SELF-CONSISTENT 3D MODELING OF ELECTRON CLOUD DYNAMICS AND BEAM RESPONSE

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Disclaimer: most of the work here was done by my collaborators.
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TUXAB01, M. Kireeff-Covo et. al.; THPAS049, A. W. Molvik et. al.; TUPMN108, C. Celata et. al. THPMN118, M. Venturini et. al.; FRPMS028, K. G. Sonnad et. al.; THPAS050, W. M. Sharp et. al.

Outline

Model and simulations

Benchmarking against experiments

Application to high energy physics storage rings

Lorentz-boosted frame (new computational algorithm)

Summary

Context

The work reported pertains to electron clouds in:

- Heavy-ion fusion science

  Long pulses, space-charge dominated heavy-ion beams

- High-energy physics

  Intense bunches, significant electron sources

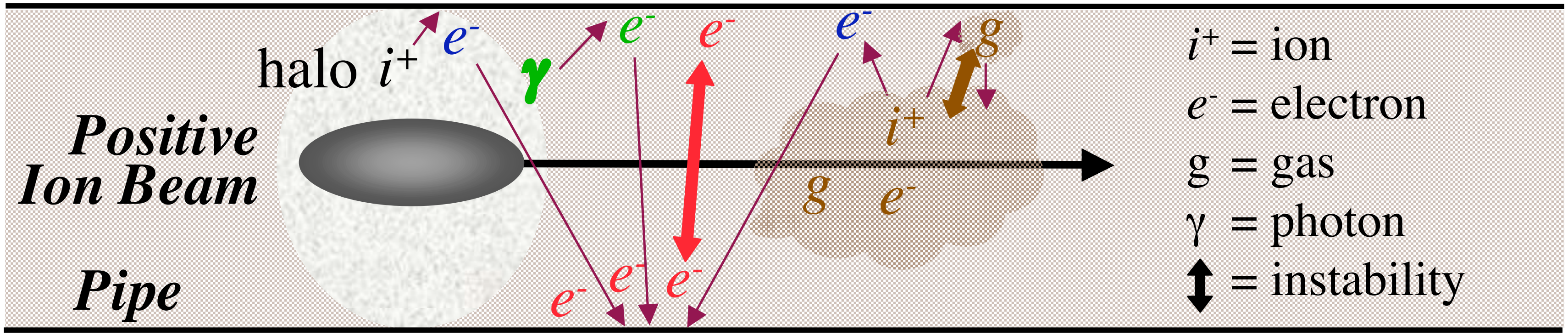
Focus on 3D effects

- Important for long pulses (encompass many lattice elements)
- In HEP: wigglers

Self-consistency (SC):

- Various degrees of SC
  - Basic: beam-ecloud mutual effects
  - Full SC: residual gas ionization, beam losses and scraping, charge exchange, gas desorption,…

Sources of electrons



Primary:

- Ionization of
  - background gas
  - desorbed gas
- ion induced emission from
  - expelled ions hitting vacuum wall
  - beam halo scraping
- photo-emission from synchrotron radiation (HEP)

Secondary:

- secondary emission from electron-wall collisions

Code WARP-POSINST physics modules

- WARP = 3D self-consistent PIC code for beam transport
- POSINST = 2D ecloud build-up code with detailed secondary electron emission models

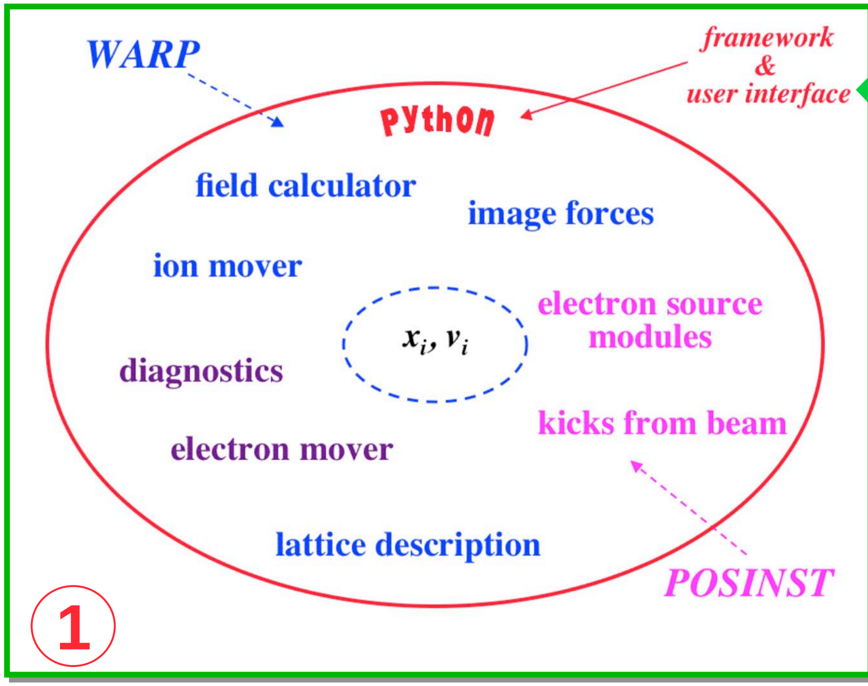
- Combined WARP-POSINST has:
  - Beam transport through arbitrary lattice (E & M)
  - Arbitrary chamber shape (perfect conductor BC's)
  - Space-charge effects
  - Gas ionization
  - Gas desorption off the walls and gas transport
  - Charge-exchange reactions
  - Primary and secondary electron emission sources
  - Tracking of electrons

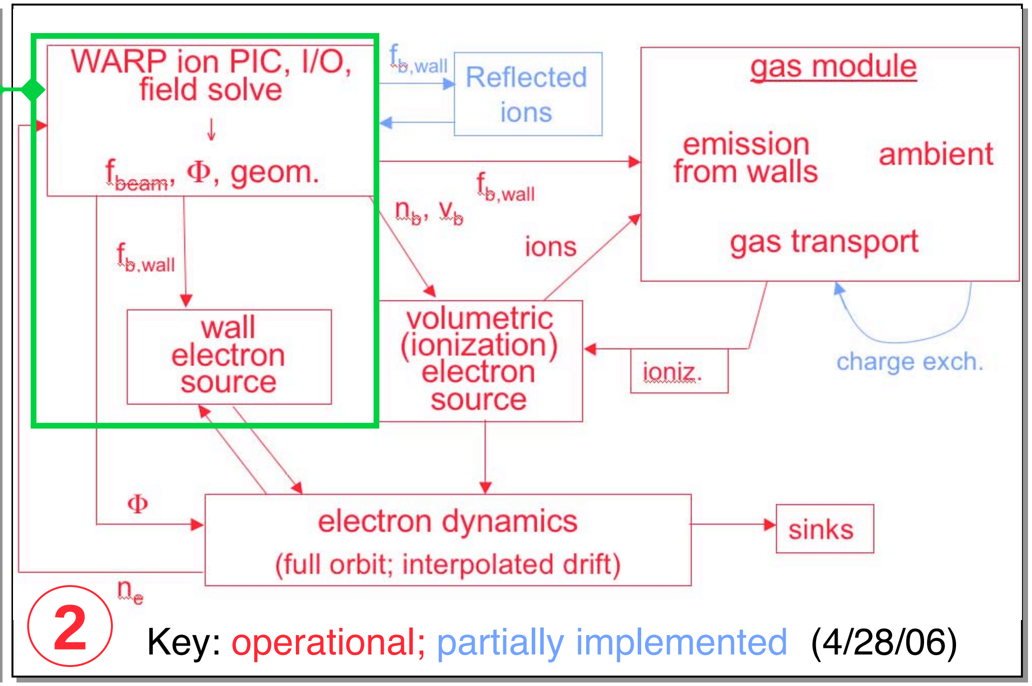
WARP code computational features

- 3D self-consistent PIC code
- Adaptive mesh refinement (AMR) --two kinds
- Field solvers: FFT, capacity matrix, multigrid
- New efficient electron mover
- Boundaries: "cut-cell" --- no restriction to "Legos"
- Bends: "warped" coordinates; no reference orbit
- Lattice: general; takes MAD input
    - solenoids, dipoles, quads, sextupoles, …
    - arbitrary fields, RF acceleration
- Diagnostics: Extensive snapshots and histories
- Parallel: MPI
- Python and Fortran: "steerable," input decks are programs
- Optional simpler modes of operation:
    - 2D (x,y), or (r,z)
    - Build-up mode (BUM) (nondynamical beam), 2D or 3D
    - Quasi-static mode (QSM) --see below

WARP-POSINST has unique features

merge of WARP & POSINST + new e^-/gas modules



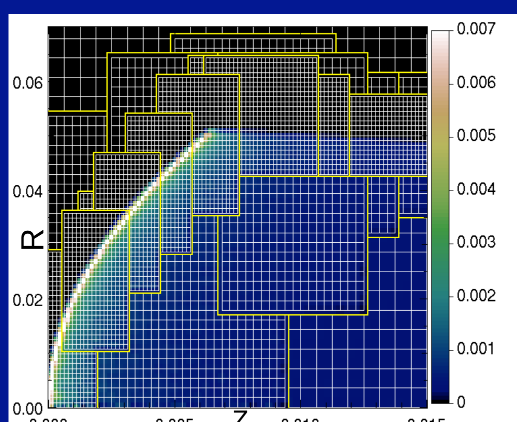


+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

Speed-up

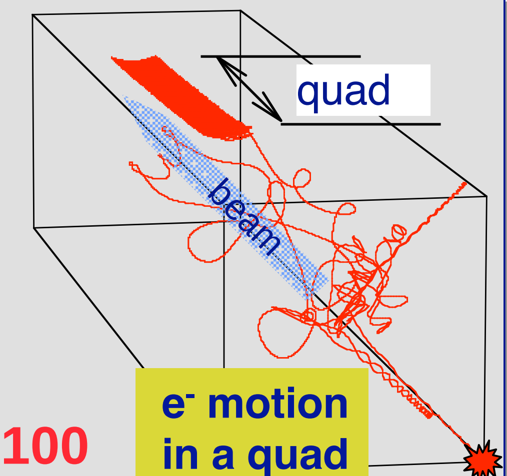
3 **x10-10[4]**



+ Novel e^- mover

Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

4 **Speed-up x10-100**



e^- motion in a quad

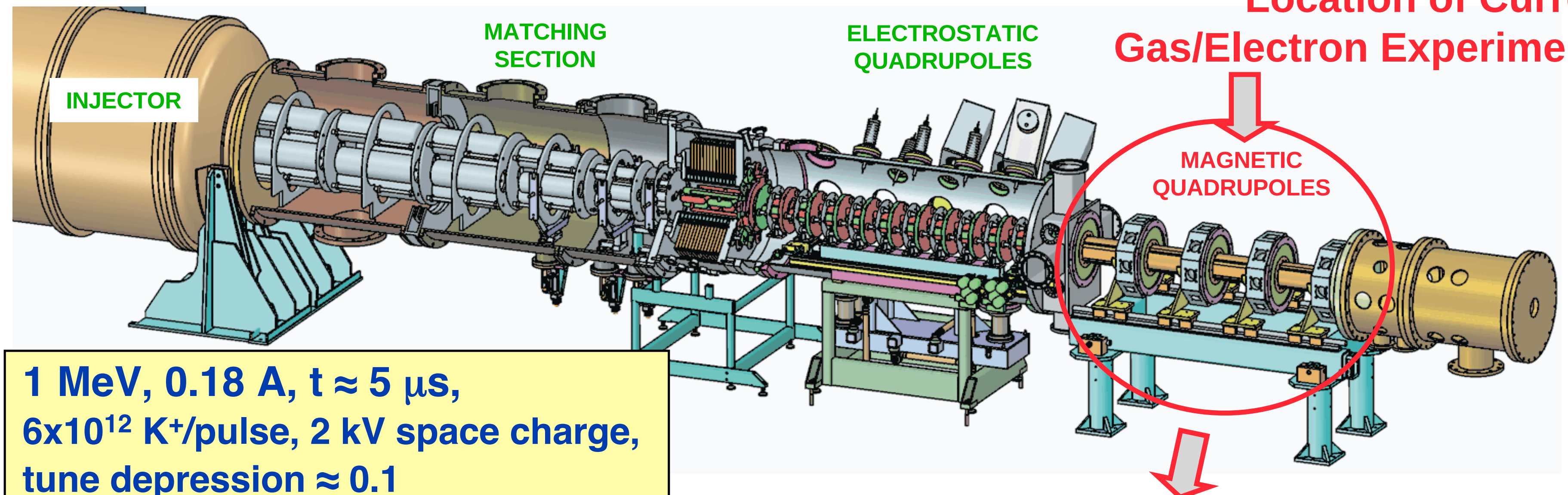
We have benefited greatly from collaborations

• ion-induced electron emission and cross-sections from the TxPhysics* module from Tech-X corporation (http://www.txcorp.com/technologies/TxPhysics),

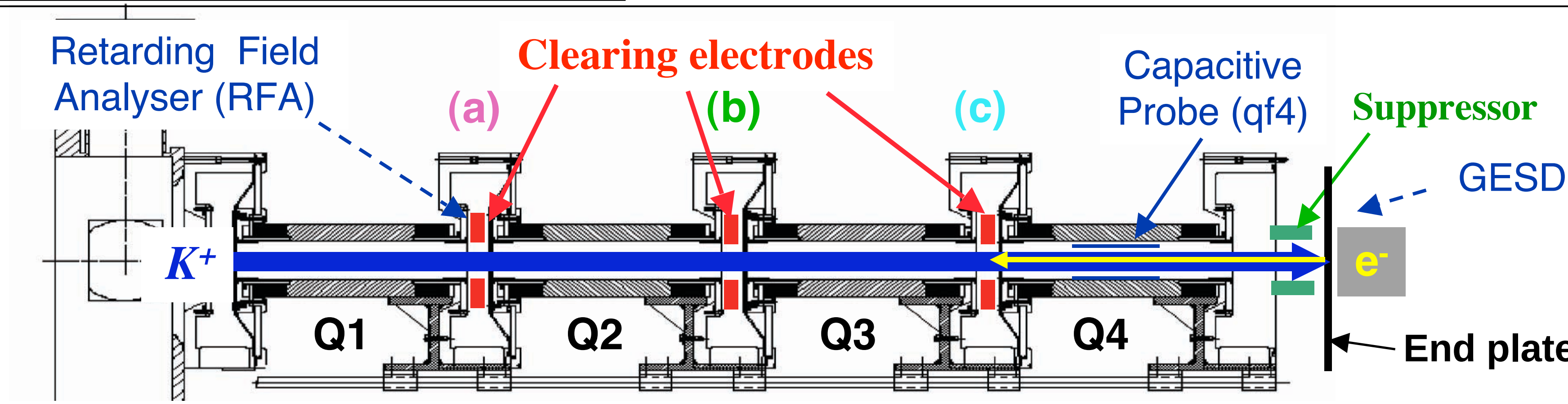
• ion-induced neutral emission developed by J. Verboncoeur (UC-Berkeley).

Experiments at HCX (Berkeley Lab.)

Location of Current Gas/Electron Experiments

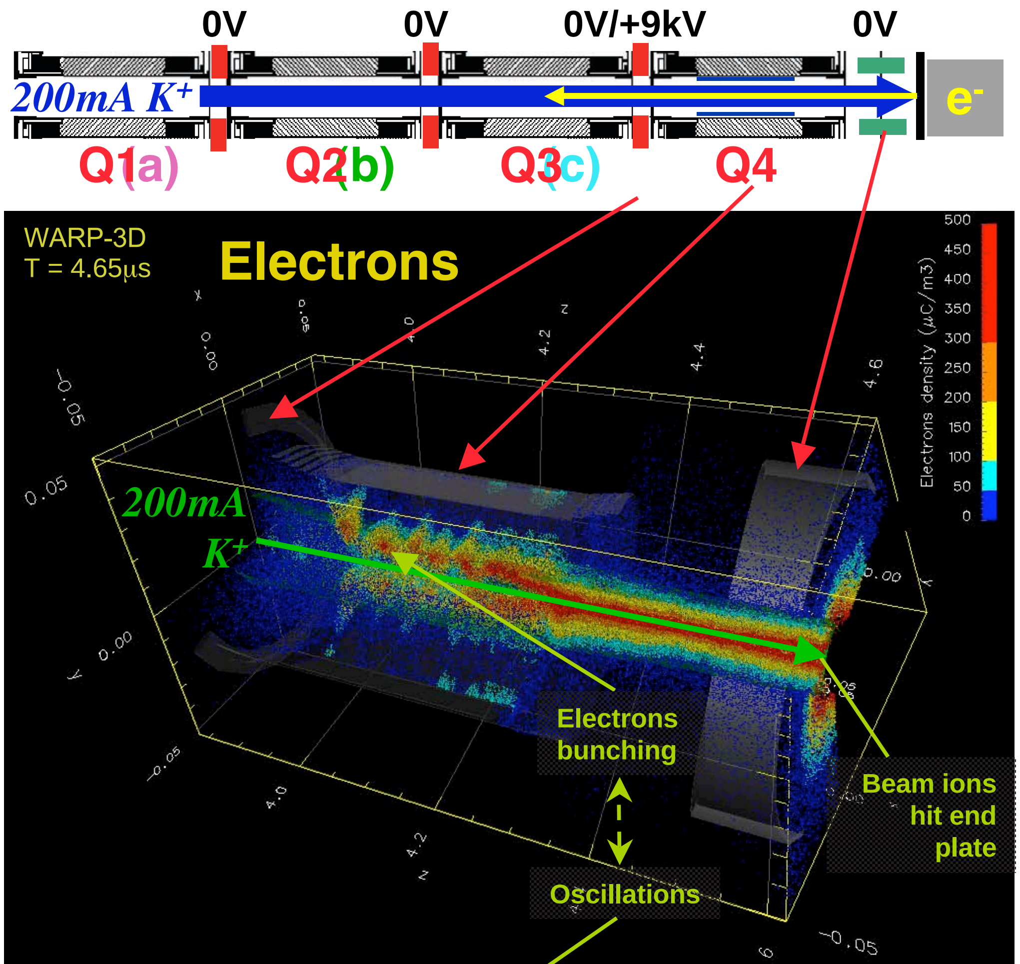


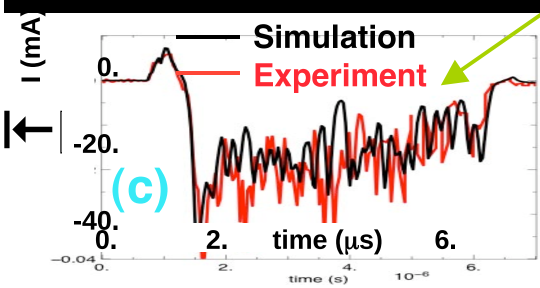
1 MeV, 0.18 A, t ≈ 5 μs,
6×10^{12} K^+/pulse, 2 kV space charge,
tune depression ≈ 0.1



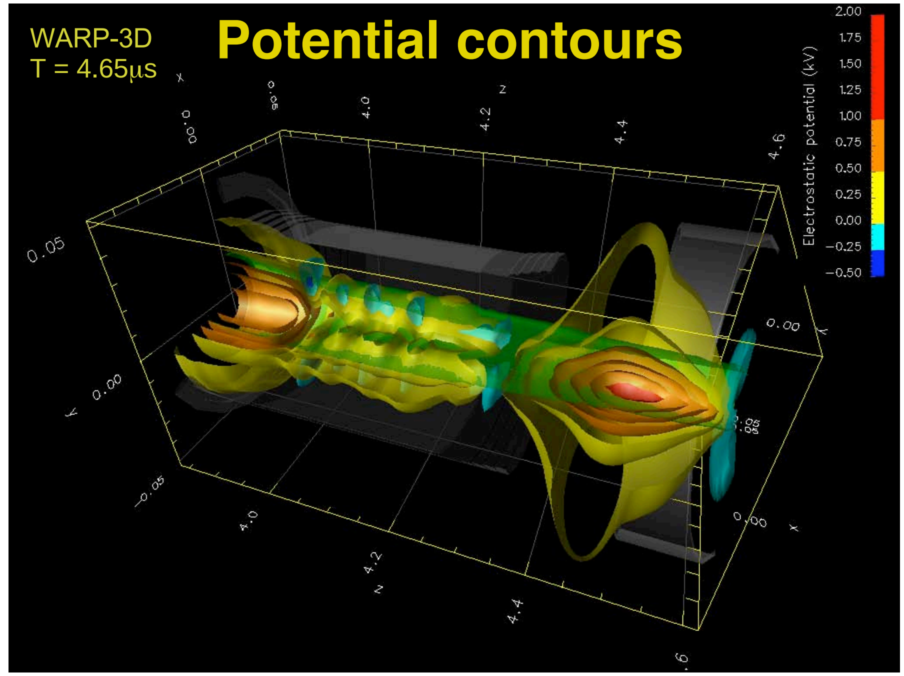
Short experiment => need to deliberately amplify electron effects:
let beam hit end-plate to generate copious electrons which propagate upstream.

WARP & experiments on electrons in quadrupole

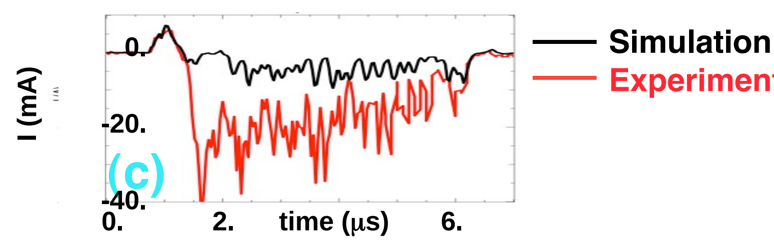




~6 MHz signal in (C) in simulation AND experiment

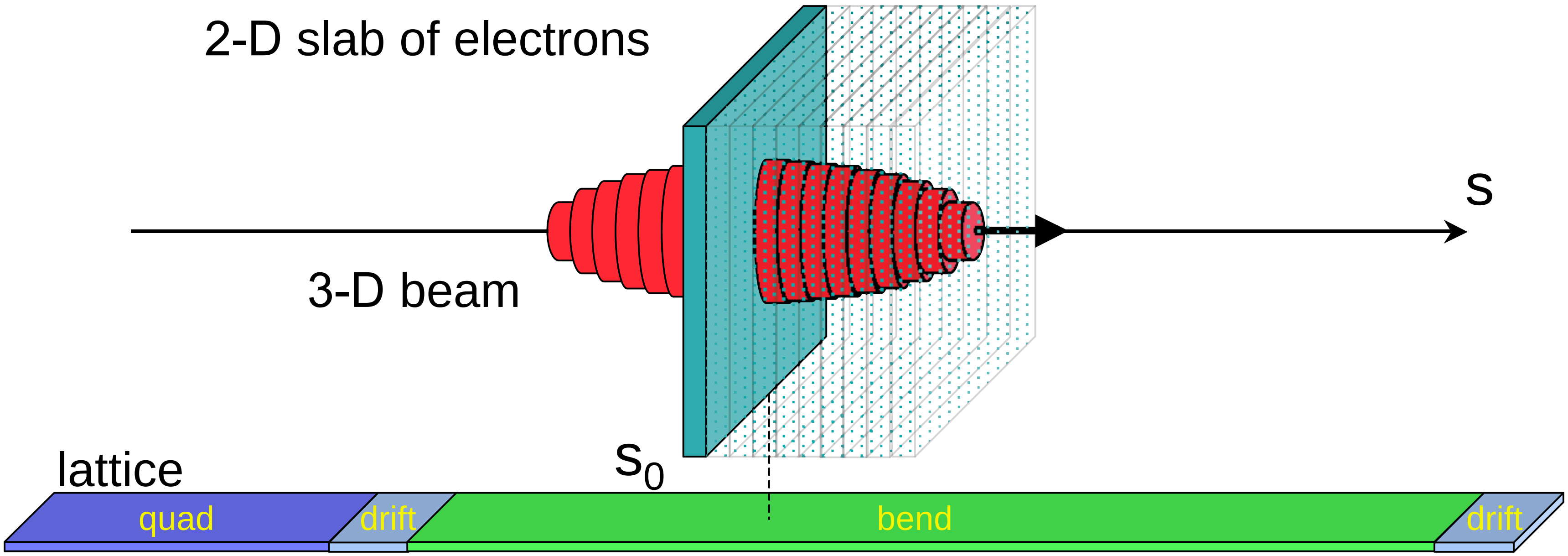


1. **Importance of secondaries**
   - if secondary electron emission turned off:



2. **run time ~3 days**
   - without new electron mover and MR, run time would be ~1-2 months!

Quasi-static mode (QSM)



A 2D slab of electrons (macroparticles) is stepped backward (with small time steps) through the beam field and 2-D electron fields are stacked in a 3-D array, that is used to push the 3-D beam ions (with large time steps) using maps (as in HEADTAIL-CERN) or Leap-Frog (as in QUICKPIC-UCLA/USC).

This beam-ecloud interaction occurs at several discrete "stations" along the ring.

WARP/QSM: CERN benchmark (~SPS)

Rationale

- we had the building blocks
- we need to reproduce HEP codes results for meaningful comparisons

Comparison WARP-QSM/HEADTAIL on CERN benchmark

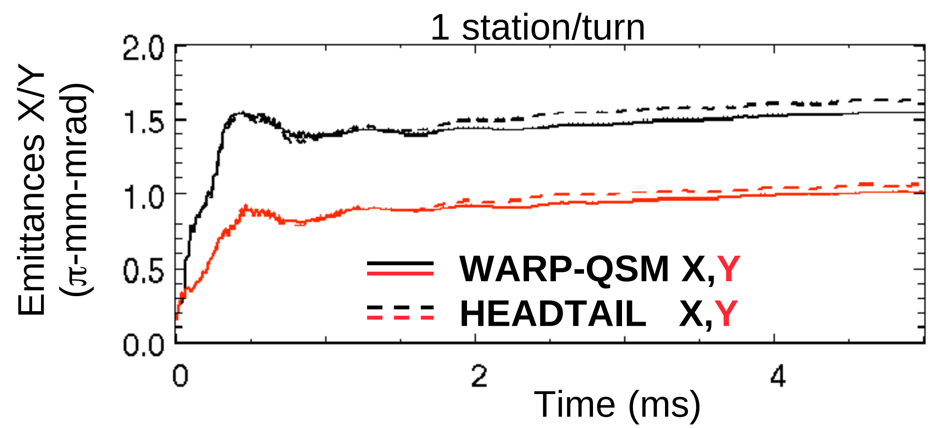
http://ab-abp-rlc.web.cern.ch/ab%2Dabp%2Drlc%2Decloud/

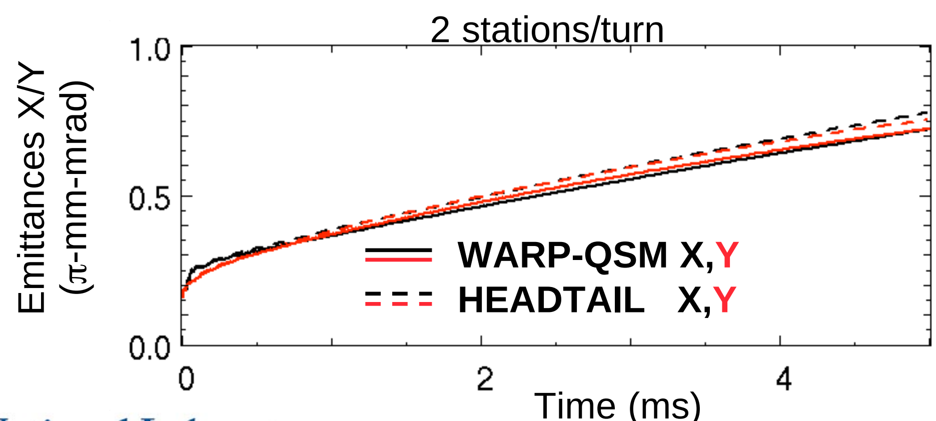
Proposed Model for Instability Simulations

round bunch in a round pipe: 1e11 protons
uniform electron cloud with density 1e12 m^-3
each bunch passage starts with a uniform cloud
chamber radius 2 cm
uniform transverse focusing for beam propagation
zero chromaticity, zero energy spread
no synchotron motion
energy 20 GeV
beta function 100 m
ring circumference 5 km
betatron tunes 26.19, 26.24
rms transverse beam sizes 2 mm (Gaussian profile)
rms bunch length 30 cm (Gaussian profile, truncated at +/- 2 sigma_z)
no magnetic field for electron motion
elastic reflection of electrons when they hit the wall

NEW: with open and/or conducting boundary conditions (please specify boundary assumed), with 1 and/or several interaction points per turn or continuous interaction (please specify)

result: plot of x&y emittances vs time



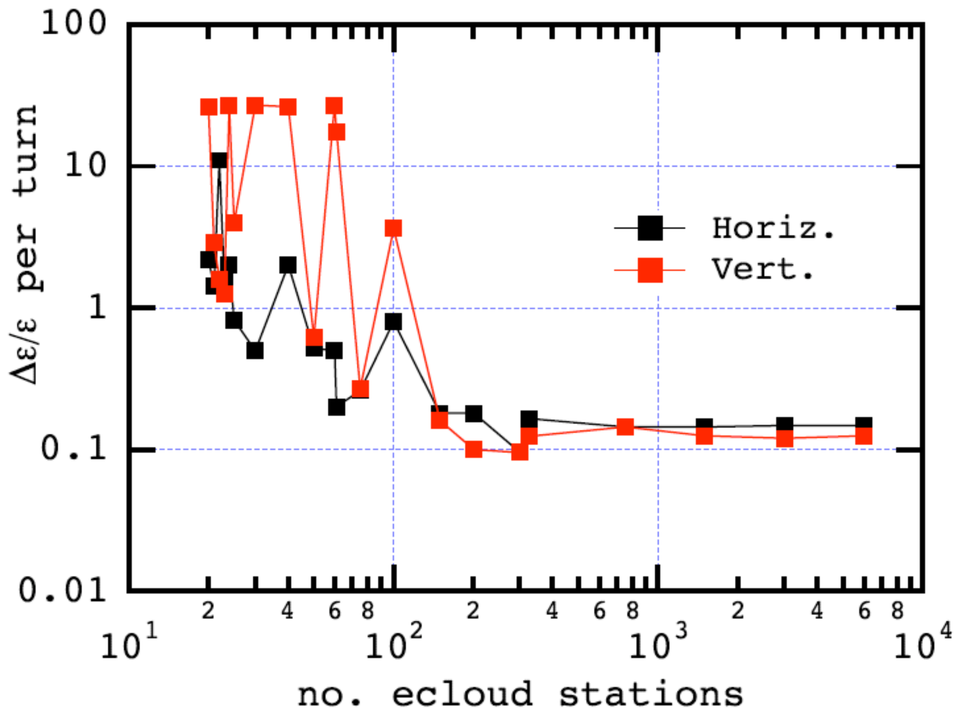


WARP/QSM: LHC simulation

- Compute emittance growth per turn
- Dependence on the number of ecloud stations N_{stn}

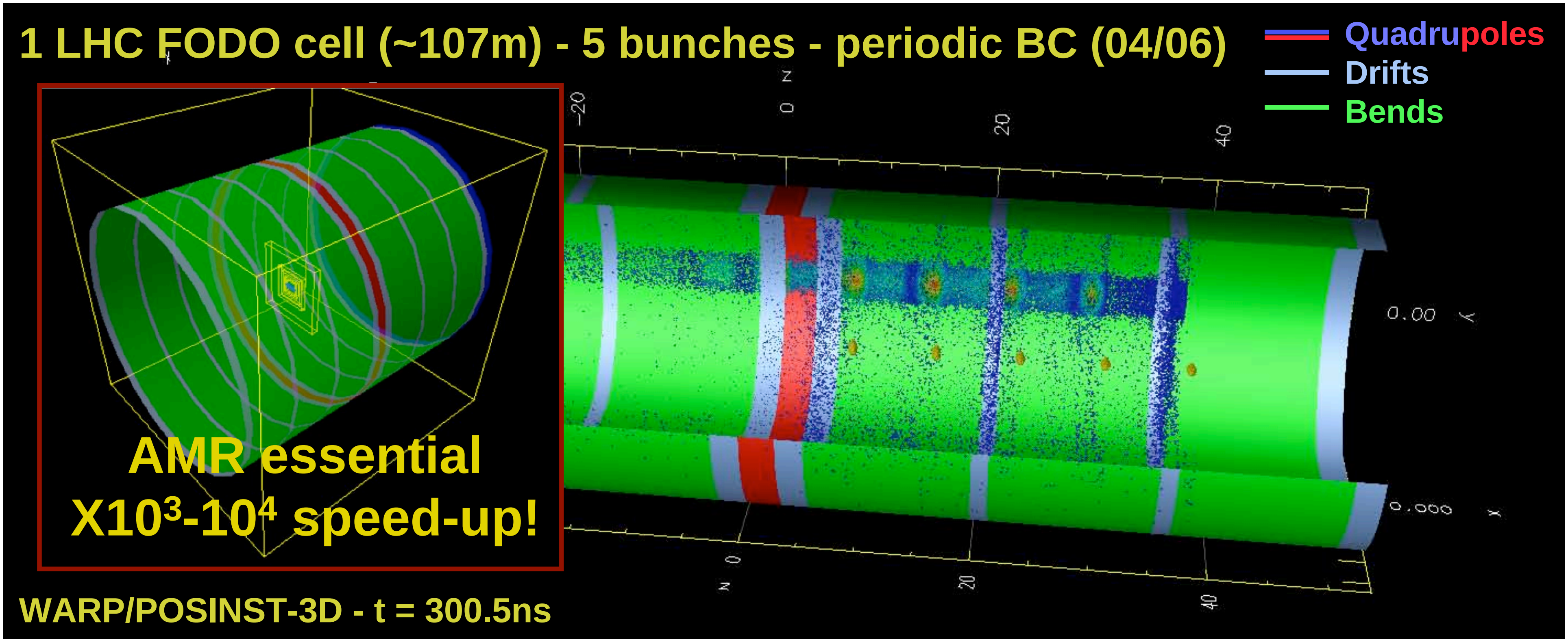
- E_b=450 GeV, N_b=1.1x10^{11}, n_e=10^{14} m^{-3}
- Continuous focusing, tunes =(64.28, 59.31)

- Conclusion: need N_{stn} =~ several times the tune for convergence
  - i.e., resolve λ_β (as expected)



WARP/POSINST applied to LHC FODO cell

- LARP program: simulation of e-cloud in LHC
  Proof of principle fully self-consistent simulation, peak SEY=2



Other cases in progress

- Fermilab Main Injector at high intensity:
  - WARP/QSM: study emittance growth **(K. Sonnad, FRPMS028)**
- ILC damping ring:
  - WARP/POSINST in BUM: study of e-cloud in positron damping ring wigglers **(C. Celata, TUPMN108)**

Boosted frame method

- Fully self-consistent simulations are very expensive
  - Wide range of time and length scales
    - -cyclotron period of electrons ---> bunch transit time
  - Recently, observation that an appropriate Lorentz transformation to a frame makes the time and length scales more conmeasurate (if beam is relativistic)
  - Boosted frame γ is $1 < \gamma < \gamma_{beam}$
  - **J.-L. Vay, PRL 98, 130405 (2007)**

- Brings self-consistent CPU time down to QSM approximation (several orders of magnitude)

- Doesn't help in QSM

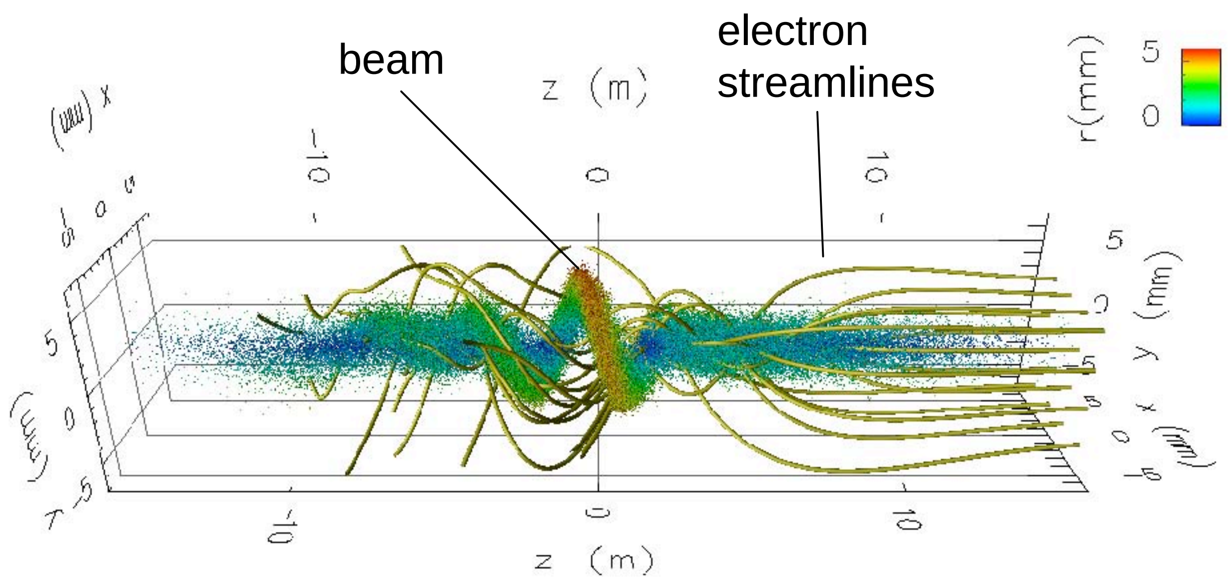
- Proof-of-principle: see next slide

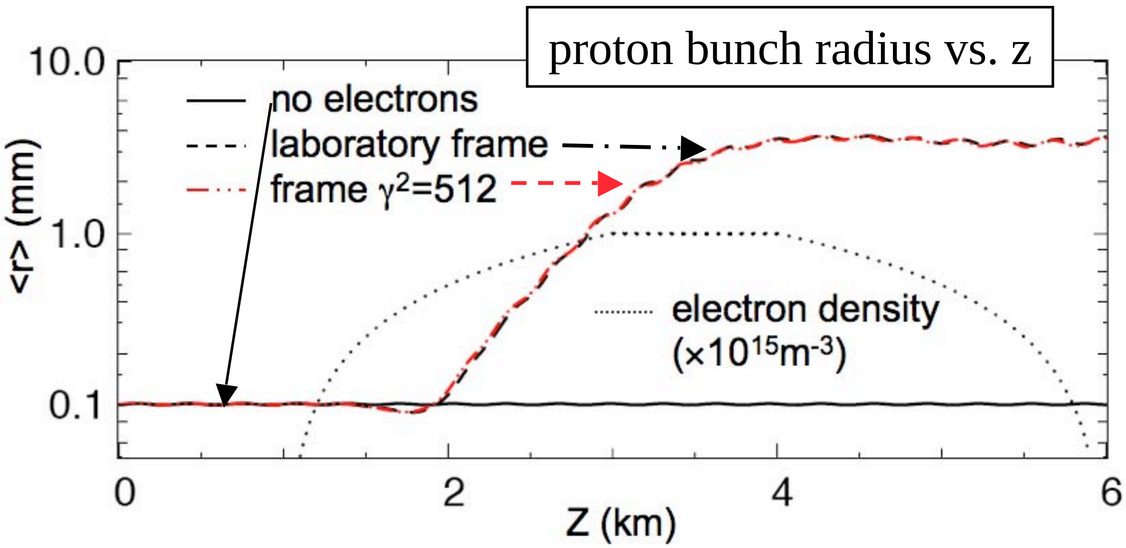
- Still need to clarify several issues:
  - Simultaneity of events is shifted (important for Lab diagnostics)
  - Curved trajectories
  - Translate beam phase space from moving frame to Lab frame at any desired time

Boosted frame calculation sample
proton bunch through a given e^- cloud*

This is a proof-of-principle computation: hose instability of a proton bunch

Proton energy: γ=500 in Lab
- **L= 5 km, continuous focusing**
- **B_θ = kr provides focusing**



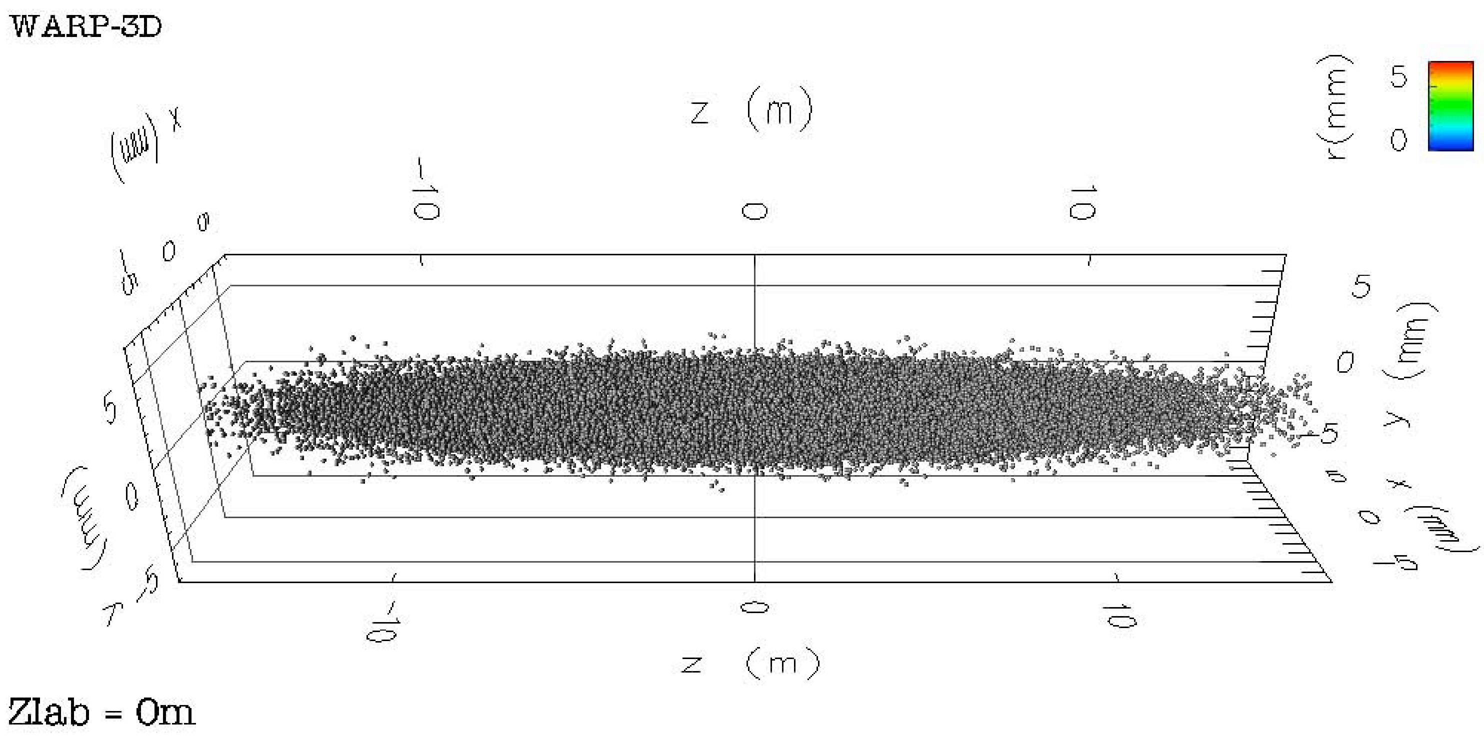


CPU time:
- **lab frame: >2 weeks**
- **frame with γ^2=512: <30 min**

Speedup x1000

***J.-L. Vay, PRL 98, 130405 (2007)**

WARP boosted frame calculation



- proton bunch (γ=500, N_b=10^{12}) through an ecloud (n_e=10^{14} m^{-3} peak)
- B-field: $B_\theta = kr$ provides focusing
- γ_{frame}=$512^{1/2}$

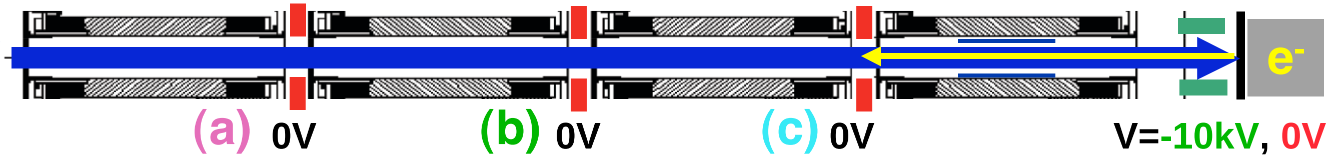
Summary

- WARP/POSINST code suite developed for HIF e-cloud studies
  - Parallel 3D AMR-PIC code for any given accelerator lattice follows beam self-consistently with gas/electron generation and evolution,
- Detailed validation at the HCX facility
  - highly instrumented section dedicated to e-cloud studies
- Successful code-to-code benchmarking
- Being applied to HEP accelerators
  - LHC, ILC damping ring, FNAL main injector, SPS, …
- Recent Lorentz-boosted frame algorithm:
  - cost of self-consistent calculation is greatly reduced thanks to relativistic contraction/dilation bridging space/time scales disparities,
  - 1000x speedup demonstrated on proof-of-principle case,
  - will apply to LHC, Fermilab MI, ILC
  - some practical issues remain to be clarified, but very promising

Backup material

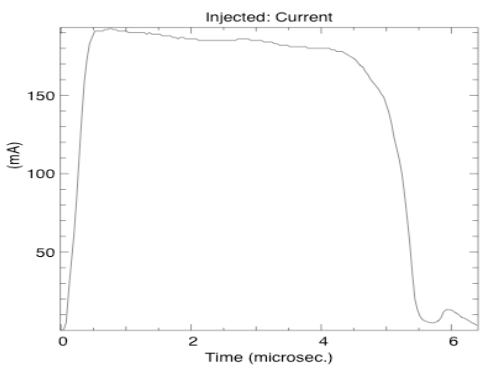
- TUXAB01 Kireeff-Covo (Absolute Measurements of Electron Cloud Density)
- THPAS049 *Arthur Molvik* Gas and Electron Desorption Under Heavy-ion Beam Bombardment,
- TUPMN108, Particle-in-Cell Calculations of the Electron Cloud in the ILC Positron Damping Ring Wigglers, *C. M. Celata*
- THPMN118, Modelling of E-cloud Build-up in Grooved Vacuum Chambers Using POSINST, *Marco Venturini*
- FRPMS028, Simulations of Electron Cloud Effects on the Beam Dynamics for the FNAL Main Injector Upgrade, *Kiran G. Sonnad,*
- THPAS050, Simulating Electron Effects in Heavy-Ion Accelerators with Solenoid Focusing, *William M. Sharp*

Comparison sim/exp: clearing electrodes and e⁻ supp. on/off

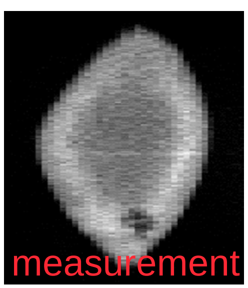


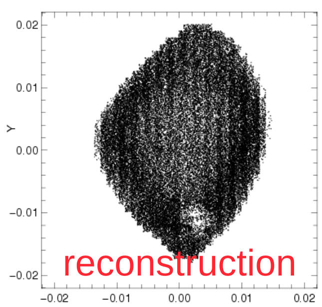
Time-dependent beam loading in WARP from moments history from HCX data:

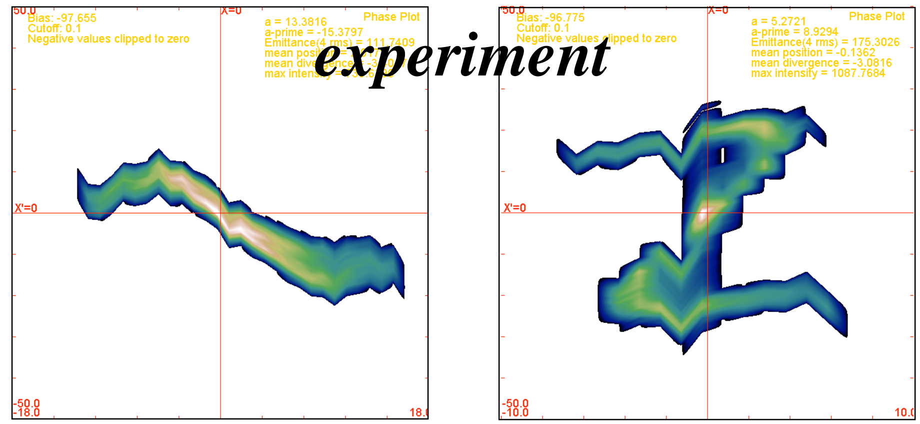
- current



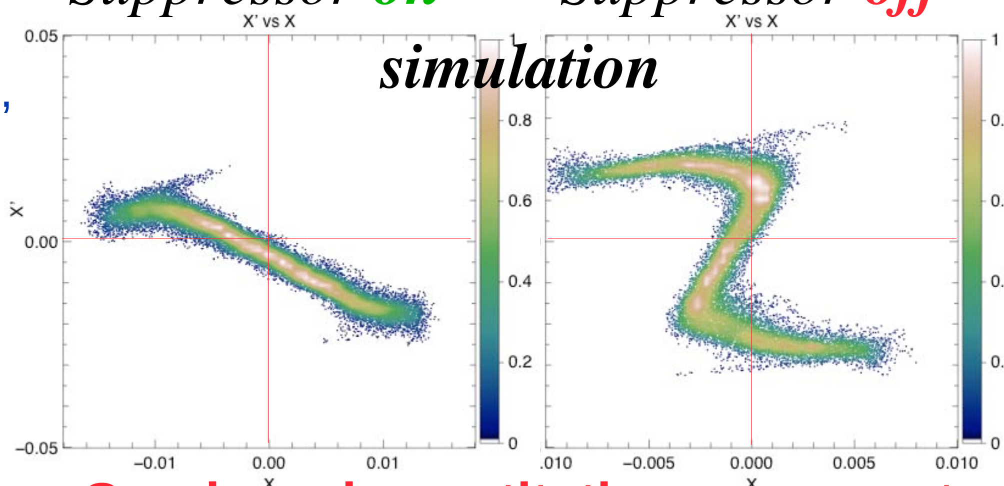
- energy
- **reconstructed** distribution from XY, XX', YY' slit-plate measurements





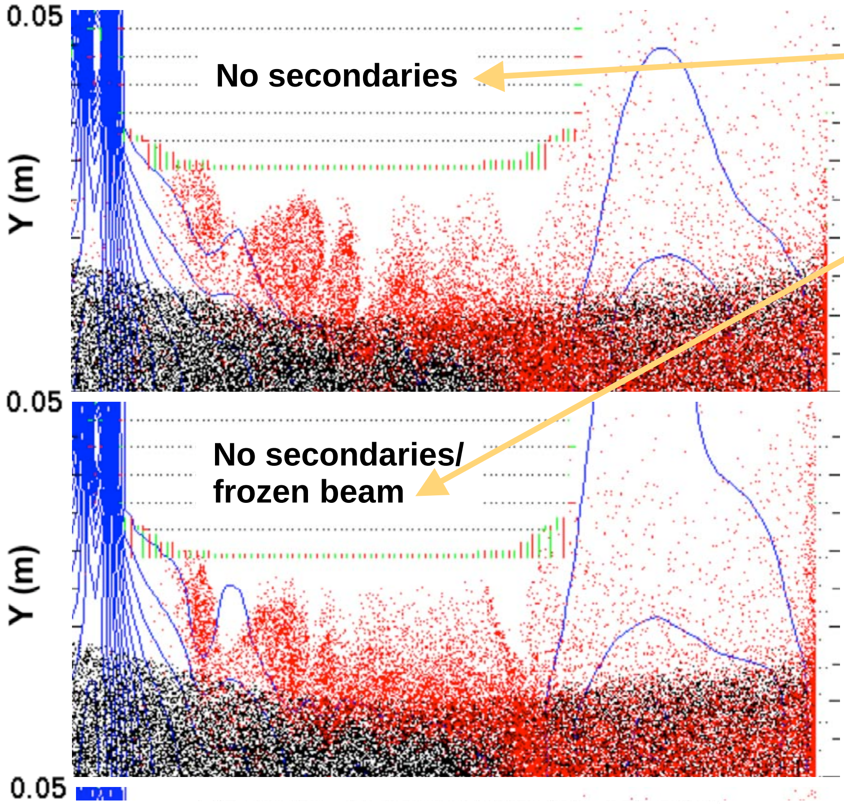


*Suppressor **on*** *Suppressor **off***



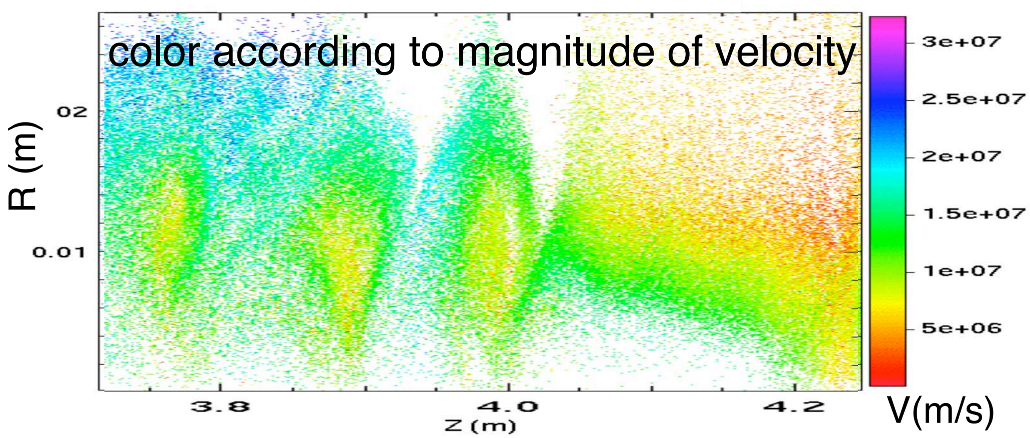
Good semi quantitative agreement.

Quest - nature of oscillations

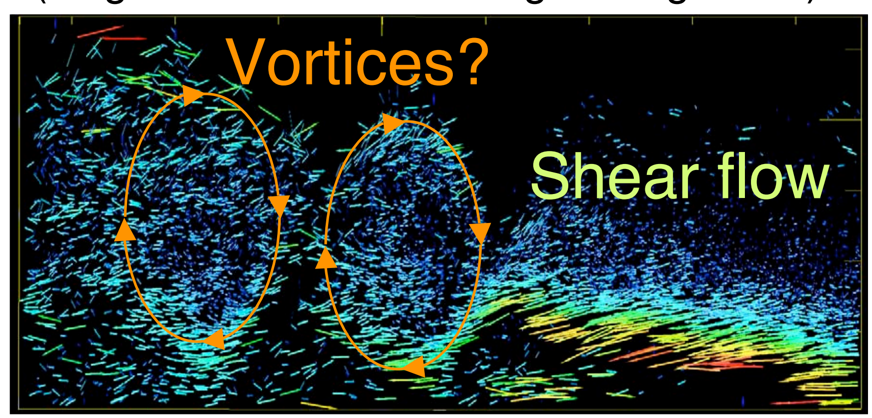


- **Progressively removes possible mechanisms**
- **Not ion-electron two stream**

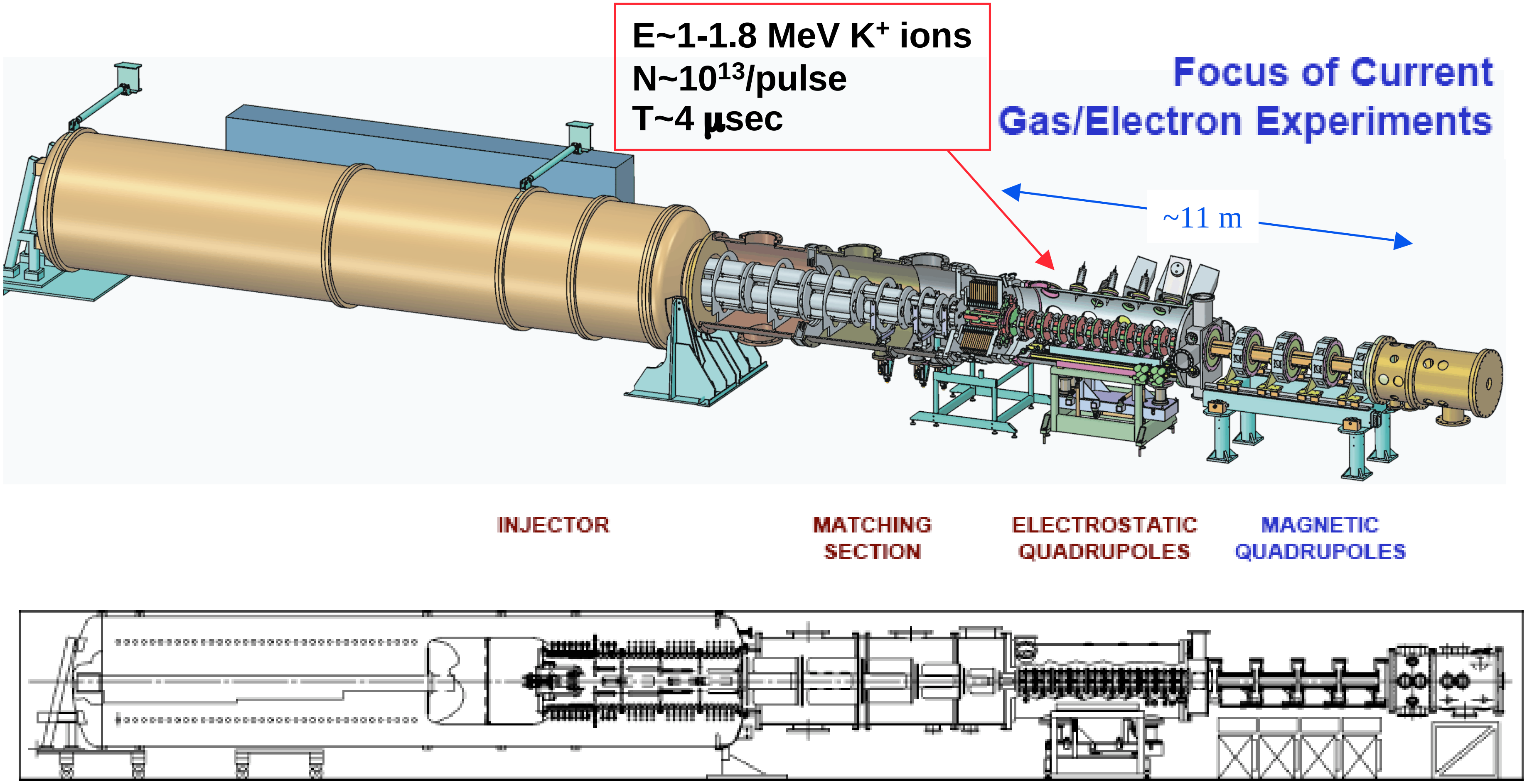
Other mechanisms:
- Virtual cathode oscillations
- δ-Density⇒δ-potential, feedbacks to drift velocity
- Kelvin Helmholtz/Diocotron (plausible, shear in drift velocities)



Fluid velocity vectors
(length and color according to magnitude)

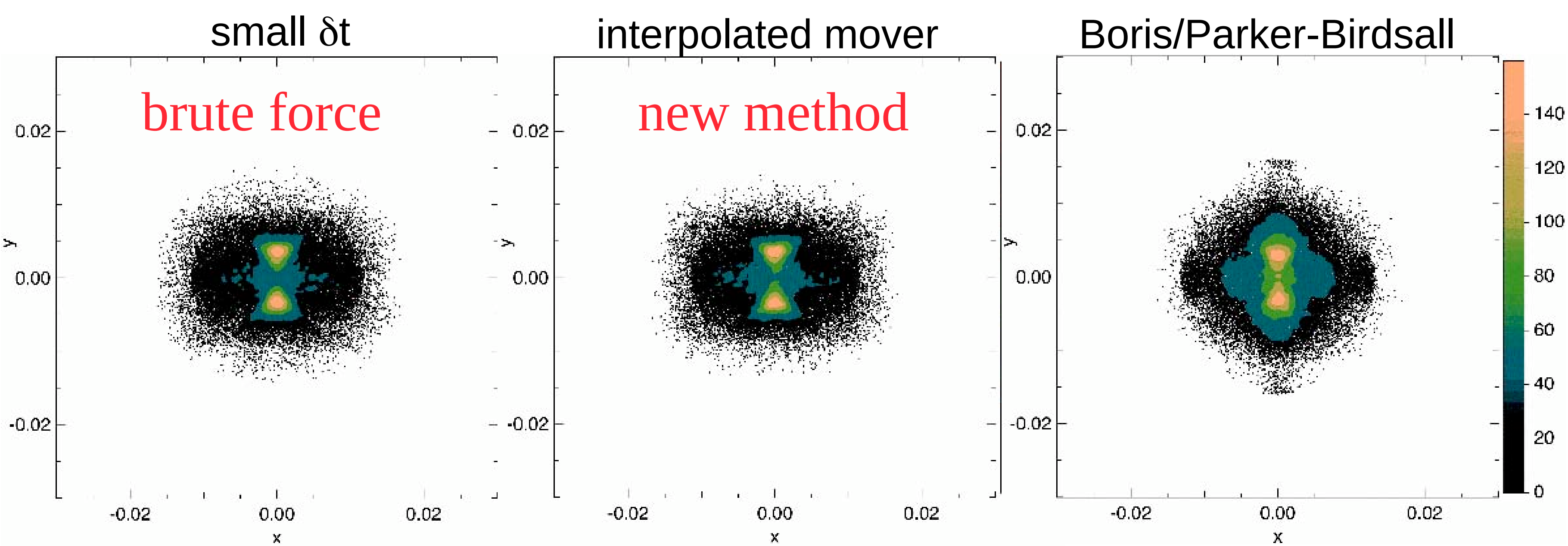


The HCX driver for HIF



Key simulation invention: large Δt electron pusher for non-uniform B-fields (eg., quads) (R. Cohen)

- Choice $\alpha=1/[1+(\omega_c\Delta t/2)^2]^{1/2}$ gives physically correct "gyro" radius at large $\omega_c\Delta t$ and also produces correct drift velocity and parallel dynamics.
- E-cloud produced by injection (at t=0) of T=10 eV electrons uniform out to nominal beam radius (e.g. ionization of neutral gas). Not stationary. Snapshot at fixed time (~50 τ_{bounce}):
- Factor ~25 increase in speed, little degradation of accuracy



Invention of an efficient electron integrator
(R. Cohen et al.)

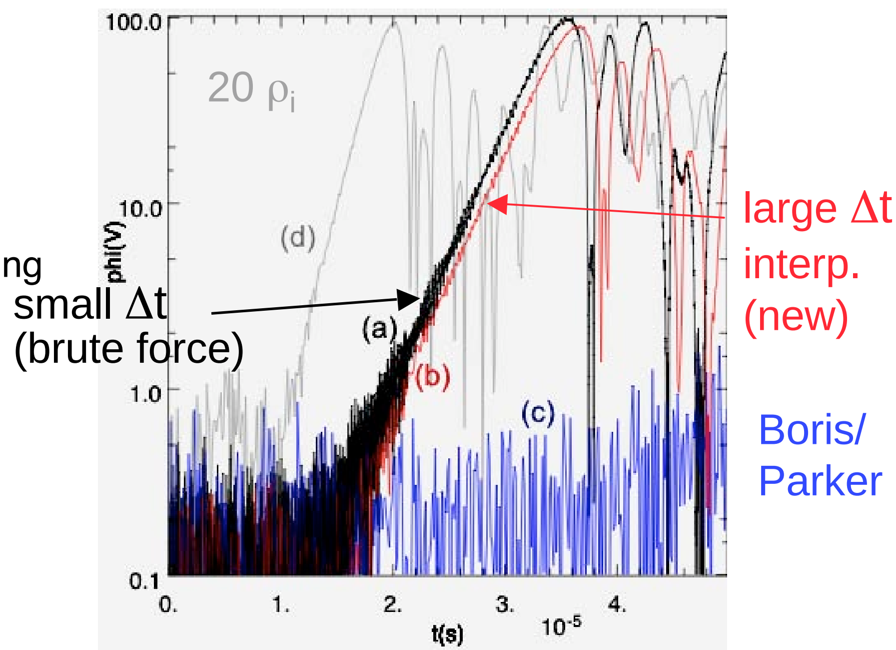
- Problem: wide range of time scales (electrons move fast!)
- ⇒ brute force integration requires small Δt when $B \neq 0$ ⇒ slow
- Our solution: interpolation between full-particle dynamics (Boris mover) and drift kinetics (motion along B plus drifts).

$$\mathbf{v}_{new} = \mathbf{v}_{old} + \Delta t \left(\frac{d\mathbf{v}}{dt}\right)_{Lorentz} + (1-\alpha)\left(\frac{d\mathbf{v}}{dt}\right)_{\mu\nabla B}$$

$$\mathbf{v}_{eff} = \mathbf{b}(\mathbf{b}\cdot\mathbf{v}) + \alpha\mathbf{v}_{\perp} + (1-\alpha)\mathbf{v}_d$$

- Particular choice: $\alpha=1/[1+(\omega_c\Delta t/2)^2]^{1/2}$ gives
  - physically correct "gyro" radius at large $\omega_c\Delta t$
  - correct drift velocity and parallel dynamics
- Ref. Cohen et al, Phys. Plasmas May '05
- Test problem: 2 stream instability of counter-streaming pencil (10 gyroradii) beams

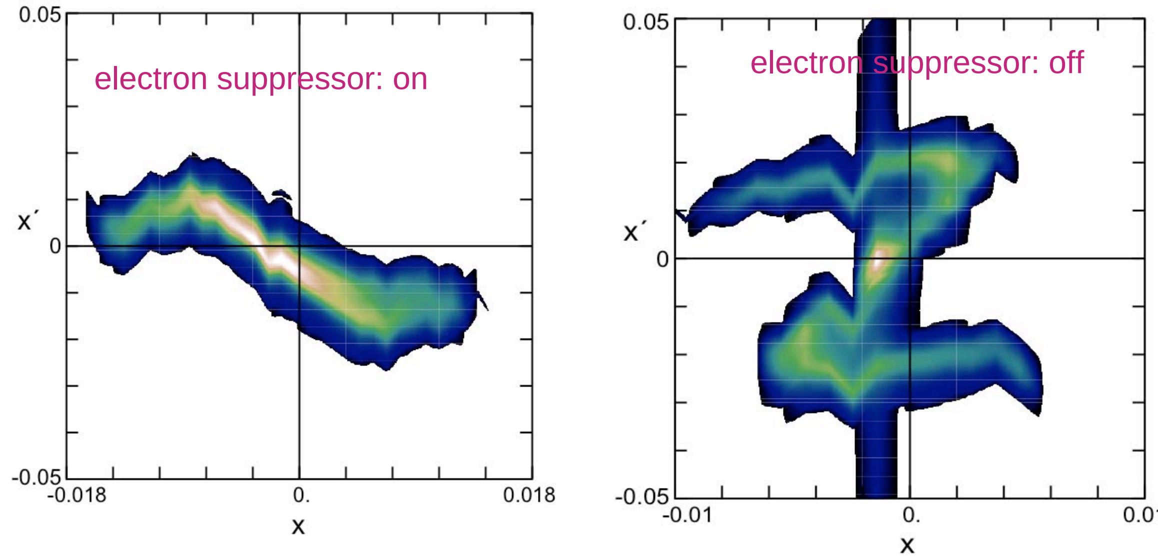
Speed-up by ~x25, ~no loss of accuracy



WARP/POSINST e-i simulations of the 4 magnet section of HCX show ion phase space similar to the experiments

HCX measurement

Phase space reconstruction from scintillator images of slit scan



3-D WARP simulation with:

Electron desorption at end wall matching desorption rate from separate experiments.
Secondary emission when electrons hit radial pipes.
NO local sources of electrons