Numerical Simulation of Cascaded Arc for Ar and H_2 gases

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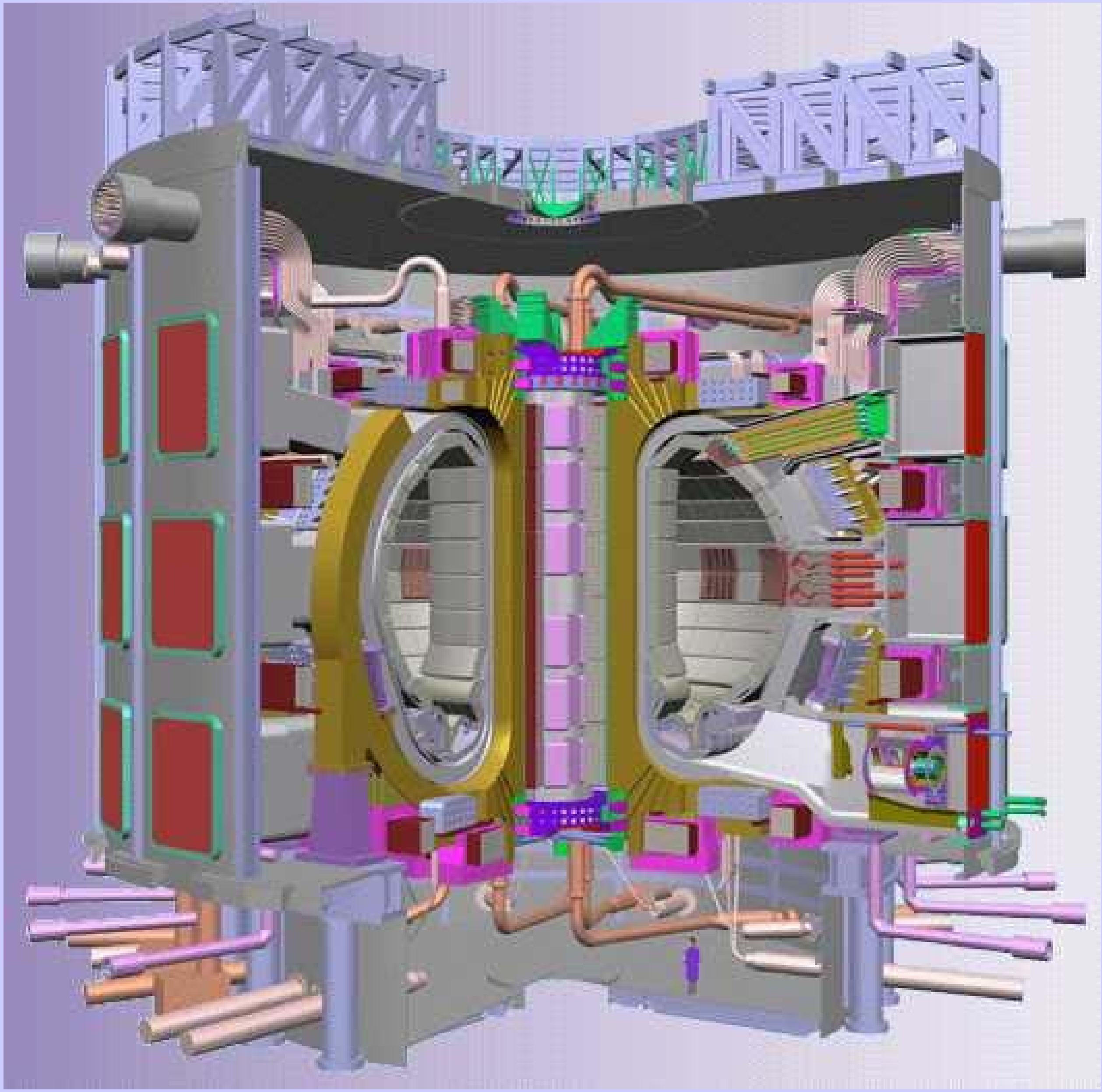
Introduction

- **Magnum-psi Project:** (MAgnetised plasma Generator and NUmerical Modelling for Plasma Surface Interaction studies)

- **Aim of Magnum-psi project:**
  - Study of plasmas expected in the divertor region of future Tokamak ITER
  - particle flux density ~ 10^{22}-10^{24} $m^{-2}s^{-1}$
  - electron and ion temperature ~ 1 eV
  - magnetic field ~ 5 T
  - Study of industrial applications of plasmas like deposition, etching etc.

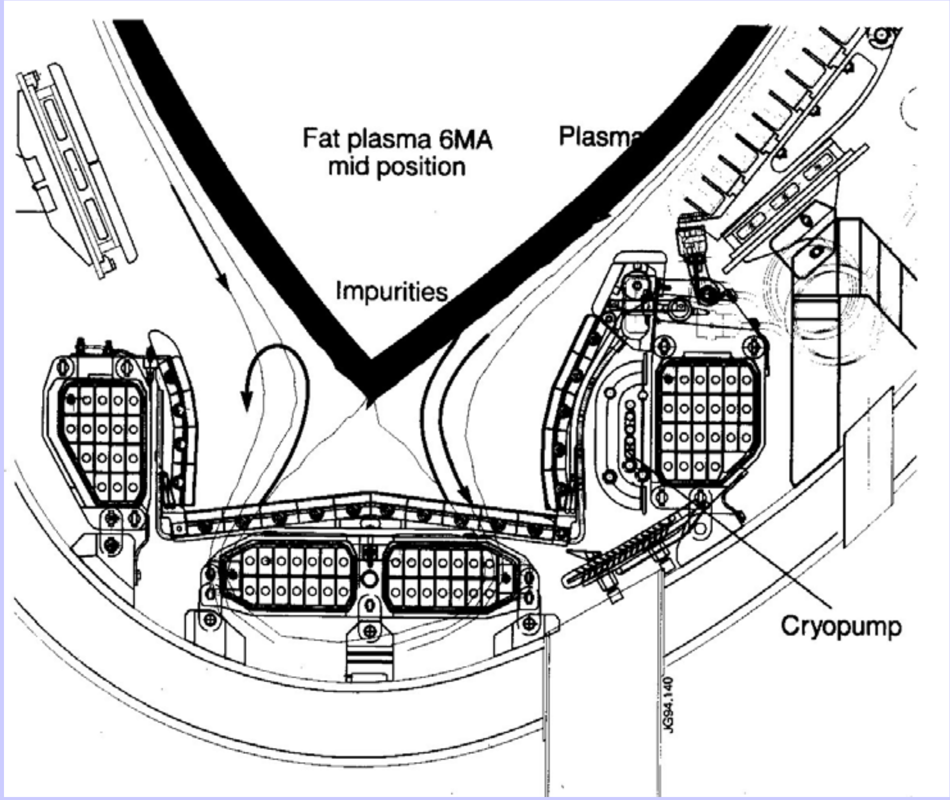
- **Plasma Source:** Cascaded Arc

- **Tool:** PLASIMO (PLAsma SImulation MOdel).



ITER Diagram

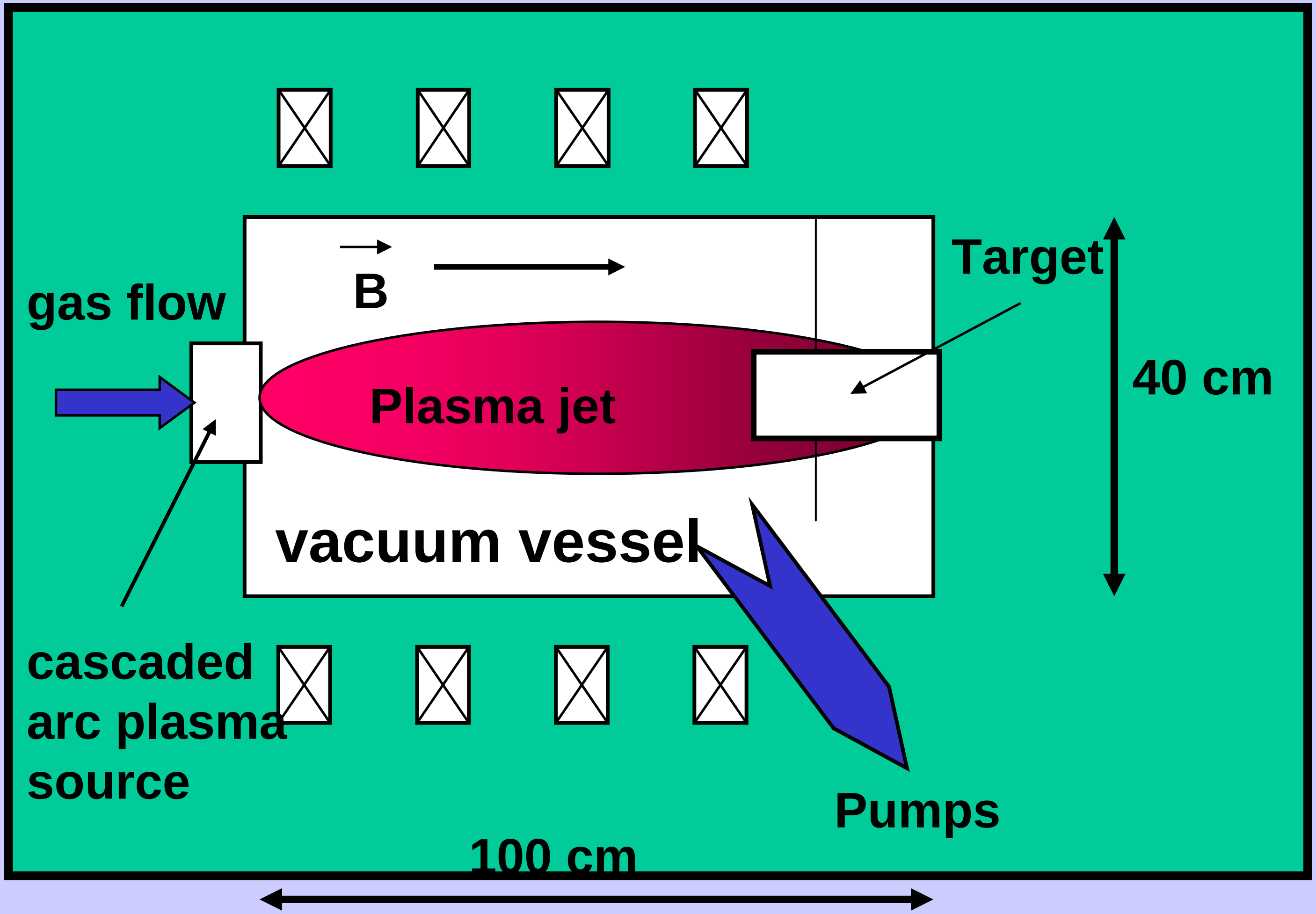
Divertor region of a Tokamak



Conditions at surface of ITER Divertor:

- particle flux density at surface ~ 10^{24} $m^{-2}s^{-1}$
- electron and ion temperature ~ 1 eV
- magnetic field ~ 5 T

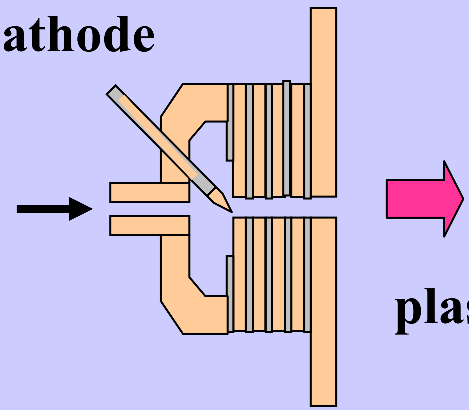
Pilot-psi experimental set-up

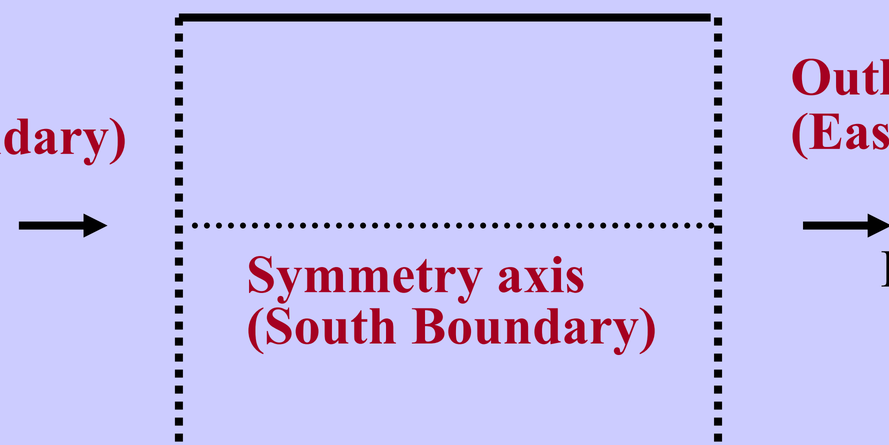


Plasma Source Geometry

Straight arc channel:

4 mm diameter, 32 mm length





Grid: 16 radial×64 axial points

Mathematical Model

With the use of a two-dimensional hydrodynamical model, plasma processes in the arc are simulated. The governing equations in the model are:

Particle balance equations : $\vec{\nabla} \bullet \left(n_h \vec{u} \right) - \vec{\nabla} \bullet \left(D_h \vec{\nabla} n_h \right) = S_h$

D_h and $\vec{u}$ are the diffusion coefficient of species *h* and the plasma bulk velocity respectively, while S_h denotes the net production of species *h* due to the collisional-radiative processes

Total Continuity equations : $\vec{\nabla} \bullet \left(\rho \vec{u} \right) = 0$

Momentum balance : $\vec{\nabla}\bullet\left(\rho \vec{u}_i \vec{u}\right) = -\left(\overrightarrow{\nabla p}\right)_i + \left(\overrightarrow{\nabla}\bullet\tau\right)_i$

where *i* denotes the axial or radial component and τ viscous stress tensor.

Energy balance heavy particles : $\overrightarrow{\nabla}\bullet\left(\rho_h \varepsilon_h \overrightarrow{u}\right) + p_h \overrightarrow{\nabla}\bullet\overrightarrow{u} + \overrightarrow{\nabla}\bullet\overrightarrow{q_h} = \tau_h : \overrightarrow{\nabla}\,\overrightarrow{u} + Q_h$

where ε_h is the internal energy per unit mass of the heavy particle. The heat flux is $\vec{q}_h = -\kappa\overrightarrow{\nabla}T$ and Q_h denotes the energy gain or loss through elastic/inelastic reactions.

Energy balance electrons : $\overrightarrow{\nabla}\bullet\left(\rho_e \varepsilon_e \overrightarrow{u}\right) + p_e \overrightarrow{\nabla}\bullet\overrightarrow{u} + \overrightarrow{\nabla}\bullet\overrightarrow{q_e} = Q_{Ohm} + Q_e$

Q_{Ohm} is the energy gain through Ohmic heating.

$$Q_{Ohm} = \sigma E^2$$

Equation of state : $p = \sum_{\alpha} n_\alpha k_B T_\alpha$

The (axial) electric field is computed from the electric conductivity integrated over the cross section of the channel as:

$$I = \int_0^a 2\pi r \sigma(r) dr$$

Boundary conditions

Q.	Inlet	Outlet	Axis	Channel wall
p	$\frac{\partial p}{\partial z}=C$	$\frac{\partial p}{\partial z}=C$	$\frac{\partial p}{\partial r}=0$	$\frac{\partial p}{\partial r}=0$
u_z	$u_z=u_{in}^{max}\left[1-\left(\frac{r}{R_{in}}\right)^2\right]$	$u_z=u_{out}^{max}\left[1-\left(\frac{r}{R_{in}}\right)^5\right]$	$\frac{\partial u_z}{\partial r}=0$	$u_z=0$
u_r	$u_r=0$	$\frac{\partial u_r}{\partial z}=0$	$u_r=0$	$u_r=0$
$T_{e,h}$	$T_h=500K$ $T_e=6000K$	$\frac{\partial T_{e,h}}{\partial z}=0$	$\frac{\partial T_{e,h}}{\partial r}=0$	T_h =500*K $T_e=6000K/\frac{\partial T_e}{\partial r}=C$

Chemical reactions inside arc channel

For reactions which are temperature dependent, Arrhenius like fit is used

$$k = c(T)^{\beta} \exp\left(\frac{-E}{T}\right)$$

Where c is the rate constant, T is the electron or heavy particle temp in eV, E is the reaction energy in eV and β is the power of Temp.

Argon ionisation: $$Ar + e \leftrightarrow Ar^{+} + 2e$$

Molecular ionisation: $$H_2 + e \leftrightarrow H_2^{+} + 2e$$

Dissociative recombination: $$H_2^{+} + e \rightarrow H + H^{*} \rightarrow H + H^{+} + e$$
$$\rightarrow H + H$$

Dissociation by electron impact: $$H_2^{+} + e \rightarrow H + H^{+} + e$$

Electron assisted dissociation: $$H_2 + e \leftrightarrow H + H + e$$

Heavy particle assisted dissociation: $$H_2 + M \leftrightarrow H + H + M$$

Hydrogen ionisation: $$H + e \leftrightarrow H^+ + 2e$$

Vibrational excitation: $$H_2^{v=2} \leftrightarrow H_2^{v=4,8} + e$$

Charge Transfer: $$H_2^{v=4,8} + H \rightarrow H_2^+ + H$$

Dissociative recombination:

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

$$H_3^+ + e \rightarrow H + H + H$$

$$H_3^+ + e \rightarrow H_2 + H$$

Dissociative attachment: $$H_2^{v=8} + e \rightarrow H^- + H$$

Recombination:

$$H^- + H^+ \rightarrow H^{**} + H$$

$$H^- + H_2^+ \rightarrow H^{**} + H_2$$

Chemical reactions at the channel walls

$$Ar^{+} + wall \rightarrow Ar$$

$$H + wall \rightarrow \frac{1}{2} H_2^{v=4,8}$$

$$H_2^{v=4,8} + wall \rightarrow H_2$$

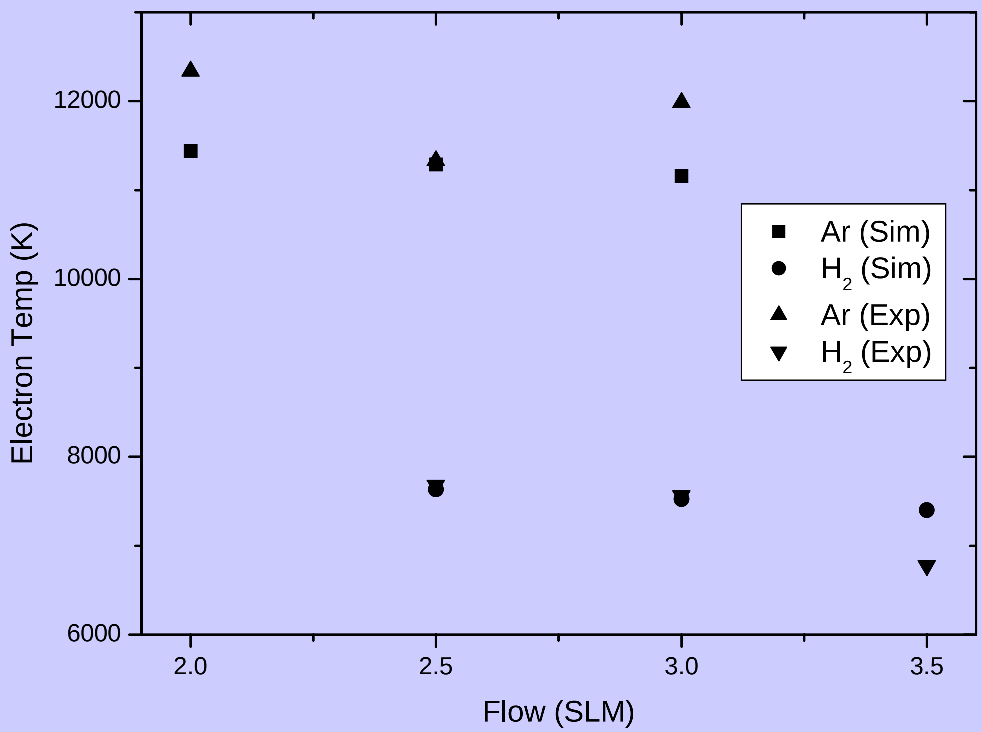
$$H^{+} + wall \rightarrow H$$

$$H_2^{+} + wall \rightarrow H_2$$

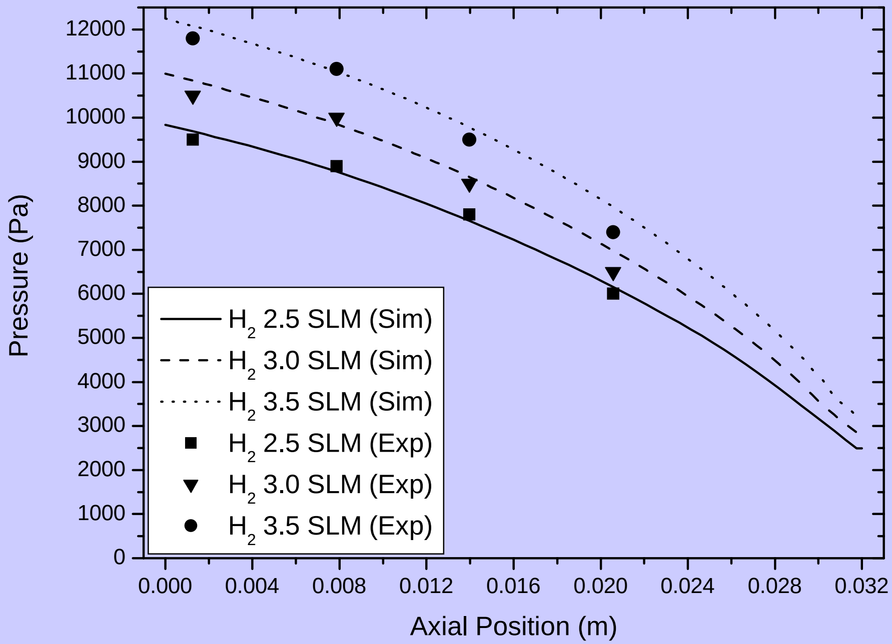
$$H_3^{+} + wall \rightarrow H_2 + H$$

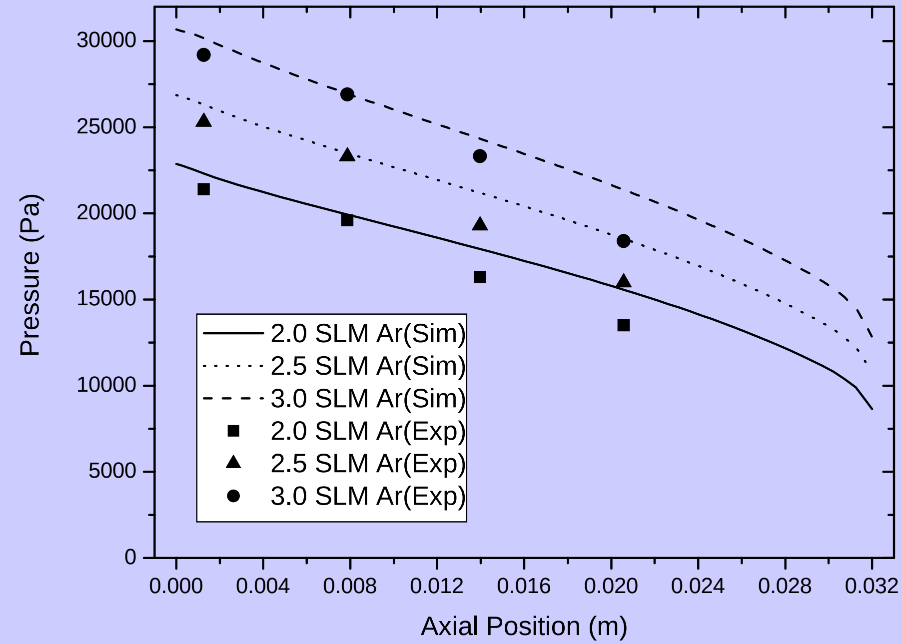
Results

Code to experiment validation for Pilot-psi



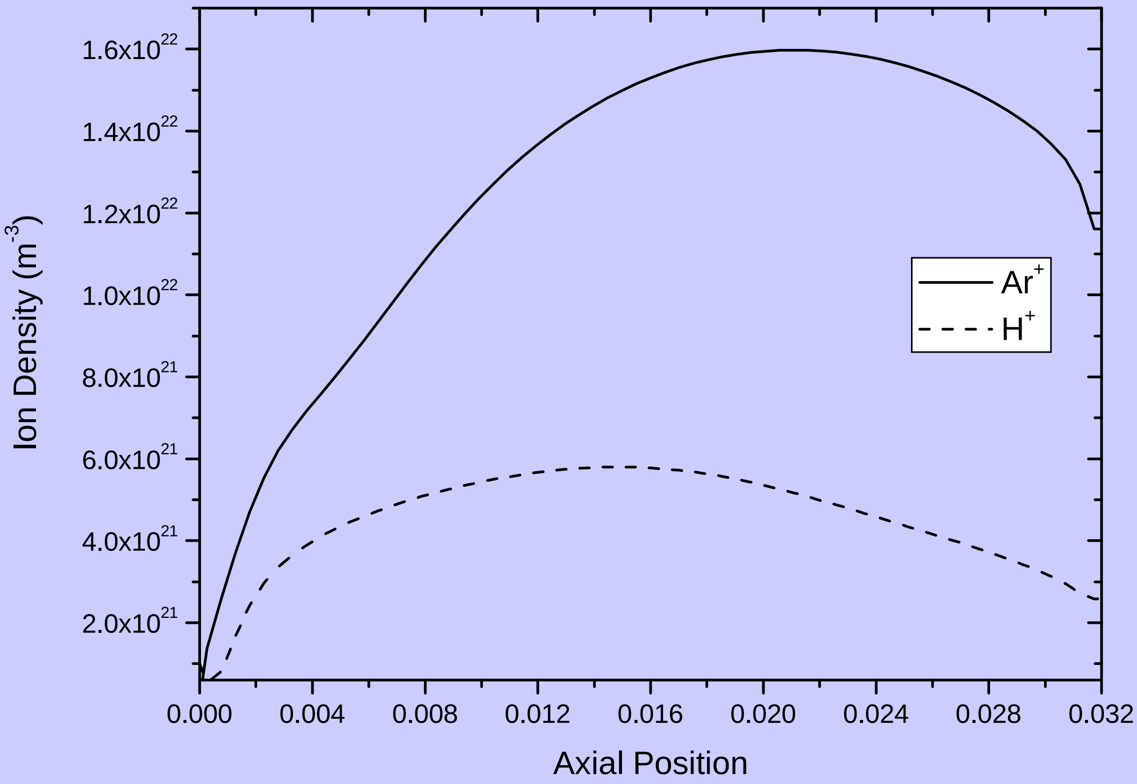
Comparison of temperature for Current 60 A, Flow 2.0, 2.5,3.0 SLM of Ar and 2.5, 3.0, 3.5 SLM of H_2





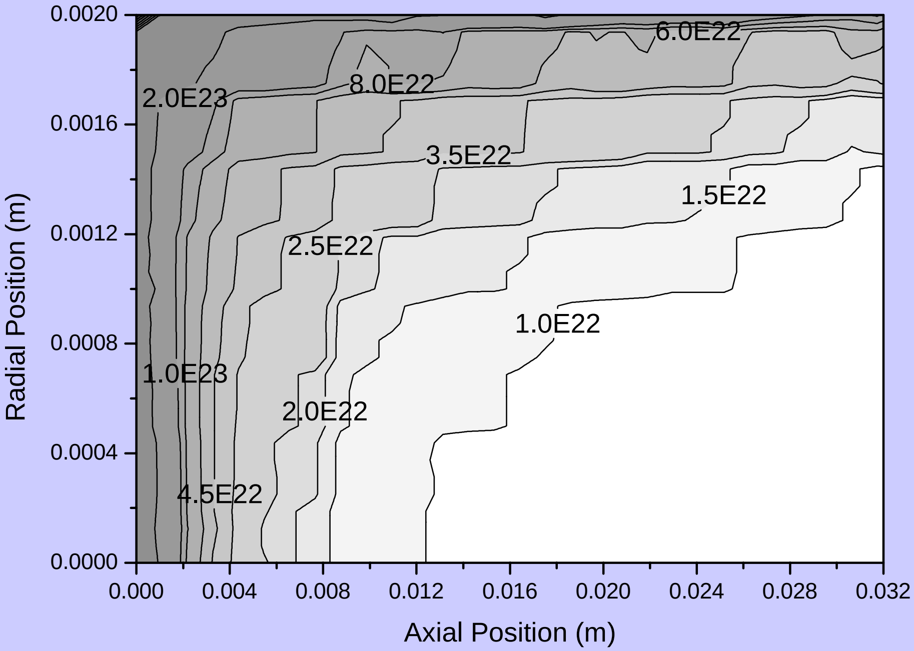
Comparison of experimental results for the pressure along the arc length

Ar^+ and H^+ densities along the axes with a 2mm radius operated at current of 60A and a flow of 2.5 and 3.0 SLM respectively

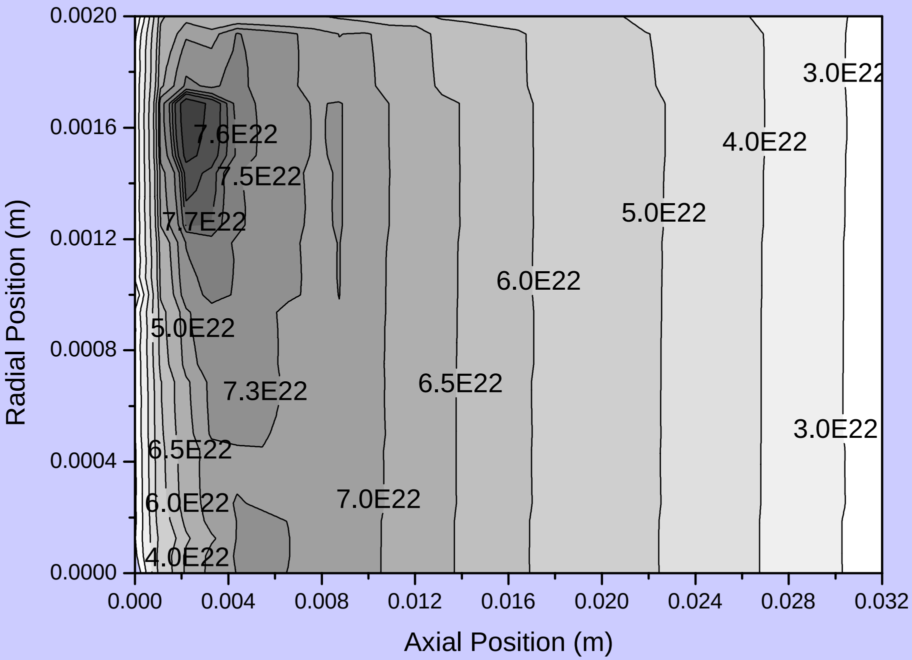


Profiles

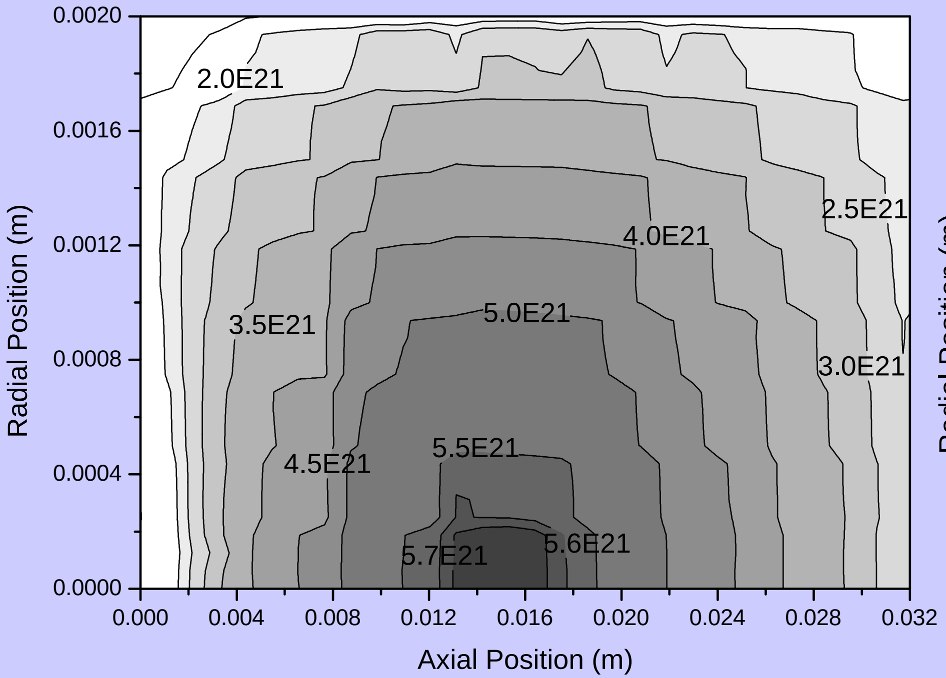
Current 60A, Flow 3.0 SLM



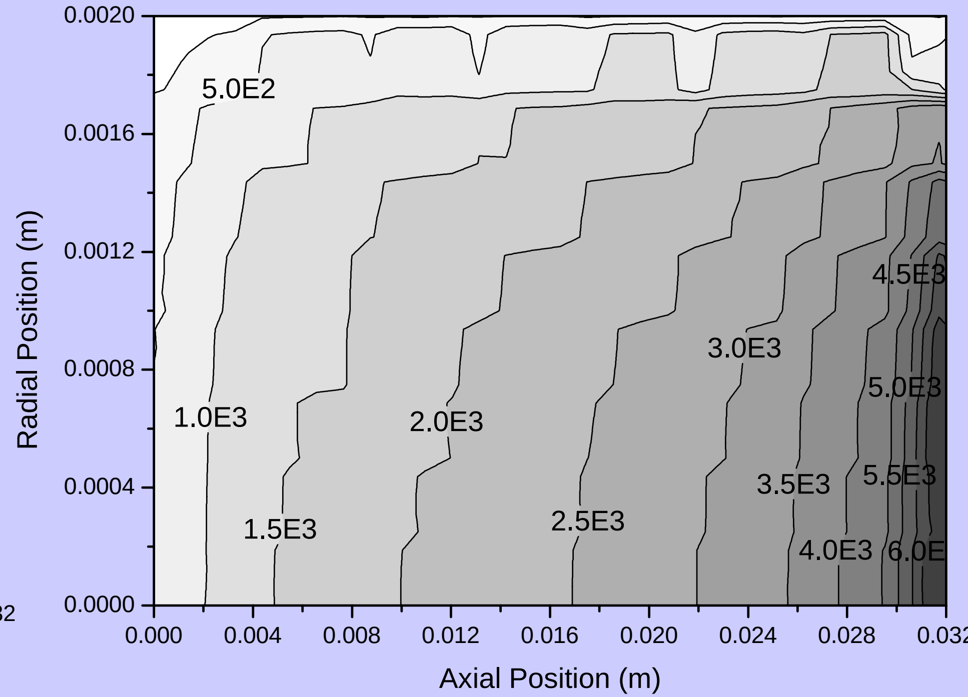
H_2



H


0.0020
0.0016
0.0012
0.0008
0.0004
0.0000
Radial Position (m)
0.000
0.004
0.008
0.012
0.016
0.020
0.024
0.028
0.032
Axial Position (m)
2.0E21
2.5E21
3.0E21
3.5E21
4.0E21
4.5E21
5.0E21
5.5E21
5.6E21
5.7E21

H^+


0.0020
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Radial Position (m)
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0.012
0.016
0.020
0.024
0.028
Axial Position (m)
5.0E2
1.0E3
1.5E3
2.0E3
2.5E3
3.0E3
3.5E3
4.0E3
4.5E3
5.0E3
5.5E3

Velocity

Ion Fluxes and energy required for per ion for different geometries

Current (A)	R (mm)	L (mm)	H^+ flux (s^{-1})	H^+ (eV/ion)	Ionization %	Ar^+ flux (s^{-1})	Ar^+ (eV/ion)	Ionization %
60	2	30	1.38×10^{20}	320	5.4	1.58×10^{20}	87	14.5
60	2	32	1.39×10^{20}	343	5.4	1.64×10^{20}	91	15.1
60	2	40	1.44×10^{20}	427	5.6	1.87×10^{20}	98	17.1
410	5	30	1.39×10^{21}	199	38	4.08×10^{20}	218	37.5
410	5	32	1.46×10^{21}	201	37.6	4.37×10^{20}	216	40.1
410	5	70	2.15×10^{21}	294	18.4	8.51×10^{20}	212	78.0

Magnetic Field Effect

Thermal Conductivity of electrons in the presence of ions and neutrals:

$$\kappa_e(0) = \frac{2.4}{\left(1.0 + \left(\frac{\nu_{ei}}{\sqrt{2}\nu_{e0}}\right)\right)} \frac{k_B^2 n_e T_e}{m_e \nu_{e0}}$$

In the presence of Magnetic filed it is modified as:

$$\kappa_e(B_{ext}) = \frac{1}{\left(1.0 + \left(\frac{\omega_{ce}}{\nu_{e0} + \nu_{ei}}\right)^2\right)} \kappa_e(0)$$

Where

$$\omega_{ce} = \frac{eB_{ext}}{m_e}$$

The Ambipolar Diffusion coefficient

$$D_a = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}$$

$$\mu_i = \frac{q}{m_i\left(\nu_{i0} + \nu_{ii} + \nu_{ie}\right)}$$

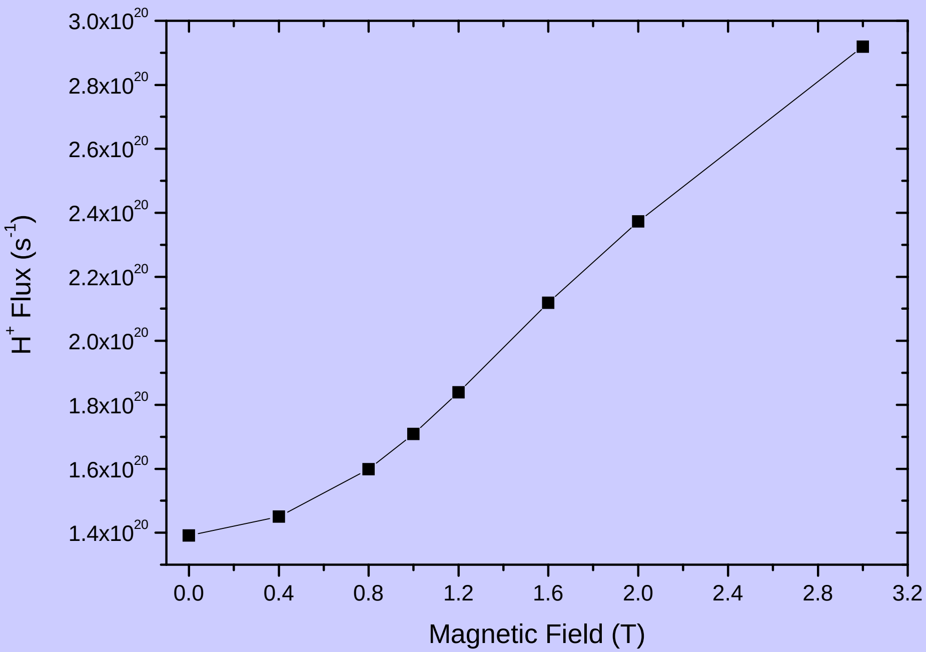
$$\mu_e = \frac{q}{m_i\left(\nu_{i0} + \nu_{ie}\right)}$$

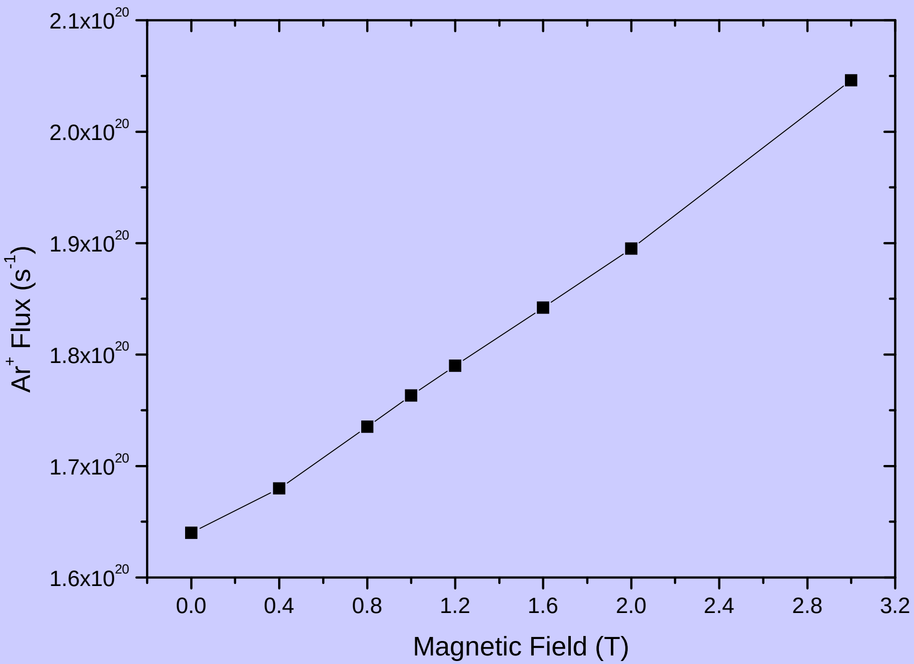
In the presence of magnetic field, the electron transport coefficient are strongly reduced, and, in the limit where ion transport is dominant, the ambipolar diffusion coefficient becomes,

$$D_a = D_i\left(1 + \frac{T_e}{T_i}\right)\left(\frac{1}{1 + \frac{\mu_i}{\mu_e}\left(1 + \left(\frac{\omega_{ce}}{\nu_{e0} + \nu_{ei}}\right)^2\right)}\right)$$

Fluxes leaving the Arc,

Current 60A, Flow 3.0 SLM





Summary

- It can be seen that simulation results are in reasonable agreement with the experimental findings.
- For the case of hydrogen arc lengthening the arc will not increase the ionization degree, however, widening the arc will increase the ionization degree which can be considered as a plasma source for Magnum-psi
- For the argon arc lengthening and widening the arc both increase the ionization degree.
- Both argon and hydrogen fluxes increase with the magnetic field. The Ar^+ flux is not much influenced by the magnetic field, only 25% at a field of 3T. The H^+ flux increases significantly, with a 3T magnetic field the flux is doubled.

Thank you very much for your attention