Master Thesis

Czech Technical University in Prague

F4

Faculty of Nuclear Sciences and Physical Engineering
Department of Physics

Investigation of the impact of the edge radial electric field on turbulence and Zonal Flows in toroidal fusion devices

Bc. Filip Papoušek

Supervisor: Ing. Ondřej Grover, Ph.D.
Supervisor–specialist: Dr. Carlos Hidalgo Vera
Field of study: Physics and Technology of Thermonuclear Fusion
January 2024

FAKULTA JADERNÁ A FYZIKÁLNĚ INŽENÝRSKÁ

KATEDRA FYZIKY

ZADÁNÍ DIPLOMOVÉ PRÁCE

Akademický rok: 2022/2023

Student:	Bc. Filip Papoušek
Studijní program:	Aplikace přírodních věd
Obor:	Fyzika a technika termojaderné fúze
Název práce: (česky)	Studium vlivu radiálního elektrického pole na okraji plazmatu na turbulenci a zonální toky v toroidálních fúzních zařízeních
Název práce: (anglicky)	Investigation of the impact of the edge radial electric field on turbulence and Zonal Flows in toroidal fusion devices
Jazyk práce:	Angličtina

Pokyny pro vypracování:

1) Studujte vliv radiálních elektrických polí na spektra lokální turbulence rozlišená ve vlnovém čísle a frekvenci, turbulentní transport a globální zonální toky v existující databázi výbojů na stelarátoru TJ-II.

2) Podílejte se na provedení a analýze experimentů, kde bude zkoumán vliv radiálních elektrických polí na zonální toky a turbulentní transport za pomoci kontroly radiálních elektrických polí různými druhy ohřevu plazmatu nebo nabíjení plazmatu se zpětnovazebním řízením zonálních toků.

3) Proveďte statistickou analýzu turbulentních charakteristik v tokamaku GOLEM s důrazem na opakovatelnost výbojů a stanovení statistické neurčitosti.

4) Studujte vliv radiálních elektrických polí na výkonová a kros spektra lokální turbulence, turbulentní transport a globální fluktuace plazmatu na tokamaku GOLEM.

5) Optimalizujte nabíjení okraje plazmatu na tokamaku GOLEM vzhledem k redukci transportu napříč magnetickým polem na základě experimentů na TJ-II a předchozích měření fluktuací plazmatu na tokamaku GOLEM.

6) Srovnejte výsledky z experimentů na TJ-II a tokamaku GOLEM.

Doporučená literatura:

[1] K. Miyamoto: Plasma Physics for Controlled Fusion, Springer, 2016

[2] J.S. Bendat and A.G. Piersol: Random Data: Analysis and Measurement procedures, John Wiley & Sons, 2011

[3] C. Silva, et al.: Experimental evidence of turbulence regulation by time-varying Ex B flows, Nucl. Fusion 58, 026017 (2017)

[4] C. Hidalgo: Multi-scale physics and transport barriers in fusion plasmas, Plasma Phys. Control. Fusion 53, 074003 (2011)

[5] B.Ph. van Millingen, et al.: Wavelet bicoherence: A new turbulence analysis tool, Phys. Plasmas 2, 3017 (1995)

Jméno a pracoviště vedoucího diplomové práce:

Ing. Ondřej Grover, Ph.D.

Ústav fyziky plazmatu AV ČR, v.v.i

Konzultant:

Ing. Vojtěch Svoboda, CSc.

Katedra fyziky, Fakulta jaderná a fyzikálně inženýrská ČVUT v Praze

Dr. Carlos Hidalgo Vera, Laboratorio Nacional de Fusión, CIEMAT

Datum zadání diplomové práce: 20.10.2022

Termín odevzdání diplomové práce: 03.05.2023

Doba platnosti zadání je dva roky od data zadání.

....

garant oboru

....

vedoucí katedry

....

děkan

V Praze dne 20.10.2022

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta jaderná a fyzikálně inženýrská

Břehová 7
115 19 Praha 1

P R O H L Á Š E N Í

Já, níže podepsaný

Jméno a příjmení studenta:	Bc. Filip Papoušek
Osobní číslo:	468017
Studijní program:	Aplikace přírodních věd
Studijní obor:	Fyzika a technika termojaderné fúze
Specializace:	-

prohlašuji, že jsem diplomovou práci s názvem:

Studium vlivu radiálního elektrického pole na okraji plazmatu na turbulenci a zonální toky v toroidálních fúzních zařízeních

vypracoval samostatně a uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

Rovněž souhlasím s porovnáním textu mé kvalifikační práce s databází kvalifikačních prací Theses.cz provozovanou Národním registrem vysokoškolských kvalifikačních prací a systémem na odhalování plagiátů.

V Praze dne 8.1.2024 ....

podpis

Acknowledgements

First of all, I would like to express my most sincere thanks to my supervisor Ondřej Grover for his never ending patience with me and his irreplaceable advice he gave me. Despite a lack of communication from my side he always act kind and was positively motivating. Than I would like to express my thanks to Carlos Hidalgo, who led me during my stay in Madrid. The third in a row would be Ing. Vojtěch Svoboda, CSc. whose inexhaustible enthusiasm gives students access to hands on experiments on the GOLEM tokamak and who was always willing to stay late or come to the tokamak during weekend. Last but not least, I thank my family for supporting me during my studies and the team around the TJ–II stellarator for providing valuable data. And thank you Bara for never letting me give up.

Abstract

Langmuir probe arrays were used to measure properties of edge plasma in the GOLEM tokamak and the TJ-II stellarator with emphasis on the characterization of ion saturation current fluctuations. The conditions on the plasma edge were modified using biasing electrode in two operating modes. Constant applied voltage (DC) and harmonic applied voltage (AC), influence on the level of ion saturation current flucutations was obeserved namely in the TJ-II stellarator, where modulation of ExB transport was observed. In the GOLEM tokamak rather enhancement of floating potential fluctuations around the AC biasing frequency of 15 kHz was observed.

Keywords: tokamak, stellarator, GAM, Langmuir probes, turbulence

Supervisor: Ing. Ondřej Grover, Ph.D.
Max Planck Institute for Plasma Physics
Boltzmannstraße 2
85748
Garching
Germany

Abstrakt

Langmuirovy sondy byly použity k měření vlastností okrajového plazmatu v tokamaku GOLEM a stelarátoru TJ-II s důrazem na charakterizaci fluktuací iontového saturovaného proudu. Podmínky na okraji plazmatu byly modifikovány pomocí nabíjecí elektrody ve dvou provozních režimech. Vliv konstantního přiloženého napětí (DC) a harmonického přiloženého napětí (AC) na úroveň fluktuací iontového saturovaného proudu byl pozorován zejména ve stelarátoru TJ-II, kde byla pozorována modulace ExB transportu. V tokamaku GOLEM bylo pozorováno spíše zesílení fluktuací plovoucího potenciálu v okolí střídavé nabíjecí frekvence 15 kHz.

Klíčová slova: tokamak, stellarator, GAM, Langmuirovy sondy, turbulence

Překlad názvu: Studium vlivu radiálního elektrického pole na okraji plazmatu na turbulenci a zonální toky v toroidálních fúzních zařízeních

Contents

Figures

Tables

Introduction

In the search for sustainable and clean energy sources, thermonuclear fusion is at the forefront of scientific research as a promising solution for the future. The quest to harness the power of fusion, the same process that powers the stars, offers the opportunity to meet the world's growing energy needs without relying on depleting fossil fuels and with minimal environmental impact. Unlike traditional nuclear fission, which splits heavy atomic nuclei, fusion involves the fusion of light atomic nuclei, typically isotopes of hydrogen such as deuterium and tritium.

At present, the most successful and widely studied configuration for achieving controlled thermonuclear fusion is the tokamak. Tokamaks, with their toroidal design, have been instrumental in advancing our understanding of plasma confinement and fusion reactions. However, they require a large plasma current to maintain magnetic confinement, which poses a challenge for continuous operation. In contrast, stellarators, with their intricate coil arrangements, offer a path to steady state operation by providing the necessary magnetic confinement without relying on a large plasma current. This advantage positions stellarators as a potentially more promising route to practical fusion energy.

Despite progress in magnetic confinement fusion, one of the major challenges that remains is the understanding and control of plasma turbulence. Turbulence, famously described by physicist Richard Feynman as "the most important unsolved problem of classical physics", is a complex phenomenon that significantly affects plasma confinement and stability. In the context of fusion devices, edge plasma turbulence plays a crucial role as it directly affects the transport of energy and particles to the walls of the confinement vessel, thus affecting the overall efficiency of the fusion process.

Langmuir probes have been used to study the effects of turbulence in fusion plasma. Arrays of Langmuir probes provide high spatial and temporal resolution measurements of plasma parameters in the edge region, where the plasma cannot damage the probes. In this work, the effect of changing the edge potential was studied using a bias electrode capable of modifying the edge plasma. The effect has been studied in two toroidal devices. Experimentally on the GOLEM tokamak, a small tokamak located in Prague, and by studying old data from the TJ–II stellarator, a medium-sized stellarator located in Madrid. The effect of the edge potential bias was observed in both cases, but was more pronounced in the case of the TJ–II stellarator, where a decrease in turbulent $E \times B$ flux $\Gamma_{E\times B}$ was observed. A frequency resolved $\Gamma_{E\times B}$

highlights the importance of the cross phase between density fluctuations and electric field fluctuations.

Theoretical introduction

Chapter 1

Introduction

In this first chapter, the principles of thermonuclear fusion are introduced. Further, the theory of turbulence is briefly described and Langmuir probe measurements introduced.

1.1 Fusion overview

In the simplest form, fusion reaction merges two lighter nuclei into one heavier nucleus. Because of mass difference Δm between the nuclei entering the reaction and the product(s) of the reaction, energy equivalent to

$$E = \Delta m c^2, \tag{1.1}$$

where c is the speed of light, is released. This results into one of the highest energy gains of reactions in nature on the unit of fuel mass (the only greater energy gain being released from annihilation, where all the mass of the reactants is being transformed into energy according to 1.1).

To overcome the repulsive Coulomb interaction between the positively charged nuclei, the nuclei need to be within a distance at which the strong nuclear force predominates over Coulombic repulsion. Achieving this necessitates sufficient relative velocity and initial proximity of the nuclei. This could be done with beam–target configuration where we would bombard a fuel target with fuel beam. In such configuration, there are fusion reactions, but the power needed to produce the beam exceeds the power gained, which is not a good approach for a power plant. In nature there is another way.

In principle, we would like to imitate the process in stars to harness energy from fusion, the process is called thermonuclear fusion, a name suggesting that the proximity of the two nuclei is attained via high temperature. However, there are a few key differences, stars like Sun reach the conditions needed to start and maintain the reaction by combination of high temperature, high density (gravitational pressure) and long time. In Earth conditions, it is not possible to use the directly same approach, but rather two distinctive ones, one of them is keeping the hot plasma for as long as possible (MCF - Magnetic Confinement Fusion) the other applies high pressure for a short period of time (ICF – Inertial Confinement Fusion), this thesis focuses on the MCF. The previous statement may be mathematically expressed via so called Lawson criterion. Lawson criterion gives the relation for the product of the confinement time τ_e and the plasma density n to achieve positive energy gain from a fusion reactor. For the D–T reaction (more in the next paragraph) the expression is

$$n\tau_\mathrm{e} \geq 1.5 \cdot 10^{20}\,\mathrm{s} \cdot \mathrm{m}^{-3}. \tag{1.2}$$

Since the energy losses from radiation are proportional to the square root of temperature [13], our goal is to use as low temperature as possible. To simplify the process of making fusion power plant feasible by lowering the temperature needed to ignite the fusion reaction, we will not use the same reaction, as for example, the Sun. In the Sun there a is so–called proton–proton chain, where the initial reactants are the nuclei of light hydrogen H, but for the conditions here on Earth, the favourable reaction is, however, the reaction of two heavier hydrogen isotopes, deuterium ($^2_1$H or D) and tritium ($^3_1$H or T). But the "as low temperature as possible" are still about 150 000 000 K as can be seen in the Figure 1.1, at this temperature any substance turns into plasma. How to prevent the hot plasma from contacting the relatively cold chamber wall is the subject of the next section.

1.1.1 Magnetic confinement

To keep the plasma from hitting the vessel walls we create an inner magnetic vessel exploiting the quasi-neutrality of plasma that can be affected by electromagnetic fields. In a very simplistic way, one would create a magnetic vessel by placing two helmholz coils next to each other with their axes of symmetry aligned, this would create so called magnetic mirror. However, such configuration may never confine plasma for long enough due to end

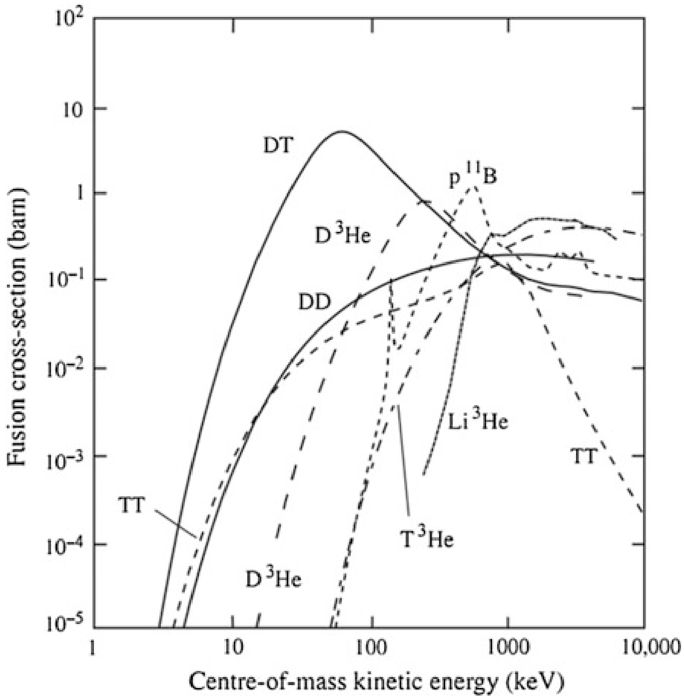

Figure 1.1: The cross section for different fusion reactions depending on temperature a clear peak can be seen for DT reaction. Reproduced from [15].

losses. This finding led to creation of toroidal shaped devices, where the open ends are not present.

1.1.2 TJ – II stellarator

The TJ-II stellarator, located in Madrid, Spain, initiated as part of Spain's National Fusion Laboratory, was developed by the Research Centre for Energy, Environment and Technology (CIEMAT – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas). The construction of TJ-II began in the early 1990s, reflecting Spain's commitment to advancing fusion technology. TJ-II is a four–period–flexible Heliac–type stellarator, a design known for its helically wound coils that together with the plasma column wrap around a central planar coil and create a magnetic field to confine plasma. Unlike tokamaks, stellarators like TJ-II do not require a current to flow through the plasma, making them potentially more stable and suitable for continuous operation. Since its first plasma in 1997, TJ-II has been a hub for international research, contributing valuable data and insights to the global fusion research community. The facility's flexibility allows for a wide range of plasma configurations, making it an invaluable tool for studying the behaviour of hot plasma and exploring different aspects of magnetic confinement fusion [5], [17]. The main parameters of the TJ–II stellaratorcan be seen in Table 1.1.

Parameter	**Value**
Type	Heliac-type Stellarator
Major Radius	1.5 m
Average Minor Radius	$\leq$ 0.22 m
Periods	4
Average Magnetic Field (Axis)	0.95 T
Plasma Volume	$\leq$ 1 m^3

Table 1.1: Basic Parameters of the TJ-II Stellarator [5].

1.1.3 GOLEM tokamak

The GOLEM Tokamak, situated at the Czech Technical University in Prague, serves as an educational and training platform for students and researchers in the field of plasma physics and nuclear fusion. Originally named CASTOR (Czech Academy of Sciences TORus), it was relocated and renamed to emphasize its renewed focus on educational purposes. GOLEM is notable for being one of the few tokamaks globally accessible remotely, offering unique opportunities for online experiments in plasma physics. This tokamak, despite its compact size, is equipped to perform a wide range of plasma experiments, making it an invaluable resource for hands-on learning and research in controlled nuclear fusion. The basic parameters can be found in Table 1.2.

Parameter	**Value**
Major Radius	0.4 m
Minor Radius	0.1 m
Magnetic Field	Up to 0.6 T
Plasma Current	Up to 10 kA
Pulse Duration	Up to 20 ms
Plasma Temperature	Up to 1 keV

Table 1.2: Basic Parameters of the GOLEM Tokamak

1.1.4 Turbulence basics

Turbulence is omnipresent (ubiquitous). It allows us to stir the sugar in coffee effectively. There is no keen definition of what a turbulence is, one may describe it as non–laminar flow, which would be a feeble and rather ambiguous definition. It can be characterised by chaotic changes in pressure and velocity.

Turbulence is a framework used as an explanation of the magnitude of observed transport, neoclassical effects are about 2 orders of magnitude weaker then what is observed. Turbulence in fusion devices are small scale fluctuations in density, temperature and plasma potential $\tilde{n}_\mathrm{e}$, $\tilde{T}_\mathrm{e}$, $\tilde{\phi}_\mathrm{e}$, where we define fluctionations as

$$\tilde{x} = x - \langle x \rangle \, .$$

This is a electrostatic turbulence, for the sake of completeness we mention a electromagnetic turbulence. Electrostatic turbulence is created by $\tilde{E} \times B$ and the resulting drift. Once there are $\tilde{B}$ then we talk about electromagnetic turbulence, caused by magnetic islands, but it is not a case we will further discussed in this thesis.

Zonal flows and GAMs

Zonal flows can suppress turbulence by shearing the small–scale eddies that drive the turbulence, but the presence of the turbulence can also modify the zonal flow, resulting in a self–regulating feedback loop. This feedback mechanism can lead to a highly dynamic and non–linear interaction between zonal flows and turbulence [4].

The interaction between zonal flows and turbulence is also affected by the geometry of the tokamak (or stellarator) device. In particular, the presence of toroidal effects, such as plasma rotation and magnetic shear, can modify the dynamics of both zonal flows and turbulence, leading to another phenomena – Geodesic Acoustic Modes (GAMs). Because of their characteristic properties, GAMs became recently [3] searched for in a number of devices (ISTTOK [11], JET [10], COMPASS–D [9]). Geodesic Acoustic Modes (GAMs) are a category of zonal flows within a tokamak, characterised by their symmetric oscillations around the toroidal shape of the device without any twist (n=0) and constant plasma potential at the magnetic surfaces ($m_\mathrm{phi} = 0$). They are influenced by the curvature of the plasma path, which links them to certain pressure variations that have a stationary wave pattern. Observations also show that these modes are associated with fluctuations in the plasma temperature [9]. The symmetry, together with well defined frequency derived for circular plasma in [18] and can be approximated as

$$f_{\mathrm{GAM}} = \frac{c_{\mathrm{s}}}{2\pi R}, \tag{1.3}$$

where R and c_{s} represent the major radius of the device and the sound wave velocity, respectively. Sound wave velocity can be be expressed as [3]

$$c_{\mathrm{s}} = \sqrt{\frac{\gamma\left(T_{\mathrm{e}} + T_{1}\right)}{m_{\mathrm{i}}}}, \tag{1.4}$$

where $_{\mathrm{i}}$ and T_{e} represent the ion temperature and the electron temperature, respectively. m_{i} represents ion mass andγ specific heat ratio and equals 5/3 for mono-atomic gas.

Characterising the fluctuation $\vec{E} \times \vec{B}$ driven particle flux requires experimental techniques for measuring the variations in parameters such as density and electric fields with good temporal and spatial resolution. Electrostatic fluctuations produce a fluctuating radial particle flux given by

$$\Gamma_{E\times B} = \frac{\left\langle \tilde{n}(t)\tilde{E}_{\Phi}(t)\right\rangle}{\mathbf{B}}, \tag{1.5}$$

$\tilde{n}$ being the fluctuating poloidal electric field and $\mathbf{B}$ the magnitude of the toroidal magnetic field. Then, the electrostatic fluctuation driven radial particle flux is given by (being the level of density fluctuations). Particle transport induced by edge electrostatic fluctuations is large enough to account for a significant part of particle transport in the plasma boundary region, although the interpretation of probe experimental measurements is still under active debate. According to [8] equation 1.5 can be modified to

$$\langle \tilde{n}\tilde{v}\rangle_{\delta\omega} = \frac{1}{B}|\gamma_{nE_{\mathrm{pol}}}|\cos\left(|\alpha_{nE_{\mathrm{pol}}}|\right) n_{\mathrm{rms}} E^{\mathrm{pol}}_{\mathrm{rms}}, \tag{1.6}$$

where

$$n_{\mathrm{rms}} = \sqrt{2P_{\mathrm{nn}}(\omega)\delta\omega} E^{\mathrm{pol}}_{\mathrm{rms}} = \sqrt{2P_{E_{\mathrm{pol}}E_{\mathrm{pol}}}(\omega)\delta\omega}$$

and

$$\left|\gamma_{nE_{\mathrm{pol}}}\right| = \frac{|P_{\mathrm{nE_{pol}}}|}{\sqrt{P_{\mathrm{nn}}P_{\mathrm{E_{pol}E_{pol}}}}}$$

$E^{\mathrm{pol}}_{\mathrm{rms}}$ denotes the root–mean–square of poloidal electric field, calculated as the square root of powerspectra of the poloidal electric field, the same holds for n_{rms}. $\left|\gamma_{nE_{\mathrm{pol}}}\right|$ is the coherence spectrum of density and poloidal electric field fluctuations. Electric field was calculated as a difference between two U_{float}measuring tips. This allows for obtaining frequency resolved transport, where the contribution to total transport can be seen for different modes.

1.2 Langmuir probes in the edge plasma

Langmuir probes are essential diagnostic tools in plasma physics, particularly for studying the edge plasma in fusion devices. These probes work by measuring current–voltage characteristics that provide insight into plasma properties. Key measurements include the floating potential (U_{float}) and the ion saturation current (I_{sat}). U_{float} is the probe potential at which the net current is zero, an approximation of the plasma potential. However, this measurement is an approximation and is affected by the electron temperature T_{e} according to [1]

$$\phi_{\mathrm{pl}} = U_{\mathrm{float}} + \alpha T_{\mathrm{e}}, \tag{1.7}$$

where α is for hydrogen plasma ≈ 2.3 and denotes the absolute value of the logarithm of ration of electron and ion saturation current respectively. for the scope of this thesis we neglect the as we focus on the fluctuating part of the signals and assume low enough and use

$$\phi_{\mathrm{pl}} = U_{\mathrm{float}} \tag{1.8}$$

To properly address the issue with neglecting electron temperature gradient a new type of probe called Ball–pen probe was developed on

The measurement of the ion saturation current is critical in determining the plasma density. When a probe is negatively biased it collects ions and the current is proportional to the ion density. The I_{sat} is given by

$$I_{\mathrm{sat}} = A_p e n_i \sqrt{\frac{kT_e}{2\pi m_i}}, \tag{1.9}$$

where A_p is the probe area, n_i is the ion density and m_i is the ion mass. However, this measurement has limitations, particularly in relation to the Debye length λ_{D} and sheath effects. λ_{D} must be much smaller than the probe dimensions to ensure accurate measurements, and sheath effects can also alter the current collected by the probe [16].

Despite these limitations, Langmuir probes offer high temporal and spatial resolution, making them invaluable for studying dynamic plasma processes. They can capture rapid fluctuations in plasma parameters, providing detailed insights into plasma turbulence and transport phenomena. The ability to place probes at different locations allows comprehensive plasma characterisation, improving our understanding of edge plasma behaviour.

In summary, while Langmuir probes are indispensable in edge plasma diagnostics, their effective use requires careful consideration of their limitations and the underlying physics. The interpretation of probe data must take into account the Debye length, sheath effects and the assumptions used to derive plasma potential and density from probe measurements.

Experimental results

Chapter 2

TJ – II

The TJ-II is a four-period heliac-type stellarator, known for its advanced design that facilitates intricate plasma studies. It features two neutral beam injection (NBI) systems and Electron Cyclotron Resonance Heating (ECRH) for effective plasma heating and control. The stellarator is also equipped with two arrays of Langmuir probes, enabling detailed measurement of plasma parameters and enhancing its research capabilities.

2.1 Experimental setup

Plasma scenario

Standard operation starts with heating the plasma by injecting microwave beams with a power of ≤ 0.6 MW at a frequency of 53.2 GHz (the second harmonic of the electron cyclotron resonance frequency at 0.95 T), followed by plasma sustained with co $[P\_mrmNBI - 1 \approx 500$ kW] or and counter $[P_{\mathrm{NBI-2}} \approx 500$ kW] neutral beam injection. In the present experiments, in some scenarios the plasma density was held constant while in others the density was ramped up until reaching the density limit. The line averaged density varied in the range $0.5 - 3 \times 10^{19}\mathrm{m}^{-3}$ and central electron temperature $T_{\mathrm{e}} = 1$ keV - 400 eV in ECRH and NBI scenarios respectively. The experimental setup on the TJ–II stellarator can be seen in Figure 2.1 showing the placement of Langmuir probe arrays in sectors B and D. Probe B was a

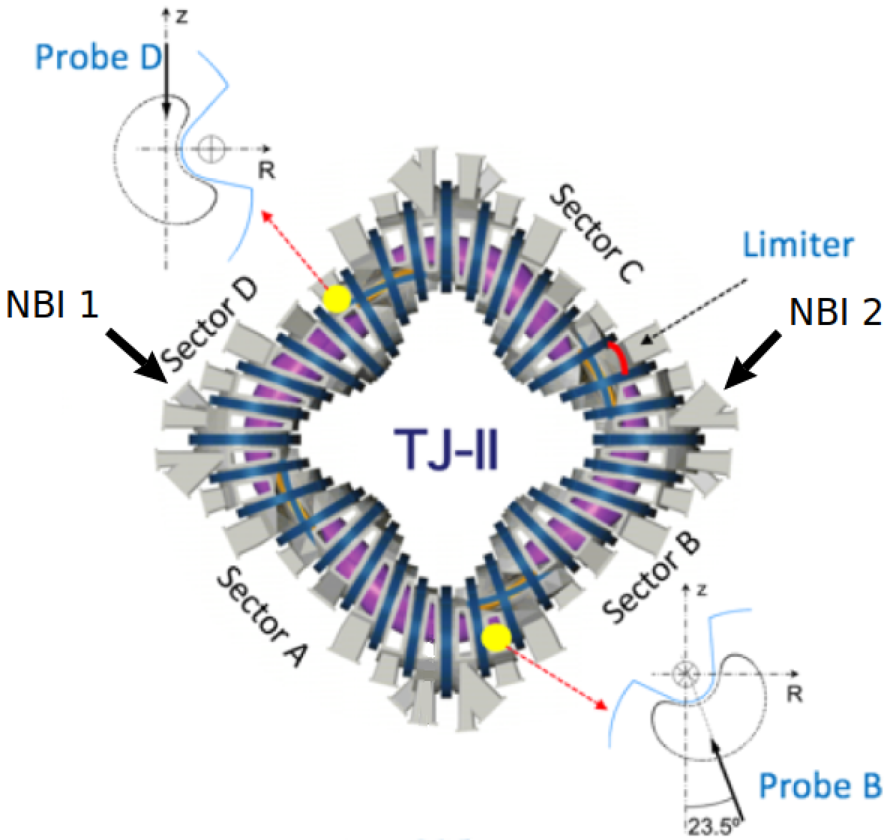

Figure 2.1: Schematic top view of the TJ–II stellarator with shown locations of Langmuir probes and NBI directions. Reproduced from [12], modified.

rake probe with three tips on the top and probe D was a multipin stepped probe capable of measuring 4 signals on the same radial position, allowing then the measurement of turbulent flux.

2.2 Results

In Figure 2.2 one can see an example of frequency resolved transport calculation, it is clear that the reduction of transport correlates with increase of low frequency of long range correlations calculated between probes D and B. This increase of long range correlations further correlates with the time when negative voltage is applied as can be seen on U_{float} measurement from probe D at the bottom of Figure 2.2.

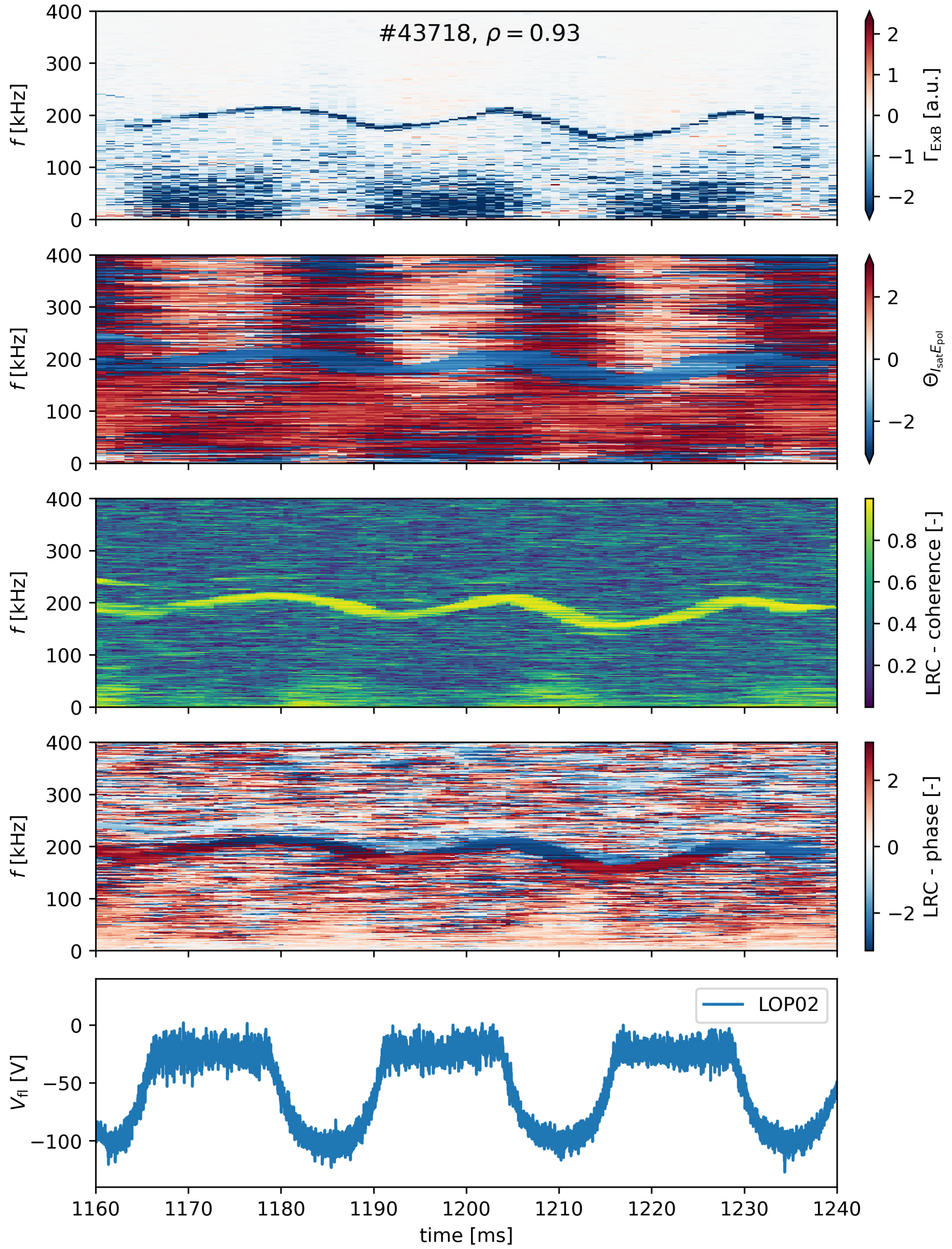

Figure 2.2: The frequency resolved transport (top) shows clear reduction at low frequencies at the time, when biasing voltage is applied as can be seen on the modulation of U_{float}measured by probe D.

Chapter 3

GOLEM

3.1 Experimental setup

The experiments on the GOLEM tokamak were performed using the basic diagnostics (plasma current I_p, loop voltage U_loop and toroidal magnetic field B_t) as well as two arrays of Langmuir probes. The probe setup is similar to the one on the TJ–II stellarator to further facilitate the comparison of results from both devices.

Figure 3.1 shows the configuration of the Langmuir probes installed in tokamak together with a scheme of the biasing electrode placement. The Double Rake Probe and the biasing electrode were mounted on the South–East ports of the GOLEM tokamak, the former on the lower port and the latter on the upper one. The Rake Probe was mounted on the North–East lower port. The probes then maintain an angular separation of 90° in the toroidal direction and 0° in the poloidal direction. This configuration allows for long correlation measurements assuming the properties of ZFs (such as m=0, n=1 symmetry).

The both Langmuir probe arrays are oriented in the radial direction allowing profile measurements during one discharge. As the name suggests, Double Rake Probe (DRP) consists of two rakes of Langmuir probes while Rake Probe (RP), sometimes called Singles Rake Probe, consists of one rake only.

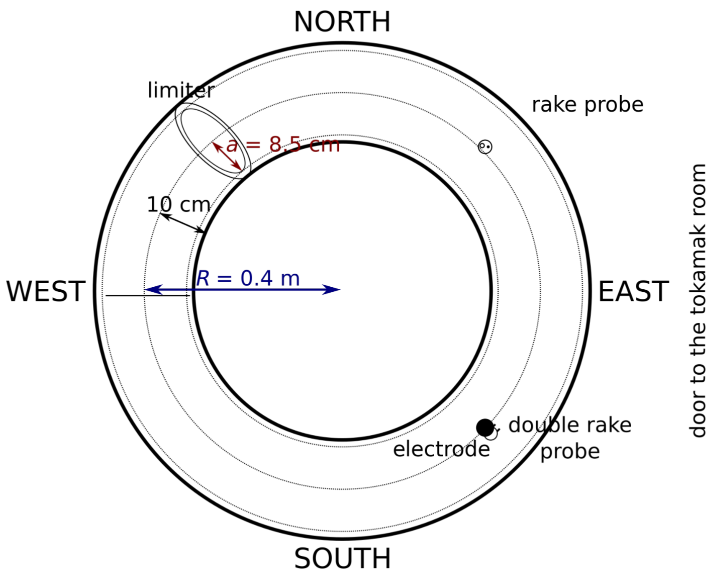

Figure 3.1: Top view of the GOLEM tokamak showing the placement of the probes in the tokamak chamber.

DRP

The DRP is attached to a manually controlled precision manipulator which allows the probe to be positioned between 100 mm and 36 mm radially from the centre of the chamber. The limitation to deeper insertion is due to the finite length of the cable within the access port. In addition, positioning the probes at a radial distance of 50mm from the plasma centre can have a significant effect on plasma parameters, making it undesirable to place the probe any deeper.

The alignment of the probe is static, configured such that the tips directly face the direction of the plasma current, denoted as I_{plasma}. Any change in the orientation of the probe requires its removal from the vacuum chamber.

The detailed configuration of the DRP is shown in Figure 3.2. The tips feature a radial and poloidal spacing of 2.5 mm, with each tip protruding 2 mm from the probe head. Previous experiments conducted until August 2020 used coarse, sharp-edged tips cut from molybdenum wire, which may have influenced the observed multiplicity of peaks in the ion saturation current (I_{sat}) signal, sometimes exceeding the Data Acquisition System (DAS) range.

To mitigate this, newly fabricated tips were used, refined by metallographic grinding, and their surface smoothness verified by microscopy at a magnification of 250 using light microscope ZEISS Axiolab 5. The fabrication of the new tips was preformed as part of this thesis. During the experiments tip R2 ceased to be operational and was therefore excluded from processing.

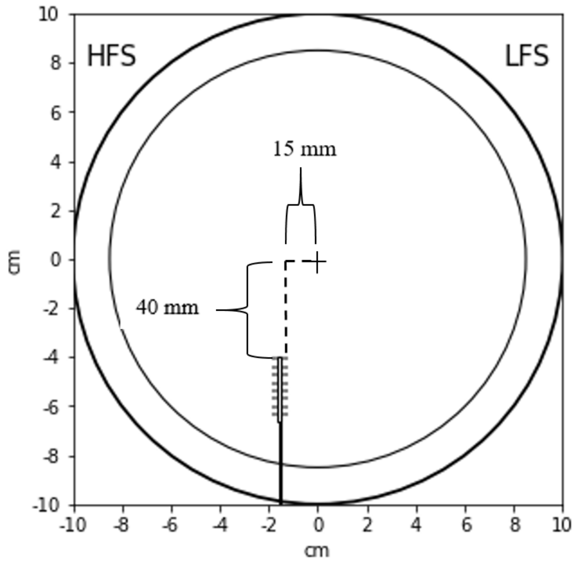

Figure 3.2: The geometry and position of DRP on the GOLEM tokamak. Reproduced from [6].

As can be further seen in Figure 3.2 the probe is not located in the centre of the port but is shifted slightly to the LFS. This shift hinders the calculation of the poloidal phase velocity of plasma fluctuations as the pairs of the tips (R1 and L1) are not on the same radial coordinate. On the other hand, neglecting the small displacement, the radial profile from one discharge can be obtained with higher resolution.

RP

Unlike the DRP, the RP is mounted on a motorised manipulator which allows the radial position and orientation of the tips to be changed. However, this facility was never used and the tips were oriented during the experiments in the same way as the tips on the DRP, i.e. in the direction of the I_{plasma}. The probe is equipped with tips spaced equidistantly 2.5 mm apart, with the deepest tip positioned 5 mm from the top of the probe head. These tips are manufactured using the same process as the DRP and also protrude 2 mm from the probe head. During the experiments tip RP1 became unreliable as it sometimes measured correctly and sometimes not at all, tip RP2 completely ceased to be operational, tips RP1 and RP2 were therefore excluded from processing.

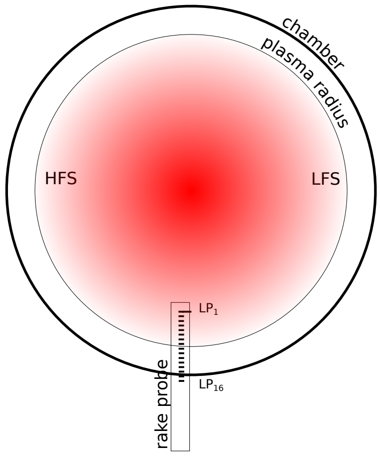

Figure 3.3: The geometry and position of RP on the GOLEM tokamak.

Biasing electrode and power source

The mushroom–shaped graphite electrode used for biasing is mounted on the top south-east port on a manual precision manipulator which allows the electrode to be positioned within a range of 126 to 20 mm from the centre of the vacuum chamber. The power source for the bias was a 400W Kepco BOP 100–4D capable of delivering up to 100 V and 4 A and the rise and fall time from 10% to 90% is in voltage mode 22 μs[7]. A Rigol DG1032Z function generator in burst mode was used to control the power source. The code that controls the function generator can be seen at the following link `http://golem.fjfi.cvut.cz/shotdir/SHOT_NUMBER/Devices/FunctionGenerators/RigolDG1032Z-a/` in the file `RigolDG1032Z-a.sh`, it is important to remark that the contents of the mentioned file may vary as different code is used for AC and DC biasing. This could be fixed in the future by using a switch between DC and AC mode. To estimate the biasing power applied via the biasing electrode a 4–channel Rigol MSO55204 oscilloscope was used. Channel 1 was reserved for U_{loop} and served as the measurement trigger, channel 2 was supposed to measure a voltage drop on 20 Ω resistor for biasing current I_{B} calculation, channel 3 was used for the measurement of the voltage applied by the power source and channel 4 was used to measure the output from Fluke i6000sFlex AC Current Probe, that measured the current drawn by the Kepco. In Figure 3.4 photograph of the electric connection used to estimate the biasing power is shown, one can see that the connection denoted as CH2, that was supposed to measure the voltage drop on the two 20Ω resistors is connected in such way that a voltage on the electrode is measured instead.

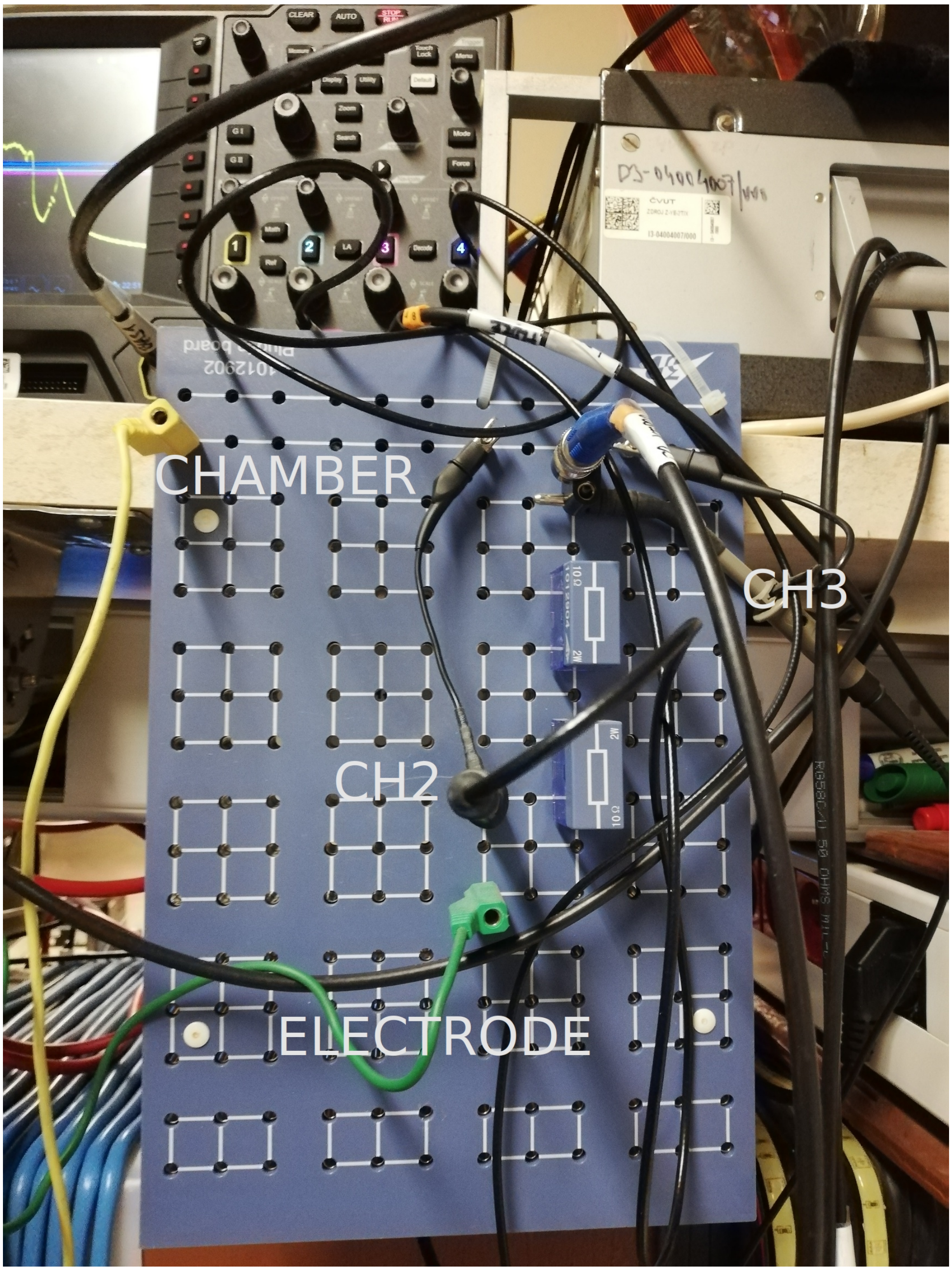

Figure 3.4: Photo of electric circuit used for biasing power estimation. CH2 should measure the voltage drop on the two 20Ω resistors, but was probably wrongly connected and measured the voltage drop on the biasing electrode in plasma. CH3 measures the voltage applied by the Kepco amplifier.

Operation

As described in the introductory part of this work, Langmuir probes can be operated in two basic regimes (and in numerous advanced ones), I_{sat} and U_{float}, the GOLEM tokamak is equipped with a measurement module that enables the change of the mode with a flip of a switch. This module is colloquially called "the silver box" referring to the shiny surface of the module. There are three modules available on the GOLEM tokamak labelled A, B and C, each can serve up to 15 Langmuir tips. The electric circuit controlling the measurement regime is shown in Figure 3.5

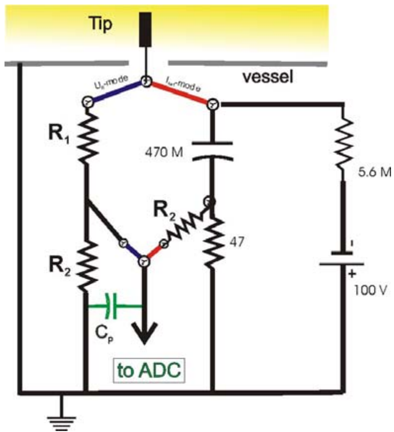

Figure 3.5: The schematics of the electric circuit for I_{sat} or U_{float} measurement. When measuring the floating potential U_{float} the voltage is divided by 100. for the ion saturation current I_{sat} measurement a 470μF capacitor charged to -100 V is used together with a 47Ω resistor on which the voltage drop is measured. Reproduced from [14]

3.2 Results

In the experimental design, it was decided not to devote separate sessions exclusively to either AC or DC biasing. This decision was made to avoid introducing an additional variable into the experiment. Had separate sessions been allocated to each type of biasing, it might have been difficult to attribute any observed discrepancies or variations in results solely to the type of biasing (AC or DC). The influence of session-specific factors, such as variations in environmental conditions or experimental setup, could potentially confound the results. By incorporating both AC and DC biasing within the same experimental sessions, confounding factors were minimised, allowing for a more reliable comparison and interpretation of the effects attributable to biasing type alone.

Probes positions

Discharges from two sessions are discussed in this thesis. On 18$^{\text{th}}$ December 2023 a U_{float} session was conducted and on 21$^{\text{st}}$ December 2023 both U_{float} and I_{sat} were measured in individual discharges. In both sessions the DRP was inserted at a radial position of 80 mm from the plasma centre, the corresponding insertion depths can be seen in Table 3.1. The RP was placed in two different positions during these sessions. On 18$^{\text{th}}$ the RP was only at 80 mm, but on 21$^{\text{st}}$ the position was changed between 50 and 80 mm. The biasing electrode was at 80 mm in all the discharges.

Signal Name	r [mm]
DRP-R1	81.1
DRP-L1	81.6
DRP-R2	83.6
DRP-L2	84.0
DRP-R3	86.1
DRP-L3	86.5
DRP-R4	88.5
DRP-L4	89.0
DRP-R5	91.0
DRP-L5	91.4
DRP-R6	93.5
DRP-L6	93.9

Table 3.1: Distribution of DRP Positions with corresponding radial positions.

Signal Name	r_{80} [mm]	r_{50} [mm]
RP01	80.0	50.0
RP02	82.5	52.5
RP03	85.0	55.0
RP04	87.5	57.5
RP05	90.0	60.0
RP06	92.5	62.5
RP07	95.0	65.0
RP08	97.5	67.5
RP09	100.0	70.0
RP10	77.5	47.5

Table 3.2: Rake Probe (RP) positional data. The positions highlighted in red (RP01 and RP02) were not used in the data processing due to tip malfunction.

3.2.1 U_{float} 18.12.2023

This session was dedicated to AC and its influence on the potential fluctuations rather than on the turbulence levels itself. As one of the side goals was to observe long range correlations and potentially GAMs the expected frequency of GAM on the GOLEM tokamak of 15 kHz was used. In Figure **??** one can see the waveform of the applied biasing voltage and the power-spectrum of the same signal. As shown in Figure **??** the biasing was applied during the almost the whole discharge. In the individual discharges, there were four different configurations of biasing applied, with negative and positive offset and with higher amplitude with lower offset and lower amplitude with higher offset.

Figure 3.6 shows the calculated power spectra from the deepest pin (R1) on the DRP. The dashed line marks the high amplitude biasing discharges, negative or positive offsets are not plotted. It can be seen that in some of the discharges there are significant peaks in the spectral density at 2 kHz and around 10 kHz. The peaks around 10 kHz seem to be present for a variety of different conditions and biasing does seem to have an effect on the fluctuations. It can be seen that for discharge #43262 the overall level of power is lower compared to later discharges where biasing is applied. One can even see that to some extent, the most evident effect may have the high amplitude biasing with positive offset, where both discharges with this type of biasing show increase in power around the biasing frequency. This may be consistent with previous DC biasing experiments on the CASTOR tokamak, where harmonic modes of 10 kHz frequency were measured in I_{sat}during positive plasma biasing, however, in the CASTOR experiments the applied voltage was more than 200 V and the current drawn from the biasing electrode was around 50 A [19]. Except for the different biasing power, the biasing electrode in aforementioned experiments was placed deeper in plasma, at about 70 mm from the chamber centre.

In Figure 3.7 it can be seen that the maximum of I_{plasma}occurred earlier in the discharge #43266, where an overall lower level of fluctuations was observed. This could be due to the relaxation of the chamber or the general temporal evolution of the conditions in the GOLEM tokamak.

3.2.2 I_{sat} 21.12.2023

In this session there were several different biasing waveform applied. Positive and negative DC biasing was applied with magnitude of 100 V and harmonic

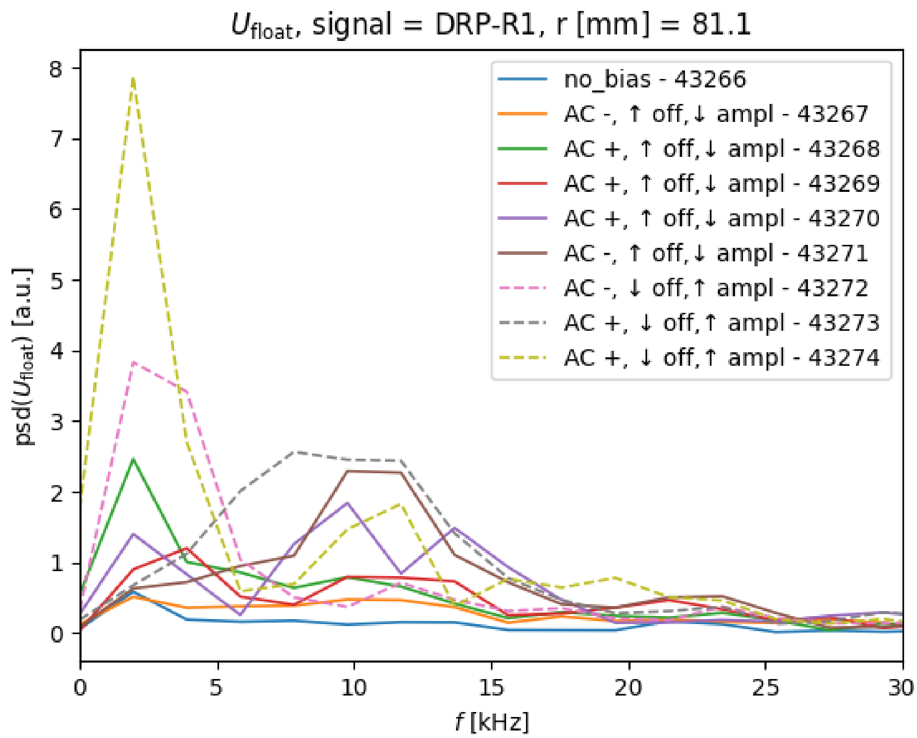

Figure 3.6: The U_{float}power-spectra calculated for the deepest DRP pin R1. The dashed line marks the discharges where the biasing with higher amplitude and lower offset was used. No clear dependence on the type of the biasing can be seen.

AC biasing with offset of either +50 V or -50 V, amplitude of 25 V and frequency 15 kHz, the biasing electrode was placed at 80 mm from the chamber centre. In Table 3.3 one can see the whole experimental session that was mostly devoted to I_{sat}measurements. One may notice that RP was during the session placed on two different positions denoted 50 mm and 80 mm, as can be seen in Table 3.2 for the 50 mm, the probe is fairly deep in the plasma. It turned out that at this position the probe could act as a limiter, because the fluctuation levels of I_{sat}, estimated as standard deviation of the signal were comparable to the fluctuation levels in the limiter shadow as can be seen in Figure 3.8.

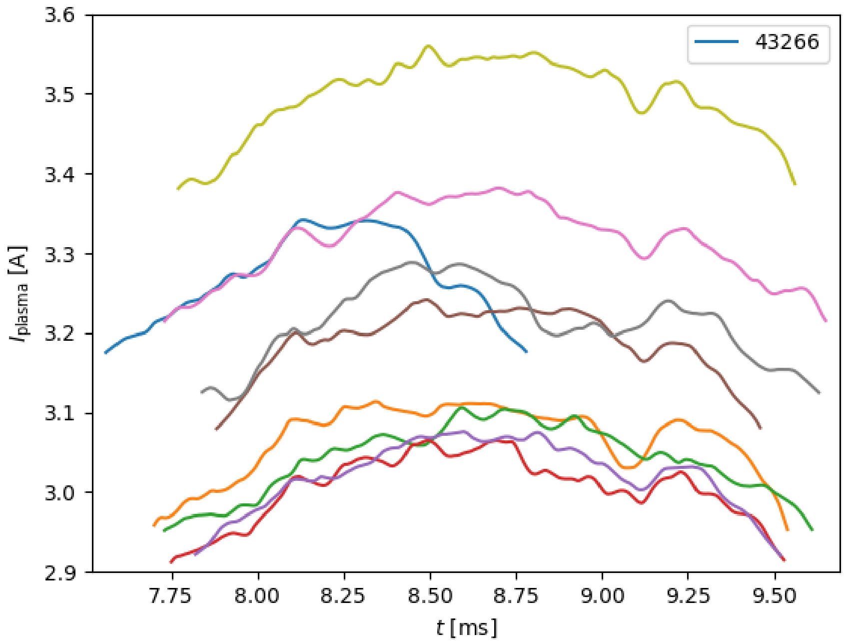

Figure 3.7: Flat–top–like parts of the following discharges: #43266 – #43274, one can see that in discharge #43266 the "flat–top" is slightly shifted to the left, i.e., the maxmium of the I_{plasma}occured earlier.

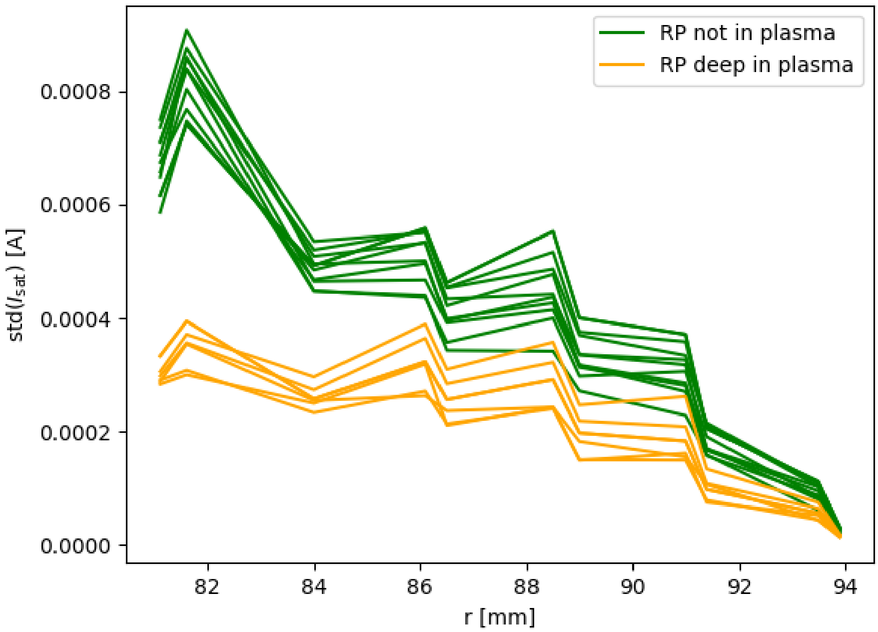

Figure 3.8: Evident effect of deep isertion of RP at 50 mm from the plasma centre on the DRP I_{sat}measurements. Limiter at 85 mm.

shot # [-]	Probe regime	r_{RP} [mm]	r_{DRP} [mm]	Biasing type
43462	Vfloat	50	80	AC pos
43463	Vfloat	50	80	DC neg
43464	Vfloat	50	80	DC neg
43465	Isat	50	80	DC neg
43466	Isat	80	80	DC neg
43467	Isat	50	80	DC neg
43468	Isat	50	80	DC pos
43469	Isat	50	80	DC pos
43470	Isat	50	80	DC pos
43471	Isat	50	80	DC pos
43472	Ufloat	50	80	DC pos
43473	Ufloat	80	80	DC pos
43474	Ufloat	80	80	NO
43475	Isat	80	80	NO
43476	Isat	80	80	AC neg
43477	Isat	80	80	AC pos
43479	Isat	80	80	NO
43480	Isat	80	80	DC pos
43481	Isat	80	80	DC pos
43482	Isat	80	80	AC pos
43483	Isat	80	80	AC neg
43484	Isat	80	80	NO

Table 3.3: Summary of mostly I_{sat}experimental session with corresponding DRP and RP position and biasing regime applied.

Conclusions

The GOLEM tokamak

Series of experiments with edge plasma potential biasing were performed on the GOLEM tokamak. When biasing in AC mode at 15 kHz frequency an enhancement of U_{float} power around 15 kHz was observed. Together with enhancement at around 10 kHz, this enhancement at 10 kHz seems to be in agreement with previous biasing experiment performed on the CASTOR tokamak [19], where coherent mode of 10 kHz frequency was observed, when high enough positive biasing voltage ($\geq$100 V) was applied. Despite the fact that the voltage was not high enough and the current drawn was substantially lower, we may attribute these to overall lower power of the plasma in GOLEM compared to CASTOR.

To improve the process data analysis, it would be helpful to implement an algorithm that would detect peaks in $I_{\mathrm{sat}}$and replace them with "NaN", this would allow in some discharges for longer time windows suitable for further processing as the I_{sat}signals are, despite the effort to mitigate this behaviour, often devalued by peaks out of DAS range.

In upcoming experiments, the first step should be to ensure proper alignment of probes in the GOLEM tokamakso that RP and DRP measure at comparable plasma depth. This would allow for long–range correlation measurements in biased plasma and thus observing GAM–like fluctuations. Further, it was evident, that when RP is much deeper, it then works as kind of a limiter and perturbed the plasma to that extent that DPR measures substantially lower fluctuations comparable to the ones in the limiter shadow. Also the biasing electrode should be placed deeper in the plasma to mimic the conditions from previous biasing experiments on the CASTOR tokamak, specially taking into account that the electrode is inserted from the top and the plasma column on the GOLEM tokamak shows a downward shift [2].

To improve the effects of biasing a more powerful source could be used. It would be interesting to apply much higher voltages around 200 V to see if the same results as on the CASTOR tokamak can be obtained, with the access to the fast KEPCOS a source capable of delivering 200 V and about 12 A could be used for the biasing. With such powerful source GAMs maybe observed. This could even lead to observable improvement in confinement that could be visible even on steepening the I_{sat}profile. Further understanding the interplay between edge radial electric field and turbulence could in principle affect the design of future fusion devices, but this is but a speculation.

TJ–II stellarator

Data from old sessions where edge plasma potential biasing was applied were analysed. In conclusion, the research conducted on the TJ-II stellarator provides insights into the impact of edge radial electric fields on turbulence and Zonal Flows in toroidal fusion devices. The experiments, facilitated by sophisticated Langmuir probe equipment, reveal significant interactions between these fields and plasma behaviour. Effect of the biasing on the edge turbulent transport and the increase of low–frequency long–range correlations was observed. There was a clear suppression of the edge transport when biasing was applied compared to time windows, where no modulation of radial electric field was made. Key findings therefore include the influence of these electric fields on the modulation of turbulence levels and the dynamics of potential Zonal Flows, which are crucial for understanding plasma confinement and stability in fusion reactors.

Bibliography

[1] Adámek, J., Stöckel, J., Hron, M., Ryszawy, J., Tichý, M., Schrittwieser, R., Ioniță, C., Balan, P., Martines, E., and Oost, G. V. A novel approach to direct measurement of the plasma potential. *Czechoslovak Journal of Physics 54*, 3 (Mar 2004), C95.

[2] Brotánková, J., Stockel, J., Horacek, J., Seidl, J., Duran, I., Hron, M., and Van Oost, G. Measurement of sheared flows in the edge plasma of the castor tokamak. *Plasma Physics Reports 35* (11 2009), 980–986.

[3] Conway, G., Smolyakov, A., and Ido, T. Geodesic acoustic modes in magnetic confinement devices. *Nuclear Fusion 62*, 1 (dec 2021), 013001.

[4] Conway, G. D. Turbulence measurements in fusion plasmas. *Plasma Physics and Controlled Fusion 50*, 12 (nov 2008), 124026.

[5] Hidalgo, C., Ascasíbar, E., Alegre, D., Alonso, A., Alonso, J., Antón, R., Baciero, A., Baldzuhn, J., Barcala, J., Barrera, L., Blanco, E., Botija, J., Bueno, L., Cabrera, S., de Castro, A., de la Cal, E., Calvo, I., Cappa, A., Carralero, D., Carrasco, R., Carreras, B., Castro, R., de Castro, A., Cebrián, L., Chmyga, A., Chamorro, M., Colino, P., de Aragón, F., Drabinskiy, M., Duque, J., Eliseev, L., Escoto, F., Estrada, T., Ezzat, M., Fraguas, F., Fernández-Ruiz, D., Fontdecaba, J., Gabriel, A., Gadariya, D., García, L., García-Cortés, I., García-Gómez, R., García-Regaña, J., González-Jerez, A., Grenfell, G., Guasp, J., Guisse, V., Hernández-Sánchez, J., Hernanz, J., Jiménez-Denche, A., Khabanov, P., Kharchev, N.,

Kleiber, R., Koechl, F., Kobayashi, T., Kocsis, G., Koepke, M., Kozachek, A., Krupnik, L., Lapayese, F., Liniers, M., Liu, B., López-Bruna, D., López-Miranda, B., Losada, U., de la Luna, E., Lysenko, S., Martín-Díaz, F., Martín-Gómez, G., Maragkoudakis, E., Martínez-Fernández, J., McCarthy, K., Medina, F., Medrano, M., Melnikov, A., Méndez, P., Miguel, F., van Milligen, B., Molinero, A., Motojima, G., Mulas, S., Narushima, Y., Navarro, M., Nedzelskiy, I., Nuñez, R., Ochando, M., Ohshima, S., Oyarzábal, E., de Pablos, J., Palomares, F., Panadero, N., Papoušek, F., Parra, F., Pastor, C., Pastor, I., de la Peña, A., Peralta, R., Pereira, A., Pons-Villalonga, P., Polaino, H., Portas, A., Poveda, E., Ramos, F., Rattá, G., Redondo, M., Reynoso, C., Rincón, E., Rodríguez-Fernández, C., Rodríguez-Rodrigo, L., Ros, A., Sánchez, E., Sánchez, J., Sánchez-Sarabia, E., Satake, S., Sebastián, J., Sharma, R., Smith, N., Silva, C., Solano, E., Soleto, A., Spolaore, M., Szepesi, T., Tabarés, F., Tafalla, D., Takahashi, H., Tamura, N., Thienpondt, H., Tolkachev, A., Unamuno, R., Varela, J., Vega, J., Velasco, J., Voldiner, I., Yamamoto, S., and the TJ-II Team. Overview of the tj-ii stellarator research programme towards model validation in fusion plasmas. *Nuclear Fusion 62*, 4 (apr 2022), 042025.

[6] Jiráková, K. Double rake probe. `http://golem.fjfi.cvut.cz/wiki/Diagnostics/ParticleFlux/DoubleRakeProbe/index`, 2024. [Online; accessed 08-January-2024].

[7] KEPCO Inc. *BOP (M) (D) 100W 200W 400W Bipolar Operational Power Supply*. Flushing, NY, USA, 2021. Order No. REV. NO. 243-1308-r21.

[8] Powers, E. Spectral techniques for experimental investigation of plasma diffusion due to polychromatic fluctuations. *Nuclear Fusion 14*, 5 (nov 1974), 749.

[9] Seidl, J., Krbec, J., Hron, M., Adamek, J., Hidalgo, C., Markovic, T., Melnikov, A., Stockel, J., Weinzettl, V., Aftanas, M., Bilkova, P., Bogar, O., Bohm, P., Eliseev, L., Hacek, P., Havlicek, J., Horacek, J., Imrisek, M., Kovarik, K., Mitosinkova, K., Panek, R., Tomes, M., and Vondracek, P. Electromagnetic characteristics of geodesic acoustic mode in the COMPASS tokamak. *Nuclear Fusion 57*, 12 (oct 2017), 126048.

[10] Silva, C., Arnoux, G., Groth, M., Hidalgo, C., Marsen, S., and Contributors, J.-E. Observation of geodesic acoustic modes in the jet edge plasma. *Plasma Physics and Controlled Fusion 55*, 2 (dec 2012), 025001.

[11] Silva, C., Duarte, P., Fernandes, H., Figueiredo, H., Nedzelskij, I., Hidalgo, C., and Pedrosa, M. A. Characterization of geodesic acoustic modes in the isttok edge plasma. *Plasma Physics and Controlled Fusion 51*, 8 (jul 2009), 085009.

[12] Silva, C., Hidalgo, C., Pedrosa, M., Carralero, D., Tamura, N., Ida, K., and team, T.-I. Coupling between long-range toroidal correlations and radial transport in the tj-ii boundary plasma. *Nuclear Fusion 51*, 6 (may 2011), 063025.

[13] Spytzer Jr., L. *Physics of Fully Ionized Gases*. Interscience Publishers Ltd, London, 1956.

[14] Stöckel, J., Adamek, J., Balan, P., Bilyk, O., Brotankova, J., Dejarnac, R., Devynck, P., Duran, I., Gunn, J. P., Hron, M., Horacek, J., Ionita, C., Kocan, M., Martines, E., Panek, R., Peleman, P., Schrittwieser, R., Oost, G. V., and Zacek, F. Advanced probes for edge plasma diagnostics on the castor tokamak. *Journal of Physics: Conference Series 63*, 1 (apr 2007), 012001.

[15] Tanabe, T. *Introduction of a Nuclear Fusion Reactor*. Springer Japan, Tokyo, 2017, pp. 3–25.

[16] Tsui, C. K., Boedo, J. A., Stangeby, P. C., and Team, T. Accounting for Debye sheath expansion for proud Langmuir probes in magnetic confinement fusion plasmas. *Review of Scientific Instruments 89*, 1 (01 2018), 013505.

[17] van Milligen, B., Pedrosa, M., Hidalgo, C., Carreras, B., Estrada, T., Alonso, J., de Pablos, J., Melnikov, A., Krupnik, L., Eliseev, L., and Perfilov, S. The dynamics of the formation of the edge particle transport barrier at tj-ii. *Nuclear Fusion 51*, 11 (sep 2011), 113002.

[18] Winsor, N. K., Johnson, J. L., and Dawson, J. M. Geodesic acoustic waves in hydromagnetic systems. *Physics of Fluids 11* (1968), 2448–2450.

[19] Zacek, F., Stoeckel, J., Kryska, L., Jakubka, K., Badalec, J., and Duran, I. Preliminary experiments with edge plasma biasing in tokamak castor. Tech. rep., Czech Republic, 1998. IPPCZ–359.