Investigation and Analysis of Plasma Turbulence and Wave–Plasma Interactions Using Doppler Backscattering Diagnostics in Tokamaks

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Preface

This report is based on the experience I gained during my internship at the Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), Singapore, under the Singapore International Pre-Graduate Award (SIPGA), from 30 September 2024 to 28 March 2025. It presents the research I carried out during this period.

This program has been a valuable opportunity that has greatly contributed to my future academic and professional development. I hope my experience will be helpful to readers and to those with similar interests.

Danis Klanurak

SIPGA program 2024

Acknowledgements

First and foremost, I would like to express my deepest gratitude to Her Royal Highness Princess Maha Chakri Sirindhorn for her gracious support in providing Thai students with the opportunity to participate in international research through the Singapore International Pre-Graduate Award (SIPGA). This internship would not have been possible without her vision and dedication to the advancement of education and research.

I am sincerely thankful to the National Science and Technology Development Agency (NSTDA) and the Princess Sirindhorn IT Foundation (PSIT) for their continued support of Thai students in pursuing international research and development opportunities. Their contributions have made this program and my participation in it possible.

I would like to extend my heartfelt appreciation to Dr. Valerian Hall-Chen for his expert guidance, encouragement, and genuine care in supporting my learning and growth. His mentorship has been truly inspiring—both academically and personally.

I also wish to thank the Institute of High Performance Computing (IHPC) and the Agency for Science, Technology and Research (A*STAR), Singapore, for providing a supportive and stimulating research environment.

Lastly, I am grateful to my university, professors, friends, and family for their constant encouragement throughout this journey.

Danis Klanurak

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Abstract

Plasma turbulence plays a crucial role in enhancing energy transport in fusion devices and remains one of the main challenges in achieving sustained performance in magnetic fusion devices such as tokamaks and stellarators. To better understand this behavior, Doppler Backscattering (DBS) is widely used as a diagnostic tool to provide localized measurements of density fluctuations and perpendicular plasma flow near the plasma edge. In this project, I investigated the behavior of DBS signals in the TCV tokamak, with a focus on identifying optimal launch conditions to maximize the received backscattered power. This analysis was performed using a beam-tracing code called SCOTTY. In addition, I analyzed experimental data from the MAST-U tokamak to examine how changes in plasma cross-section shaping influence plasma turbulence characteristics. I also contributed to the development of the SCOTTY DBS module within OMFIT, a software framework commonly used in the magnetic fusion research community. These efforts support both diagnostic optimization and improved analysis of turbulence behavior in magnetically confined plasmas.

Keywords: Tokamaks, Doppler Backscattering (DBS) diagnostic, Plasma turbulence, OMFIT, SCOTTY, Beam tracing, Turbulence diagnostics

Contents

Page

Page

Chapter 1

Introduction

1.1 Introduction to A*STAR

A*STAR, or the Agency for Science, Technology and Research, is a statutory board and a leading public sector agency under Singapore's Ministry of Trade and Industry. Established on 11 January 1991 as the National Science and Technology Board (NSTB), it was renamed A*STAR in January 2002. As a leading public sector agency, A*STAR spearheads scientific research and development, focusing on fostering world-class research and talent to drive economic growth and innovation. A*STAR collaborates with local and international partners including universities, research institutions, and industries—across a broad range of scientific and technological fields.

ASTAR's research spans from biomedical sciences to physical sciences and engineering, with most institutes located in Singapore's innovation hubs, Biopolis and Fusionopolis.

- **Biopolis:** A premier biomedical R&D hub focused on Singapore's biomedical sciences research. It supports innovation in areas such as molecular biology, bioinformatics, and clinical research, fostering collaboration among scientists, clinicians, and industry partners.
- **Fusionopolis:** A multidisciplinary research complex focused on engineering, infocomm technologies, and physical sciences. It fosters innovation in areas such as advanced manufacturing, robotics, materials science, and artificial intelligence, and provides a collaborative environment for researchers and developers.

1.2 Overview of the SIPGA Program

The Singapore International Pre-Graduate Award (SIPGA) provides international students with a unique opportunity to experience in scientific research at A*STAR. Eligible applicants include those pursuing a bachelor's or master's degree in computing and information science, Biomedical Science, Physical Science, or Engineering and Technology, for research attachments lasting two to six months.

In Thailand, Her Royal Highness Princess Maha Chakri Sirindhorn has supported this initiative by awarding four SIPGA scholarships to Thai science students, promoting scientific exchange and research experience at A*STAR.

1.3 Background and Research Motivation

Magnetic confinement fusion devices, such as tokamaks, aim to achieve sustained energy production by confining high-temperature plasmas. A major challenge in this process is turbulence near the plasma edge, which strongly affects energy transport and can significantly reduce plasma performance. Understanding controlling and suppressing this turbulence is essential for improving the efficiency and stability of tokamak operation.

To address this challenge, diagnostic tools are needed to measure and analyze turbulent behavior. One widely used method is Doppler Backscattering (DBS), which sends microwaves into the plasma and measures the backscattered signals to observe local density fluctuations and perpendicular plasma flow.

1.4 Objectives of the Study

This project aims to enhance the understanding and improvement of Doppler Backscattering (DBS) diagnostics for studying plasma turbulence in tokamaks. The main objectives of this study are as follows:

- To investigate the behavior of DBS signals under various launch conditions, with the goal of identifying optimal launch angles that maximize received DBS backscattered power.
- To analyze how variations in plasma cross-section shaping within a tokamak influence plasma turbulence characteristics.
- To contribute to the development and integration of the SCOTTY DBS module within the OMFIT framework to support more advanced analysis workflows.

Chapter 2
Theoretical Background

2.1 Tokamak

A tokamak is a type of nuclear fusion device designed to produce electrical energy from fusion reactions by confining hot plasma using a strong magnetic field. It typically uses isotopes of hydrogen—such as deuterium and tritium—as fuel, as they provide higher fusion cross-sections and energy output compared to other light nuclei. The fusion reaction is shown below.

$$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 17.59\mathrm{MeV}$$

When these nuclei fuse, they release a large amount of energy, primarily carried by high-energy neutrons. As neutral particles, these neutrons are not confined by the magnetic field and can escape the plasma, eventually colliding with the tokamak's first wall or the surrounding blanket within the vessel. The blanket absorbs the neutron energy and converts it into heat, which is then transferred to a coolant circulating through nearby heat exchangers. As the coolant heats up, it produces steam, which drives turbines to drive generators and produce electricity.

Many tokamaks have been developed worldwide for fusion research. In this project, the focus is placed on the TCV and MAST-U tokamaks.

2.1.1 Tokamak à configuration variable (TCV tokamak)

The Tokamak à Configuration Variable (TCV) is an experimental nuclear fusion device located at the Swiss Plasma Center (SPC), part of the École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland. TCV is designed to explore a wide range of plasma cross-section shapes and magnetic configurations, making it especially useful for studying the effects of magnetic geometry on plasma behavior and transport phenomena. The technical parameters of TCV are shown in Table 2.1.

Parameter	**Value**
Major radius	0.88 m
Minor radius	0.25 m
Magnetic field	1.43 T
Plasma current	1.2 MA

Table 2.1 Technical specifications of the TCV tokamak [1]

2.1.2 Mega Ampere Spherical Tokamak - Upgrade (MAST-U tokamak)

The Mega Ampere Spherical Tokamak – Upgrade (MAST-U) is an experimental fusion device located at the Culham Centre for Fusion Energy (CCFE) in Oxfordshire, United Kingdom. As an upgraded version of the original MAST tokamak, MAST-U is designed to investigate plasma behavior in a spherical tokamak configuration, which offers potential advantages in confinement efficiency and compactness. It plays a key role in advancing understanding of plasma exhaust, magnetic reconnection, and turbulence in next-generation fusion devices. The technical parameters of MAST-U are shown in Table 2.2.

Parameter	Value
Major radius	0.85 m
Minor radius	0.65 m
Magnetic field	0.5 T
Plasma current	1.3 MA

Table 2.2 Technical specifications of the MAST-U tokamak [2]

2.2 Plasma transport

Plasma transport refers to the movement of particles, energy, and momentum within a confined plasma, typically from the hot core region to the cooler edge, driven by plasma gradients and other effects. In magnetic confinement fusion devices such as tokamaks, understanding plasma transport is essential for improving energy confinement and overall performance.

Transport processes are generally categorized into two types. Neoclassical transport arises from collisional effects and magnetic geometry and is relatively well understood. In contrast, anomalous transport, primarily driven by plasma turbulence, represents non-classical behavior in the transport of particles and energy. Anomalous transport, especially in the core and edge regions, often exceeds neoclassical predictions and remains one of the major challenges in achieving sustained fusion conditions.

Turbulent fluctuations can significantly enhance radial transport, resulting in increased energy and particle losses. Therefore, understanding and accurately modeling turbulent transport are crucial for improving plasma confinement and advancing the design of future fusion reactors.

2.3 Doppler Backscattering (DBS)

Doppler Backscattering (DBS) is a microwave diagnostic technique widely used in magnetic confinement fusion experiments to study plasma turbulence and measure perpendicular plasma flow. It works by launching a microwave beam into the plasma at an oblique angle. When the beam encounters density fluctuations with a wavevector that matches the Bragg condition, a portion of the wave is backscattered. The Bragg condition for backscattering is expressed as:

$$k_{\perp} = -2K_{\mathrm{i}}$$

where $k_{\perp}$ is the perpendicular wavenumber of the density fluctuations and K_{i} is the incident wavevector of the probing microwave beam.

The backscattered power, which corresponds to the intensity of the backscattered signal, serves as a proxy for the amplitude of density fluctuations at the scattering location. The backscattered spectral power is given as in Eq. (5) of Hall-Chen, V.H. et al. (2022) [3] as:

$$p_r = C \int F_i \times F_m \times \delta \tilde{n}_e{}^2 dl$$

where C is constant, l is the arc length along the central ray, $F_m = \exp\left[-2 \frac{\theta_m^2}{(\Delta\theta_m)^2}\right]$ accounts for mismatch attenuation, and F_i represents the product of other instrumental functions, accounting for effects such as beam curvature, polarization, finite beam size, and detection system characteristics.

Mismatch attenuation refers to the reduction in backscattered power due to a misalignment between the probing microwave beam and the magnetic field direction at the scattering location in a plasma. The term θ_m, known as the mismatch angle, is the angle between the wavevector of the probing beam and the local magnetic field direction. The attenuation is modeled as a Gaussian function of θ_m. The parameter $\Delta\theta_m$ represents the $1/e^2$ width of the mismatch attenuation function and is referred to as the mismatch tolerance.

This power is influenced by both the strength and motion of density fluctuations. In particular, the motion induces a frequency shift of the backscattered signal, known as the Doppler shift, is related to the velocity of the density fluctuations. This relationship is expressed as [4]:

$$v_{\perp} = \frac{2\pi f_{Dopp}}{k_{meas}}$$

where $v_{\perp}$ is the perpendicular velocity, f_{Dopp} is the Doppler frequency shift, and k_{meas} is the measured wavenumber, which is obtained from ray- or beam-tracing codes. This allows DBS to provide localized measurements of the perpendicular flow velocity.

The perpendicular velocity generally consists of two components: the $\mathrm{E} \times \mathrm{B}$ drift velocity $(v_{E\times B})$ and the phase velocity (v_{ph}) of plasma fluctuations. It can be expressed as:

$$v_{\perp} = v_{E\times B} + v_{ph}$$

where $v_{E\times B} = \frac{\mathrm{E}\times\mathrm{B}}{B^2}$ is the drift velocity due to the electric and magnetic fields. Generally, $v_{E\times B}$ is the dominant component of the perpendicular velocity.

Due to its ability to provide spatially and temporally resolved data near the plasma edge, DBS is particularly useful for investigating turbulence behavior. The simulation and interpretation of DBS can be performed using ray- or beam-tracing codes such as GENRAY and SCOTTY.

Chapter 3
Methodology

3.1 Simulation Tools

To study Doppler Backscattering (DBS), this project employed two key simulation tools for magnetic confinement fusion research: SCOTTY and OMFIT.

3.1.1 SCOTTY Beam-Tracing Code

The SCOTTY beam-tracing code is a computational tool developed to simulate the propagation of microwave beams in magnetically confined plasmas, for diagnostics such as Doppler Backscattering (DBS) in tokamaks [5]. It requires input parameters such as launch frequency (in GHz), poloidal and toroidal launch angles, beam width, curvature, launch position, among others. SCOTTY provides detailed outputs such as the backscattered power, microwave beam trajectory, cutoff location, turbulence wavenumber, mismatch angle, and other key parameters relevant to DBS analysis.

In this project, SCOTTY was used to identify optimal launch conditions for maximizing the received backscattered power in the TCV tokamak. In addition, the SCOTTY module in OMFIT was updated from version 2.3.1 to 3.0.2 to incorporate the latest improvements and ensure compatibility with the most recent SCOTTY features. Minor modifications to the graphical user interface (GUI) were also made to support the new version.

3.1.2 GENRAY Ray-Tracing Code

GENRAY is a ray-tracing code widely used in fusion research to model the propagation and absorption of radiofrequency (RF) waves in magnetically confined plasmas [6]. GENRAY requires inputs such as plasma equilibrium (typically in the form of EFIT files), wave frequency, and launch geometry. GENRAY solves the cold plasma dispersion relation along the ray trajectory and outputs key parameters such as ray coordinates, refractive index, and wavevector components at each point along the path.

In this project, GENRAY was used within the OMFIT framework to investigate the local wavenumber at the scattering location in the MAST-U tokamak.

3.1.3 OMFIT Framework Integration

OMFIT (One Modeling Framework for Integrated Tasks) is a modular, Python-based framework widely used in the fusion research community to integrate data processing, analysis, and simulation workflows [7]. It provides a unified environment for handling equilibrium reconstructions, diagnostic data, and physics codes, making it a powerful tool for coordinating simulations with experimental analysis.

In this project, OMFIT was used to analyze experimental data from the MAST-U tokamak, providing tools for processing Doppler Backscattering (DBS) signals and investigating key turbulence characteristics using outputs from GENRAY and SCOTTY.

3.2 DBS Analysis in TCV and MAST-U

This section presents the methods used to investigate Doppler Backscattering (DBS) in two different tokamak devices: TCV and MAST-U. In TCV, DBS behavior was studied through numerical simulations using the SCOTTY beam-tracing code to identify optimal launch conditions for improved diagnostic performance. In contrast, the analysis of plasma cross-section shaping effects in MAST-U was based on experimental DBS data processed using the OMFIT framework.

3.2.1 Beam-Tracing Simulations in TCV

In this study, beam-tracing simulations were conducted using the SCOTTY code to investigate the behavior of Doppler Backscattering (DBS) in the TCV tokamak. The objective was to explore how different launch configurations affect the received backscattered signal and to identify optimal conditions that maximize the backscattered power.

The simulations were performed over a range of key launching parameters, including:

- **Poloidal launch angles ($\boldsymbol{\varphi_p}$):** 45° - 75°
- **Toroidal launch angle ($\boldsymbol{\varphi_t}$):** -20° - 35°
- **Launch frequencies ($\boldsymbol{f}$):** 45 - 75 GHz (V-band)
- **Wave mode:** X-mode

The SCOTTY simulations provided output such as the beam trajectory, cutoff location, and mismatch angle. These results serve as a guide for experimental planning and help in understanding the limitations and sensitivity of the DBS diagnostic in TCV.

3.2.2 Experimental Analysis of DBS Signals in MAST-U

Experimental DBS data from the MAST-U tokamak were analyzed using the OMFIT framework. The analysis focused on how variations in plasma squareness affect turbulence behavior near the plasma edge.

I/Q signals are the in-phase (I) and quadrature-phase (Q) components of the DBS receiver output, carrying the amplitude and phase information needed to extract Doppler shifts and backscattered power. The perpendicular flow velocity $v_\perp$ was then computed using the Doppler shift and the measured wavenumber k_{meas}, which was estimated from GENRAY simulation. The main analysis outputs included:

- **Doppler shift (f_{Dopp})**
- **Perpendicular velocity ($v_{\perp}$)**
- **Turbulence wavenumber ($k_{\perp}$)**
- **Normalized turbulence scale ($k_{\perp}\rho_{s}$)**
- **Backscattered power (P_{s})**

Chapter 4

Results and Discussions

4.1 Simulation Results from TCV

This section presents the results of Doppler Backscattering (DBS) beam-tracing simulations performed for TCV shot #79747 at $t = 1$s, using the SCOTTY code. The aim of the simulations was to identify optimal launch conditions that maximize the received backscattered power (P_{S}). A range of poloidal launch angles (φ_{p}), toroidal launch angles (φ_{t}), and microwave frequencies (f) were scanned. In this report, only the case with $\varphi_{\mathrm{p}} = 60°$ is shown, as the results for other angles exhibit similar behavior.

Efficient backscattering requires the incident beam to be nearly perpendicular to the local magnetic field at the scattering layer, corresponding to a small mismatch angle. Increasing misalignment reduces backscattered signal strength. Changes in the toroidal launch angle affect this alignment, and thus the mismatch angle and mismatch attenuation, as shown in Figure 4.1.

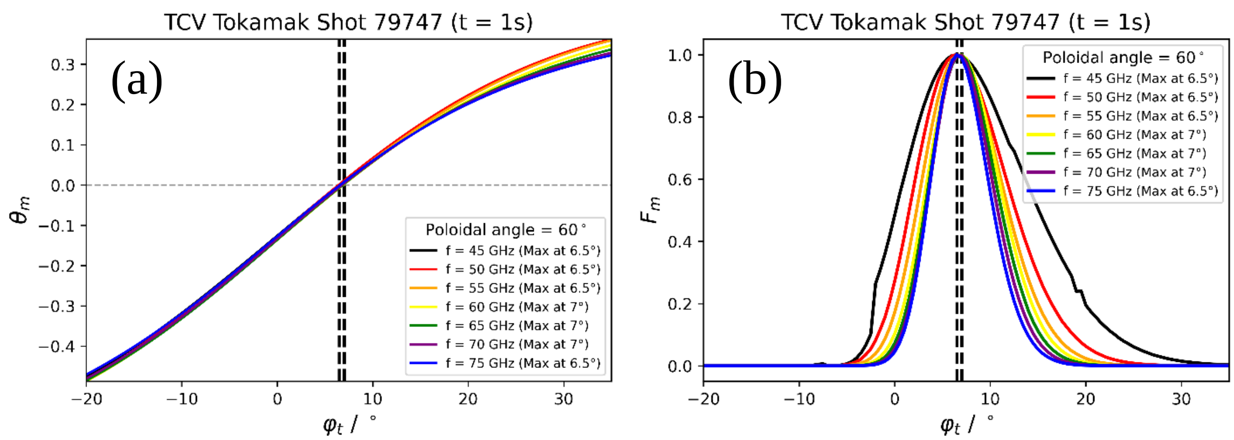

Figure 4.1 Mismatch angle θ_m and (b) mismatch attenuation factor F_m as a function of toroidal launch angle φ_{t} for different microwave frequencies in TCV shot #79747 at $t = 1$s, with a fixed poloidal launch angle of 60°.

As shown in Figure 4.1(a), the mismatch angle θ_m varies systematically with toroidal launch angle φ_{t} for all microwave frequencies. This reflects the changing misalignment between the incident beam and the magnetic field at the cutoff location. The vertical dashed lines indicate the toroidal angles where the backscattered power is maximized for each frequency, corresponding to points where θ_m is closest to zero. These points lead to the maximum of the mismatch attenuation factor F_m, as shown in Figure 4.1(b). These results demonstrate that optimal launch configurations occur between $\varphi_{\mathrm{t}} = 6.5° - 7°$, depending on the frequency, where the beam alignment is most favorable for backscattering.

4.2 Experimental Results from MAST-U

In this study, experimental Doppler Backscattering (DBS) data from the MAST-U shots #50934 to #50937 were analyzed to investigate plasma turbulence behavior during changes in plasma cross-section shaping. The analysis focused on time-resolved signals from eight DBS channels. Each channel provides localized measurements of backscattered power and Doppler shift, providing turbulence dynamics and perpendicular flows across different radial positions.

The digitized in-phase (I) and quadrature (Q) signals were combined to form a complex time series $S(t) = I(t) + iQ(t)$, which was then processed using a windowed short-time Fourier transform (wSTFT) to extract the time-resolved amplitude and phase information. The backscattered power spectrum was calculated by integrating the squared magnitude of the quadrature amplitude spectrum, while the Doppler shifts were determined from the spectral centroid. These quantities are directly related to turbulence intensity and perpendicular flow velocity at different radial positions in the plasma. Variations in signal amplitude were observed across different channels, reflecting spatial variations in turbulence intensity and flow characteristics.

Temporal evolution of the backscattered power spectra and Doppler shifts showed distinct patterns before and after a change in plasma cross-section shaping. This indicates that the turbulence characteristics and perpendicular flow velocity were affected by the shaping configuration. These observations highlight the role of DBS as a powerful diagnostic for characterizing turbulence in tokamaks.

4.3 Upgrade of the SCOTTY Module in OMFIT

In this study, the SCOTTY module in OMFIT was upgraded from version 2.3.1 to 3.0.2. This update was essential to incorporate new features and improvements.

A key change in version 3.0.2 is the replacement of multiple .npz output files into a single unified .h5 output format. The Python script for DBS analysis and minor GUI components in OMFIT were updated to ensure compatibility with the latest version of SCOTTY. These modifications preserved access to essential analysis outputs such as beam trajectories and scattering localization.

The updated module was successfully implemented and is well-positioned to support future diagnostic studies within OMFIT.

Chapter 5
Conclusions

5.1 Conclusions from DBS Diagnostic Studies

This project explored plasma turbulence and the optimization of Doppler Backscattering (DBS) diagnostics through a combination of beam-tracing simulations and experimental data analysis on two tokamaks: TCV and MAST-U.

- **TCV Simulations:** SCOTTY beam-tracing simulations were conducted to optimize the launch conditions for maximizing the received backscattered power. Optimal toroidal launch angles, where the mismatch angle is minimized and the backscattered power is maximized, were found to lie in the range $\varphi_{\mathrm{t}} = 6.5° - 7°$ for a fixed poloidal angle of $\varphi_{\mathrm{p}} = 60°$. Additionally, a broad range of poloidal launch angles were also investigated to further optimize the received backscattered power.
- **MAST-U Experiments:** Experimental DBS signals from MAST-U revealed clear changes in fluctuation levels and Doppler shifts before and after magnetic shaping transitions. These variations suggest that plasma turbulence and perpendicular flows are sensitive to plasma cross-section shaping.
- **SCOTTY Upgrade in OMFIT:** The SCOTTY beam-tracing module in OMFIT was upgraded from version 2.3.1 to 3.0.2 to incorporate new features and improvements. The Python script for DBS analysis and the GUI were also updated to ensure compatibility with the latest SCOTTY version.

5.2 Future Work

This project has laid the groundwork for further advancements in the use of Doppler Backscattering (DBS) diagnostics and beam-tracing simulations for turbulence analysis in magnetically confined plasmas. Several directions are proposed for future research and development:

- **Expanded Simulation Campaigns:** Further simulations using the SCOTTY beam-tracing code across a broader range of magnetic configurations, plasma scenarios, and DBS launch conditions could provide deeper insights into plasma behavior and turbulence characteristics.
- **Application to Other Devices:** Applying the DBS diagnostic and SCOTTY beam-tracing code to additional devices such as Thailand Tokamak 1 (TT-1) could support the investigation of plasma behavior and turbulence characteristics in various magnetic confinement configurations.

These directions aim to build on the current work and support ongoing efforts toward more precise and efficient turbulence diagnostics in fusion plasmas.

Appendix A
Personal Reflection

A.1 Daily Life During the Project

Over the course of six months, my research experience at A*STAR was both smooth and fulfilling. While some aspects of the work were new to me and required time to adapt, the adjustment period was relatively short. My supervisor was extremely supportive, providing consistent guidance and arranging weekly progress meetings.

In terms of daily life, things went smoothly. Although my accommodation was relatively far from Fusionopolis (the research site), the public transport system in Singapore is excellent, and my MRT commute took about 40–50 minutes. Meals were affordable, with most hawker centers offering options between SGD 5–8. Essentials such as toiletries and medications were easy to find and reasonably priced—comparable to those in Thailand.

A.2 Budget and Living Expenses

The monthly stipend of SGD 2000 was somewhat limited for individuals renting a place without sharing. My expenses were approximately as follows:

- **Food:** SGD 450/month (~SGD 15/day)
- **Transport (MRT/Bus):** SGD 150/month (~SGD 5/day)
- **Personal and recreational expenses:** SGD 200/month
- **Rent:** SGD 600/month (shared with a roommate; actual rent was SGD 1200)
- **Emergency savings:** SGD 600/month

Thanks to modest spending on food and shared accommodation, I was able to save a portion of my stipend. Without such cost-saving measures, expenses could easily exceed the budget, especially with solo housing. In that case, only a small portion of the stipend would remain for other expenses. A more suitable stipend for single accommodation living might be around SGD 2500 per month.

A.3 Challenges and Suggestions

One minor issue was the delay in receiving the first payment, which took about 1.5 months. This delay was primarily due to the time required for setting up a Singpass account and a local bank account. While not a major problem, it did affect initial budgeting.

Another challenge was finding housing. It would be helpful if the supporting foundation could assist future scholars in finding suitable accommodation, possibly by connecting them with students or researchers already based in Singapore.

A.4 Contribution to Thailand

This internship experience has equipped me with skills in plasma diagnostics, beam-tracing simulation, and integrated modeling using tools like SCOTTY and OMFIT. These tools are widely used in international fusion research, and the knowledge gained can directly support ongoing fusion initiatives in Thailand, such as the development and operation of Thailand Tokamak 1 (TT-1).

Beyond technical skills, this experience also enhances academic exchange opportunities and may serve as a model for future Thai students and researchers to collaborate with international institutions like A*STAR, potentially strengthening long-term partnerships in nuclear fusion research.

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