Multi-scale Characterization of Adverse Satellite Surface Conditions in a Thruster Backflow Environment

Deborah Levin, UIUC

Students: Revathi Jambunathan, Ozgur Tumuklu, and Nakul Nuwal

Raymond Sedwick, U of Md

Students: Jarred Young, Eric Smith, and Joshua Sloane

Space Power Workshop, 17-19 May 2017, Arlington, VA

AFOSR Grant No. AF FA9550-16-1-0193

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications.

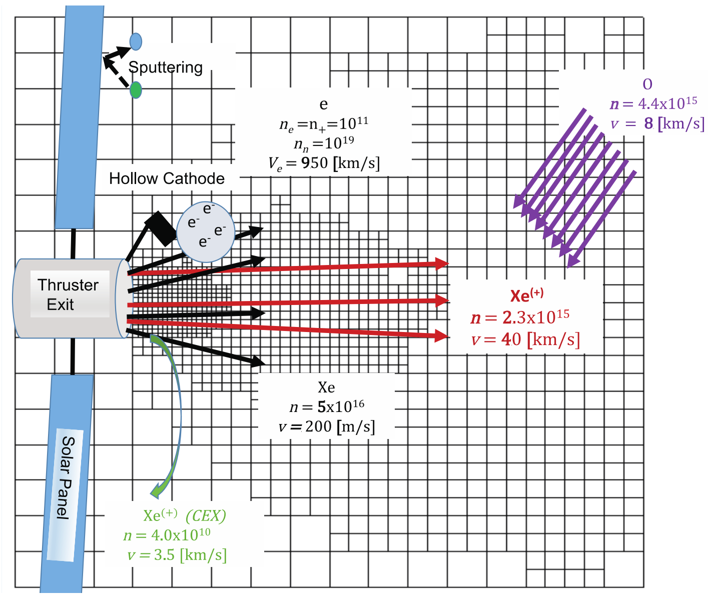
Multi-scale Characterization of Adverse Satellite Surface Conditions in a Thruster Backflow Environment

Deborah Levin

Raymond Sedwick

Project Goals

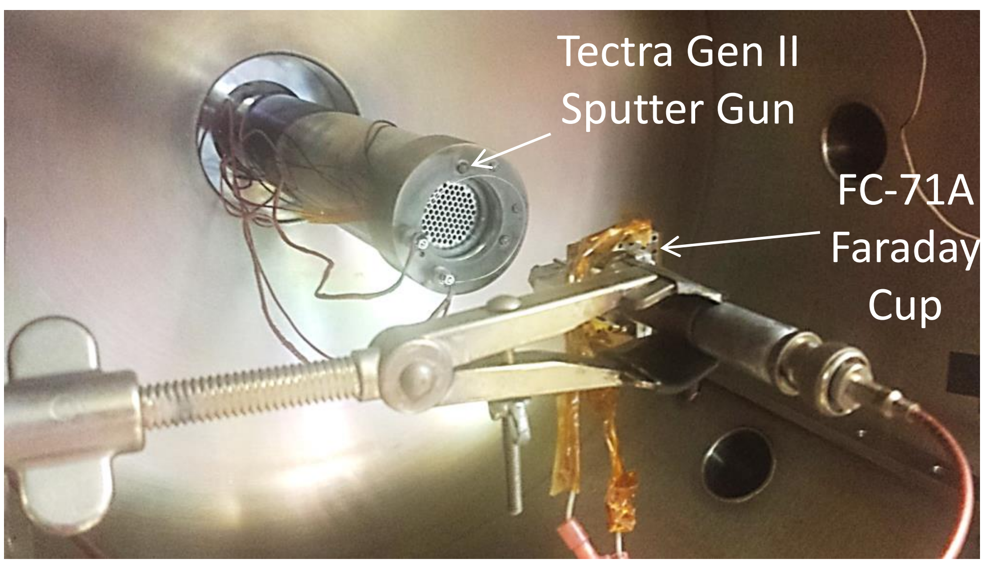
Multiple, complex phenomena, huge length and time scale variations



- **Main objective is to characterize the back flow contamination environment created by EP plumes, their interaction with the spacecraft environment, and neutralizer sources, using state-of-the-art high performance peta-scale computations and accurate measurements of anti-reflective (AR) coating erosion due to both ion and particulate sources.**
- **Measure sputtering rates and erosion depths of MgF_2 and ITO coated silicon wafers with well characterized ion and space debris sources.**
- **Generalize the AMR/Octree PIC approach to include a full solution of Poisson's equation**
- **Target erosion of solar cell anti-reflective (AR) coatings and aluminized Mylar since both the AR coating (0.05 - 0.1 μm) and the aluminized Mylar layer (0.5 μm) are very thin and significant material loss can greatly impact power generation and thermal control.**
- **Use flexible grid-free linear octree structure to capture the complex surface regression of micron-sized degradation measurements.**

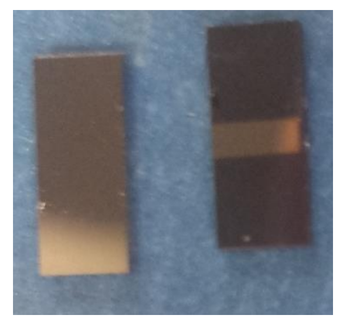
Evaluation of AR/Mylar coatings to Xe ion exposure

- Loss of thin antireflective (AR) coverglass and aluminized Mylar coatings due to plume sputter can significantly impact spacecraft power generation and thermal protection
- Previous methods of measuring sputter yield rely on measuring mass change
  - Large amount of sputter gas and sample sputtering required for measurable yield
- Current approach uses optical profilometry to measure erosion depth
  - 100s of silicon wafers coated with almost any material using vapor deposition
  - Edges of sample shielded for reference
  - Current measured w/Faraday cup



3x7 silicon wafers coated with:

- 1000 nm of Al
- 500 nm of ITO
- 600 nm of MgF_2

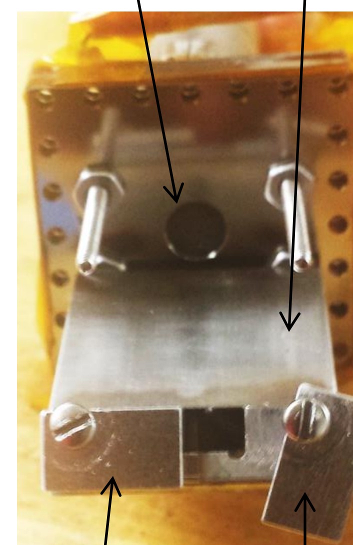


Pre-Sputter

Post-Sputter

Angled Sample Holder

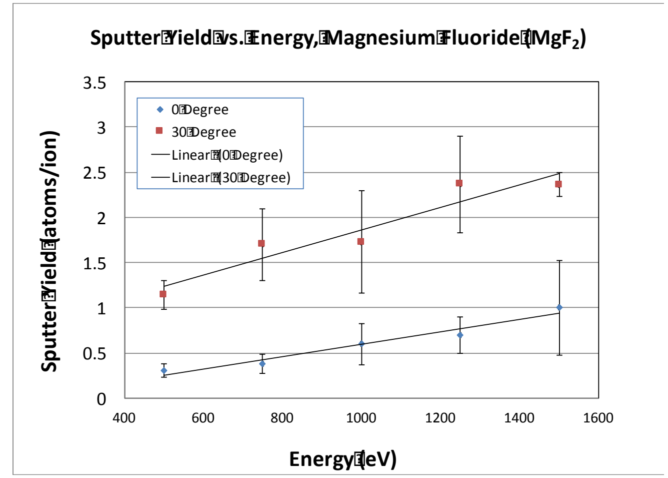
Beam Orifice

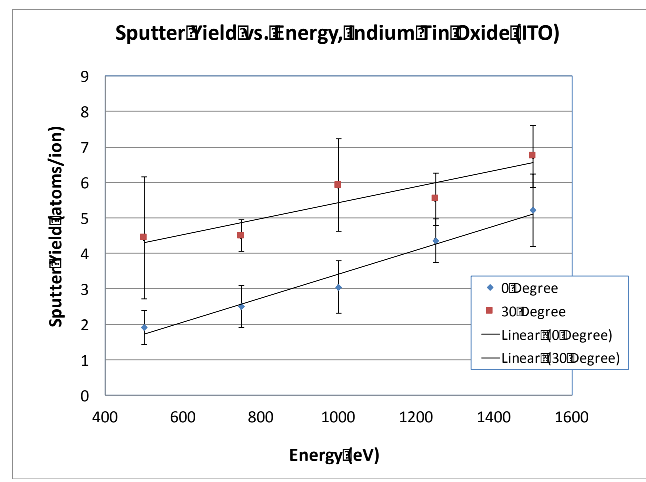


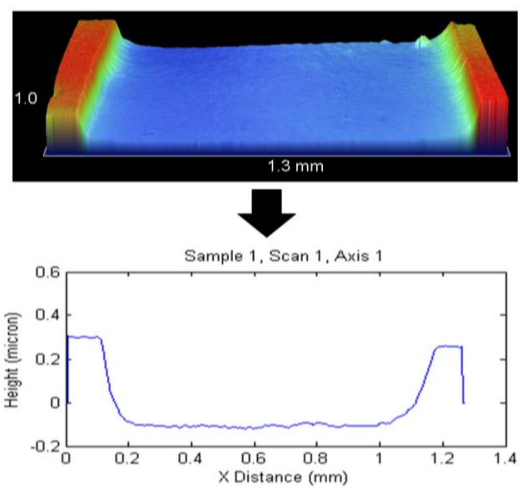
Sputter Shields

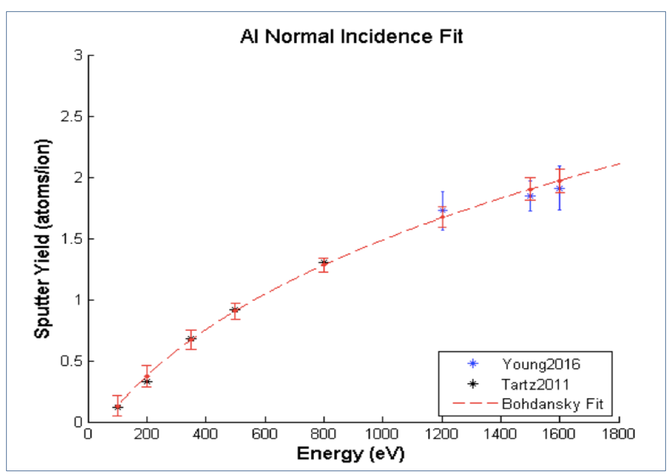
Profilometer Output and Preliminary Results

- Full 2-D map of surface depth can be obtained from optical profilometer
  - Sputter depth relative to unexposed reference height is calculated as an average across the majority of the exposed surface
- Preliminary results obtained for Al, ITO and MgF_2 at multiple incidence angles
  - Can reduce error by increasing erosion depth
- Example of empirical fit (Bohdansky) to Al data
  - New data extends out to 1600 eV







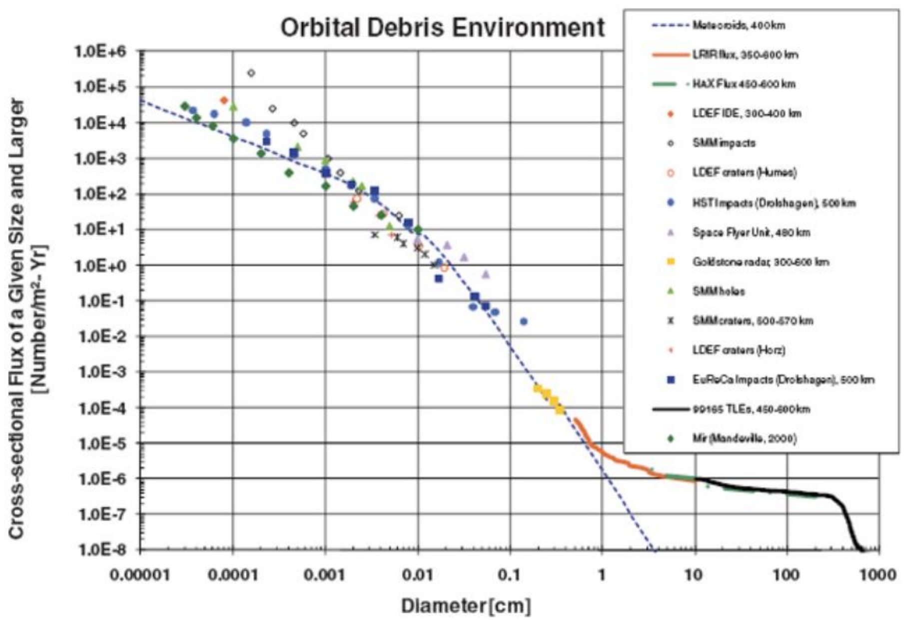


Hypervelocity Dust Impact Damage

- Extrapolation of micrometeoroid flux models to nanometer+ scales
  - Fluxes of at least 10-100 /mm^2/yr are predicted

- At orbital velocities, such particles will have kinetic energies of ~0.5 eV/amu
  - For 1-10 nm Al particles (e.g.), this is 10 keV – 10 MeV per particle
  - May substantially damage thin coatings beyond impact location
  - Difficult to generate representative particles in lab using electrostatic acceleration
  - Charge/mass decreases as particle size increases
- Laser ablation (1064 nm laser)
  - 120 µm spot @ ~70 mJ/mm^2/pulse
  - Ablation depth ~435 nm (Al)
  - ~17 eV/atom deposited into surface
  - Melting+Vaporization ~ 3eV/atom
  - ~14 eV/atom --> 0.51 eV/amu

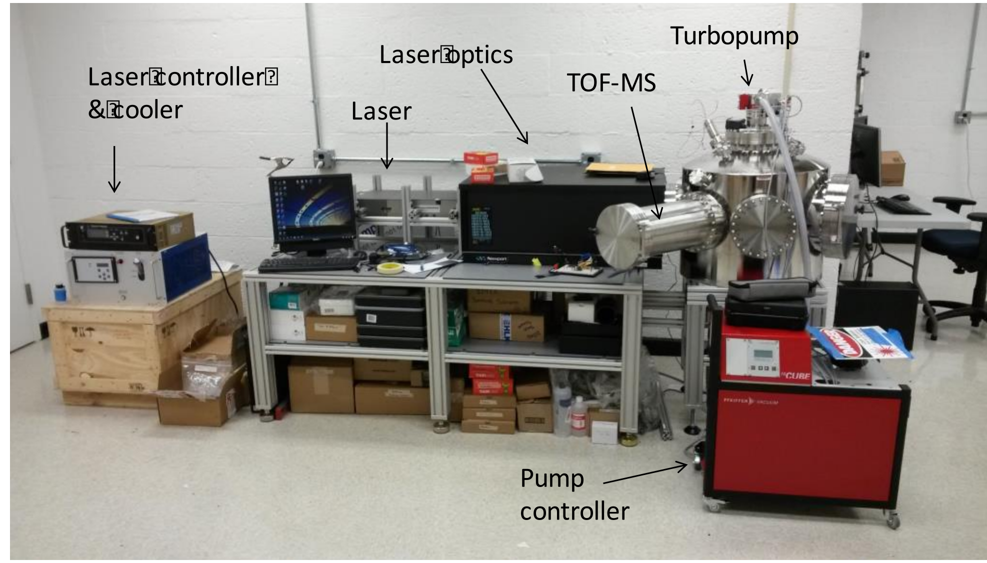
- Ablation products can achieve orbital relevant particle energies
- Can particles of desired size be created?

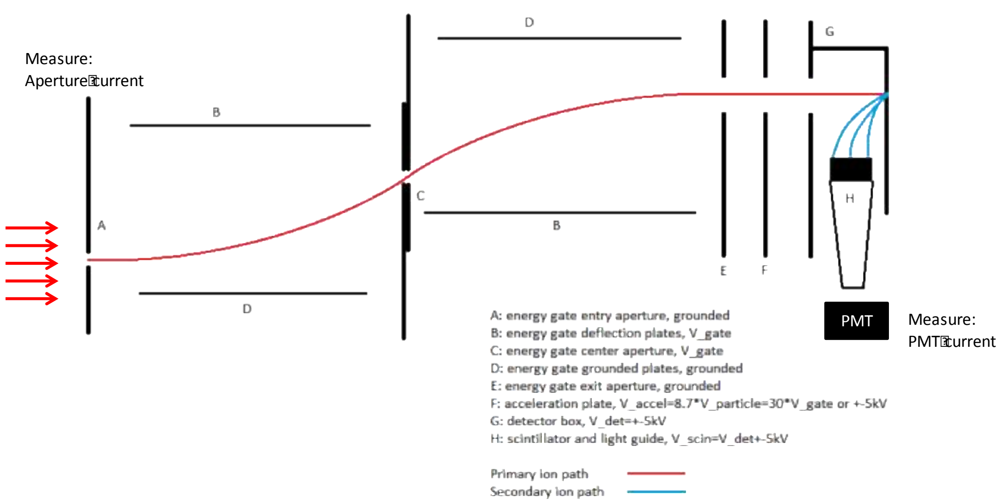


Source: NASA JSC Orbital Debris Program Office

Space Hazard Response Characterization (SHaRC)

- AFOSR funded DURIP
- Laser ablation of targets in vacuum
  - 1064 nm, 0.7 ns pulse @ 0.8 mJ
  - 40-90 kHz pulse rate
  - Spot diameter 10-3000 μm
- 3-axis positioning of target provides laser spot location (and flux) control
- Ablation plume measured by Time-of-Flight Mass Spectrometer (TOF-MS)



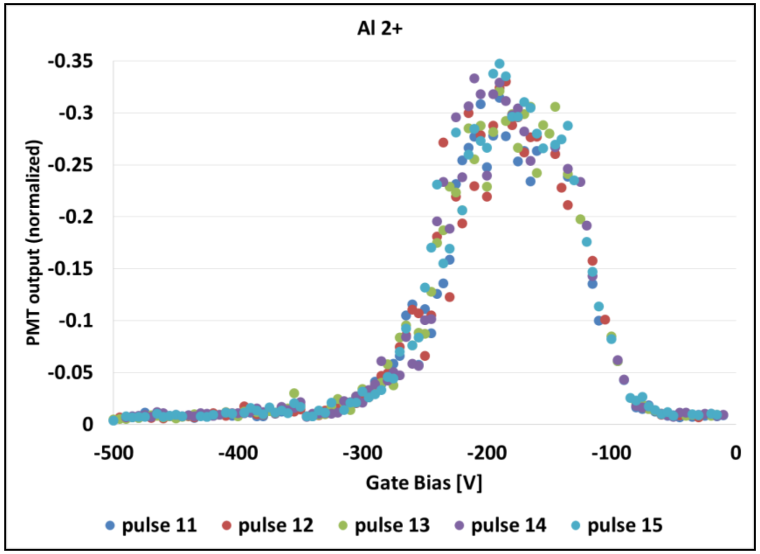


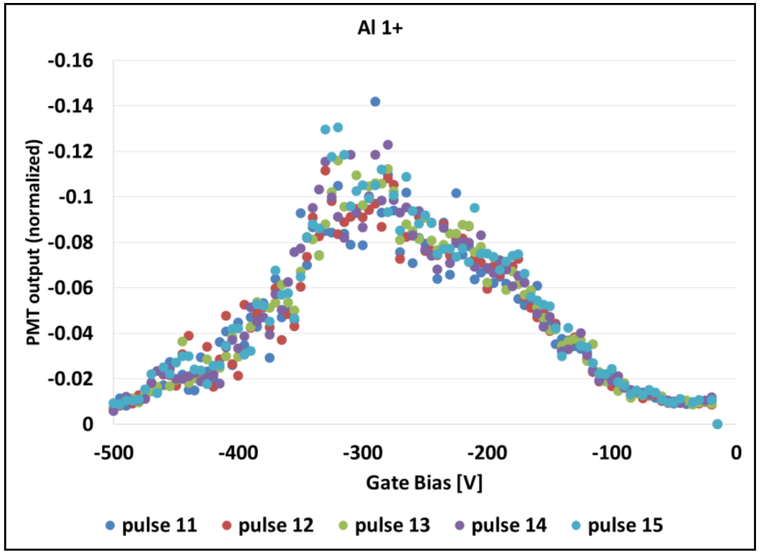
Instrument diagram (Josh Sloane)

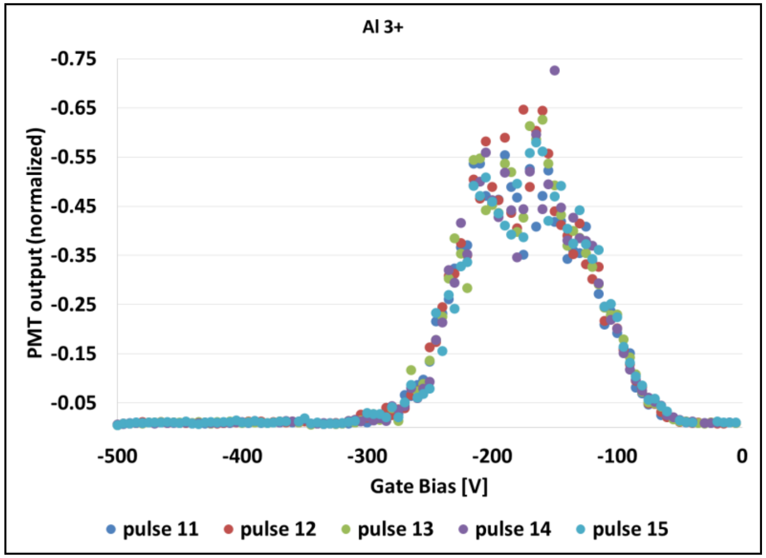
- TOF-MS
  - Independently determines
    - Mass
    - Charge
    - Velocity
- Fully characterizes ablation plume
- Replace detector plate with target
  - Can select specific particle types to impact target surface

SHaRC Facility Preliminary Results

- Initial calibration accomplished using well-characterized electrospray source (MIT)
  - Heavy(-ish) particle detection (~300 amu)
  - Nanoparticles up to ~50,000 amu
- Preliminary characterization of ablation
  - Detection of Al 1+, Al 2+ and Al 3+
  - Excellent selectivity
  - Particle energies shown are in keV range
- Early indication of nanoparticle generation
- Significant amount of data to analyze

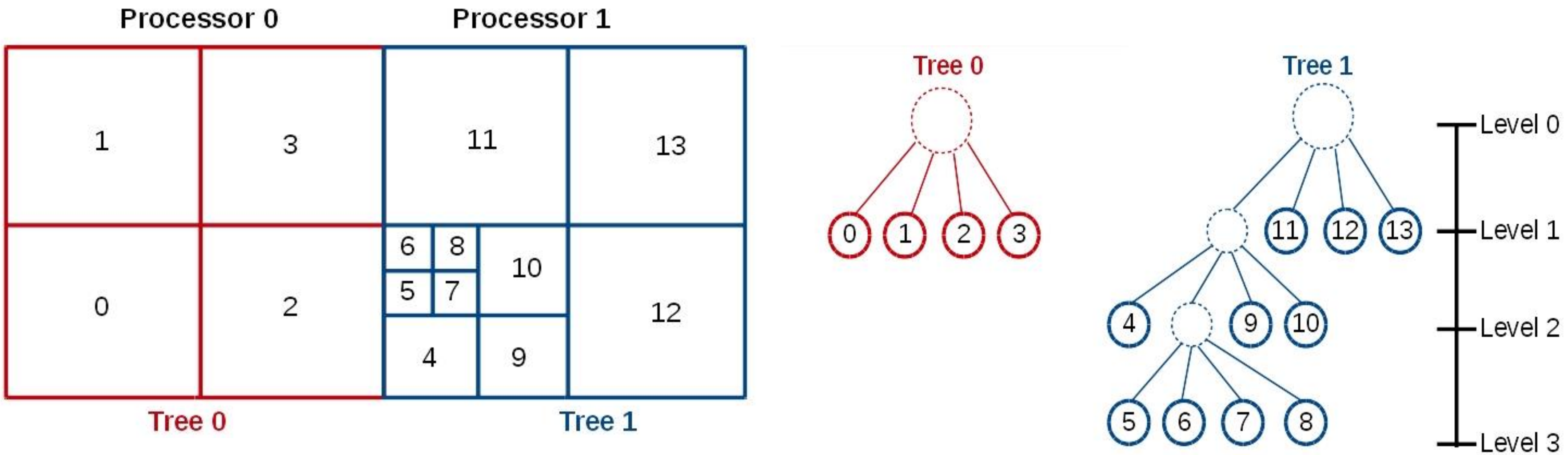






Computational challenges – new algorithmic developments for DSMC/PIC on GPUs

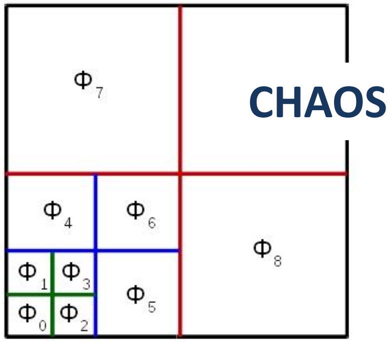
- **Collisions (DSMC), $\lambda \sim O(10^{-3}m)$ and Electric Field (PIC), $\lambda_D \sim O(10^{-6}m)$**
- **Same octree cannot be used for DSMC & PIC since required leaf node sizes differ $O(10^3)$**
- **Solution : use two linearized Morton-ordered FOTs with own, λ or λ_D**



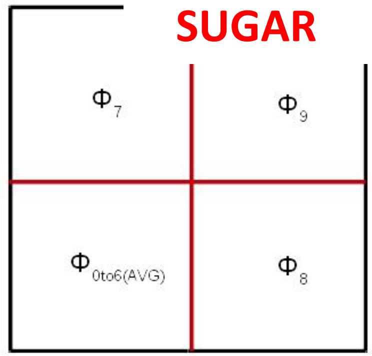
2:1 criteria for E-FOT (PIC)

- **Max difference between neighboring leaf nodes should be ONE, aka 2:1.**
- **Why 2:1? Maintain accuracy in gradient calculations for solution of Poisson's eq.**
- **Achieve 2:1 balance in two stages: local and global.**

Methodology for E-field Computation : SUGAR & CHAOS



VS



At interface of leaf nodes 3 and 5 :

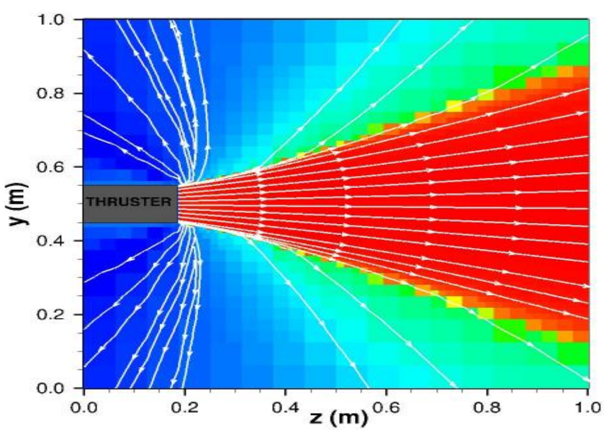
CHAOS $$\left(\frac{dF}{dx}\right)_{3,5} = \frac{F_5 - F_3}{dx_{3,5}}$$

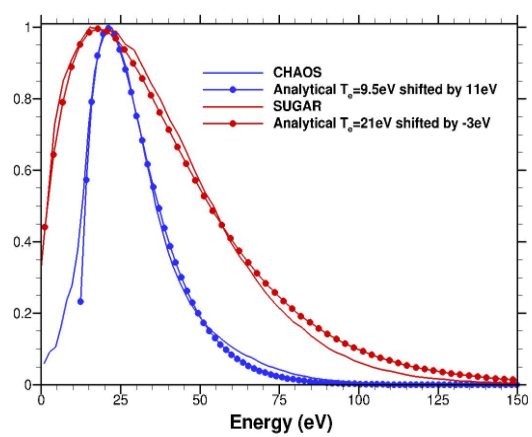
SUGAR $$\left(\frac{dF}{dx}\right) = \frac{F_8 - F_{0to6}}{dx}$$

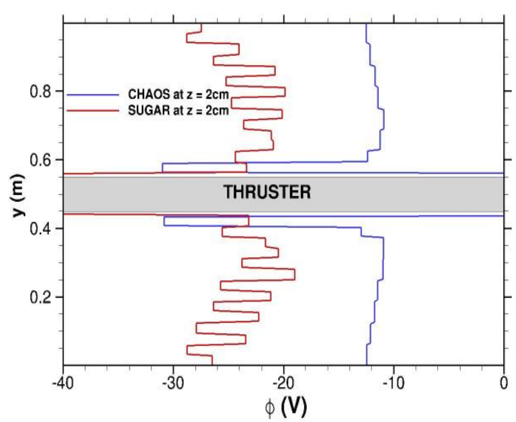
- CHAOS with Morton encoding, determines face neighbors and computes gradient exactly.
- Can capture gradients

- SUGAR with pointer tree, does not recognize face neighbors from different levels.
- Potential is averaged, and gradient is computed at coarsest level.
- Cannot capture gradients

Both Assuming Boltzmann Distribution

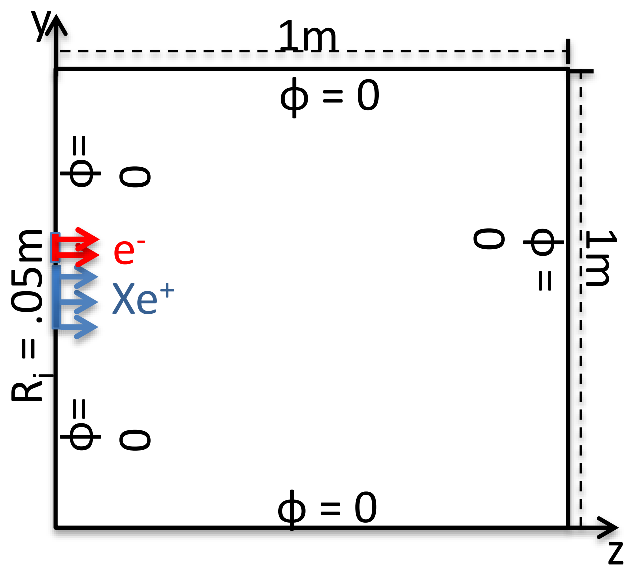




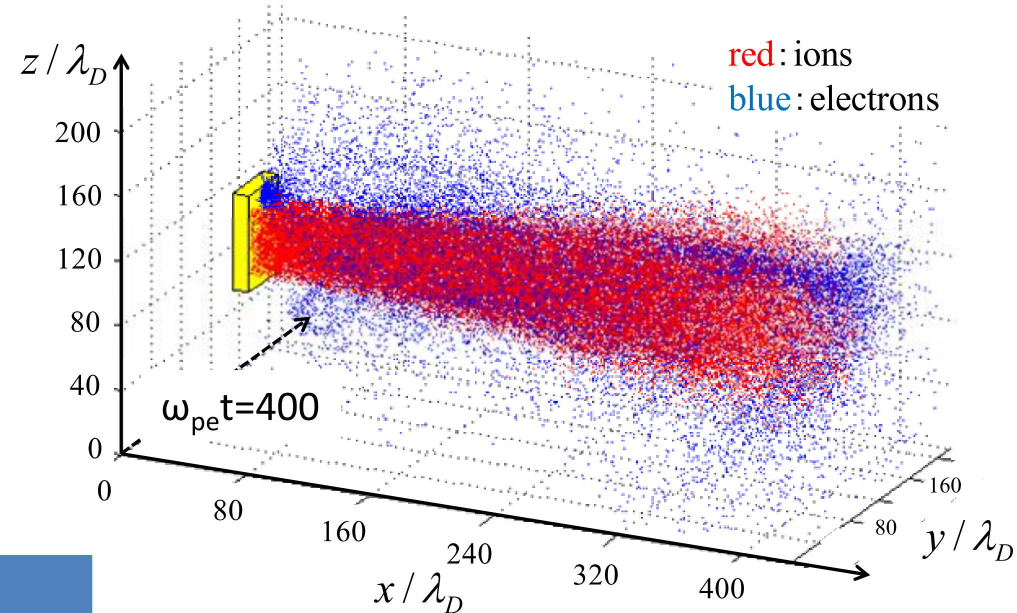


Mesothermal Collisionless Plasma : Shifted e^- Source

- Motivation : To study the effect of a shifted electron source on the neutralization and electron dynamics of the plume.
- Validate CHAOS with Usui et al.



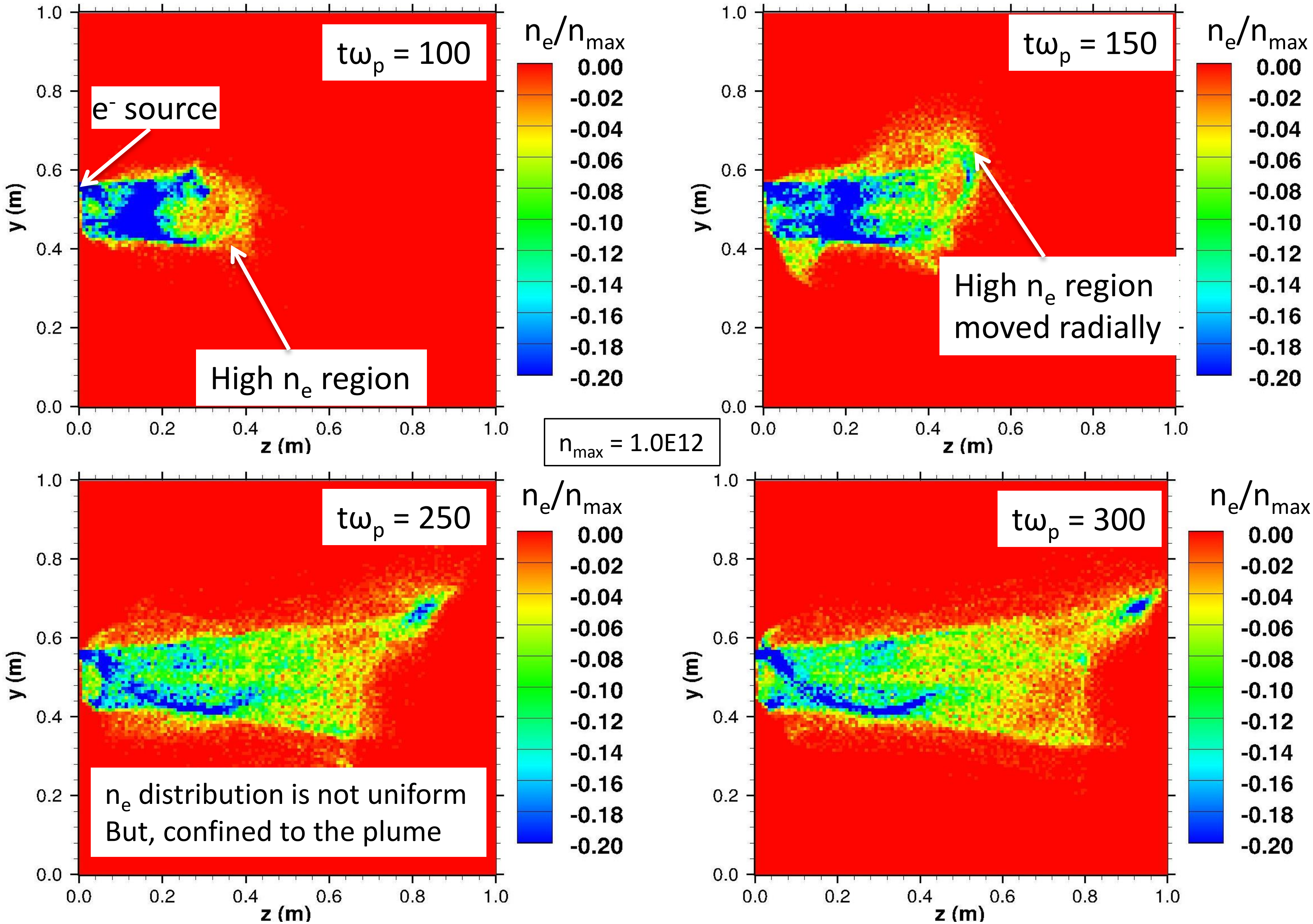
Source : Usui at el.,IUPAP Conf. Comp Plas. 2017.



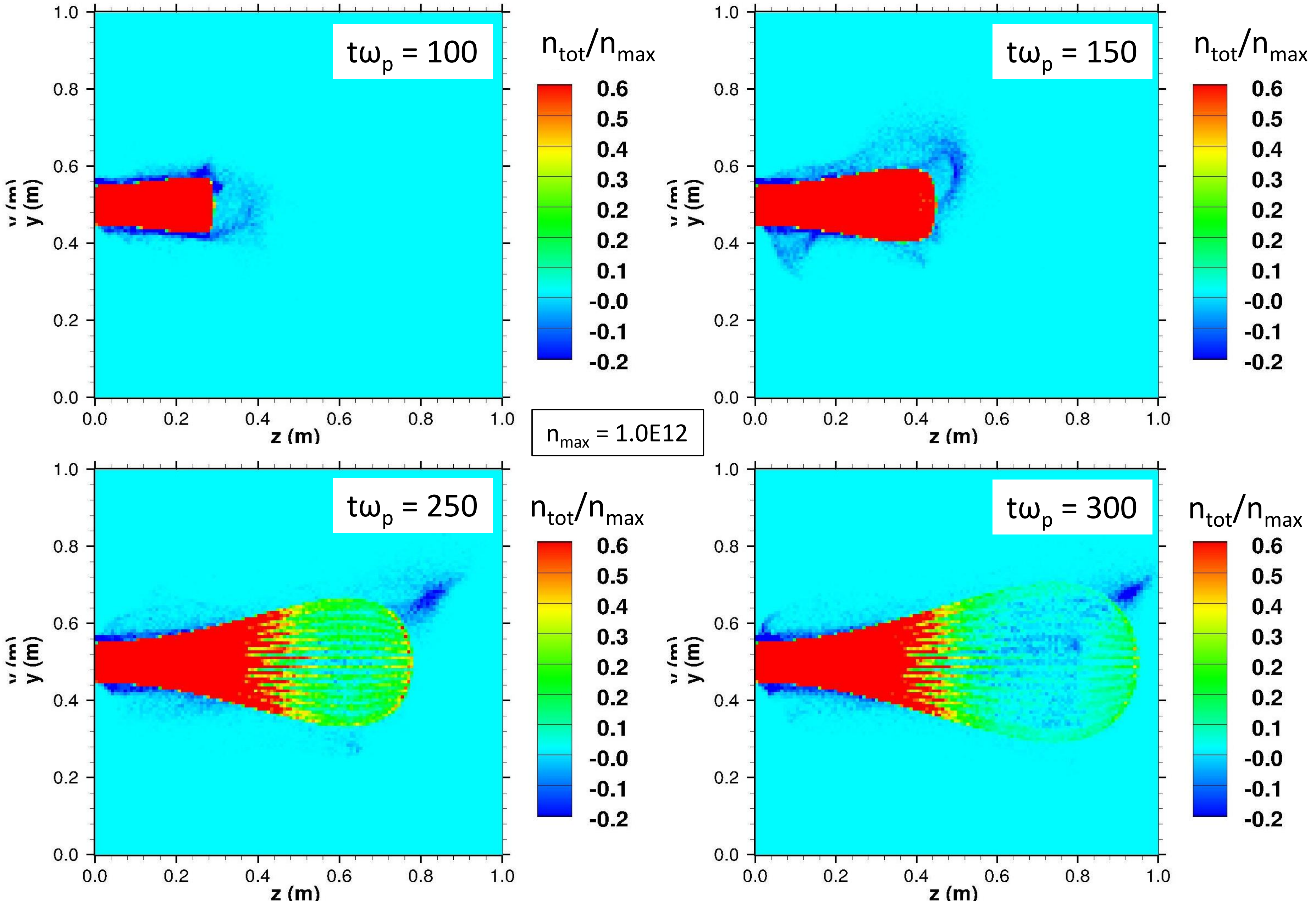
Input Parameter	Xe^+	e-
Num. density (#/m³)	5×10^{12}	1.0×10^{13}
Temperature (eV)	0.04	2
Bulk Velocity (m/s)	472,000	0.
[illegible]	[illegible]	[illegible]

- e^- source above ion source, with $R_e = 0.01$m.
- e^- thermal vel = 5.9×10^5 m/s
- Plasma freq (w_p) = 1.78×10^8 rad/s
- $dt = 0.05/w_p$
- $v_{te}/v_{ib} = 1.25$

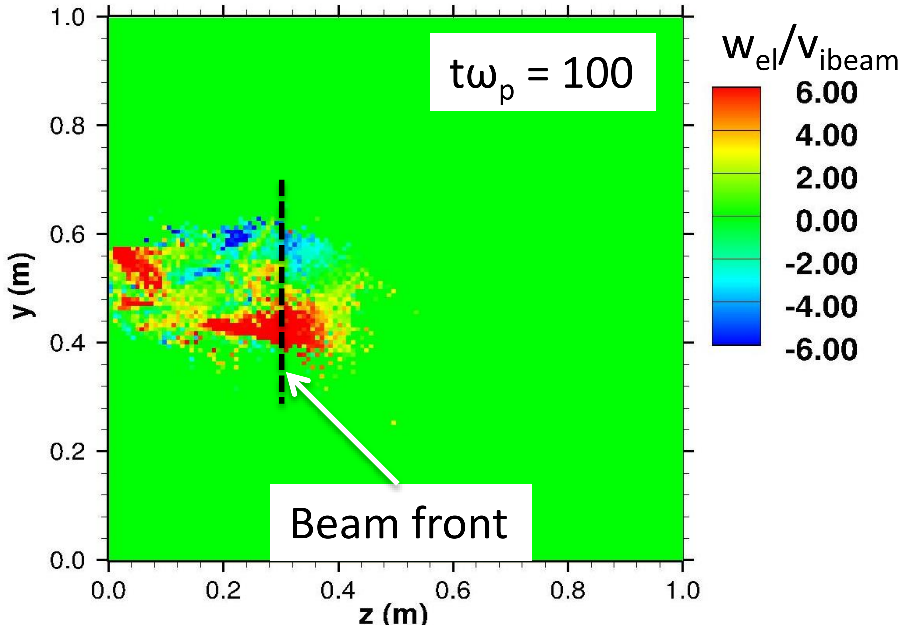
Transient electron charge distribution

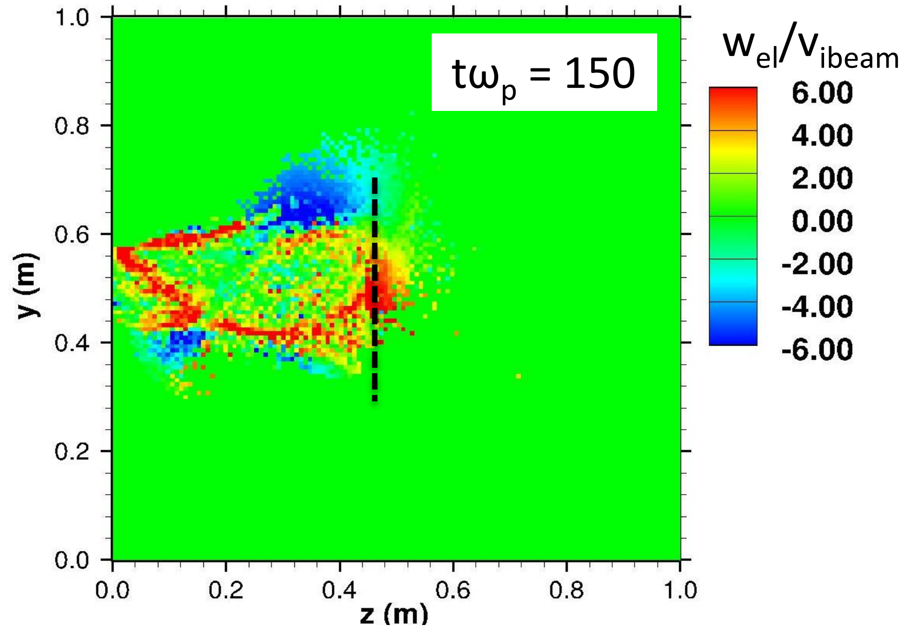


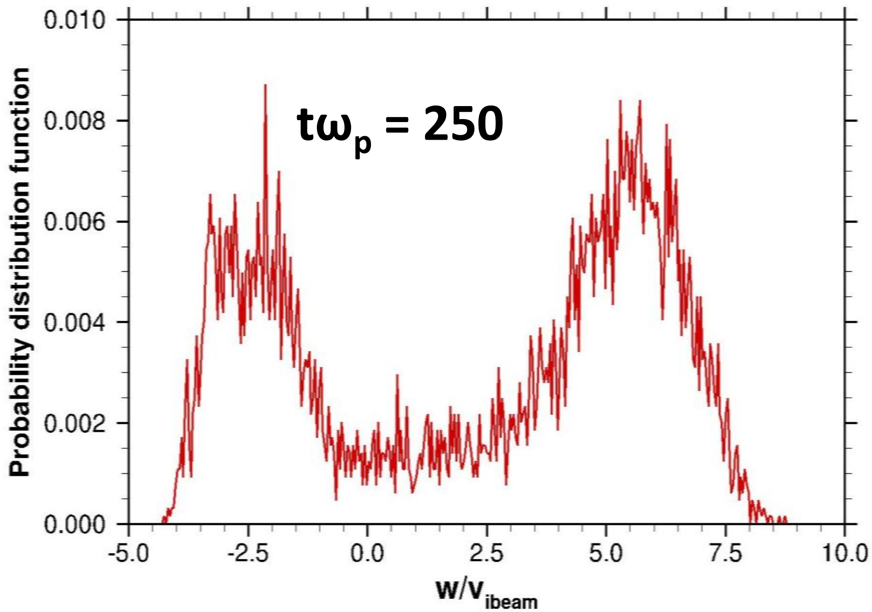
Transient total charge distribution

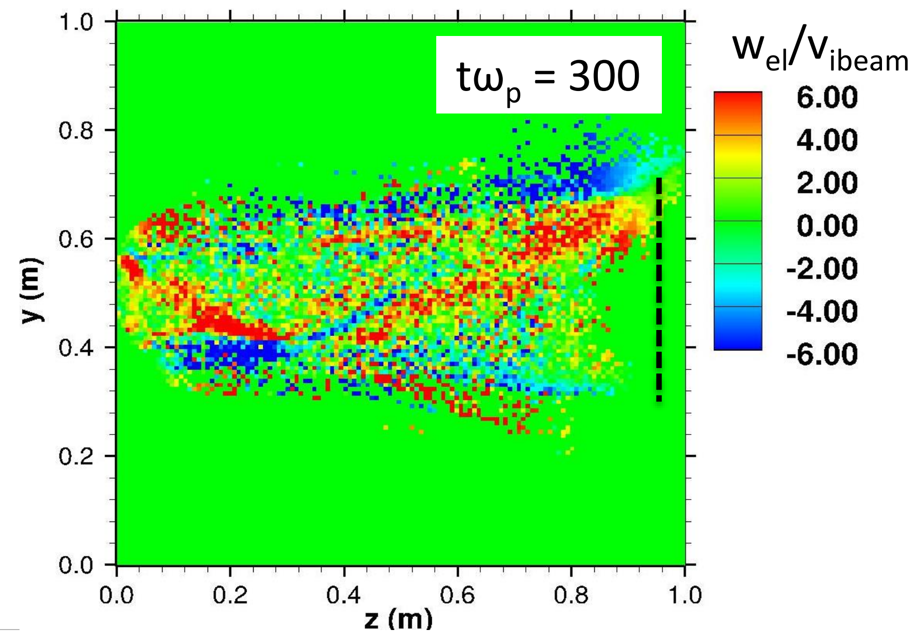


Transient e⁻ streamwise velocity : Bouncing effect

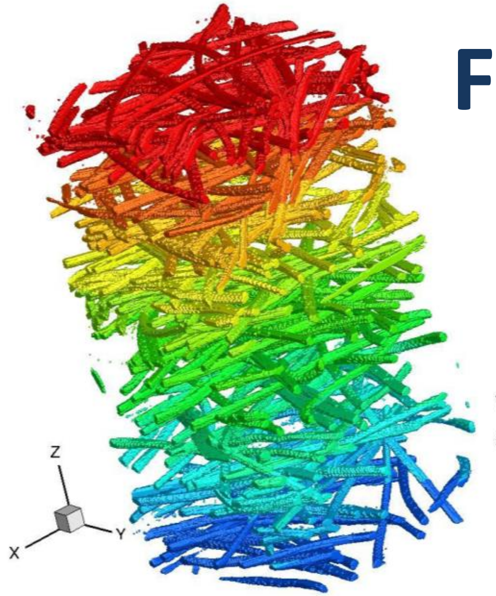


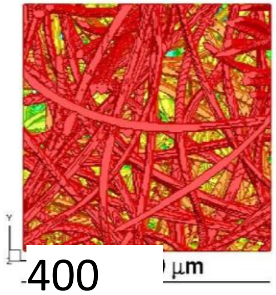




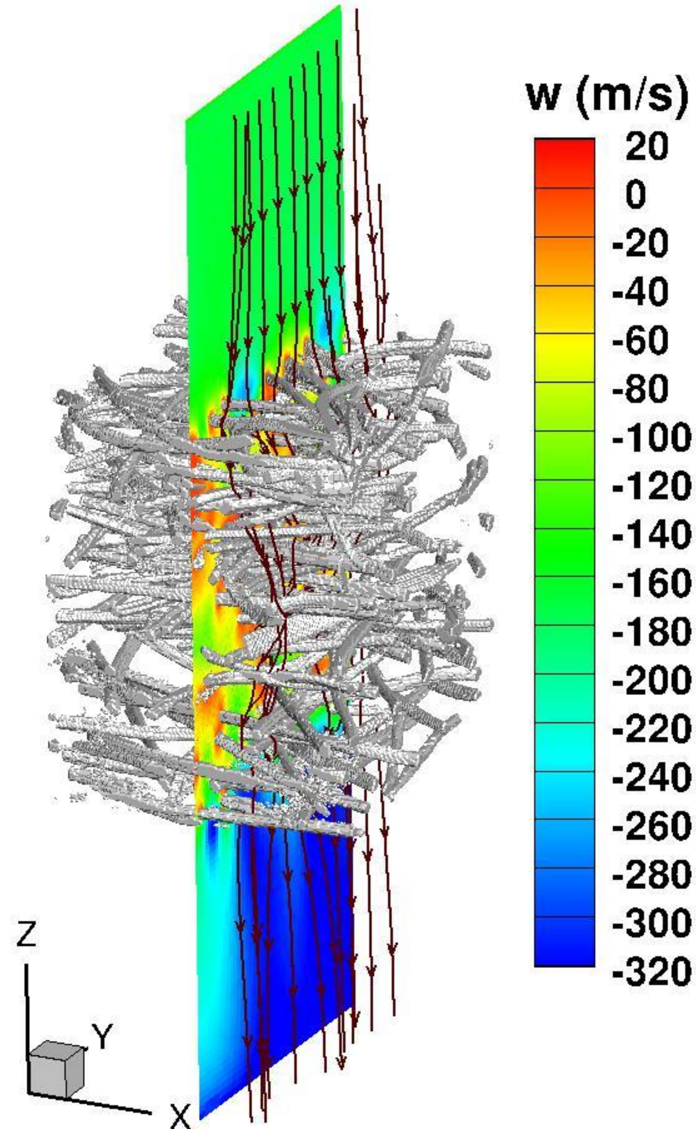


Fiber Felt TPS Material – Test Cases

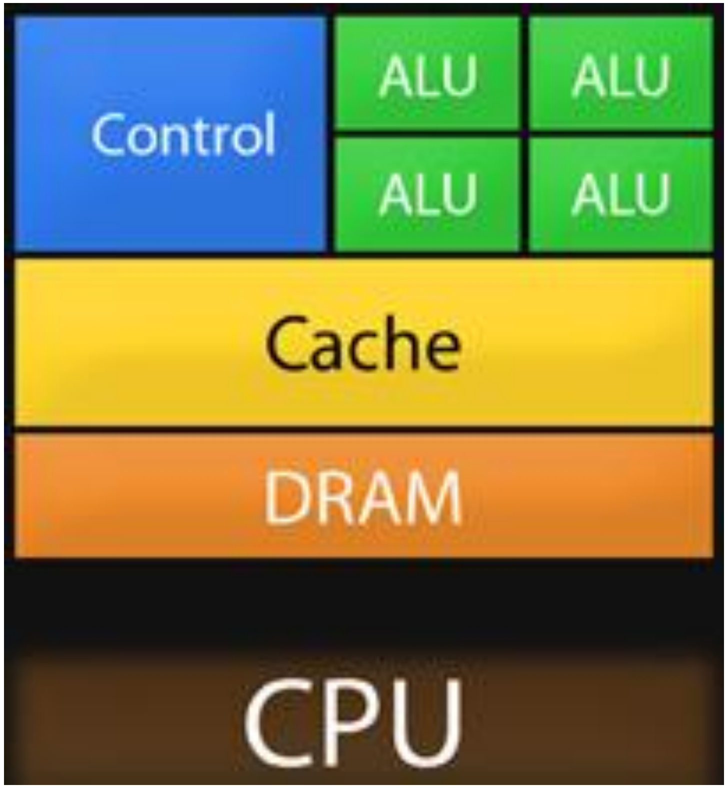




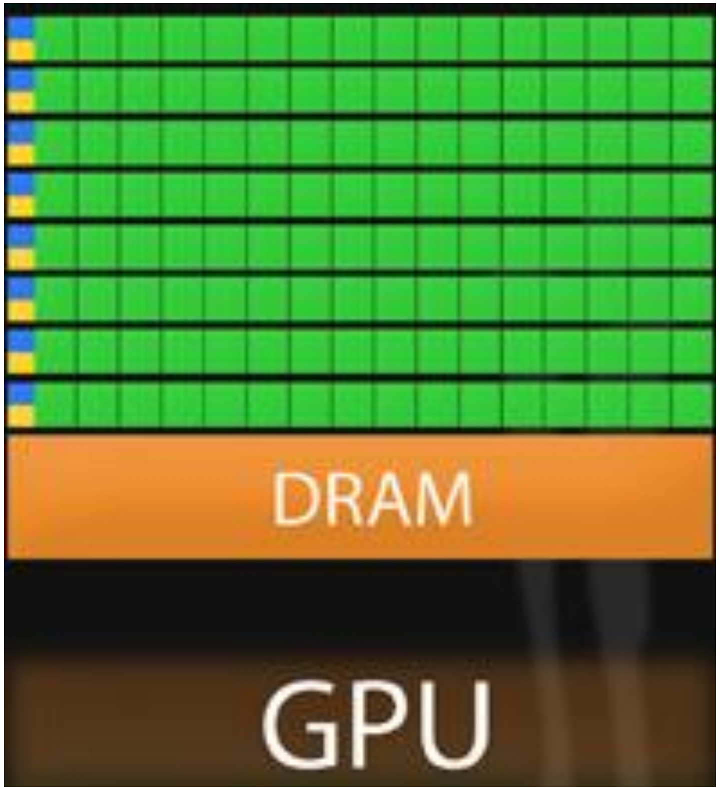
Input Parameter	Case A	Case B
Domain size (µm)	400 x 400 x 1200	
Number density (#/m³)	9×10^{21}	9×10^{22}
Number of simulated particles in domain	3 M	60 M
Time step (s)	2×10^{-9}	1×10^{-9}
Number of Samples	100,000	250,000
Inlet Temperature (K)	2000	2000



GPU Architecture



Low latency



High bandwidth

Tesla K20 : 2880 cores

Courtesy: NVIDIA talk

Hybrid MPI-CUDA Philosophy

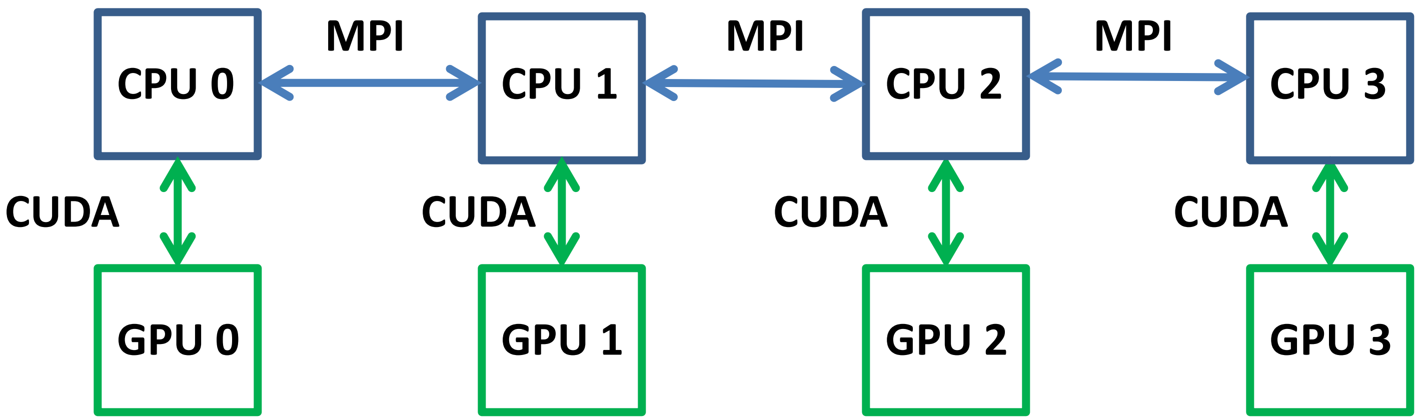
Why multi-GPU?

For large scale problems, ~1 billion particles, 1.5 million surface elements (IB) :

1 GPU limited memory (6GB in Tesla K20)

General principle for multi-GPU codes :

- Equal distribution of computational work
- Transfer data : CPU -> GPU using CUDA-API
- Data communication between GPUs : using CUDA + MPI + CUDA



Simulation and Run-time comparison : Single Source

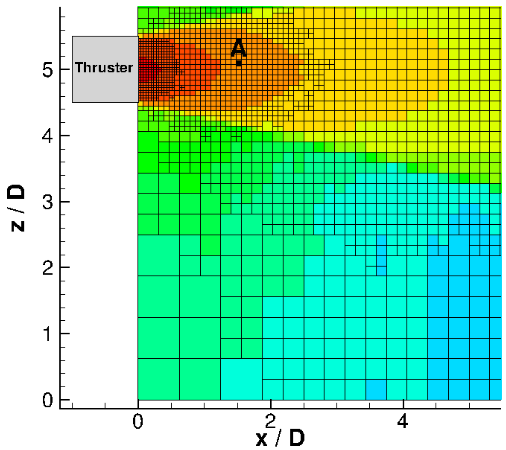
Computational Parameters	CHAOS (3D)	Hu et al. (2D)	CHAOS estimation (for Hu et al case)
Thruster Exit number density	1.0 E+13	1.0E+15	1.0E+15
Grid Size (total leaf nodes for octree in CHAOS)	262,144	409,600 (2D uniform grid)	15 Million
Number of particles, million	5	25	100
No. of GPUs (CPUs for Hu et al.)	8 GPUs	128 CPUs	16 GPUs
Simulation Run Time	5 h	8 h	24 h

- A uniform grid in 3D would require ~100 million cells, octree reduces it by a factor of 7.
- GPUs vs. CPUs, decreases the run time by at least a factor of 5.
- Octrees in combination with GPUs, decreases the total run-time by at least a factor of 10, compared to uniform grid solvers on CPUs.
- ***Next step: implement and validate MCC :*** Model hollow cathode plume and effect of thruster exit T_e on plume characteristics.

***Hu.Y and Wang,J., "Electron Properties of collisionless mesothermal plasma expansion: Fully kinetic Simulation", Plas.Sc., IEEE Trans., 2015.**

Ambient Atomic O Interactions with EP Thruster Species (1/2)

- Challenge: velocity and species densities vary by orders of magnitude. Therefore, species specific time step and particle weighting factors are used.



DSMC on AMR/Octree grid is used to model collision processes among neutral and ion species.

Collision mechanisms:

$$\mathrm{Xe}(p_1) + \mathrm{Xe}(p_2) \rightarrow \mathrm{Xe}(p_1') + \mathrm{Xe}(p_2')$$

$$\mathrm{Xe}^+(p_1) + \mathrm{Xe}(p_2) \rightarrow \mathrm{Xe}^+(p_1') + \mathrm{Xe}(p_2'), \mathrm{MEX}$$

$$\mathrm{Xe}^+(p_1) + \mathrm{Xe}(p_2) \rightarrow \mathrm{Xe}^+(p_2) + \mathrm{Xe}(p_1), \text{ CEX}$$

$$\mathrm{Xe}(p_1) + \mathrm{O}(p_2) \rightarrow \mathrm{Xe}(p_1') + O(p_2')$$

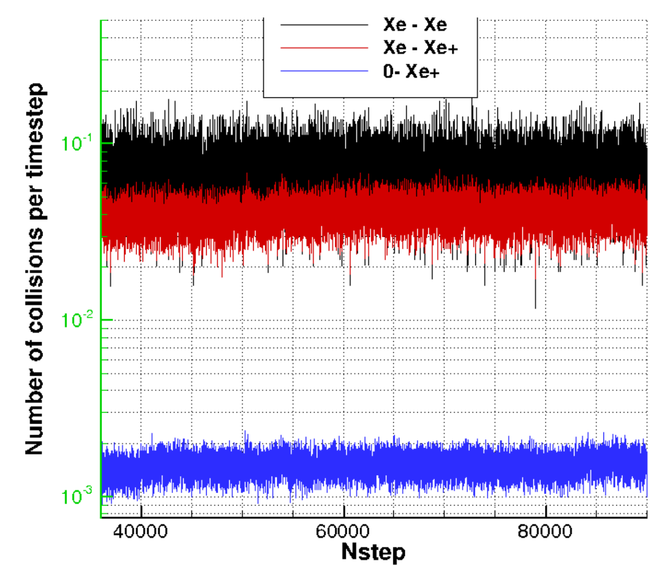
$$\mathrm{Xe}^+(p_1) + \mathrm{O}(p_2) \rightarrow \mathrm{Xe}^+(p_1') + \mathrm{O}(p_2'), \mathrm{MEX}$$

$$\mathrm{Xe}^+(p_1) + \mathrm{O}(p_2) \rightarrow \mathrm{O}^+(p_2) + \mathrm{Xe}(p_1), \text{ CEX}$$

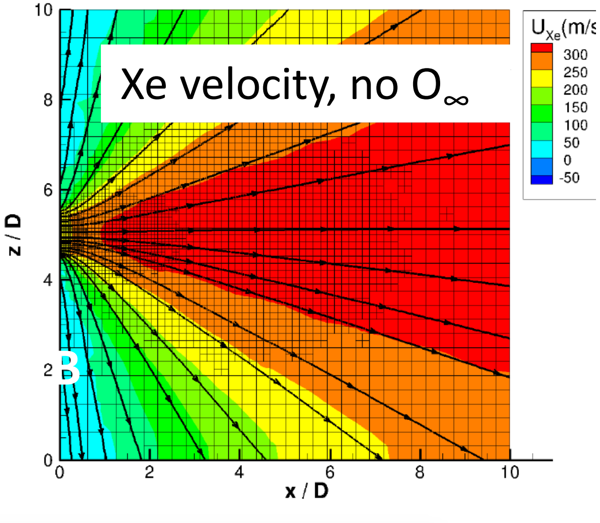
Thruster Plume Exit Conditions

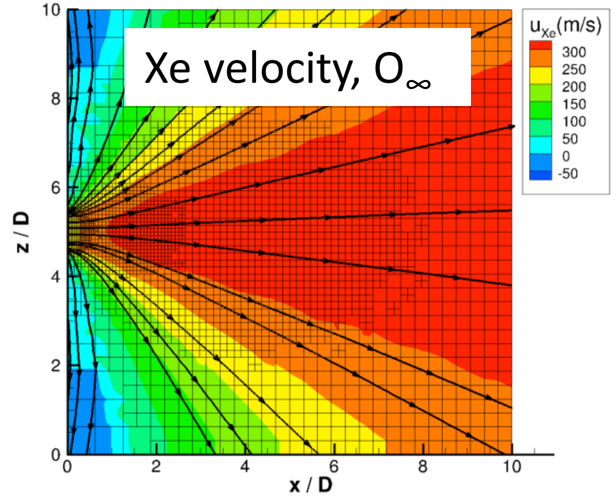
	Xe	**Xe^+**	**O**
n [m^{-3}] at thruster exit	4.6×10^{17}	2.3×10^{15}	6.0×10^{15}
u [m/s] at thruster exit	200	40,000	7,700
Timestep [s], Δt	4.9×10^{-6}	2.44×10^{-8}	2.44×10^{-7}
Weighting Factor, W	1.0	0.002	0.03
Tempe			

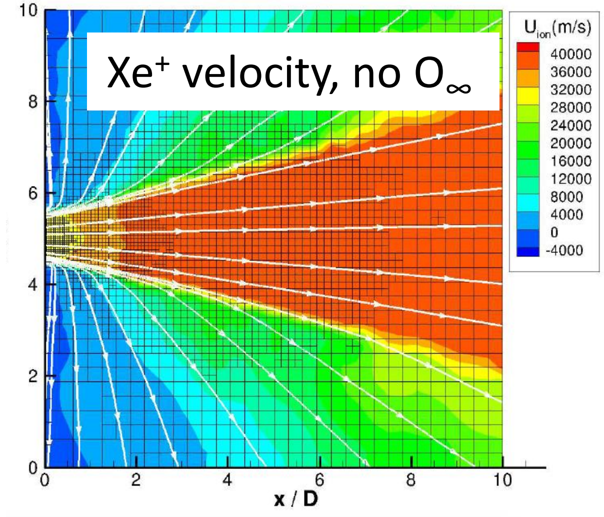
Number of Collisions at A

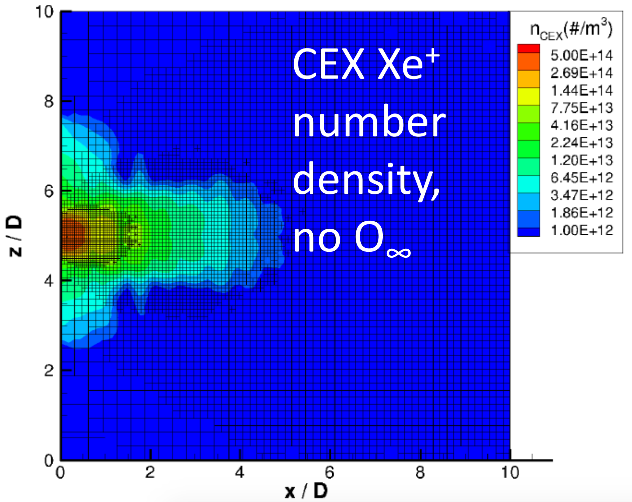


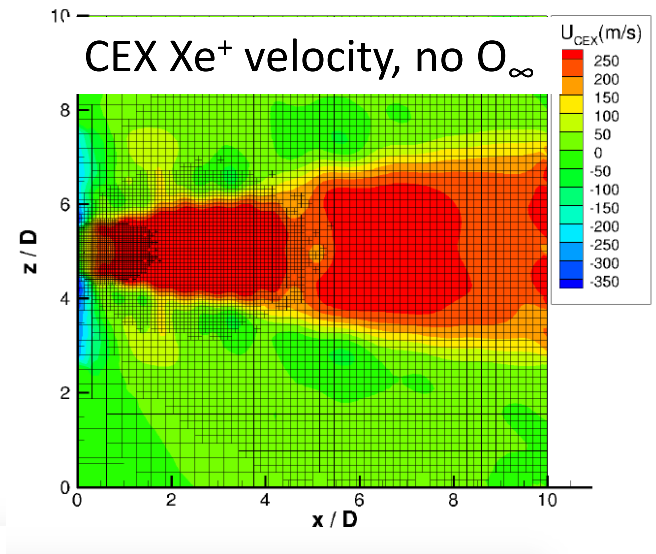
Ambient Atomic O Interactions with EP Thruster Species (2/2)











Fluxes at pt. B

Case	Xe/m^2s x 10^{15}	Xe^+/m^2s x 10^{14}
No O_∞	5.7	-4.0
O_∞, 0^o	1.3	-4.5
O_∞, 180^o	-0.55	-5.
O_∞, 225^o	-1.43	-5.9

- **Xe – O back scattering scales with altitude from 185 to 300 km.**

Multi-scale Characterization of Adverse Satellite Surface Conditions in a Thruster Backflow Environment

Potential Transitions

Deborah Levin

Raymond Sedwick

- The 2:1s method working on the AMR/Octree grid for a *kinetic* electron approach enables modeling electron ***non-equilibrium*** behavior as well as the time accurate evolution of electron distributions. Future work in understanding meta-materials formed by plasma columns will be possible through coupling of these simulations to Maxwell's equations.
- Important implications for electric plume modeling **by *continuum*** approaches that can also use the 2:1 development. Standard approaches use a "fluid-electron", which can be cast into a Laplace/Poisson equation form that can use the AMR/Octree. This work will be directly useful to plume modelers at Air Force Research Laboratories, Edwards AFB.
- Laser ablation of materials produces energetic plumes containing a broad spectrum of particle sizes, energies and charge to mass ratios that are well beyond the capabilities of laboratory-scale direct electrostatic acceleration to produce. These particle energies are comparable to what would be found in granular orbital debris that is too small to track, and allows for low cost investigation of long term exposure to spacecraft components.
- Predicted performance degradation of power generation and thermal management systems due to environmental exposure will help AF/DoD mission designers to better predict mission lifetimes at different orbits, and for subsystem developers to evaluate new materials that are more capable of extending these mission lifetimes.

Backups

Transient e⁻ Cross-stream Velocity : Bouncing effect