QuickTime™ and a
decompressor
are needed to see this picture.

Numerical Modeling of E-Cloud Driven Instability and its Mitigation using a Simulated Feedback System in the CERN SPS*

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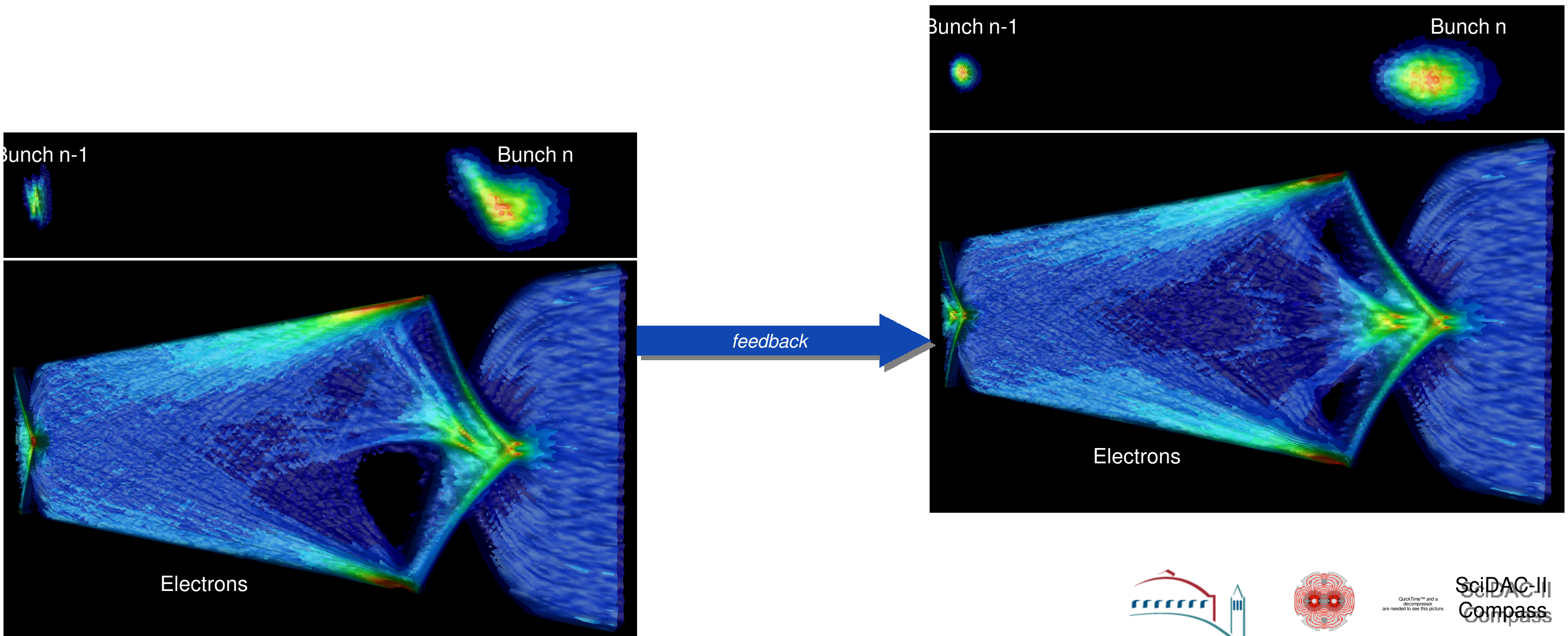


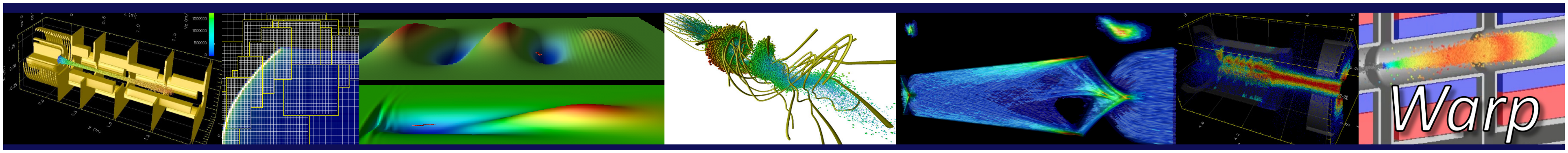
SciDAC-II
Compass

Outline

- **Simulation codes and benchmarking**
- **Application to the modeling of e-cloud effects in the SPS**
  - beam dynamics: 2 bunches
  - beam dynamics + EC buildup: 1 batch of 72 bunches
  - comparison with experimental data
  - feedback model
- **Conclusion**

Warp: a parallel framework combining features of plasma (Particle-In-Warp) and accelerator codes

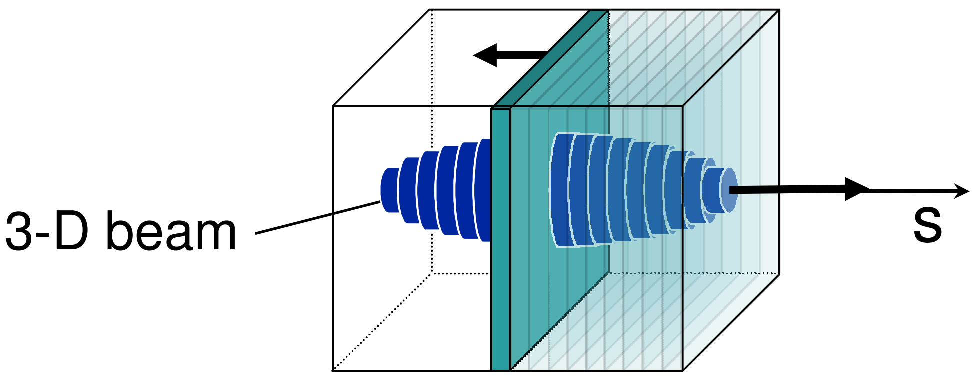
- **Geometry:** 3D (x,y,z), 2D-1/2 (x,y), (x,z) or axisym. (r,z)
- **Python and Fortran:** “steerable,” input decks are programs
- **Field solvers:** Electrostatic/Magnetostatic - FFT, multigrid; AMR; implicit
  Electromagnetic - Yee, Cole-Kark.; PML; AMR
- **Parallel:** MPI (1, 2 and 3D domain decomposition)
- **Boundaries:** “cut-cell” --- no restriction to “Legos”
- **Lattice:** general; non-paraxial; can read MAD files
  - solenoids, dipoles, quads, sextupoles, linear maps, arbitrary fields, acceleration
- **Bends:** “warped” coordinates; no “reference orbit”
- **Particle movers:** Boris, large time step “drift-Lorentz”, novel relativistic Leapfrog
- **Reference frame:** lab, moving-window, Lorentz boosted
- **Surface/volume physics:** secondary e^-/photo-e^- emission, gas emission/tracking/ionization
- **Diagnostics:** extensive snapshots and histories
- **Misc.:** **trajectory** tracing; quasistatic & steady-flow modes; space charge emitted emission; “equilibrium-like” beam loads in linear focusing channels; maintained using CVS repository.



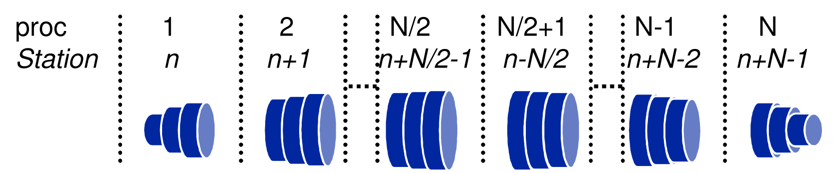
Our simulation framework encompasses the Warp and Posinst PIC codes

Warp quasistatic model similar to HEADTAIL, PEHTS, QuickPIC, CMAD.

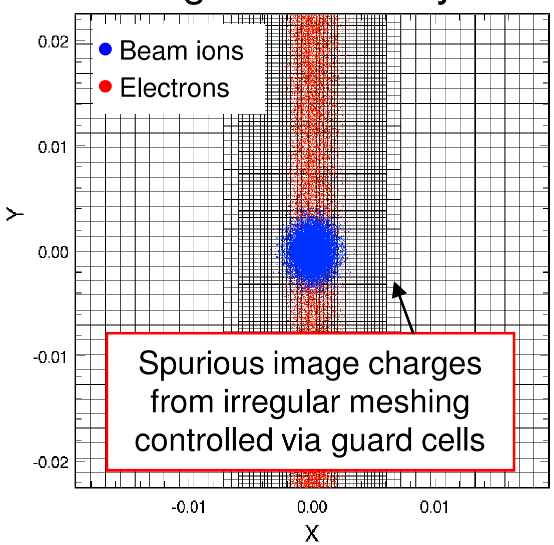
2-D slab of electrons



parallellized using pipelining

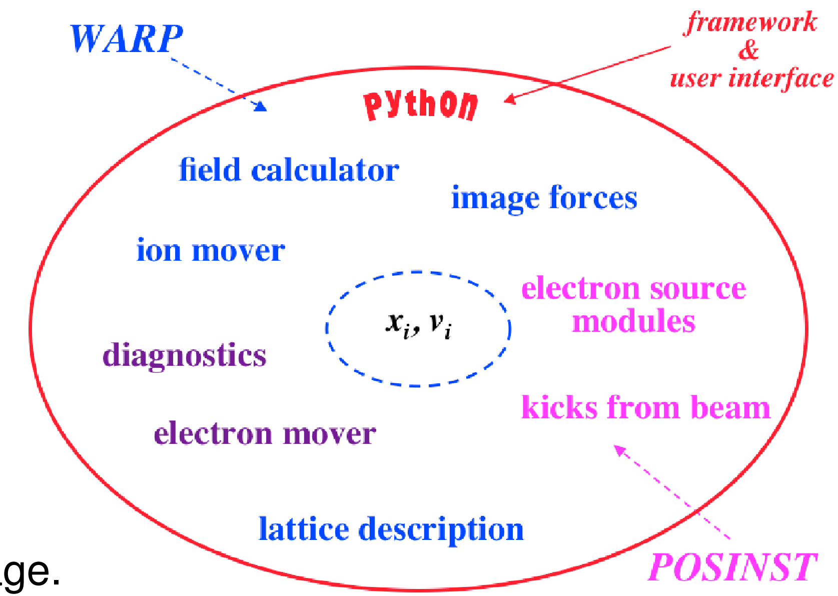


Mesh refinement provides higher efficiency

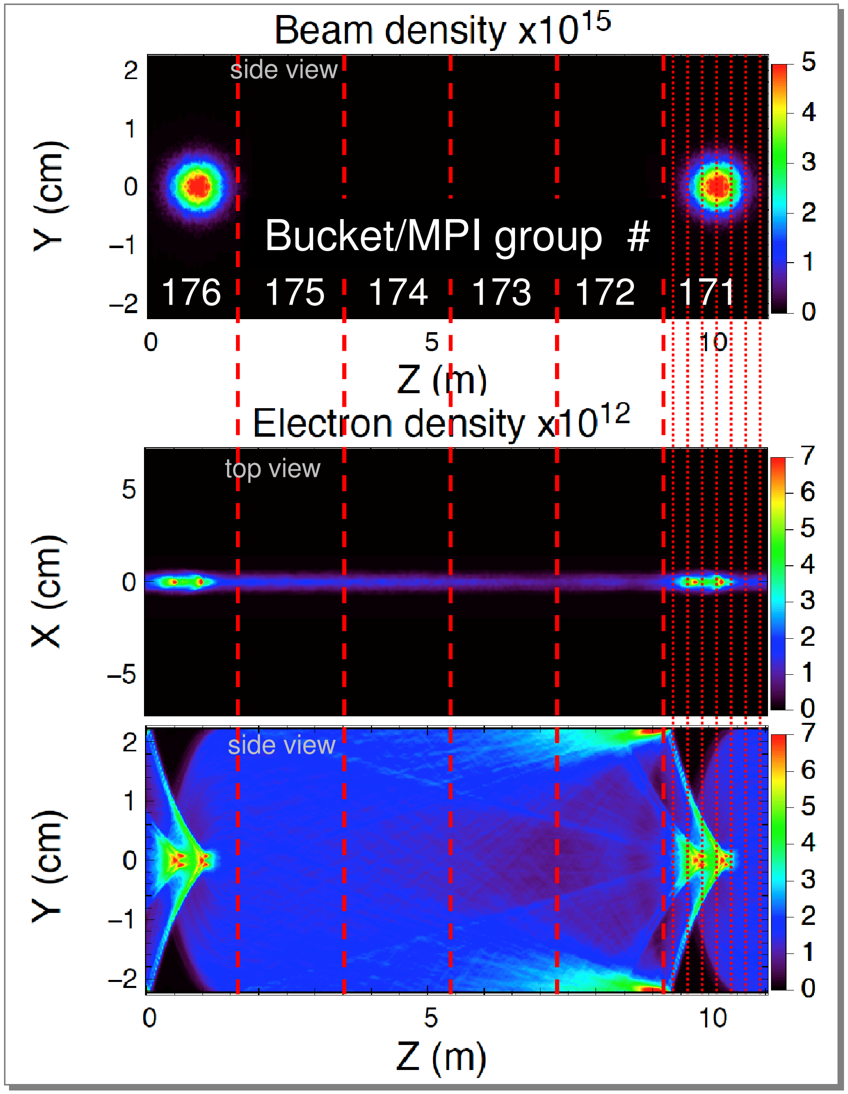


Secondary emission from Posinst:

Warp+Posinst integration via Python language.



Quasistatic mode recently upgraded to handle multiple bunches using MPI groups



- MPI groups:
  - 1 bucket = 1 group;
  - each group diagnoses beam in its own bucket
- Allowed for minimal changes to the code.

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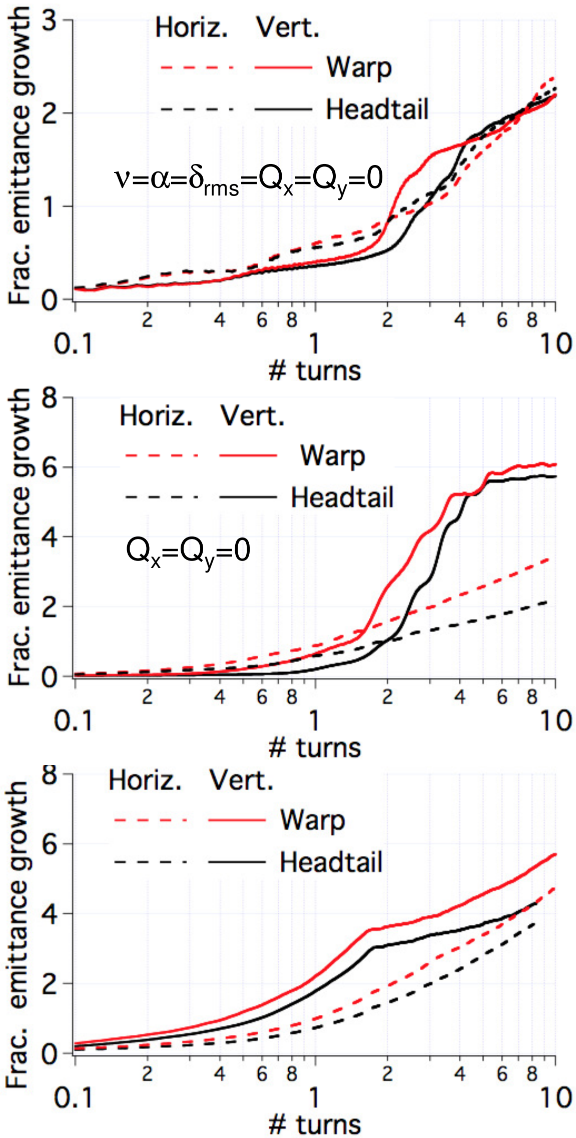
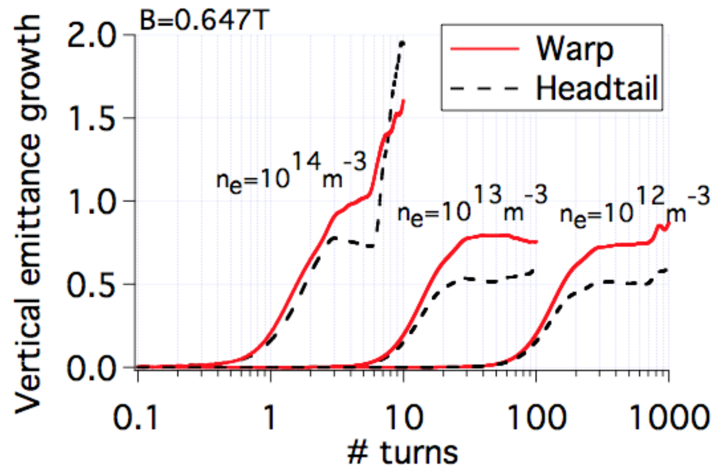
Warp benchmarked with Headtail w/ LHC parameters

Drift



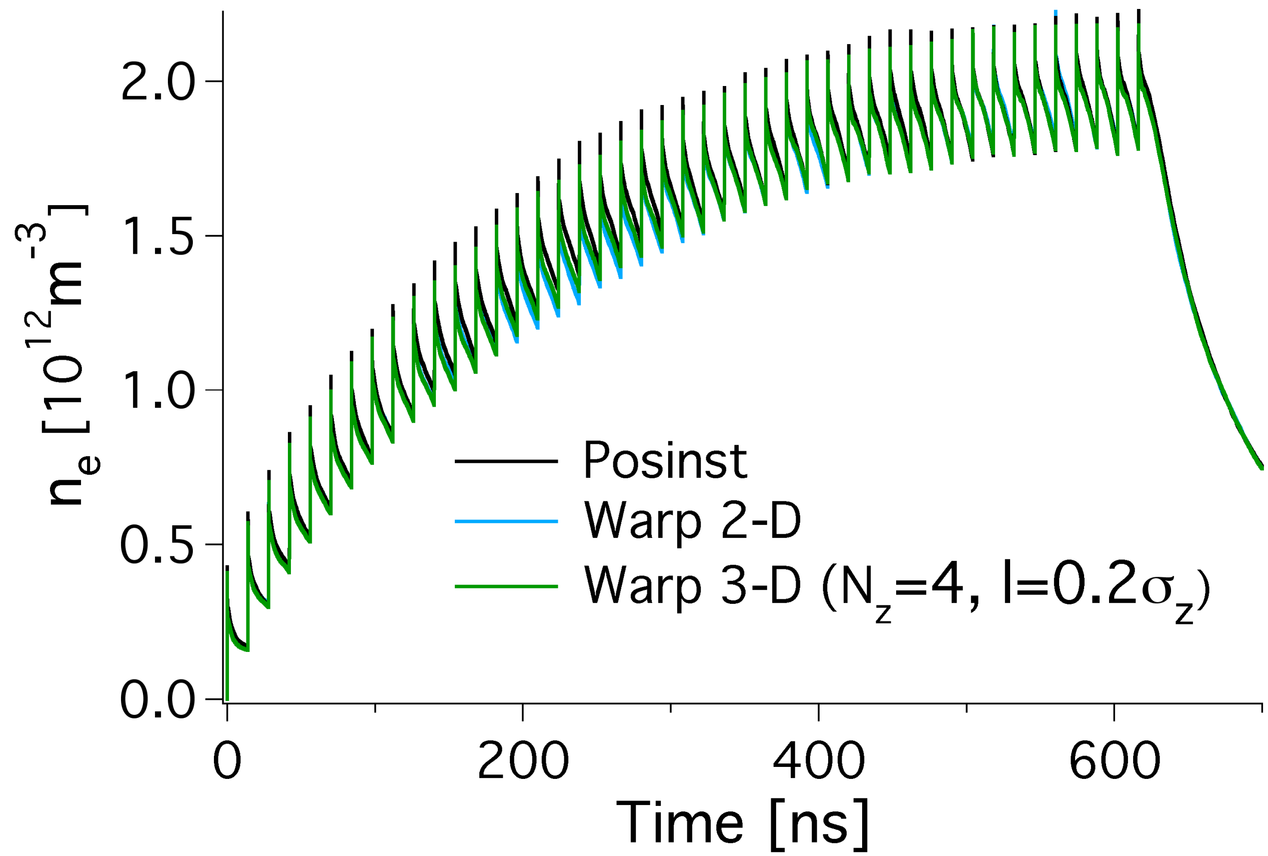
circumference	C	26.659 km
beam energy	E_b	450 GeV
bunch population	N_b	1.1×10^{11}
rms bunch length	σ_z	0.13 m
rms beam sizes	$\sigma_{x,y}$	0.884, 0.884 mm
beta functions	$\beta_{x,y}$	66., 71.54 m
betatron tunes	$Q_{x,y}$	64.28, 59.31
chromaticities	$Q'_{x,y}$	1000., 1000.
synchrotron tune	ν	0.59
momentum compaction factor	α	0.347×10^{-3}
rms momentum spread	δ_{rms}	4.68×10^{-2}

Dipole



And against Posinst for short CESR-TA wiggler section

(approximated by a dipole magnetic field)



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SPS at injection

- Bunch
  - energy — $W=26.$ GeV
  - population — $N_p=1.1\times10^{11}$
  - RMS length — $\sigma_z=0.23$ m (Gaussian profile)
  - momentum spread — $\delta p/p=2\times10^{-3}$
  - transverse normalized emittance — $\varepsilon_x= \varepsilon_y=2.8$ mm.mrad
  - longitudinal normalized emittance — $\varepsilon_z=0.3$ eV.s
- $\perp$: continuous focusing
  - beta functions — $\beta_{x,y}= 33.85, 71.87$
  - betatron tunes — $\nu_{x,y}= 26.13, 26.185$
  - chrom. — $Q_{x,y}=0.,0.$
- // : continuous focusing
  - momentum compaction factor — $\alpha=1.92\times10^{-3}$
  - cavity voltage — $V = 2$ MV
  - cavity harmonic number — $h = 4620.$
- assumed 100% dipole
- 10 interaction stations/turns

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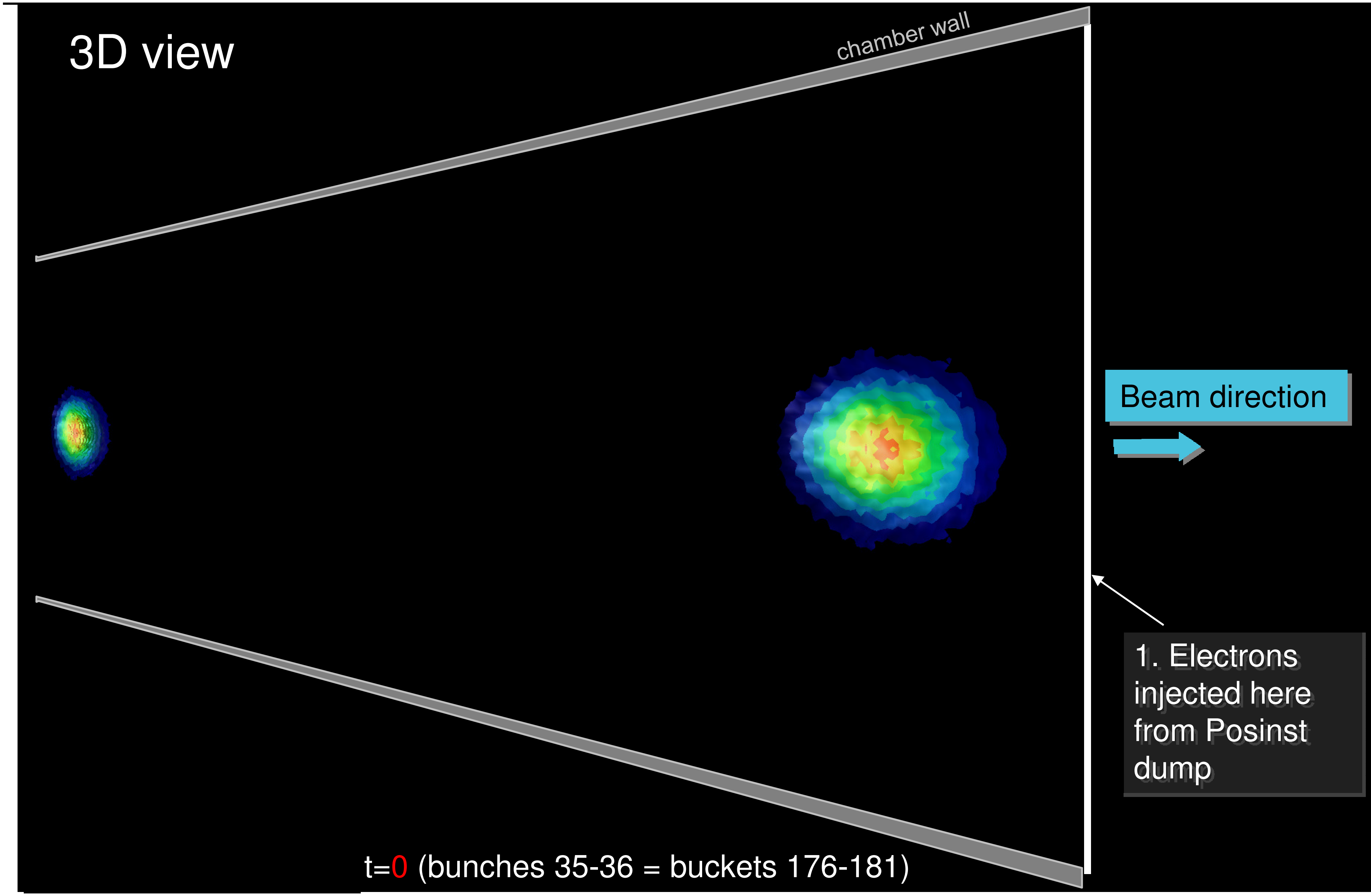
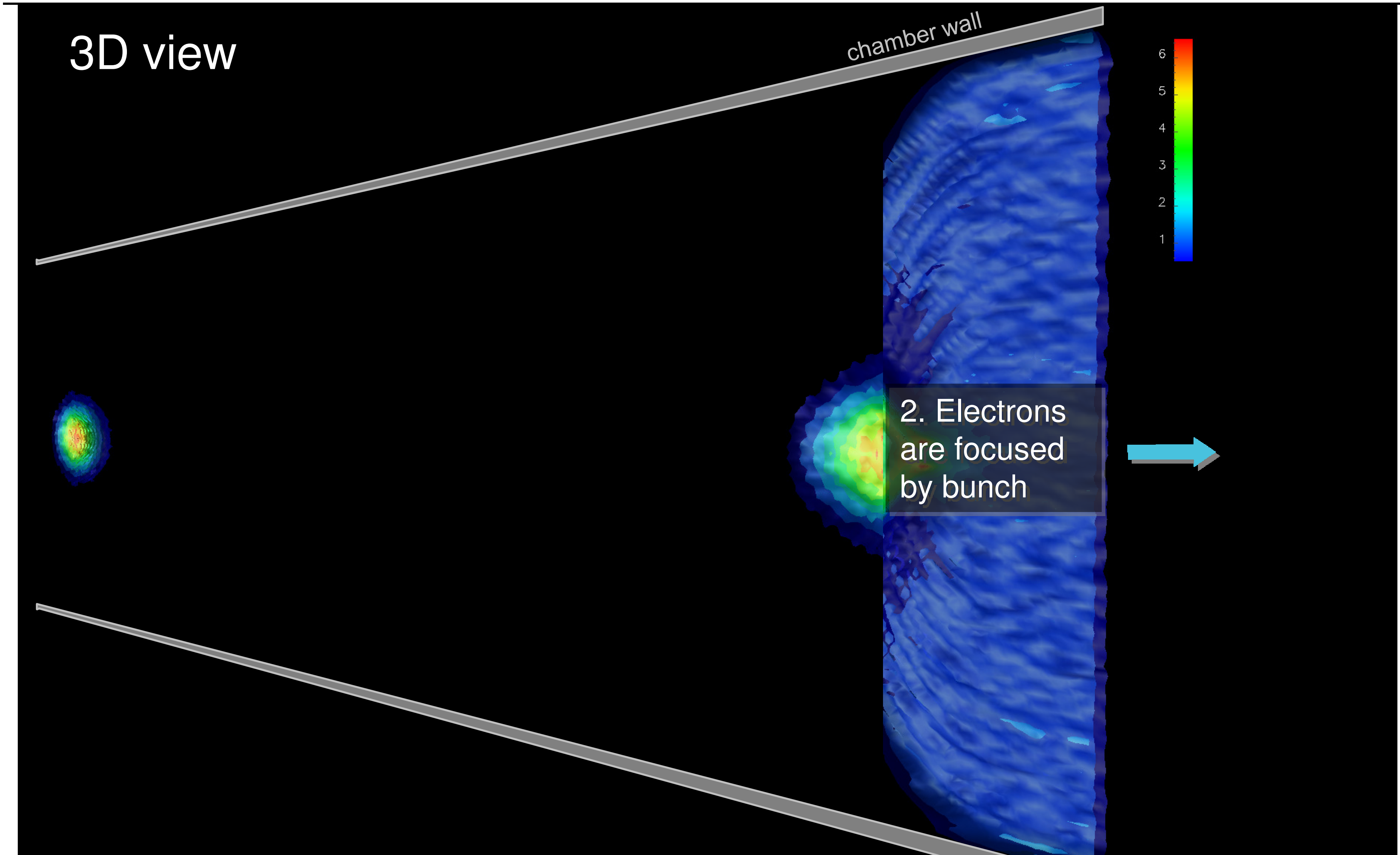
Physics of electron interaction with bunches

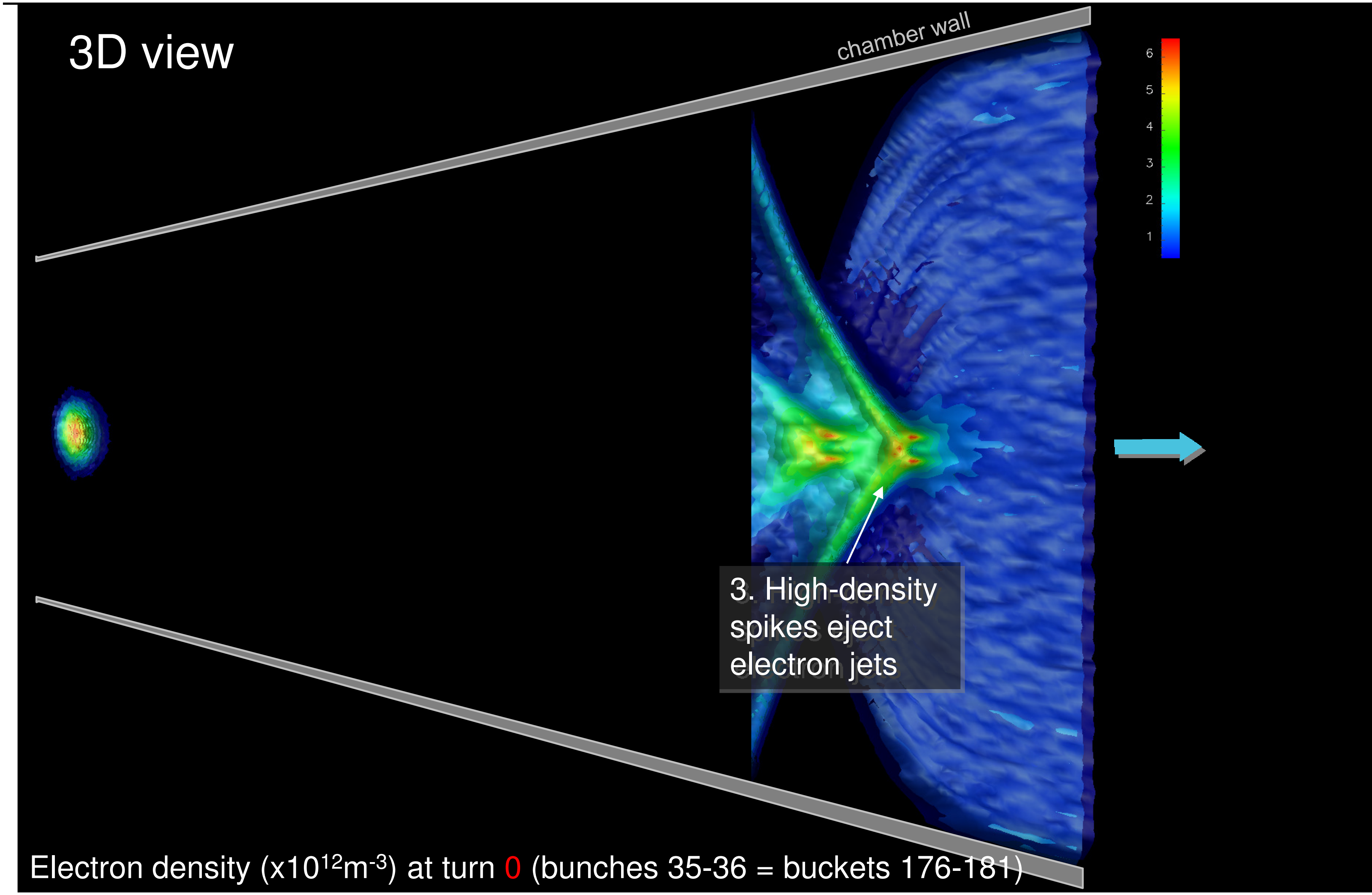


Physics of electron interaction with bunches



Electron density ($\times 10^{12} m^{-3}$) at turn 0 (bunches 35-36 = buckets 176-181)

Physics of electron interaction with bunches



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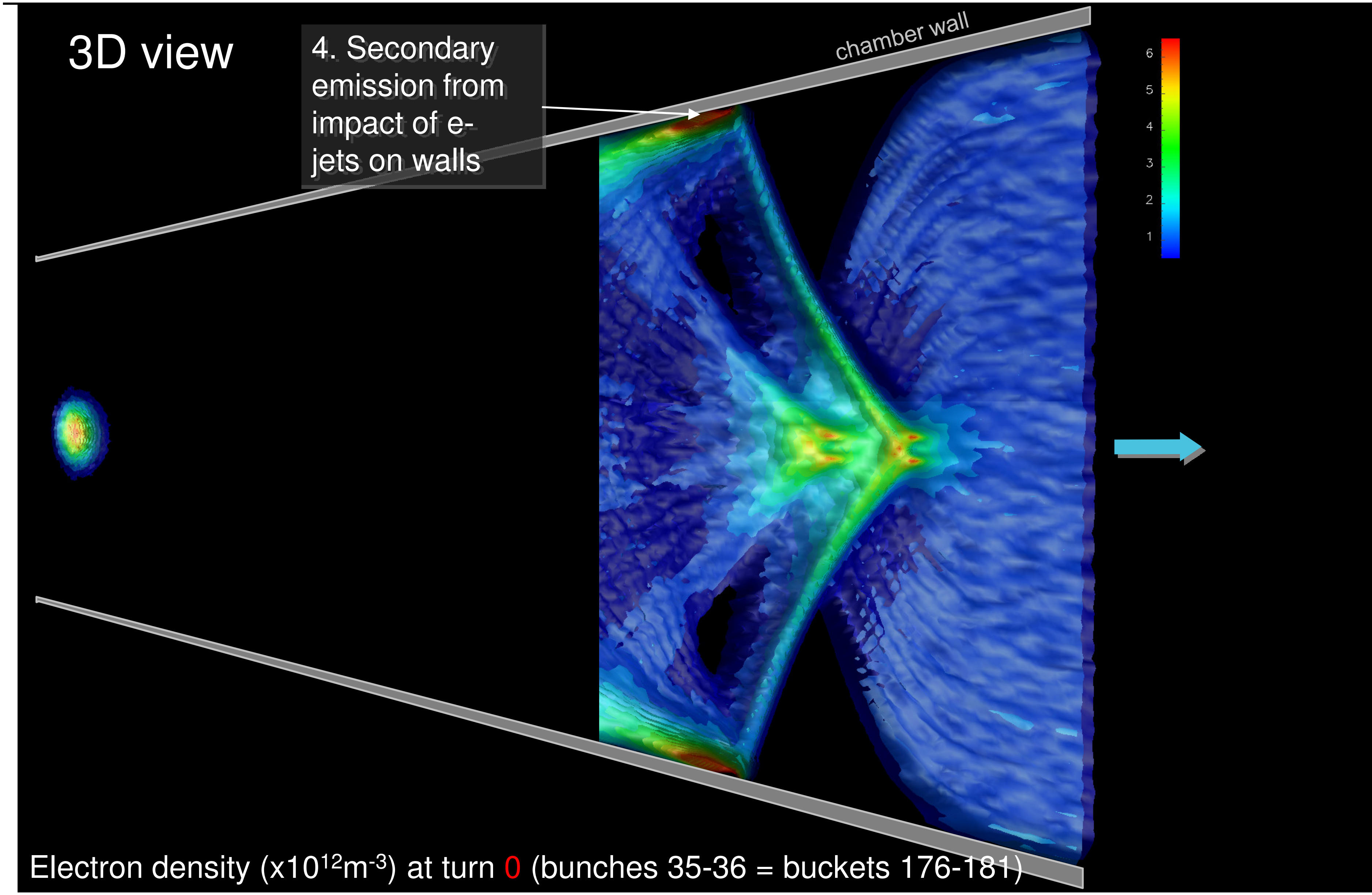

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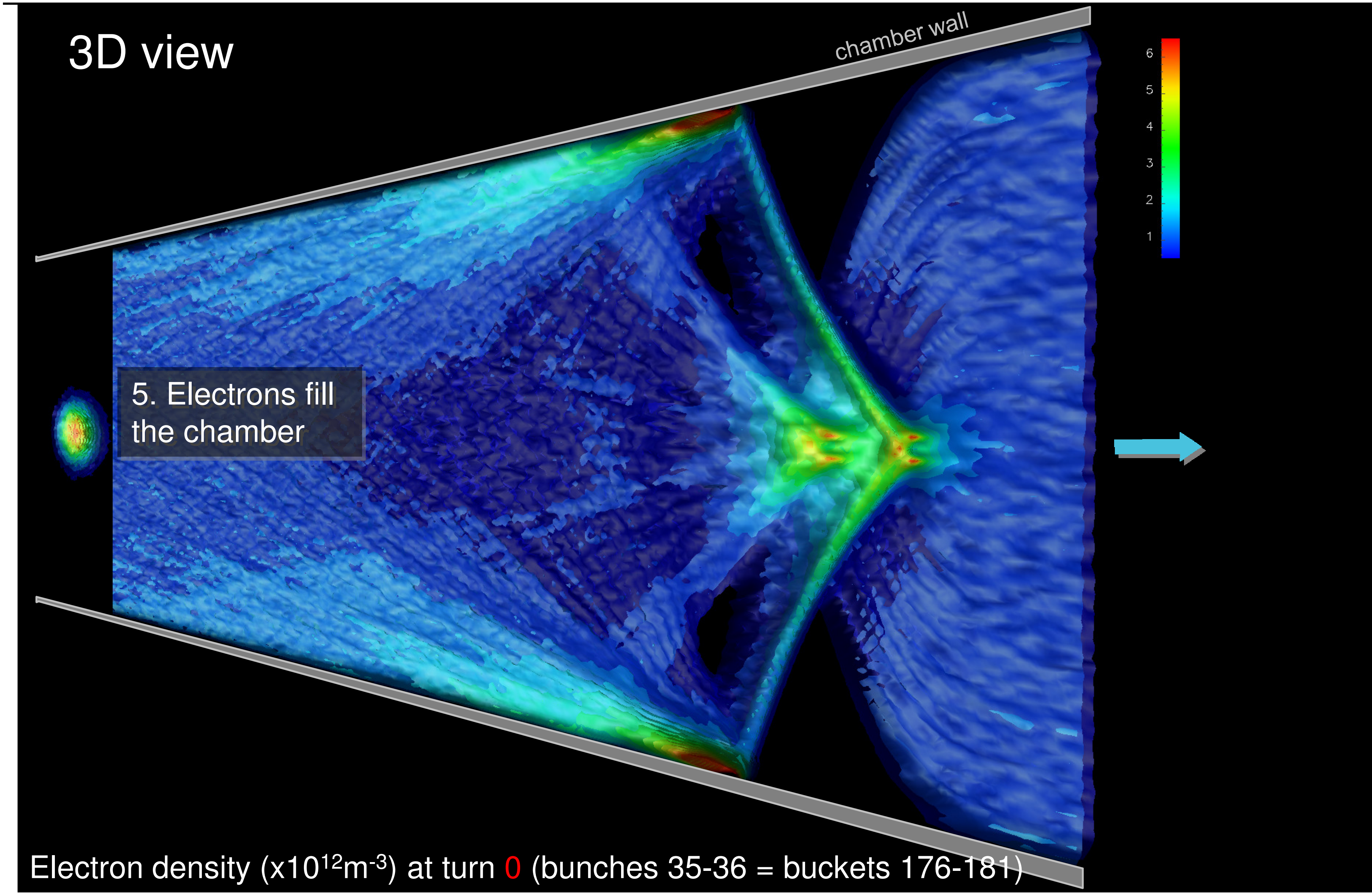
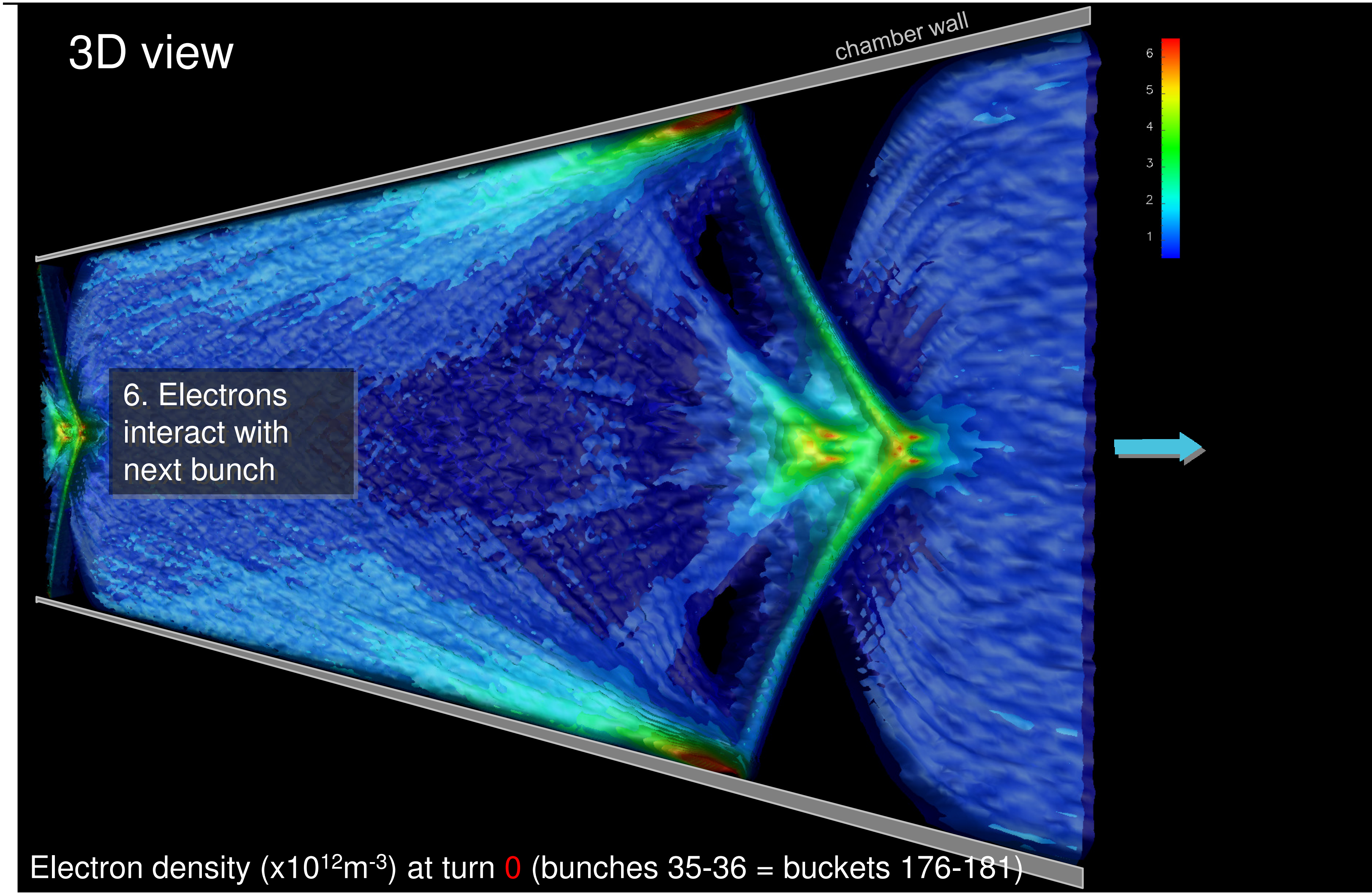
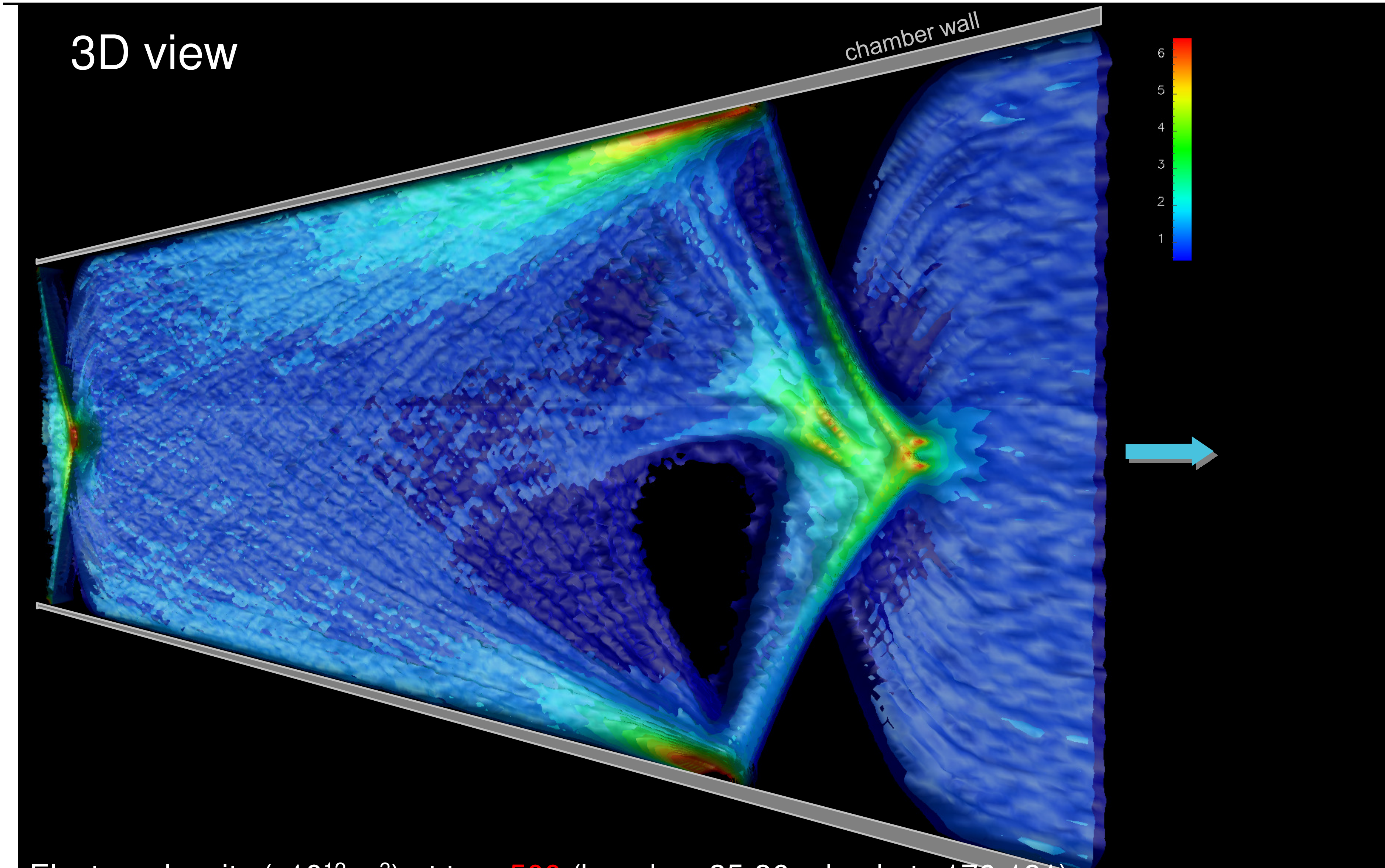


Physics of electron interaction with bunches

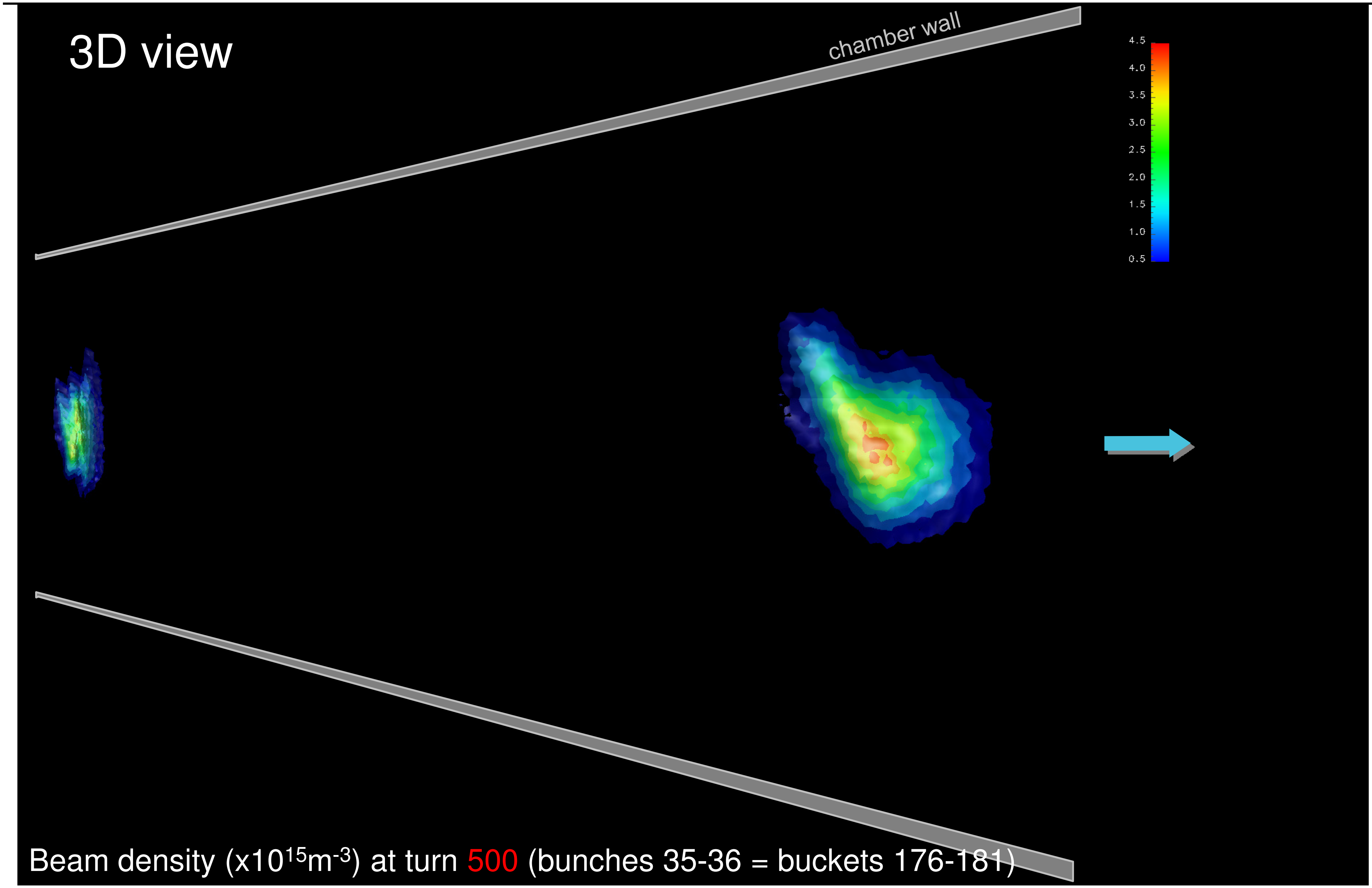


Electrons after **500** turns



Electron density (x10^{12}m^{-3}) at turn 500 (bunches 35-36 = buckets 176-181)

Bunches 35 and 36 after **500** turns



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Full batch of 72 bunches can now be simulated on available supercomputers

- 72 bunches*300k macro-particles/bunch = ~22M macro-particles/batch

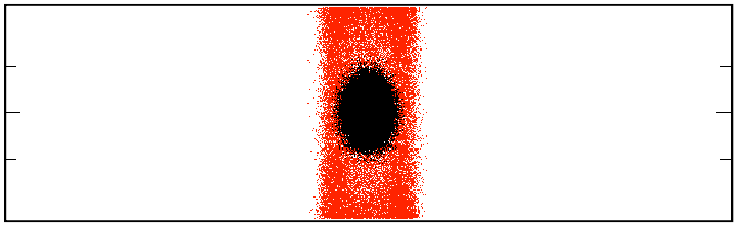
- 72 bunches = 360 buckets
  - 360*64 cells ~23,000 cells longitudinally
  - 100k macro-electrons/slice*23k=2.3 billion macro-electrons

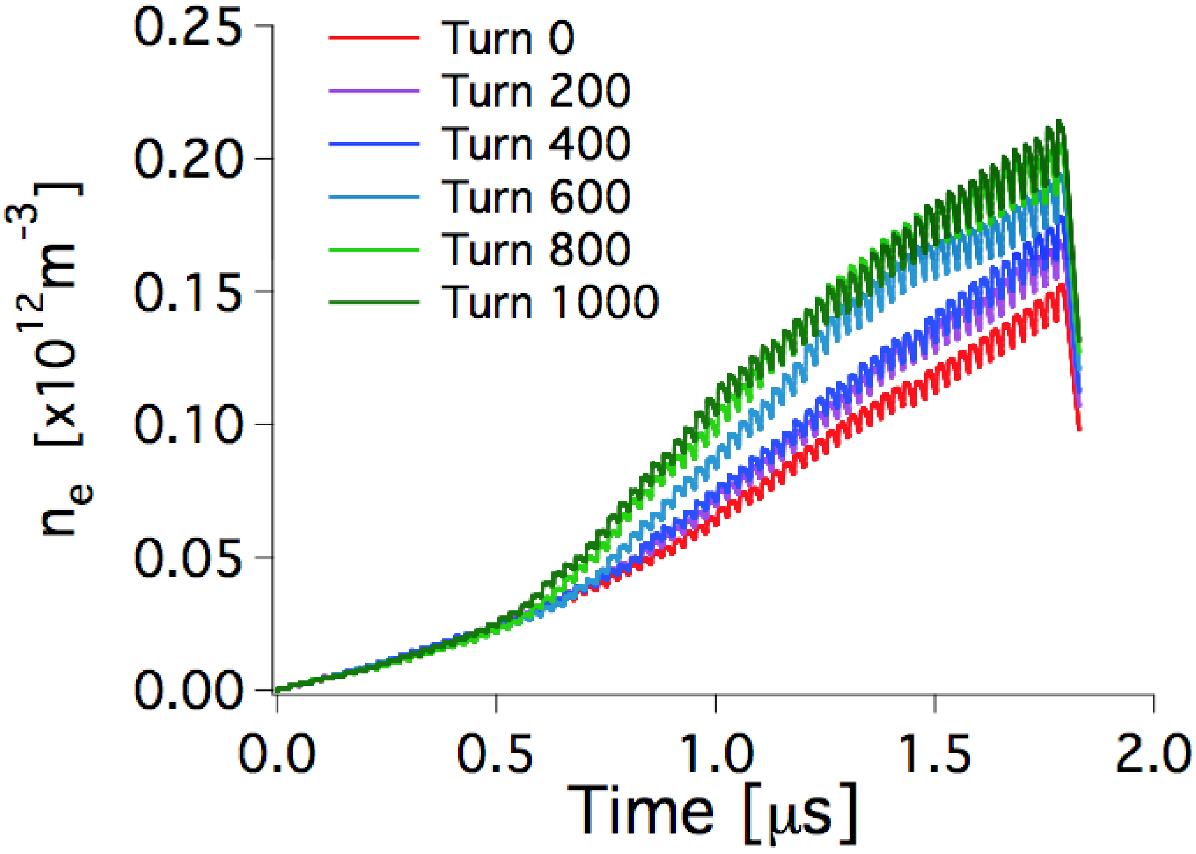
- Assuming order 1μs/macro-particle push and 8 CPUs/bucket = 2880 CPUs,
  $\Rightarrow$ order hours runtime for 1000 turns with 10 interaction stations/turn

- 2880 CPUs for a few hours readily available on 38,122 CPUs NERSC Cray Franklin

- Phase II of NERSC Cray Hopper (2011) will have 153,408 CPUs

Average electron cloud density history at fixed station

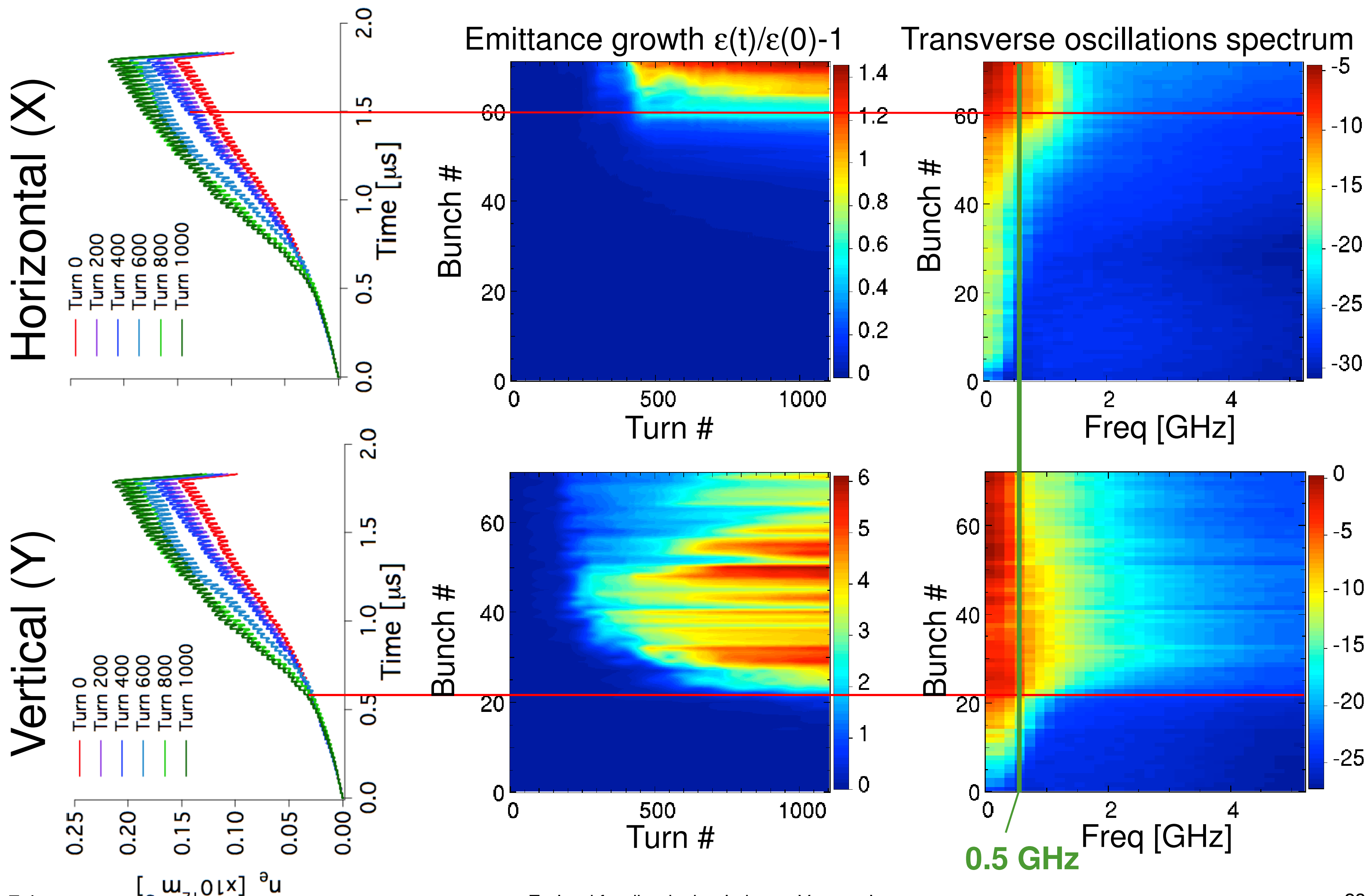




Note:
density averaged over entire chamber. Local density is higher.

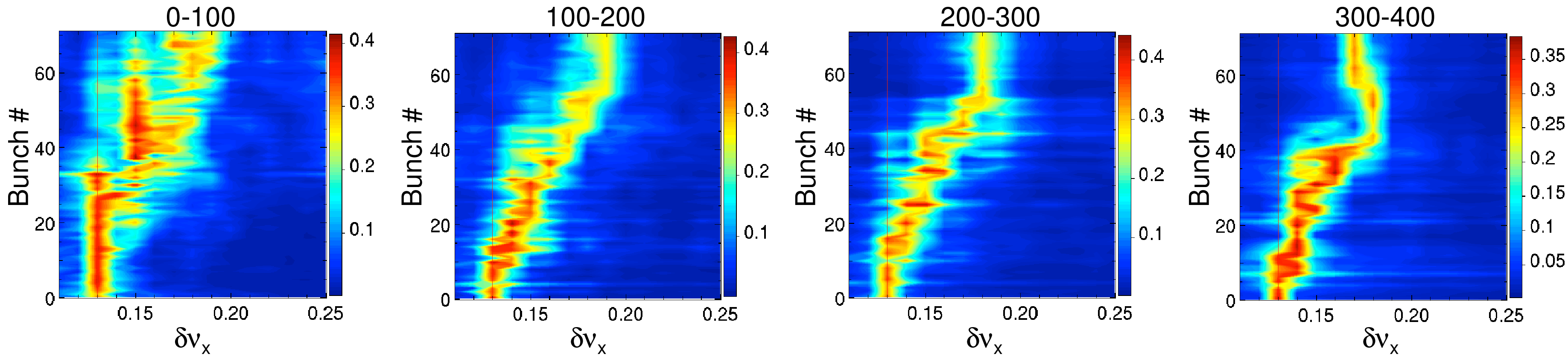
Fast rising instability develops for bunches 22 and +

Spectrum content mostly <0.5GHz

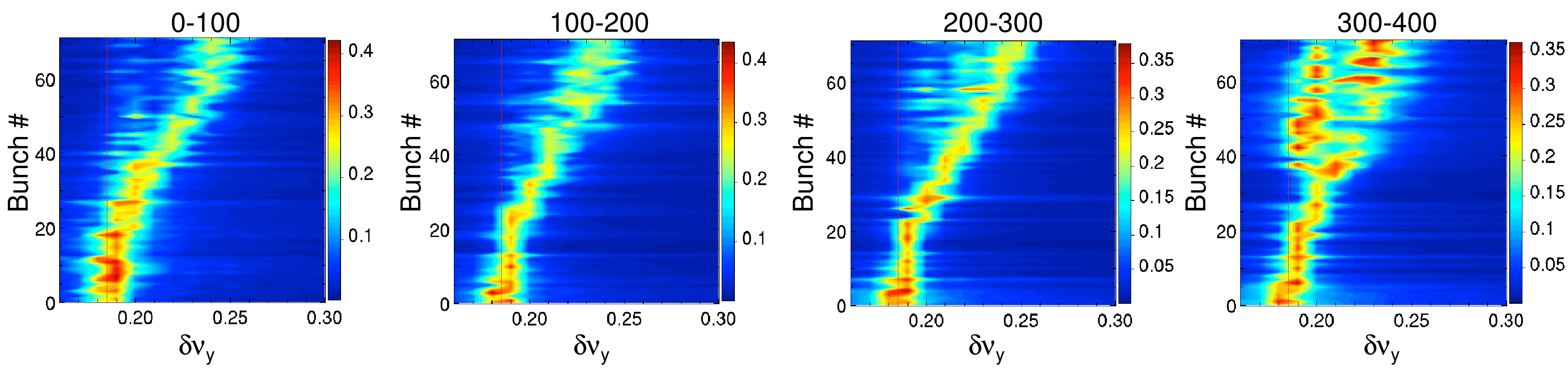


Average fractional tune

Horizontal (X)

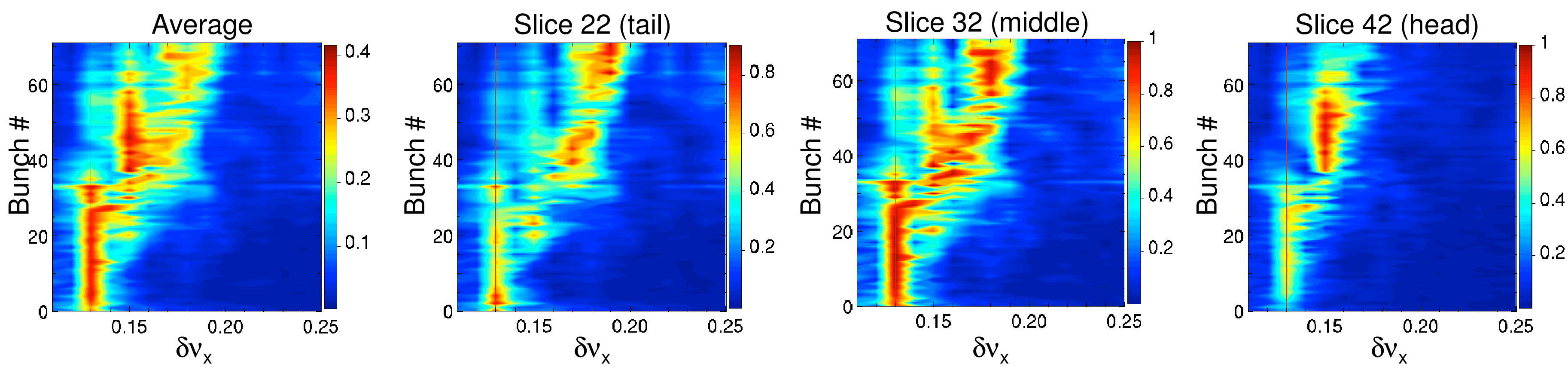


Vertical (Y)

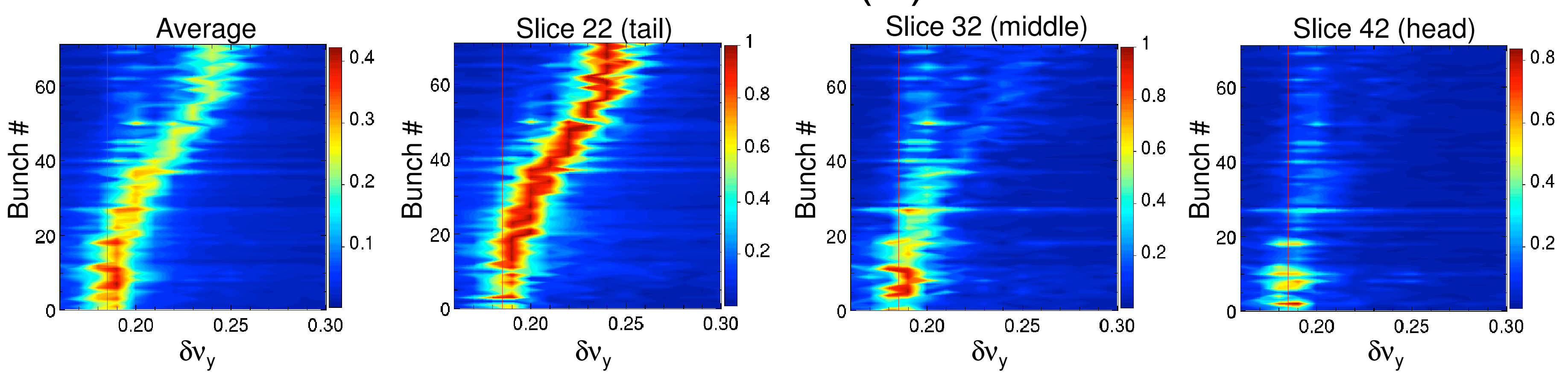


Fractional tune over turns 0-100

Horizontal (X)



Vertical (Y)



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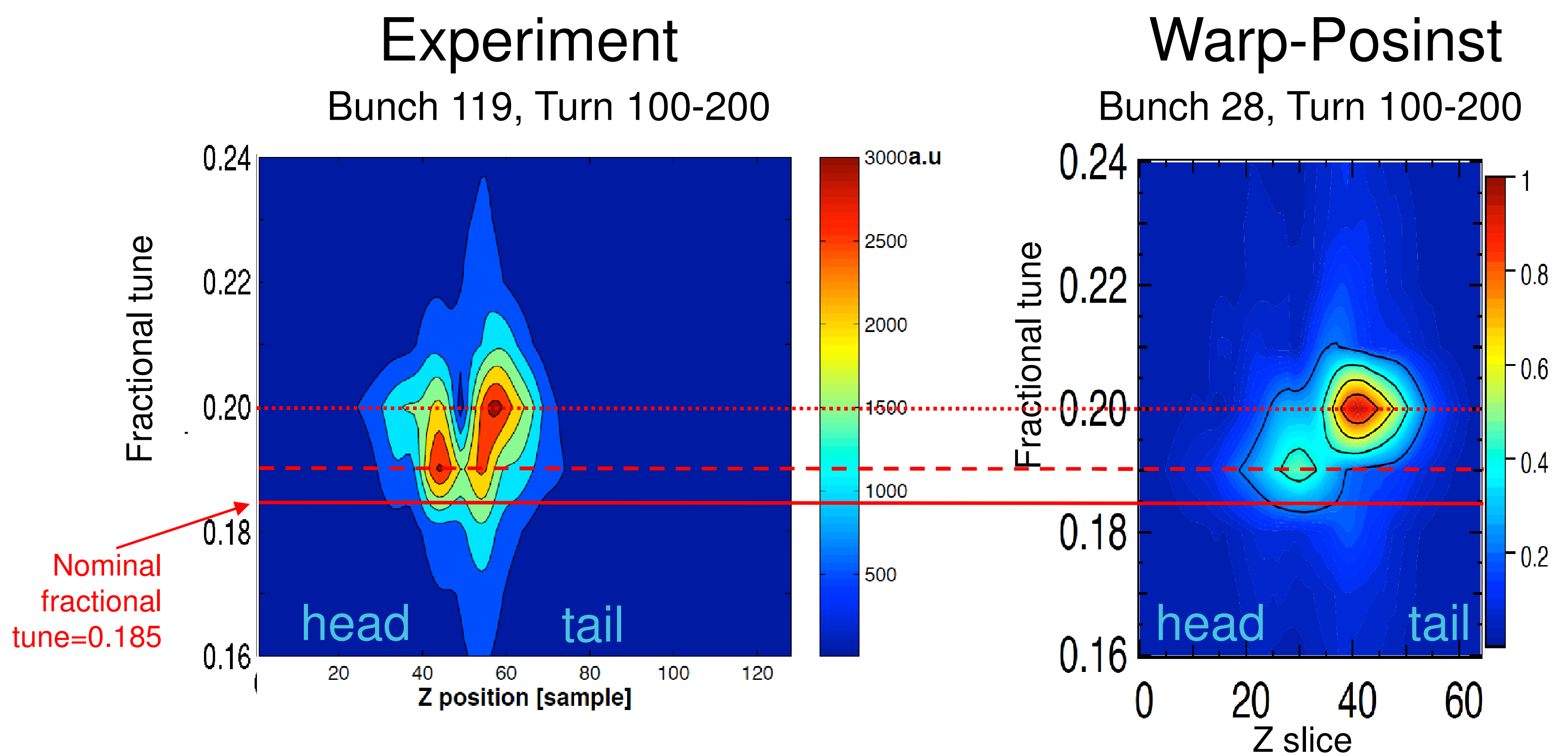
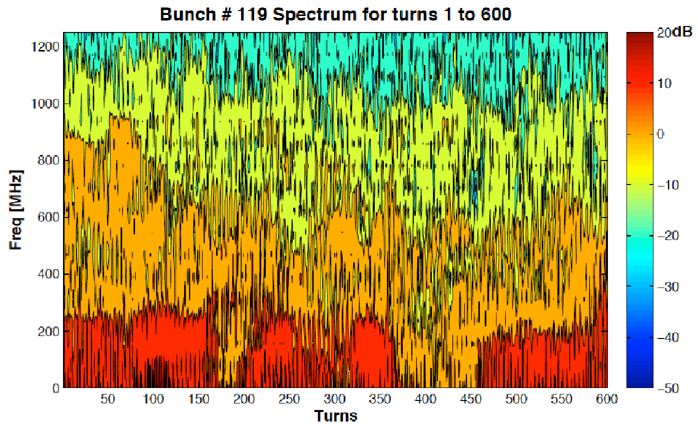
Comparison with experimental measurements



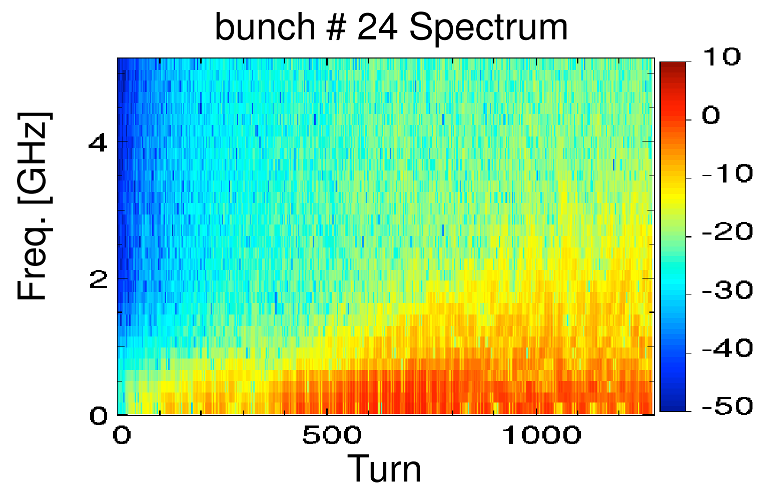
- Separation in two parts, core and tail, with similar tune shift
- Effect appears earlier and is stronger in simulations, suggesting that the electron density might be higher than in experiment

Comparison with experimental measurements - 2

Experiment



Warp-Posinst



- Both expt. and sim. show activity level inversely proportional to frequency
- Interesting difference: instability grows in simulation but is already there at turn 0 in experiment

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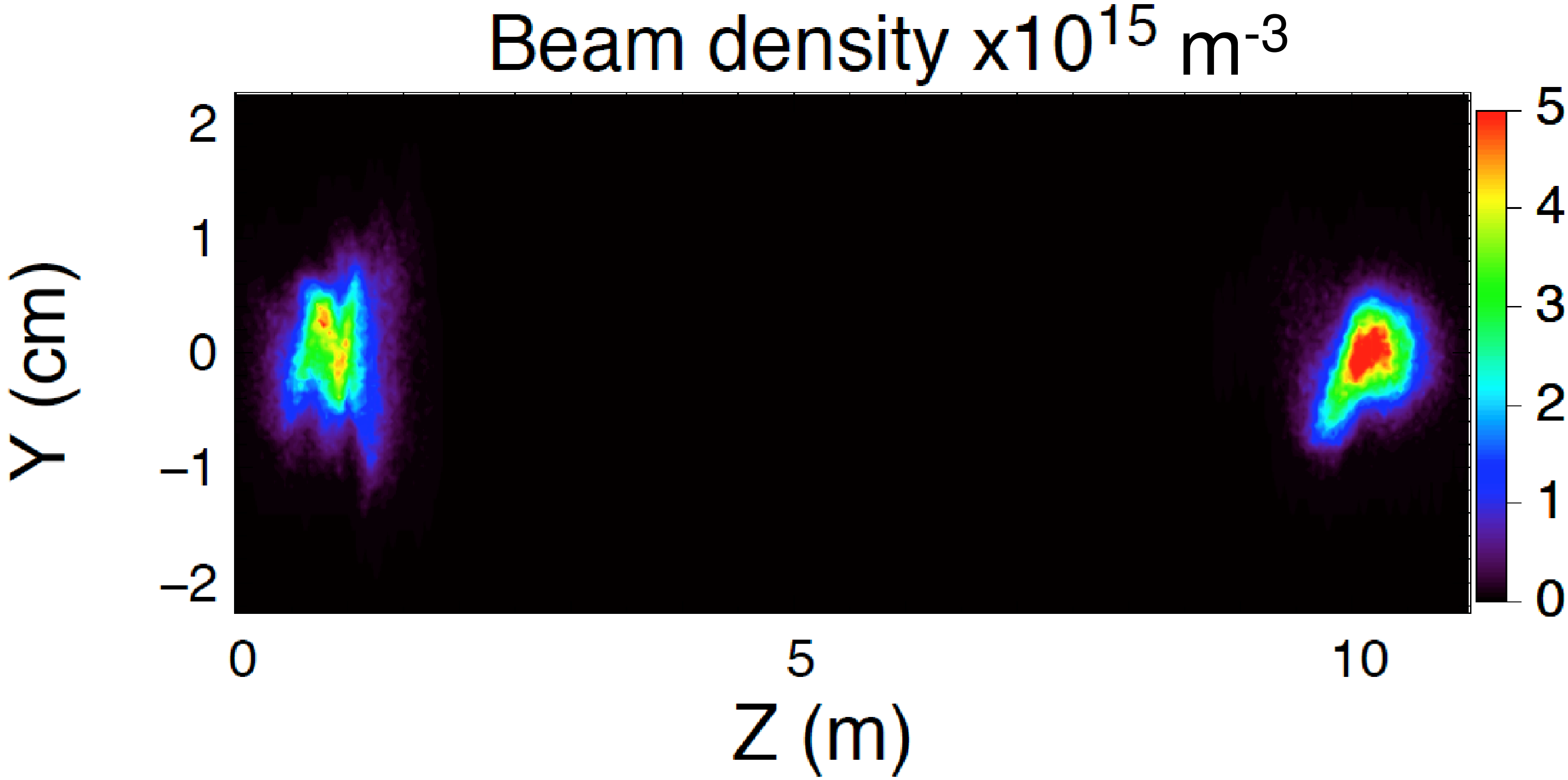
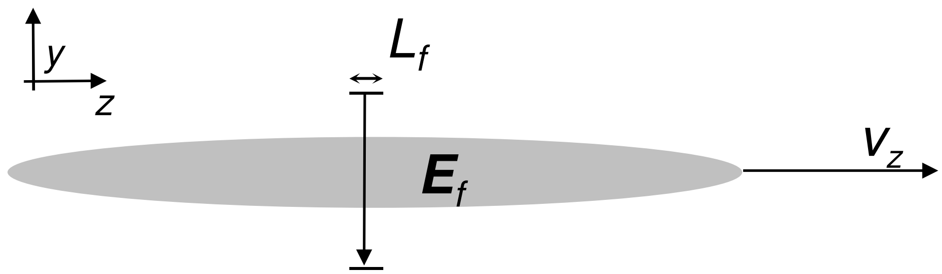
Bunches transverse internal structure has fairly long wavelength component



• Can a feedback system resolving the bunch control the instability?

• What characteristics are needed, (amplitude, frequency range, noise level, delay, …)?

Simulated feedback model



Kick in transverse velocity

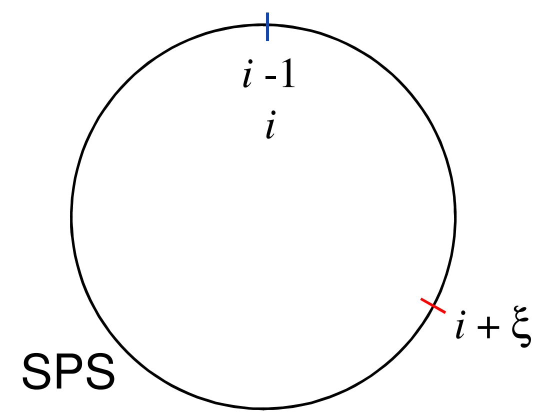
$\Delta v_y = (q/\gamma m)\, E_f\, L_f / v_z$

- $\boldsymbol{E_f}$ is set from estimated velocity offset δv_y: $E_f = g\, \delta v_y\, (\gamma m/q)\, v_z / L_f \quad (0 < g \leq 1)$

- **predicts** $y'(t) = \delta v_y / v_z$ from records of centroid offsets at two previous turns $y_{i-1}(t)$ and $y_i(t)$ using **linear maps**, ignoring longitudinal motion and effects from electrons

$$y'_{i+\xi} = \frac{(cc_\xi - ss_\xi)\, y_i - c y_{i-1}}{\beta_y s}$$

with $\begin{cases} c = \cos(2\pi Q_y) & c_\xi = \cos(2\pi \xi Q_y) \\ s = \sin(2\pi Q_y) & s_\xi = \sin(2\pi \xi Q_y) \end{cases}$

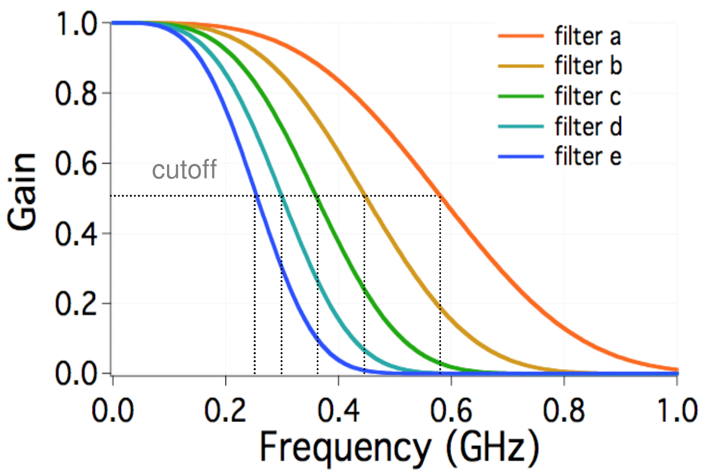


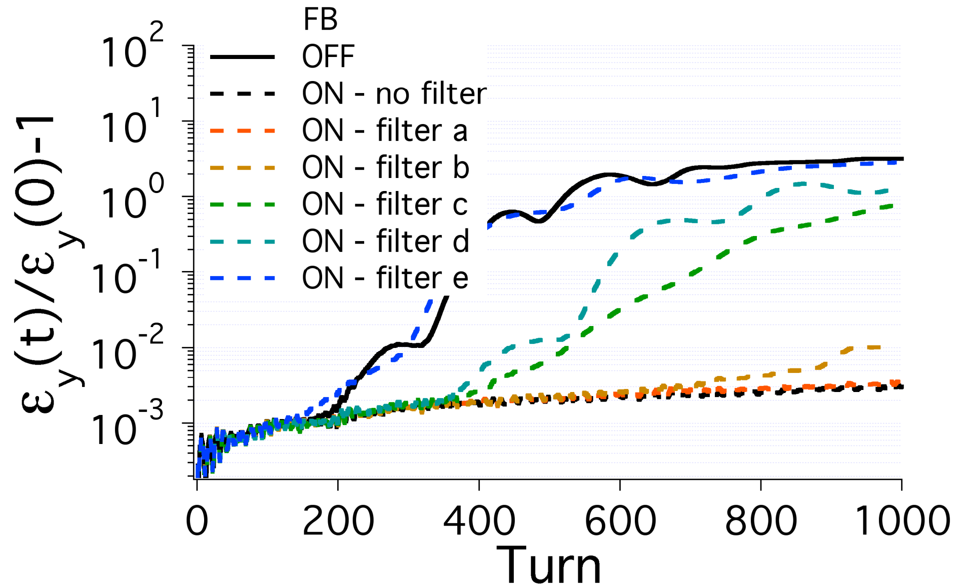
In following results, ξ=1.

(for ξ=0, same as Byrd PAC95 and Thompson et PAC09)

Tests with finite bandwidth

Runs with 5 different digital filters with cutoffs (-3 dB) around 250, 300, 350, 450 and 575 MHZ.

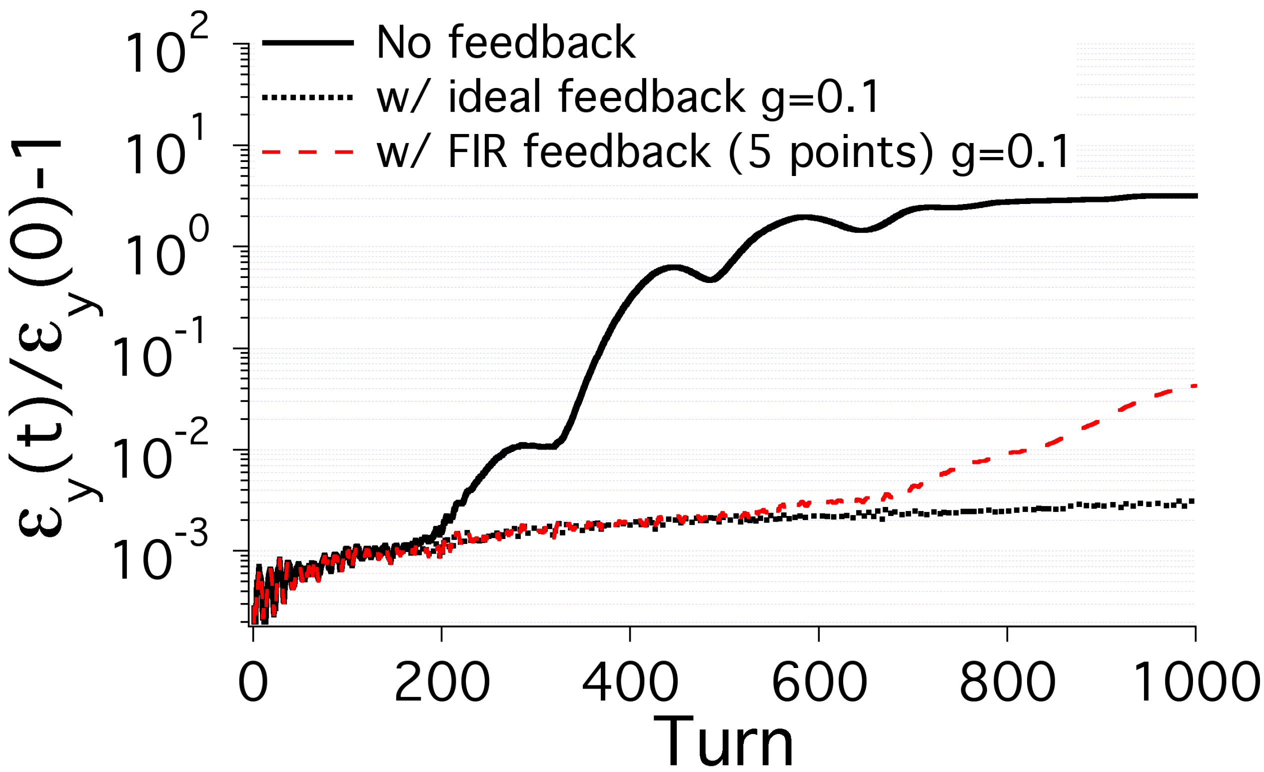




With these filters, cutoff>450 MHz needed for maximum damping.

Tests with 5 pts FIR filter

Experiment will use FIR filter (see talks from C. Rivetta and R. Secondo)



Summary and future work

- Fully self-consistent simulations of bunch trains including e-cloud buildup, its effect on the bunches and inter bunch coupling are feasible on today's supercomputers.
- Applied to the modeling of SPS batch of 72 bunches, toward a detailed understanding of the dynamics and control of beam instability via feedback systems.
- Some qualitative and semi-quantitative agreement with experiment.
- Effective damping from simulated feedback, provided that bandwidth cutoff>450 MHz.
- Future work includes: implementation of more realistic feedback models; replace smooth focusing with linear optics; etc.