Reducing Uncertainties of Thomson Scattering Measurements with Multi-Passband Polychromator Optical Filters

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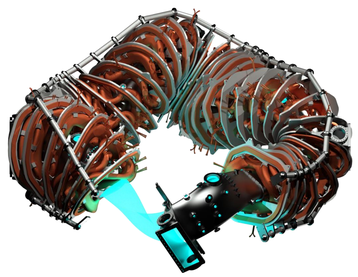
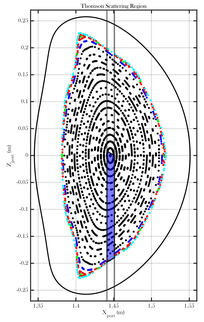
Motivation

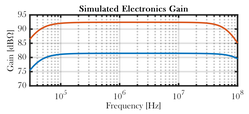
- Reduce uncertainty of existing diagnostic without increasing spectral channel density
- Minimize spectral channel density requirements
- Some third thing

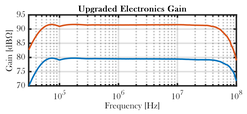
Improved Thomson Scattering on HSX



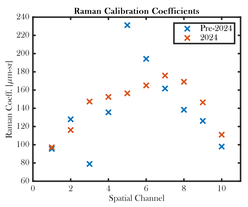


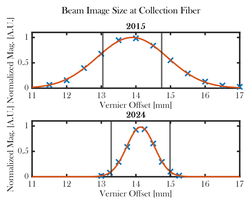
- Current source: Litron TRL850
  - 1064 nm, 850 mJ, 10 Hz [1]
- Future source: InnoLas Spitlight EVO-IV
  - 1064 nm, 900 mJ, 0.4/2 kHz
- Ten spatial channels covering one half radius
- Optimized for detection up to 5 keV
- High-bandwidth, low-noise, AC-coupled detection electronics designed in-house [2]





- Recent Improvements:
  - Shortened beam path by 24%
  - Reduced beam path optics from five to just one
  - Removed stray light reduction baffled beam tube
    - Focus laser to 1/3 previous beam waist
  - Textured broadband anti-reflective window
  - Scattered energy increased 168%
  - New spectral calibration method





Error Analysis

- A χ^2 minimization routine is used to determine T_e and n_e from the measured signal

$$\chi^2 = \sum_{j=1}^{M} \frac{\left(N_j - N_{m,j}(T_e, n_e)\right)^2}{{\sigma_j}^2} \quad (2)$$

- Model number of photons [3]

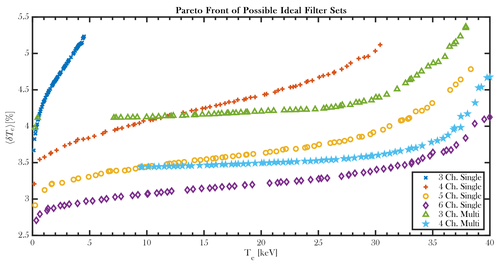
$$N_{m,j} = n_e \Omega_s L \frac{E_{in}\lambda_{in}}{hc} \int_{\varepsilon_{j,1}}^{\varepsilon_{j,2}} \frac{d^2\sigma_p}{d\Omega_s d\varepsilon} T_{opt}(\varepsilon) T_{filt,j}(\varepsilon) \quad (1)$$

- Error analysis of Equation (2) leads to a first-order estimate for the variance in T_e for a detection system as

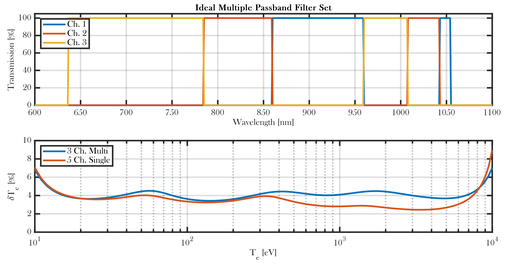
$${\sigma_{T_e}}^2 = \frac{\Sigma\left(\frac{N_{m,j}}{\sigma_j}\right)^2}{\Sigma\left(\frac{\partial N_{m,j}}{\partial T_e}\frac{1}{\sigma_j}\right)^2 * \Sigma\left(\frac{N_{m,j}}{\sigma_j}\right)^2 - \left[\Sigma\left(\frac{\partial N_{m,j}}{\partial T_e} * \frac{N_{m,j}}{{\sigma_j}^2}\right)\right]^2} \quad (3)$$

Filter Set Optimization

- A controlled, elitist genetic algorithm was developed to optimize filter sets for use in polychromator based systems
- FOM $\delta T_e = {}^{\sigma_{T_e}}/_{T_e}$
- Vary passbands of $T_{filt,j}$
- Available objectives:
  - Maximize T_e bandwidth, $\delta T_e(T_e) \leq 10\%$
  - Minimize average error, $\left\langle {}^{\sigma_{T_e}}/_{T_e} \right\rangle$
  - Minimize error deviation, $\sigma_{\delta T_e}$



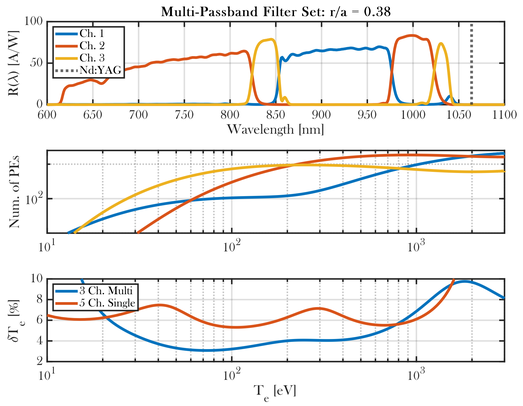
- Three channel multi-passband vs. five channel single passband



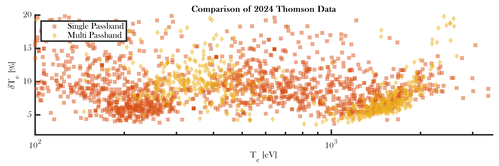
HSX Multi-Bandpass Filter Set

- Optimized filter set designed and manufactured by Alluxa
- Installed on two spatial channels, ${}^{r}/_{a}$ = 0.10 & 0.38
- Calculated $\delta T_e(T_e)$ for ${}^{r}/_{a}$ = 0.10
  - 3-2-1 arrangement
  - 1064 nm notch filter, 44 nm width

- Calculated $\delta T_e(T_e)$ for ${}^{r}/_{a}$ = 0.38
  - 1-3-2 arrangement
  - 1050 nm low-pass filter

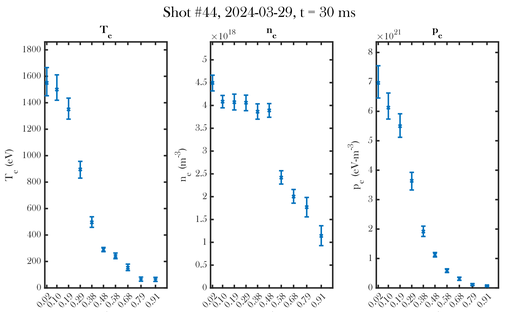


- Three channels of multi-bandpass filters performs equivalently to existing five channel filter set on HSX for range of T_e
- Exceptional performance at high T_e for only three spectral channels

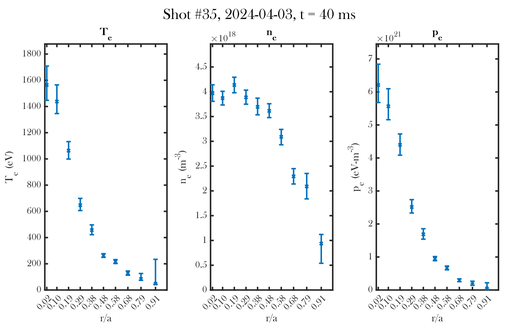


Results

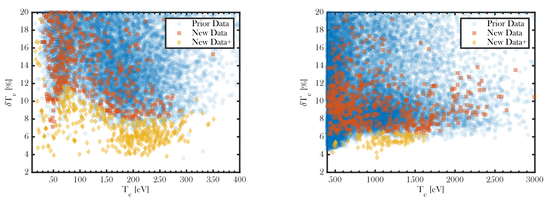
- Only one discharge needed for a reliable profile
- He plasma in 1 T, QHS configuration



- H plasma in 1 T, QHS configuration



- Compare pre-upgrade Thomson measurements from 2014 to post-upgrade measurements
- Lower uncertainty for 27% of new data than previously achievable



References

- [1] K. Zhai et al, Rev. Sci. Instrum., *75*, 3900-3902 (2004)
- [2] W. R. Goodman et al, Rev. Sci. Instrum, **93**, 093518 (2022)
- [3] O. Naito et al, Phys. Fluids B, *5*, 4256-4258 (1993)

Acknowledgements

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