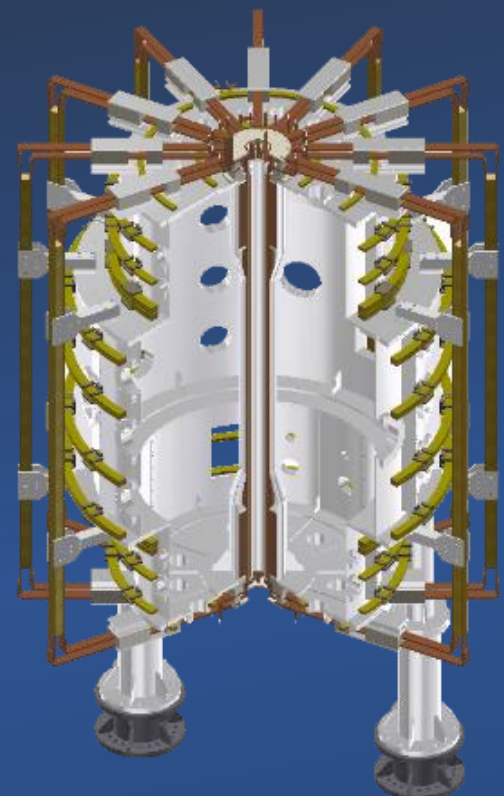




Systemic error analysis of Thomson scattering system on VEST with rotational Raman calibration

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1. Introduction

1.1. Rayleigh & Raman scattering¹

- Rayleigh scattering(RS) is elastic scattering of EM wave by particles(bounded electrons).
 - Rayleigh scattered light has the same wavelength as the incident laser.
- Raman scattering is inelastic scattering which undergo a rotational or vibrational transition.
 - Specific wavelength shift is occurred; Anti-Stokes rotational Raman scattering(RRS) is suitable for Thomson scattering(TS) system calibration.

1.2. Calibration factor¹⁻⁴

- Common geometry factor → Calibration experiment result

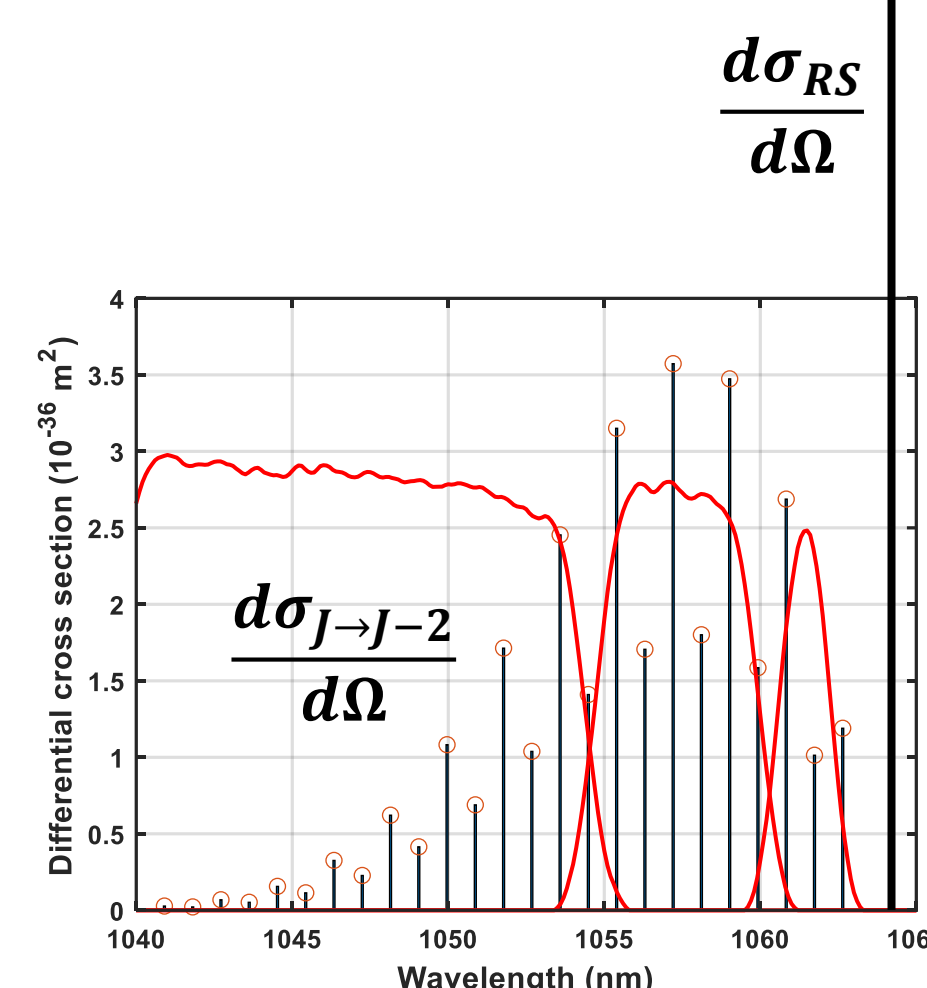
$$V_i^{RRS}(t) = E_L(t) \frac{\lambda_0}{hc} \cdot \eta \cdot \Delta L \cdot \Delta \Omega \cdot T \cdot n_{N_2} \sum_j \left(\frac{n_j}{n_{N_2}} \frac{d\sigma_{j \rightarrow j-2}}{d\Omega} \cdot R_i(\lambda_{j \rightarrow j-2}) \right)$$

$$V_1^{RS}(t) = E_L(t) \frac{\lambda_0}{hc} \cdot \eta \cdot \Delta L \cdot \Delta \Omega \cdot T \cdot n_{N_2} \frac{d\sigma_{RS}}{d\Omega} \cdot R_1(\lambda_i)$$

$$V_i^{TS}(t) = E_L(t) \frac{\lambda_0}{hc} \cdot \eta \cdot \Delta L \cdot \Delta \Omega \cdot T \cdot n_e \frac{d\sigma_{TS}}{d\Omega} \cdot \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$$

$$= \frac{V_i^{RRS}(t)}{n_{N_2}} \cdot \frac{\frac{d\sigma_{TS}}{d\Omega}}{\sum_j \left(\frac{n_j}{n_{N_2}} \frac{d\sigma_{j \rightarrow j-2}}{d\Omega} \cdot R_i(\lambda_{j \rightarrow j-2}) \right)} \cdot n_e \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$$

$$= \frac{V_i^{RS}(t)}{n_{N_2}} \cdot \frac{\frac{d\sigma_{TS}}{d\Omega}}{\frac{d\sigma_{RS}}{d\Omega} \cdot R_1(\lambda_i)} \cdot n_e \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$$



- Calibration factor C

$$V_i^{TS}(t) = C \times n_e \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$$

$$C = E_L(t) \frac{\lambda_0}{hc} \cdot \eta \cdot \Delta L \cdot \Delta \Omega \cdot T \cdot \frac{d\sigma_{TS}}{d\Omega} \rightarrow C_{RRS,i} = \frac{V_i^{RRS}(t)}{n_{N_2}} \cdot \frac{\frac{d\sigma_{TS}}{d\Omega}}{\sum_j \left(\frac{n_j}{n_{N_2}} \frac{d\sigma_{j \rightarrow j-2}}{d\Omega} \cdot R_i(\lambda_{j \rightarrow j-2}) \right)}, C_{RS} = \frac{V_1^{RS}(t)}{n_{N_2}} \cdot \frac{\frac{d\sigma_{TS}}{d\Omega}}{\frac{d\sigma_{RS}}{d\Omega} \cdot R_1(\lambda_i)}$$

- Necessary to measure the absolute electron density from the TS signals.

2. Experimental setup

2.1. VEST Thomson scattering system

- Versatile Experiment Spherical Torus (VEST)
 - The first and the only ST in Korea
 - Specification

	Value
Toroidal B Field (T)	0.05 ~ 0.2
Main Chamber Radius (m)	0.8
Major Radius R (m)	0.45
Minor Radius a (m)	0.33
Aspect Ratio	> 1.3
Plasma Current (kA)	< 170

- Target VEST plasma n_e, T_e

	Unit	Low limit	Typical	High limit
n_e	m^{-3}	2×10^{18}	$1 - 3 \times 10^{19}$	1×10^{20}
T_e	eV	5	50 ~ 150	300

2.2. Relative calibration

- Spectral responsivity of the polychromator is necessary to measure the electron temperature.
- Tungsten halogen lamp + monochromator
 - The grating is rotated for scanning.
 - Wavelength resolution: ~ 0.5 nm

- Thomson scattering diagnostic system⁵

- Time resolution: 1 ms, 10 temporal points
- Measuring points: 5 spatial points per single discharge
 - R = 0.255, 0.31, 0.37, 0.425, 0.475 m
- Polychromator system
 - 5 EA, 5 filters at each polychromator
 - Transmission: > 90%
 - Optical density @ 1064 nm: 5-6

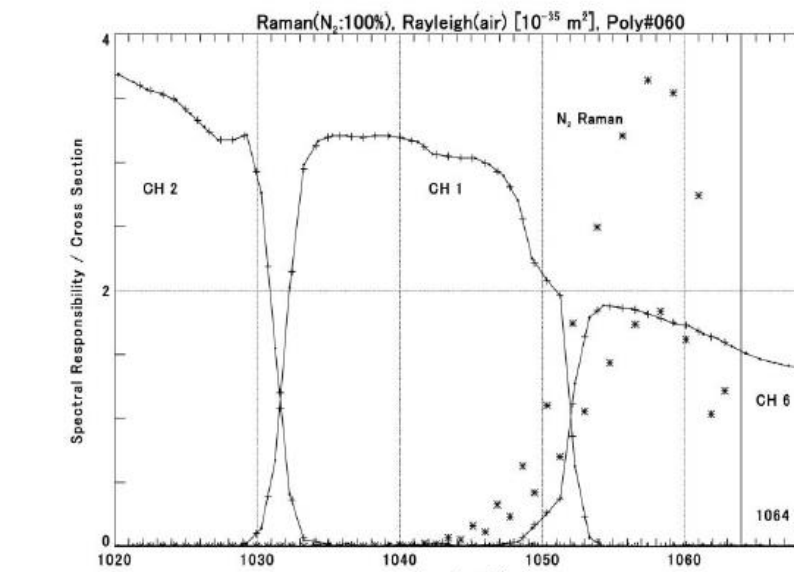
2.3. RRS calibration experiment

- Pressure gauge: Piezo/Pirani combined type
 - Measurement range: 900 – 5e-4 torr
- Accuracy
 - 900 – 30 torr: 0.3% full scale
 - 30 – 5e-4 torr: 10%
- Experiment pressure
 - 23.5, 32.9, 49.8, 71.3, 85.3 torr
- 50 shots at each pressure

3. Motivation & Objective

3.1. Pros and cons of RRS calibration on VEST⁶

- Rayleigh scattering has the same wavelength as the incident laser.
 - Difficult to distinguish scattered signal from the stray light signal due to the small size of VEST chamber
 - Additional system adjustment such as laser wavelength channel and saturation suppression are required.
 - RRS calibration is expected to provide more accurate calibration factors compared to RS on VEST.
- Cons of RRS calibration
 - Sensitive to accuracy of the position and shape of the spectral responsivity of polychromator
 - Since overlap of the rotational Raman transition and the spectral responsivity of filter 1 is small, RRS calibration is expected to provide less accurate results on LHD.⁶
 - On the other hand, since the temperature of the target plasma on VEST is relatively low, RRS signals can be obtained from three filters.



3.2. Objectives

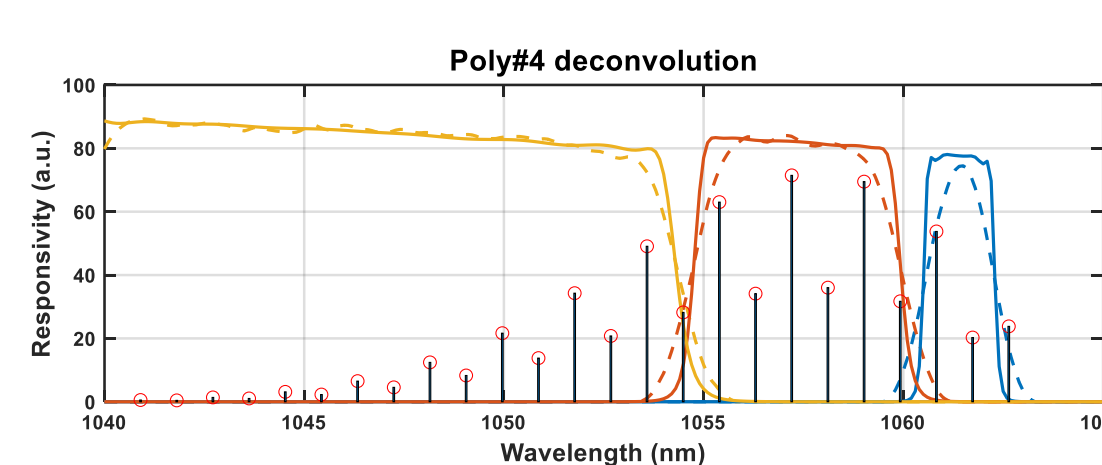
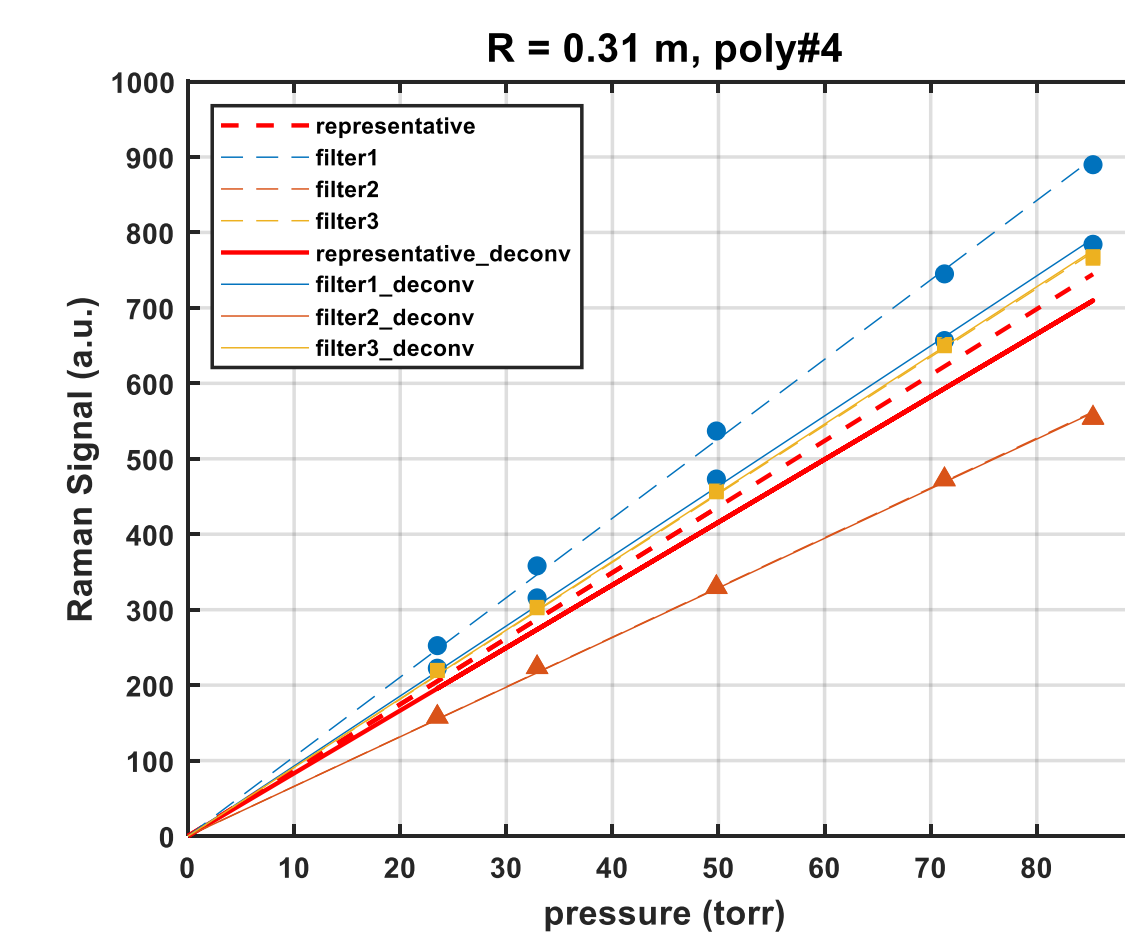
- The relative responsivity is corrected by analyzing the systemic errors appeared in the RRS calibration.
- The calibration factor and its uncertainty are obtained by corrected relative responsivity to measure the electron density and temperature.

4. Deconvolution

4.1. Deconvolution⁷

- The monochromator which is used to scan the spectral responsivity of the polychromator has the wavelength resolution limit.(~0.5 nm)
- Distortion due to instrumental broadening can be the cause of the error.
 - Especially, filter 1 has the narrowest bandwidth of 1.8 nm.
 - Other filters can also introduce errors at the edge of the spectral responsivity.

- Deconvolution of the spectral responsivity reduces the error between the calibration factors of filter 1-3.

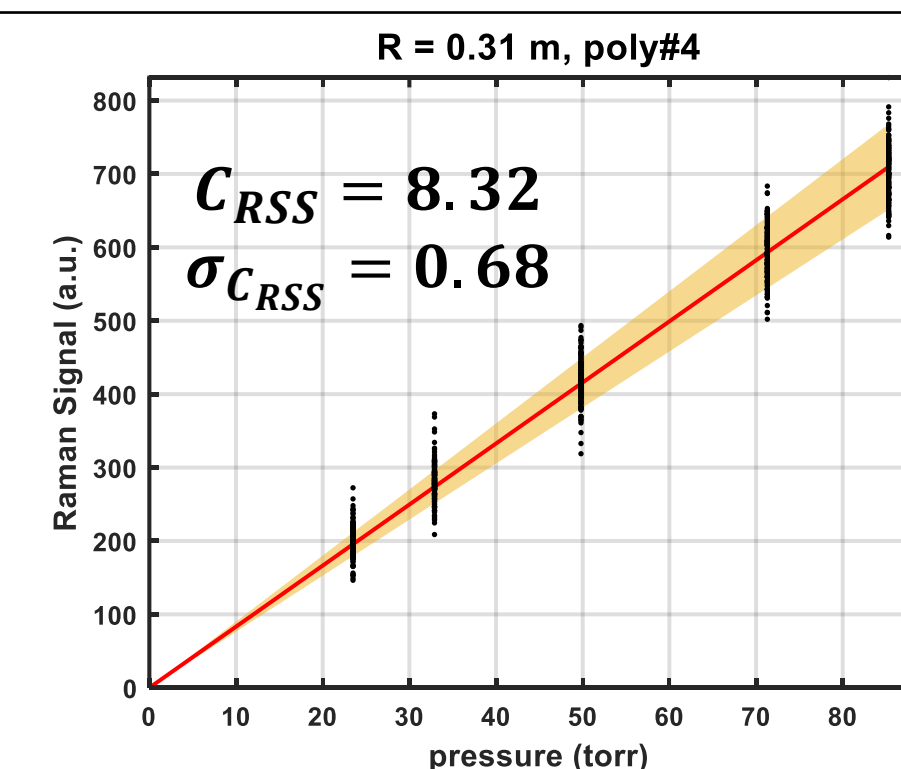
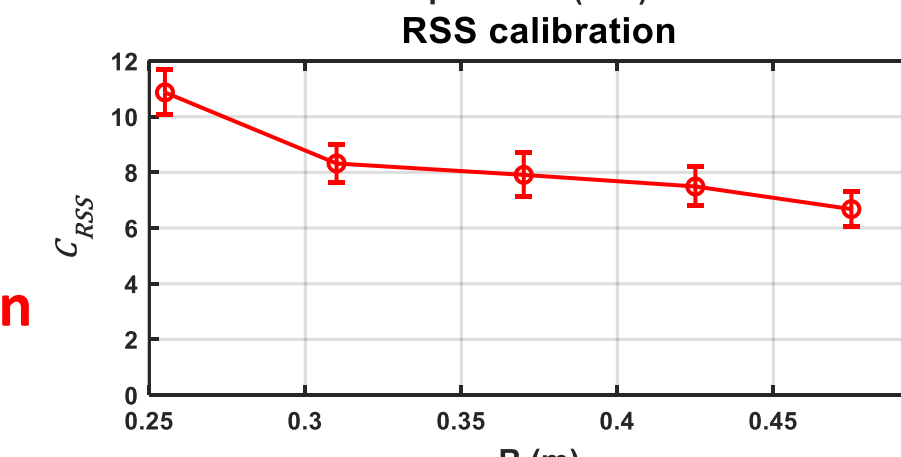


R^2	Poly#1	Poly#2	Poly#3	Poly#4	Poly#5
Before	0.93	0.92	0.84	0.82	0.82
After	0.96	0.92	0.93	0.87	0.89

6. T_e, n_e measurement

6.1. T_e, n_e estimation method

- Minimum Chi-squared method is used.
- $\chi^2 = \sum_i \frac{(V_i - D_i(T_e, n_e))^2}{\sigma_i^2}$
 - V_i : TS measured signal for i-th filter
 - $D_i(T_e, n_e) = C_{RSS} n_e \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$: Expected TS signal
 - $\sigma_i = \sqrt{(\sigma_{shot}^2 + \sigma_{background}^2 + \sigma_D^2)}$: Standard deviation
 - $\sigma_D = \sigma_{C_{RSS}} \cdot n_e \int R_i(\lambda) S(\lambda, T_e, \theta) d\lambda$
- Find T_e, n_e that minimizes the χ^2 .
- For this measurement, $C_{RSS}, \sigma_{C_{RSS}}$ obtained through RRS calibration are required.



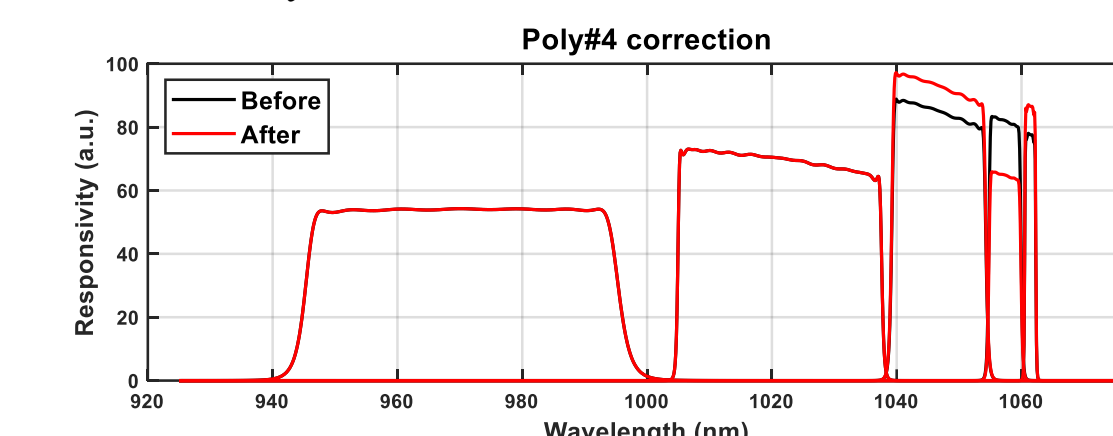
7. Result

- 1 kHz time evolution of radial profiles during 306 – 315 ms is successfully measured.

5. Relative calibration correction

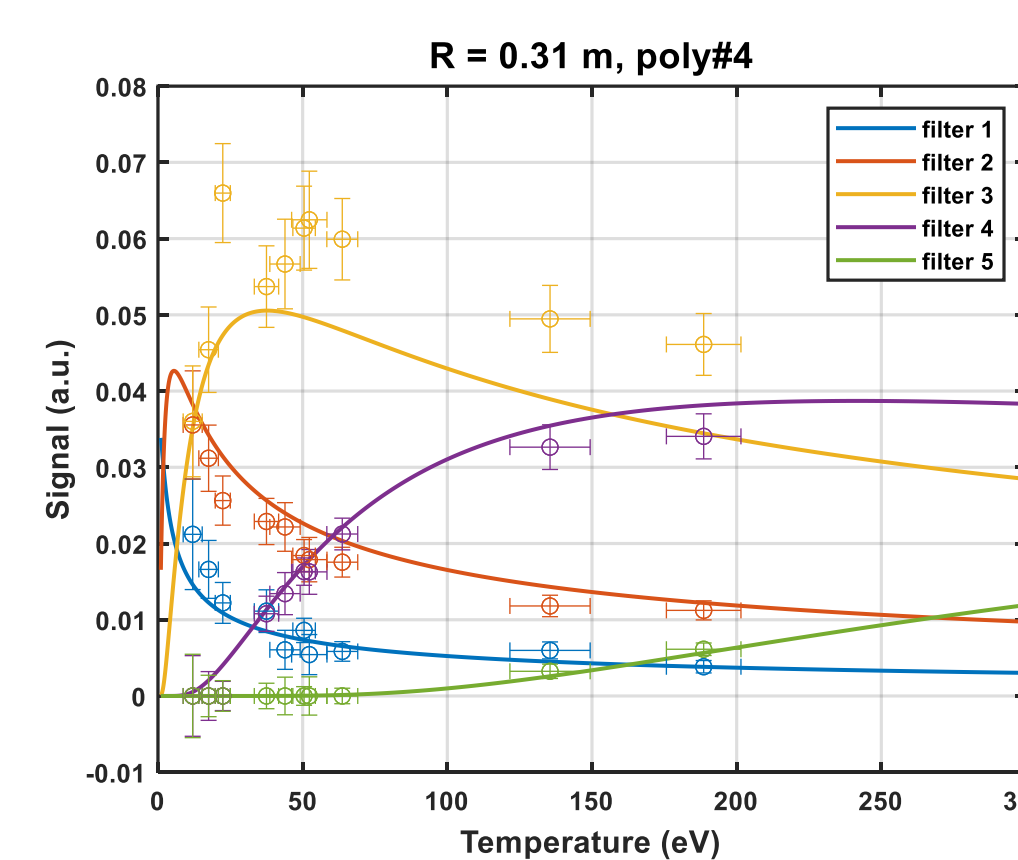
5.1. Relative calibration correction²

- After deconvolution, $C_{RRS,1-3}$ are still slightly different from each other.
 - The relative calibration measurement has a different light source geometry from the RRS or TS measurement.
 - APD gain is affected by temperature.
 - Tungsten lamp spectrum inaccuracy, etc.
- The correction factor F_i is obtained through the $C_{RRS,1-3}$.
 - $C_{RRS,i} \propto \frac{1}{R_i} \rightarrow \frac{C_{RRS,i}}{C_{RRS}} \times R_i = F_i \times R_i = R'_i$
 - $C'_{RRS,i} = C_{RRS,i} \times \frac{1}{F_i} = C_{RRS}$



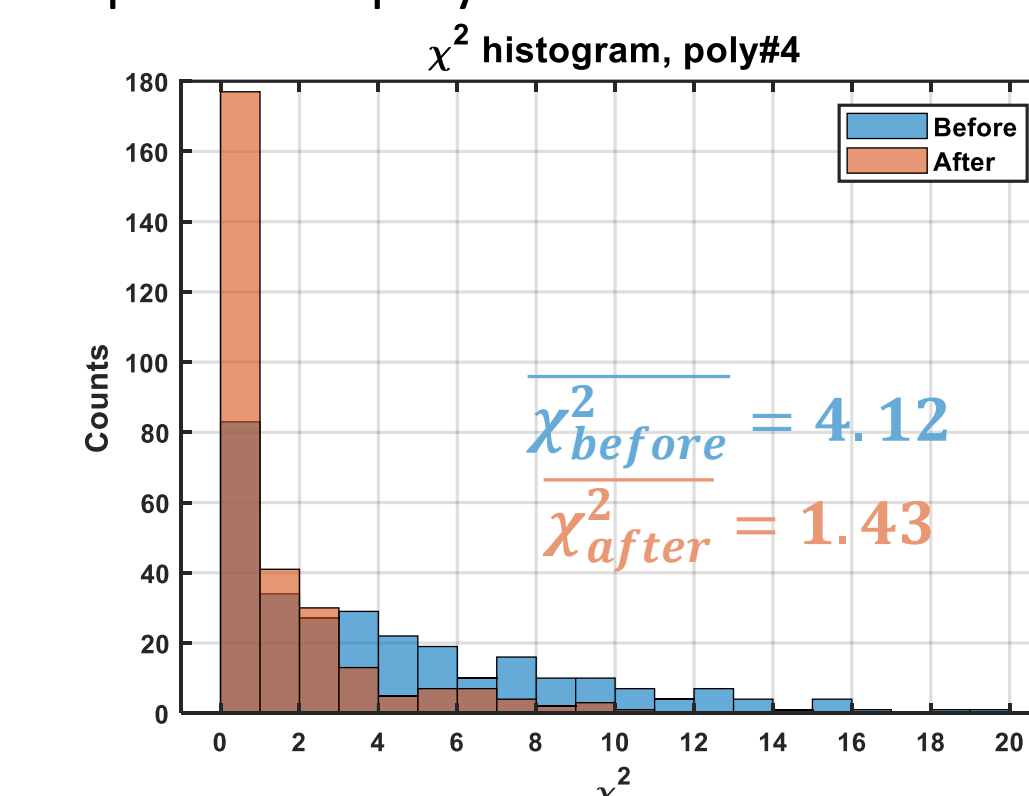
5.2. Agreement with TS measurement

- Corrected relative responsivity shows better agreement with TS measurements than before the correction.



- Left figures show the normalized signals as a function of temperature for Poly#4 at Shot#37444.
- The solid lines are the expected TS signals, calculated based on the TS spectra by Matoba.⁸

- The figure below shows the chi-squared distribution for 290 measurement points for poly#4.



χ^2	Poly#1	Poly#2	Poly#3	Poly#4	Poly#5
Before	0.61	1.29	1.26	4.12	4.00
After	0.72	0.57	0.93	1.43	1.85

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