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Means of alignment observation and evaluation integrated into plasma diagnostics based on Thomson scattering[a)]

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Concerning plasma diagnostics based on Thomson scattering (TS), precise adjustment and proper alignment is of great importance in order to provide reliable and accurate measurements. Any misalignment could result in incorrectly determined plasma density or prevent the feasibility of this type of diagnostic. Suitable means of alignment monitoring should be integrated into each TS diagnostic system. Variations of commonly used methods are discussed in this article. Correlation of results from alignment control with performed measurements of vibrations on the COMPASS tokamak is presented. Various techniques of optimization of alignment monitoring are shown. The optimal technique, which could be accommodated during construction of TS diagnostic systems on future fusion devices, is proposed.

Keywords: tokamak, Thomson scattering, alignment

I. INTRODUCTION

The Thomson scattering (TS) diagnostic is one of the key diagnostics used on recent and planned for the future tokamaks (e.g. ITER[1]). Its ability to measure electron temperature and density profiles without perturbing the plasma is invaluable. The alignment of the collection optics with respect to the probing laser beam is crucial for reliability of the TS system; if the whole cross-section of the beam is not imaged onto the detector input, the collected light intensity drop is interpreted as a decrease of the electron density, in the worst case the measurement is impossible. The lower signal also increases the statistical error of the temperature measurement. A tool for alignment evaluation is therefore necessary. It helps during installation and preparation of the TS system, during measurements it serves as a feedback tool for either validation of the measurement or even as an input for active alignment correction system.

II. THOMSON SCATTERING DIAGNOSTIC ON COMPASS TOKAMAK

Analyses of the alignment methods presented below are related to the case of the TS system on the COMPASS tokamak[2]. The view of the COMPASS TS covers the upper half of the plasma with two collection optics. The system is optimized for edge plasma physics, therefore the edge region is observed with a high resolution of approx. 1/100 of the plasma radius in 30 spatial points, the core plasma is covered by 24 spatial points. The collected light is analyzed in filter polychromators with avalanche photodiode detectors. The 4 probing lasers, with a repetition rate of 30 Hz each, allow either a 120 Hz repetition rate when synchronized equidistantly, or 4 subsequent measurements with an arbitrary delay.

III. LASER AND OPTICS ALIGNMENT

One method how to check the alignment is observation of a ratio of signals collected on the respective sides from the axis of the collection system. It can be so called "split-fiber" - the bundle of the fibers collecting the light from one spatial point of the TS system is divided into halves along the laser beam propagation direction[2,4]. Any deviation of the signals ratio from unity indicates the laser beam image is not in the middle of the fiber bundle. When light from both split-fiber halves is detected in polychromators and the signals are added, the electron temperature and density can be evaluated in this spatial point as in other spatial points.

Another method of alignment evaluation requires extra fibers mounted on the sides of the regular fiber bundles used for TS light collection - the method can be called "side-fiber", it is used e.g. on NSTX-U[5]. If the laser beam is misaligned, the wings of its profile reach out to the side-fiber and some signal is detected in the alignment fiber. Contrary to the split-fiber, the side-fiber signal is usually not evaluated for electron temperature and density, a single channel detection with a suitable filter is sufficient and easier to implement.

Theoretically, design with e.g. three regions in the fiber bundle could be a variation of the side-fiber method with an advantage of summing all signals for TS evaluation, i.e. without discarding any collected light. But any further splitting of collected light increase the statistical error of its detection, the advantage is questionable. Example of such a fiber bundle arrangement is in FIG. 7c.

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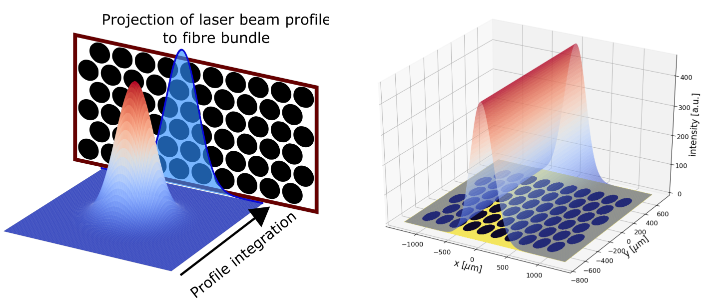
IV. SIMULATION OF SPLIT FIBERS

Split-fiber method plays a key role during the alignment process of Thomson scattering diagnostic. In order to optimize this technique, a simulation of Thomson scattering signal detected by split-fiber bundle was carried out for various arrangements of fibers within the fiber bundle. Profile of the laser beam that is used for the TS diagnostic on the COMPASS tokamak varies between Gaussian and Top-hat shape along the beam path therefore both shapes were used in the simulation. Existing fiber bundle arrangement[6] of the core and edge TS system on the COMPASS tokamak can be found in FIG. 2. Spatial resolution is determined by fiber bundle size and collection lens magnification. According to requirements for spatial resolution in edge and core plasma region the orientation of the longer side of the fiber bundle was set perpendicular and parallel, respectively, to the laser beam propagation direction.

Scattered light originated from the plasma is focused by the collecting optics on the fiber bundles. It can be assumed that scattered light profile corresponds to the laser beam profile. In order to obtain projection of the laser beam on fiber bundle it is integrated along the line of sight, which is shown for the Gaussian shape in FIG. 1a. The result of the projection on the whole fiber bundle is demonstrated in FIG. 1b.



(a) (b)

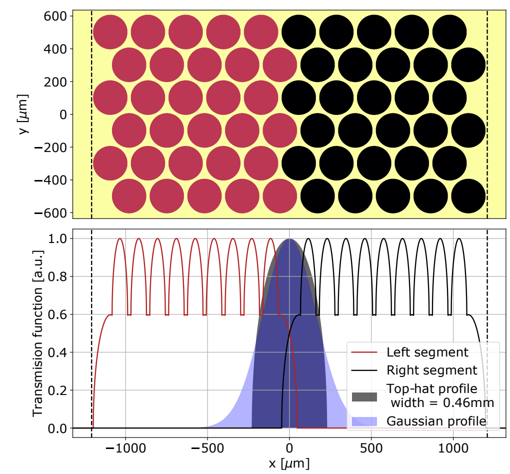
FIG. 1: (a) Gaussian laser beam projection into the plane of the fiber bundle, (b) projected integrated Gaussian beam on the whole fiber bundle.

A. Fiber bundle throughput function

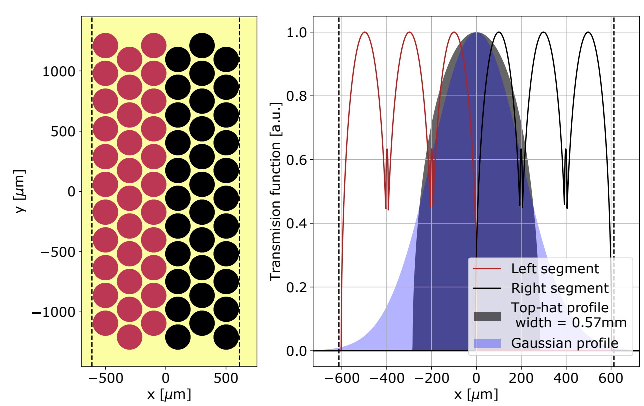
Scattered light imaged onto the bundle is collected by individual fibers and transmitted towards the detection unit outside the tokamak hall. Simulation of the efficiency of light collection of one fiber bundle requires to move projected function along the x-axis and record the ratio between collected and lost signal using simple multiplication. Since it can be assumed the laser beam is co-linear with the y-axis (or very close to co-linear) within the fiber bundle, the profile is expected to be the same along the y-axis and the problem can be reduced to one dimension using so called *throughput function* f_T, which is given by the bundle geometry. It can be calculated from the bundle image or analytically using following function

$$f_T(x) = \sum_{x_i \in S} 2\sqrt{r^2 - (x - x_i)^2}, \tag{1}$$

where x_i represents i-th fiber center position on the x-axis (horizontal) from a given set of fibers S with fiber radius r. Formula for f_T is derived by integrating the fiber (circle) along y-axis. Throughput function for a typical edge TS split-fiber bundle is shown in FIG. 2, for each segment of the split-fiber separately, together with typical beam shapes projected on the fiber bundle with width corresponding to TABLE. I. Gaussian profile width at $1/e$ of amplitude is equal the width of Top-hat function.



(a) Edge TS split-fiber bundle



(b) Core TS split-fiber bundle

FIG. 2: Fiber bundle with highlighted halves of split-fiber (top,left), with corresponding throughput functions and beam profiles (bottom,right)

B. Simulation

Estimated laser beam size on the tokamak COMPASS TS in the toroidal direction, along the x-axis, is presented in TABLE. I. Vertical positions correspond to those observed by split-fibers on COMPASS TS. Magnification of the optical systems is 0.34 and 0.35 for the core and edge TS, respectively[2] and was used to estimate the width of the scattered signal on split-fiber bundles, written in the last row of the table. Values were extrapolated from beam diameter measurements during commissioning phase[3].

Split-fiber	Edge		Core	
Vertical position	277	215	187	-14
Beam width in vessel	1.32	1.54	1.68	3.10
Beam width at fiber	0.46	0.54	0.57	1.05

TABLE I: Laser beam size in the toroidal direction at vertical position (over mid-plane) observed by split-fiber after focusing to the vessel. Values are in mm.

In order to evaluate the split-fiber performance, given beam function is moved along the x-axis and signal acquired by corresponding split-fiber bundle segment is recorded. Both the total acquired signal and ratio of signal in particular segments can be inquired. From the first the signal loss can be determined and the latter can be used to assess the beam position on the bundle, thus serving as an alignment tool.

C. Results of simulation

Results of simulation of split-fiber performance are presented in two steps. Firstly, current status of the method on the TS diagnostic of the COMPASS tokamak is evaluated and afterwards alternative approaches with possible upgrades are proposed.

1. Current approach performance

In FIG. 3 the total acquired signal is shown for both edge and core split-fibers, where values $T_G^{90\%}$ and $T_T^{90\%}$ represent the value of beam center displacement that corresponds to a threshold of 10% loss of useful signal. In general edge TS fiber bundle is more resistant to beam shift, as $T_{G,T}^{90\%} \approx 1$mm, while for the core TS this value decreases, in the plasma center even down to 0.25mm. This is the result of different geometry of the fiber bundles for core and edge TS and the fact, that laser is focused in the edge vessel region, due to higher requirements on spatial resolution in the plasma edge region.

Current COMPASS TS diagnostic accommodates split fibers divided vertically in two identical halves as shown in FIG. 2. Ratios of signals acquired by these particular segments are shown in FIG. 4 as a result of the same simulation. Reddish region signifies the range of sensitivity of the analog-to-digital converter used to digitize signal with a resolution of 8 bits, therefore ratios outside the range (1 : 128, 128 : 1) are unfeasible to record. This range is certainly overestimated as a signal noise has to be considered. Edge split-fiber ratios show that beam deflection of less than 0.5mm cause the ratio to exceed the measurable level and become inapplicable as

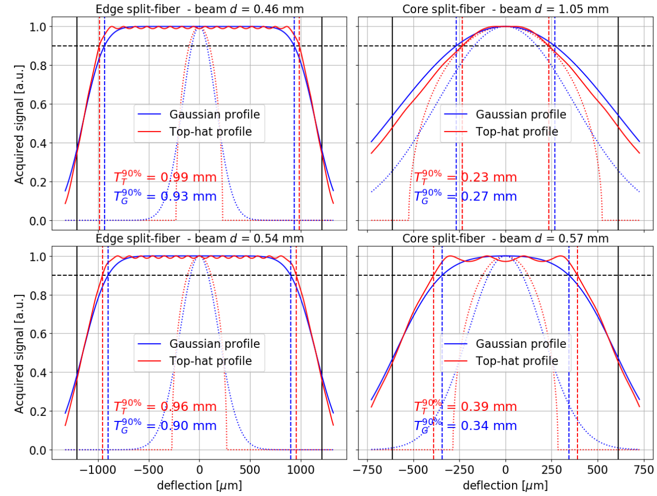


FIG. 3: Total acquired signal while the beam function (Gaussian,Top-hat) was moved along the x-axis. Black vertical lines represents split-fiber boundaries. Horizontal dashed line is the 10% threshold of signal loss, which is exceeded when the Gaussian or Top-hat beam is shifted over $T_G^{90\%}$ or $T_T^{90\%}$, respectively. Vertical dashed lines in corresponding color signify this threshold.

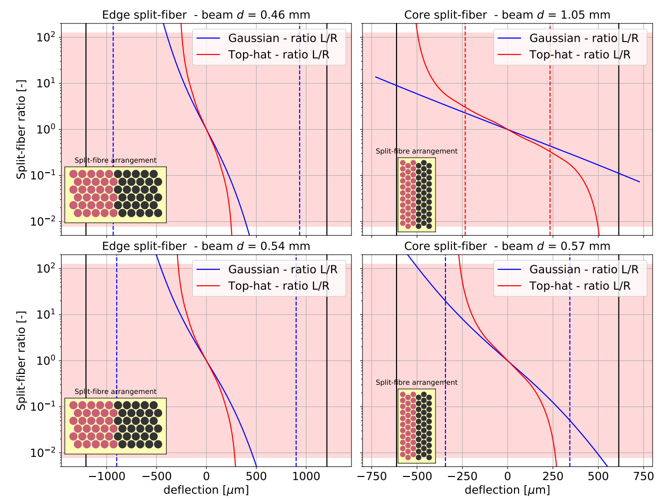


FIG. 4: Simulated split-fiber ratio signal for given beam profile and split-fiber arrangement. Reddish region represents data acquisition ADC resolution (8-bit).

a tool for alignment, despite the fact that there is no significant loss of useful signal. On the other hand, in the core region one could benefit from the split-fiber ratio as it remains in the measurable range even for significant displacement. However, in this case the loss of signal is noticeable therefore for the core TS on the COMPASS tokamak it is advisable to keep the ratio closer to unity.

Measured signal ratio with four split-fibers is presented in FIG. 5 for discharge 15978. Using split-fiber simulation the ratio evolution can be quantified and corresponding deflection can be calculated, which is presented in FIG. 6, where green region represents the beam size and horizontal dashed lines given fiber bundle dimension.

In the edge TS results indicate relatively small deflection to bundle size. For the core TS, where the beam is significantly wider, the deflection reaches larger values and in the case of core bottom split-fiber bundle partly reaches out the fiber bundle area during the initial phase of the discharge. Such misalignment might result in not negligible signal loss. Impact of such defect on determined electron density is yet to be evaluated and quantified.

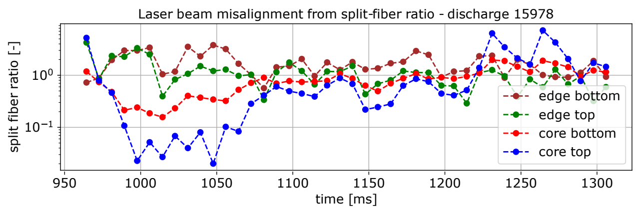


FIG. 5: Split-fiber ratio measured for discharge 15978.

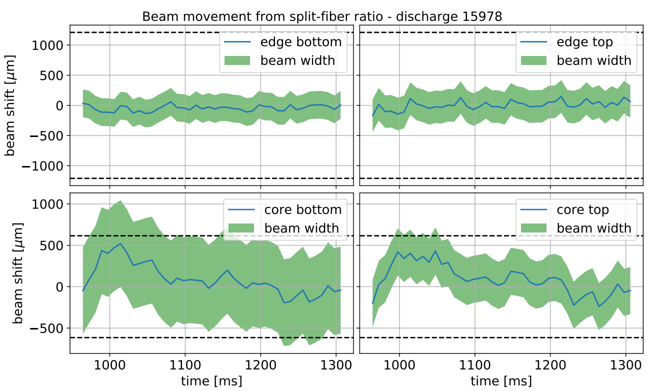


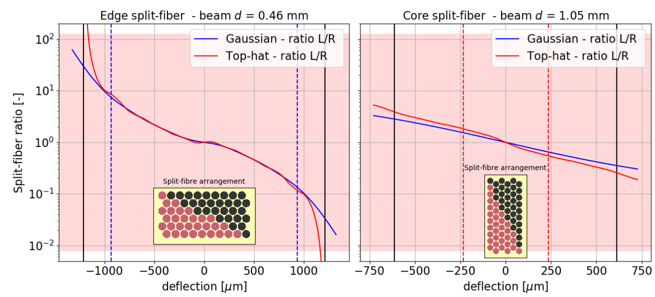
FIG. 6: Beam movement on the split-fiber bundle calculated from measured split-fiber signal compared with simulation.

2. Alternative approach

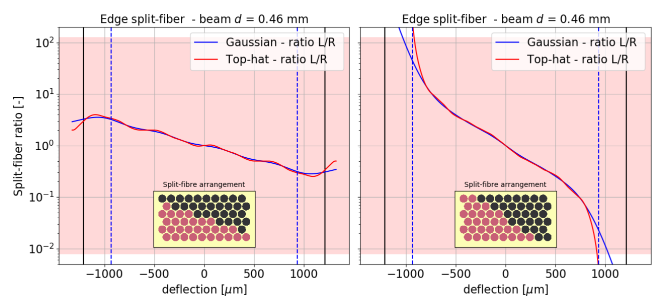
From FIG. 4 one can easily deduce that the steep evolution of split-fiber ratio exceeding the limit in the edge TS is a result of narrow beam profile enough to fit onto one half of the split-fiber. Dividing the fiber bundle vertically is not an optimal solution. Several alternative approaches are evaluated within this section. Simulations are performed for beam size of 1.05mm and 0.46mm for core and edge fiber bundle arrangement, respectively. Signal loss in dependence on the misalignment is the same as in FIG. 3 for given laser beam and fiber bundle widths. Results are presented in FIG. 7 for different fiber arrangements, 90% signal level loss is shown by vertical dashed lines. Split-fiber arrangement is demonstrated in miniature scale within each graph.

Signal ratios for diagonal arrangement of split-fiber for the edge TS better utilize the whole measurable range with the deflection extent, shown in FIG. 7a (left) and 7b. The inclination of dividing line has significant effect on the ratio dynamic. The option in FIG. 7b(left) shows rather low ratio even behind the 90% limit, while in both other cases the ratio rises rapidly approaching this limit, which is more suitable as significant misalignment is thus clearly observed. On the other hand, diagonal arrangement for the core TS does not provide better dynamic range of ratio compared to current approach, therefore, vertical distribution is more applicable. However, signal ratio for different profiles has similar evolution, which is beneficial when the beam profile is uncertain.

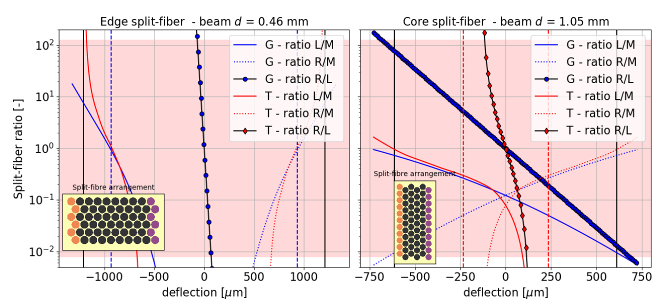
Results of the side-fiber method, see FIG. 7c, provides comparable tool for alignment, as the ratio is well quantifiable in the region close to the 90% limit, for both core and edge case. However, this technique requires more detailed optimization process considering either a signal loss or accommodation of additional detectors designated for alignment purposes only.



(a) Diagonal arrangement



(b) Diagonal arrangement variations - edge split-fibers



(c) Fibers arranged to three vertical segments

FIG. 7: Simulated split-fiber ratio for various fiber arrangements of both core and edge TS.

V. CORRELATION WITH VIBRATION MEASUREMENTS

In order to investigate the effect of vibrations, components of TS diagnostics were mounted with four 3-axis accelerometers (ADXL335). Different locations, which are assumed to be crucial for the alignment, were selected (collection lenses, fiber holders, tokamak port). Accelerometer measurement is synchronized with tokamak discharge and data is collected during proper time period with a sampling frequency of 12 kHz.

Measurement of vibrations at all positions shows high level of reproducibility for discharges with similar main parameters, namely plasma current I_p and toroidal field B_T, which is presented in FIG. 8. From spectrograms, calculated for discharge 15978 using wavelet transformation and showing the frequency evolution of the vibrations shown in FIG. 8, one can see that in the beginning of the discharge higher frequency ~ 100 Hz appear, which suggest initial "kick" during the plasma ramp-up. Afterwards the frequency decreases as the mounted structure starts to vibrate with characteristic frequency of approximately 20 Hz. In order to calculate the displacement, accelerometer data is twice integrated with respect to time. High-pass filter was used to reduce undesirable trend resulting from integrating non-zero offset.

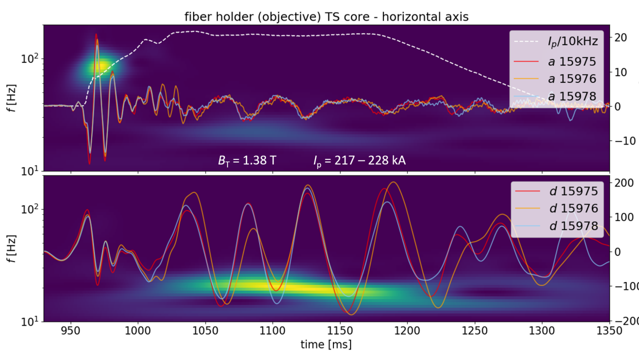


FIG. 8: Spectrograms of measured acceleration a (top) and calculated deflection d (bottom) for discharge 15978 on core TS fiber holder.

Calculated deflection from accelerometers and results from split-fiber method, presented in FIG. 5, are compared for discharge 15978 in 9. Linear trend from split-fiber results was reduced as this is impossible to record using accelerometer measurement, due to the undesirable offset. However, oscillation character evident from FIG. 8(bottom) is present also in the split-fiber measurement. Results from these two methods are in a good agreement both in amplitude and frequency of approximately 20 Hz. This suggests that vibrations of collection lens structure are responsible for the oscillation of split-fiber ratio signal. Impact of such vibrations on the TS measurement and possible means of mitigation are yet to be evaluated.

VI. SUMMARY

The well established alignment methods based on "split-fibers" and "side-fibers" were described and compared. It was shown that the "split-fiber" bundle arrangement can be optimized to particular laser width and fiber bundle width. Such optimization can be interesting for future TS systems for tokamaks like COMPASS-Upgrade or ITER. Besides this analysis, the practical use of split-fibers on the COMPASS tokamak was presented, reconstructing the evolution of the laser beam image position on the fiber bundle during the tokamak discharge. The results are in agreement with collection lens vibrations measurement.

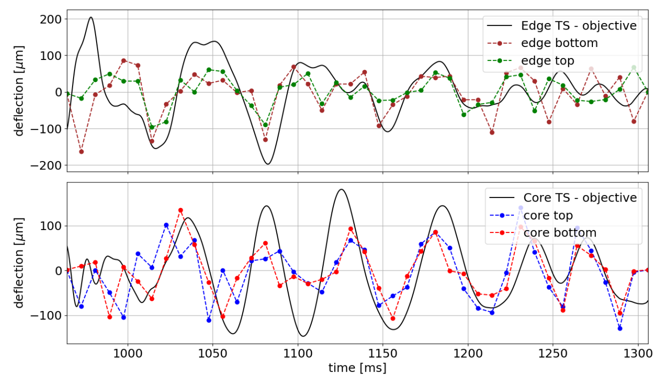


FIG. 9: Correlation of calculated deflection from split-fiber method and vibration measurements.

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REFERENCES

[1]M. Bassan, P. Andrew, G. Kurskiev, E. Mukhin, T. Hatae, G. Vayakis, E. Yatsuka, and M. Walsh. Thomson scattering diagnostic systems in iter. *Journal of Instrumentation*, 11(01):C01052, 2016.

[2]P. Bilkova, P. Bohm, M. Aftanas, M. Sos, A. Havranek, D. Sestak, V. Weinzettl, M. Hron, R. Panek, the COMPASS team, and the EUROfusion MST1. High resolution thomson scattering on the compass tokamakextending edge plasma view and increasing repetition rate. *Journal of Instrumentation*, 13(01):C01024, 2018.

[3]P. Bohm, D. Sestak, P. Bilkova, M. Aftanas, V. Weinzettl, M. Hron, R. Panek, L. Baillon, M. R. Dunstan, G. Naylor, and M. J. Walsh. Laser system for high resolution thomson scattering diagnostics on the compass tokamak. *Review of Scientific Instruments*, 81(10):10D511, 2010.

[4]J. Figueiredo, G. Naylor, M. Walsh, M. Dunstan, R. Scannell, and F. Serra. Mast yag thomson scattering upgrade alignment system. *Review of Scientific Instruments*, 81(10):10D521, 2010.

[5]B P LeBlanc and A Diallo. Alignment of the thomson scattering diagnostic on nstx. *Journal of Instrumentation*, 8(11):C11004, 2013.

[6]P. Bilkova, et al. Design of new Thomson scattering diagnostic system on COMPASS tokamak. *Nucl. Instrum. and Meth. in Phys. Res. A*, pages 1273–1276, 2010.