Plasma Thruster Plume Simulation:
Effect of the Plasma Quasi Neutrality Hypothesis

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Presentation Overview

- Introduction
- PICPluS-2 code overview
- Code validation results
- Quasi-neutrality effect analysis
- Conclusions

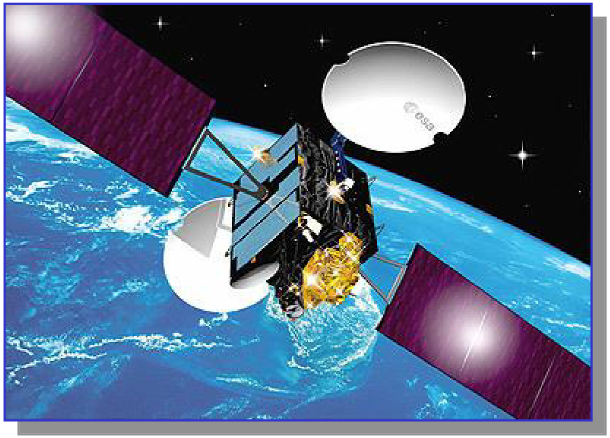
Introduction (1)

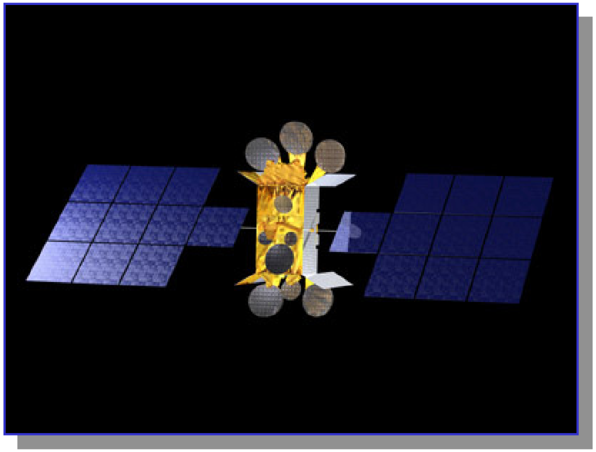
Electric thrusters for spacecraft

- Hall Effect Thrusters and Gridded Ion Engines are consolidating as two of the most effective new spacecraft technologies

- 5 kW class HET are developed for application in 5-8 year timeframe (next generation GEO telecoms, e.g. Alphabus), 1 kW class models were successfully flown on Russian and Western spacecraft (ESA's SMART-1)

- Several GIE were already successfully employed in space (NASA's Deep Space 1, ESA's Artemis)





Introduction (2)

Issues about plasma thruster integration with spacecraft

- Direct ion impingement onto spacecraft surfaces, sputtering, re-deposition and degradation of material properties, e.g. solar panels
- Back flow ion impingement caused by charge exchange plasma collisions
- Erosion of acceleration channel walls/grids: erosion products expansion and re-deposition
- EMI compatibility issues, plasma interference with telecommunication signals

Therefore necessity of:

- Appropriate numerical simulation of device operation
- In flight and vacuum chamber testing

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EP Plume Simulation – Requirements

A L T A

Issues about plasma plume simulations

- Detailed physical models (plasma non-neutrality, effect of different plasma species, effect of collisions and their type)

- Reliable and fast numerical methods (Poisson solvers, particle-mesh sorting algorithms, …)

- Realistic data for injection and interaction parameters (possibly experimental)

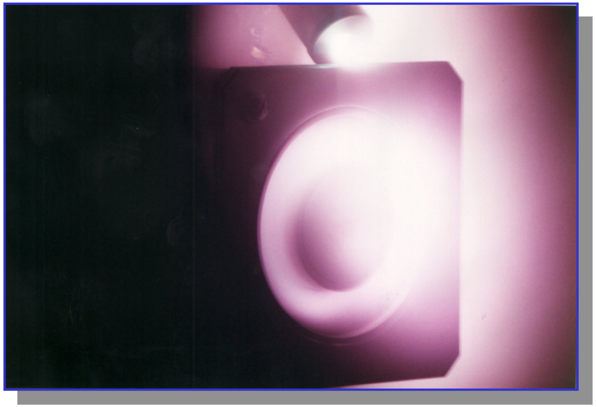
- Realistic geometric configurations (proper assessment of electric/magnetic interactions and spacecraft surface interactions)

- Validation with respect to vacuum chamber and flight experimental data

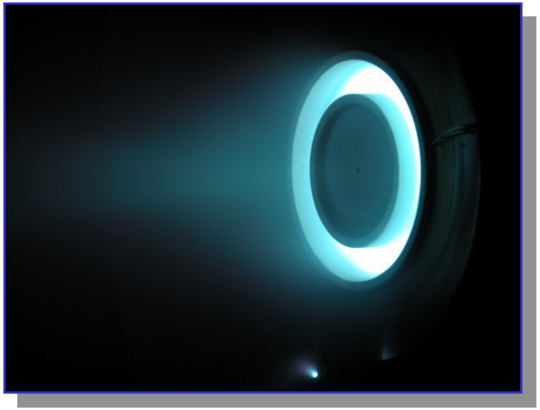
Centrospazio-Alta EP Activity (1)

EP activity

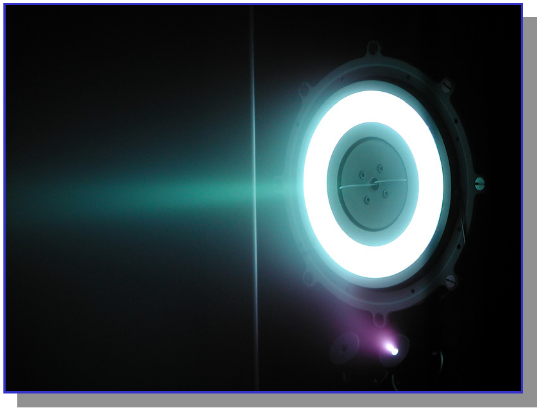
- Presently involved in virtually all HET/GIE development efforts in Europe
- Own technology (HET, DS-HET) or in partership with SNECMA Moteurs, Astrium Ltd & Gmbh, QinetiQ, …
- Operating the best array of EP test facilities in Europe, 10 UHV test facilities with size up to 5.7 x 12 m and pumping speed up to 1,500,000 l/s [Xe]



Alta 700 W HET, lab model



Alta 5 kW HET, lab model

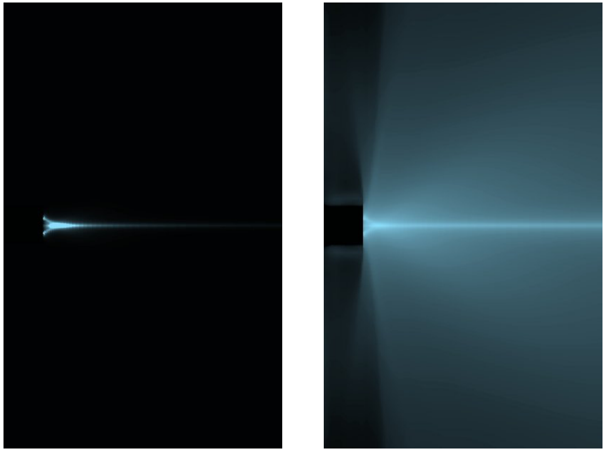


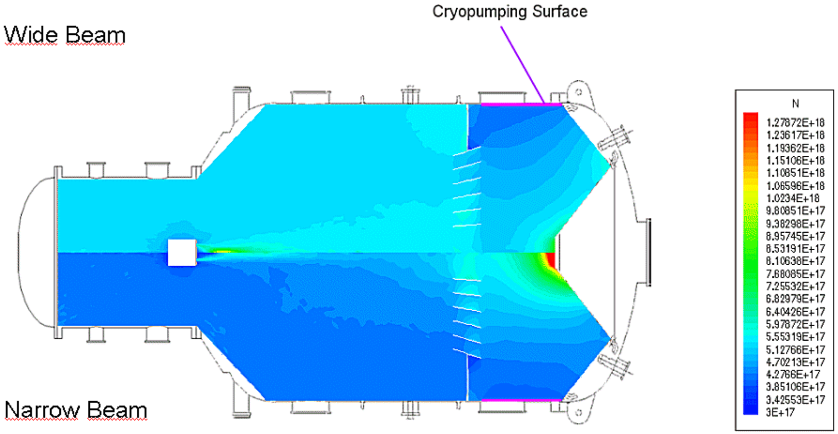
Alta-Astrium 2 kW HET, EQM

Centrospazio-Alta EP Activity (2)

Computational activities

- EP computational activity centered on plume simulation, integration with spacecraft, and complex laboratory configuration simulations
  - – hybrid PIC (kinetic ions+non isothermal fluid electrons), 2D axially symmetric, non neutral (SOR Poisson solver) for accurate plume calculation and impact of backflow of vehicle surface (simple geometries)
  - – charge neutral DSMC, 2D axially symmetric, for analysis of complex configurations, e.g. thruster in vacuum chamber with realistic pumping arrangement

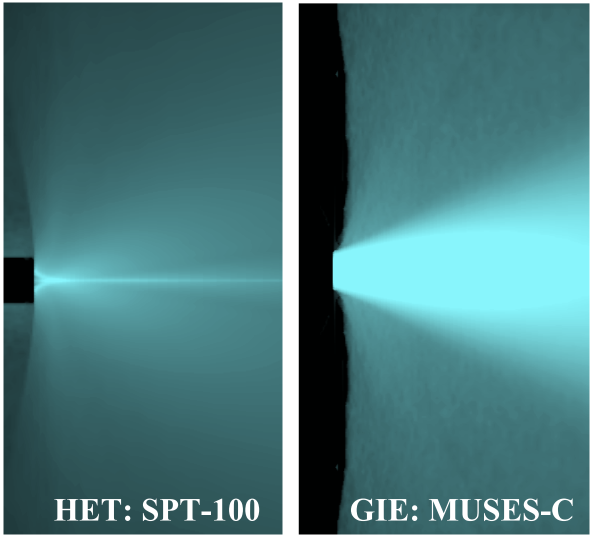




PICPluS-2 – Characteristics (1)

PICPluS features

- 2D axisym, 3 components of velocity
- Structured grid with variable cell size (scaled to local Debye length)
- Xe+, Xe++, Xe simulated particles
- Elastic, CEX collisions (2 different algorithms)
- Effect of background pressure
- Input from experimental distributions or from external simulations (magnetostatic FEM)
- Simulated engines: Hall Effect Thruster or Gridded Ion Engine



Ion Number Density: log scale

Particle Species	PICPluS v.2.0
Xe$^+$ ions	Simulated
Xe^{+2} ions	Simulated
Xe^{+n} ions	Can be added
Xe atoms	Can be added
CEX ions	Simulated

Particle species presently simulated

PICPluS-2 – Characteristics (2)

Algorithms

- Particle in Cell with Ruyten weighting
- Nanbu-Kitatani TPMC or Szabo MCC collisions
- 3 models for collision cross-sections
- Potential from Poisson solver (SOR method, Chebishev acceleration, checker-board ordering) or quasi-neutrality (Boltzmann relation)
- 3 models for electron temperature (constant, adiabatic, first order Chapman-Enskog) or experimental distribution
- Full DSMC option for neutrals
- All input fields/distributions from experiments, simulations, or simplified models

$$T_e = const.$$

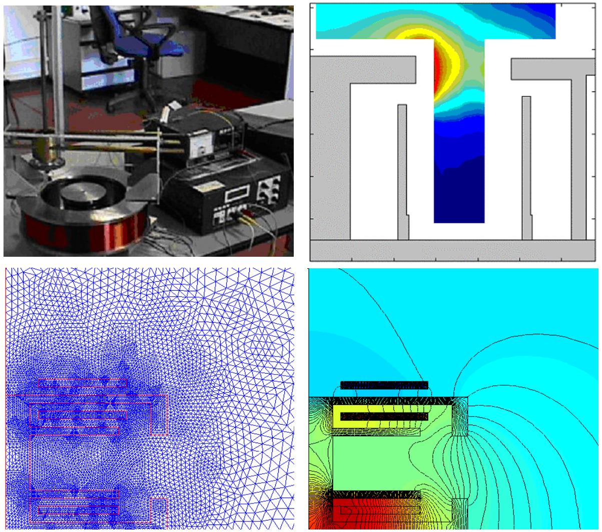
$$\nabla^2(T_e) = 0$$

Pre-processed

$$T_e(r,z) = T_{ref}\left(\frac{n_e(r,z)}{n_{ref}}\right)^{\gamma-1}$$

Updated step-by-step

Electron temperature models

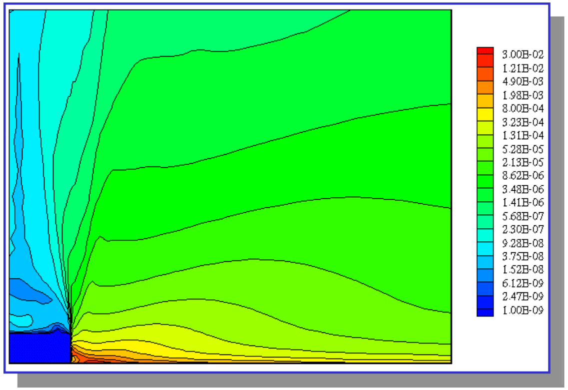


Magnetic field: from experiments or simulations

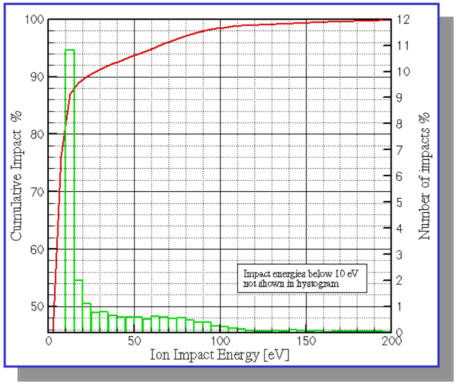
PICPluS-2 – Characteristics (3)

Outputs

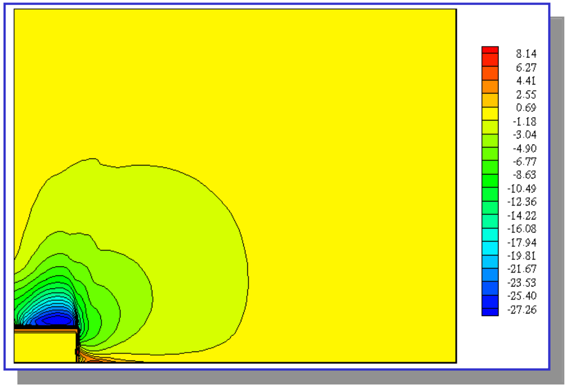
- Instantaneous and averaged fields at steady state (species by species)
- Instantaneous and averaged thrust and beam ion current
- Ion current density measured with virtual Faraday's probe rakes
- Impact history on (possible) solid external surface and related statistics



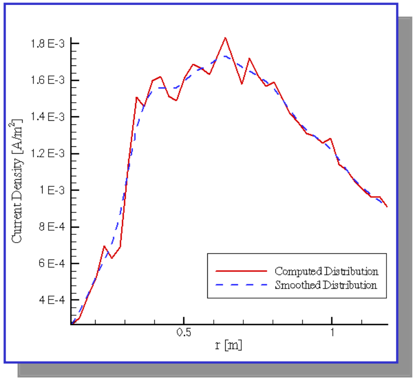
Ion number density



Back-flow impact energy



Plasma potential



Back-flow charge deposition

PICPluS-2 Validation – Test Cases

Code results compared with similar programs and experimental data from literature and in-house tests:

- Four test cases for HET and one for GIE
- All test cases achieved stationary conditions in about 40,000 time steps
- Computed thrust and ion beam current within ±1% of measured values
- Peak on axis (GIE) and slightly low current density at high angles (HET) are usually seen

Thruster Model	SPT-100	SPT-100	SPT-100	Alta-XH5	MUSES-C
Mass Flow Rate [mg/s]	4.99	5.12	5.084	9.2	0.21
Discharge Voltage [V]	300	300	300	350	1500
Discharge Current [A]	4.5	4.5	4.5	11.16	0.14
Background Pressure [mbar]	$2.9\cdot10^{-6}$	$4\cdot10^{-5}$	$5.32\cdot10^{-5}$	$8.32\cdot10^{-5}$	$2.0\cdot10^{-6}$
Thrust [mN]	84.54	90.39	84.07	181.6	8.85
Ion Beam Current [A]	4.61	4.82	3.87	8.96	0.149
Domain Size [m]	1.2 x 1.5	1.2 x 1.5	1.2 x 1.5	1.0 x 1.5	1.0 x 2.5
Total Particle number	$\sim1.\cdot10^{6}$	$\sim 1.\cdot10^{6}$	$\sim 1.\cdot10^{6}$	$\sim 1.5\cdot10^{6}$	$\sim 0.5\cdot10^{6}$
Reference	Manzella *1995*	Kim *1996*	King *1998*	Biagioni *2003*	Matsushiro *2003*

Test case matrix

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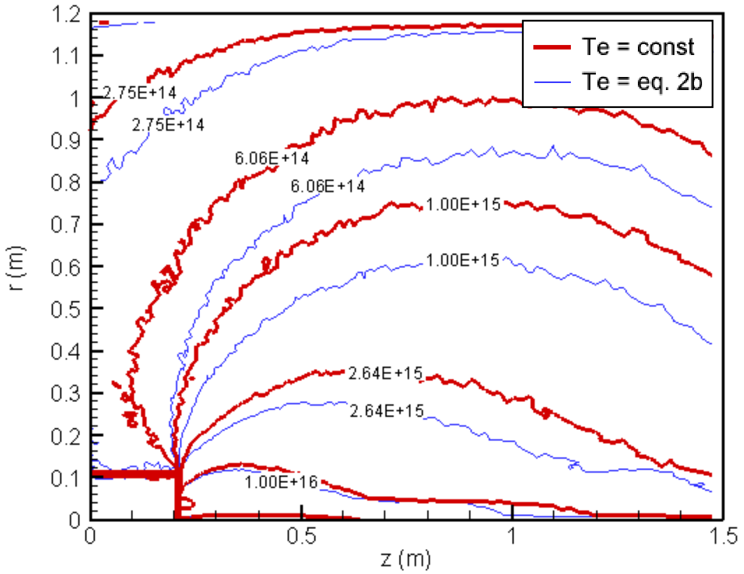
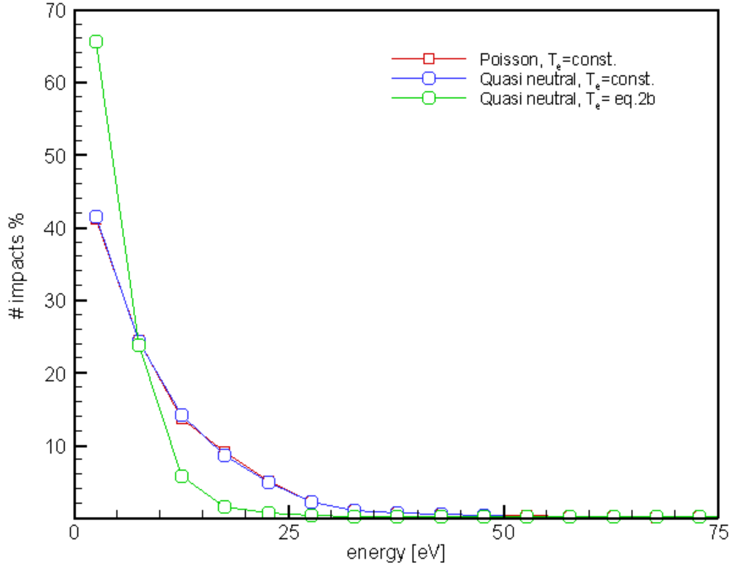
PICPluS-2 Validation

- Injection ion temperature has no big impact on results
- Electron temperature has significant effect, especially for ion distribution and impact energy of backflow CEX
- Divergence angle at inflow boundary has largest impact on current density and plasma field



Effect of T_e on ion number density



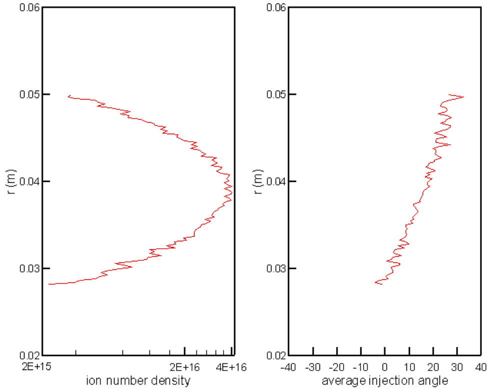
Effect of T_e on back-flow impact energy

SPT-100 Simulations

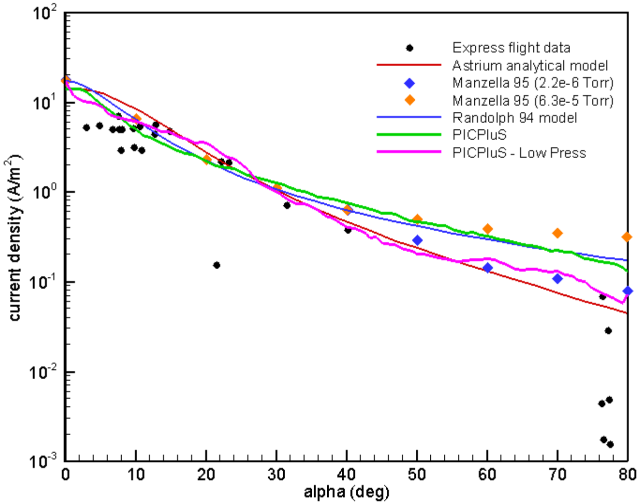
Optimal injection distribution (inflow boundary) fitting near and medium distance measurements of current density:

- Gaussian distribution for number density
- Linear distribution (with radius) for average divergence angle
- Gaussian distribution of actual divergence angle around the average value

Good agreement for different background pressure and test conditions (in particular different fraction of double ionized propellant)



Optimal injection distribution for SPT-100



Comparison with literature and Express data

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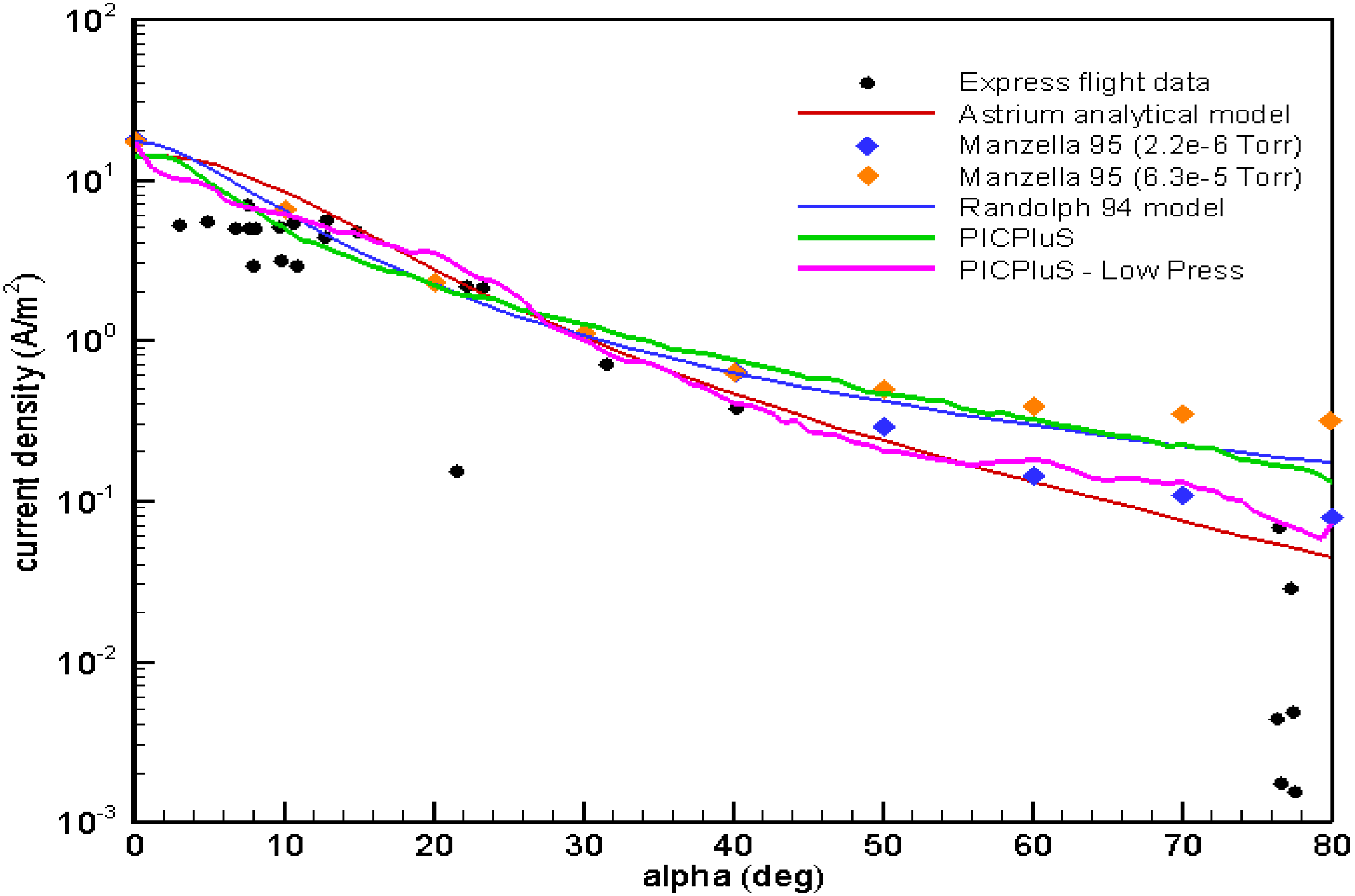
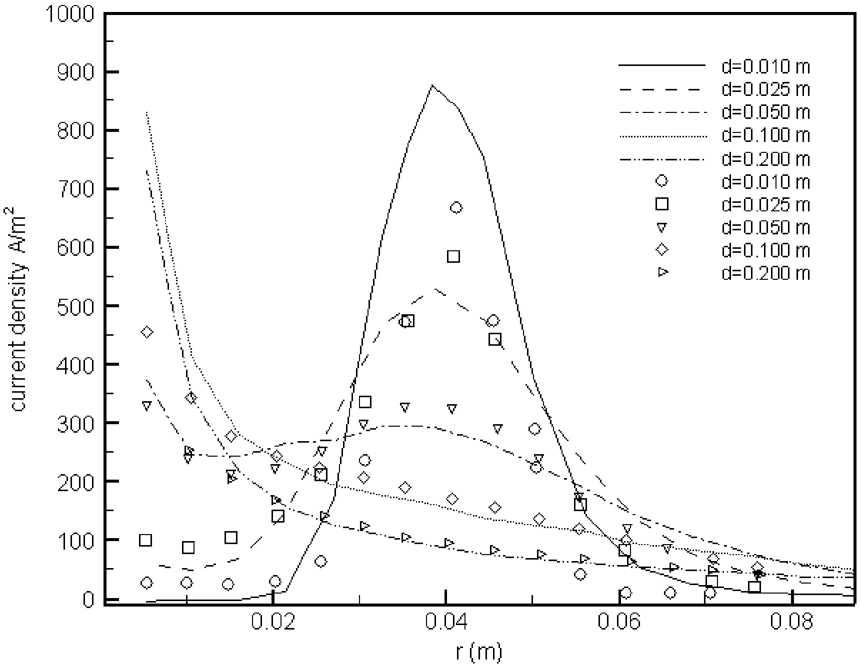
SPT-100 Simulations

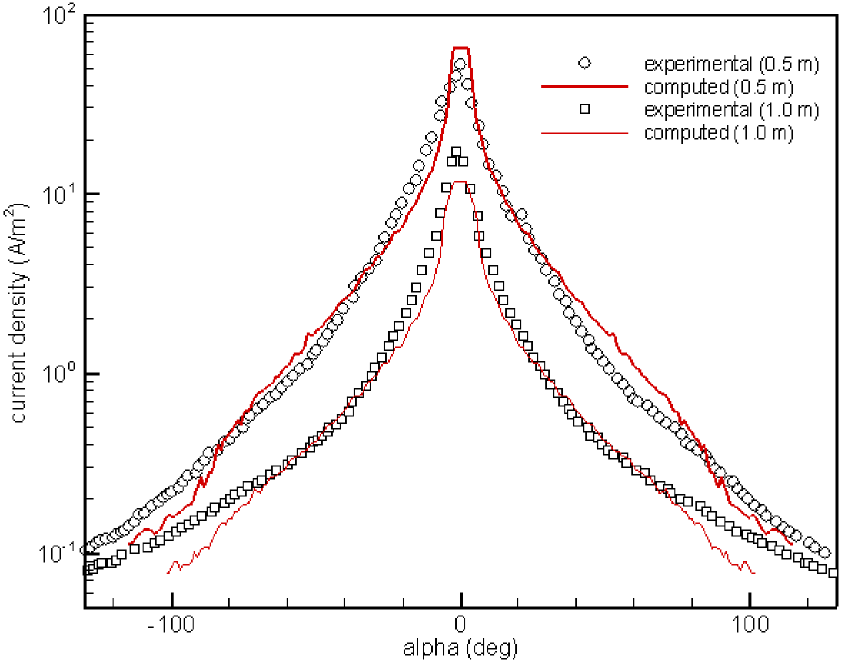


SPT-100 Simulations

Ion current density



Comparison with near field data (Kim)

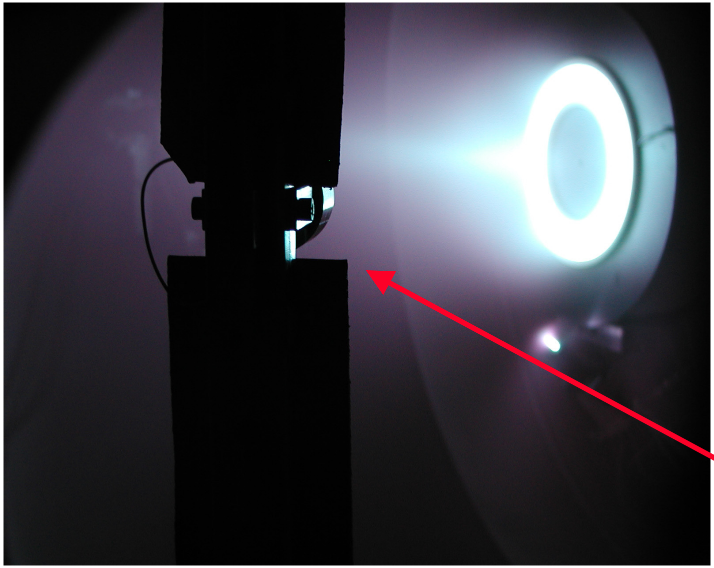


Comparison at 0.5 and 1.0 m distance (King)

Alta-XH5 Simulations

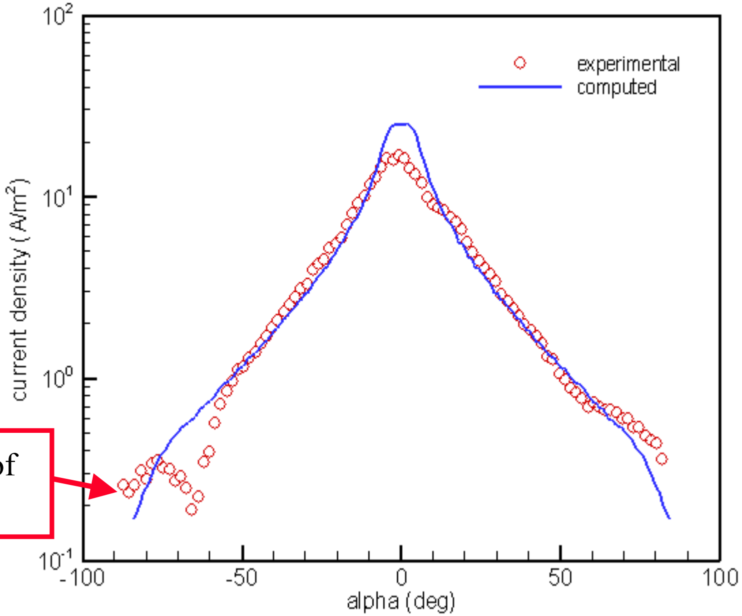
- Optimal distribution for SPT-100 scaled to 5 kW thruster, showing good agreement with measurement

- Measurement of external magnetic field performed, no significant effect on simulated current density over wide range of variation



Alta-XH5 firing in IV-4 facility

Shadowing of probe rake



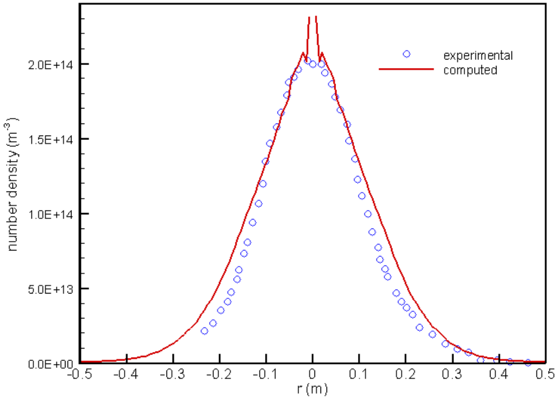
Current density comparison

MUSES-C Ion Engine Simulations

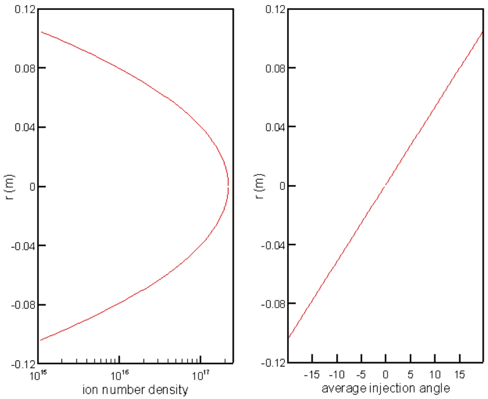
Small GIE, excellent agreement obtained with simple injection distribution:

- Gaussian distribution for number density
- Linear distribution for divergence angle

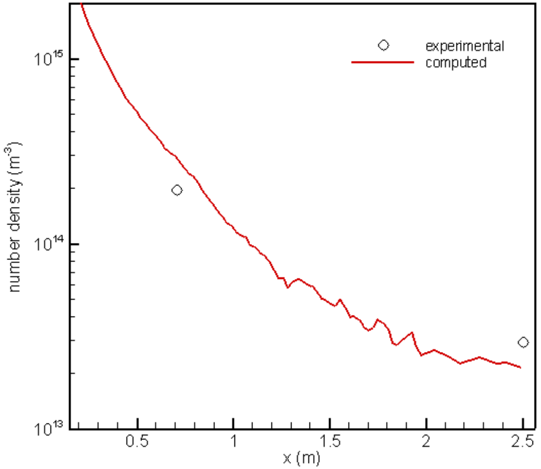
Strong peak on thruster axis: issue evidenced with other PIC codes, presently under further investigation



Radial number density profile comparison



Optimal injection distribution for MUSES-C



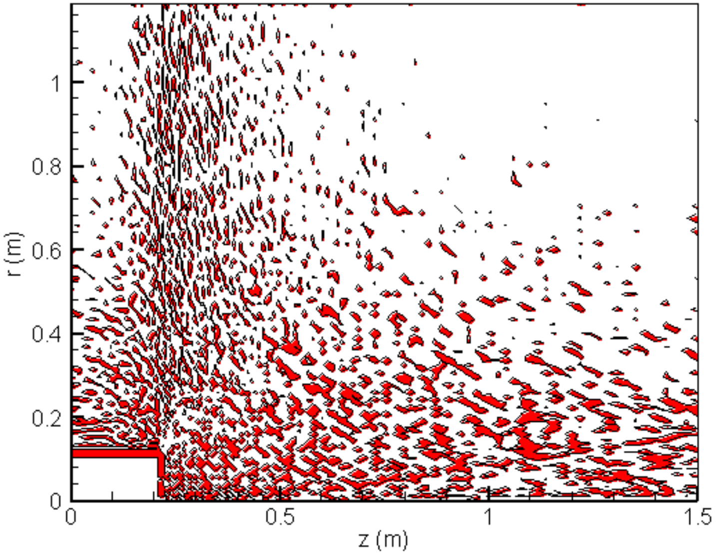
Axial number density profile comparison

Quasi Neutrality – Test Cases

- Quasi-neutrality examined from physical and numerical points of view
- Three configurations chosen:
  - 2 for HET (SPT-100, low/high background pressure)
  - 1 for GIE (MUSES-C)
- Simulations runs performed on 2.5 GHz P4 1Gb RAM, different conditions and models
- As expected plasma appears mostly neutral:
  - non neutral spots in regions where gradients are stronger
  - unbalance always less than 1% ion charge density

Run #	Test Case	QN/ Poi	Te Model	Magnetic Field	Collision Model
1	Kim	POI	Const.	ON	A
2	Kim	QN	Const.	ON	A
3	King	POI	Const.	ON	A
4	King	QN	Const	ON	A
5	King	QN	Const	ON	B
6	King	QN	Eq.2b	ON	A
7	Ion	POI	Laplace	OFF	A
8	Ion	QN	Laplace	OFF	A

Test case matrix



Non-neutral zones

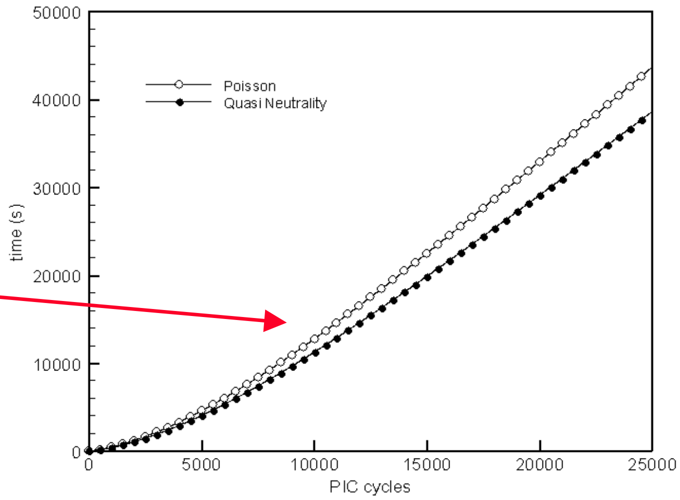
Quasi Neutrality – Numerics

Computational cost of Poisson and quasi-neutrality solvers increases with grid size and total number of simulated molecules, but:

- QN not always the winner, for fine grid and large number of simulated particles Poisson can be faster
- QN more stable in any condition, especially for unregular grid geometry

Test Case	QN/Poi	Grid size	Particle #	Step Length [s]
1	QN	50x65	$5\cdot10^5$	1.27
2	Poi	50x65	$5\cdot10^5$	1.30
3	QN	100x120	$5\cdot10^5$	1.9
4	Poi	100x120	$5\cdot10^5$	2.1
5	QN	100x120	$1\cdot10^6$	2.72
6	Poi	100x120	$1\cdot10^6$	2.69

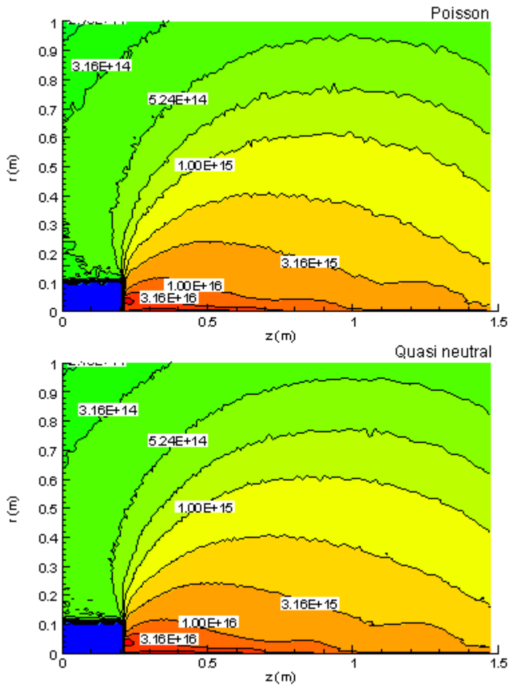
Computation speed test case matrix



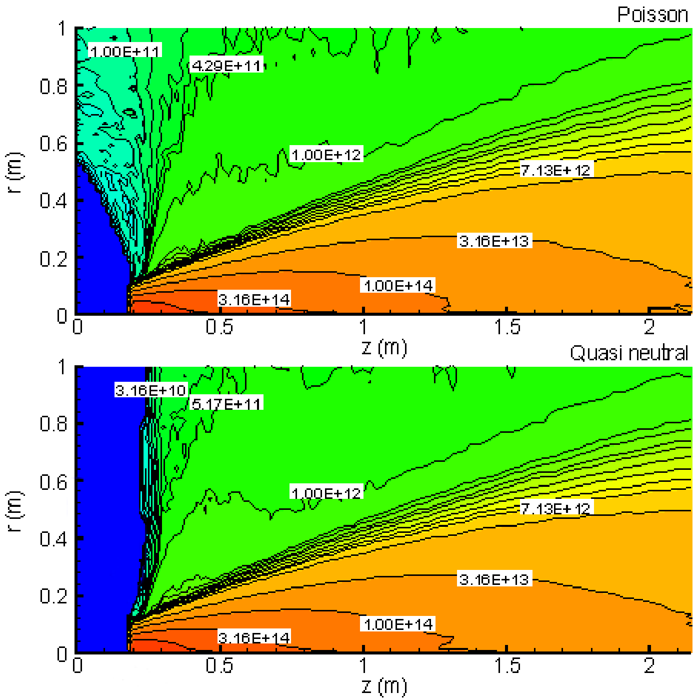
Simulation time for cases 3 and 4

Quasi Neutrality – Ion Density

- HET: no significant difference between Poisson solver and QN approach
- GIE: differences in back-flow region, QN under-predicting ion density



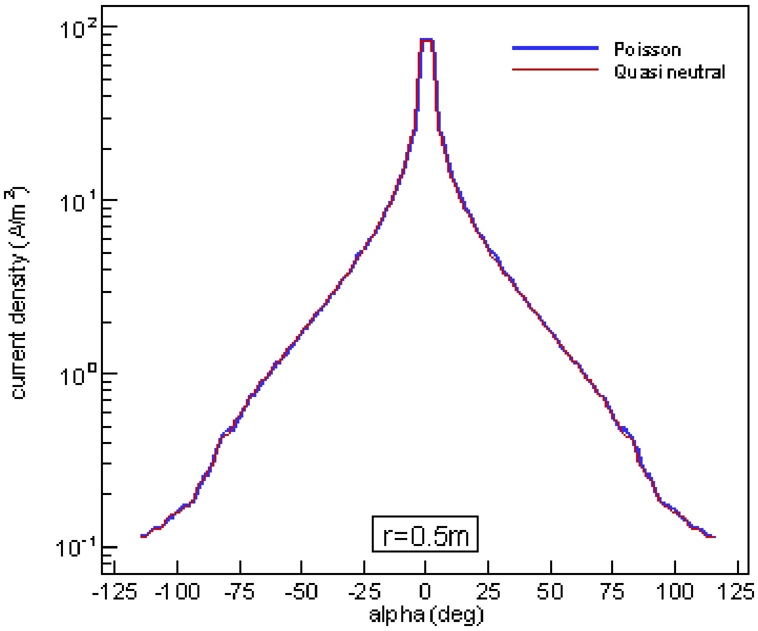
Number density field for HET



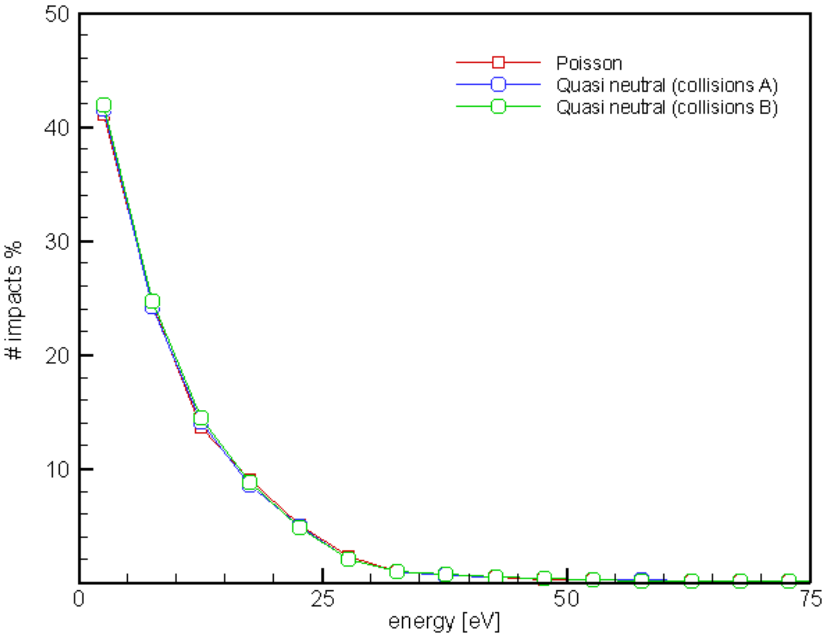
Number density field for GIE

Quasi Neutrality – Ion Current

- Ion current density and backflow impact energy distribution not significant affected by QN approach



Ion current density at 0.5 m from SPT-100 exit plane



Back-flow impact energy

PICPluS – Future Developments

Code Developments

- Upgrade to 3D configurations (3D version presently under alpha testing)
- Routines for plasma-wall interaction (partnership with Univ. Bari)
- Routines for re-deposition of sputtered particles (DSMC method)
- Extension to HET inner channel (ionization, acceleration, …)
- Integration of channel/plume codes

New Test Cases

- Double Stage HET (collaboration with SNECMA Moteurs)
- HET Beam steering (3D, collaboration with SNECMA Moteurs)
- HET cluster on realistic geometry (3D)

Conclusions

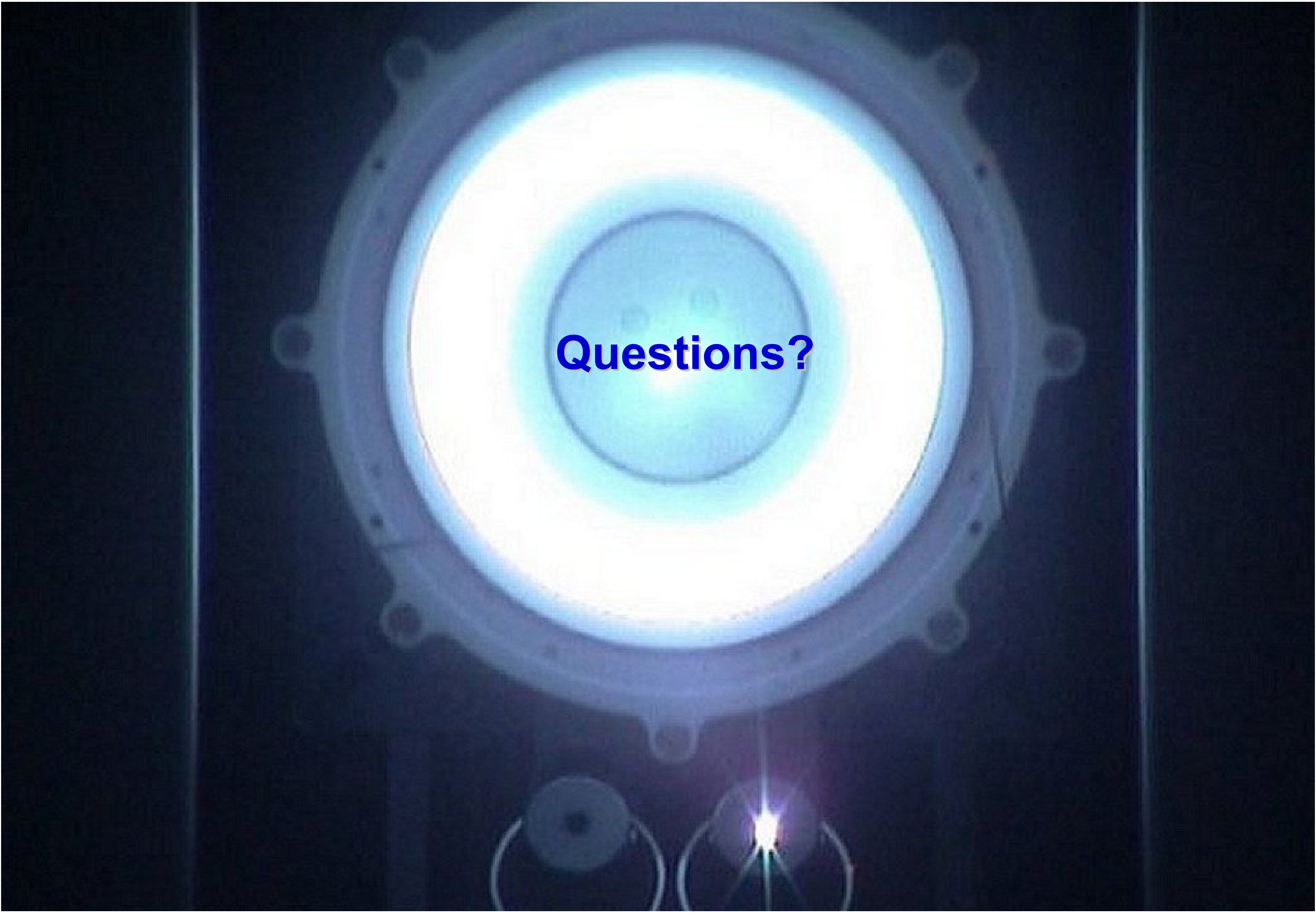
- Effect of plasma quasi-neutrality (QN) assumption on ion/plasma thruster plume simulations was examined using 2D hybrid PIC code

- Validation runs show that consistently good agreement can be obtained with respect to experimental data: key role played by plasma inflow boundary

- Effect of QN is mostly small except for backflow region of GIE cases, where charge density is under-predicted by QN algorithm

- Poisson solver solution is not significantly slower than QN approach, although algorithm is more sensitive to mesh geometry and initial conditions

- Few issues still to be addressed (especially for GIE), probably related to inconsistencies in hybrid formulation of plasma model



Questions?