Beam dynamics with realistic bunches at the European XFEL

Ye Chen
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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

➔ 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 (!?)

→ Recheck in 01.2020

[diagram showing QE maps for May 2016, Dec. 2016, July 2018, and Nov. 2019, with notes on homogeneity and effective spot size changes.]
Re-measured QE map in 01.2020 for the same cathode
→ decision made for cathode exchange on 14th Jan. 2020

→ the worn Cs$_2$Te 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

cathode #681.1 (in)
cathode #680.1 (already out)
Measurements of temporal cathode UV laser profile

→ measured / cross-checked with streak camera & autocorrelation

Credits: L. Winkelmann

FWHM ≈ 7.3 ps
RMS ≈ 3.1 ps
Summary

*What observed?*

→ QE & QE map homogeneity degradation

*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$_2$Te thin film

→ an extensively used photocathode (after 5+ years operation at XFEL)
Quantum efficiency map (measured) of Cs$_2$Te thin film
⇔ an extensively used photocathode (after 5+ years operation at XFEL)
Quantum efficiency map (measured) of Cs$_2$Te 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)
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


- **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)

"With ideal laser and ideal cathode"

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)

"With measured laser and measured cathode QE"

Deviation reduced from ~30% to ~5%
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 ~10 nm) → sensitive
  - Simulation time step (down to ~25 fs)
  - 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 bunch length starts to grow (w.r.t. laser) faster than in the experiments
- Gun & A1 both on-crest
Behavior of bunch lengthening w.r.t. gun phasing (in astra)

- **A. Bunch length (variable phase)**
  - 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

- **B. Charge (variable phase)**
  - 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

![Graph showing extracted bunch charge vs. cathode laser pulse energy with two regimes: Quantum Efficiency Dominated and Space-Charge Dominated. The graph includes data points for different working conditions.](image_url)
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

Projected emittance vs. solenoid field strength

- 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

- **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)

- missing plot(s) due to inaccessible remote desktop of my DESY PC since last Thursday
Thank you for your attention!