Simulation-Driven Optimization of Heavy-Ion Production in ECR Sources

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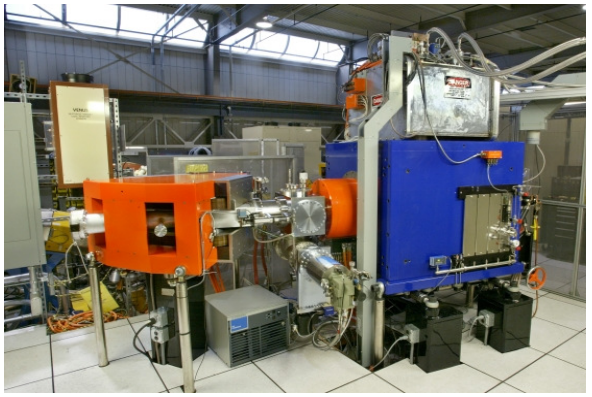
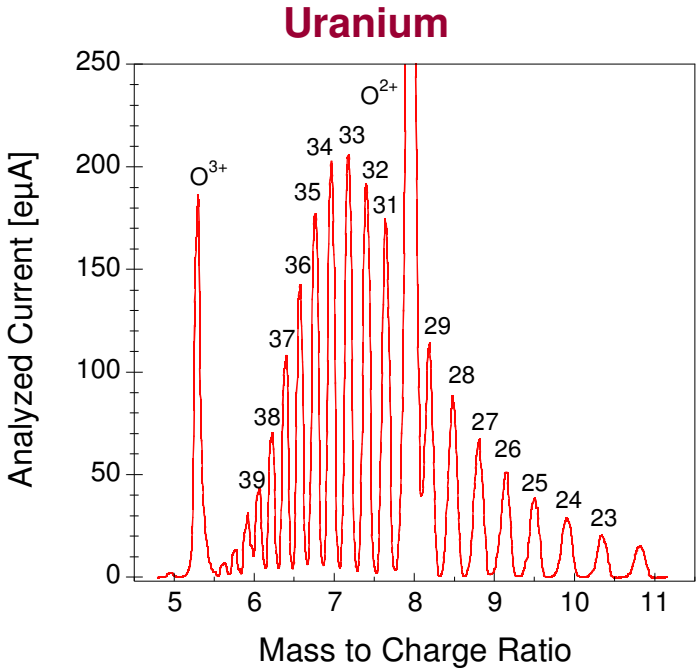
VENUS R&D focus: generation of high intensity Uranium beams

- Versatile ECR ion source for NUclear Science
  - LBNL Superconducting ECR
  - 18/28 GHz
- World record beam of 200 eμA U^{32+} - U^{34+}
- Further oven developments (ongoing) are needed to improve the reliability and output of the oven
- The beam intensities are limited by the vapor flux of uranium into the plasma

⇒ **Use simulations to investigate plasma loading process**



Figures: VENUS Group

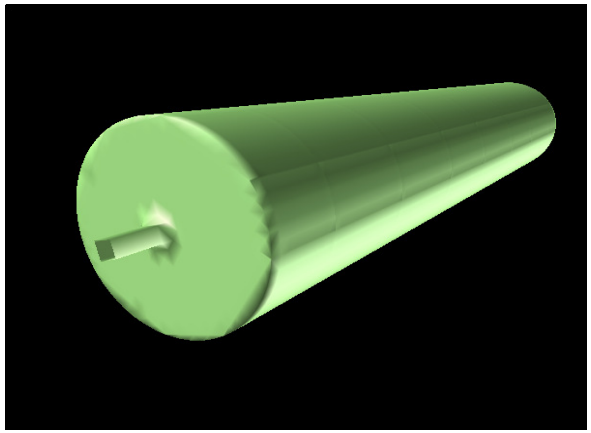


Vapor loading in ECR poses various modeling challenges

- Complex field topology
  - Requires full 3D treatment
- Large discrepancy of length/timescales
  - Debye-length ~ μm, system size ~ m
  - Cyclotron period ~ 10^{-10}s, ionization time ~ ms
- Ionization model
  - Impact ionization for broad range of electron energies

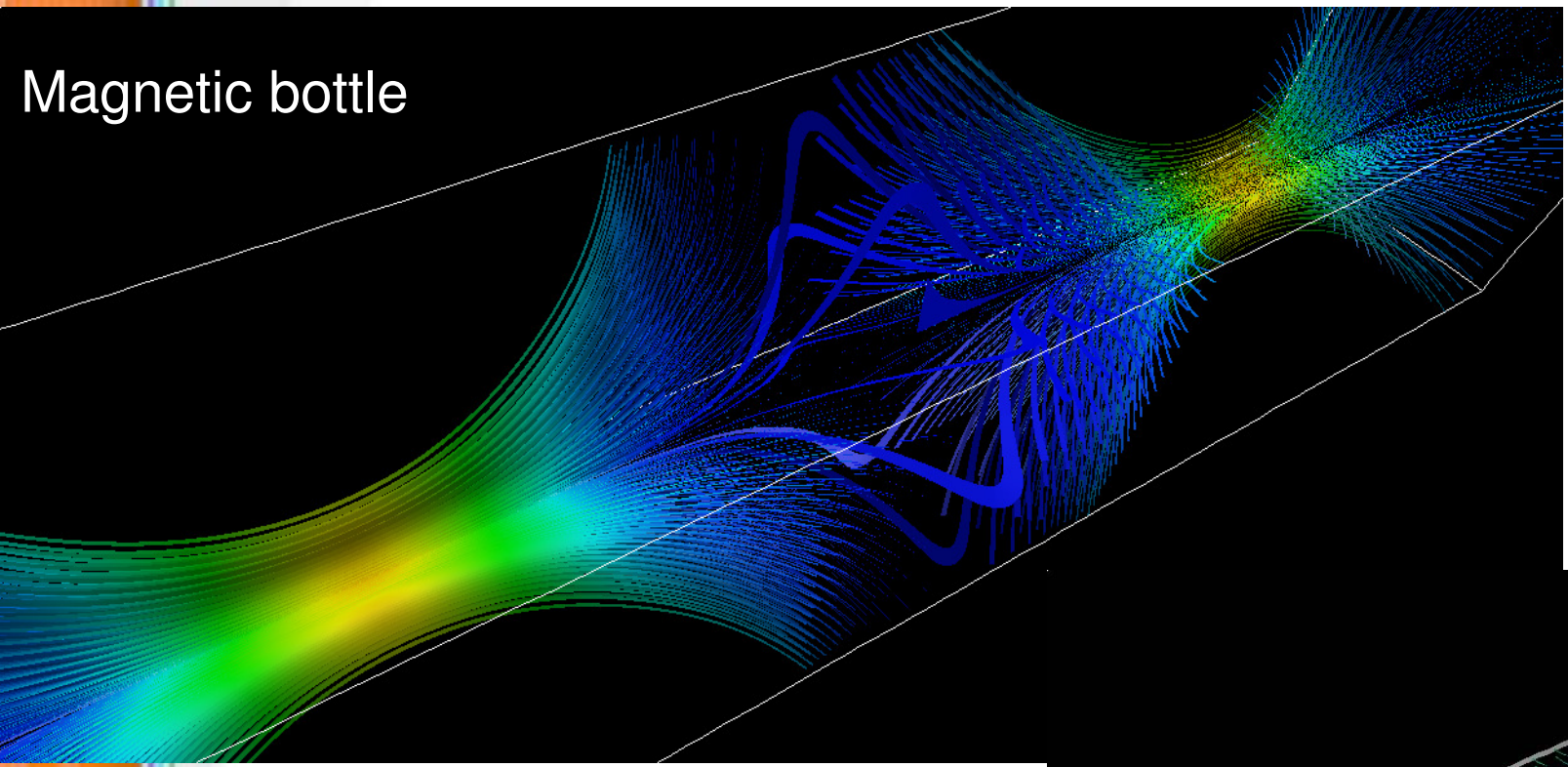
=> VORPAL includes now all the models to perform these simulations!

VORPAL allows both electrostatic and electromagnetic simulations



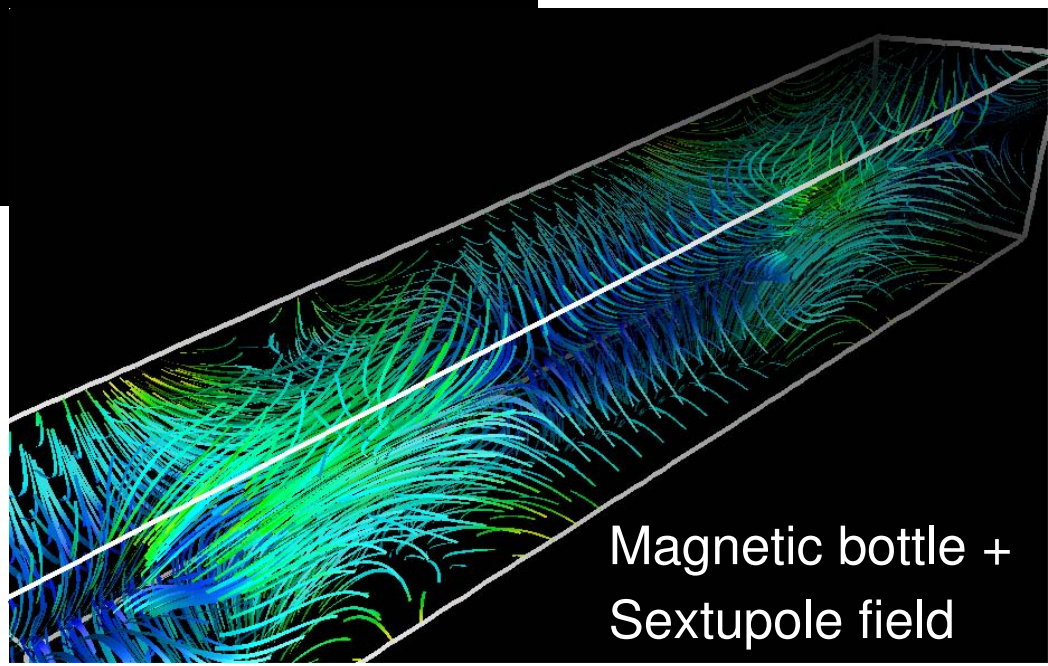
- Parallel ES solver
  - Based on Sandia's AztecOO/Trilinos
  - Variety of solvers, preconditioners
    - Krylov subspace solver, AMG
  - Scales to large number of processors
    - E.g Speedup 111x on 128 PEs for 513 x 65 x 65 cell problem
  - Arbitrary complex boundary condition
- Same simulation setup can be used to run electromagnetic simulation
  - E.g. for investigation of RF power absorption

VORPAL allows easy setup of complex magnetic field topologies



$$B_z = B_0(z) + \frac{r^2}{4}\partial_z^2 B_0(z)$$

$$B_r = -\frac{r}{2}\partial_z B_0(z) - \frac{r^3}{16}\partial_z^3 B_0(z)$$



Two methods to avoid numerical heating: Super-heavy electrons and High-order particle shapes

- Noise in electron motion artificially heats plasma until grid resolves electron Debye-length
  - Requires fine meshes
- **Solution 1: Super-heavy electrons**
  - Contribute charge to electrostatic field
  - Electrons not affected by field
- **Solution 2: High order particle shapes**
  - Requires only resolution of skin depth
  - See: K. Paul et al., PAC07 THPAS023

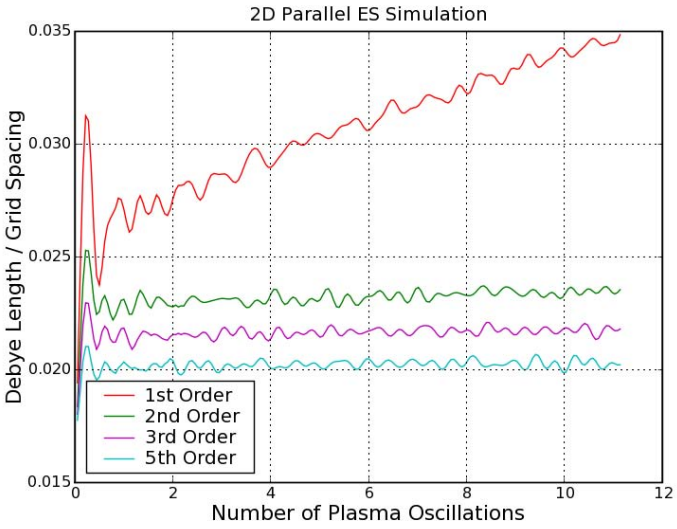
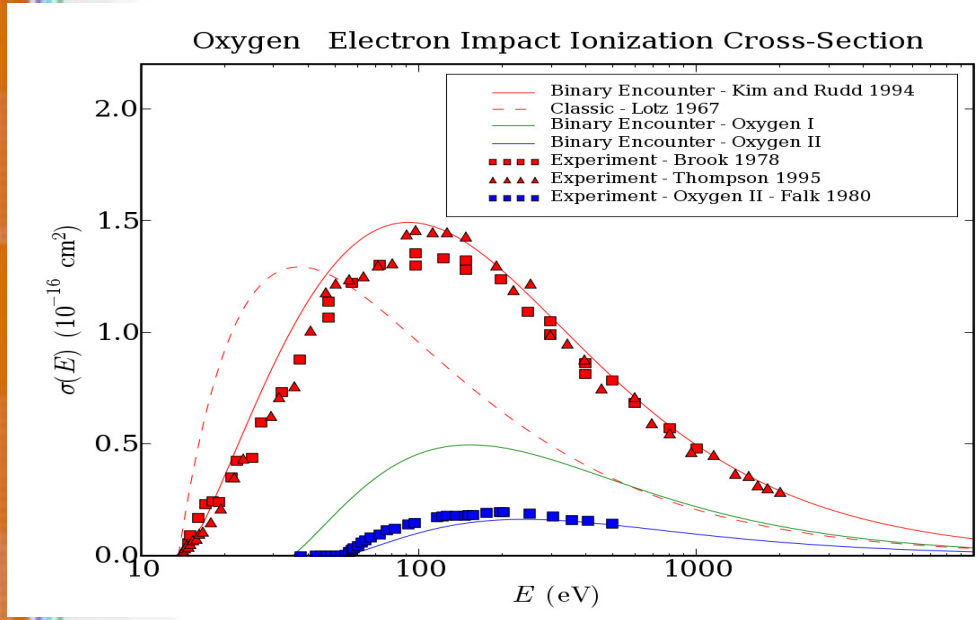
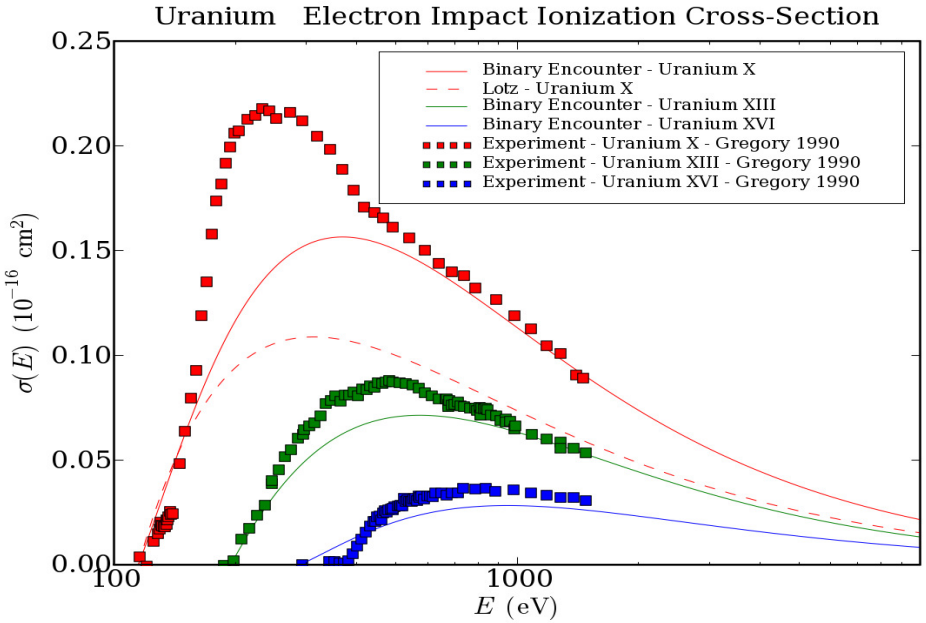


Figure: Paul Mullowney

Kinetic ionization model in VORPAL uses cross-section models in TxPhysics library

- Kinetic ionization based on DSMC algorithm
- Requires cross-section model for electron impact ionization
  - Variety of cross-section models available: Lotz, Shull&VanSteenberg, Kim&Rudd

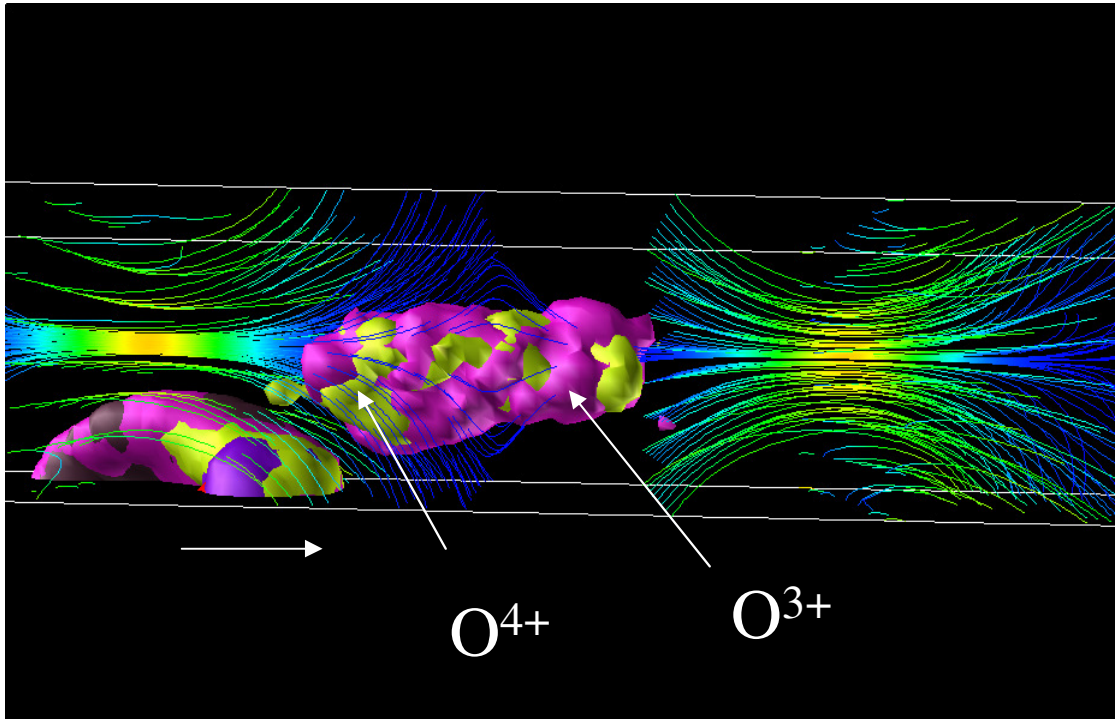




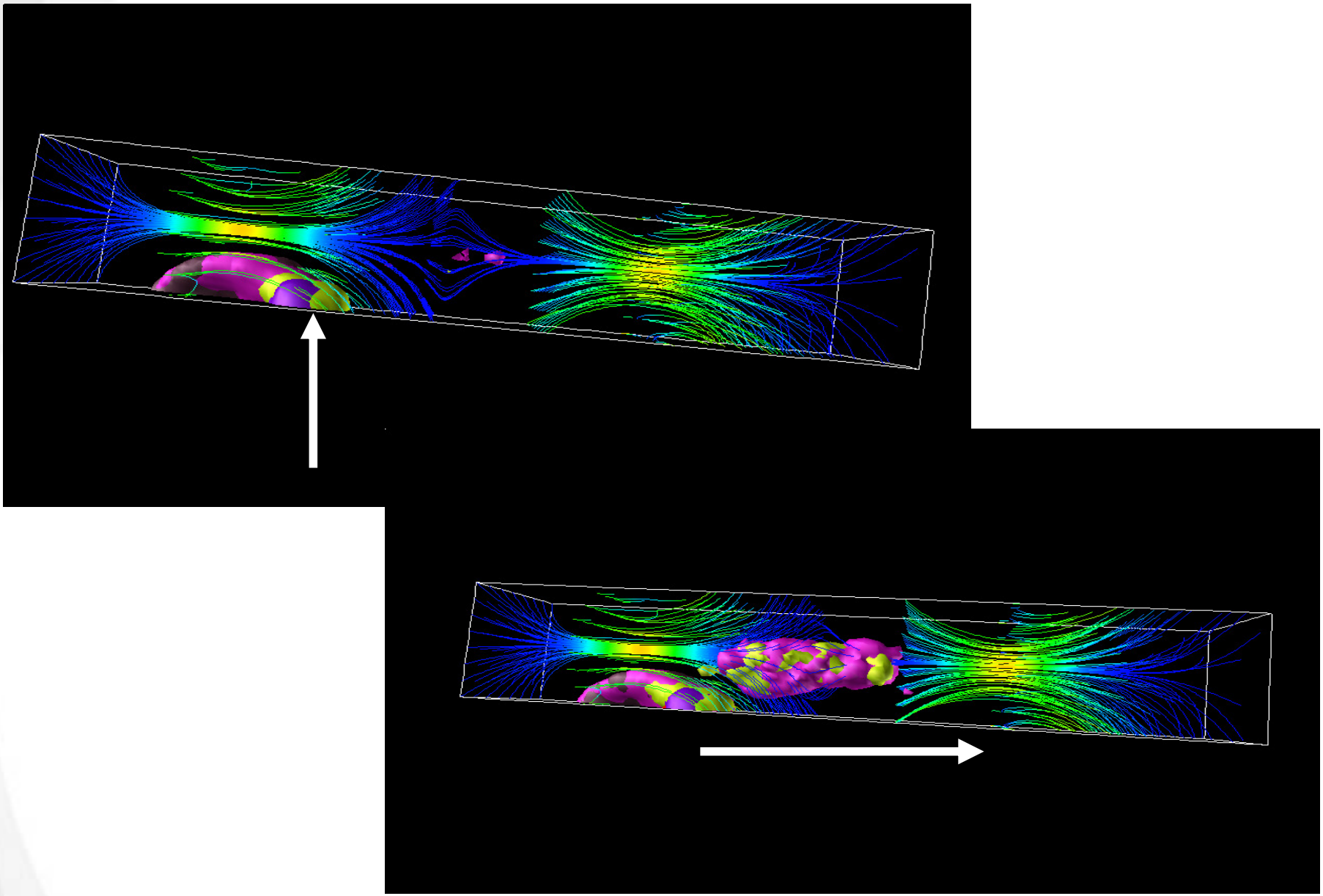
Figures: David Fillmore

Simulations show different ion populations for different neutral loading angles

- VENUS-like setup
- Neutral Oxygen injected at wall, close to bottle neck, radially or axially
- Initial simulations using scaled cross-sections

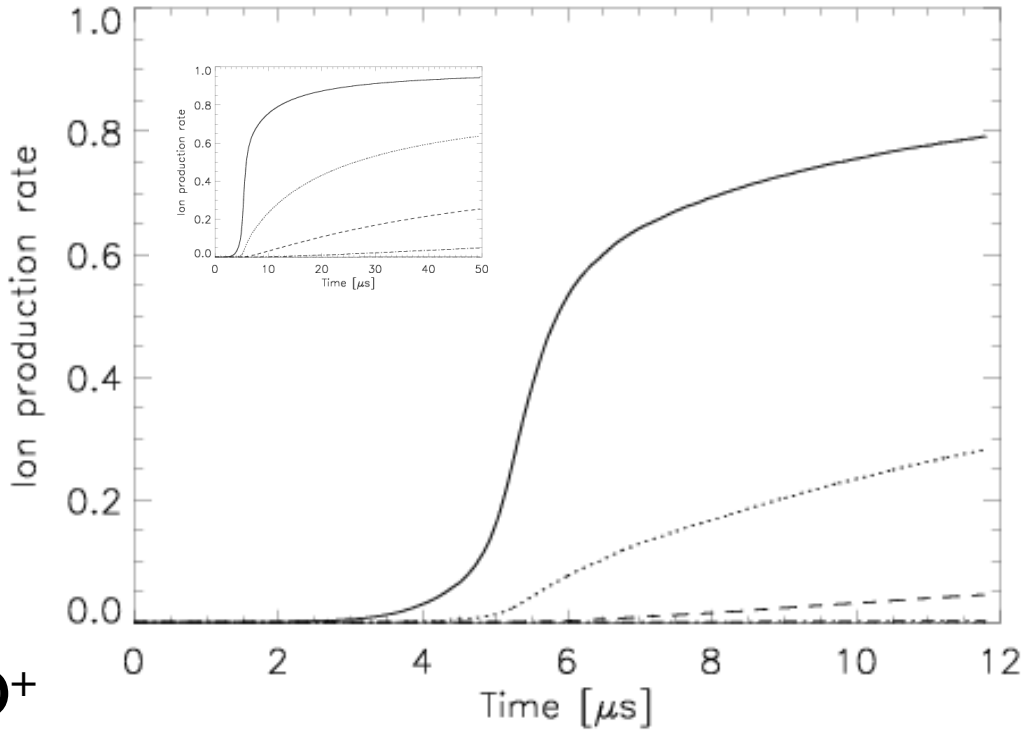


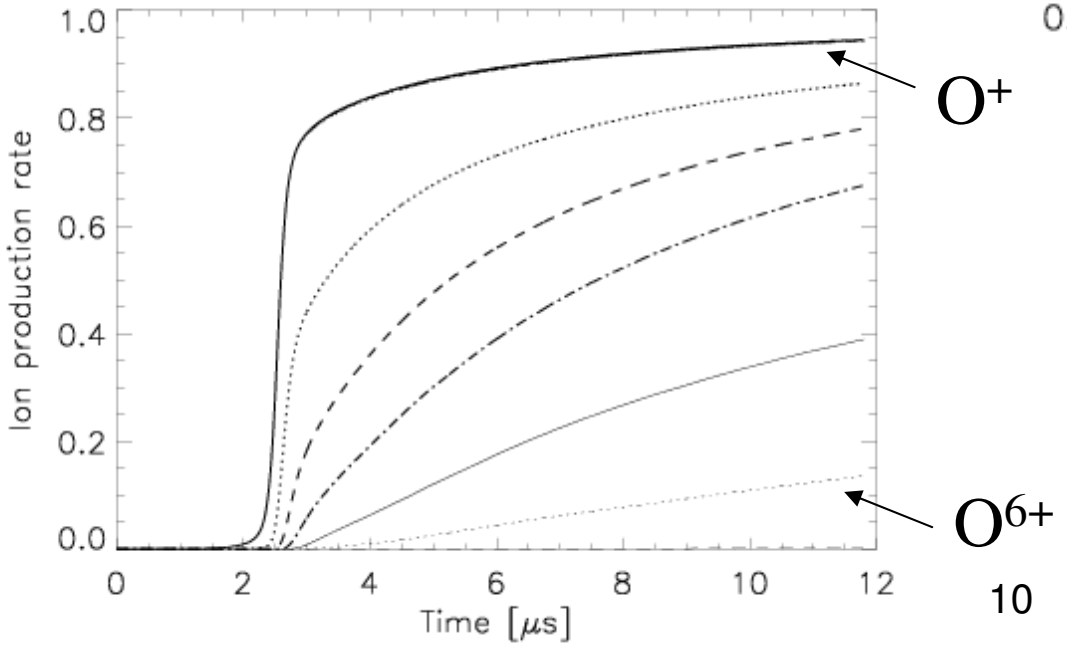
Loading angle effects ion population



Comparison for different loading angles

Radial loading





O^{+}

O^{6+}

Axial loading

Conclusions

- VORPAL is capable of simulating vapor loading in ECR
  - Parallel ES solver, ionization model, higher-order particles
- Preliminary simulations show effect of different loading angles
  - Need more convergence studies
- Future work: Benchmarks with measurements
  - Loading at different oven locations