# Impurity Characterization in LHI-Driven Discharges on the Pegasus Spherical Tokamak


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# Layout Slide (Include for Posters)

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Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique

Injector Location Emphasizes Different Current Drive

Helicity Input Balanced By Resistive Dissipation

Impurity Measurements Needed for LHI Assessment

Plasma Contaminant Species Monitored by SPRED Spectrometer

N and O main impurity Species During LFS Injection

HFS Injection: Indicates Increased Impurity Influx

High Resolution Grating Planned For Metallic Impurity Identification

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AXUV Bolometers on Pegasus

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Bolometer Upgrades To Include a New Pre-Amp Design And New Thermistor Bolometer Array

Continuum Emission Coupled With Thomson Scattering Determine $Z_{eff}$

VB Spectrometer Used to Acquire Time Evolving Spectra

Spectral Survey Reveled a Line-free Region for VB Measurements

Unrealistic High $Z_{eff}$ Suggest VB is not Dominant Source of Emission

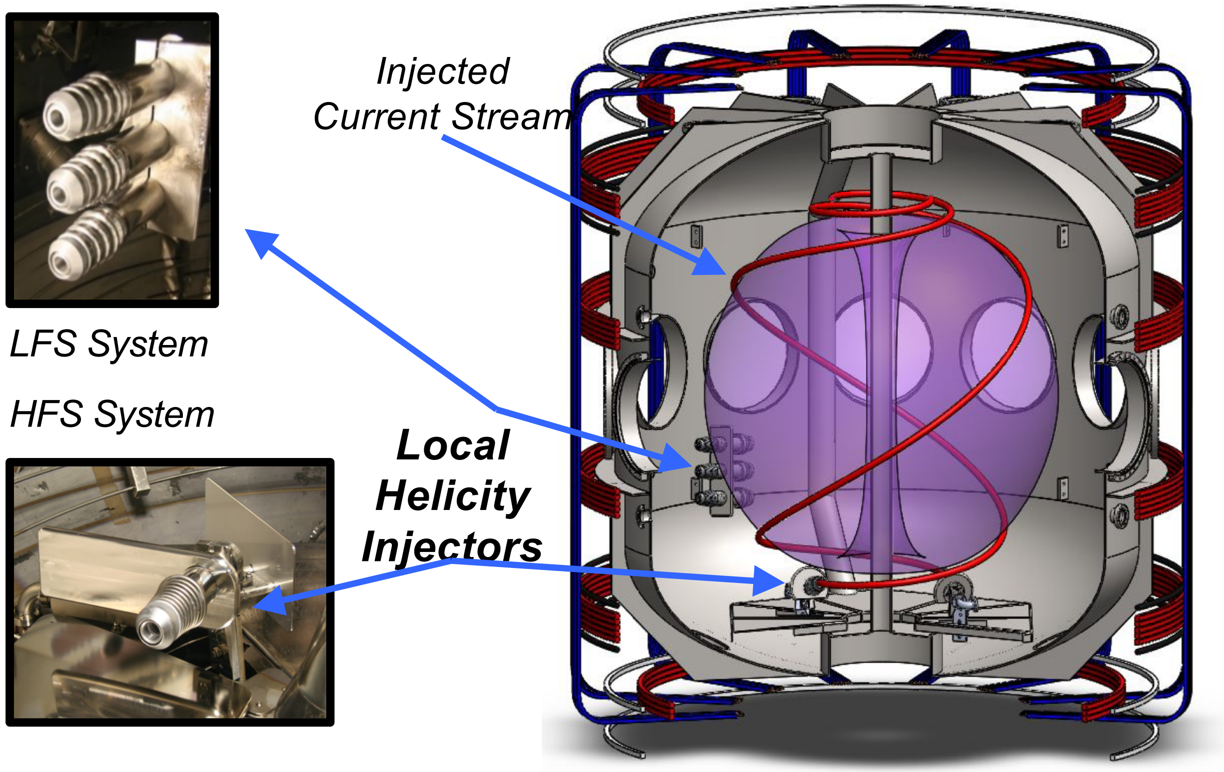
Plasma Resistivity Analysis Can Be Used To Infer $Z_{eff}$

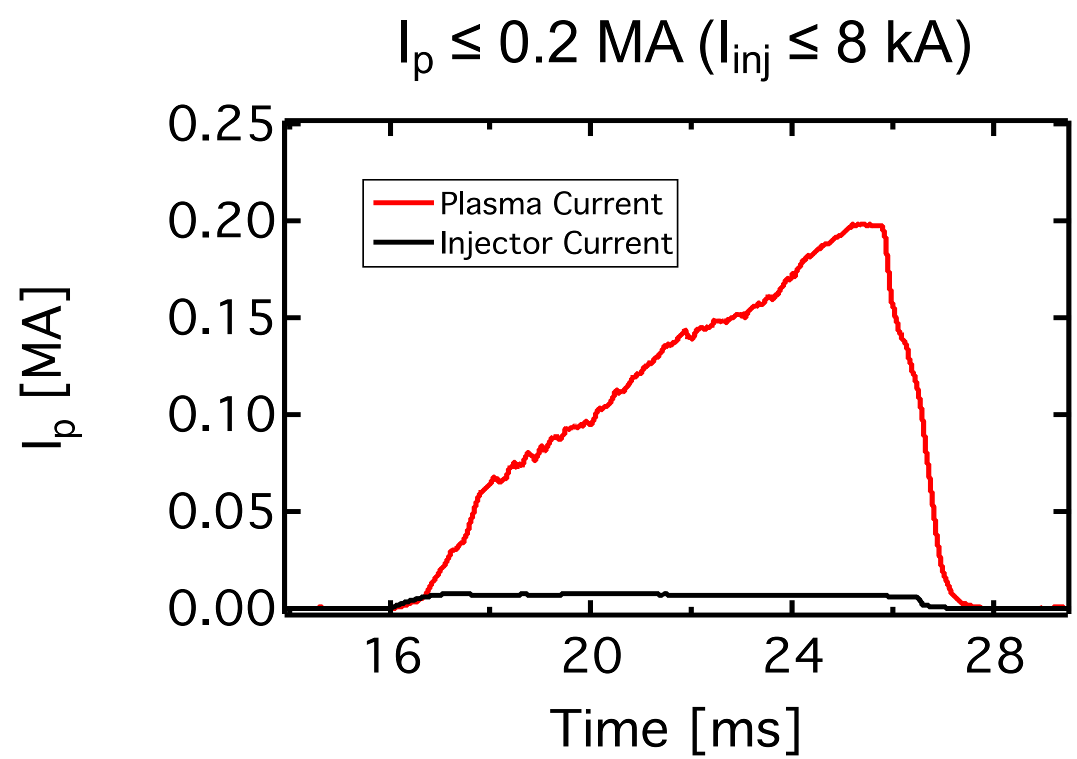
Equilibrium Reconstruction Provide $R_p$

Thomson Scattering $T_e$ and $n_e$ Provide a Second $R_p$ estimate

Conclusions and Future Work

# Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique



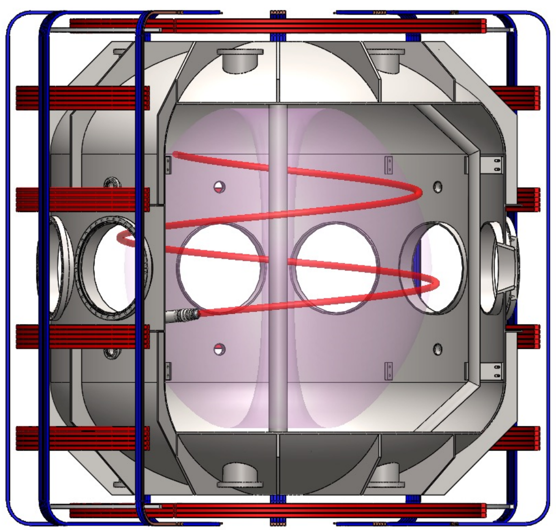



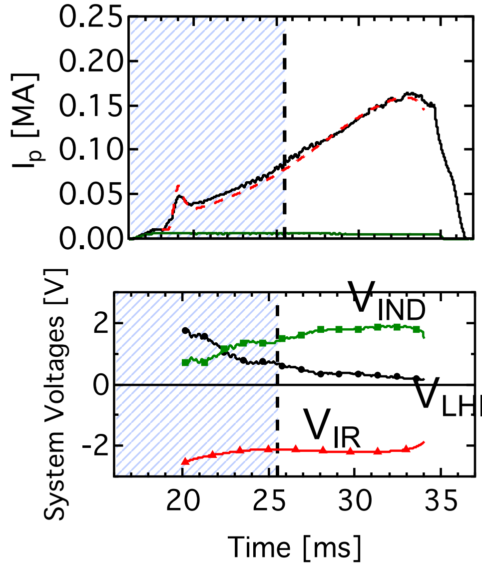

- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on Pegasus

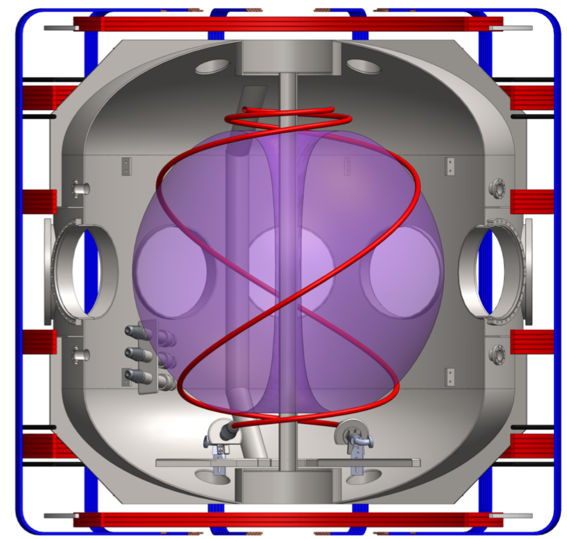
- Current drive quantified by:

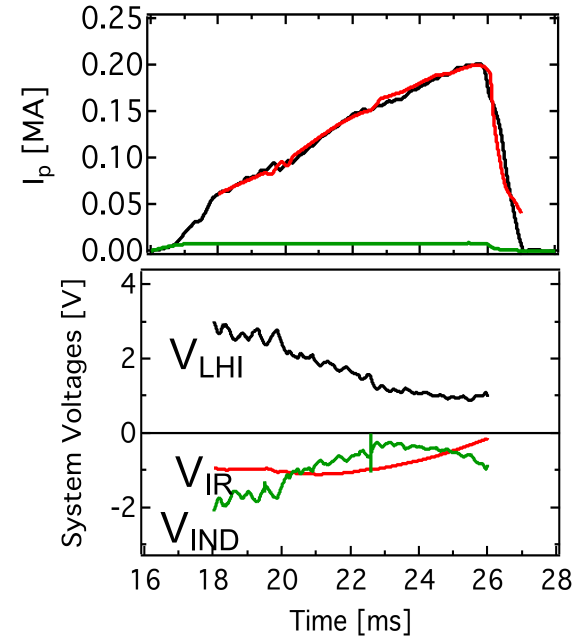
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

# Injector Location Emphasizes Different Current Drive








## Low-Field-Side (LFS) Injection:

- Injectors on outboard mid-plane
- LFS injection maximizes inductive drive
- Low $P_{inj}$ ~ 2 MW

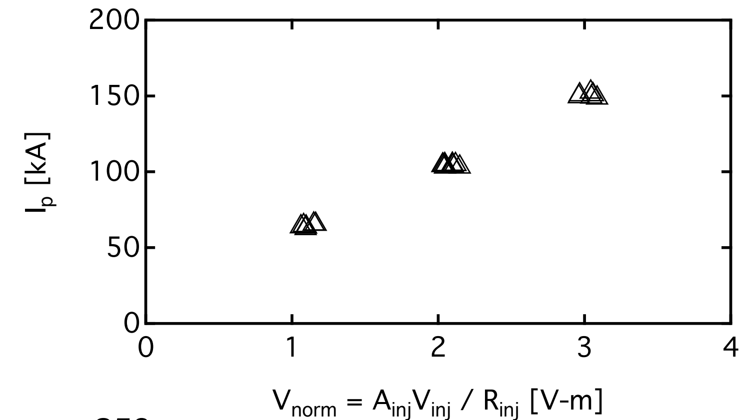
## High-Field-Side (HFS) Injection:

- Injectors in lower divertor
- HFS injection dominated by helicity drive
- High $P_{inj}$ ~ 4 MW

# Helicity Input Balanced By Resistive Dissipation

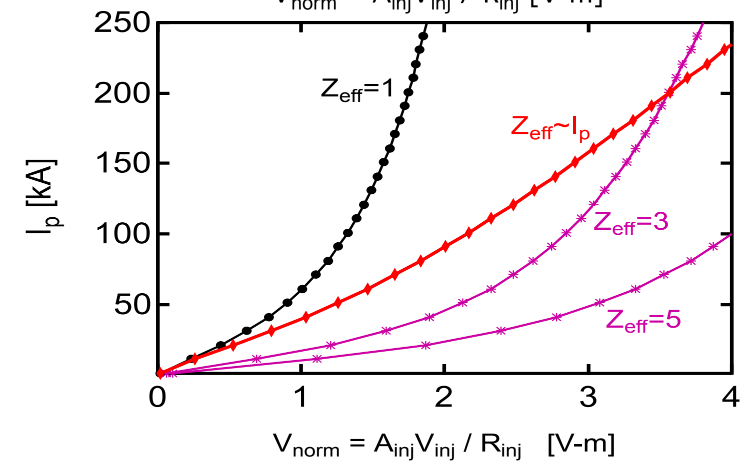
$$\frac{dK}{dt} = -2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B}\cdot d\mathbf{s} - 2\int_V \eta \mathbf{J}\cdot\mathbf{B}\, d^3x \quad \Rightarrow \quad \dot{K}_{res} \approx -\frac{2\pi R_0}{A_p}\langle \eta \rangle I_p \Psi$$

- $I_p \propto V_{LHI}$
  - Implies constant $\langle \eta \rangle$




- Incompatible with simple Ohmic confinement
  - $Z_{eff}$ strongly affects current drive scaling
  - If $Z_{eff}$ increases with $I_p$, a more linear scaling results

- Motivates efforts to determine $Z_{eff}$

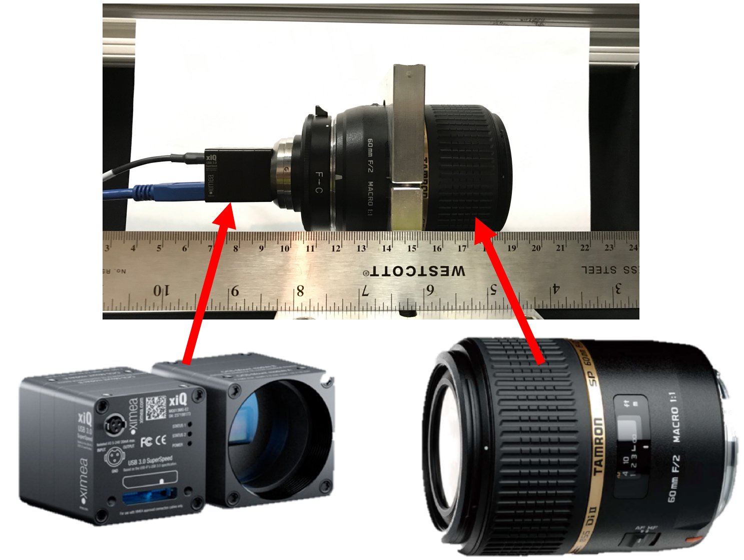


# Impurity Measurements Needed for LHI Assessment

- Impurity Roles
  - Helicity dissipation and plasma resistivity $I_p \sim \frac{V_{LHI}}{R_p} \sim \frac{V_{LHI}}{<\eta>}$
  - Radiation and recombination losses
    - $\tau_e$ determined by confinement and $P_{RAD}$
  - Plasma quality for subsequent current drive
- Plasma contaminants to be monitored by multiple diagnostics :
  - VB Spectroscopy
  - SPRED VUV Spectrometer to identify impurity species
  - Bolometer array to determine $P_{RAD}$ & $P_{TOTAL}$
  - Future: CHERS for individual species measurements

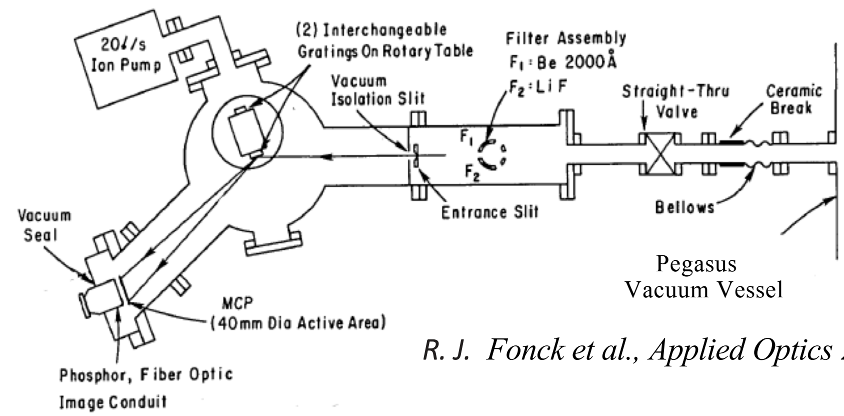
# Plasma Contaminant Species Monitored by SPRED Spectrometer

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



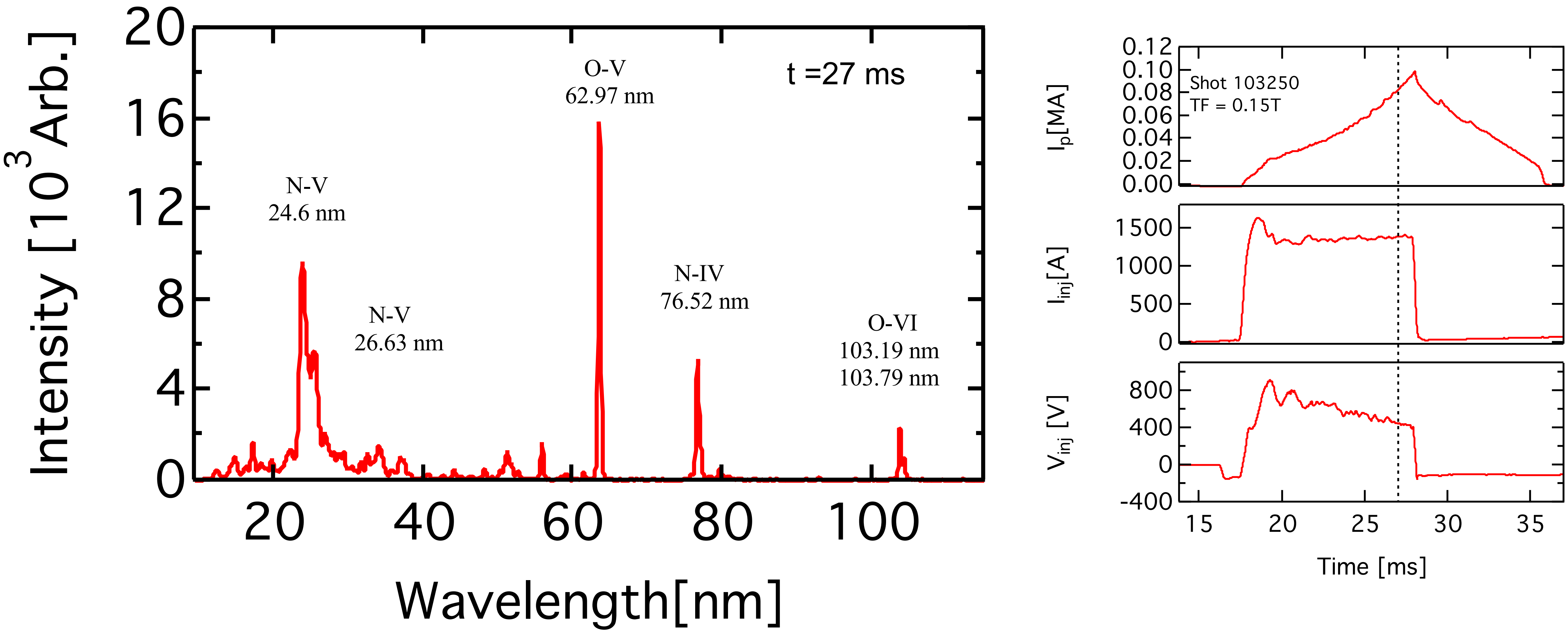
- New imaging system
  - Economic CMOS image sensor: xiQ MQ022MG-CM
  - 2.2 Mpix, 5.5 µm pixel size
  - Resolution 2048 x 1088
    - 1464 fps @ 2048 x 120, Δt =0.683 ms
  - Spectral resolution ~0.2 nm

Spectrometer Layout

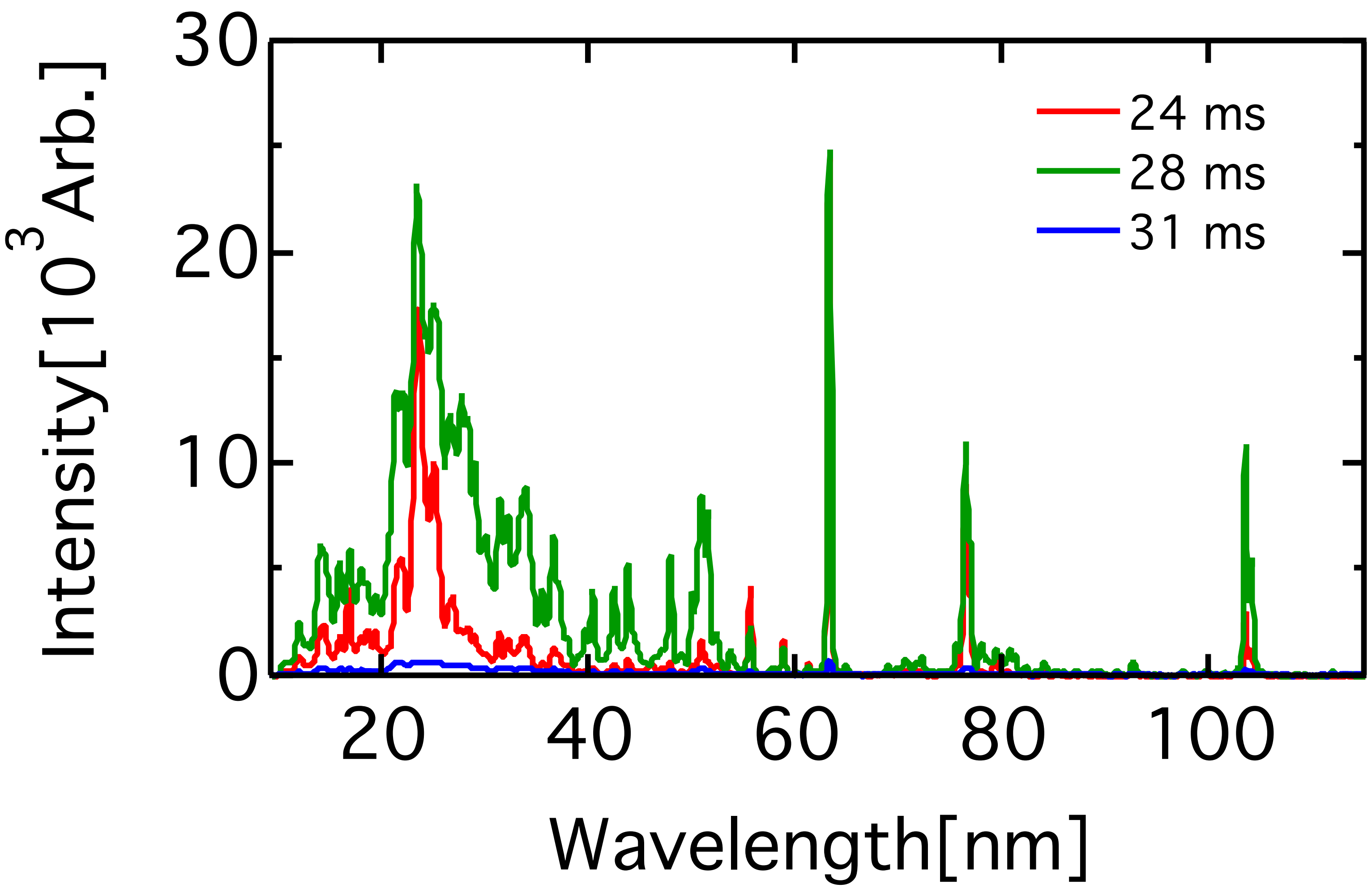


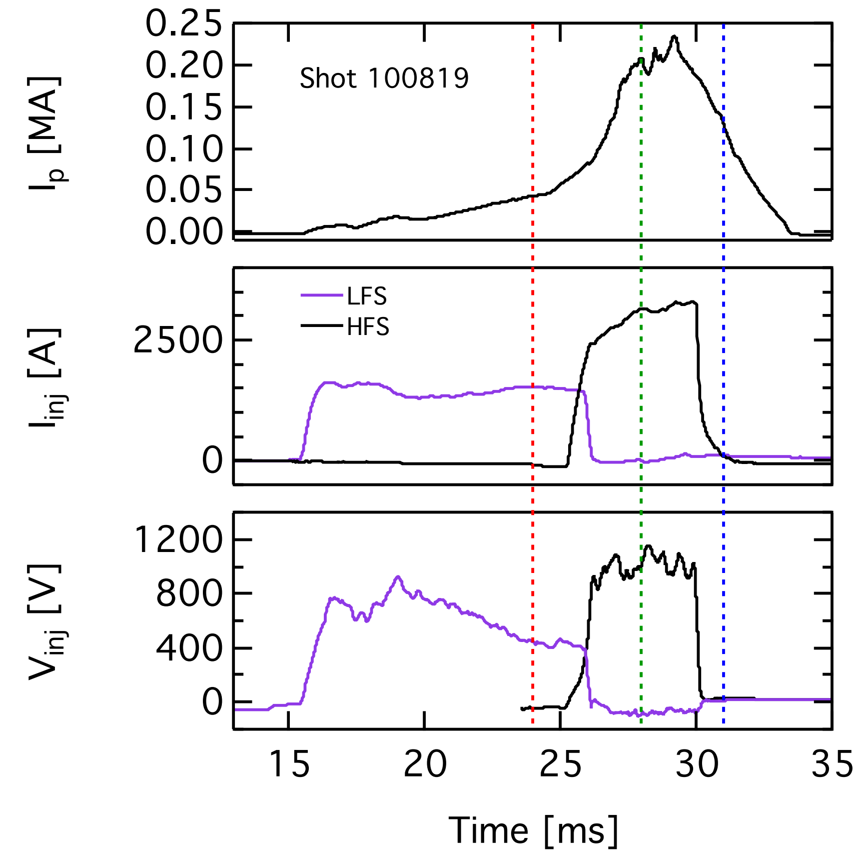

*R. J. Fonck et al., Applied Optics 21.12, 2115 (1982)*

# N and O Main Impurity Species During LFS Injection



# HFS Injection: Indicates Increased Impurity Influx



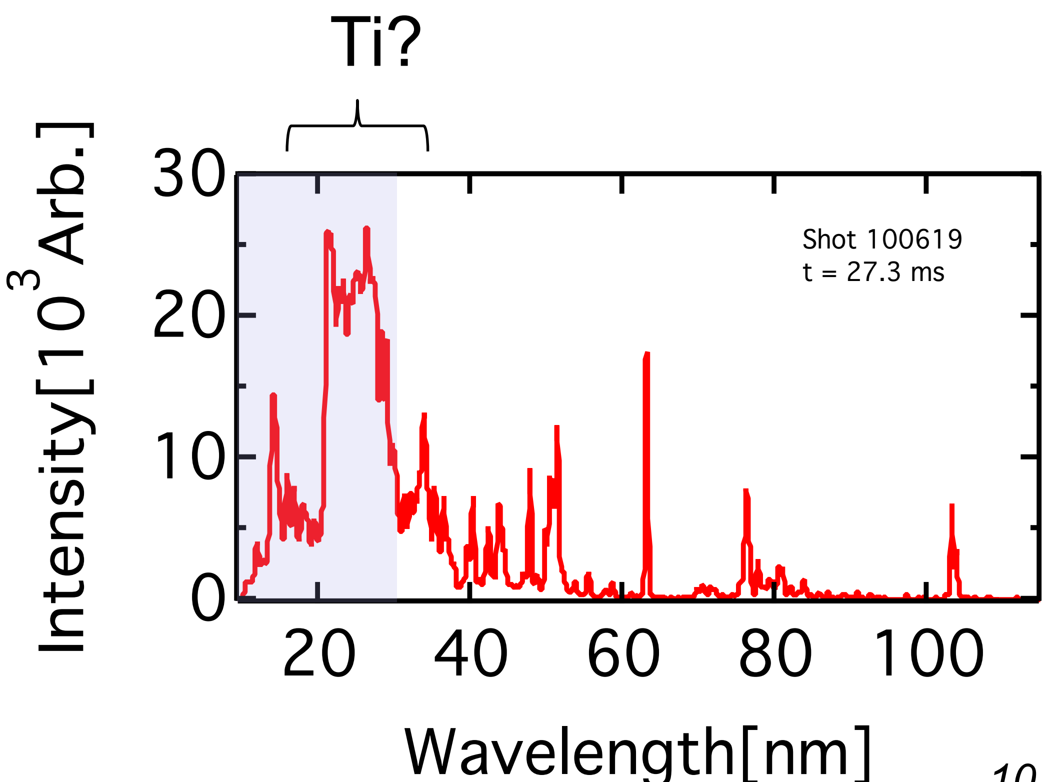

- Presumably increased PMI in divertor injector region

# High Resolution Grating Planned For Metallic Impurity Identification

- Injector PMI is a known impurity source
  - Cathode spots, arcing, etc.

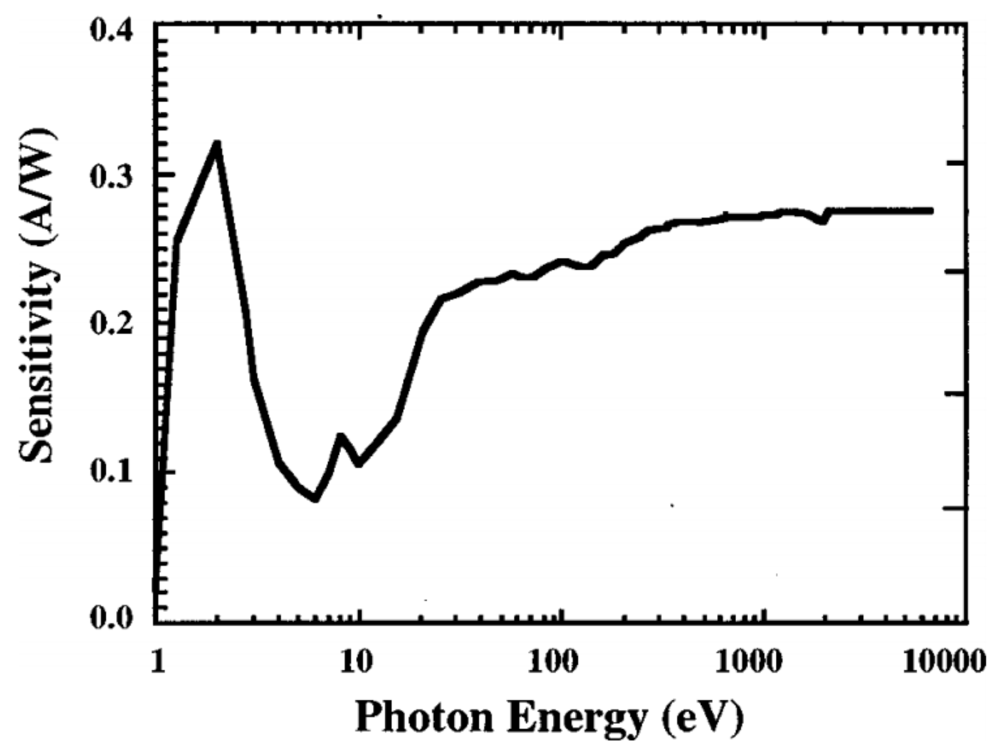
*Stratton, B. C., et al. Review of scientific instruments 57.8 (1986): 2043-2045.*

- New grating is being installed to resolve low-$\lambda$ metal lines
  - 2100-g/mm grating
  - Spectral resolution 0.04 nm
  - Spectral range 10 to 32 nm



# AXUV Photodiodes Allow High Spatial and Temporal Resolution Measurements of $P_{RAD}$

- High quantum efficiency
  - Flat response over a wide range of energies
  - Pegasus $T_e$ ~ 100 eV
    - Photodiode sensitivity drops at lower energies
- High Sensitivity ~ 0.24 A/W
  - High spatial resolution
- Fast temporal resolution ~ μs

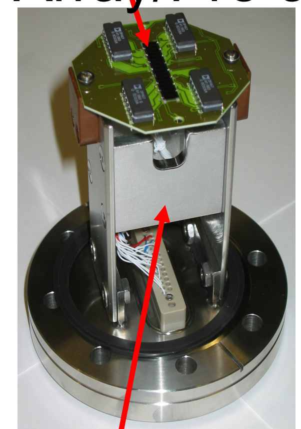


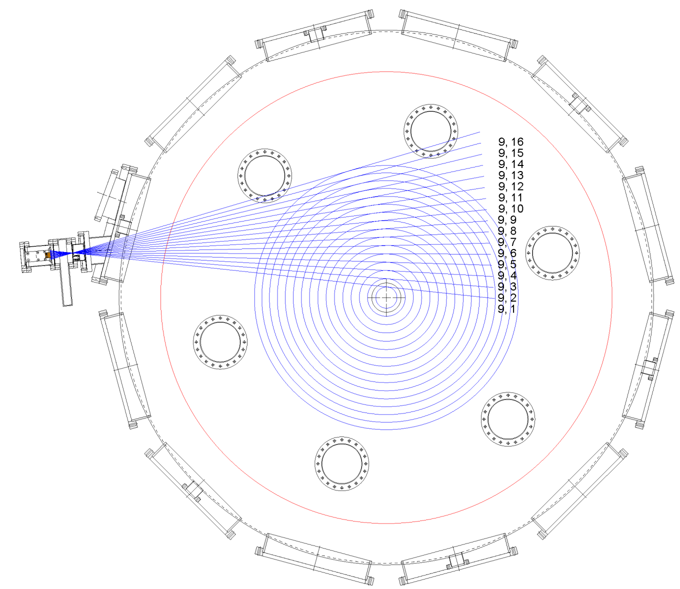

R.L. Boivin *et al*., Rev. Sci. Instrum. **70**, 260 (1999).

# AXUV Bolometers on Pegasus

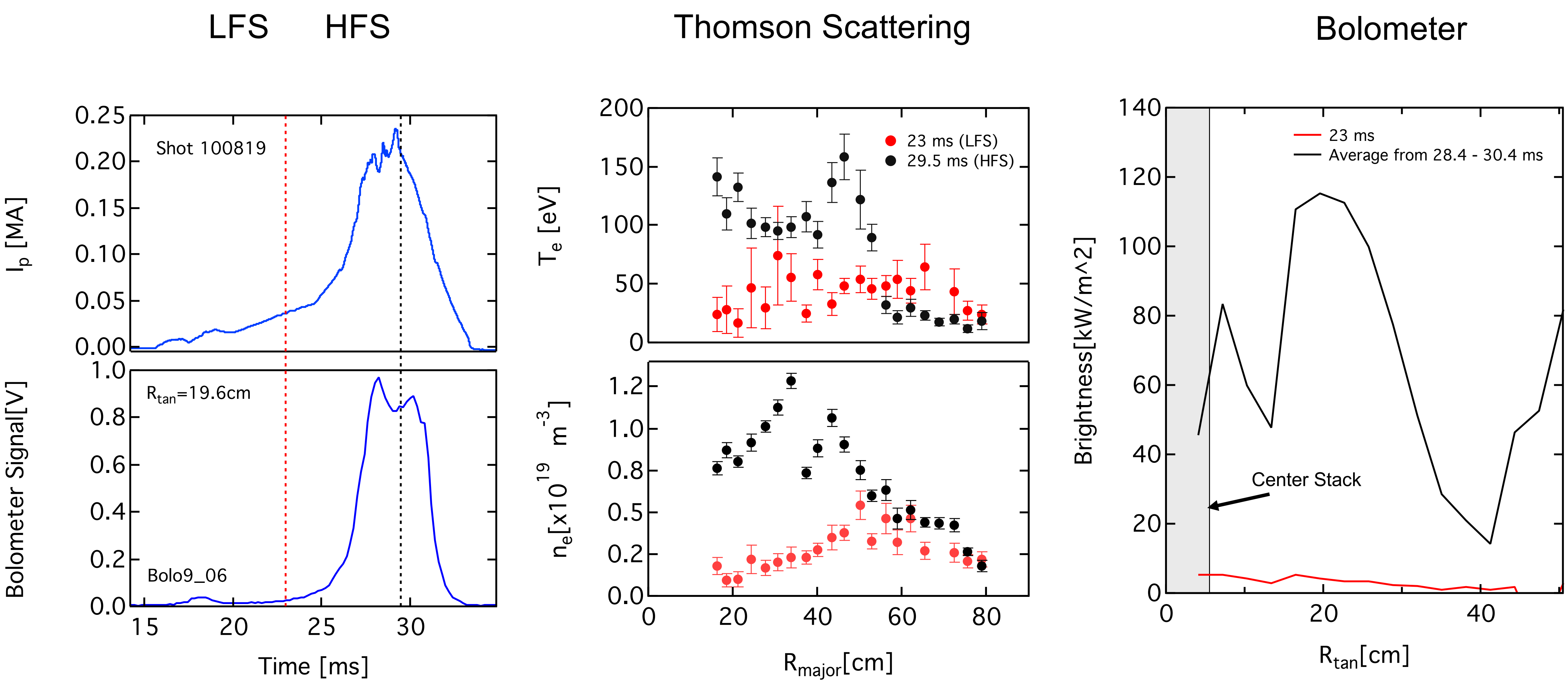
- IRD AXUV-16ELOHBY1
  - Vacuum compatible array and pre-amp assembly
  - Transfer Function 100 kV/A
  - Bandwidth 400 kHz

- One 16-channel array installed on Pegasus
  - Looking at midplane
  - Tangency radii from 5 to 50 cm
  - Spatial resolution ~ 3.1 cm



# Bolometers Suggest Lower $P_{RAD}$ in LFS Compared to HFS Injection And Hollow Profiles



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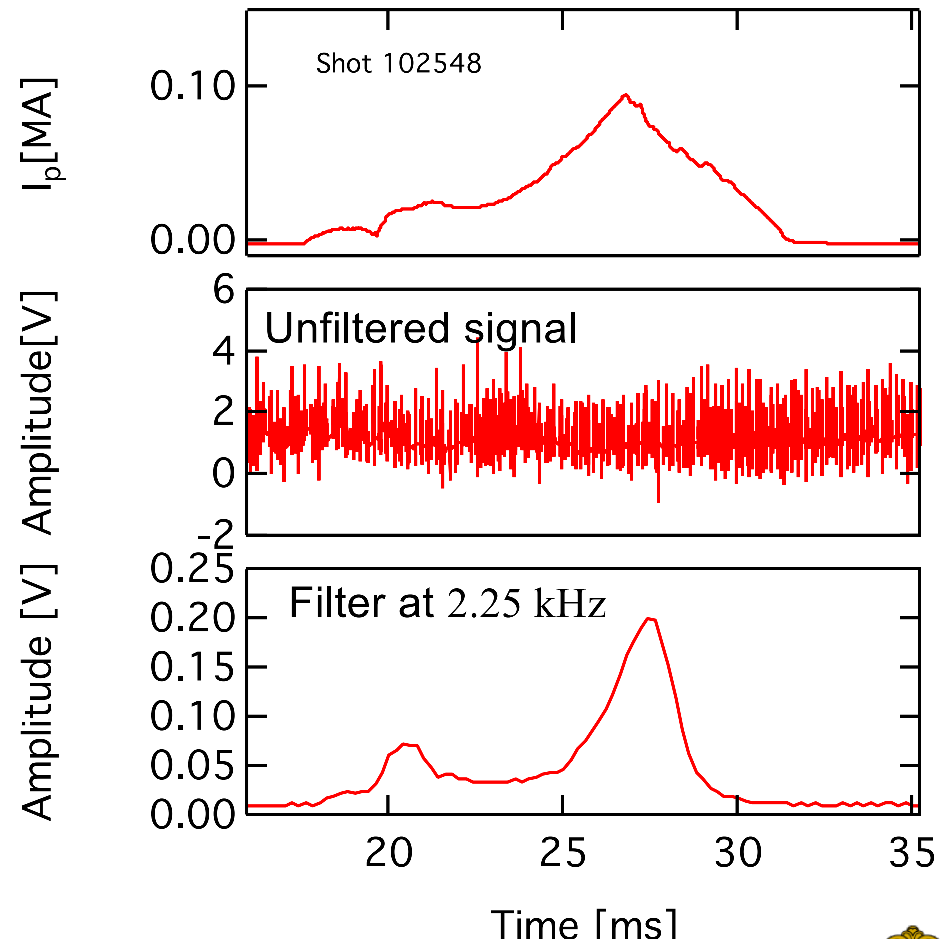
# Bolometer Upgrades To Include a New Pre-Amp Design And New Thermistor Bolometer Array

- New pre-amp design for AXUV diodes
  - Switching noise from power supplies requires signal filtering
  - Fully differential
  - Increase bandwidth
  - Cat7 cable run, shielded shielded twisted pair
  - Second 16-channel array from $R_{tan}$ = 46 to 90 cm

- 16-Channel Thermistor Array
  - Sensitivity to neutrals as well as photons
  - Temporal resolution ~ ms
  - Coarse spatial resolution



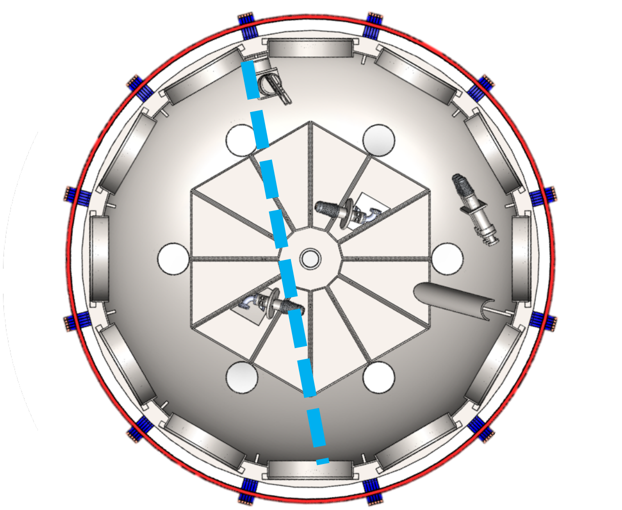
# Continuum Emission Coupled With Thomson Scattering Determine $Z_{eff}$

- Light emitted by continuum radiation

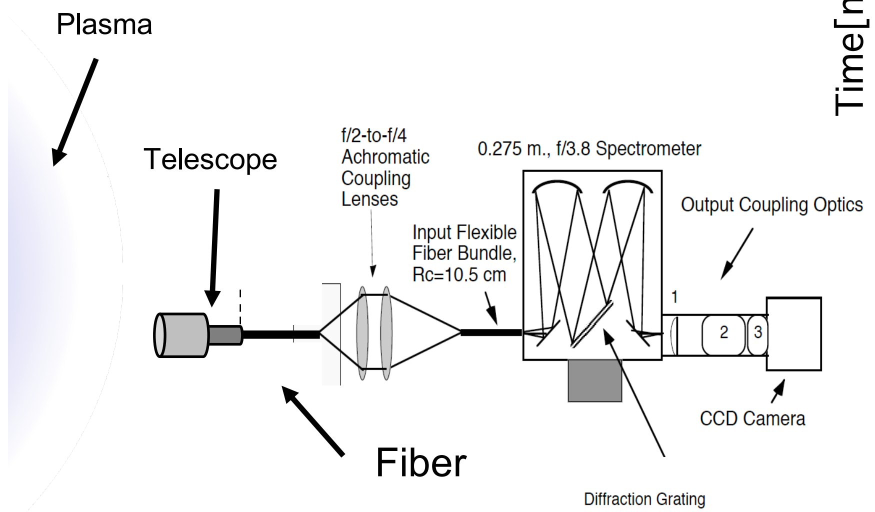
$$\frac{d\epsilon}{d\lambda} = 9.5x10^{-14}\frac{n_e^2 g_{eff} Z_{eff}}{{T_e}^{1/2}\lambda} e^{-\frac{hc}{\lambda T_e}}\left[\frac{\gamma}{s}\frac{1}{\mathrm{cm}^3}\frac{1}{\mathrm{nm}}\right]$$

- VB Spectroscopy at Pegasus
  - Deployed absolutely calibrated spectrometer that measures continuum radiation
  - Multi-Point Thomson Scattering measure $\mathrm{T_e}(R)$ and $\mathrm{n_e}(R)$

- Single line of sight through the plasma
  - $R_{tan} = 18$ cm
- Temporal resolution ~2 ms

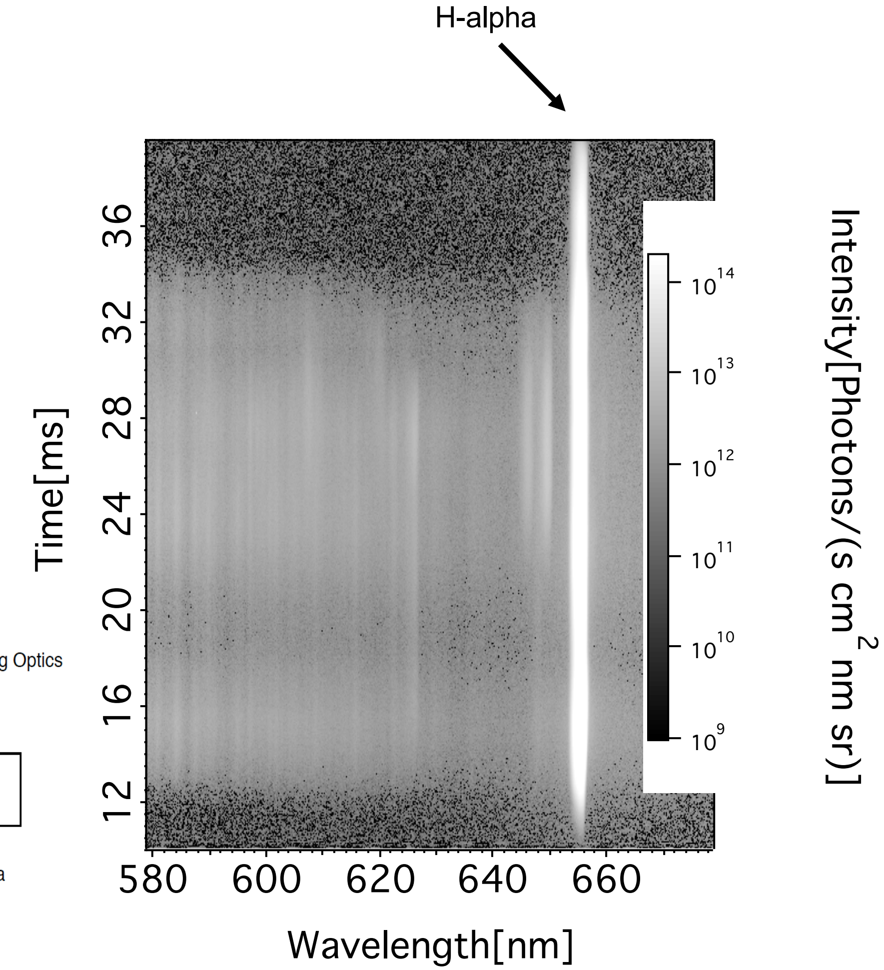


$R_{tan} = 18\ cm$



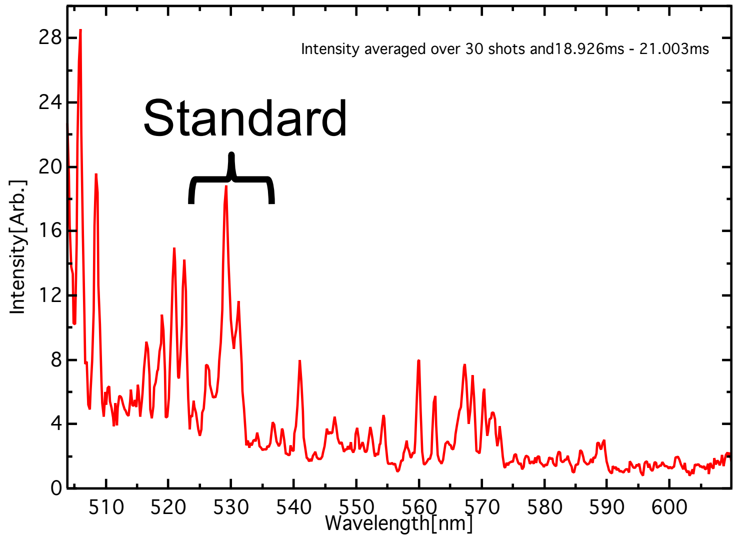

Diagnostic Layout

*G McKee, UW-Madison NEEP (1995)*



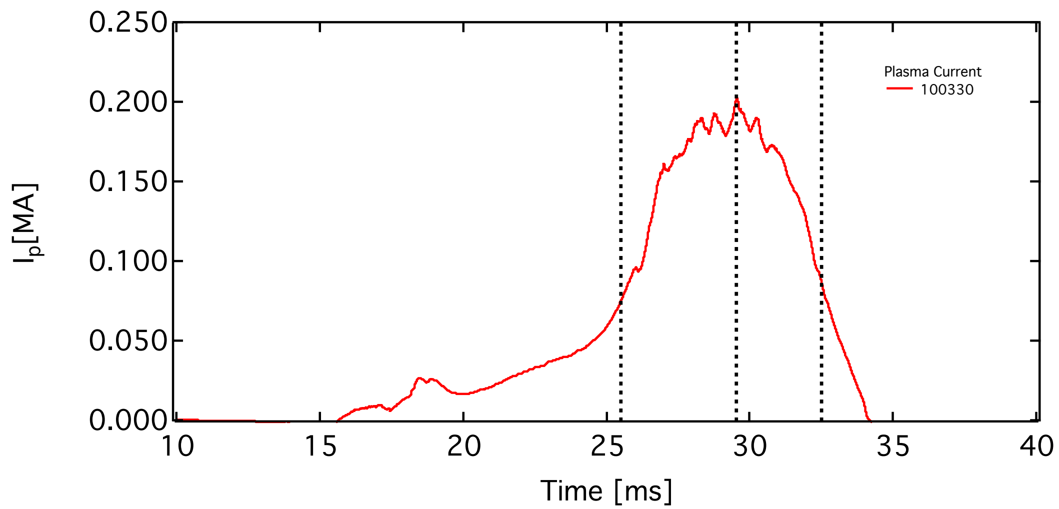
# Spectral Survey Revealed a Line-free Region For VB Measurements

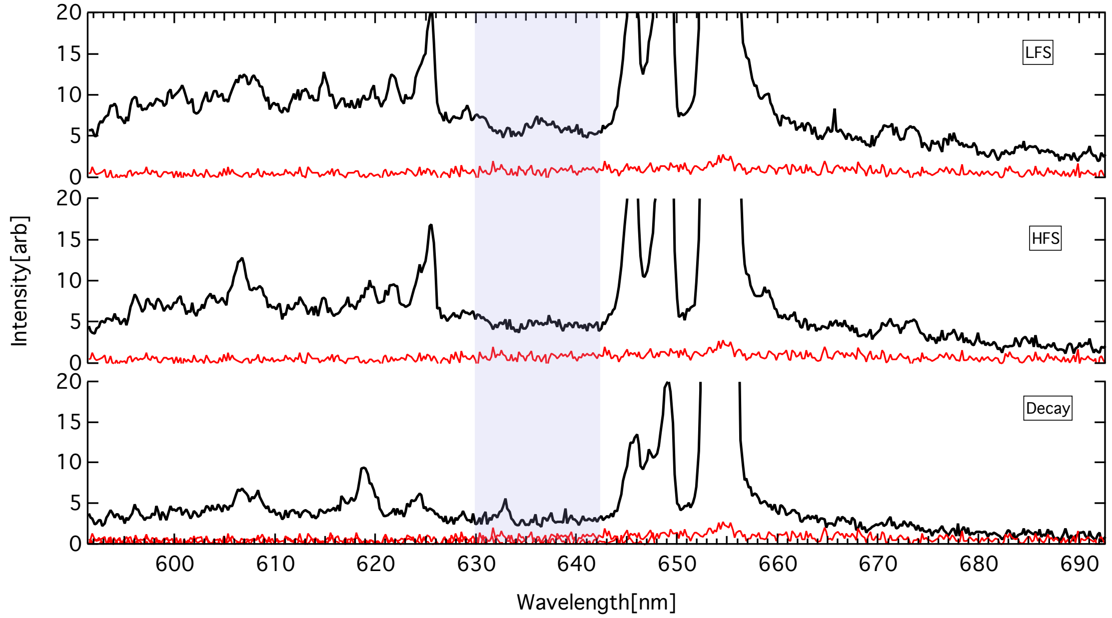
- Standard region in large tokamaks: 523-536nm *




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

- Spectral Survey for line-free region
  - Suitable region indicated near 635nm
  - Region could be used during LHS and HFS injection



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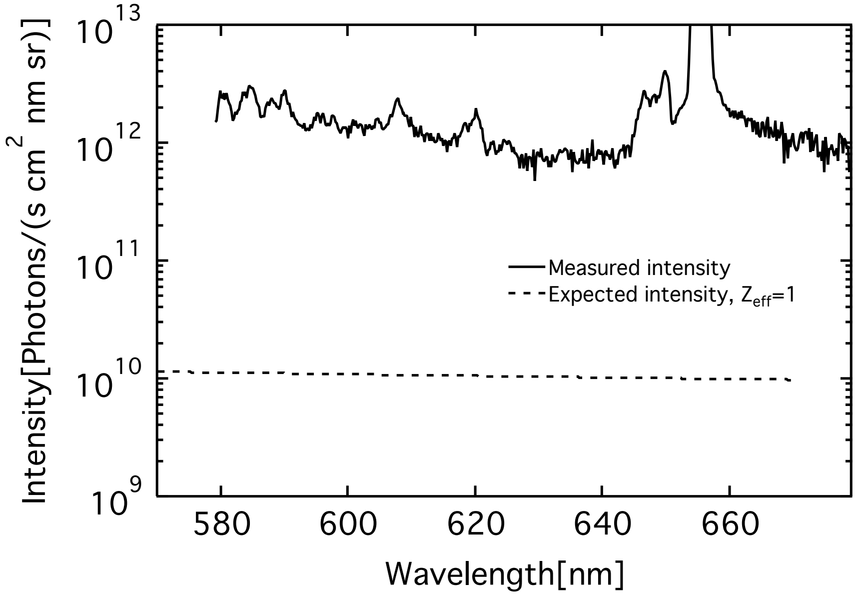
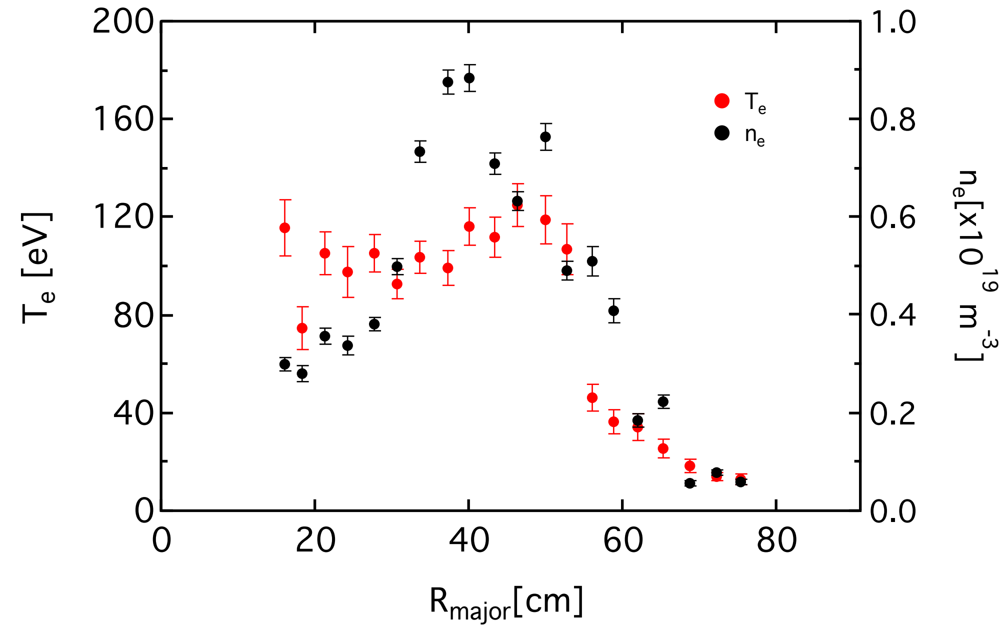
# Unrealistic High $Z_{eff}$ Suggests VB is not Dominant Source of Emission

- Issues with VB measurements at low $T_e$, $n_e$[1]
  - Recombination
  - Molecular hydrogen emission
  - Electron-neutral Bremsstrahlung

- Results in unrealistic high $Z_{eff}$ inferred if standard VB assumed

- VB may be useful in future at high $n_e$, $T_e$




[1]Anderson, J. K., et al. *Review of scientific instruments* 74.3 (2003): 2107-2110

*C. Rodriguez Sanchez, 60th APS-DPP 2018*

# Plasma Resistivity Analysis Can Be Used To Infer $Z_{eff}$

- Assuming impedance is fully resistive

$$V_{LHI} = I_p R_p = Ip\left(\frac{\langle\eta_p\rangle 2\pi R_0}{A_p}\right)$$

- Assume Spitzer resistivity with neoclassical corrections

$$\eta_{Spitzer} = 1.65 \times 10^{-9} Z_{eff} \frac{ln\Lambda}{T_e^{3/2}} \Omega\mathrm{m}$$

$$\eta_{neo} = \eta_{Spitzer} M_{neo}$$

- Neoclassical enhancement factor can be calculated using formulas from Sauter[1]

[1]Sauter, O., et al. Phys. Plasmas 6 (1999) 2834.

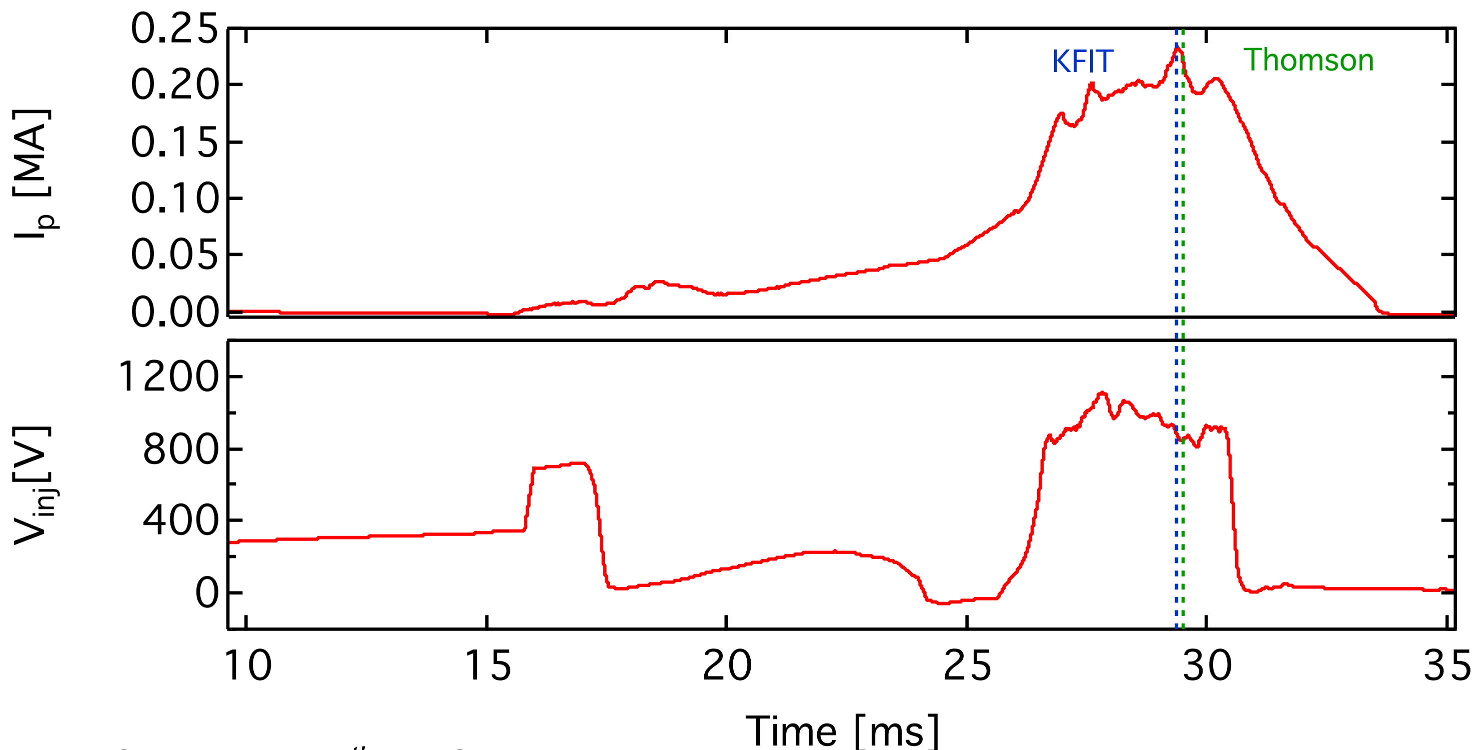
# Equilibrium Reconstruction Provides $R_p$

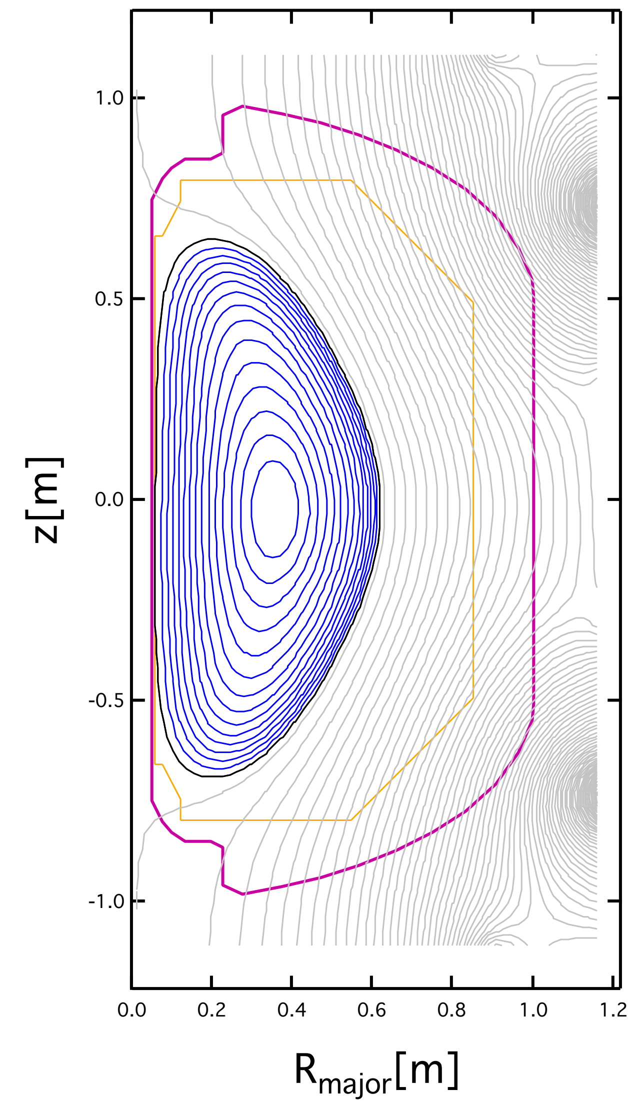
$V_{inj}$ = 890 V
$A_{inj}$ = 8 $cm^2$
$B_{inj}$ = 0.34 T
$\Psi$ = 0.159 Wb

$$V_{LHI} \approx \frac{V_{inj} A_{inj} B_{inj}}{\Psi} \approx 1.5V$$

$$1.5\ V = 210\ kA \times R_p$$

$$R_p = 7.14 \times 10^{-6}\ \Omega$$



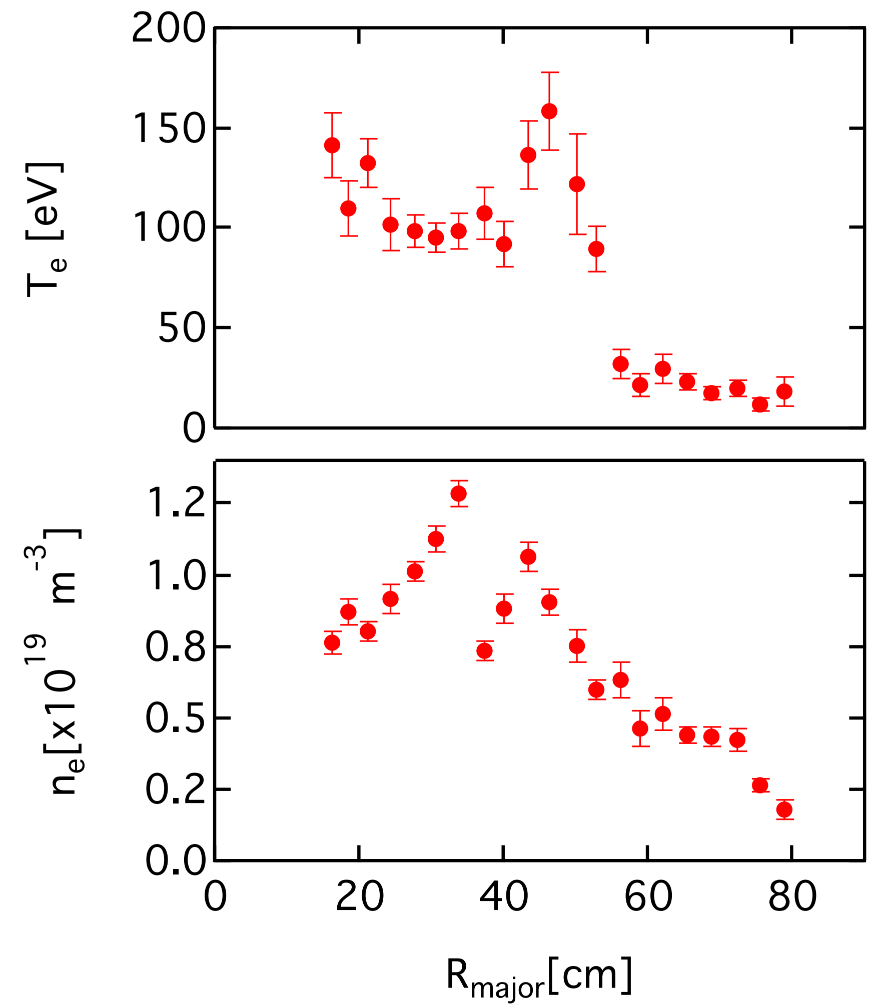
# Thomson Scattering $T_e$ and $n_e$ Measurements Provide a Second $R_p$ Estimate

- 1D Thomson Measurements mapped into flux space
- $Z_{eff}$ used as input parameter in Sauter's formulas and varied to match $R_p$

$$M_{neo} = \frac{1}{1 - \left(1 + \left(\frac{0.36}{Z_{eff}}\right)\right) X + \left(\frac{0.59}{Z_{eff}}\right) X^2 - \left(\frac{0.23}{Z_{eff}}\right) X^3}$$

$$X = \frac{f_t}{1 + (0.55 - 0.1ft)\sqrt{\nu_{e*}} + \frac{0.45(1-ft)\nu_{e*}}{Z_{eff}^{3/2}}}$$

- This analysis implies $Z_{eff}$ ~ 1.7 in HFS phase
  - Valid only at reconstruction and TS time
  - Needs to account for inductive drive



# Conclusions and Future Work

- Pegasus modest $T_e$ and $n_e$ present a problem to measure $Z_{eff}$ using VB spectroscopy
- SPRED improved resolution permits proper impurity species identification that can be coupled with bolometers and impurity transport code
  - Possible absolute calibration of SPRED
- LHI to Ohmic handoff with high $T_e$ and high $n_e$ for validation of VB and bolometers
  - Two new bolometer arrays under consideration
- CHERS under consideration

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