Pegasus-III
Experiment

Local Helicity (Impurity?) Injection in Pegasus

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UW Fusion Experiment Workshop:
Managing Neutrals and Impurities
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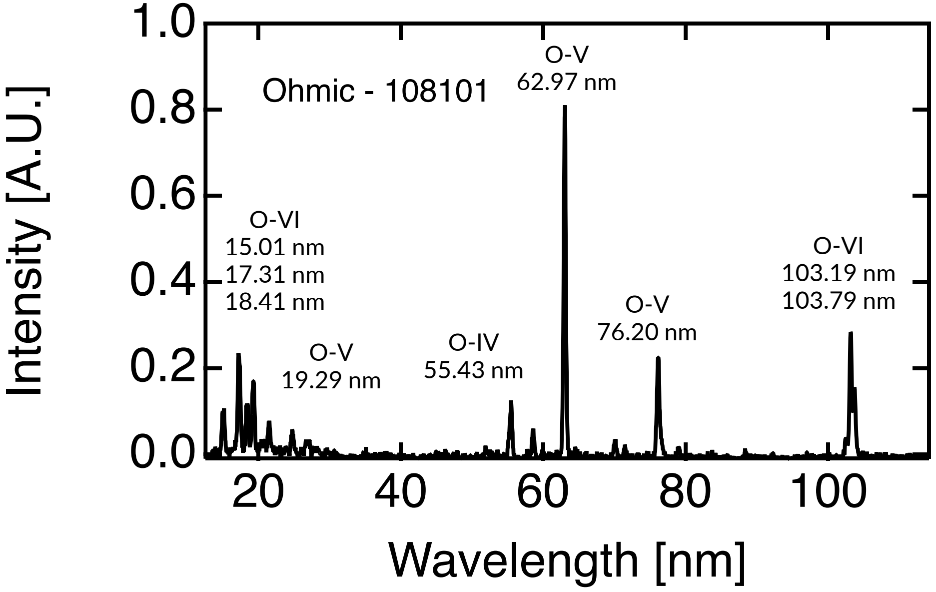
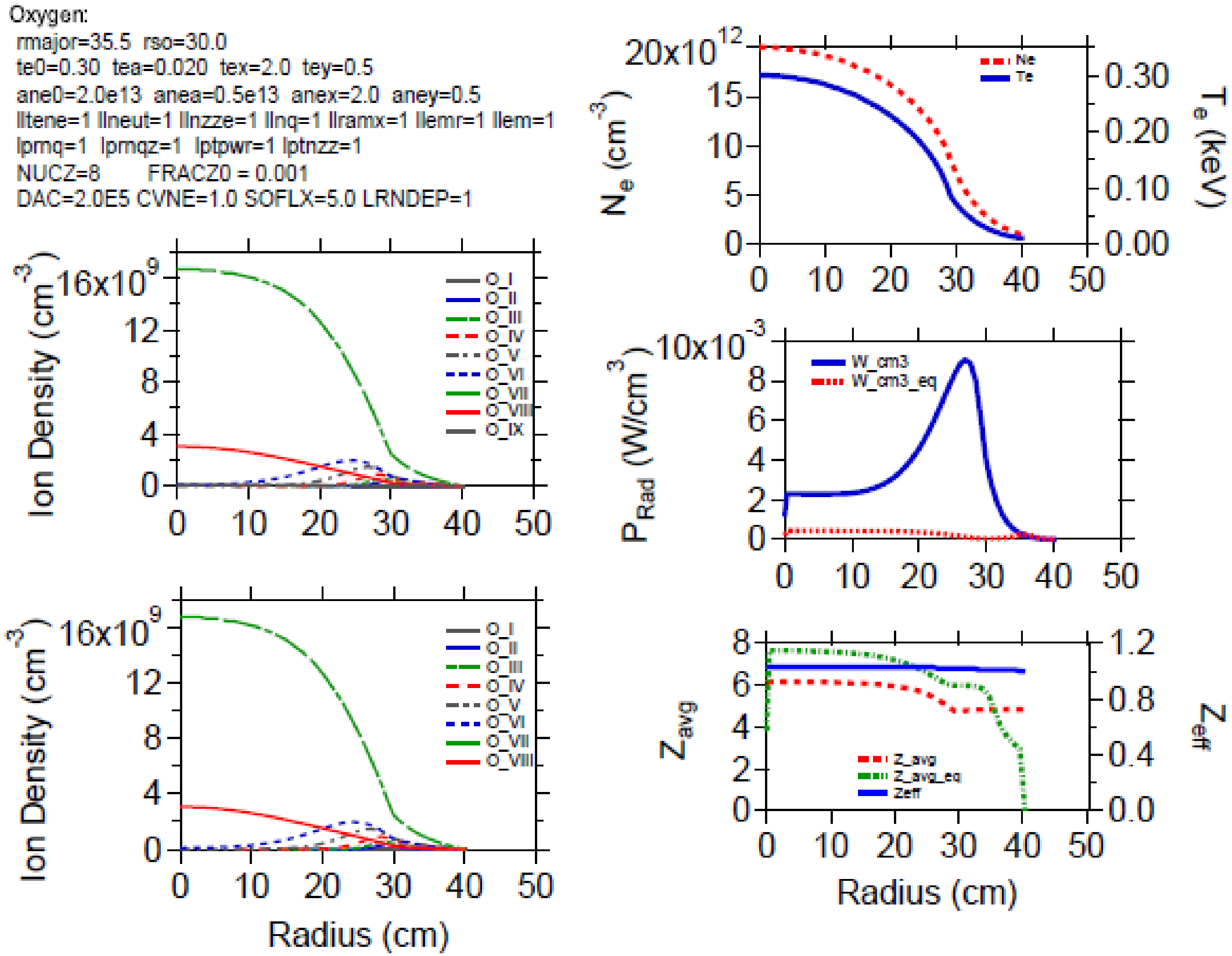
Pegasus is (was) Considered a Clean Machine

- Impurity studies by K. E Thome circa 2010[1]
  - Ohmic operations
  - Zeff ~ 1.2, estimated with MIST
  - Oxygen is the main impurity
  - Extremely hollow radiation profile





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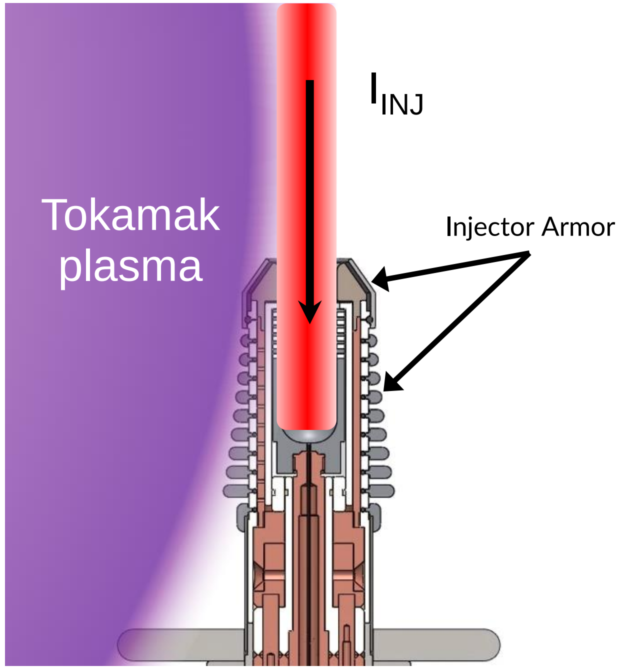
[1]https://pegasus.ep.wisc.edu/wp-content/uploads/sites/1310/2020/01/KET_APS10.pdf

MW-class Local Helicity Injection System Could be an Impurity Source

Injector structures

- Erosion of injector limiter and/or armor

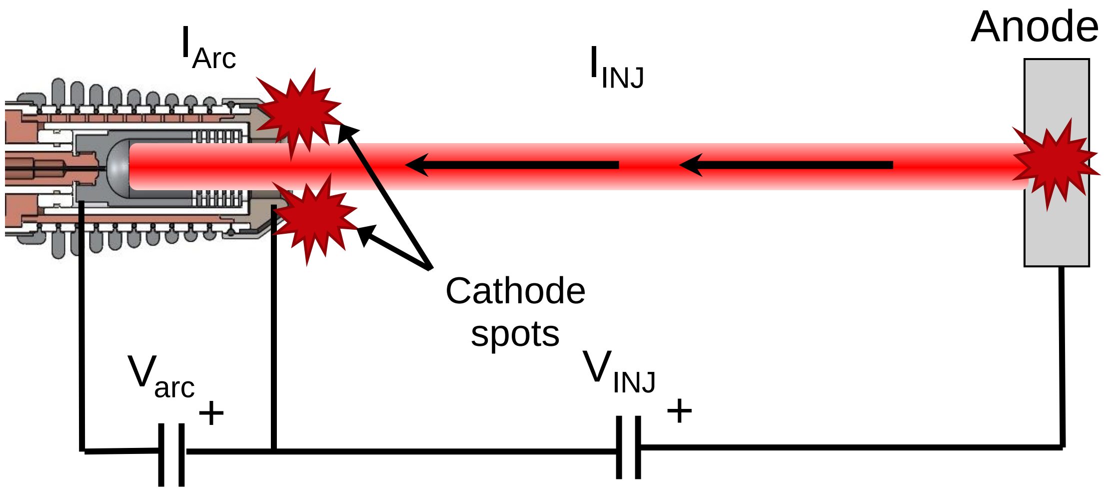


Cathode spots

- Trigger at high V_{inj}
- Erosion of adjacent surfaces

Electron beam

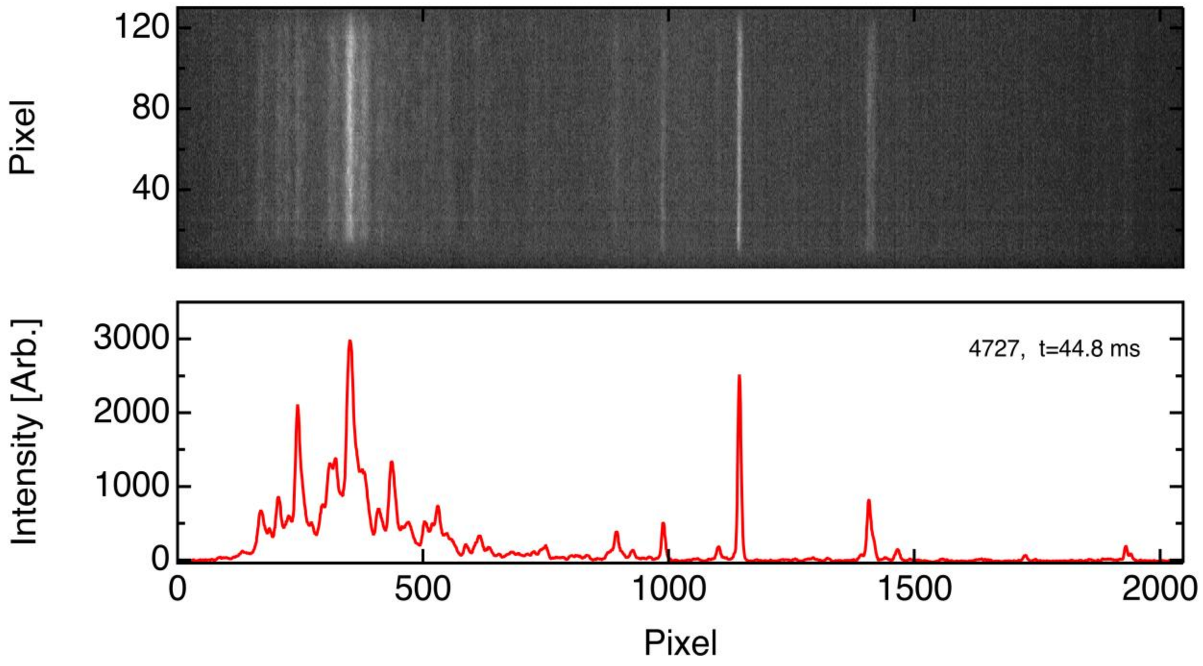
- Desorption of trapped gases
- Sputtering



Impurity Species Monitored With VUV Spectroscopy

- SPRED VUV Spectrometer[1]
  - Single line of sight at R_{tan} =15.9 cm
- CMOS image sensor
  - 2048 x 1088 Resolution
  - Temporal resolution is 1.25 kHz at 2048 x 120
- Two interchangeable gratings
  - 450 g/mm
    - Spectral range 10 to 110 nm, resolution ~0.3 nm
    - Coverage for Li-like to B-like low-z impurity lines
  - 2100 g/mm
    - Spectral Range 10 to 32 nm, resolution 0.04 nm
    - Useful for metallic lines like Ti, Fe, Mo, W, etc.

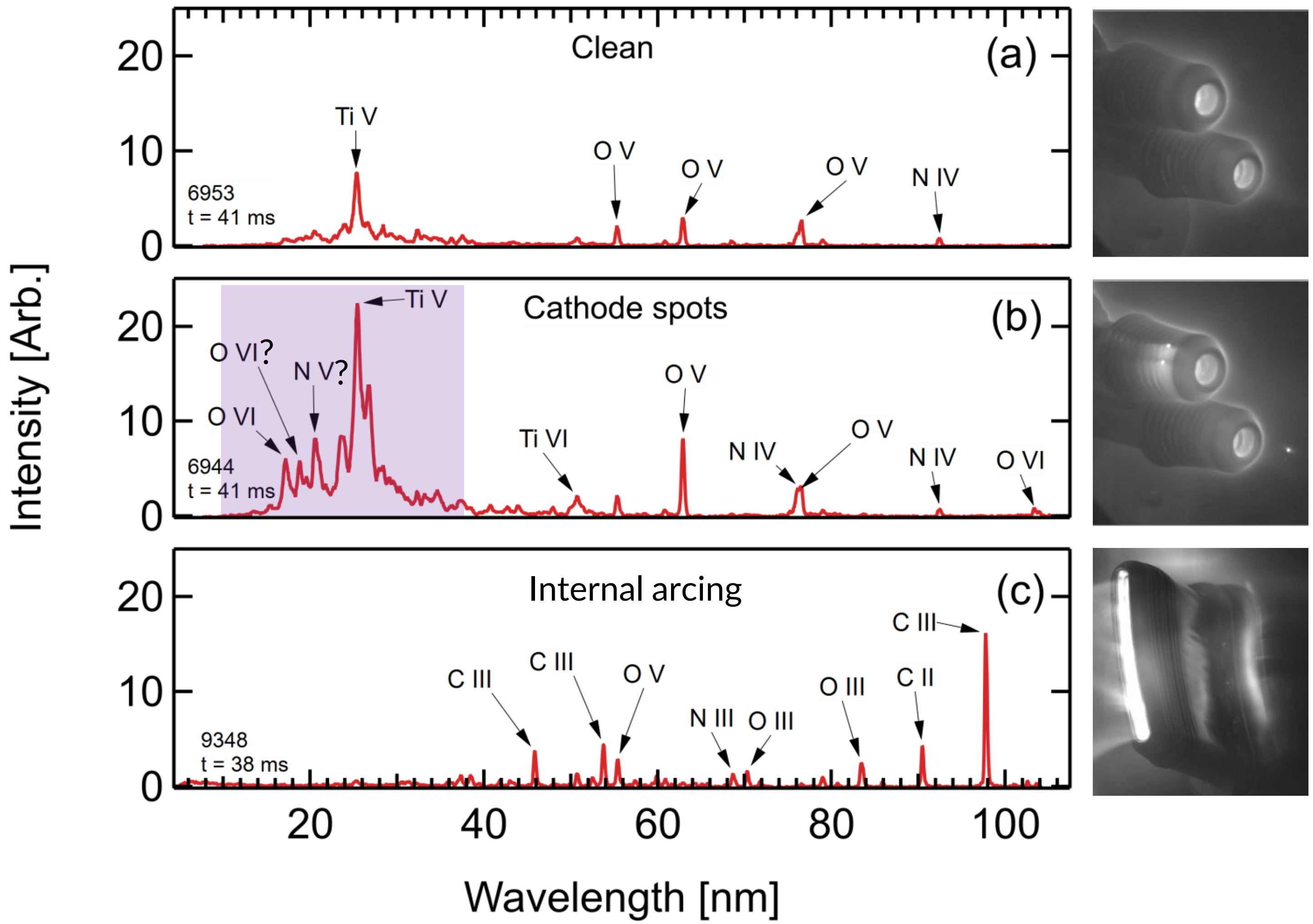
Raw image from a SPRED frame and constructed spectrum



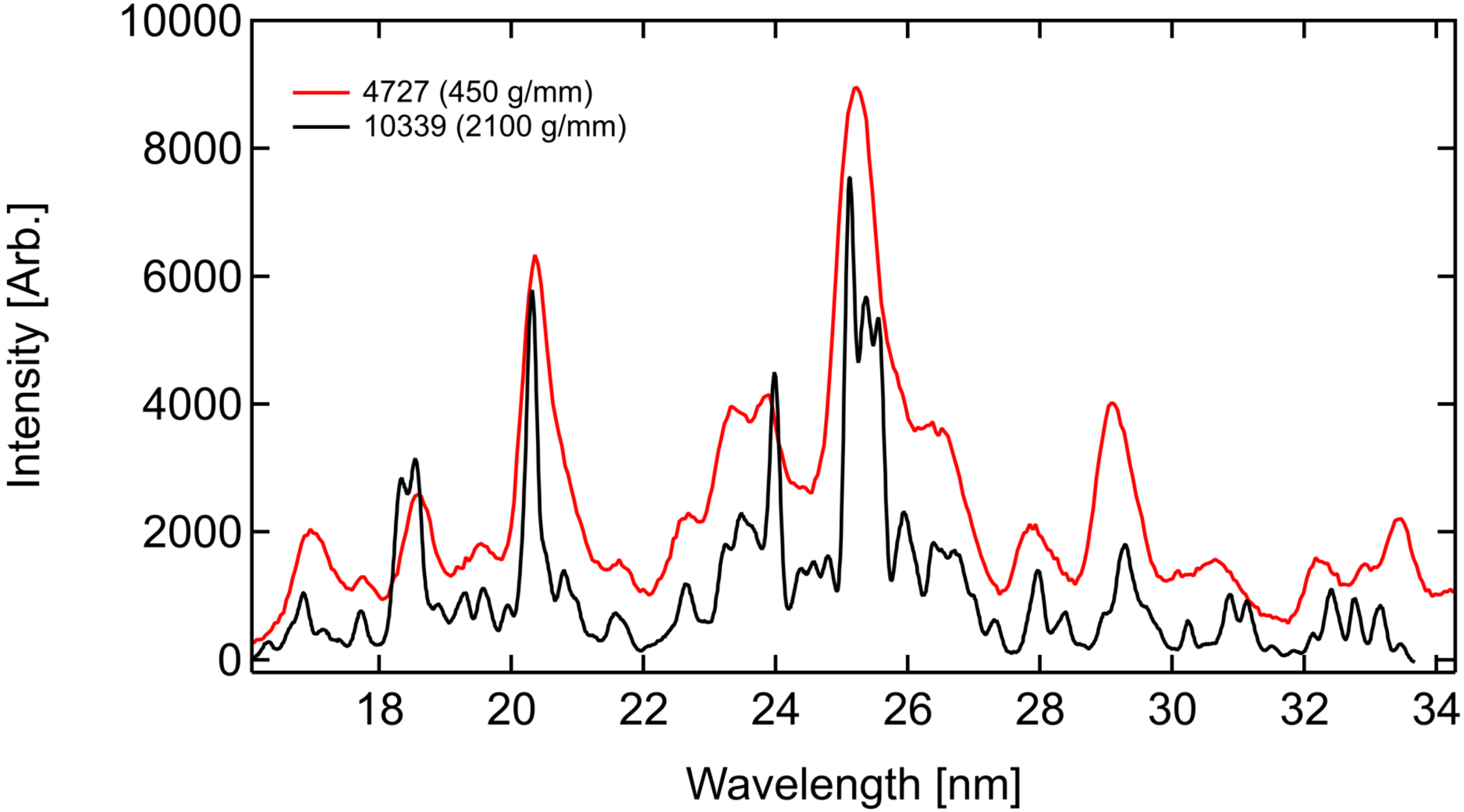
[1]R.J. Fonck, A.T. Ramsey, and R. V. Yelle, Applied Optics **21**, 2115 (1982).

VUV Spectra in LHI Discharges Includes O, N and Ti

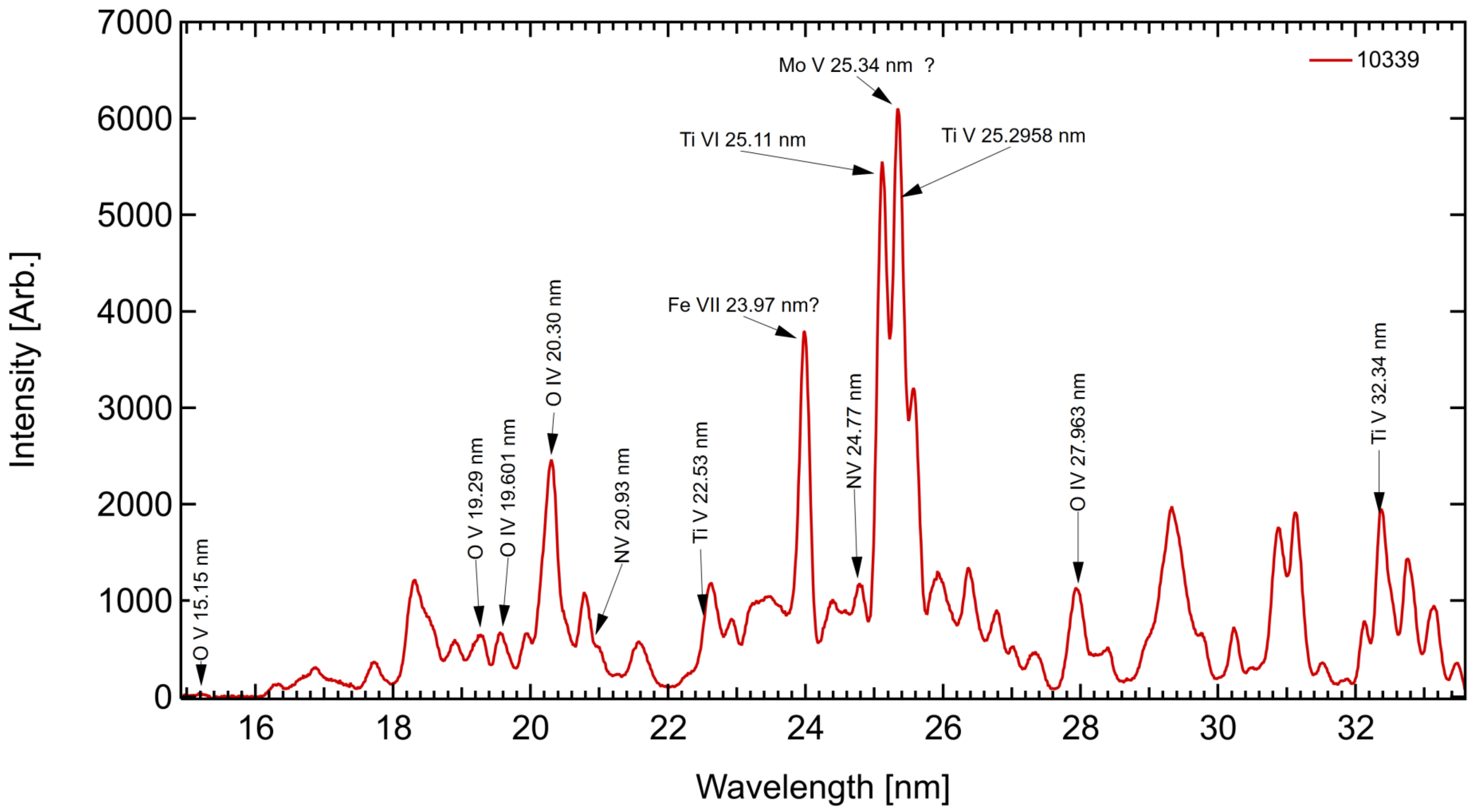
- Typical impurity species are N, O and Ti
- Off-normal scenarios result in more or different impurities
- Cathode spots and PMI with local limiter increase line intensity
  - Higher resolution grating can help identify metals
- Internal arcing sources Carbon
  - Lower charges states of N and O suggest colder plasma



Recently Installed HiRes Grating to Resolve Lower Wavelength Lines



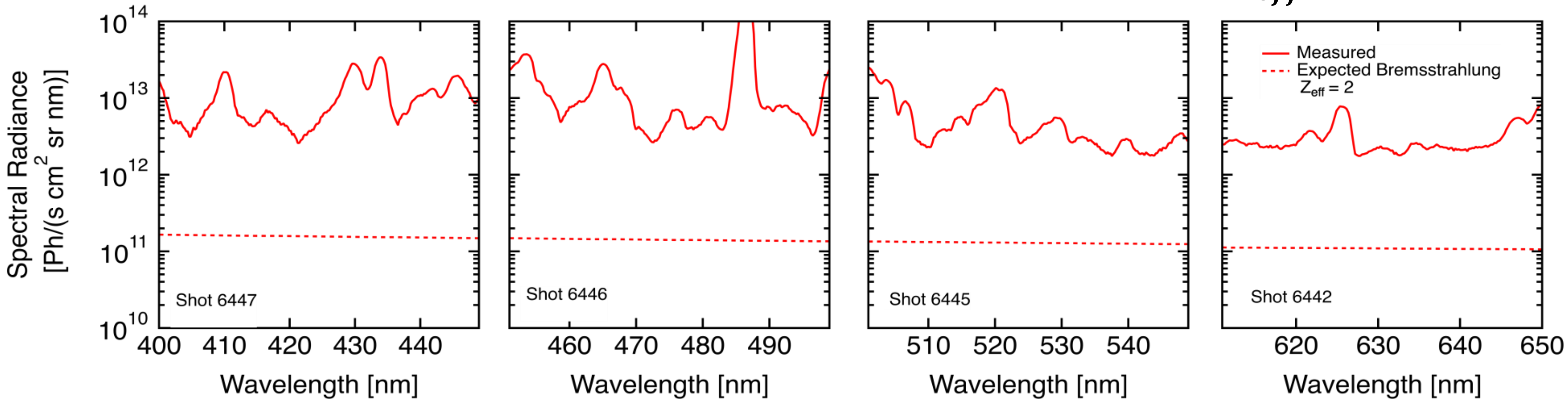
Line Identification of High-Resolution Grating Still Going



Measuring Impurity Concentration Via Visual Bremsstrahlung not Applicable in Pegasus

- High performance tokamaks typically use Bremsstrahlung emission for 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]
- At modest T_e and n_e other mechanisms play an important role
  - E.g. molecular deuterium emission, electron-neutral Bremsstrahlung, increased resistivity (collisionality) due to partially ionized atoms[1,2]

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



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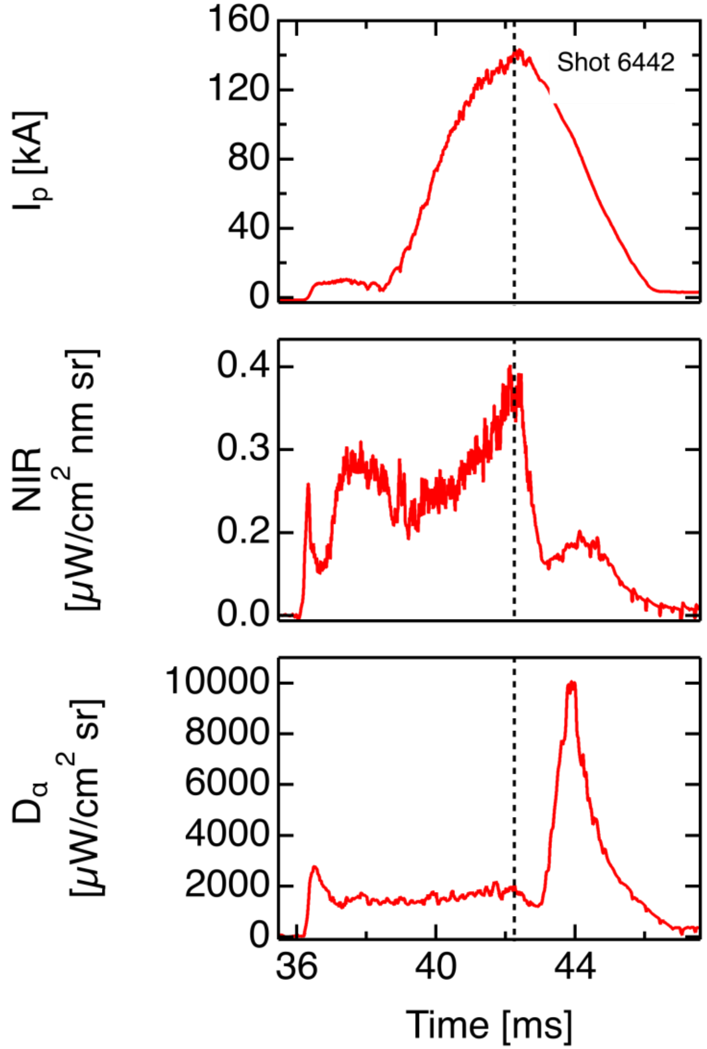
[1]E.S. Marmar et al., Review of Scientific Instruments **72**, 940 (2001)
[2]V.D. Kirillov, et al., Sov J Plasma Phys **1**, 117 (1975)

Other techniques to Measure Z_{eff} are Being Investigated

- Following J. Anderson *et al* technique[1]
  - Electron-neutral pollution can be removed from NIR emission: $\epsilon_{NIR} = \epsilon_{e-i} + \epsilon_{e-n}$; $\epsilon_{e-n} \propto D_\alpha$
  - Needs a simultaneous measurement of ϵ_{NIR} and D_α
    - We borrowed the hardware from MST (thank you!)
  - Modified original amplifier circuit to make it fully differential
    - Necessary to suppress EM noise broadcasted by switching power supplies

- Results are inconclusive in Pegasus-III
  - Wall reflections
  - Contributions from the injector arc and/or stream
  - Spectral survey in the NIR to confirm there's no line emission at this wavelength



[1]J.K. Anderson, P.L. Andrew, B.E. Chapman, D. Craig, and D.J. Den Hartog, Review of Scientific Instruments **74**, 2107 (2003);

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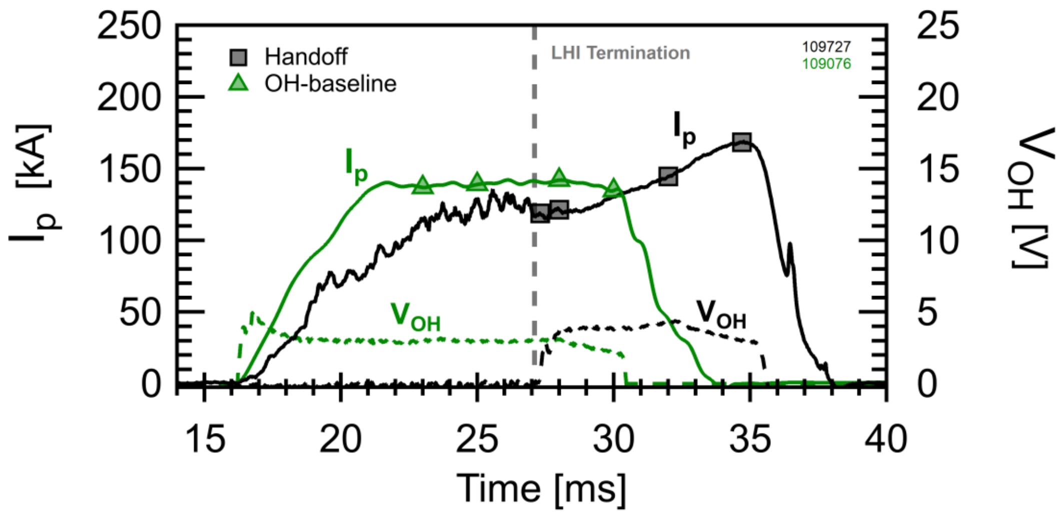
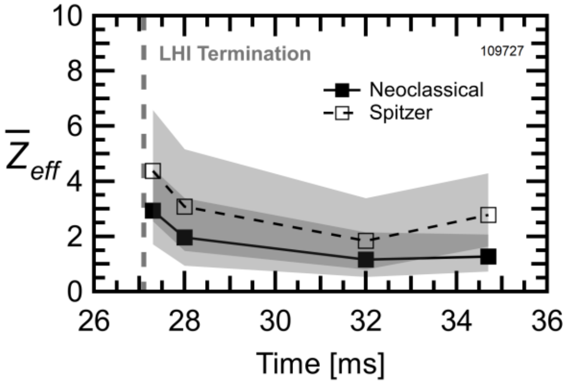
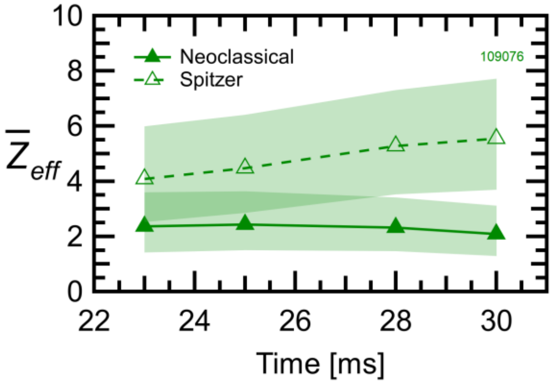
Estimates of Z_{eff} Using Ohm's Law: $R_p = V/I_p$ Yield a Value Similar to that of Ohmic Discharges[1]

- Estimate effective charge by calculating Z_{eff} that results in $R_p = R_{Sauter\ (neo\ or\ Spitzer)}$
- Plasma resistance computed from time-evolving reconstructions during OH-phase
  - Drive voltage is a well-defined quantity during OH, but not for LHI
- T_e and n_e are mapped to the equilibrium grid
- Z_{eff} in Sauter model varied until total effective $R_p = R_{neo}$
  - Assumes flat Z_{eff} across plasma → $\bar{Z}_{eff}$
- Handoff $\bar{Z}_{eff}$ similar to OH-only.
  - $\bar{Z}_{eff,OH} \approx 2 \pm 1$
  - $\bar{Z}_{eff,handoff} \approx 3 \pm 1 \rightarrow 1.5 \pm 0.5$







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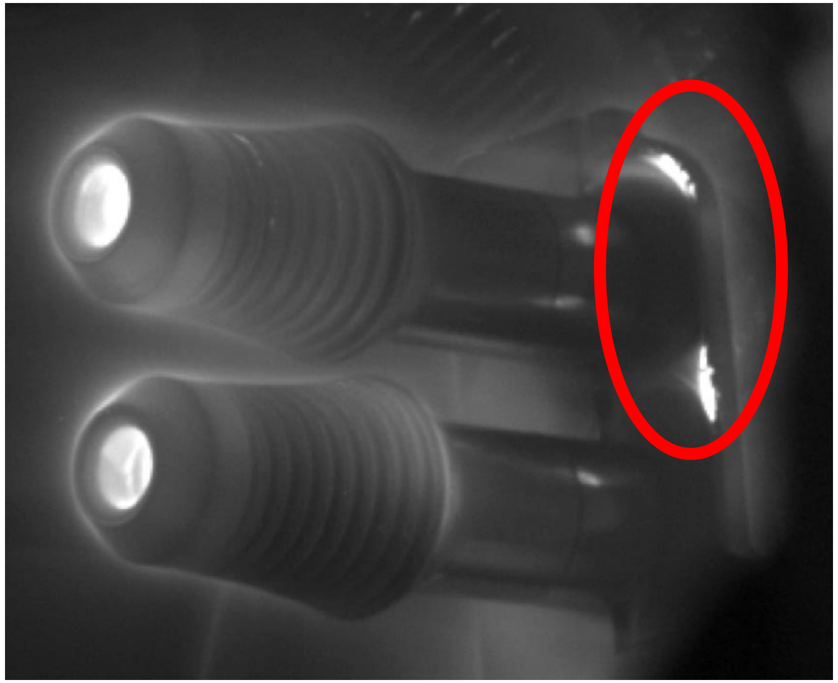
[1]Pierren, C. M. B., An Assessment of the Startup Target Quality of Local Helicity Injection Initiated Plasmas via Ohmic Current Drive Sustainment on the Pegasus Spherical Tokamak, UW-Madison NEEP thesis, 2024

Next Steps

- Mitigation of PMI
  - New local limiters (shape and materials)
  - Optimize plasma shape and position
- Experimental determination of Z_{eff}
  - Will a hotter plasma unlock the possibility of Bremsstrahlung measurement?
- Absolute calibration of SPRED via branching ratio technique
  - Will help to pin down specific ion densities



Summary and Conclusions

- LHI system can be a source of impurities
- Impurity species are identified with SPRED
- Main impurity species during LHI include N, O and Ti
  - Most likely residual atmospheric trapped by getters and released when the plasma or current stream hits this surface
- Z_{eff} is hard to measure experimentally, but other techniques had been used
- A “clean” LHI discharge has similar impurity content as an Ohmic discharge
  - VUV spectrum is similar, Z_{eff} estimated to be similar to Ohmic plasmas
  - Important to avoid cathode spots and PMI