ICAP 06

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Chamonix Mont-Blanc

Self-consistent simulations of high-intensity beams and electron-clouds.

Jean-Luc Vay

Heavy Ion Fusion Science Virtual National Laboratory
Lawrence Berkeley National Laboratory

Many thanks to collaborators

M. A. Furman, C. M. Celata, P. A. Seidl, M. Venturini
Lawrence Berkeley National Laboratory

R. H. Cohen, A. Friedman, D. P. Grote,
M. Kireeff Covo, A. W. Molvik
Lawrence Livermore National Laboratory

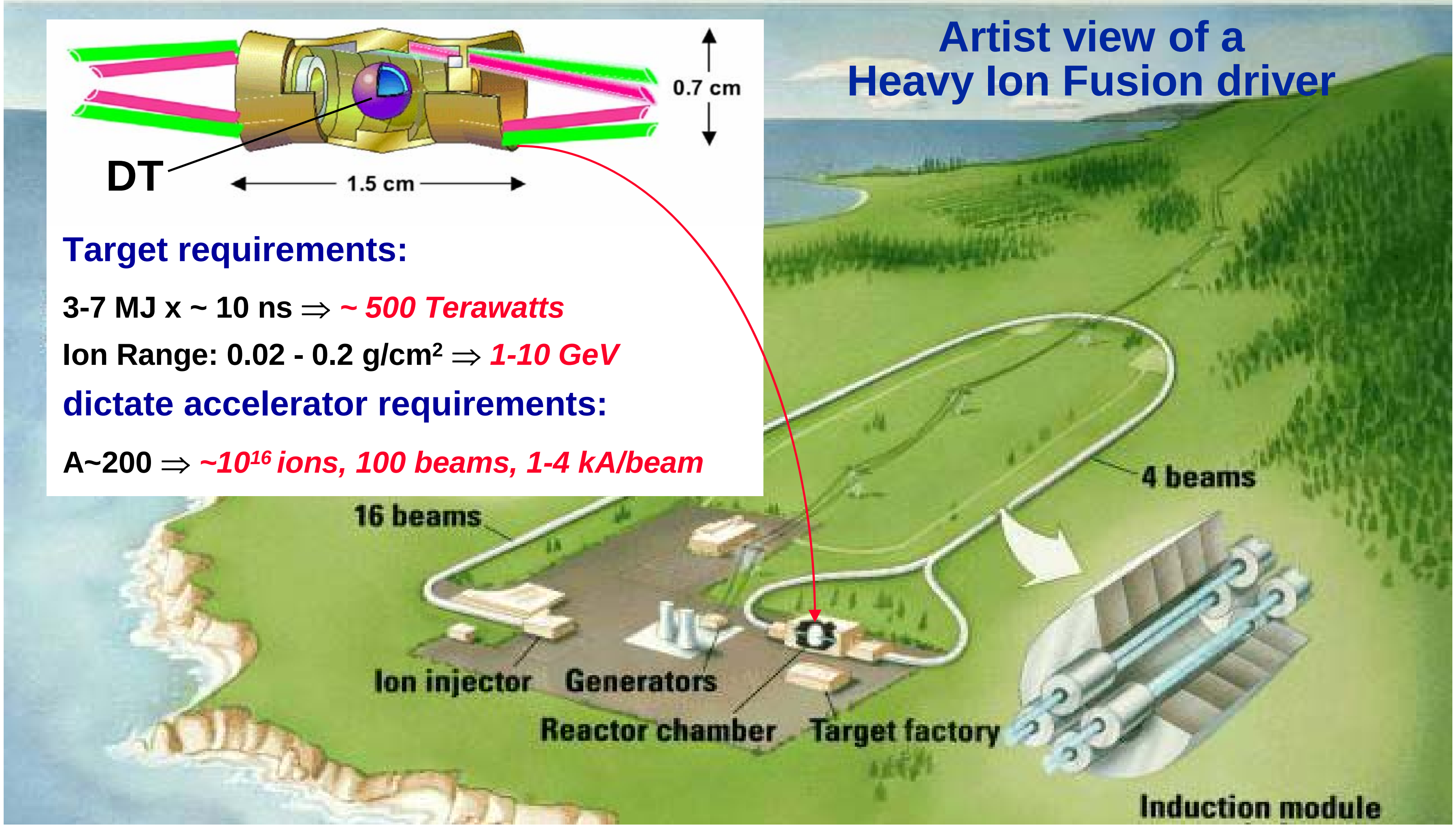
P. H. Stoltz, S. Veitzer
Tech-X Corporation

J. P. Verboncoeur
University of California - Berkeley

Outline

1. Who we are and why we care about electron cloud effects
2. Our tools and recent selected results
3. Application to High-Energy Physics
4. Conclusion

Heavy Ion Inertial Fusion (HIF) goal is to develop an accelerator that can deliver beams to ignite an inertial fusion target



Target requirements:

3-7 MJ x ~ 10 ns ⇒ *~ 500 Terawatts*

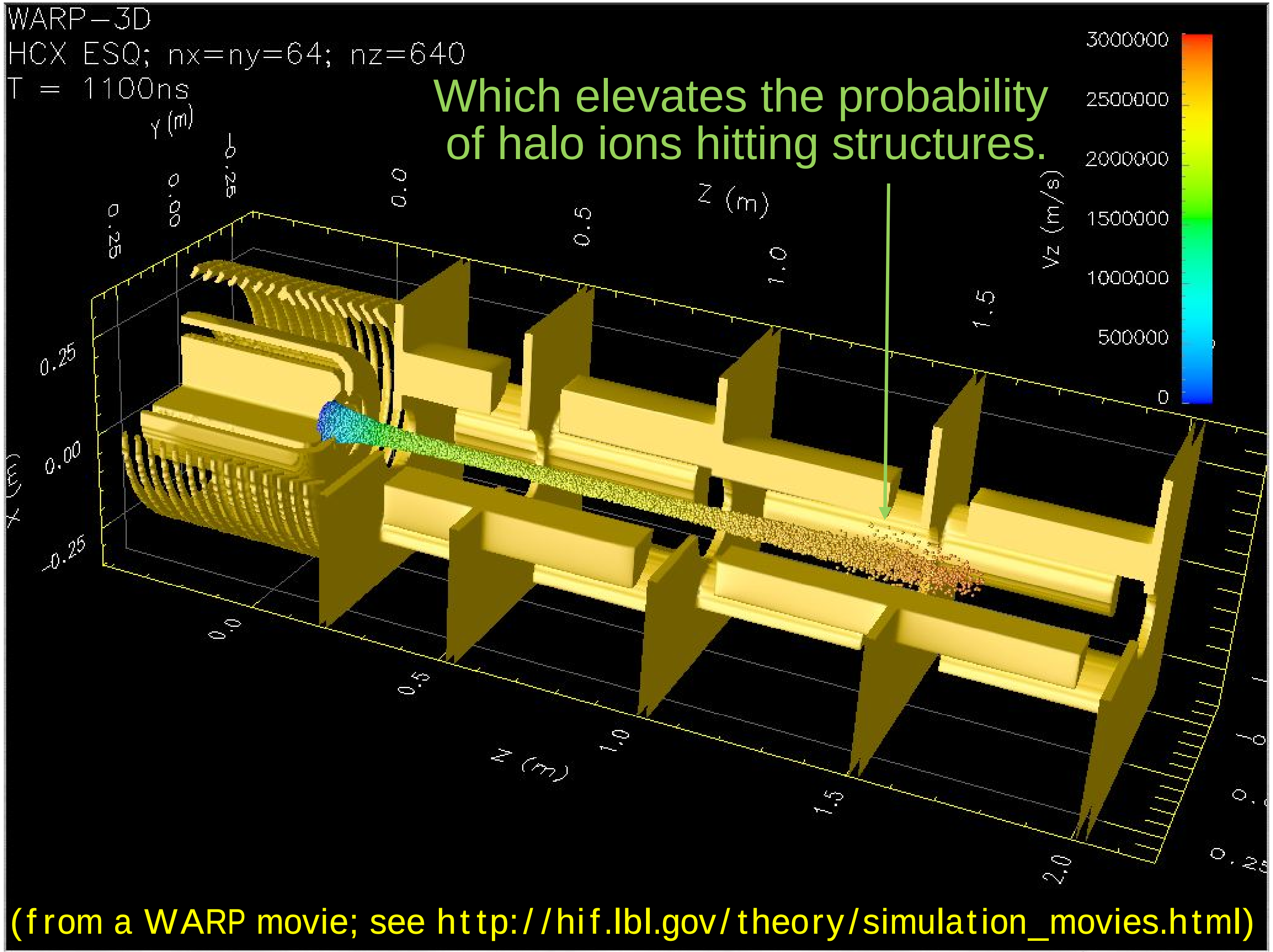
Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1-10 GeV*

dictate accelerator requirements:

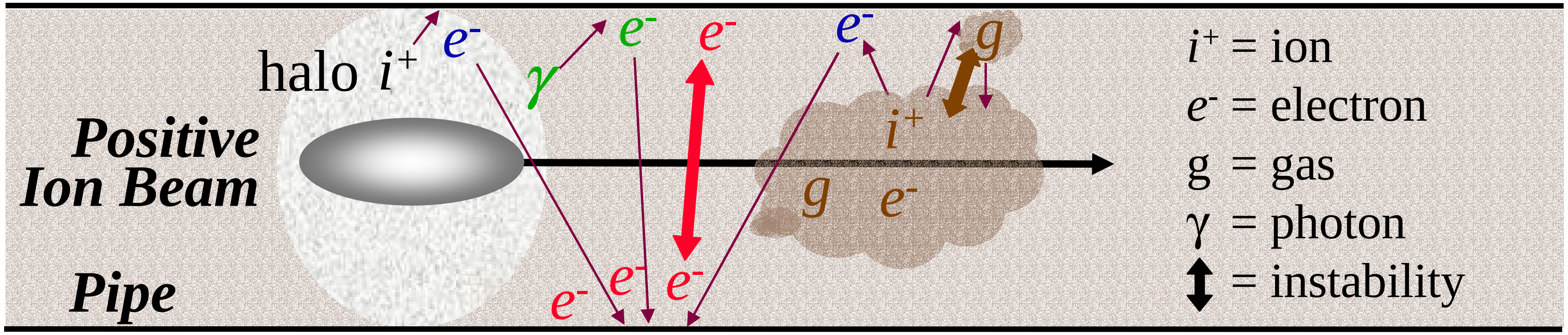
A~200 ⇒ *~10^{16} ions, 100 beams, 1-4 kA/beam*

Our near term goal is High-Energy Density Physics (HEDP)...

We have a strong economic incentive to fill the pipe.



Sources of electron clouds



Primary:

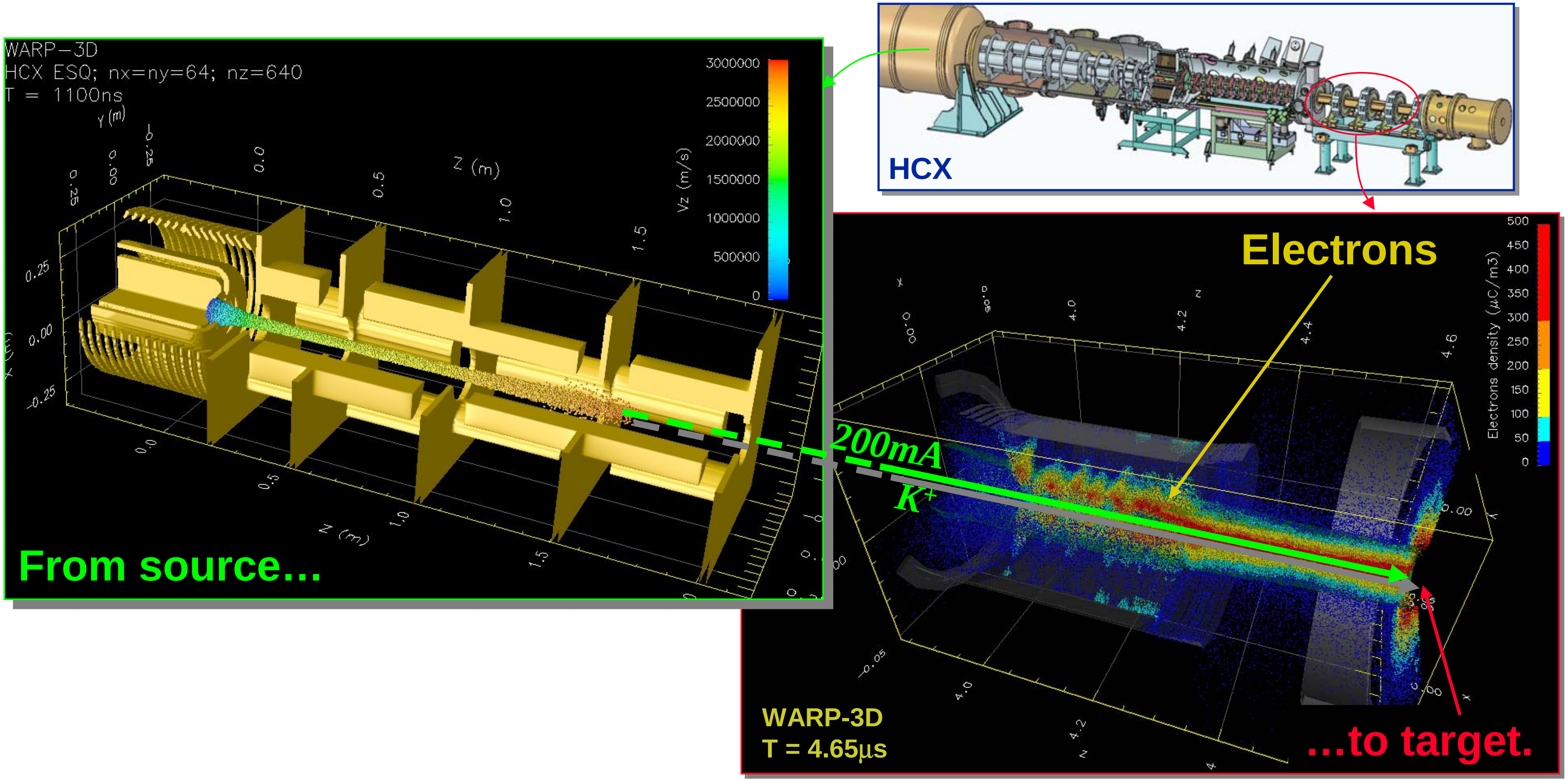
- **Ionization of**
  - **background gas**
  - **desorbed gas**
- **ion induced emission from**
  - **expelled ions hitting vacuum wall**
  - **beam halo scraping**
- **photo-emission from synchrotron radiation (HEP)**

Secondary:

- **secondary emission from electron-wall collisions**

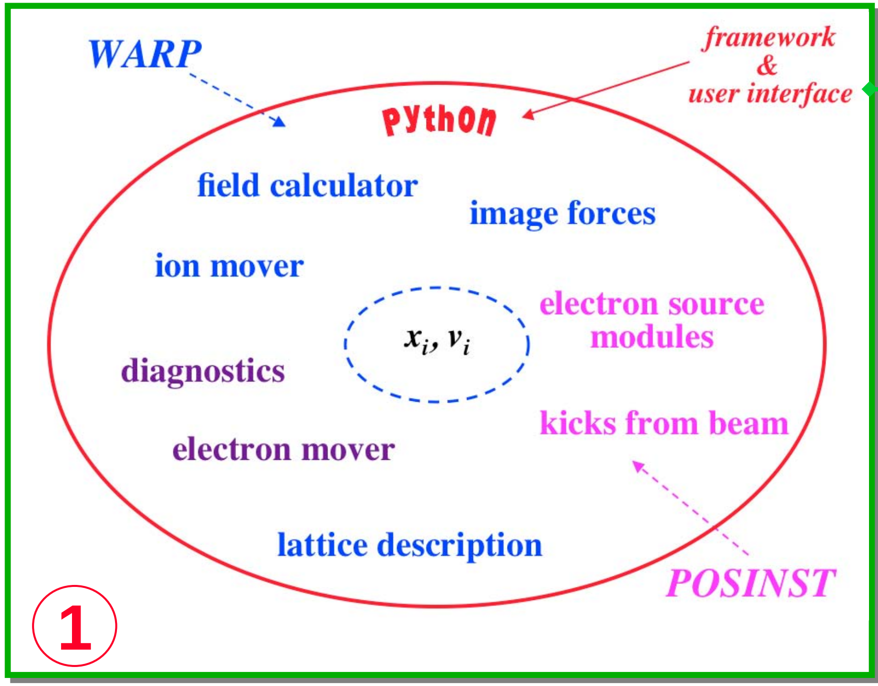
Simulation goal - predictive capability

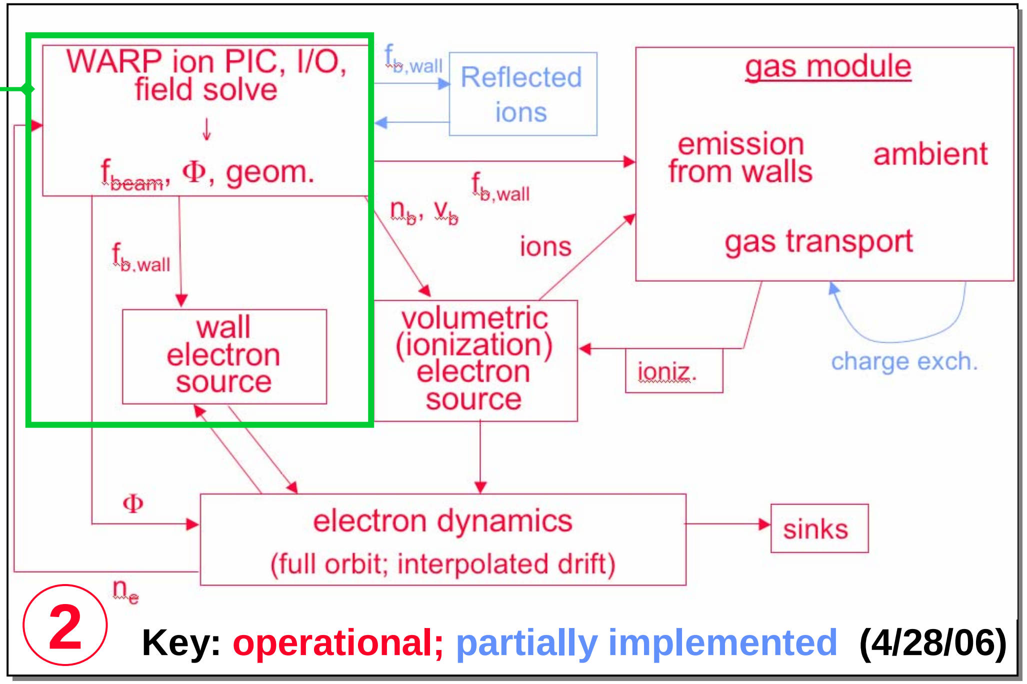
End-to-End 3-D **self-consistent** time-dependent simulations of beam, electrons and gas with self-field + external field (dipole, quadrupole, …).



The means - WARP-POSINST code suite

merge of WARP & POSINST + new e⁻/gas modules



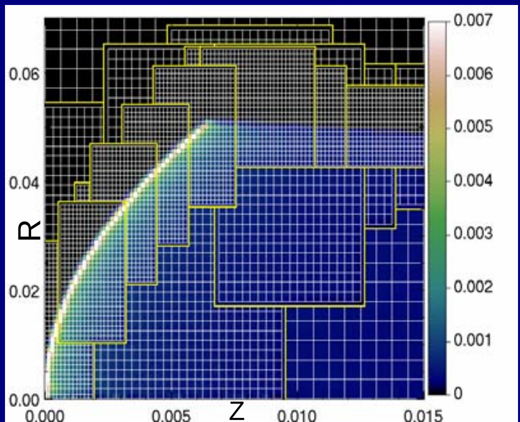


+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

Speed-up

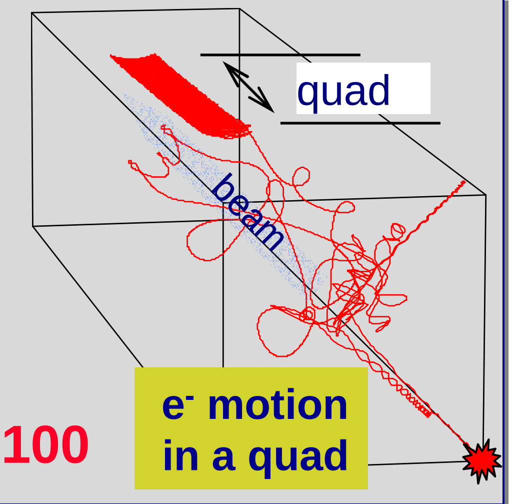
3 x10-10^4



+ New e⁻ mover

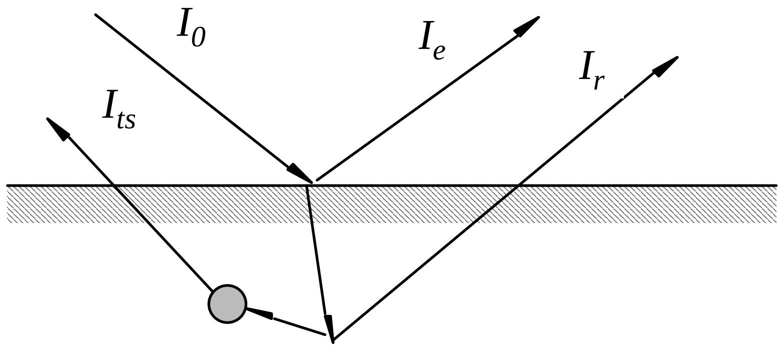
Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

4 Speed-up x10-100



POSINST provides advanced SEY model.

Monte-Carlo generation of electrons with energy and angular dependence.
Three components of emitted electrons:



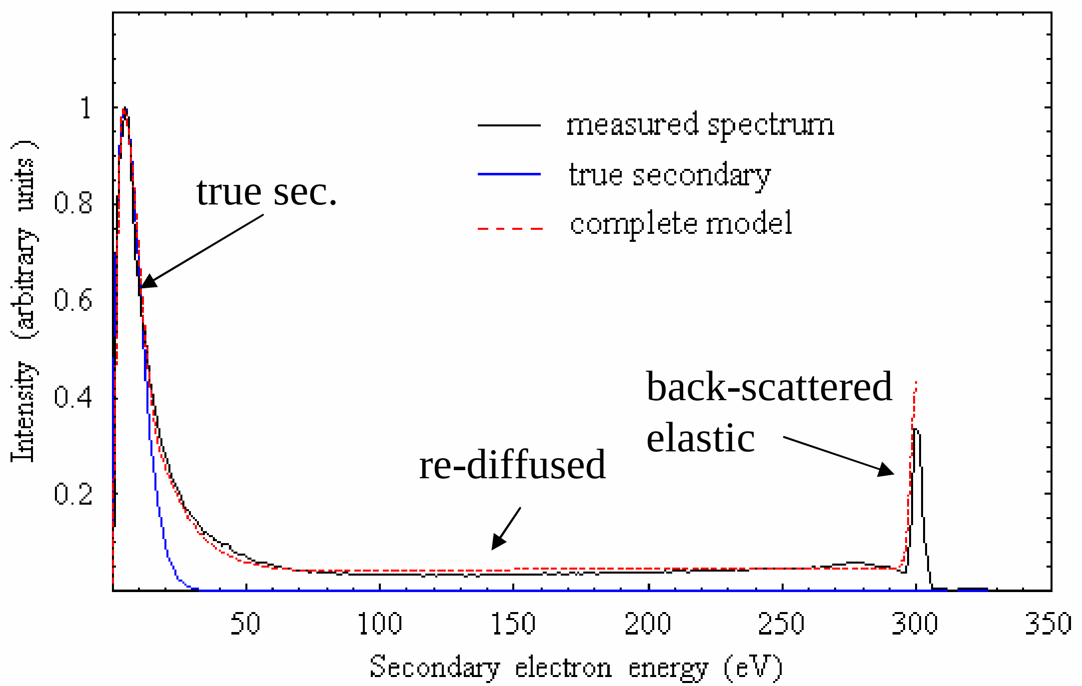
backscattered: $\delta_e = \frac{I_e}{I_0}$,

rediffused: $\delta_r = \frac{I_r}{I_0}$,

true secondaries: $\delta_{ts} = \frac{I_{ts}}{I_0}$

Phenomenological model:

- based as much as possible on data for δ and $d\delta/dE$
- not unique (use simplest assumptions whenever data is not available)
- many adjustable parameters, fixed by fitting δ and $d\delta/dE$ to data

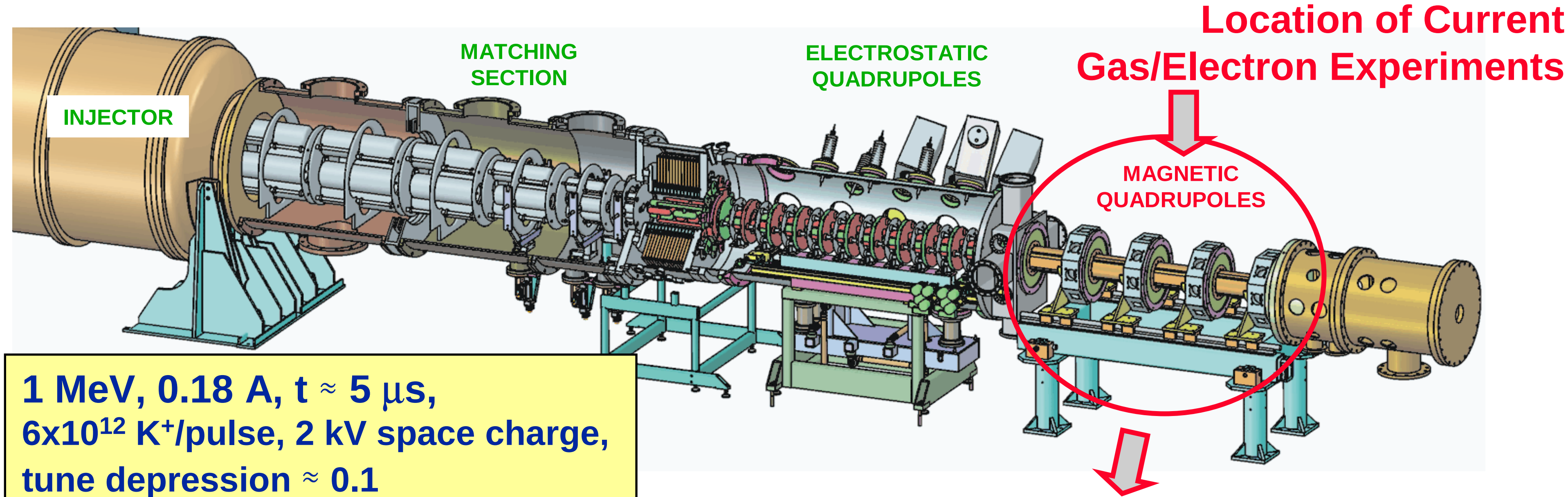


We use third-party modules.

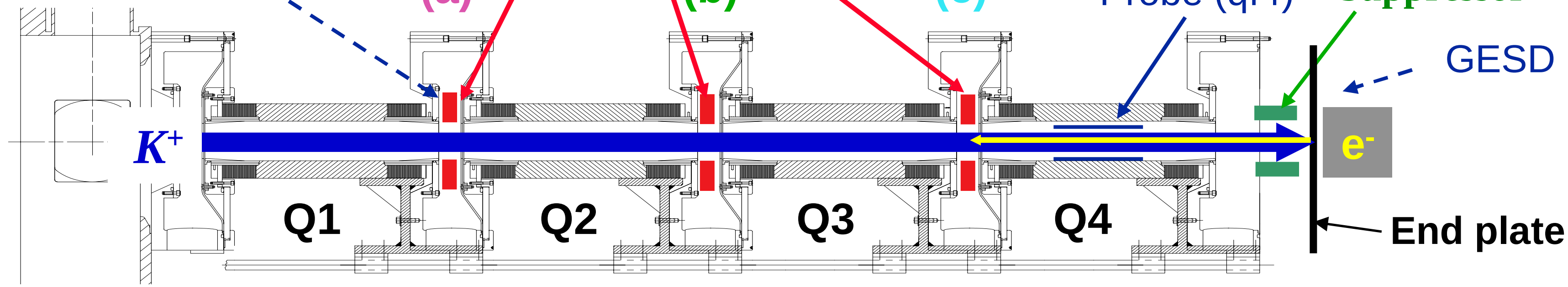
• ion-induced electron emission and cross-sections from the TxPhysics* module from Tech-X corporation (http://www.txcorp.com/technologies/TxPhysics),

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

Benchmarked against dedicated experiment on HCX

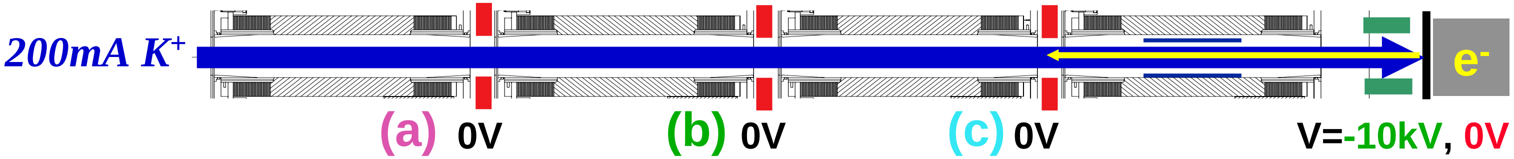


1 MeV, 0.18 A, t ≈ 5 μs,
6×10^{12} K^+/pulse, 2 kV space charge,
tune depression ≈ 0.1



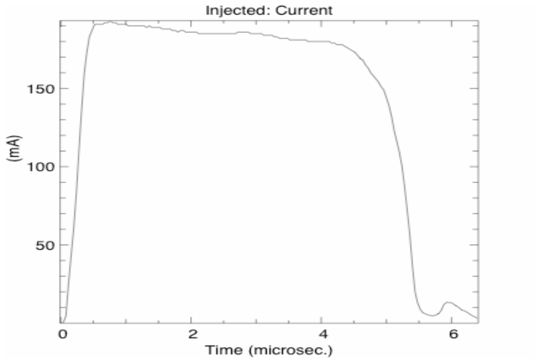
Short experiment => need to deliberately amplify electron effects:
let beam hit end-plate to generate copious electrons which propagate upstream.

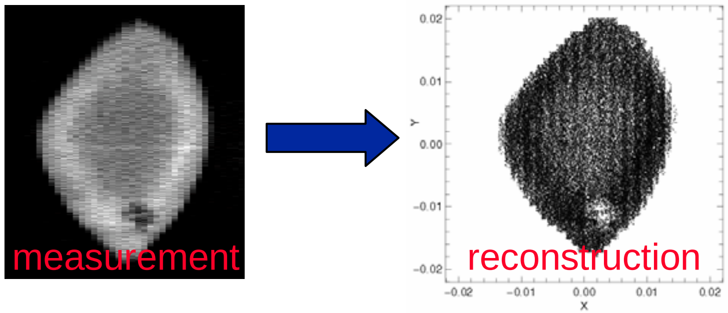
Comparison sim/exp: clearing electrodes and e⁻ supp. on/off

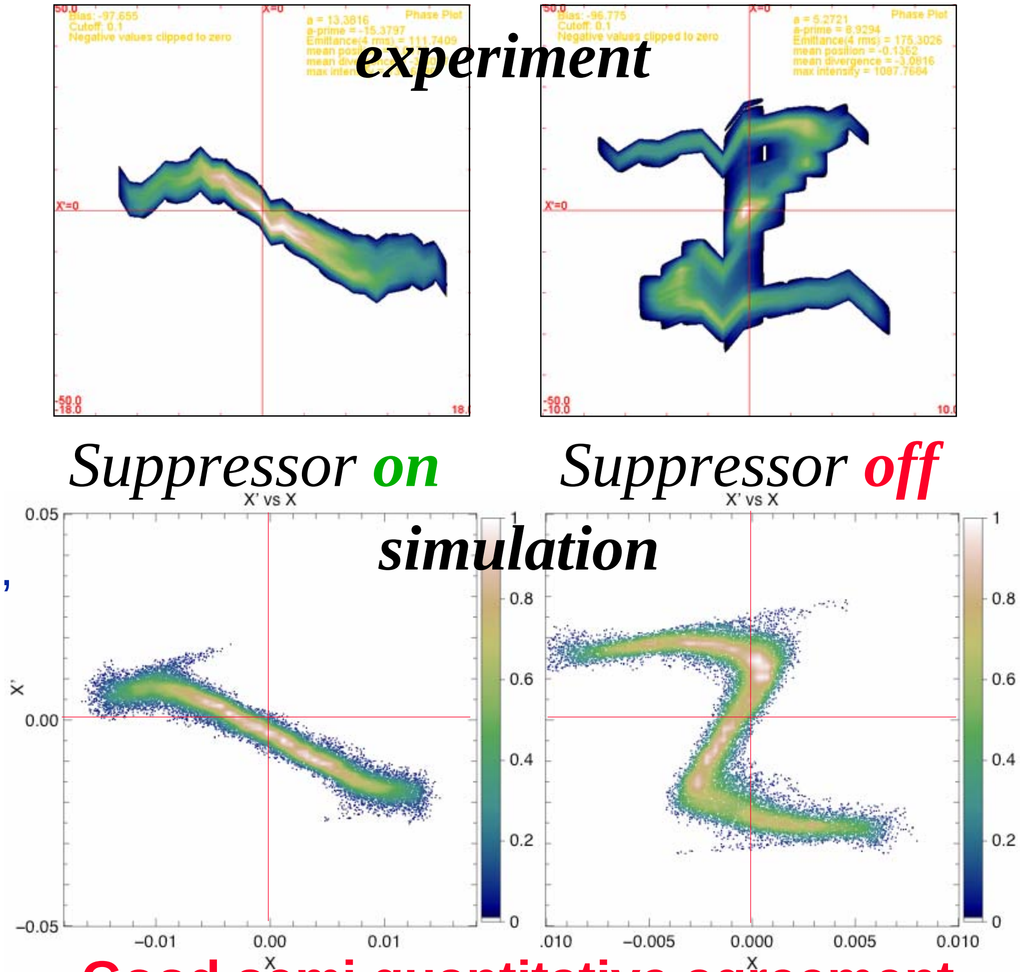


Time-dependent beam loading in WARP from moments history from HCX data:

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

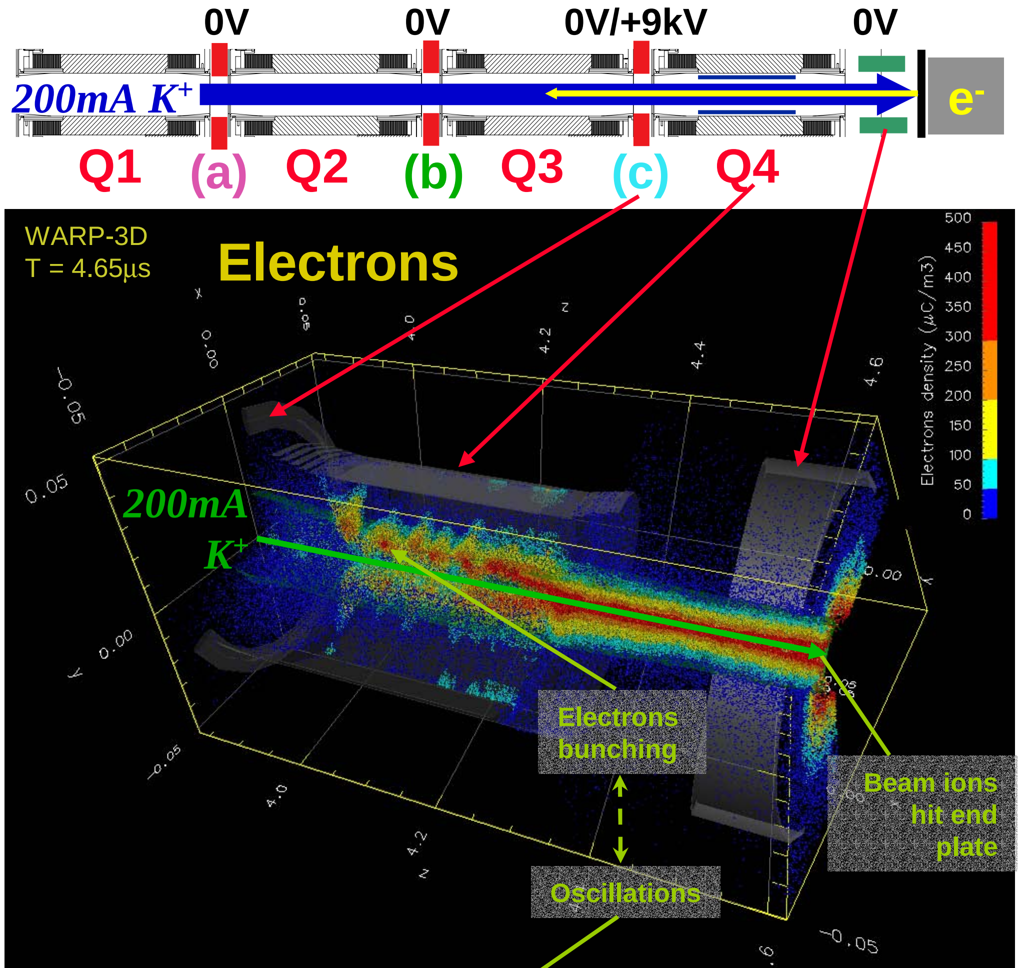


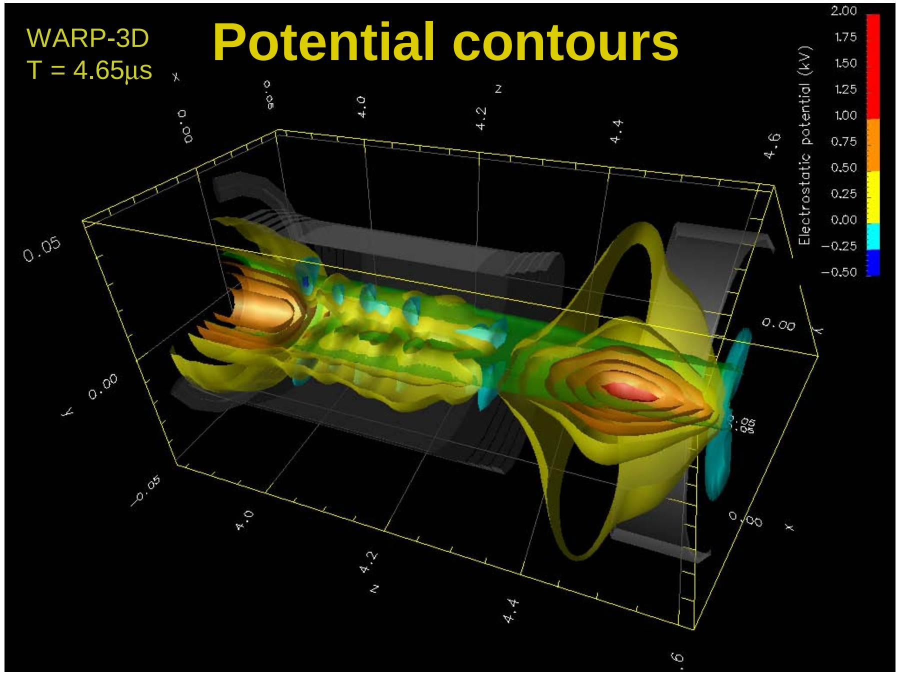


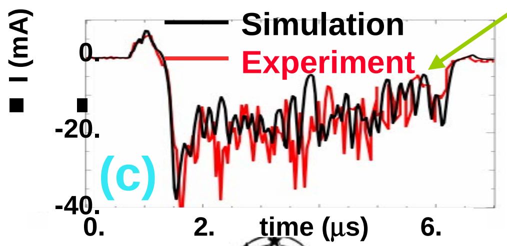


Good semi quantitative agreement.

Detailed exploration of dynamics of electrons in quadrupole

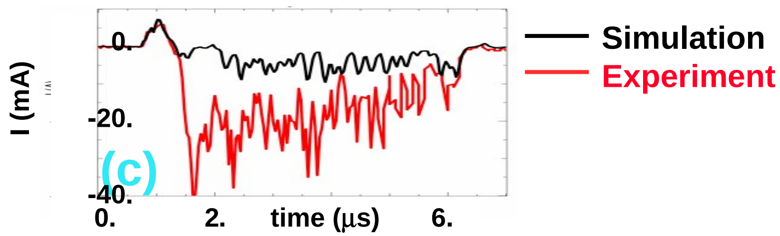






~6 MHz signal in (C) in simulation AND experiment

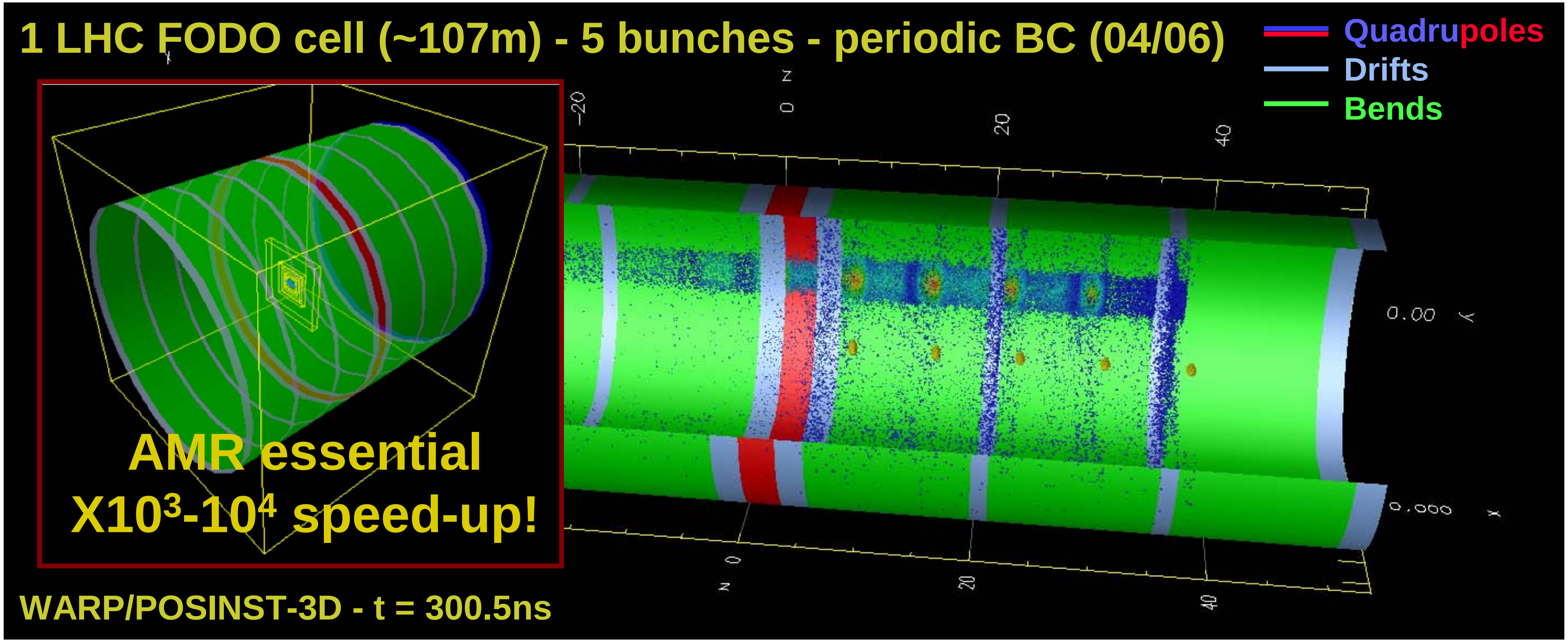
1. **Importance of secondaries**
   - if secondary electron emission turned off:



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

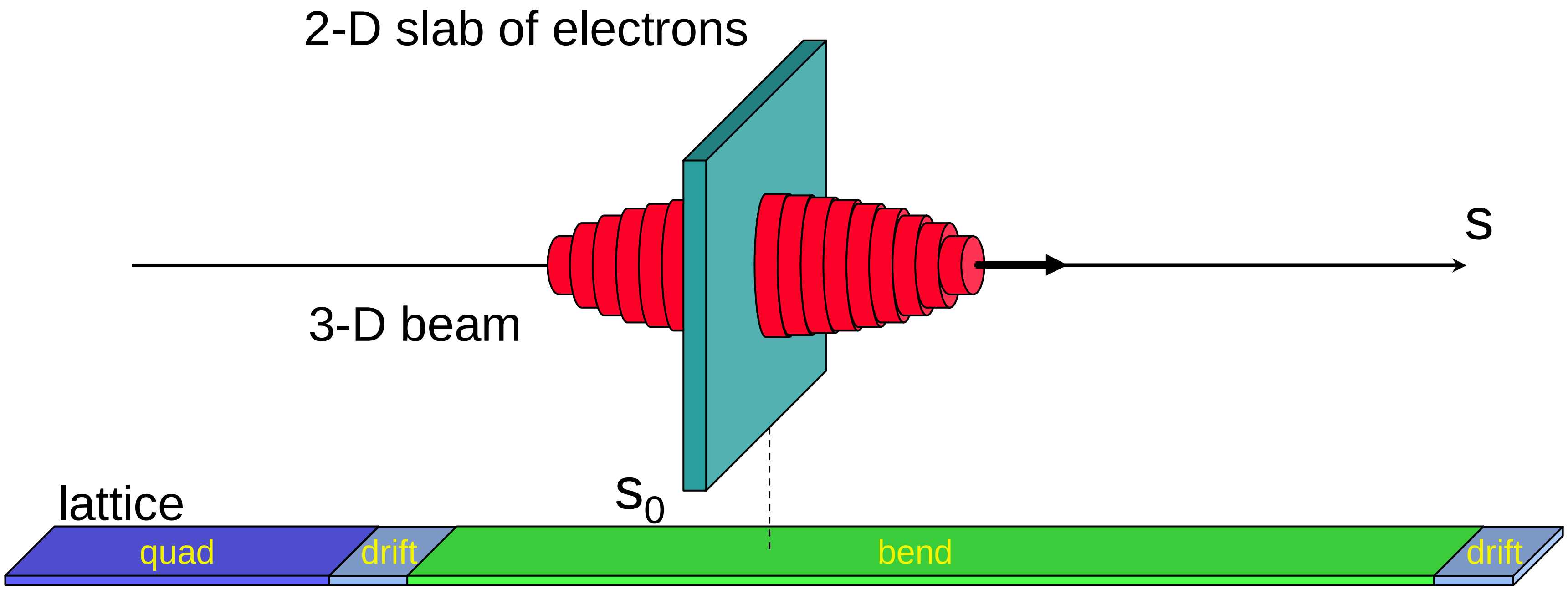
WARP/POSINST applied to High-Energy Physics

- LARP funding: simulation of e-cloud in LHC



- Fermilab: study of e-cloud in MI upgrade
- ILC: start work in FY07

"Quasi-static" mode added for codes comparisons.



A 2-D 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), allowing direct comparison.

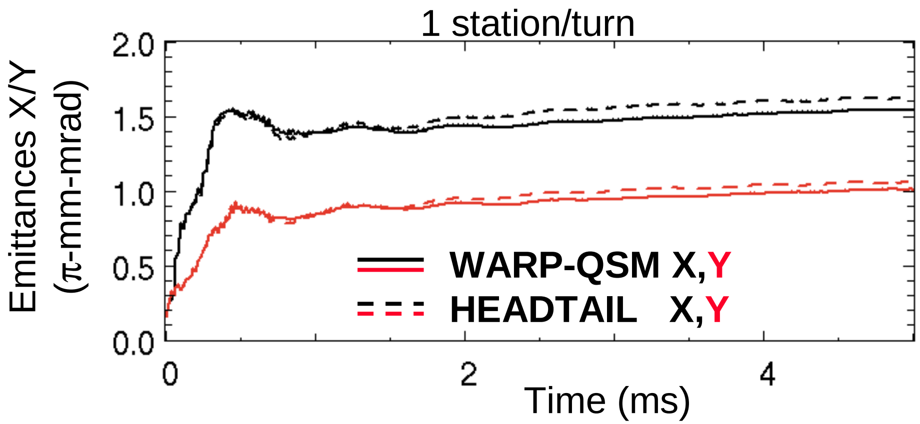
Comparison WARP-QSM/HEADTAIL on CERN benchmark

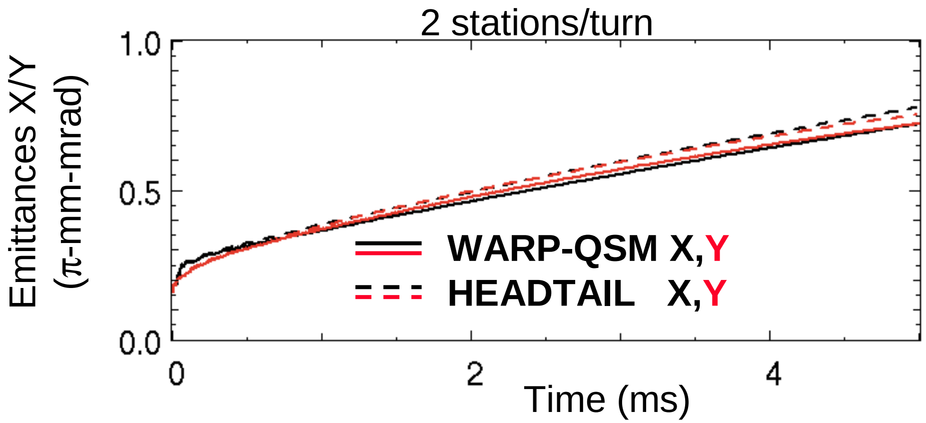
Proposed Model for Instability Simulations

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)**

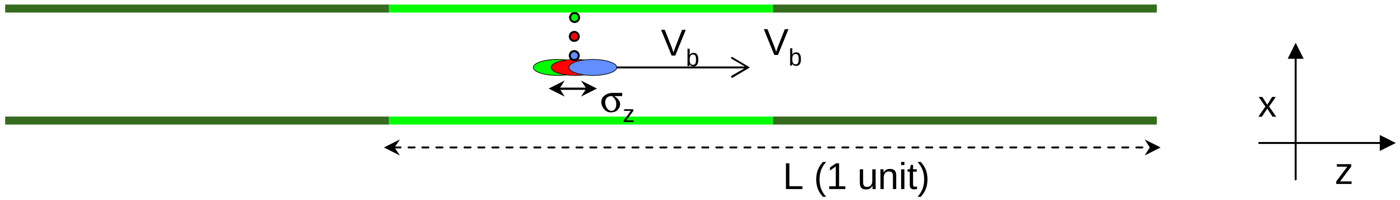
result: plot of x&y emittances vs time





Can 3-D self-consistent compete with quasi-static mode?
- computational cost of full 3-D run in two frames -

Lab frame



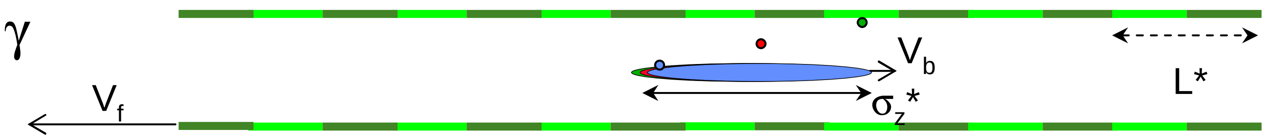
$\delta x = \sigma_x/n$; $\delta z = \min(\sigma_z, L)/n$

$\delta t < \min[\ \delta x/\max(v_x), \delta z/\max(v_z)\ ]$;

$T_{max} = N_{units} \times L/V_b$

$N_{op} = N_e \times T_{max}/\delta t$

Frame γ



$\delta x^* = \sigma_x/n$; $\delta z^* = \min(\sigma_z^*, L^*) = \gamma \delta z$

$\delta t^* < \min[\ \delta x^*/\max(v_x^*), \delta z^*/\max(v_z^*)\ ] = \min[\ \delta x/(\max(v_x/\gamma)), \gamma \delta z/v_z] = \gamma \delta t$

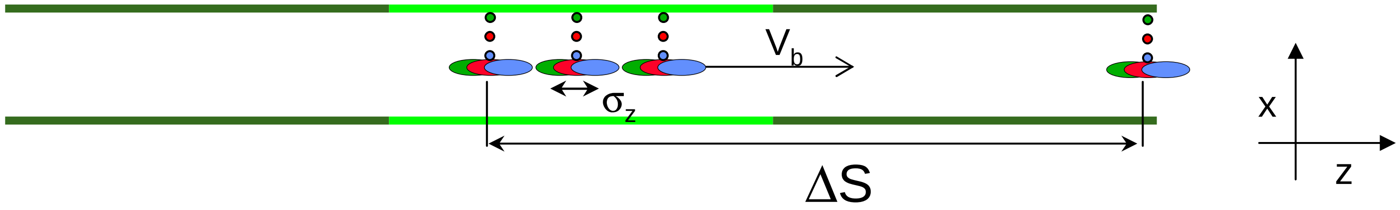
$T^*_{max} = N_{units} \times L^*/(V_b - V_f) \sim T_{max}/\gamma$

$N^*_{op} = N_e \times T^*_{max}/\delta t^* \sim N_{op}/\gamma^2$

=> Computational cost greatly reduced in frame γ

Comparison between quasi-static and full 3-D costs.

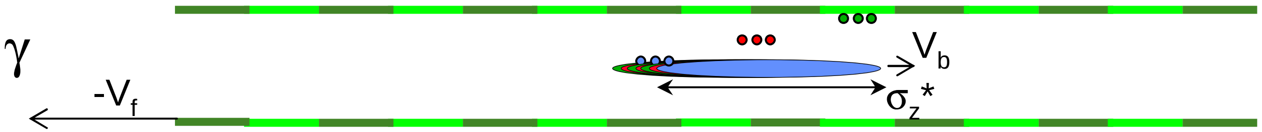
Lab frame



Quasi-static (HEADTAIL, QUICKPIC):

$$\alpha \sim \Delta S/\sigma_z$$
$$N_{op,qs} = N_{op}/\alpha$$

Frame γ



if $\sigma_z{}^* = \Delta S^*$, $\gamma^2 = \alpha$, $N^*_{op} = N_{op,qs}$

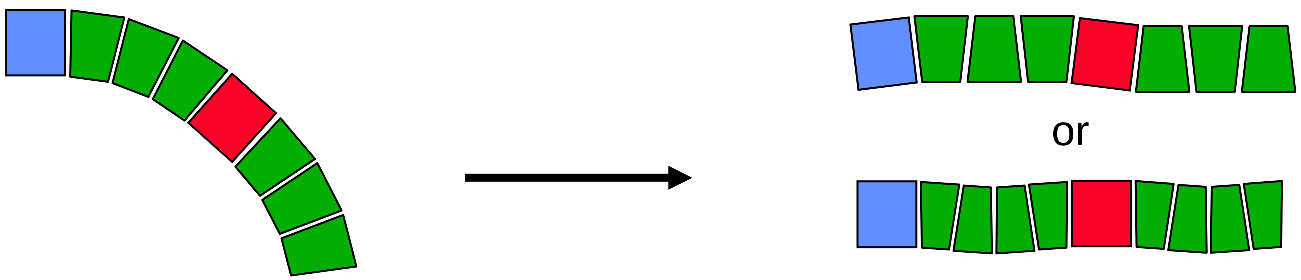
=> **cost of full 3-D run in frame γ = cost of quasi-static mode in lab frame**

Application to rings

- **In bends, WARP uses warped coordinates with a logically cartesian grid. If solving in a frame moving at constant γ along s, we need to extend existing algorithm to allow treatment of motion in relativistic rotating frame in bends.**

- **Meanwhile, in order to study electron cloud effects, including bends, where effects are dominated by the magnitude of the bending field rather than its sign, we propose to substitute a ring by a linear lattice with bends of alternating signs.**

- **For example, diagram 1 LHC FODO cell (** quadrupole; bend **)**



or…

Conclusion

- **We developed a unique combination of tools to study ECE**
- **WARP/POSINST code suite**
  - **Parallel 3-D PIC-AMR code with accelerator lattice follows beam <u>self-consistently</u> with gas/electrons generation and evolution,**
- **HCX experiment adresses ECE fundamentals (HIF/HEDP/HEP)**
  - **<u>highly instrumented</u> section dedicated to e-cloud studies,**
  - **extensive methodical <u>benchmarking</u> of WARP/POSINST,**
- **Being applied outside HIF/HEDP, to HEP accelerators**
  - **LHC, Fermilab MI, ILC,**
  - **Implemented "quasi-static" mode for direct comparison to HEADTAIL/QUICKPIC,**
  - **fund that self-consistent calculation has <u>similar cost</u> than quasi-static mode if done in <u>moving frame (with γ>>1)</u>, thanks to relativistic contraction/dilatation bridging space/time scales disparities (applies to FEL, laser-plasma acceleration, plasma lens,…).**