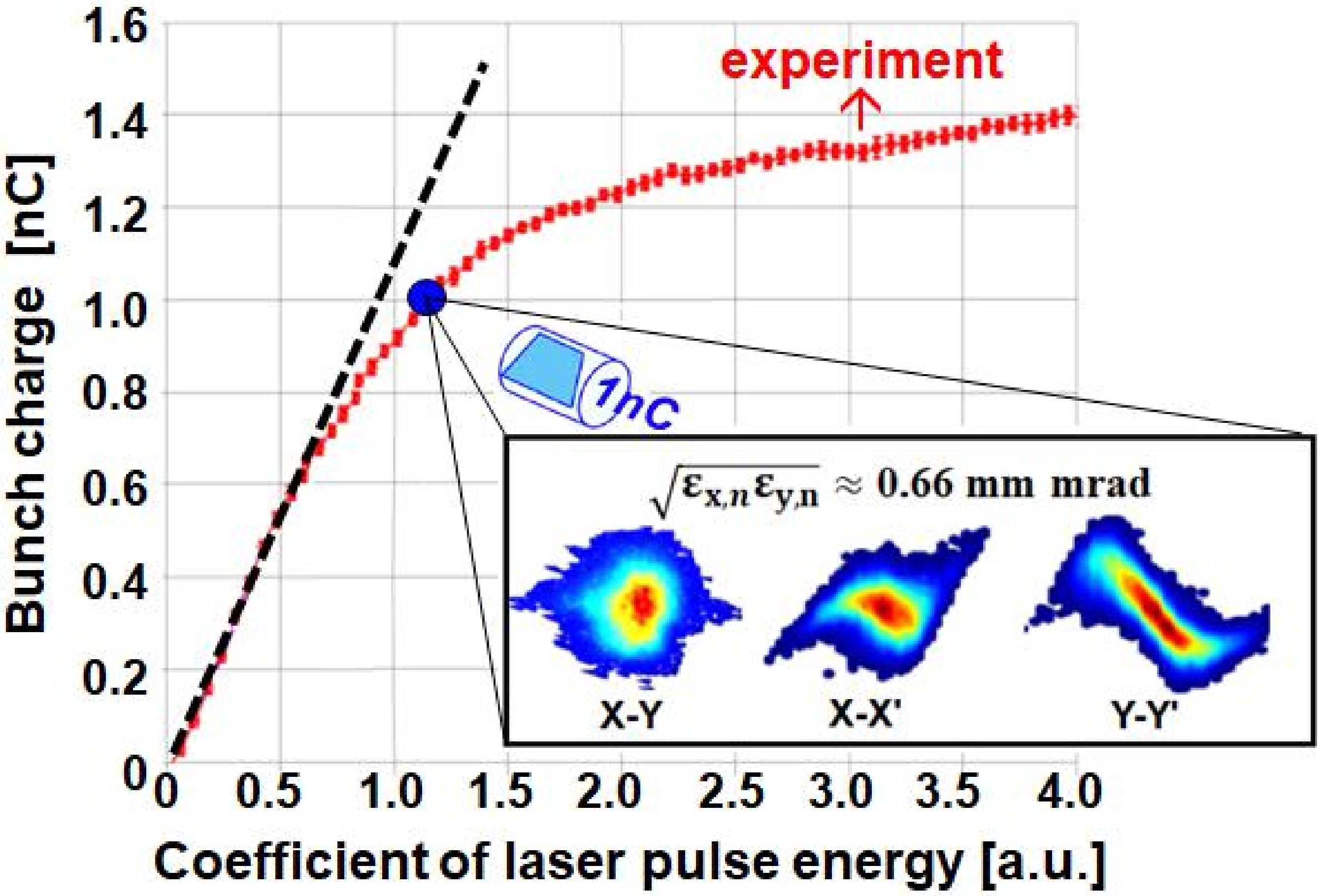


QE: Quantum Efficiency
SP-CH: Space-Charge
Spot Size: transverse laser spot size on cathode
Trans. distributions used only for illustration purpose

Experimental observation on emittance in transition regime of emission



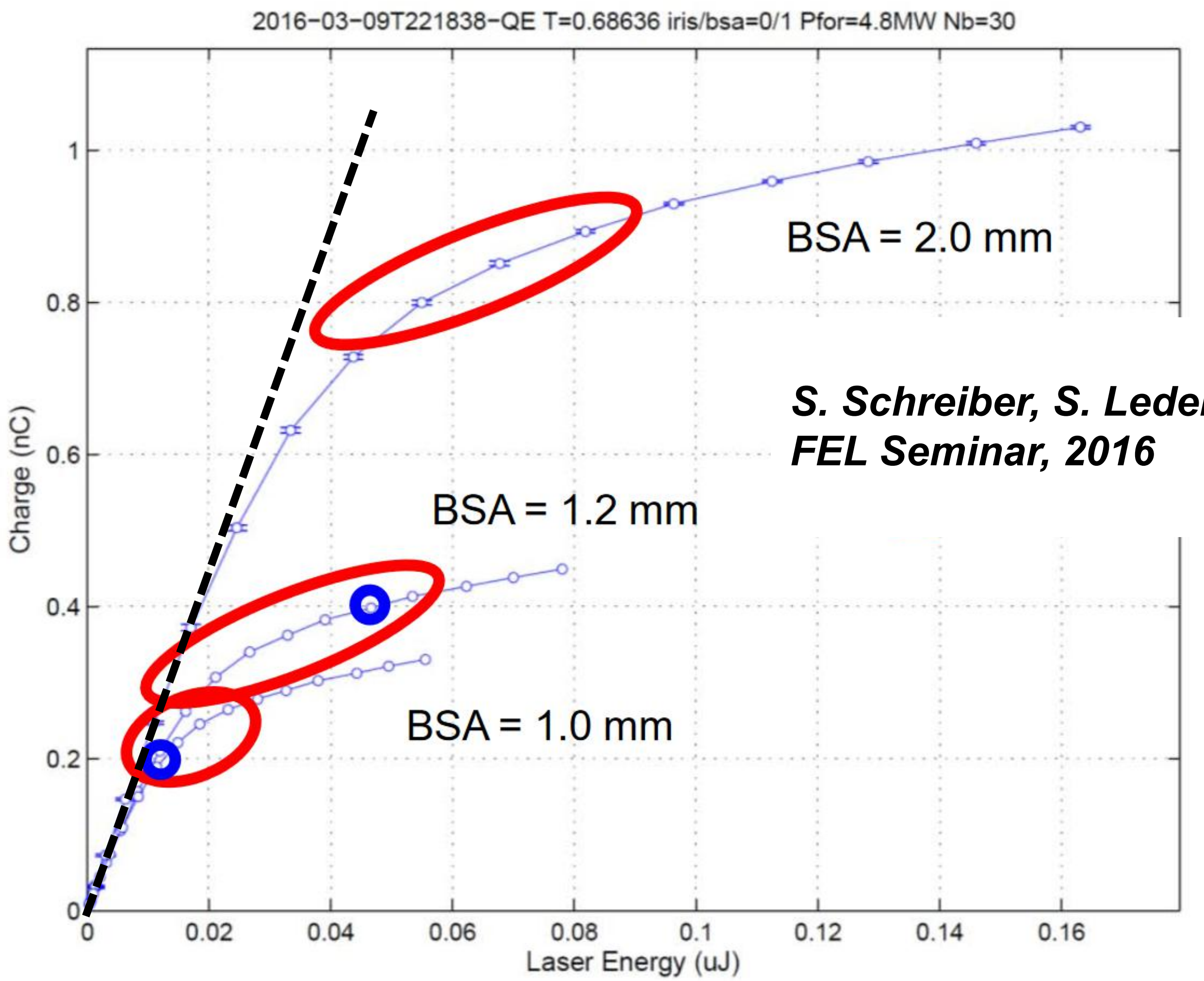
Under standard operation conditions at PITZ, best emittance obtained in transition regime of emission!



Typical working points for the gun at FLASH

FLASH.
Free-Electron Laser in Hamburg

Accelerator actually operated at the photoemission regimes with strong space-charge effects at cathode



S. Schreiber, S. Lederer, FEL Seminar, 2016

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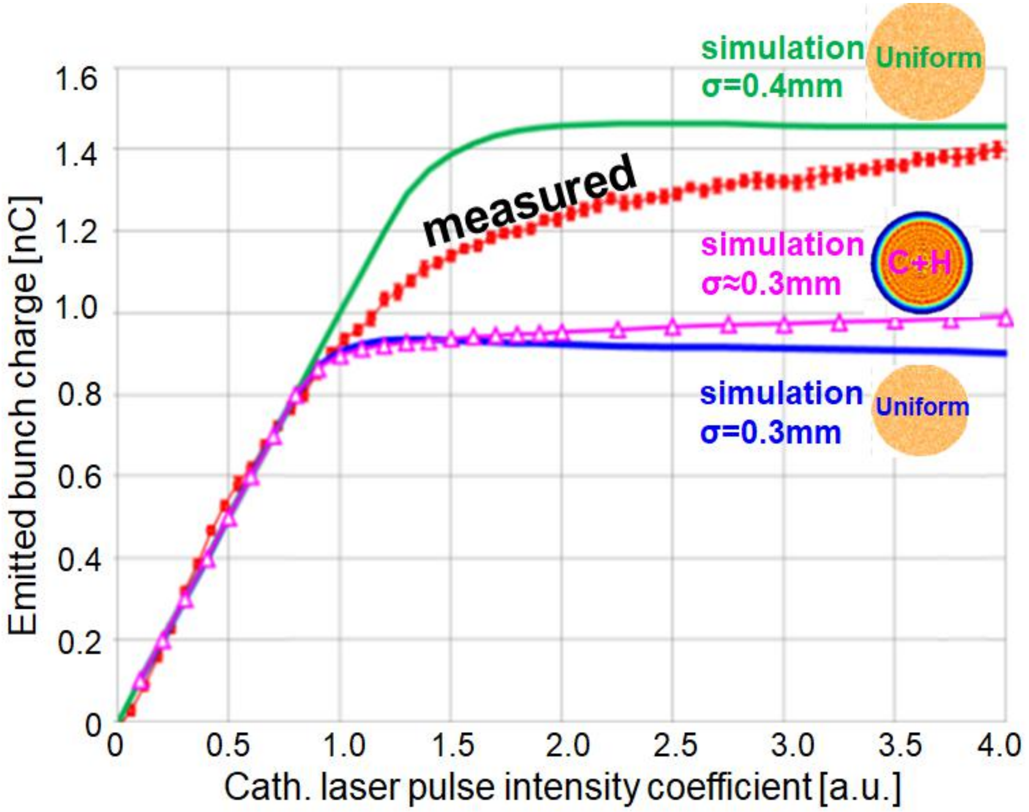
DESY.

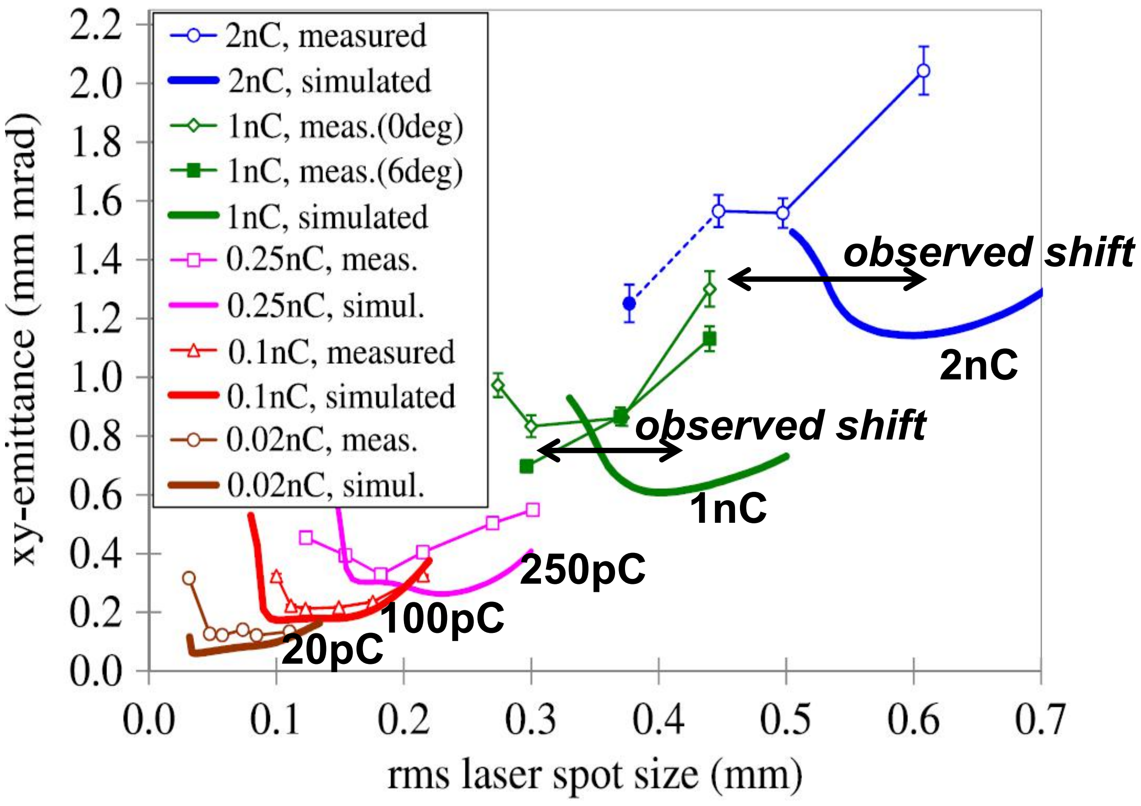
Dynamics in TRE **cannot** be well reproduced by simulations

Simulated emission curve ≠ measured one



NIM A 889, 129-137 (2018) *NIM A 871, 97–104 (2017)*

Simulated optimum laser spot size ≠ measured one



M. Krasilnikov, et al., Phys. Rev. ST Accel. Beams 15, 100701 (2012)

Bring cathode and electron emission physics to beam dynamics

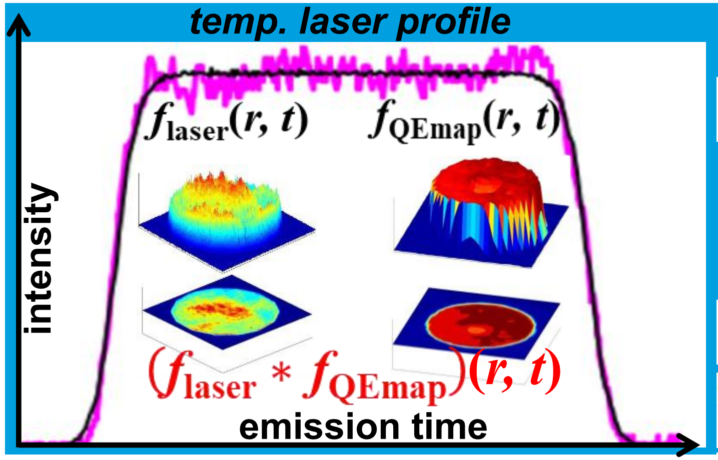
- Not yet straightforward consideration of cathode effects[1-3] in particle simulations
- **Emission model needed for particle dynamics with collective effects at cathode**

→ **first priority: model emission dynamics in strong fields**

  - incorporating an emission model[4-6] with a **Lienard-Wiechert approach**[7-9]
  - transient charge packet creation by interplays of cathode QE with **time and space dependent rf and beam self-fields**

- **Features**

→ measurement-based model training
→ dynamic beam production through cathode physics model
→ taking into account impacts of cathode **field effects onto intrinsic beam slice formation**



In collaboration with TU Darmstadt

Charge production per time step

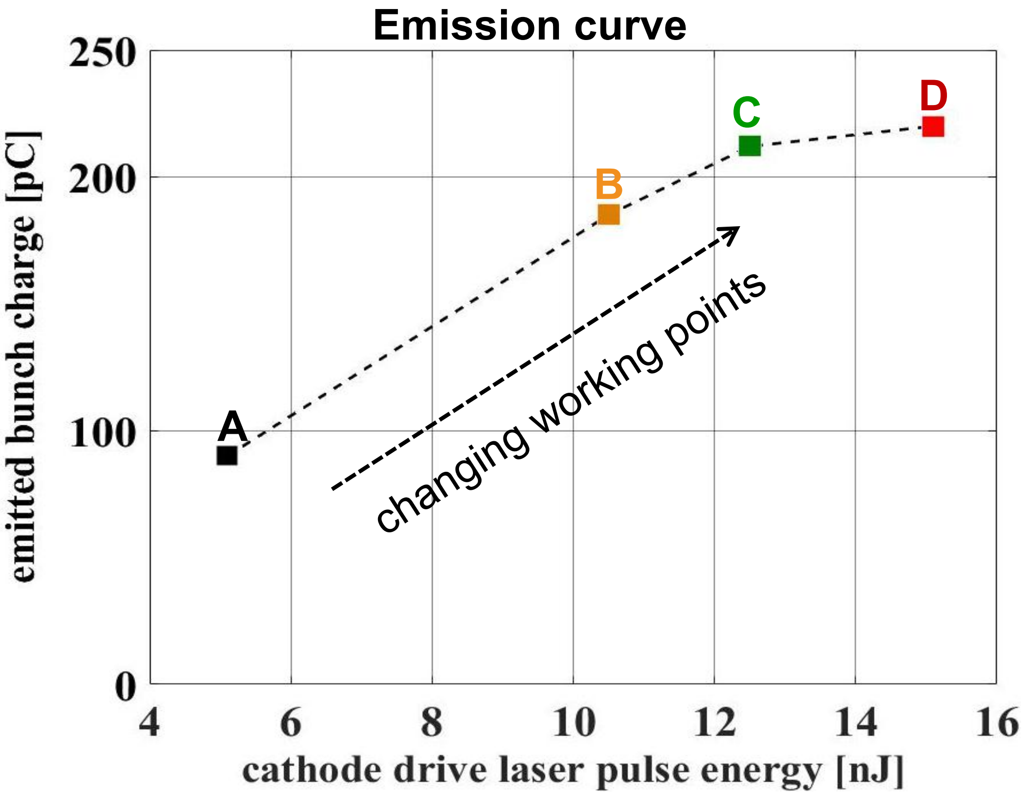
$$dQ(r_\perp, t) = \frac{e\alpha dE_{las}(r_\perp, t) dr_\perp dt}{\hbar\omega \{1 + E_a / [\hbar\omega - \Phi_{eff}(r_\perp, t)]\}^2}$$

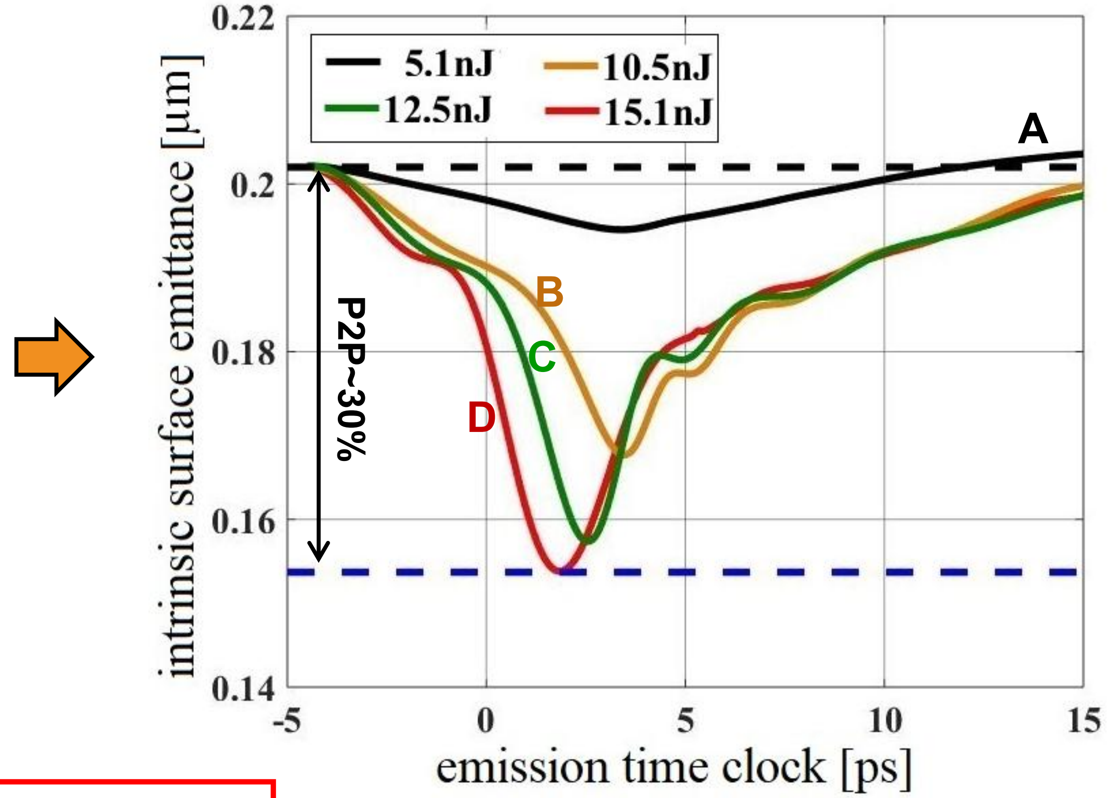
Field-dependent cathode work function

$$\Phi_{eff} = \Phi_0 \pm \sqrt{e[E_{rf}(r_\perp, t, z = 0) + E_{sc}(r_\perp, t, z = 0)]/4\pi\epsilon_0}$$

[1] Nathan A. Moody, Kevin L. Jensen, et al., Phys. Rev. Applied 10, 047002 (2018)
[2] D. H. Dowell and J. F. Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009)
[3] J. Smedley, et al., An Engineering Guide to Photoinjectors Photocathode Theory (2016)
[4] Kevin L. Jensen, et al., Phys. Rev. ST Accel. Beams 17, 043402 (2014)
[5] Kevin L. Jensen, et al., J. Appl. Phys. 104, 044907 (2008)
[6] John Petillo, et al., IEEE Trans. Electron Devices Sci., 52(5),742-748 (2005)
[7] Y. Chen, M. Krasilnikov, E. Gjonaj, et al., NIM A 889, 129-137 (2018)
[8] R. Ryne, C. Mitchell, J. Qiang, et al, FEL 2013
[9] F. Ciocci, L. Giannessi, A. Marranca, et al., NIM A 393 (1997), 434-438.

Effect on intrinsic surface emittance

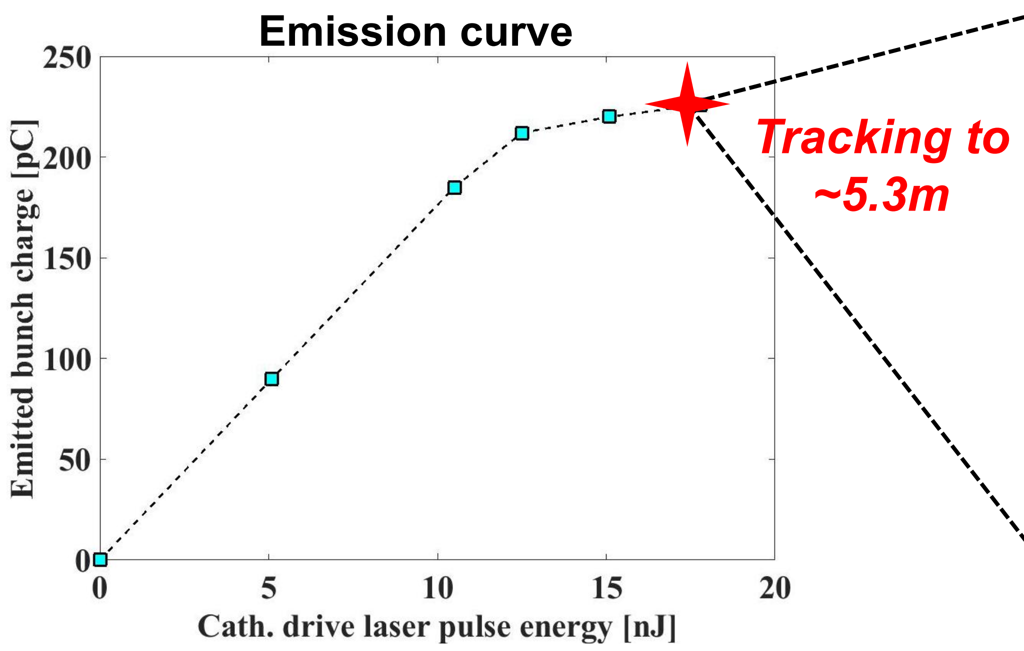


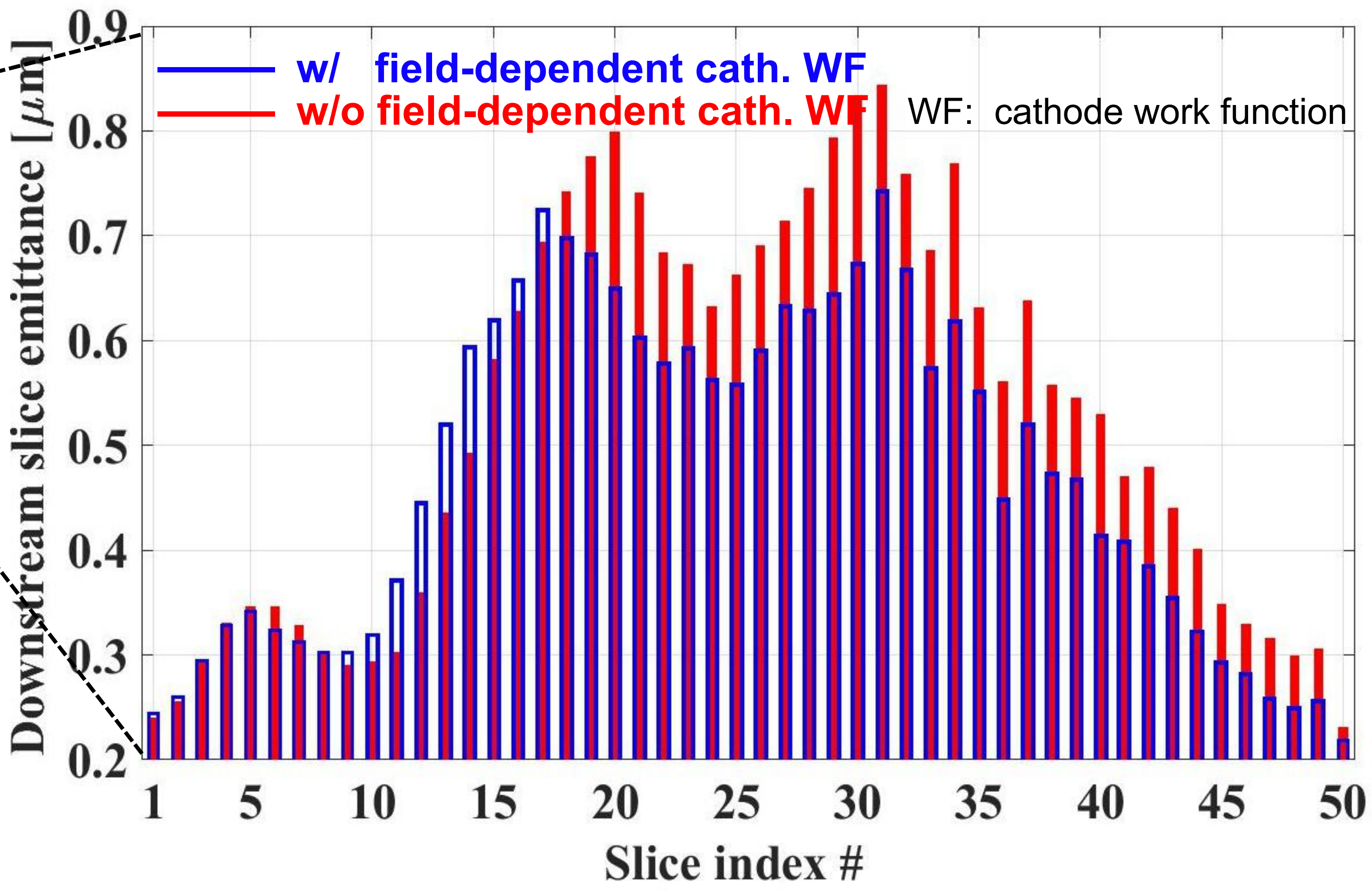


- **Varying working point along emission curve**
  - → changing **intra-bunch modulation of intrinsic surface emittance**
  - → **overall surface emittance reduction** by space charge fields
  - → peak to peak ~30% and ~10% in average
  - → stronger effects for higher local charge densities at cathode

IPAC'19 WEPTS013

Tracking accelerated bunches (~19 MeV/c) downstream till ~5.3m





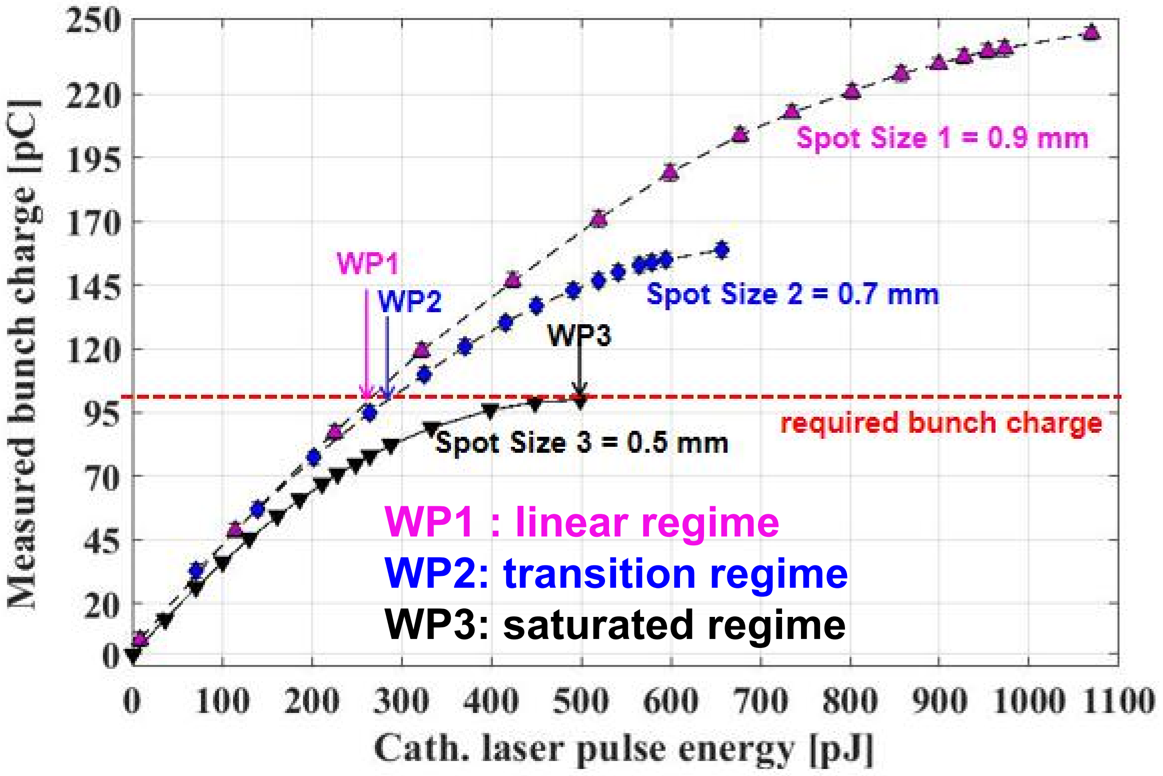
→ **Photoemission details influence downstream beam quality**

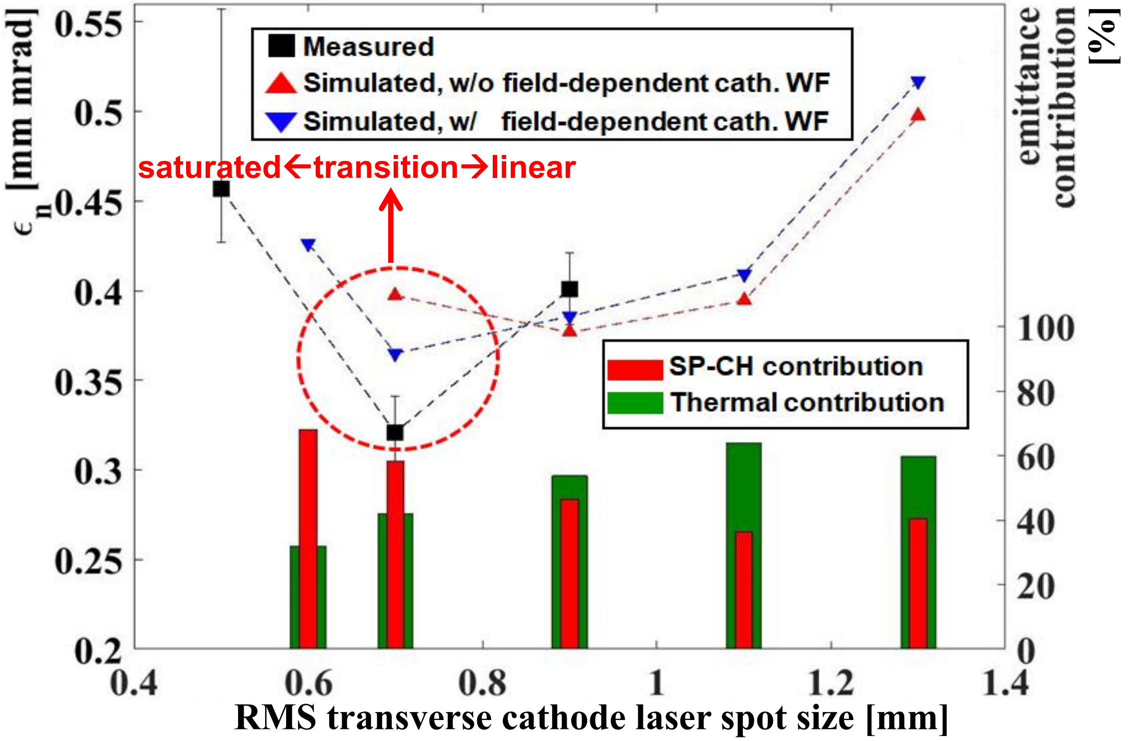
→ High local charge density at cathode reduces slice emittance and the effect **transported downstream**

→ **Stronger effect** for **higher** local **charge** density

Measurement vs. Simulation: optimized emittance vs. cathode laser spot size

Measured emission curve vs. cath. spot size





- **Interplay** between space charge emittance and intrinsic emittance gives optimum spot size for **best emittance in transition regime**
- **Improved simulation** suggests optimum spot size same as measured

Summary I

Budgeting injector emittance in a transition regime of photoemission

- **Working at transition regime of emission delivers best experimentally optimized emittance**
- **Photoemission details influence** downstream beam qualities
- Emission modeling helps **better understand beam dynamics**
- **Cathode physics important** for better emission modeling
- **More detailed modeling approach needed** for strong space charge fields at cathode

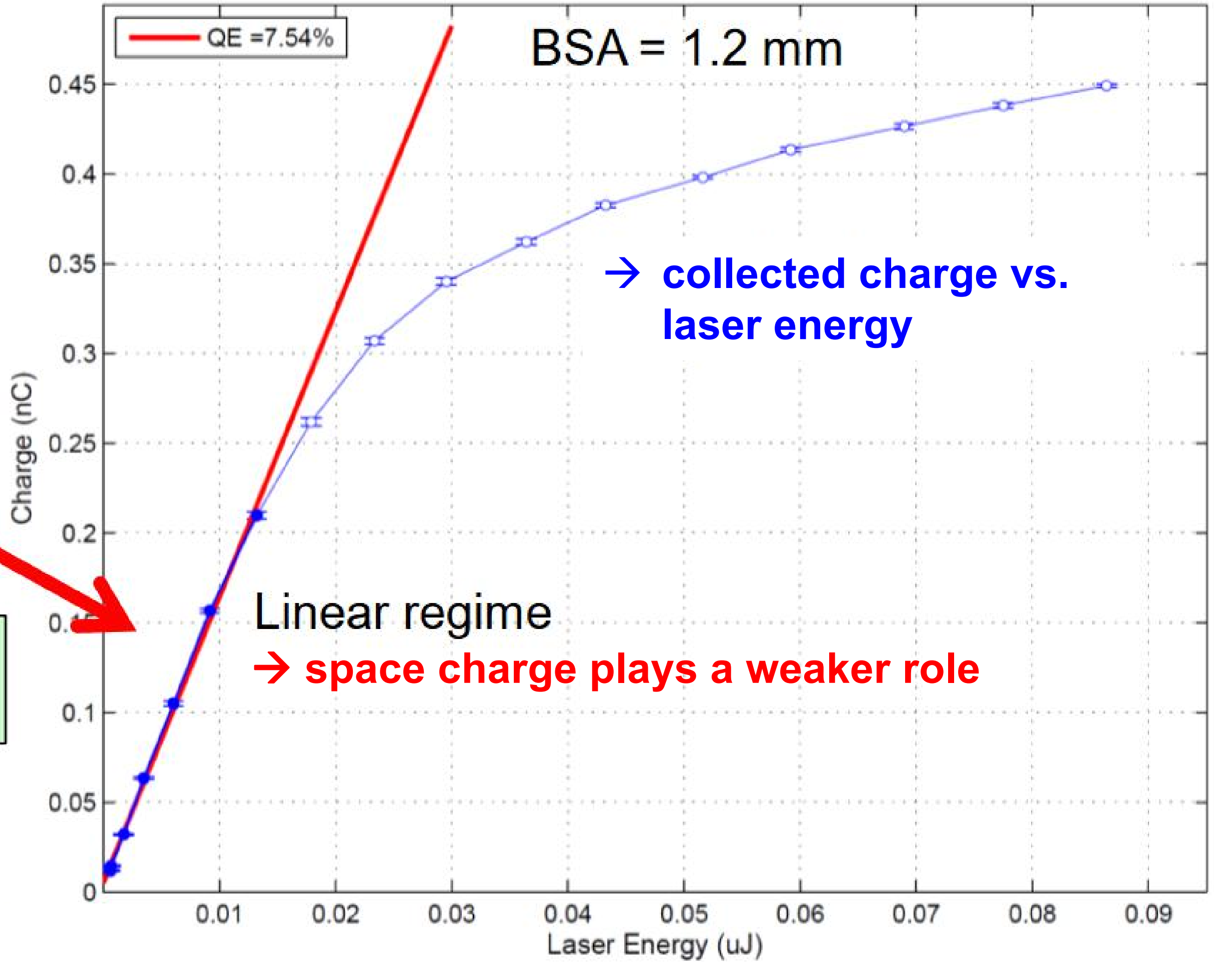
Observation of (strong) field dependencies of measured QE in the gun

QE measurement in the gun

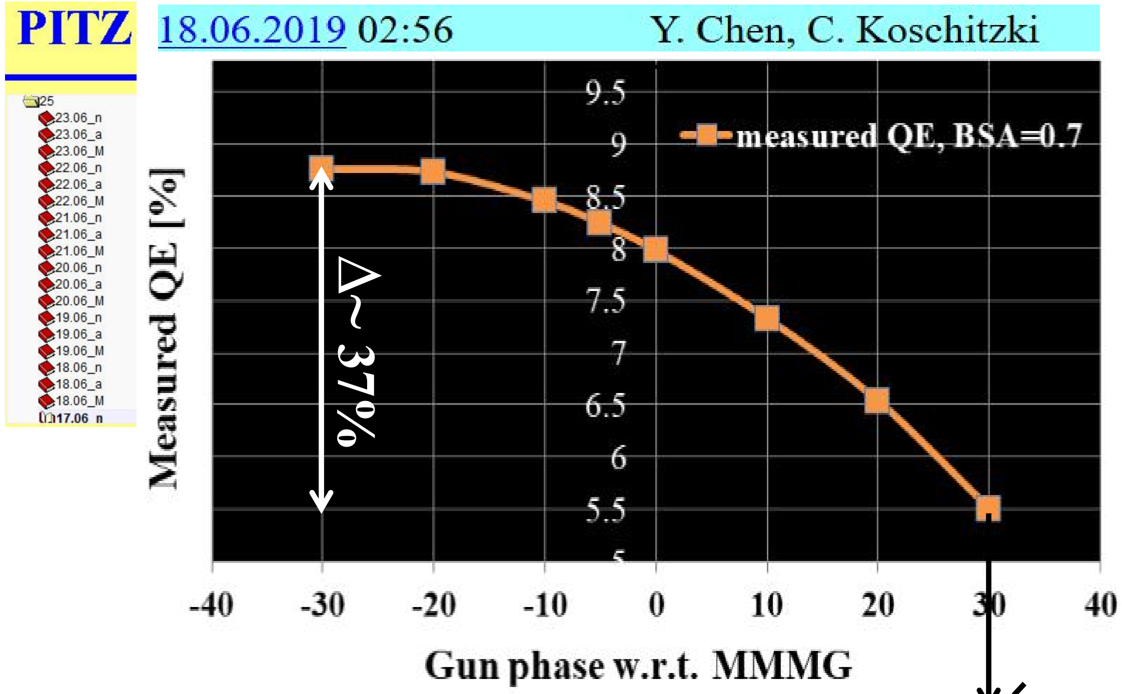
S. Schreiber, S. Lederer, FEL Seminar, 2016

- Laser wavelength 262 nm
- Charge is measured with the 3GUN toroid T1
- QE is defined as the slope of laser energy vs charge, obtained by a linear fit

QE = 5% →
Laser pulse energy = 0.1 µJ for 1 nC



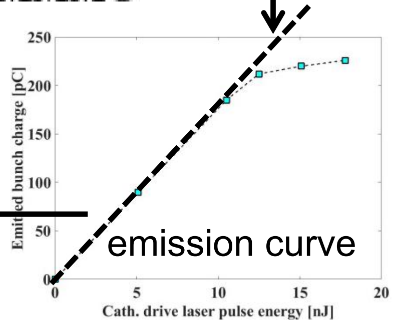
Example of measured QE vs. cathode fields in the PITZ gun by charge-phase scan



- Cs_2Te
- Gun phase **~ [-30 30] deg** (not full range scan)
- Cathode field **~ [5 38] MV/m** (relatively low fields)

  → **Measured QE enhanced as cathode fields increased,** (stronger) effect routinely observed

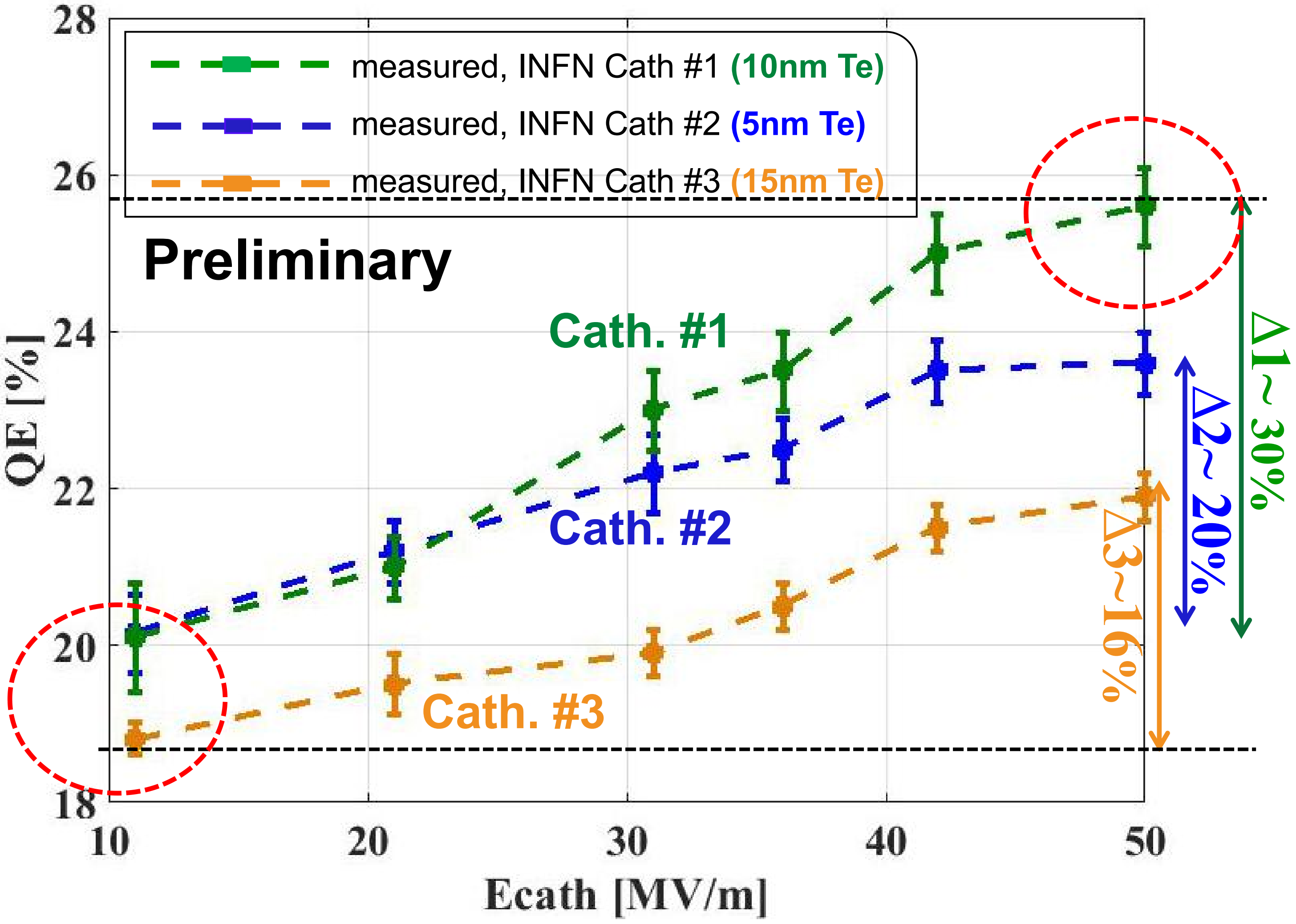
Each point corresponds to a cathode **QE measurement** in the **linear** regime at a fixed gun phase



Experimental results on QE vs. cathode fields for fresh Cs_2Te cathodes

[1]WEA04, FEL2019 [2]WEP062, FEL2019

Cathodes produced at INFN and recently tested at PITZ[1-2]



Measured QE change

Cath. #1: ~6%

Cath. #2: ~4% ***Cath. #3: ~3%***

→ **QE ≥ 19%, increased to 26% for Ecath up to 50 MV/m**

→ **Strong field-dependency trend of measured QE**

→ Stronger than Schottky-like effect

→ +Roughness induced field enhancement and local beam divergence change: seems still difficult well explaining both QE and thermal emittance by tests

→ **More detailed cathode-field-dependent photoemission model needed!!!**

Summary

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Observation of (strong) field dependencies of measured QE in the gun

- **Experiments show measured cathode QE strongly depends on surface fields**
- **Effect stronger than expected (modelled)**
- Improvements of emission models needed (e.g. effects of penetrating fields, detailed surface roughness modeling)

Thank you for your attention!