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Upgrade to resolution of TCV Thomson scattering diagnostic system and performance analysis

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Improving spatial and spectral resolution of TCV Thomson scattering

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Abstract: The recently completed MST2 upgrade to the Thomson scattering (TS) system on the TCV Tokamak at the Swiss Plasma Center aims to provide an enhanced spatial and spectral resolution while maintaining the high level of diagnostic flexibility for the study of TCV plasmas. The MST2 (Medium Sized Tokamak) is a work program within the Eurofusion ITER physics department, aimed at exploiting Europe′s medium sized tokamak programs for a better understanding of ITER physics. This upgrade to the TCV Thomson scattering system involved the installation of 40 new compact 5-channel spectrometers and modifications to the diagnostics fiber optic design. The complete redesign of the fiber optic backplane incorporates fewer larger diameter fibers, allowing for a higher resolution in both the core and edge of TCV plasmas along the laser line, with a slight decrease in the signal to noise ratio of Thomson measurements.

The 40 new spectrometers added to the system are designed to cover the full range of temperatures expected in TCV, able to measure electron temperatures (T_e) with high precision between (6eV and 20keV). The design of these compact spectrometers stems originally from the design utilized in the MAST TS system, implemented on TCV with the overall layout of optical fibers and spectrometers to achieve a spatial resolution of approximately 1% of the minor radius. These spectrometers also enhance the diagnostic spectral resolution, especially within the plasma edge, due to the low T_e measurement capabilities. These additional spectrometers allow for a much greater diagnostic flexibility, allowing for quality full Thomson profiles in 75% of TCV plasma configurations.

Keywords: Plasma diagnostics - charged-particle spectroscopy, Nuclear instruments and methods for hot plasma diagnostics, Spectrometers, Optics

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1 Introduction

Thomson scattering (TS) is deemed an essential diagnostic system on TCV, providing absolutely calibrated spatial profiles of electron temperature and density within the tokamak plasma. The TCV tokamak is a medium sized tokamak located at the Swiss Plasma Center as part of École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland. In order for the TCV TS system to continue to provide the high quality diagnostic data required in future plasma experiments, a major upgrade has been performed. This upgrade was designed to substantially improve the spatial resolution in the plasma edge. The primary goal was to achieve a spatial resolution of 1% of the minor radius, i.e. 2.5 mm, in the outer magnetic mid-plane in the high confinement mode (H−mode) pedestal region. In order to achieve this a lot of changes were made to the system, such as; the addition of 40 new spectrometers, a complete redesign of the fiber optic system, running of all new optical fibers, modification of existing electronics, and change in the data acquisition system.

In order to understand the full extent of the upgrade, it is important to first look at the previous iteration of the diagnostic. This design consisted of 47 spectrometers, with only 12 of these spectrometers designed to measure within the plasma edge, able to dependably measure at electron temperature levels down to approximately 6eV. This is an incoherent Thomson scattering system where the measured light emission is due to laser scattering off of the free electrons in the plasma. The light is emitted as a spectrum that is broadened from the laser emission wavelength as a function of electron temperature. Also, the spectrum is increasingly blue shifted, or skewed to lower wavelength as the electron temperature increases. In incoherent Thomson scattering, the intensity of the collected light increases linearly with the electron density. Electron temperature however is calculated via the ratios of scattered signal in at least two distinct wavelength bands, defined in the spectrometer [1]. On TCV the scattered light is collected by an optical lens system with a magnification of 4, consisting of three identical sets of collection optics located in three vertically aligned ports on TCV. These three collection cells image the fiber optics of each distinct spectrometer onto the laser line within the plasma, allowing for each spectrometer to measure T_e and n_e within distinct spatial positions within the Tokamak. The three Nd:YAG Thomson lasers on

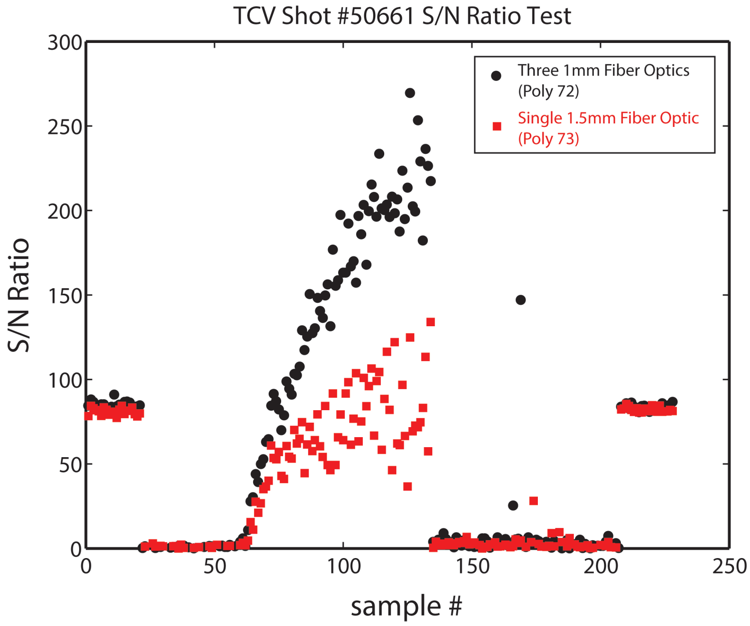

Figure 1. Signal to Noise Ratio test between existing plasma edge fiber optic and the new single 1.5mm diameter fiber for the upgrades TS system.

TCV are injected into the machine at a major radius position of R = 0.9m, input at the bottom of the machine with the beam dump present at the top in a corresponding port.

The previous systems fiber optic design allowed for a good signal to noise ratio in each of the spectrometers but was not without some flaws that prohibited the ability to obtain the level of spatial resolution desired for future research on TCV. The following chapters of this paper covering the EUROfusion work program MST2-13: *Improving spatial and spectral resolution of TCV TS*, will go into the details of the major optical components of the upgrade (fiber optics, spectrometer optics, fiber support) and a performance analysis in order to validate the upgrade. Beyond the content in this paper, a major amount of work was done on the development of the Thomson scattering spectrometer electronics and data acquisition systems, these topics will not be discussed in detail here but shall be published in a future paper by P. Blanchard [3].

2 Redesign of fiber optics

In order to achieve the targeted spatial resolution of 1% of the minor radius in the pedestal region, it was evident that a complete redesign of the fiber optics was necessary. The previous system utilized bundles of three or four 1mm diameter fibers for the edge and core respectively. These fiber bundles were set in a support system / backplane that allowed to a high level of flexibility in the spatial location of each fiber bundle i.e. spectrometer. While the previous fiber support and fibers allowed for a good signal to noise ratio and good flexibility, it created gaps in the observational volume that limited the achievable spatial resolution.

In order to eliminate these gaps in the TS collection volume and have the proposed spatial resolutions, two fiber possibilities were investigated, each with their own set of advantages. The two possibilities explored were the use of a fiber bundle of 210μm diameter fibers in close hexagonal packing, or a single / double 1.5mm pure silica fiber (single fiber for the edge spectrometers). In order to make this decision and design the new fiber support, tests were performed with a single 1.5mm fiber and adapted core fibers, where two of the four fibers were blocked within the previous fiber system. In these tests it was found that going from three fibers of a diameter of 1mm to a single fiber with a 1.5 mm diameter at the edge and from four fibers of 1mm to two fibers of 1.5mm in the core that the desired spatial resolution can be achieved but at the cost of a reduction in the measured signal to noise ratio. With the current lasers with an injected energy of 1.2J the spectrometers can measure down to a electron temperature (T_e) of 10eV with a single 1.5mm fiber down to a electron density of $1 \times 10^{19} m^{-3}$ and the core spectrometers with two fibers down to a density of $5 \times 10^{18} m^{-3}$ at a T_e = 20eV.

Considering only the optical changes, this design would result in a reduction in the lower density limit by $1/2$ for the edge and $1/3$ for the core, as seen in the data in Figure 1. If the completed upgraded TS system is considered, the signal to noise ratio is actually near the same level as it was pre upgrade, even with the reduced fiber acceptance area. This is most likely explained by the combination of several other factors that have changed between the pre and post upgrade systems. The new fibers having a wider diameter results in capturing a wide observational volume, allowing for better collection of the tail components of the laser pulse. Coupling this with the slight increase in collected light through the removal of polarizers in front of the fibers, the application of an anti reflective fiber coating, and the lasers operating at approximately 15% higher energies than previously, the signal to noise ratio remains fairly consistent post upgrade in experiments.

After these tests and considering the pros and cons of the two possible fiber considerations, it was chosen to go with large fibers of 1.5mm diameter. This decision was based on the good results in the tests performed, the fact they are easier to handle, an anti-reflecting coating is possible, long time experience at SPC handling fibers of this dimension, and nearly half the cost of a close hexagonally packed option. These positives outweigh the slight negatives of some vignetting, primarily in the large refurbished spectrometers and being twice as susceptible to signal reduction due to laser / fiber misalignment, requiring more stringent alignment protocol for laser positioning and correction.

With the fiber design and dimensions defined, the fiber back plane was then designed to accommodate the fibers for the existing 47 installed spectrometers plus the additional 42 to be installed, eliminating all previous view gaps. The design is to have a 12mm resolution along the laser line in the core and 6mm at the edge, with spectrometers having a double fiber or single fiber respectively. This new fiber back plane and new fibers were installed for each of the three ports and for each installed spectrometer, the design for the fiber backplane can be seen in Figure 2.

The design must not only incorporate the existing $f/\# = 2.2$ collection optics in each of the three vertically aligned collection ports but also consider the fiber dimensions and the imaging of each fiber onto the laser line. Once the new fiber backplane was manufactured and installed, all of the 89 fibers were carefully installed into the support each in a defined position for the corresponding spectrometer. For each of the fiber supports there is the possibility for slight adjustments in 3−dimensions, which was necessary for the alignments of each fiber image onto the correct position onto the laser line. To achieve this alignment each fiber was backlit onto a measurement bar following the precise laser line position within the tokamak. This allowed for adjusting the alignments to minimize any misalignment issues of each fiber support and ensure

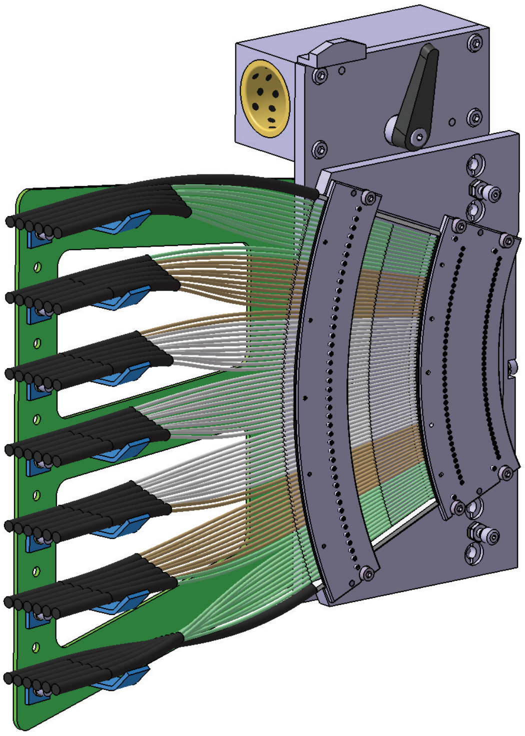

Figure 2. Design of the new TCV Thomson scattering fiber support / backplane as installed on all three TS view ports with all new fiber optics.

that the design criteria were properly met in manufacture. In the alignment process the design was validated and it was observed that all gaps between measurement volumes were indeed removed.

3 New TCV spectrometer optical design

The compact spectrometer design used for this upgrade is based on a design that originated at the Culham Centre for Fusion Energy (CCFE) for the MAST tokamak TS system [2]. The new spectrometers are designed with five spectral channels, allowing them to cover a range in T_e from 6eV to 20keV. The design incorporates APD detectors manufactured by Excelitas and interference filters from Chroma Optics, whose specifications can be seen in Table 1.

The spectral design of these 40 spectrometers allows for the kind of flexibility that TCV requires, suitable for both edge and core plasma conditions. The optical design of these spectrometers can

Table 1. Specifications for new compact spectrometer filters, CWL = central wavelength and BW = Bandwidth.

Filter	1	2	3	4	5	T_e Range
CWL [nm]	1059	1046	1016	946	836	6eV to 20keV
BW [nm]	6	17	34	85	128	

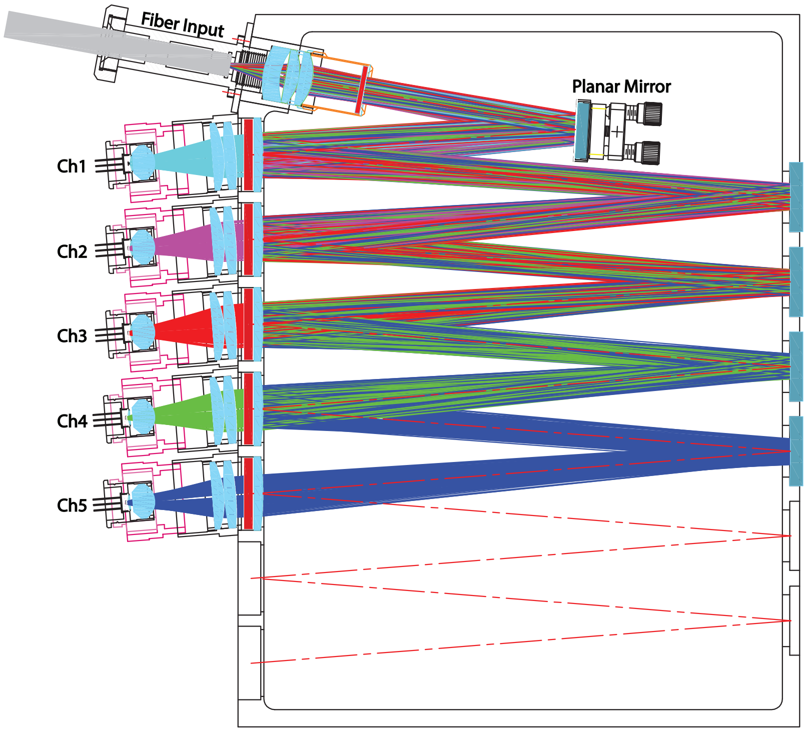

Figure 3. Optical design of the new 5-channel compact spectrometers with ray tracing of collected TS light.

be seen in Figure 3. In this design the collected Thomson scattered light is brought into the spectrometer via the associated fiber bundle, where it reflects off a planar mirror and continues through the spectrometer, interacting with each of the interference filters, where the appropriate light is transmitted through the filter and focused onto the associated APD detector.

Maintaining a high level flexibility in the spectrometer design is important as TCV has a lot of variability in plasma shape and position, resulting a large range of electron temperatures and densities are possible in all TS collection volumes. Through the analysis of plasma positions of 5400 plasma discharges with respect to the possible Thomson view chords we were able to define a final proposal for the fiber and spectrometer positioning for the newly updated system, highlighted in Figure 4. The resulting design provides the following for TCV experiments: All plasma discharges will have good half-profiles, 75% of the plasmas will have good full profiles, and plasmas centered at vertical position (Z) of 0 m will benefit from an enhanced spatial resolution of 1% mid-radius over 12 cm from Z = [-0.216m to -0.338m].

As part of the design and installation process of these 40 new spectrometers and adaption of the old spectrometers to the new system, each individual spectrometer underwent a spectral calibration as well undergoing a temperature compensation process. This process was performed to help ensure consistent and absolutely calibrated operation of each spectrometer within its electronics operational temperature and signal ranges. In order to have an increased level of certainty in diagnostic operations, we have incorporated an LED system within each of the installed TS spectrometers. This system utilizes an experimentally documented LED signal that is reflected into each APD detector within the spectrometer. This signal is acquired both before and after the plasma discharge

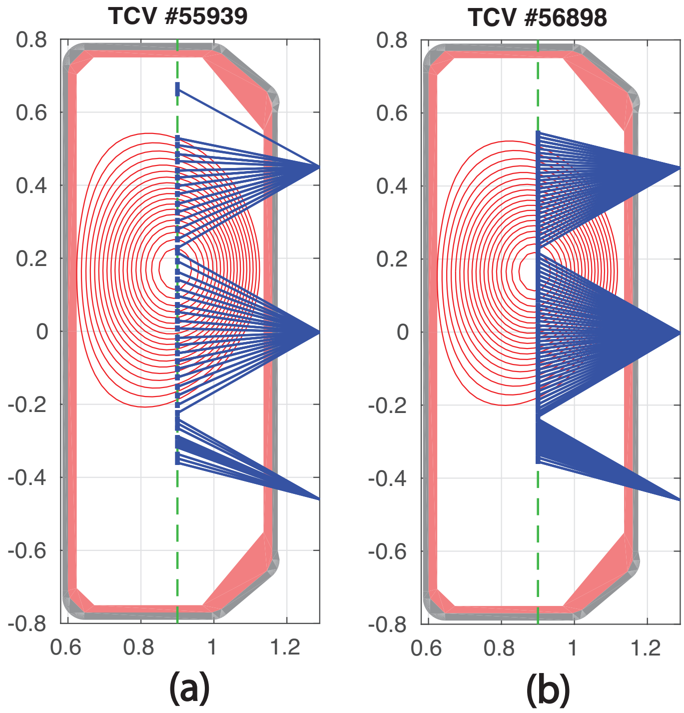

Figure 4. Comparison of TCV TS view chords of (a) before upgrade and (b) after upgrade.

for all spectrometer channels. Using this LED signal we can more effectively monitor the gain settings on the APD′s as well as any degradation or issues with the detector itself, adding an additional level of certainty when validating the diagnostics measurements.

During this upgrade process there were also changes in the spectrometer electronics, data acquisition, and gate integration. These details are also of high importance and make up a substantial part of this large-scale upgrade to the entire Thomson scattering system and is the focus of a sister paper [3].

4 Analysis and performance validation

After the upgrade to the TCV Thomson scattering diagnostic was successfully completed and calibrated the focus shifted to the diagnostics performance with regards to experiments on TCV. This section covers the verification of the systems enhanced performance through the analysis of experimental results over the recent internal and MST1 campaigns in 2017.

The scale of the enhanced spatial coverage the newly upgraded TS system provides is best displayed by comparing plasma discharges with the newly upgraded system in operation to reference discharges performed prior to the upgrade. A good example case is with the TCV discharge of 57040 with a reference discharge of 52934. Looking at the electron density profiles in both of these shots, the upgraded system covers the entire profile with a higher spatial resolution; this is most evident in the pedestal region. Where in discharge 52934 the pedestal region (at Z = -0.3m) is covered by four spectrometers, giving n_e measurements at four spatial positions, while this same region in 57040 is covered by nine spectrometers, as seen in Figure 5.

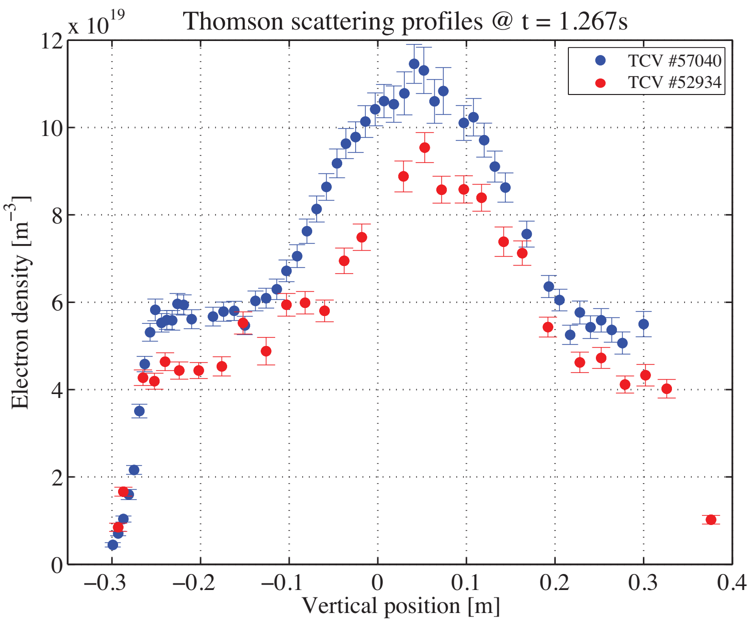

Figure 5. Measured Thomson Profiles for the pre-upgrade (shot #52934) and post-upgrade (shot #57040) system on TCV.

The overall spatial coverage is a great improvement, providing a complete high-resolution profile for the majority of plasma discharges. The spectral resolution of the system is also increased due to all the 40 new spectrometers cover all TCV plasma temperature ranges from the plasma edge to core, covering at T_e range from approximately 6eV to 20keV. Allowing for flexibility in plasma position while maintaining ability to measure the plasma pedestal / edge.

Observing the TS view chord layout as shown in Figure 4, the lower view chords covering the Z-position from [-0.216m to -0.338m] have a 6 mm fiber resolution with no gaps between each fiber view region. This region is tailored for edge and pedestal plasma measurements for Z = 0m and slightly up/down shifted plasmas. In this region the aim is to provide the proposed enhanced spatial resolution of 1% of the minor radius, Figure 7 shows the TCV discharge 57782 TS radial resolution as a function of the plasma minor radius. In order to get the clearest picture that this level of spatial resolution was reached, a half profile was mapped (spatial positions Z < 0 m) from their flux surface coordinates to radial location along the TCV discharges magnetic axis. This results in the High Field Side (HFS) radial resolution profile presented in Figure 7 and verification of the spatial resolution set forth in the upgrade proposal. Along with this, a substantial increase in the the spectral resolution due to the increased T_e measurement range of the newly added spectrometers, highlighted in Figure 6 showing a reduced T_e error, especially where $\rho > 0.6$.

5 Conclusions

With the recent upgrade to the TCV Thomson scattering system being successfully designed, installed, and analyzed it is already evident that it allows for a greater level of both flexibility and quality in its plasma measurements. As well it is highlighted that we have managed to prove the

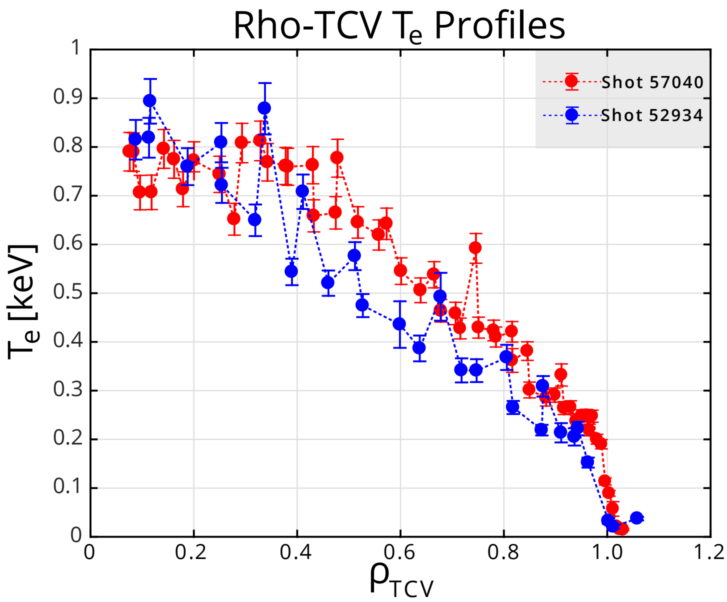

Figure 6. Thomson T_e profile in TCV ρ-coordinates for the pre-upgrade (shot #52934) and post-upgrade (shot #57040), highlighting increased spectral resolution.

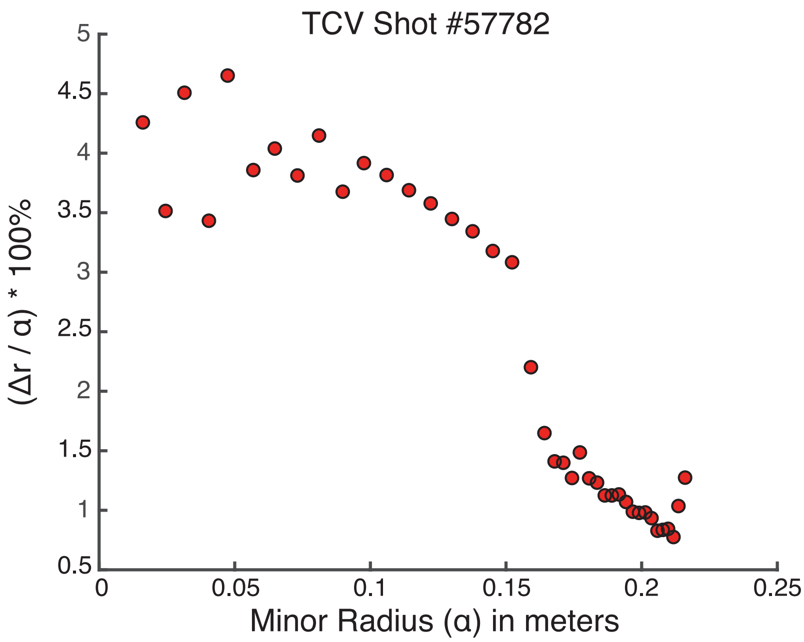

Figure 7. Thomson radial resolution as percentage of the TCV minor radius at T=1.0s for TCV shot #57782. Half TCV Thomson profile mapped from flux coordinates to TCV High Field Side (HFS) radial coordinates.

capability of obtaining a spatial resolution within the H-mode pedestal region of 1% of the minor radius through the use of single fibers of 1.5 mm diameter imaged on the laser line with 6 mm resolution with no gaps between observational volumes.

Thomson scattering can be described as a *work horse* diagnostic in plasma research and is often seen as essential in magnetic confinement fusion studies. The upgrade to the TS system on TCV helps plasma researchers gain a great deal of freedom in preparing discharges, confident that changing a wide range of parameters such as plasma position, density, and temperature should remain with good diagnostic coverage from the TCV Thomson scattering system.

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Acknowledgments

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