

Collective and surface charge effects

in high brightness electron bunch production for FCC-ee

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Content:

01 Motivation

02 Dynamic Photoemission Model

03 Experimental Benchmarking

05 Conclusion and Outlook



Content:

01 Motivation

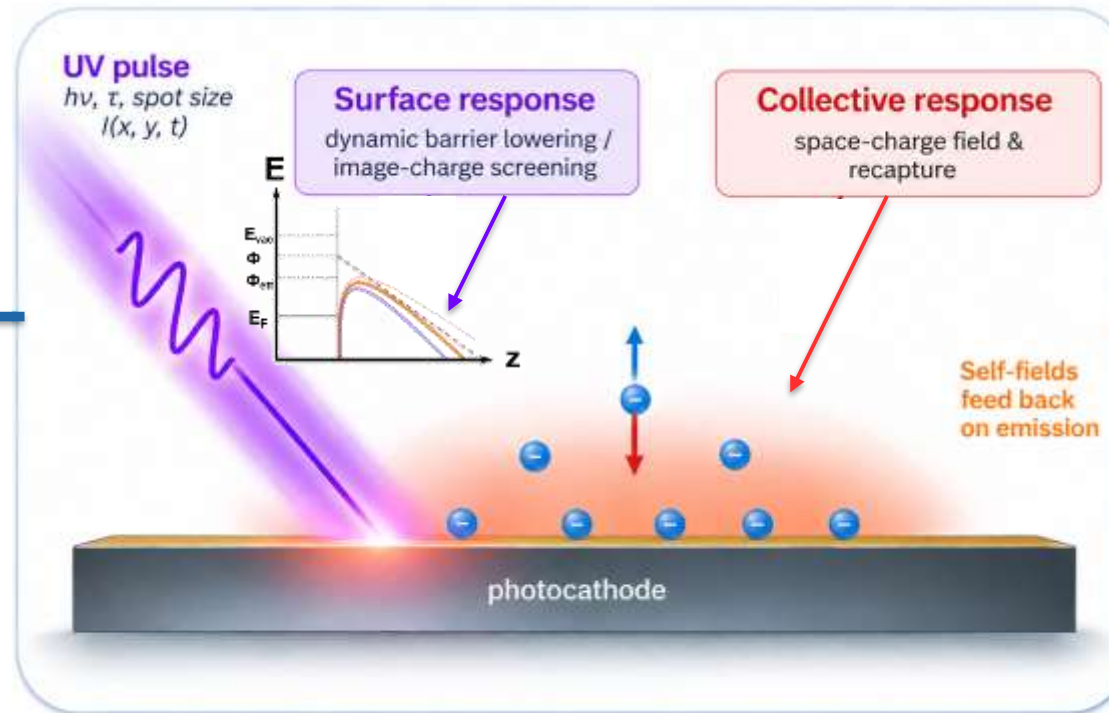
Motivation — Why collective & surface effects matter

A general challenge for high-brightness photoelectron sources

The high-brightness objective

More charge
+
Shorter bunch
+
Smaller emittance
→ high phase-space density at the cathode

What changes at high charge density?



Why it matters

Extractable charge
saturation / clamping

Temporal dynamic
bunch-shape distortion

Transverse dynamic
emittance growth

At high brightness, photoemission is no longer only a material response to the laser: the emitted bunch modifies the surface and extraction conditions while emission is still occurring.

Motivation — Why this is critical for FCC-ee

The source must combine high charge, fast tunability and controlled phase space

BASELINE OPERATION

Bunch charge

5-7 nC

Bunch spacing

25 ns

Bunch per train

2 - 4

Maximum repetition rate

≤ 200 Hz

Bunch duration

~ 3 ps (rms)

Energy spread

390 keV (0.2%)

TOP-UP SCHEME

Dynamic charge range

0-7 nC

Response time

< 25 ms

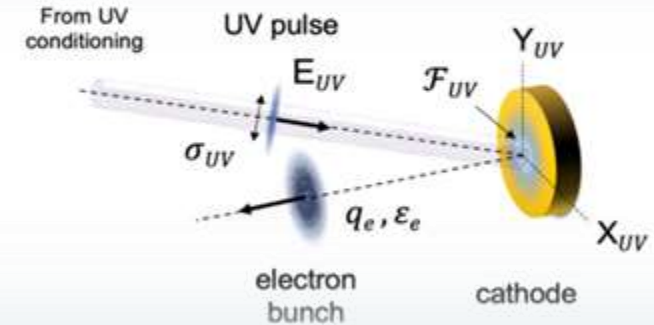
Transverse profile

**On-demand
shaping capability**

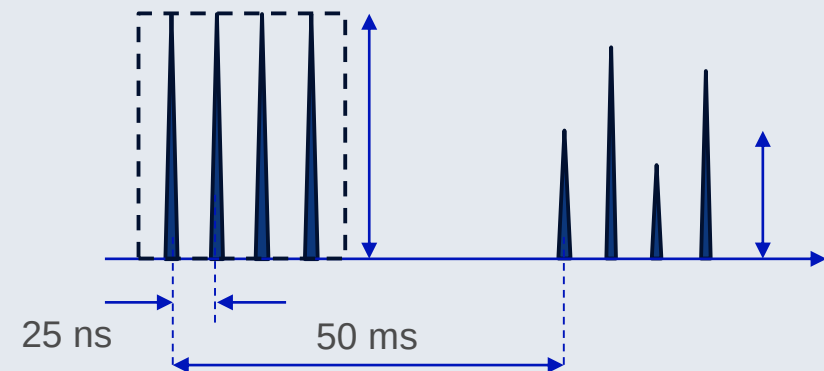
Transverse emittance

**~ 7 mm.mrad*
(depending on the
damping ring)**

1- TAILORING OF TRANSVERSE BEAM PROFILE



2- FAST AND PRECISE AMPLITUDE MODULATION SCHEME



From source requirements to a predictive photoemission model

State of the art: the relevant physics exists — but usually in separate descriptions

Analytical / canonical models

Fast & interpretable

- Fast, local estimates of emission
- Microscopic barrier physics / scaling laws
- Typically prescribed or quasi-static fields
- No self-consistent collective feedback

Microscopic / quantum emission models

Detailed surface physics

- Time-dependent emission
- Barrier transmission / tunneling
- Near-threshold physics
- No self-consistent collective feedback

PIC / particle tracking

Self-consistent beam dynamics

- Evolving space-charge fields & transport
- Realistic geometries and boundaries
- Requires a cathode emission law / closure
- Expensive for wide parameter scans and source optimization

Our goal: a reduced self-consistent model that couples dynamic surface-barrier physics to collective charge evolution — fast enough for scans, yet rich enough to predict saturation and losses.

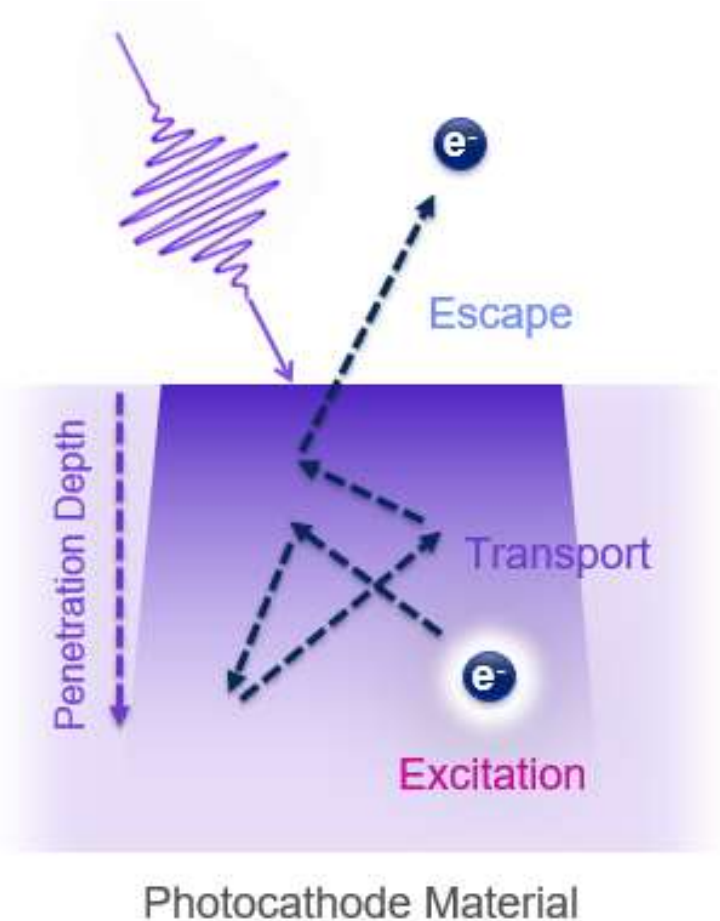


Content:

01 Motivation

02 Dynamic Photoemission Model

From Laser Pulses into Electron Bunches



$$J(\hbar\omega) = \frac{2}{(2\pi)^3} \iiint \left(\frac{\hbar k_z}{m} \right) \mathbf{A} \times \mathbf{T} \times \mathbf{E} dk_z dk_{\perp}$$

A

Absorption

$R(\omega), \delta(\omega)$
Moment Model (MM)
DFT

T

Transport

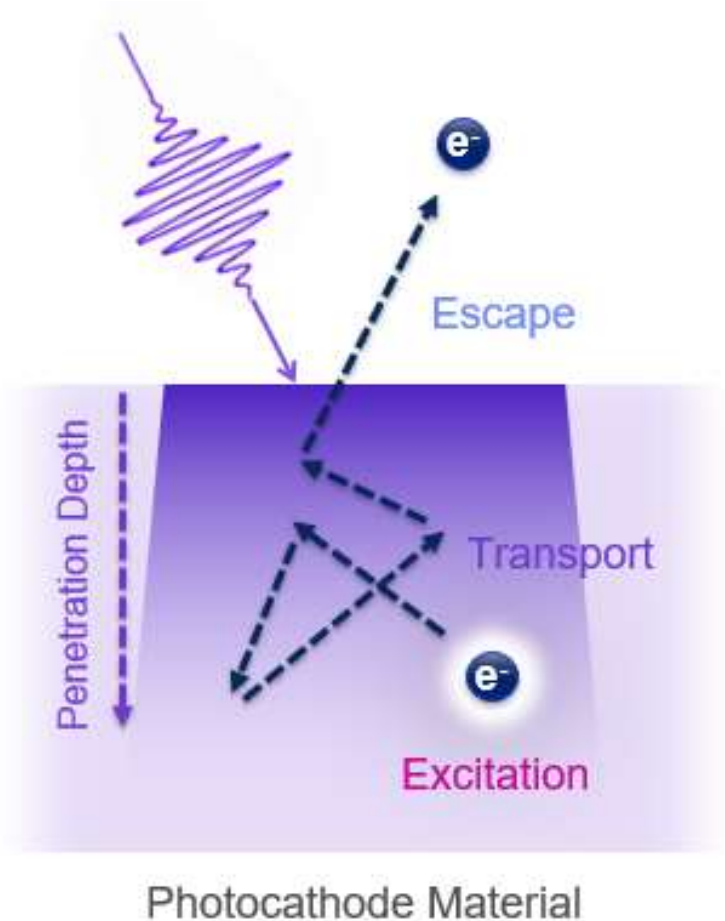
τ, f_{λ}
Relaxation time
e- scattering losses

E

Emission

$D(k)$
Dynamic Field
Temperature

From Laser Pulses into Electron Bunches



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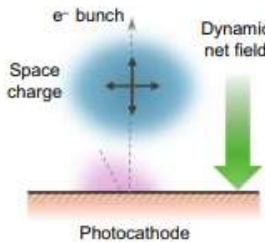
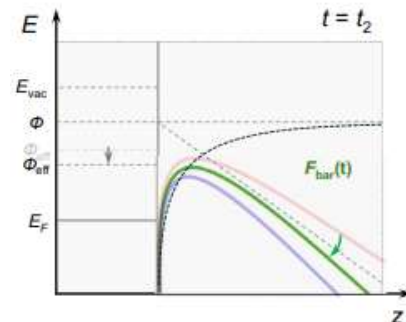
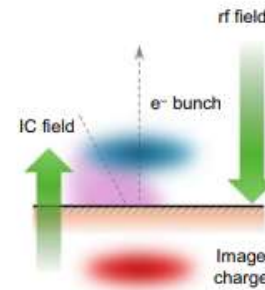
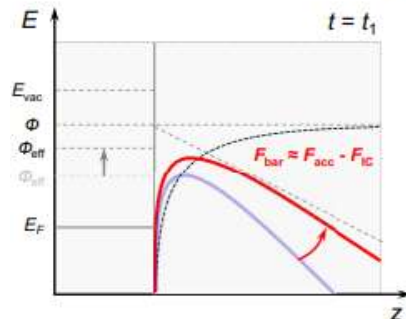
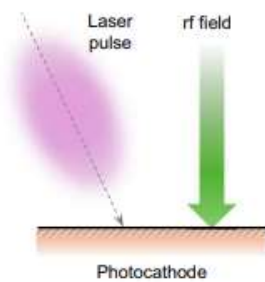
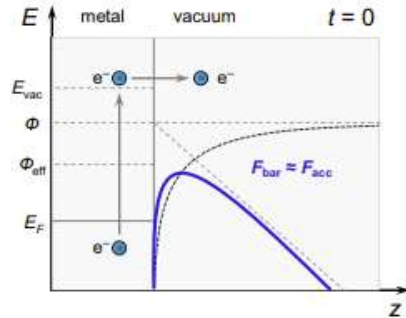
$D(k)$
Dynamic Field
Temperature

A Time-resolved Photoemission Model

WHY

Top-up injection needs high, tunable bunch charge

At high charge density, the photocathode is no longer a passive emitter.



CORE PHYSICS

Emission modifies the field that controls subsequent emission.

$$F_{bar}(t) = F_{RF} - E_{IC}$$

surface barrier

$$F_{dyn}(t,z) = F_{RF} - E_{SC}$$

vacuum transport

UV pulse

Emission

IC / SC fields

Barrier

FIELD DECOMPOSITION

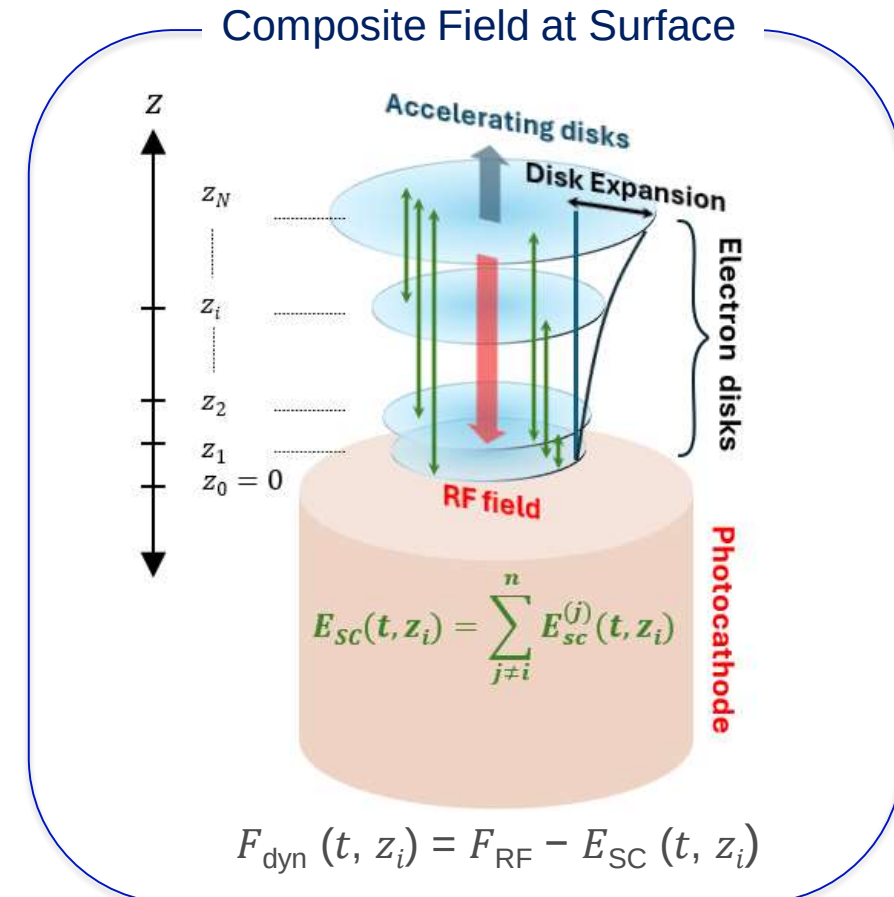
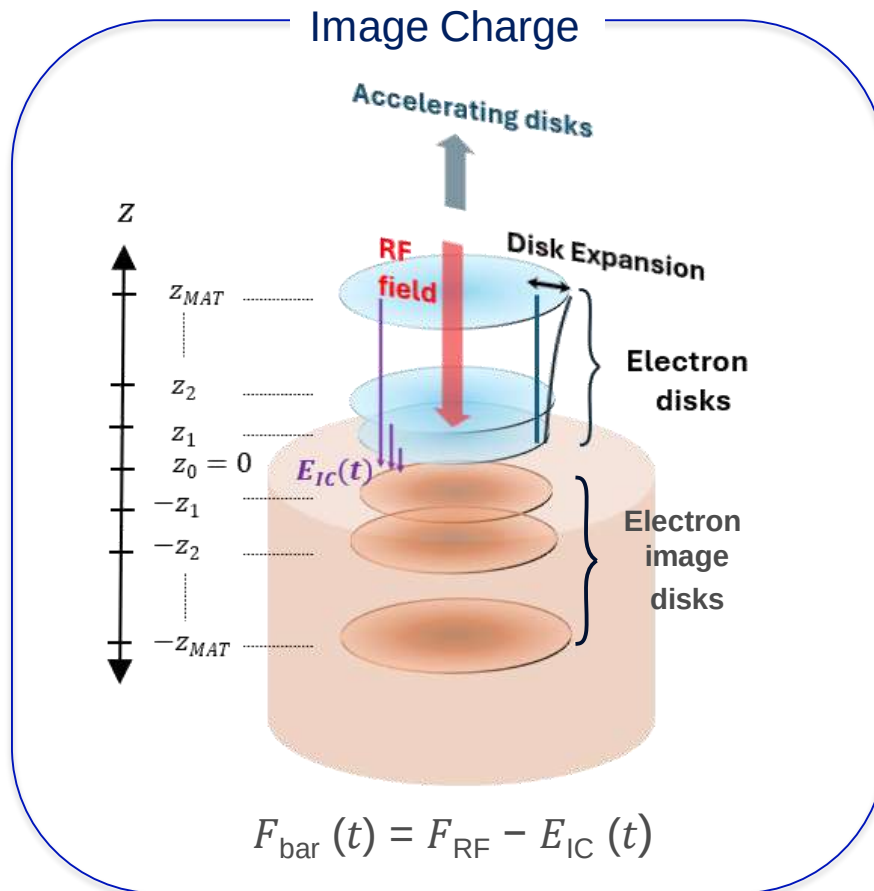
- The image field affects the barrier.
- The space charge field affects transport.

Finite Disc Model

! Infinite sheet → Constant field → Overestimates screening → Artificial clamping

➔ We consider instead, finite uniformly charged disks of radius a :

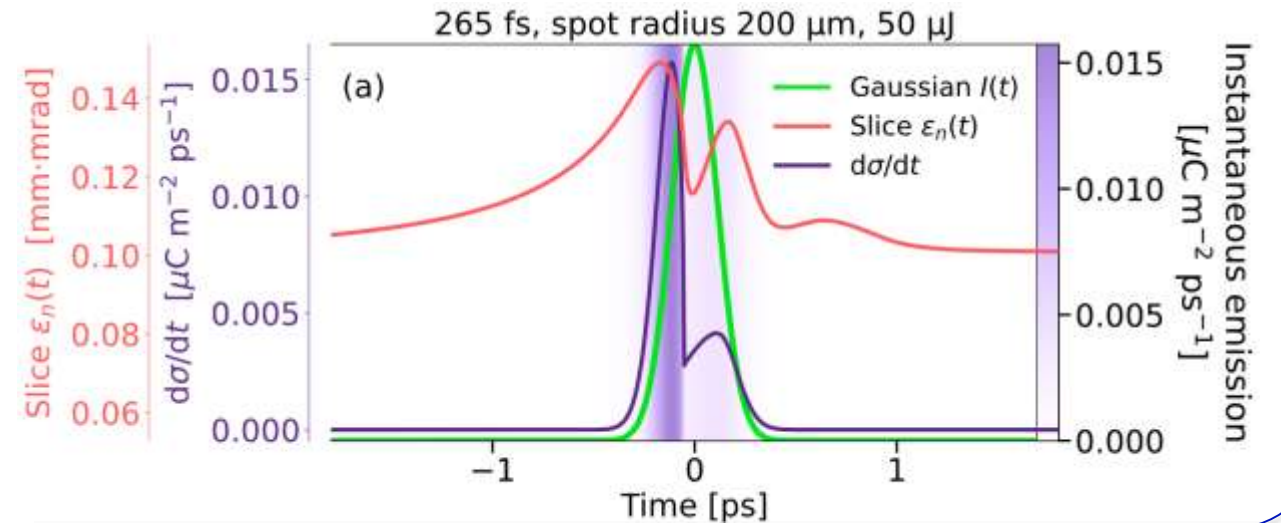
$$E_z(\Delta z) = \frac{\sigma}{2\epsilon_0} \left(1 - \frac{\Delta z}{\sqrt{\Delta z^2 + a^2}} \right)$$



Time-Resolved Emission Dynamics

For 265 fs:

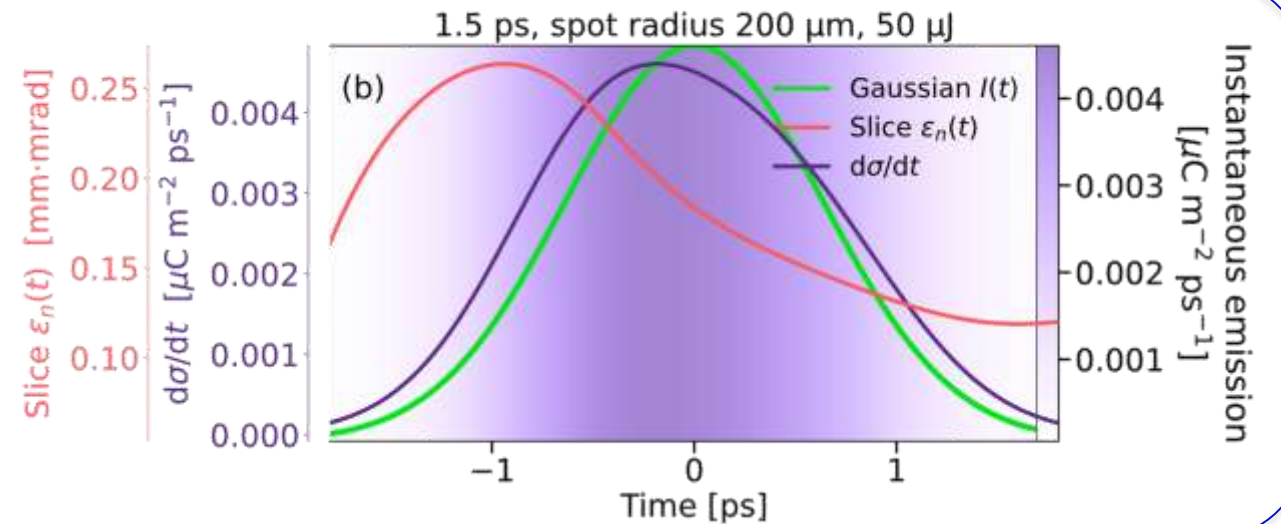
- Rapid image buildup
- Mid-pulse suppression
- Double emittance peak



For 1.5 ps:

- Slower buildup
- Smoother emittance evolution

Faster pulses enhance dynamic barrier modulation.





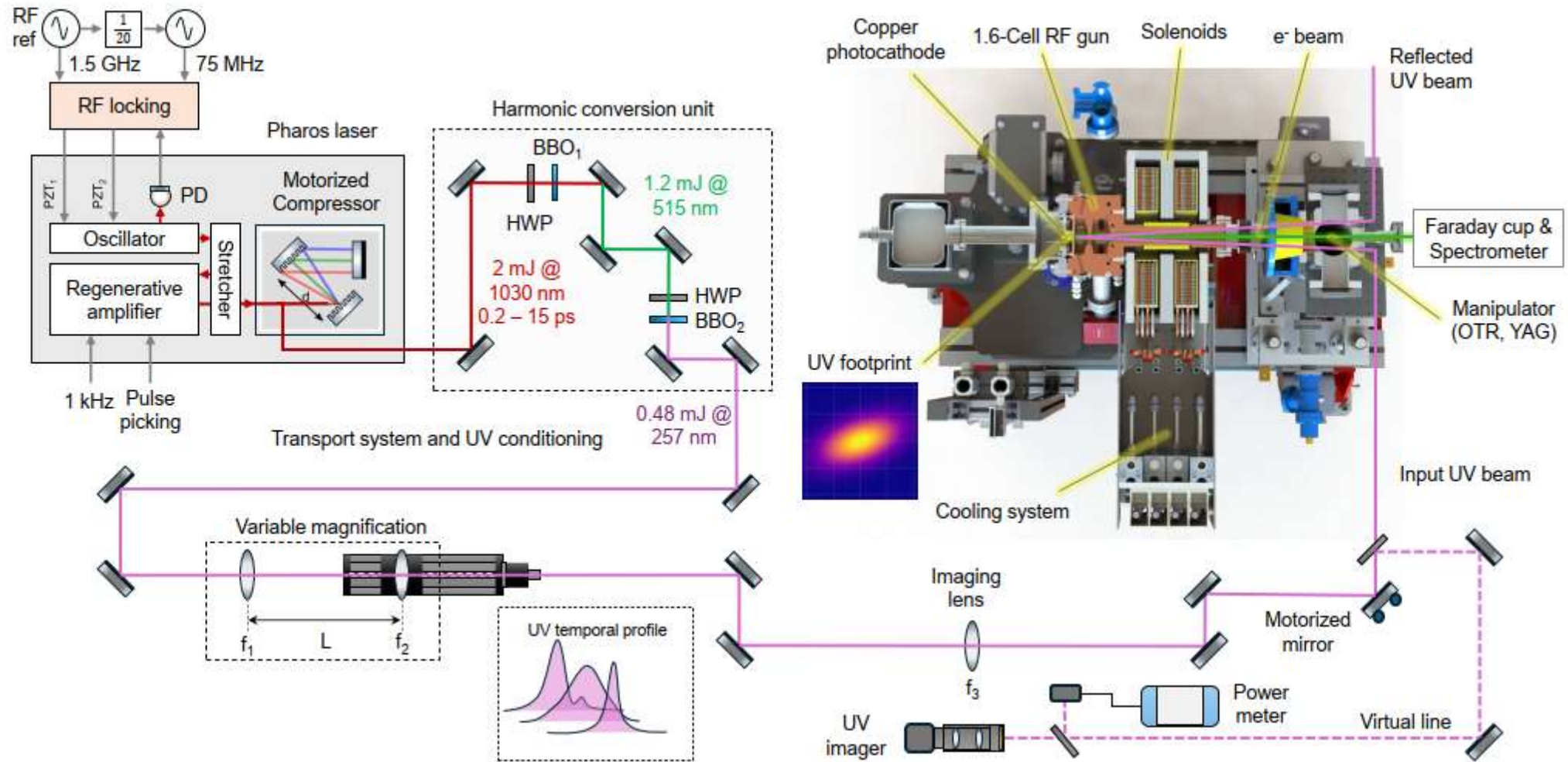
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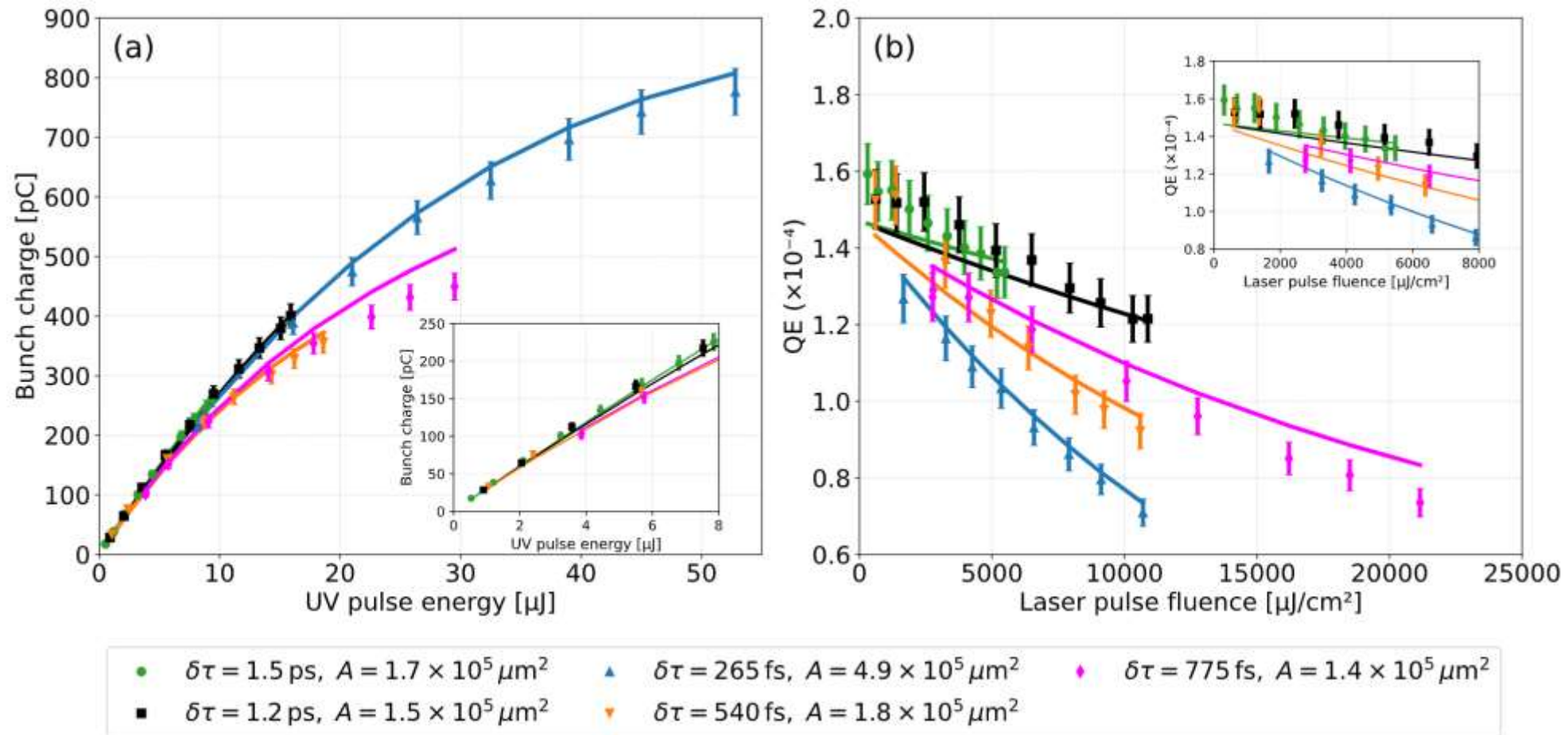
02 Dynamic Photoemission Model

04 Experimental Benchmarking

Experimental Setup for Charge Production Tests at CTF2



Charge vs Laser Energy



The model reproduces saturation without invoking ad-hoc limits, it emerges naturally from dynamic field screening.

Benchmarking the Model: SLAC Results

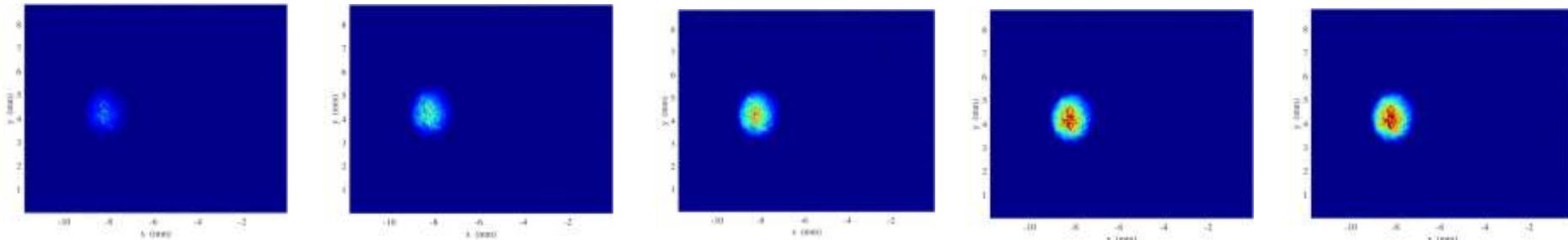
FACET-II Injector Parameters:



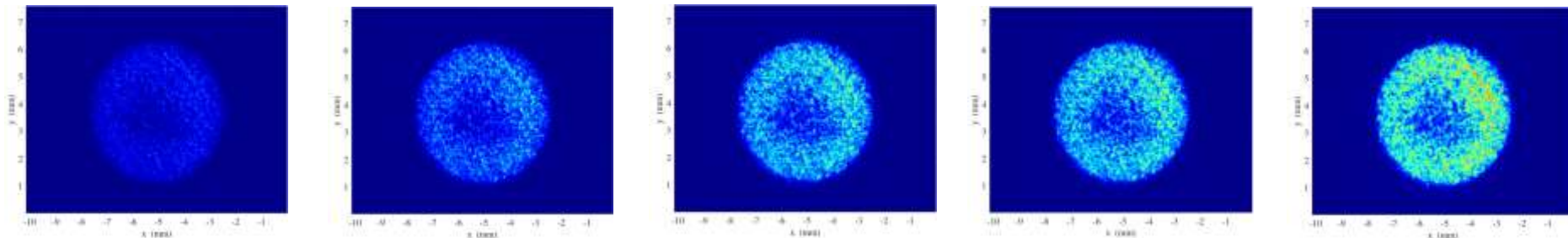
Charge (nC)
Laser pulse energy (μJ)
Flat-top spot size (mm)
Pulse length (ps rms)

1.0	1.6	2.0	2.5	2.8
56	87	112	145	172
5.5	5.5	5.5	5.5	5.5
1.2	1.2	1.2	1.2	1.2

Cathode

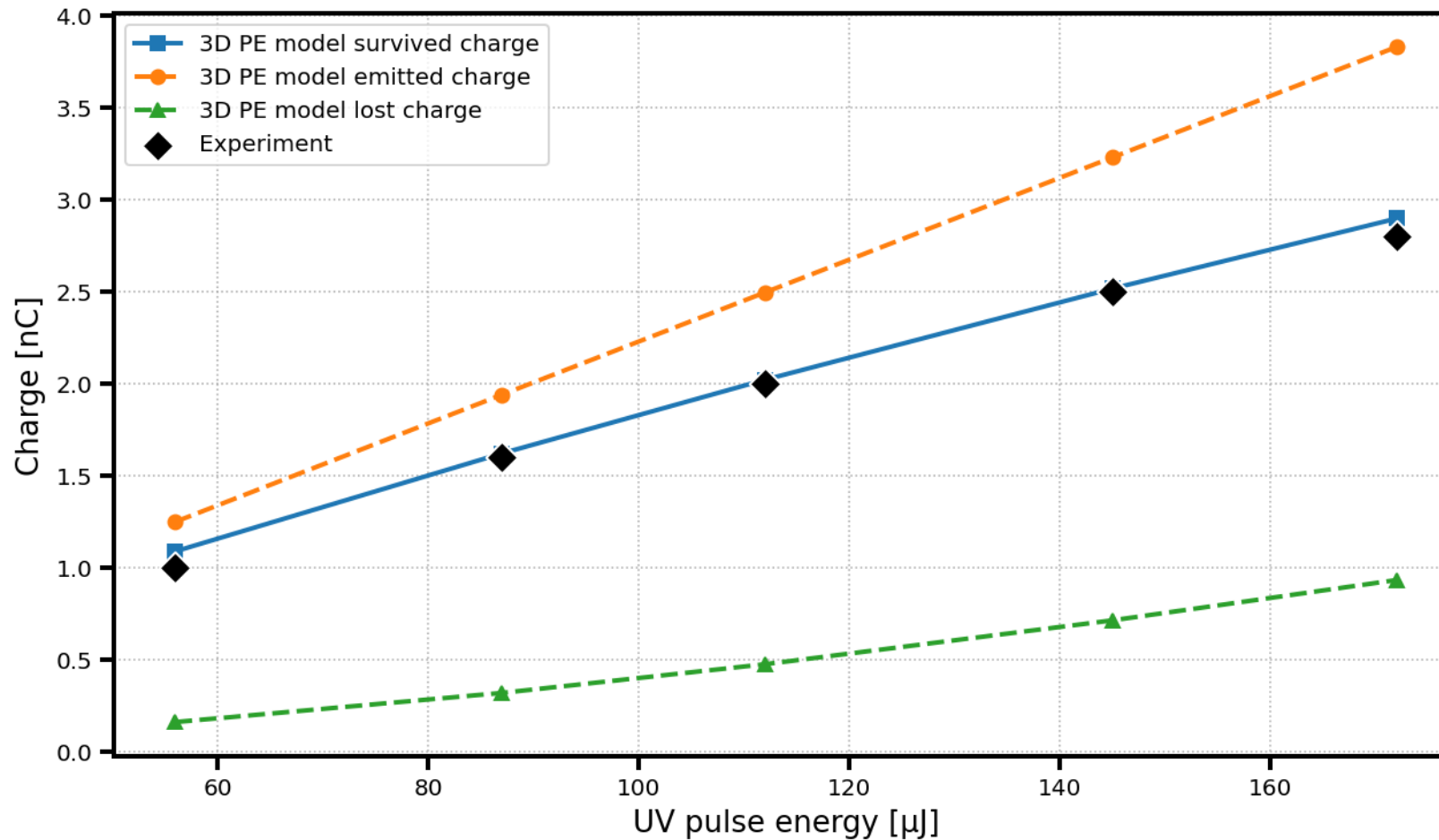


VCCF



Benchmarking the Model: SLAC Results

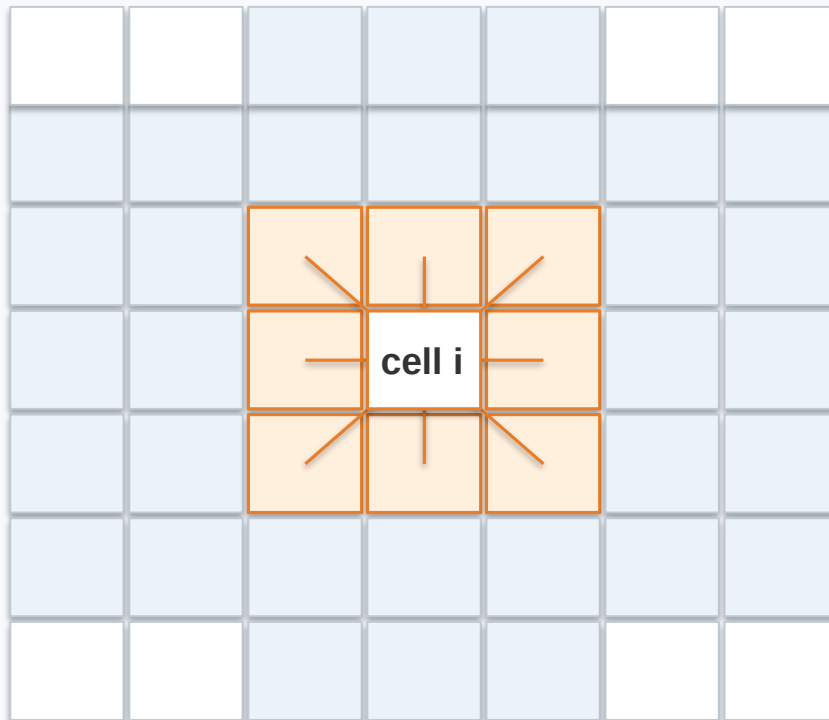
FACET-II Charge vs. UV Pulse Energy | Flat-top 5.5 mm | Pulse RMS 1.2 ps



From “charge dynamics” to “spatially resolved emission and emittance”

3D emission grid

Each cell carries a local emitted charge $q_i(t)$



surrounding cells j

Each surrounding cell contributes according to its charge and relative position.

Local space-charge field

$$E_{SC}(x_i, y_i, t) = \sum_j K_{ij}(t) q_j(t)$$

K_{ij} : geometrical coupling between source cell j and observation cell i

- 1 **Laser profile** sets q_j across the grid
- 2 **Neighbour coupling** each cell feels surrounding charge
- 3 **Local field** E_{SC} differs from cell to cell
- 4 **3D dynamics** local forces feed transverse phase space

Key idea: the model is cell-to-cell coupling on a 2D transverse grid.

Collective and surface charge effects in high-brightness ultrafast electron sources

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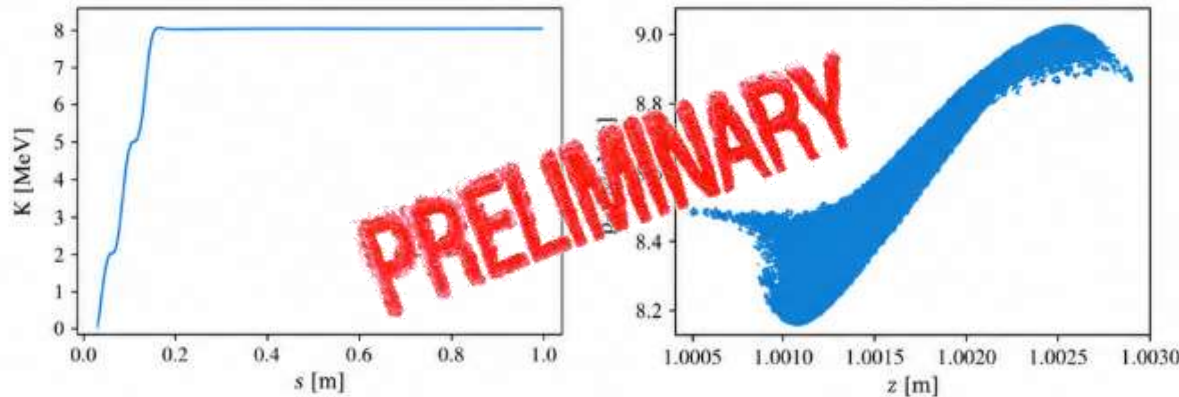
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(Received 16 December 2025; accepted 22 May 2026; published 29 June 2026)



[Read the paper](#)



Example: RF-Track simulation of 5nC bunch in the CLEAR photoinjector using the dynamic photoemission model

[RF-Track on Git-Lab](#)





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Motivation — High-brightness beams start at the cathode

- Charge scaling production is studied for copper-based photoinjectors.
- A new model including dynamic field effects on the photocathode surface is presented:
 - Sub-ps field dynamics strongly affect the scaling laws
 - The real-time QE becomes nonlinear as a function of illumination parameters
- The model has been benchmarked with RF guns at CERN and SLAC, showing good agreement.
- To deliver up to 7 nC per bunch, several limitations need to be addressed:
 - The spot size on the cathode needs to be very large → implications for RF frequency and gun design
 - Pulse duration → it can be a knob for changing the extracted charge, but also, for charge scaling longer pulses are preferred.
- Emittance: Transverse emittance is included, longitudinal emittance coming soon...

Outlook

- We need to:
 - Complete the 3D extension of the model
 - Enable the capability of simulating arbitrary UV wavepackets → detailed studies of UV shaping techniques
 - Explore the modeling of semiconductor photocathodes
 - How can we reliably modulate the bunch charge and emittance in a shot-to-shot basis?

Thank you!

