Towards measurement-based S2E beam dynamics modeling & simulations for XFEL operation (1. start-up & gun)

Ye Chen

Beam dynamics meeting, Hamburg

November 19, 2019

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

European XFEL

DESY.

European XFEL

Outline

- Motivation
- XFEL injector studies in October
- Strategy of studies
- Status: measurement vs. simulation
- Intermediate summary
- Roadmap

Motivation

- **Reduce** discrepancies between measurement & simulation
- **Develop** models to describe effects routinely observed in XFEL operation
- **Optimize** machine parameters for improved FEL performance
- **Explore** new working conditions / working scenarios

Injector measurements in Oct.

- **Joint proposal** by Yauhen Kot, Mikhail Krasilnikov et al. for XFEL injector studies

Injector Characterization. Proposals for the machine studies.

Yauhen Kot, Igor Zagorodnov, Martin Dohlus, Chen Ye Lining and Mikhail Krasilnikov

I. Goals

1. Characterisation of the gun

   a) Determination of the basic gun "zero" state (GZS) i.e. characterization of the gun in the usual operation mode.
   b) Find out the solenoid calibration $(s0, s1)$: $B_{main} = s0 + s1 \cdot I_{main}$ (database: SOLA: s0=0, s1=4E-4 T/A, SOLB: s0=0, s1=6E-4T/A)
   c) Find out generated input charge Q_{input} at the cathode needed to achieve nominal charge of 250pC after the gun: $Q(Q_{input}, GZS) = 0.25nC$
   d) Measure laser pulse energy needed to get Q_{input}
   e) Measure the emission curve for charge vs laser transmission LT: Q=Q(LT)
   f) Measure maximum beam mean energy (momentum) gain in the gun vs. gun gradient

2. Characterization of the longitudinal beam profile:

   a) Establish alternative calibration of A1 and AH1 with respect to each other comparing the results of the energy measurement with and without third harmonic module
   b) Document longitudinal beam profile after A1 (with switched off AH1).
   c) Document beam profile after AH1 with A1 operated on crest.
   d) Document longitudinal beam profile for various settings of the chirp, 2nd and 3rd derivatives around the usual SASE WP.

Injector measurements in Oct.

- Carried out **on 29th-30th.10.2019**
- **Joint efforts:**

  Beutner, Bolko
  Brinker, Frank
  Chen, Ye
  Dohlus, Martin
  Kot, Yauhen
  Krasilnikov, Mikhail
  Scholz, Matthias
  Tomin, Sergey
  Zagorodnov, Igor

  & the XFEL operation team

- **Not everything finished as planned, but managed to measure:**
  1. Schottky scans (Q vs. Φ)
  2. Emission curves (Q vs. Elas)
  3. Phases of MMMG and zero-crossing
  4. Beam momentum after gun (using BK24)
  5. Emittance measurements
  6. TDS measurements

XFEL e-Logbook **Wednesday 30. October 2019 Morning**

shift summary

Operators
* Abo Ghaloun, Essam
* Goldbeck, Olaf
* Pfeiffer, Sven
* Schmid, Peter
* Steffen, Bernd
* Chen, Ye Lining

Status	* Injector studies
Goal	* Injector studies
Achievements	* systematic TDS scan measurements in the injector for different parameters * L3 gradients lowered
Difficulties	* Logbook server crashed (fixed) * DAQ server crashed (fixed) * nameserver crashed (fixed)

ACCELERATOR Operation summary

Development: 8.00 h

Operation details

new

30.10.2019 14:59 **Shift summary**

```
7:00 shift docu
7:15 Injector setup
7:30 RF on crest setup
7:45 Matching of the beam
We have tried to reduce horizontal emittance without succsess.
8:45 TDS measurement.
Axis calibrartion.
All cavities are on crest but we see chirp.
9:25 We decided to spend time and obtain reasonable emittance and beta functions. Matthias Scholz
 helped us. We have nice emittance with the quad scan tool. Before we have used 4 screens
 tool.
10:10 We have done on crest RF correction again and proceed with calibration of TDS axis.
10:30 AH1 is switched off. Scan of phase of A1 from -30 t0 30 degree with step of 1 on two crests
 of TDS.
10:45 A1 oncrest. AH1 phase scan from 160 to 200 degree.
11:20 Working point for SASE is set. Scan of chirp parameter from -12 to 5.
11:45 lower energy in L3 by about 100MV each station and re-tune cavities.
12:30 We have finished the scans with TDS as planned and will do some supplementary measurements.
13:30 we have redone main scans with laser heater off (the fist set was done with laser heater on).
14:00 slice emittance measurement
```

Strategy

of measurement-based studies

1. **Identify** realistic (not ideal) beam & machine parameters (w.r.t. theory / used in previous simulations)
2. **Clarify** significance of identified properties (with vs. without)
3. **Demonstrate** parametric dependences of the properties ("from a point to a range")
4. **Develop** models to describe observed behaviours
5. **Implement** models in existing tools
6. **Compare** simulation with measurement for consistency
7. **Transfer** knowledge gained from simulation to machine operation
8. **Optimize** FEL performance

Resources

Codes

- ALICE (Igor.Zagorodnov@desy.de)
- ASTRA (Klaus.Floettmann@desy.de)
- CSRtrack (Martin.Dohlus@desy.de)
- ECHOz (Igor.Zagorodnov@desy.de)
- Elegant (Michael Borland, ANL)
- Genesis 1.3 (Sven Reiche, PSI)
- MAD 8
- OCELOT (Sergey.Tomin@xfel.eu)
- Parallelized Astra (Sascha.Meykopff@desy.de)
- QField (Martin.Dohlus@desy.de)

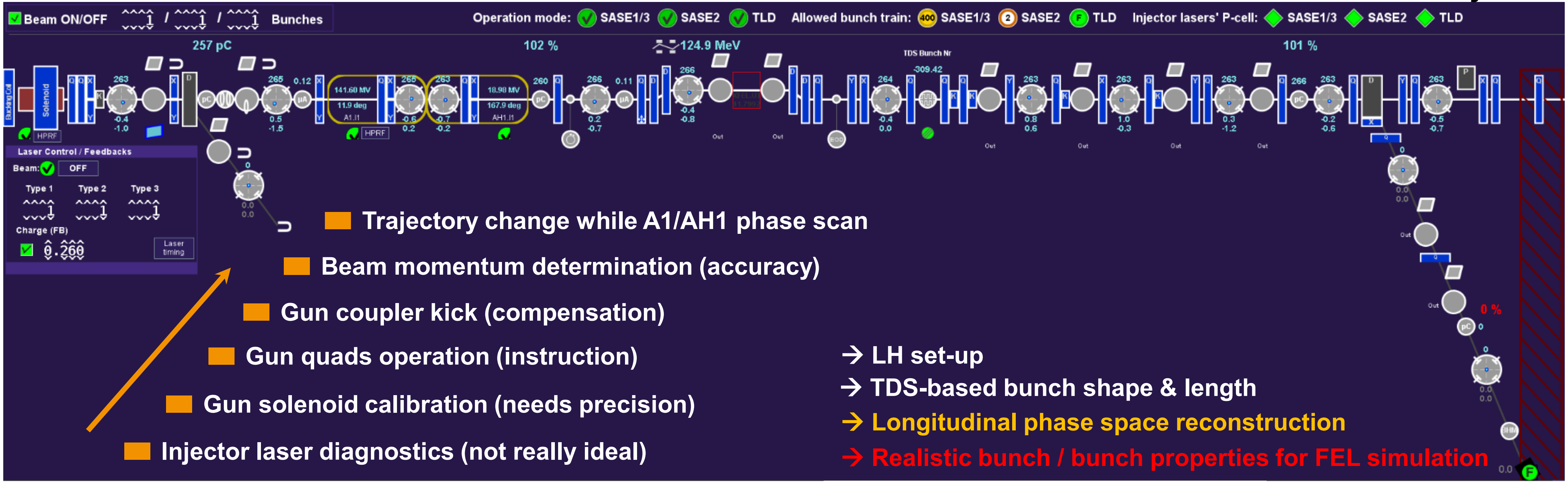
www.desy.de/fel-beam/s2e/codes.html

Tools

- Gun cavity field maps 2018 (ackermann@temf.tu-darmstadt.de & Martin.Dohlus@desy.de)
- TESLA field maps 2018 (ackermann@temf.tu-darmstadt.de & Martin.Dohlus@desy.de)
- TESLA field maps 2014 (ackermann@temf.tu-darmstadt.de & Martin.Dohlus@desy.de)
- 3rd harmonic field maps 2017 (ackermann@temf.tu-darmstadt.de & Martin.Dohlus@desy.de)
- 3rd harmonic field maps 2014 (gjonaj@temf.tu-darmstadt.de & Martin.Dohlus@desy.de)
- Steady-state resistive wake with oxid layer and roughness (Martin.Dohlus@desy.de & Igor.Zagorodnov@desy.de)
- ASTRA2Genesis (Igor.Zagorodnov@desy.de)
- Elegant2ASTRA (Martin.Dohlus@desy.de)
- Excel2Elegant for EXFEL (Hyunchang.Jin@desy.de)
- PS Viewer (Torsten.Limberg@desy.de)
- Data GUI library for Matlab (Sascha.Meykopff@desy.de)
- Impedance Database for XFEL: "\\win.desy.de\group\mpy\4all\public\XFEL Datenbank\XFEL_MDB"(Igor.Zagorodnov@desy.de)
- Impedance Database for FLASH: "\\win.desy.de\group\mpy\4all\xxl\zagor\public_xxl\FLASH_MDB"(Igor.Zagorodnov@desy.de)

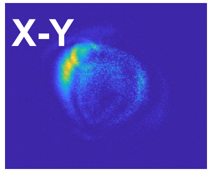
Details re-noticed in measurements of Oct.

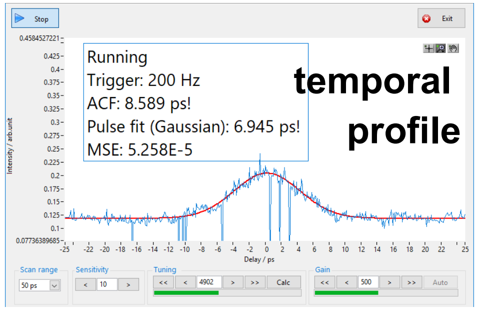
XFEL Injector



- Trajectory change while A1/AH1 phase scan
- Beam momentum determination (accuracy)
- Gun coupler kick (compensation)
- Gun quads operation (instruction)
- Gun solenoid calibration (needs precision)
- Injector laser diagnostics (not really ideal)

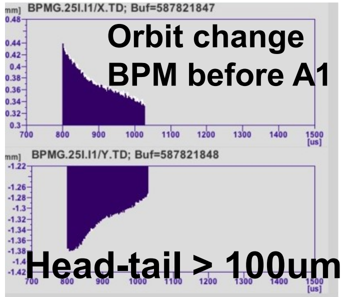
→ LH set-up
→ TDS-based bunch shape & length
→ Longitudinal phase space reconstruction
→ Realistic bunch / bunch properties for FEL simulation

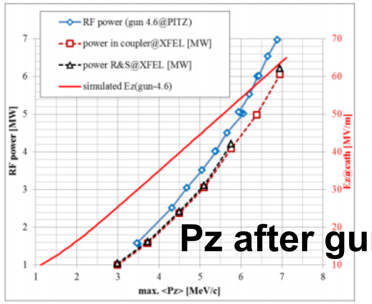


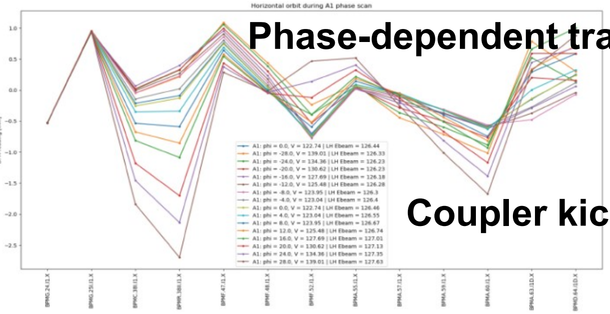


$$B_{main} = s0 + s1 \cdot I_{main} \quad \text{e.g. } B_z[\mathrm{T}]=5.889\times10^{-4}\times I_{main}[\mathrm{A}]+7.102\times10^{-5}$$

(database: SOLA: s0=0, s1=4E-4 T/A, SOLB: s0=0, s1=6E-4T/A)







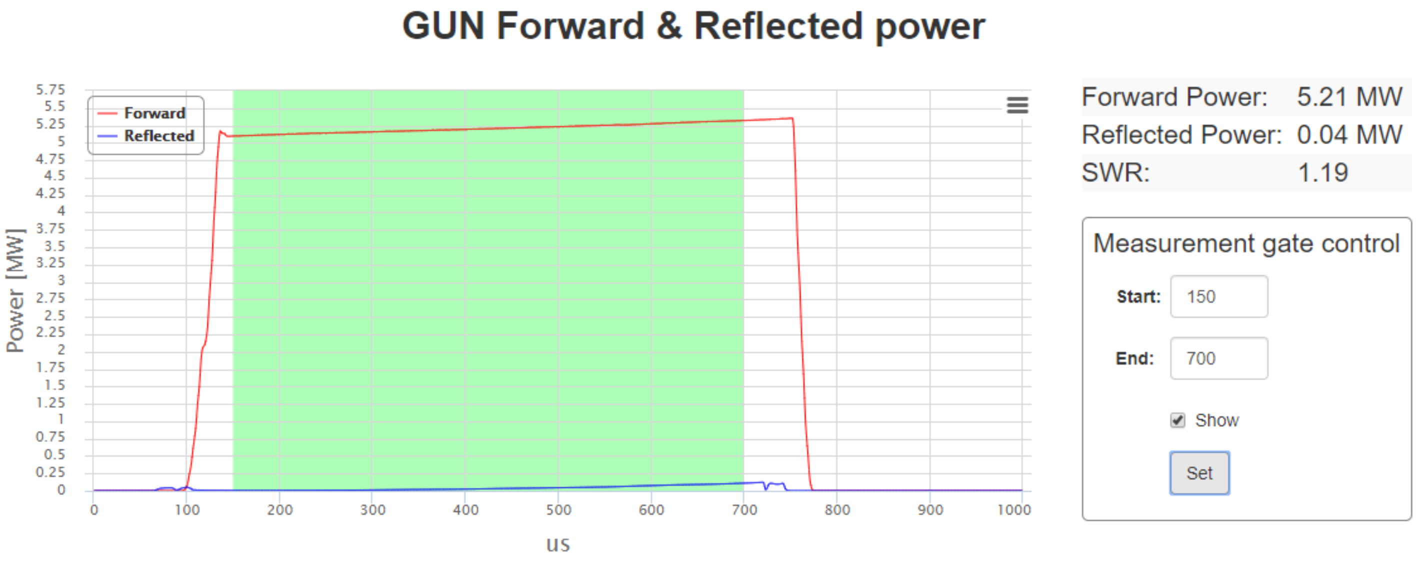
Gun power measurements

- Mhfpw10xfelgun: ~5.2 MW
- Directional coupler
  (LLRF calibration based?)

Directional Coupler

Pfor. 5.40 MW

→ **Deviation exists**



- **Latest XFEL database* 01. 2018**
  - Set-point power
  - Measured power
  - Beam momentum after gun
  - Cathode field gradient

  e.g. Power ≈ 5.21MW
  Pz ≈ 6.67 MeV/c
  Ecath ≈ 58.35 MV/m

Table 1: Results of momentum measurements at XFEL

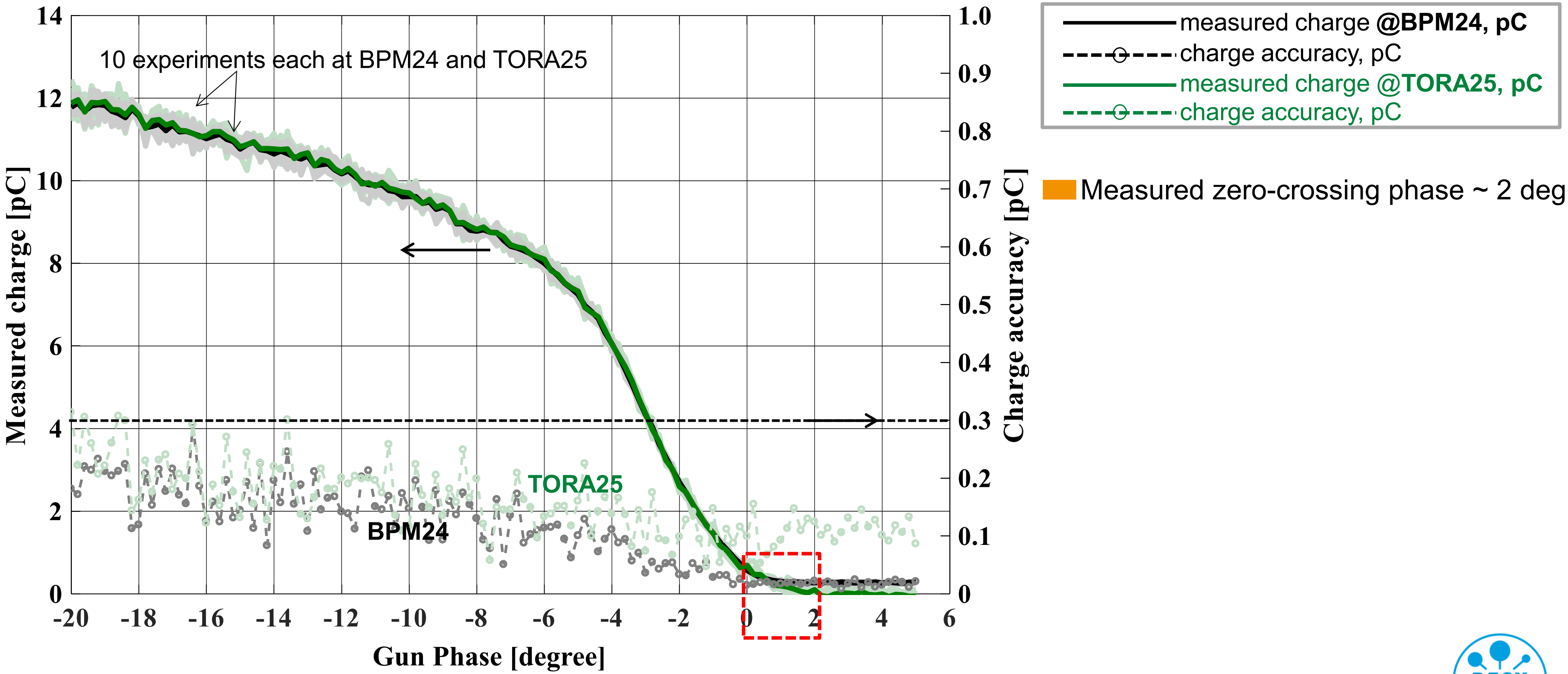
sp power	power in coupler@XFEL [MW]	power R&S@XFEL [MW]	momentum, MeV/c	gun phase, deg	Imain, A	Ibucking =0
25	1	1.04	2.99	-16	178	
31	1.58	1.62	3.73	-25.5	214	
38	2.37	2.42	4.5	-32	257	
34	3.05	3.11	5.1	-37	288	
50	4.09	4.21	5.76	-40.5	329	
55	4.98		6.38	-43.5	359	
60.6	6.05	6.21	6.95	-45	394	

for directional coupler at XFEL $P^{RF}_{XFEL}[MW] = 0.00148 \cdot (E_{cath}[MV/m])^2$

for R&S device at XFEL $P^{RF}_{R\&S}[MW] = 0.00153 \cdot (E_{cath}[MV/m])^2$

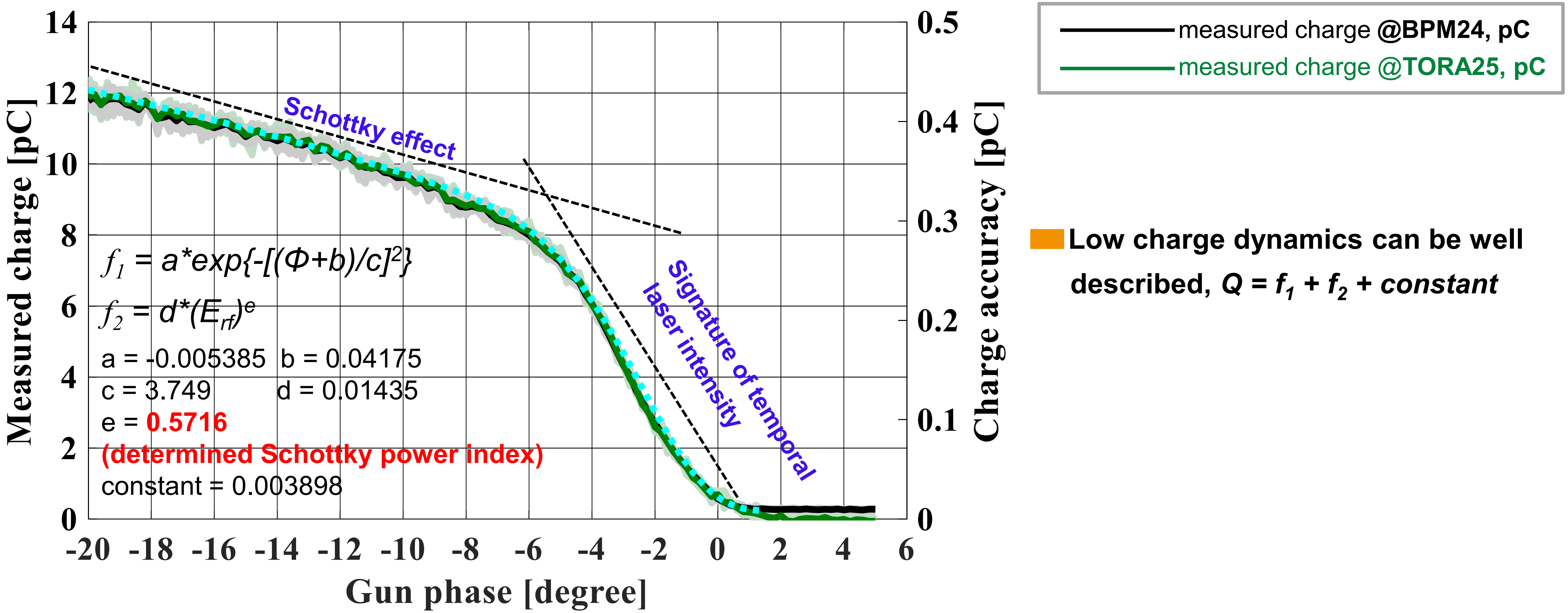
Credits*: I. Isaev, M. Krasilnikov, R. Niemczyk

Low-charge measurement of zero-crossing phase



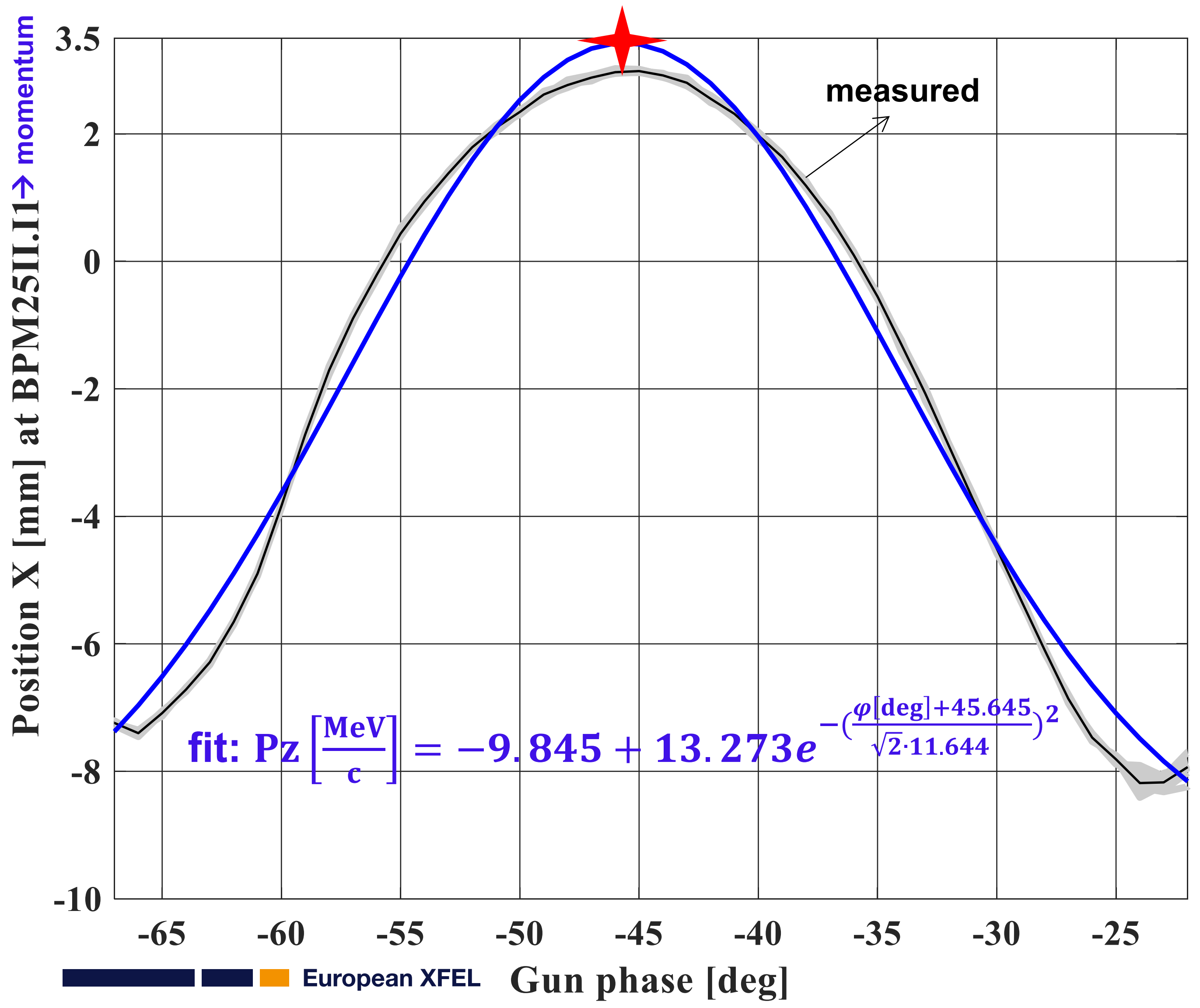
Measured zero-crossing phase ~ 2 deg SP

Low charge dynamics



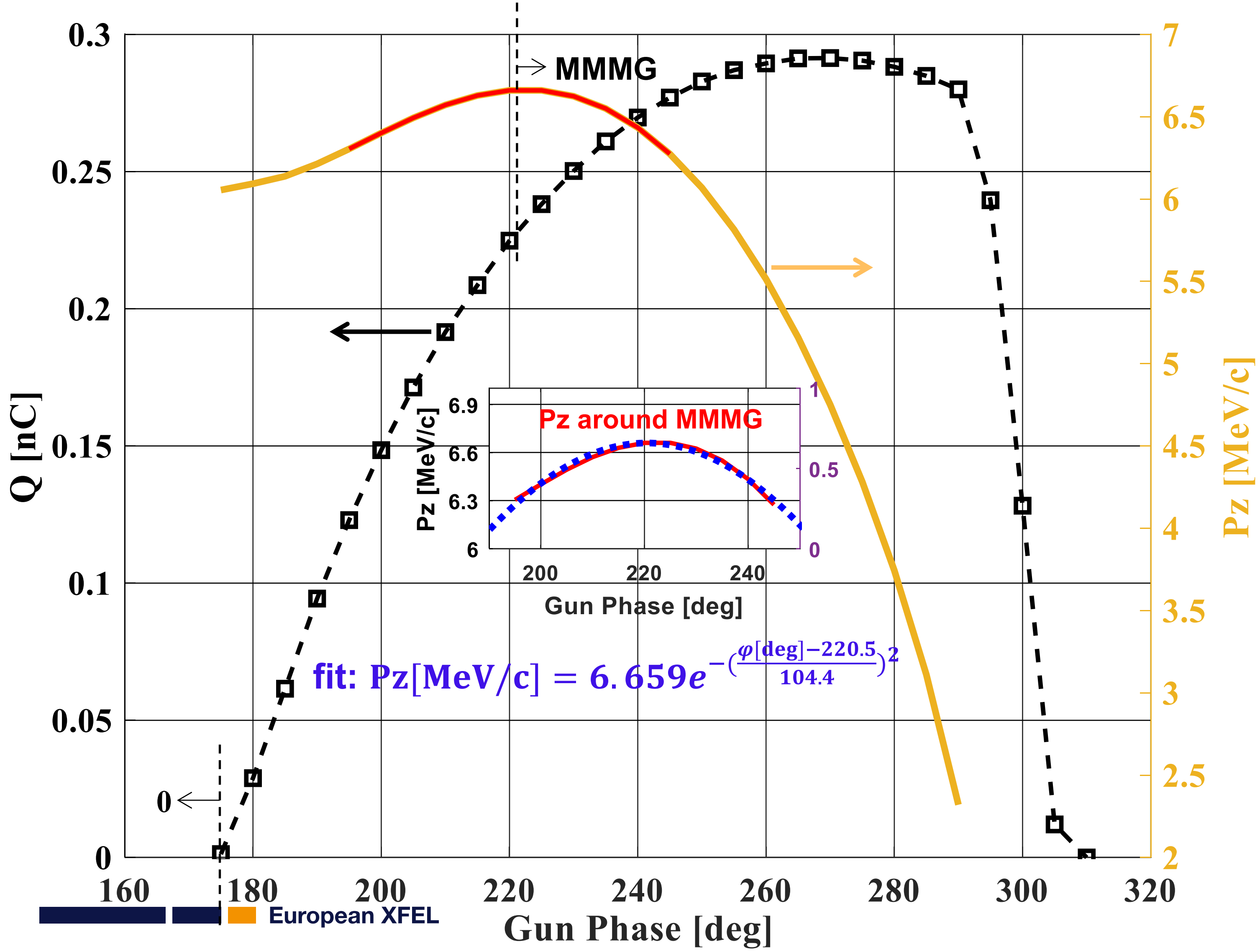
- **Low charge dynamics can be well described, $Q = f_1 + f_2 + constant$**

Measurement of MMMG phase



Measured MMMG at ~ -46 deg SP
(47 ~ 48 deg w.r.t. zero-crossing)

Simulation of beam momentum after gun



- Laser intensity SP (Qin=320pC) indicated from a measured emission curve (→Slide 15)
- Simulated Pz ~ 6.66 MeV/c at MMMG
- Simulated MMMG: ~46 deg from zero-crossing

→ **~ consistent with the measured one**

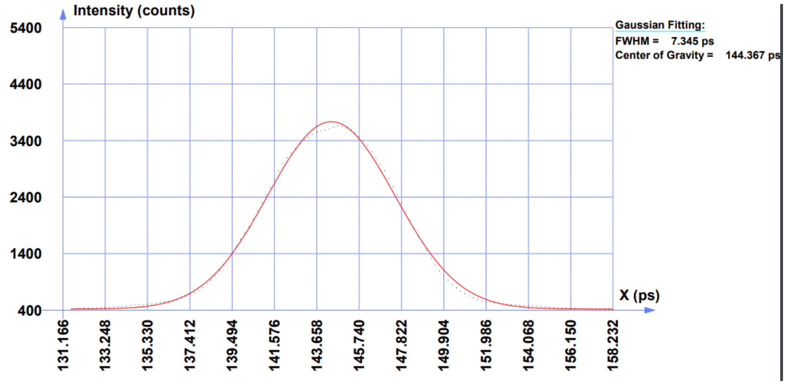
- Charge at MMMG ≈ 230 pC

→ **20 pC (8%) off measured 250 pC**

Diagnostics of injector laser ('Laser 2')

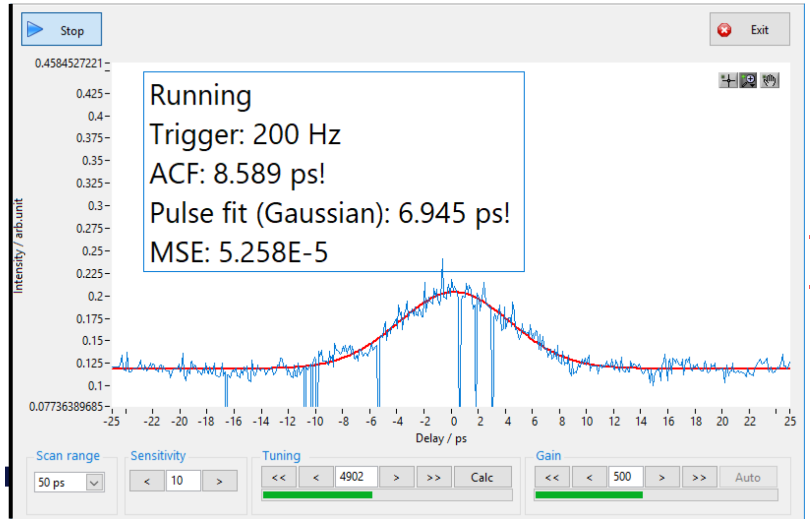
Measured laser temporal profiles

Streak camera measurement



Gaussian-like shape
7.345 ps FWHM
3.126 ps RMS

Autocorrelation measurement



Gaussian-like shape
6.945 ps FWHM
2.955 ps RMS

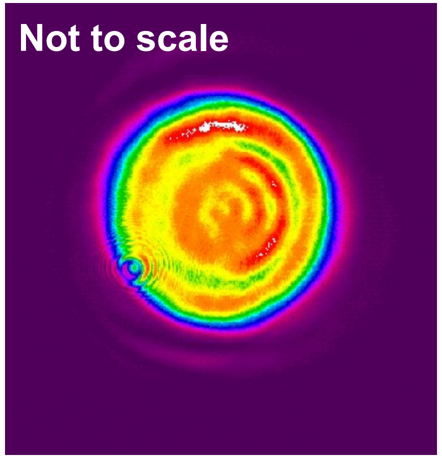
→ **close numbers off by 5%**
→ **a bit noisy in the AC case**

Credits: Lutz Winkelmann

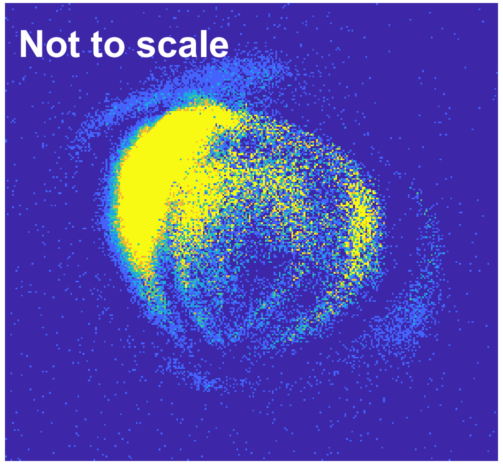
Measured transverse laser distributions

Laser beam on virtual cathode
BSA SP = 1.0 mm

Standard

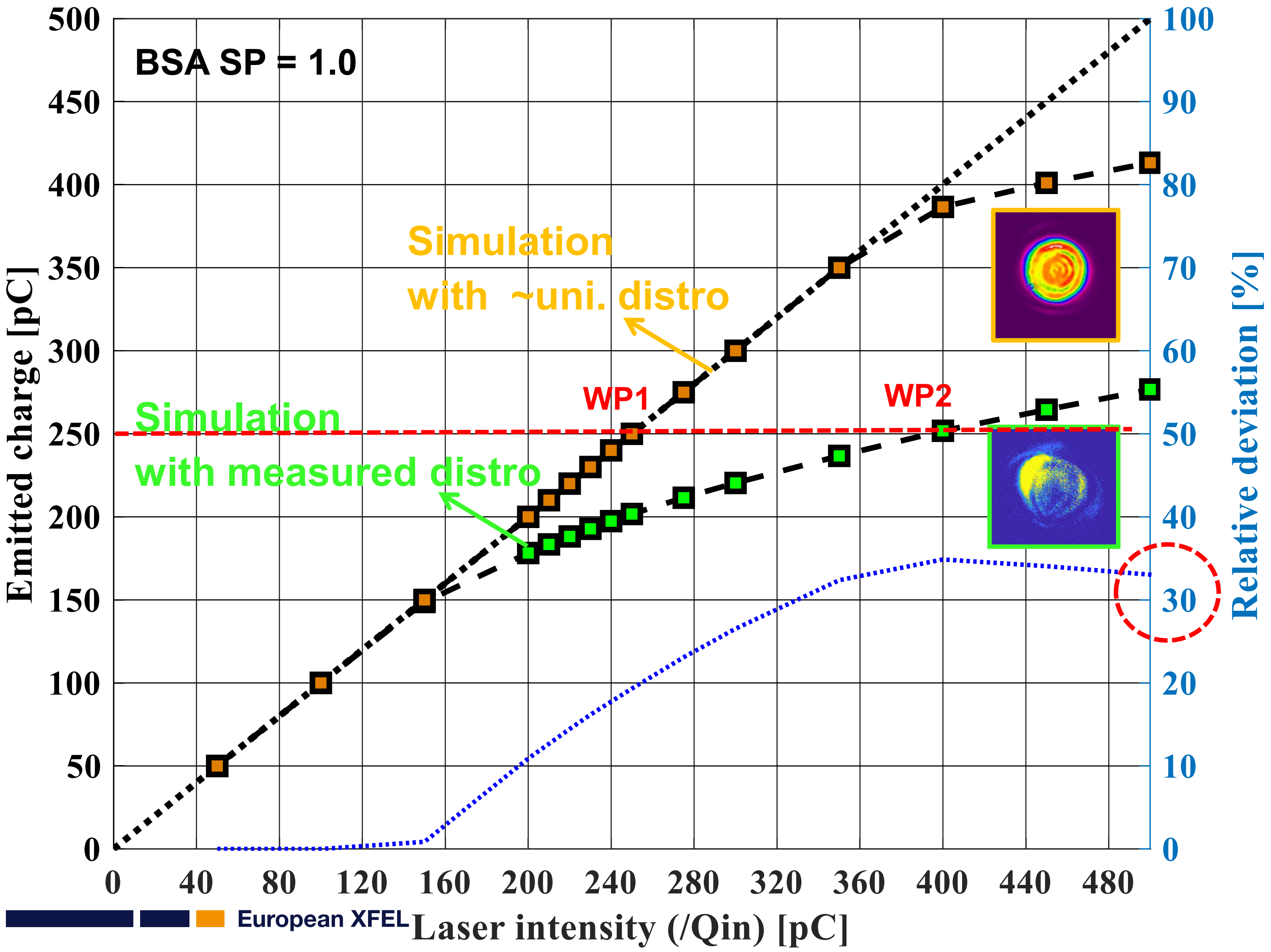


29-30.10.2019



→ **'irregular' shape w.r.t. standard case**
- → unclear cause
- → **charge-weighted map** used to represent realistic trans. distro for simulations

Simulations: Uniform Trans. Distro vs. Measured Trans. Distro



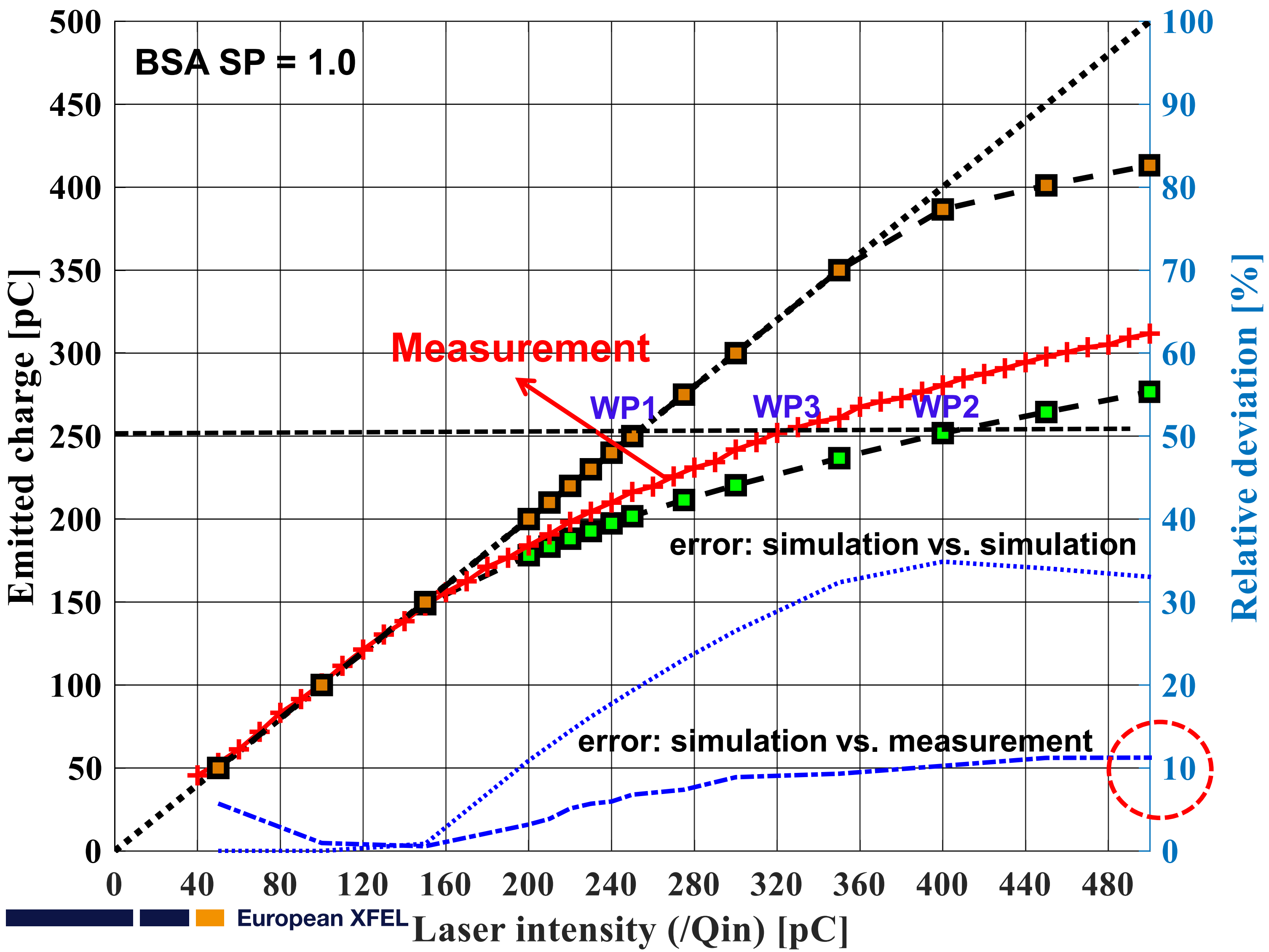
- Gun phase set at MMMG
- ("an extreme case") Using irregular trans. laser distribution results in up to 35% deviation w.r.t. using an uniform one

→ **Different dynamics at Working Points (WP) for 250 pC**

→ **Linear regime in ideal simulation**

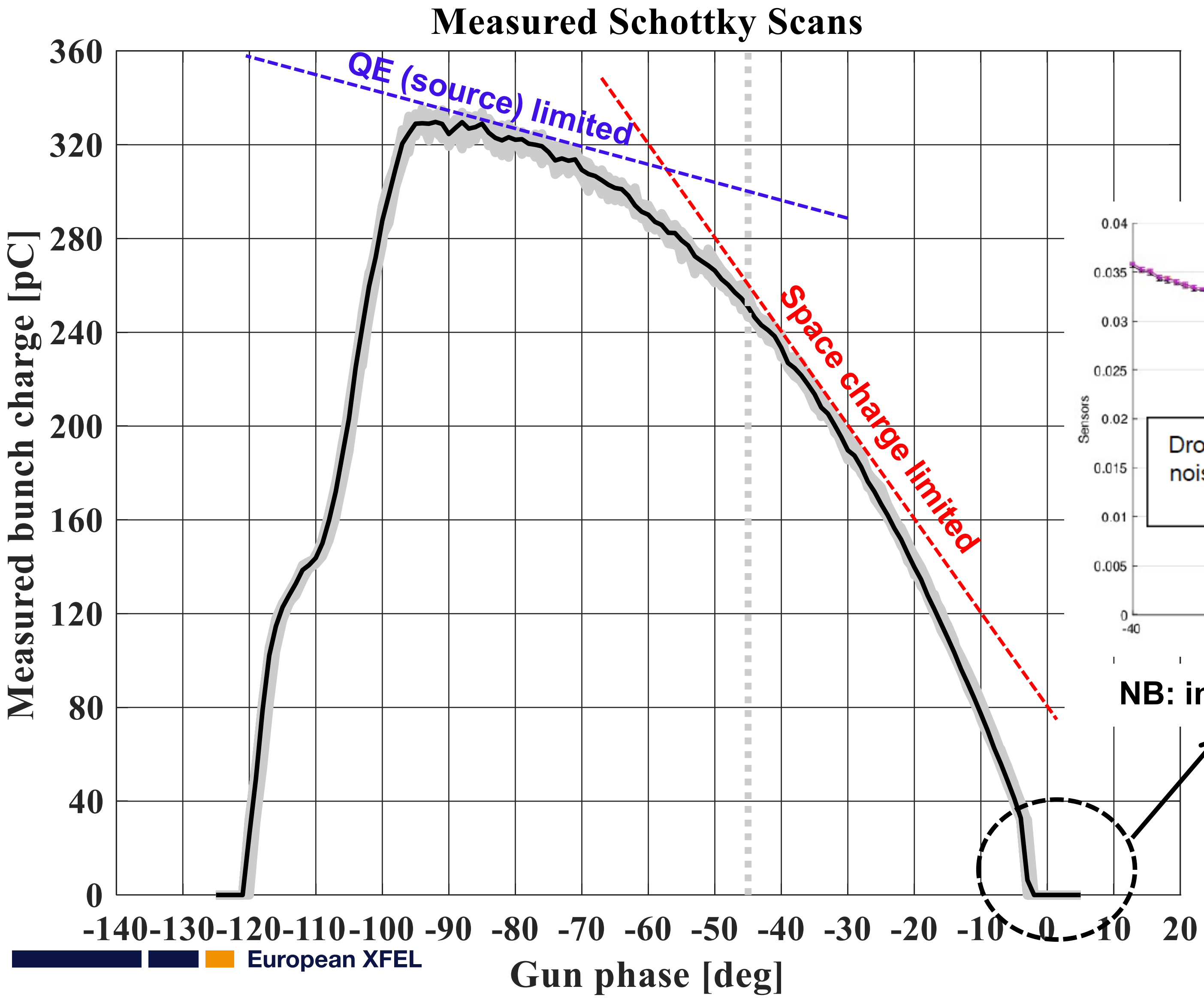
→ **Nonlinear regime already when using measured trans. distro**

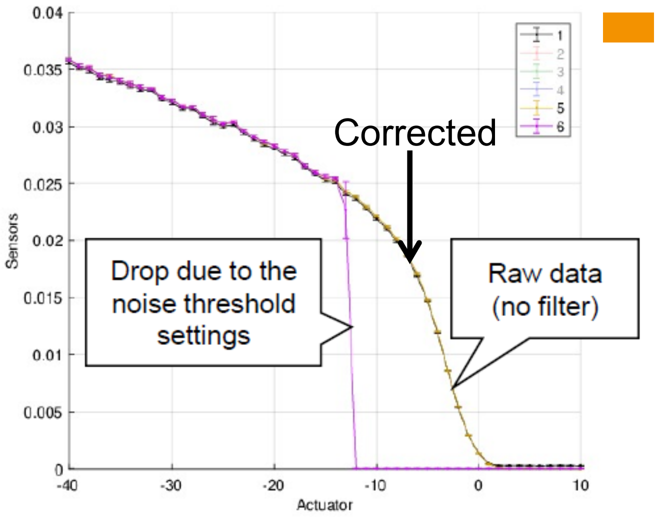
Simulations vs. Measurement



- Discrepancy drops to 10% when using measured trans. distro, but still…
- **Simulated saturation** WP2: **38%**
- **Measured saturation** WP3: **22%**
- → **WP for 250pC in nonlinear regime**
- For more accurate simulation one needs to consider e.g.
  - **'virtual cathode' formation** in strong space charge density case
  - photoemission model (**field dependency of QE** on cathode surface)
  - to use a tool with 3D space charge solver from the cathode

Phase dependency of charge: measured Schottky scan

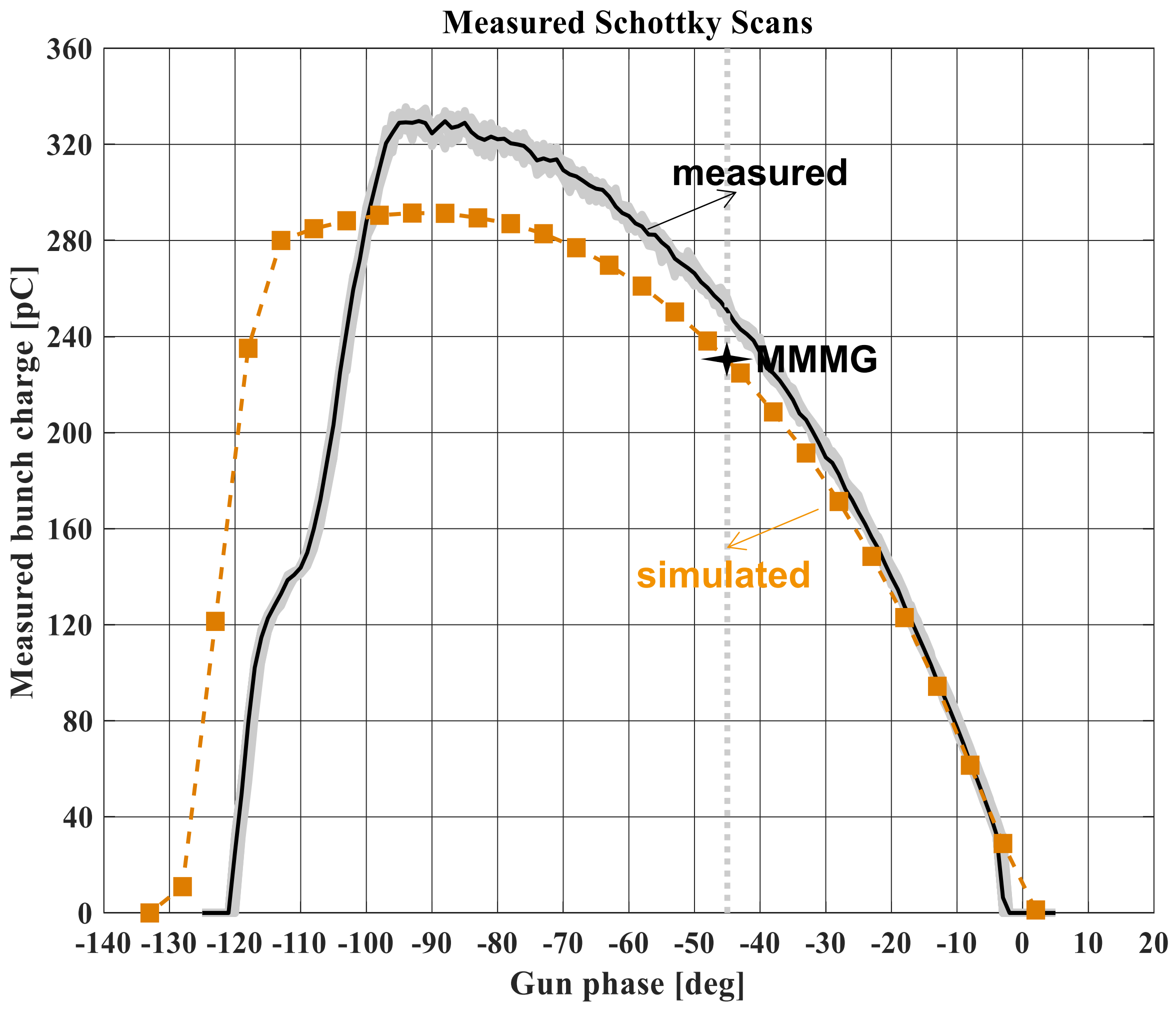




NB: influence of noise threshold

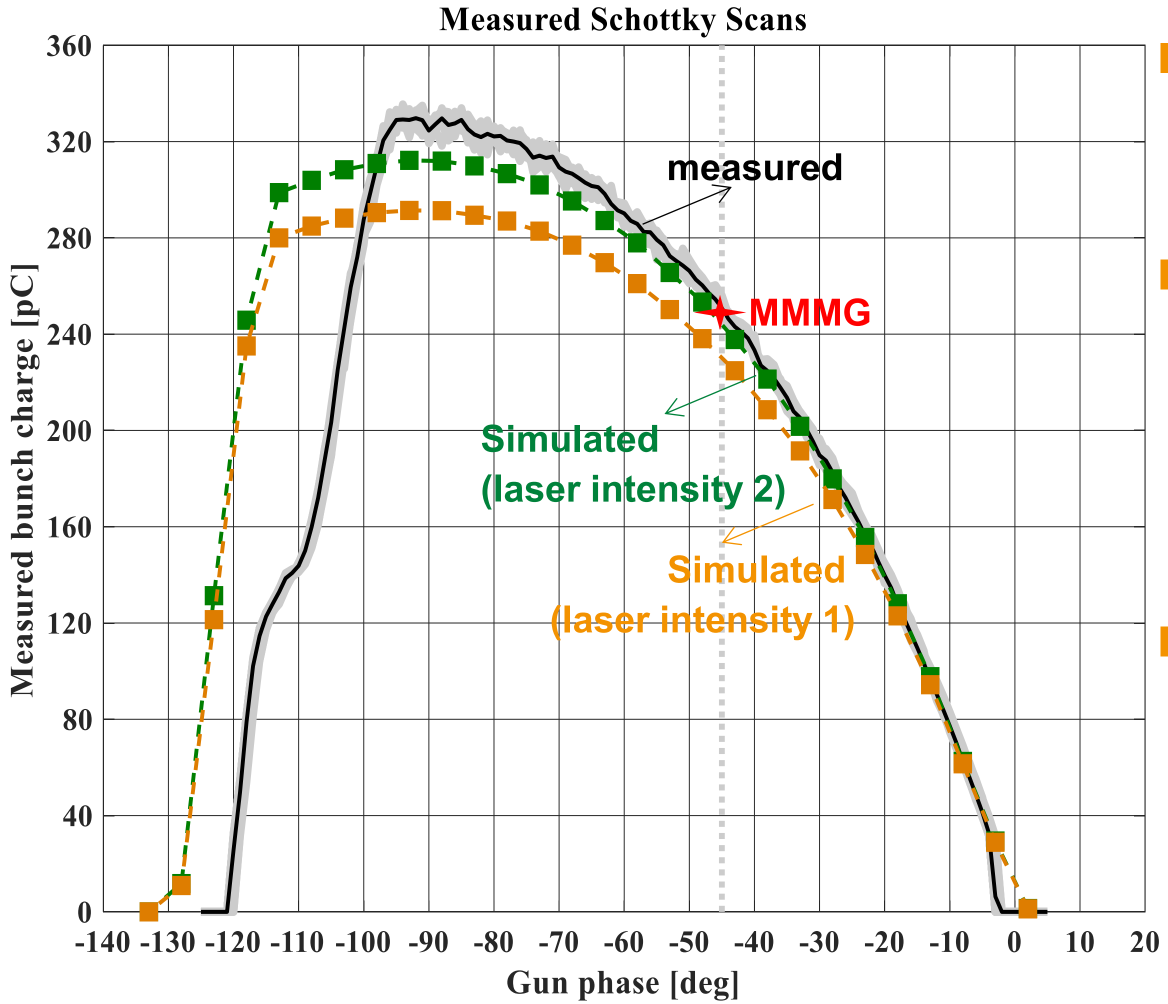
- The corrected behaviour fits the expected low-charge extraction mechanism versus phase

Simulation vs. Measurement: Schottky scan



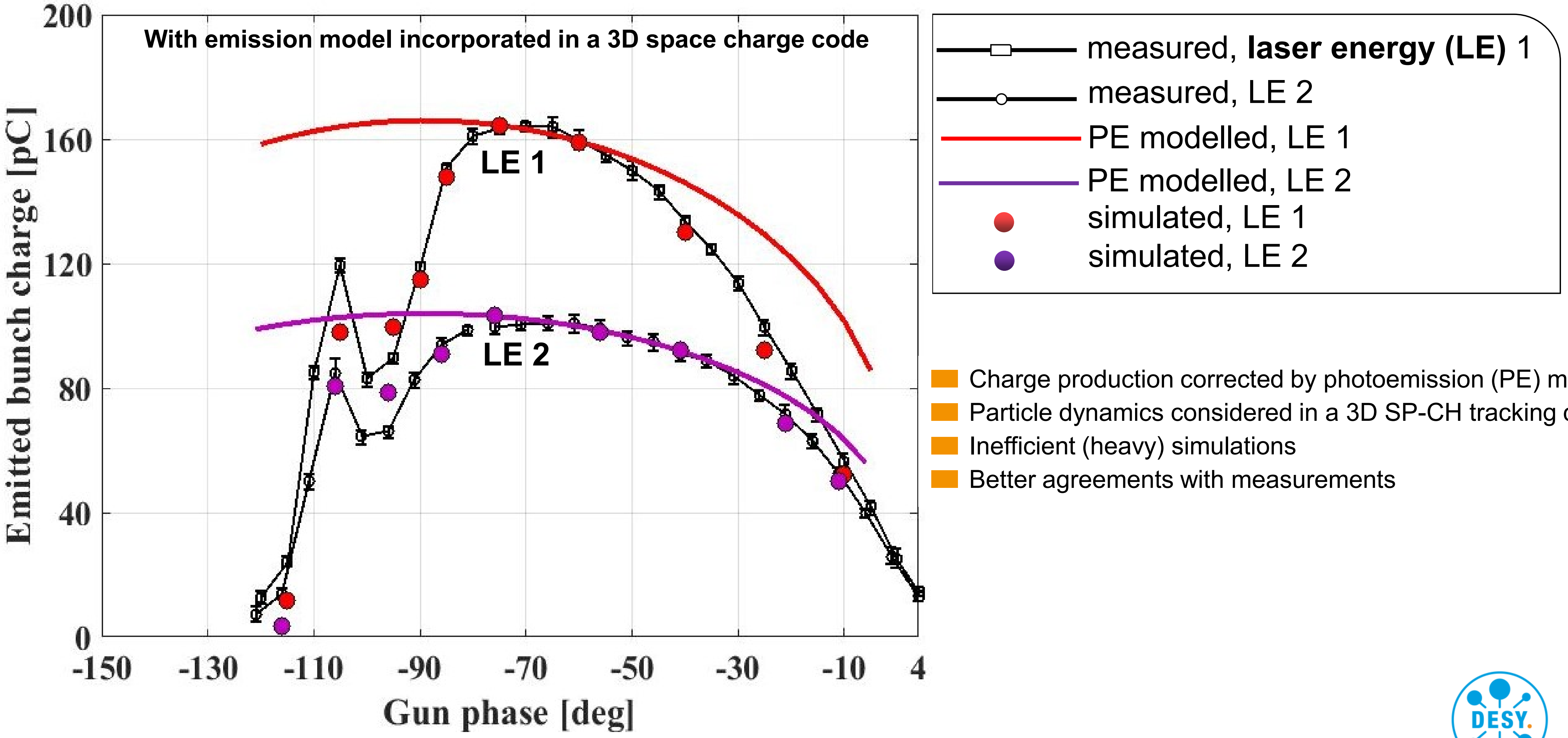
- Laser intensity SP (Qin = 320 pC) indicated from the measured emission curve
- Using measured trans. laser distributions
- Laser pulse length ~ 2.96 ps rms
- Pz ≈ 6.66 MeV/c
- **Stronger saturation compared to measurement**
- **Large discrepancies exist for higher phases**

Simulation vs. Measurement: Schottky scan



- From the simulated emission curve Laser intensity SP (Qin = 400 pC) indicated for 250pC at MMMG
  →smaller discrepancies for other phases?
- **Increasing laser intensity by ~20% renders better agreements for [MMMG-50, MMMG+46] degrees**
  → more charge actually produced in the measurements through field effects (i.e. higher effective QE for given laser pulse energy) and / or space charge force overestimated in simulations
- **Measured behaviours for higher phases (<MMMG-60) not yet clear**

Reference to simulations performed in July 2019 (for the PITZ case)

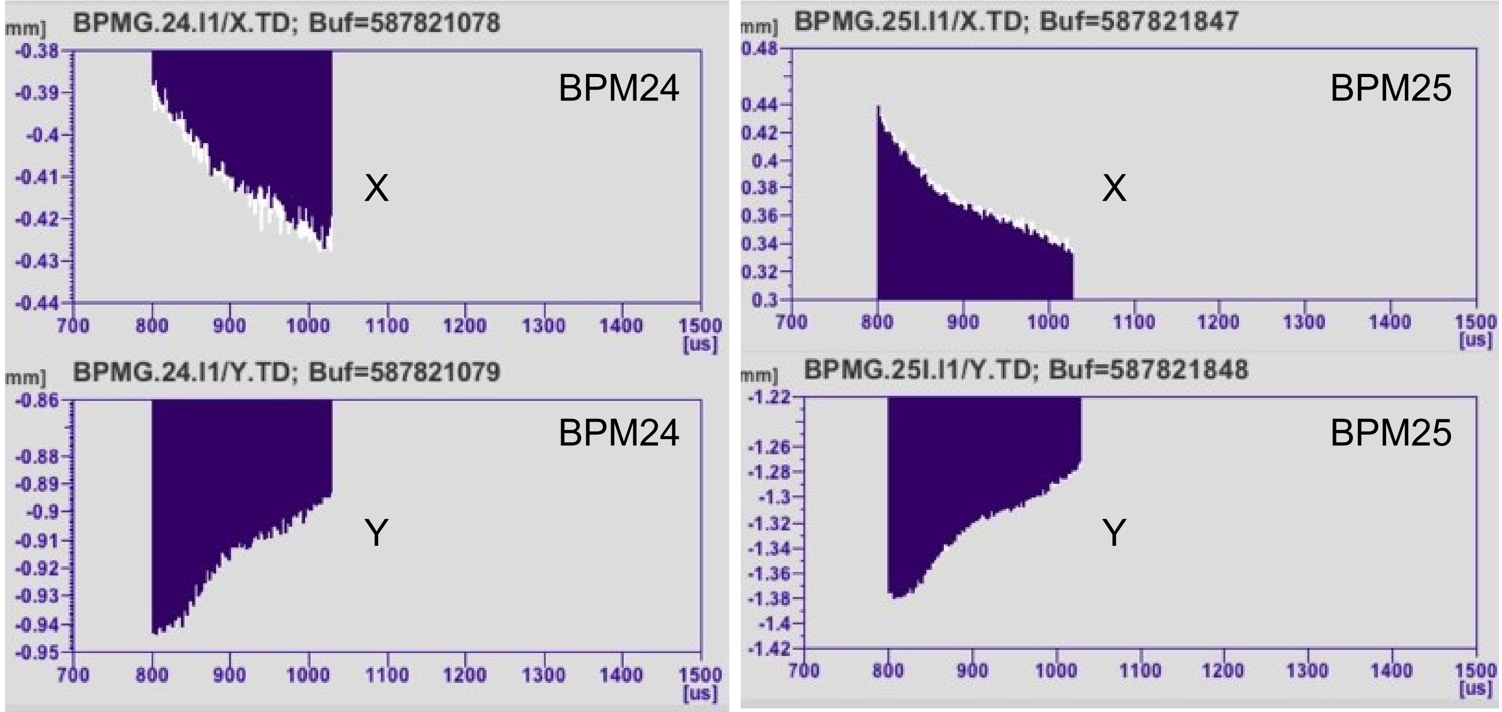


- Charge production corrected by photoemission (PE) model
- Particle dynamics considered in a 3D SP-CH tracking code
- Inefficient (heavy) simulations
- Better agreements with measurements

Effect of gun coupler kick: measured orbit change along train

Cross-checked orbit change over long bunch trains due to gun coupler kick

BPM	Z [mm]	ΔXp2p [um]	ΔYp2p [um]	Δr_meas [um] / Δr_sim [um]
BPM.24.I1	1039	35	50	61 / 78
BPM.25I.I1	2139.7	110	110	156 / 160



- Simulation **results reported** in doi:10.3204/PUBDB-2018-05590
- Simulated Head-tail kick difference: **~ 0.112 mrad (300us)**
- Simulated orbit change at BPM24 ~ 78 um
- .... at BPM25 ~ 160 um
- **Effect stronger for longer train operation**
- **Kick compensation (→ MSK involved)**

Intermediate Summary

- Simulations **performed** for measurements in Oct. **(gun part)**
  - BSA1.0, PL 2.96 ps rms, PS Gauss
  - Gun SP 55.6, Prf ≈ 5.2 MW@200μs
  - Simulated Pz ≈ 6.66 MeV/c, Ecath ≈ 58.4 MV/m
  - Simulated MMMG@46 deg from zero-crossing

- **Status** of measurement vs. simulation
  - Simulated charge at MMMG **20 pC lower, i.e. 8% at 250pC**
  - ………… emission curve **roughly 10% lower**
  - ………… MMMG (w.r.t. zero-crossing) phase **~same** (uncertainly from measured 0 phase)
  - ………… phase scan **for [MMMG-50, MMMG+46] ~10-15% lower**
  - ………… **charge extraction vs. phase slippage not yet understood**
  - ………… **orbit change along bunch train still consistent** with current XFEL observations

- Results **suggest:**
  - Relative increase of laser intensity by 20% leads to fairly good agreements with measured charge extraction behaviours vs. RF phase & laser intensity **→ more charge actually produced on the cathode (→ QE model) and / or space charge force overestimated (→ new tool)**
  - **Use measured trans. & temp. laser distro for simulation**
  - **Current XFEL machine working point in strong space charge dominated regime (→ more careful modelling required)**
  - Given asymmetric bunches at cathode & possible numerical issues, **Krack 3 should be used**

Roadmap

1. Measurements for XFEL injector re-characterization (→ done)
2. Corresponding gun simulations and comparisons with a set of measurements (→ done)
3. Reconstruction of measured longitudinal phase space by Igor (→ ongoing)
4. **Try to improve simulations by Krack 3 simulation (→ ongoing)**
5. Investigate trajectory change while A1 / AH1 phase scan (→ e.g. use Martin's kick model)
6. Benchmark projected & sliced emittance under (measured-) nominal conditions
7. TDS & longitudinal phase space by injector exit (→ compare with Igor's data)
8. Use e-bunches with measured properties for S2E simulations (→ ocelot + Genesis)

Thank you for you attention.