# Beam Halo Formation in Continuous-Wave Photoinjectors

## Longitudinal–transverse coupling below 1 MeV

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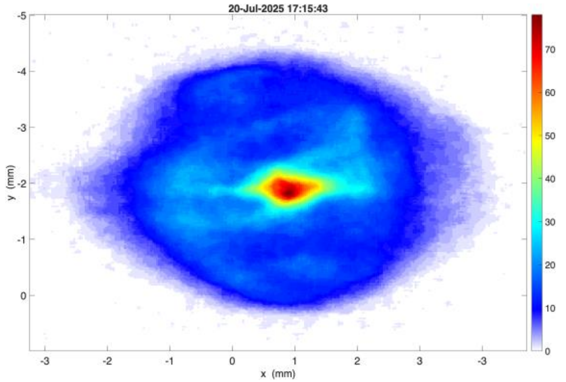
42nd International Free Electron Laser Conference (FEL2026)
August 23 – 28, 2026
Li Ka Shing Center, Stanford University

# Outline

## From an operational nuisance to a quantitative mechanism

- Why beam halo limits CW FEL operation
- What we saw during LCLS-II injector commissioning
- A three-step mechanism from longitudinal–transverse coupling
  - r-dependent chirp → hollow bunch ends → over-focusing
- Experimental validation
  - solenoid scans, controlled ring formation
- Mitigation: buncher compression tuning, now used in operation

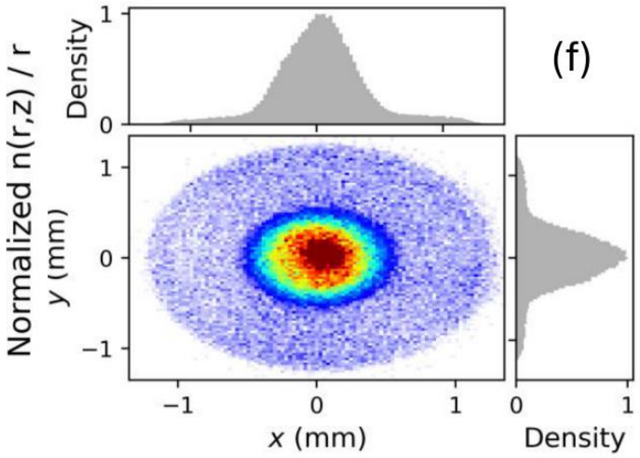



*Halo around the core, measured at LCLS-II injector*

# Why beam halo matters for CW FELs

## High average current plus tight loss budgets

- Superconducting FELs — LCLS-II, SHINE, European XFEL— run at MHz rates and high average current
- Halo causes uncontrolled loss, component activation and a machine-protection burden that interrupts operation
- It also degrades brightness and makes matching and emittance measurement unreliable
- Well studied elsewhere, but not here:
  - hadron beams: space-charge resonances, particle–core models
  - ERLs and rings: mismatch, nonlinear RF, diffusion, scattering
  - single-pass photoinjectors: little attention so far

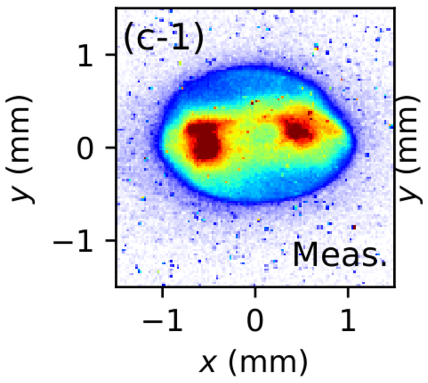



*Simulated core–halo profile after the cryomodule*

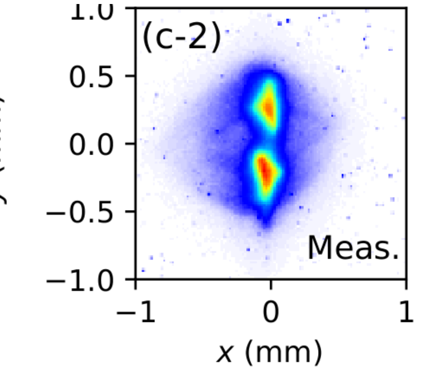
**The dominant halo mechanism of CW photoinjectors had not been identified — that is the gap this work closes.**

# What we saw during LCLS-II commissioning

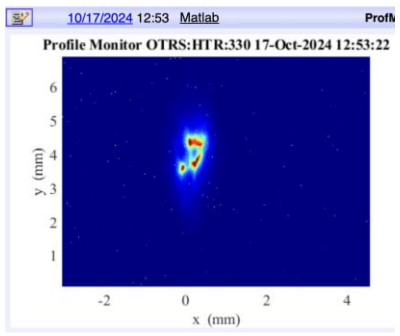
## Non-Gaussian transverse profiles downstream of the injector

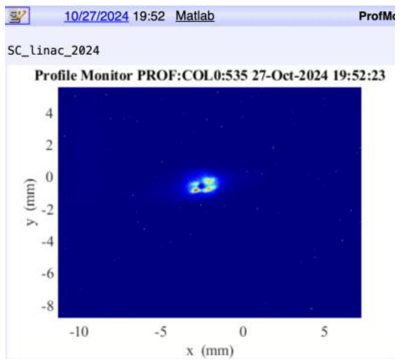



two horizontal lobes

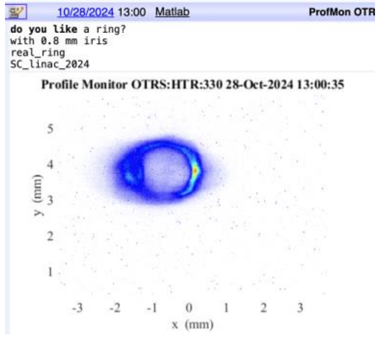



two vertical lobes

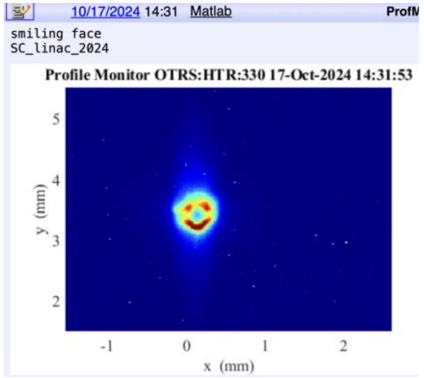



Four spots




Diamond ring



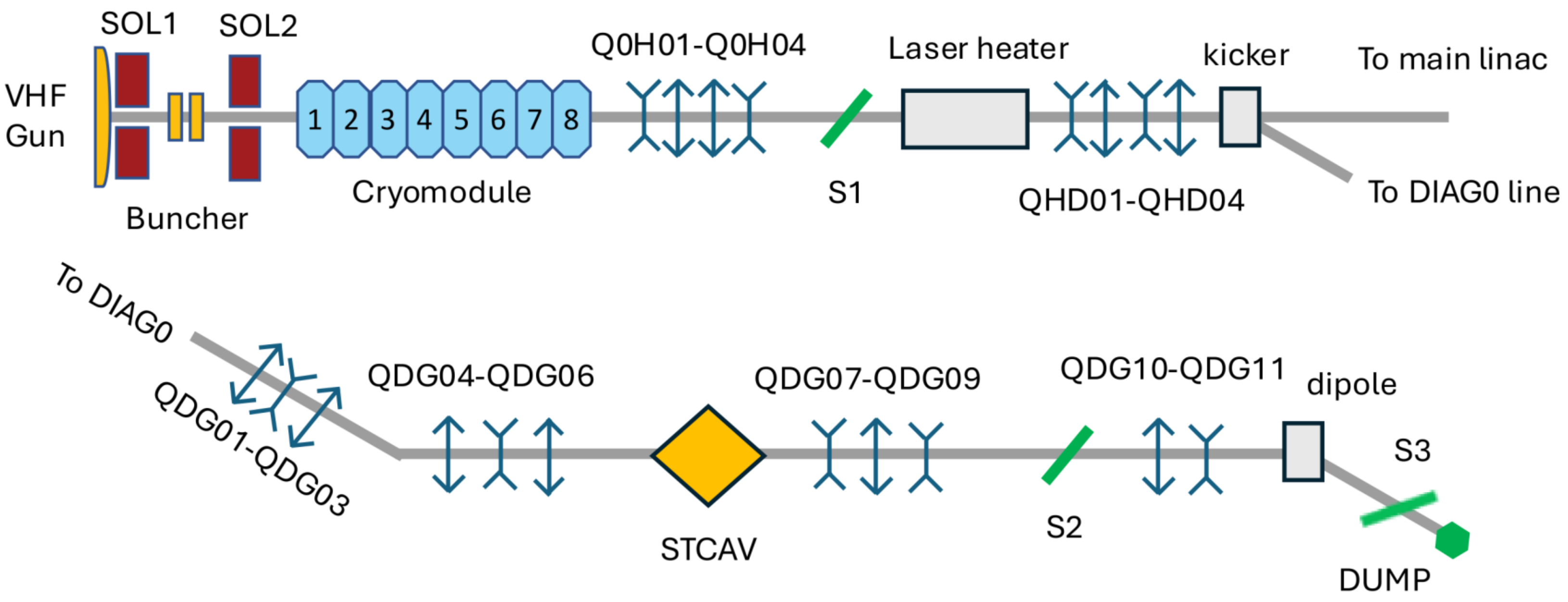

Smiling face

**Blame the laser!!!**

- Bright compact core wrapped in a diffuse outer population; the shape follows the optics
- Reproduced later in dedicated experiments with nominal laser, cathode and RF settings
- Intrinsic to core–halo dynamics, so **it cannot be tuned away by cleaning up the laser or the cathode**

# The LLCS-II CW photoinjector

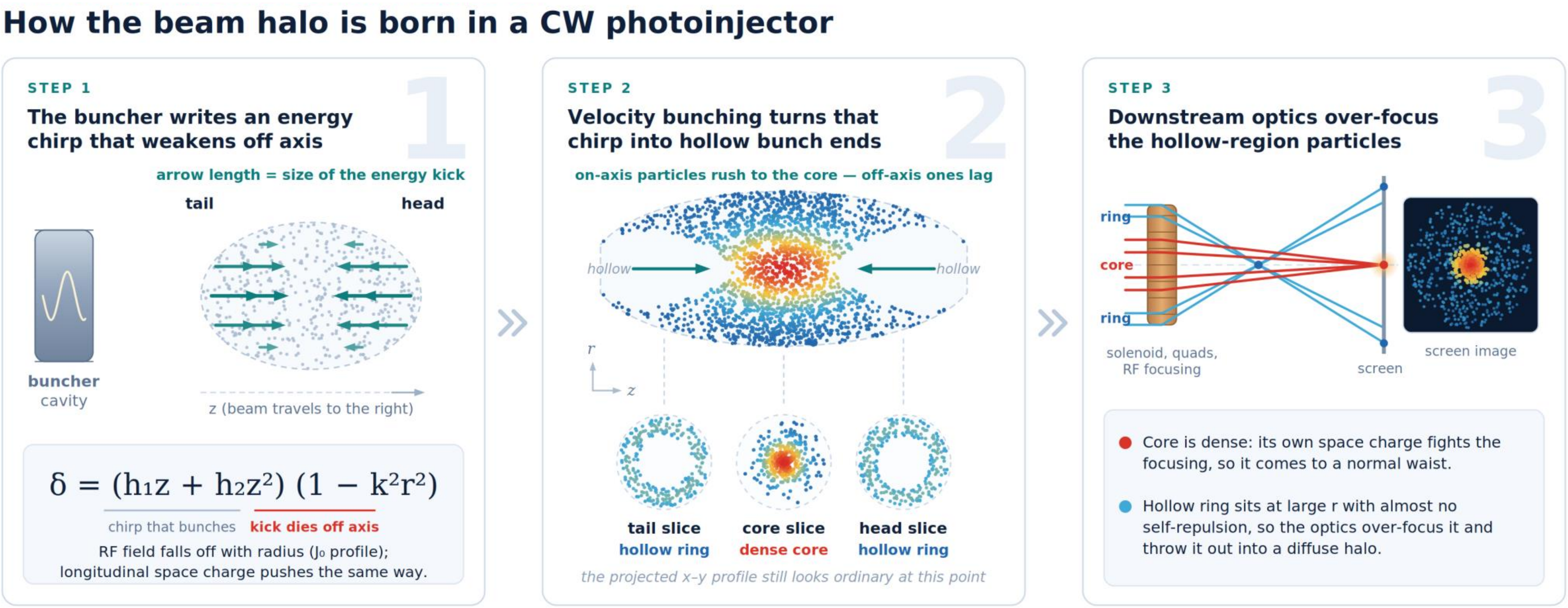
## Velocity bunching at sub-MeV energy, then acceleration to 75 MeV




- 70 pC from a VHF normal-conducting RF gun, ≈650 keV after the gun
- SOL1 for emittance compensation, SOL2 matches into the cryomodule
- Buncher writes the chirp for velocity bunching — all below 1 MeV
- Halo screens S1, S2 (after TCAV) and S3; $\sigma_z \approx 0.9$ mm

# Three steps, one coupled mechanism

## Longitudinal–transverse coupling below 1 MeV

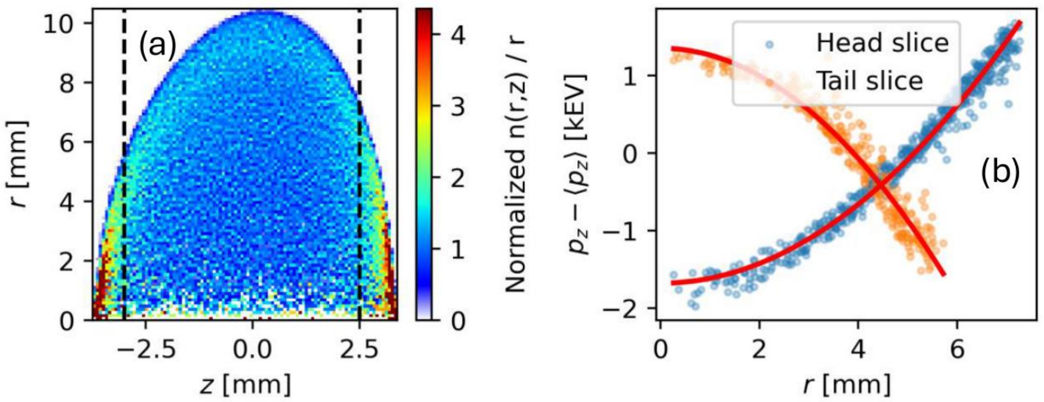



**Chirp that fades off axis → hollow bunch ends after velocity bunching → over-focused hollow regions = halo**

# Step 1: the buncher writes an r-dependent chirp

## The energy kick is strongest on axis and dies off axis

- In the buncher the longitudinal field follows a Bessel profile: the amplitude falls quadratically with radius
- Longitudinal space charge acts the same way — it accelerates the on-axis head and decelerates the on-axis tail more than off-axis particles
- Both add up to a quadratic pz–r correlation inside every slice




*Astra: density after the buncher (left) and pz vs r for head and tail slices (right)*

$$E_z(r) = E_z(0) J_0(k_r r) \simeq E_z(0)\left(1 - \frac{k_r^2 r^2}{4}\right)$$

$$\delta = (h_1 z + h_2 z^2)\,(1 - k^2 r^2)$$

**Astra confirms the prediction: off-axis particles gain pz in the head and lose it in the tail.**

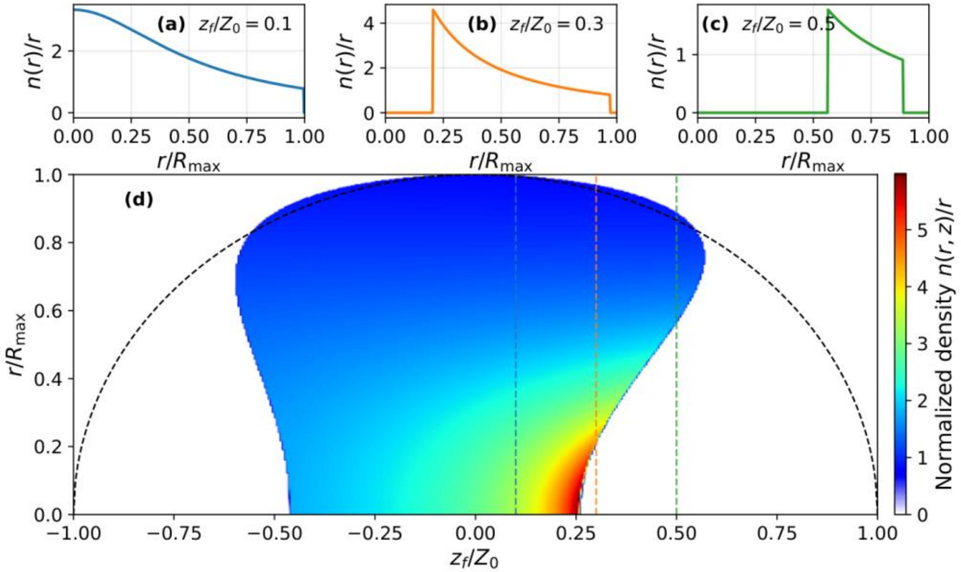
# Step 2: velocity bunching hollows out the ends

## An r-dependent chirp curves the compression surface in (r, z)

- Below 1 MeV small energy differences change the drift velocity, so faster particles overtake slower ones
- On-axis particles get the largest chirp and compress into the core; off-axis particles lag and stay at the ends
- Head and tail therefore become hollow — ring-like in every slice
- r is unchanged here, so the projected profile looks ordinary

$$z_f = z + R_{56}\,\delta + T_{566}\,\delta^2$$

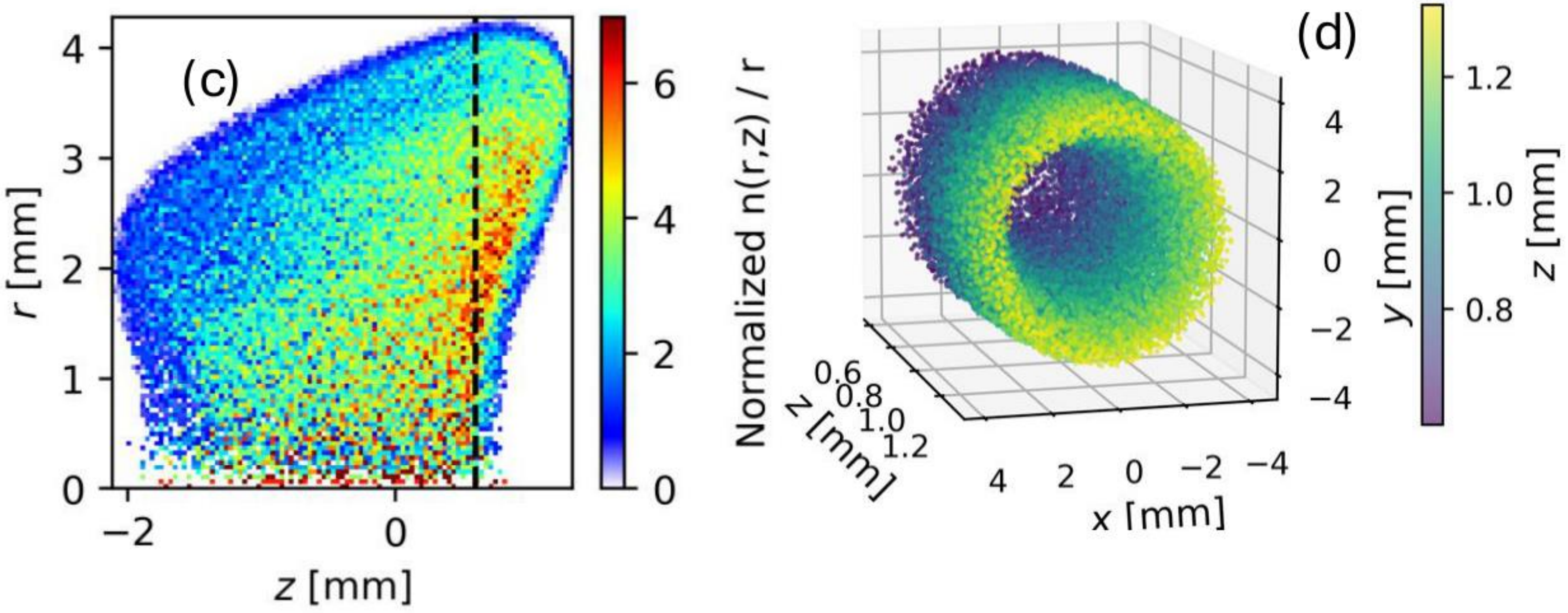
$$R_{56} \simeq \frac{L}{\beta\gamma^2}\,, \qquad T_{566} \simeq -\frac{L}{\beta}\frac{3\gamma^2-1}{2\gamma^4}$$




*Analytic model of a uniformly filled football bunch: hollow head and tail develop during bunching (head on the right)*

# Step 2 in start-to-end simulation

## Astra, 70 pC: hollowed structures at the cryomodule entrance

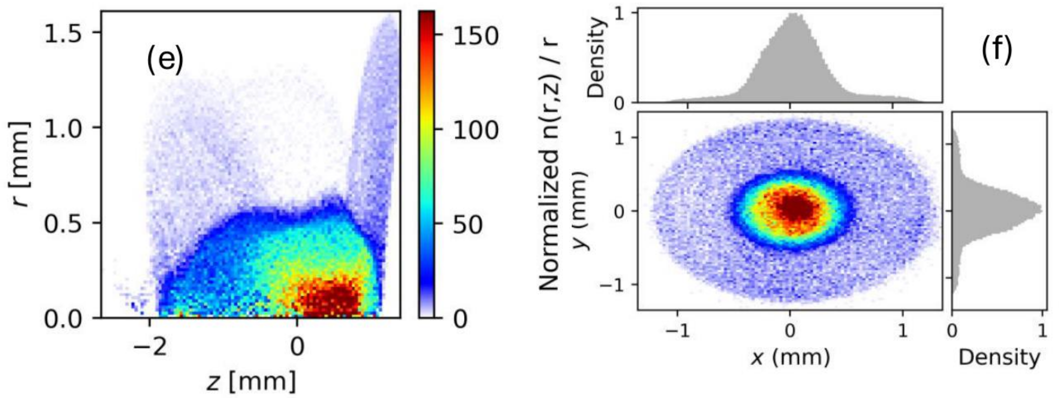



- The (r, z) curvature grows increasingly nonlinear along the drift to the cryomodule
- Hollowed regions appear at both ends — the 3-D view of the head shows a clear ring
- Space charge amplifies it: advancing or lagging off-axis particles get an extra push from their self-fields

# Step 3: the hollow regions get over-focused

## Weak self-repulsion at large radius gives a diffuse halo

- Inside a ring the net radial space-charge force is small: the inner edge encloses almost no charge, the outer edge far less than a dense core would
- All hollow-region particles sit at large radii, so they see stronger external focusing from solenoids, quadrupoles and RF
- Weakly repelled and strongly focused, they are over-focused and pushed to even larger radii
- The result is a bright core enveloped by a diffuse halo




*Mid-cryomodule (r, z) density and the final transverse profile with its projections*

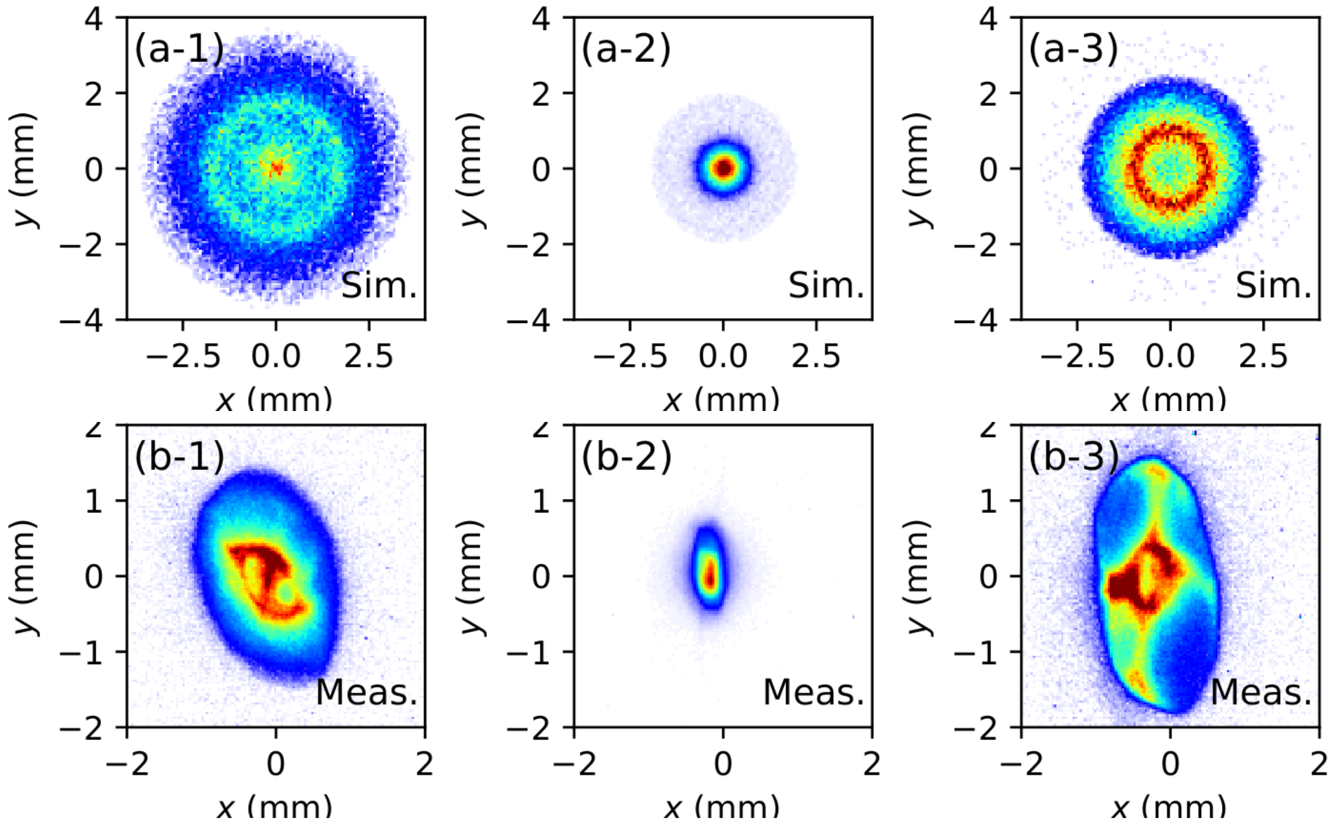
**Simulation reproduces the whole chain — chirp, hollowing, halo — from the machine settings alone.**

# Experiment: core and halo focus differently

## Matching quadrupoles off, buncher at −60°, SOL2 scanned

**Simulation**

**Measured**

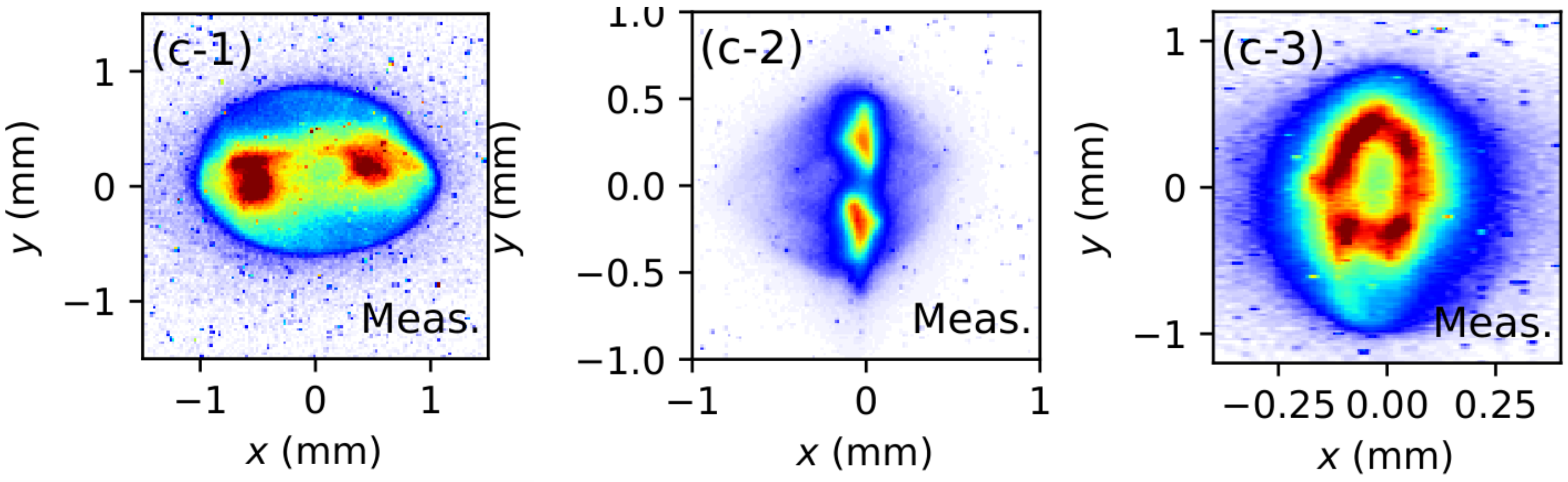


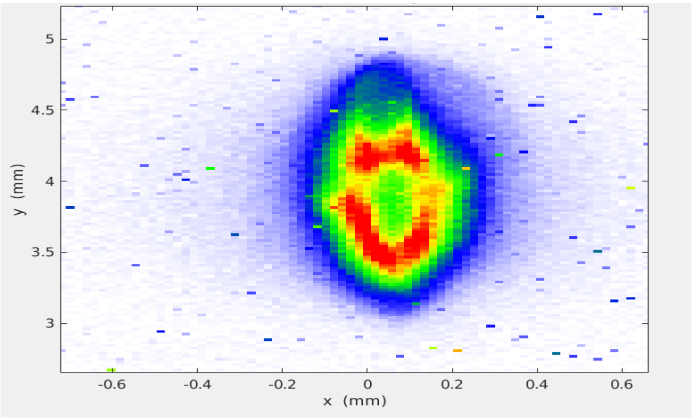

*increasing SOL2 strength →*

**Ring with a bright core → compact spot → over-focused ring: exactly the differential focusing the model predicts.**

# The halo can be reshaped on demand

## Quadrupoles back on: horizontal lobes, vertical lobes, or a clean ring




*We caught the smiling face as well.*

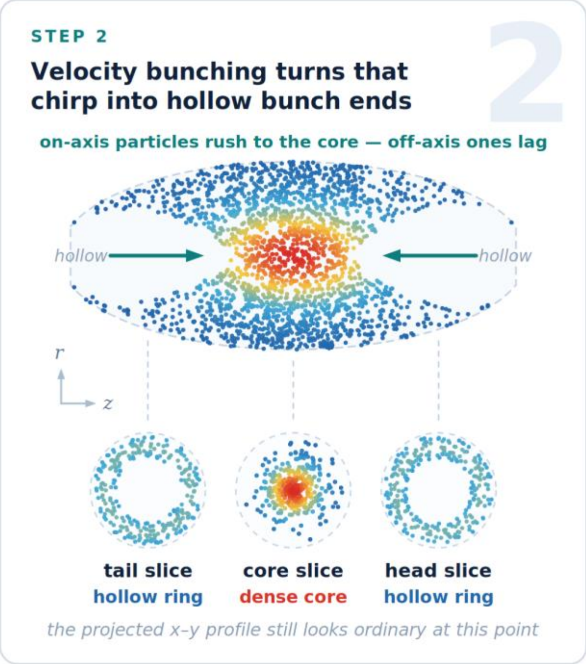
*Measured at S1; the same patterns first appeared during commissioning*

- A strong halo component is what makes these shapes possible — they are now produced deliberately
- They appear with no special laser, cathode or field imperfection, so they are intrinsic to core–halo dynamics
- They corrupt emittance measurements and seed downstream beam loss

# Mitigation: bunch less at low energy

## Shallower hollowing means less halo

- The model points straight at the knob: weaken the buncher compression, which limits the depth of the hollowed structures that seed the halo
- Buncher phase moved from −55° to −46° and −40° from on crest
- CAV2 at zero crossing then provides modest bunching at ≈7 MeV, where the beam is smaller and space charge weaker — same bunch length at the injector exit




**Move the compression to where the beam is stiffer: same bunch length, much weaker coupling into the transverse plane.**

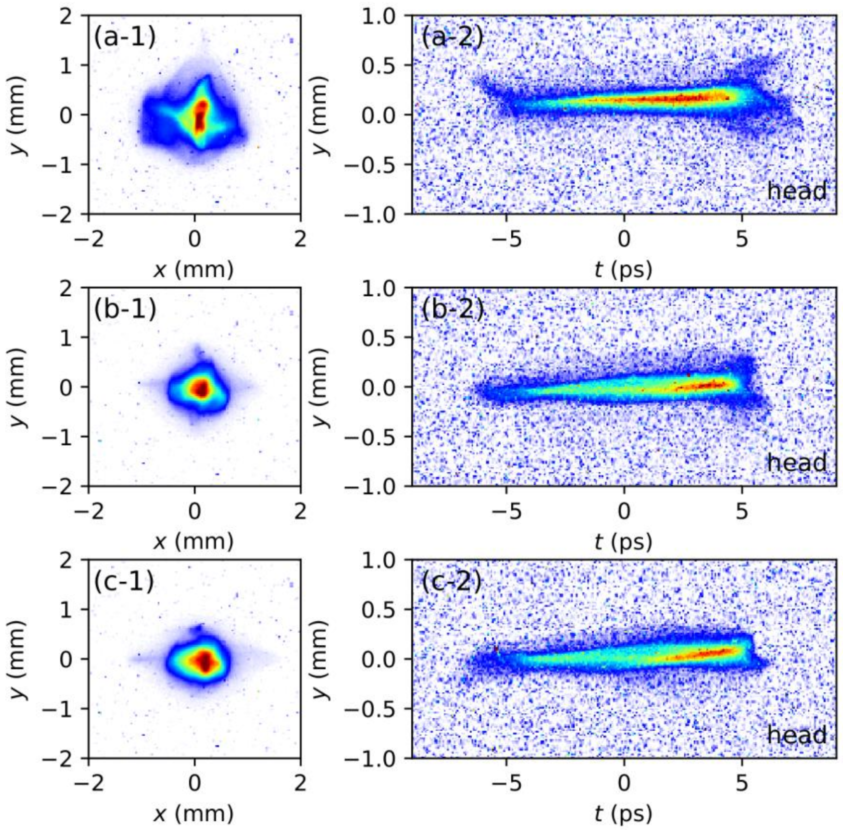
# Mitigation works, in profile and in time

## Halo at S1 and head/tail expansion at S2 shrink with weaker bunching

**−55°**
strong

**−46°**

**−40°**
weak




- Left: x–y at S1. Right: y–t streak images at S2 from the S-band TCAV, beam head on the right
- At −55° a diffuse halo surrounds the bright core, and the streak image shows pronounced head- and tail-side expansion
- Those expansions are the hollowed structures predicted by the model
- At −46° and −40° the halo features at both screens progressively diminish

**Reduced velocity bunching suppresses halo formation — the mechanism and its cure both confirmed.**

# Now part of LCLS-II operation

## From diagnosis to an operational recipe

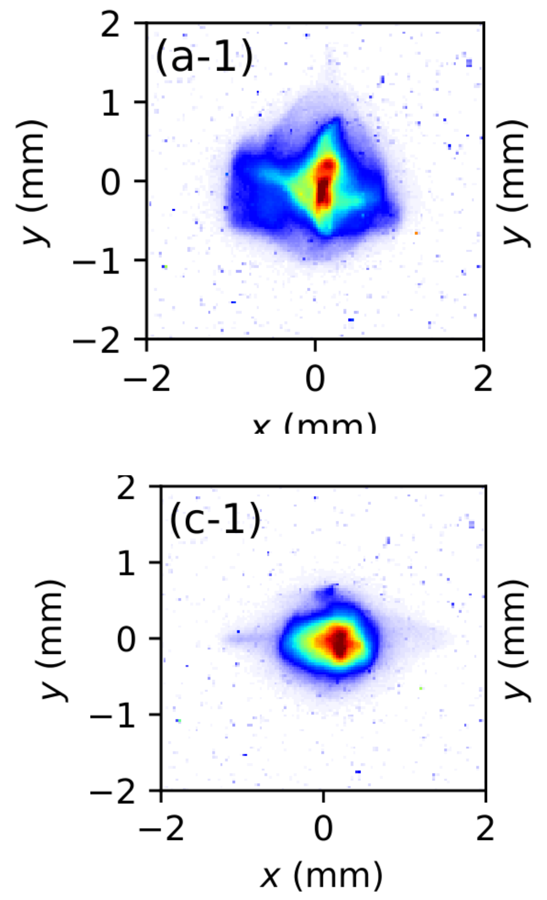
The buncher-compression strategy has been implemented at LCLS-II

Result: a marked reduction in beam halo and in the associated downstream losses, supporting sustained high-repetition-rate operation

Halo became a controlled knob — buncher phase — instead of an unexplained feature of the injector

Practical guidance for tuning:

- watch the time-resolved image, not only the projected profile
- share the compression between buncher and CAV2
- rematch the optics after each change so halo and mismatch are not confused




*S1 profile before and after the change*

# Generic to CW photoinjectors

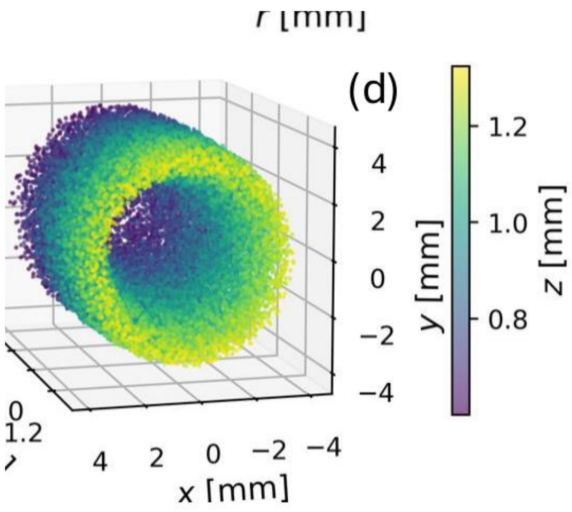
## The ingredients are shared by nearly every CW SRF FEL injector

All the mechanism needs is sub-MeV velocity bunching, a radially dependent chirp, and downstream focusing

That configuration is used at LCLS-II, SHINE, the European XFEL CW upgrade and VHF-gun ERL injectors

Design implications:

- minimize compression below ≈1 MeV; move it to higher energy where the beam is smaller and stiffer
- treat halo as a constraint on the buncher–solenoid working point, not only an operational issue
- include time-resolved transverse diagnostics early in the beamline




*3-D view of the hollowed bunch head*

**Halo control belongs in the injector design loop for the next generation of high-repetition-rate FELs.**

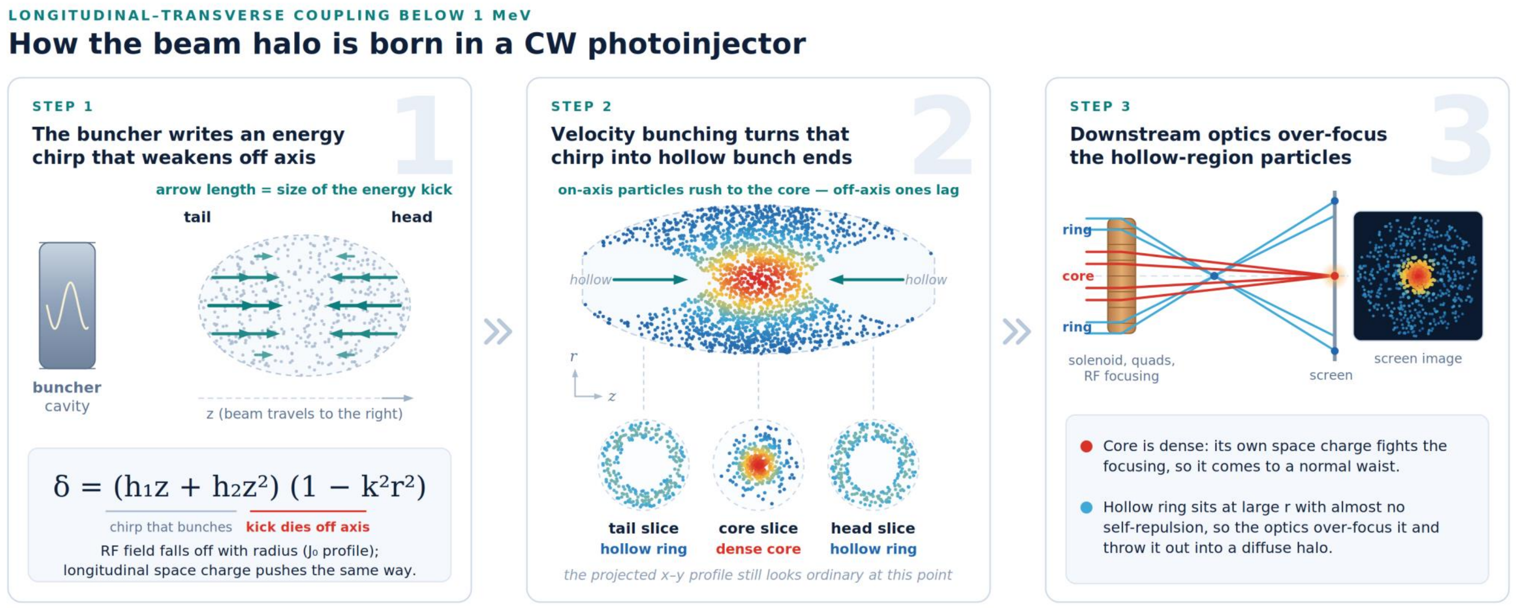
# Summary

## A previously unrecognized halo mechanism, validated and mitigated

Three coupled steps: r-dependent chirp, hollow bunch ends, over-focusing into a halo

Confirmed by an analytic model, Astra simulation and direct measurement at LCLS-II

Mitigated by weaker buncher compression — now standard in LCLS-II operation



# Thank you

## Questions welcome

Thanks to David Dowell, Theodore Vecchione and Jingyi Tang for their help and for many useful discussions

Supported by the U.S. Department of Energy under Contract No. DE-AC02-76SF00515

Zhen Zhang, Yuantao Ding, David Cesar, Feng Zhou, Ji Qiang and Zhirong Huang, "Beam halo formation via longitudinal–transverse coupling in continuous-wave photoinjectors" *arXiv preprint arXiv:2511.05831* (2025).

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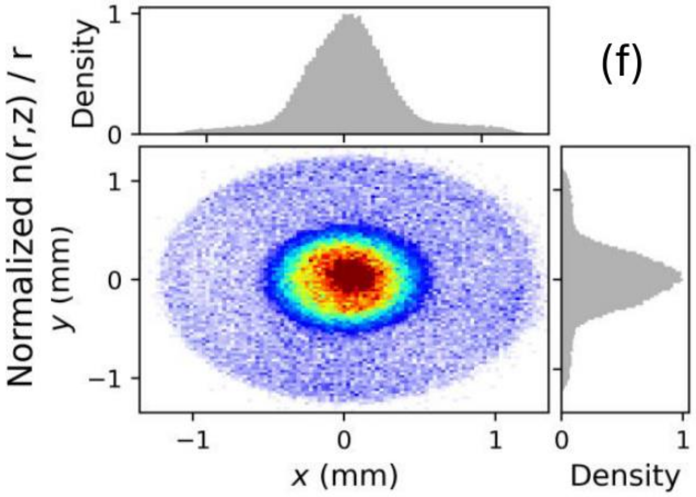


*Simulated core–halo profile after the cryomodule*