Implementation of an Impurity Diagnostic Suite on the Pegasus-III Experiment

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25th Topical Conference on High Temperature Plasma Diagnostics, Asheville, NC, Presentation 4.2.4, 25 April 2024

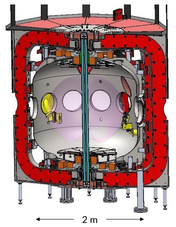
Work Supported by US DOE Grant DE-SC0019008

Pegasus-III Experiment

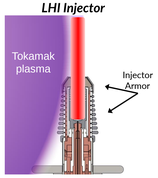
The Pegasus-III Experiment

- Pegasus-III is a major upgrade to the Pegasus ST
  - **Mission:** compare, contrast and combine startup techniques
  - New high power Local Helicity Injection (LHI) system
- Helicity input balanced by resistive dissipation and radiation losses
  - Impurity concentration directly affects resistivity via Z_{eff} and radiative cooling
- MW-class LHI system could be an impurity source
  - Erosion of injector armor/limiter (C, Fe, W, Mo)
  - Cathode spots (B, N, W, Mo)
  - Desorption of trapped gases, ablation (N, O, Ti)
- Diagnostic suite deployed to characterize impurities in startup plasmas with T_e ~ 50 eV and n_e~ 1 × 10^{19}m^{-3}

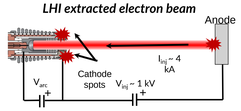
Pegasus-III



LHI Injector



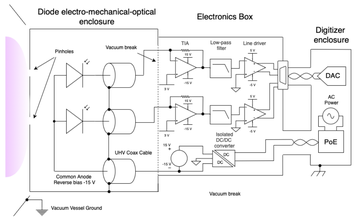
LHI extracted electron beam



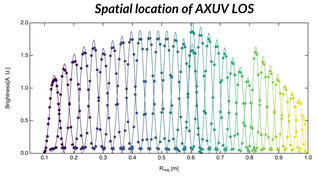
Spatial Localization of Impurity Emission

- AXUV16ELG photodiodes
  - Fast temporal resolution
  - High quantum efficiency
  - Compact size
  - Non-uniform sensitivity complicates P_{rad} analysis
    - May underestimate P_{rad} (T_e < 100 eV) by a factor of ~2 [3,4]
- 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

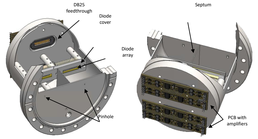
AXUV Diagnostic shielding scheme



Spatial location of AXUV LOS



AXUV diagnostic assembly

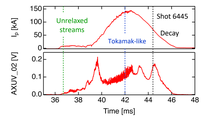


- Processing electronics and shielding scheme provide good noise immunity
  - Switching power supplies broadcast volt-level EMI
- Multi layer PCB with three stages and 5 kV/A gain
  1. I-V conversion with transimpedance amplifier, calibrated to 0.02%
  2. Anti-aliasing filter, fc= 60 kHz
  3. Differential line driver
- Abel inversion w/onionskin algorithm [5]
  - Assumed 2% uncertainty in irradiance due to geometry, calibration, and stray light
  - Quantum efficiency not yet addressed

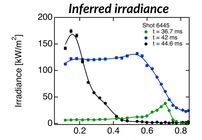
Fast camera images of an LHI discharge



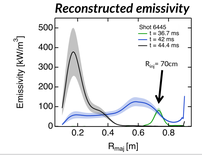
Example of AXUV measured signal in LHI plasma



Inferred irradiance



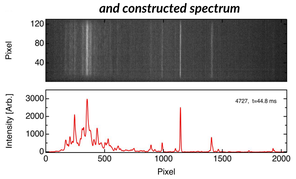
Reconstructed emissivity



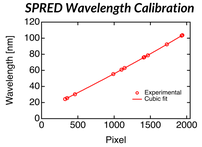
Impurity Species Identification

- SPRED VUV Spectrometer [10]
  - Single line of sight at R_{tan}= 15.875 cm
- xiQ MGQ022MG CMOS sensor
  - 2048 x 1088, 5.5 um pixels
  - Temporal resolution 1.25 kHz at 2048 x 130
- 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
- Enhanced nitrogen emission observed in LHI plasmas

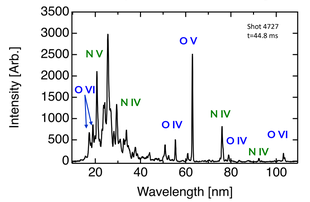
Raw image from a SPRED frame and constructed spectrum



SPRED Wavelength Calibration

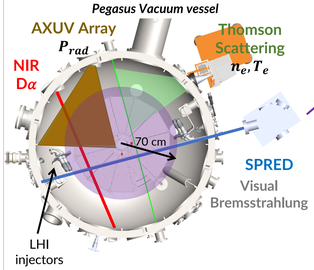


SPRED spectrum in an LHI discharge

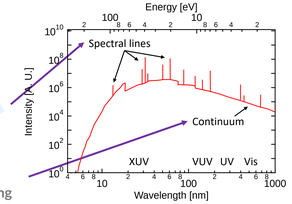


Impurity Diagnostics on Pegasus-III

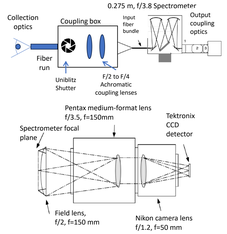
Top-down view of Pegasus Vacuum vessel



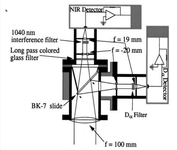
EM spectrum of a plasma with impurities



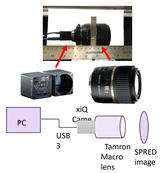
VB Spectrometer layout, adapted from [2]



Near IR/Dα collinear filterscope [1]



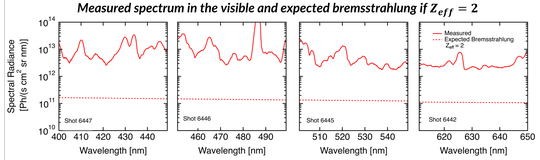
SPRED imaging system



Estimating Impurity Concentration

- Bremsstrahlung continuum used to infer Z_{eff}
  - $\epsilon = 7.632 \times 10^{-15} n_e^2 T_e^{-1/2} \bar{g}_{ff} \lambda^{-1} e^{-\frac{hc}{T_e \lambda}} Z_{eff}$ [photons/s cm^2 sr]
- Absolutely calibrated high throughput SP275 visible survey spectrometer fielded to measure bremsstrahlung continuum
  - R_{tan} = 15.875 cm
  - Exposure > 2ms
  - High-quality viewing dump to minimize reflections/stray light
  - Measured emission reveals radiation in addition to electron-ion bremsstrahlung

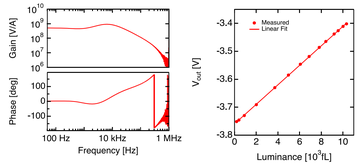
Measured spectrum in the visible and expected bremsstrahlung if $Z_{eff} = 2$



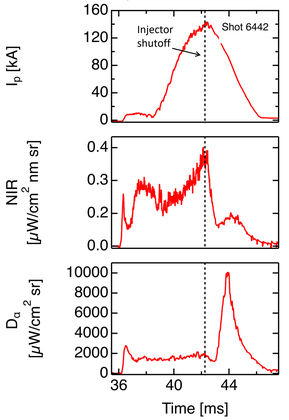
- Standard bremsstrahlung model not applicable for Pegasus-III startup plasmas
  - At modest T_e and n_e other mechanisms play an important role
    - Molecular deuterium emission [6]
    - Electron-neutral bremsstrahlung
    - Increased resistivity (collisionality) due to partially ionized atoms [7]

- Collinear NIR/D$_\alpha$ filterscope to extract Z_{eff} [1]
  - Electron-neutral pollution can be removed from NIR emission: $\epsilon_{NIR} = \epsilon_{e-i} + \epsilon_{e-n}$; $\epsilon_{e-n} \propto D_\alpha$
  - H_2 emission negligible between 1030-1050 nm [8]
  - Bandpass (~10 nm) filter centered at 1040 nm to measure emission
    - Low radiance → high gain > 100 MV/A, transimpedance amplifier (TIA)
    - Four stage TIA based on [9] with additional differential driver for noise immunity
      1. I-V conversion with large feedback resistor
      2. Frequency compensation stage
      3. Voltage-to-voltage gain
      4. Differential driver
  - Photometric calibration with integrating sphere

AC and DC response of D$_\alpha$ filterscope

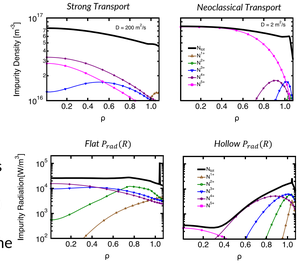


Ip, NIR and Dα evolution



Impurity Modeling

- STRAHL: Impurity transport code
  - Solves the continuity equation
  - Outputs impurity densities and emission
- Charge-state balance determined by transport
  - Low impurity concentration ~ 2 %
  - Strong transport → high $P_{rad,0}$
    - Low, highly radiative charge states can exist in the core
    - $P_{rad,0} > \eta_0^2$ leads to hollow $T_e(R)$
  - Reduced impurity transport
    - Low charge states reside only at the edge
    - Hollow $P_{rad}(R)$



Summary

- Diagnostics and tools that help with the analysis of impurities have been developed, upgraded, and deployed for Pegasus-III
  - Species identification with SPRED
  - AXUV radiometry for P_{rad}
  - VB and NIR spectroscopy for Z_{eff}
  - Impurity modeling with STRAHL

References: [1] J.K. Anderson, P.L. Andrew, B.E. Chapman, D. Craig, and D.J. Den Hartog, Review of Scientific Instruments **74**, 2107 (2003); [2] G.R. McKee, UW Madison, NEEP (1995) ; [3] L. Delgado-Aparicio et al., Review of Scientific Instruments **85**, 2 (2014); [4] M.L. Reinke and I.H. Hutchinson, Review of Scientific Instruments **79**, 261 (2008); [5] C.J. Dasch, Applied Optics **31**, 1146 (1992); [6] E.S. Marmar et al., Review of Scientific Instruments **72**, 940 (2001);[7] V.D. Kirillov, B.A. Trubnikov, and S.A. Trushin, Sov J Plasma Phys **1**, 117 (1975); [8] J.K. Anderson, Measurement of the Electrical Resistivity Profile in the Madison Symmetric Torus, Wisconsin, 2001; [9] R.J. Fonck, R. Ashley, R. Durst, S.F. Paul, and G. Renda, Review of Scientific Instruments **63**, 4924 (1992); [10] R.J. Fonck, A.T. Ramsey, and R. V. Yelle, Applied Optics **21**, 2115 (1982).

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