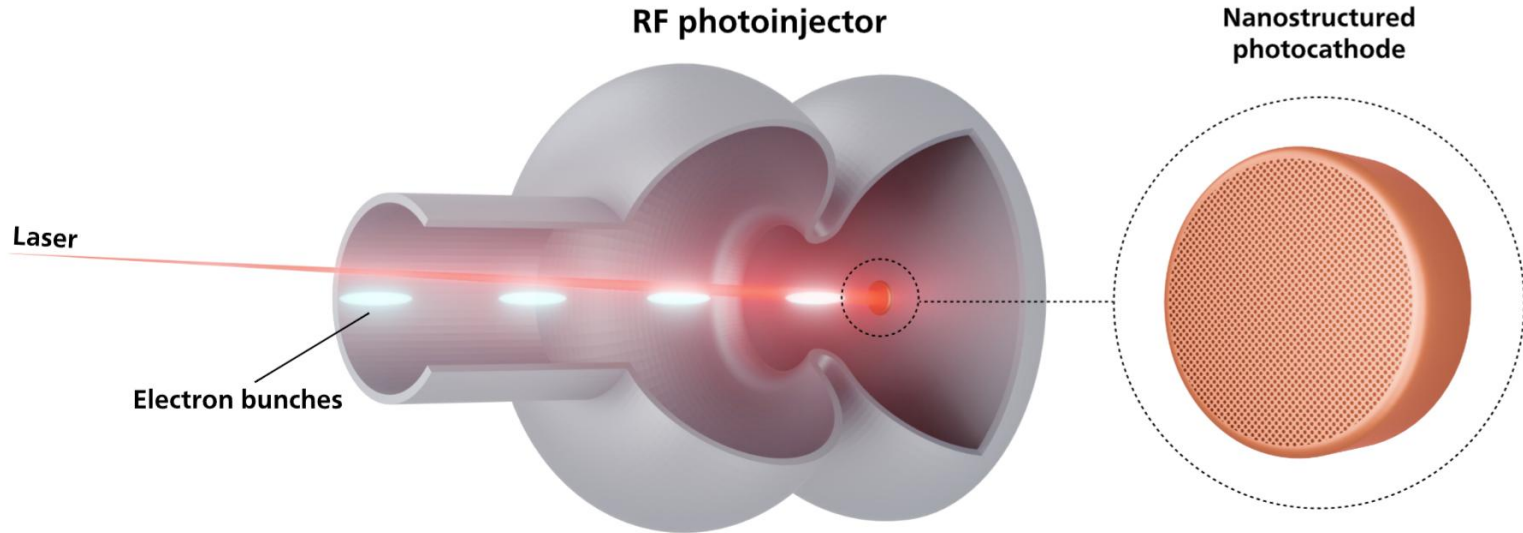


Simulation study of nanostructured plasmonic metallic photocathodes

M.Bulgacheva, E.Gjonaj

Technical University of Darmstadt, Germany



Motivation & workflow

Nanostructured copper photocathodes use surface-plasmon field enhancement to increase QE and therefore photocurrent, which means: **the laser energy needed to generate the bunch can be reduced.**

The open question: what impact does the enhanced emission have on the beam quality?

Workflow:



Surface-plasmon-enhanced photoemission

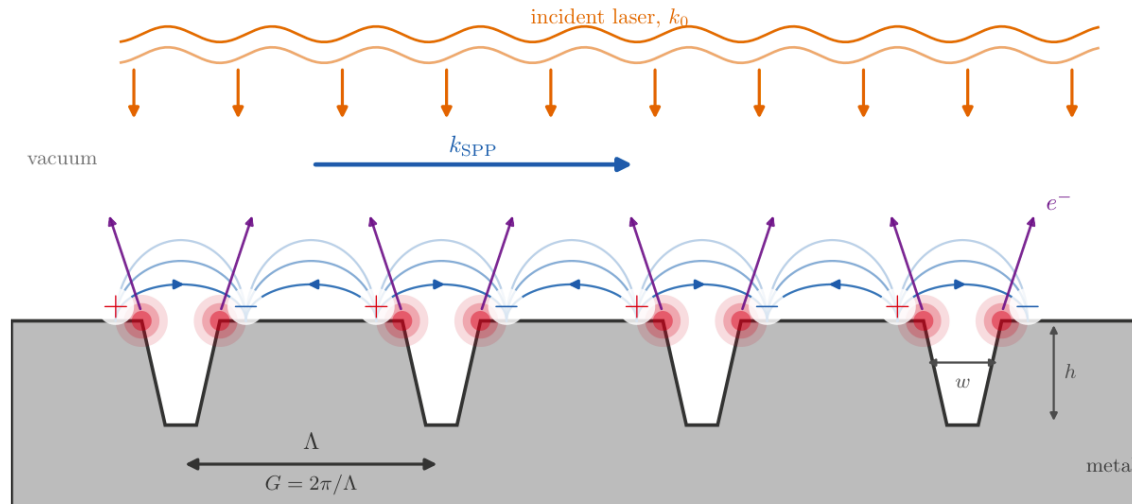
Periodic structure

+

Laser pulse

Surface Plasmon
Polariton (SPP) modes

Increased local
absorption



Electromagnetic characterization

Geometry: conical nanoholes

Periodic boundary conditions

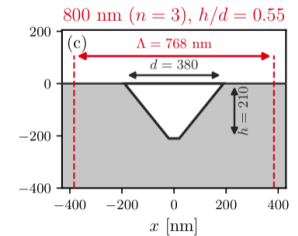
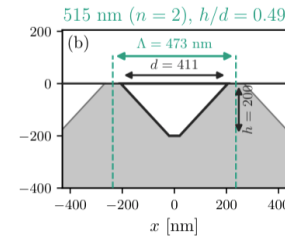
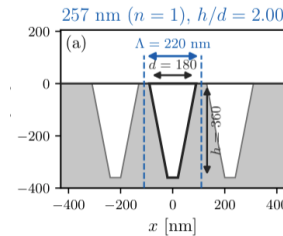
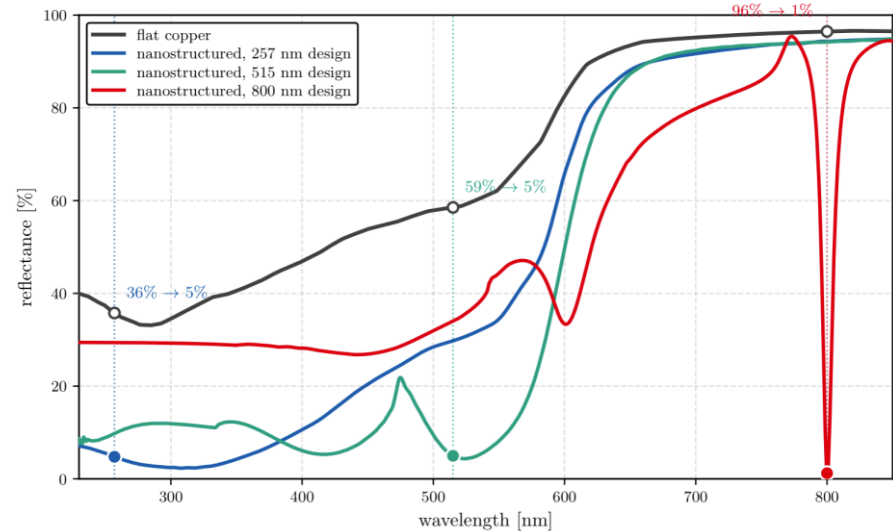
Plane wave excitation

Optimization objective:

Reflectance minimization at given λ

3 drive wavelengths:

257 nm (UV), 515 nm (green), 800 nm (IR)



Nanostructured photocathode simulation

Electromagnetic simulation

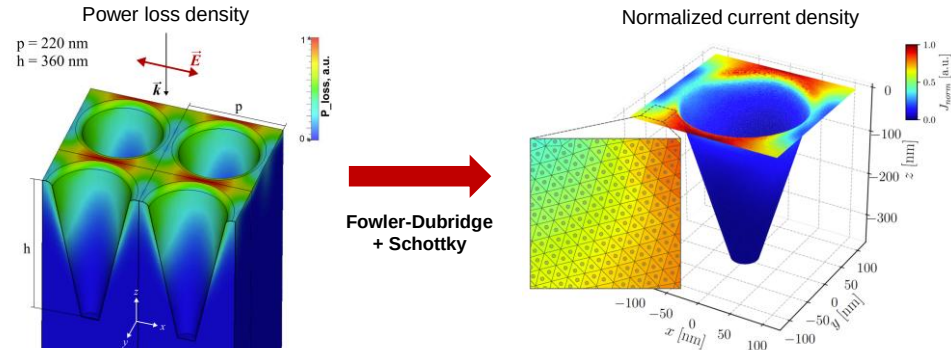
- FIT-TD with plane wave excitation
- Geometry optimization

Photoemission model

- Spatially-resolved photocurrent calculation including Schottky
- Emission samples (particle interface)

Beam dynamics simulations

- Near-cathode PIC
- Micro- to macroscale



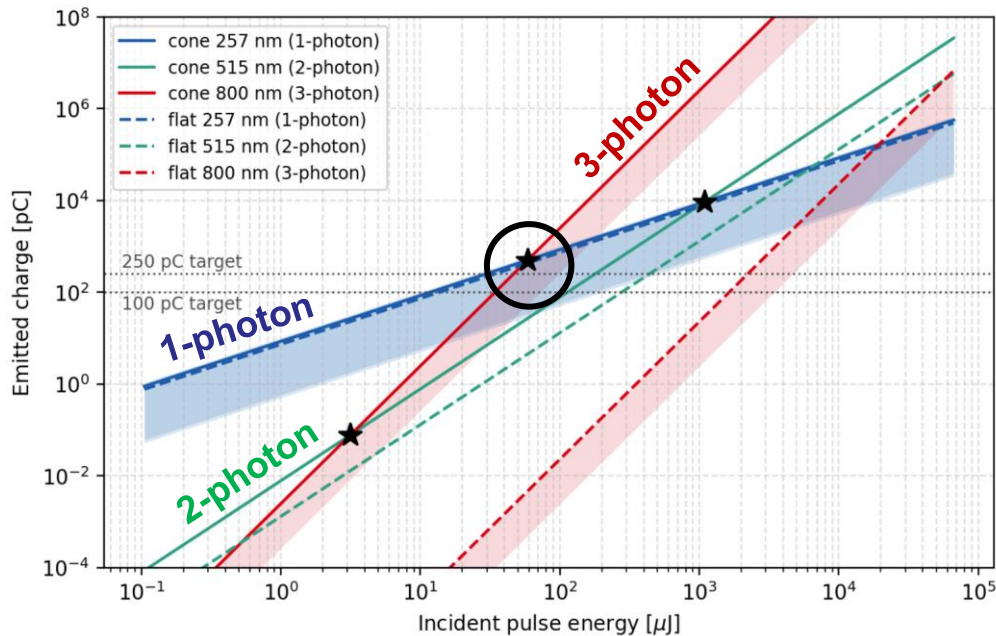
Fowler-Dubridge photoemission model

$$J_n(\mathbf{r}, \omega) = a_n A_0 \left(\frac{e}{h\nu} P_\lambda(\mathbf{r}, \omega) \right)^n T^2 F \left(\frac{nh\nu - e\Phi(\mathbf{r})}{k_B T} \right)$$

- P_λ — absorbed power from FIT (spatially resolved)
- $\Phi(\mathbf{r})$ — work function, lowered by the Schottky effect
- n — photoemission order **from local work function**

Charge yield grows sharply with photon order

Emitted charge vs laser pulse energy (Schottky, a_n band)



1-photon (257 nm)
 $\sim 1.2\times$

2-photon (515 nm)
 $\sim 6\times$

3-photon (800 nm)
 $\sim 10^5\times$

Which NS cathode requires less pulse energy to produce a 100pC/250pC bunch?

- UV
- When noting IR→DUV conversion: IR

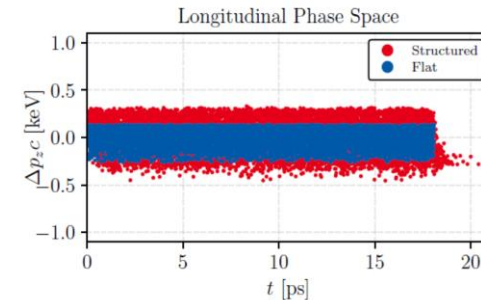
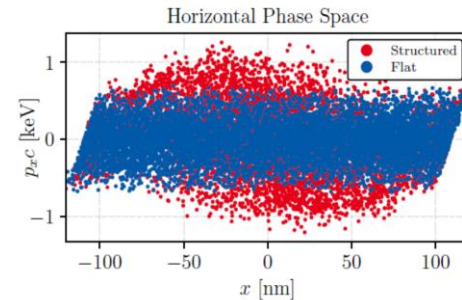
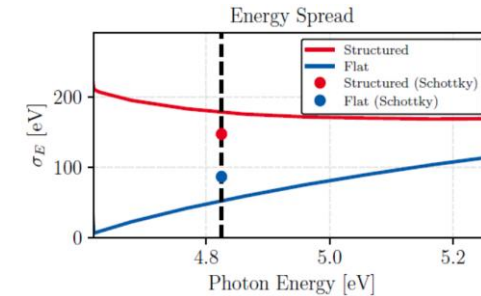
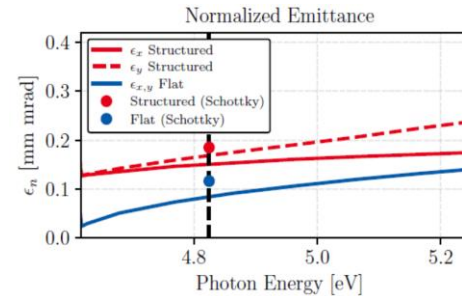
a_n caveat: the multiphoton coefficients are empirical, with a spread of about an order of magnitude. They affect absolute yields and the comparison between emission orders, not the NS-vs-flat ratio at a fixed wavelength.

$$J_n(\mathbf{r}, \omega) = a_n A_0 \left(\frac{e}{\hbar v} P_\lambda(\mathbf{r}, \omega) \right)^n T^2 F \left(\frac{\hbar v - e\Phi(\mathbf{r})}{k_B T} \right)$$

Beam dynamics near the cathode

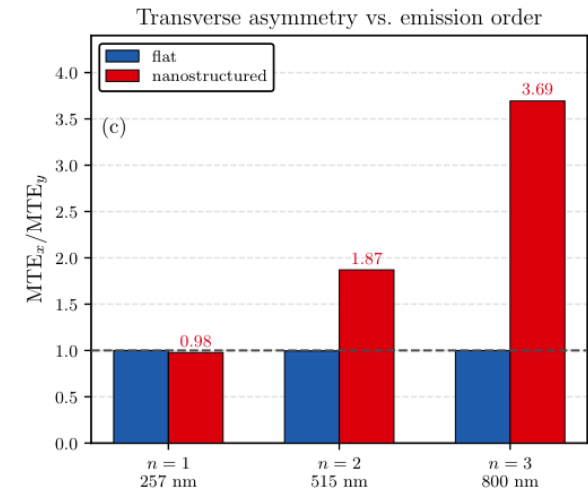
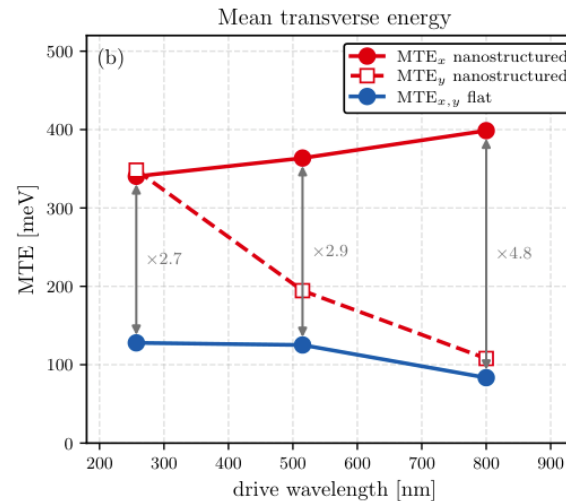
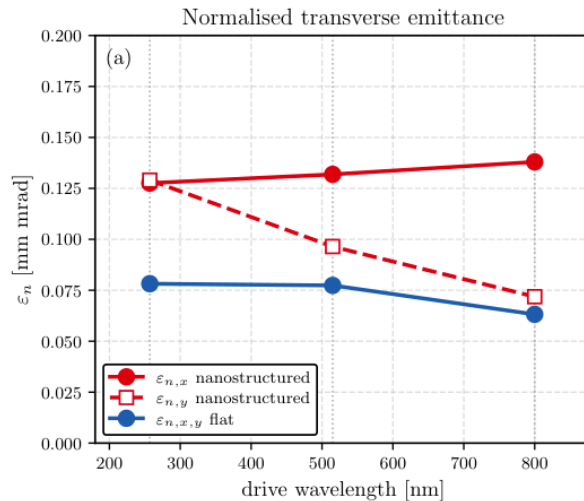
UV (257 nm) cathode

- **Asymmetric transverse phase space** aligned with laser polarization due to SPP field localization at nanohole edges
- **Larger energy spread** than flat Cu: low-energy tail from electrons emitted deep inside the nanohole
- **Schottky effect** suppresses low-energy tail by enhancing top-surface emission
- The **geometry** causes a charge loss inside the UV nanostructure



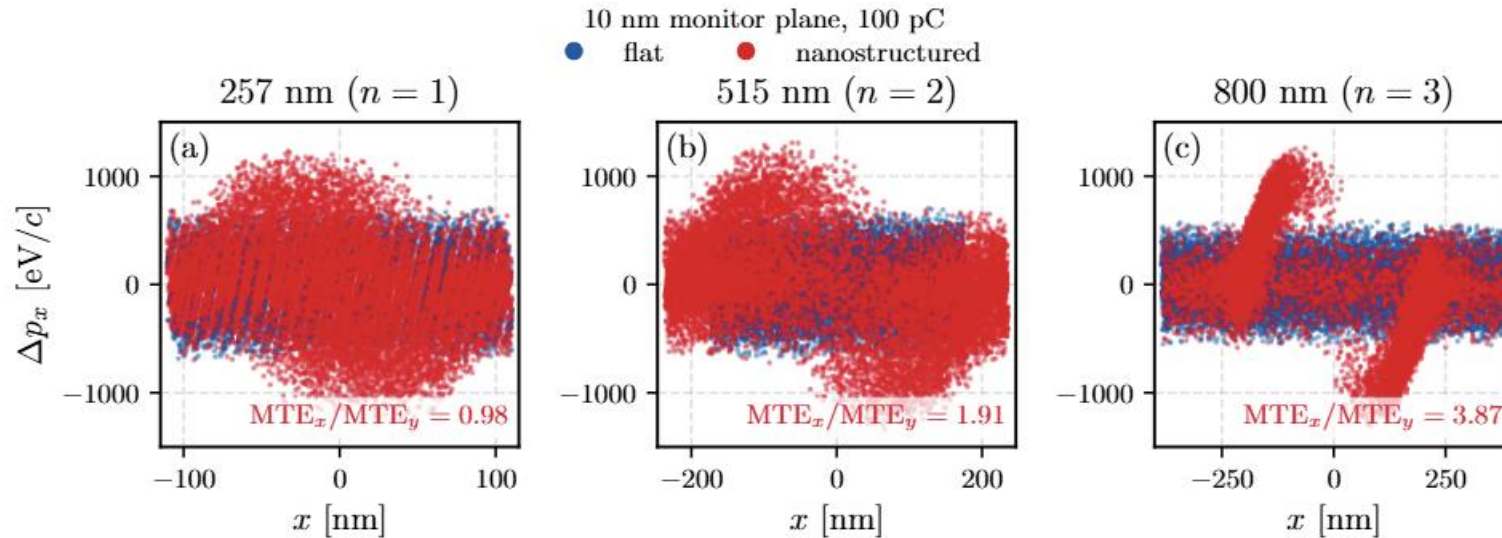
Anisotropy vs. photoemission order

With the photoemission order increasing, the **beam asymmetry also increases** because of the stronger enhanced field localization on the rims of the nanohole.



Anisotropy vs. photoemission order

With the photoemission order increasing, the **beam asymmetry also increases** because of the stronger enhanced field localization on the rims of the nanohole.



Charge loss is geometric

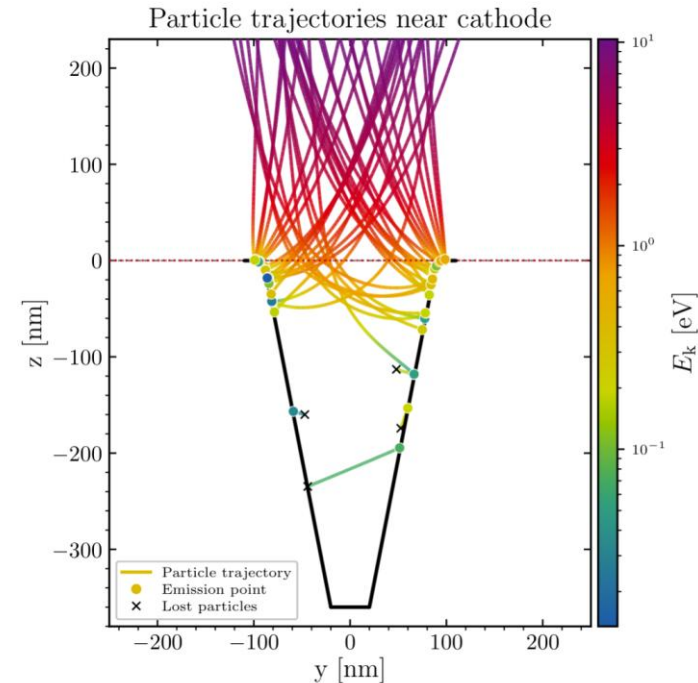
	100 pC	250 pC
transverse	flat-top, $\sigma = 0.16$ mm	flat-top, $\sigma = 0.25$ mm
temporal	Gaussian, $\sigma_t = 7$ ps	Gaussian, $\sigma_t = 3$ ps

Transmission at 100 pC (10 nm plane): flat cathode 99% at all wavelengths; NS: **92% (UV)**, >98% (green, IR).

UV: the deep nanohole (360 nm) traps electrons emitted from the inner walls: about 8% are lost, plus a further 1% during the drift to 500 nm → the loss is **geometric**.

IR, green: negligible charge loss at 100 pC and 250 pC.

Space charge maximum is located at roughly **100 nm above the surface**; inside the cones the charge density decreases.



Micro- to macroscale: scale-up procedure

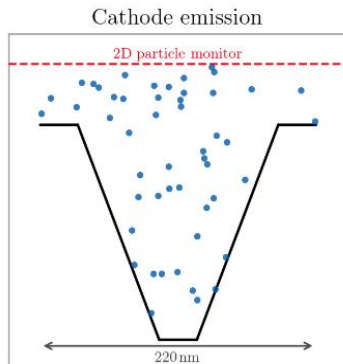
PIC near-cathode
simulation (micro-scale)

Homogenization with
ML and scale-up

Full-scale e-gun
simulations (cluster)

Virtual cathode

Planar reference plane
at a distance above the
nanostructure.

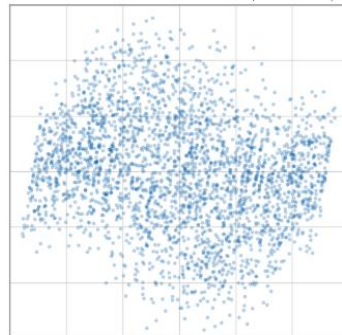


particle
interface

Discrete 6D data

Macroparticle
distributions from
single-cell PIC runs.

Horizontal phase space (discrete)

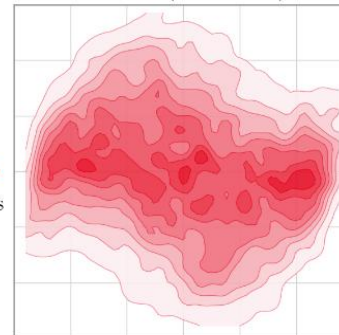


normflows

Normalizing flows

Invertible network
mapping particles →
continuous 6D density.

Sampled (continuous)

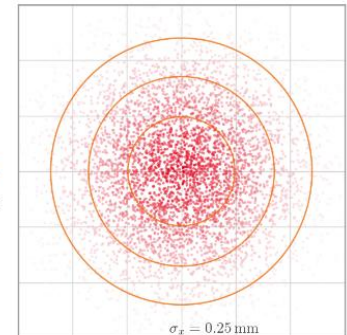


seed over
cathode

Full-cathode seeding

Model replicated across
the cathode, weighted by
the laser intensity profile.

Full-cathode seeding



Conclusions

- **Charge yield increases sharply with photon order:** nanostructuring increases the charge by $\sim 1.2\times$ (1-photon, 257 nm), $\sim 6\times$ (2-photon, 515 nm), and $\sim 10^5\times$ (3-photon, 800 nm) vs flat copper.
- **Nanostructuring leads to beam quality degradation:** emittance and energy spread increase over flat copper; the Schottky effect partially compensates by suppressing the low-energy tail.
- **UV charge loss is geometric:** geometric trapping in the deep UV structure (92% transmission), independent of bunch charge; no space-charge-driven loss at any wavelength.

