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PRELIMINARY DESIGN OF OPTICAL EMISSION SPECTROSCOPIC DIAGNOSTICS FOR THAILAND TOKAMAK 1 (TT-1)†

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Abstract. Thailand Tokamak 1 (TT-1), which employs a circular poloidal cross-section, has been operated with a set of poloidal limiters since its installation was completed in June 2023. This device currently lacks essential plasma diagnostics and auxiliary heating systems. At present, light emission is observed only by a visible camera. Although intense line emission has been detected, it remains poorly characterized. To support further research on impurity transport in TT-1, even in Ohmic mode, spectroscopic diagnostics are necessary. This study reports on the development progress of optical emission spectroscopic (OES) diagnostics, including the preliminary design, fabrication, and optical calculations.

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Keywords: edge tokamak plasma, line emission, optical emission spectroscopic (OES) diagnostics, UV-Visible Spectrometer, Thailand Tokamak 1 (TT-1).

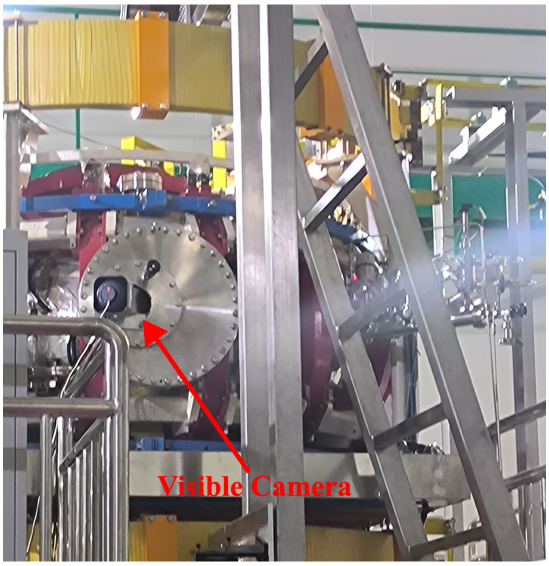
1. Introduction

Thailand Tokamak 1 (TT-1) was successfully installed at the Thailand Institute of Nuclear Technology (Public Organization), Nakhon Nayok, Thailand, in June 2023. TT-1 [1] is a limiter tokamak with a chamber featuring a circular poloidal cross-section, a major radius of 0.65 m, and a minor radius of 0.2 m. Its plasma edge is primarily limited by a set of poloidal limiters, consisting of one main fixed limiter and two movable limiters with partial poloidal coverage. The movable limiters are positioned near the fixed limiter at the same toroidal section and serve to control the plasma minor radius (a). The toroidal magnetic field (B_ϕ) reaches up to 1.5 T, the flat-top current period is up to 100 ms, and the peak plasma current (I_p) is currently approximately 100 kA. Plasma heating is solely Ohmic. There are no separated tiles acting as plasma-facing components (PFC); instead, the inner-chamber surface itself functions as the PFC. Both the main chamber and the limiters are made of stainless steel. At this initial operational phase [1], available diagnostics include magnetic sensors, a microwave interferometer using an HCN gas-discharge laser with a 337 µm wavelength [2], and a visible digital camera (resolution: 1280 × 1024 pixels; frame rate: 2000 fps). Figures 1a–1c show the exterior of TT-1, the location of the visible camera (opposite the main pumping port), and the diagram of the poloidal limiters, respectively. The HCN interferometer, with three channels measuring central electron densities at the midplane, low-field side, and high-field side, indicates a density of approximately $1.6 \times 10^{-19}\,\mathrm{m}^{-3}$. The plasma current and the loop voltage suggest a central electron temperature of about 100 eV. Currently, there are no edge diagnostics for plasma parameters.

During vacuum preparation, light species such as H_2, He, H_2O, CO_2, N_2, O_2, NO have been monitored using a residual gas analyzer (RGA). This allows identification of residual species inside TT-1. The RGA records the partial pressure of these species with a time resolution 2.5 s. The visible images show line emission light (Figure 2). The RGA and camera help prioritize which species to investigate, but they cannot directly monitor specific spectral lines. Therefore, the charged and excited states of the species, and the associated atomic or molecular processes, remain unidentified. Consequently, spectroscopic diagnostics are required to investigate the wavelengths of emitted light and related processes.

At this stage of TT-1 operation, visible line emissions should be analyzed to characterize hydrogen lines (H_α: 656.27 nm, H_β: 486.13 nm, and H_γ: 434.05 nm) and impurity lines (e.g. He I: 667.82, and 587.56 nm, and some visible lines of N_2, O_2 and H_2O), particularly from edge plasma. The objective of this project is to develop optical emission spectroscopic (OES) di-

(a).



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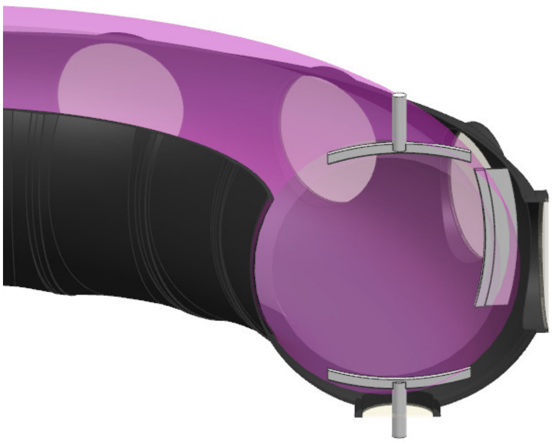

(c).

Figure 1. (a) Thailand Tokamak 1 (TT-1), (b) TT-1 Visible Camera Location Being Opposite to Pumping Port and (c) Fixed (Midplane) and Movable (Top and Bottom) Poloidal Limiters.

agnostics for observing and characterizing visible line emissions. Once installed, despite the limited time resolution of RGA data, comparison with OES re-

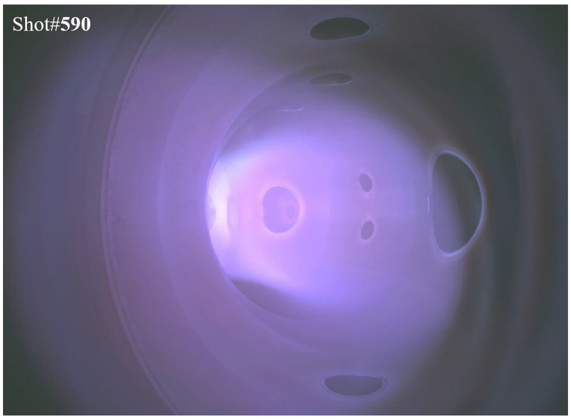

Figure 2. Visible Light Emission in TT-1 (Shot No. 590).

sults may help identify and validate impurity species. Beyond general impurity monitoring, the OES diagnostics will enable TT-1 to investigate disruption precursors, such as intense radiation from impurities at high-field side (HFS), or MARFEs [3].

This study reports only the preliminary design of the OES diagnostics. The system has not yet been fabricated or installed on TT-1. Section 2 outlines the current development progress, including the preliminary design (Section 2.1), fabrication plans based on optical calculations (Section 2.2), and optical calculations for collecting light from the HFS to the planned diagnostic site (Section 2.3). Section 3 concludes the work.

2. TT-1 OES Diagnostics

2.1. Preliminary Conceptual Design

The primary objective of the OES diagnostics is to collect light along lines of sight (LOS) spanning the poloidal angle range of $\theta = 150° - 210°$ of TT-1. The schematics in Figures 3 and 4 illustrate the main optical components required for the preliminary conceptual design, along with the TT-1 chamber showing the observed poloidal positions and LOS, and the anticipated installation area for part of the diagnostics system within the TT-1 main hall. At this stage, the OES diagnostics is designed to observe emission at eight poloidal angles between $\theta = 150°$ and $210°$, with a step size of $\Delta\theta = 7.5°$.

Eight convex lenses, referred to as viewport lenses, will be mounted at the low-field-side (LFS) mid-plane viewport on the exterior of TT-1. These lenses will be slightly inclined upward or downward, or aligned horizontally relative to the mid-plane level. The lenses have fixed focal lengths. The light source is assumed to originate from the high-field-side (HFS) surface, as intense radiation from MARFE is expected to occur at the HFS of TT-1, an event typically observed there in other tokamaks with circular poloidal cross-section. Emission from these positions will be focused behind the lenses to form distinct images. Additionally, the

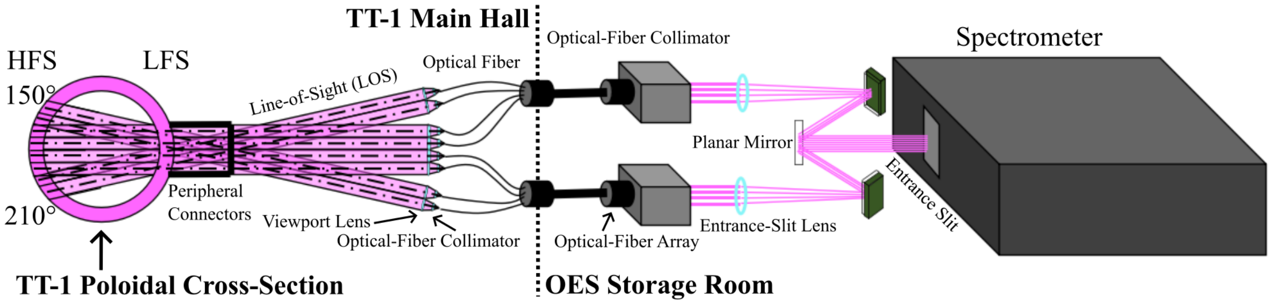

Figure 3. Optical Components, Observed Positions and Lines-of-Sight (LOS).

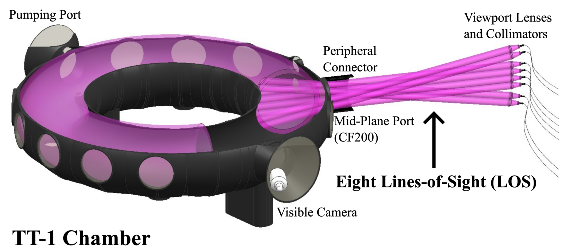

Figure 4. TT-1 Chamber Equipped with One Visible Camera, Together with Expected Viewport Lenses and Collimators of Eight Lines-of-Sight (LOS).

light emitted from other points along each LOS will also pass through the corresponding viewport lens within the solid angle determined by the lens aperture. Consequently, the light collected for each LOS corresponds to the line-integrated emission intensity over each $\Delta\theta$.

Each LOS will then be directed through the aperture of an optical fiber collimator. The collimator focuses the collected light onto the surfaced of an optical fiber. Ideally, the convex lens inside each collimator will be positioned at the focal point of the viewport lens to maximize light coupling efficiency. As designed, light from all eight LOSs will be transmitted through each optical fibers, with each fiber corresponding to an individual input channel of the spectrometer. These optical components and their assemblies will be enclosed in an opaque metallic housing, installed at the LFS mid-plane viewport, which allows the optical fibers to be routed from TT-1 to the OES diagnostics storage room in the main hall.

In the diagnostics storage room, additional optical components and the spectrometer will be mounted on an optical table. Each optical fiber entering from the TT-1 main hall will serve as an input channel to the spectrometer. The spectrometer's sensor array will be oriented such that horizontal pixels record the intensity of diffracted light as a function of diffraction angle, which is then interpreted as wavelength, while vertical pixels indicate the $\Delta\theta$ corresponding to each LOS. The entrance slit of the spectrometer has limited height. To match this constraint, the vertically arranged light from each fiber array will be spatially compressed and evenly spaced using a convex lens, referred to as the entrance-slit convex lens. In the current design, each vertical light array includes four input channels. These will first reflect off a tilted planar mirror, then onto a second planar mirror aligned toward the spectrometer entrance slit. Since there are eight input channels in total, two tilted mirrors are used to ensure proper alignment and leveling of both signal arrays before they enter the spectrograph and are finally detected by the digital sensors.

2.2. Fabrication

Previous studies [3–5] have demonstrated the implementation of optical emission spectroscopic (OES) diagnostics in tokomaks. Since TT-1 currently lacks such a system, it will be developed following the conceptual design described in Section 2.1. The present design utilizes commercially available UV-Visible spectrometers and optical components, rather than custom-made parts, for cost efficiency. The diagnostics system is intended to observe a wide range of visible wavelengths.

The OES system includes a Czerny–Turner spectrometer configuration consisting of an entrance slit, concave mirrors, a diffraction grating, and an exit slit, combined with a digital sensor array. The selected spectrometer is the Andor Kymera 193i [6], which features a 193 mm focal length with 1.07× magnification and an F-number of F/3.6. It achieves a spectral resolution of 0.21 nm using 1200 lines/mm reflective grating and a nominal dispersion of 3.53 nm/mm. The entrance slit measures 6 mm in width and 4 mm in height. This spectrometer is coupled with the Andor iDus 401 (DV401A) CCD detector [7], which contains a 1024 × 127 pixel array with a pixel size of 26 µm × 26 µm, giving a total image size of 26.6 mm × 3.3 mm. The optical design and alignment must conform to the specification of this spectrometer.

All optical components used in the system have been selected from commercial vendors [8–10] to ensure compatibility and cost-effectiveness. For beam redirection, planar mirrors with high reflectivity—Thorlabs BB1-E02 and BB2-E02— are used, offering reflectance greater than 99% between 400 nm and 750 nm. Light collection and focusing are managed using a series of plano-convex lenses. The entrance-slit convex lens, Thorlabs LA4647, is fabricated from UV fused silica with a focal length of 20.1 mm, an F-number of F/1.58, a refractive index of 1.458, and a numerical aperture of 0.3165. The viewport convex lens, Daheng GCL-010820, also made of UV fused silica, has a focal length of 40 mm, an F-number of F/1.57, a refractive index of 1.458, and an NA of 0.3185. The chamber viewport is a Kurt J. Lesker VPZL-1000 model made of Kodial borosilicate glass. These lenses and the chamber viewport allow efficient transmission of light in the 400 – 2200 nm range.

The system employs Thorlabs FP400ERT multimode optical fibers with a 0.4 mm core diameter, an NA of 0.5, and a transmission range from 400 nm to 2200 nm. Light collected from each LOS is collimated using Thorlabs CFCS5-A fiber collimators, which incorporate Thorlabs A390-A convex lenses with a focal length of 4.6 mm. These collimators feature an adjustable lens-to-fiber distance of 2.4 – 4.9 mm, an aperture diameter of 6.08 mm, a depth of 5.21 mm, a beam diameter of 0.82 mm (at the $1/e^2$ definition), and a refractive index of 1.724. Their NA is 0.53. These collimators are installed in both TT-1 main hall and OES diagnostics storage room.

In the storage room, optical signals from the TT-1 main hall are grouped using a vertical fiber array (Thorlabs BFL44LS01), which consists of four bundled multimode fibers (0.4 mm core diameter, NA = 0.39) transmitting over 400 – 2200 nm. The individual fibers in the main hall are connected to the fiber array using SMA905 mating sleeves, while all fiber connections throughout the system employ SMA905 connectors.

Given the flat-top plasma current duration of approximately 100 ms in TT-1, the spectrometer integration time is set to 1 ms. The current system design achieves an estimated spatial resolution of approximately 2 mm per pixel.

2.3. Optical Calculation

The design is based on plano-convex lenses, which are thinner than bi-convex lenses and therefore allow application of the thin lens approximation. The fundamental equations used are the thin lens equations, $\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$, and the magnification relation, $m = \frac{I}{O} = -\frac{s'}{s}$, where f is a focal length, s is the object distance, s' is the image distance, m is the magnification, I is the image size, and O is the object size.

The light source is assumed to be line emission from the high-field-side (HFS) of TT-1 covering the poloidal angle range of $\theta = 150° - 210°$ in steps of $\Delta\theta = 7.5°$. The TT-1 minor radius is 200 mm, and the extended length from peripheral components, such as the chamber port, viewport and gate valve, is currently about 154 mm, although this may change. Additionally, to prevent overlap among the lens holders, the minimum required length of the line of sight (LOS) from the viewport lens is 554 mm. Based on this, the LOS length was fixed at $s = 800$ mm.

Each LOS, covering $\Delta\theta = 7.5°$, requires a viewport lens with an aperture of at least 25 mm. The design employs 25.4 mm diameter plano-convex lenses with a focal length of $f_1 = 40$ mm for each LOS. These lenses focus the light, which is then directed to the lens of each optical fiber collimator positioned at $s'_1 = 42.1$ mm from the viewport lens. The size of the emission region on the HFS is estimated at 26.2 mm, corresponding to $\Delta\theta = 7.5°$, which is imaged to a size of 1.38 mm at the collimating lens. This is well below the collimator's 6.08 mm aperture diameter. The numerical aperture (NA) of the viewport lens provides a maximum acceptance angle $\beta_{max} = 18.6°$, significantly larger than the actual incident angle, measured from the emission location at the HFS to the viewport lens, $\beta = 1.97°$, ensuring sufficient light collection. Thus, each channel captures both focused and unfocused light, providing line-integrated intensity along LOS.

Each optical fiber collimator, which is commercially adjustable, optimizes coupling efficiency by maximizing intensity at the fiber surface. The convex lens within each collimator, with $f_c = 4.6$ mm (see Section 2.2), focuses the incoming light onto the optical fiber. The light intensity is optimized using a silicon photodetector (Thorlabs DET10A2 [8]) to ensure maximum coupling.

Following the collimator, the vertically aligned light beams are adjusted using a plano-convex lens, referred to as the entrance-slit convex lens, which reduces the image size and ensures even spacing. The vertical height of the combined two arrayed signals is $O = 3.46$ mm. The vertical dimension of the CCD sensor array in the spectrometer is $I' = 3.3$ mm. Given the spectrometer magnification of $m' = -1.07$, the vertical size at the entrance slit is calculated as $I = 3.08$ mm. Using the entrance-slit convex lens with $f_2 = 20$ mm, and a magnification of $m_2 = -\frac{I'}{I} = -0.89$, the thin lens equation gives the object and image distances as $s_2 = 42.5$ mm and $s'_2 = 37.8$ mm, respectively. Therefore, the optical fiber array and the first tilted planar mirror are positioned 42.5 mm and 37.8 mm from the entrance-slit convex lens, respectively (Figure 5).

The system incorporates two tilted planar mirrors, each inclined at 45° relative to the surface normal of the entrance-slit mirror. To ensure alignment, the two arrayed signals, optical fiber arrays, entrance-slit lenses, and mirrors must be offset by a small vertical distance corresponding to the height of one light array while remaining parallel. Moreover, the path length for both signals must be identical to ensure intensity normalization across all LOS channels. Accordingly, the design uses 1-inch and 2-inch planar mirrors for the tilted and entrance-slit mirrors, respectively.

3. Conclusion

The optical emission spectroscopic (OES) diagnostics is currently under development for Thailand Tokamak

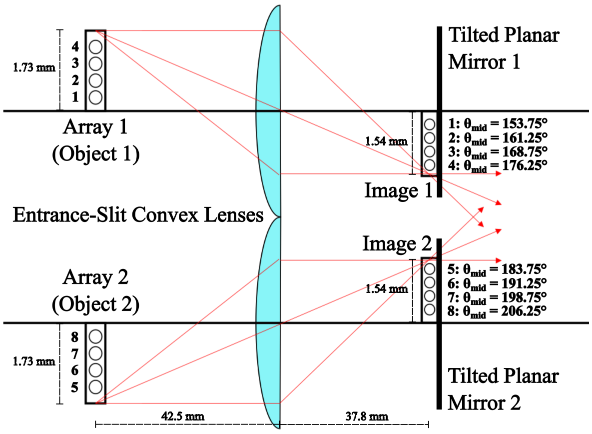

Figure 5. Designed Alignment of Arrayed Channels Passing through Entrance-slit Convex Lenses towards Tilted Planar Mirrors, where θ_{mid} is the poloidal angles at the middle of each line-of-sight (LOS).

1 (TT-1) to support impurity monitoring via visible line emission and enable future research into impurity transport. The preliminary design prioritizes simplicity and cost-efficiency by relying on commercially available vacuum and optical components. The diagnostics targets poloidal angles from 150° – 210°, with installation planned at the low-field-side mid-plane port. Considering of peripheral components such as gate valve and viewport has guided LOS geometry and angular coverage. The optical layout employs a combination of plano-convex lenses and planar mirrors to guide, collimate, and resize emission from eight LOS channels into optical fibers routed from the TT-1 main hall to the spectrometer. Optical calculations are based on the thin lens approximation, with design parameters verified to ensure effective light collection, proper magnification, and optical path matching. Alignment and calibration using emitted light sources will be conducted in subsequent stages to validate and refine the design prior to full system integration.

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