Emittance budget in the transition regime between linear emission and space charge dominated photoemission

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Contents

- *Why high-brightness **electron injectors** for FELs?*
- *How **transition regime of emission** (TRE) defined?*
- *Why TRE interesting?*
- *How to model **dynamics in TRE**?*
- *How the TRE dynamics **impacting downstream beam qualities**?*

FEL-based X-ray facilities require high-brightness electron injectors

- High peak current (I) & **low emittance** (ε_n) → **high beam brightness** (B_n)
  - → High I → high charge and short length → high FEL gain and efficiency
  - → Low ε_n → required beam energy at a given wavelength (λ)
- Fixed charge → **emittance minimization**
- **Emittance** can only be improved **in** the **injector**
- **Emittance budget** & **optimization strategy**
  - → Minimizing space charge contribution
  - → Improving cathode intrinsic emittance
  - → Making other items negligible
- **Intrinsic emittance → lower limit** of final emittance

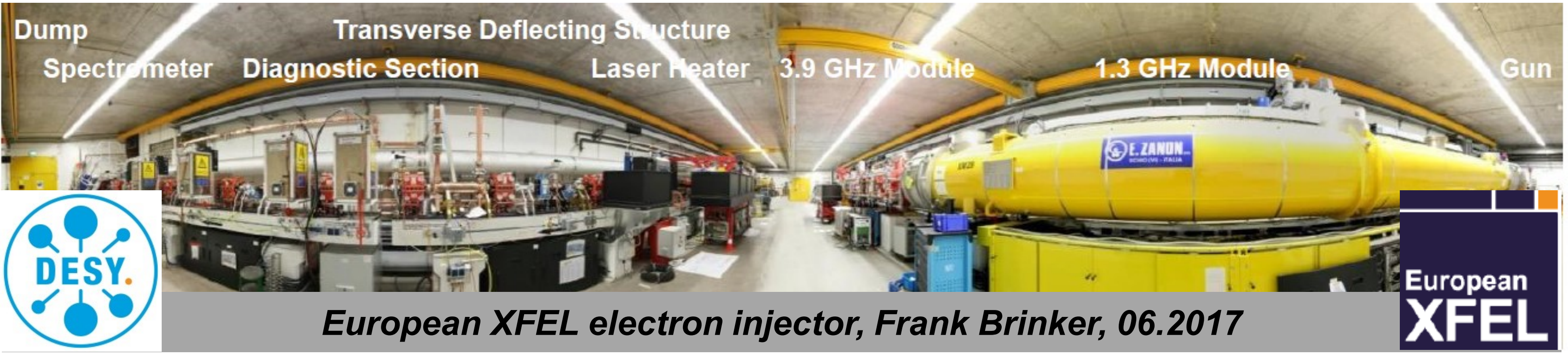
$$B_n \propto \frac{I}{\varepsilon_n{}^2}$$

$$\frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

$$\varepsilon_n \propto \sqrt{\varepsilon_{th}{}^2 + \varepsilon_{spch}{}^2 + \varepsilon_{rf}{}^2 + \varepsilon_{Bz}{}^2 + \cdots}$$

+ coupling items

intrinsic emittance (ε_{th})
space charge emittance (ε_{spch})
rf emittance (ε_{rf})
cathode magnetic field caused emittance (ε_{Bz})



European XFEL electron injector, Frank Brinker, 06.2017

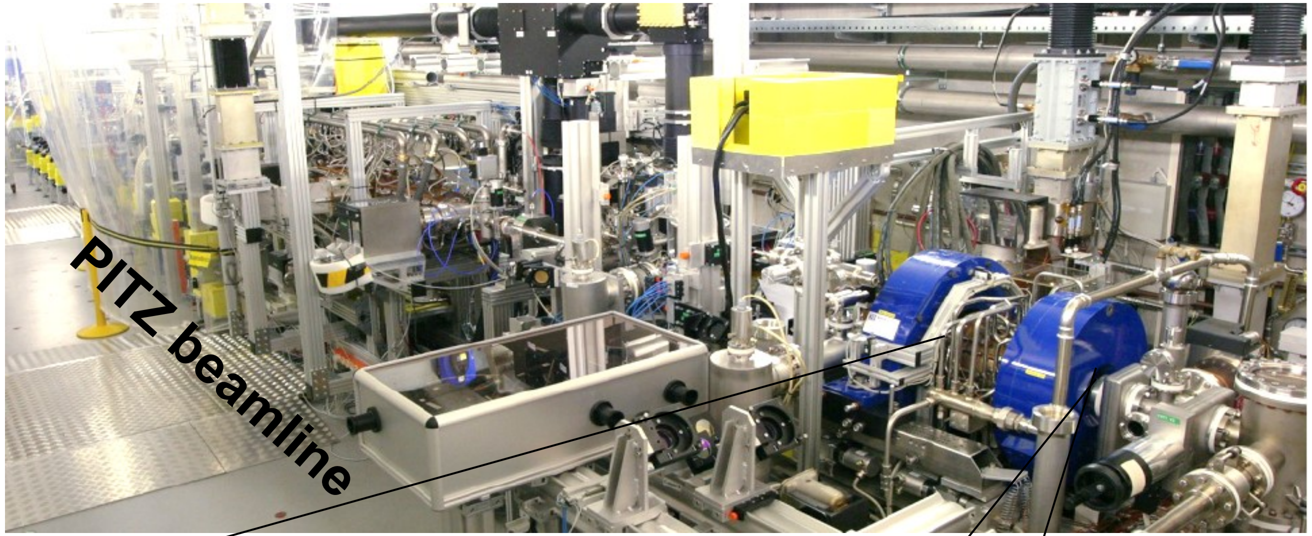
W. Decking, H. Weise, Commissioning of the European XFEL accelerator, Paper MOXAA1, IPAC 2017

F. Stephan, M. Krasilnikov, High Brightness Photo Injectors for Brilliant Light Sources, Chap. Of "Synchrotron Light Sources and Free-Electron Lasers", 2016

Ch.-X. Tang, Paper MO2A04, LINAC 2016

F. Sannibale, W.S. on High Repetition-rate XFEL Physics and Technology, 2017

Emittance optimization at PITZ for FLASH and European XFEL



RF Gun[1-2]

- **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[3] (QE~5-20%) → up to 6 nC / bunch

- Photo Injector Test facility at DESY in Zeuthen (PITZ)
- Typical **optimization scheme** at PITZ
  - **Slit-Scanning emittance vs. gun solenoid current at a given transverse cathode laser spot size**
  - **Optimize the spot size for smallest achievable emittance**

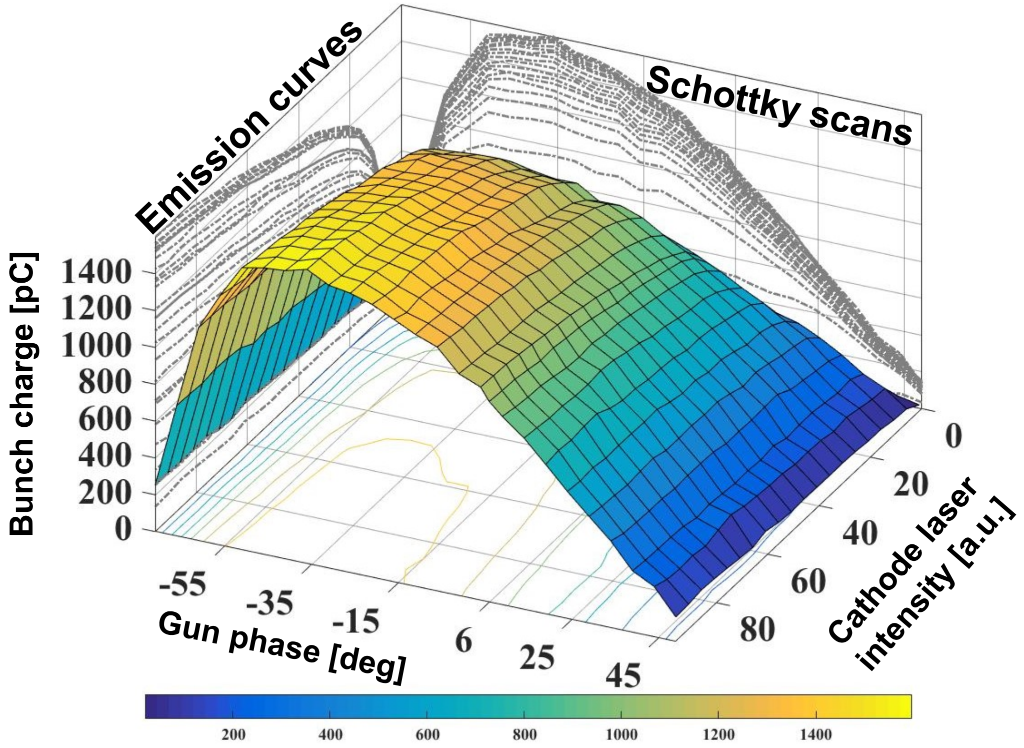
(fixed bunch charge, cathode laser pulse length and shape, gun and booster gradient and phase)

[1]*Phys. Rev. ST Accel. Beams 13, 020704 (2010)*
[2]*Phys. Rev. ST Accel. Beams 15, 100701 (2012)*
[3]*Cathode production: S. Lederer, L. Monaco, D. Sertore, P. Michelato*

Cathode R&D → next talk of Laura Monaco

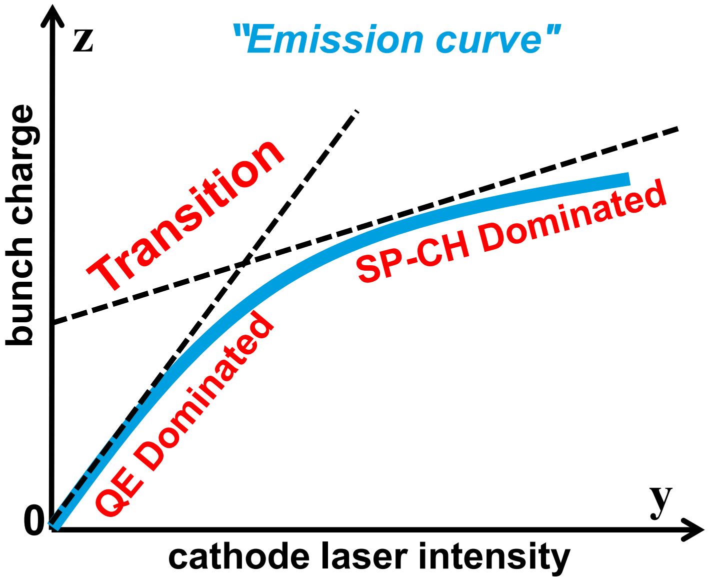
Transition regime of photoemission in RF gun environment

Emission characterization in the gun
Cs_2Te, 60 MV/m



LINAC'18 THPO116

Concept: transition regime



QE: Quantum Efficiency
SP-CH: Space-Charge

Transition regime of photoemission in RF gun environment

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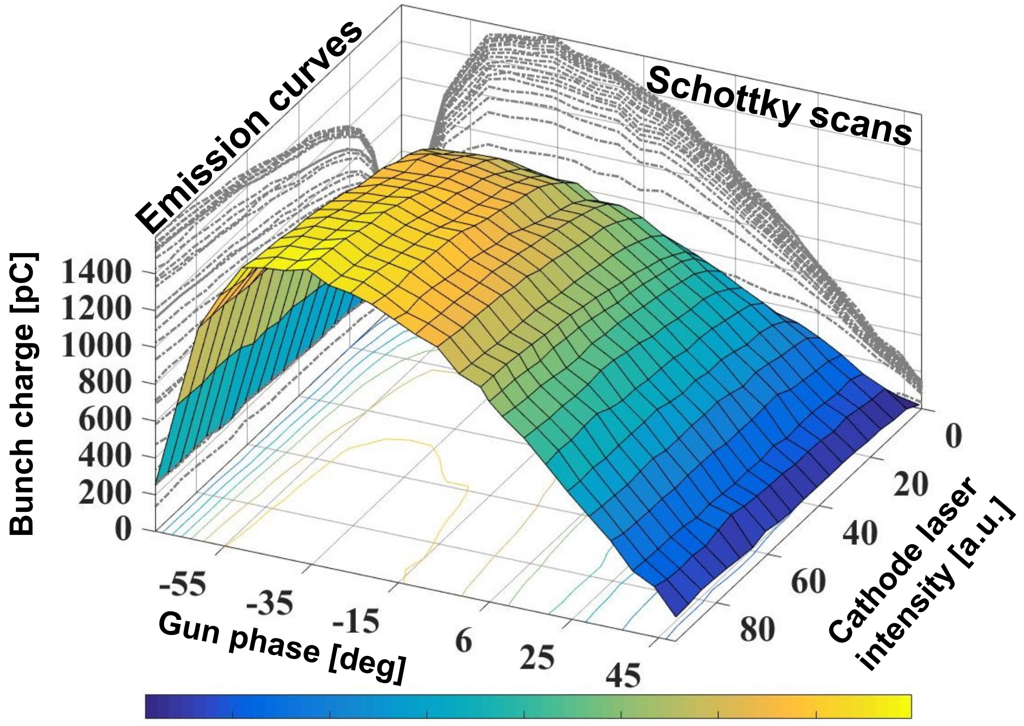
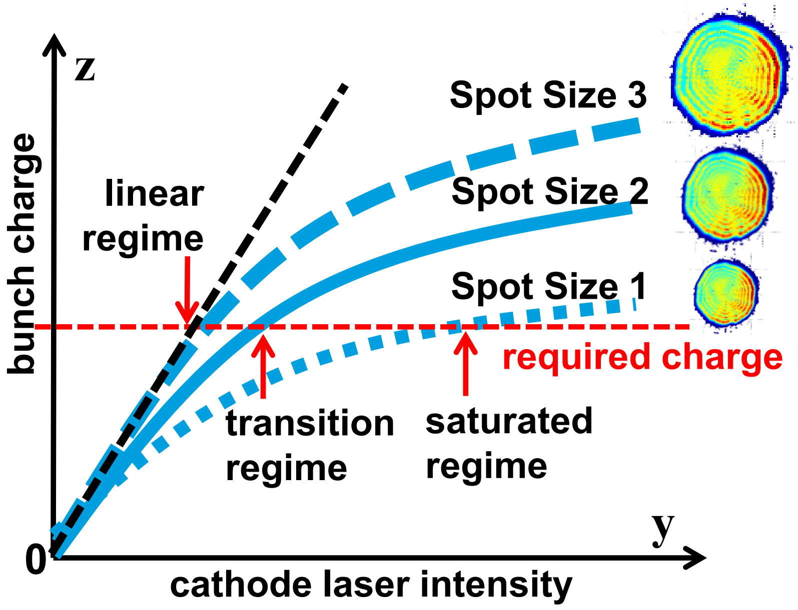


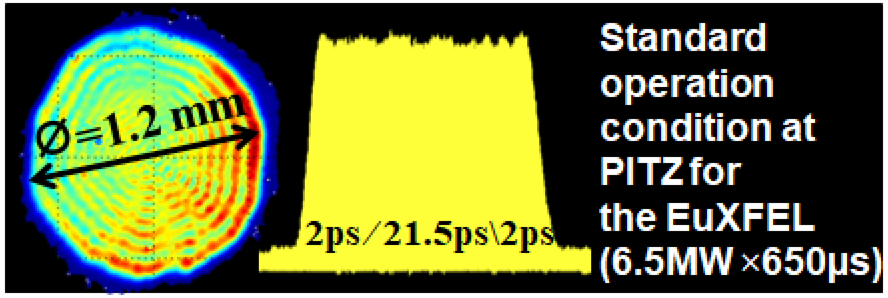
LINAC'18 THPO116

Concept: working point

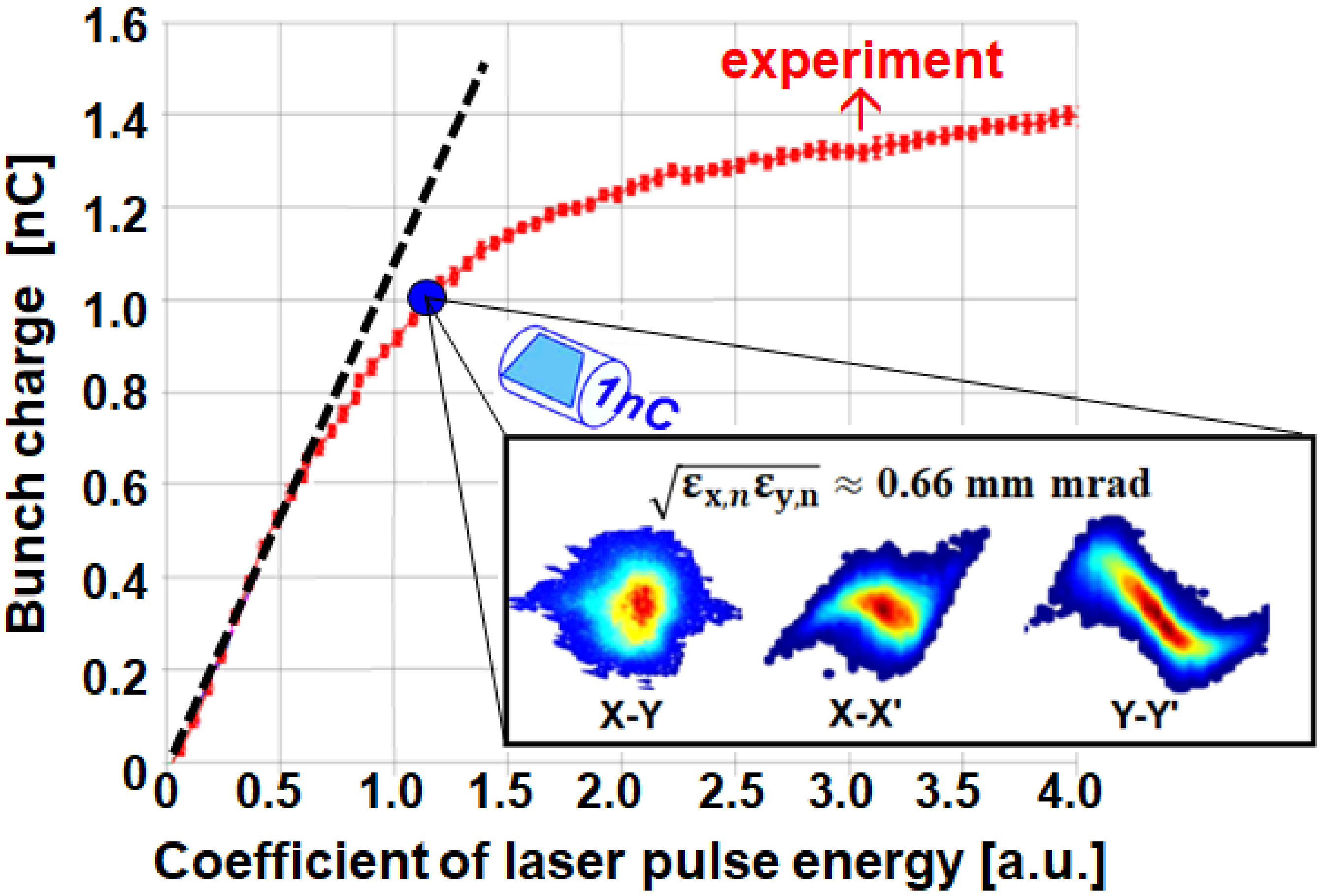


QE: Quantum Efficiency
SP-CH: Space-Charge
Spot Size: transverse laser spot size on cathode
Trans. distributions used only for illustration purpose

Experimental observation on emittance in transition regime of emission

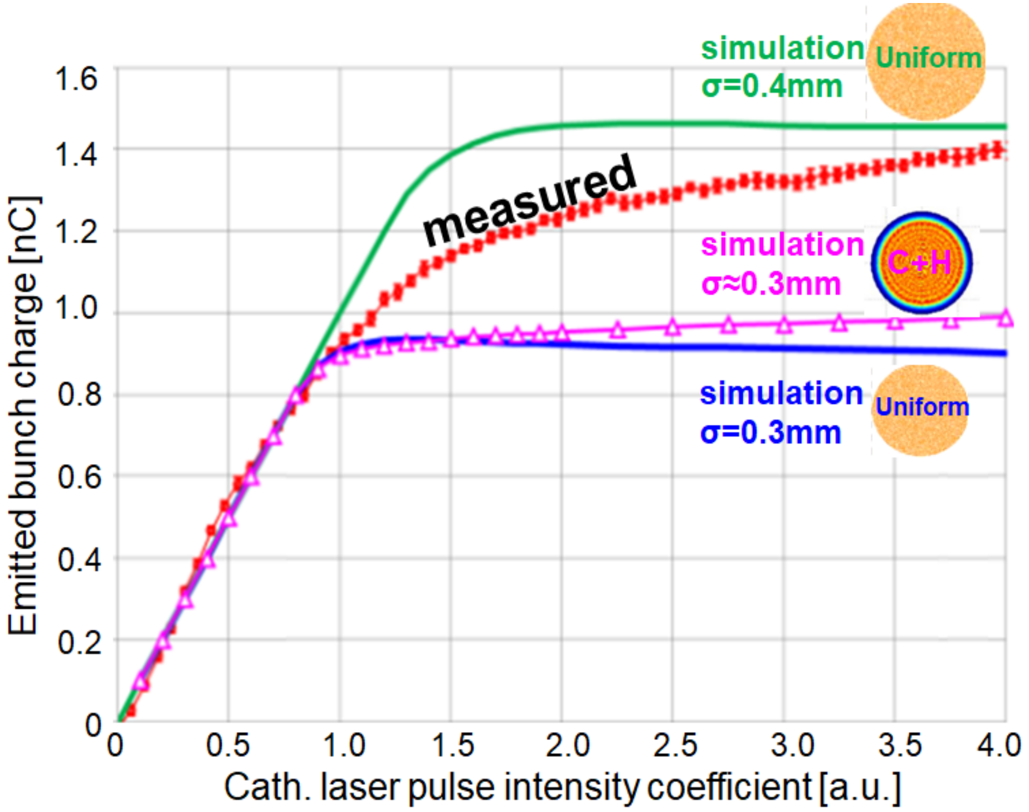


Under standard operation conditions at PITZ, best emittance obtained in transition regime of emission!



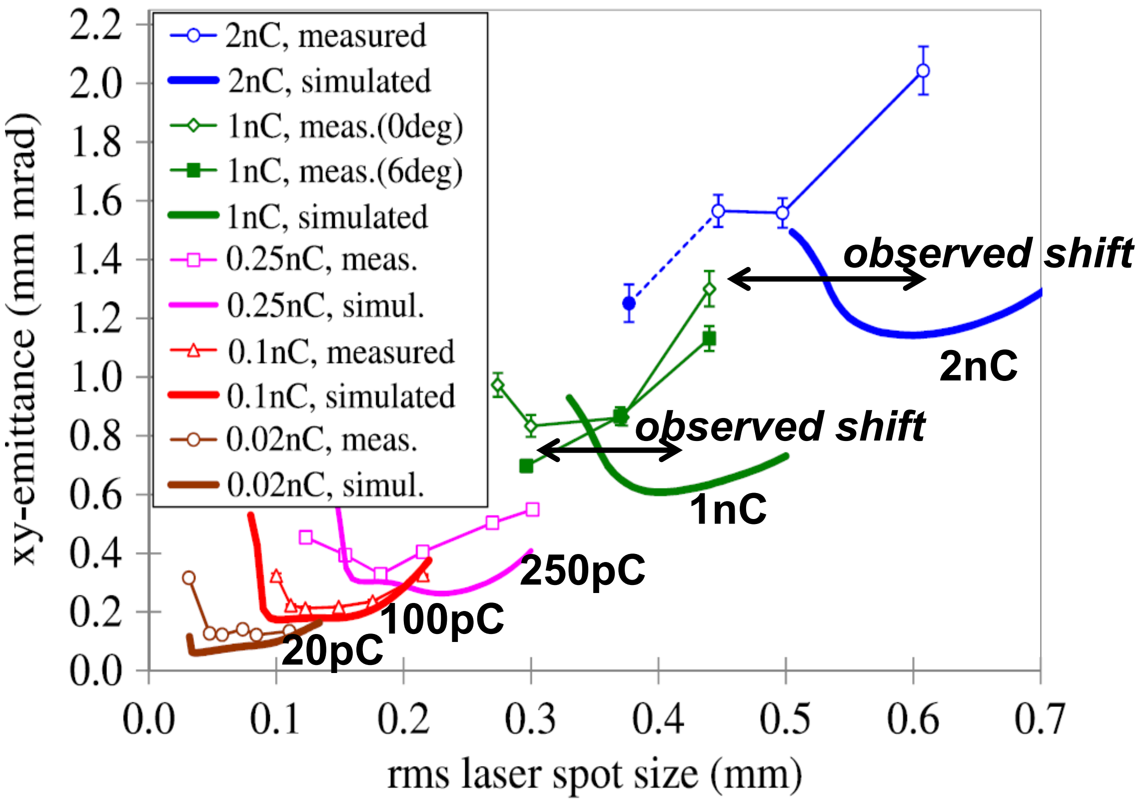
Dynamics in TRE **cannot** be well reproduced by simulations

Simulated emission curve ≠ measured one



NIM A 889, 129-137 (2018) *NIM A 871, 97–104 (2017)*

Simulated optimum laser spot size ≠ measured one



M. Krasilnikov, et al., Phys. Rev. ST Accel. Beams 15, 100701 (2012)

Bring cathode and electron emission physics to beam dynamics

- Not yet straightforward consideration of cathode effects[1-3] in particle simulations
- **Emission model needed for particle dynamics with collective effects at cathode**

→ **first priority: model emission dynamics in strong fields**

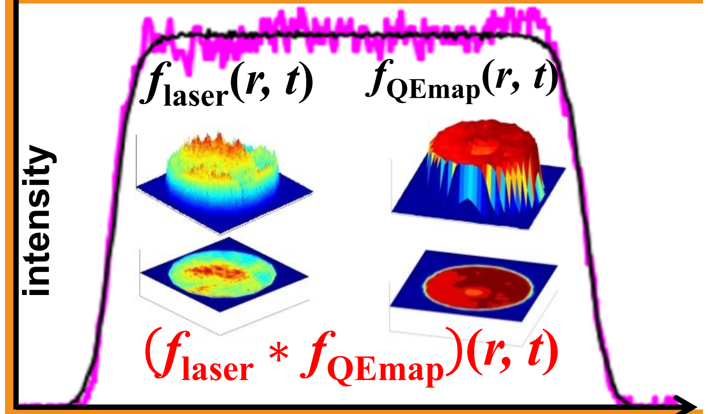
  - incorporating PIC-ready emission model[4-6] with a **Lienard-Wiechert approach**[7-9]
  - transient charge packet creation by interplays of cathode QE with **time and space dependent rf and beam self-fields**

- **Features**

→ measurement-based model training
→ dynamic beam production through cathode physics model
→ taking into account impacts of cathode **field effects onto intrinsic beam slice formation**

In collaboration with TU Darmstadt

temp. laser profile



emission time

Charge production per time step

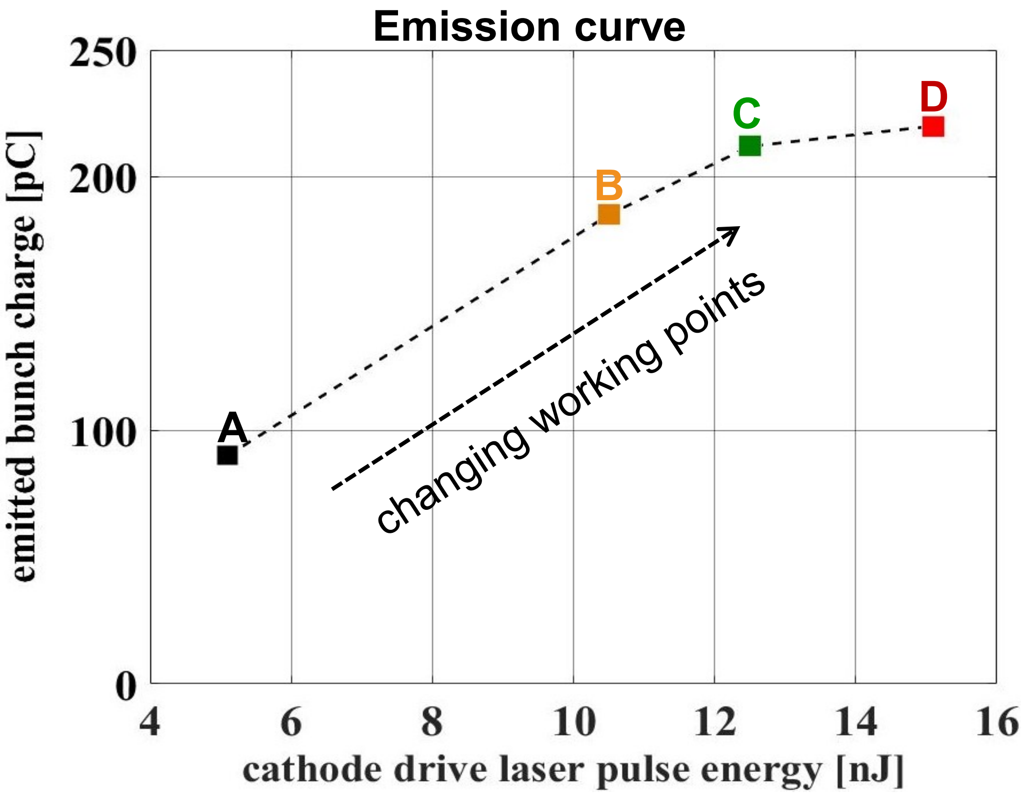
$$dQ(r_\perp, t) = \frac{e\alpha dE_{las}(r_\perp, t) dr_\perp dt}{\hbar\omega \{1 + E_a / [\hbar\omega - \Phi_{eff}(r_\perp, t)]\}^2}$$

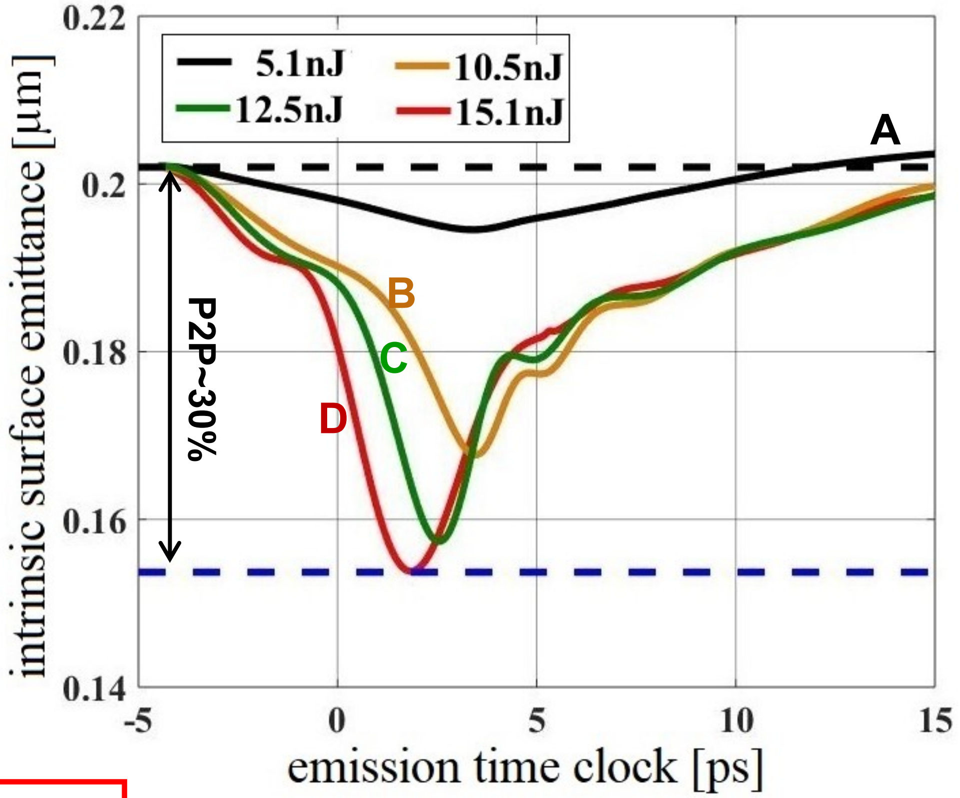
Field-dependent cathode work function

$$\Phi_{eff} = \Phi_0 \pm \sqrt{e[E_{rf}(r_\perp, t, z=0) + E_{sc}(r_\perp, t, z=0)]/4\pi\epsilon_0}$$

[1] *Nathan A. Moody, Kevin L. Jensen, et al., Phys. Rev. Applied 10, 047002 (2018)*
[2] *D. H. Dowell and J. F. Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009)*
[3] *J. Smedley, et al., An Engineering Guide to Photoinjectors Photocathode Theory (2016)*
[4] *Kevin L. Jensen, et al., Phys. Rev. ST Accel. Beams 17, 043402 (2014)*
[5] *Kevin L. Jensen, et al., J. Appl. Phys. 104, 044907 (2008)*
[6] *John Petillo, et al., IEEE Trans. Electron Devices Sci., 52(5),742-748 (2005)*
[7] *Y. Chen, E. Gjonaj, et al., NIM A 889, 129-137 (2018)*
[8] *R. Ryne, C. Mitchell, J. Qiang, et al, FEL 2013*
[9] *F. Ciocci, L. Giannessi, A. Marranca, et al., NIM A 393 (1997), 434-438.*

Effect on intrinsic surface emittance





- **Varying working point along emission curve**
  - → changing **intra-bunch modulation of intrinsic surface emittance**
  - → **overall surface emittance reduction** by space charge fields
  - → peak to peak ~30% and ~10% in average
  - → stronger effects for higher local charge densities at cathode

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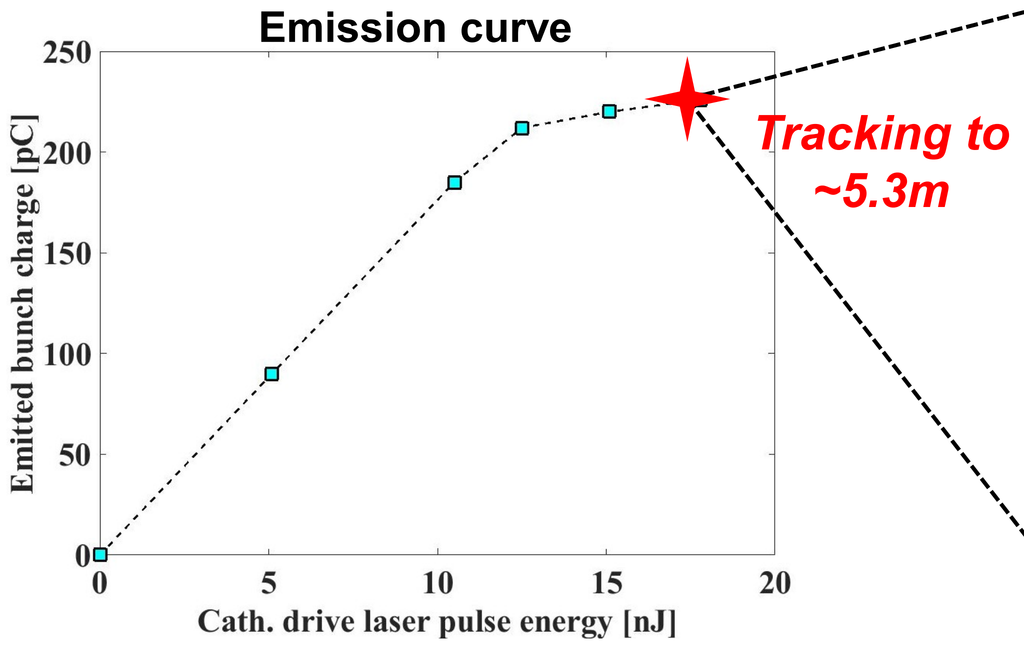
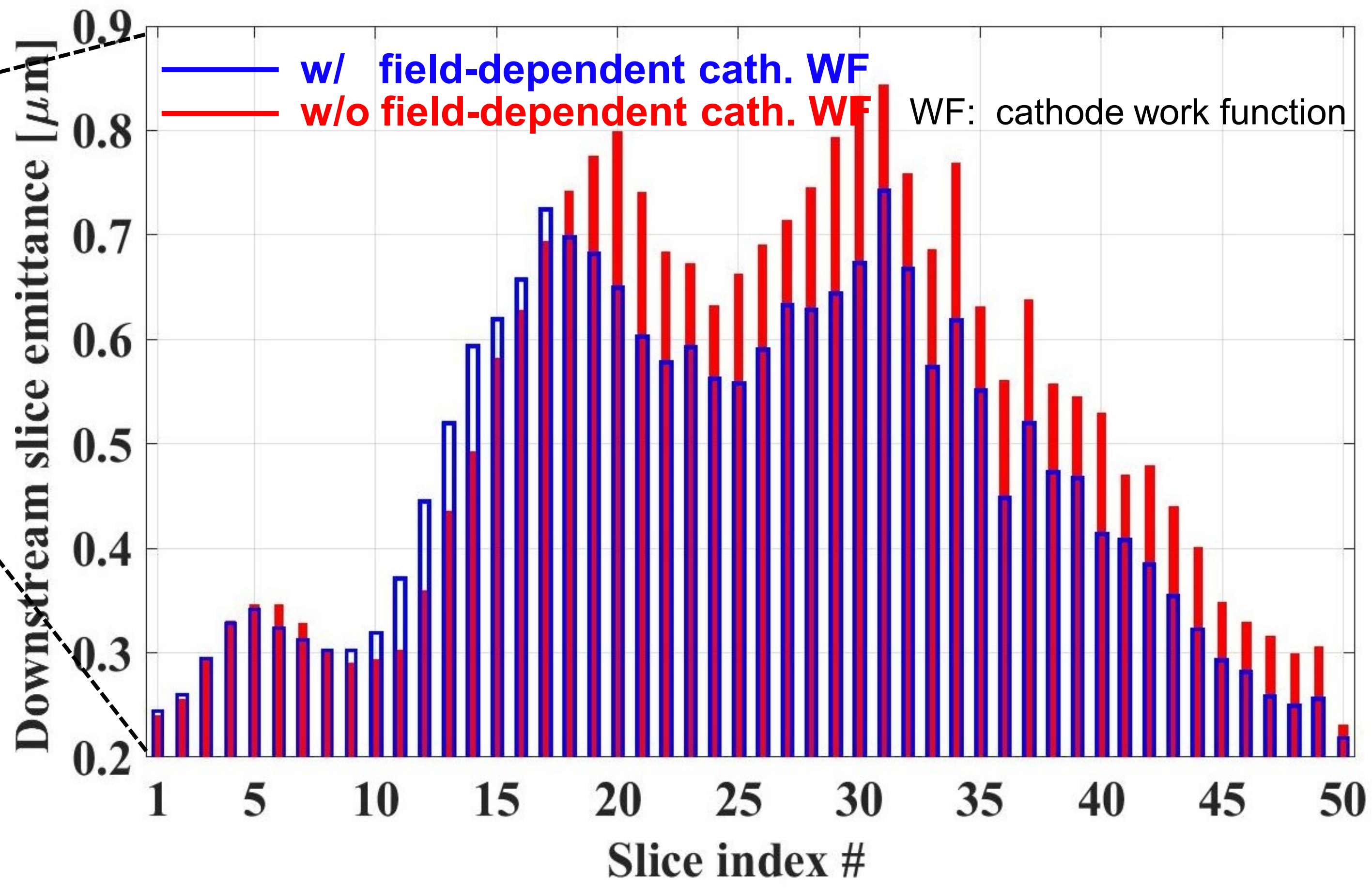
ASTRA

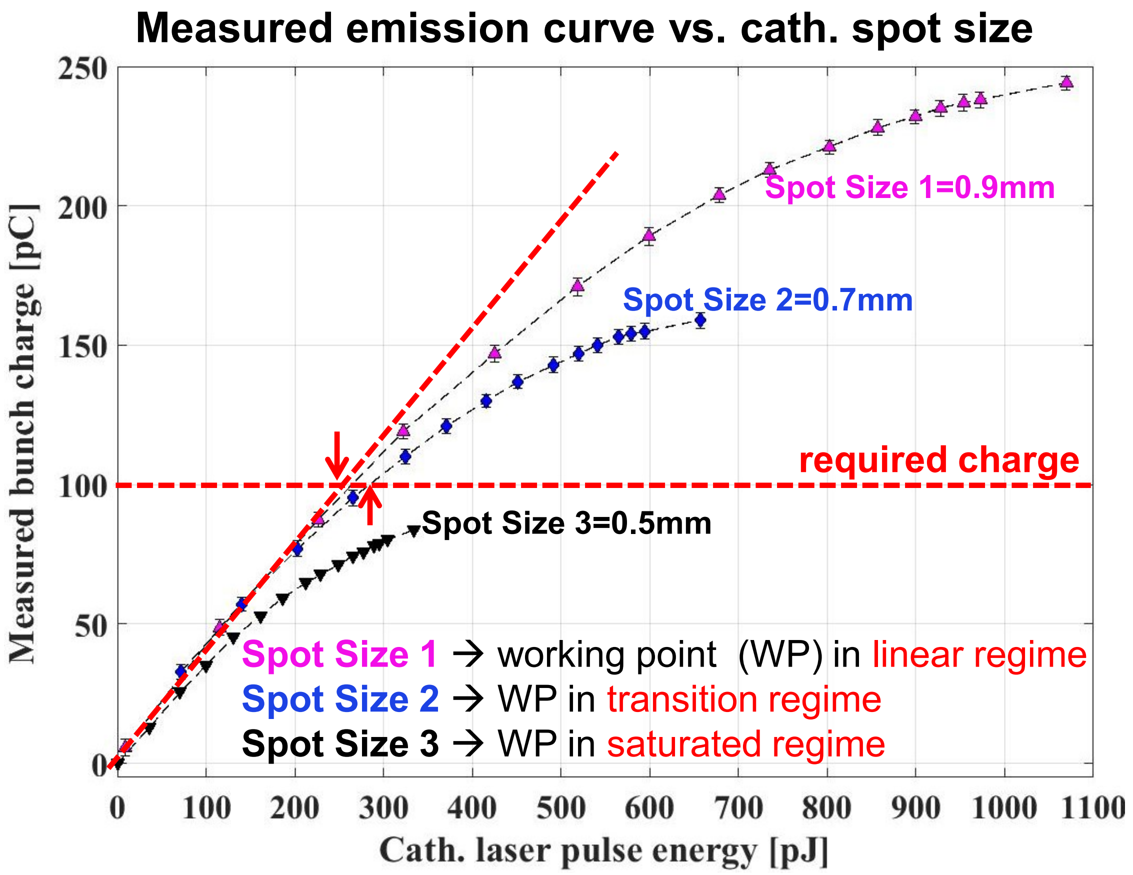
Tracking accelerated bunches (~19 MeV/c) downstream till ~5.3m

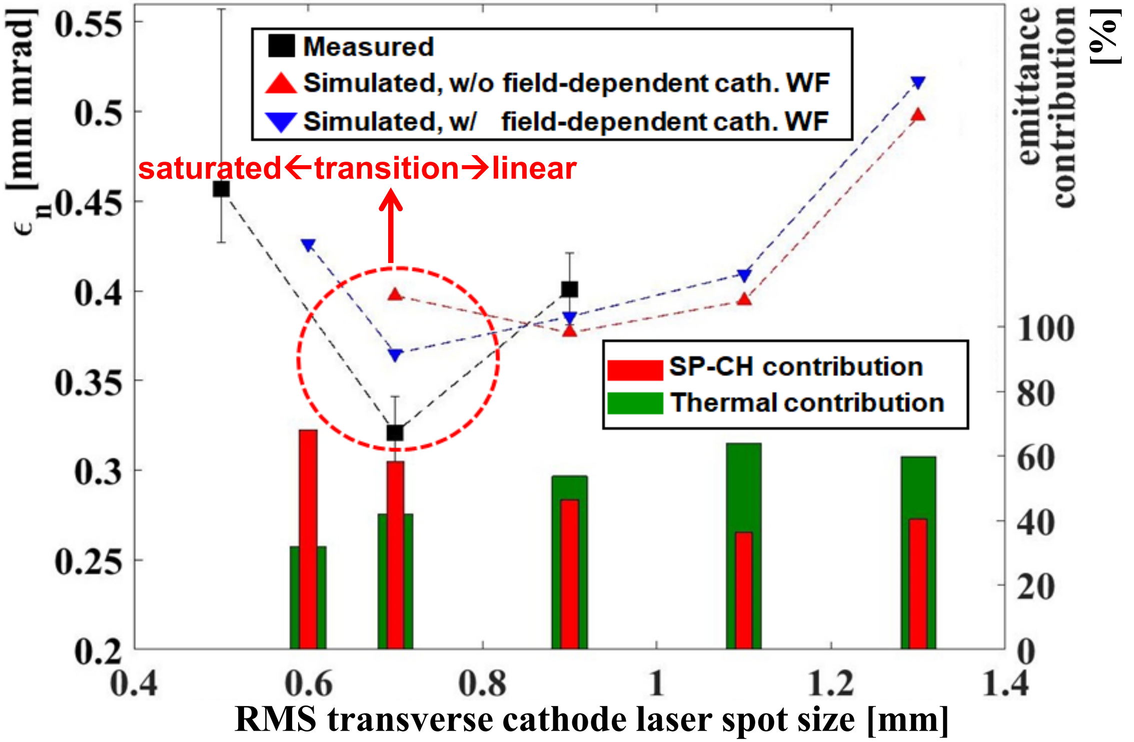




- → **Photoemission details influence downstream beam quality**
- → High local charge density at cathode reduces slice emittance and the effect **transported downstream**
- → **Stronger effect** for **higher** local **charge** density

Measurement vs. Simulation: optimized emittance vs. cathode laser spot size





- **Interplay** between **space charge emittance** and **intrinsic emittance** gives optimum spot size for **best emittance in transition regime**
- **Improved simulation** suggests optimum spot size same as measured

Summary

- **Working at transition regime of emission delivers best experimentally optimized emittance**
- **Photoemission details influence** downstream beam qualities
- Emission modeling helps **better understand beam dynamics**
- **Cathode physics important** for better emission modeling
- **More detailed modeling approach needed** for strong space charge fields at cathode

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and many others…

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