SIMULATION STUDY OF NANOSTRUCTURED PLASMONIC COPPER PHOTOCATHODES

Margarita Bulgacheva[1], Erion Gjonaj[1], Dmitry Bazyl[2]

[1] TEMF, Technische Universität Darmstadt, Darmstadt, Germany
[2] Deutsches Elektronen-Synchrotron, Hamburg, Germany

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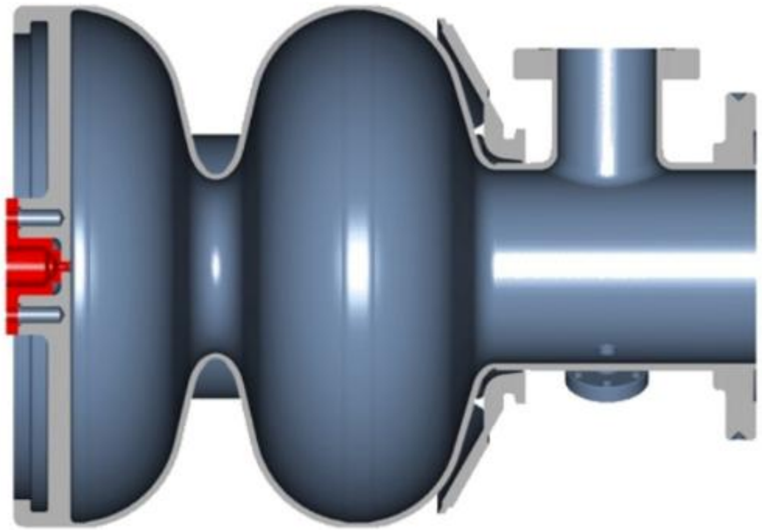
INTRODUCTION

- A Continuous Wave (**CW**) **electron source** is necessary for the future operation of the CW and High-Duty-Cycle EuXFEL.
- DESY is currently developing a 1.6-cell superconducting radio-frequency (**SRF**) **gun cavity**, designed to operate at 1.3 GHz.
- This gun can only be used with **metal photocathodes** due to construction (no load lock system).
- It is necessary to design a **copper photocathode with increased Quantum Efficiency** (QE).



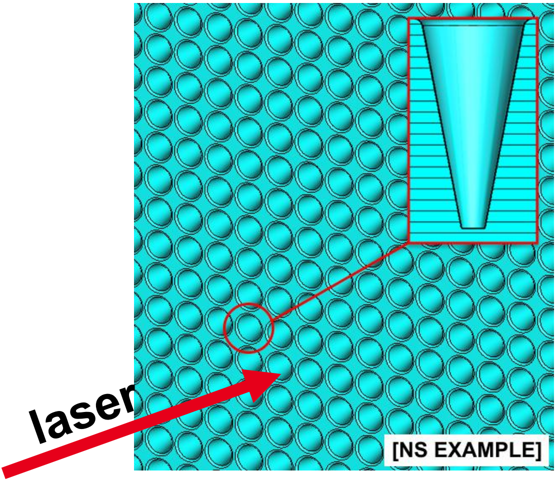
D. Bazyl, et al. “CW Operation of the European XFEL: SC-Gun Injector Optimization, S2E Calculations and SASE Performance.” (2021)
D. Bazyl, “Nanostructured photocathode RnD for CW photoinjector at DESY”, Deutsches Elektronen-Synchrotron (DESY), unpublished.

SHORT REMINDER OF PLASMONICS

Periodic structure

+

Laser pulse



Array of nanoholes

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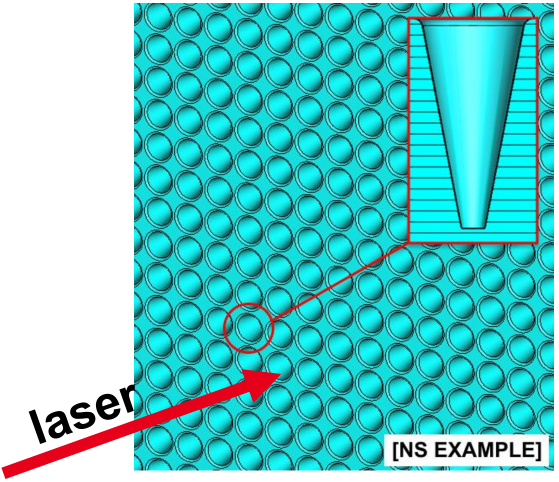
Laser pulse

→ Surface Plasmon Polariton (SPP) modes



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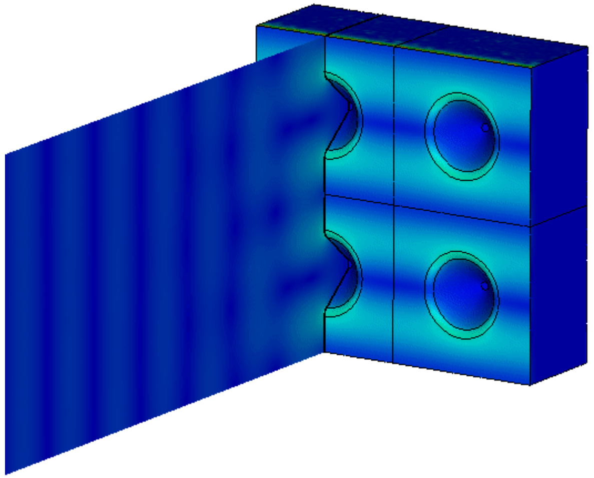

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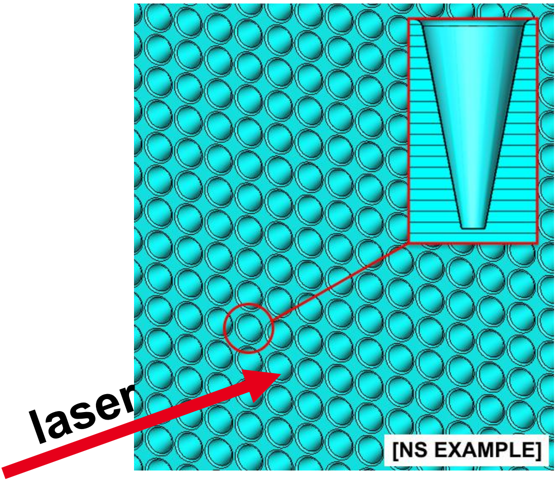
SHORT REMINDER OF PLASMONICS

Periodic structure

+

Laser pulse

→ Surface Plasmon Polariton (SPP) modes → Increased local absorption



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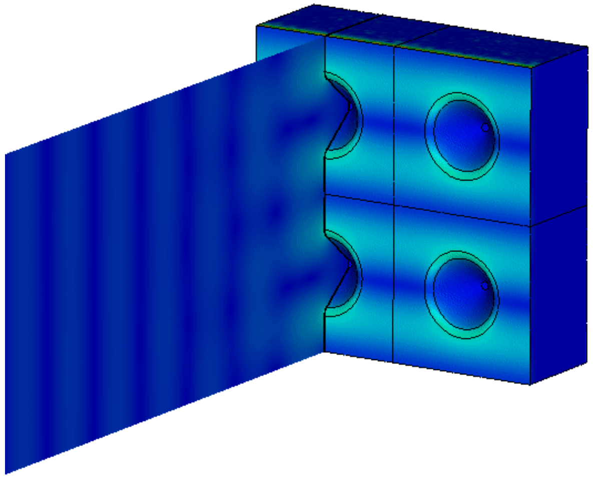
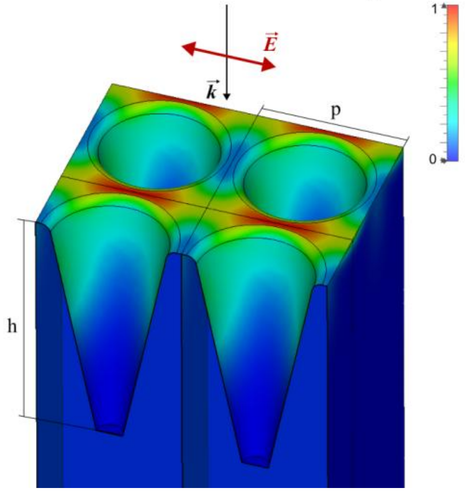


Surface Power Loss Density



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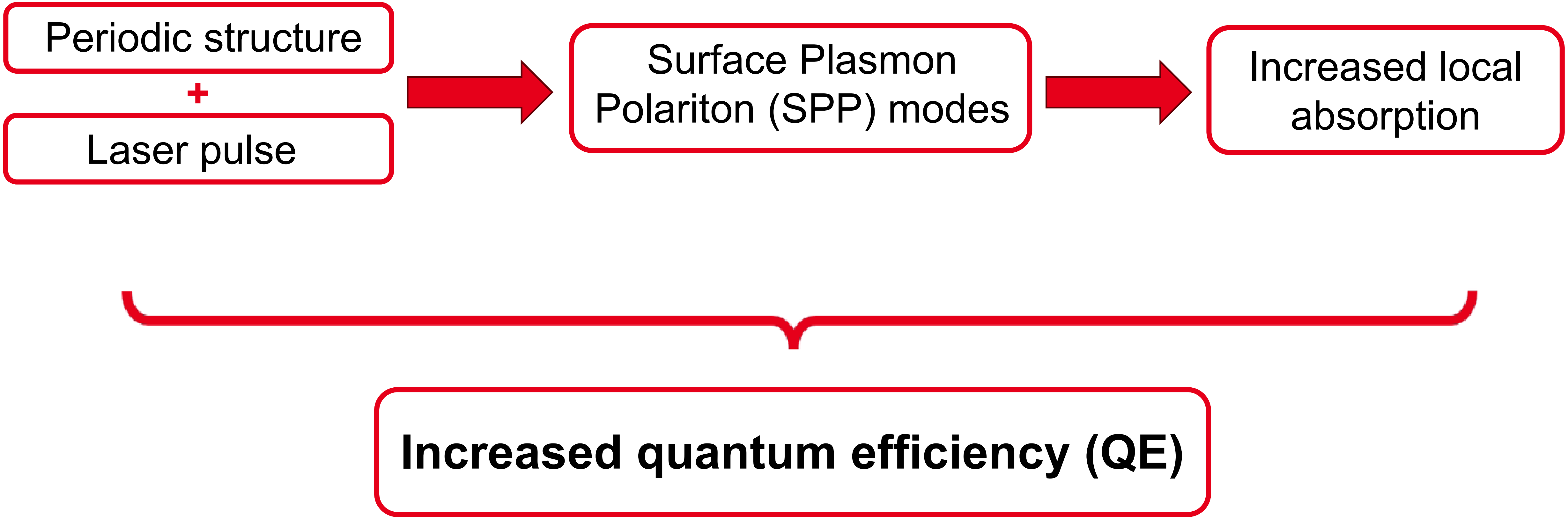
SHORT REMINDER OF PLASMONICS



SIMULATION PROCESS

- **Electromagnetic simulation**
- Photoemission model
- Beam dynamics

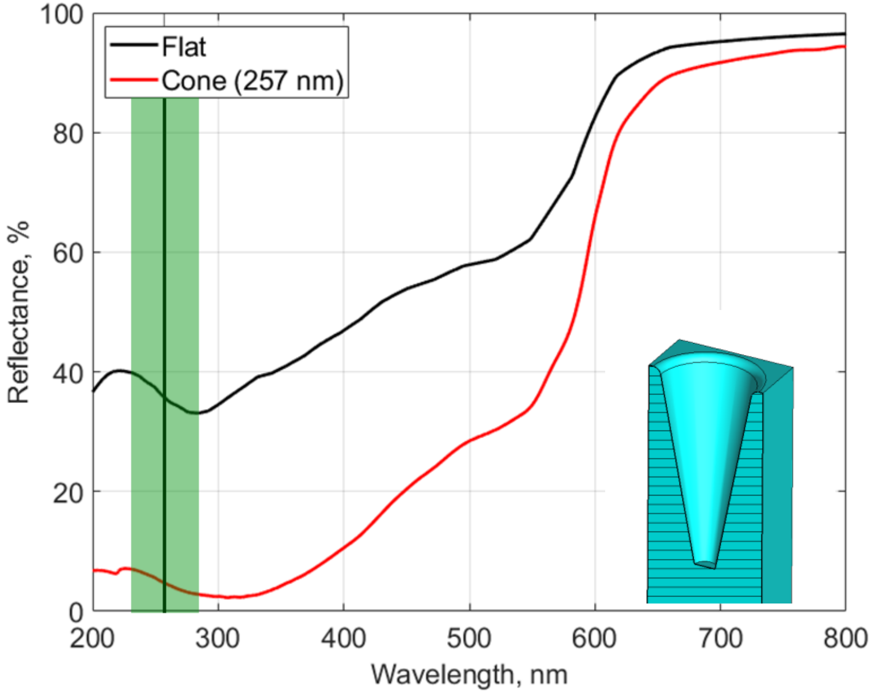
ELECTROMAGNETIC SIMULATION

- Excitation: **linearly polarized** plane wave
- Material **dispersion**: based on Johnson&Christy data
- Target laser wavelength: **257 nm (UV)**
- Optimization goal: **minimize reflectance**

- Geometry: **conical nanostructure**, periodicity = 220 nm, depth = 360 nm

Reflectance is decreased from 36% to 6%

Broadband reflectance spectra compared to the flat copper surface in UV



SIMULATION PROCESS

- Electromagnetic simulation
  - Plane wave excitation
  - Geometry optimization
  - Export power losses in volume
- **Photoemission model**
- Beam dynamics

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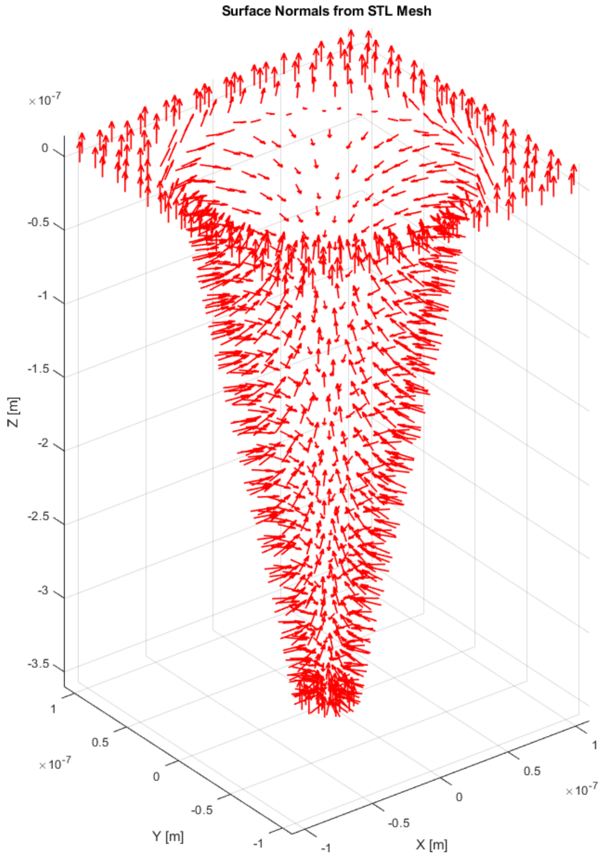
PHOTOEMISSION MODEL
PHOTOCURRENT DISTRIBUTION

- Define triangular **mesh**: facets, normals



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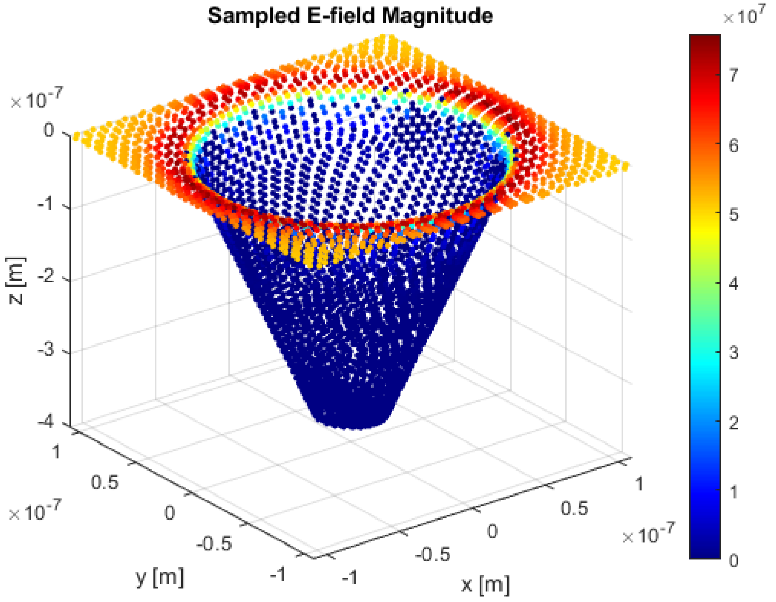
PHOTOEMISSION MODEL
PHOTOCURRENT DISTRIBUTION

- Define triangular mesh: facets, normals
- Integrate losses along the normal inside the material limited by optical depth
- Calculate photocurrent for each facet (emission point)
- Apply **Schottky correction to the work function** based on local accelerating field

$$\phi_{\text{eff}} \equiv \phi_w - \phi_{\text{Schottky}} = \phi_w - e\sqrt{\frac{eF_a}{4\pi\varepsilon_0}} = \phi_w - 0.037\,947\sqrt{F_a\ (\text{MV/m})}\ \text{eV}.$$



 [D. Dowell, "Quantum efficiency and thermal emittance of metal photocathodes", Phys. Rev. ST Accel. Beams, 2009]

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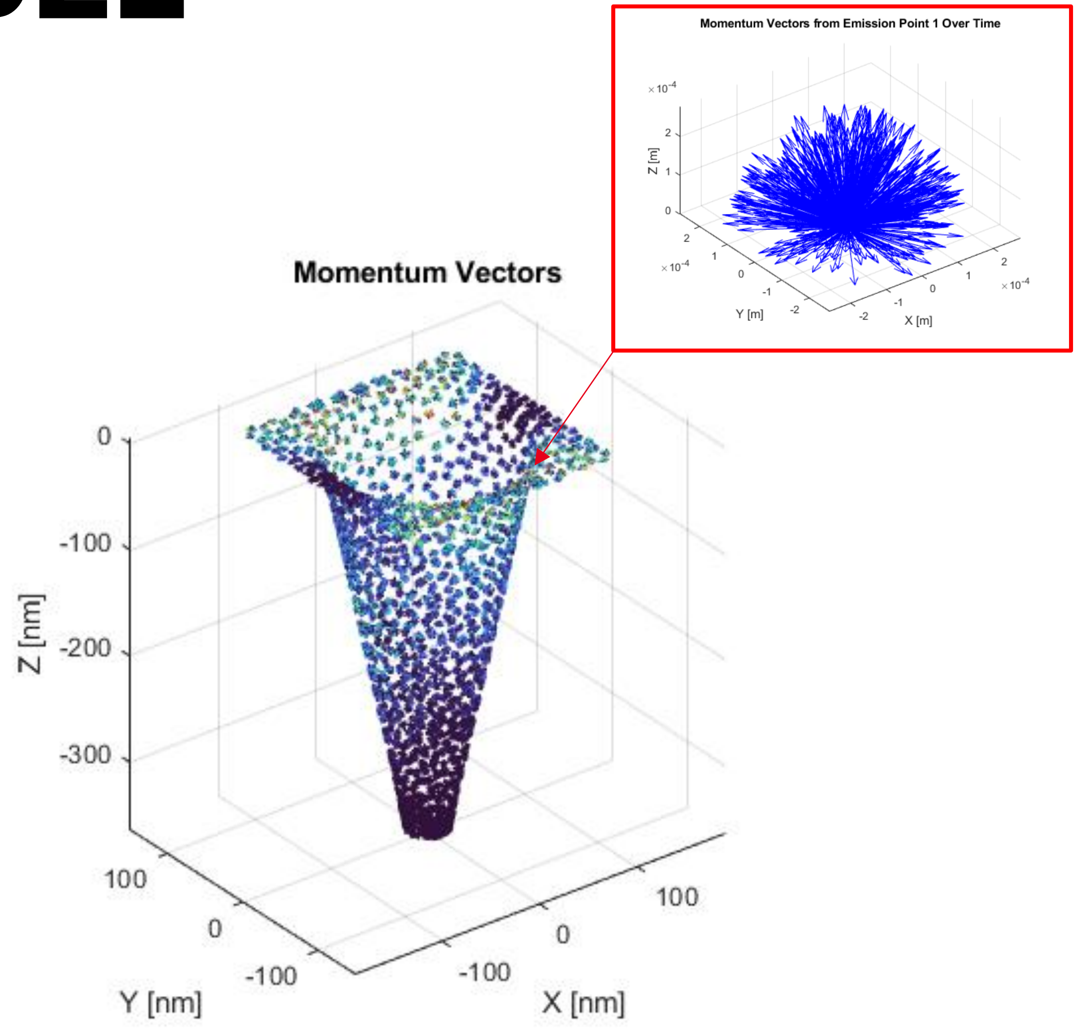
PHOTOEMISSION MODEL
EMISSION SAMPLES

- **Emission points** are located in the facet centers
- The electron **kinetic energy** is distributed in the range $0 \leq E_{electron} \leq h\omega - \phi_{\text{eff}}$
- **Angle distribution** is customizable (here: Lambert distribution)
- **Truncated Gaussian** longitudinal current distribution
- Electrons are emitted randomly from part of the emission points
- Macroparticle **charges are normalized** to the total emission charge

Every timestep 1 macroparticle per N emission points with normalized charge is emitted with randomized angle, energy and time between [t; t+Δt]



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  - Photocurrent calculation using electromagnetic solver results
  - Emission samples (bunch construction)
- **Beam dynamics**

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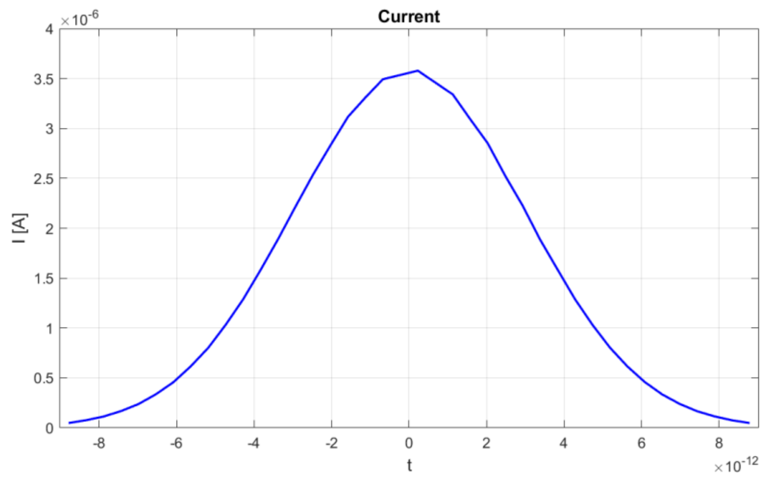
BEAM PARAMETERS

$\lambda = 257$ nm, $\phi = 4.6$ eV

Parameters	Flat cathode	Structured cathode
Total charge (full cathode)	50 pC	60 pC
Normalized Emittance	0.16 mm x mrad	0.211 mm x mrad
MTE	126 meV	317 meV

Scaling parameters:
Average power = 2 W; Pulse width = 8 ps;
Repetition rate = 1 MHz;
RMS laser spotsize = 0.25 mm



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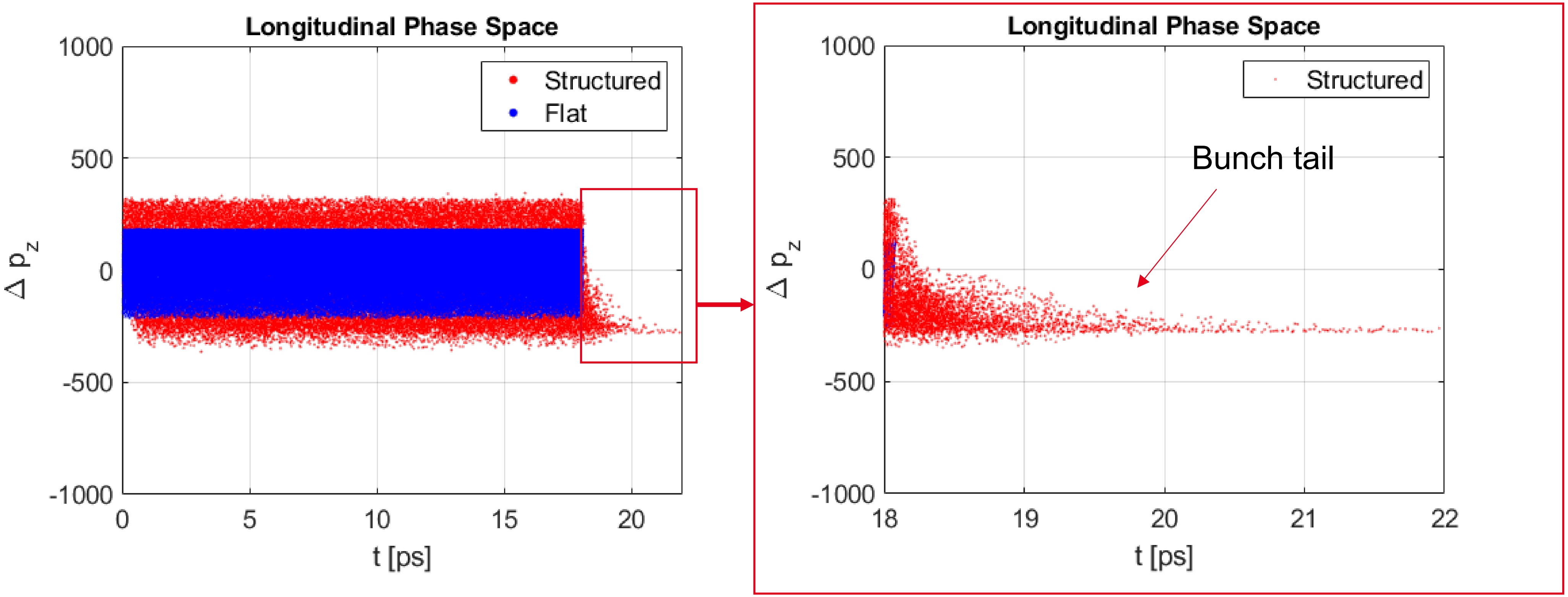
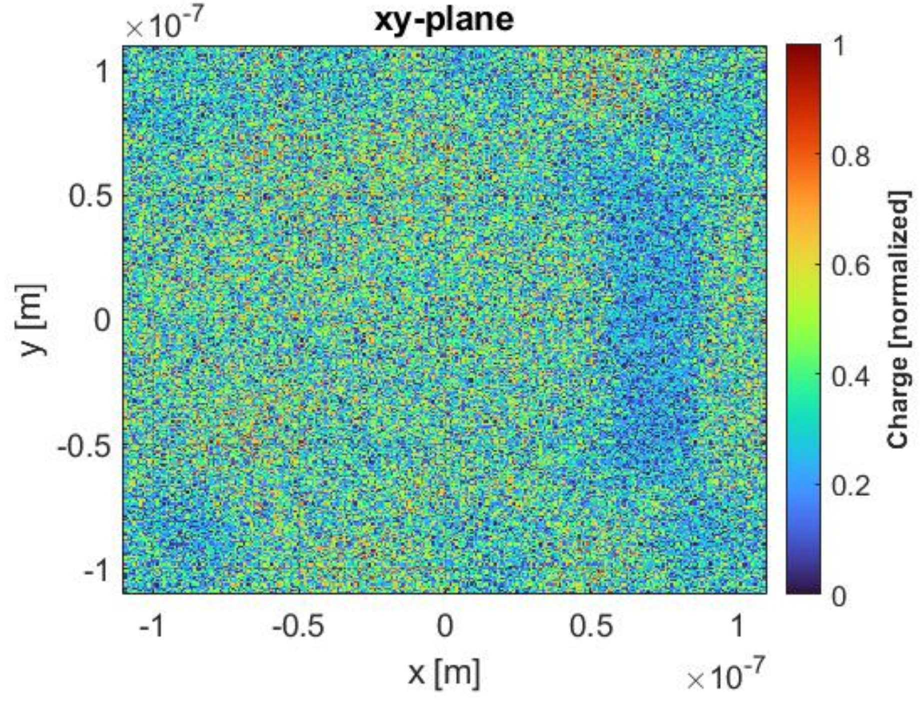
BEAM PARAMETERS
LONGITUDINAL



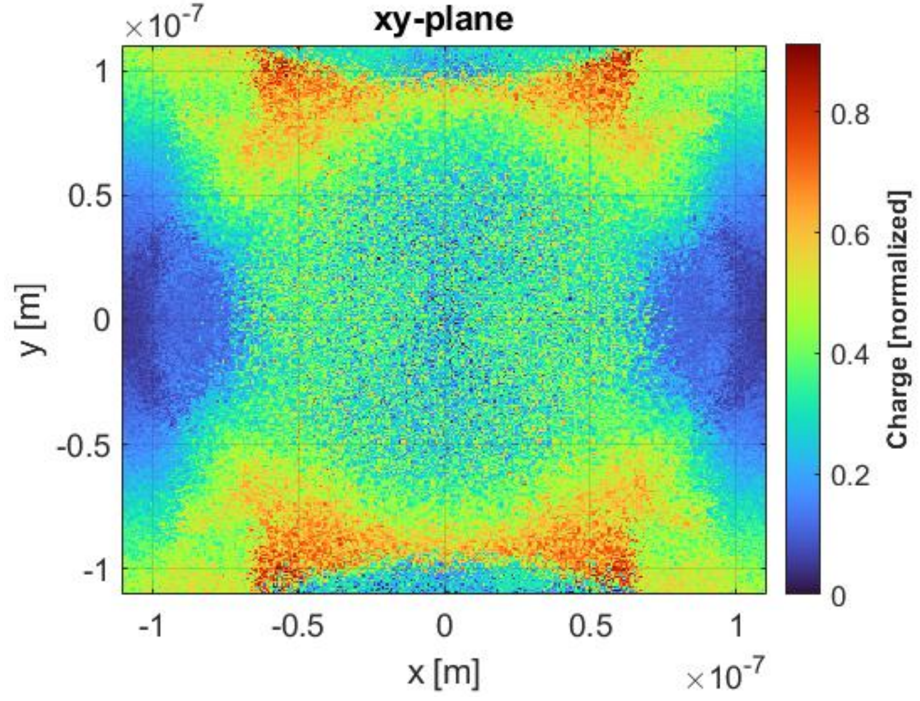
- The electrons emitted from the **cone depth** are **less accelerated** by the cavity field, which causes energy spread growth and longitudinal phase-space bending at the bunch tail.

BEAM PARAMETERS
TRANSVERSAL

Flat cathode



Structured cathode



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  - PIC simulation
  - Beam parameters

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RESULTS

- **Electromagnetic simulation** of plasmonic cathodes:
  - Electromagnetic model
  - Geometrical **optimization**
  - Electric field and **absorptance enhancement (50%)**

- **Beam dynamics** simulation:
  - **Spatial photocurrent distribution** on the cathode surface
  - Plasmon-enhanced **photoemission model**
  - **Schottky correction:** up to 0.3 eV
  - Effect on **transversal and longitudinal beam characteristics**: emittance, MTE, and energy spread increase