3-D self-consistent simulations of e-cloud physics using WARP/POSINST Validation on the HCX experiment and application to LHC

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Lawrence Berkeley National Laboratory
and the
Heavy Ion Fusion Virtual National Laboratory

LARP Collaboration Meeting 4

Port Jefferson, NY, April 6-8, 2005

OUTLINE

- Who we are and why we care about e-cloud
- Our tools
  - WARP-POSINST code suite
  - High Current Experiment (HCX)
- Example of comparisons of WARP-POSINST with HCX
- Application to High Energy Physics: 1 LHC FODO cell
- Conclusion

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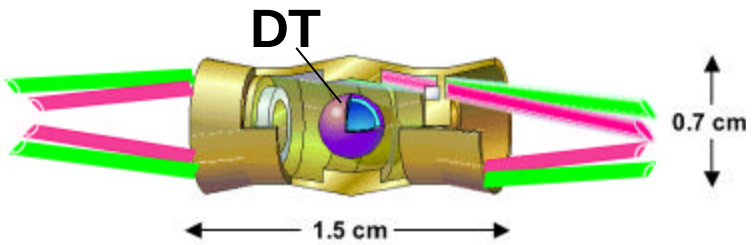
Heavy Ion Inertial Fusion or "HIF" goal is to develop an accelerator that can deliver beams to ignite an inertial fusion target



Target Requirements:

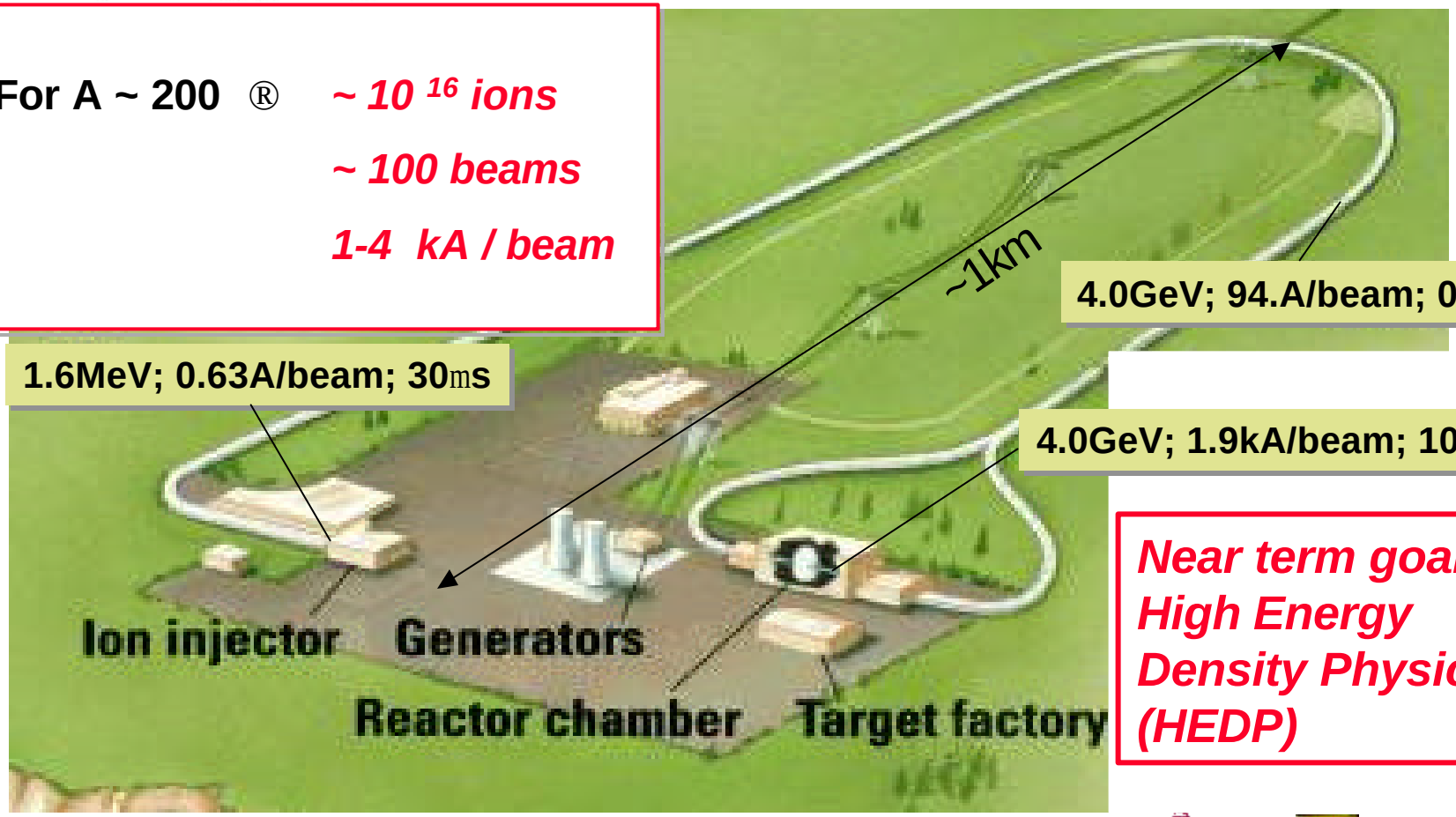
3 - 7 MJ x ~ 10 ns Þ *~ 500 Terawatts*

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

For A ~ 200 ® *~ 10 ^{16} ions*

~ 100 beams

1-4 kA / beam



Near term goal: High Energy Density Physics (HEDP)

HIF-VNL/e-cloud team (LDRD's at LLNL & LBNL)

The Heavy Ion Fusion Virtual National Laboratory:

LBNL
LLNL
Princeton Plasma Physics Laboratory

Working on e-cloud (in addition to R. Davidson and H. Qin):

Miguel Furman (LBNL)

LBNL is lead lab for LARP on e-cloud

Ron Cohen (LLNL)
Jean-Luc Vay (LBNL)
Alex Friedman (LLNL)
Dave Grote (LLNL)

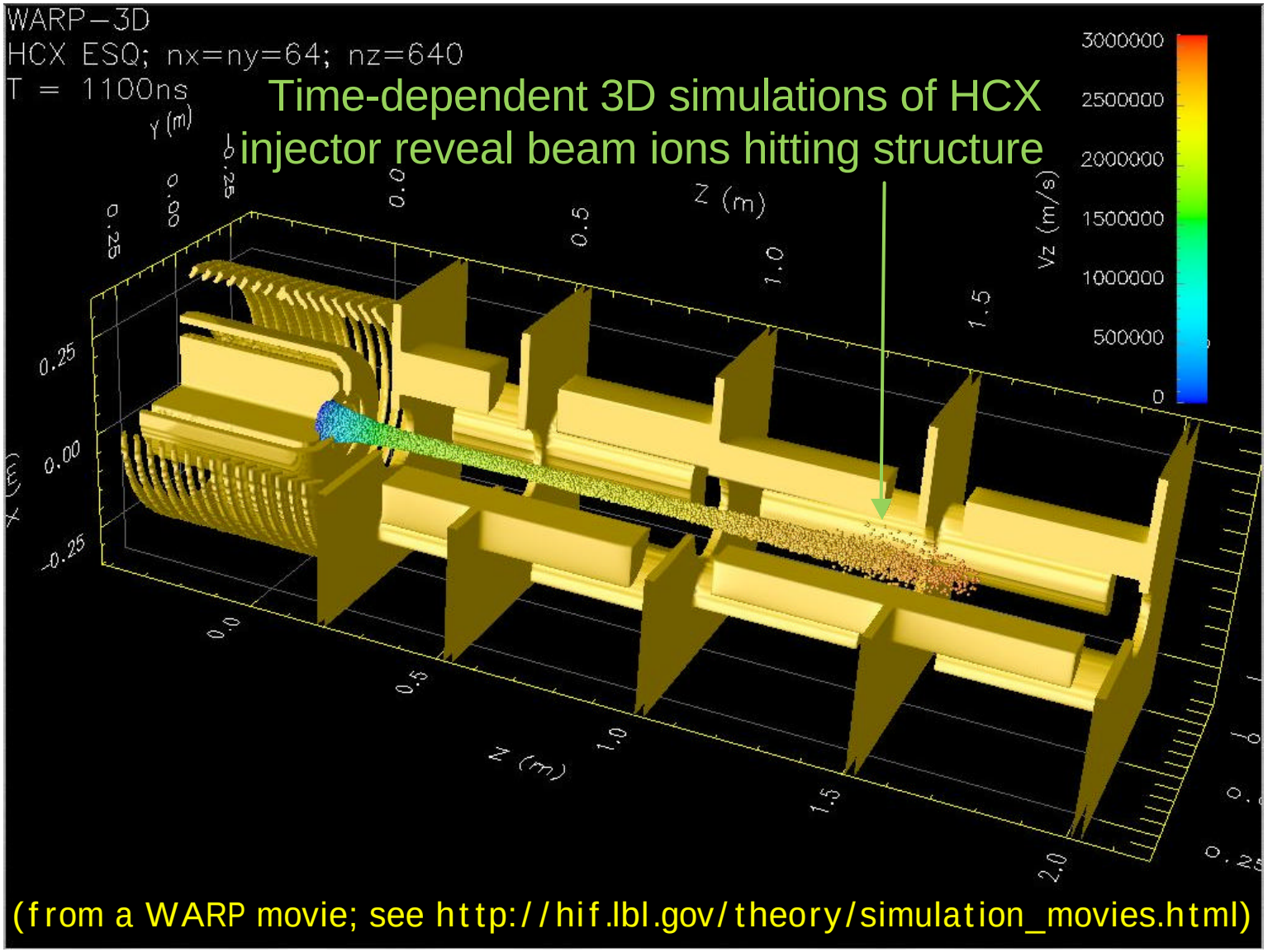
Simulation & theory (~ 1.25 FTE)

Art Molvik (LLNL)
Peter Seidl (LBNL)
Frank Bieniosek (LBNL)
Michel Kireef-Covo (GS, LLNL)

Experiment (~ 2 FTE)

Also: Peter Stoltz, through coordinated SBIR at Tech-X
Prof. John Verboncoeur, UCB NE

Why do we care about electrons?
We have a strong economic incentive to fill the pipe.



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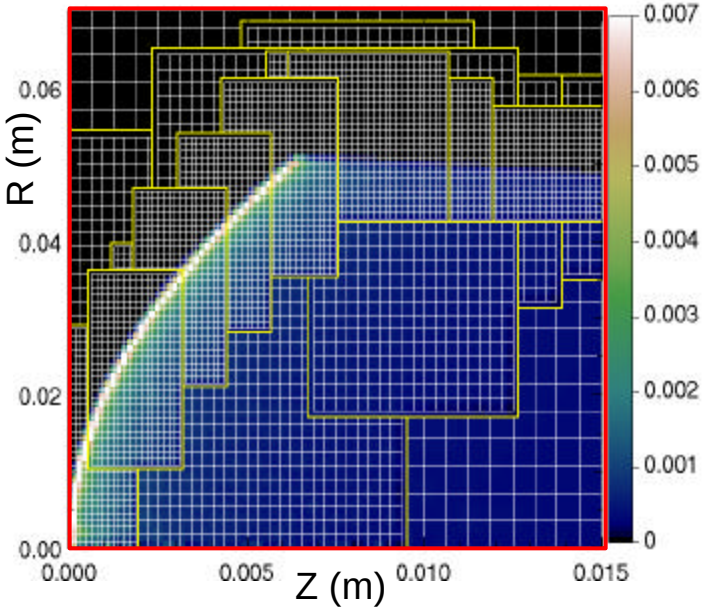
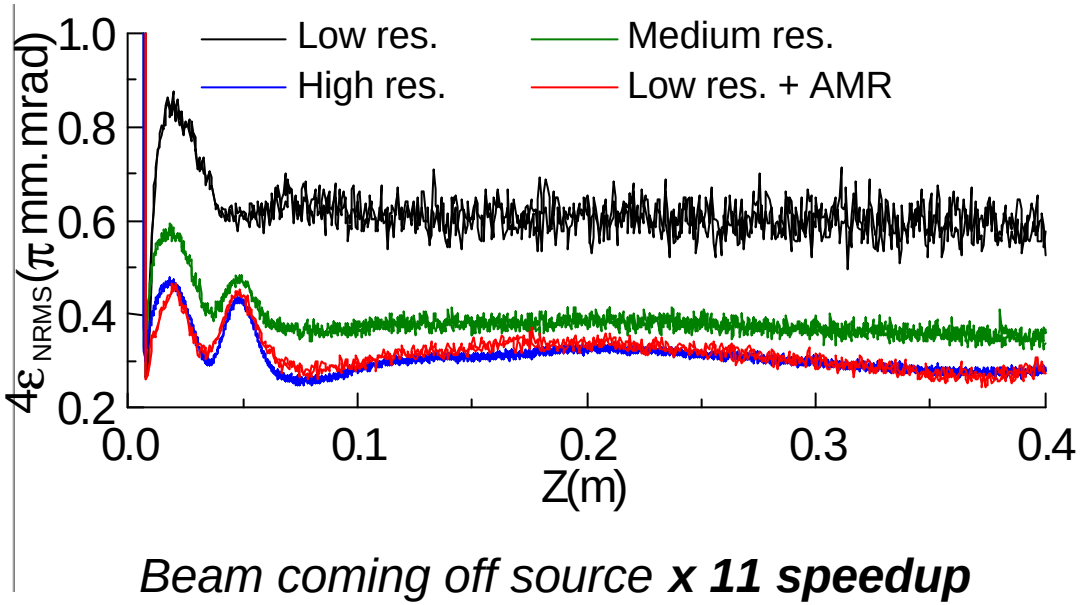
WARP has many well-tested features …

- **Geometry:** 3D, (x,y), or (r,z)
- **Field solvers:** FFT, capacity matrix, multigrid
- **Boundaries:** "cut-cell" --- no restriction to "Legos"
- **Bends:** "warped" coordinates; no "reference orbit"
- **Lattice description:** general; takes MAD input
  - solenoids, dipoles, quads, sextupoles, …
  - arbitrary fields, acceleration
- **Beam injection:** Child-Langmuir, and other models
- **Diagnostics:** Extensive snapshots and histories
- **Parallel:** MPI
- **Python and Fortran:** "steerable," input decks are programs
  - a GUI is also available

… and *new features* advancing the state of the art ...

- **Adaptive mesh refinement (3-D , x-y, and r-z)**





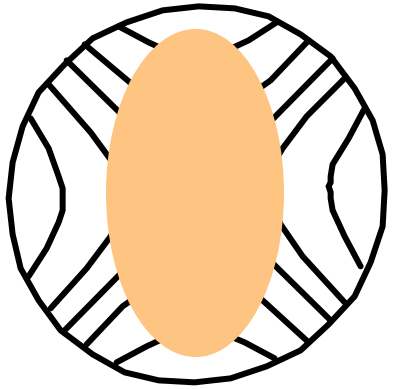
Beam coming off source ***x 11 speedup***

- LHC 3-D simulation: Cell count reduced 20,000x

- **New electron mover that allows large time steps**
- **E-cloud and gas models**
- **Prototype Vlasov solver (for halo)**

We have invented a new "mover" that relaxes the problem of short electron timescales in magnetic field

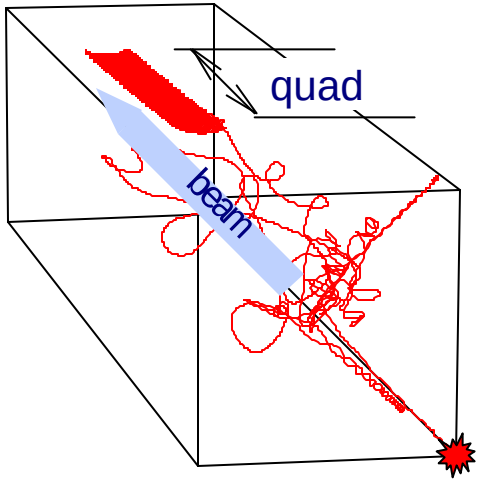
Magnetic quadrupole



Problem: **Electron gyro timescale << other timescales of interest**

Þ brute-force integration very slow due to small Dt

Solution*: **Interpolation between full-particle dynamics ("Boris mover") and drift kinetics (motion along B plus drifts)**

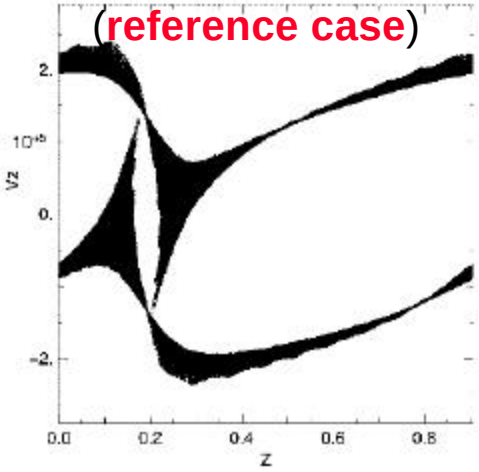


Sample electron motion in a quad

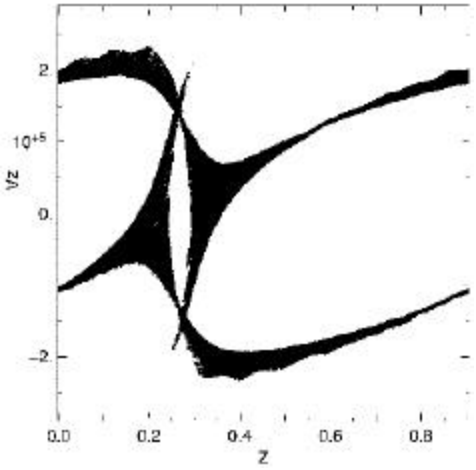
Test:

Magnetized two-stream instability

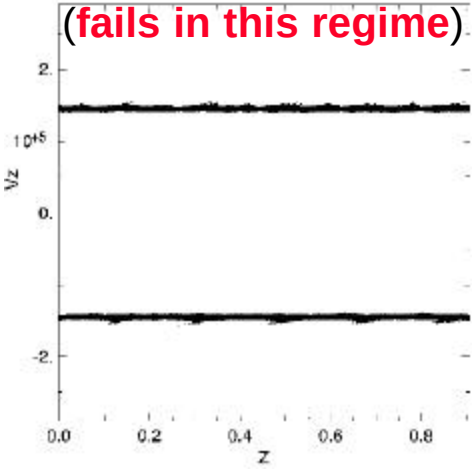
small $\delta t=0.25/\omega_c$
Standard Boris mover
(**reference case**)



large $\delta t=5./\omega_c$
New interpolated mover

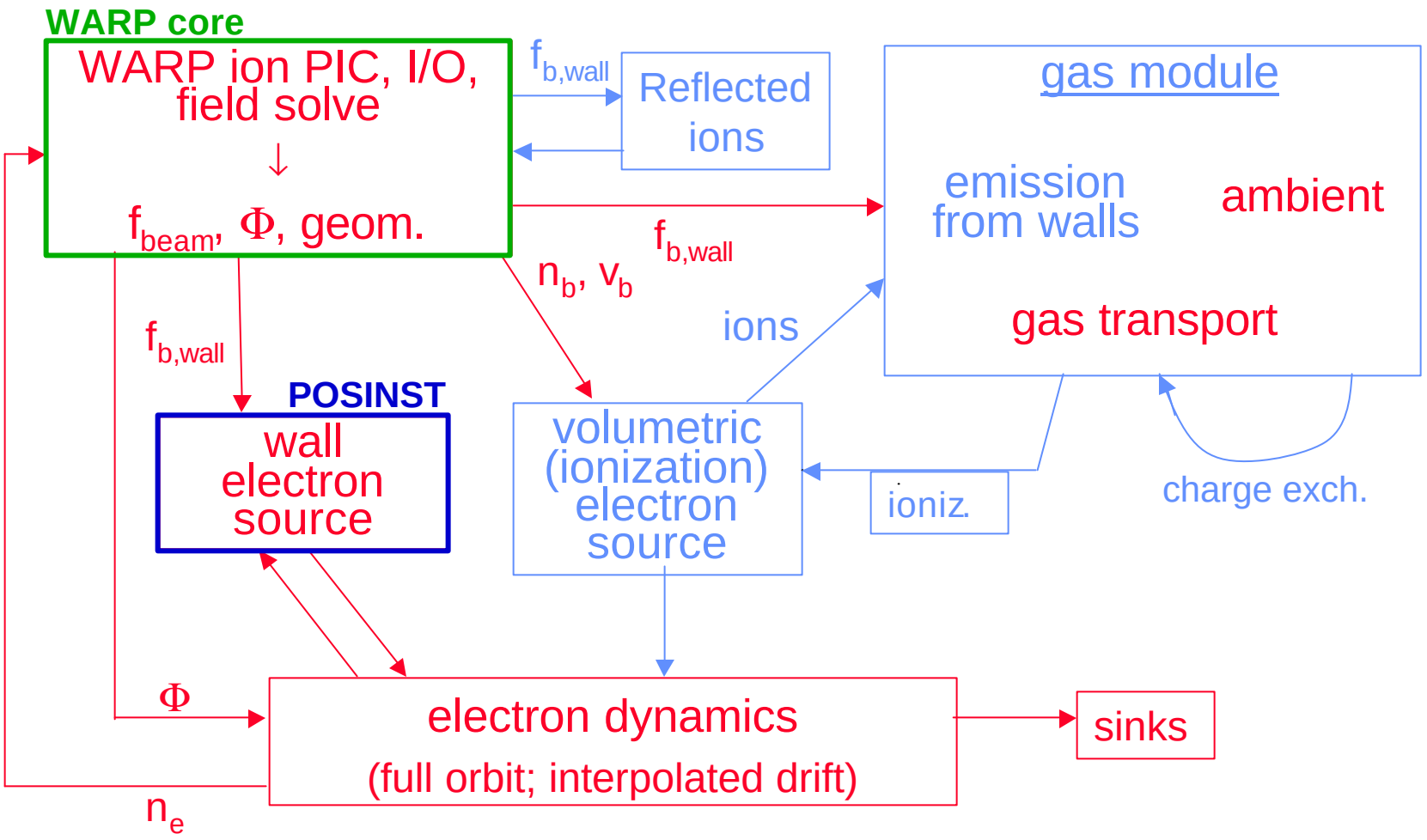


large $\delta t=5./\omega_c$
Standard Boris mover
(**fails in this regime**)



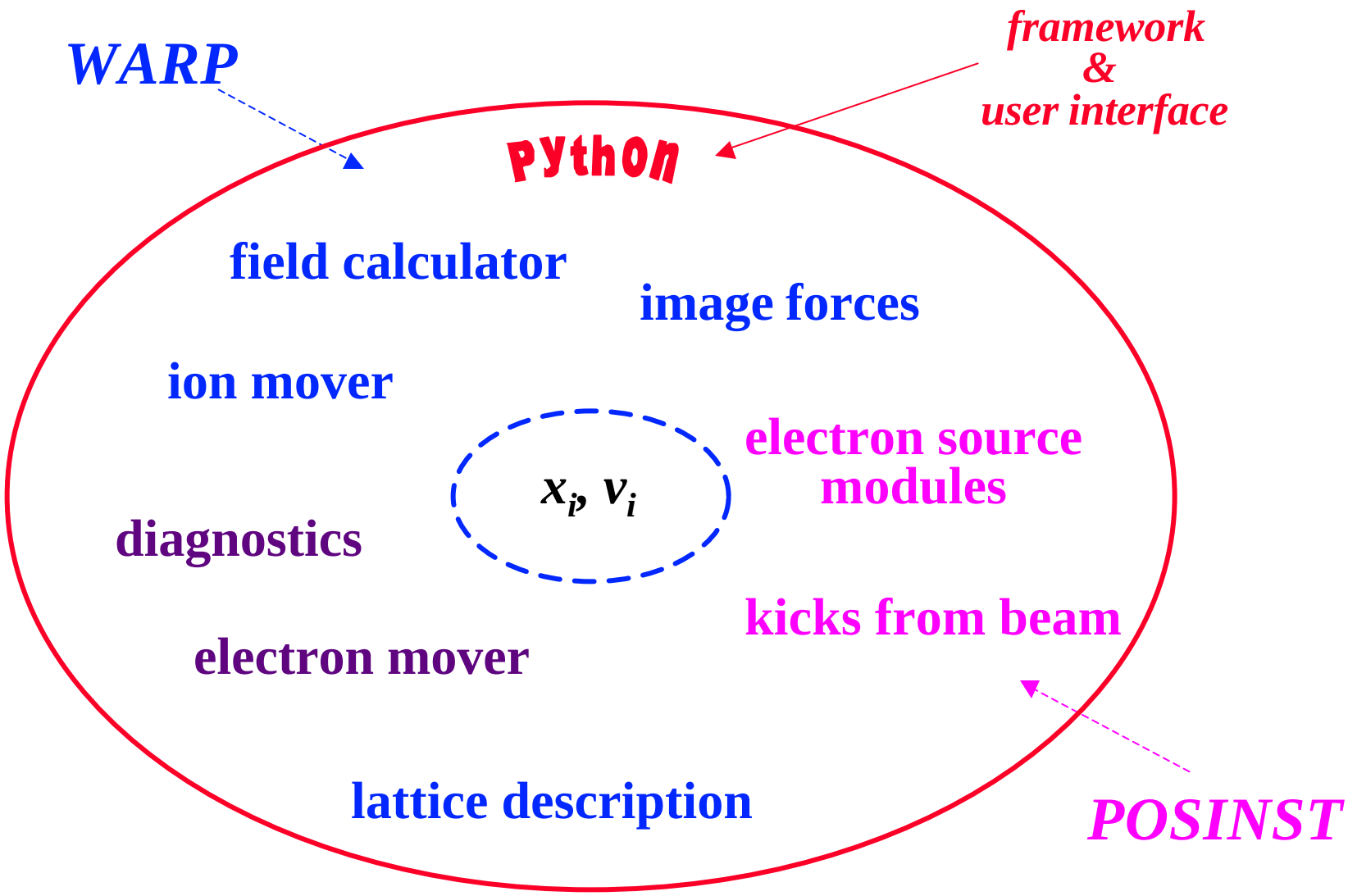
*R. Cohen et. al., Phys. Plasmas, May 2005

Self-consistent model of beam with e-cloud & gas effects.
Built around HIF code WARP and HEP code POSINST.



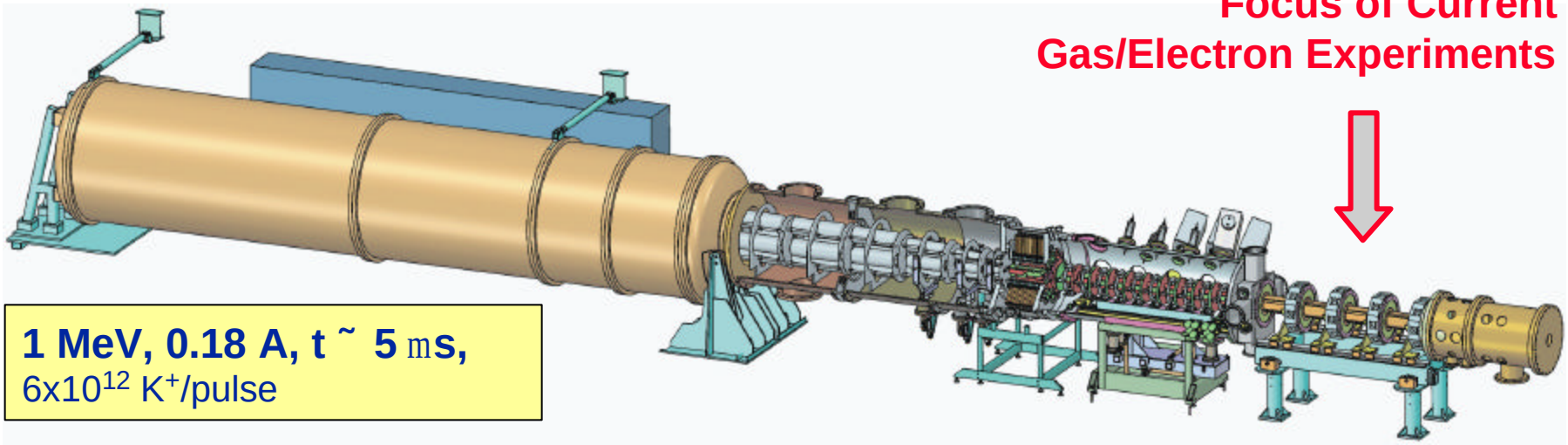
Key: operational; partially implemented (3/9/05)

We have merged WARP and POSINST (with support of coordinated LBNL & LLNL LDRD's)



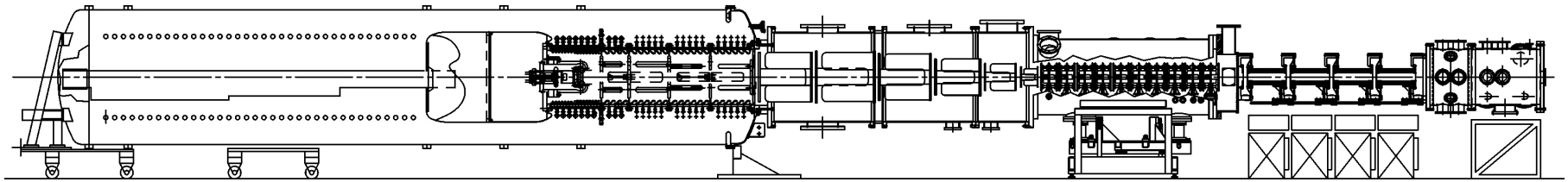
Current HCX Configuration
(High Brightness Beam Transport Campaign, 2005)

Focus of Current Gas/Electron Experiments



1 MeV, 0.18 A, t ~ 5 ms,
6×10^{12} K^+/pulse

INJECTOR | MATCHING SECTION | ELECTROSTATIC QUADRUPOLES | MAGNETIC QUADRUPOLES

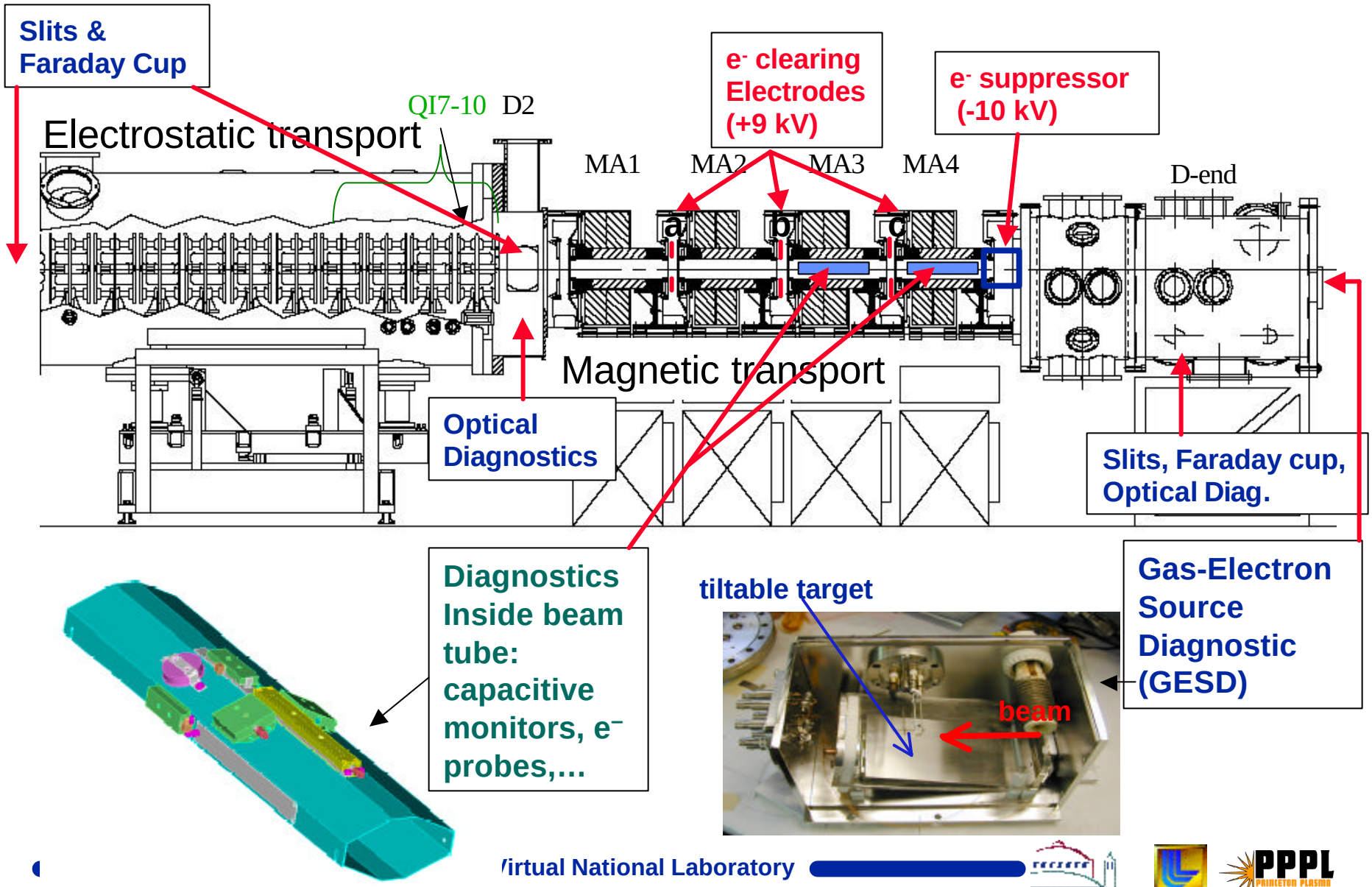


Additional Experiments: Fill-Factor Measurements, Head-Tail Correction, Wave Experiments

We are looking at fundamental questions

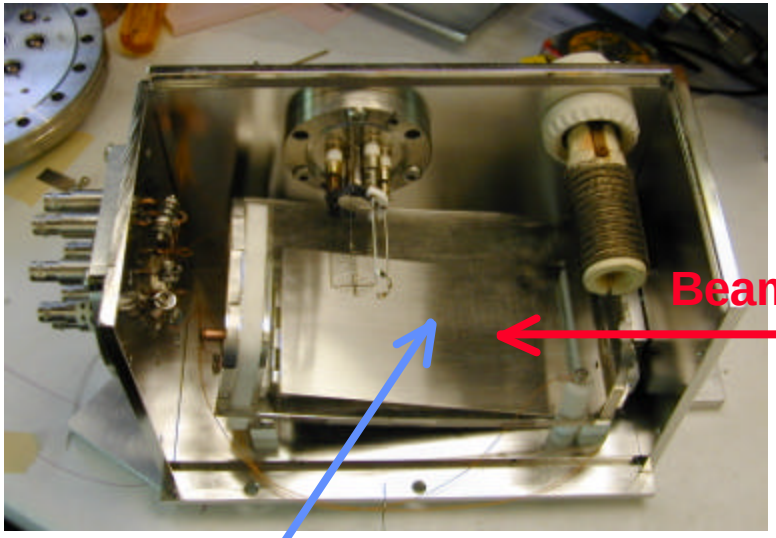
- Primary electron emission
  - yield & velocity distribution
- Secondary emission
  - yield & velocity distribution
- Desorbed gas
  - mechanism, yield & velocity distribution
- Accumulation & retention in quads
  - loss mechanisms, sources
- Effects of electrons on beam
  - harder - must exaggerate sources because of short experiment
- Efficacy of mitigation methods

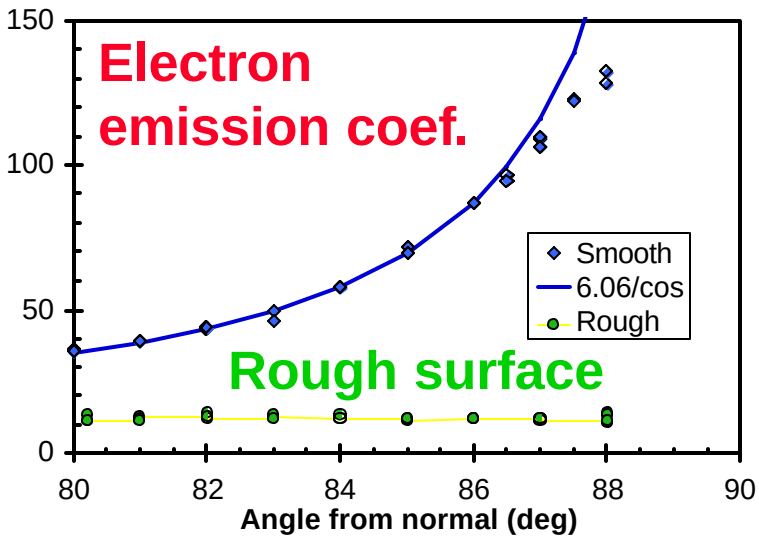
HCX instrumented to carry out electron cloud experiments

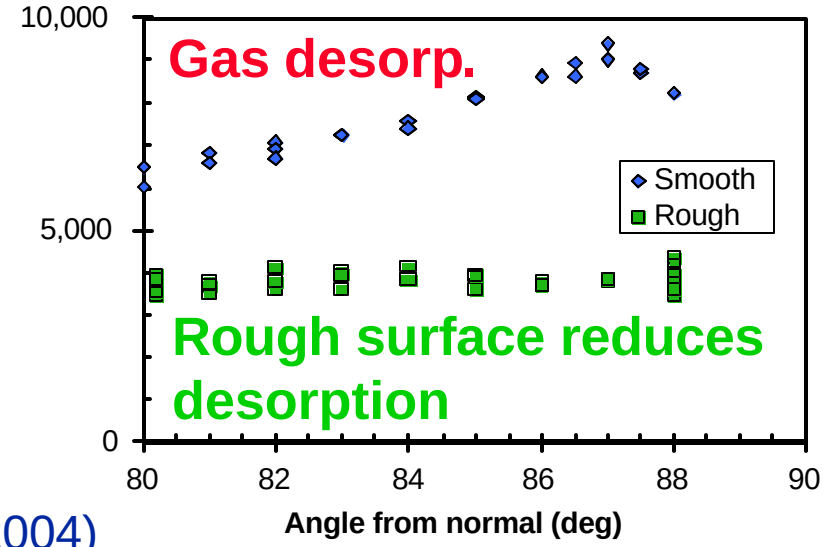


Gas desorption / electron emission measurements have led to understanding and mitigation

Gas-electron source diagnostic (GESD)







Beam-induced electron emission results* similar to :
O. Thieberger, A. L. Hanson, D. B. Steski, S. Y. Z. V. Zajic, and H. Ludewig, Phys. Rev. A **61**, 042901 (2000)

*A. W. Molvik, et al, PRST-AB **7**, 093293 (2004)

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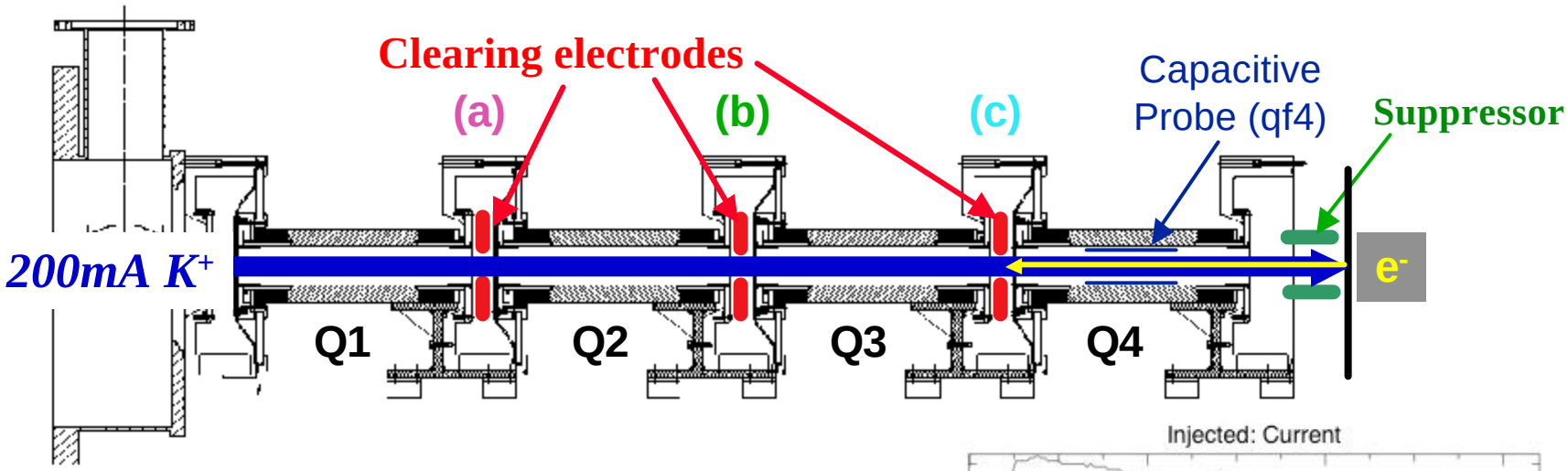
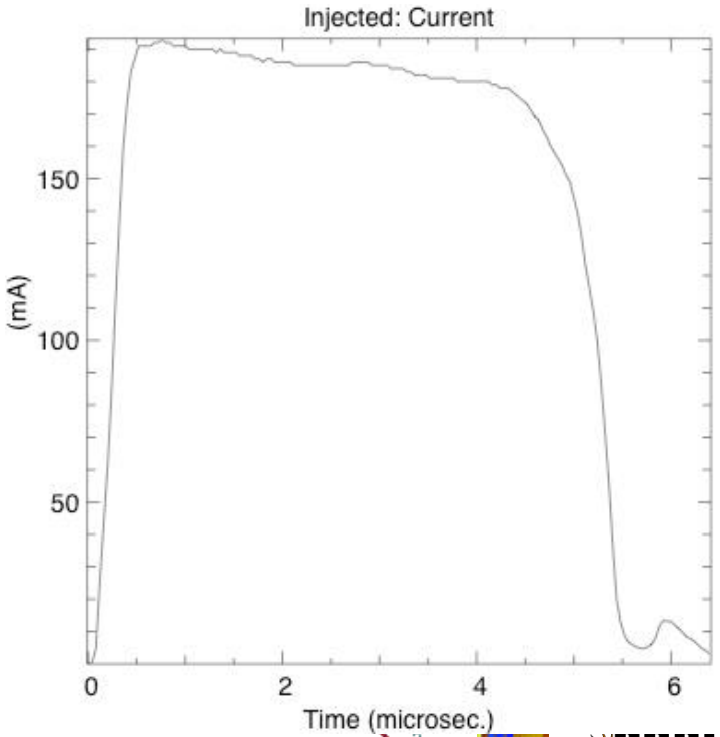


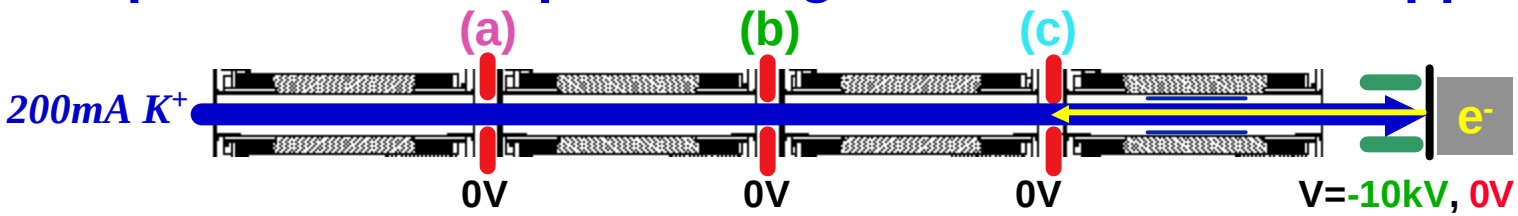
Time-dependent beam loading in WARP from moments history from HCX data:

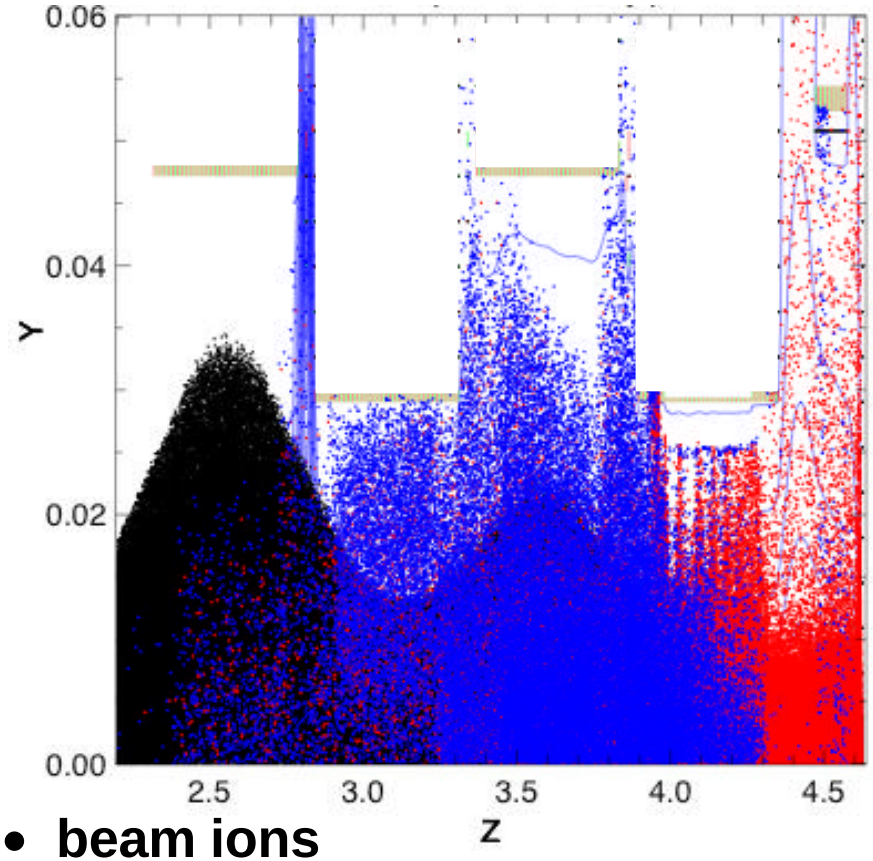
- current
- energy
- X-Y (assume semi-gaussian)
  - RMS envelopes, emittances
  - slopes
  - beam centroids
  - slopes average

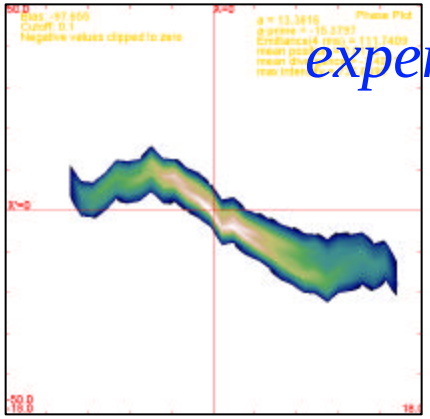
(4-D phase-space reconstruction in develop.)

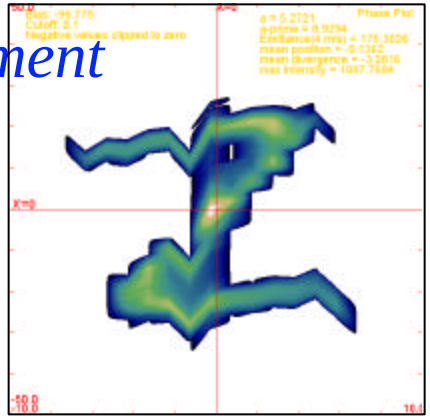


Comparison sim/exp: clearing electrodes and e-supp. on/off





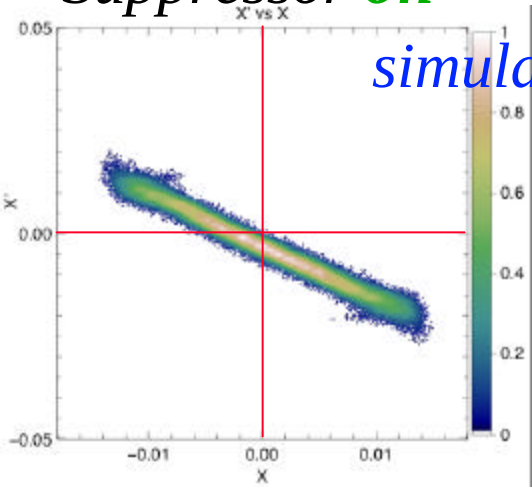


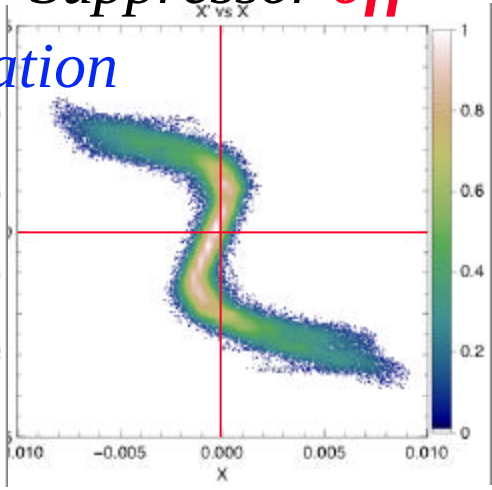


experiment

*Suppressor **on***

*Suppressor **off***





simulation

- **beam ions**
- **electrons from ions hitting surfac**
- **secondary electrons**

Exp./Sim. data agree on sign & order of magnitude on effect of e- on beam.

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LDRD is supporting study of e-cloud in LHC FODO cell

SPS sees surprisingly long-lasting e-cloud (~ second)

The problem:

Simulate "multibunch, multiturn" passage of beam through FODO cell (100 m):

dipoles

quadrupoles

drifts

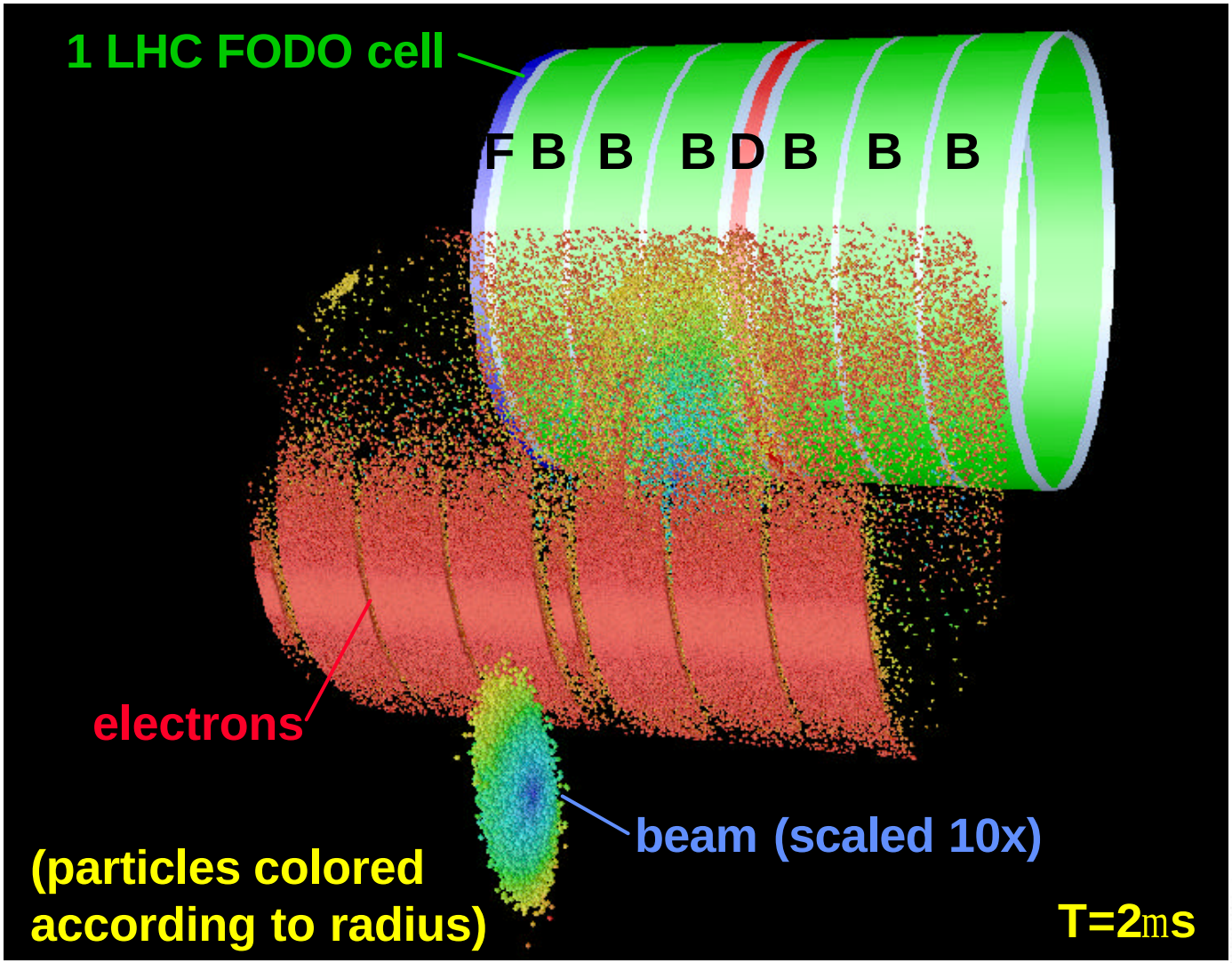
Electrons $\Leftarrow$ synchrotron radiation, secondary emission

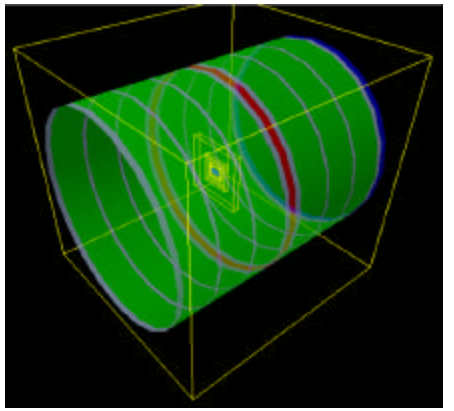
Study:

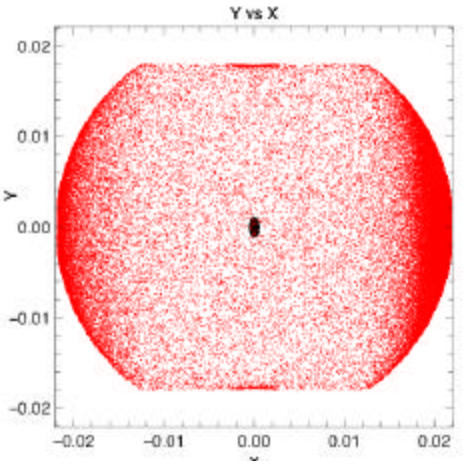
Electron accumulation and trapping in quads

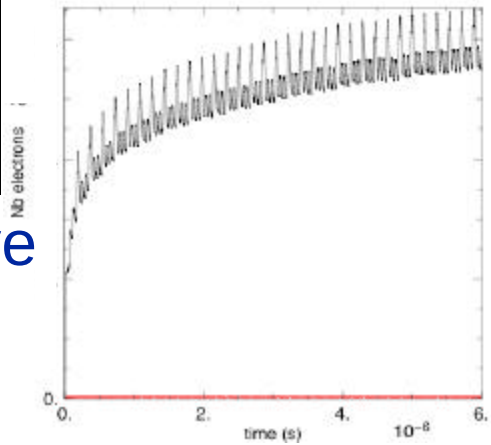
Power deposition from electrons

We are beginning to use WARP to study e-cloud in LHC









- AMR provides speedup of **x20,000** on field solve
- LHC pipe shape
- Histories of Nb electrons, power deposition, …

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We have a unique modeling capability

3-D time-dependent

Ions, electrons, gas

Self-consistent

Lattice description

AMR, new electron mover

5-6 orders of magnitude speedup for LHC

And a dedicated experiment

We have:

- **All the beam time**
- **Flexibility -**
  - **add or change diagnostics**
  - **add components (e.g., solenoids)**
  - **test mitigation methods**
- **Ideal for code benchmarking**

Where are we going?

Depends on the problem /support –

1 pass, many bunches?

1 bunch, many passes?

emission coefficients from cold or NEG surfaces?

RHIC simulations of dynamic vacuum and e-cloud?

… or, where we may not be going ...

LDRD ends at the end of FY05

We are exploring new applications and looking for new customers.

Suggested HIF-VNL contributions to LHC: Theory/Computation

1. **Apply WARP/POSINST to LHC arcs ~2 years at 0.75 FTE/year**

   3-D self-consistent studies (beam, e-clouds, lattice, realistic pipe, photo-electrons, secondaries, gas, …)

   - **start with 1 bunch in 1 FODO cell (in progress); then short trains/multiple cells**
   - **various bunch spacings and intensities, surface modifications, SEY, …**
   - **reduced models: 'POSINST' mode for electrons, 'HEADTAIL/QUICKPIC' mode for beams**
   - **push toward longer systems: 2-D/3-D WARP/POSINST with maps (longer term)**

2. **Seek understanding of ~1s electron lifetimes in SPS 0.75 FTE+$25K hardware**
   - **HCX exp'ts can measure e- lifetime in quads**
   - **modeling will build on our Magnetic Fusion experience**

3. **Detailed validation of code: comparison with other codes and exp't 0.5FTE (est.)**

4. **Model microwave transmission through beam tube (SPS, PEP-II) 0.2FTE**

Suggested HIF-VNL contributions to LHC: Experiment

1. Measure gas desorbed by beam 1FTE+$20K supplies
   - species
   - desorption coefficient
   - distribution f(v,q) (near grazing incidence)

2. Measure gas desorption coef's from NEG coatings 0.5FTE+$10K supplies
   - image direct gas desorption unperturbed by NEG's pumping

3. Extend above to cryo surfaces 1.25FTE+$250K supplies
   - Would require a UHV addition to the present high-vacuum HCX, probably isolating the UHV tank with 4 or more UHV magnetic quads.

4. Simulate ECE multipactoring by driving electrodes with rf 0.5FTE+$20K supplies
   - near the electron bounce frequency in a long (5 μs) beam pulse, with a beam potential of up to 2 kV.
   - RF voltage low enough to pump-out electrons. RF voltage higher to build up e-.