AETHER: Inductively Coupled Plasma Simulation Software

Emre Turkoz, Murat Celik
Bogazici University, Bebek, Istanbul, 34342, Turkey

Abstract

An in-house code is developed to simulate the inductively coupled plasma (ICP), focusing on the discharge chamber of a Radio-Frequency (RF) ion thruster. The modeling effort consists of three submodels, which are namely the fluid model, the electromagnetic model and the transformer model. Fluid equations are solved to evaluate the plasma flow parameters, whereas the electromagnetic model handles the calculation of the electromagnetic fields and the transformer model captures the effect of the matching circuit utilized in the real life experiments for constant power deposition. The equations are discretized with the finite volume method and the resulting linear systems are solved with iterative solvers including Jacobi and GMRES. The solved equations are continuity and momentum for ions and neutrals, electric potential equation, energy equation for electrons, and magnetic vector potential equation to evaluate the electromagnetic fields. The code is written using the C++ programming language, works in parallel and has graphical user interface. The results obtained from the developed model are verified with commercial software results.

Problem & Model

Two different configurations for plasma modeling are investigated.
a) ICP confined within dielectric walls
b) Plasma enclosed within grounded walls with a small section of bias to extract current

Plasma is modeled using the fluid model. Continuity equations:

(1) $$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \boldsymbol{v_i}) = \dot{R}$$

(2) $$\frac{\partial n_n}{\partial t} + \nabla \cdot (n_n \mathbf{v_n}) = -\dot{R}$$

Ion and neutral momentum equations:

(3) $$m_i n_i \left(\frac{\partial \mathbf{v_i}}{\partial t} + \mathbf{v_i} \cdot \nabla \mathbf{v_i}\right) + k\nabla(n_i T_i) = e n_i \mathbf{E} + e n_i \mathbf{v_i} \times \mathbf{B} - m_i n_i \upsilon_{in}(\mathbf{v_i} - \mathbf{v_n}) - m_i n_i \upsilon_{ie}(\mathbf{v_i} - \mathbf{v_e})$$

(4) $$m_n n_n \left(\frac{\partial \mathbf{v_n}}{\partial t} + \mathbf{v_n} \cdot \nabla \mathbf{v_n}\right) + k\nabla(n_n T_n) = -m_n n_n \upsilon_{in}(\mathbf{v_n} - \mathbf{v_i}) - m_n n_n \upsilon_{en}(\mathbf{v_n} - \mathbf{v_e})$$

Electron energy equation:

(5) $$\frac{3}{2}\frac{\partial}{\partial t}(n_e e T_e) + \nabla \cdot \mathbf{Q_e} = -e\mathbf{E_a} \cdot \mathbf{\Gamma_e} + P_{dep} - P_{coll}$$

Divergence-free current constraint with drift-diffusion approximation for electron flux to evaluate the electric potential:

(6) $$\nabla \cdot \mathbf{j} = (n_i \mathbf{v_i} - n_e \mathbf{v_e}) = 0$$

$$\mathbf{\Gamma}_e = -D_e \nabla n_e - \mu_e n_e \left[\left(\nabla\phi + \frac{\partial \mathbf{A}}{\partial t}\right) - \mathbf{v}_e \times \mathbf{B}\right]$$

Electromagnetic fields are calculated from magnetic vector potential equation:

(7) $$\nabla^2 \mathbf{A} = \mu_0 \sigma \frac{\partial \mathbf{A}}{\partial t}$$

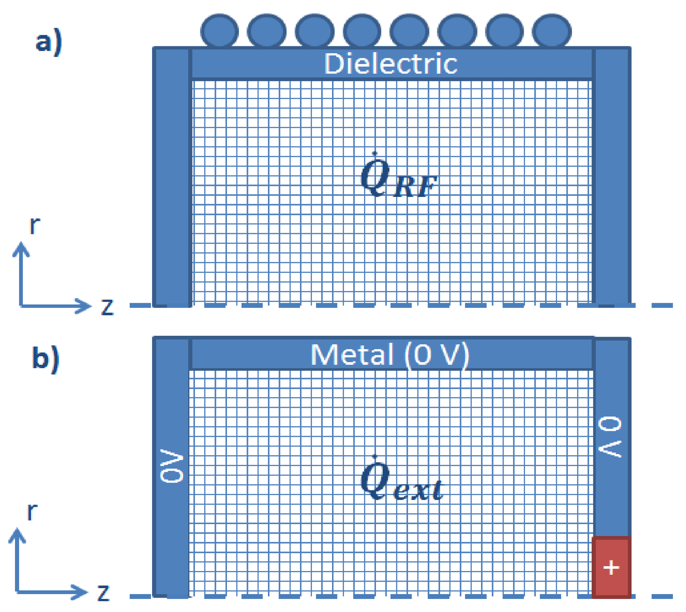


Figure: Examples for configurations that can be simulated with AETHER

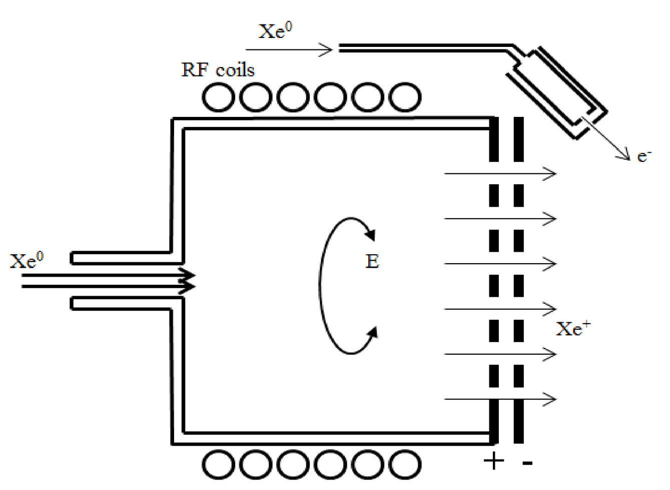


Figure: Representation of an RF ion thruster discharge chamber

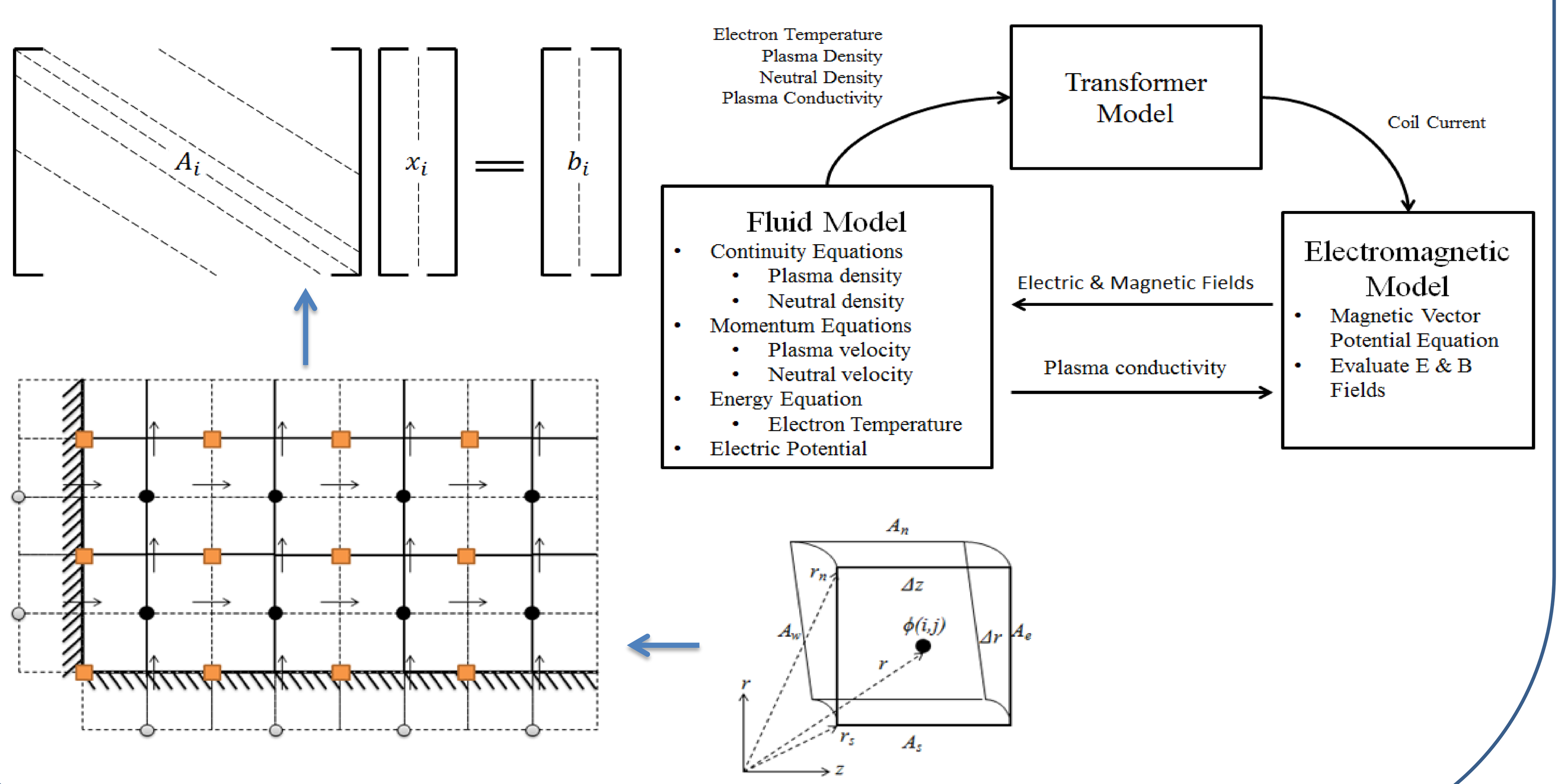
Software & Algorithm

Before starting to solve the model equations, AETHER needs some input parameters from the user. Some of these parameters must be given (or calculated) to perform the simulation. These input parameters for the dielectric wall configuration are listed as below:

- RF coil frequency
- Physical length of the domain in both axial and radial directions
- Number of coil windings around the chamber
- Coil radius
- Effective length of the coils
- Number of mesh nodes in radial and axial directions
- Time step for fluid and EM equations

The software developed in the scope of this work, AETHER, is built according to the model-view-controller design methodology in C++ programming language. The user interface is developed using the WxWidgets cross-platform user interface C++ library. The graphical user interface (GUI) of AETHER is shown in Fig.8. The software has an OpenGL renderer for results visualization. The Visualization Toolkit (VTK) is utilized for visualization purposes. The solvers and the mathematical calculations are implemented mostly parallel, providing 100% CPU usage during the solution process. For the multi-core parallelization Microsoft's Parallel Patterns Library is utilized. The implementation is performed using Microsoft Visual Studio 2010 Express C++. The runs are given on a dual processor 3.30 GHz Intel Xeon workstation.

Benchmark problem: The model is used to solve a benchmark ICP configuration to verify the results with the Plasma Module of the commercial software COMSOL. For the verification, the modeled geometry is a cylindrical discharge chamber with dielectric walls. The chamber is 7 cm long and has a diameter of 8 cm. RF power is deposited into the plasma through a 10 coil-winding antenna around the chamber, which extends 5 cm in the axial direction. Driving frequency is 13.56 MHz. ICP is generated using Argon gas at an initial pressure of 20 mTorr, which corresponds to 3.0E+20 m³ neutral density. There is no neutral gas inlet to the system. All the ions that reach the wall go through a recombination process and are directed back into the system as neutrals. The same configuration is also solved with COMSOL and the obtained results are compared. For comparison, two different power deposition values, that result in steady-state solutions, are chosen. These values are 3000 W and 6500 W.



Results

The results from AETHER and COMSOL show agreement to a great degree with a little amount of overshoot from AETHER. Plasma density values from both platforms show the same tendency both quantitatively and qualitatively. Electron temperature is almost uniform, with the mean value of 3.76 eV for 3000 W. This value is lower than the value evaluated by COMSOL Plasma Module, which is 4.47 eV. For the verification of the transformer model, a simple test case within AETHER is considered to be sufficient. Transformer model takes the power to be deposited into the plasma as one of the inputs. According to the desired input power value, it arranges the current to be supplied to the RF coils. For the verification, a case of 400 W RF power deposition into the plasma is investigated. It is observed that after about 4 RF cycles, the amount of power deposited into the plasma becomes equal to the input given to the transformer model.

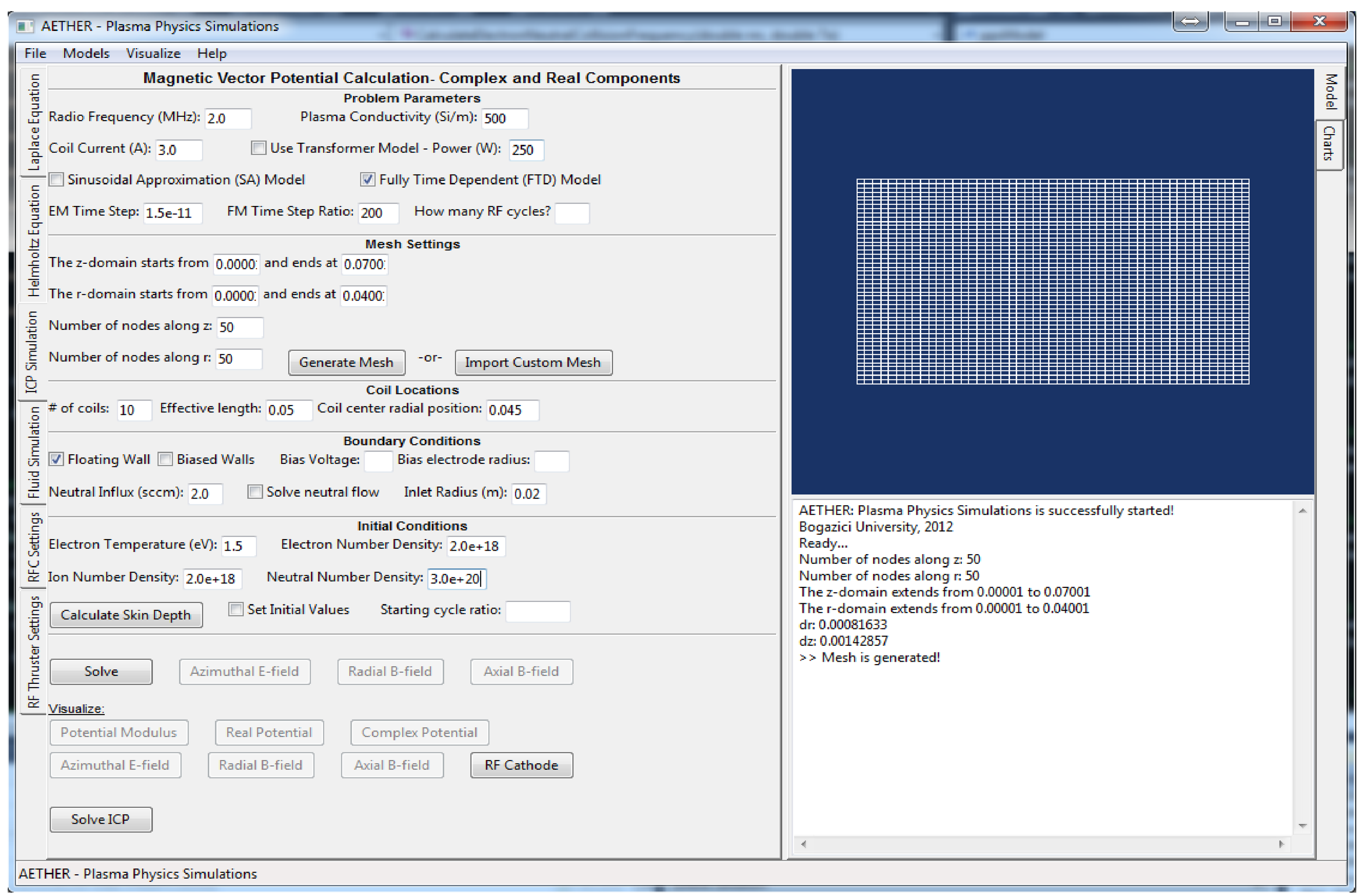


Figure: Graphical user interface of AETHER

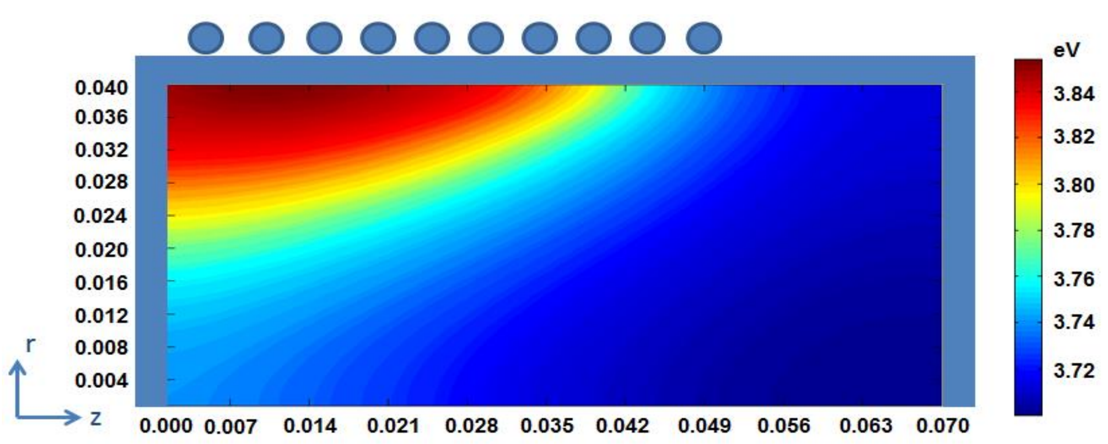


Figure: Electron temperature distribution

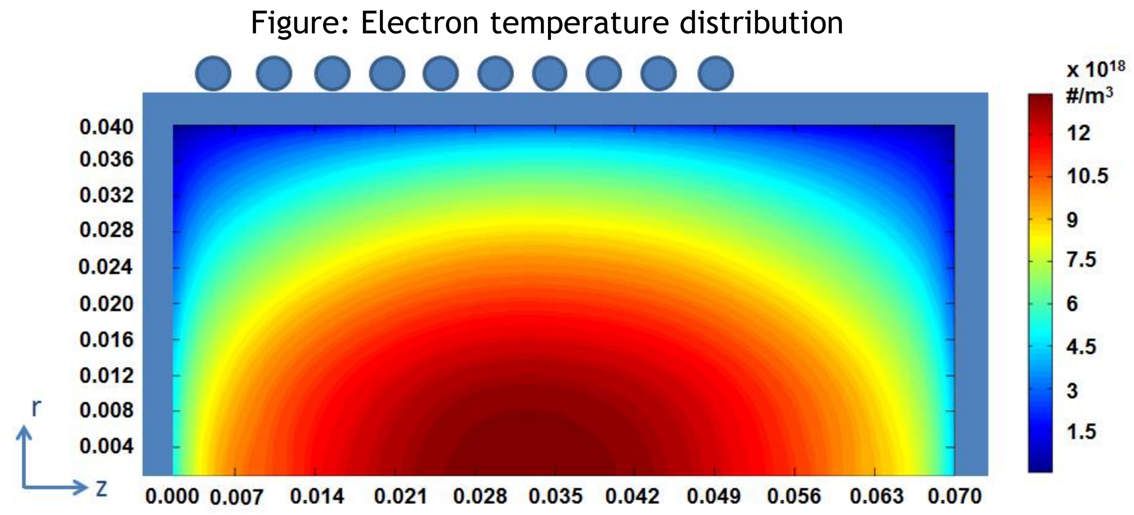


Figure: Plasma density distribution

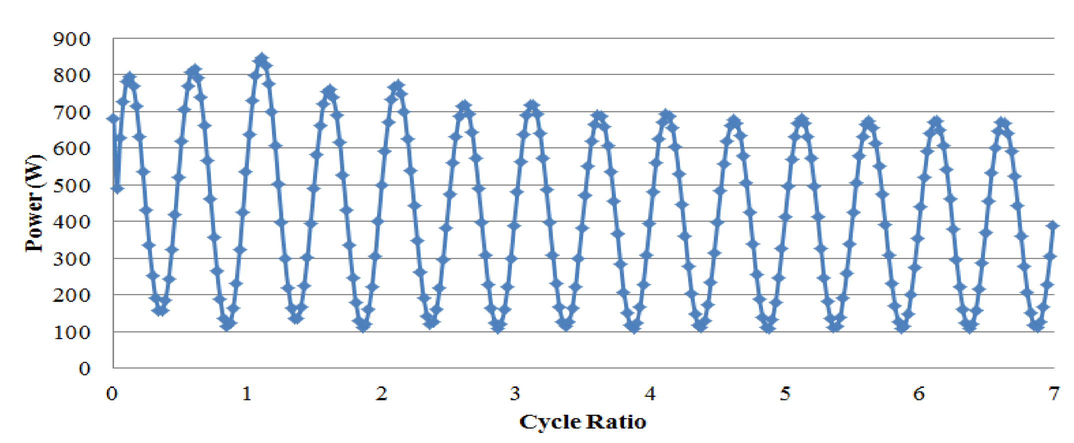


Figure: Power deposition vs. time

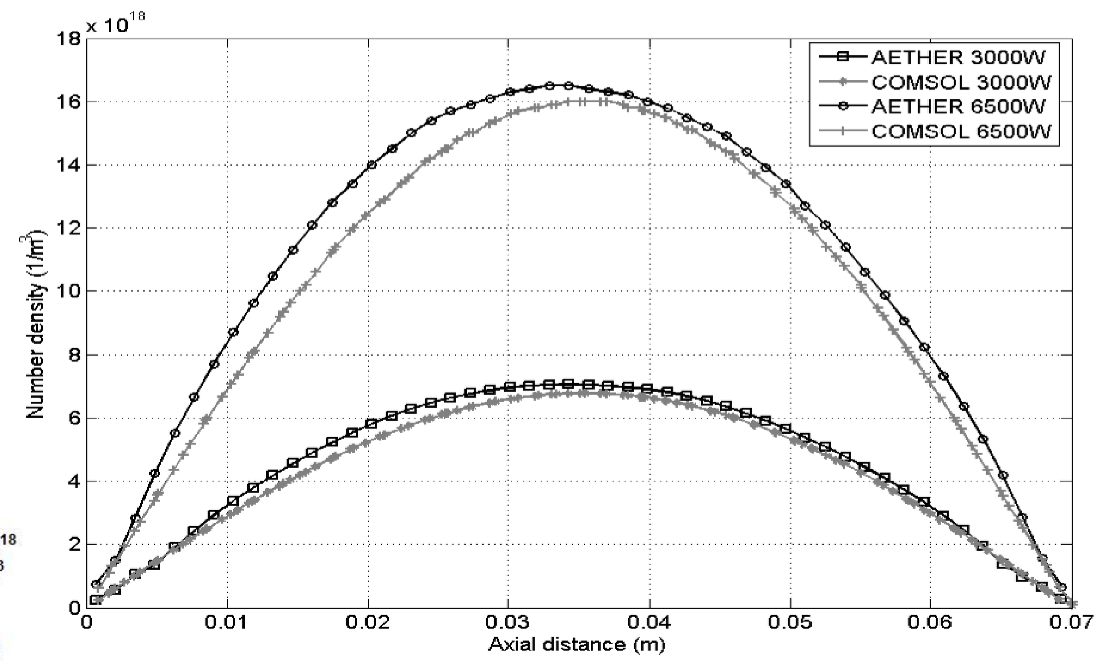


Figure: Comparison of axial number density results from AETHER and COMSOL for 3000 W and 6500 W

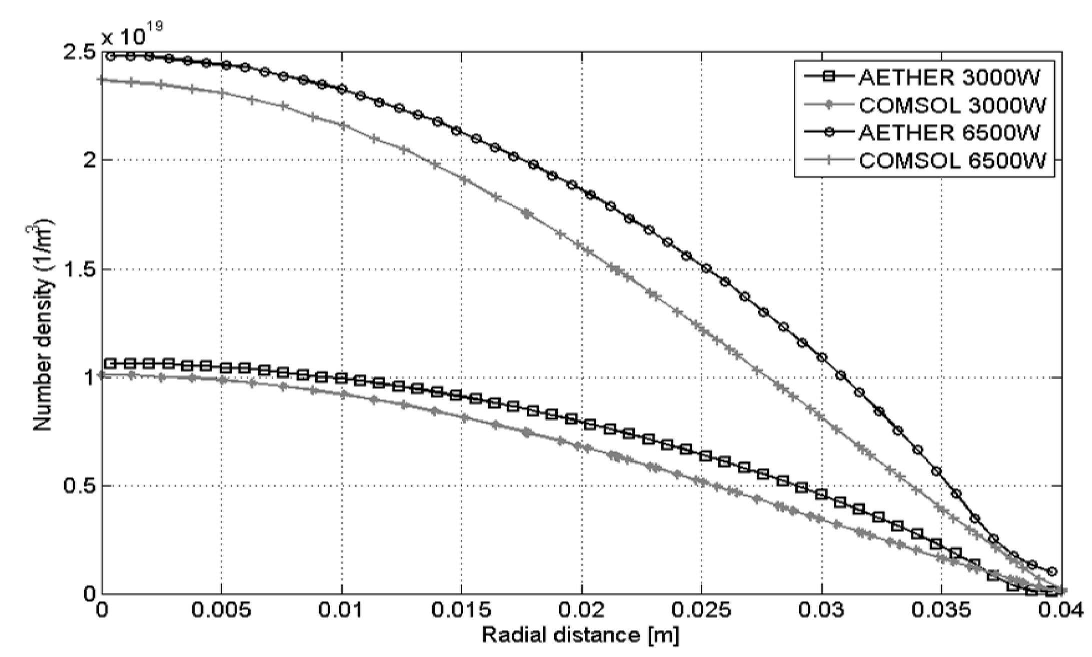


Figure: Comparison of radial number density results from AETHER and COMSOL for 3000 W and 6500 W

Presented at the International Middle East Plasma Science Conference, 23-25 April, 2014, Belek, Antalya, Turkey