Beam dynamics with realistic bunches at the European XFEL

Ye Chen

BD Meeting, DESY Hamburg

14.04.2020

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

European XFEL

an online talk given in the COVID-19 period

Introduction / Motivation

- One of the follow-ups for the talk given by F. Brinker, BD meeting, Dec. 2019:

  "Beam dynamics at the XFEL injector: Collection of ***observations*** *and questions"*

- This work deals with "realistic" bunches used for **improving beam dynamics** simulations
  - ***What*** *observed?*
  - ***Why*** *important?*
  - ***How*** *to improve?*
  - ***Some results****?*

- Another recent work on **statistical simulations of photocathode** for the XFEL

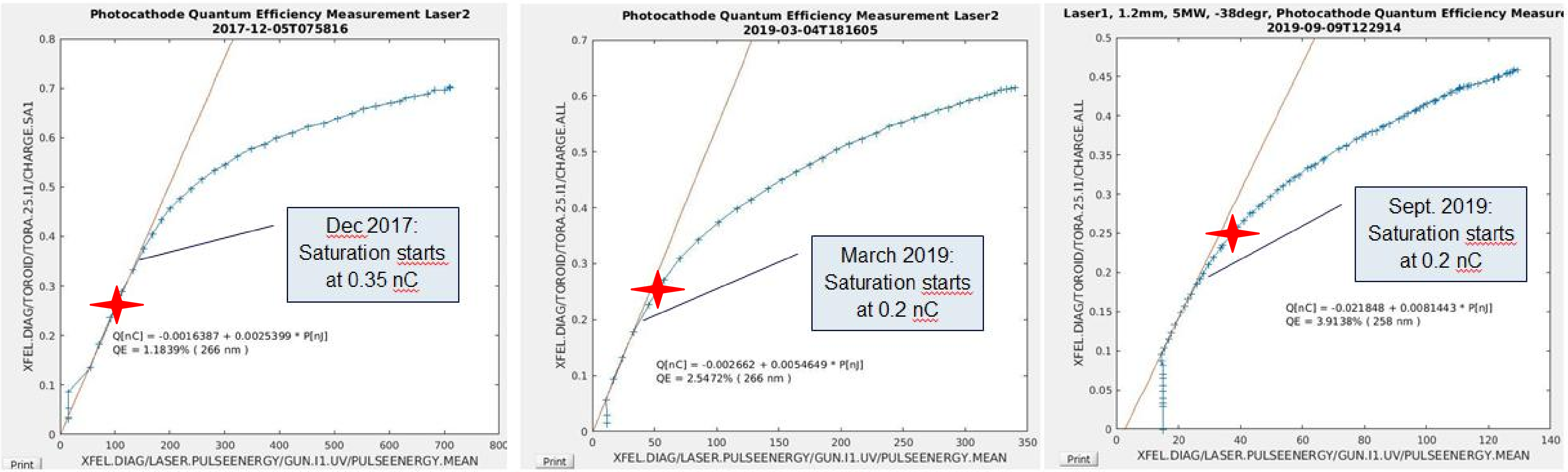
OBSERVATIONS

Experimental observation of emission curve (charge vs. UV energy)

Dec. 2017→ Sept. 2019

→ working point shifting to stronger space-charge affected regime

✦ **XFEL working point, 250 pC**   Credits: F. Brinker



➢ Remeasure in January

→ directly injecting 250 pC for simulation may not be sufficient to represent beam dynamics correctly

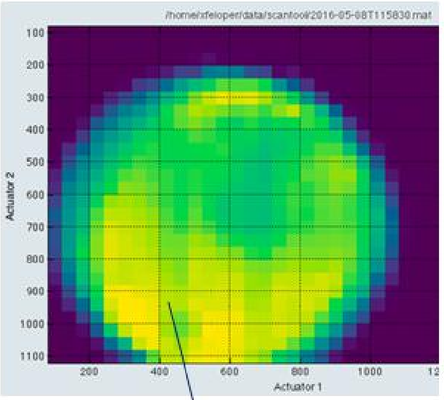
- **→ due to different space-charge densities near cathode**
- **→ dynamics described by the emission curve → reproducing measured curves is the basis for BD simulations**

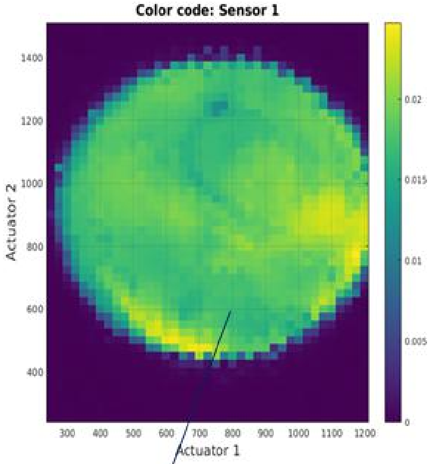
Experimental observation of QE map

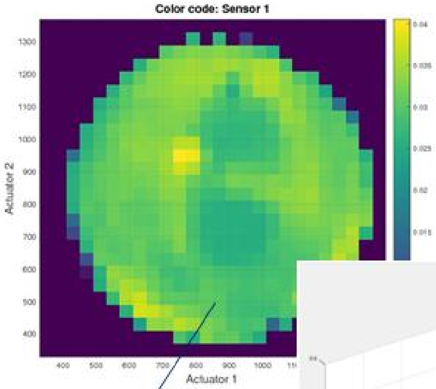
May 2016 → Nov. 2019

→Homogeneity of cathode QE map seems degraded

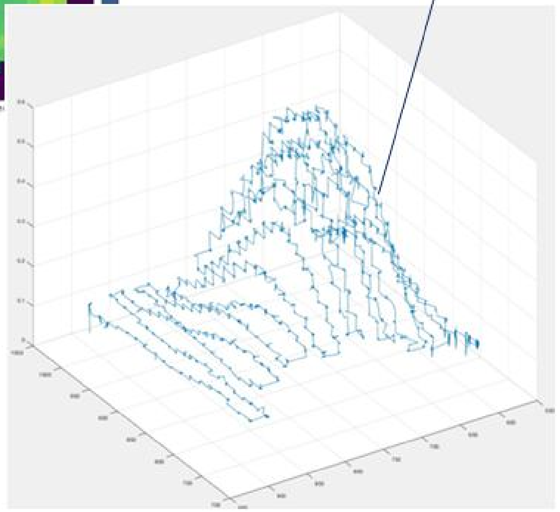
→ effective spot size on cathode reduced (!?)







Nov. 2019:
Factor 7 intensity variation
~750 um FWHM
-> Might be caused by layer on laser window



May 2016

Dec. 2016

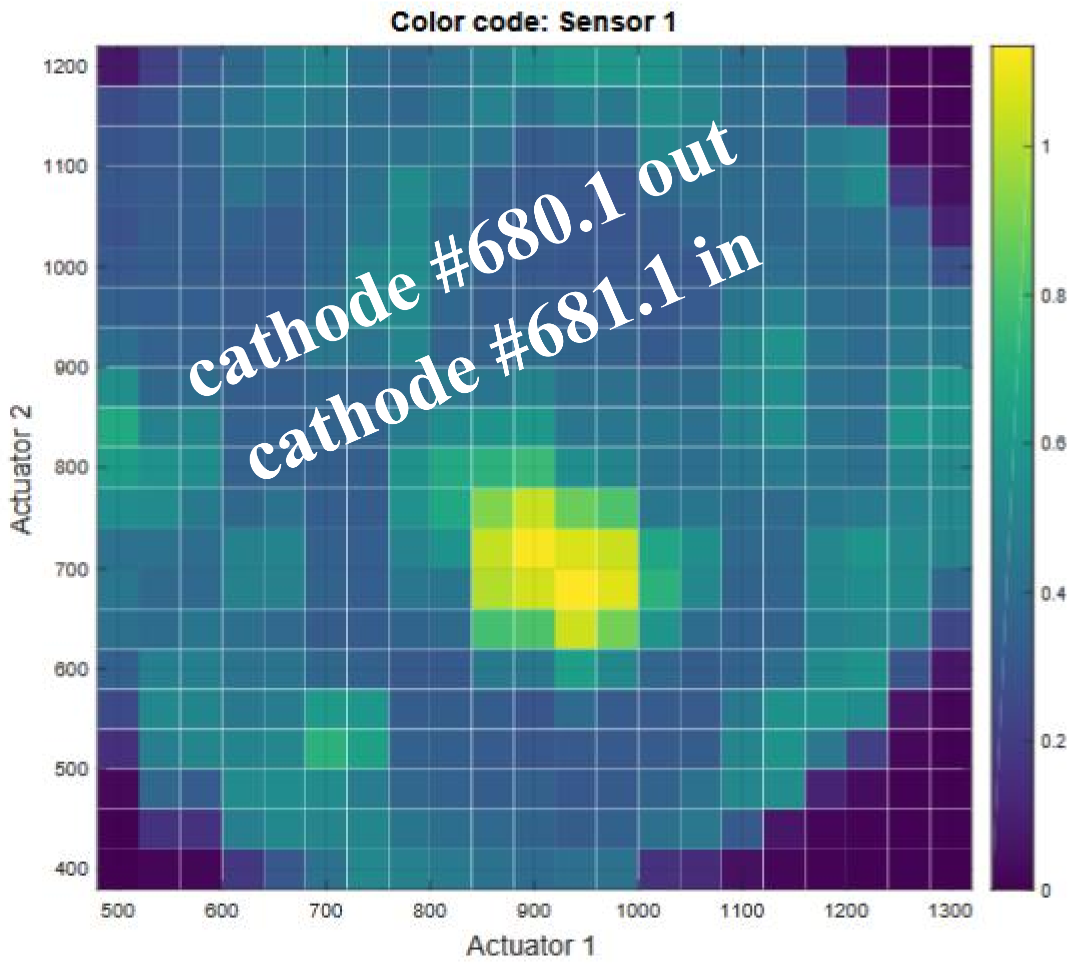
July 2018

- Remeasure full QE Map in January
  - Clean window
  - 2nd camera replaced
  - Working laser pos. feedback

→ Recheck in 01.2020

Re-measured QE map in 01.2020 for the same cathode

→ decision made for cathode exchange on 14th Jan. 2020



10.01.2020 10:55 brinker QE Map, BSA 0.2mm, 30 bunches

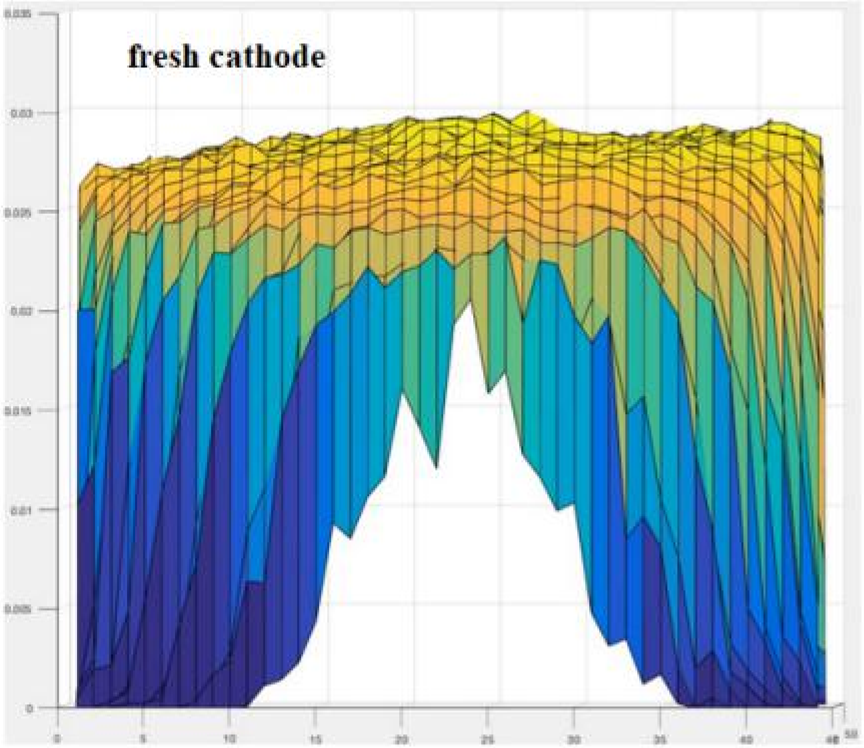
The property XFEL.DIAG/CHARGE.ML/TORA.25.I1/CHARGE.TRAIN delivers the sum over the train.
So for the peak value of 1.1 nC we have 36 pC bunch charge

This elogbook entry was sent to following experts:
Lederer Decking Noelle

- → the worn Cs_2Te cathode has been in operation for **5+ years**
- → **natural degradation** shows up causing observable effects
- → its **performance** was already very **impressive**

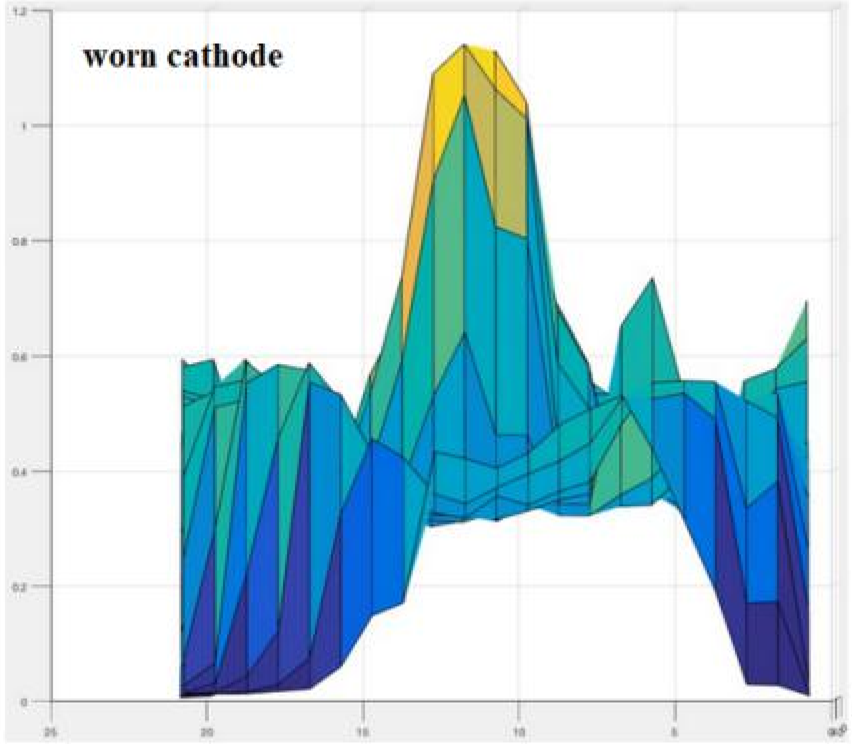
Homogenetiy of measured QE maps (projections) before & after the exchange

16.01.2020 13:10 **not set** Brinker, Chen Cathode QE map from last night (after cathode exchange)



cathode #681.1 (in)

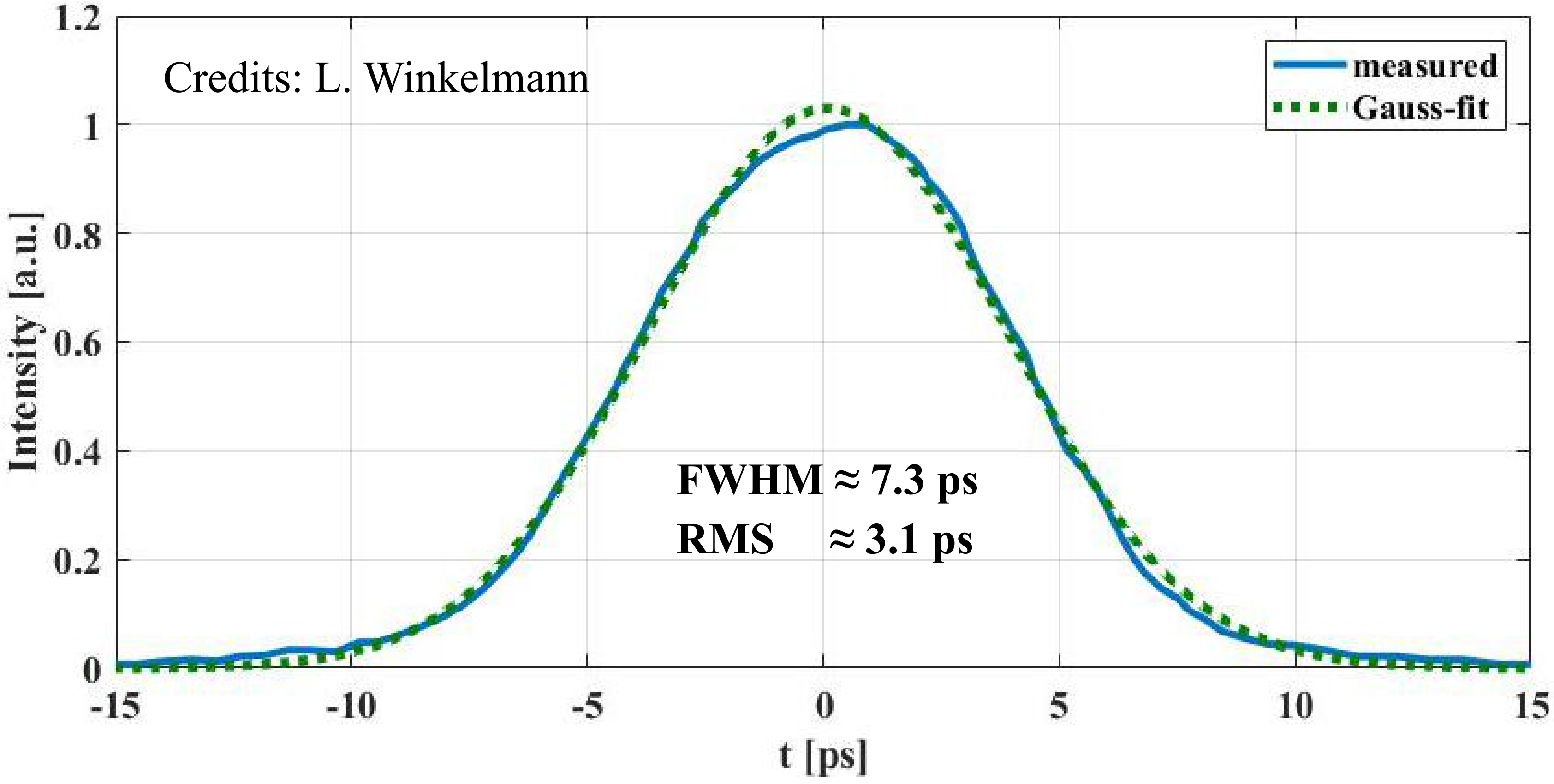
16.01.2020 13:10 **not set** Brinker, Chen Cathode QE map before the cathode exchange



cathode #680.1 (already out)

Measurements of temporal cathode UV laser profile

→ measured / cross-checked with streak camera & autocorrelation



Summary

What observed?

→ QE & QE map homogeneity degreation

Why important?

→ affecting e-bunch production via photoemission (convolution of QE map & laser intensity distribution)

→ affecting emission dynamics (accelerator working point shifted to stronger space-charge regime)

NB: not only the QE map, but also the degradation of laser intensity map, temporal profile, cathode surface conditions could result in similar effects.

How to improve?

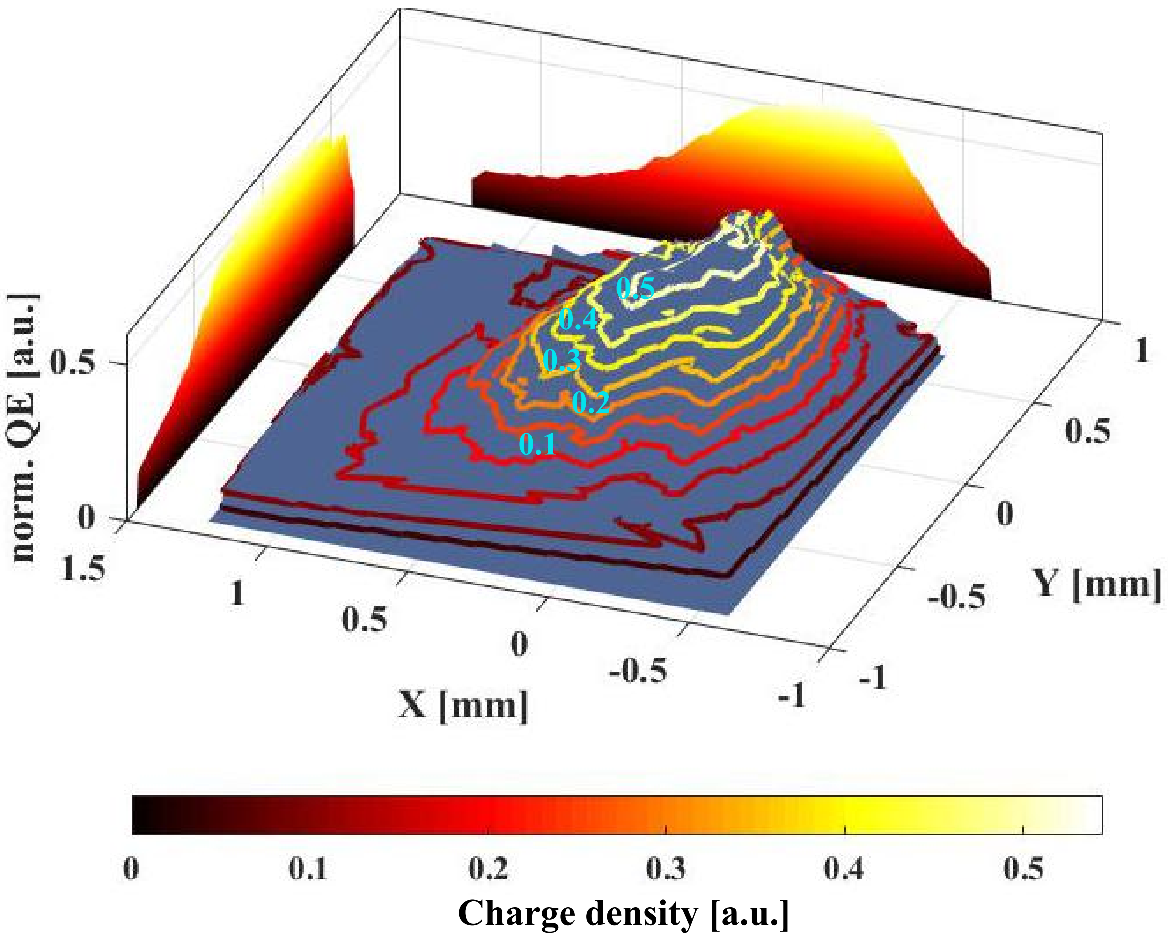
→ model produced e-bunch based on routinely updated measurements

→ consider it for beam dynamics with a proper numerical tool (presumably in 3D)

MODELING OF 3D E-BUNCH VIA PHOTOEMISSION

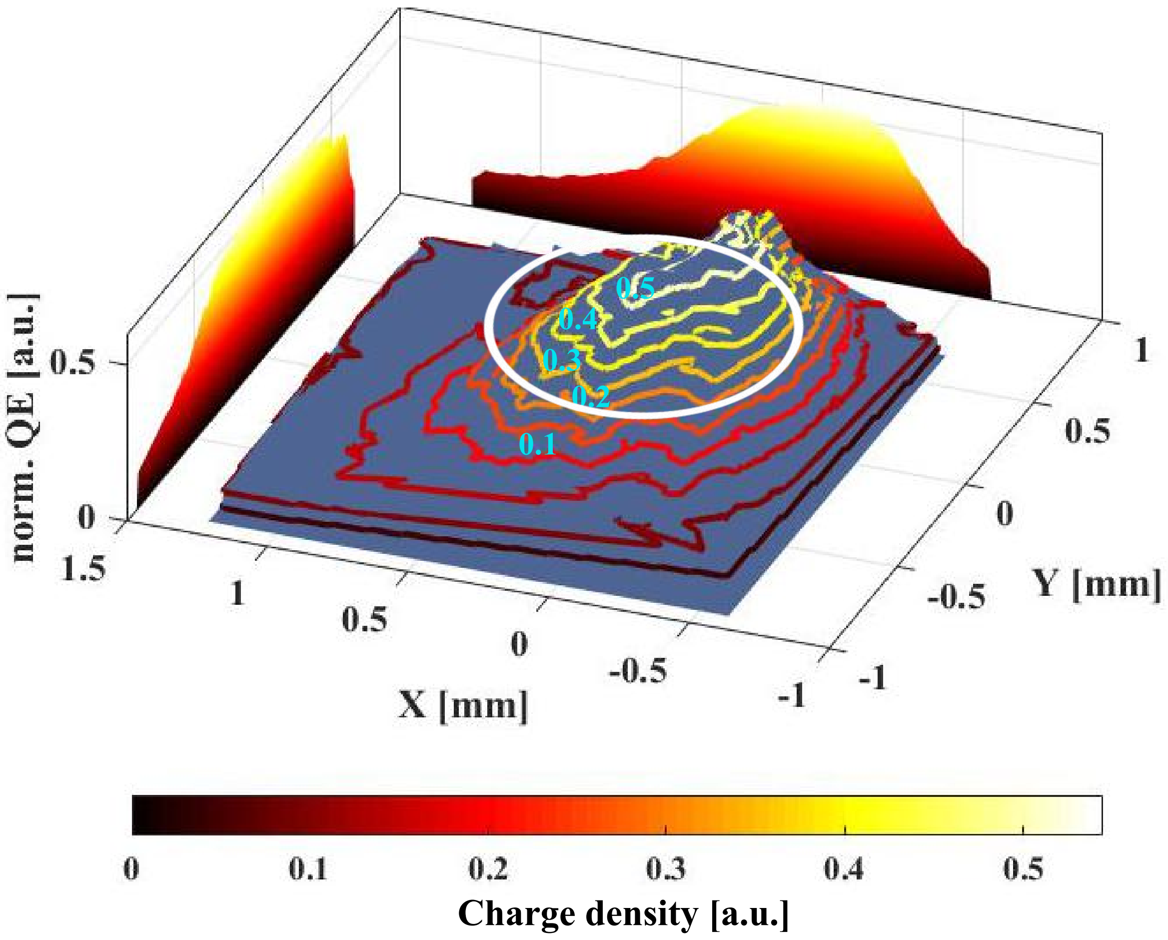
Quantum efficiency map (measured) of Cs_2Te thin film

→ an extensively used photocathode (after 5+ years operation at XFEL)



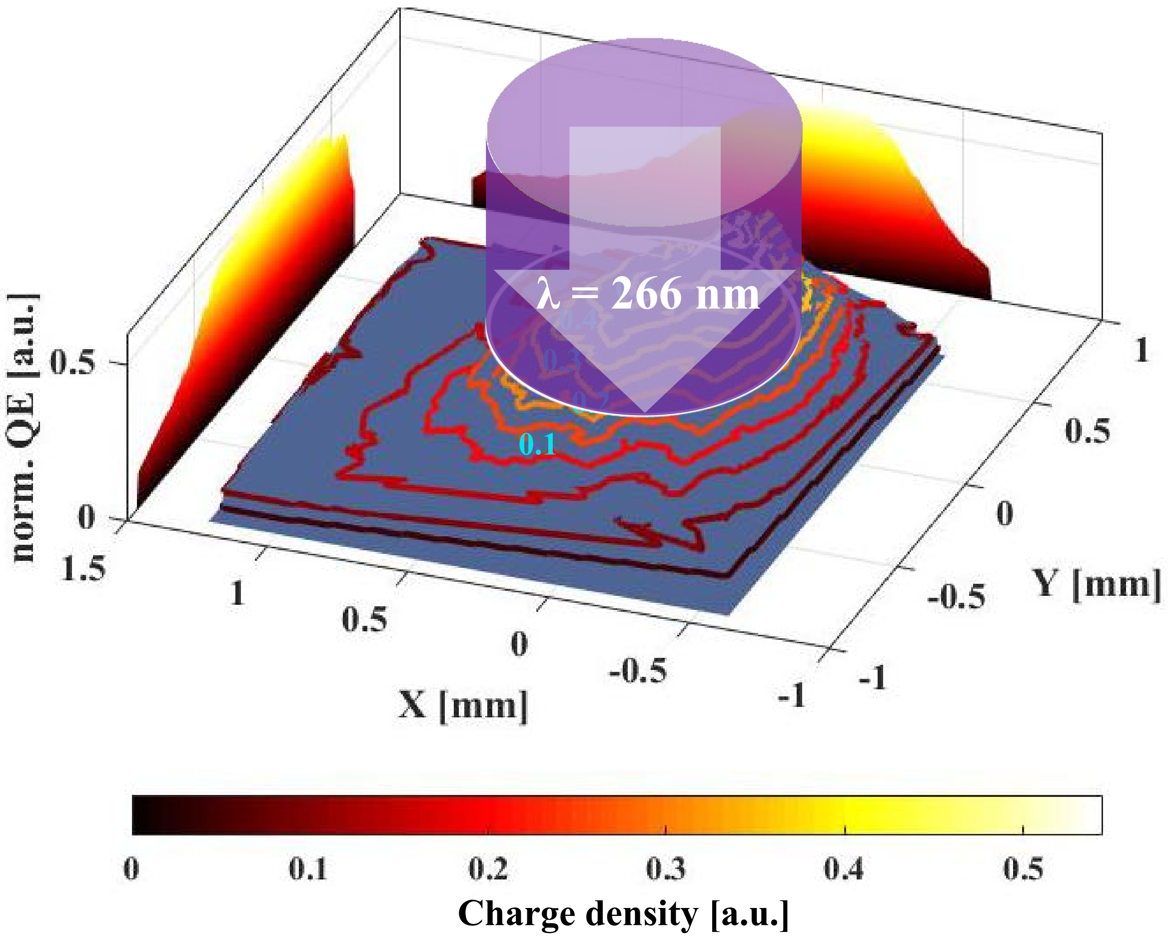
Quantum efficiency map (measured) of Cs_2Te thin film

→ an extensively used photocathode (after 5+ years operation at XFEL)



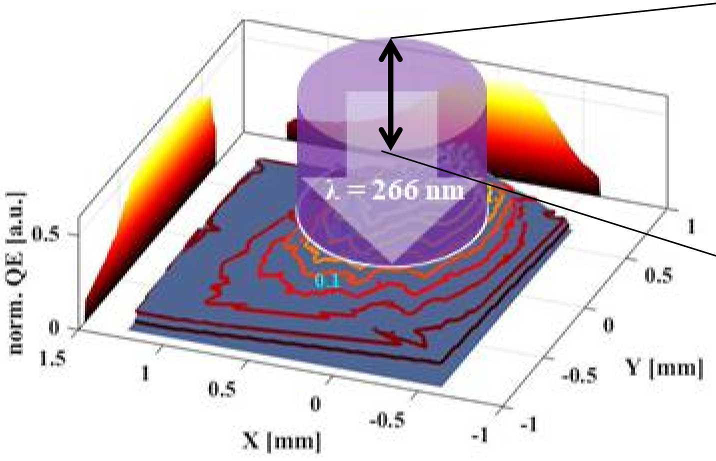
Quantum efficiency map (measured) of Cs_2Te thin film

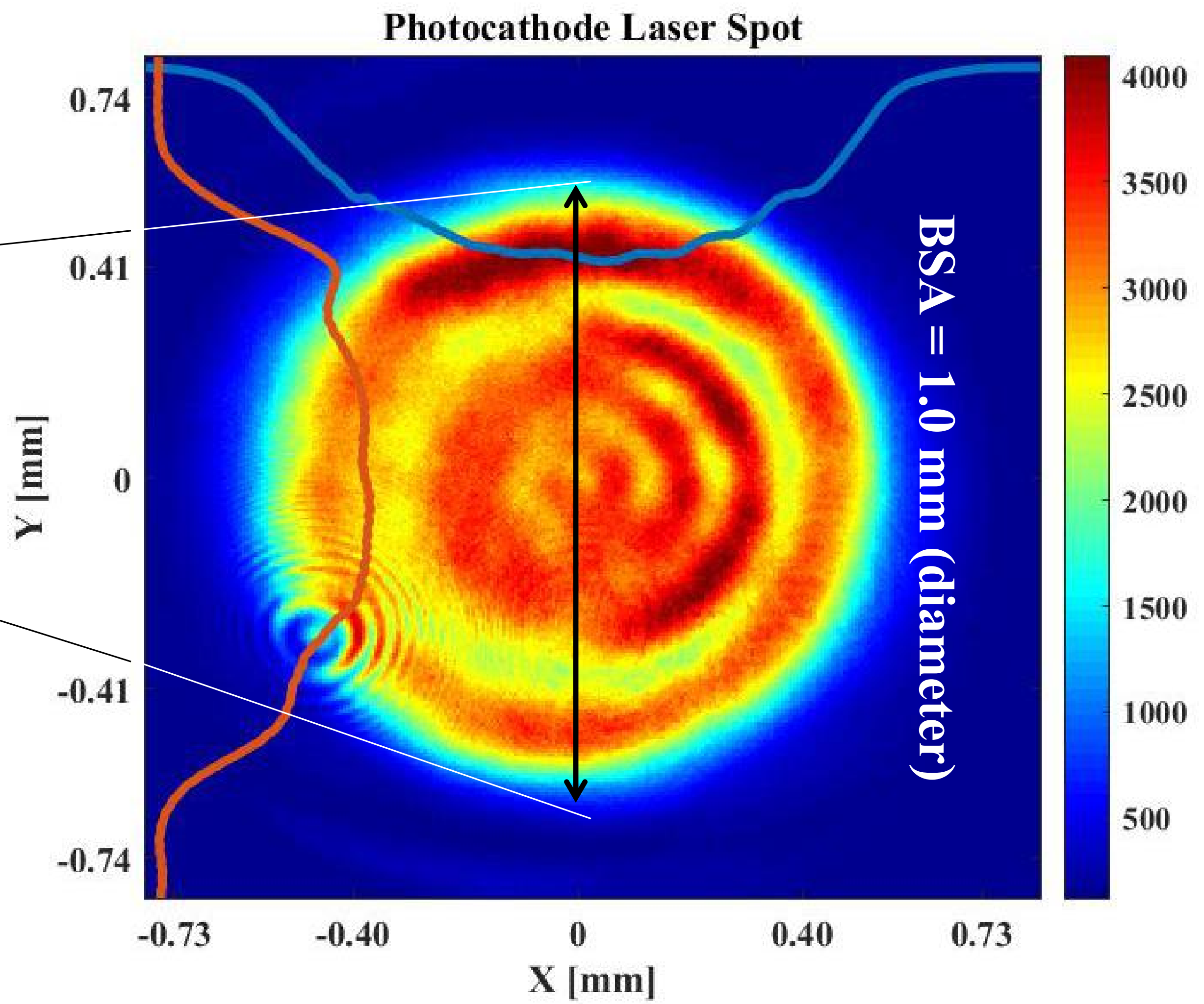
→ an extensively used photocathode (after 5+ years operation at XFEL)



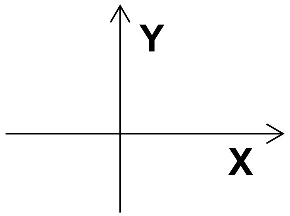
Photocathode drive laser spot (measured)

→ shaped trans. distro. with beam shaping aperture (BSA)

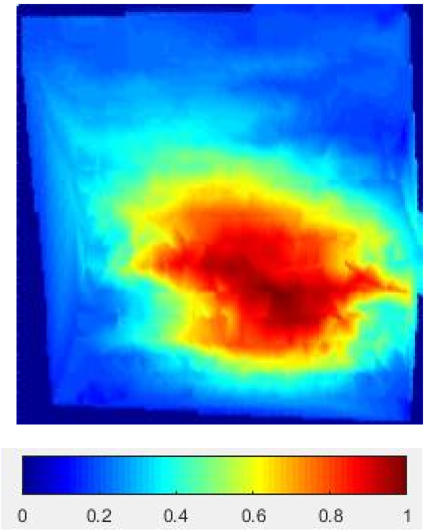




Measurement-based 3D e-bunch generation at photocathode (transverse)

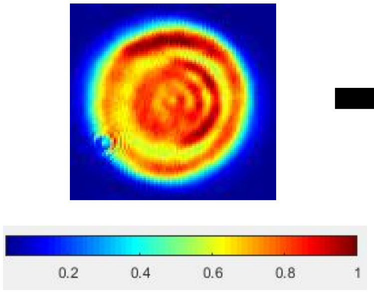


Measured QE map

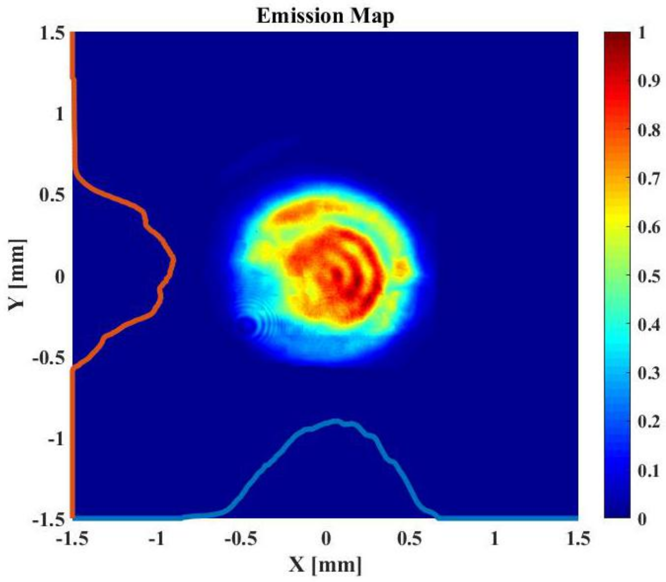


*

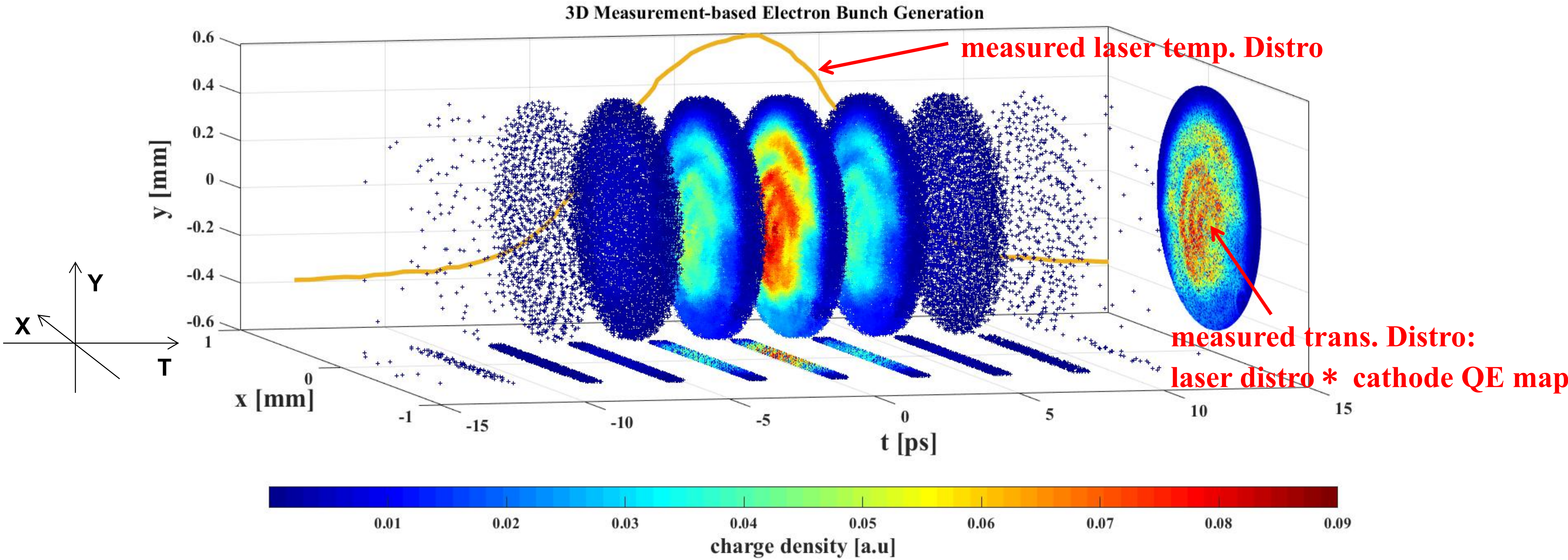
Measured laser intensity map



"Emission map"



Measurement-based 3D e-bunch generation at photocathode (transverse & temporal)



- Laser spot size ≠ e-bunch size on cathode
- Laser spot distribution ≠ e-bunch distribution
- For the old cathode, transverse e-bunch size reduced by ~17% w.r.t. laser spot size
- Re-locating laser spot on the emissive area could not solve the issue due to large QE map inhomogeneties

USING REALISTIC E-BUNCHES FOR BEAM DYNAMICS

Simulation tools

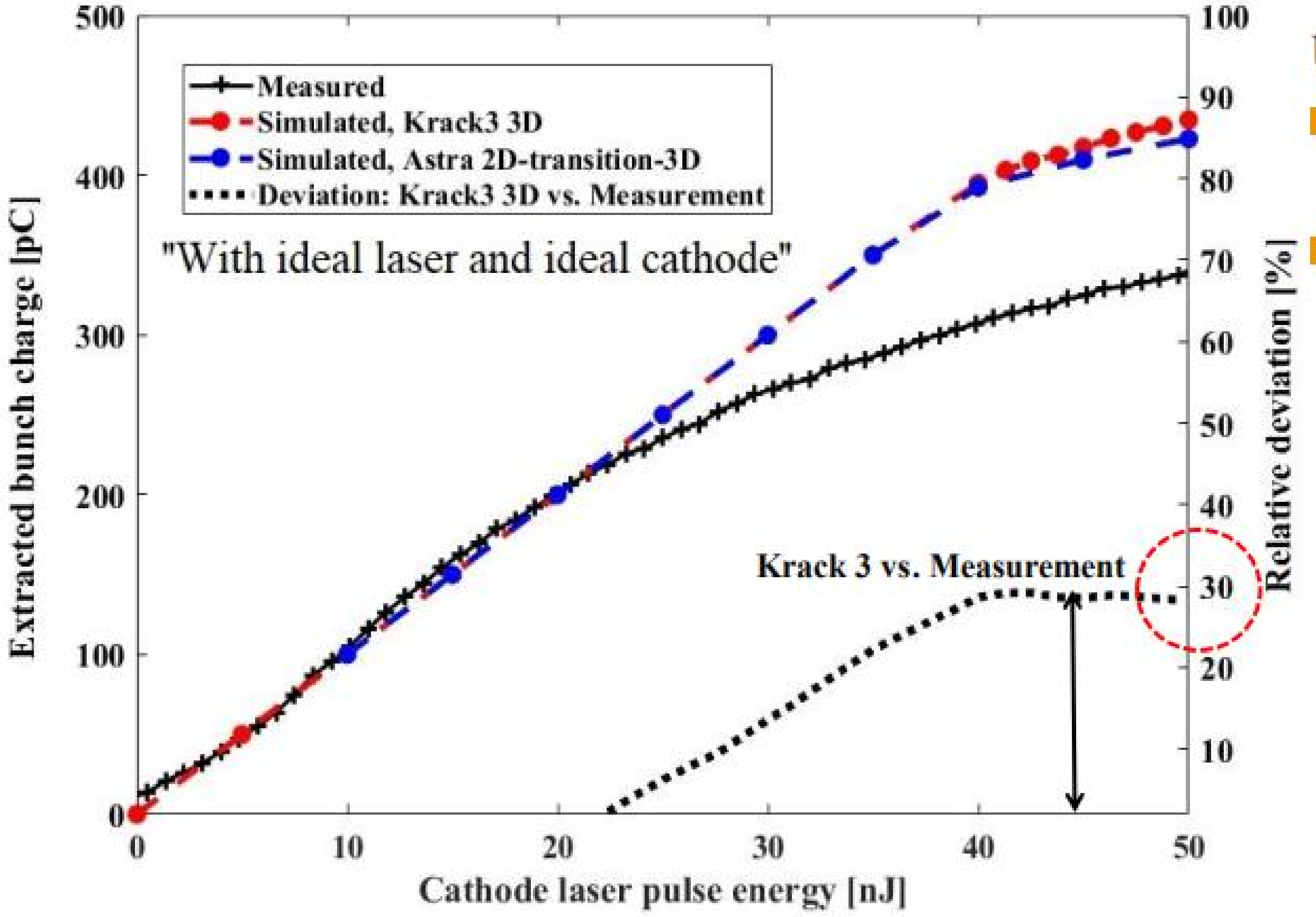
- **KRACK3 (3D)**, Martin Dohlus, gun / injector simulations

  3D space-charge (SP-CH) solver from cathode

  Introduction: http://www.desy.de/fel-beam/data/talks/files/2017.00.31_11_26_26_53_1_NonUnifCathode.pdf

- **ASTRA (2D/3D)**, Klaus Floettmann, gun / injector simulations
- **OCELOT**, Sergey Tomin, particle tracking with collective effects, gun → undulators
- **Naming convention in this talk**
  - **Krack3 3D:** 3D SP-CH solver from cathode (start-to-end)
  - **Astra 2D-transition-3D:**
    - ► Transition from cylindrical symmetric SP-CH algorithm to 3D SP-CH algorithm at e.g. z=10 cm where image-charge no longer plays

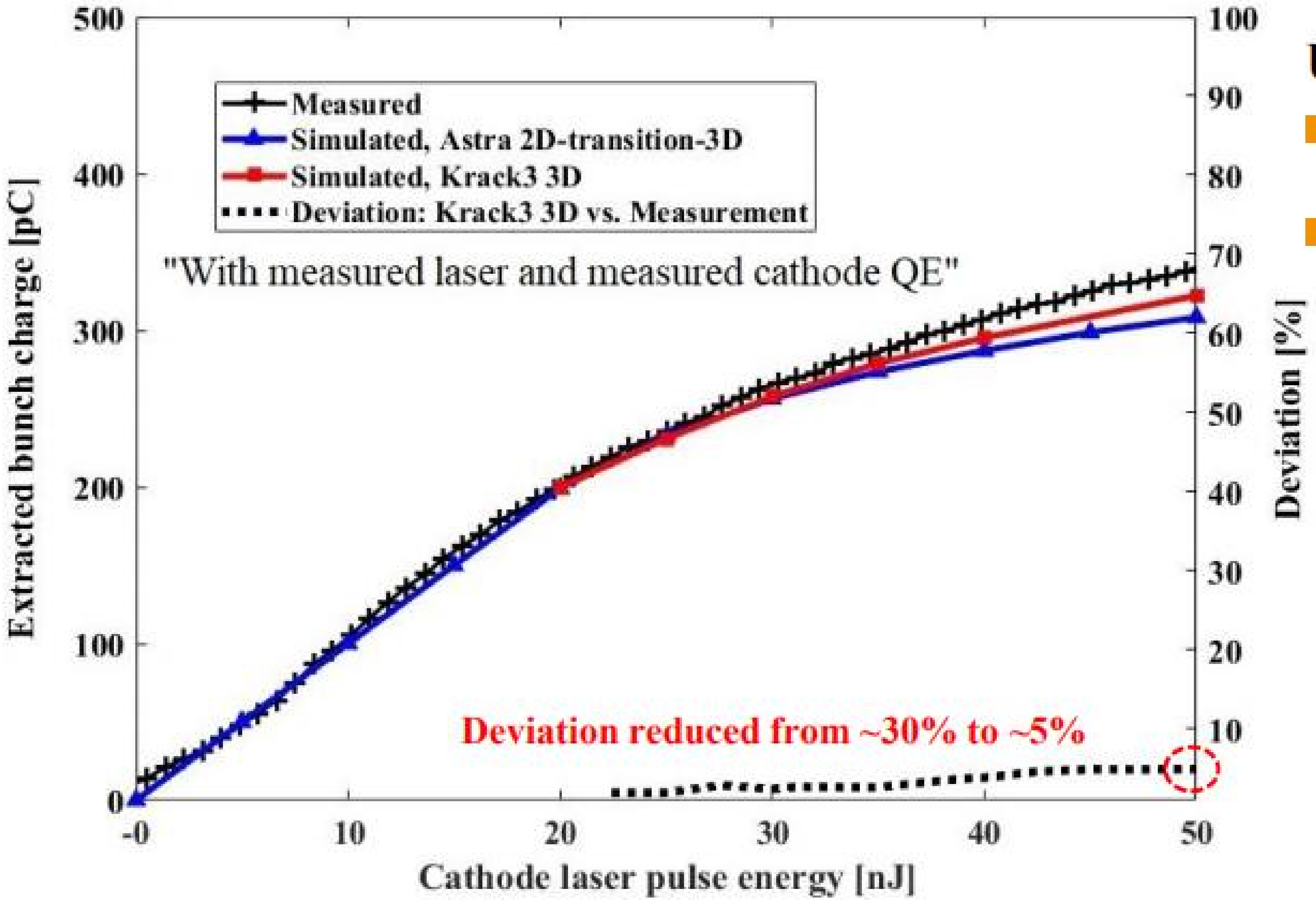
Improving beam (emission) dynamics (1)



Using ideal e-bunches

- Krack 3 vs. Measurement
  - → large deviations up to 30%
- Astra 2D-transition-3D vs. Krack 3
  - → tiny numerical difference

Improving beam (emission) dynamics (2)



Using asymmetric e-bunches

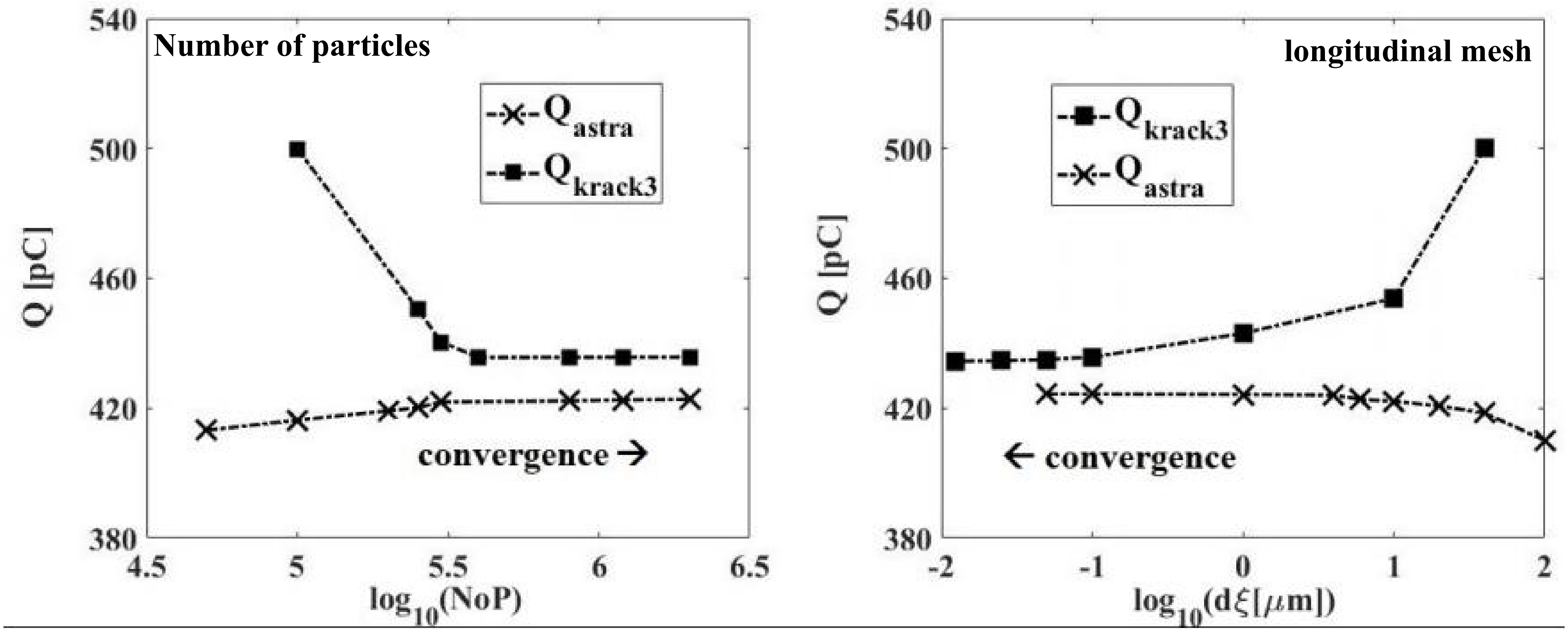
- Krack 3 vs. Measurement
  - → significant improvements
- Astra vs. Krack 3
  - → Astra can still provide a good approximation for the case with asymmetric bunches

(depends on where the working point settles along the emission curve)

Extensive convergence studies performed in Krack 3 & Astra

- First done by Martin, then rechecked by Ye and Igor
- **Numerical convergence rechecked in terms of / combinations of**
  - Number of simulation particles (up to 2M) → **sensitive**
  - Longitudinal mesh dz (down to ~10nm) → **sensitive**
  - Simulation time step (down to ~25fs)
  - Transverse mesh steps (≥50 steps per sigma)

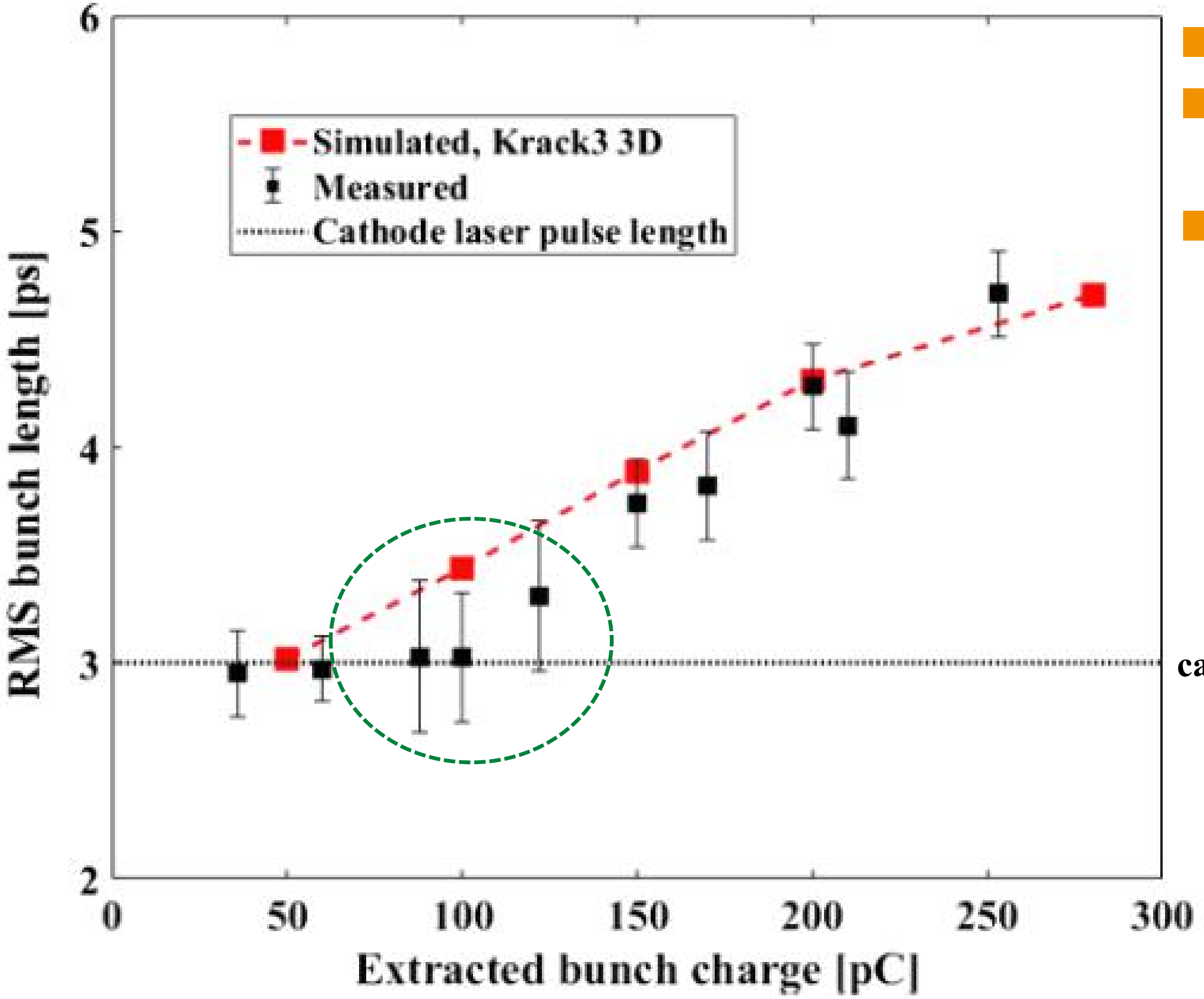
An example



Both codes converging, however, to slightly different bunch charges

BUNCH LENGTH & SHAPE AT INJECTOR EXIT

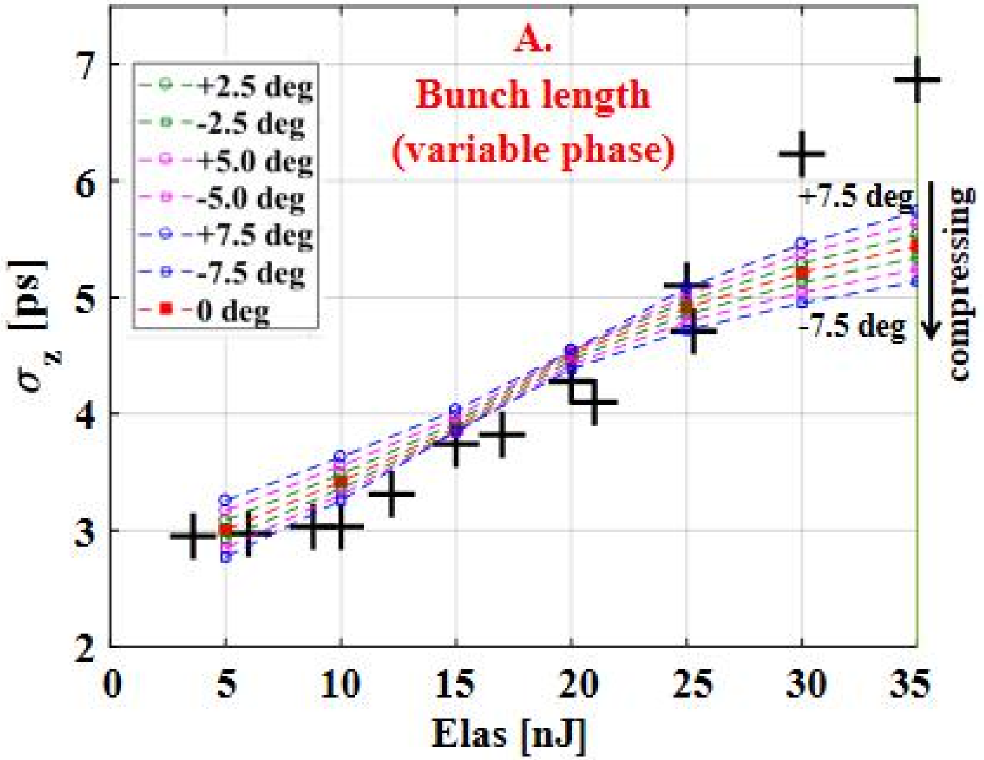
Bunch length vs. bunch charge (130 MeV at injector exit)

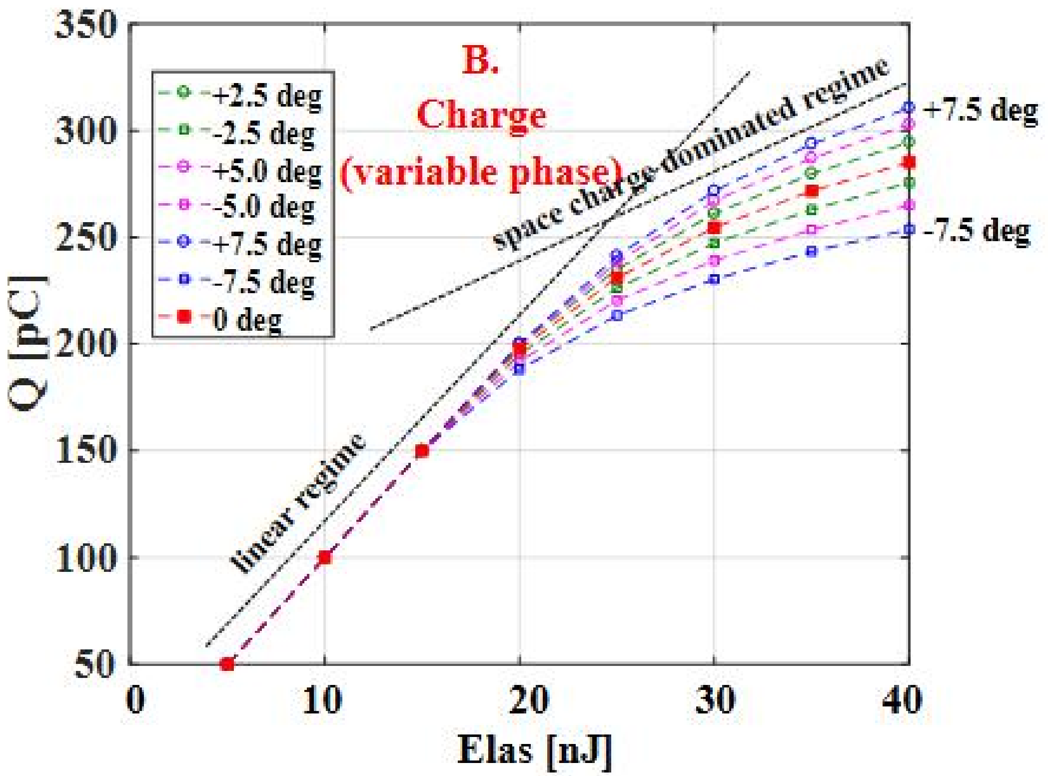


- Bunch lengthening due to space-charge
- Simulated buch length starts to grow (w.r.t.laser) faster than in the experiments
- Gun & A1 both on-crest

cathode laser pulse length

Behavior of bunch lengthening w.r.t. gun phasing (in astra)

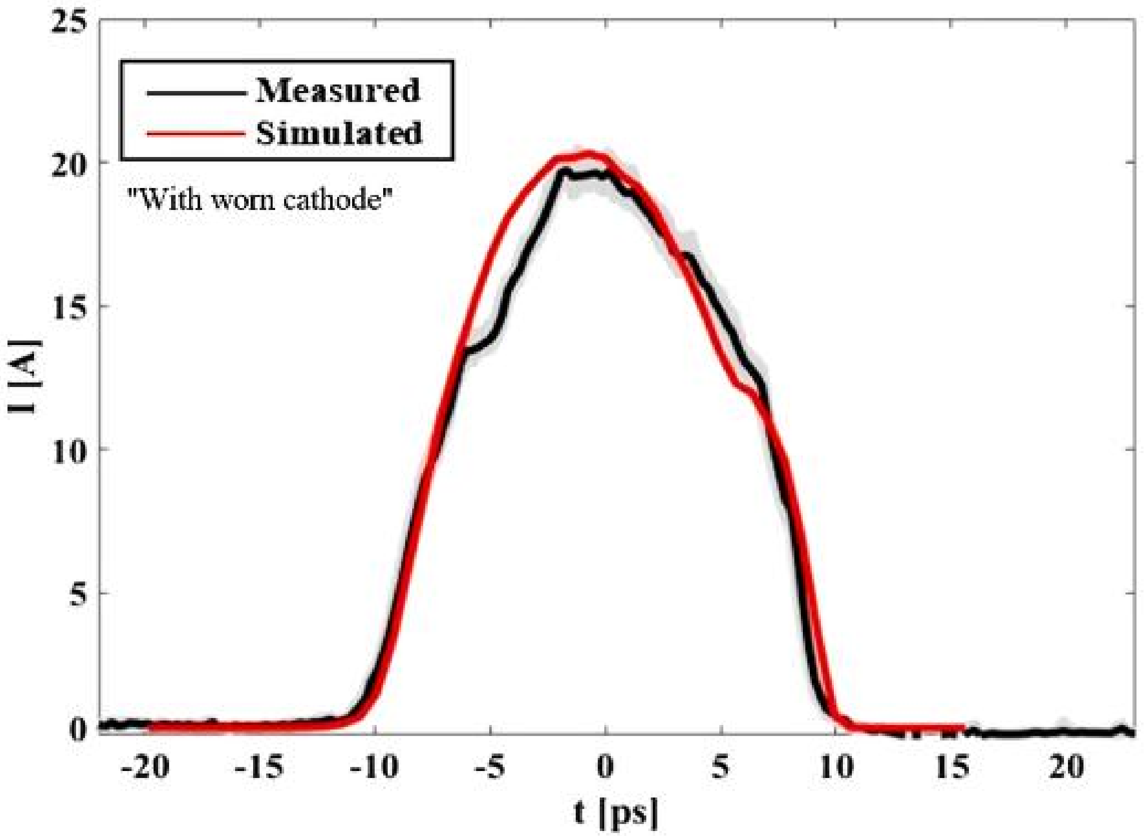




- Linear regime in B: bunch length in A is phase dependent
- Space charge dominated regime in B: compression leads to stronger charge loss, even shorter bunch length in A
- **Phase variation seems not reproducing the behaviors observed in the measurements**

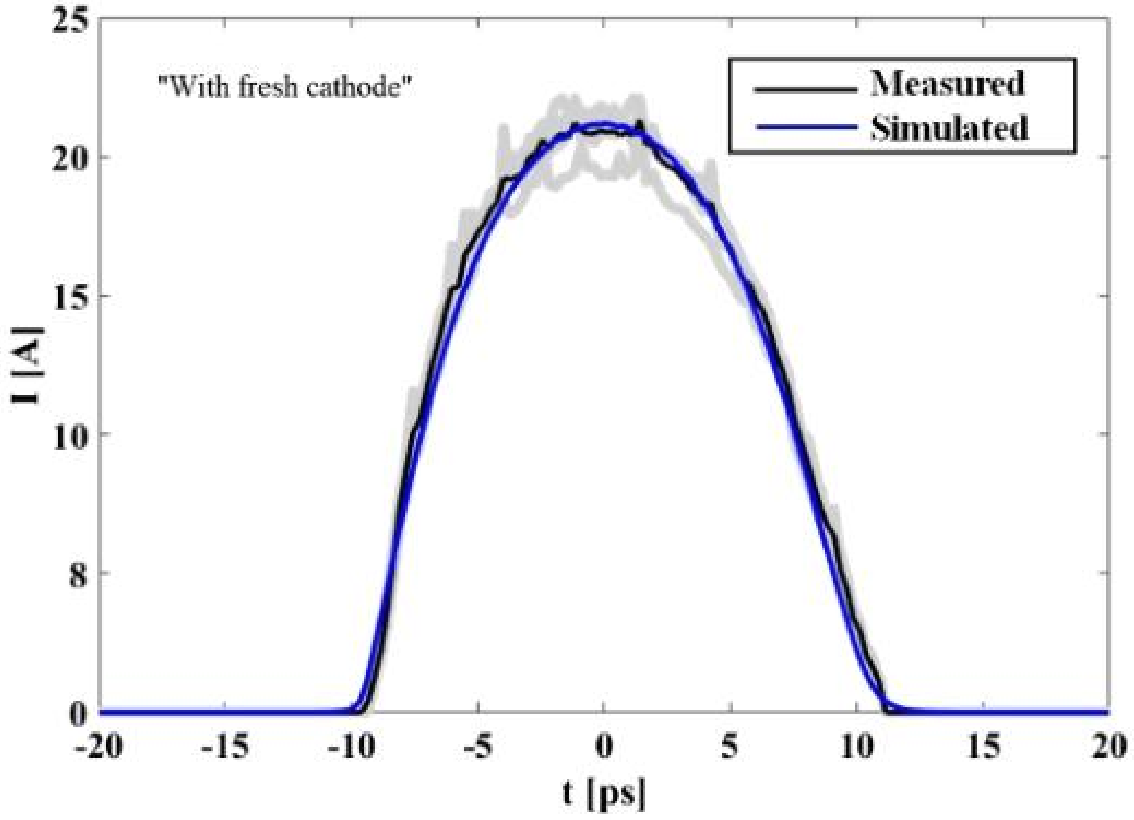
Bunch shape: with worn cathode, 130 MeV, 250 pC, injector exit

close bunch length but no agreement on the bunch shape



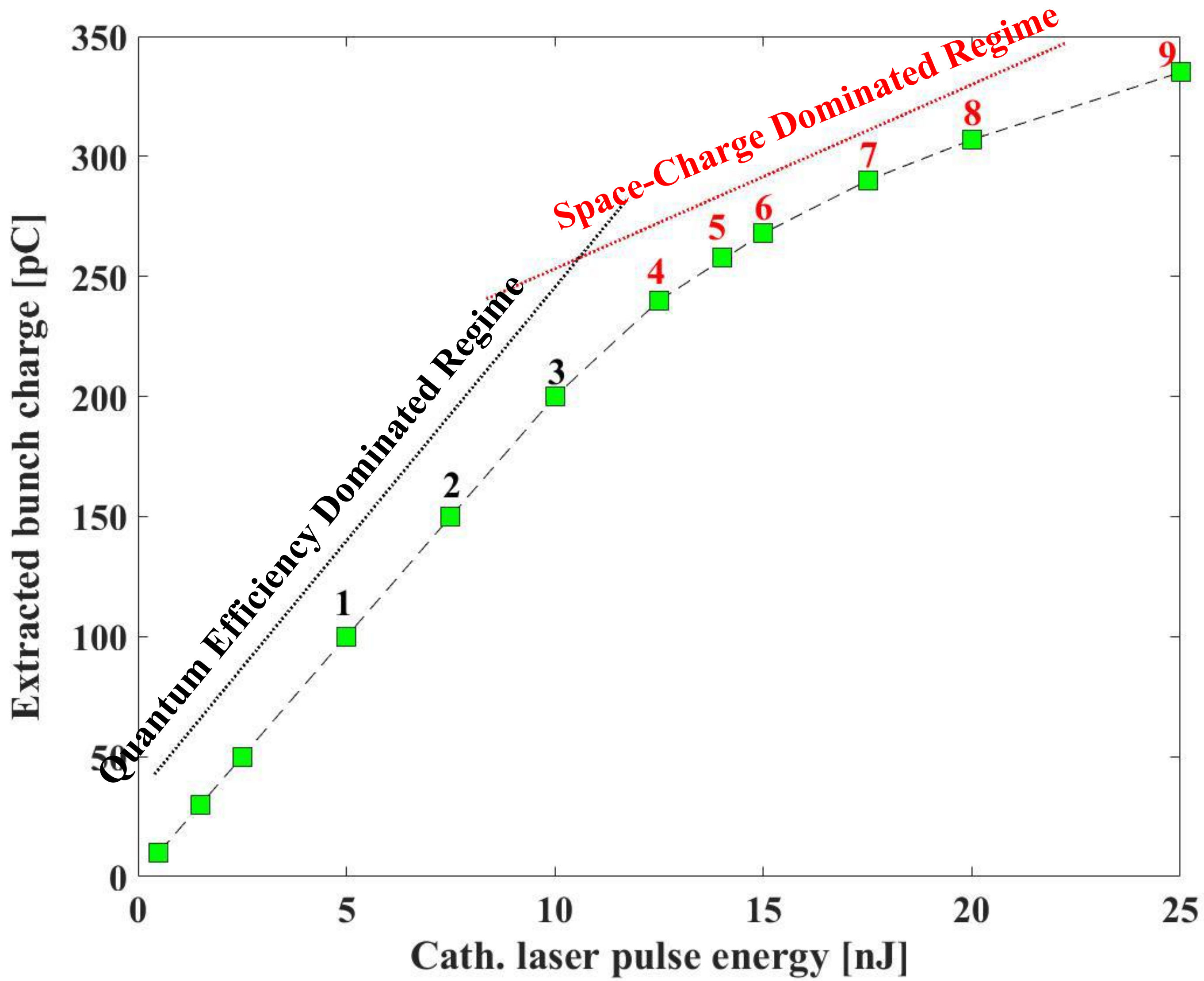
Bunch shape: with fresh cathode, 130 MeV, 250 pC, injector exit

close bunch length and similar bunch shape

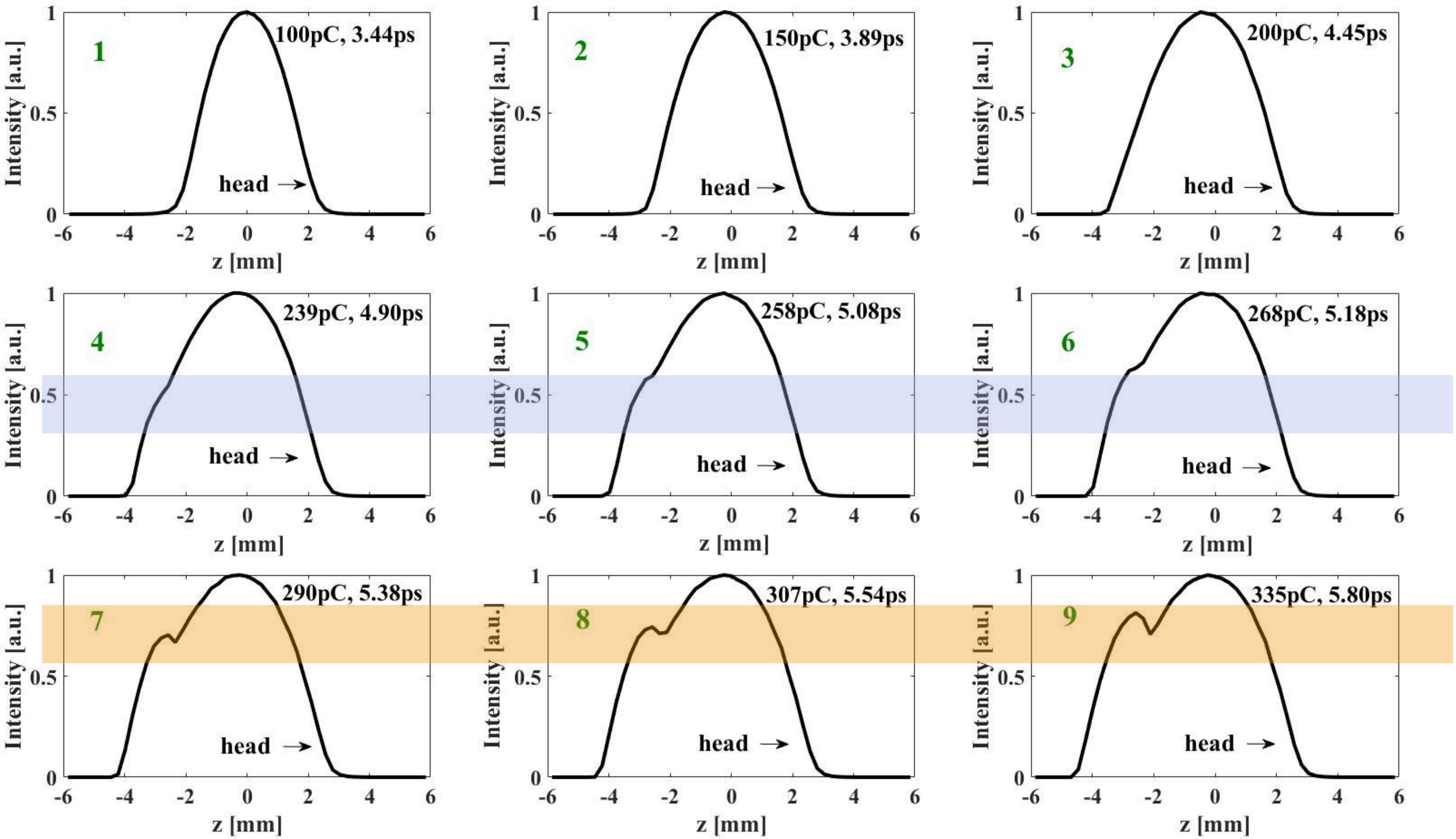


Simulation studies on bunch shapes due to space-charge

→ defining several cases (working conditions) for simulations

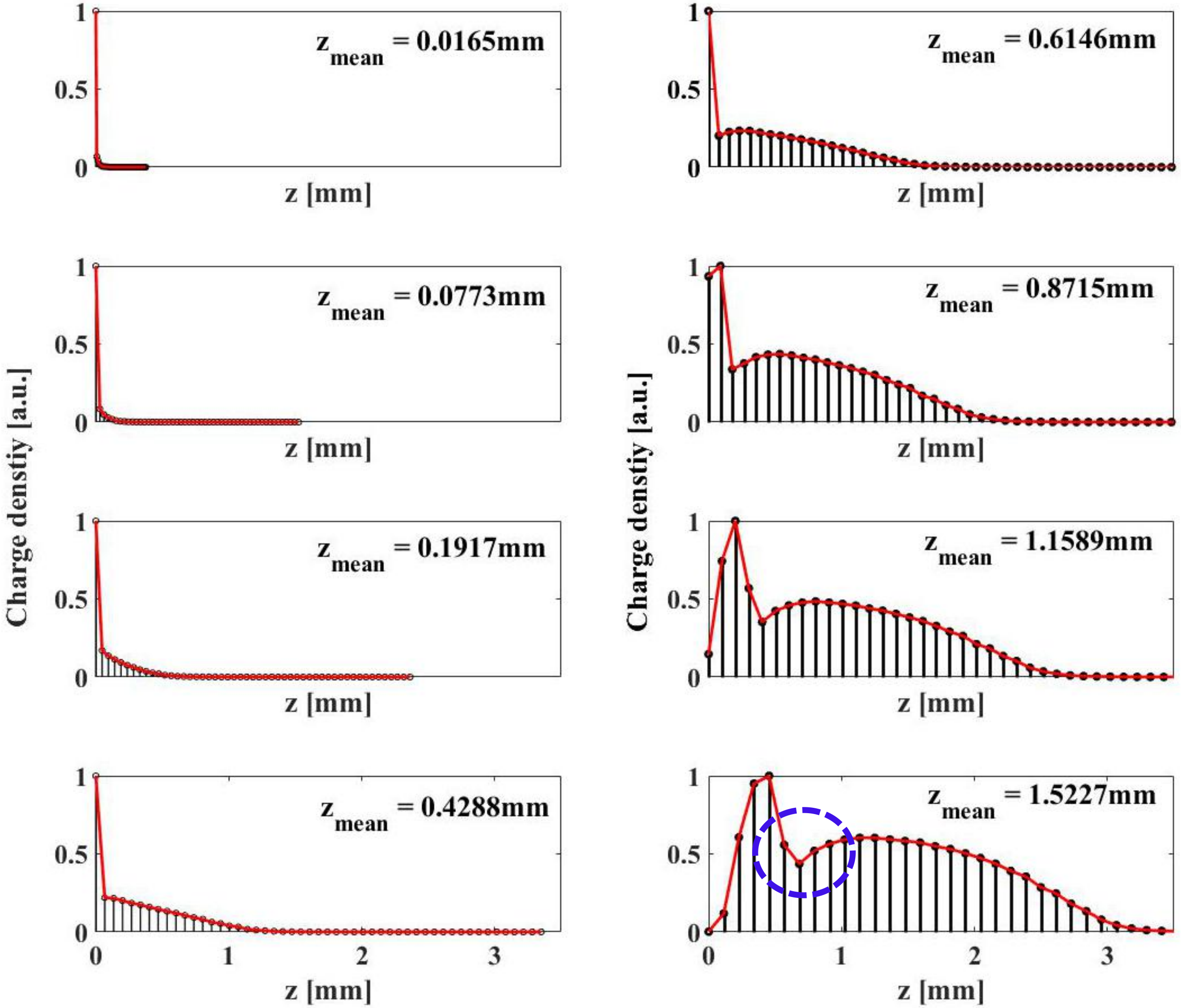


Simulated bunch shapes vs. space-charge (worn cathode case)



An example: curvature formation in bunch profile

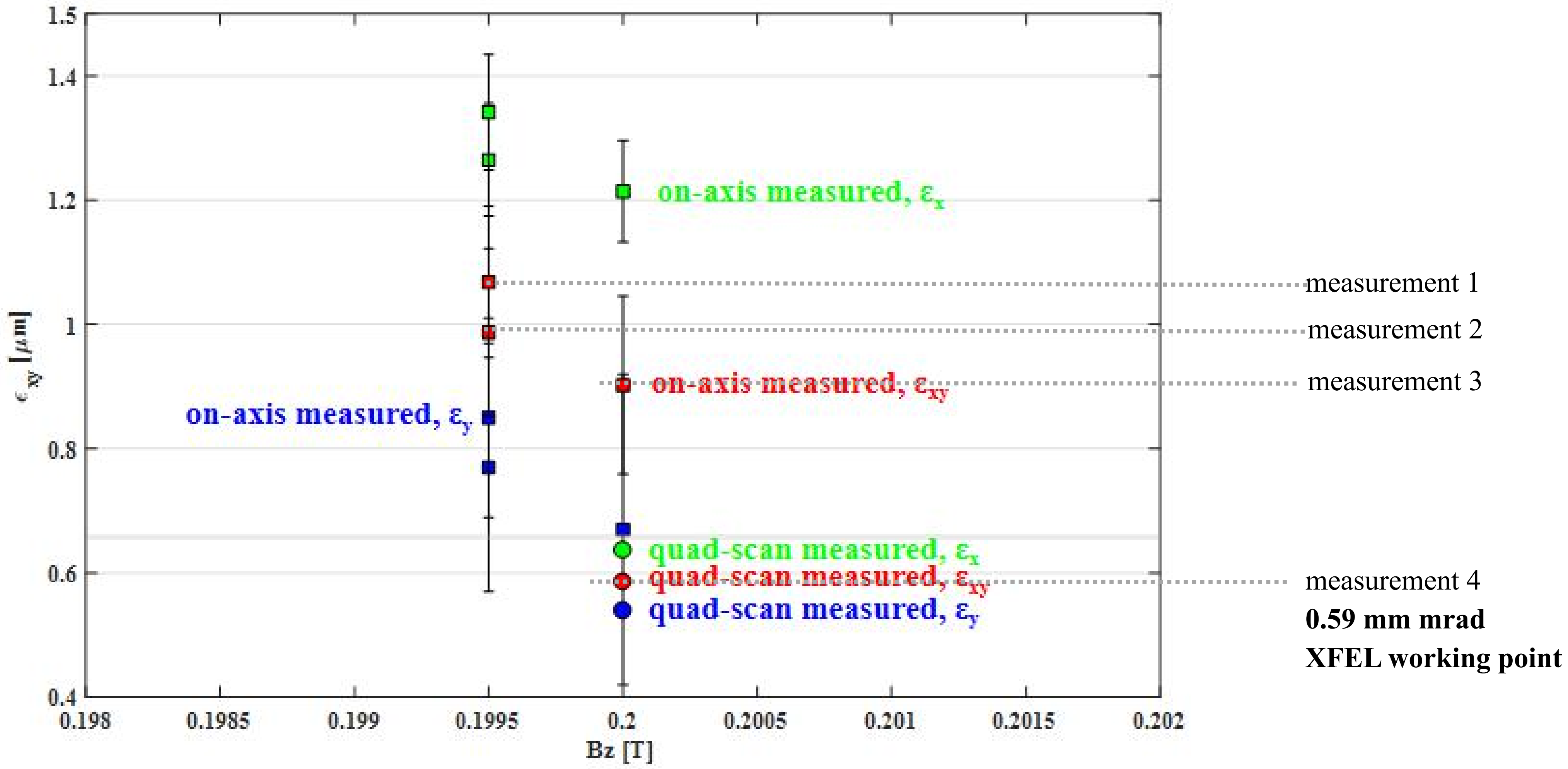
→ strongly space-charge affected case



ON EMITTANCE (ONLY OLD DATA)

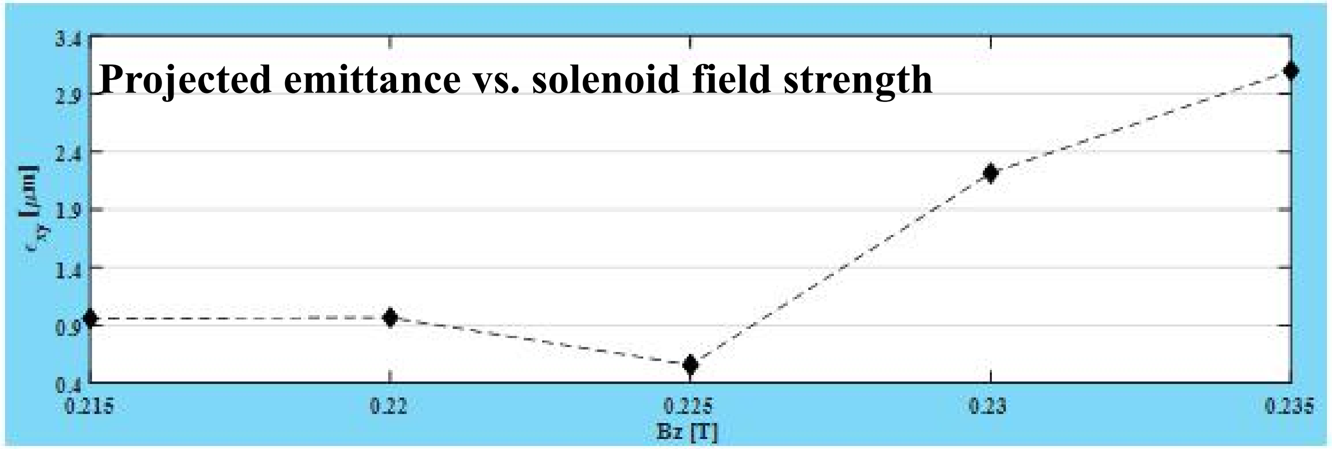
→ new systematical studies by Yauhen in a later talk

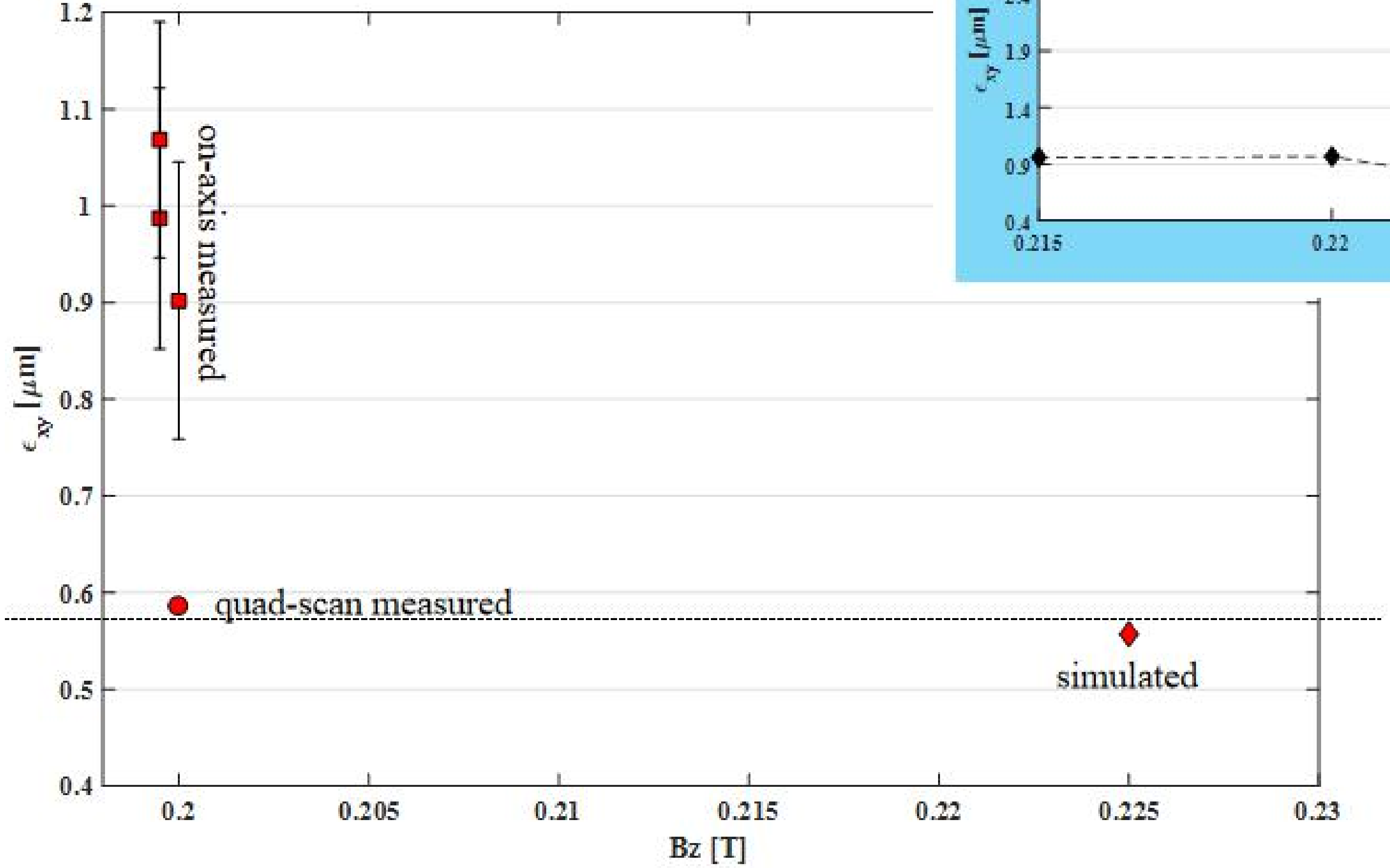
Measured projected emittance (old data, worn cathode)



→ on-axis measured emittance higher than quad-scan (could be by chance)

Simulations for the old data





- Quad scan vs. simulation → **close**
- Discrepancy in simulated solenoid strength for opt. emittance → **within 10%**
- Central slice emittance **0.46 µm**

CODE DEVELOPMENT: STATISTICAL PHOTOCATHODE SIMULATION AT XFEL

A Monte-Carlo approach developed for cathode simulations at XFEL

Goal (cathode performance evaluation) & Status (coding finished)

Features

- Density of States based
- MC modeling of scattering effects (electron-electron, electron-hole, electron-phonon)
- implemented in Matlab, flexibilities to incorporate with Martin's "eddy gun" solver and Krack 3

Benchmarking

- comparisons with INFN data & simulations (→ O.K.)
- applications to response time measurements

missing plot(s) due to
inaccessible remote desktop of my DESY PC
since last Thursday

Matlab-Package for photocathode gun simulations

- XFEL MC code (cathode properties)
- Eddy gun (consideration of field penetration)
- Krack 3 (3D particle tracking with valid image-charge on cathode)

Thank you for your attention!