Space-Charge Dominated Photoemission in High Gradient Photocathode RF Guns

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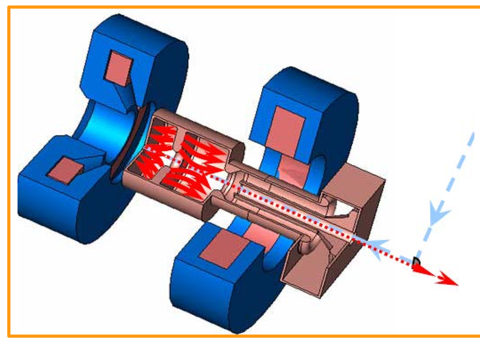
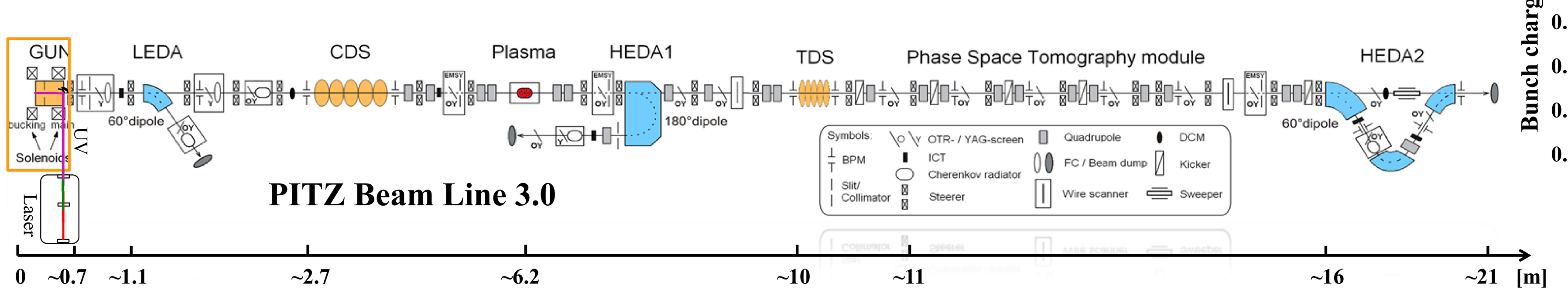
THPO116 (THOP11)

INTRODUCTION

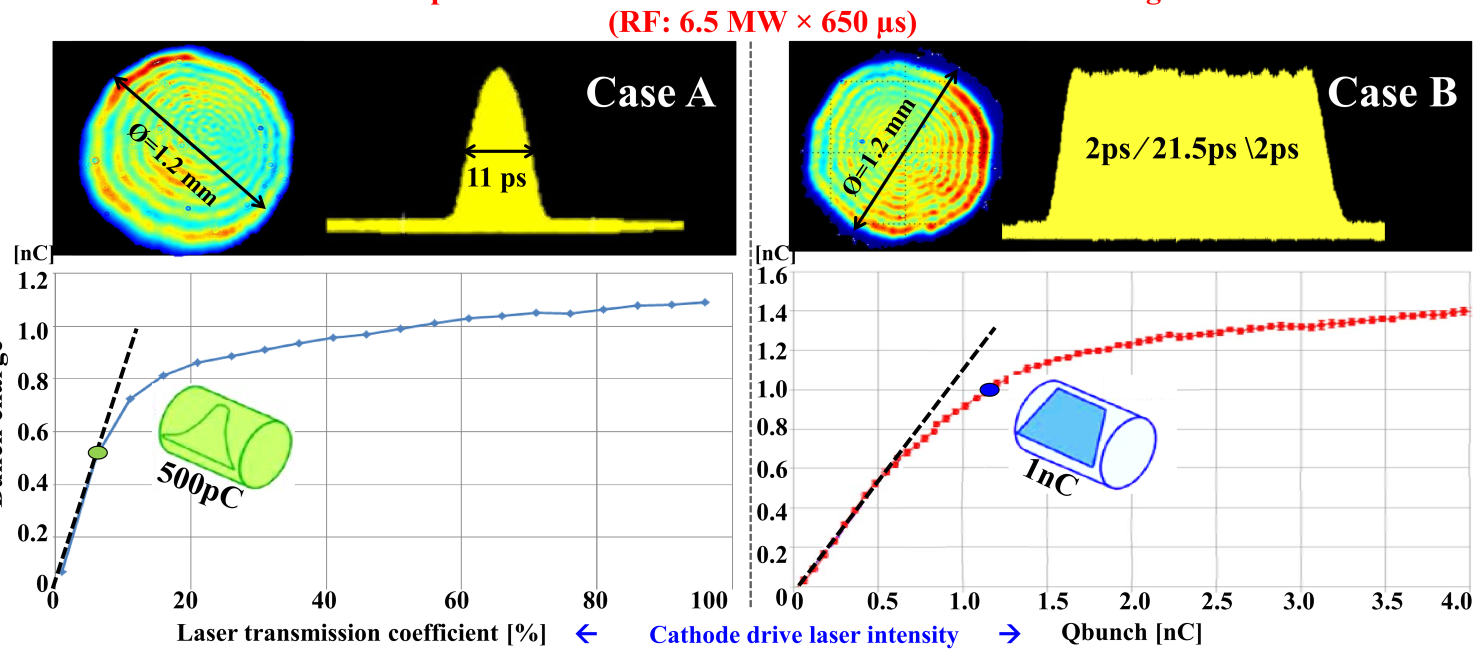


RF Gun
- **L-band** (1.3 GHz) 1.6-cell copper cavity
- Ecath ≥ **60 MV/m** → 7 MeV/c e-beams
- 650 µs ×10 Hz → up to **45 kW** av. RF power
- **Cs_2Te** PC (QE~5-10%) → up to 5 nC/bunch
- LLRF control for amp & phase **stability**
- Solenoids for emittance compensation

The PITZ gun copies are in use at the European X-ray Free Electron Laser (E-XFEL) and the Free electron LASer in Hamburg (FLASH).



Standard Operation Conditions at PITZ for the E-XFEL Working Points (RF: 6.5 MW × 650 µs)

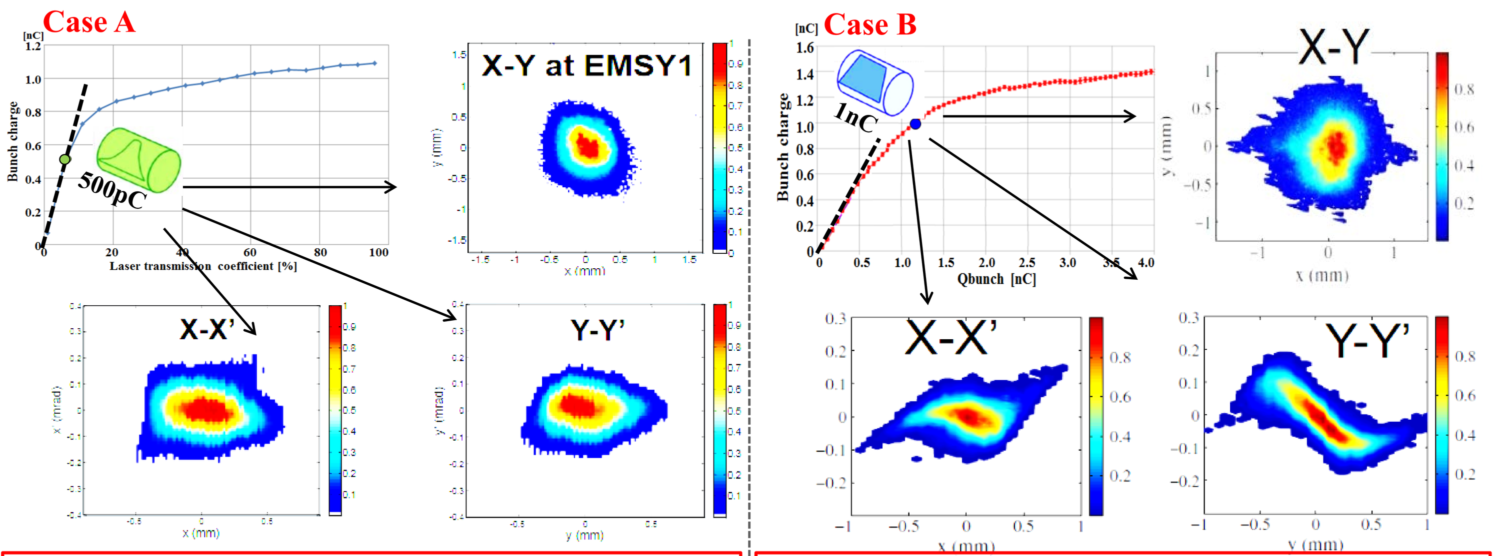


Beam Extraction at Cathode Already Strongly Influenced by Space Charge Effects!

EMITTANCE MEASUREMENT

Best Emittance Experimentally Demonstrated Using Space-Charge Dominated Beams

Measured Transverse Phase Spaces and Beam Profile @ Injector Exit



$\varepsilon_{x,n} \approx 0.82$ mm mrad $\varepsilon_{y,n} \approx 0.84$ mm mrad $\sqrt{\varepsilon_{x,n}\varepsilon_{y,n}} \approx 0.83$ mm mrad | $\varepsilon_{x,n} \approx 0.72$ mm mrad $\varepsilon_{y,n} \approx 0.60$ mm mrad $\sqrt{\varepsilon_{x,n}\varepsilon_{y,n}} \approx 0.66$ mm mrad

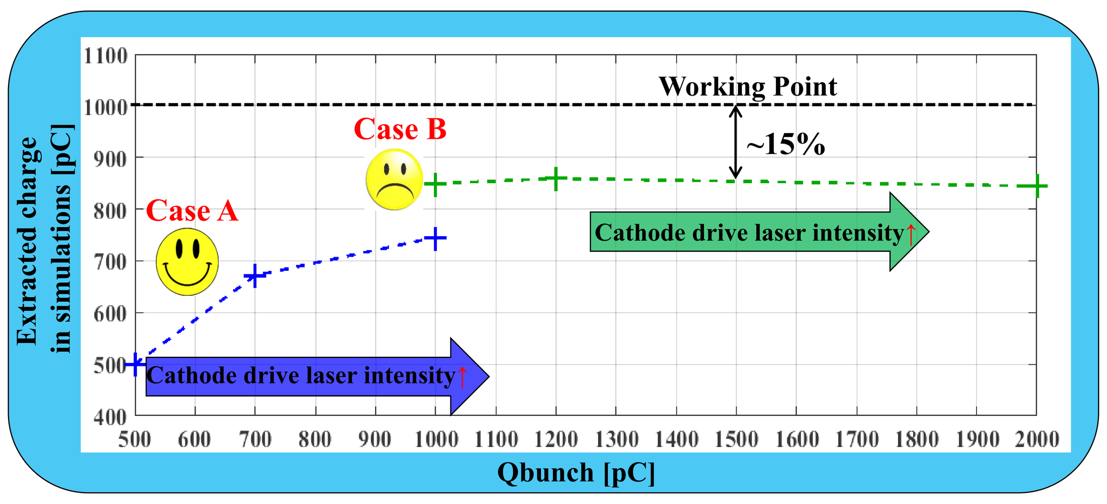
NB: quadrupoles at gun exit applied in Case A for compensating beam asymmetries

BEAM DYNAMICS

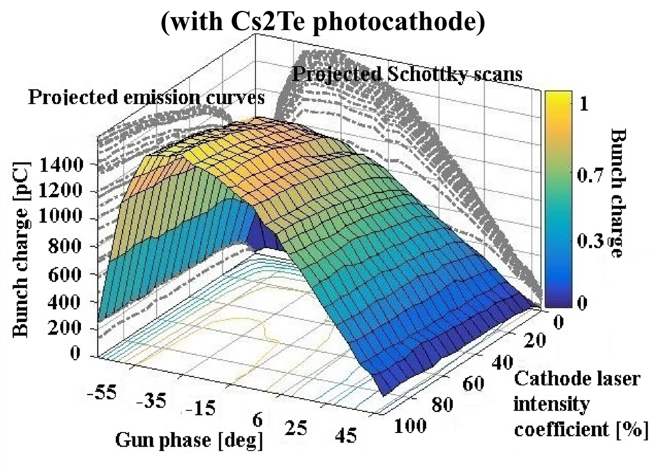
Charge Packet Creation in Simulations at E-XFEL Working Points

Directly plugging experimental parameters in simulations,

→1 nC could not be extracted →500 pC can be extracted

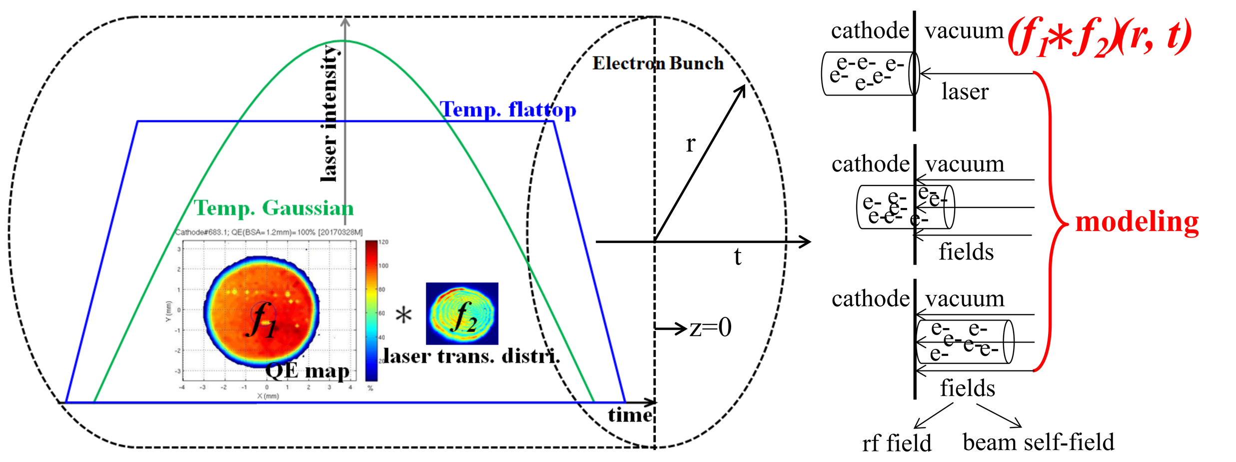


Reconstructed Measurement Data of Photoemission (with Cs2Te photocathode)



Discrepancies of emitted bunch charge in beam dynamics simulation w.r.t. measurement present in the characteristic emission curves

PHOTOEMISSION PROCESS



Simplified photoemission model(s)

→ **"Bridging beam dynamics in vacuum with the effective cathode QE"**

For metal cathodes*
$$QE = \frac{\alpha(\hbar\omega - \Phi_{eff})^2}{8\Phi_{eff}(E_F + \Phi_{eff})} \qquad \Phi_{eff} = \Phi_0 \pm \Phi_{schottky} + \cdots$$

Φ_{eff} :effective cathode work function
Φ_0 :intrinsic cathode work function
$\Phi_{schottky}$:Schottky term
α :free parameter
$\hbar\omega$:photon energy
E_F :Fermi energy

For semiconductor cathodes**
$$QE = \frac{(1-R)}{2(p_0+1)(1+\frac{E_a}{\hbar\omega - \Phi_{eff}})^2} \qquad \Phi_{eff} = E_g + E_a \pm \Phi_{schottky} + \cdots$$

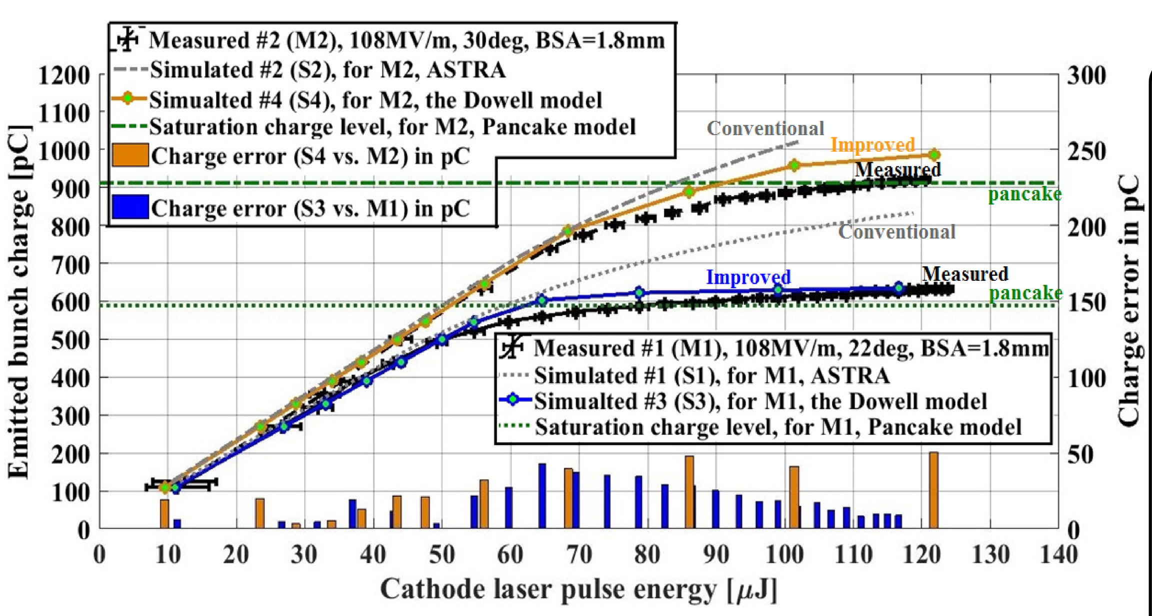
R :reflection coefficient
E_g :band gap
E_a :electron affinity
p_0 :free parameter

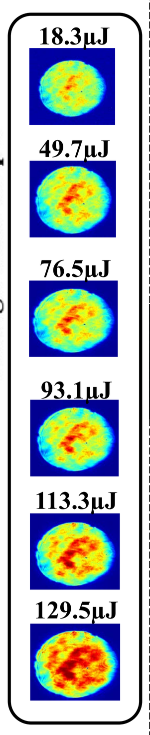
*D. Dowell **K. Jensen

$$\Phi_{schottky}(r_\perp, t) = e\sqrt{\frac{e[E_{RF}(r_\perp, t, z=0) \pm E_{Spch}(r_\perp, t, z=0)]}{4\pi\varepsilon_0}}$$

$QE(r_\perp, t, z=0)$ during emission, determined according to the RF field and the self-field of the beam at extraction, BUT, the latter is NOT prior known.

MEASUREMENT (METAL CASE)





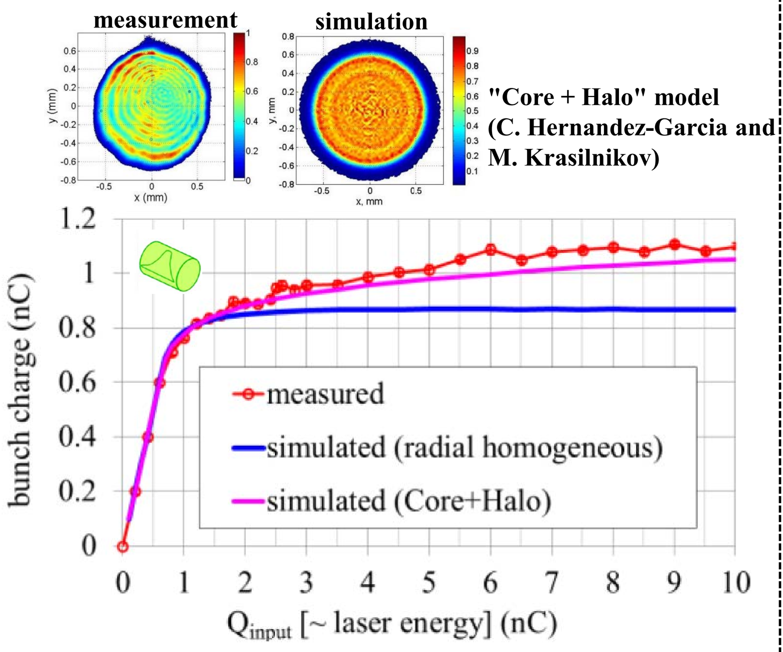
Measurement conditions

Parameters	Values
Diameter of emission area	1.8 mm
Cathode laser pulse energy	18 – 131 µJ
Temp. cathode laser distri.	flattop, 0.5/10\0.5 ps
Max. RF E-field gradients	108 , 84.9 MV/m
RF phase w.r.t. zero crossing	30° and 22°

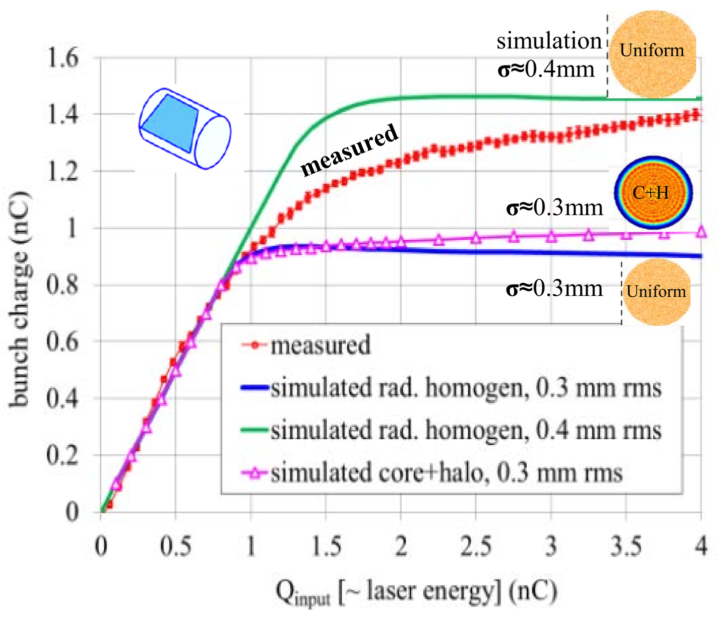
- **For simulations: realistic trans. emission map used while temporal emission profile being modulated**
- **Measurements performed using an S-band Copper RF gun at Tsinghua University**

BEAM DYNAMICS MODELING DURING EMISSION

Emission over full range of laser pulse energy



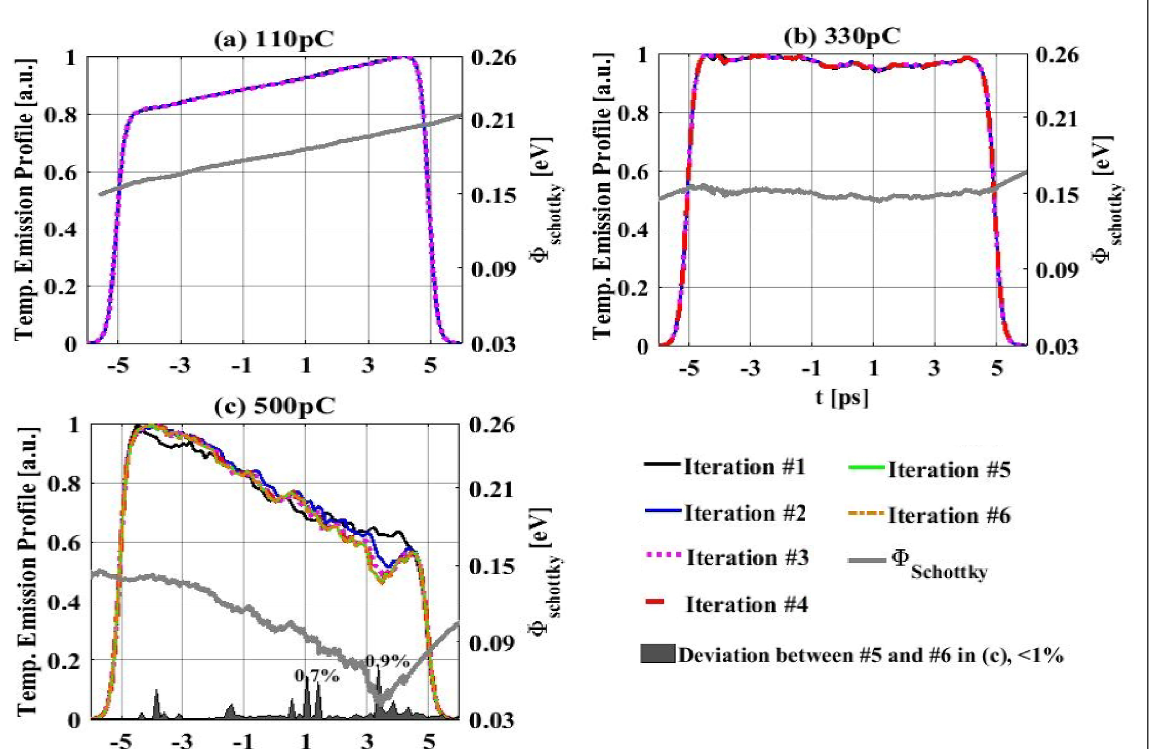
→Temp. Gaussian case fairly explained
→Trans. emission profile does play a role



→Discrepancy remains
→ temporal emission profile needs more treatment

A simple space charge iteration approach

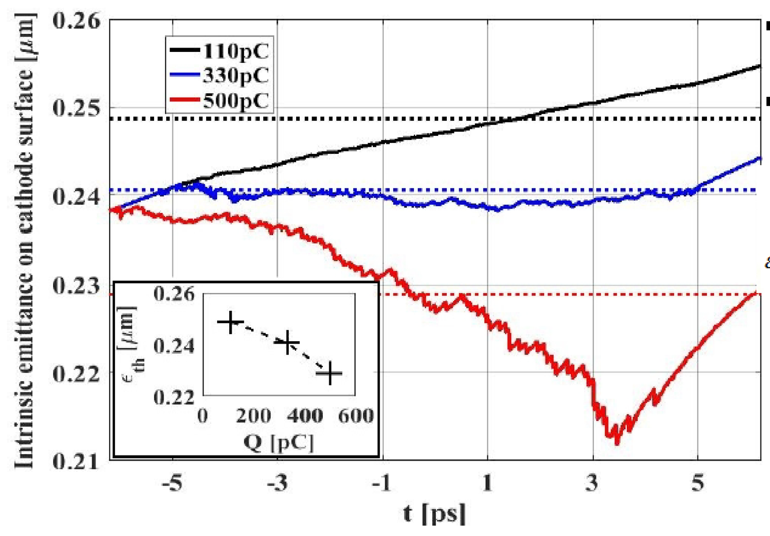
Step 1. Generate laser-produced beam distribution (trans. + temp.)
Step 2. Inject the bunch in particle simulation
Step 3. Obtain time- and space-dependent full fields @cathode
Step 4. Apply emission model with obtained fields to modulate QE(r, t)
Step 5. Modify beam distribution in Step 1 according to QE(r, t)
Step 6. Repeat Steps 2 to 5 until the relative change of the emission profile between two subsequent iterations is below the numerical tolerance



Space-charge cooling effect on intrinsic beam emittance

For **metal** cathodes,
$$\varepsilon_{nth}{}^{*} = \sigma_x\sqrt{\frac{\hbar\omega - \Phi_{eff}}{3mc^2}}$$
*D. Dowell

For **semiconductor** cathodes,
$$\varepsilon_{nth}{}^{\zeta} = r_{rms}\sqrt{\frac{2E_{kin}}{mc^2}}\frac{1}{\sqrt{3}} \times \sqrt{\frac{2+\cos^3\phi_{max} - 3\cos\phi_{max}}{2(1-\cos\phi_{max})}}$$
$$\cos\phi_{max} = \sqrt{\frac{E_a}{E_{kin}}}$$
K. Floettmann



- Time-dependent transient (surface) emittance
- Smaller mean emittance for higher charges

Overall emittance budget

$$\varepsilon_n = \sqrt{\varepsilon_{th}^2 + \varepsilon_{sc}^2 + \varepsilon_{rf}^2 + \varepsilon_{mp}^2 + \varepsilon_{Bz}^2 + 2\eta\varepsilon_{sc}\varepsilon_{rf}^2}$$

→ Further studies in progress

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OUTLOOK

→ Extending to semiconductor photocathode case(s)
→ Beam dynamics modeling for slice emittance formation at cathode

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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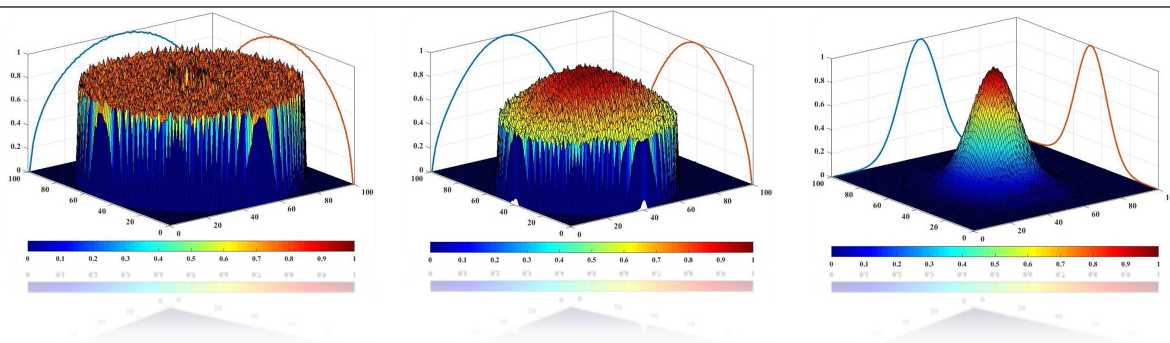

Radial Uniform Electron Bunch Truncated Gaussian Electron Bunch Gaussian Electron Bunch