Advances in Numerical Simulations of Intense Ion Beams in the U.S.

D. P. Grote

(with thanks to R. Cohen, A. Friedman, I. Haber, J. L. Vay, and many others)

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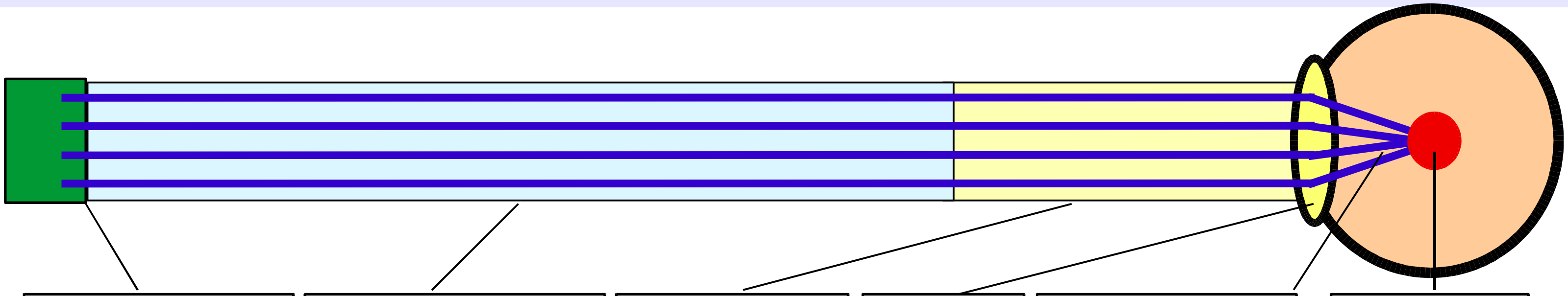
Utsunomiya, Japan

Outline

- **Overview of codes**
- **Advances in development and applications**
- **Future plans**
- **Summary**

HIF-VNL's approach to self-consistent beam simulation (HEDP & IFE) employs multiple tools



Ion source & injector | **Accelerator** | **Buncher** | **Final focus** | **Chamber transport** | **Target**

ES/Darwin PIC and moment models
Warp: 3d, xy, rz , Hermes

EM PIC
LSP

rad-hydro

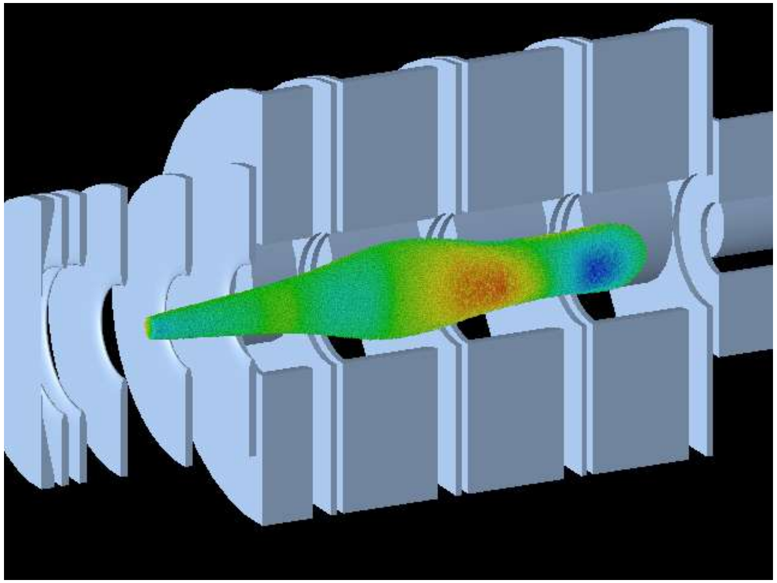
ES PIC,	EM PIC,	δf,	Vlasov
Warp	LSP	BEST	Warp-slv

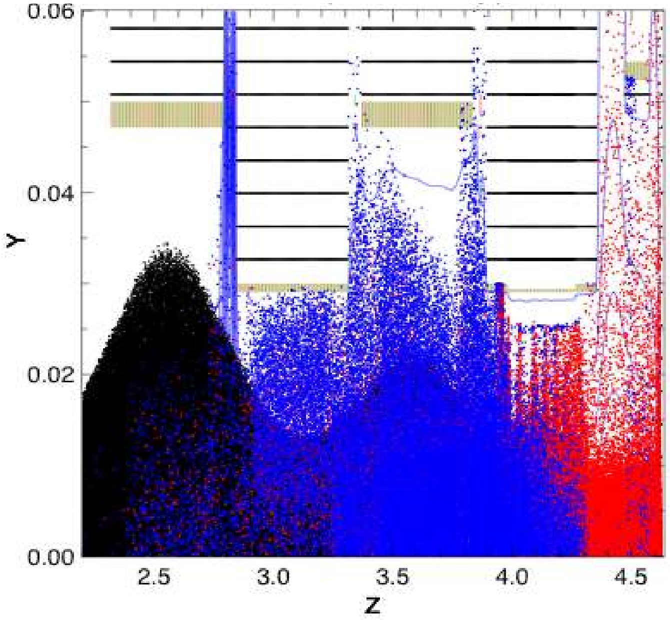
Track beam ions consistently along entire system

Study instabilities, halo, electrons, ..., via coupled detailed models

WARP – primarily developed at LLNL and LBNL

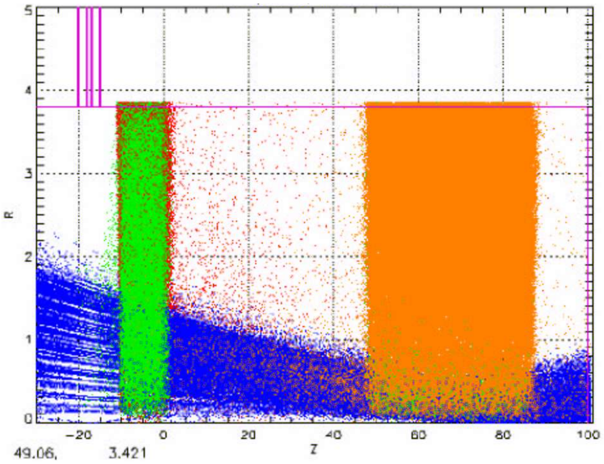
- **WARP is multi-dimensional PIC**
  - **3D, RZ, XY**
  - **Electro- and magnetostatic – multiple field solvers**
  - **Time-dependent and steady-state models**
  - **Detailed description of accelerator lattice – MAD input**
  - **Steerable (via Python), serial and parallel (via MPI)**



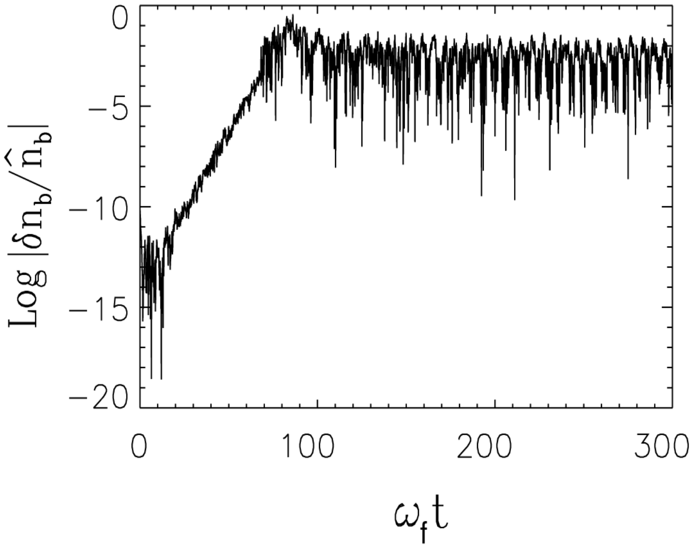


Other major codes are developed and used

- **LSP – Mission Research**
  - **3D, 2D**
  - **implicit electromagnetic**
  - **PIC/fluid hybrid**



- **BEST - PPPL**
  - **3D, 2D**
  - **electrostatic/Darwin**
  - **delta f**



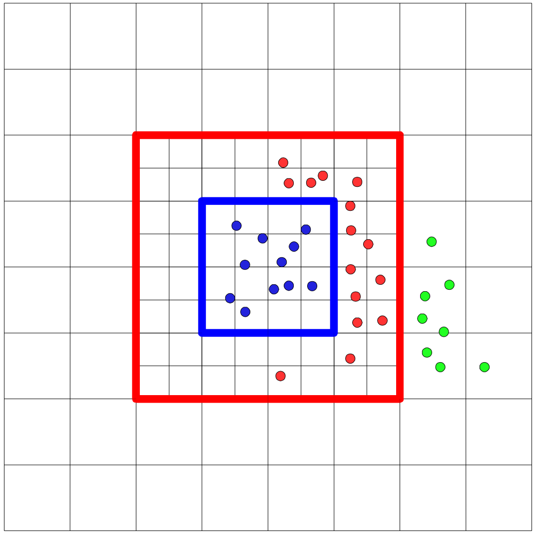
Challenges are addressed by new computational capabilities

- **Resolution challenges (Adaptive Mesh Refinement-PIC)**
- **Dense plasmas (implicit, hybrid PIC+fluid)**
- **Short electron timescales (large-Δt advance)**
- **Electron-cloud & gas interactions (new “road map”)**
- **Slowly growing instabilities (δf for beams)**
- **Beam halo (advanced Vlasov)**
- **Initial conditions (data reconstruction, equilibrium distributions)**

Adaptive mesh refinement (AMR)
- Resolve only what's interesting

- **AMR in Warp – 3D, RZ, and XY**
- **Potential issues in integration with PIC:**
  - **Spurious self-force**
  - **Possible violation Gauss' Law**
  - **For EM - shortest wavelengths from fine grid not can not propagate on coarse grid – may reflect with factor > 1**
- **Algorithms must be chosen carefully!**
- **But significant pay-off in reduced computations!**

AMR algorithms chosen to minimize errors



“Guard” cells to reduce self force

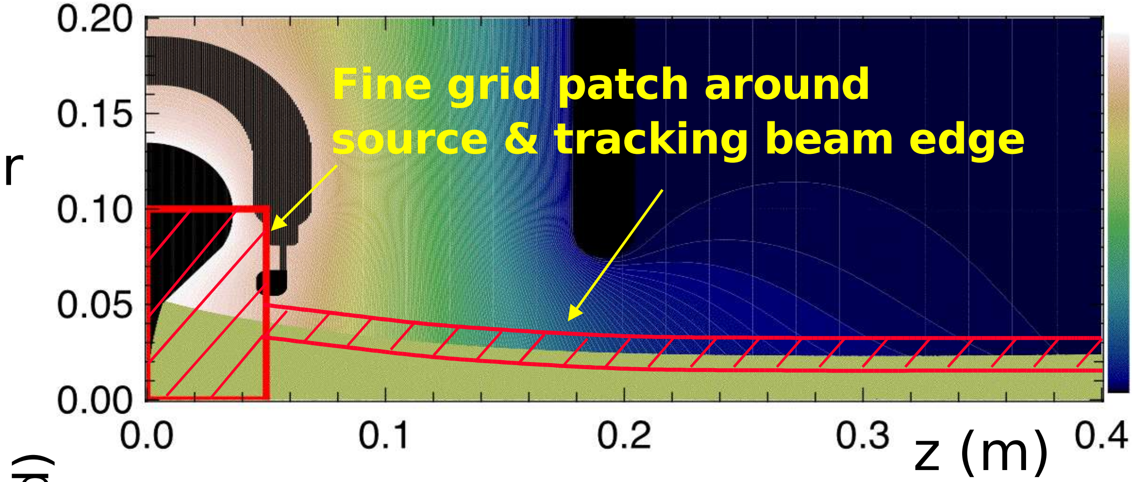
- Spurious self-force largest near transition
- Potential calculated in all of fine mesh (inside red box)
- Refined field only applied to blue particles
- Coarse field applied to red and green particles

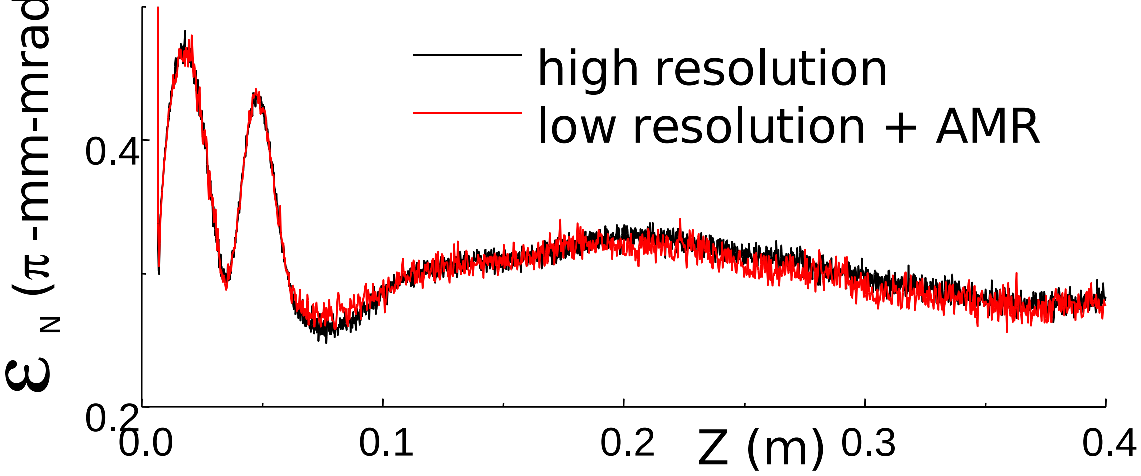
“One pass” field solution

- Find solution on coarse grid first
- Use that as boundary condition on fine mesh
- Gauss' law satisfied since Poisson satisfied locally everywhere

WARP simulations of HCX triode illustrate the integration of PIC and AMR

Application to HCX triode in axisymmetric (r,z) geometry

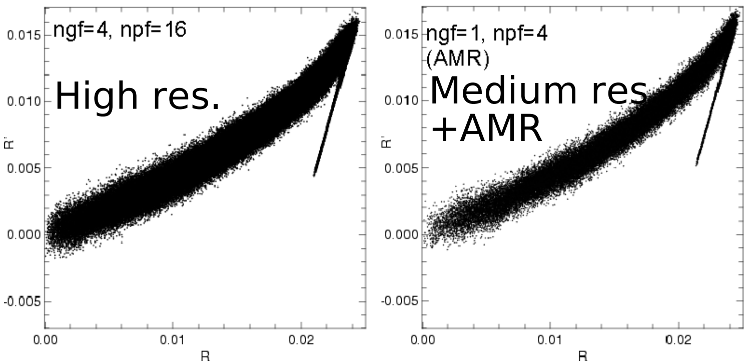




This example:

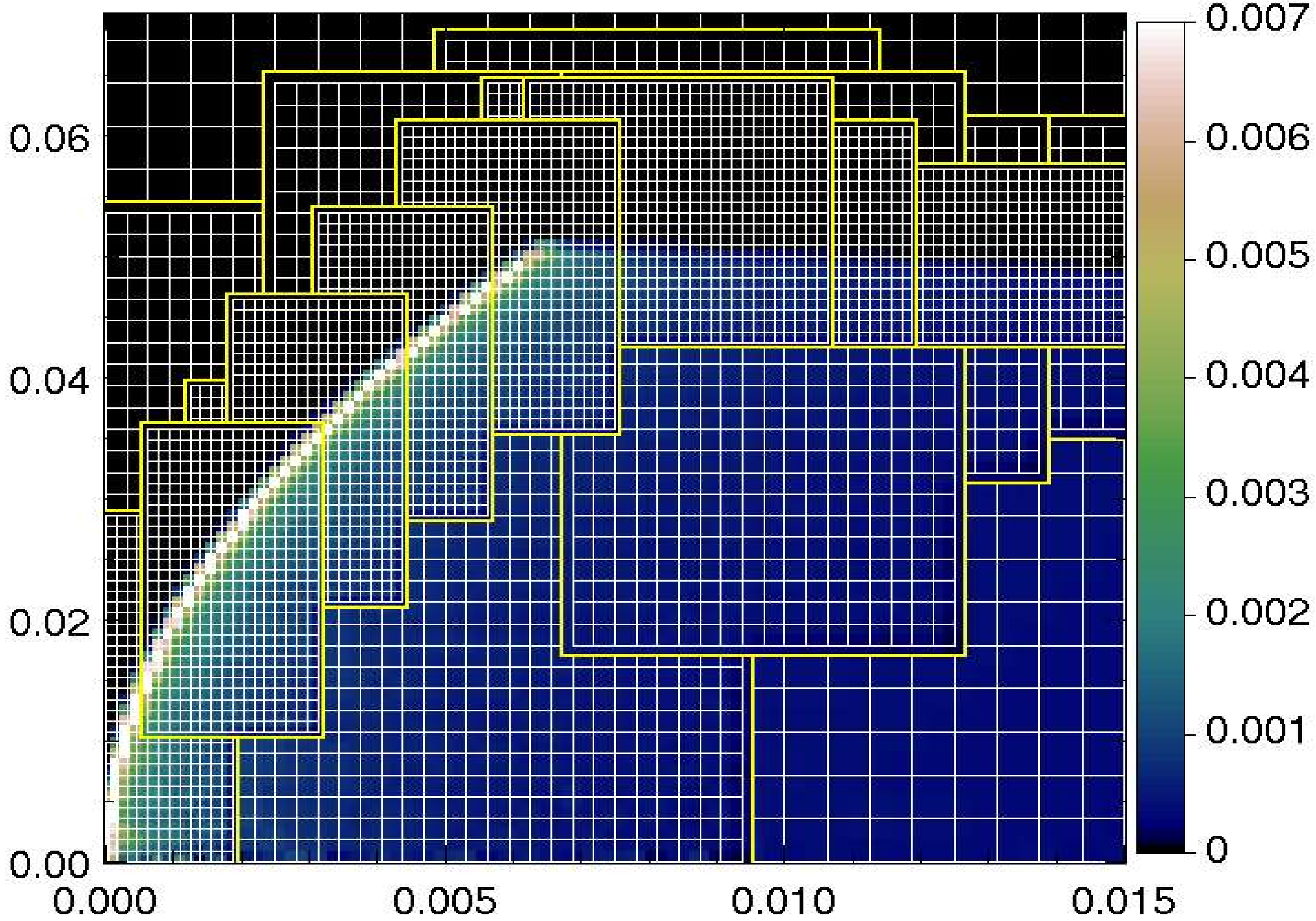
~ 4x savings in computational cost

(in other cases, far greater savings)



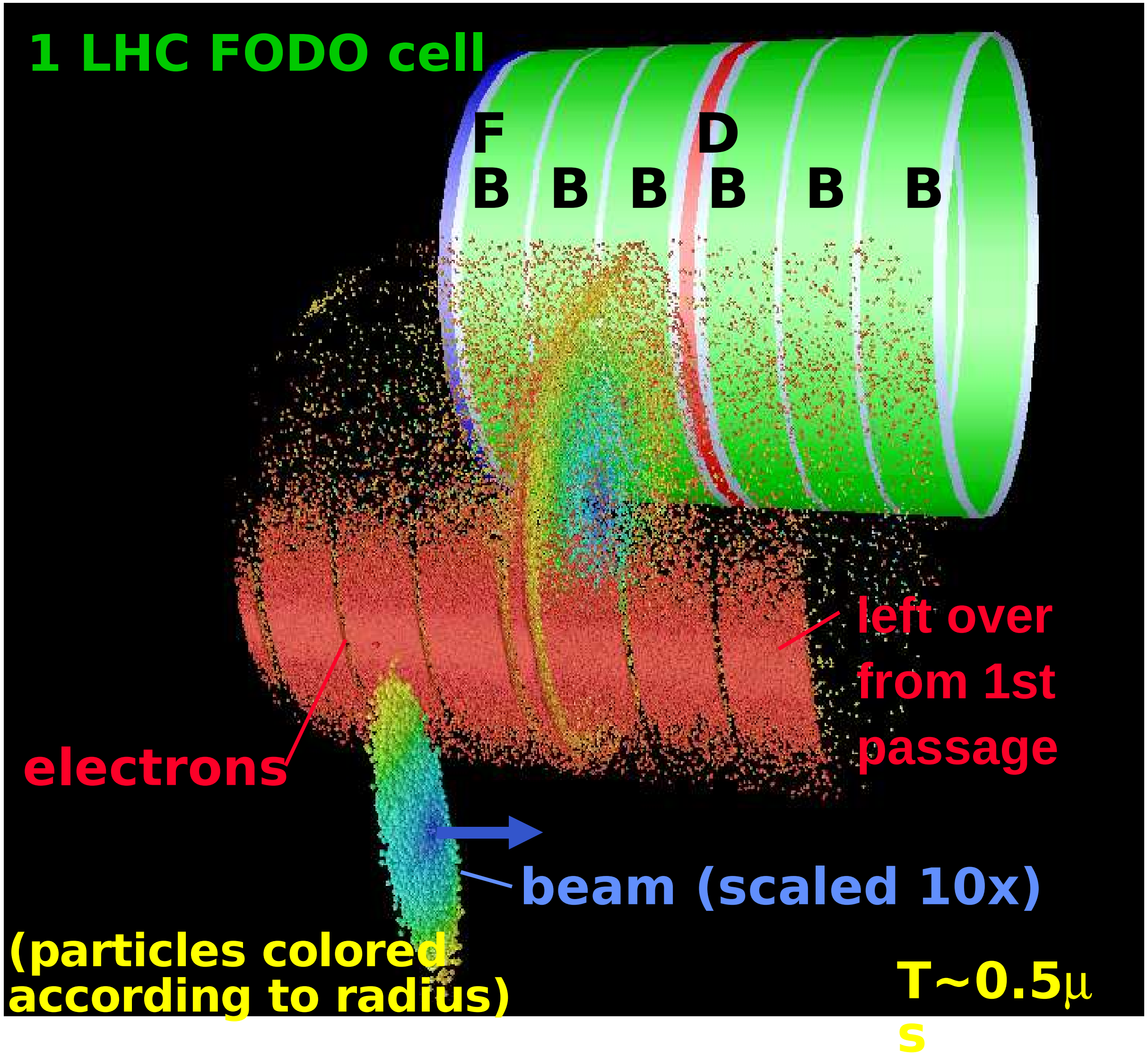
(Simulations by J-L. Vay)

Adaptive Mesh Refinement requires automatic generation of nested meshes with “guard” regions

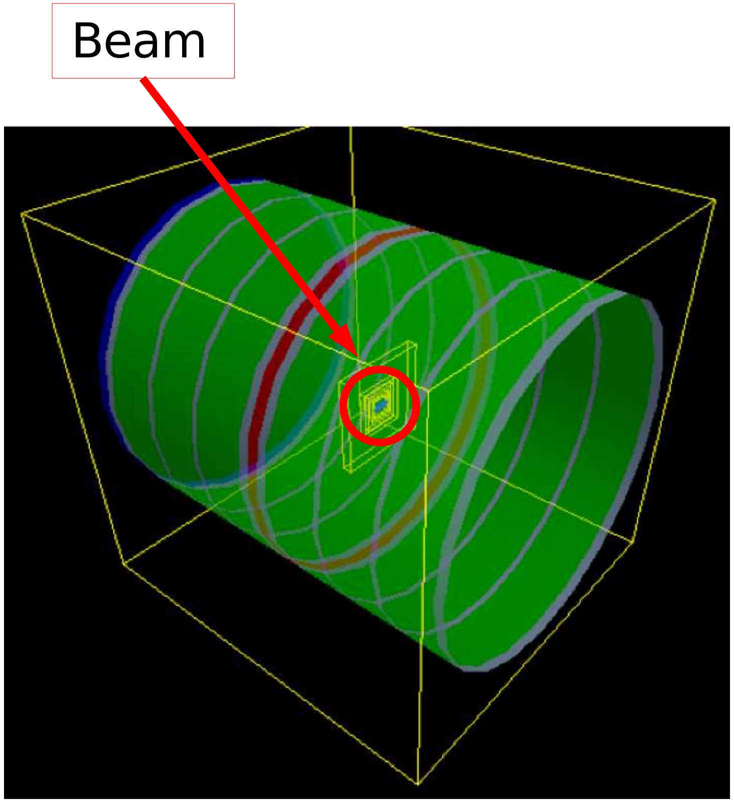


Simulation of diode using merged Adaptive Mesh Refinement & PIC

LHC: Warp simulations of electron cloud take great advantage from AMR

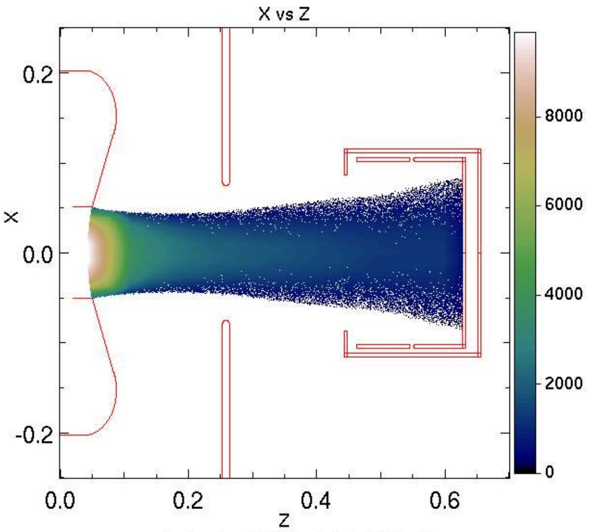


AMR provides a speed up of 20,000 times!

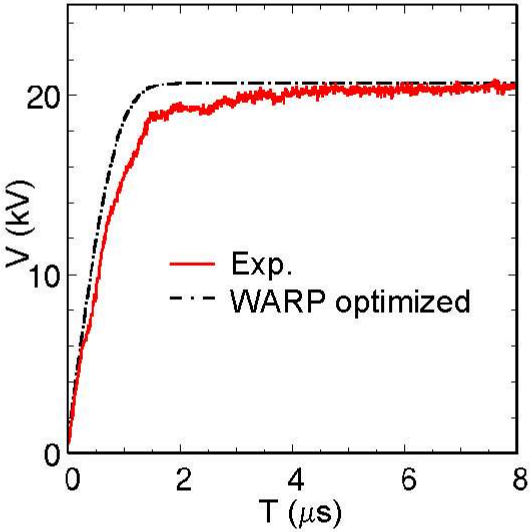


Mesh refinement of source critical for time dependence

STS500 (Source Test Stand) Experiment

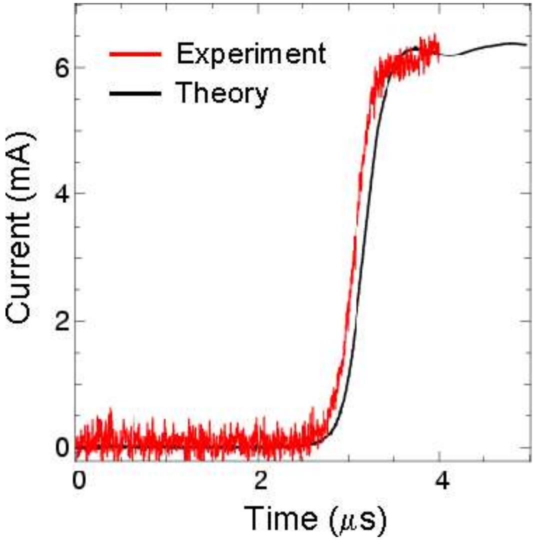


Experimental voltage lowered so that risetime = particle transit time

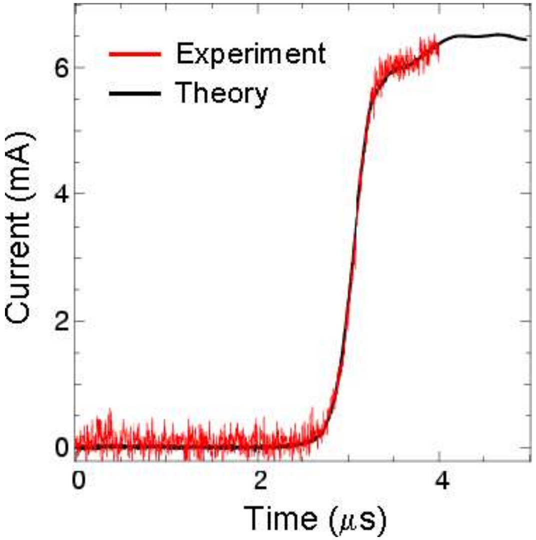


No MR

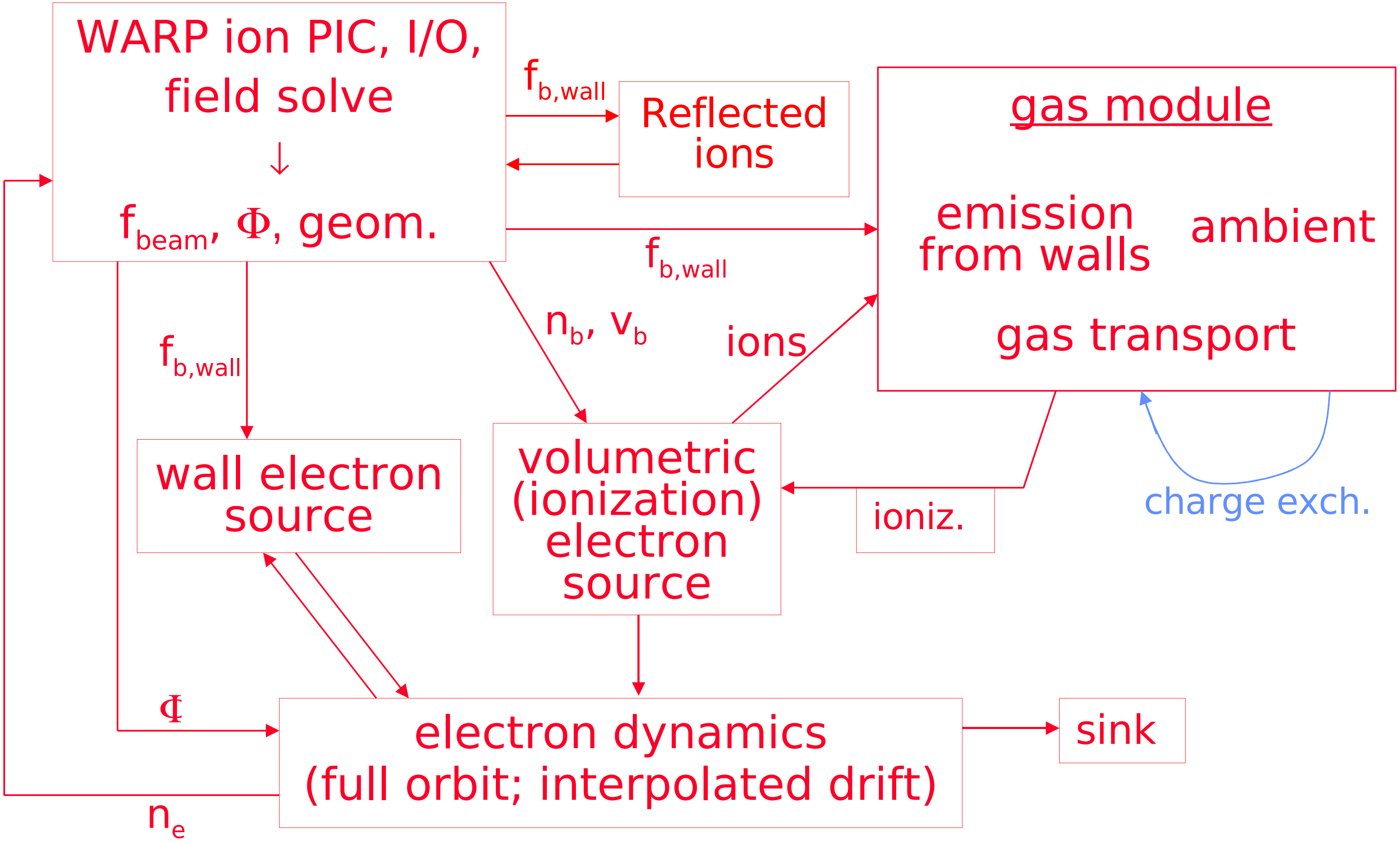
Current history (Z=0.62m)



Ratio of smaller mesh to main grid mesh ~ 1/1000



Road map for electron cloud simulations nearly complete



WARP ion PIC, I/O, field solve

↓

f_{beam}, Φ, geom.

$f_{b,wall}$

Reflected ions

gas module

emission from walls

ambient

gas transport

$f_{b,wall}$

n_b, v_b

ions

$f_{b,wall}$

wall electron source

volumetric (ionization) electron source

ioniz.

charge exch.

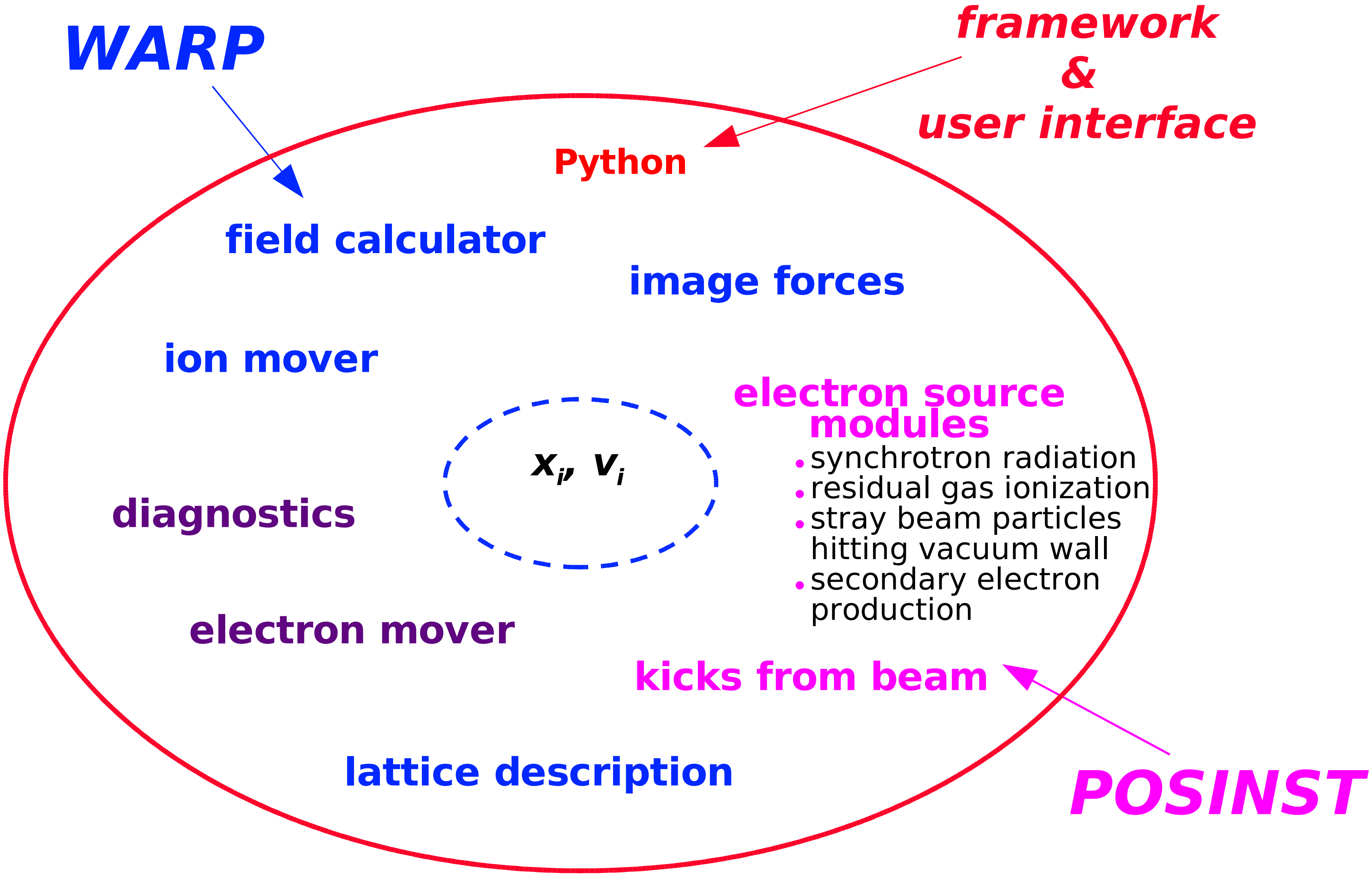
Φ

electron dynamics (full orbit; interpolated drift)

sink

n_e

We have merged WARP and POSINST



WARP

framework & user interface

Python

field calculator

image forces

ion mover

electron source modules

- synchrotron radiation
- residual gas ionization
- stray beam particles hitting vacuum wall
- secondary electron production

x_i, v_i

diagnostics

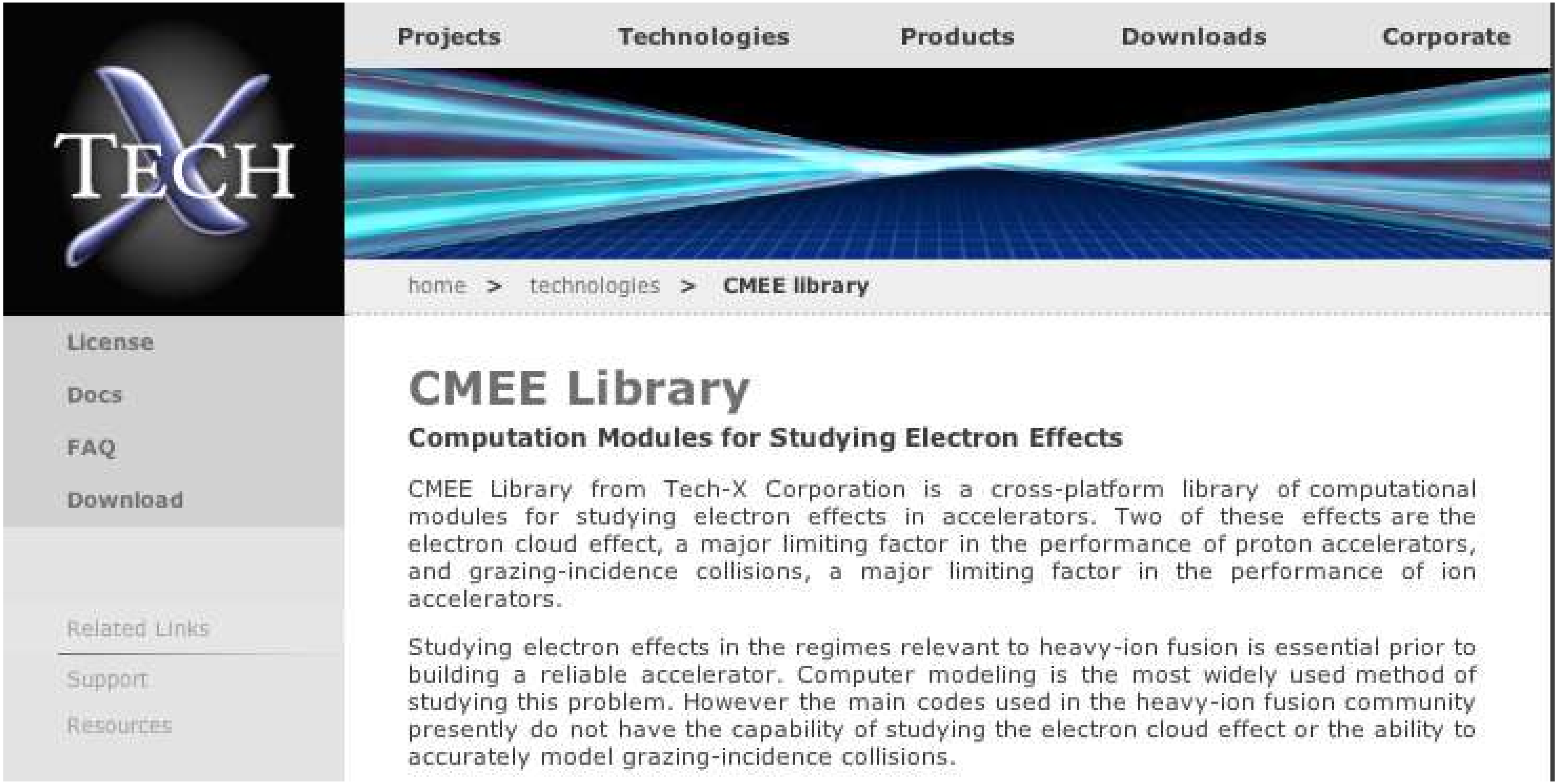
electron mover

kicks from beam

lattice description

POSINST

POSINST SEY routines repackaged in CMEE library



CMEE Library

Computation Modules for Studying Electron Effects

CMEE Library from Tech-X Corporation is a cross-platform library of computational modules for studying electron effects in accelerators. Two of these effects are the electron cloud effect, a major limiting factor in the performance of proton accelerators, and grazing-incidence collisions, a major limiting factor in the performance of ion accelerators.

Studying electron effects in the regimes relevant to heavy-ion fusion is essential prior to building a reliable accelerator. Computer modeling is the most widely used method of studying this problem. However the main codes used in the heavy-ion fusion community presently do not have the capability of studying the electron cloud effect or the ability to accurately model grazing-incidence collisions.

CMEE library distributed by Tech-X corporation
(http://www.txcorp.com/technologies/CMEE/index.php)

Models for neutrals and ionization also developed

- **Gas module**
  - **Emit neutrals (as particles) from beam ion impact according to incident particle energy and angle of incidence**
  - **Neutrals free stream until collision with boundary**
  - **Density of neutrals provides a background for ionization**

- **Ionization module**
  - **Create ions and electrons resulting from impact ionization of gas molecules**
  - **New particles included in the simulation**
  - **Background unaffected (assuming large reservoir)**

Short electron time scales – circumvented by new particle mover

- **Often, electron gyro timescale << other timescales of interest**
  - **Want to skip the gyro timescale →** $\omega_c\Delta t > 1$
  - **But then Boris algorithm gives gyro radius** $r_c \sim r_{c0}\omega_c\Delta t$
  - **Problem if** $r_c \sim$ **gradient scale lengths**
- **New mover interpolates between full particle and drift kinetics**

Speedup of factor of 25 without loss in accuracy!

Interpolate to give correct gyro radius and drift kinetics in weak and strong B fields

- **The velocity update includes the full particle and some of the drift kinetic**

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

- **An effective velocity is used to advance the particle position**

$$\mathbf{v}_{\mathrm{eff}} = \mathbf{b}(\mathbf{b}\cdot\mathbf{v}^{\mathrm{new}}) + \alpha \mathbf{v}_{\perp}^{\mathrm{new}} + (1-\alpha) \mathbf{v}_{\mathrm{d}}$$

- **Choose so** $\alpha \mathbf{v}_{\perp} \Delta t$ **gives correct gyro radius**

$$\alpha = \left[1 + \left(\frac{\omega_{\mathrm{c}} \Delta t}{2} \right)^2 \right]^{-\frac{1}{2}}$$

- **Polarization drift in development**

Example – two stream instability

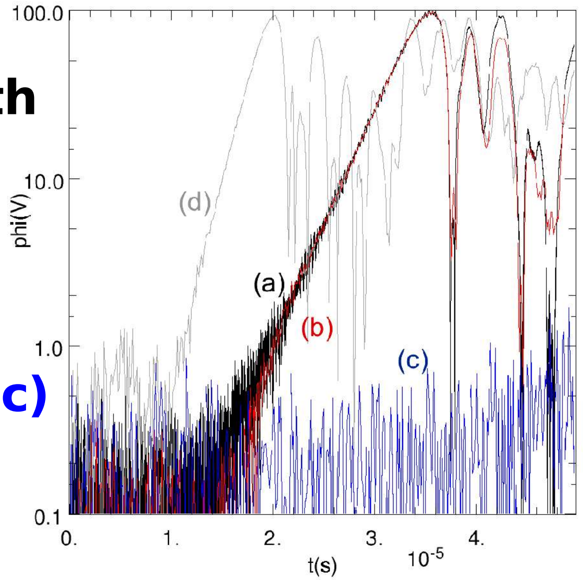
Counter-streaming ion beams in solenoid field radius ~ 10 $r_{cyclotron}$

Growth of potential with

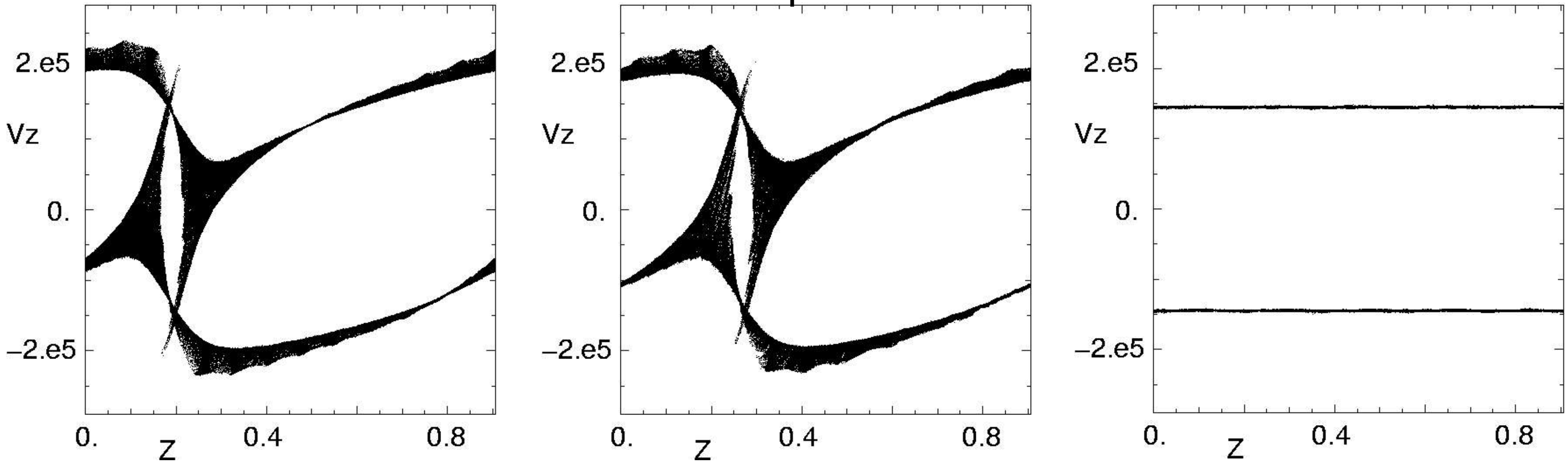
- **small Δt (a)**
- **large Δt-interp (b)**

are identical

- **Large Δt-Boris fails (c)**



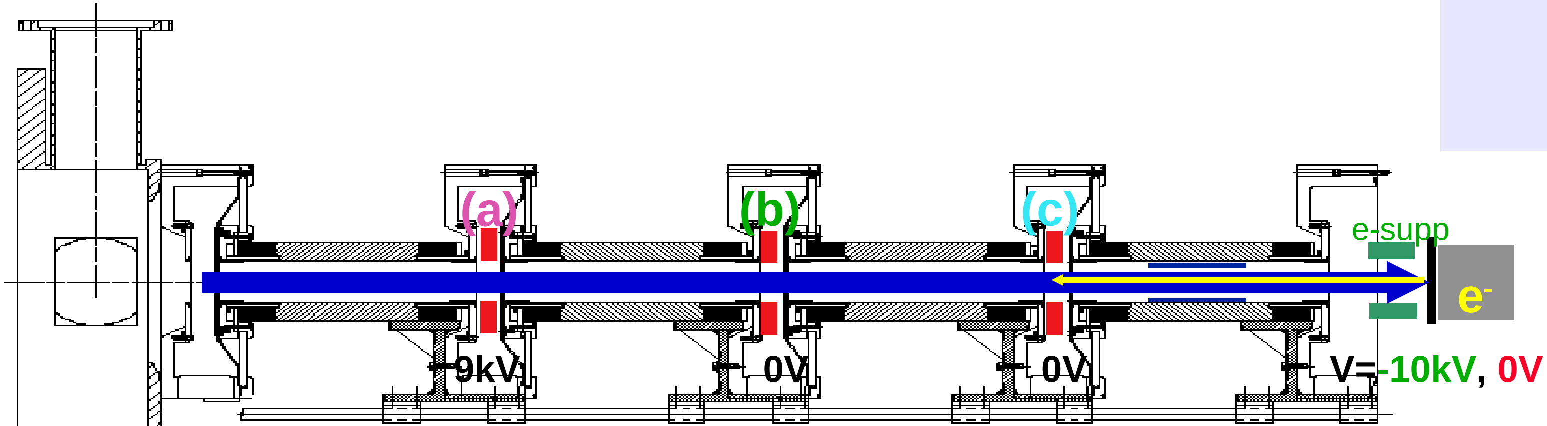
25 times faster

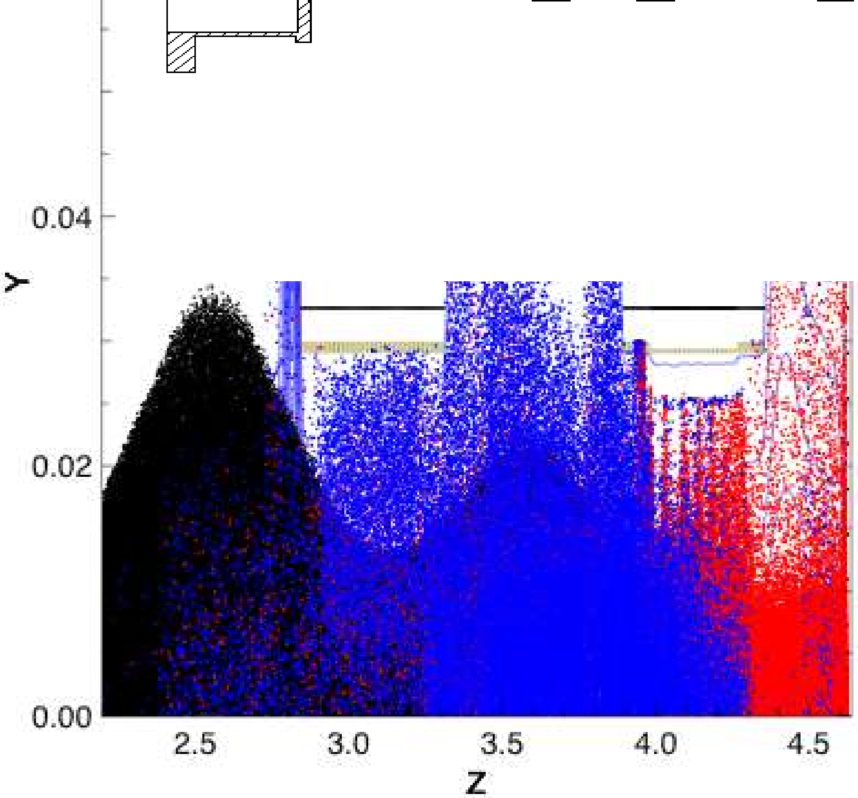


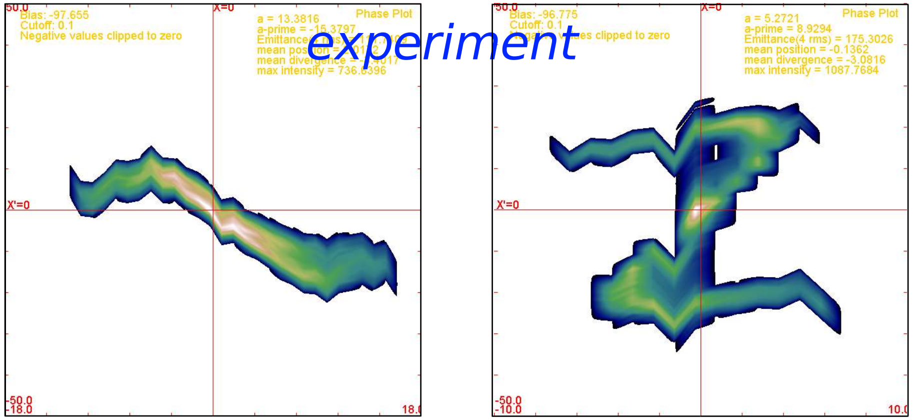
Small Δt

Large Δt Interpolated

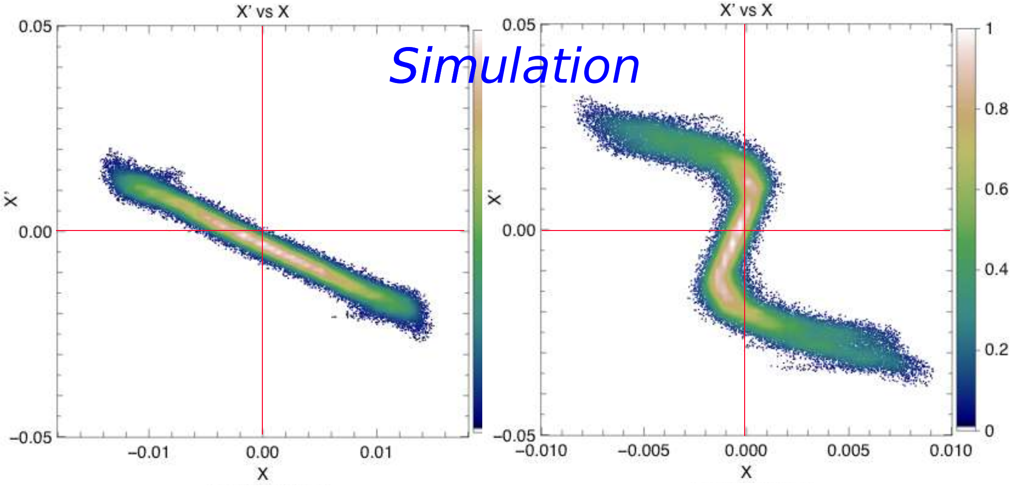
Large Δt Boris







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



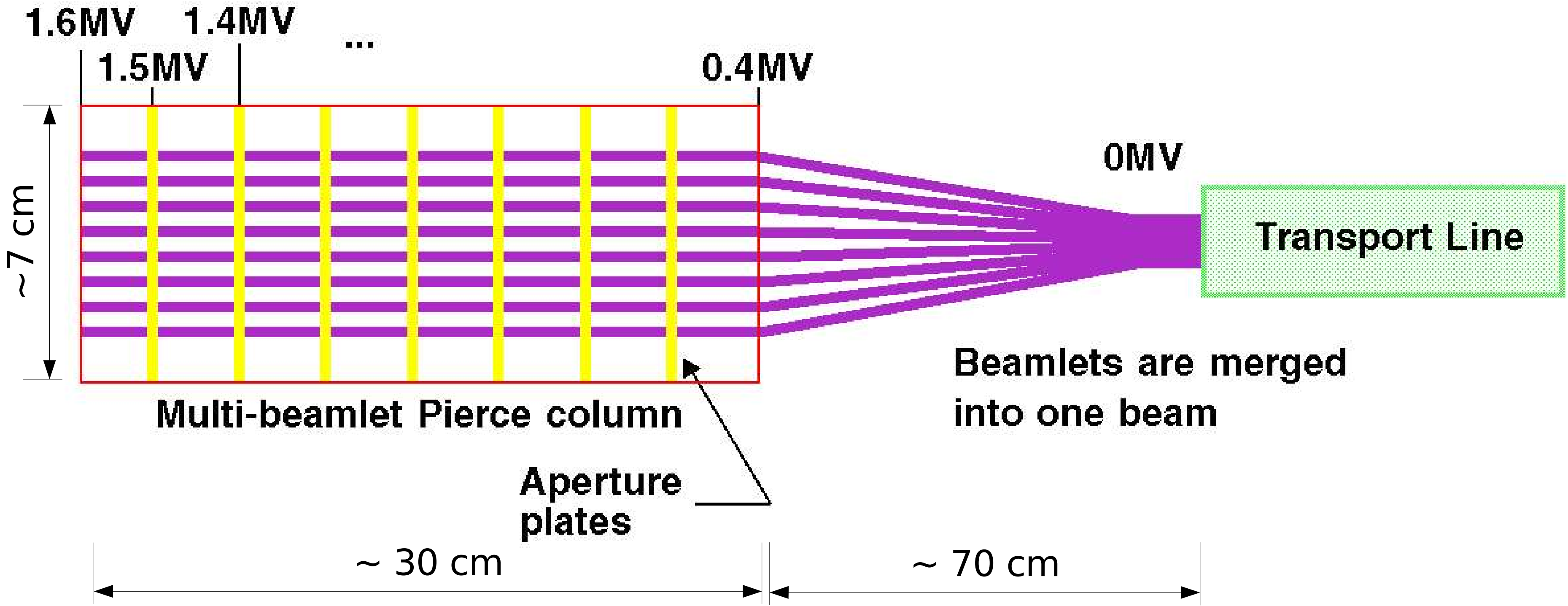
- beam ions
- electrons from ions hitting surface
- secondary electrons

Other recent applications of Warp

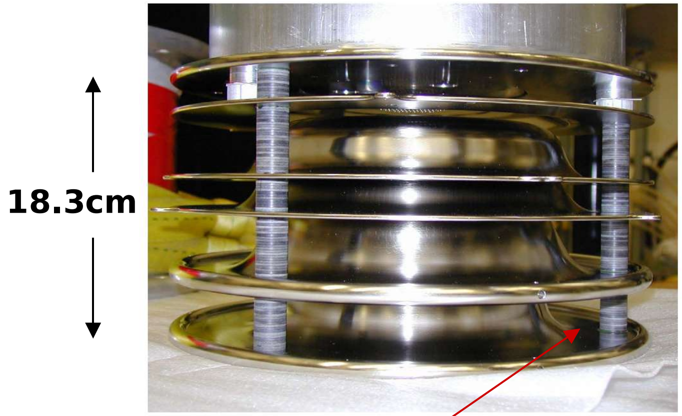
- **Merging beamlet injector – STS500 merging experiment**
- **PLIA – for NDCX1c and d**
- **DARHT – Ion hose instability**
- **ECR Ion source – VENUS**
- **Positron trap – prototype for Anti-hydrogen trap**

Merging beamlet injector

- **Many small beamlets are accelerated independently and then merged**
  - **Circumvents poor scaling of single source – Area $\propto I^{8/3}$**
  - **Allows a compact source**
  - **Removes need for matching (beamlets can be arranged to match exactly into the transport lattice)**

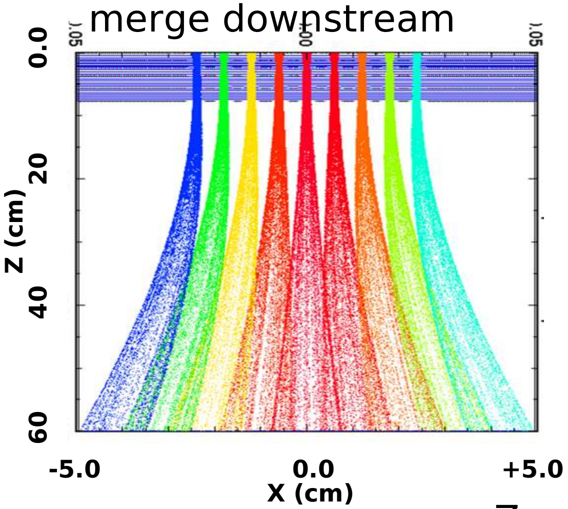


Merging beamlet high gradient experiment

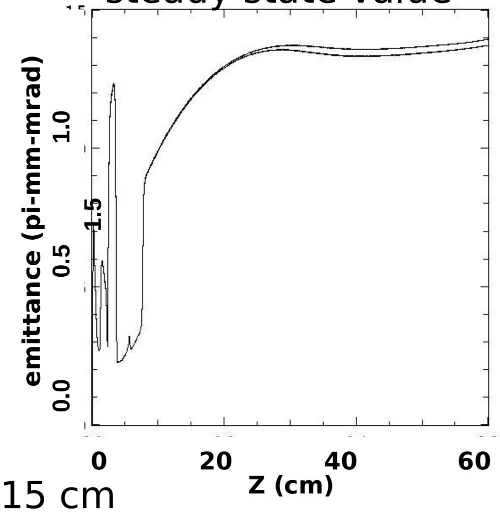


High Gradient Insulators held 30 kV/cm

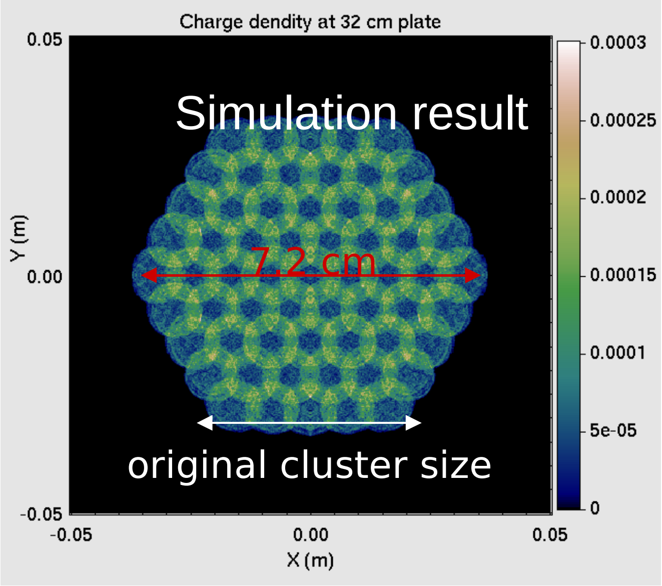
Warp 3D simulation of beamlets expand and merge downstream

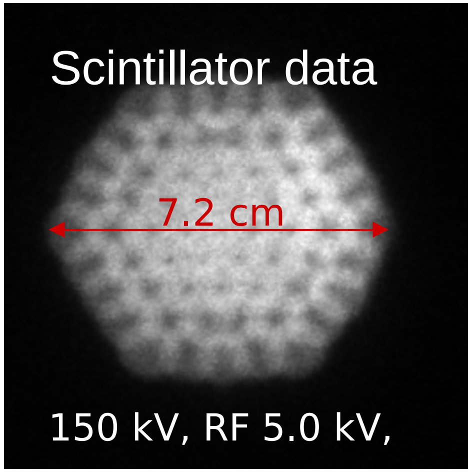


Normalized emittance (x and y) reaches steady state value



Z = 15 cm





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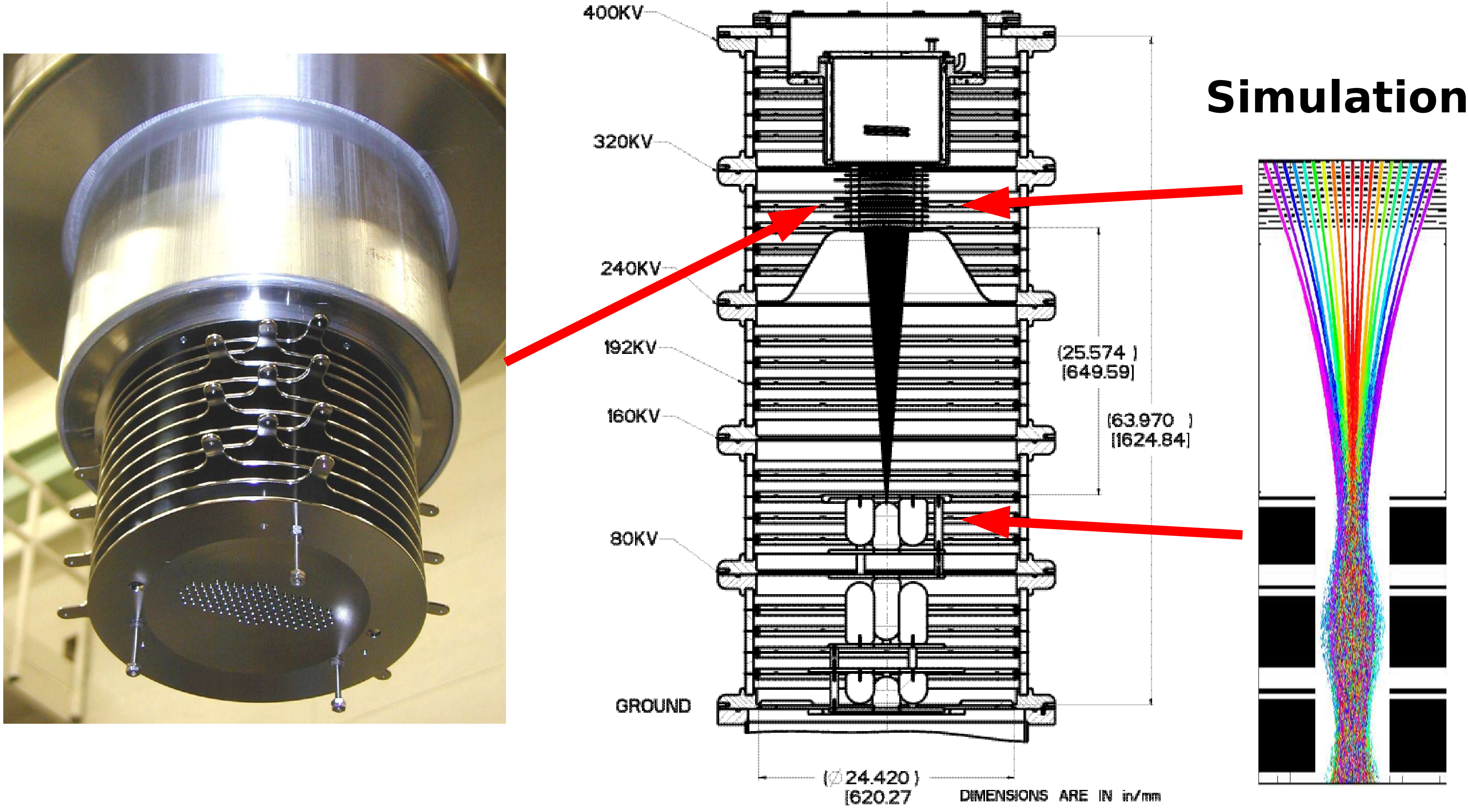
STS500 Beamlet merging experiment

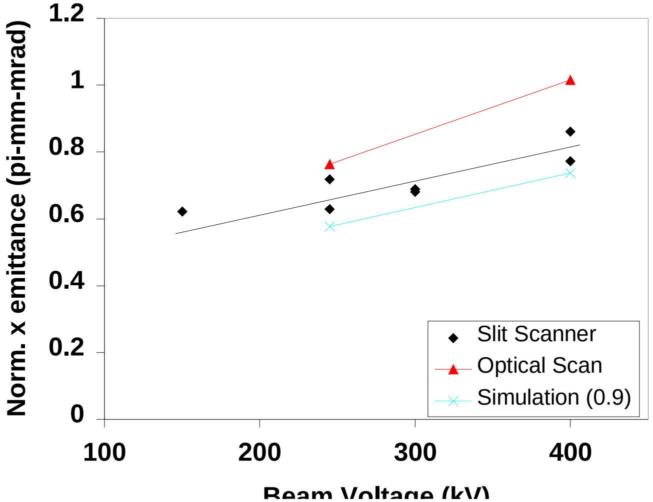
Reduced voltage by 1/4, current by 1/8, but full physical size

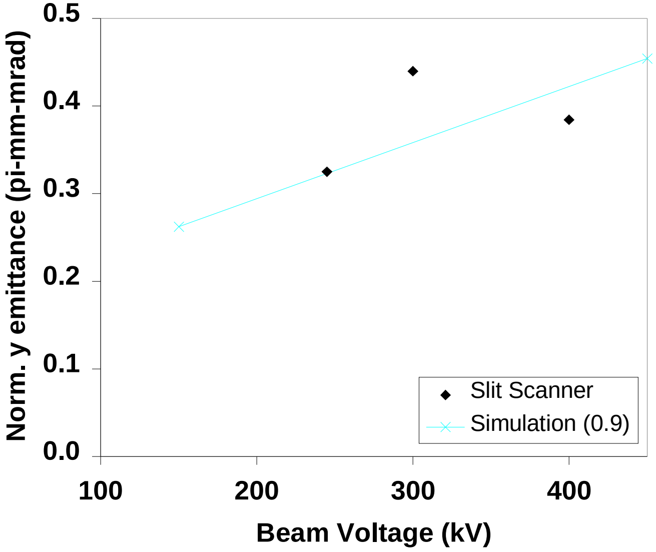


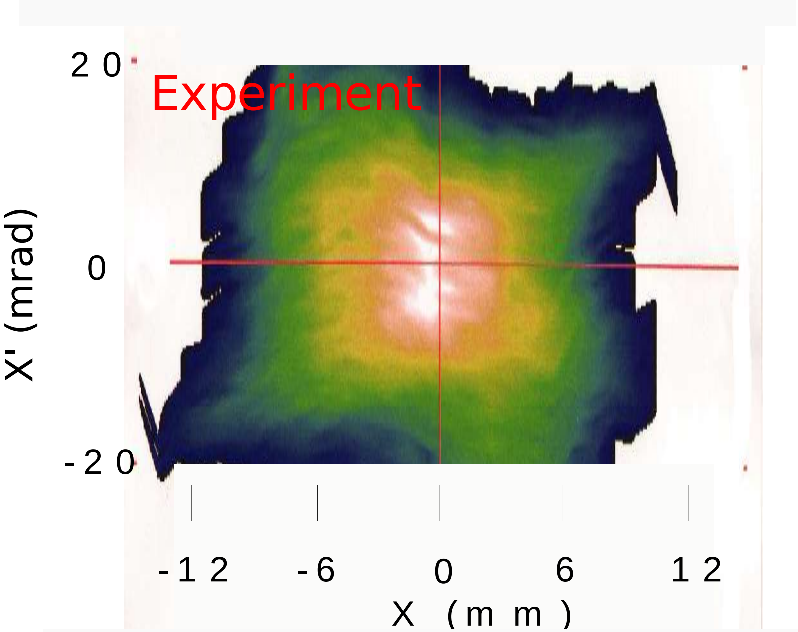
Simulation

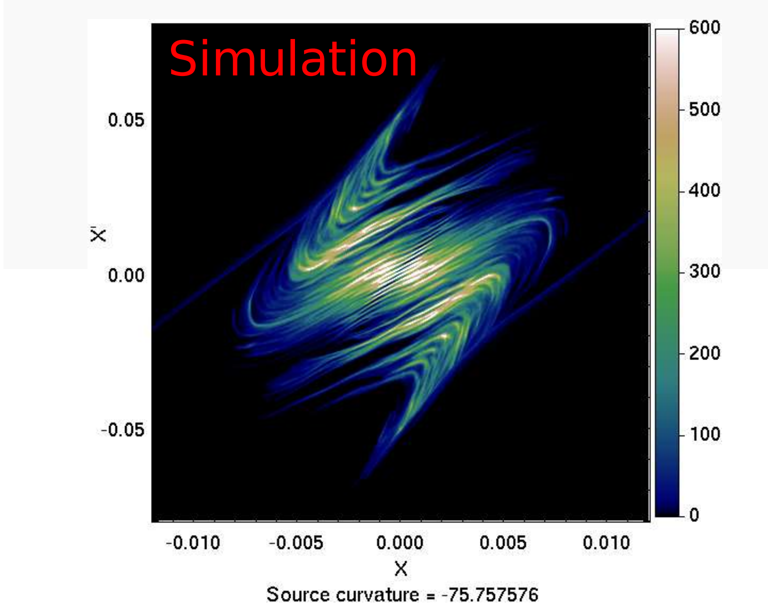
Good agreement found in results – concept validated

Experiment gives the expected emittance



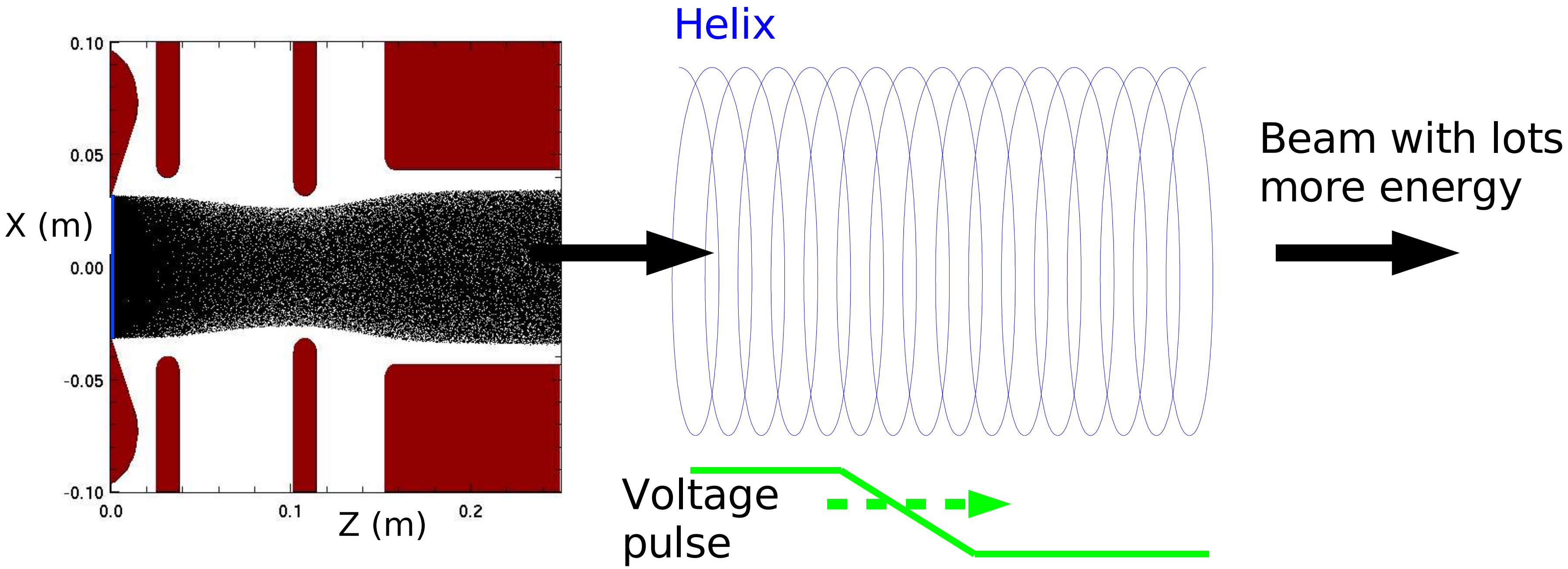






PLIA simulations with WARP

- **Study designs for NDCX-1c and NDXC-1d**
- **Full system simulated, starting from source**
- **Detailed models for the helix**



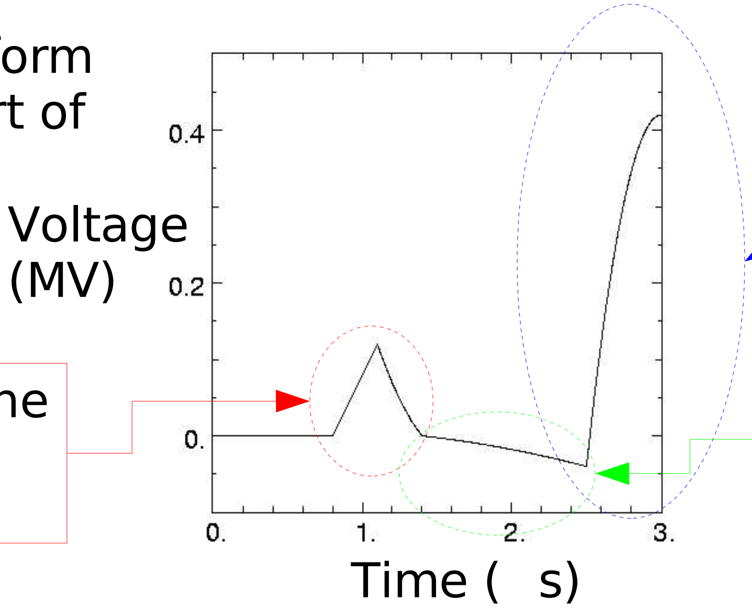
Helix model

- **Several variations:**
  - **Simplest – specify V(t) at start, and advect at $v_{circuit}$**
    - No dispersion, no short wavelength filtering
  - **Better – specify V(t) at start, advance V, I with circuit equations. V(z) is boundary condition for Poisson.**
    - Only approximate capacitive and inductive coupling
    - Can include beam loading
  - **Even better – specify K on secondary, solve reduced set of Maxwell equation plus continuity**
    - Full calculation of capacitive and inductive coupling
    - Includes beam loading

“Snow plow” mode gives both acceleration and compression

- **Whole beam is loaded into helix before helix pulse launched**
- **Wave speed is much higher than beam speed – pulse sweeps from beam tail to head**
- **Tail is accelerated first, catching up to the head, leading to compression**
- **Additional “knobs” to control beam ends and to adjust compression factor**

Voltage waveform applied to start of helix



Main snowplow:
Shaped so that tail of pulse arrives at end of helix as beam end arrives there. This gives the beam an overall tilt.

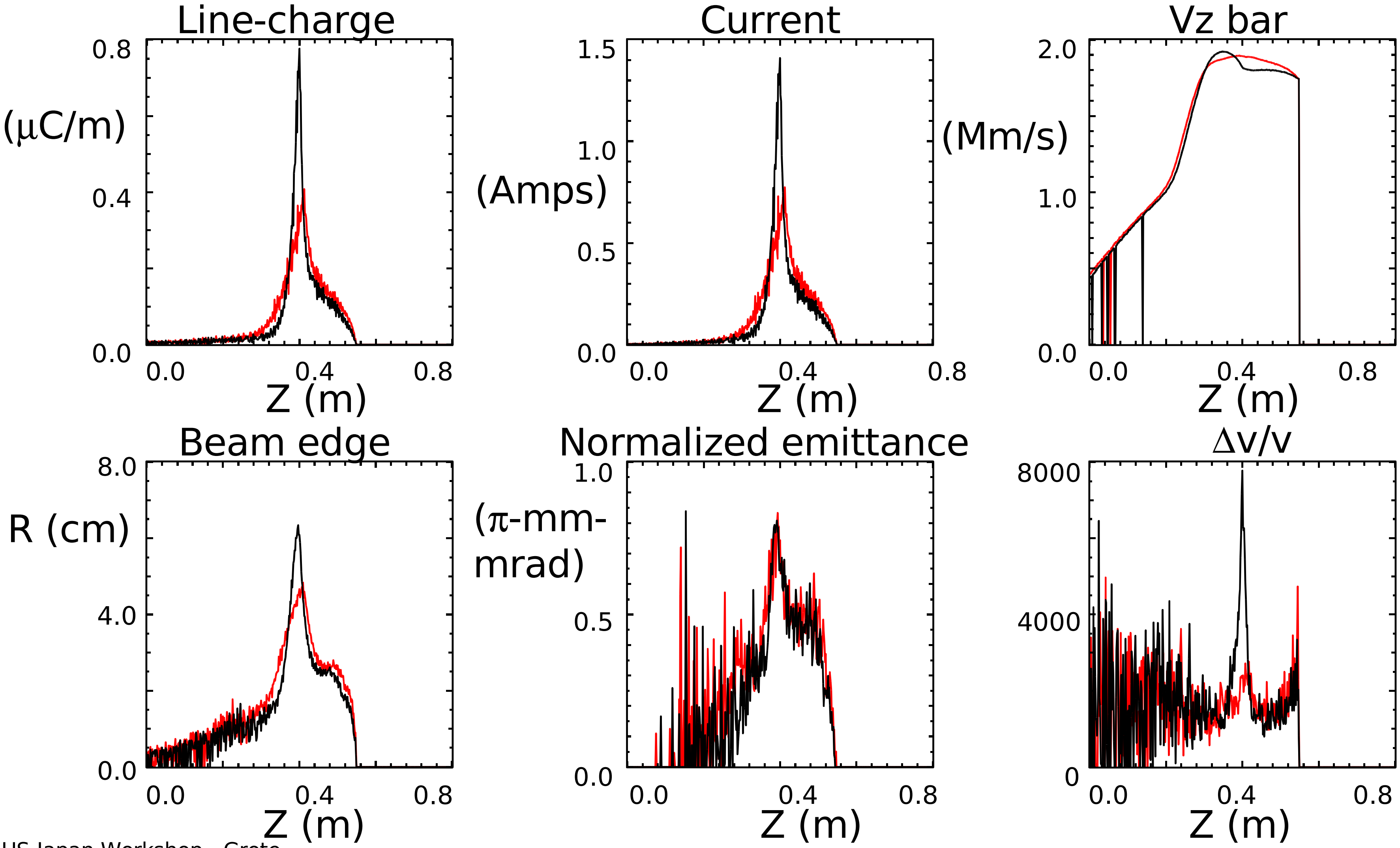
Negative pulse accelerates tail more than head giving a tilt

Deccelerate the beam head

Snowplow simulation from NDCX-1c

Black is with circuit model, red is simplified model

Largest difference in beam size – no surprise since better model introduces radial fields



New models for high energy electron beams - DARHT

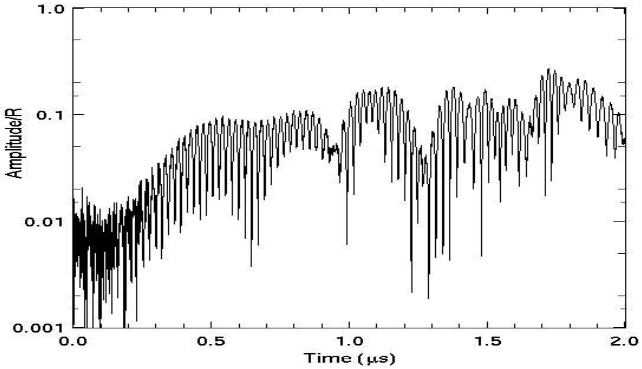
- **New field solver**
  - **Solves only transverse Poisson, at many independent z locations**
  - **Include self-magnetic fields – paraxial approximation**

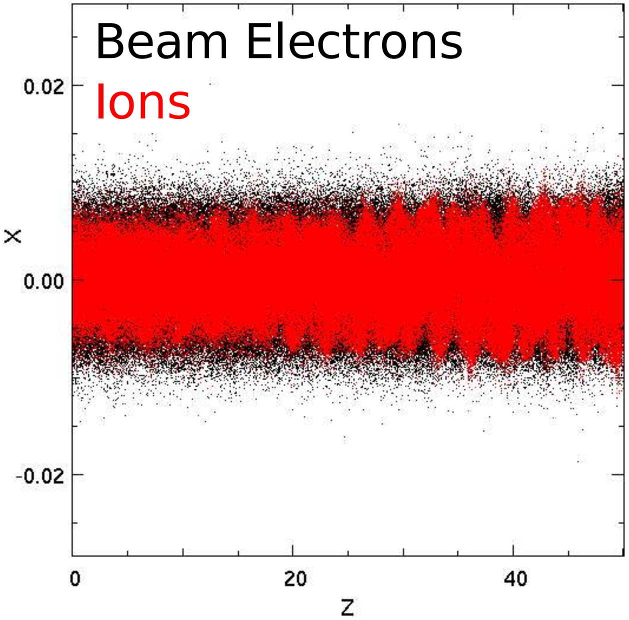
    $$\nabla^2 A_z = -\mu_0 J = -\mu_0 \rho v_z$$
    $$\Rightarrow A_z = v_z \phi$$

  - **Apply either E and B directly, or only E/γ^2**
- **Full transport length simulated**
  - **Beam electrons injected at left, exit at right, 50 meters**
  - **Background ions and electrons created randomly based on fractional neutralization**
  - **All three species are propagated**

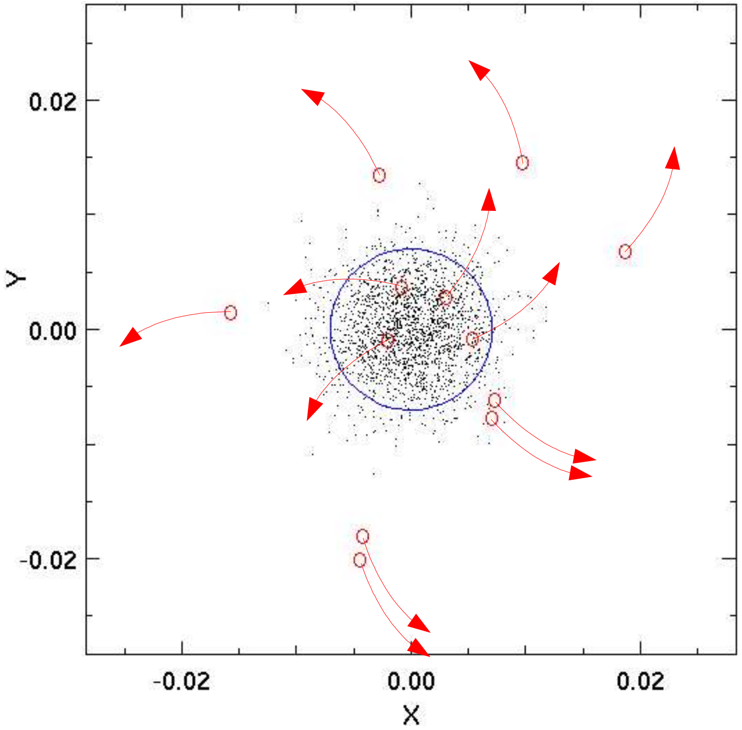
DARHT – WARP applied to ion hose instability

Reproduced ion hose growth rates





Simulations show that background electrons escape too fast to have an effect



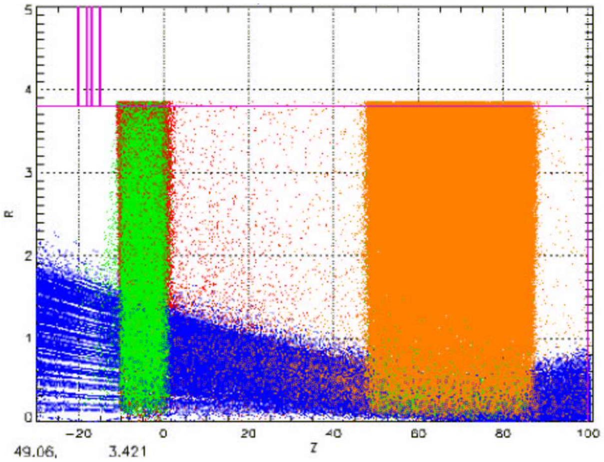
Other WARP applications

- ECR ion source – VENUS (at LBNL)
  - Used to analyze multiple ion/multiple charge state beam emerging from the source
  - Some agreement found between experiment and simulation
- Positron trap – prototype for Anti-hydrogen trap
  - Study of stability of positron plasma in Penning trap with additional high order multipole B fields
  - Multipoles will confine Anti-H via the dipole moment
  - Simulations show that with quadrupole B, most positrons lost
  - But with octopole, most are confined

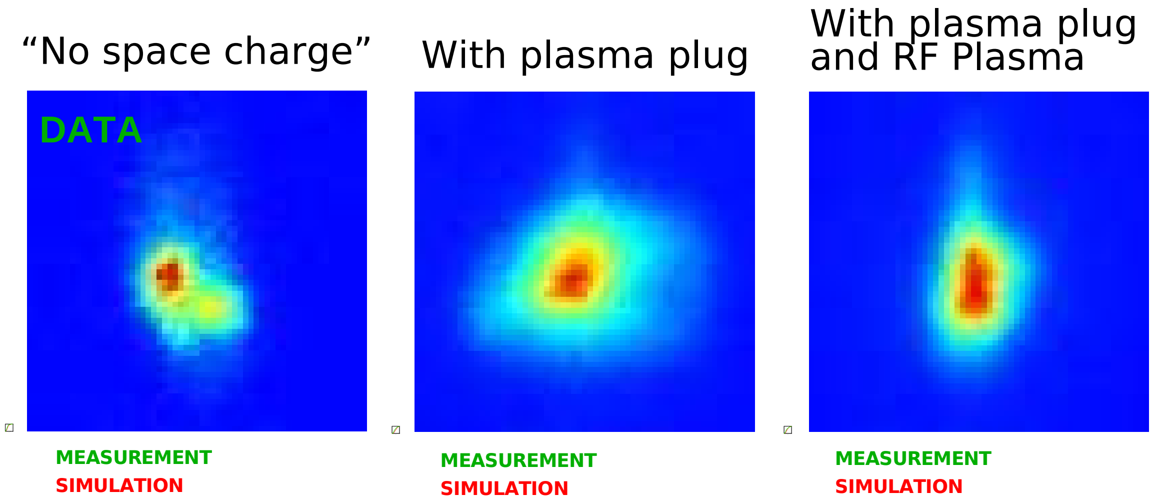
Other WARP developments

- **Plasma source modeling**
  - **Includes Boltzmann electron distribution** $\nabla^2\phi = -\rho_{\mathrm{ion}} + \rho_0 \mathrm{e}^{-\phi/\mathrm{T_e}}$
  - **3-D, RZ, and XY**
- **Magnetostatic solver**
  - **Solves either $\nabla^2 A = -\mu_0 J$ or $\nabla^2 B = \mu_0 \nabla\times J$**
  - **3-D and RZ**
- **Particle loading into equilibrium distributions**
  - **Thermal equilibrium, Waterbag, Parabolic – equilibrium with no space charge**
  - **Thermal equilibrium, Waterbag, KV – equilibrium with space charge**
  - **Result of US-Japan collaboration (Drs. Lund and Kikuchi)**

LSP simulations of NTX
Agreement with data at focal plane for different neutralization methods (within error bars)

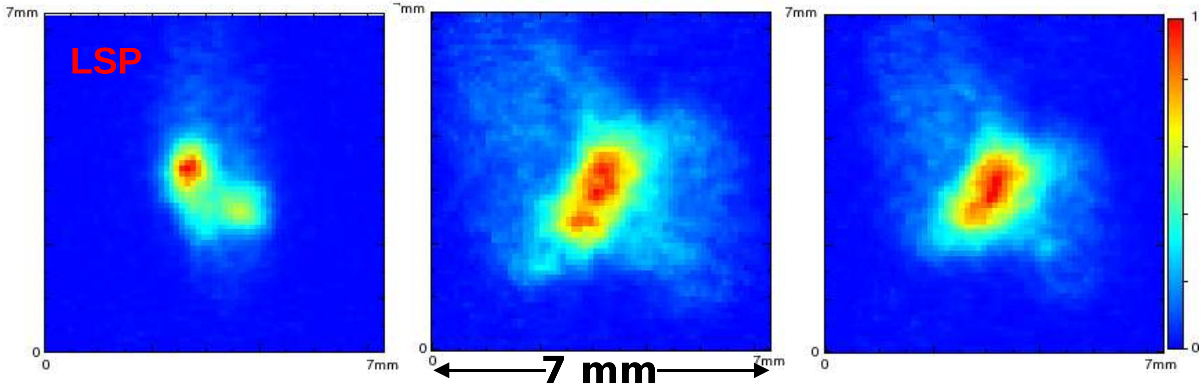


- **EM, 3D cylindrical geom., 8 azimuthal spokes**
- **3 eV plug 3x10⁹ cm⁻³, volume plasma 10¹⁰ cm⁻³**
- **6 mA, 10 mm initial radius**



0.8 **1.0 mm** **1.3** **1.7 mm** **1.1** **1.4 mm**

(radius containing half the current)



Carsten Thoma, et al.

Linear
color scale

Future plans

- **Short term**
  - **Take advantage of the new capabilities to further advance the current applications**
  - **Clean up, optimize, and parallelize WARP capabilities**
- **Long term**
  - **Plans to move WARP toward toward more general plasma code**
    - Possibly Darwin, and/or Electromagnetic models
    - Possibly hybrid fluid description
    - More aggressive with multiscale techniques

Summary

- Many new capabilities being developed in US
  - AMR
  - e-cloud tools - SEY, gas desorption, ionization
  - Advanced electron mover
  - ...
- And being applied to a broad range of applications
  - Merging beamlet injector
  - HCX with electrons
  - NTX with neutralized focusing
  - LHC with electrons
  - ECR source
  - DARHT
  - Penning trap/Anti-H experiments
  - ...