Towards Kinetic Modeling of Ion Transport in an ECRIS Plasma

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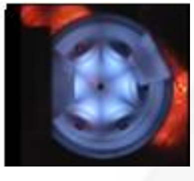
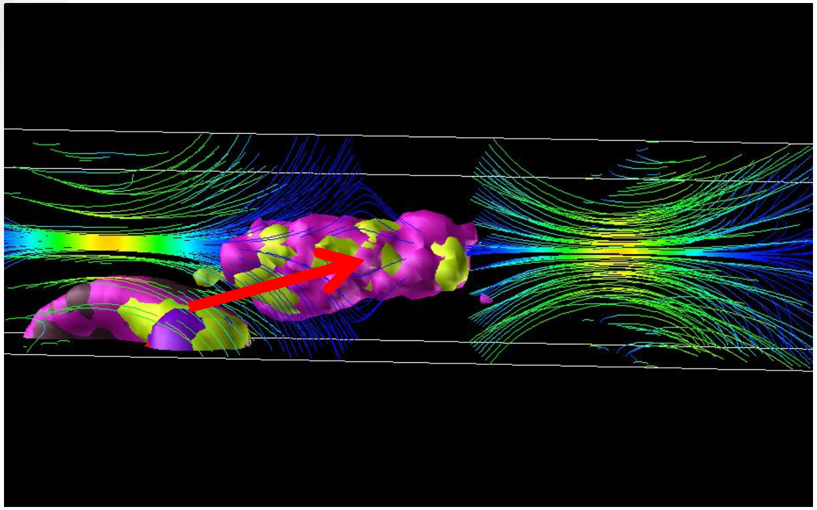
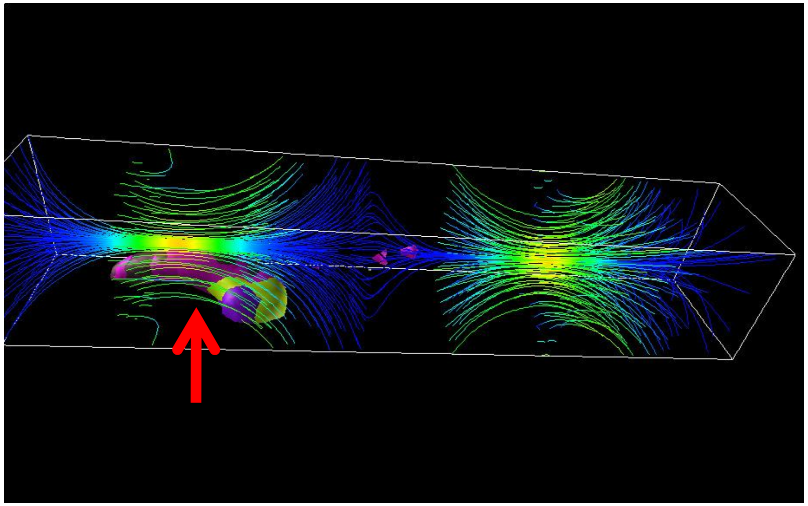


Abstract

Next generation heavy ion beam accelerators require intense, high charge state ion currents of exotic materials. ECRIS devices can generate these currents however detailed kinetic simulations are needed to optimize the loading of these materials into the plasma. Full Particle-In-Cell simulations of the plasma are highly challenging due to the large discrepancy between length and time scales. However, separation of time-scales provides a means of making progress. Electrostatic simulations on ion timescales, though demanding, are capable of modeling the kinetic behavior of the ions. Similarly, electromagnetic simulations on electron time scales can provide the non-thermal kinetic properties of the electron population. In this work, we treat the electrons as a simplified fluid for the longer time-scale evolution of the ions. We characterize and diagnose the electron distribution for use in the ion simulations. Ionization and recombination processes are then modeled in a hybrid fluid-electron / kinetic-ion formulation using the prescribed electron distribution as one of the interaction partners. Progress in the electrostatic modeling of the ion dynamics is also presented.

We are focused on heavy ions, high charge states, and evaporation sources

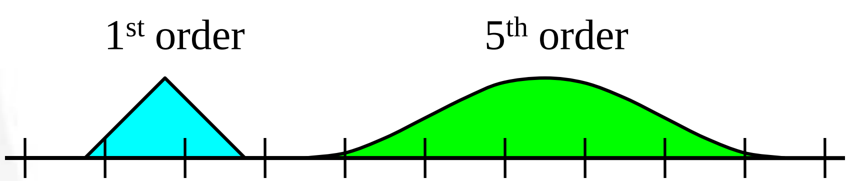


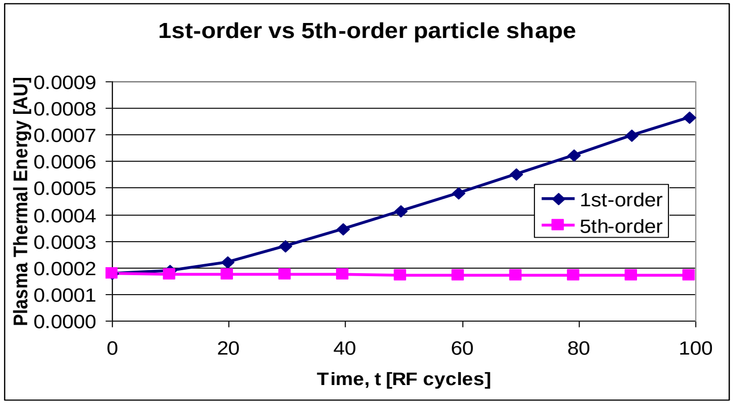


- Source of heavy neutrals is localized.
- Goal is to determine evolution and spatial distribution of the multiple charge-state ion populations.

Simulation of dense plasmas presents challenges

- There are several widely varying time-scales associated with ECR waves, electron dynamics, electron heating, ion dynamics, ionization, recombination, and transport.
- There are two widely separated spatial-scales, one associated with the debeye length, the other associated with the device size. We use high-order particles to address the grid-heating problem on the electron time-scales, caused by $\lambda_{debye} << \delta x$.



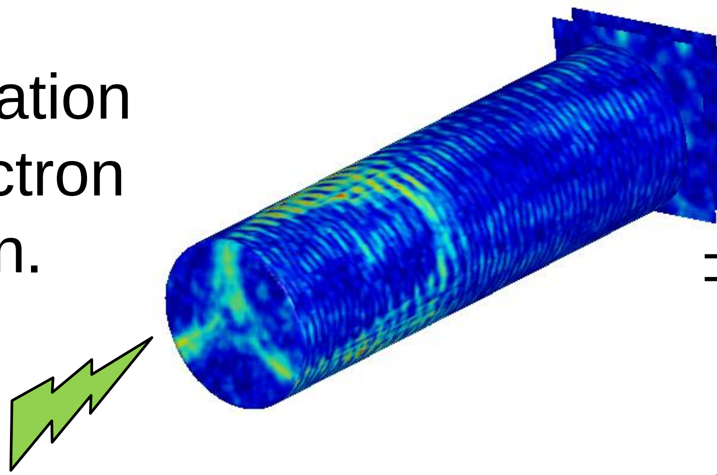


Fullly-integrated, entirely-kinetic simulation has not been very successful

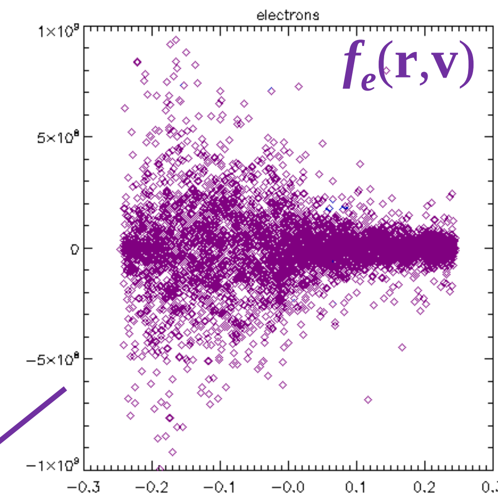
- Higher-order particles solve the spatial-scale difficulties, but cannot solve the electron-ion time-scale difficulties.
- In order to make some progress, we had to use scaled cross-sections (to bring ionization time-scale closer to electron time scale).
  - But this is dangerous, and not very satisfactory.
- <u>New approach:</u> Separation of timescales
  - EM simulation: ions fixed, electrons kinetic
  - ES simulation: electrons fixed, ions kinetic
- <u>New approach:</u> AECR, instead of VENUS.

Electron population is moved between fast (EM) and slow (ES) time scale simulations

- EM simulation gives electron population.



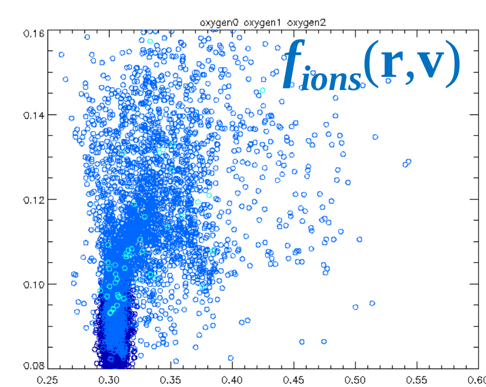
$\Rightarrow$



- ES simulation gives ion population.

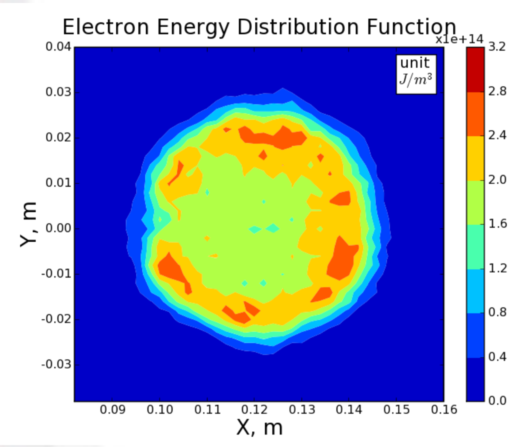
$f_e(\mathbf{r},\mathbf{v})$

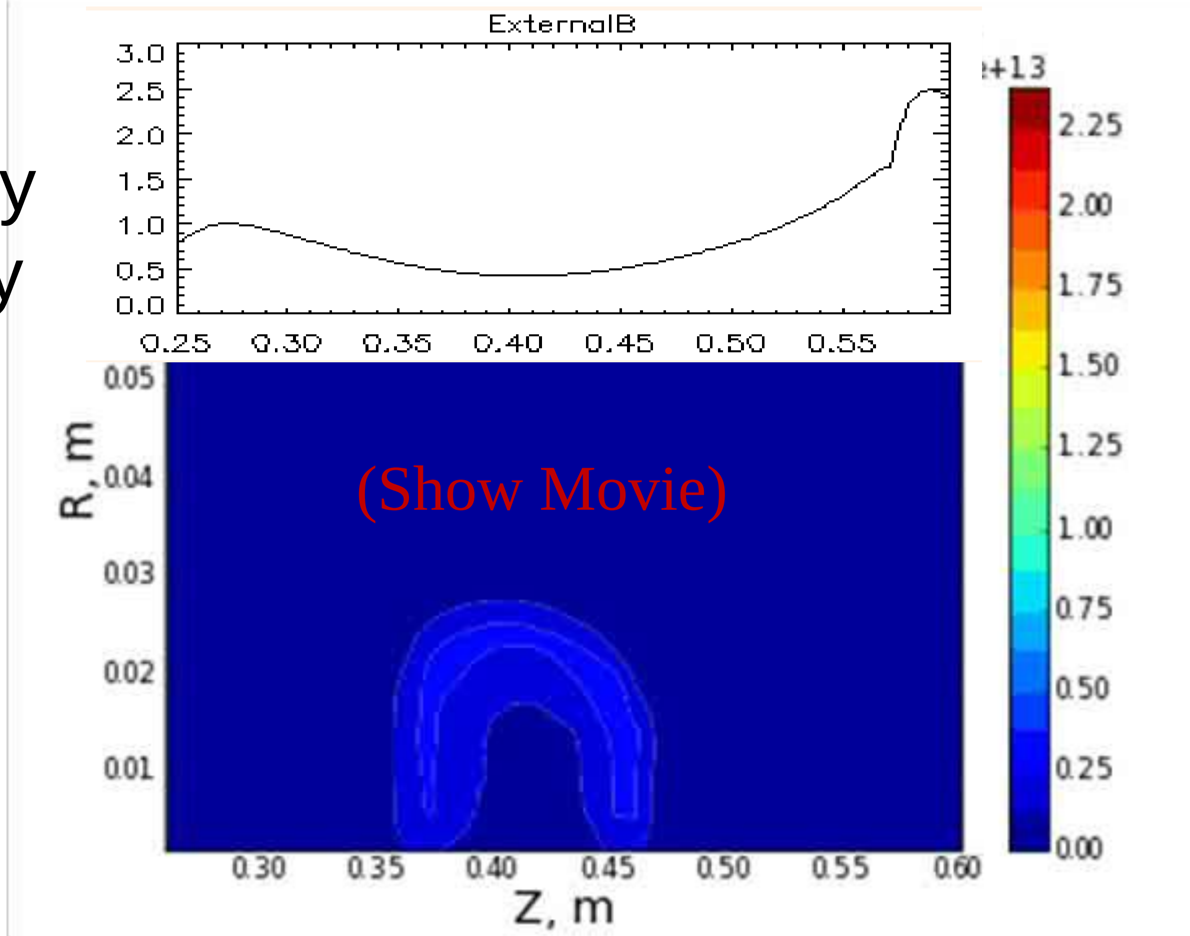
$f_{neut}(\mathbf{r},\mathbf{v})$ $\Rightarrow$



EM Simulation: Global electron population created, stored to disk.

- Evolution of electron energy shows spatially distribution.

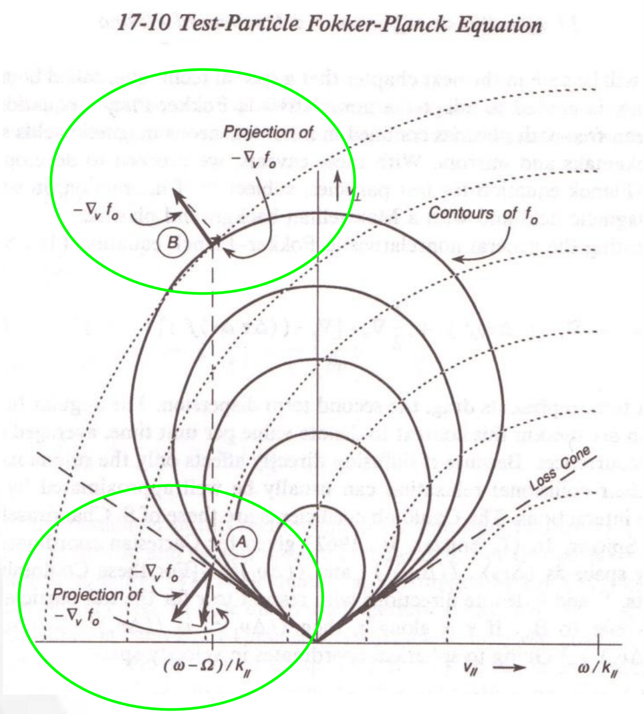


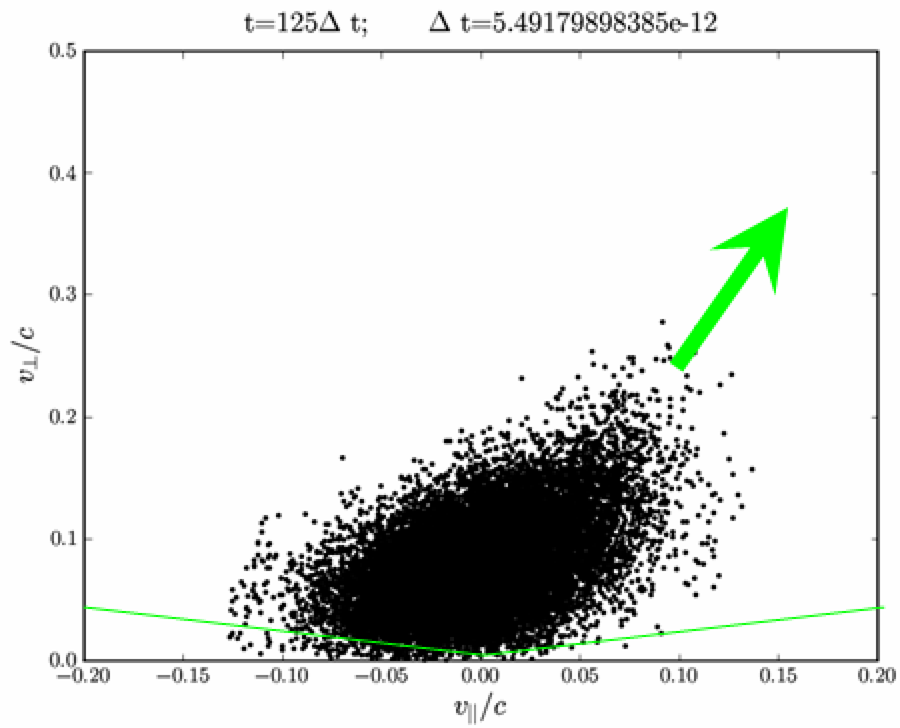


EM Simulation: previous work has demonstrated realistic ECR interaction

- Look at single point on axis.
- Observed electron distributions in $v_{\perp} - v_{||}$ space similar to what is expected in QL analysis.

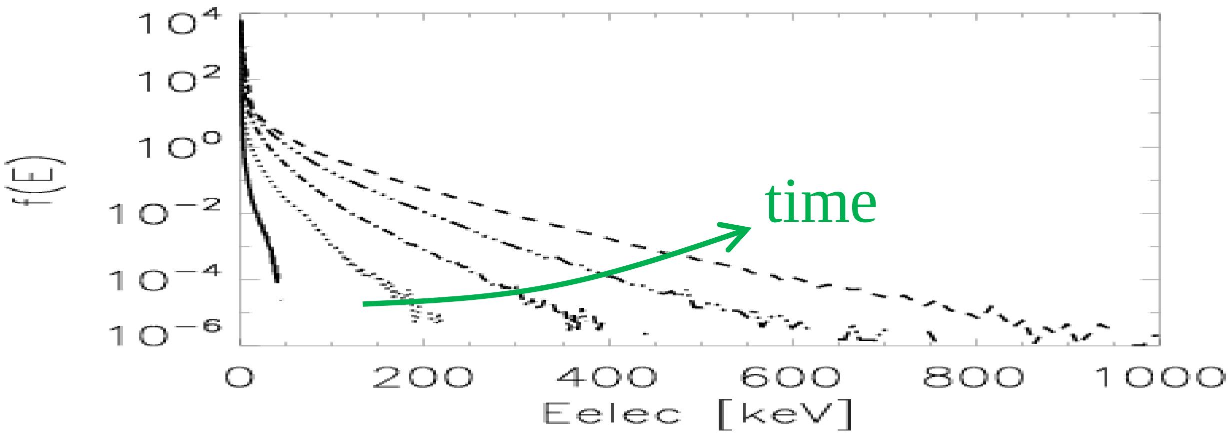
From "Waves in Plasmas,"
T. H. Stix, AIP 1992.





EM Simulation: global electron distribution shows tail formation

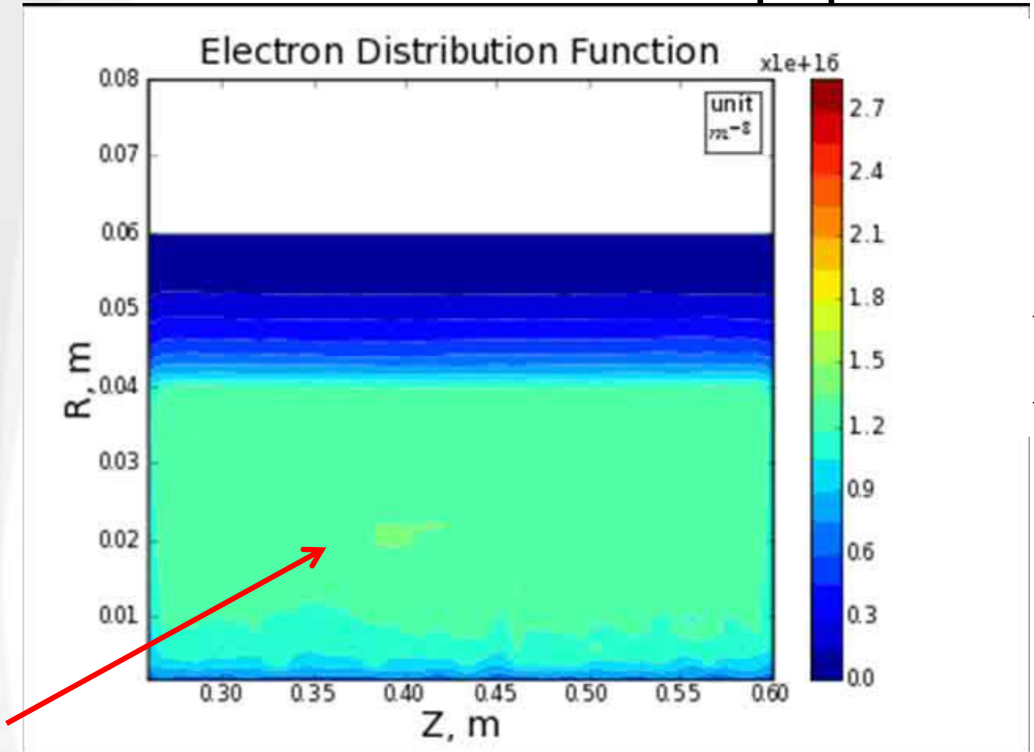
- One problem is lack of collisional effects, which would provide a natural saturation mechanism.

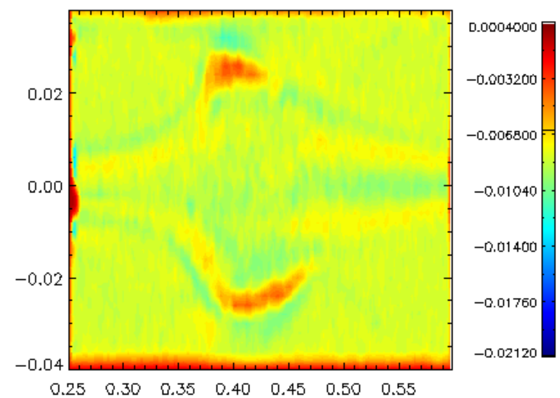


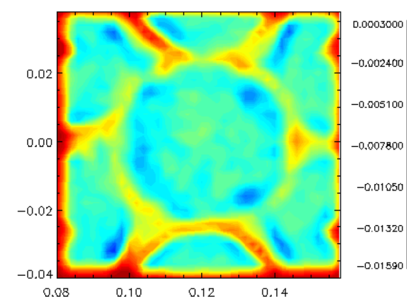
- This information could be used to compute X-ray production, but so far, we are not really focused on that issue for this project.

EM Simulation: electron density perturbation visible

- Started from uniform ion population.





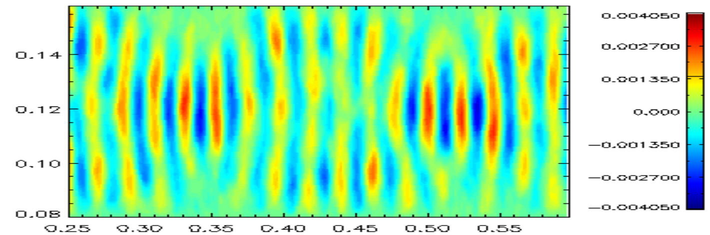


(Show Movie)

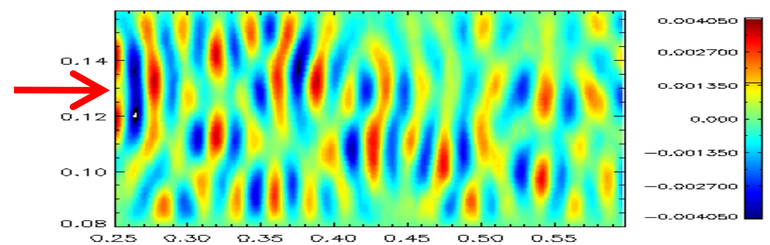
- Not yet fully self-consistent, e.g., have not closed loop back from ionization / transport time scales.

EM simulation: we've compared our previous plane-wave excitation to having a localized source

- A plane wave source illustrates the dispersive properties of plasma nicely
  - But is not very realistic.

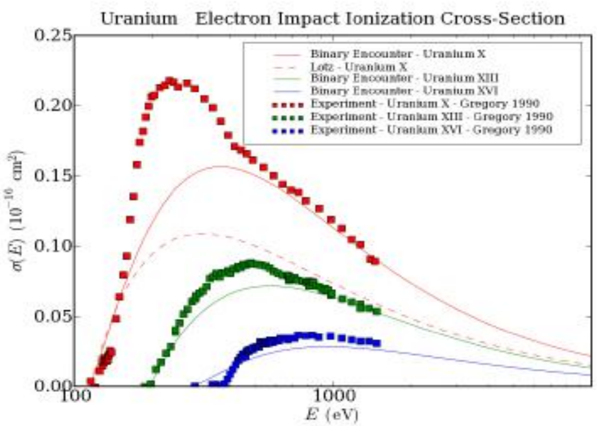


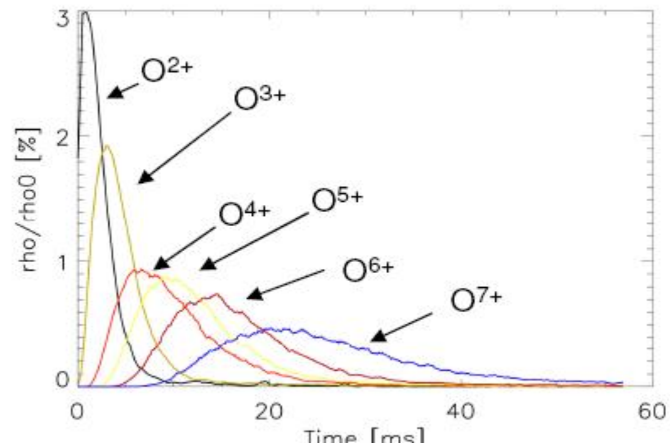
- Localized antenna shows some greater transverse behavior, but effective performance is not significantly difference.
  - Result might depend on density in front of antenna.



ES Simulation: accurate ionization, charge-exchange, and recombination

Kinetic Ionization Model

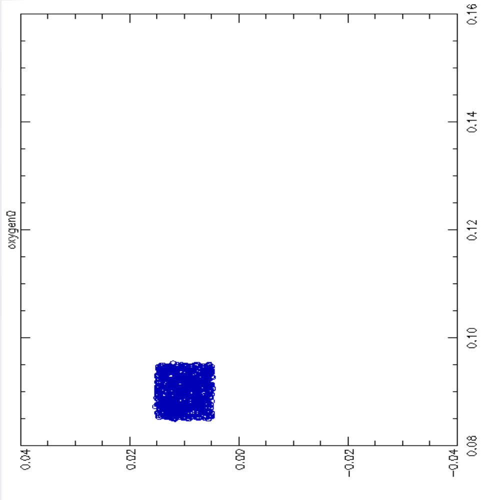


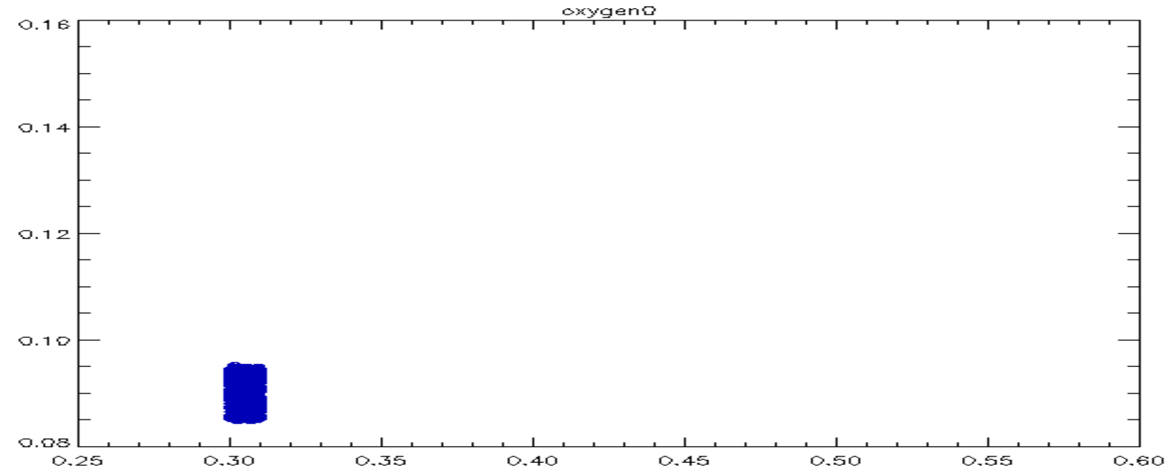


- Model for ion impact ionization enables simulation of ionization cascade.
- Variety of cross-section models for different species
  - [1] Lotz, W., *Ap.J. Suppl*., **14**, 207, 1967.
  - [2] Shull, M.J., VanSteenberg, M., *Ap.J. Suppl*., **48**, 95, 1982.
  - [3] Y.-K. Kim and M. E. Rudd, "Binary-Encounter-Dipole Model for Electron-Impact Ionization", Phys. Rev. A, **50(5)**, 1994.
- Under development: Ionization model for variable weight particles to enhance resolution in low density regions.

ES simulations: simulate time-scale of ionization physics

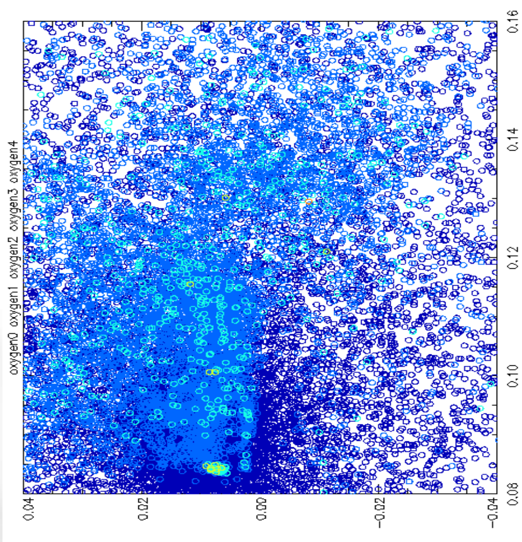
- Electron population, including hot electrons, is read in from previous EM simulation, taken to be static.
- We assume an initial cloud of Oxygen neutral gas. Neutral gas particles are also kinetic.

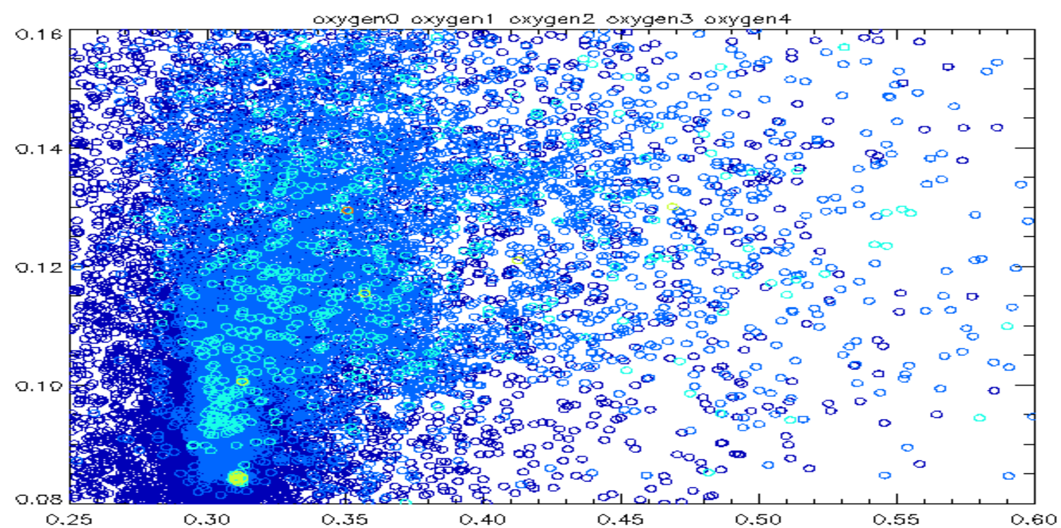




ES Simulation: run for ~100 microseconds

- So far, evolution of the neutral and ion populations tracked until O^{4+} appeared.
- Includes charge-exchange, and recombination.
  - But recombination appears negligible.
- Ions appear in ECR central volume when gas moves to axial locations and is subsequently ionized.





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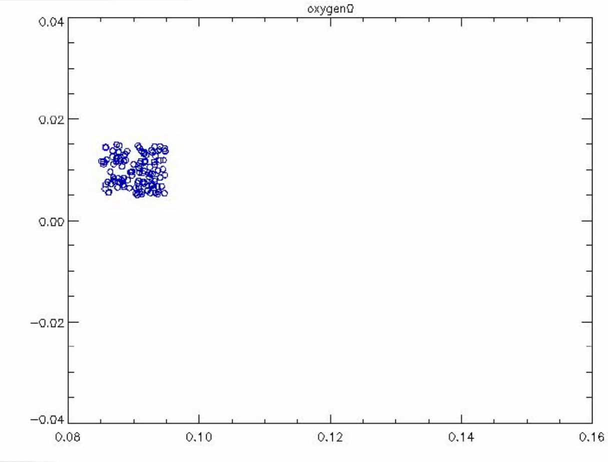
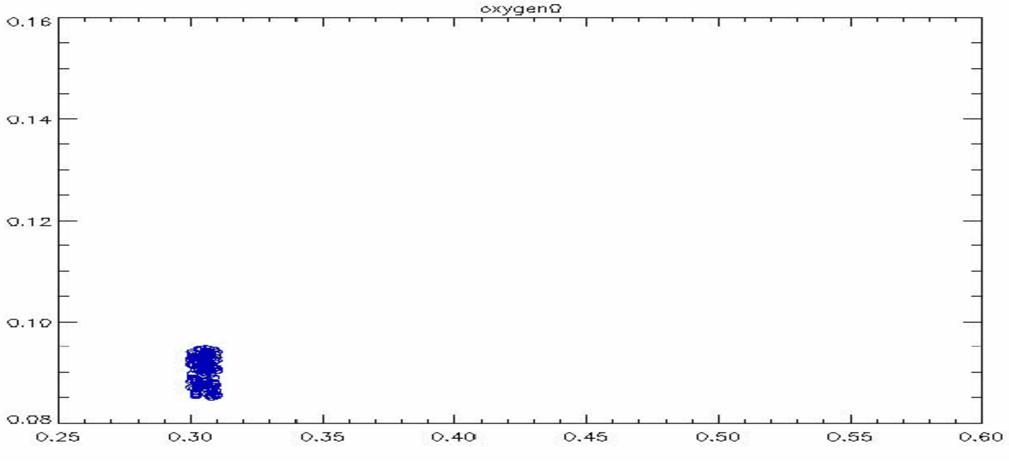
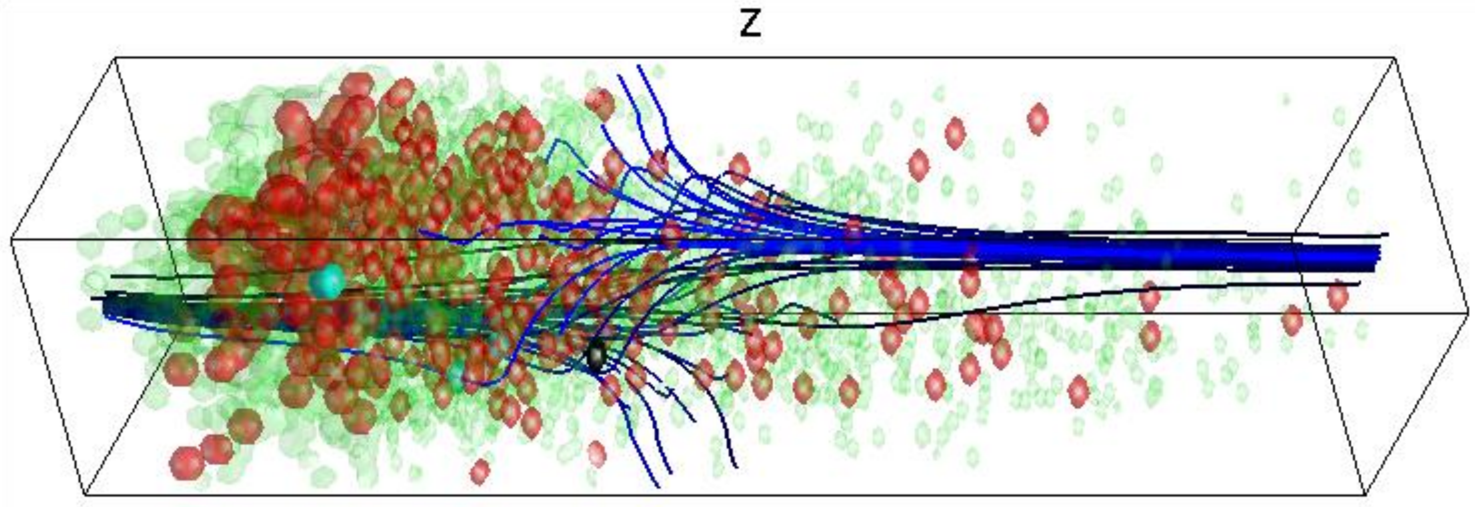
Movies of Ion Populations

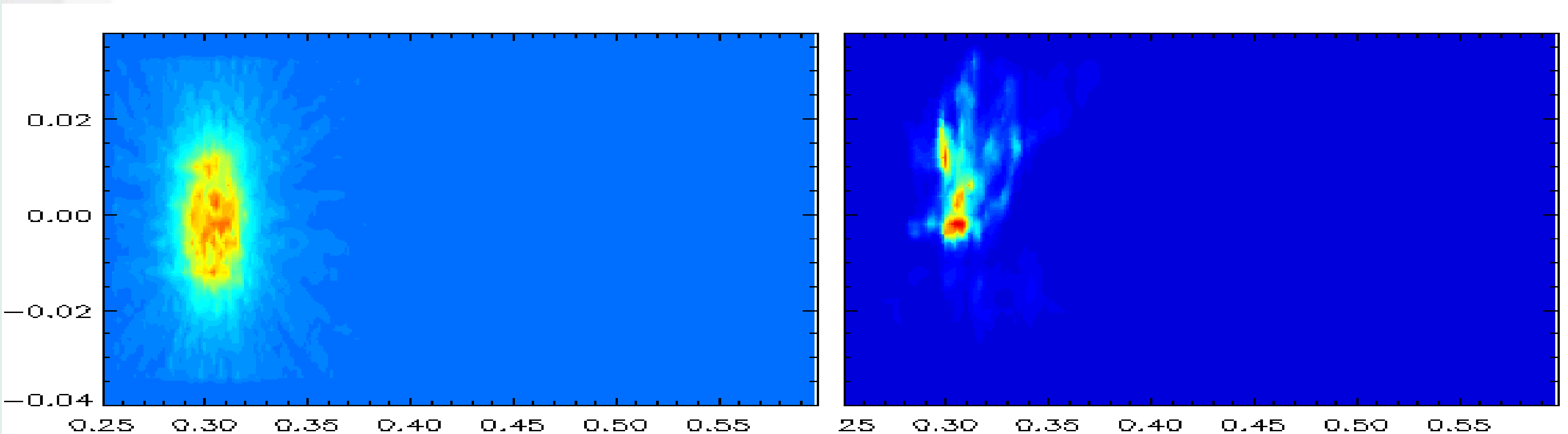






ES Simulation: Diagnostics exist to look directly at ionization rates

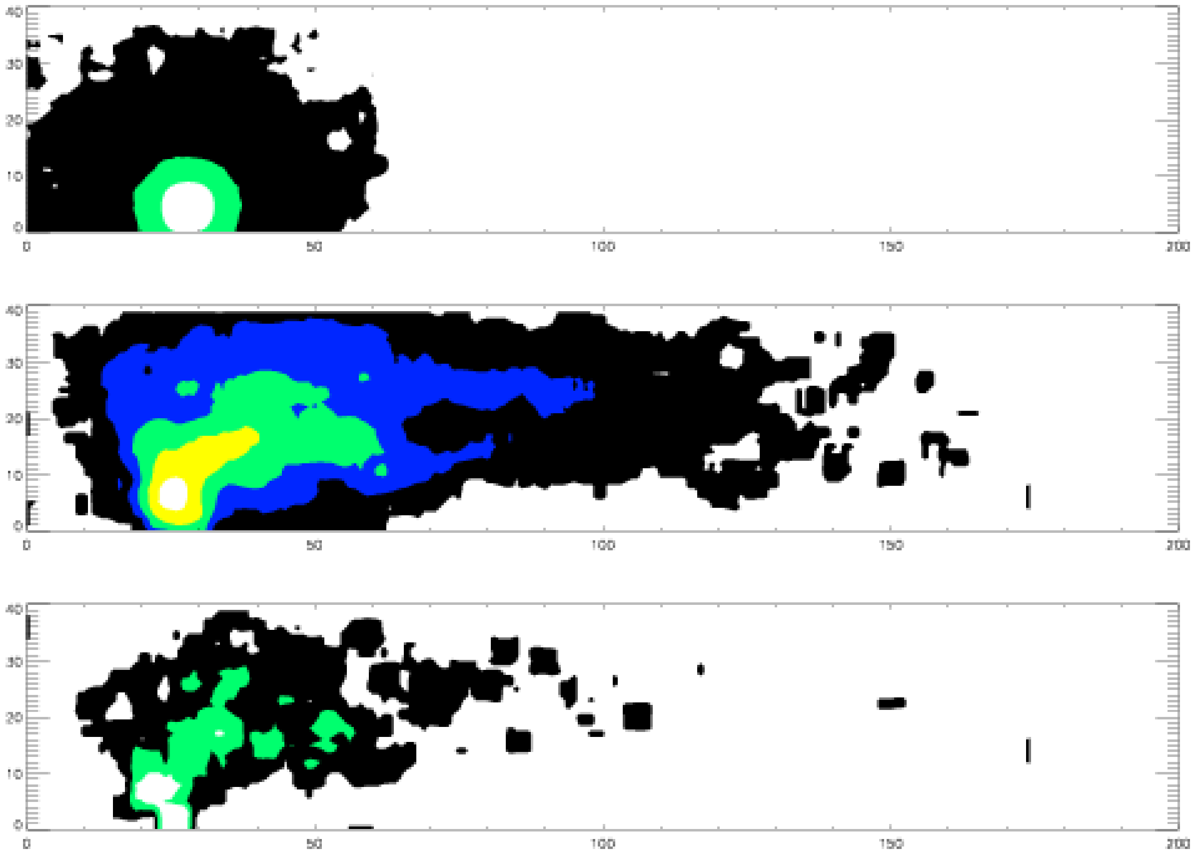
Neutral $\rightarrow O^{1+}$ $O^{1+} \rightarrow O^{2+}$



- Ionization occurs where neutrals and hot electrons occur simultaneously.

ES Simulation: Results in Distribution of Ion Populations

Neutrals, O^{1+}, and O^{2+} (log-scale)



Summary

- Always fully 3-D simulation.
- Previous attempts to model with full kinematics in single simulation was proving difficult.
- Have now switched to separate time scale simulation, one EM the other ES.
- Electron population data is stored to disk and connects simulations.

- Future work:
  - Parametric scans for different loading positions.
  - Feed Ionization information back to EM density profile.
  - Include ion extraction, X-ray production?