COLISEUM: An Application Programming Interface for 3D Plasma Simulations

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Introduction

Tasks:

- Developing software to simulate thruster-spacecraft interaction
- Supporting EP Lab tasks:
  - EP device modeling
  - Chamber interaction modeling
- Supporting DoD flight programs

National Program

- AFRL/PRSS and PRSA
- Massachusetts Institute of Technology
- Virginia Tech
- University of Michigan
- Advatech Pacific
- Lockheed Martin

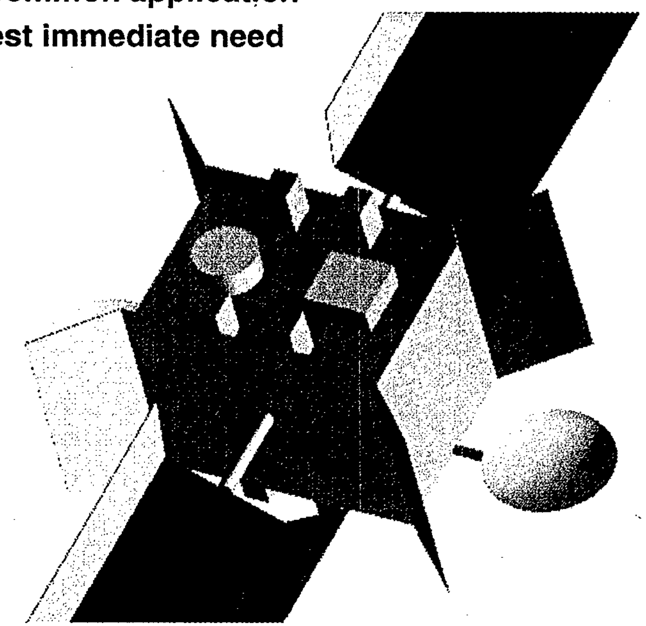
Objective

Requirement: - Detailed description of plume properties (plasma expansion)

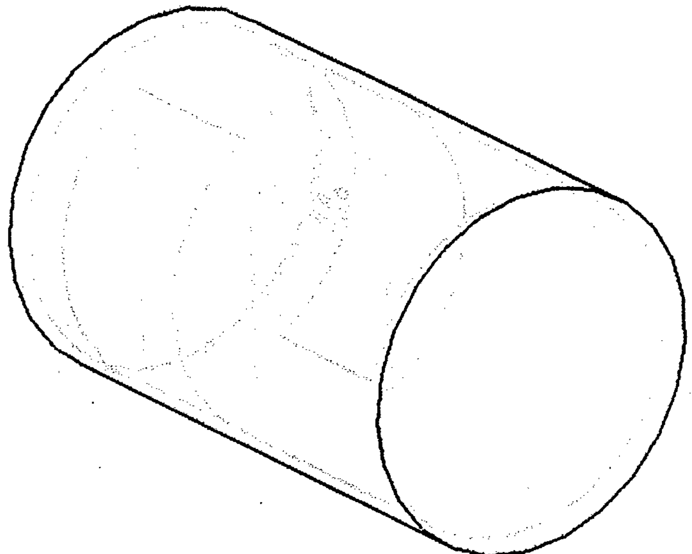
- Knowledge of plume – surface interactions (models from data)

A single FLEXIBLE, USABLE 3-D code which can be used to model thruster plume/surface interaction in the following situations:

Spacecraft in LEO or GEO
- Most common application
- Greatest immediate need



Inside a vacuum test facility
- Necessary for strong code validation
- Independent utility: Design of vacuum test facilities



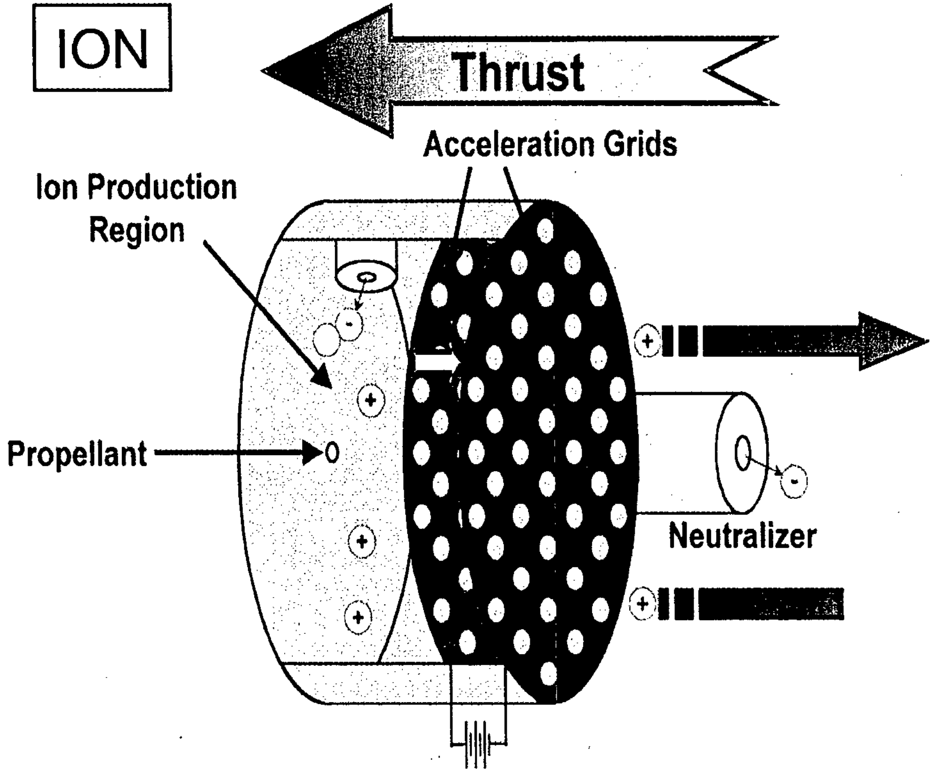
USABLE: A typical simulation can be set up and run in less than 1 day by a user with less than 3 days training.

Technical Challenges

- Differing time scales and mean free paths for neutrals, ions, and electrons
- Orders of magnitude changes in density in same domain
- Collisionality (charge exchange, momentum exchange, recombination) on long length scales in the space environment.
- Modeling interaction (sputtering, deposition, chemistry) of primary ions, charge exchange ions, and neutral effluent with S/C surfaces - self-consistently.

Electrostatic Thrusters

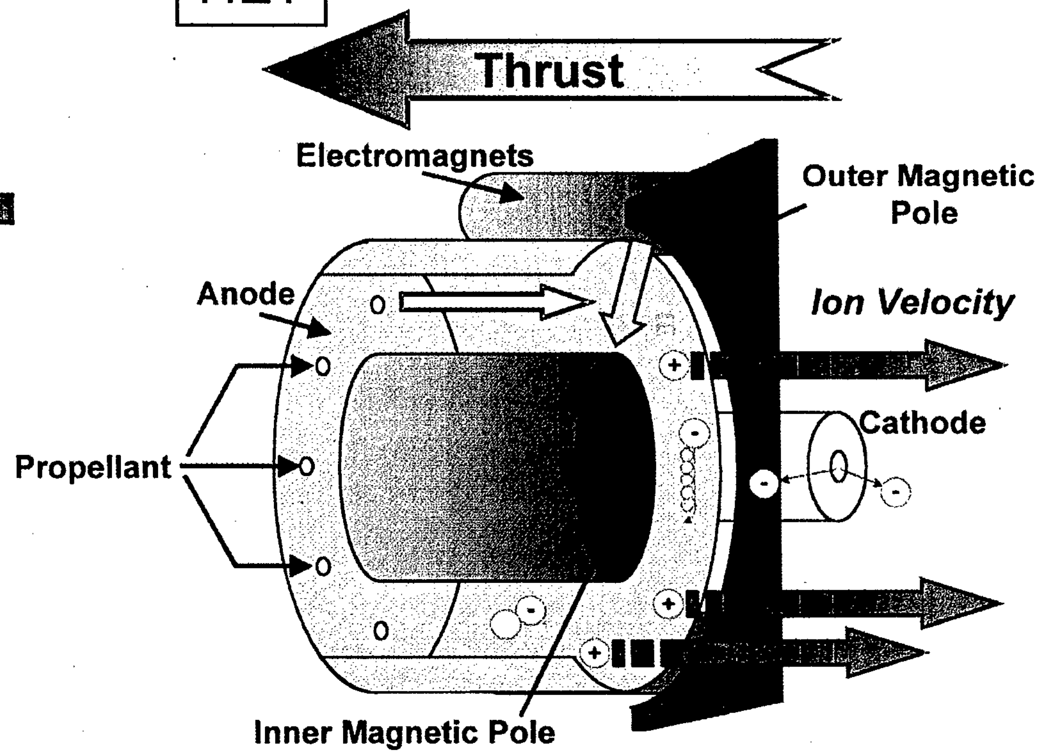
ION



Propellant is ionized via electron bombardment and then accelerated by high voltage grids

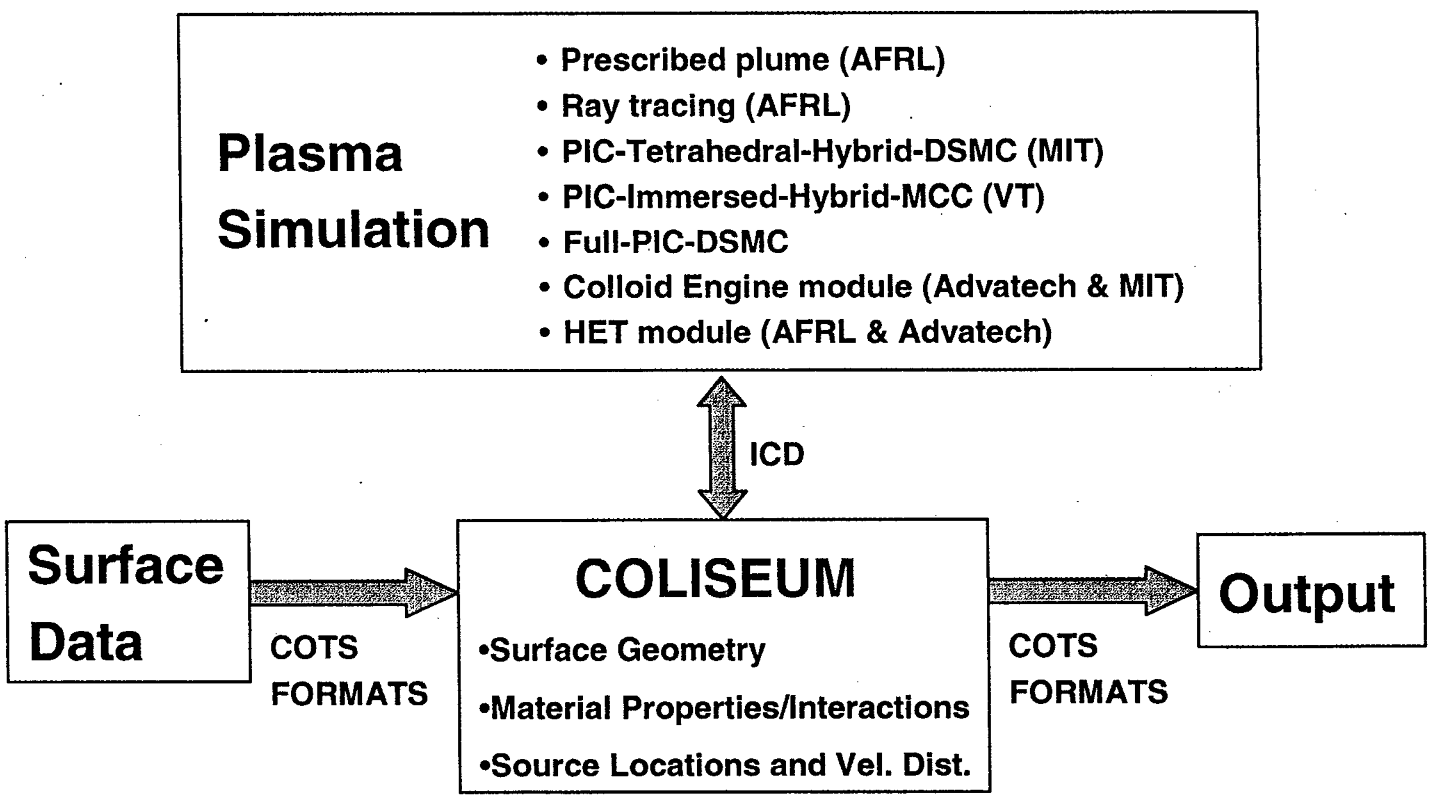
HET

Propellant is ionized by electrons trapped in a magnetic field
Ions are then accelerated by an electric field between anode and electron cloud



APPROACH

Approach: Build a STANDARD FRAMEWORK into which various types of 3D plasma simulations can be easily developed and INTERCHANGED.



Execution Sequence

Define 3D Geometry
SolidWorks

↓ SolidWorks .geo Format

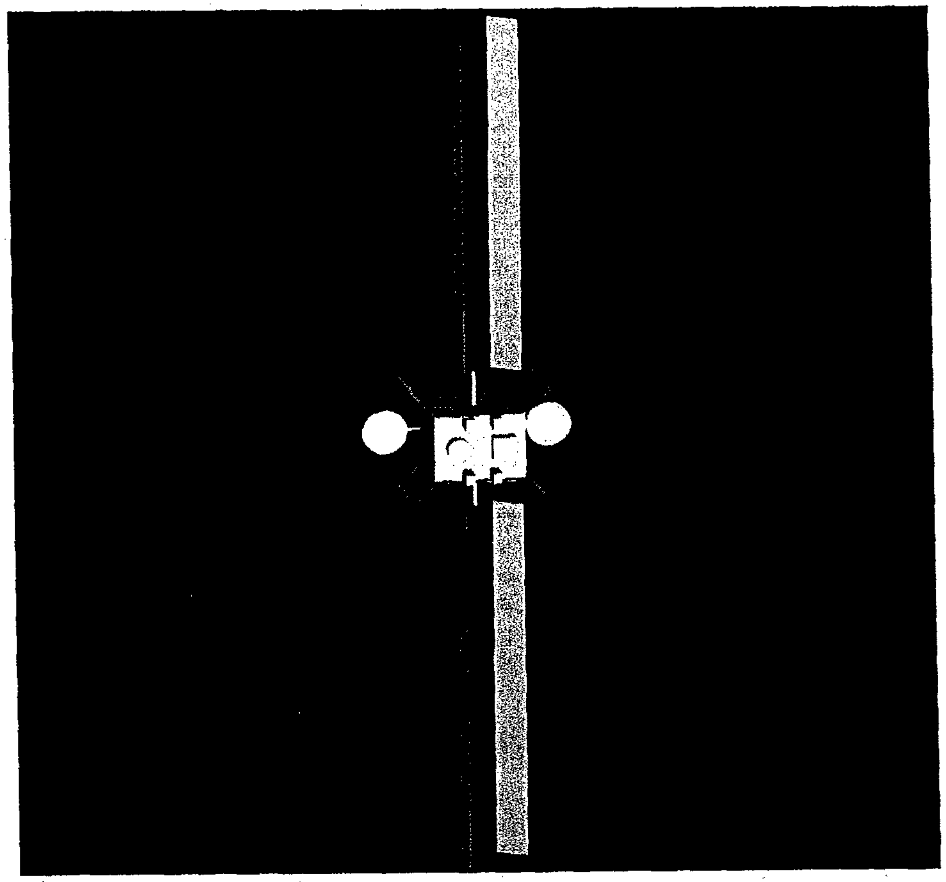
Mesh Surface
COSMOS, ICEM-CFD, SolidWorks Plug-In

↓ ANSYS, ABAQUS, MGEN, NASTRAN, or Tecplot Format

COLISEUM

↓ Tecplot Format

Output Visualization
Tecplot



GEO spacecraft solid object generated using SolidWorks

Collaboration

Organization	Responsibility
AFRL/PRSS	• Lead -- Project Planning and Management • Top Level Software Development • Ray Tracing Simulation – RAY
MIT	• Plasma Simulation Module Using Unstructured Tetrahedron Meshes and Hybrid Algorithms – AQUILA • Colloid modeling support
Virginia Tech	• Plasma Simulation Module Using Immersed Cartesian Meshes -- DRACO
AFRL/PRSA	• Basic Research in Model Development: Hybrid Particle-Continuum-Kinetic Algorithms • Visualization (jointly with PRSS)
Advatech Pacific, Inc.	• COLISEUM support • Transient Colloid Droplet Simulation • Hall source model
U. of Michigan	• PPT modeling • Application to plasma diagnostics • Generalized collision models
Lockheed	• Surface Sputter Yield Measurement Data & Models • Customer

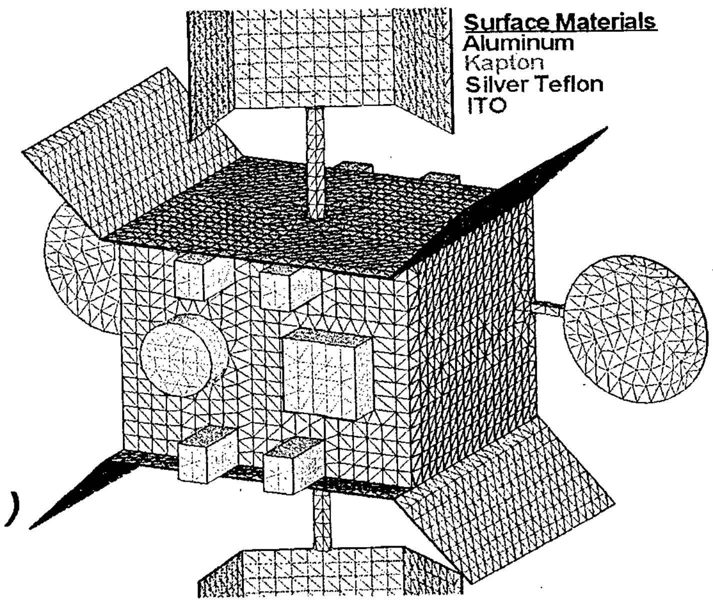
Modular Top-down Approach

- Develop an API
  - Set of support libraries with ICD for use
    - e.g. col.lib and futil.lib
  - Set of specialized libraries which support certain types of simulations
    - e.g. voltet.lib and collision.lib

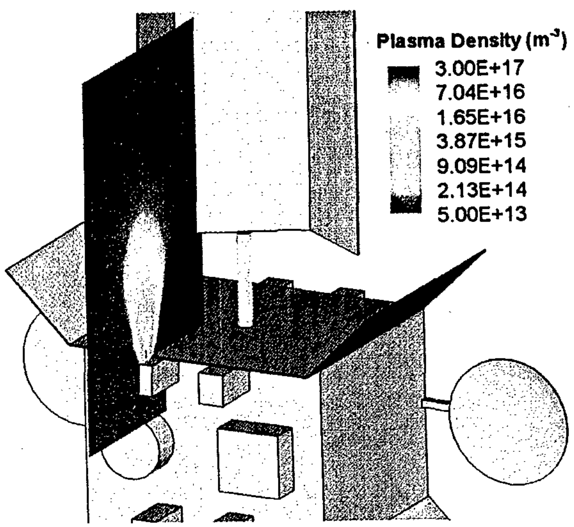
- Integrate plasma simulation modules various levels of fidelity as they are developed
  - e.g. ray-tracing, Hybrid-PIC, Hybrid PIC-DSMC
- Sharing of libraries

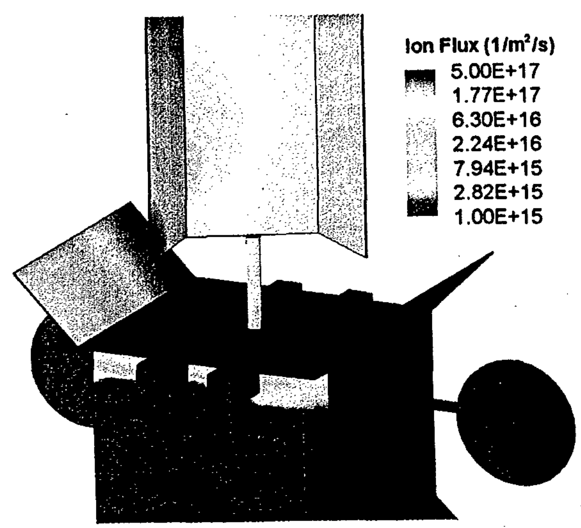
Prescribed_plume

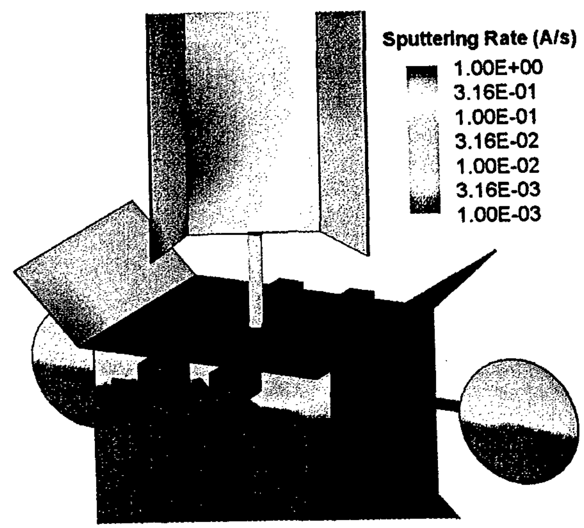
- Precomputed 2D/axisymmetric plume is superimposed on 3D Spacecraft geometry
- Sputtering calculated based on choice of models



Generalized geosynchronous spacecraft using ***prescribed_plume()*** with 200W Hall thruster plume model







AQUILA

- Hybrid PIC code with neutral and ion particles and fluid electrons
- 3-D unstructured (tetrahederal) grid generated from (triangulated) surface mesh
- Source model divides particles into separate populations
- DSMC collision method implemented with different particle weights to enable simulation with a background
- Potential solver for handling both quasineutral and non-neutral regions
- Surface interactions include reflection, absorption, accommodation, and sputtering

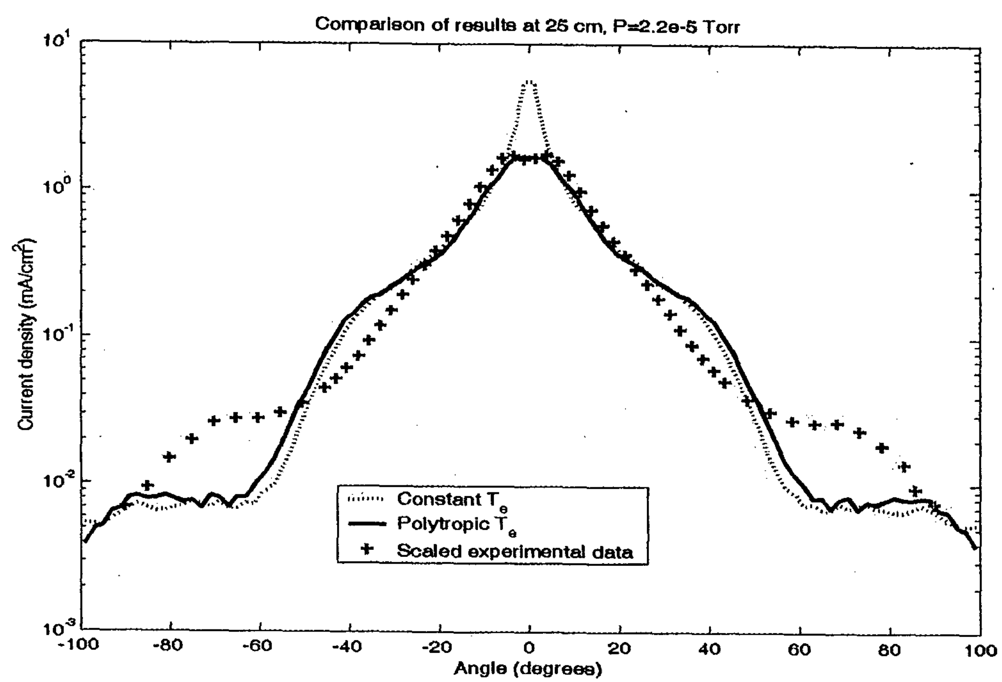
BHT-200 thruster:

Current density results at 25 cm

Chamber Pressure: 2.2e-5 Torr

Temperature models:

1. **Constant $T_e = 2.0$ eV**
2. **Polytropic T_e with $T_{e0} = 2.8$ eV, n = 1.3 at 25 in front of thruster**



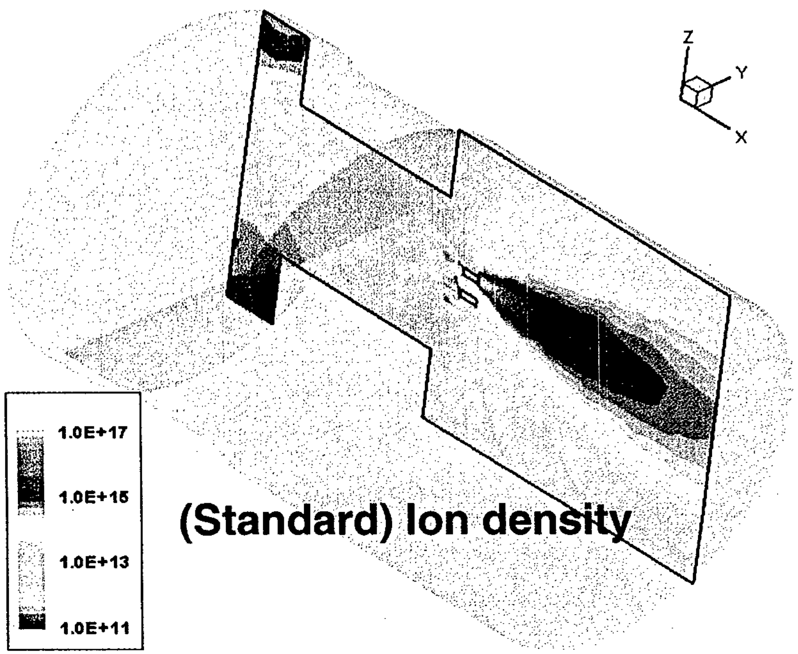
AQUILA Result

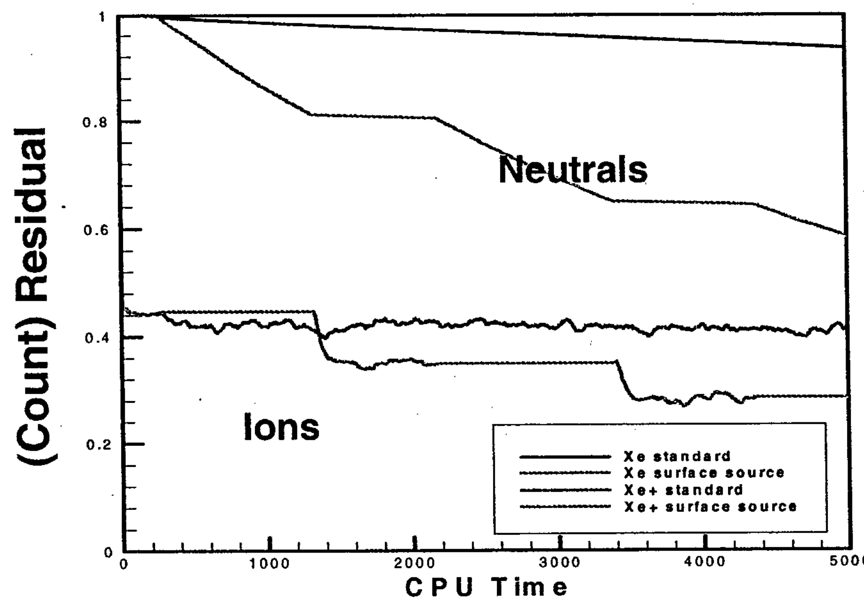
Code Speedup Results

Vacuum Chamber w/ drifted Maxwellian sources

Xe+: mass flow 5e-7 kg/s,
v = 20000 m/s , T = 100 eV
Xe: mass flow = 1e-7 kg/s,
v = 200 m/s, T = 700 K

Simulation Type	Relative CPU Time
Standard	33
Standard with subcycle	11
Surface Source with subcycle	1





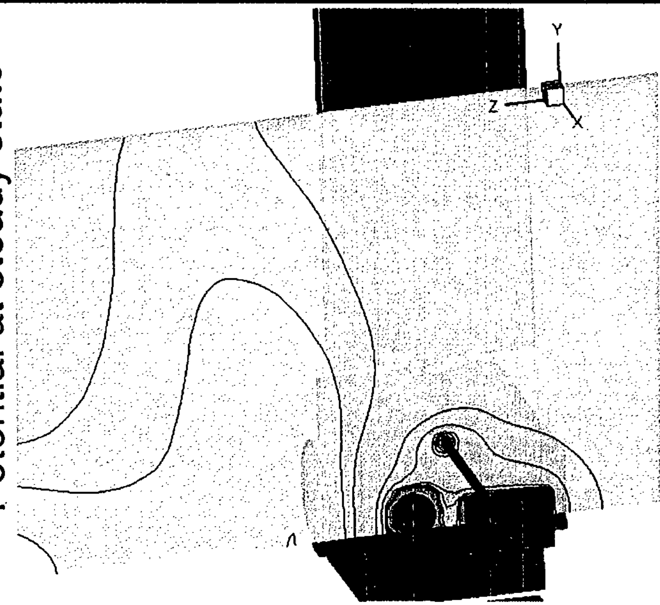
DRACO

- 3D ES-PIC Code
- Based on a uniform Cartesian mesh with tetrahedral subdivision
  - Complicated surfaces can be resolved
  - Computational efficiency of a Cartesian mesh is retained
  - Each Cartesian cell divided into five tetrahedrons
- Mesh generated automatically based on:
  - triangular surface definition
  - grid span and discretization
- Multiple Poisson solvers:
  - Uniform background field
  - Boltzmann inversion
  - DADI
  - Finite Element IFE
    - Immersed FE formulation
    - surface boundary is part of the solution domain
    - boundary defined by planar intersection of the finite element

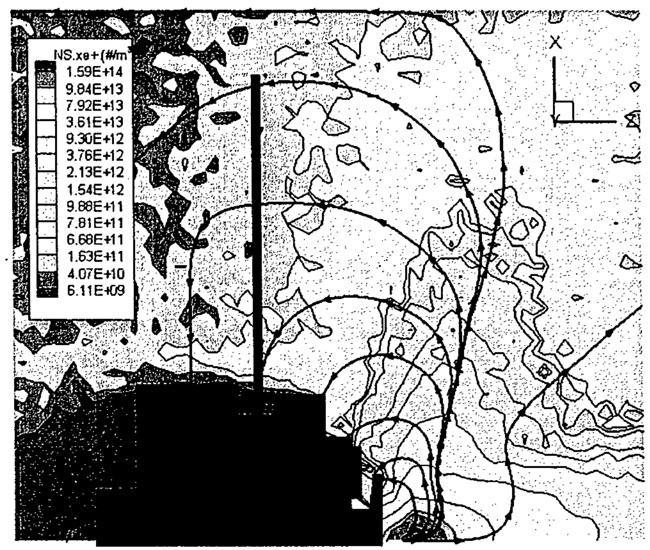
DRACO Results

- Open external boundary (Neumann condition)
- IFE potential solver
- Quarter domain, simulation time ~ 3 hours (1.5 mil. CEX macro-particles)
- Beam input based on NSTAR (30cm diameter thruster) operating at ML83
  - $n_{b0} = 3.22\times10^{15}\ m^{-3}$
  - $n_{n0} = 2.30\times10^{17}\ m^{-3}$
  - $v_{b0} = 38{,}700$ m/s
  - $\sigma_{cex}=3.37\times10^{19}\ m^2$ (CEX $\lambda_D = 5cm$)
- Background ion density, $n_{i0}=2.76\times10^{7}\ m^{-3}$
- Beam exit set to plasma potential (+19V)
- Charged plume shield, $\Delta\phi=-19V$

Potential at steady state

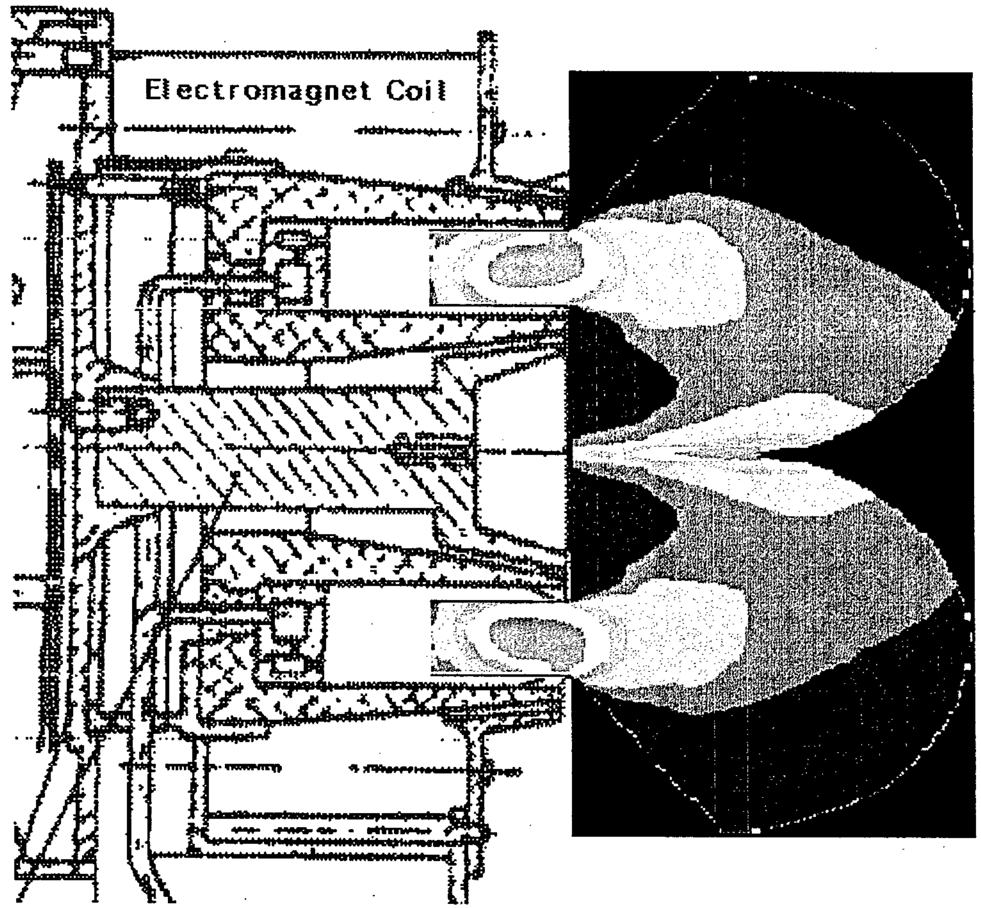


CEX number density



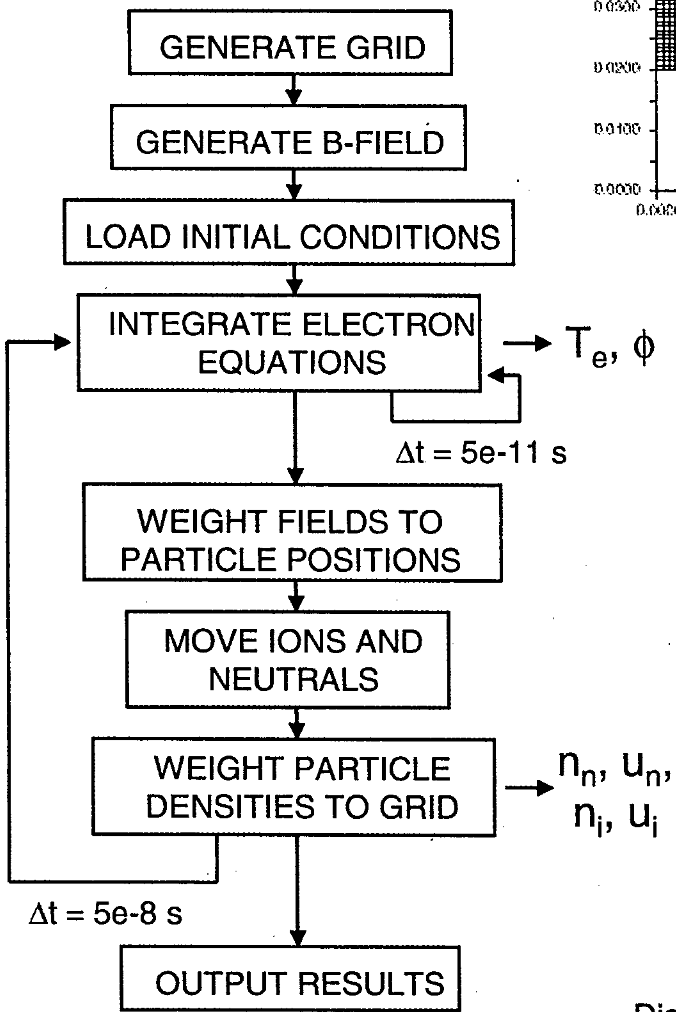
Current HPHall Code

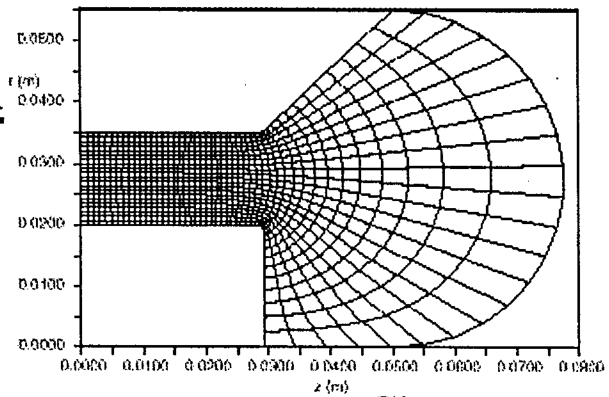
- Better understanding of the plasma acceleration process
- Predict performance and lifetime
- Provide data for spacecraft interaction studies
- Result: a flexible tool useful for thruster design



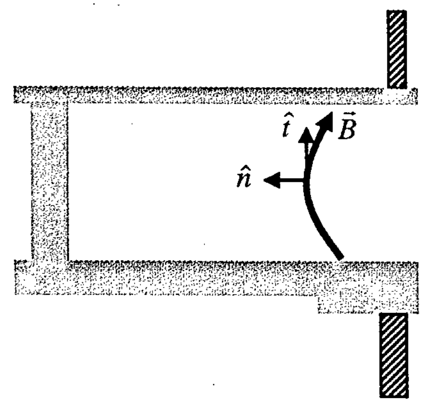
Current HPHall Code

Hybrid-PIC Method





Electron Equations



Charge Neutrality

$$n_e = Z n_i$$

Isothermal Along **B**

$$\phi - \frac{kT_e}{e}\ln(n_e) = \phi^*(\lambda)$$

Across **B**:

Continuity

$$I_a = I_i + I_e + I_w$$

Ohm's Law

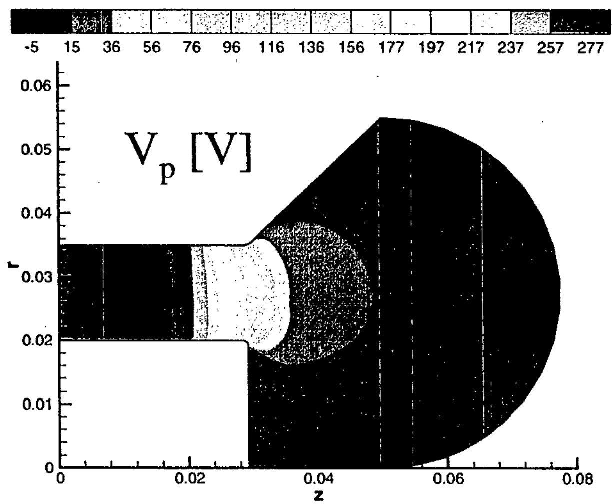
$$u_{e,\hat{n}} = -\mu_{e,\perp}\left(E_{\hat{n}} + \frac{1}{en_e}\frac{\partial p_e}{\partial \hat{n}}\right)$$

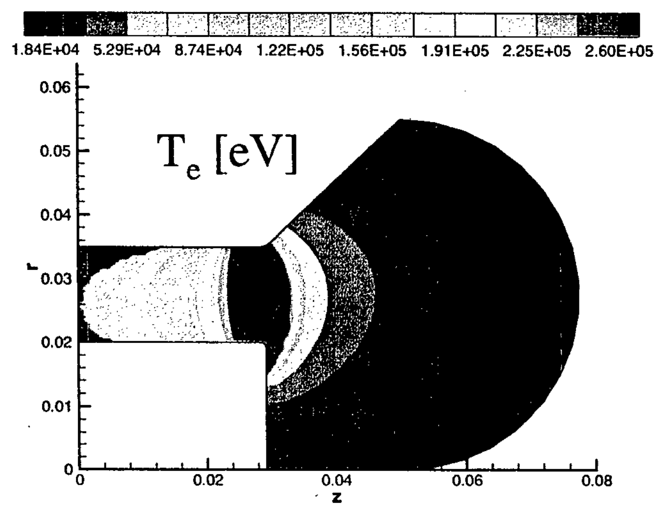
Conservation of Energy

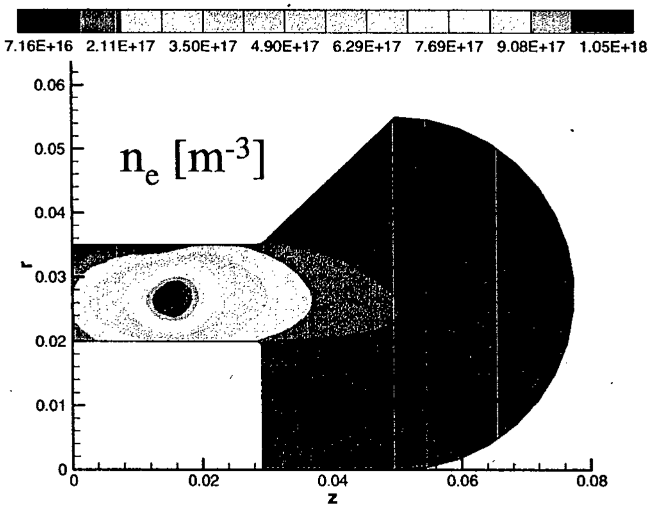
$$\frac{\partial}{\partial t}\left(\tfrac{3}{2} n_e kT_e\right) + \nabla\cdot\left(\tfrac{5}{2} n_e \vec{u}_e kT_e + \vec{q}_e\right) = \vec{j}_e \cdot \vec{E} - \dot{n}_i \varphi' E_i$$

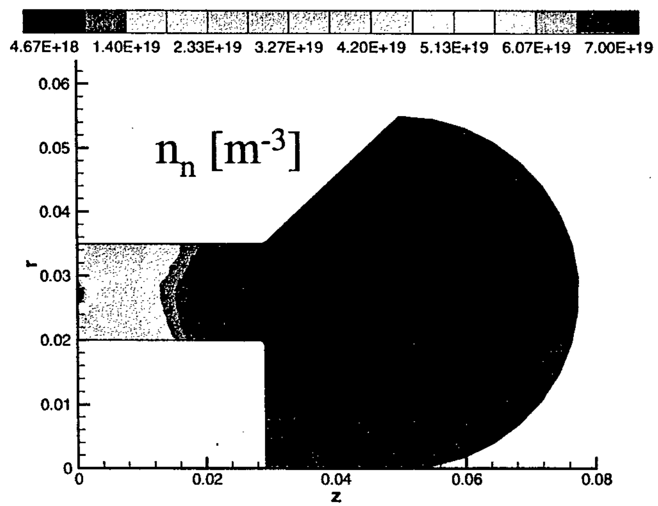
Current HPHall Code Results

CASE 2: SPT-70, 300V, 2.34 mg/s, NEAR CATHODE









Summary

- Approach: A new 3D plasma simulation system (COLISEUM) is being developed
  - Allows easy implementation of various plasma simulation modules for quicker code development & controllable fidelity
  - Using COTS extensively
- Current Status
  - Low-fidelity Plume: Prescribed_plume & ray tracing
  - High-fidelity Plume: AQUILA & DRACO
  - Thruster modeling: HET & Colloid
- Future Work
  - DRACO: charging, sputtering, surface contamination
  - AQUILA: Parallel, generalized collisions
  - Device modeling: HET extensions
  - Plasma diagnostics