Studies of Impurities in the Pegasus Spherical Tokamak

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PEGASUS Toroidal Experiment

Layout Slide (Include for Posters)

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

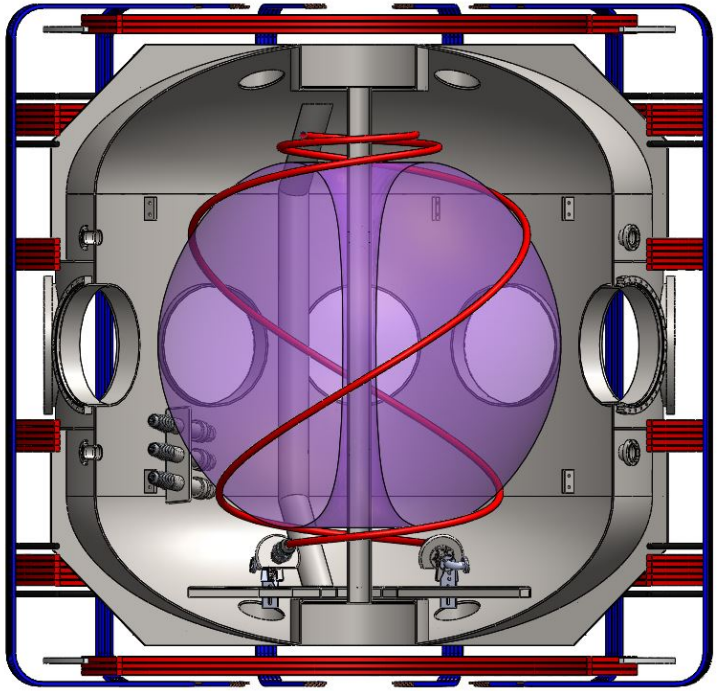
Populate with section titles, final slide titles

Studies of Impurities in the Pegasus Spherical Tokamak

Pegasus is a Compact Ultralow-A ST	Deployed Absolutely Calibrated VB Spectrometer to test viability of Visible Bremsstrahlung Measurements	VUV Spectroscopy Acquires Time Resolved Impurity Spectra	New Imaging System Produces High Quality Spectra
Non-Solenoidal Startup via LHI	Multi-point Thomson Scattering Provides $T_e(R)$ and $n_e(R)$ for Z_{eff} Measurement	Detector Improvements Desired to Optimize Spectral Resolution	Full Spectral Resolution Achieved with New Imaging Detector
Helicity Injection is Current Drive	VB Measurements Requires Suitable Continuum Spectral Width	New Detector System for SPRED	Time-evolving Spectra Suggest PMI Between Edge Plasma and LHI Injectors
Impurity Measurements Needed for LHI Ass.	Spectral Survey Performed to Identify Suitable VB Spectral During LHI	NI Vision Acquisition Software Allows Automated Data Collection	Future Work: Impurity Assessment

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Pegasus is a Compact Ultralow-A ST

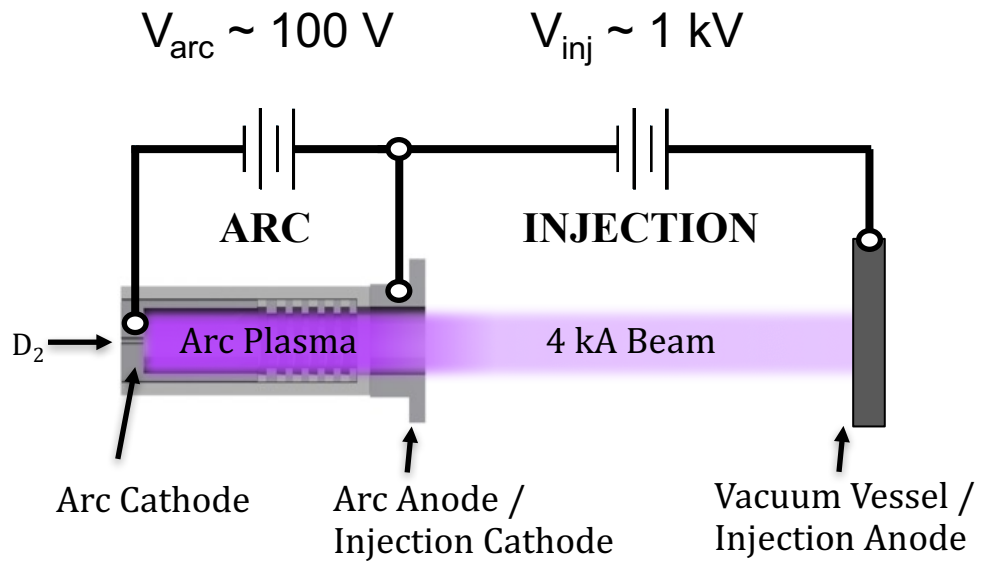


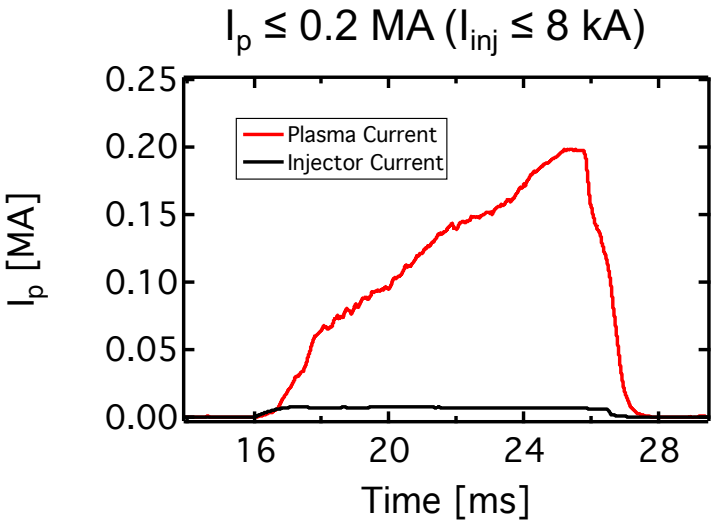
Experimental Parameters	
I_p	≤ 0.23 MA
τ_{shot}	≤ 0.025 s
A	$1.15 - 1.3$
B_T	0.15 T
R	$0.2 - 0.45$ m
a	≤ 0.4 m
κ	$1.4 - 3.7$

- 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

Non-Solenoidal Startup via Local Helicity Injection

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





- Current drive quantified by:

$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

Helicity Injection is Current Drive

$$K = \int_V (\mathbf{A}\cdot\mathbf{B})\,\mathrm{d}^3\mathrm{x} \quad \Rightarrow \quad \frac{dK}{dt} = -2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot\mathrm{ds} - 2\int_V \eta\mathbf{J}\cdot\mathbf{B}\,\mathrm{d}^3\mathrm{x}$$

- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial\psi}{\partial t}\Psi = 2V_{loop}\Psi$
- DC Helicity Injection: $\dot{K}_{DC} = -2\int_A \Phi\mathbf{B}\cdot\mathrm{ds} = 2V_{inj}B_{\perp}A_{inj}$
- 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

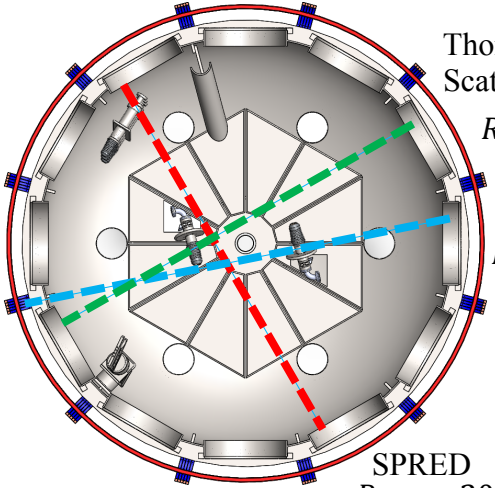
$$I_{p,SS} \approx \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind}+V_{eff}\right) \qquad V_{eff} \approx \frac{A_{inj}B_{\perp,inj}}{\Psi_T}V_{bias}$$

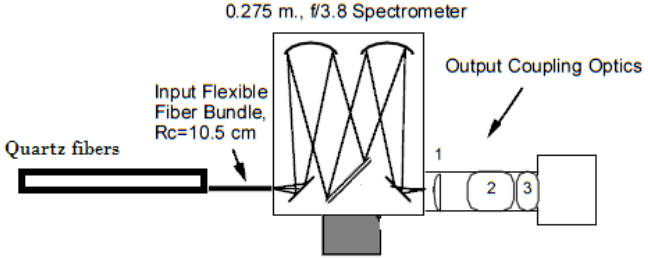
Impurity Measurements Needed for LHI Assessment

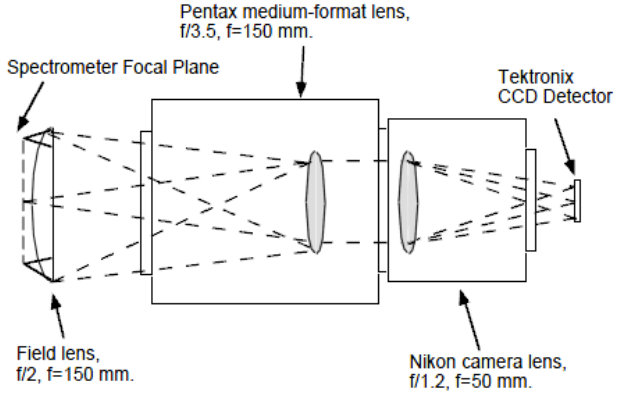
- Helicity input balanced by resistive dissipation $\dot{K}_{res} \approx -\frac{2\pi R_0}{A_p}\langle\eta\rangle I_p \Psi$
- Impurity Roles
  - Helicity dissipation and plasma resistivity $I_p \sim \frac{V_{LHI}}{R_{pl}} \sim \frac{V_{LHI}}{<\eta>}$
  - Radiation losses
    - τ_e determined by confinement and P_{RAD}
- Plasma contaminants to be monitored by three diagnostics :
  - VB Spectroscopy to measure $\langle Z_{eff} \rangle$
  - SPRED VUV Spectrometer to identify impurity species
  - Bolometer array to determine P_{RAD}

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

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



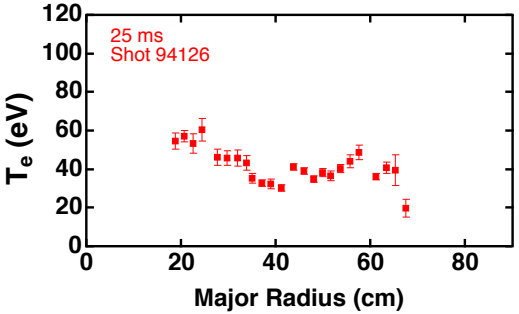


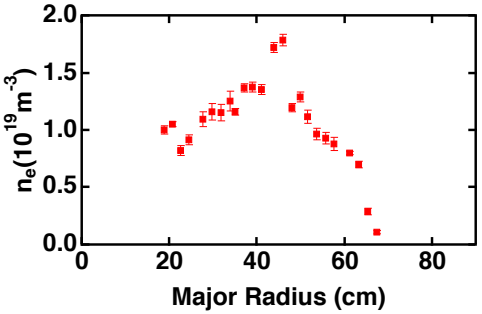


G McKee, UW-Madison NEEP (1995)

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

- VB spectrometer measures: Intensity = $\int \frac{\epsilon \lambda}{4\pi} ds$
- $< Z_{eff} > = \frac{\lambda}{9.5\ x\ 10^{-14} \overline{g_{ff}}} \int \frac{\epsilon_\lambda}{n_e^2 T_e^{-1/2} e^{-hc/\lambda T_e}} ds$
- Avg. Gaunt factor $\overline{g_{ff}}$ in the order of unity for low frequencies*

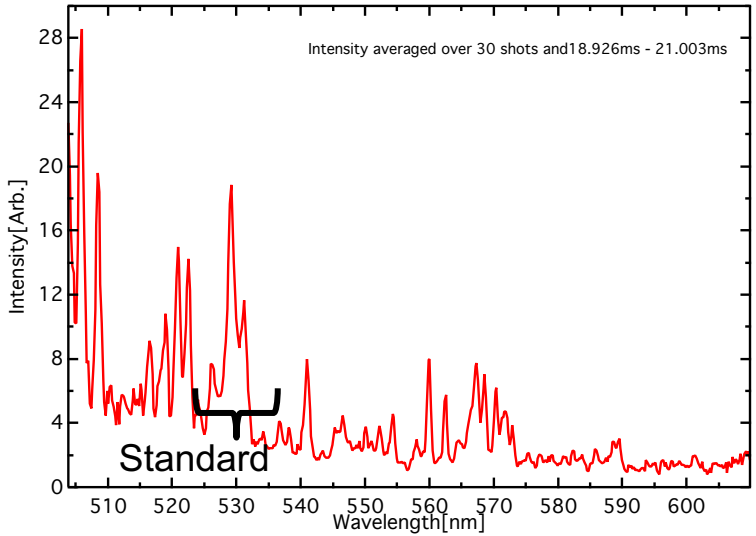




*Hutchinson, I H . (2002)
Schlossberg, D.J. RSI (2016)

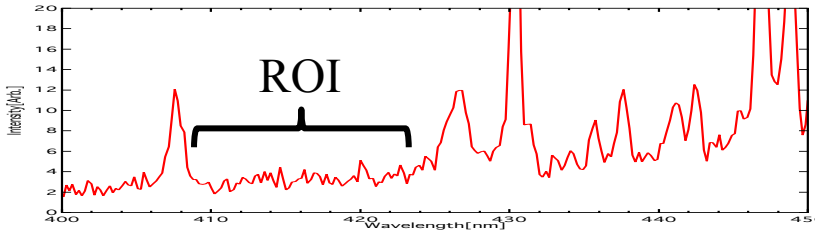
VB Measurements Requires Suitable Continuum Spectral Width

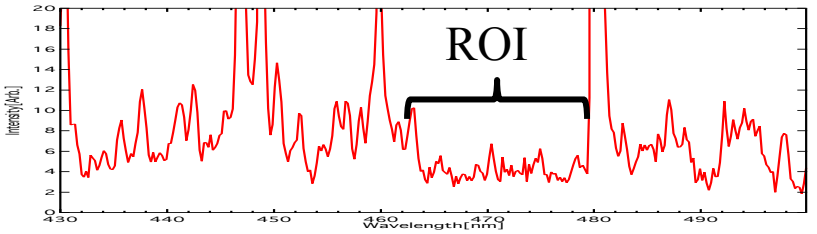
- Standard region in large tokamaks: 523 – 536 nm *
- Spectral continuum polluted by LHI in this region

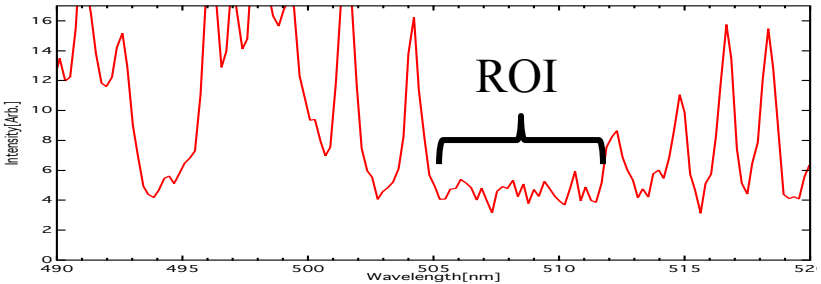


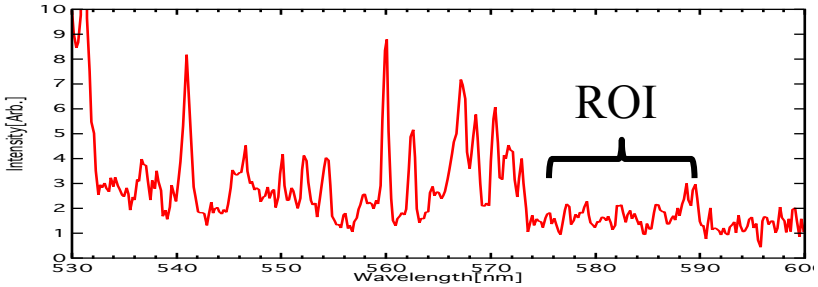
*Foord et al., Review of Scientific Instruments 53.9 (1982)

Spectral Survey Performed to Identify Suitable VB Spectral During LHI







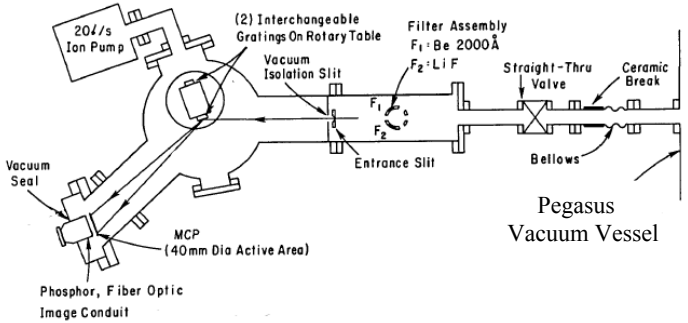


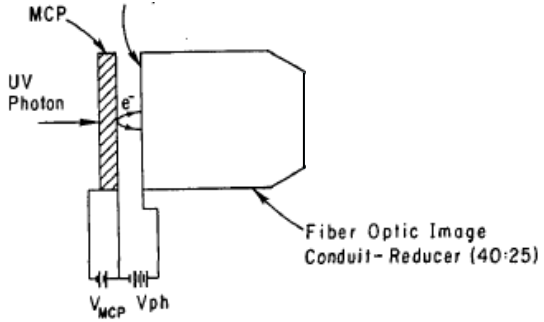
- Next Step: Verify ROI Suitability
  - Spectral evolution/reduction post LHI phase
  - T_e and n_e variaitons
  - Future: compare to P_{RAD} measurements

VUV Spectroscopy Acquires Time Resolved Impurity Spectra

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

Spectrometer Layout





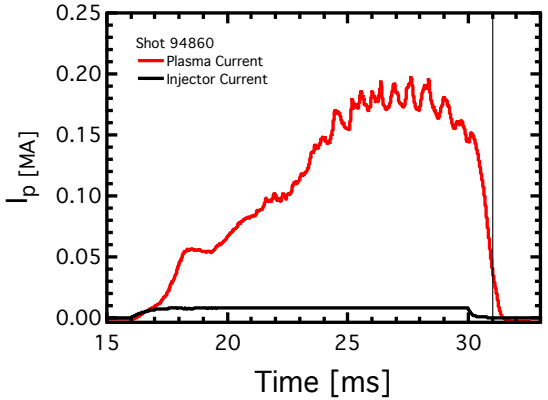
VUV to Visible imaging System

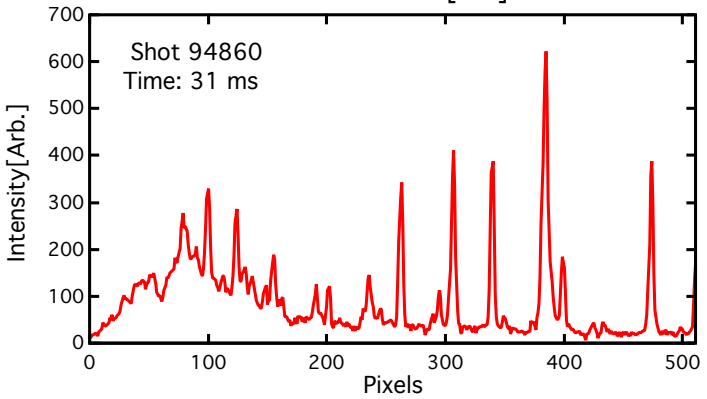
R. J. Fonck et al., Applied Optics 21.12, 2115 (1982)

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



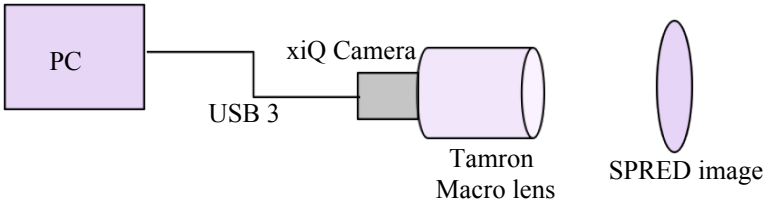




New Detector System for SPRED

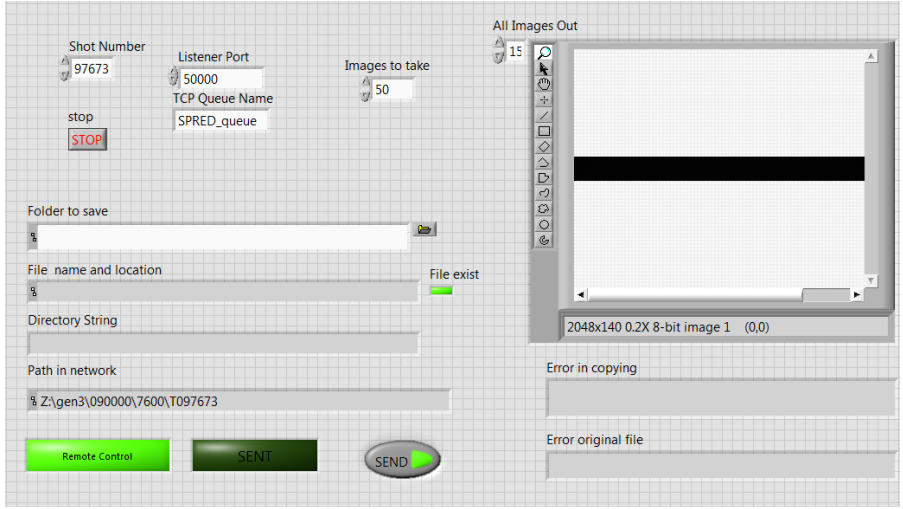
- Tamron G005N II macro lens
  - F/2
  - Focal length 60 mm
  - Max. mag. ratio 1
- xiQ MQ022MG-CM camera
  - Economic CMOS image sensor
  - 2.2 Mpix, 5.5 µm pixel size
  - 170 Hz @ 2048 X 1088 pixels
  - USB3 Vision standard compliant
  - External hardware trigger



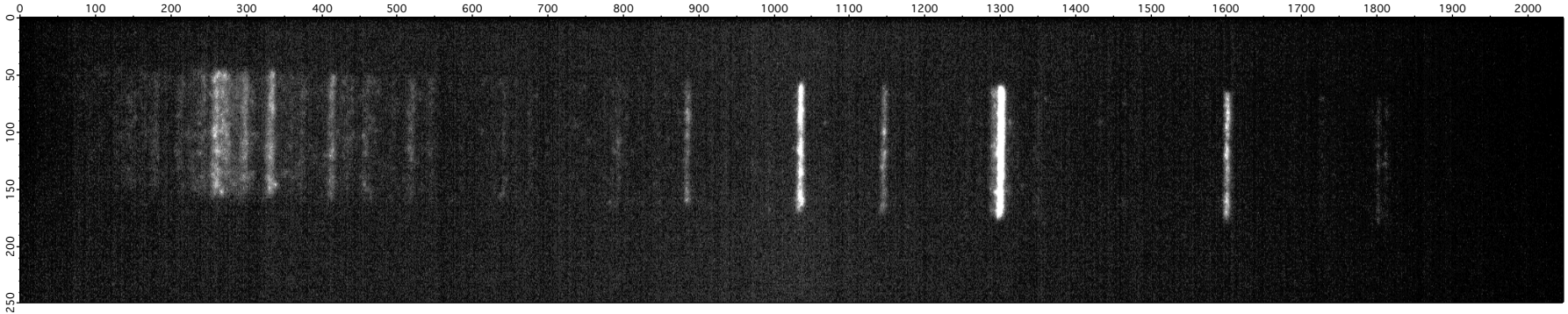


NI Vision Acquisition Software Allows Automated Data Collection

- 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



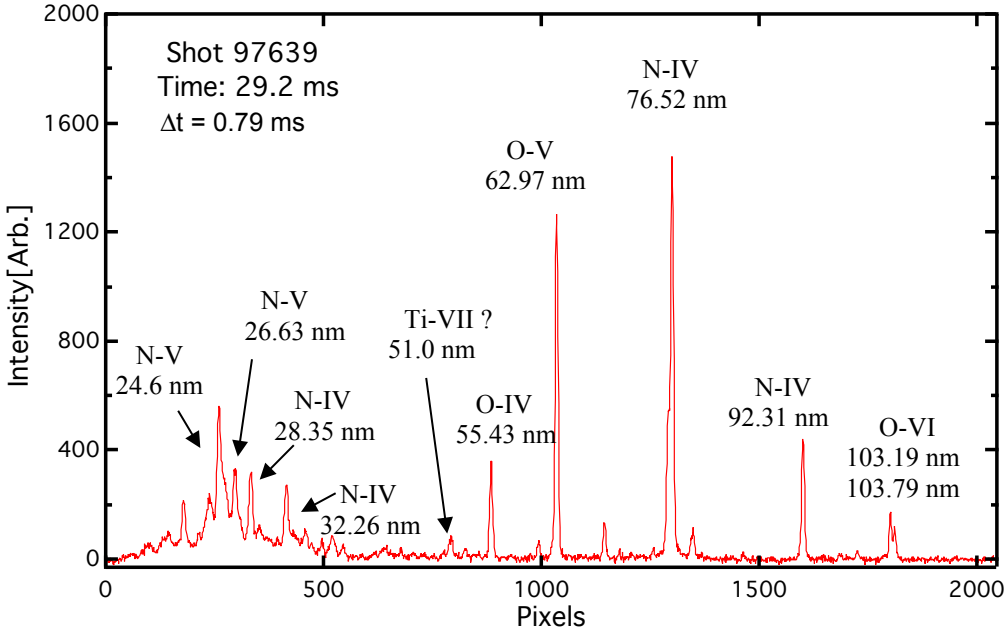
New Imaging System Produces High Quality Spectra



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

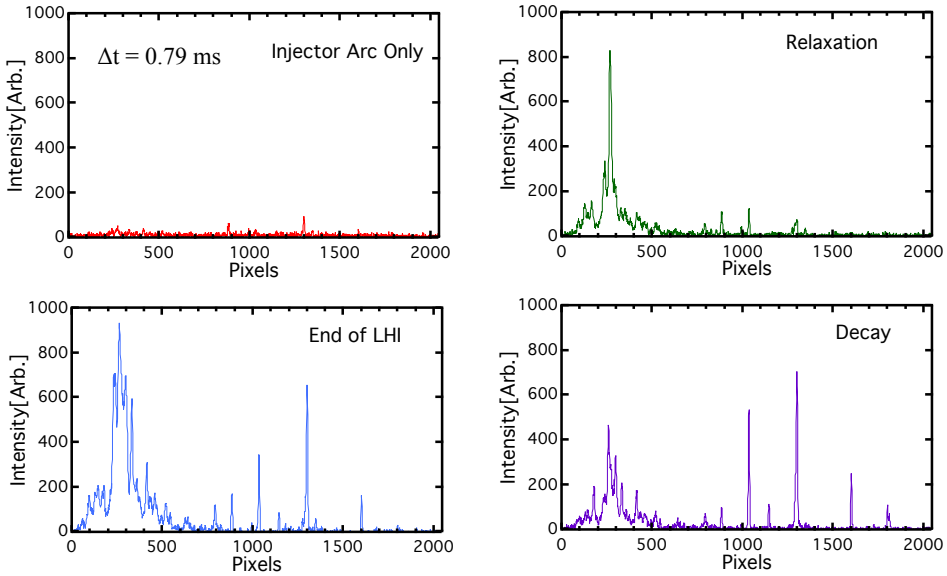
Full Spectral Resolution Achieved with New Imaging Detector

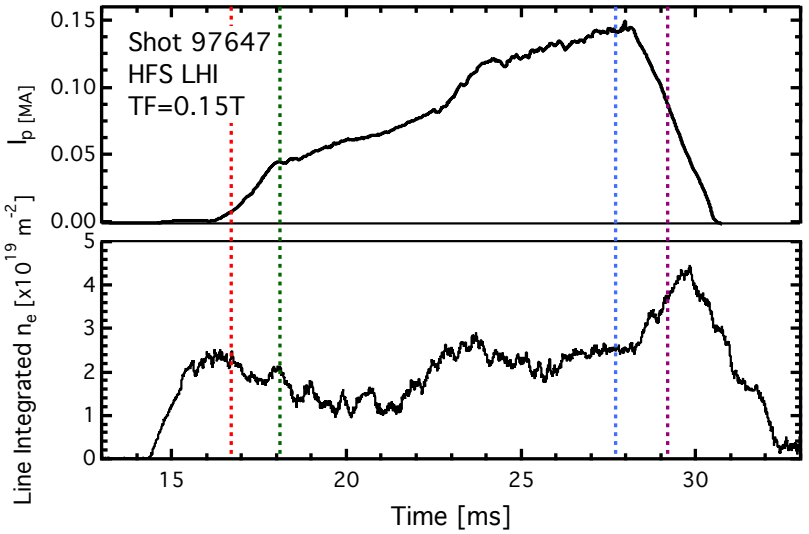
- White Field measurements indicated minimal vignetting
- Resolution limited by spectrometer



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





Future Work: Impurity Assessment

- Validation and expansion to an imaging array to provide $Z_{eff}(R,t)$
- 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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