The Thomson scattering System at Wendelstein 7-X[a)]

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This paper describes the design of the Thomson scattering (TS) system at the Wendelstein 7-X stellarator. For the first operation campaign we installed a 10 spatial channel system to cover a radial half profile of the plasma cross section. The start-up system is based on one Nd:YAG laser with 10 Hz repetition frequency, one observation optics, five fiber bundles with one delay line each, and five interference filter polychromators with five spectral channels and silicon avalanche diodes as detectors. High dynamic range ADCs with 14 bit, 1 GS/s are used to digitize the signals. The spectral calibration of the system was done using a pulsed super continuum laser together with a monochromator. For density calibration we used Raman scattering in nitrogen gas. Peaked temperature profiles and flat density profiles are observed in helium and hydrogen discharges.

I. INTRODUCTION

The Thomson scattering system was one of more than 20 start-up diagnostics of W7-X. During the first operation phase (OP1.1) Wendelstein 7-X was equipped with five uncooled inboard-side carbon limiters. In order to protect the limiters and other in-vessel components, the maximum plasma energy was first restricted to 2 MJ which was later increased to 4 MJ. The maximum available ECRH heating power was 5 MW. In OP 1.1, the TS system provides electron temperature and density at a half profile of the plasma with 10 spatial points. One of them was located in the limiter shadow (SOL). The TS system is optimized to measure electron temperatures between 20 eV and 10 keV and electron densities from $2\cdot10^{18}$ m^{-3} up to $5\cdot10^{20}$ m^{-3}. Examples of measured electron temperature and density profile are given, showing the possibilities of the system under several plasma conditions. T_e and n_e are reconstructed by Bayesian analysis with Minerva[1]. Details will be published later. The spectral calibration was done using a pulsed super continuum radiation source together with a monochromator. For density calibration we used Raman scattering in nitrogen gas.

II. Design

The basic design of the Thomson scattering system at W7-X follows a traditional TS system using periodically pulsed Nd:YAG laser together with interference filter polychromators and silicon avalanche diodes as detectors; which was first realized at the ASDEX tokamak[2].The linear polarized Nd:YAG laser operating at the fundamental wavelength of λ=1064.14 nm, with laser energies tunable between 0.7 and 1.5 J depending of the requirements of the plasma operation, is located outside the torus hall in a separated diagnostic room. The laser beam enters the torus hall via a concrete labyrinth structure for shielding of neutron radiation expected in later experimental phases. A piped 30 m laser beam path guides the laser beam to the entrance port at W7-X. It includes seven high-reflection mirrors, the deflection angles vary between 35° and 56°. This mirror set-up allows to maintain the linear polarization of the laser radiation, and to set the required polarization direction in the plasma vessel for Thomson scattering. In front of the entrance port the laser beam is focused by a lens with 4 m focal length. Due to the dimensions of W7-X, the focus is inside the laser entrance port. The diameter of the laser beam is about 4 mm at the plasma core and about 7 mm at the edge. The change of the beam diameter fits well with the change of demagnification of the observation optics, so that the same dimensions of fiber bundles can be used at the core and the edge. The entrance and exit ports are located nearly horizontal at the midplane of the plasma vessel. This also provides the possibility to measure the Shafranov shift. The beam dump (laser Components, model LC-ABD-2) is located at the outer tower of the Thomson bridge

Two observation optics (160 mm diameter, f=172 mm, f/1.3, NA=0.37), cover the whole plasma cross section of 1.6 m along the laser beam line with an overlap of 10 cm at the plasma core. The observation optics were optimized[3] with the optical engineering program ZEMAX to minimize losses of the collected light from 700 up to 1064 nm. The optics are located in air inside their immersion tubes which are used as vacuum barrier. Each optical component is mounted on a manipulator to have the possibility to remove the optics reproducibly from the port for spectral calibration or to close the observation ports during baking of the plasma vessel. In OP1.1 only one of the observation

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The scattered light was imaged onto 10 rectangular (1.1x3.2 mm^2) fiber bundles. During OP1.1 two types of pure fused silica core fibers (dia 300 µm) with high numerical aperture (NA) were employed. Two fibers with a germanium doped fused silica cladding (NA=0.37) and eight fibers with two fluorine doped silica claddings (NA=0.29) are applied.

According to the geometry of the observation ports with respect to the laser ports, the demagnification is not uniform along the laser beam line. The demagnification changes from 7.8:1 at the plasma core to 11.5:1 at the plasma edge. Therefore, the length of the scattering volumes changes from 25 mm at the core to 37 mm at the edge. The image size of about 86 mm fits well to the dimensions of the port. Also all optical rays of the scattering volumes are unvignetted (NA=0.37) from the core up to the scattering volume behind the limiter which is located closely behind the last closed flux surface of the plasma for the OP1.1 standard limiter configuration. Figure 1 illustrates the laser beam line (horizontal black line), the observation optics with the optical rays (red lines) of the scattering volumes, the immersion tubes (shown in brown) with bellows to compensate the movement of the ports during baking of the plasma vessel (in blue), the manipulators (blue components outside the ports) for reproducible movements of the optics, the water cooled ports protection for later operation phases with long high power plasma discharges (in pink) and a water cooled shutter (blue element in front of the plasma vessel) to protect the quartz windows in front of the immersion tubes during wall conditioning by glow discharges or for the later planned boronization of the plasma vessel.

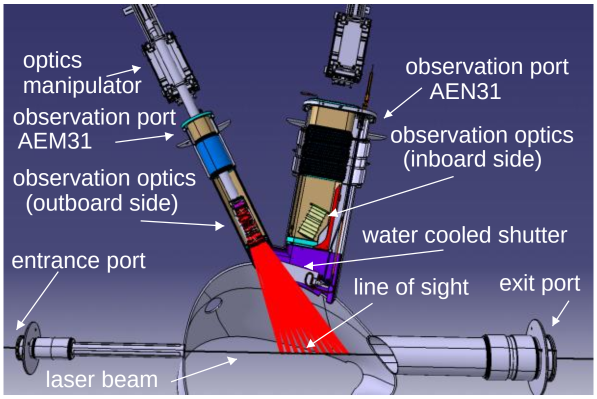

Fig. 1: Set-up of TS components inside W7-X.

After leaving the plasma, the laser beam is absorbed by a laser beam dump 3 m behind the exit port.

To make the TS system at W7-X as mechanically stable as possible, the observation optics, deflecting mirrors, laser beam entrance and the laser beam dump are mounted to the so called “Thomson bridge” support structure, which is fixed to the concrete floor and has no connection to the plasma vessel, the cryostat vessel or the basis of W7-X. This gives us the possibility to determine the position of the scattering volumes in the global W7-X coordinate system within an error of ±1 mm. The Thomson bridge is about 10 m long and 10 m high stainless steel support structure which is also used for access to the machine center. Figure 2 shows an overview of the Thomson scattering components inside the torus hall.

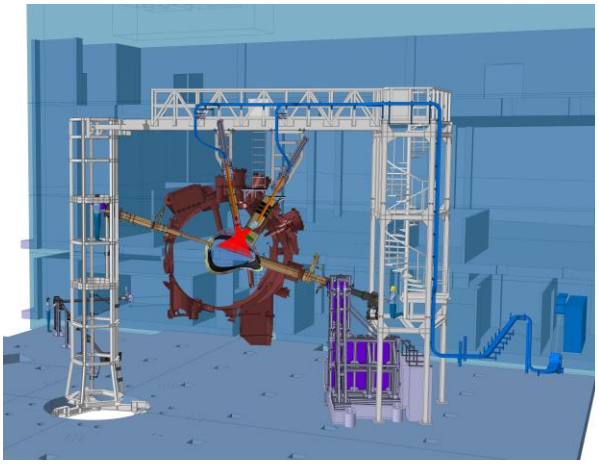

Fig.2: Overview of the TS system inside the torus hall of W7-X.

Fiber bundles guide the scattered light to the polychromators. At the polychromators, the fiber bundles are combined to pairs of two fibers, where one has a delay line of 20 m length (bundle length 57 m and 77m). The shape changes from rectangular to circular shape with 3 mm diameter (surface area of 7 mm^2) which corresponds to the dimension and the circular shape of the detector (d=3 mm). The polychromators are located outside of the torus hall in the air-conditioned polychomator room inside temperature-controlled electrical cabinets. The polychromators are use interference filters and Si-avalanche diodes. The main design parameters of such an optical system are the numerical aperture, internal transmittance, aperture and vignetting. The optimization of the optical components was made to achieve a high throughput, a compact design and to reduce the cone angle of the light onto the interference filters to a minimum. The W7-X polychromators are designed for six spectral channels (of which only five are used in OP1.1), a numerical aperture up to NA=0.37 for fiber bundles with 3 mm diameter. Figure 3 shows an overview of the design. Table 1 presents the optical parameters. Table 1 also includes the choice of the spectral transmission of the interference filters for OP1.1 to measure electron temperatures up to 10 keV. Two filters are designed for Raman calibration using nitrogen gas. Rayleigh calibration is not possible due to the suppression at the laser wavelength of OD 6 to avoid any laser stray light on the detectors.

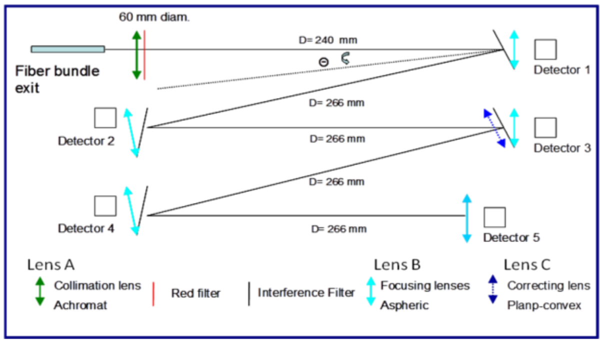

Figure 3: Optical design of the W7-X polychromators

Collimation lens Lens A	**Focusing lens Lens B**	**Relay lens Lens C**	**Interference Filter**
Achromat F= 59 mm D=60mm BK7 glass Antireflection Coated T=0.99	Aspheric F= 39mm D=60mm B270 glass Uncoated	Plano-convex F=1900 mm D=60 mm BK7 glass Antireflection Coated T=0.99	D=60 mm $T > 0.95$ $R > 0.95$ OD 6 @ 1064 nm $750 < \lambda < 920$ nm $920 < \lambda < 1000$ nm $1000 < \lambda < 1035$ nm $1035 < \lambda < 1051$ nm $1051 < \lambda < 1061$ nm

Table 1: Parameters of the optical components of the W7-X polychromators.

III. DATA ACQUISITION

The data acquisition supports time resolved measurements of the scattered light pulses with a duration of about 10 ns. For this an analog bandwidth of at least 300 MHz and a sampling rate of 1 GS/s is required for each input channel. We use high performance ADCs from Signal Processing Devices (SP Devices, model ADQ14). This model has a dynamic range of 14 bits. The combination of 14 bits dynamic range and 1 GS/s sampling rate is taking the performance of digitizer for TS system to an unprecedented performance level compared to the normally used 10 or 12 bit ADC. The used ADC boards are also equipped with Kintex-7 FPGAs for real-time signal processing (not used during OP1.1).

IV. RESULTS

Starting from the first plasma in December 2015, the TS system provided half profiles of electron temperature T_e and density n_e every 100 ms in helium and hydrogen discharges. In OP1.1 the energy input by ECRH (140 GHz, 4 MW) was limited by the admitted 4 MJ total energy. In helium we reached only short discharges with an uncontrolled density evolution and a radiation collapse terminating the discharge. After wall glow discharge conditioning, hydrogen discharges up to 6 s were performed. Electron temperatures up to 8 keV and densities up to $7 \cdot 10^{19}$ m^3 have been measured in hydrogen plasmas. Peaked temperature and flat density profiles are typically observed, as shown in fig’s 4 to 6 (the error bars indicate the 95% confidence interval as obtained by the aforementioned Bayesian analysis). For density calibration we used rotational anti-Stokes Raman scattering in nitrogen gas. For the required Raman cross section we used the values published by B.P. LeBlanc[4]. In most cases the absolute values of TS density profiles agrees with line integrated measurements by a single channel interferometer (will be published later in RSI) within ±10 %.

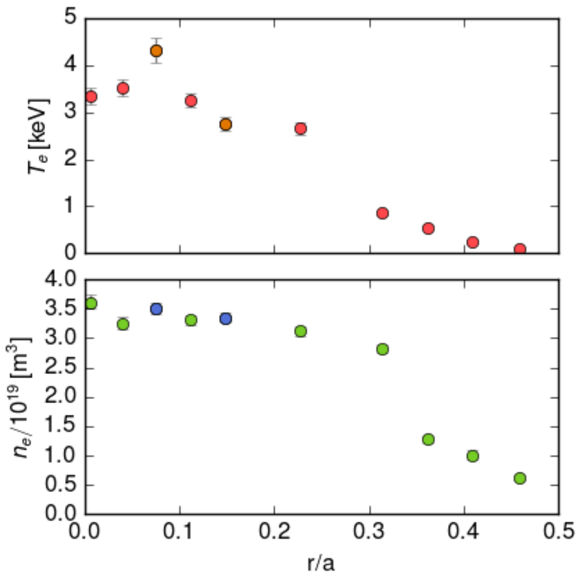

Fig. 4: electron temperature and density profiles from the helium discharge 2016-03-10.025 (2 MW ECRH power, t=500 ms). (Orange/blue dots from germanium doped fibers, red/green dots from fluorine doped fibers).

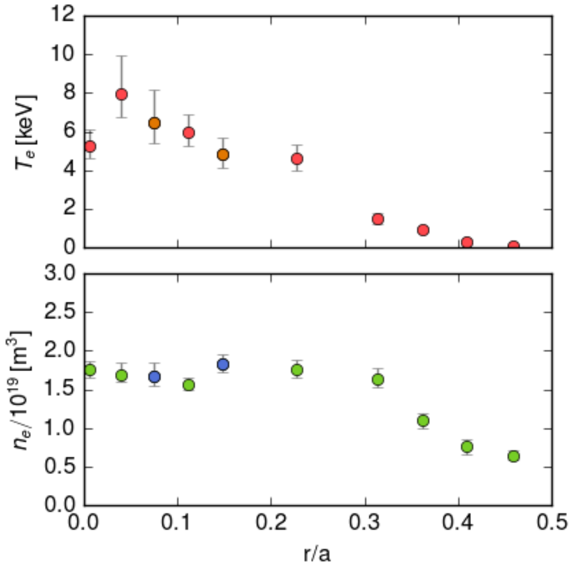

Fig 5: Temperature and density profiles from the hydrogen discharge 2016-03-03.006 (4 MW ECRH power, t=700 ms). (Orange/blue dots from germanium doped fibers, red/green dots from fluorine doped fibers).

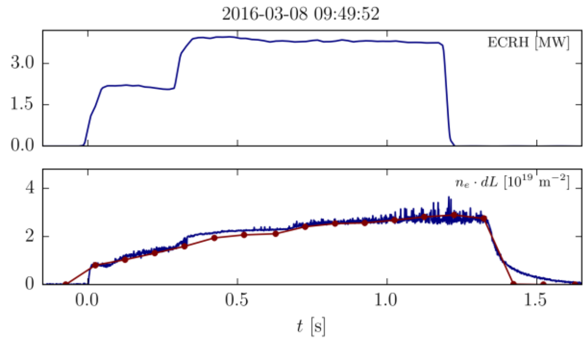

Fig 6a: Time traces of ECRH power and line integrated electron density from interferometer (blue), together with TS density values (red) in a hydrogen discharge.

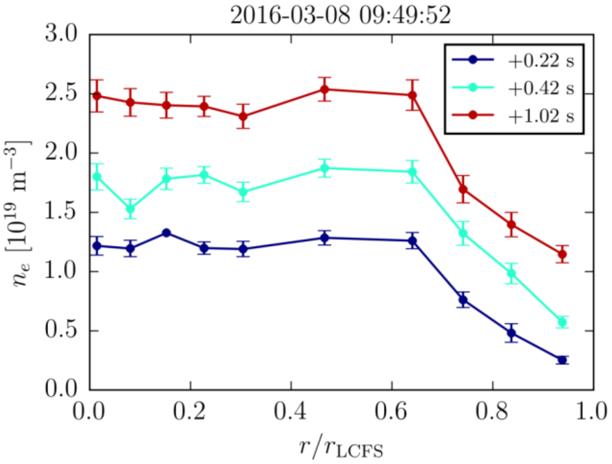

Fig 6b: TS density profiles at different time points, according figure 6a.

V. SUMMARY AND OUTLOOK

We have described the design and first electron temperature and density measurements of the Thomson scattering system at Wendelstein 7-X stellarator. The design follows a multipulse Thomson scattering system with Nd:YAG laser, interference filter polychromators and Si-avalanche diode detectors, together with high-performance ADCs (14 bits, 1 GS/s). The choice of appropriate filters (spectral bandwidth) was fixed for electron temperatures up to 10 keV. Starting with the first plasma in December 2015, the TS system provides every 100 ms a half profile of the outboard side of the plasma cross section with 10 spatial points, sufficient for profile variation analysis. For the next operation phase OP1.2a in 2017 Wendelstein 7-X will be equipped with an inertially cooled graphite divertor and up 9 MW ECRH power will be available. Higher electron temperatures in the plasma center are expected. Therefore, an upgrade of the TS system is necessary. The polychromators for the plasma center will be equipped with six interference filter, optimized for electron temperatures up to 15 keV. To cover the whole plasma cross section the second observation optics will be installed and equipped with fiber bundles. Due to the expected steeper gradients at the edge, the length of the scattering volumes will be reduced and the numbers will be increased.

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