The Behavior of Plasma Impurities and Radiation Losses During LHI and their Effect on Helicity Dissipation

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Pegasus-III Experiment

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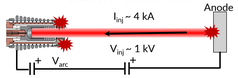
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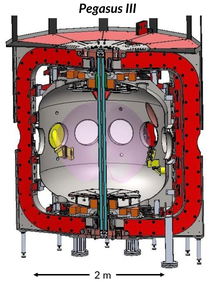
The Pegasus-III Experiment

- Pegasus-III: a dedicated US experiment to study solenoid-free tokamak startup
  - Complete removal of the Ohmic solenoid
  - New toroidal field coil capable of $B_T \leq 0.6$ T
- Helicity input balanced by resistive dissipation and radiation losses
  - $I_p[V_{LHI} + V_{IND} - V_{IR}] = 0$
  - Impurity concentration directly affects resistivity via Z_{eff} and radiative cooling
- MW-class LHI system designed to minimize impurity sourcing
- Possible sources of impurities include:
  - Erosion of injector armor/limiter
  - Cathode spots
  - Desorption of trapped gases, ablation
- Diagnostic suite deployed to characterize impurities in startup plasmas [1]

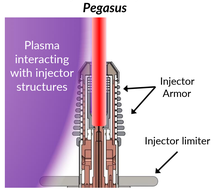
LHI extracted electron beam



Pegasus III



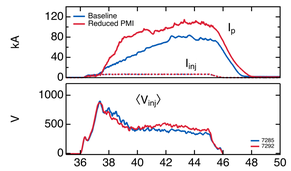
LHI injector deployed on Pegasus



Reduced Plasma Material Interaction Enhances Plasma Performance

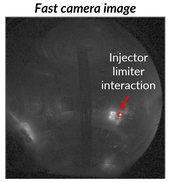
- LHI produces plasmas with $I_p \gg I_{inj}$
- Under some conditions, Ip achieves a higher value despite similar P_{inj} and field programming
- Increased resistivity due to plasma material interaction (PMI) can prevent current growth

Different realized I_p with similar drive voltage

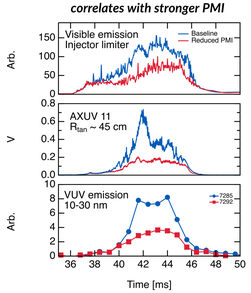


- Fast camera images are useful to detect PMI
  - Injector local limiter interaction is observed
- VUV emission measured with SPRED and radiation losses estimated AXUV increase with PMI

Fast camera image

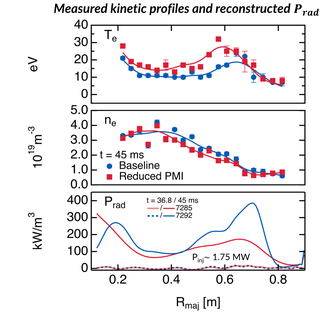


Enhanced VUV emission and P_{rad} correlates with stronger PMI

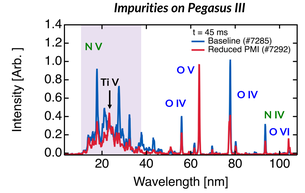


- Identified impurity species with SPRED on Pegasus-III include N, O and Ti
  - Likely residual atmospheric gases trapped by Ti gettering and released upon impact
  - Other metallic impurities may be present, but lack spectral resolution to resolve them

Measured kinetic profiles and reconstructed P_{rad}



Impurities on Pegasus III

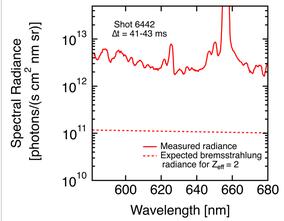


- Higher I_p and T_e attained when PMI is reduced
- Stronger PMI leads to more outboard radiated power
- Streams have small contribution to AXUV signal
- Persistent hollow $T_e(R)$
  - Combination of low heating power ηJ^2 and high P_{rad} may explain observations [2]
  - Available Ohmic power $I_p(V_{LHI} + V_{IND}) \sim P_{rad}$

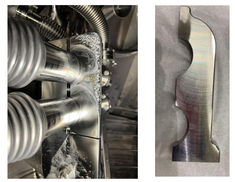
Upgrades to Diagnostics & PMI Mitigation

- A higher resolution grating for SPRED is being installed [5]
  - Spectral resolution of 0.04 nm covering the 10-32 nm range
  - Enabling identification of metallic impurities
- Filtered photodiodes to measure specific impurity lines
  - Incorporate measurements to increase fidelity of Aurora modeling
- Near-IR spectral survey planned to identified continuum region
  - Can be combined with a D_α filterscope to extract Z_{eff} [6]
  - In the visible, other sources overwhelm electron-ion bremsstrahlung continuum
  - High gain, high bandwidth fully differential amplifiers developed to measure low radiance in the NIR

Measured emission ≫ expected electron-ion bremsstrahlung



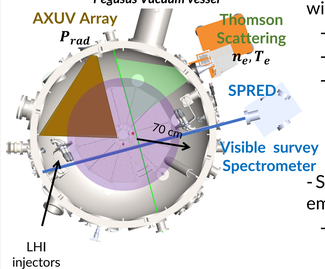
Modified injector limiter



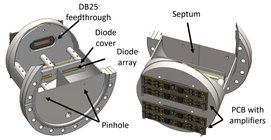
- Optimize injector position and shielding to minimize PMI
  - New injector local limiter fabricated and installed
  - Removed excess material strongly interacting with plasma

Impurity Diagnostics on Pegasus-III

Top-down view of Pegasus Vacuum vessel



AXUV diagnostic assembly

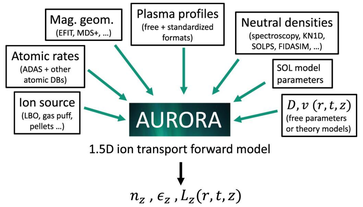


- Impurity species identification with a SPRED VUV Spectrometer
  - Single line of sight at R_{tan}= 15.9 cm
  - Time resolution, 1.25 kfps
  - 450 g/mm mid resolution grating
    - Spectral resolution 0.38 nm
    - Spectral range 9.7 -109.8 nm
    - Good for Li-like and Be-like low-Z impurities
- Spatial localization of Impurity emission using AXUV photodiodes
  - Two 16-channel arrays mounted on tangential port
    - Electrostatic shield
    - Placed behind pinhole for 32 LOS
    - R_{tan} 12-90 cm with 2-3 cm spatial resolution
- Transimpedance amplifiers with nominal 5kV/A gain and 60 kHz bandwidth
- Used to infer radiation losses

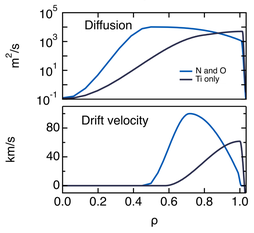
Aurora Provides Impurity Concentration and Radiation Estimates

- Aurora is an open-source package used for 1.5D impurity transport modeling [3]
  - Aurora solves the continuity equation $\frac{\partial n_{I,Z}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left(D\frac{\partial n_{I,Z}}{\partial r} - v n_{I,Z}\right) + Q_{I,Z}$
  - Impurity flux separated in diffusive and convective terms $\Gamma_{I,Z} = -D\frac{\partial n_{I,Z}}{\partial r} + v\, n_{I,Z}$
  - "Radial" coordinate given by $r = \sqrt{V/2\pi^2 R_0}$
  - Coupling to ADAS enables radiation predictions

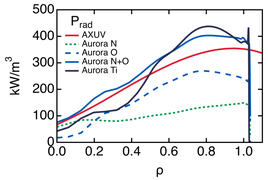
Aurora 1.5D forward model [3]



Fitted transport coefficients

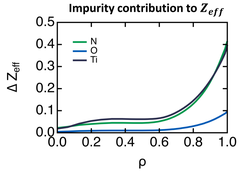


Aurora Radiation predictions

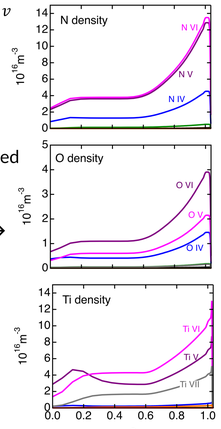


- Impurity densities inferred with Aurora
  - Iteratively running the code while varying D and v
  - Minimize the error between the predicted radiation and measurements
- Calculated transport levels consistent with neoclassical predictions from FACIT [4]
- Low charge states are dominant
  - Small concentrations can account for measured P_{rad} due to strong line emission
  - Consistent with electron temperatures
- High transport and low impurity charge states → small contributions to Z_{eff}

Impurity contribution to Z_{eff}



Calculated impurity densities



Summary

- First operational campaigns in Pegasus-III with LHI completed
- Diagnostics that help with the analysis of impurities and helicity dissipation have been developed, upgraded, and deployed
- Access to better plasma performance accomplished by PMI reduction
- Impurity concentrations is estimated to be low with $Z_{eff} < 2$
- Combination of low heating power and fast transport result in partially ionized impurities with high radiation
- Upcoming upgrades to diagnostics will help with impurity assessment

References: [1] C. Rodriguez Sanchez, M.W. Bongard, S.J. Diem, *et al*, Review of Scientific Instruments 95, (2024). [2] G.M. Bodner, M.W. Bongard, R.J. Fonck, *et al*, Physics of Plasmas 28, 102504 (2021). [3] F. Sciortino, T. Odstrčil, A. Cavallaro *et al*, Plasma Physics and Controlled Fusion 63, (2021). [4] D. Fajardo, C. Angioni, F.J. Casson, *et al*, Plasma Physics and Controlled Fusion 65, (2023). [5] B.C. Stratton, R.J. Fonck, K. Ida, *et al*, Review of Scientific Instruments 57, 2043 (1986). [6] J.K. Anderson, P.L. Andrew, B.E. Chapman, *et al*, Review of Scientific Instruments 74, 2107 (2003).

For More information,