Interferometric and Spectroscopic Diagnostics for Plasma Transport Studies in the High Current Pulsed Cathodic Arc

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Abstract

• Early results are presented from interferometric and spectroscopic diagnostics being installed on the University of Sydney pulsed high-current cathodic arc [1].

• These diagnostics are being used to study and optimise plasma transport through the arc’s quarter-torus magnetic macroparticle filter.

• In high-current pulses (~3 kA) measured electron densities are >2×10^{20} m^{-3} in the middle of the filter and are ~2×10^{18} m^{-3} in the substrate region at the filter exit.

• A two-fluid model of the transport [2] has been implemented in Matlab. Initial results show qualitative agreement with measurements.

• Early spectroscopic measurements are reported. These identify potential lines for use with a high-resolution MOSS [3] interference spectrometer being developed for ion Doppler measurements on the arc.
Pulsed Arc Layout

- Duct Coil
- 2mm Interferometer Beam Path
- Anode
- 8mm Interferometer Beam Path
- Cathode
- Rogowski Coil
- Substrate
8mm Interferometer measures electron density at Substrate.

- Probe Source (38GHz Gunn)
- Directional Coupler (3dB)
- Isolators
- Reference Source (38GHz Gunn) [Behind translator]
- Reference Detector
- Probe Detector
- Plasma in Substrate Region

4 horns inside port and flexible waveguide enable radial profile measurements.
Schematic Layout of 8mm Interferometer
2mm Interferometer measures electron density in toroidal duct

- Breadboard table mounted on horizontal translators - enables radial profile measurements of the plasma in the toroidal duct.
- Plasma ducted from cathode source to substrate by toroidal duct inside vacuum vessel.
- 2mm wavelength radiation detector.
- Quasi-optical beam path.
- 2mm IMPATT swept frequency (140-141 GHz) source.
  - Sweep bandwidth selected to match one wavelength path difference between probe and reference arms of interferometer, producing sinusoidal wavefunction at detector.
  - Sweep rate: 100kHz.
New 2mm Interferometer - First Results

Cathode Current (Scale 0→3000 A)
Anode Current
Net Available Current (Cathode-Anode)
Duct Magnetic Field (Scale 8→18 mT)
Duct Bias (Scale -20→0 V)
Substrate Bias (Scale -200→0 V)
[Note: substrate floating this pulse]
Substrate Current (Scale 0→0.5 A)
Plasma Current $\phi=9^\circ$ (Scale 0→800 A)
[Before Duct]
Plasma Current $\phi=30^\circ$ (Scale 0→800 A)
[1/3 into Duct]
Plasma Current $\phi=60^\circ$ (Scale 0→500 A)
[2/3 through Duct]
Plasma Current $\phi=75^\circ$ (Scale 0→300 A)
[After Duct]
Electron density (Scale 0→5x10^{18} m^{-3})
[Centre of Duct - from 2mm interferometer]
Electron density (Scale 0→1.2x10^{17} m^{-3})
[At Substrate - from 8mm interferometer]
New High-Speed Data Acquisition System Installed

D-TACQ ACQ216CPCI
16 channel 10MS/s Simultaneous Digitiser
• Connected via gigabit ethernet to MDSPlus data server running on linux.
• Currently recording 16 channels of data for a pulse every two seconds.
• Potentially able to record faster than the maximum 10 pulse/second rate of the pulsed arc.
MDSPlus Database Sample Data Set
Early Results:
Effect of Varying Duct Bias on Electron Density in Centre of Duct

![Graph showing electron density over time for different duct biases. The x-axis represents time in microseconds (µs) ranging from 0 to 800, and the y-axis represents electron density in m⁻³ ranging from 0 to 4.0e19. The graph includes traces for 0V, 20V, 40V, and 60V biases.](image)
Early Results:
Effect of varying Cathode Current on Electron Density in Substrate Region
Early Results:
Effect of varying Duct Magnetic Field on Electron Density in Substrate Region
Discussion of Early Interferometer Results

• Increased arc current produces increased electron density.

• Increased duct magnetic field improves plasma transport to the substrate.

• Positive biasing of the duct aids plasma transport. There is a bias voltage of maximum transport efficiency.

• With high currents and moderate duct magnetic fields, the duct plasma reflected the 2mm interferometer beam, implying electron densities can exceed $2.4 \times 10^{20} \text{m}^{-3}$ in the duct.
Development of a Two-Fluid Model of Plasma Transport through the Toroidal Duct

\[ (\mathbf{v}_i \cdot \nabla) \mathbf{v}_i + \frac{kT_i}{m_i} \nabla \ln(n) - \frac{Ze \mathbf{E}}{m_i} + v_{ie} \frac{m_e}{m_i} (\mathbf{v}_i - \mathbf{v}_e) = 0 \]

\[ (\mathbf{v}_e \cdot \nabla) \mathbf{v}_e + \frac{kT_e}{m_e} \nabla \ln(n) - \frac{Ze \mathbf{E}}{m_e} + v_{ei} \frac{m_e}{m_i} (\mathbf{v}_e - \mathbf{v}_i) + \omega_{ce} (\mathbf{v}_e \times \mathbf{h}) = 0 \]

- These equations are rearranged and, after applying continuity and quasi-neutrality conditions, give two linked 3-D PDE's.
- These PDE's are numerically solved simultaneously to compute ion number density and electric potential throughout the duct.
Toroidal Coordinates used to simplify boundary conditions in duct

\[
x = \frac{a \cos(\varphi) \sinh(\tau)}{\cosh(\tau) - \cos(\sigma)}
\]

\[
y = \frac{a \sin(\varphi) \sinh(\tau)}{\cosh(\tau) - \cos(\sigma)}
\]

\[
z = \frac{a \sin(\sigma)}{\cosh(\tau) - \cos(\sigma)}
\]

\[\sigma, \tau = \ln(r/r')\]

(B Alterkop, 1996)
Key model parameters affecting plasma transport

- Generalised collision frequency $\nu$.
- Average ionization state $Z$. For titanium $Z$ is typically 2.5.
- Tangential velocity around the duct $v_0$. Note $v_0$ is hypersonic, $v_0 \sim 1.4 \times 10^4 \text{ ms}^{-1}$.
- Magnetic field strength $B$, for example:

Ion density at 30º toroidal angle
(1/3 through duct)
Ti Arc Spectra 200-860 nm
(Lots of spectral lines!)

View perpendicular to plasma jet (φ=22.5°)
Ti Spectra Detail with Candidate Line for MOSS Spectrometry

Ti II (Ti⁺) 450.1273 nm line a candidate for use with MOSS interference spectrometer
References

