SIMULATION STUDY OF NANOSTRUCTURED 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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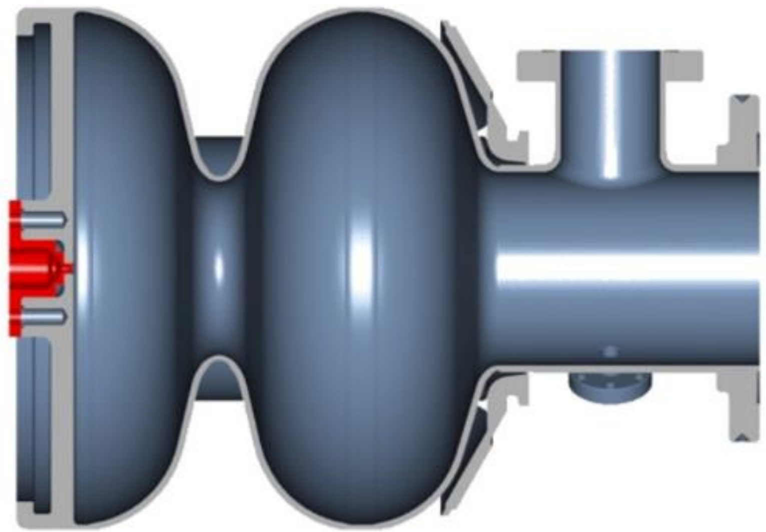
INTRODUCTION

- 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).



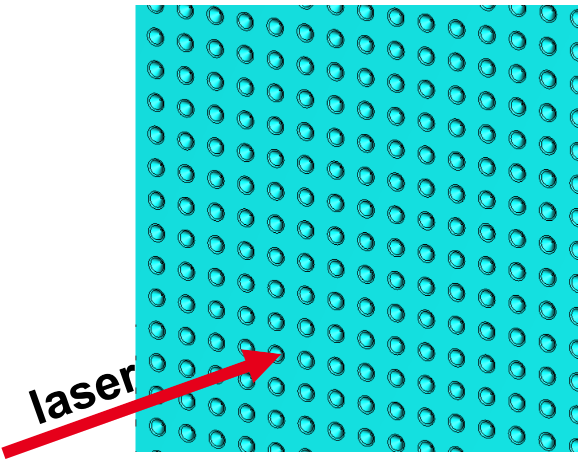
D. Bazyl, et al. "CW Operation of the European XFEL: SC-Gun Injector Optimization, S2E Calculations and SASE Performance." (2021)
D. Bazyl, "Nanostructured photocathode RnD for CW photoinjector at DESY", Deutsches Elektronen-Synchrotron (DESY), unpublished.

SHORT REMINDER OF PLASMONICS

Periodic structure

+

Laser pulse



Array of nanoholes

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SHORT REMINDER OF PLASMONICS

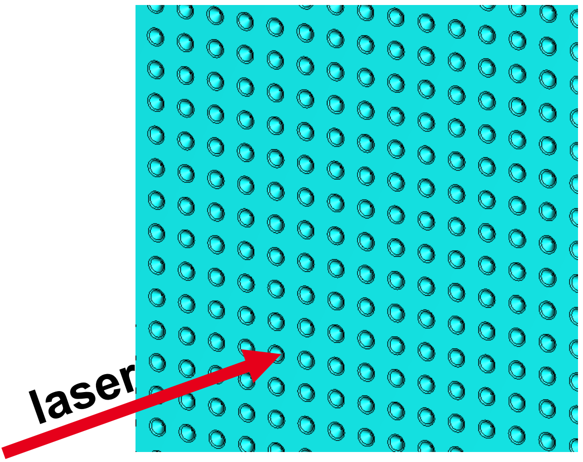
Periodic structure

+

Laser pulse

→

Surface Plasmon Polariton (SPP) modes



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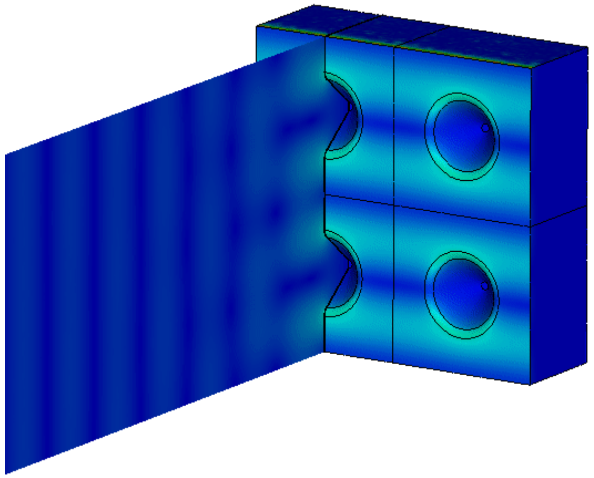
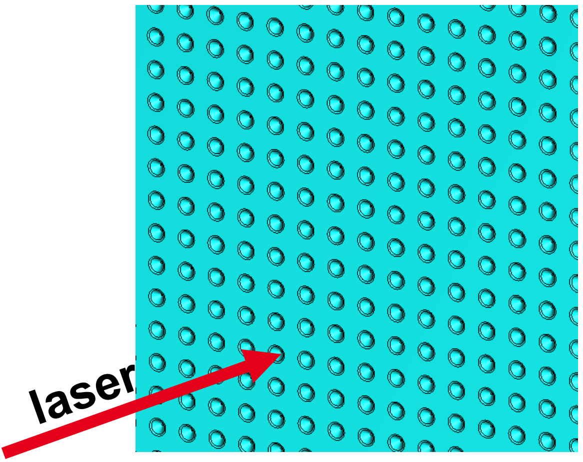


E-field

SHORT REMINDER OF PLASMONICS

Periodic structure
+
Laser pulse
→ Surface Plasmon Polariton (SPP) modes
→ Increased local absorption



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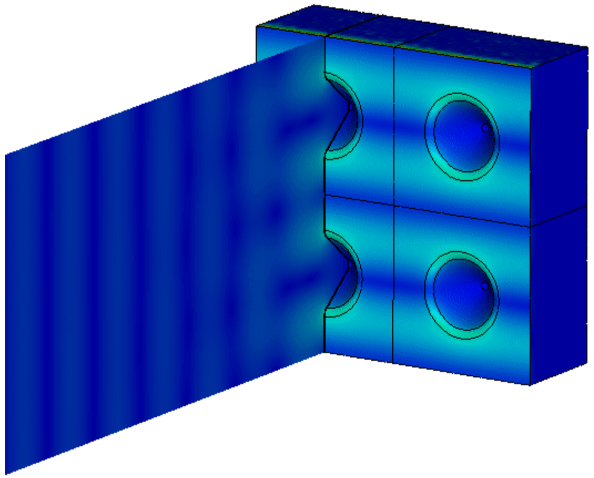
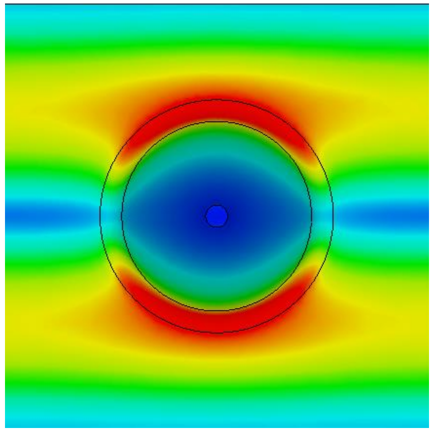

E-field


Single nanohole
E-field

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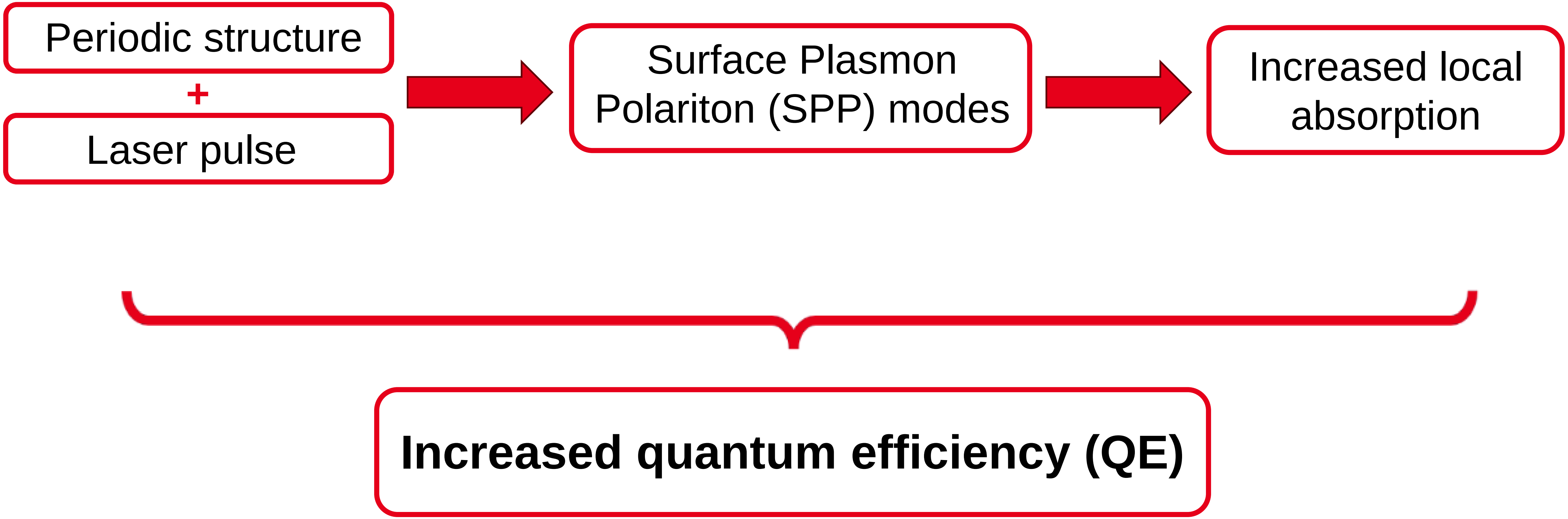
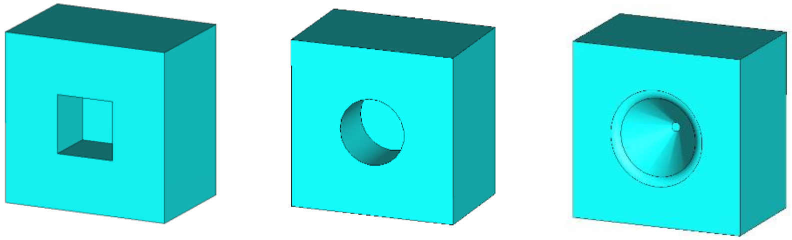
SHORT REMINDER OF PLASMONICS



ELECTROMAGNETIC SIMULATION

Shapes considered for optimization:



- Defined dispersive material properties (permittivity of copper)
  - Own fitting of permittivity data

- **Optimized three basic geometries of the nanohole**
  - **Square, round, conical nanoholes**
  - **Model: plane wave, periodic BCs**
  - **Goal: minimize reflectance (1% and less)**

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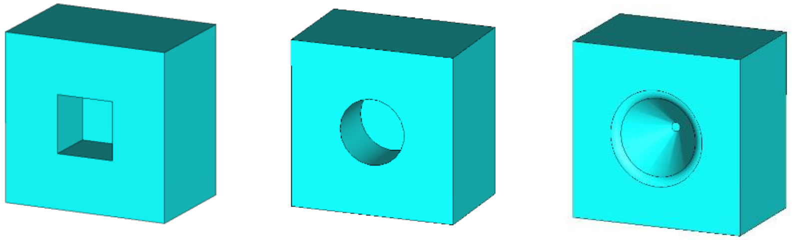
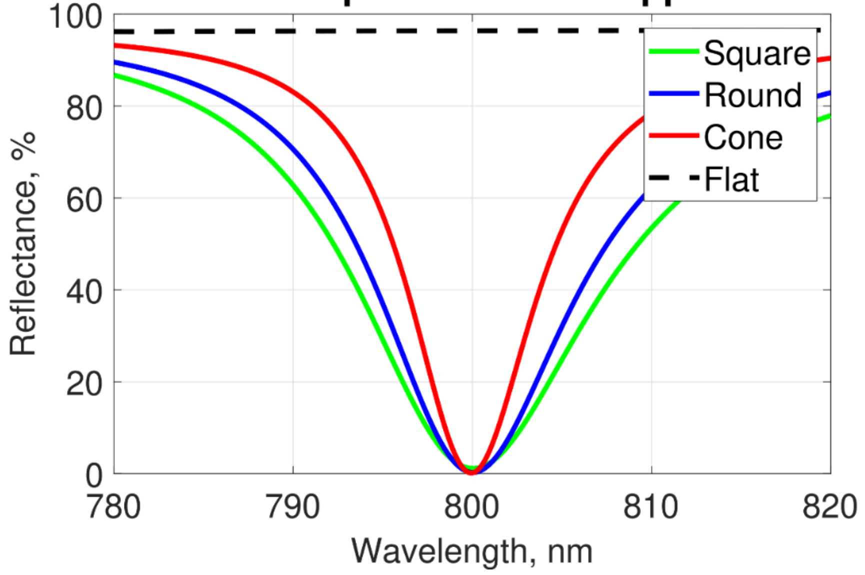


Reflectance spectra of the optimized models in comparison to flat copper

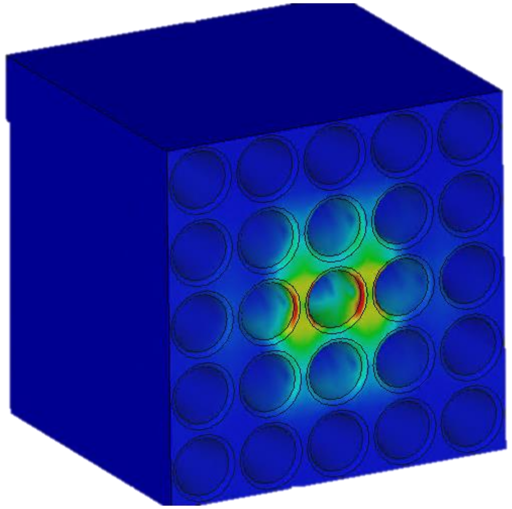


Optimized geometrical parameters

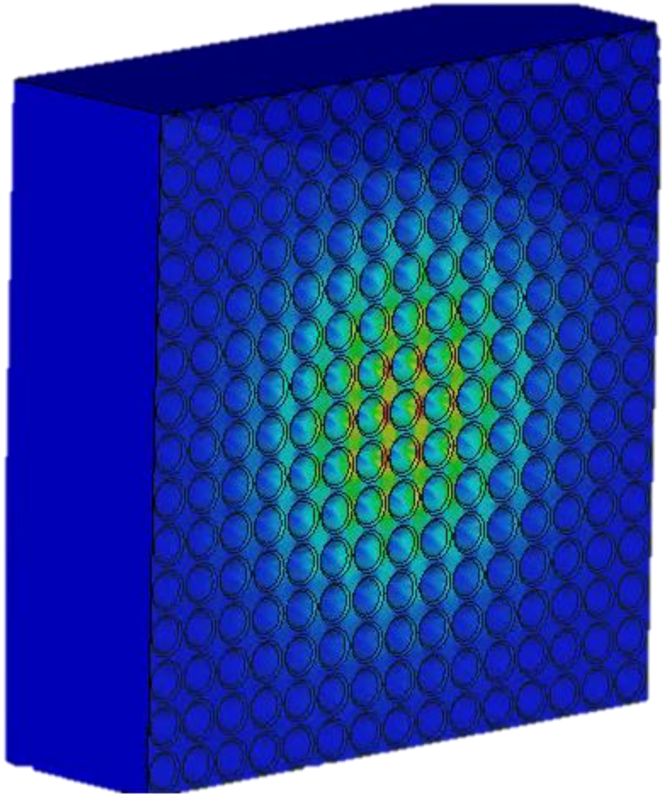
Parameter	Square	Round	Cone
Periodicity, nm	751	756	768
Nanohole width, nm	260	300	372
Nanohole depth, nm	240	240	210
Reflectance, %	**1**	**0.26**	**0.14**

GAUSSIAN LASER BEAM

Spotsize = 220 nm

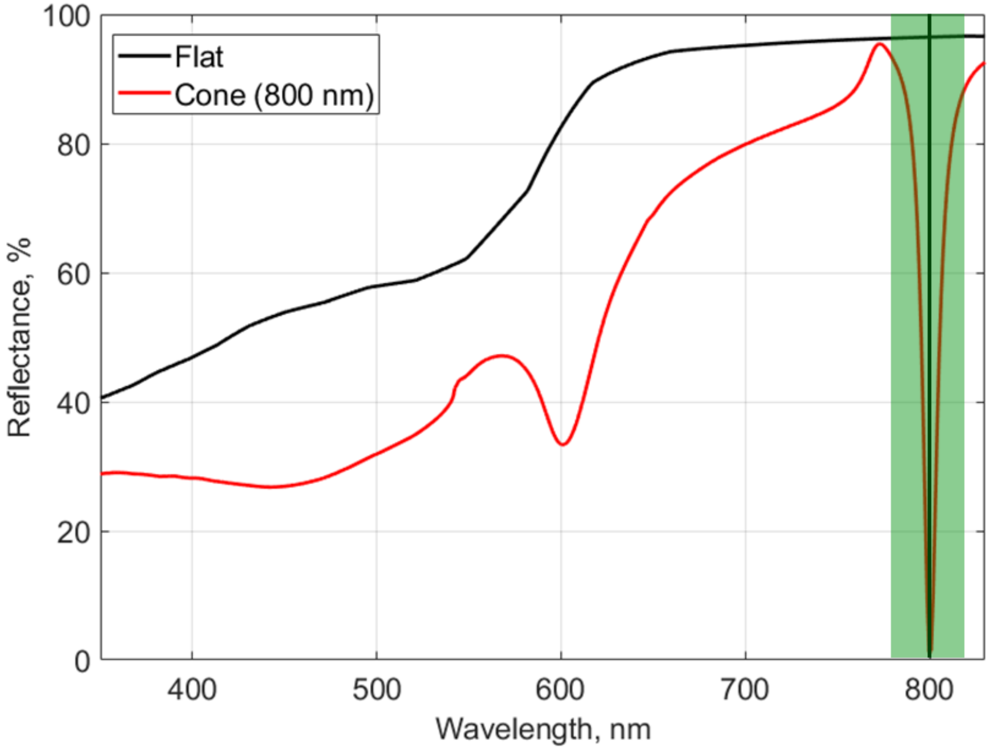


Spotsize = 1.1 µm

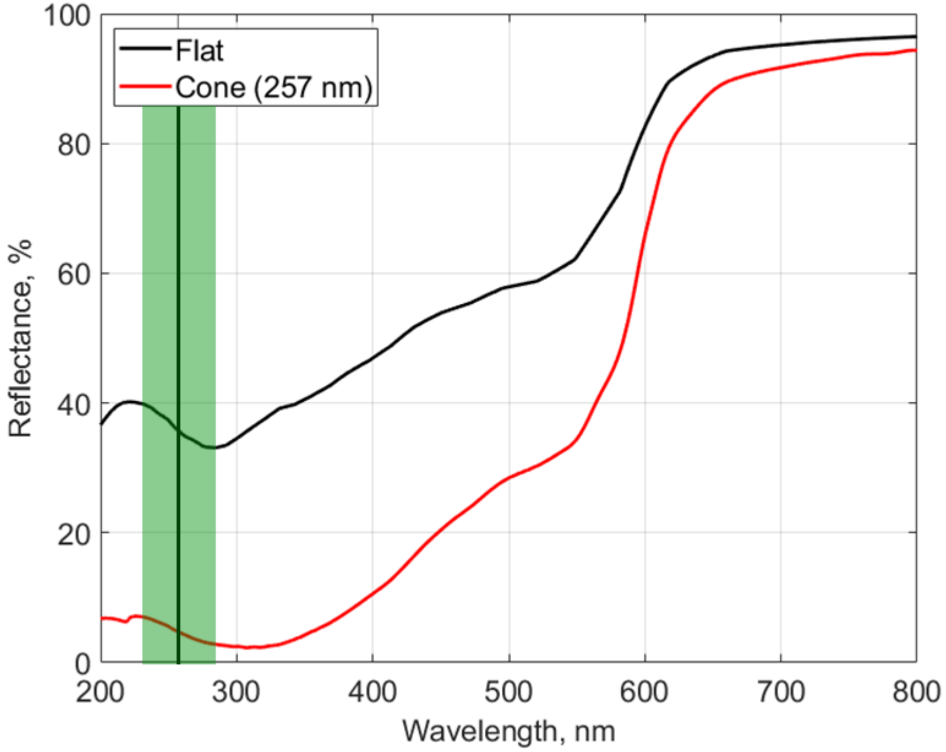


ELECTROMAGNETIC SIMULATION
BROAD RANGE REFLECTANCE SPECTRA

IR



UV



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ELECTROMAGNETIC SIMULATION
BROAD RANGE REFLECTANCE SPECTRA

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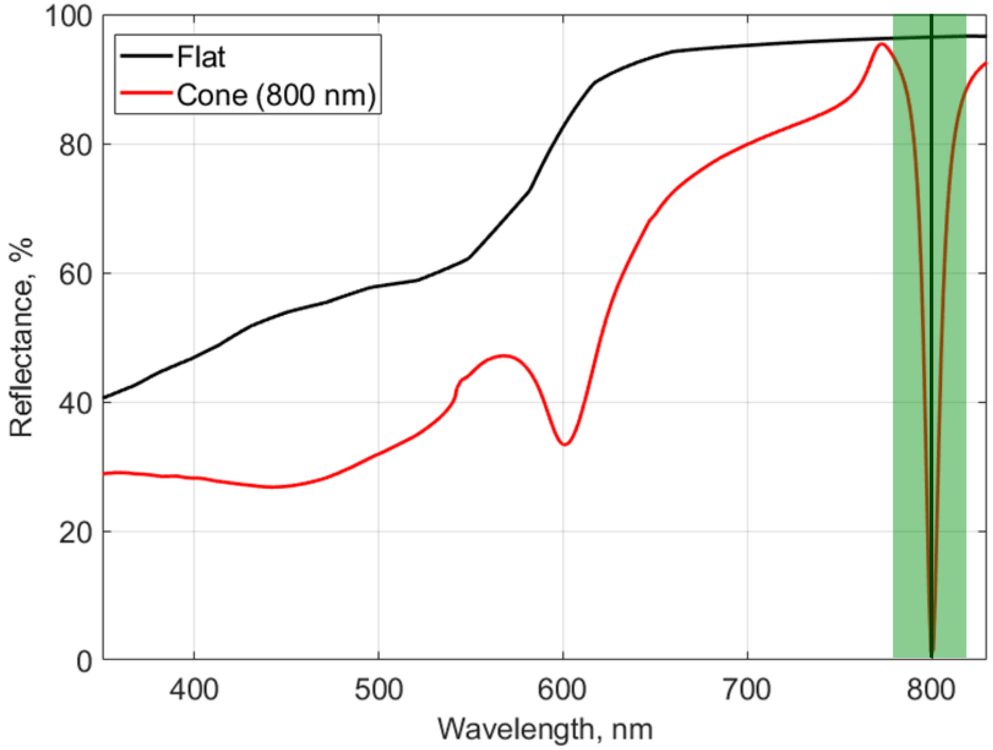

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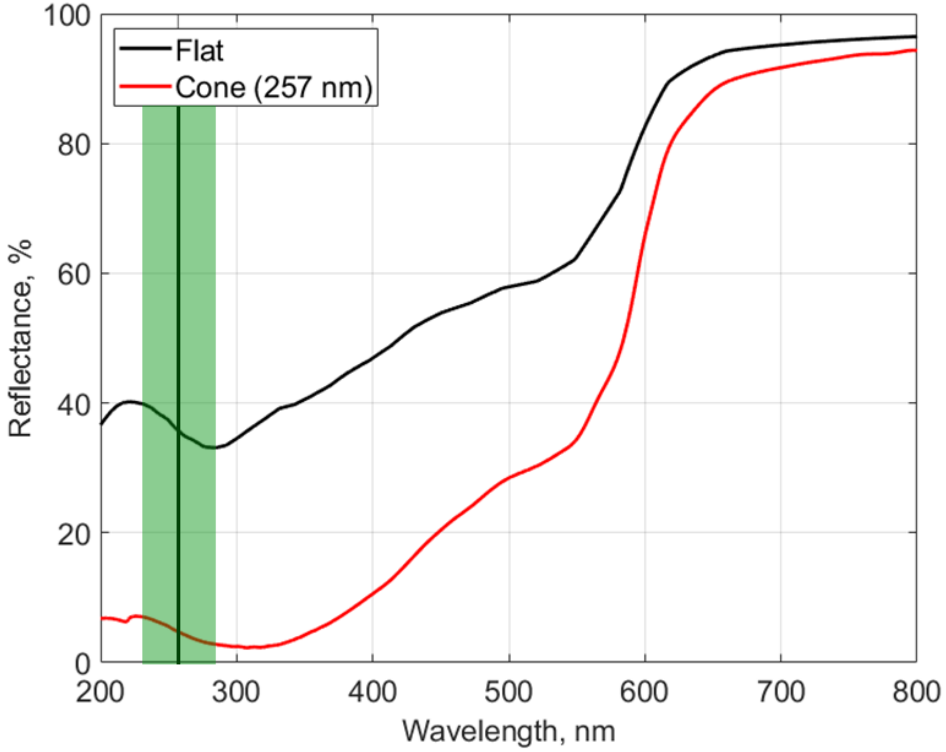

PLASMONIC PHOTOEMISSION MODEL

How to simulate photoemission from structured plasmonic cathodes?

Most beam dynamics codes are suitable **only for flat cathodes**

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CST simulation allows to use **non-flat cathode** geometry

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PLASMONIC PHOTOEMISSION MODEL

How to simulate photoemission from structured plasmonic cathodes?

Most beam dynamics codes are suitable **only for flat cathodes**

CST simulation allows to use **non-flat cathode** geometry

No **photoemission** in Particle-in-Cell solver

PLASMONIC PHOTOEMISSION MODEL

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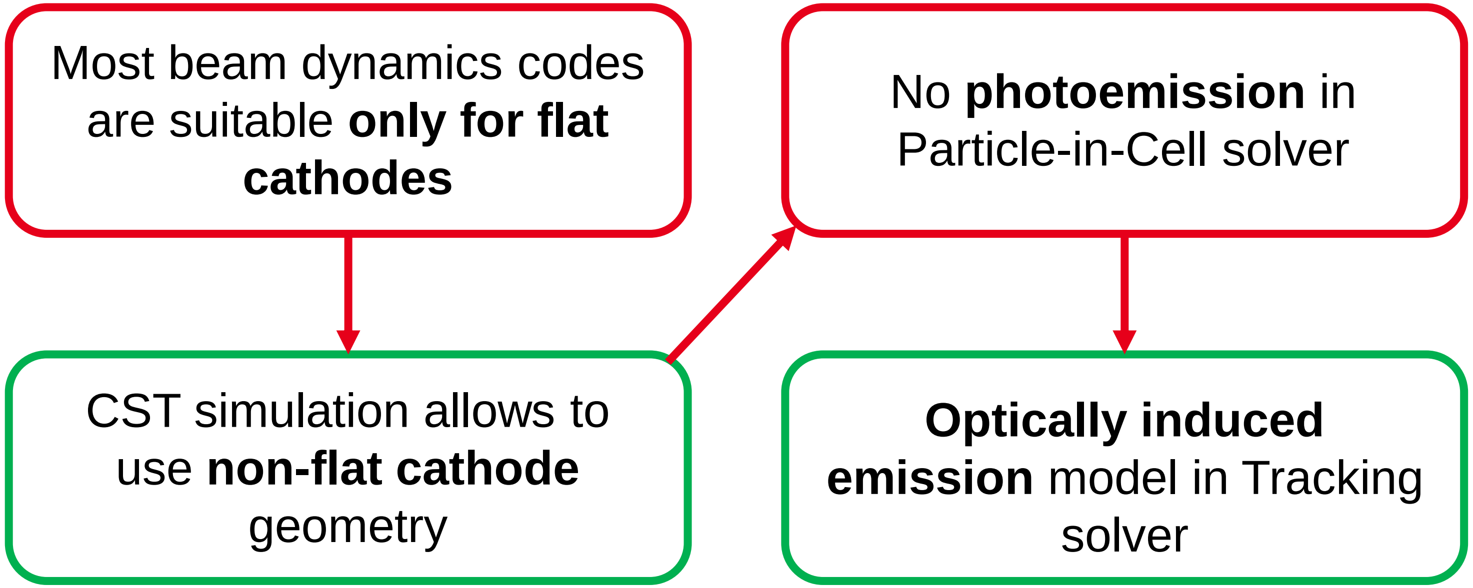

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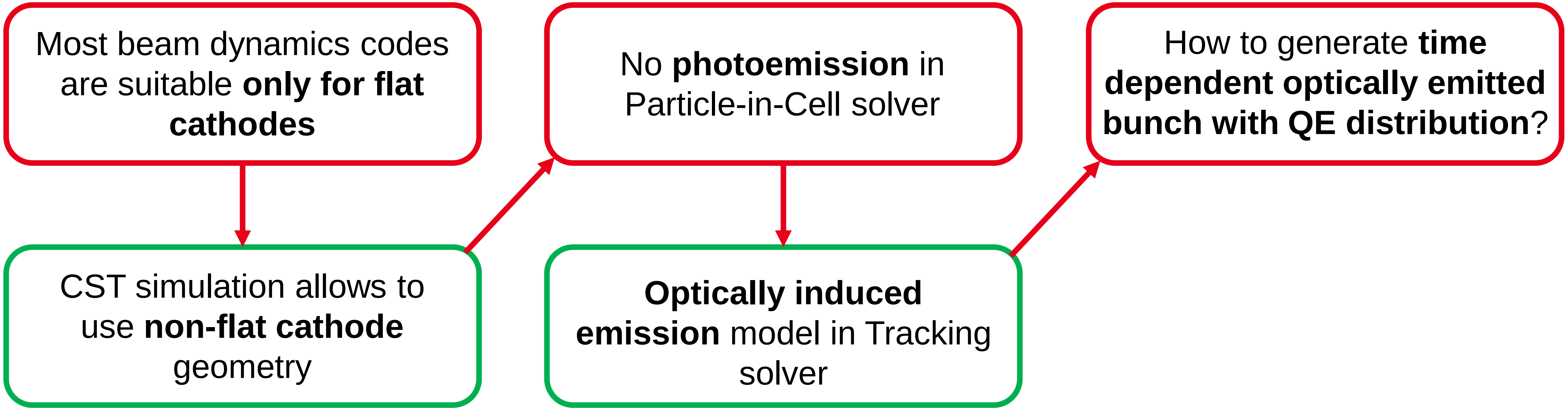


SPATIAL QE DISTRIBUTION

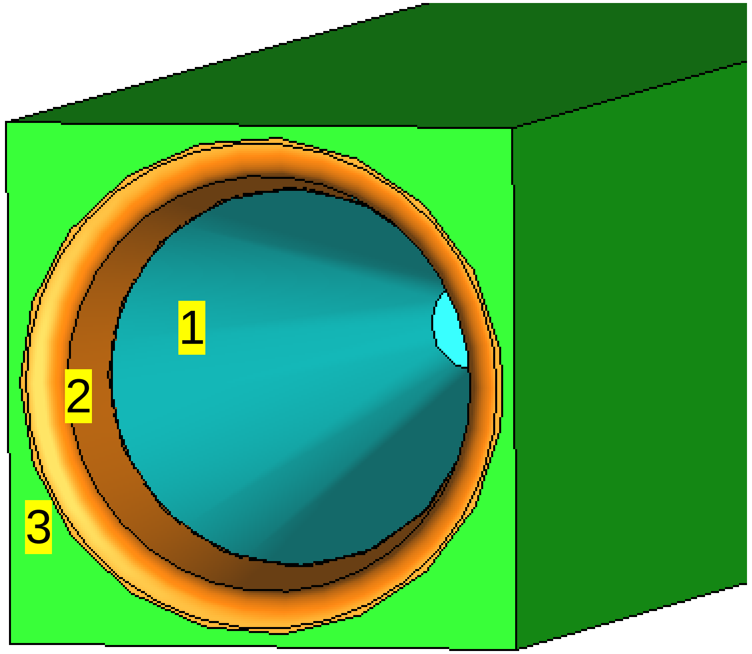
Electromagnetic simulation (257 nm):

- Separate the whole cathode into subvolumes and assign different materials
- Calculate total power loss and absorptance per material
- Compute QE using simplified 3 step model

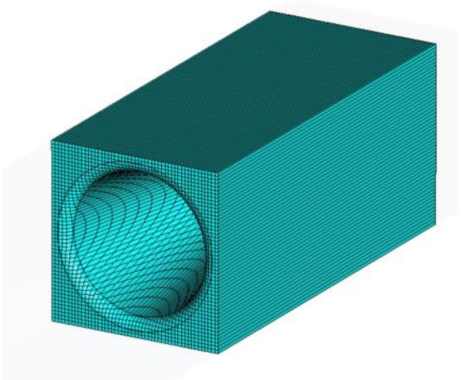
$$A_i = \frac{P_i}{P_{stimulated}}$$

Absorptance

$$\mathrm{QE}(\omega) \approx \frac{\boxed{1 - R(\omega)}}{1 + \frac{\lambda_{\mathrm{opt}}(\omega)}{\lambda_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{\mathrm{eff}})^2}{8\phi_{\mathrm{eff}}(E_F + \phi_{\mathrm{eff}})}.$$



SPATIAL QE DISTRIBUTION



- **Export power loss distribution in volume from electromagnetic simulation with a fixed step**

SPATIAL QE DISTRIBUTION

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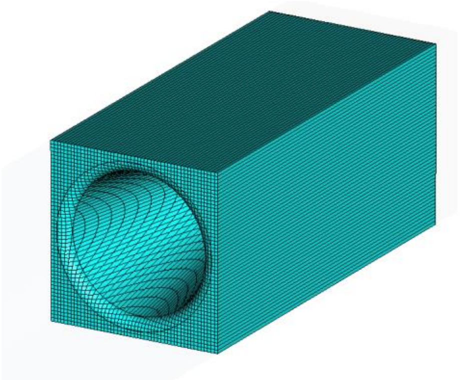

- Export power loss distribution in volume from electromagnetic simulation with a fixed step
- **Calculate QE using simplified 3 step model**

Absorptance

$$\mathrm{QE}\,(\omega) \approx \frac{\boxed{1 - R(\omega)}}{1 + \frac{\lambda_{\mathrm{opt}}(\omega)}{\lambda_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{\mathrm{eff}})^2}{8\phi_{\mathrm{eff}}(E_F + \phi_{\mathrm{eff}})}.$$

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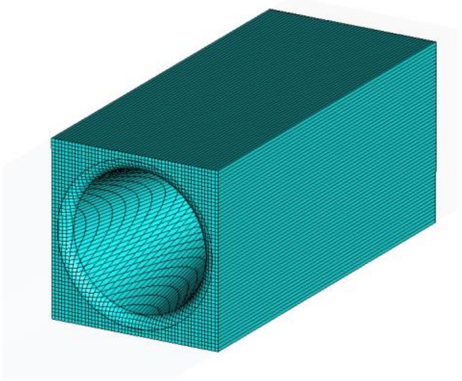
SPATIAL QE DISTRIBUTION



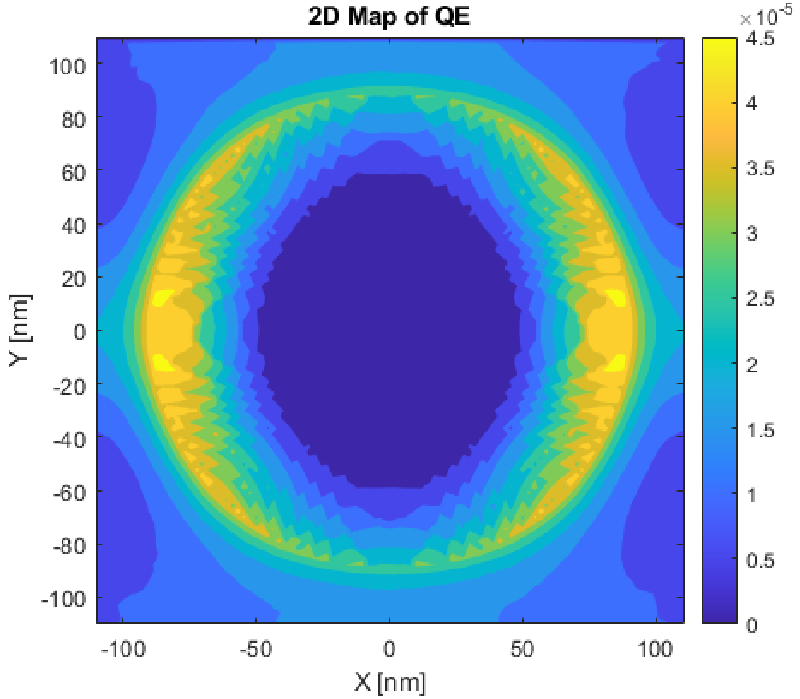
- Export power loss distribution in volume from electromagnetic simulation with a fixed step

- Calculate QE using simplified 3 step model

- **Assign calculated QE to every vortex**

Absorptance

$$\mathrm{QE}(\omega) \approx \frac{\boxed{1 - R(\omega)}}{1 + \frac{\lambda_{\mathrm{opt}}(\omega)}{\lambda_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{\mathrm{eff}})^2}{8\phi_{\mathrm{eff}}(E_F + \phi_{\mathrm{eff}})}.$$

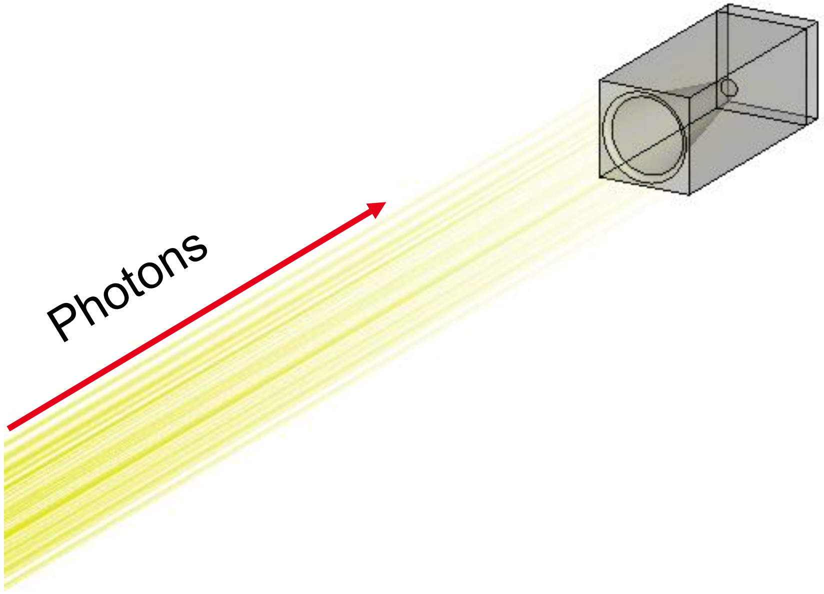


BEAM DYNAMICS IN THE CATHODE VICINITY

Optically induced emission model (photoemission):

- **Use light source with given wavelength and power**

$$J = \frac{e\, QE(\lambda)\, \phi(\lambda)}{\hbar\omega}$$



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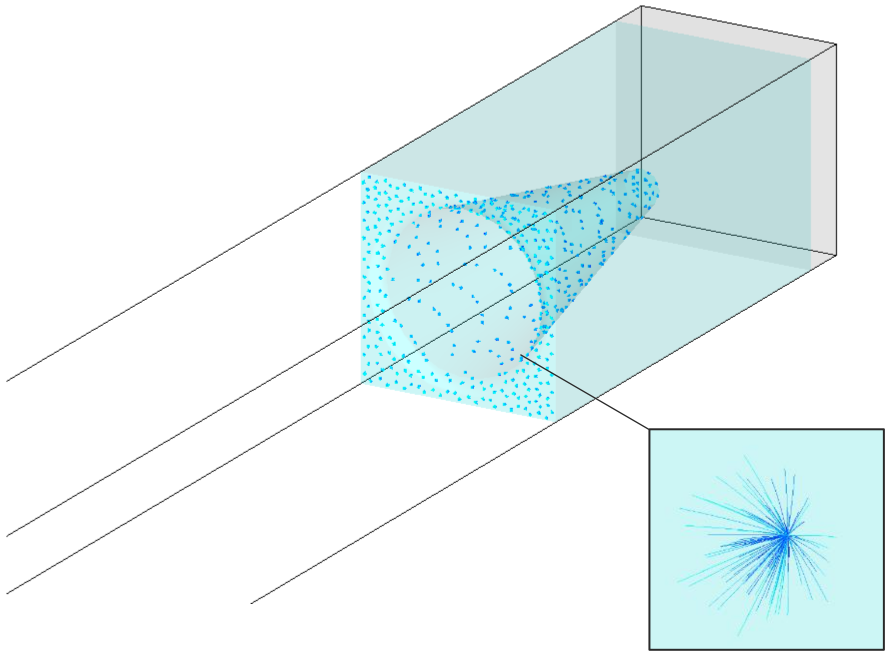
BEAM DYNAMICS IN THE CATHODE VICINITY

Optically induced emission model:

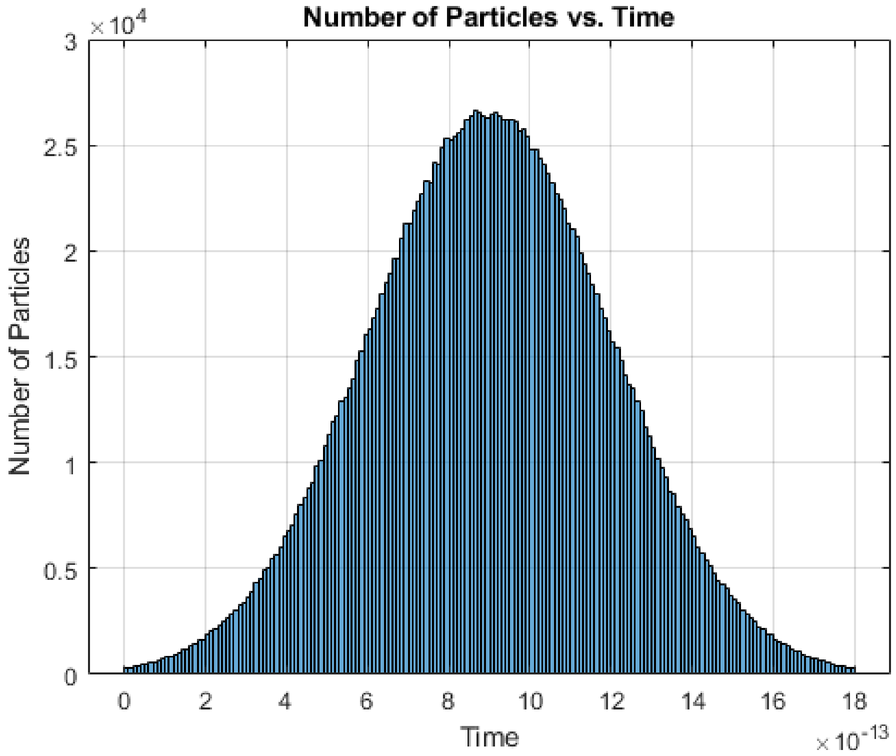
- Use light source with given wavelength and power
  - **Get sample distribution on the cathode**
  - **Get emission angle distribution at the cathode**
  - **Get emission current for given power**



BEAM DYNAMICS IN THE CATHODE VICINITY

Optically induced emission model:

- Use light source with given wavelength and power
  - Get sample distribution on the cathode
  - Get emission angle distribution at the cathode
  - Get emission current for given power
- **Construct temporal current profile for each cathode sample according to the laser pulse**



BEAM DYNAMICS IN THE CATHODE VICINITY

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  - Get sample distribution on the cathode
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- Construct temporal current profile for each cathode sample according to the laser pulse
- **Import particle data into E-static PIC solver as a particle interface**

RESULTS

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

- Preliminary **beam dynamics** simulation:
  - **Spatial Quantum Efficiency distribution** on the cathode surface
  - Plasmon-enhanced optically induced **emission model (photoemission)**
  - **Preliminary beam dynamics (Electrostatic-PIC simulation)**
  - Effect on transversal and longitudinal beam characteristics