

Improving Electron Density Calibration Techniques for the DIII-D Thomson Scattering Diagnostic

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¹**General Atomics**

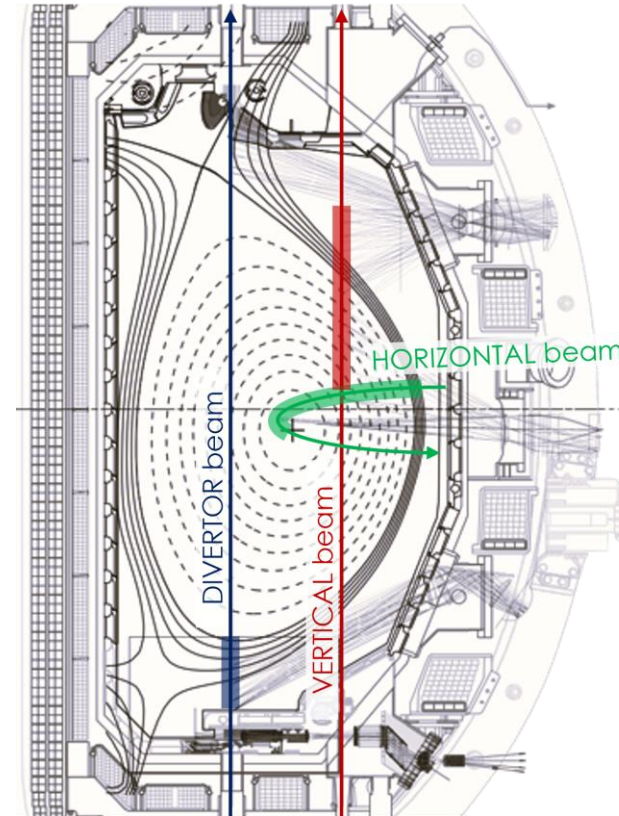
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Background & Motivation

- Accurate electron density (n_e) **profiles are crucial**:
 - plasma control, performance evaluation, study confinement, transport, edge physics, & exhaust
 - require **absolute calibration of system response**

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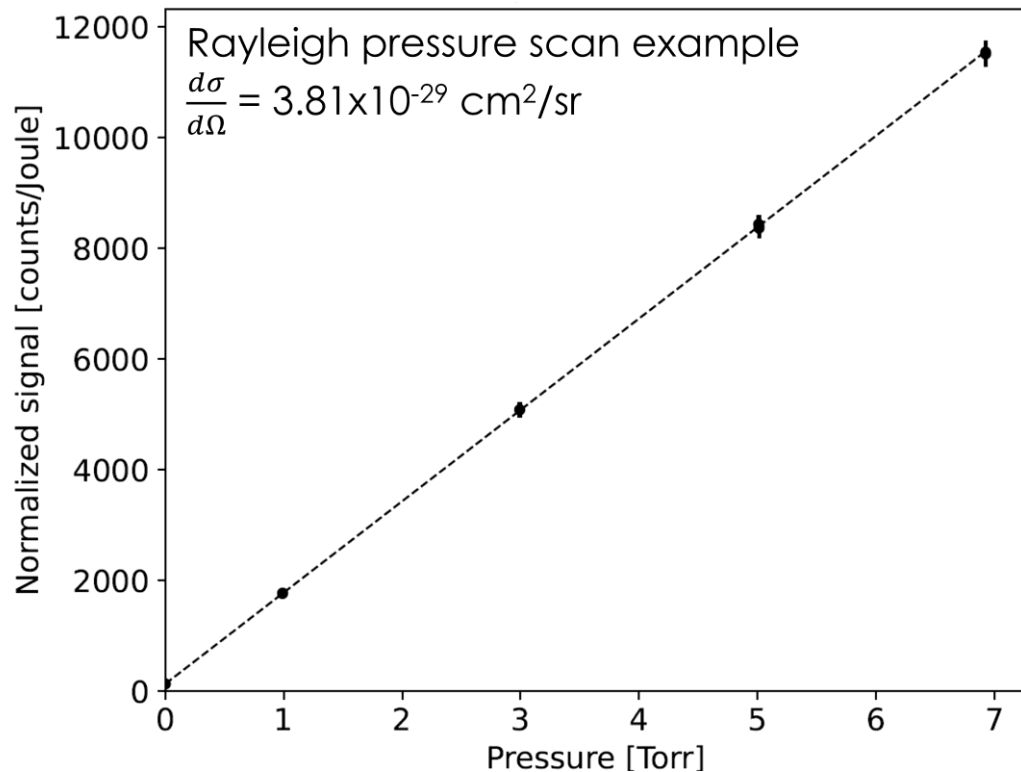
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- Rayleigh scattering-based calibration of DIII-D Thomson scattering^[1] **vulnerable to stray laser light contamination**
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- **Rotational Raman scattering** from diatomic gas shifts scattered wavelengths away from laser wavelength^[2]

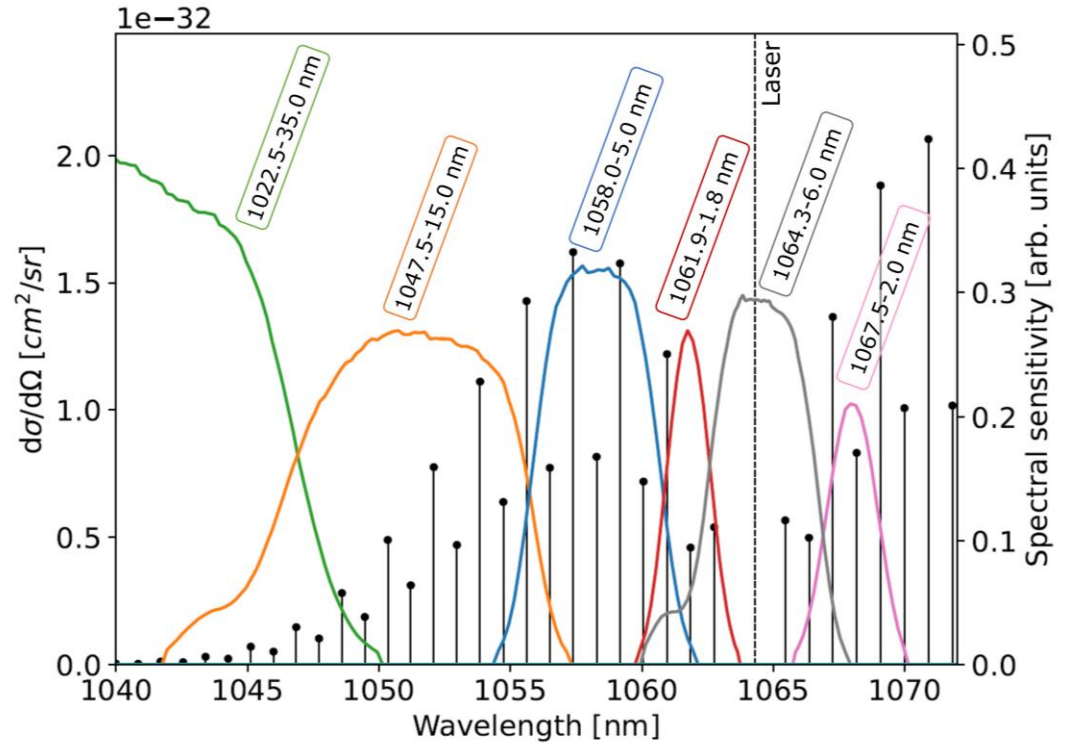
Rayleigh scattering

- System response measured at **various gas fill pressures**
- Signal normalized to laser energy
- Slope of linear fit provides calibration factor
- **Single spectral channel** only (1064nm)
- Well-known cross section



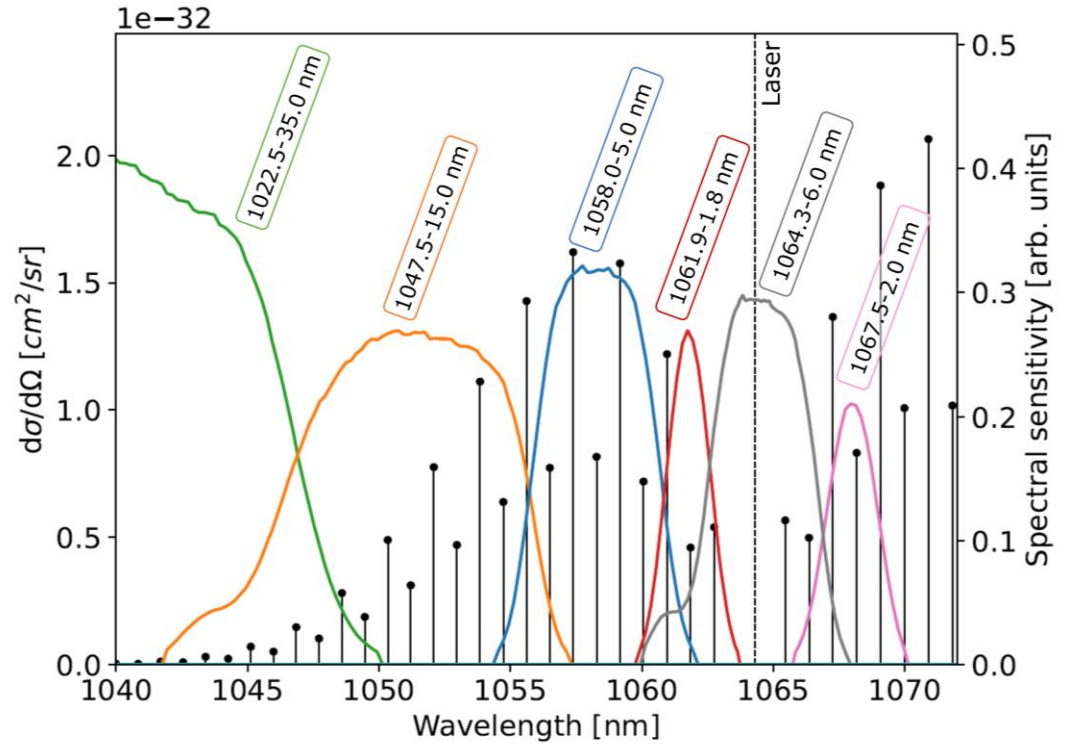
Raman scattering

- **Sum of Raman lines**
weighted by filter
transmission



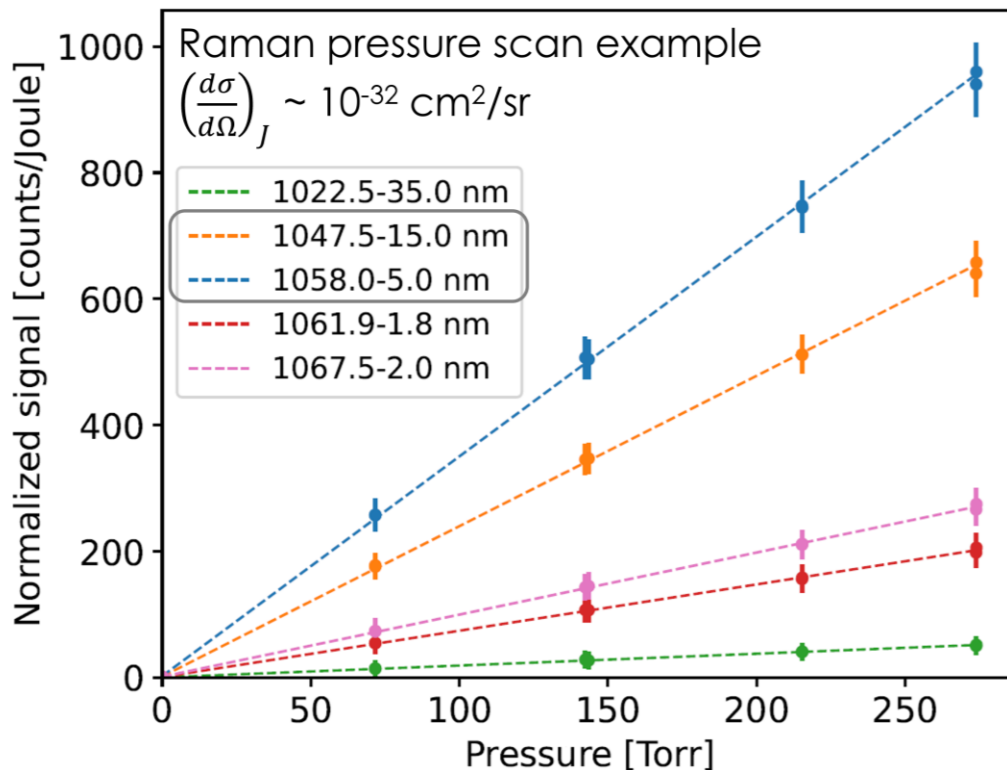
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channels:
 - **1047nm, 1058nm**
reliably good signals
 - 1062nm, 1067nm possible
Rayleigh bleed-through
 - 1022nm low Raman signal



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 - 1022nm low Raman signal
- 100-1000x lower signal
(per filter) vs Rayleigh



Rayleigh vs Raman

- 56 scattering volumes (42 vert. + 14 hor.) over (6 vert. + 1 hor.) lasers
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- **Geometry factor Φ** should be the same for Rayleigh / Raman (& Thomson)
- For each spectral channel:

$$\Phi_{\text{ch}} = \frac{k_B T_{\text{gas}}}{\left(\frac{d\sigma}{d\Omega} \tau_{\text{rel}}\right)_{\text{ch}} \left(G_{\text{PL}}/G_{\text{DC}}\right)_{\text{ch}}} \left[\nabla \frac{(S/E_{\text{las}})}{P_{\text{gas}}} \right]_{\text{ch}}$$

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cross-section

relative transmission of collection optics + filter

ratio of detector gains (DC spectral calibrations)

ratio of detector signal to laser energy

Rayleigh vs Raman

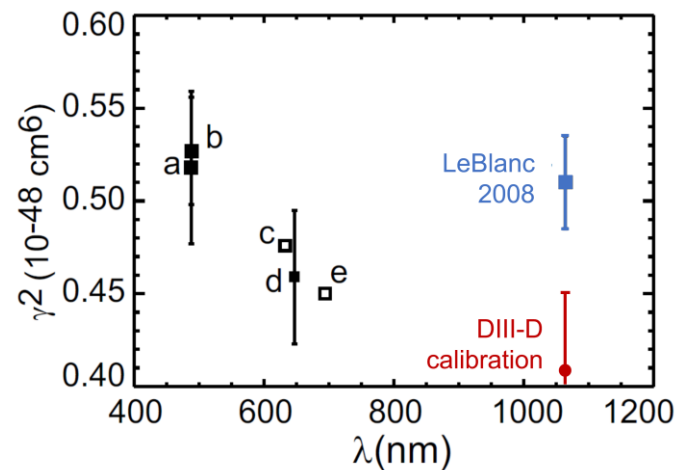
- **Geometry factor Φ** should be the same for Rayleigh / Raman (& Thomson)
- DIII-D Thomson system produces lower Raman sensitivity than Rayleigh:

$\langle \Phi \rangle_{\text{Raman}} \sim 0.8 \langle \Phi \rangle_{\text{Rayleigh}}$

 $\rightarrow$ gives $\sim 25\%$ higher n_e for same Thomson signal

Rayleigh vs Raman

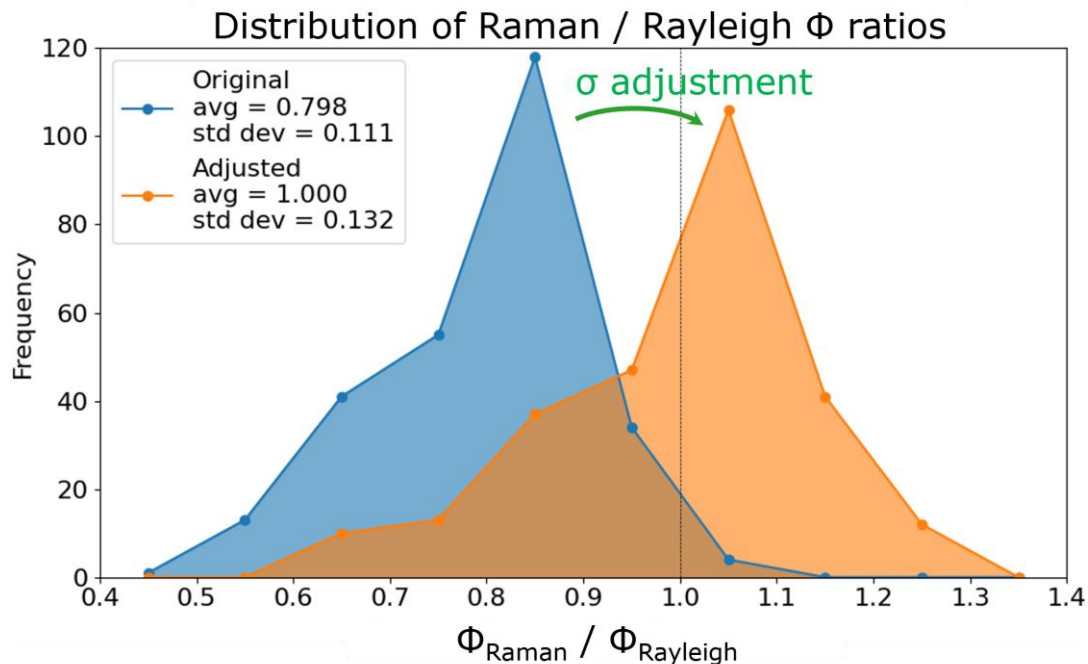
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- DIII-D Thomson system produces lower Raman sensitivity than Rayleigh:
 $\langle \Phi \rangle_{\text{Raman}} \sim 0.8 \langle \Phi \rangle_{\text{Rayleigh}}$ → gives ~25% higher n_e for same Thomson signal
- Raman $\sigma \propto \gamma^2$ where
 γ = molecular polarizability anisotropy^[3]
- **Manually adjust value** to improve agreement
 $\gamma^2 = 0.51 \rightarrow 0.40 \times 10^{-48} \text{ cm}^6$
- **Still use Rayleigh** where possible
until discrepancy is resolved



[3] B. P. LeBlanc, RSI 79, 10E737 (2008)

Rayleigh vs Raman

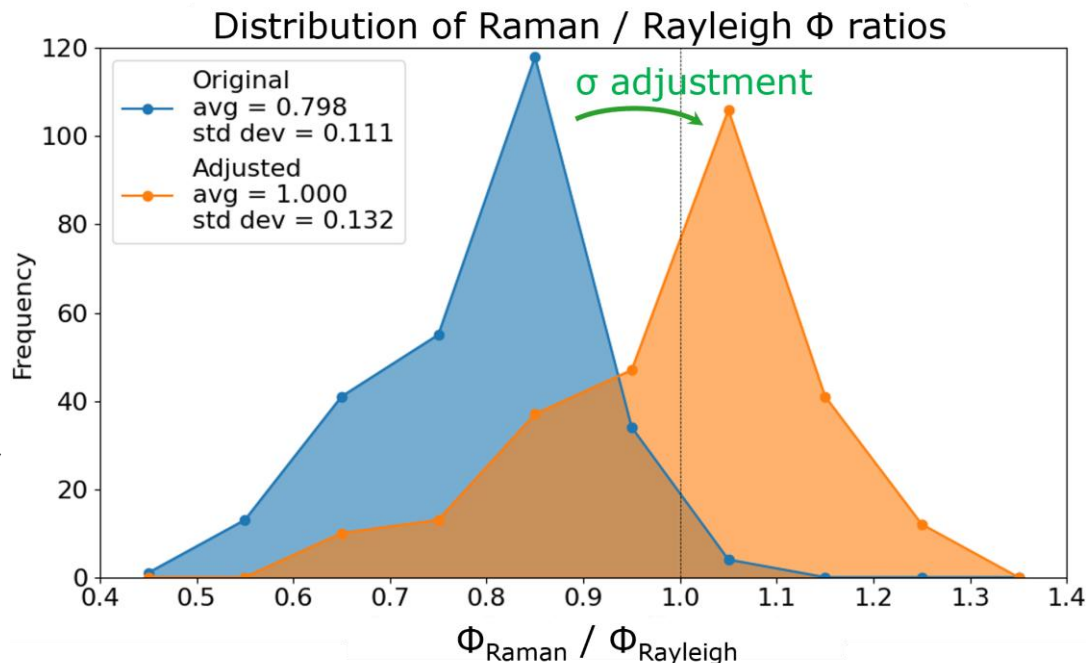
- Ratio $\Gamma_{\text{Raman}} / \Gamma_{\text{Rayleigh}}$ has **~20% point-to-point variability**



[Raman value is mean of 1058 & 1047 nm channels]

Rayleigh vs Raman

- Ratio $\Gamma_{\text{Raman}} / \Gamma_{\text{Rayleigh}}$ has **~20% point-to-point variability**
- Possible causes:
 - measurement accuracy of detector **Pulse / DC gain**
→ *whole system pulsed calibration*
 - accuracy of optics **spectral calibrations**: angle-of-incidence, coating, aging, irradiation
→ *in situ (re)calibrations*
 - Residual Rayleigh cross-filter bleed-through during high-pressure Raman? → *measure*

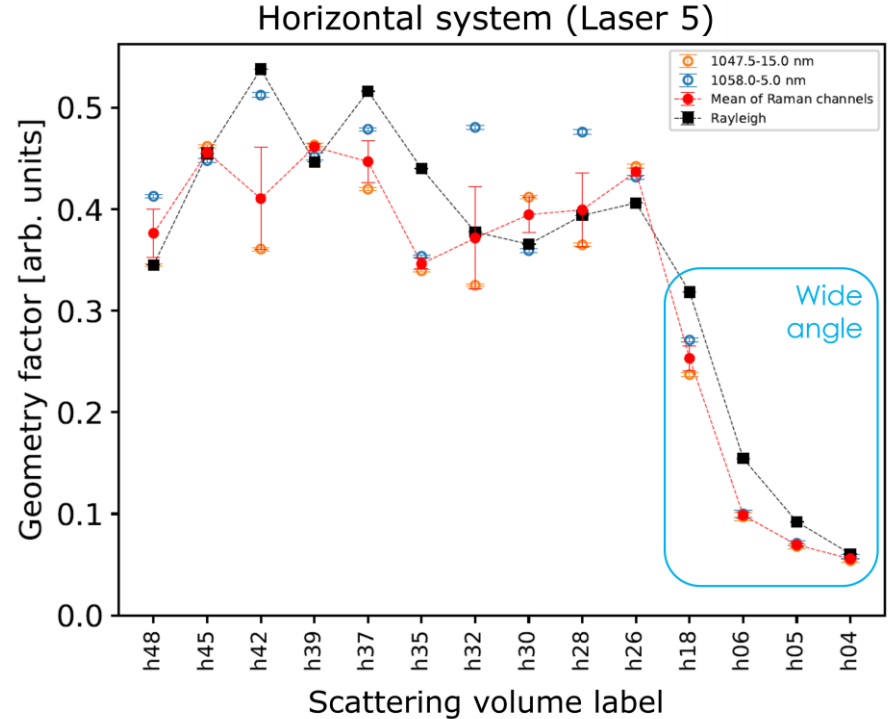


[Raman value is mean of 1058 & 1047 nm channels]

Rayleigh vs Raman

- **Neither** 1047nm nor 1058nm factor alone **is better matched** to Rayleigh
- If 'good' is **within 10%** of Rayleigh:

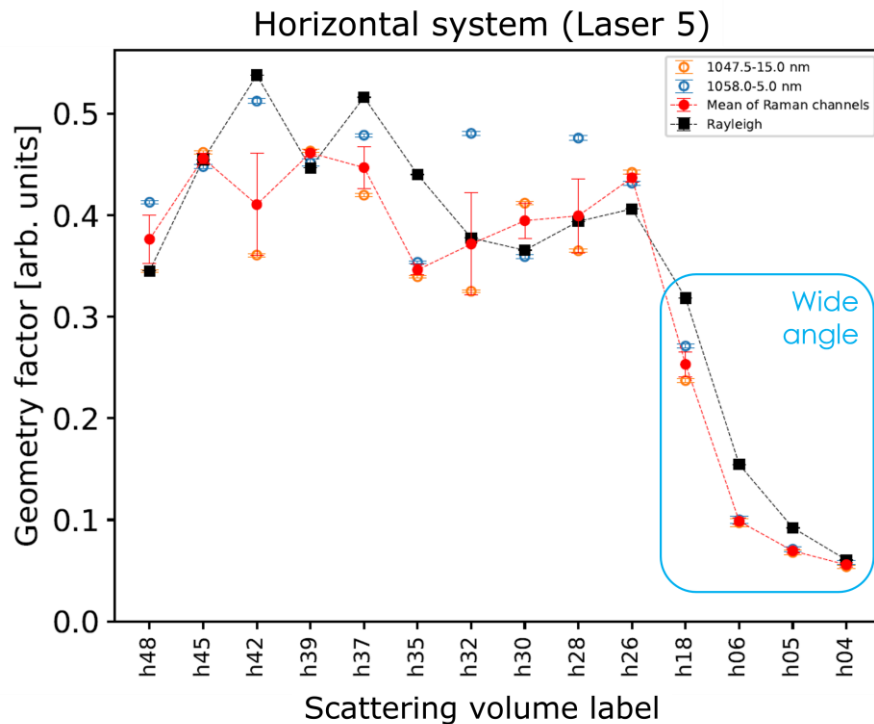
Good channel(s)	Frequency
1047nm only	28%
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Neither	23%
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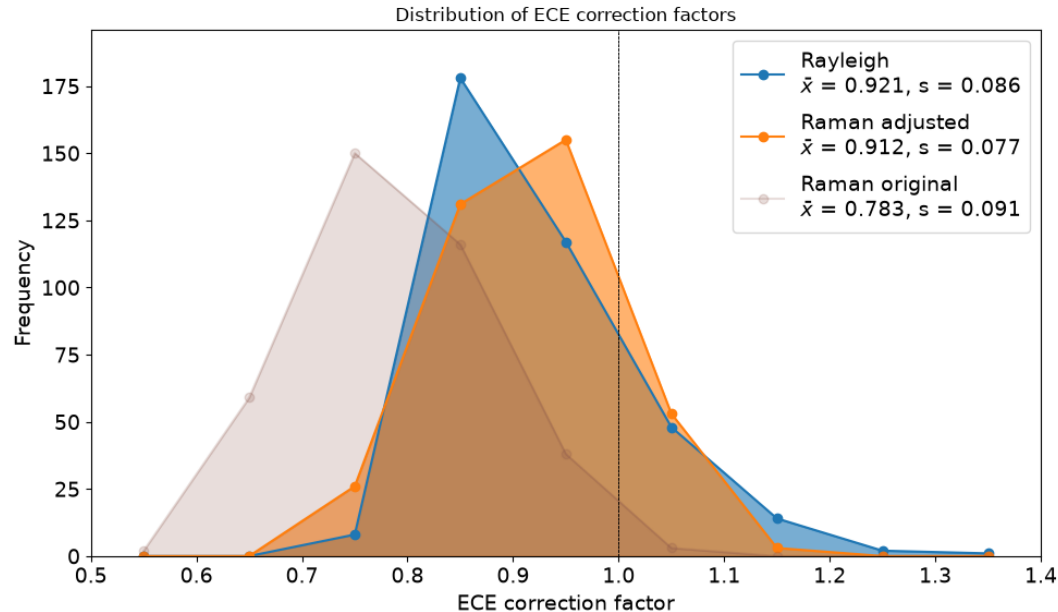
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Where both are available, Raman is not clearly better than Rayleigh at DIII-D

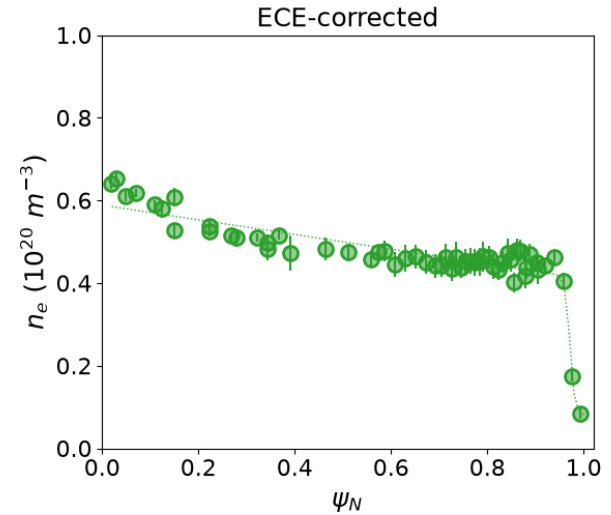
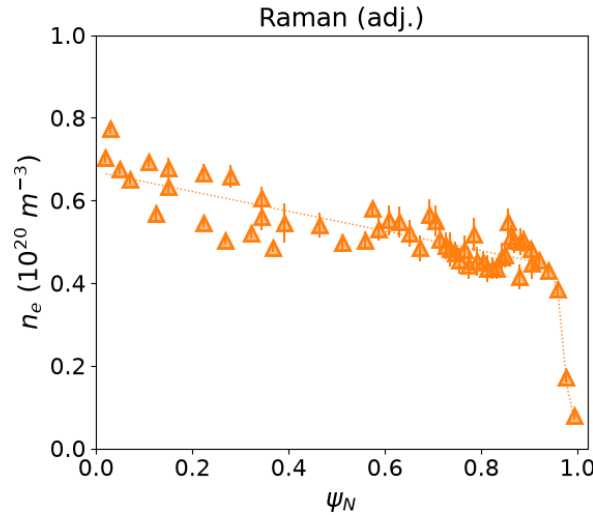
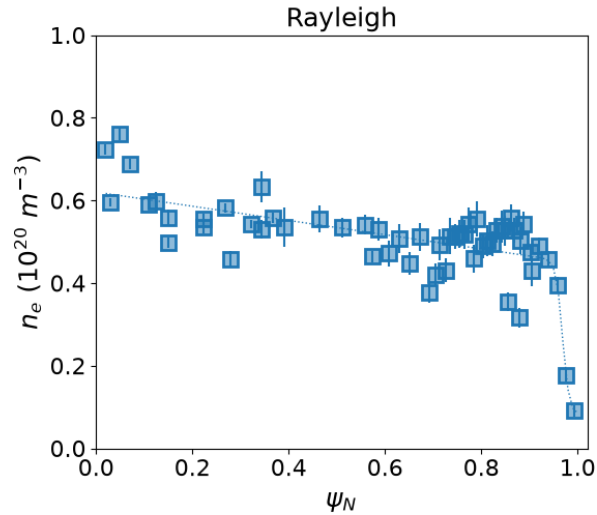
Cross-calibration with ECE improves n_e calibration and profiles

- Dedicated shots with gradual ramp-up of n_e and I_p to **send ECE channels into cutoff**
- Fit signal extinction: known ECE f_n and $B(R)$ gives $n_e(R_n, t_n)$ [4, 5]
- **Mapping + interpolation** in ψ space to get correction factors for Rayleigh/Raman
- Can introduce errors $\propto \nabla\psi$



Cross-calibration with ECE improves n_e calibration and profiles

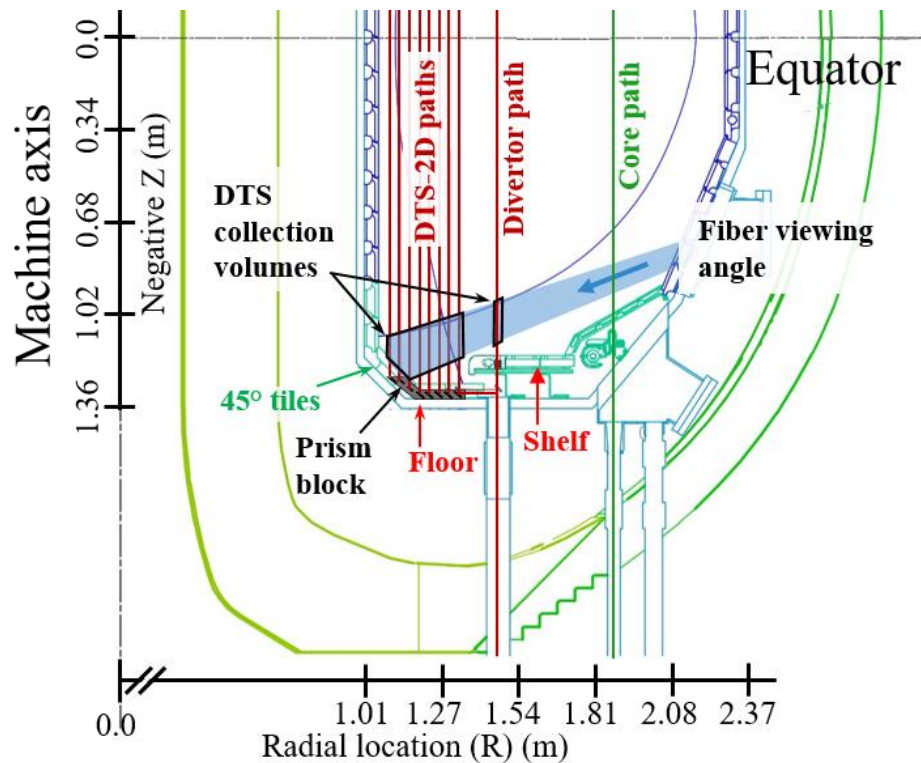
DIII-D shot 205686, $t = 2750$ ms



Use ECE correction to Rayleigh/Raman in
plasma core & edge (53/56 volumes)

Density calibration is more challenging in divertor

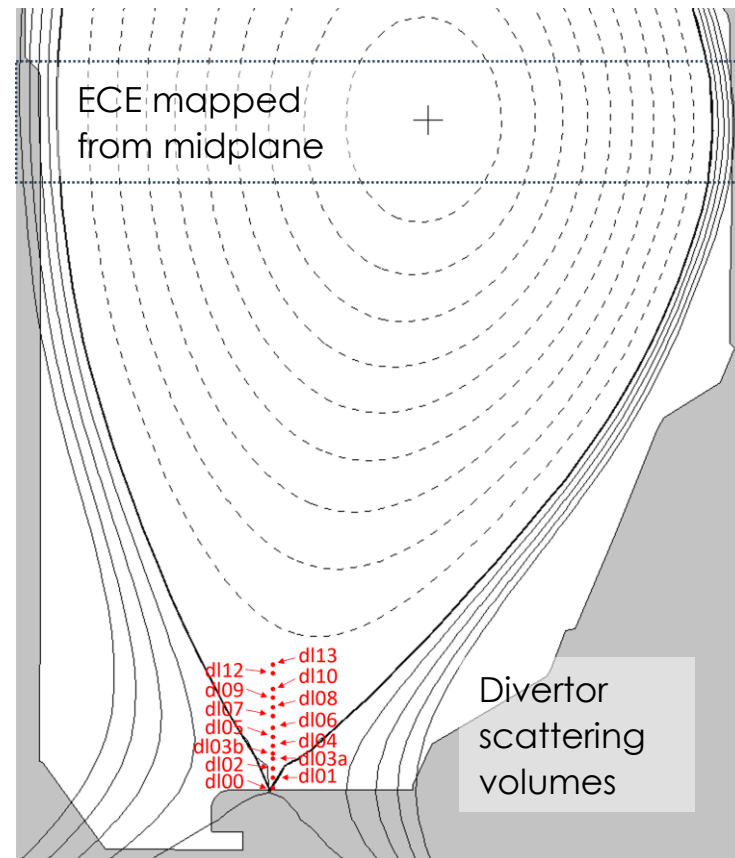
- Ultra-narrowband filters **reduce cross-filter stray light contamination**
 - Rayleigh calibration not possible
- Raman calibration **used with adjusted σ**
- Possible cross-checks / corrections being evaluated
 - ECE-based
 - P_e based



Calibration of Divertor Density – ECE and P_e checks

1) ECE: expanded plasma shape, **divertor TS locations inside separatrix**

- ECE mapped from mid-plane (steep $\nabla\Psi$) to expanded flux in divertor



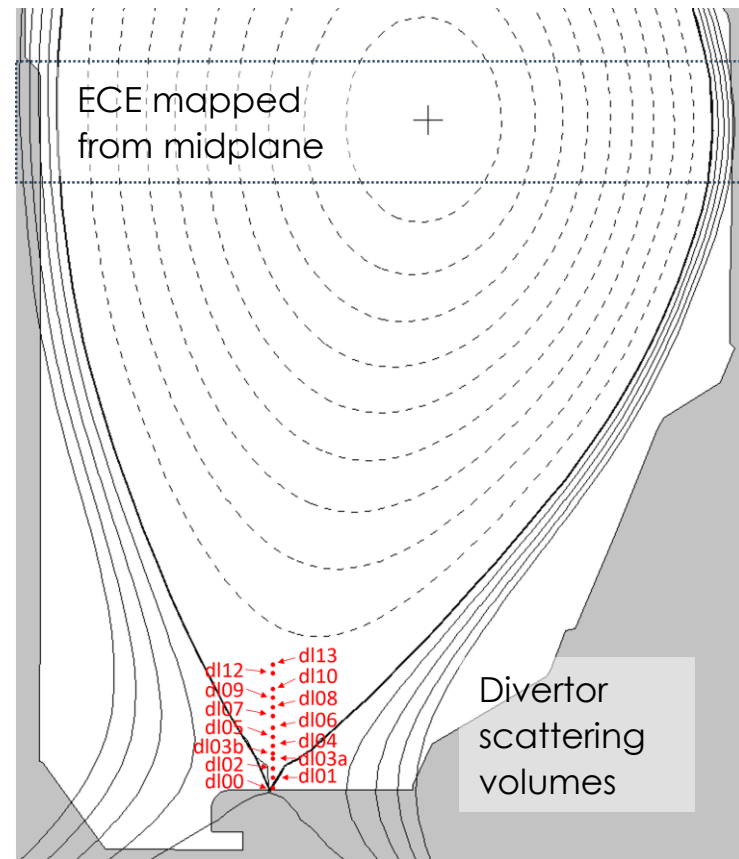
Calibration of Divertor Density – ECE and P_e checks

1) ECE: expanded plasma shape, **divertor TS locations inside separatrix**

- ECE mapped from mid-plane (steep $\nabla\Psi$) to expanded flux in divertor.

2) Assuming P_e balance along field lines for independent check

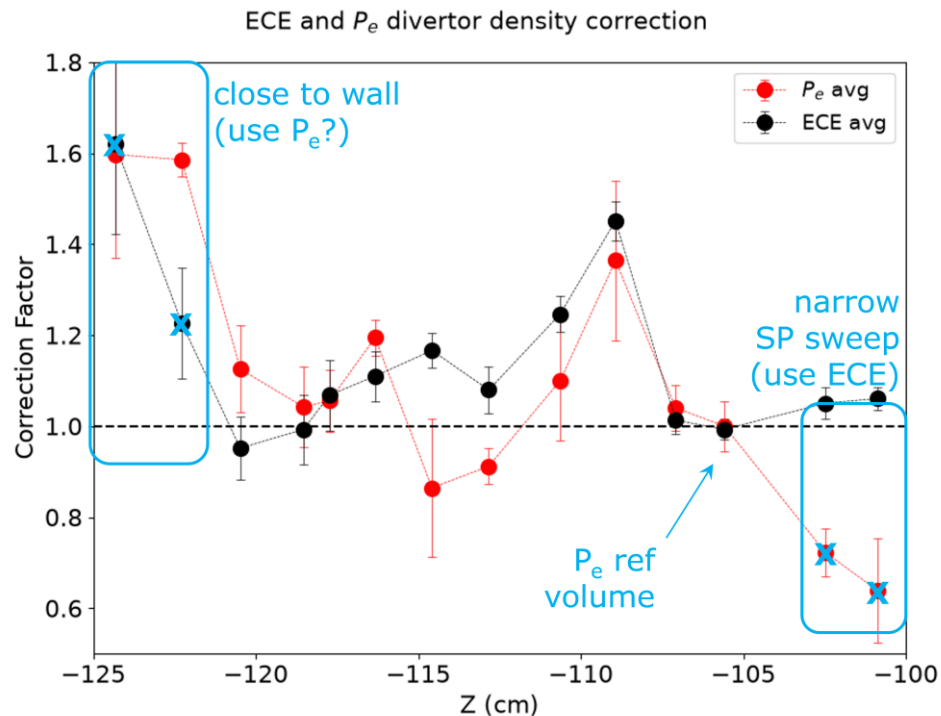
- Radial sweep of strike point, L-mode steady state. Each volume sees varying $\Psi(t)$.
- Corrections relative to a reference volume



Calibration of Divertor Density – ECE and P_e checks

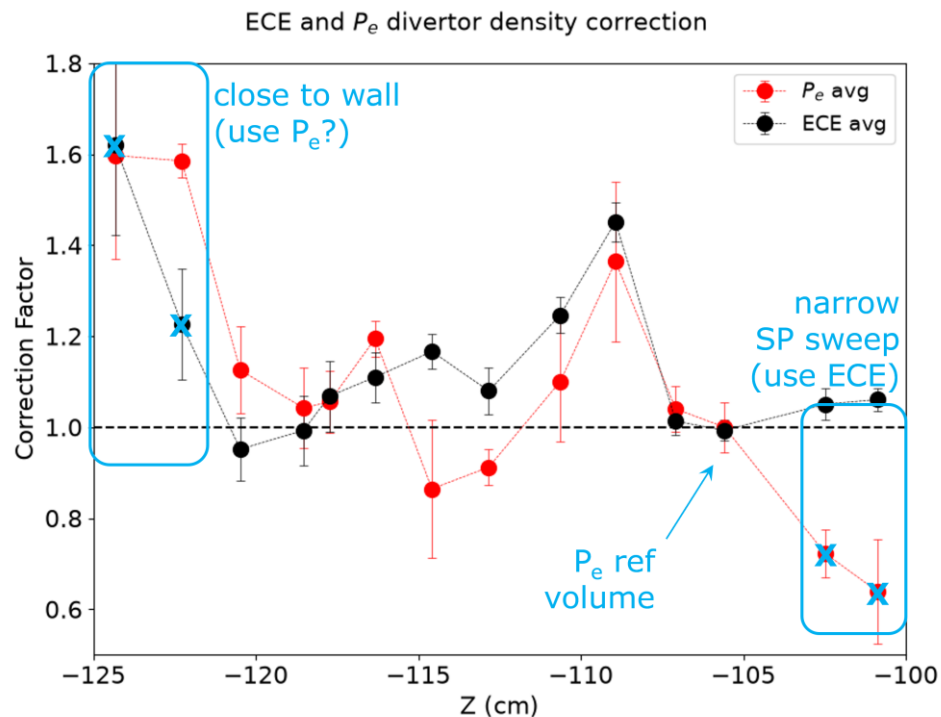
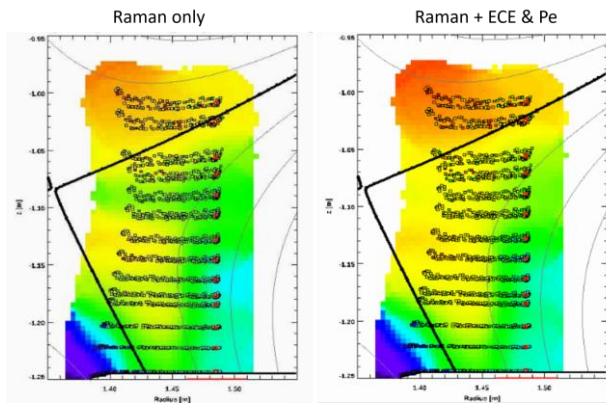
- Independent ECE and P_e methods **complement each other**

- agreement within ~10% in most locations
- Can use P_e near wall and ECE in top-most volumes



Calibration of Divertor Density – ECE and P_e checks

- Independent ECE and P_e methods **complement each other**
 - agreement within ~10% in most locations
 - Can use P_e near wall and ECE in top-most volumes
 - To be implemented in new data for smoother profiles

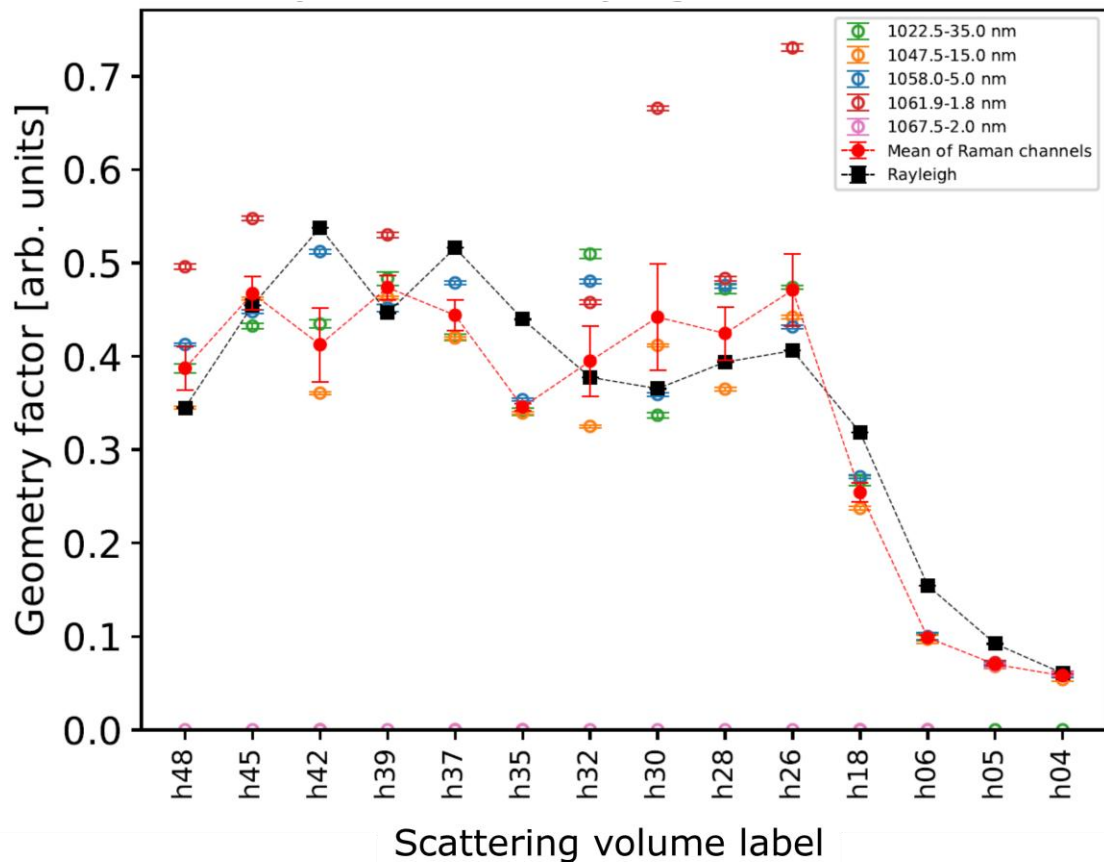


Conclusion & Further Development

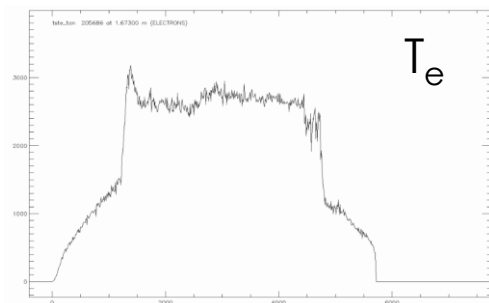
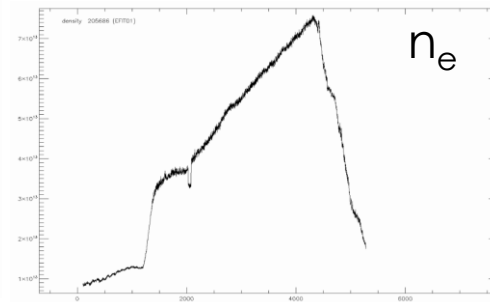
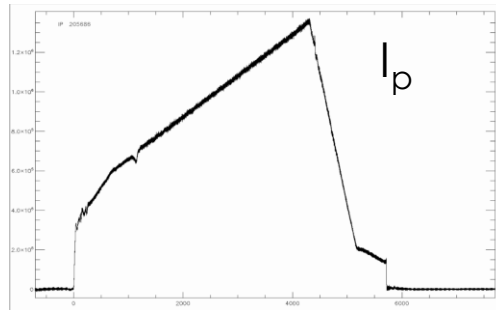
- Raman and Rayleigh scattering used to calibrate DIII-D TS for n_e
- Raman underestimates sensitivity: systematic error or adjust γ
Where both are available, Raman is not clearly better than Rayleigh
- **ECE cutoff used to refine Rayleigh calibrations / n_e profiles**
in plasma core & edge beam paths
- **Divertor regions use adjusted- γ Raman; ECE and P-balance** used to cross-check results, combining the two seems to work well
- Calibrating diagnostics in multiple ways – **understand discrepancies**
 - point-to-point and spectral channel-to-channel variation
 - consistency between techniques
 - improve ECE and P -balance correction methods
- **Calibration process improvements:** whole system pulsed calibration, measure Rayleigh cross-filter bleed-through

THANK YOU

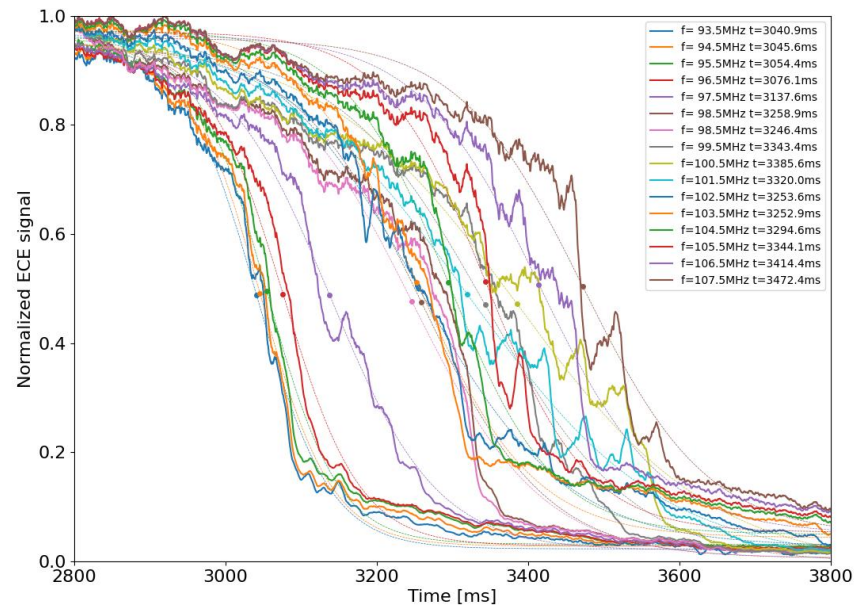
Comparison of Raman spectral channels



ECE cutoff



ECE signals for shot 205686



Divertor strike point sweep

