Studies of Impurities in the Pegasus Spherical Tokamak

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Studies of Impurities in the Pegasus Spherical Tokamak

Pegasus is a Compact Ultralow-A ST

Non-Solenoidal Startup via LHI

Helicity Injection is Current Drive

Impurity Measurements Needed for LHI Ass.

Deployed Absolutely Calibrated VB Spectrometer to test viability of Visible Bremsstrahlung Measurements

Multi-point Thomson Scattering Provides $T_e(r')$ and $n_e(r')$ for $Z_{eff}$ Measurement

VB Measurements Requires Suitable Continuum Spectral Width

Spectral Survey Performed to Identify Suitable VB Spectral During LHI

VUV Spectroscopy Acquires Time Resolved Impurity Spectra

Detector Improvements Desired to Optimize Spectral Resolution

New Detector System for SPRED

NI Vision Acquisition Software Allows Automated Data Collection

New Imaging System Produces High Quality Spectra

Full Spectral Resolution Achieved with New Imaging Detector

Time-evolving Spectra Suggest PMI Between Edge Plasma and LHI Injectors

Future Work: Impurity Assessment

Populate with section titles, final slide titles
Pegasus is a Compact Ultralow-A ST

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$</td>
<td>$\leq 0.23$ MA</td>
</tr>
<tr>
<td>$\tau_{shot}$</td>
<td>$\leq 0.025$ s</td>
</tr>
<tr>
<td>$A$</td>
<td>$1.15 - 1.3$</td>
</tr>
<tr>
<td>$B_T$</td>
<td>$0.15$ T</td>
</tr>
<tr>
<td>$R$</td>
<td>$0.2 - 0.45$ m</td>
</tr>
<tr>
<td>$a$</td>
<td>$\leq 0.4$ m</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1.4 - 3.7$</td>
</tr>
</tbody>
</table>

- Non-Solenoidal Startup via LHI
  - Edge current extracted from injectors
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - Used routinely for startup on PEGASUS

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Non-Solenoidal Startup via Local Helicity Injection

- 4 kA of electron current extracted from internal arc plasma source

\[
V_{\text{arc}} \sim 100 \text{ V} \quad V_{\text{inj}} \sim 1 \text{ kV}
\]

- Current drive quantified by:

\[
V_{LHI} \approx \frac{A_{\text{inj}} B_{\varphi,\text{inj}}}{\Psi} V_{\text{inj}}
\]

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Helicity Injection is Current Drive

\[ K = \int_V (A \cdot B) d^3x \rightarrow \frac{dK}{dt} = -2 \frac{\partial \psi}{\partial t} \Psi - 2 \int_A \Phi B \cdot ds - 2 \int_V \eta J \cdot B \ d^3x \]

- AC Helicity Injection:

\[ \dot{K}_{AC} = -2 \frac{\partial \psi}{\partial t} \Psi = 2V_{loop} \Psi \]

- DC Helicity Injection:

\[ \dot{K}_{DC} = -2 \int_A \Phi B \cdot ds = 2V_{inj} B_{\perp}A_{inj} \]

- Resistive Helicity Dissipation:

\[ \dot{K}_{res} \approx -\frac{2\pi R_0}{A_p} \langle \eta \rangle I_p \Psi \]

- In steady state, Source = Sink

\[ I_{p,SS} \approx \frac{A_p}{2\pi R_0 \langle \eta \rangle} (V_{ind} + V_{eff}) \]

\[ V_{eff} \approx \frac{A_{inj}B_{\perp,\text{inj}}}{\Psi_T} V_{bias} \]
Impurity Measurements Needed for LHI Assessment

- Helicity input balanced by resistive dissipation
  \[ K_{\text{res}} \approx -\frac{2\pi R_0}{A_p} \langle \eta \rangle I_p \Psi \]

- Impurity Roles
  - Helicity dissipation and plasma resistivity
  \[ I_p \sim \frac{V_{LHI}}{R_{pl}} \sim \frac{V_{LHI}}{<\eta>} \]
  - Radiation losses
    - \( \tau_e \) determined by confinement and \( P_{\text{RAD}} \)

- Plasma contaminants to be monitored by three diagnostics:
  - VB Spectroscopy to measure \( \langle Z_{\text{eff}} \rangle \)
  - SPRED VUV Spectrometer to identify impurity species
  - Bolometer array to determine \( P_{\text{RAD}} \)
Deployed Absolutely Calibrated VB Spectrometer to test viability of Visible Bremsstrahlung Measurements

- Single line of sight through the plasma
- New Automated Data Acquisition

\[ R_{\text{tan}} = 15 \, \text{cm} \]
\[ R_{\text{tan}} = 16.6 \, \text{cm} \]
\[ R_{\text{tan}} = 20 \, \text{cm} \]


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Multi-point Thomson Scattering Provides $T_e(R)$ and $n_e(R)$ for $Z_{eff}$ Measurement

- VB spectrometer measures: Intensity = $\int \frac{\varepsilon \lambda}{4 \pi} ds$

- $< Z_{eff} > = \frac{\lambda}{9.5 \times 10^{-14} g_{ff}} \int \frac{\varepsilon \lambda}{n_e^2 T_e^{-1/2} e^{-hc/\lambda T_e}} ds$

- Avg. Gaunt factor $g_{ff}$ in the order of unity for low frequencies*  


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• Standard region in large tokamaks: 523 – 536 nm *
• Spectral continuum polluted by LHI in this region

*Foord et al., Review of Scientific Instruments 53.9 (1982)
Spectral Survey Performed to Identify Suitable VB Spectral During LHI

- **Next Step: Verify ROI Suitability**
  - Spectral evolution/reduction post LHI phase
  - $T_e$ and $n_e$ varaitons
  - Future: compare to $P_{RAD}$ measurements

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VUV Spectroscopy Acquires Time Resolved Impurity Spectra

- **SPRED spectrometer**
  - 10 – 110 nm range
  - Line of sight along $R_{tan} = 20 \text{ cm}$

- **Imaging System**
  - MCP absorbs VUV and emits photo electrons
  - Phosphor surface liberates visible photons
  - Fiber optic conduit reducer 40:25
  - Image height set by spectrometer slit width


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Detector Improvements Desired to Optimize Spectral Resolution

- Present spectral measurements constrained by camera pixel density and coupling optics
- Limited Spectral Range
- MotionPro X4
  - 512 X 512 pixels
  - 5kfps
  - CMOS image sensor
New Detector System for SPRED

- Tamron G005N II macro lens
  - F/2
  - Focal length 60 mm
  - Max. mag. ratio 1

- xiQ MQ022MG-CM camera
  - Economic CMOS image sensor
  - 2.2 Mpix, 5.5 μm pixel size
  - 170 Hz @ 2048 X 1088 pixels
  - USB3 Vision standard compliant
  - External hardware trigger
NI Vision Acquisition Software
Allows Automated Data Collection

• Compatible with LabVIEW
  – Direct access to raw data

• Pegasus Control Code send commands to arm the camera

• Hardware triggering via Timing Sequence Module

• Images automatically stored in the data archive

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New Imaging System Produces High Quality Spectra

- Resolution 2048 x 140, $\Delta t = 0.79$ ms
- Line Profiles obtained by summing ~100 pixels vertically
- Dark subtraction performed using time before plasma

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Full Spectral Resolution Achieved with New Imaging Detector

- White Field measurements indicated minimal vignetting
- Resolution limited by spectrometer

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Time-evolving Spectra Suggest PMI Between Edge Plasma and LHI Injectors

- **First Observations**
  - Spectra dominated by N(+) maybe Ti) during LHI
  - After LHI termination $T_e$ increase indicated by O-VI evolution

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Future Work: Impurity Assessment

- Validation and expansion to an imaging array to provide $Z_{\text{eff}}(R,t)$
- New high-resolution grating for SPRED for metallic line identification
- 16-channel bolometer array to quantify $P_{RAD}$
- Impurity transport code coupled to measurements to estimate absolute impurity content
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