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Design, Construction, Operation, Improvement and Future Prospects of LHD Thomson Scattering Diagnostic
LHDトムソン散乱の設計・建設・改良と将来展望

Kazumichi Narihara, Hiroshi Hayashi, Ichihiro Yamada, Hisayoshi Hunaba, Ryo Yasuhara, Toshikazu Kohmoto
成原一途、林浩、山田一博、舟場久芳、安原亮、河本俊和

National Institute for Fusion Science, Toki 509-5292, Japan
核融合研究所 〒509-5292 岐阜県土岐市下石町322-6

Looking back on our past activities in the LHD Thomson scattering diagnostic, we examine what were sucesses and what were failures. Based on these, we propose a somewhat different TS system.

1. Introduction

It is almost 20 years since we started the design of the Thomson scattering (TS) diagnostic for LHD experiment. We tried to construct a TS system which would give useful information as much as possible for understanding LHD plasma. On the occasion that the first author retires this fiscal year, we would like to look back on what we strove and examine what were successes, and what were failures [1]. We also propose a revised TS system that would be more attractive for the LHD experiment.

2. Basic Design

2-1 Choice of TS Type: Twenty years ago, and still now, there were three types of TS: TV-TS, YAG-TA and LIDAR. In view of the LHD port configuration, LIDAR seemed to be very attractive, but we abandoned it because we could not anticipate a big progress in its spatial resolution of 10 cm. In considering the overall performance, i.e., brightness, spatial resolution and repetition, we chose YAG-TS.

2-2 Scattering configuration: Looking at the LHD port configuration, we considered several TS configurations, i.e., the combination of the observation region and the view window. Among them, we chose the heavily oblique back scattering configuration that can measure whole plasma from edge-to-edge along a major radius passing the magnetic axis. This choice was proved to be a success by the fact that the observed electron temperature (Te) and density (ne) profiles directly give the positions of magnetic axis and the magnetic islands without a time-consuming magnetic-surface reconstruction.

2.3 Light collection optics: We compared a lens system and a mirror system. Lens system has much better imaging performance than mirror. However, the normally used lens materials are likely to be darkened by intense neutron flux expected in the DD-experiment, hence we abandoned lens system. The poor imaging problem of the mirror was partly solved by setting the center of the mirror curvature at the center of the viewing window. A rectangular mirror of 1.5m×1.8 m size was fabricated by patching 11×12=132 hexagonal mirrors of 88 mm side length. Each hexagonal mirror was glued by Epoxy on a mirror mount, which introduced a distortion on the mirror surface and degraded the imaging performance, which was a big failure.

2.4 Optical fibers: Large spherical aberration of the light-collection mirror necessitated the large diameter (2 mm) of the optical fibers onto the end of which the image of laser beam is focused. Our serious concern was a large transmission loss induced by an intense neutron irradiation expected in the DD-experiment. We made three fiber-companies to develop optical fiber that has a strong resistance against radiation. Finally we purchased 200 optical fibers with the specifications: length 45m; N.A~0.22; the transmission loss induced by 1MR CO-60 γ ray irradiation <20dB/km for λ>650nm.

2.5 Observation region: The end tips of 200 optical fibers cut at 60° were placed on a fiber holder and precisely aligned along the image of the laser beam running in the region 2.2m<R<5.3m. This expected observation length was much longer than the real plasma region (2.5m<R<4.7 m), thus making ~1/3 of fibers and polychromators useless, which is a bitter failure caused by relying on an unreliable information. If we want to see the plasma region with 200 fibers, we should set the viewing window a little farther away from the laser input window.

2.6 Polychromators: We fabricated 200 conventional 5-color-filter polychromators. The gain of photo detectors (APD) is very sensitive both to the bias voltage and to the ambient room temperature, thereby introducing systematic errors in Te and ne. In addition to the conventional room temperature and voltage regulation, we took the following measure: we first classified 1000 APDs by their recommended bias voltages V_C into 200 groups, and then allotted five APDs in each group to each polychromator. Like a 'common mode rejection' method, this helped appreciably to reduce systematic errors in Te, which is deduced from relative magnitudes of APD's outputs. This may be a reason why Te profile is better in quality than ne profile.

2.7 Data Acquisition: To acquire a large number of signals of 200*5=1000 in a short time, we adopted Lecroy 1881M charge ADC modules running on FASTBUS, which is now not available. We should have purchased much more ADC modules for the future extension of the TS system.

3. FIRST DATA and Subsequent Improvements

Soon after the start of the 2^{nd} LHD run, the LHD-TS began to yield Te and ne profile data. Initial failures were solved step by step, but the following two problems remained to be solved for a long time.

3-1 Effect of background radiation: In the early phase of the series of LHD-runs, fairly good Te profiles were obtained. However, as plasma heating power increased, Te and ne profiles sometimes showed up irregularities on the channels which 'see' the region where there is carbon divertor plates in the background view scope. Guessing this was caused by the background radiation from the divertor plates, we made grooves on the surface of the divertor plates to decrease the reflectivity, which had some favorable effect for a few years. However, as the heating power increased further, the irregularities on profiles began to appear again. Next, we replaced the divertor plates with those with a higher heat removal ability. The surfaces were grooved again. This replacement had favorable effect for a few years, but as the heating power increased further, the same phenomenon reappeared. To see what was happening, we modified the APD circuits so that the DC level as well as AC (pulse) can be read. Afterwards we found that when Te and ne profiles become irregular, the APD's DC outputs get large and often exceed the dynamic range of the circuits. The blackbody radiation temperature up to 2700K was estimated from the APD's DC outputs. Considering that the grooved structure is likely to be heated upon intense heat flux, we removed the grooves on the surface, which resulting in less frequent appearance of the profile irregularities. Tungsten diverter plates with high heat removal ability will be necessary if the plasma heating power is further increased.

3.2 Density calibration: In the adopted heavily oblique backscattering configuration, the light collection optics is likely to pickup intense stray light, invalidating the conventional Rayleigh scattering calibration of the absolute sensitivity of each polychromator. Hence, we intended to calibrate by applying hydrogen Raman scattering and checked its validity in CHS, a pilot machine for LHD. However, for a safety reason it was forbidden without any scientific discussion to fill H_2 gas in the LHD chamber after the LHD-TS construction was almost completed. This was the start of our time-consuming painful efforts. Firstly, we tried N_2-Raman scattering, but in vein: the #1 filter catch only small portion of the N_2-Raman spectra and the resultant calibrated ne profile fluctuated channel to channel. Next we replaced the #1 filter with new one that can cache wider N_2-Raman spectra, but also in vein. This effort, however, gave a reward that the minimum detectable Te lowered down to ~3eV. Thereafter an idea of "high-pressure low laser energy Rayleigh scattering" came to our minds. Firstly we tried with a tunable laser (OPO) tuned to the #3 filter, but in vein. There was a difficulty in shaping the OPO beam envelope as the YAG laser. Finally, we newly added #6 filter-APD combinations dedicated for YAG laser Rayleigh scattering in 2007. After two years intense efforts to stabilize the beam transverse positioning, we finally are able to obtain ne profile, the line integral of which agrees fairly well with the HCN laser interferometer data in 2010.

4. Possible Revised TS

If we were able to go back to the past, we would like to construct a TS somewhat differently. Disregarding the neutron radiation effects on the optics, we use a lens system and set polychromators in the LHD room, thereby saving much expenditure on the optical fibers. A lens system enables us to set arrays of fiber-tip along the focal lines of many laser beams, one of which is moved synchronously with the laser beam transverse position, thereby giving 2-D profiles. The plasma region along **R** passing the magnetic axis is dissected by 300 optical fibers of ~1.5 mm in core diameter. An array of fibers with different length can distinguish the scattering positions by the time delay in fibers like a LIDAR. This LIDAR-like scheme, which has a high spatial resolution of ~1 cm, will reduce the number of the APDs necessary for a 2D-profile measurement. The radiation effects on optics, if any, would rather give us valuable information.

References

[1] K.Narihara et al.: Rev. Sci. Instrum. **72** (2001) 1122.