Control of FADIS and ECE Line-of-Sight measurements at ASDEX-Upgrade

by

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May 31, 2012

DIFFER
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Fundamental Energy Research

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Abstract

Nuclear fusion is seen as one of the future technologies for producing electrical power. In a hot and confined plasma deuterium and tritium will melt together and form a helium nucleus and a neutron. This process produces a total of 17.6 MeV energy. In the plasma instabilities occur. Suppression of these local weaknesses in magnetic confinement is needed. This can be done with Electron Cyclotron Resonance Heating, μm-wave injection in the center of these islands.

For heating the plasma with ECRH, a Fast Directional switch, FADIS, is inserted for either fast power switching or as frequency band filter in a line-of-sight ECE-setup. The line-of-sight ECE setup is next step in detecting and suppressing weaknesses in magnetic confinement in the plasma.

Control of FADIS, with dynamic mirror, is needed for both fast power switching and frequency band filtering. The control routine written by TNO Delft requires the parameters of the mirrors and cavity length to be known accurately. In this report one of the main goals is developing a graphical user interface, GUI, with a fit functionality to find these parameters.

The fit routine for finding the cavity length (L_0) and the mirror coefficients(r_q, r_0, r_1) are found with the use of Matlab. First the best L0 is found with the matlab FMINBND function. This function searches for a minimum in a Error function by changing the L0 between two boundaries. This Error function uses the least squares method. After finding a value for L0 a similar method is used for finding the other parameters. Because these constants have influence on each other, they are fitted at once with the Matlab function FMINSEARCH.

The developed FADIS GUI with fit routine showed promising results with old measurements at the Wendelstein 7-X tokamak in Greifswald. Testing the fit routine on the new measurements at ASDEX-Upgrade tokamak in Garching was not possible due to the short time(80ms) of the calibration shots.

For measuring the location of NTMs Electron Cyclotron Emission is used. The plasma emits μm-waves and with a radiometer these waves can be detected. The line-of-sight ECE setup uses the same transmission line as used for ECRH. This makes it easier to construct a control for suppression of the NTMs. But before the ECE signal can be measured, the high-power from the gyrotron must be filtered out. This is done with FADIS, a Mach-Zehnder filter, two notch filters and a pin-switch.

At the end of April 2012 measurements were performed at the ASDEX-Upgrade tokamak in Garching, Germany. The first results with the line-of-sight ECE setup showed similar signals as the conventional ECE setup. It was possible to detect NTMs. It can be concluded that the line-of-sight ECE setup is a working technique for measuring the plasma heat and detecting magnetic islands in the plasma. However further improvement in signal/noise ratio is needed before a complete magnetic island control system can become operational.

Preface

This bachelor thesis is the result of 17 weeks research at the FOM Dutch institute for fundamental energy research, Differ.

During my time as a student I did see a lot of different research areas and a visit to FOM DIFFER made me interested in fusion research. Fusion research is not new, but is still facing big challenges before a working fusion power plant can be constructed. This led me to send an email to Marco de Baar, to ask if there was a graduation place available in the Tokamak physics group. This was possible and Marco gave me a graduation project, for this I'm thankful.

Most of all I would like to thank my tutor Waldo Bongers for his advice and guidance. Waldo was, besides a great help for my project, also a great colleague and we had a lot of good talks and discussions about Solar fuels and other work related or non-work related subjects.

Further I would like to thank Martijn Graswinckel for his help with Matlab. Adelbert Goede for reading and helping improve this thesis. Niek Doelman and Rens van den Braber of TNO Delft for helping me with the FADIS control GUI. Jarno ten Pierik, who was also working on his bachelor thesis, for his help.

At last I would like to thank all the other people at FOM DIFFER for their collegiality and making me feel welcome during my stay.

Contents

Acronyms

DIFFER	Dutch institute for fundamental Energy Research
ECCD	Electron Cyclotron Current Drive
ECE	Electron Cyclotron Emission
ECRH	Electron Cyclotron Resonance Heating
FADIS	Fast Directional Switch
FOM	Fundamenteel Onderzoek der Materie
ICRH	Ion Cyclotron Resonance Heating
NBI	Neutral Beam Injection
NTM	Neoclassical Tearing Modes

Chapter 1

Introduction

The fusion reactor will be a complex device and before an energy producing device exists a lot of research is needed. This report focuses on one of the key problems with current tokamaks. Due to instabilities in the plasma it is harder to get a profitable fusion reaction. The research goals of this report are devided into two main subjects. First the control and calibration of a Fast Directional Switch (FADIS) and second measurements with line-of-sight Electron Cyclotron Emission (ECE.) Chapter 2 will explain the working of fusion in a tokamak and what the above mentioned instabilities in the plasma are.

Control and Calibration of FADIS
A technique for fast control and calibration of FADIS is needed because the current process takes time and a lot of calibration shots. The calibration procedure involves sweeping the FADIS mirror during one gyrotron shot. By recording a number of different signals the parameters of FADIS can be calculated. During the next gyrotron shots FADIS can be tuned correctly with the use of the previous collected parameters and data. This procedure will be implemented in the control software.

Line-of-sight ECE Measurements
Line-of-sight ECE is a technique for measuring the plasma temperature and instabilities in the plasma. The Line-of-sight ECE setup is constructed and ready for testing. These measurements are done on the ASDEX-upgrade Tokamak. The Line-of-sight setup is described in this report as well as the first measurements.

FOM DIFFER
The research in this report is realized at FOM DIFFER (Dutch Institute For Fundamental Energy Research). FOM DIFFER is the leading institute for plasma physics in the Netherlands. After the name change in 2011 the institute will be moved from the current location at the castle of Rijnhuizen, Nieuwegein, to the university campus in Eindhoven. The new institute has a clear mission: "To perform leading fundamental research in the fields of fusion energy and solar fuels, in close partnership with academia and industry, and to have a national coordinating role in the field of fundamental energy research." Work on tokomak research is perfomed as a part of ITER-NL. ITER-NL is a collaboration between TNO, FOM, NRG and TU Eindhoven with the goal of dutch participation on the international ITER project. For more information about ITER see appendix C.

Chapter 2

Fusion and Tokamaks

In the 20th century society has become increasingly dependent on electricity. Besides the current application, electricity is seen as the future replacement of natural resources like petroleum and natural gas. To make this possible new methods of electricity generation are necessary, because today's electricity is for 86% generated with oil, gas and coal. The first step to overcome this problem would be to exploit the current alternatives, renewable and nuclear energy. But renewable energy will probably never produce enough to meet the current needs and nuclear energy has a safety and a nuclear waste problem.

Maybe the solution to the energy problem is still to be found. A possible option might be the use of fusion energy. In nuclear fusion the nuclei of atoms melt together and form a heavier element. In this process the rest energy will be released. The sun and all other stars in the universe are powered by fusion. For fusion to take place high temperature and pressure are required. The core temperature of the sun is about $15 \cdot 10^6$K and the density is up to $1.5 \cdot 10^5$ kg m^{-3}. On earth it is not possible to reach these high densities, but it is possible to reach higher temperatures in fusion reactors.

2.1 Fusion

Only fusion between light elements will produce power. The best candidates for the first fusion reactors are the hydrogen isotopes tritium and deuterium, because those have the highest cross section of possible fusion reactions and a high energy yield. This will give a reaction

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + \mathrm{n} = 17.6 \text{ MeV} \tag{2.1}$$

The reaction produces a helium nucleus and a neutron together with an energy of 17.6 MeV. This energy corresponds to the difference in mass between the tritium and deuterium on the one hand, and the helium and neutron on the other hand. The process is shown in figure 2.1

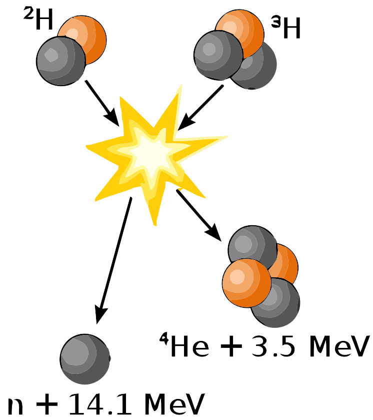


Figure 2.1: In fusion reactors deuterium and tritium will melt together and form a helium nucleus and a extra neutron. 17.6 MeV of Energy is released [1].

2.2 Tokamak

High temperatures are needed to make a fusion process work. At these temperatures the molecules and atoms are split into their constituents, nuclei and electrons, forming a gas called plasma. At these high temperatures a normal container would not suffice because all the heat would be transferred out through the wall and the wall would melt. So the plasma will have to be confined in a magnetic field in a tokamak. This is achieved by a combination of a strong magnetic toroidal field and a current in the poloidal direction, see figure 2.2.

The toroidal field is the strongest of the magnetic fields and the electrically charged nuclei and electrons are bound to follow the imaginary field lines of this field. This toroidal field is achieved with a set of coils surrounding the vacuum chamber. The outer poloidal coils will make, in combination with the inner poloidal coils, another magnetic field. Together the toroidal and polodial will make a resulting helical magnetic field [2][3].

2.3 Plasma heating

Ohmic dissipation will heat the plasma, but the plasma resistivity decreases with increasing temperature. So the ohmic heating becomes ineffective at high temperature. For heating at high temperature there are several alternatives: Neutral Beam Injection (NBI), Ion Cyclotron Resonance Heating (ICRH), Lower Hybrid (LH) and Electron Cyclotron Resonance Heating (ECRH). This report will focus only on ECRH.

Electron Cyclotron Resonance Heating
High power microwave beams, produced by gyrotrons, can be injected into the plasma. A gyrotron produces microwaves at the electron cyclotron frequency by accelerating electrons and letting them interact with a magnetic field.

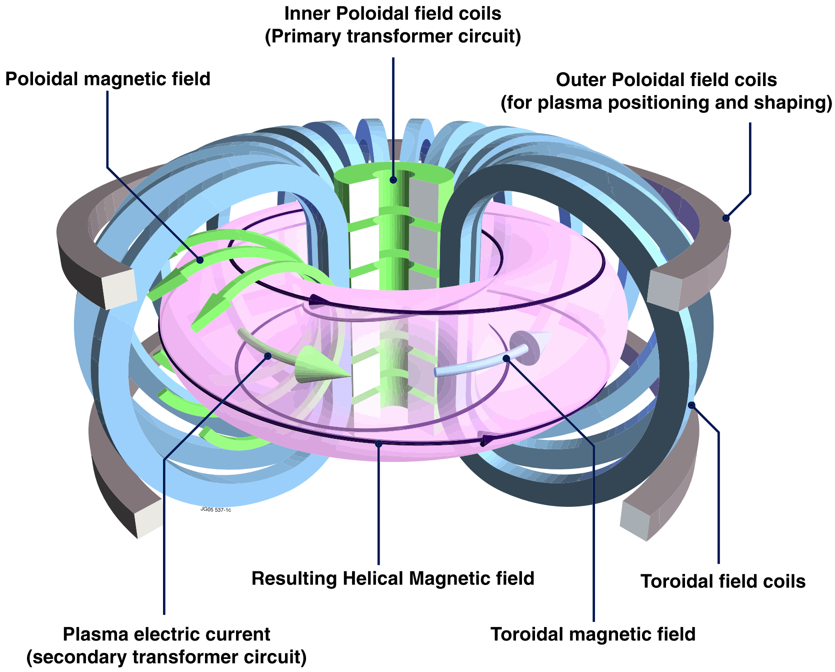


Figure 2.2: Schematic representation of a tokamak with the various magnetic fields. [1]

2.4 Plasma instabilities

In a tokamak plasma, instabilities appear when the performance of the plasma increases. These instabilities, neo classical tearing modes or so called magnetic islands, are local weaknesses in magnetic confinement. Due to the magnetic islands the pressure drops and this does have a negative effect on the plasma temperature and efficiency of the whole. The magnetic islands can occupy a considerable fraction of the plasma volume. Figure 2.3 is an illustration of the magnetic islands. The dynamic behavior of the magnetic islands makes it hard to suppress them. They rotate typically with a frequency of 1 to 20 kHz.

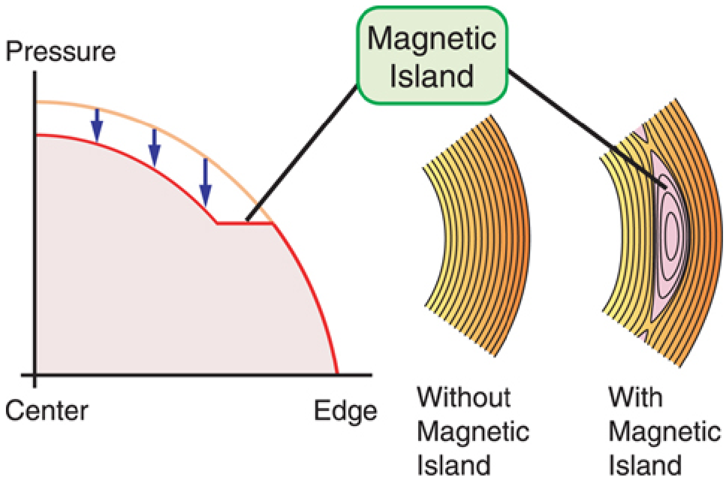


Figure 2.3: Magnetic islands are local weaknesses in density in the plasma.

The islands O-point is a local minimum in current density and the X-point a local excess. When, under particular conditions, the magnetic islands grow and deteriorate the plasma confinement, due to which the plasma can lose its thermal energy to the tokamak wall. This can, in the end, lead to damage to the tokomak. Suppression of these magnetic islands is important for fusion in tokamaks[2].

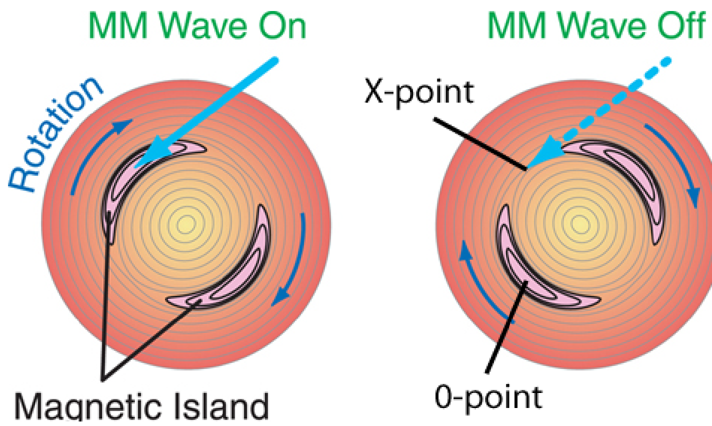


Figure 2.4: Magnetic islands are rotating in the plasma, the islands O-points are local minimum and the X-points are local maximum in the plasma.

Electron Cyclotron Current Drive

Electron Cyclotron Current Drive (ECCD) can be used to suppress the magnetic islands. ECCD uses an electron cyclotron (EC) wave to fill up the current deficiency. Due to the dynamic properties of the islands, the EC should be tuned on when an island O-point is passing by and off when a X-point is passing by, see also figure 2.4.

Chapter 3

FADIS (Fast Directional Switch)

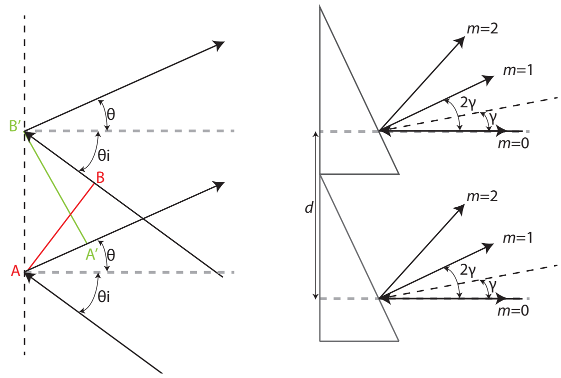
FADIS is a ring resonator consisting of two focusing mirrors, two coupling gratings and matching elements from waveguide to the resonator beam. FADIS is used for two purposes, it can be used for switching between different launchers and it also can be used as a frequency filter with the purpose of measuring the temperature of the plasma. In this chapter the working principle of FADIS is explained.

3.1 Gratings

To split frequencies a diffraction grating can be used. Diffraction gratings are a periodic grooved structure that changes the amplitude and phase of the reflected waves. The relation between groove spacing(d), wavelength(λ) and output beam can be found by using figure 3.1a. A plane wave front falls in under an angle θ_i. The reflected wave front $A'B'$ exits under angle θ. The optical path between A and A' is $d(2\pi/\lambda)\sin(\theta)$ and the optical path between B and B' is $d(2\pi/\lambda)\sin(\theta_i)$. Maxima occur when the optical path differences are multiples of 2π giving:

$$d(\sin(\theta) - \sin(\theta_i)) = m\lambda \tag{3.1}$$

From equation 3.1 follows that different beams will occur with orders m, m can be a positive or a negative integer. If $m = 0$ then $\theta = \theta_i$ no frequency split will occur. In higher order however θ is a function of wave-length, resulting in an angular spread of frequencies. To put maximum power into the higher order mode gratings are "blazed" as shown in figure 3.1b. By choosing θ_i such that the specular reflection on the diffraction groove occurs in the direction of a desired higher order, the power in that order is maximized [2].



(a) **(b)**

Figure 3.1: (a) Reflection of micro-waves. (b) Gratings, a splitting of frequecies occur in higher orders.

3.2 Fabry-Perots and resonators

The Fabry-Perot interferometer principle is displayed in figure 3.2a and 3.2b. The reflections between mirror 1 and mirror 2 create in phase waves and waves out of phase. The waves out of phase cause destructive interference. The distance between the mirror specifies at which frequency destructive interference takes place so that certain wavelengths are allowed to pass and others are reflected.

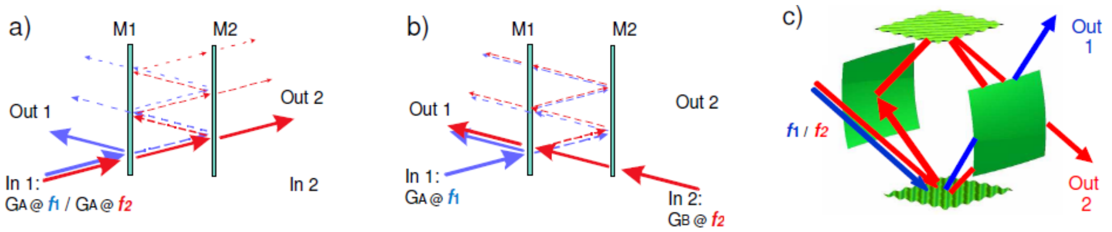


Figure 3.2: FADIS based on the Fabry-Perot interferometer. (a) principle for switching by frequency-shift keying, (b) combination of two sources with small frequency difference, (c) high-power design using a 4-mirror quasi-optical cavity with grating couplers[4].

FADIS is based on this principle. When in resonance, the diplexer transmits a narrow frequecy band. Figure 3.2 is a sketch of FADIS. The high power gyrotron beam from the gyrotron enters the cavity (the red and blue line on the left in figure 3.2c). This beam is split with a corrugated mirror, a mirror with a grating. The resonant frequency, red line, goes into the loop and leaves at the resonant output 2, while the non-resonant frequencies are directed to the non-resonant output 1 [3][5].

The two corrugated mirros are rotated by 45° in respect to the incoming beam and the distance d is less then $1/2\lambda_{gyr}$ and a depth of $1/2\lambda_{gyr}$. The specifications are needed to split a specific frequency. This frequency, 140GHz in this case, is bend into the loop. In figure 3.3 the current FADIS setup in Garching, Germany, is displayed.

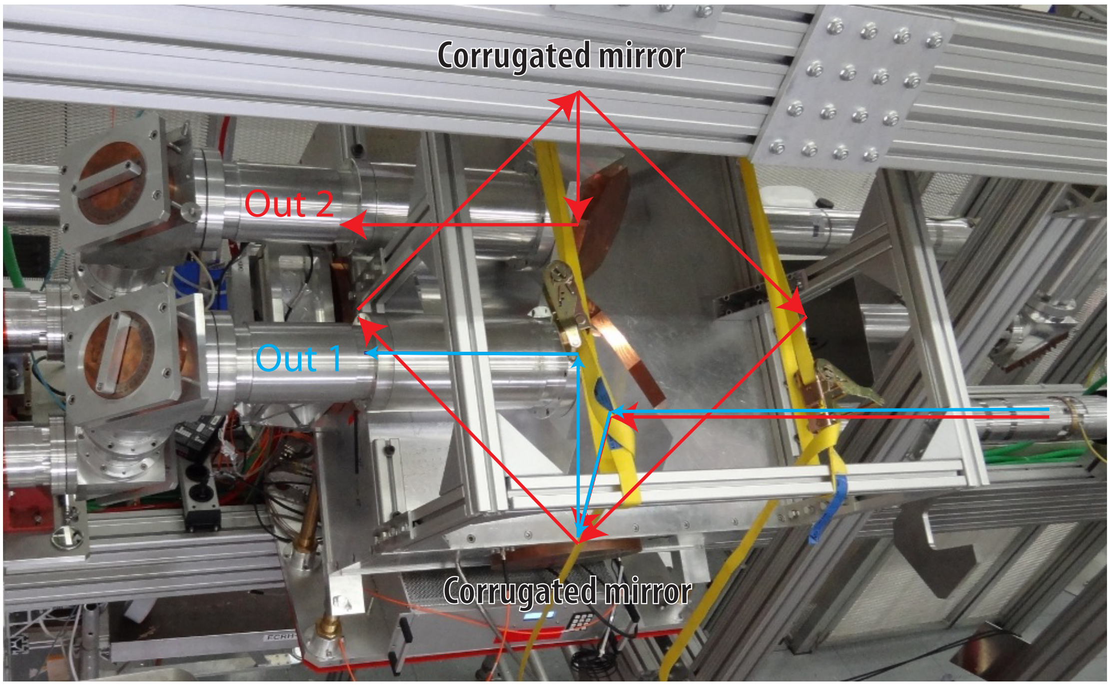


Figure 3.3: Current FADIS setup in Garching, Germany. The blue line shows the non-resonant frequencies and the red line shows the resonant frequency.

3.3 FADIS as a Fast Power Switch

Suppression of neoclassical tearing modes (NTMs) is important, as discussed in section 2.4. The highest efficiency for NTM stabilization is reached when power is applied in the center of the magnetic island. The islands rotate with frequencies 1 to 20 KHz, because of this only half of the gyrotron power is used. A solution for this problem is found bij synchronous toggling the gyrotron power between two launchers. The power of one output can be used for NTM Suppression, while the other output feeds a launcher for an independent ECRH or ECCD experiment. This toggling can be done with FADIS.

FADIS can be designed as a four-port device, so two gyrotrons can be fed into it. When both gyrotrons are shifted between frequencies f_1 and f_2, but in opposite phase, then the power of both gyrotrons is combined into one output. The power then is switched between the output 1 and 2 in the rhythm of the frequency-shift keying (see figure 3.2b) [4].

3.4 FADIS as a Frequency Filter

Fadis can also be used as a frequency filter in a ECE-ECCD setup, see also chapter 5. In this setup FADIS is used for separating the high-power gyrotron signal and the low power ECE signal. When in resonance, FADIS transmits a narrow frequency band and when detuned the beam is directly reflected out of the diplexer. In figure 3.4 the ECE signal (the blue dotted line), emerged from the plasma, enters FADIS at port "Out 2" and is reflected via the non-resonant channel into the detection system [5].

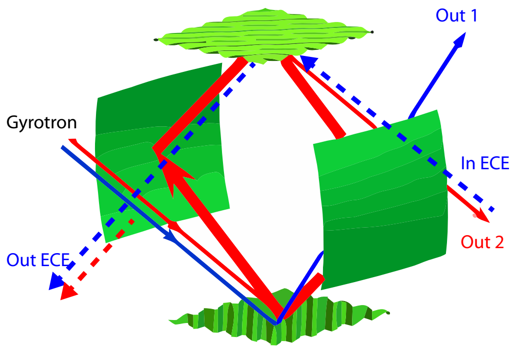


Figure 3.4: Schematic representation of FADIS used in a line-of-sight ECE setup.

3.5 Dynamic mirror

The gyrotrons used for ECRH have a big disadvantages, one of these is the frequency droop of the gyrotron. This occurs in the first second of a gyrotron shot, the frequency drops about 200 Mhz (see figure 3.5). Because FADIS is specifically build for one frequency, about half a second of gyrotron power is lost. This problem can be overcome by adding a dynamic mirror. The length between the four mirrors, cavity path length, is a key parameter for FADIS. The cavity path length must be an integer times the wavelength. Besides the startup frequency change also other external factors like structural vibrations, mechanical creep, or thermal expansion may change the path length away from optimal [3][5].

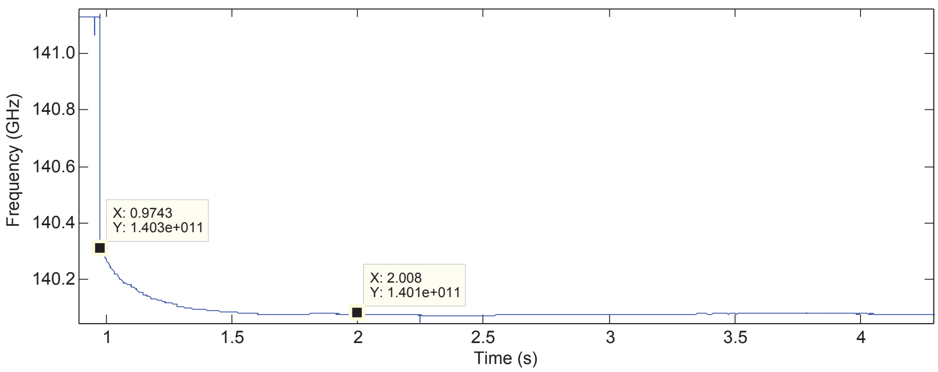
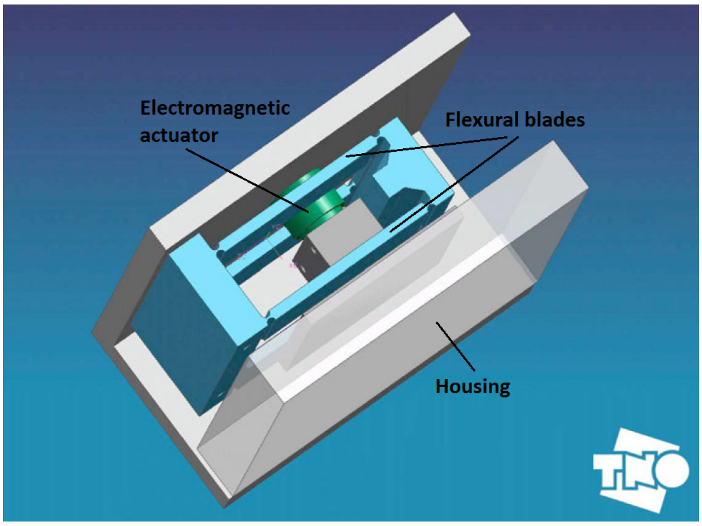
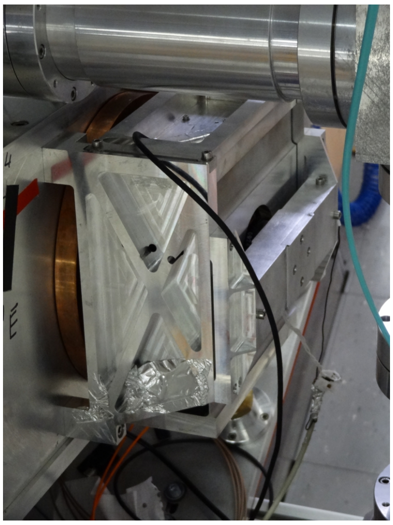


Figure 3.5: During the startup of the gyrotron the frequency has a shift of about 200 MHz.

The dynamic mirror is developed by FOM Differ and TNO Delft. The design, see figure 3.6a, consists of four flexible blades on which an electromagnetic actuator and mirror are mounted. The actuator is a large coil and moves the mirror up and down to change the path length inside FADIS. A optical sensor strip measures the position on micrometer scale. The mirror is constructed and mounted on FADIS, figure 3.6b shows the mirror in Garching.



(a) Design



(b) Actual

Figure 3.6: Design(a) and actual(b) pictures of the dynamic mirror as designed and constructed by TNO.

Chapter 4

FADIS control calibration

When using FADIS as a Fast Power Switch or as a Frequency Filter it is important that control of the dynamic mirror runs fast and smoothly so minimal gyrotron shot power is lost. The amplitude transmission coefficients from the output 1 and 2 are given by:

$$t_1(\Delta f) = r_0 \cdot \frac{1 - |r_q|\, exp(\frac{i \cdot \Delta f \cdot 2\pi \cdot L}{c})}{1 - \left|r_q r_0^2\right| exp(\frac{i \cdot \Delta f \cdot 2\pi \cdot L}{c})} \tag{4.1}$$

$$t_2(\Delta f) = \frac{r_1^2 \sqrt{r_q} exp(\frac{i \cdot \Delta f \cdot 2\pi \cdot L}{2c})}{1 - \left|r_q r_0^2\right| exp(\frac{i \cdot \Delta f \cdot 2\pi \cdot L}{c})} \tag{4.2}$$

Here the scattering coefficients of the gratings are r_0 for 0^{th} order and r_1 for the -1^{st}. The internal losses are taken into account by r_q. L is the round-trip length of the cavity and Δf the detuning of the resonator. These transmission coefficients as function of frequency will give a signal like shown in figure 4.1. Here the blue line is the non-resonant output, t_1, and the red line is the resonant output, t_2.

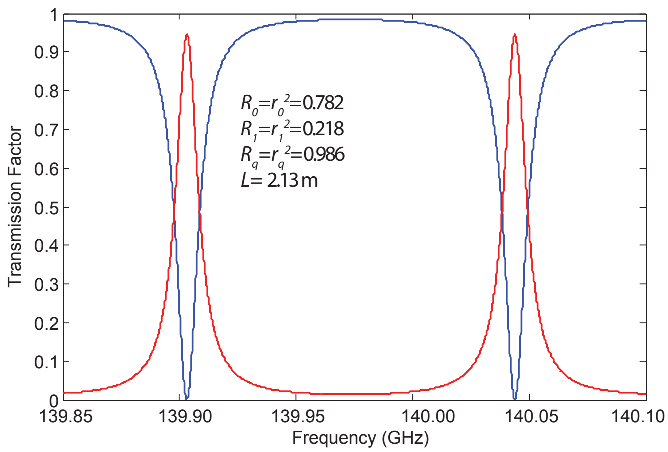


Figure 4.1: The transmission factors of the FADIS outputs as a function of the frequency.

When the dynamic mirror, discussed in section 3.5, is moving the cavity length L changes. This change can be described by:

$$L = L_0 + x \cdot \sqrt{2} \tag{4.3}$$

x is here the mirror change in meters. If the frequency is known the mirror can be moved so that the gyrotron power is directed into the reference channel.

4.1 Requirements

To use FADIS as frequency filter it is nessacery to move the dynamic mirror in correlation with the change in the gyrotron frequency. Figure 4.2 shows the change in frequency, mirror posistion and the output of the resonant and non-resonant channel. The patern of the outputs looks simulair to those in figure 4.1, this could be expeccted with formulae 4.2, 4.1 and 4.3.

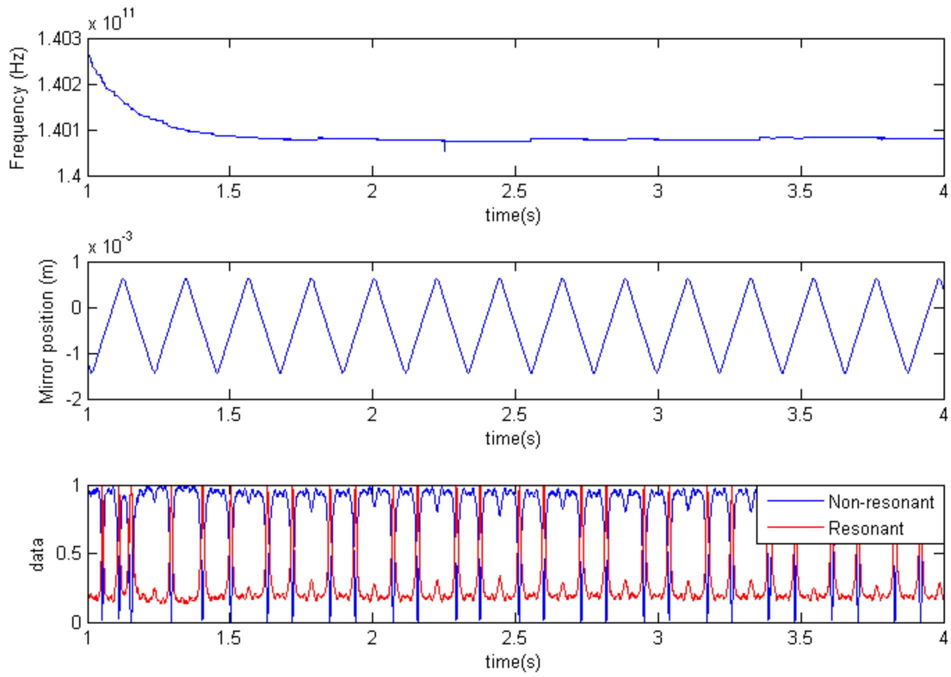


Figure 4.2: Overview of a calibration shot. The first graph shows the frequency shift in the first seconds. The second graph shows the mirror posistion, the mirror is moving constantly over the full range. The last graph shows both the resonance and the non-resonance output.

The calibration control of FADIS has to determine the parameters of the mirrors, r_q, r_1, r_0 and the cavity length L_0. Decided is that the FADIS calibration control must be a easy to use Graphic User Interface(GUI). The GUI should have, besides the calibration control, the following functions:

- Start calibration shot

- System identification
- Controller selecting
- Controller tuning
- Data storage
- Data plotting
- Trigger enabling
- Fool proof

The focus of this report is the calibration routine, but in a later stadium the other functions can be implemented. The GUI will be written in MATLAB, this is beceause the current manual control of FADIS is already performed in MATLAB.

4.2 Calibration routine

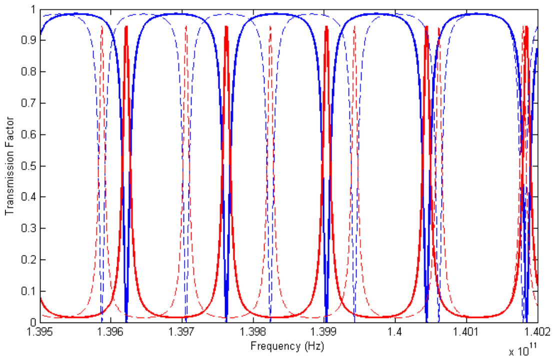
When reviewing the formulae 4.2, 4.1 and 4.3 four constants(r_q, r_0, r_1, L_0), and two variables (Δf, x) can be obtained. The frequency variable is dependent on the gyrotron, and is measured during the entire shot. With this frequency and the four constants a position for the mirror is to be calculated. For example in a line-of-sight ECE setup the mirror is tuned so that most of the gyrotron power goes to the resonant output. The calculations for the mirror posistion are performed by a routine written by TNO.

For this routine to work properly, the four constants are to be determined exactly. Each constant has it's own influence on the output. In figure 4.3a it is shown that L_0 determines the width between the notches. Both r_q, figure 4.3b, and r_0, figure 4.3c influence the peak of the notch at the resonant output and the steapness towards the notch at the non-resonant output. r_1 has only effect on the height of the peak in the resonant output, as is shown in figure 4.3c.

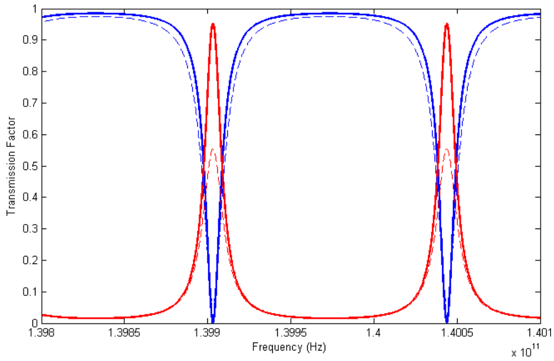
To determine the parameters a Matlab function is written. This function takes a calibration shot, as the one in figure 4.2, and tries to fit function 4.2. First the best L_0 is found with the matlab FMINBND function. This function searches for a minimum in a *Error* function by changing the L_0 between two boundaries. This *Error* function, see equation 4.4, uses the least squares method. How smaller the error how closer the guessed L_0 is to the real value.

$$Error = \sum (Measurement - t_2)^2 \tag{4.4}$$

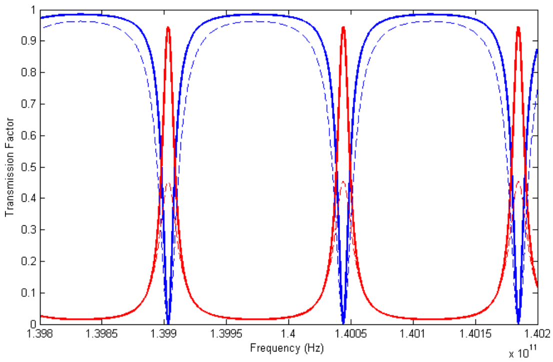
After finding a value for L_0 a similar method is used for finding r_q, r_0 and r_1. Because these constants have influence on each other, they are fitted at once with the Matlab function FMINSEARCH. This function does not allow boundaries, but it is not allowed to have higher value then one. So the error function returns a high number when Matlab tries a one or more.



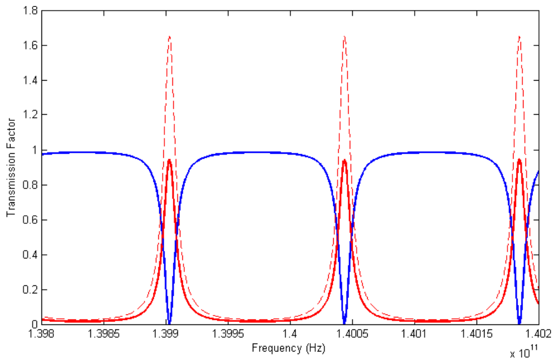
(a) Change in L_0 thick lines 2.13 m and dotted lines 2.53 m.



(b) Change in r_q thick lines $\sqrt{0.988}$ and dotted lines $\sqrt{0.846}$



(c) Change in r_0 thick lines $\sqrt{0.782}$ and dotted lines $\sqrt{0.682}$



(d) Change in r_1 thick lines $\sqrt{0.218}$ and dotted lines $\sqrt{0.288}$

Figure 4.3: The transmission factors of the FADIS outputs, with changing parameters. In all figures the red lines are the resonant output and the blue line are the non-resonant output.

4.3 Development of GUI for FADIS

In Matlab it is possible to create a graphical user interface(GUI). Such a GUI can be designed to combine the different functions of FADIS and to implement the routines for finding the constants and for sweeping the mirror.

In figure 4.4 the GUI is displayed. When pressing the "Start fit" button (nr. 3), the calibration routine will start. In the "FADIS settings"(nr. 8) the guesses and boundaries for the parameters can be given, these settings will be saved for use in later measurements. The output parameters are shown in the "Output" panel, these parameters can be tested by pressing the "Test Values" button. This will open in another GUI window and the found parameters can be tested on other measurement files.

Before using the GUI on location, it is possible to open old measurements files. With this functionality the GUI is tested with old measurement files.

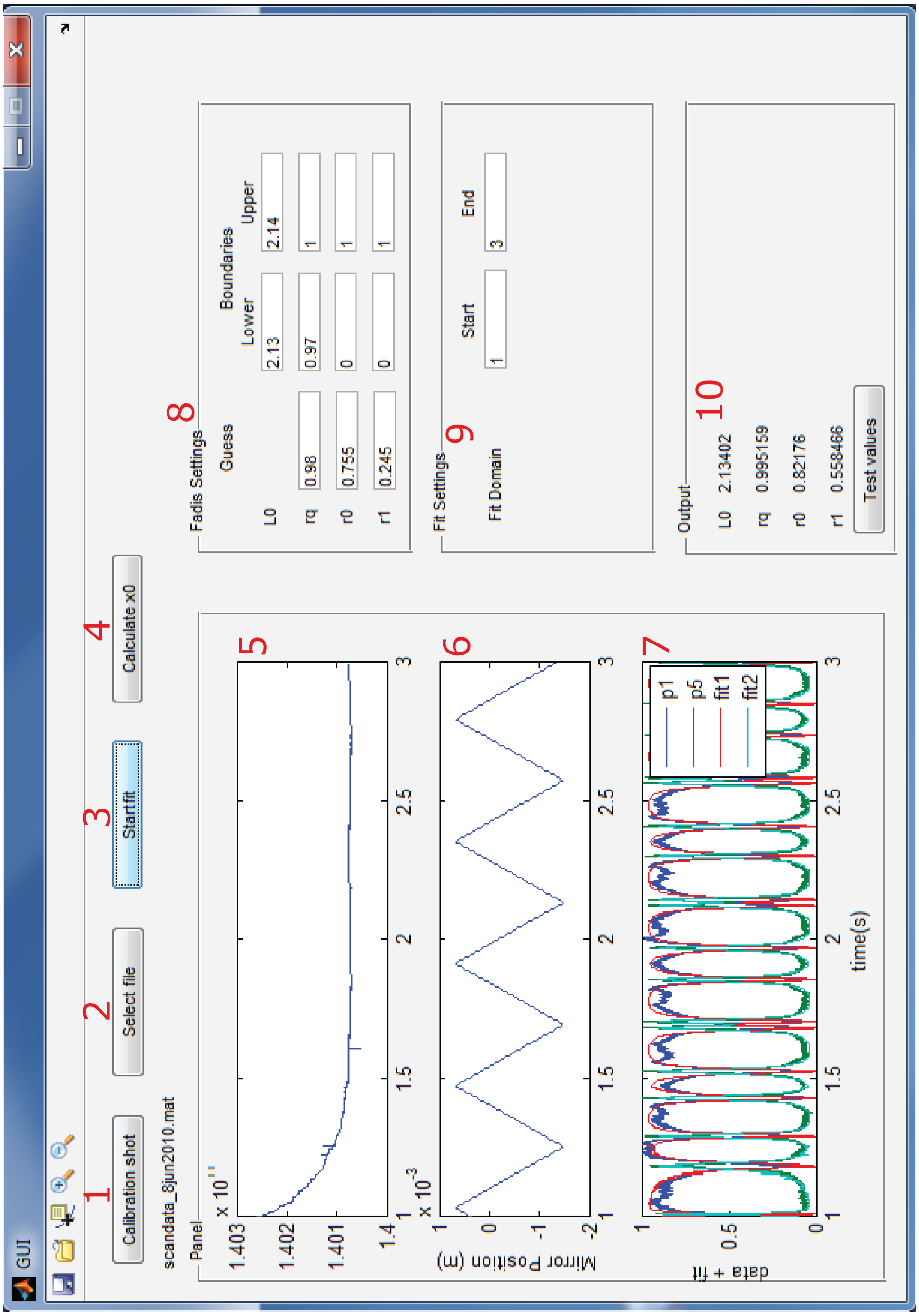


Figure 4.4: Screenshot of FADIS control calibration GUI.
1. Control button for starting a calibration shot.
2. Button for selecting a calibration file.
3. Start fit.
4. Extra function to find start of gyrotron.
5. Graph with frequency.
6. Graph with mirror posistion.
7. Measured outputs and fits.
8. Settings for FADIS, guesses and boundaries.
9. Settings for fit routine, fit domain.
10. The parameters as found with the fit routine.

4.4 GUI for FADIS results

During development the fit routine is tested on old measurement files. These measurements are performed at the Wendelstein 7-X tokomak in Greifswald. The calibration shots on the dummy(no plasma) at Greifswald are typically 5 seconds long. FADIS is currently installed at ASDEX-Upgrade, Garching. Calibration shots on the dummy here are only 80ms long.

4.4.1 Results with old measurements

The first tests with the GUI control routine are with old files. In figure 4.5 a measurement at 8th of June 2010 is displayed. On the right is the calibration GUI and parameters found with the fit routine; on the left are these parameters compared with measurements later that day. In this measurement the FADIS mirror has a small oscillation. The parameters seem to be right, the calculated and original measured outputs do match.

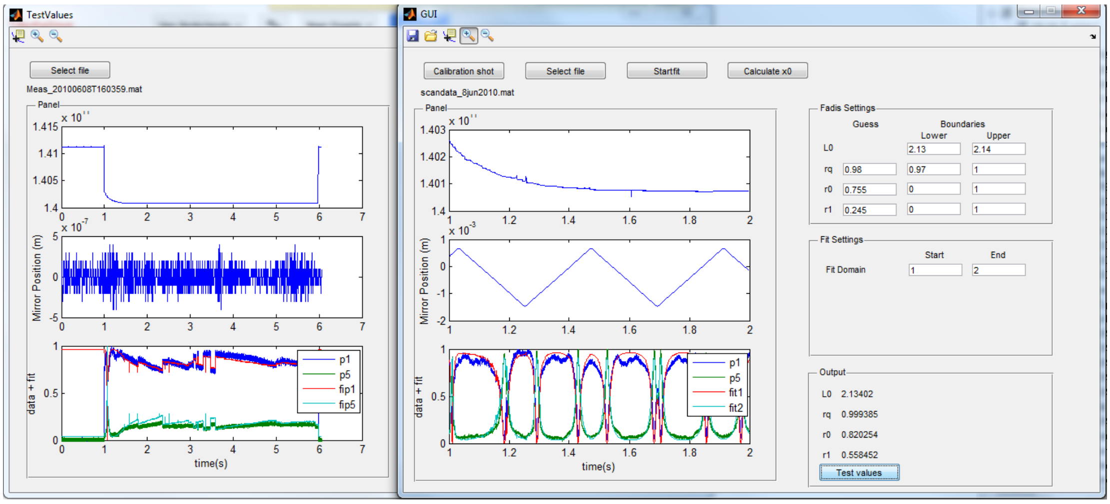


Figure 4.5: This figures shows, on the right, a calibration shot and on the left a measurement with FADIS controled so most gyrotron power goes into the resonant channel. The calculation with found parameters do show this same behavior. Both shots are performed at the 7-X tokomak in Greifwald on June 10, 2010.

Figures 4.6 and 4.7 show fits with different calibrations shots and different data. The calibration data and the compared data are taken on the same day. But the different calibration shots give different parameters; this can be due to adjustments on FADIS. In both these figures the calculated data with found parameters also do match other the measurement files of that day.

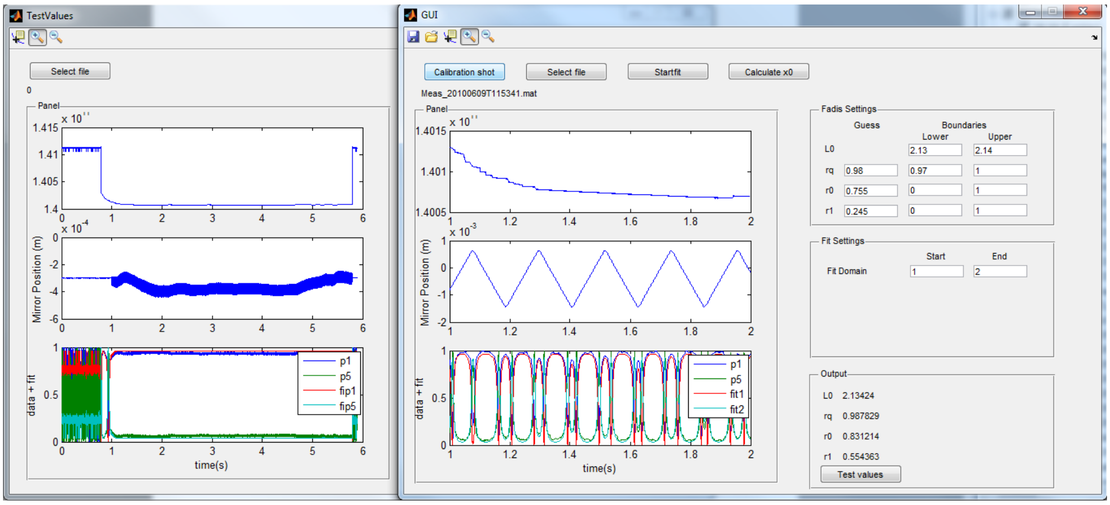


Figure 4.6: This figures shows, on the right, a calibration shot and on the left a measurement with FADIS controled so most gyrotron power goes into the resonant channel. The calculation with found parameters do show this same behavior. Both shots are performed at the 7-X tokomak in Greifwald on June 9, 2010.

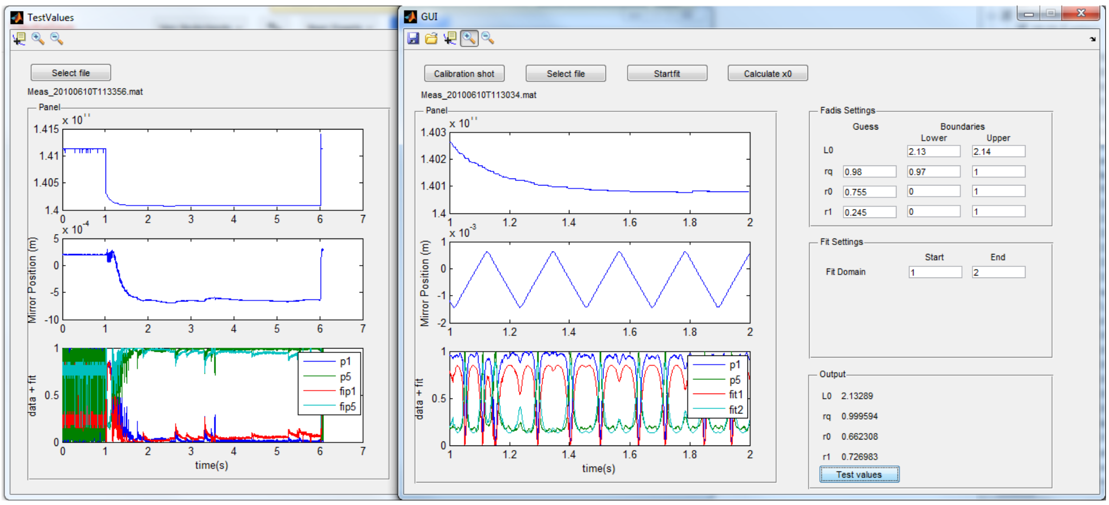


Figure 4.7: This figures shows, on the right, a calibration shot and on the left a measurement with FADIS controled so most gyrotron power goes into the resonant channel. The calculation with found parameters do show this same behavior. Both shots are performed at the 7-X tokomak in Greifwald on June 10, 2010.

4.4.2 Results with measurements at ASDEX-Upgrade

At the end of April 2012 measurements with FADIS at ASDEX-Upgrade are performed. To calibrate FADIS gyrotron, shots on the dummy are performed. the problem of using these shots is duration of only 80ms. In this period the mirror does move less then one period. With such a short time period it is impossible to use the developed fit routine. In figure 4.8 such a shot is displayed. It can be observed that the fit is not correct.

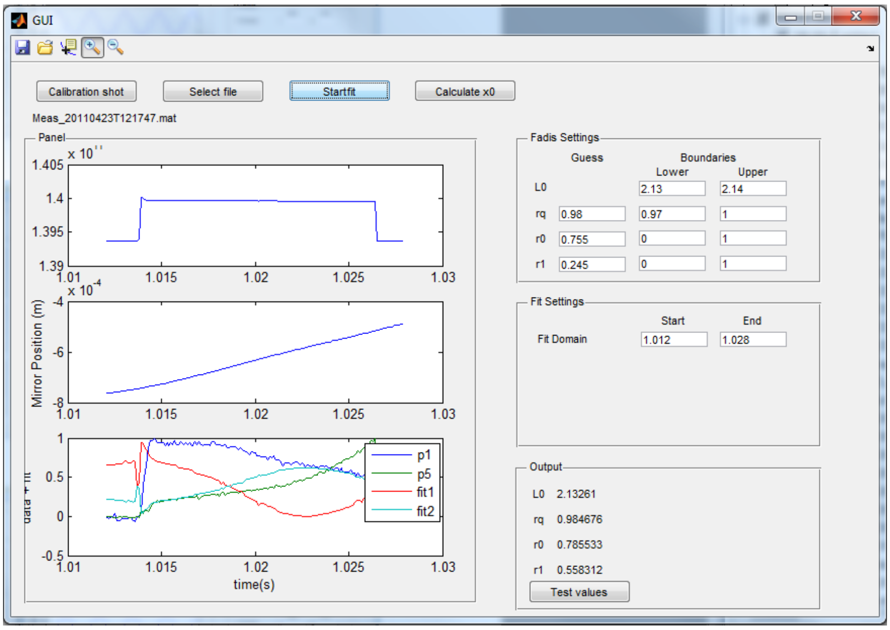


Figure 4.8: Calibration shots at ASDEX-Upgrade were to short for good fitting.

4.5 Future development of GUI for FADIS

The current fit routine developed for FADIS for finding the parameters has a too long reaction time to act on short discharge pulses for the setup in Garching. However, if longer calibration shots are possible, it can be designed to work. The calibration shots in Garching where carried out on the dummy, but it should be possible to do a calibration shot on the plasma. Such a pulse can be extended to 5 seconds and allow enough time for the fit routine.

Another possibility for finding the FADIS parameters might be to automate the current manual calibration. But even if this is possible more then one calibration shot is needed end this does take more time then extending time too a longer shot. In this report this option is not futher discussed.

If the fit routine works the GUI can be extended with the control of FADIS. At the moment FADIS is controlled by entering codes in Matlab. This takes too much time for daily use of FADIS. Implenting these codes inside the GUI gives the user the possibilty to use FADIS without complete understanding the control.

Chapter 5

Line-of-Sight ECE

Detection of magnetic islands(NTMs) is an important step to suppress them. The suppressing of these islands is important for future fusion reactors, as discussed in section 2.4. Electron Cyclotron Emission(ECE) is the commonly used technique for detecting NTMs. With detection of microwave radiation emitted by the plasma, weaknesses in the plasma can be found. With a feedback system and Electron Cyclotron Current Drive it is possible to suppress magnetic island.

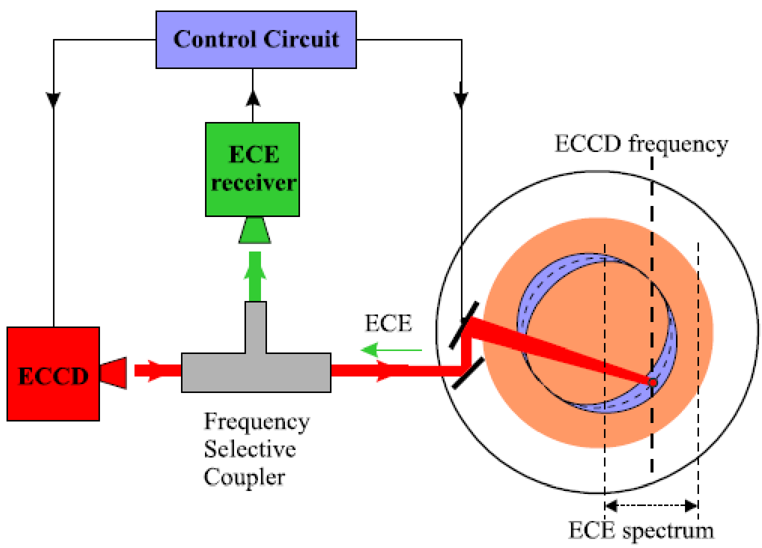


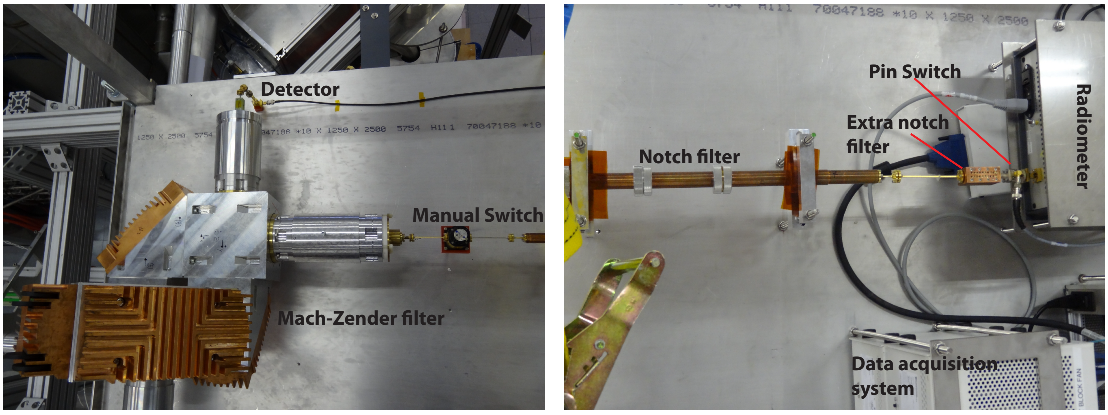
Figure 5.1: Schematic of the line-of-sight ECE setup. The ECCD power(from the left) enters the plasma at the same point as the ECE signal is emitted. Frequency selective coupler is used for splitting the signals, this is necessary to prevent damage to the ECE receiver due to high power from the ECCD system.

The line-of-sight ECE setup is the next step in magnetic island suppressing. This setup requires only one transmission line, where the old setup needed two (one for detection, one for heating). Figure 5.1 shows the schematic of the line-of-sight ECE principle.

5.1 Line-of-Sight ECE Setup at ASDEX-Upgrade

The current line-of-sight setup, at ASDEX-Upgrade, FADIS is used as a frequency selective coupler, this use of FADIS is discussed in section 3.4. However FADIS does not filter out all of the high-power signals. These high-powers signals can damage the radiometer, so it is necessary to install additional components.

Figure 5.2 shows the ECE line-of-sight setup in Garching, Germany. After leaving FADIS the ECE signal enters the Mach-Zehnder filter from the bottom and after a manual switch, a Notch filter, an extra notch filter and a Pin-Switch, the signal is then measured with the radiometer. Most of the components are necessary to make a large enough notch to protect the radiometer against high-powers. The manual switch is used to install a reference source for testing the notch-filters and radiometer. An extra detector is installed at the load of the Mach-Zehnder filter, this detector is used for reference.



(a) (b)

Figure 5.2: Actual line-of-sight ECE setup as it has been released at ADEX-Upgrade in Garching, Germany.

5.1.1 Mach-Zehnder filter and Notch filters

To filter out the power leakage from FADIS a Mach-Zehnder interferometer is used. The Mach-Zehnder filter, see figure 5.3, is a very flexible in customizing frequency filter characteristics. Its operation can be explained as a beating of the interferometer frequency response with that of dielectric plates. At the frequencies, where the dielectric plates act as beam splitters, the system features a symmetric transmission function with relatively wide notches and high isolation compared with resonant diplexers such as FADIS and other options[5].

The Mach-Zehnder filter in this setup has a wide notch of about 0.5 GHz. This wide notch is needed because leakage from FADIS could damage the rest of the ECE setup. Figure 5.4a shows the diplexer characteristic for over a frequency bandwidth of 136 - 144 GHz. T. port 1-3 Measurement is the path towards the radiometer and T. port 1-4 Measurement ends in the macor load. Figure 5.4b shows the actual Mach-Zehnder as it has been realized.

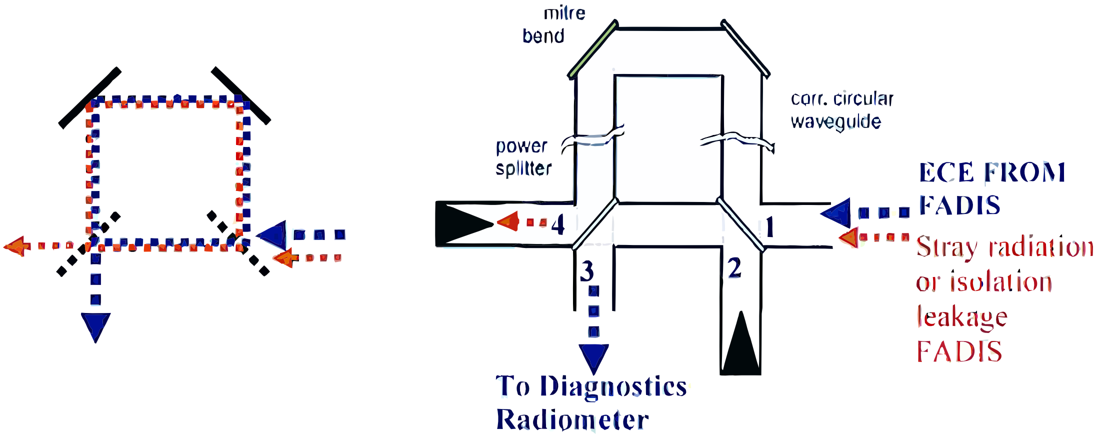
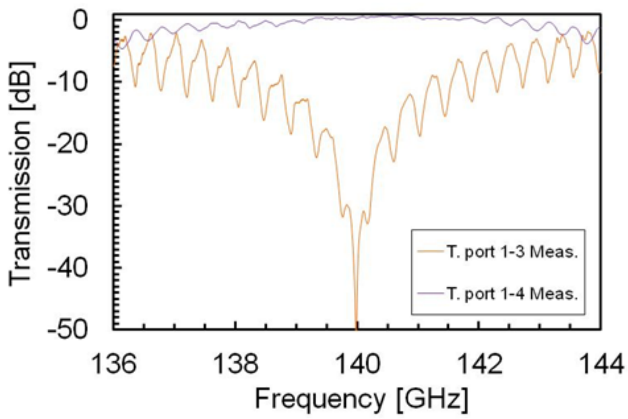
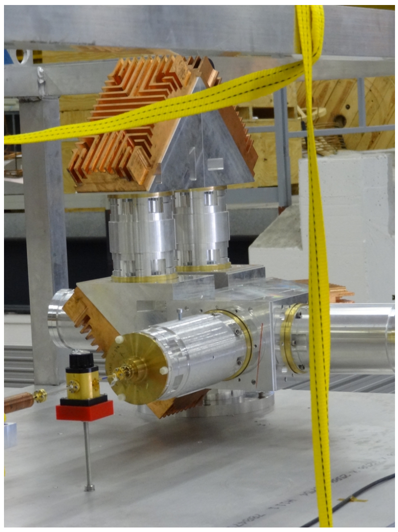


Figure 5.3: Mach-Zehnder interferometer used as a rejection filter for the stray gyrotron radiationand transmission filter from port 1 to port 3 for the ECE diagnostics signal. [5].

Besides the Mach-Zehnder filter more damping is needed to protect the radiometer, so a Notch filters is used. In figure 5.5a this filter is shown. The Notch filter has 7 segments and 6 flanges. Each segment can block a certain wavelength, making it a band stop filter. However this in experiments the notch filter together with FADIS and the Mach-Zehnder filter might still be not enough, so an additional notch filter is installed. This notch filter, see figure 5.5b, has 20 cavities. Each cavity has its own adjustable notch [3].

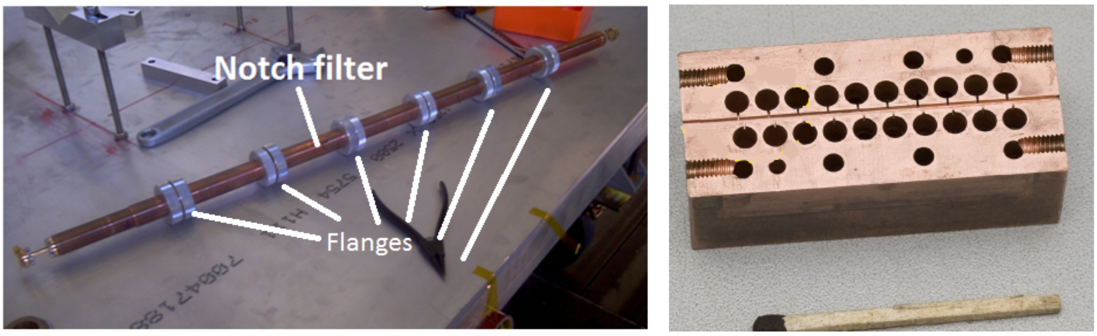


(a) Mach-Zehnder characteristic. The accuracy of the measurement is about 1 dB[3].



(b) Actual Mach-Zehnder at ASDEX-Upgrade.

Figure 5.4: Mach-Zehnder Filter



(a) Bragg reflector notch-filter. **(b)** additional notch filter

Figure 5.5: Both notch filters.

5.1.2 Radiometer

The radiometer, used for detecting the ECE frequencies, is a single side band heterodyne receiver with local oscillator (LO) at 126.6 GHz and an intermediate frequency (IF) band from 5.6 to 21.2 GHz. The radiometer converts the high frequencies of the ECE down to a signal, the IF, that can be used in the data acquisition system. The radiometer has seven output channels, but only 6 are used for line-of-sight ECE. Each channel has a bandwidth of 500 MHz and there is a space between channels of 3 GHz. The radiometer with the values of the six channels is shown in figure 5.6 [2].

Figure 5.6: Radiometer used for detecting the ECE frequencies. Six chanels with different frequencies (channel 1: 132.5 GHz; channel 2: 134.5 GHz; channel 3: 138.5 GHz; channel 4: 141.5 GHz; channel 5: 144.5 GHz; channel 6: 147.5 GHz)

5.1.3 The Pin-Switch

The first experiments with the inline ECE setup showed high power peaks when the gyrotron shot starts and ends. These peaks are due to large frequency jumps at the start and end of the shot. The frequencies do not fall inside the notch and can damage radiometer. The solution to this problem was found by adding a pin-switch. This device is installed just before the radiometer and will interrupt the signal for about 1 ms at the start and end of the gyrotron shot.

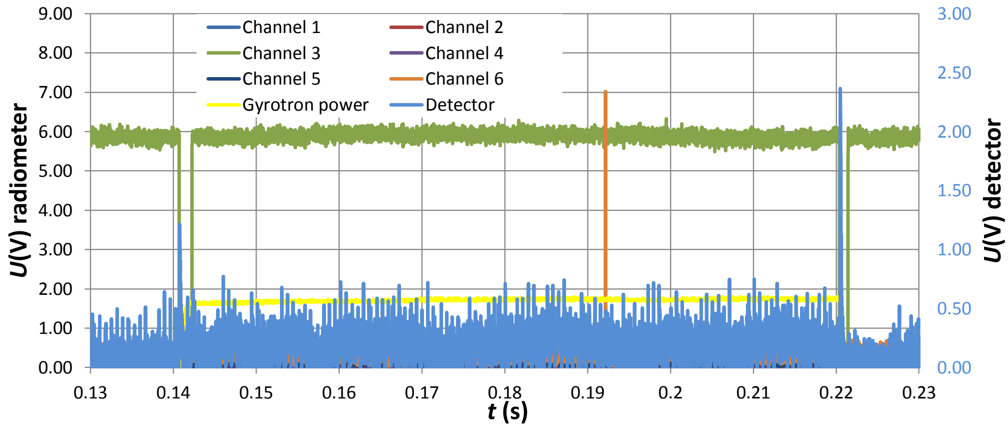


Figure 5.7: Overview of pin-switch experiment with reference source. The reference source, the green line, gives a signal visible on channel 3. Peaks in the detector signal can be observed when the pin-switch works. The yellow line is the gyrotron power.

Before testing the pin-switch, with a real gyrotron shot, a reference source is used to ensure that the complete power peak is interrupted. In figure 5.7 the complete output of the radiometer is shown together with another detector installed on the Mach-Zehnder filter. Figures 5.8 and 5.9 show the same test shot, but zoomed in on the start and end of the gyrotron shot. As can be seen the reference signal on channel 3 shows a notch when the detector has a power peak. So the pin-switch seems to work properly.

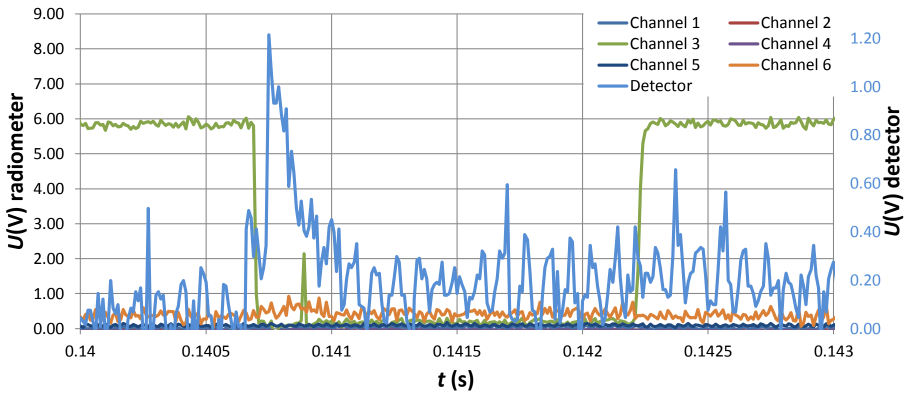


Figure 5.8: Zoom in at the start of the gyrotron shot. The pin-switch is switched on for about 1.5 ms, in this time interval the detector shows a peak.

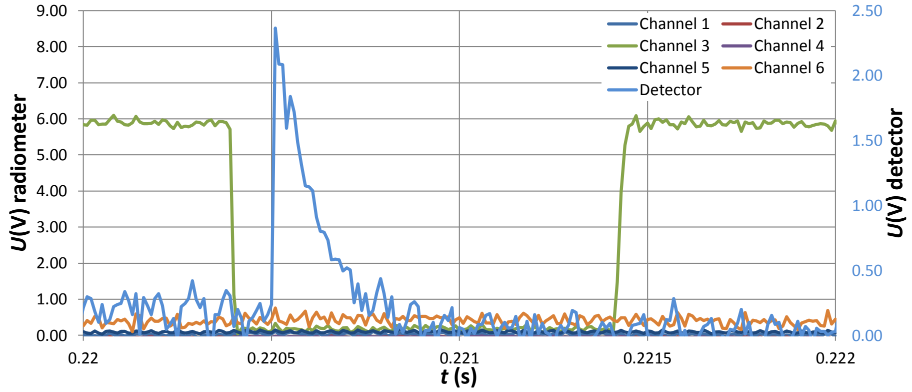


Figure 5.9: Zoom in at the end of the gyrotron shot. The pin-switch is switched on for about 1 ms, in this time interval the detector shows a peak.

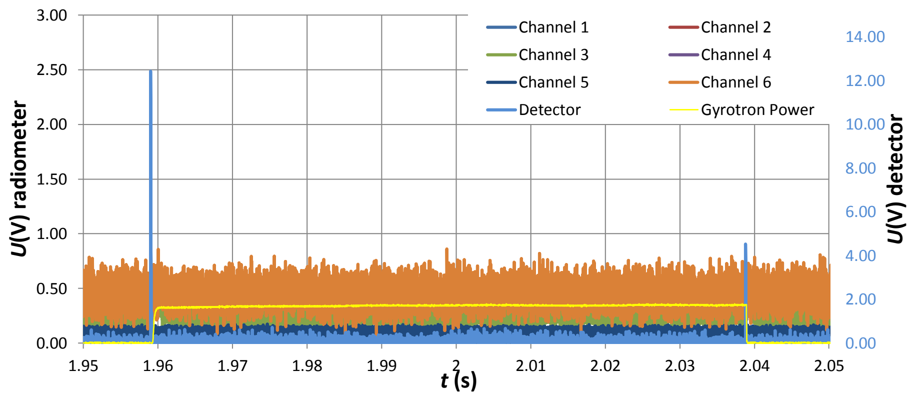


Figure 5.10: Overview of pin-switch measurement with real gyrotron. The yellow line is the gyrotron power.

Finally the reference source was removed and the pin-switch is tested with a gyrotron shot, not on plasma but on a dummy. In figure 5.10 the output of the radiometer and the detector is shown. The figures 5.12 and 5.11 show the starting en ending of the gyrotron shot. The radiometer outputs show no peaks when the detector does. This shows that the pin-switch works as expected.

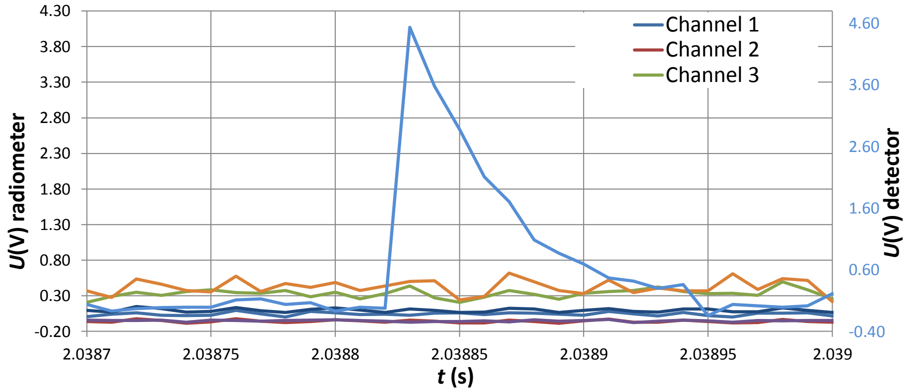


Figure 5.11: Zoom in at the end of the gyrotron shot. When the detector shows a peak no significant change in one of the radiometer channels is observed.

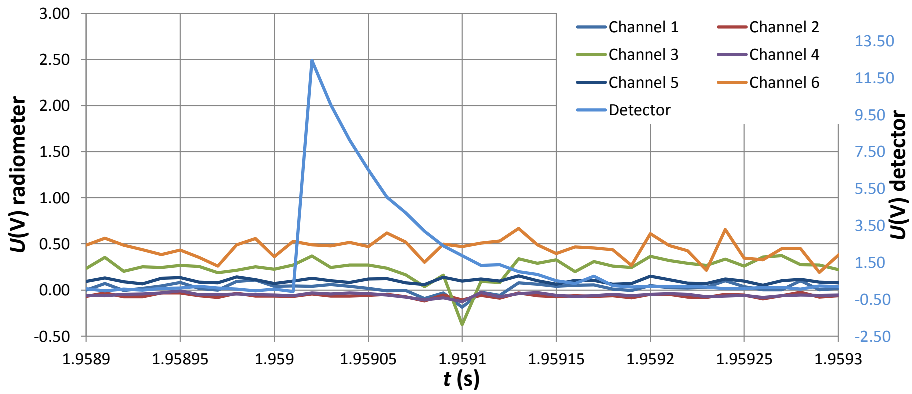


Figure 5.12: Zoom in at the start of the gyrotron shot. When the detector shows a peak no significant change in one of the radiometer channels is observed.

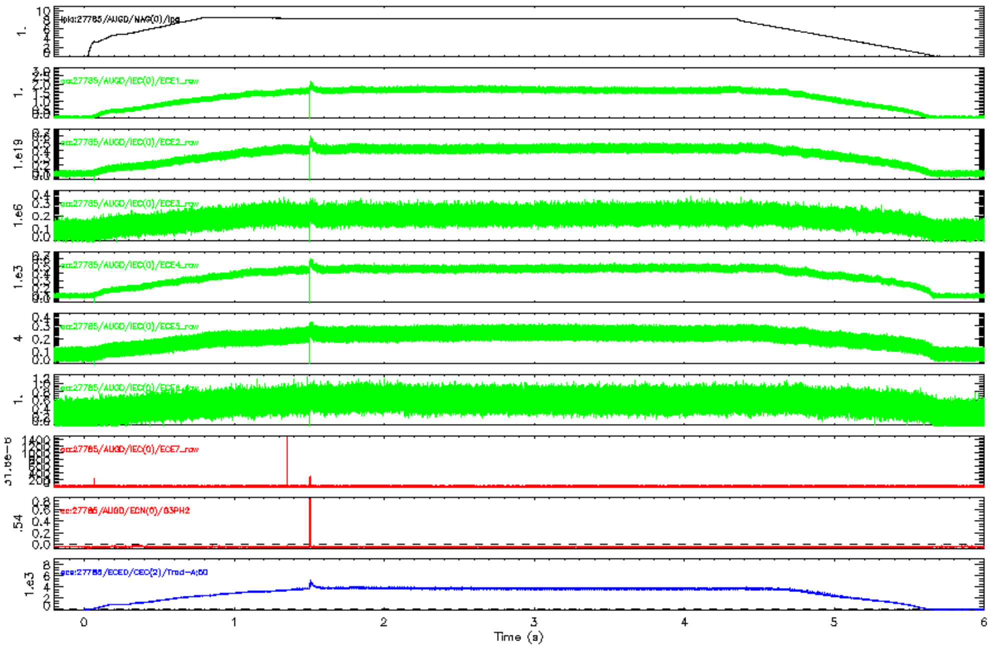


Figure 5.13: The first measurements(nr. 27785), in this measurement FADIS has smooth mirrors so has no effect on the scan. This results shows that the line-of-sight setup works. The graphs show:
1. The current in the Plasma. **2.** Line-of-sight ECE channel 1. **3.** Line-of-sight ECE channel 2. **4.** Line-of-sight ECE channel 3. **5.** Line-of-sight ECE channel 4. **6.** Line-of-sight ECE channel 5. **7.** Line-of-sight ECE channel 6. **8.** Not connected. **9.** Output power of FADIS. **10.** Conventional ECE signal.

5.2 Measurements with ECE at ASDEX-upgrade

To test the line-of-sight ECE setup, measurements were scheduled at the end of April 2012 on the ASDEX-Upgrade tokamak. This Tokamak at the Max-Planck-Institut für Plasmaphysik, Garching is the largest fusion experiment in Germany. First measurements were performed to measure the plasma heating and in the end a measurement with magnetic islands in the plasma. Besides the line-of-sigh setup a conventional ECE setup is installed at ASDEX-Upgrade, these measurements can be used as reference.

5.2.1 Plasma Measurements

Figure 5.13 shows the first measurements with the line-of-sight ECE setup. When the outputs of the line-of-sight ECE setup (graph 2 - 7) are compared with the conventional ECE (graph 10) the outputs look similar. The signals on Chanel 3 and 6 show too much noise, this can interfere with future NTM detection. After 1.5 seconds the graph of the ECE output show an error followed by a small peak. This error may indicate a high power peak. To prevent damaging the radiometer a pin-switch is installed, see section 5.1.3. In appendix B three other scans can be found, in these scans FADIS is functioning.

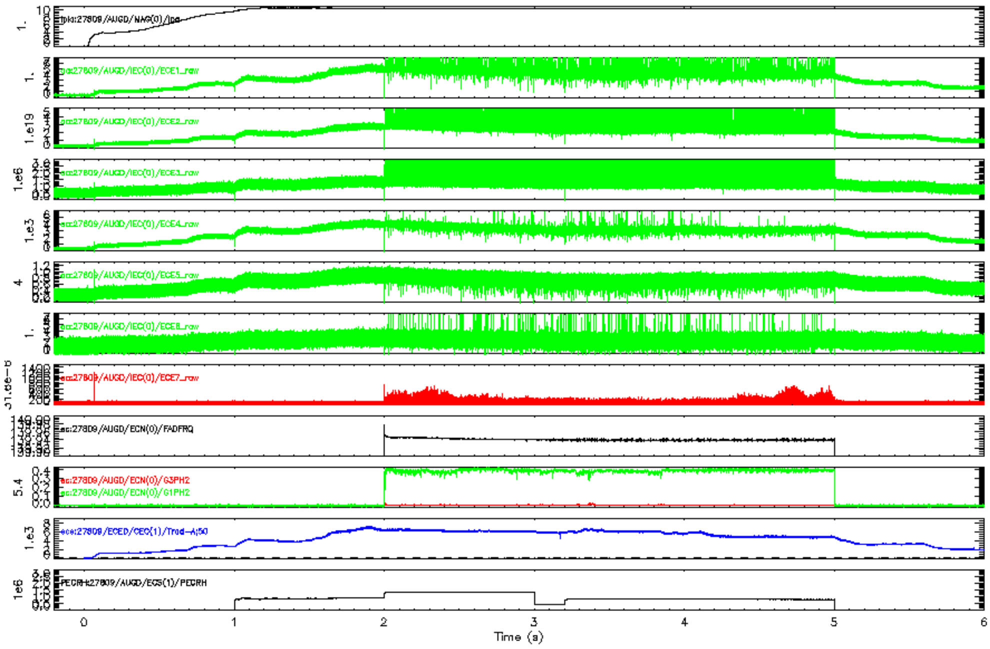


Figure 5.14: Line-sight measurements(nr. 27809) with NTMs in the plasma. The graphs show:
1. The current in the Plasma. **2.** Line-of-sight ECE channel 1. **3.** Line-of-sight ECE channel 2. **4.** Line-of-sight ECE channel 3. **5.** Line-of-sight ECE channel 4. **6.** Line-of-sight ECE channel 5. **7.** Line-of-sight ECE channel 6. **8.** Detector on the Mach-Zehnder load. **9.** Frequency used for FADIS control. **10.** Resonant(green) and non-resonant(red) FADIS outputs. **11.** Conventional ECE signal. **12.** Powers of different gyrotrons.

5.2.2 NTM Detection

After successful measurements with the line of sight setup a measurement with NTMs in the plasma was performed. The measured signals can be found in figure 5.14. To see if NTMs are detected the signal can be Fourier transformed. Figure 5.15 is the short time Fourier transform of the conventional ECE. The color shows if a NTM signal is present and what amplitude it has. The major yellow areas indicate that a signal is present, and that it changes frequency over time. These are the rotating magnetic islands, rotating with frequencies between 10 KHz and 30 KHz.

The figures 5.16 and 5.17 show short time Fourier transforms of two line-of-sight channels. In figure 5.16, ECE channel 1, the magnetic island can be seen, starting from around 1.7 seconds. The signal then disappears in the noise, and returns at 5 seconds. Figure 5.17, ECE channel 4, also shows a small signal from 1.7 second for about 0.5 second. The found NTM signal is, when detected, similar to that in figure 5.14. This proves that it is possible to detect NTMs with line-of-sight measurement.

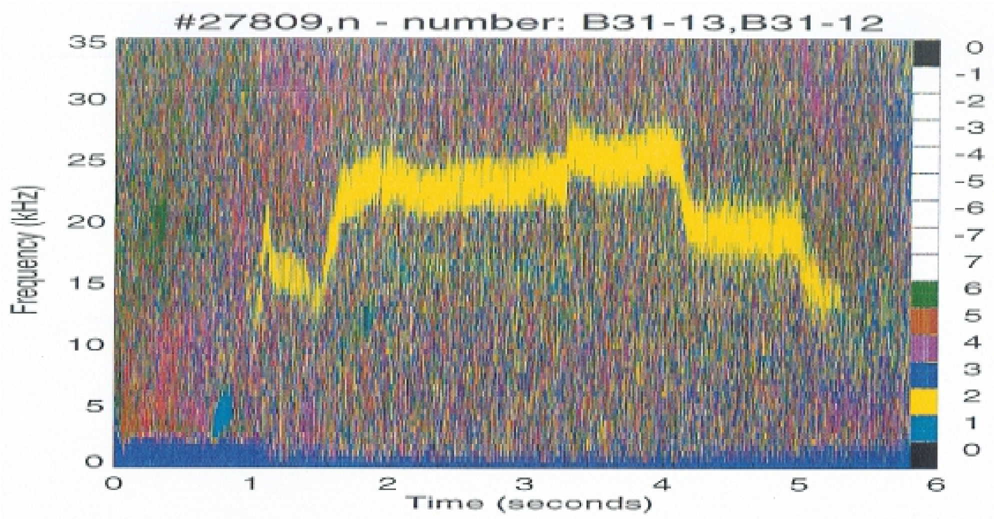


Figure 5.15: Short time Fourier transform of the conventional ECE.

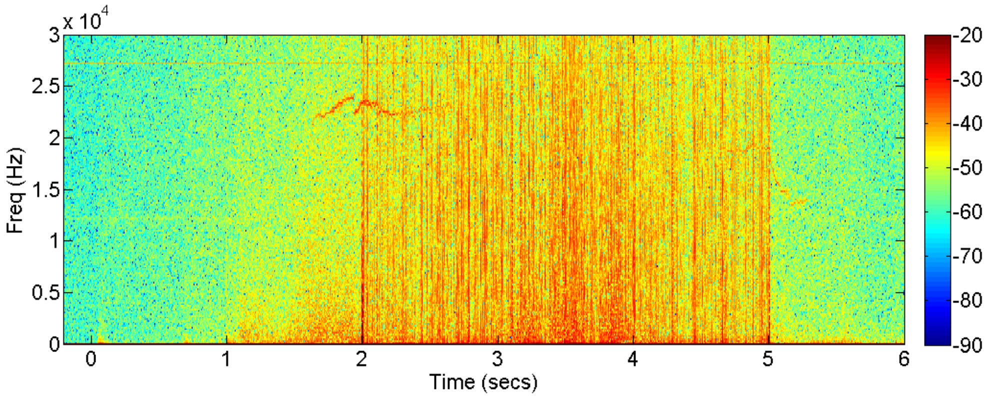


Figure 5.16: Short time Fourier transform of the line-of-sight ECE channel 1.

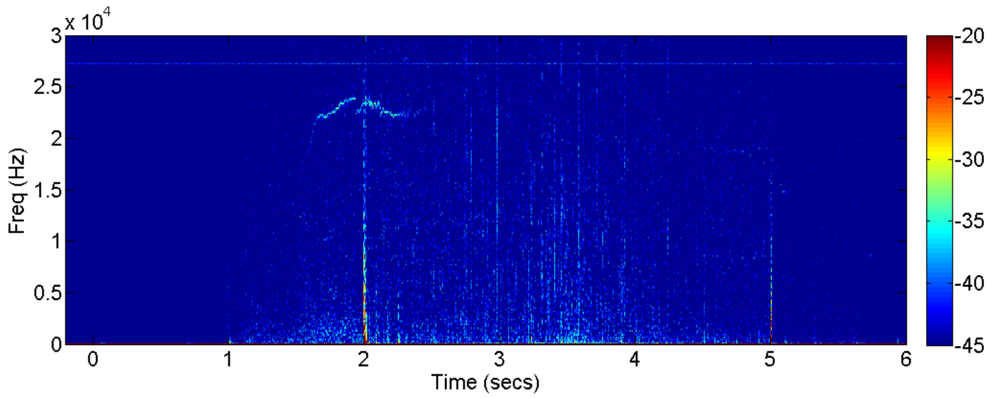


Figure 5.17: Short time Fourier transform of the line-of-sight ECE channel 4.

5.3 Future Line-of-Sight ECE setup

The detected NTM signals are not as clear visible as the signals detected with the conventional ECE setup. Improvement in the line-of-sight ECE is needed, for the setup to be used in a control setup for suppressing weaknesses in the magnetic confinement.

The first improvement would be replacing the bragg reflector notch-filter. This would make the additional notch-filter obsolete. This new notch-filter is already ordered and first results are expected this year.

Other improvements can be replacing the current radiometer with an intermediate frequency band digitized high dynamic range radiometer [6]. Also work is already being done on improving FADIS with vacuum waveguides.

Chapter 6

Conclusion

Development of a control graphic user interface, GUI, for FADIS is started allowing a fit routine for finding the mirror and cavity length parameters. The first results with the fitting routine are:

- For calibration shots performed at the Wendelstein 7-X tokamak in Greifswald, the fit routine works as expected. The calculated FADIS transmissions, with the found parameters, correlates with measured signals.
- Calibration shots at the ASDEX-Upgrade tokomak on the dummy are only 80ms long and too short for finding the correct parameters with the developed fitting routine.

In future, longer duration time pulses at ASDEX-Upgrade are needed to determine that the routine is working properly. It should be possible to test this with a calibration shot on the plasma instead of the dummy. For further development of the GUI for FADIS control it is necessary to get this routine working.

The first measurements with the line-of-sight ECE setup were performed on the ASDEX-Upgrade tokamak at the end April 2012. These measurements gave the results:

- Due to the detuning of FADIS in the first millisecond of a gyrotron shot a Pin-Switch is installed to protect the radiometer against high-power.
- The line-of-sight ECE setup was able to measure a ECE signal during ECRH at the same launcher, with FADIS controlled on the Gyrotron frequency.
- NTMs are measurable with line-of-sight ECE.

It can be concluded that the line-of-sight ECE is a working technique for measuring the plasma heat and detecting magnetic islands in the plasma. However further improvement in signal/noise ratio is needed before a complete magnetic island control system can become operational.

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[7] ITER Organization. *ITER - the way to new energy.* May 2012. URL: `http://www.iter.org/proj/iterhistory`.

Appendix A

Original trainee assignment

Field of study	:	**Technical Physics**
Trainee	:	**Jan Willem Slob**
Starting date	:	**7 February 2012**
Title	:	**Preparations line of sight ECE measurements; FADIS Control of by phase and acceptance tests in Garching**

Introduction

In a tokamak, a toroidal, magnetized plasma is confined using magnetic fields. The fusion power of tokamak plasma goes to the power 2^{th} of the normalized pressure. At such reactor grade pressures, instabilities are likely to occur, which degrade the fusion performance. To generate fusion, the plasma in tokamak has to be heated up to hundreds of millions degrees Centigrade. One heating scheme is the resonant heating of electrons: High power millimeter waves are deposited into the plasma for heating or to control magnetic perturbations.

The FOM Institute for Plasma Physics "Rijnhuizen" carries-outs research in the field of tokamak plasma heating with the view to stabilize fusion-grade high pressure plasma such as foreseen in ITER.A real-time system for the stabilization of these so called NTMs has been constructed on the TEXTOR tokamak in Juelich. In this system the Electron Cyclotron Emission (ECE) of the plasma inside the tokamak is measured along the same transmission which is used for the millimeter wave heating. In essence, the set-up shows how the control system for NTMs simplifies with line-of-sight ECE. In collaboration with the Max-Planck institute for plasma physics a new line-of-sight system is being developed, to be installed on the tokamak ASDEX Upgrade (AUG), which should bring the concept of line-of-sight to maturity. A key component of this system is the diplexer FADIS, this system separates the low power ECE waves (from the plasma) from the High power waves (to the plasma). Since the operation of FADIS is frequency dependent and frequency of the high power source, the Gyrotron, deviates during start up FADIS must be tuned or controlled synchronously during the Gyrotron pulse. As control sensor we measure the phase between the output-signals of FADIS

Description of the assignment

1) Get experienced with low power mm-wave measurements
2) To create a calibration procedure for FADIS in the high power set-up.
3) In-Line ECE at AUG using FADIS control test (at IPF).

Executed at
FOM Instituut "Rijnhuizen"
TNO Delft and IPF Stuttgart

FOM Instituut "Rijnhuizen"
Edisonbaan 14
3439 MN Nieuwegein
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Company supervisors:
Dr. Waldo Bongers (main FOM)
Dr. Marco de Baar (FOM)
In cooperation with:
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Dr. Niek Doelman and Rens den Braber (TNO)
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Appendix B

Line-of-Sight ECE measurements

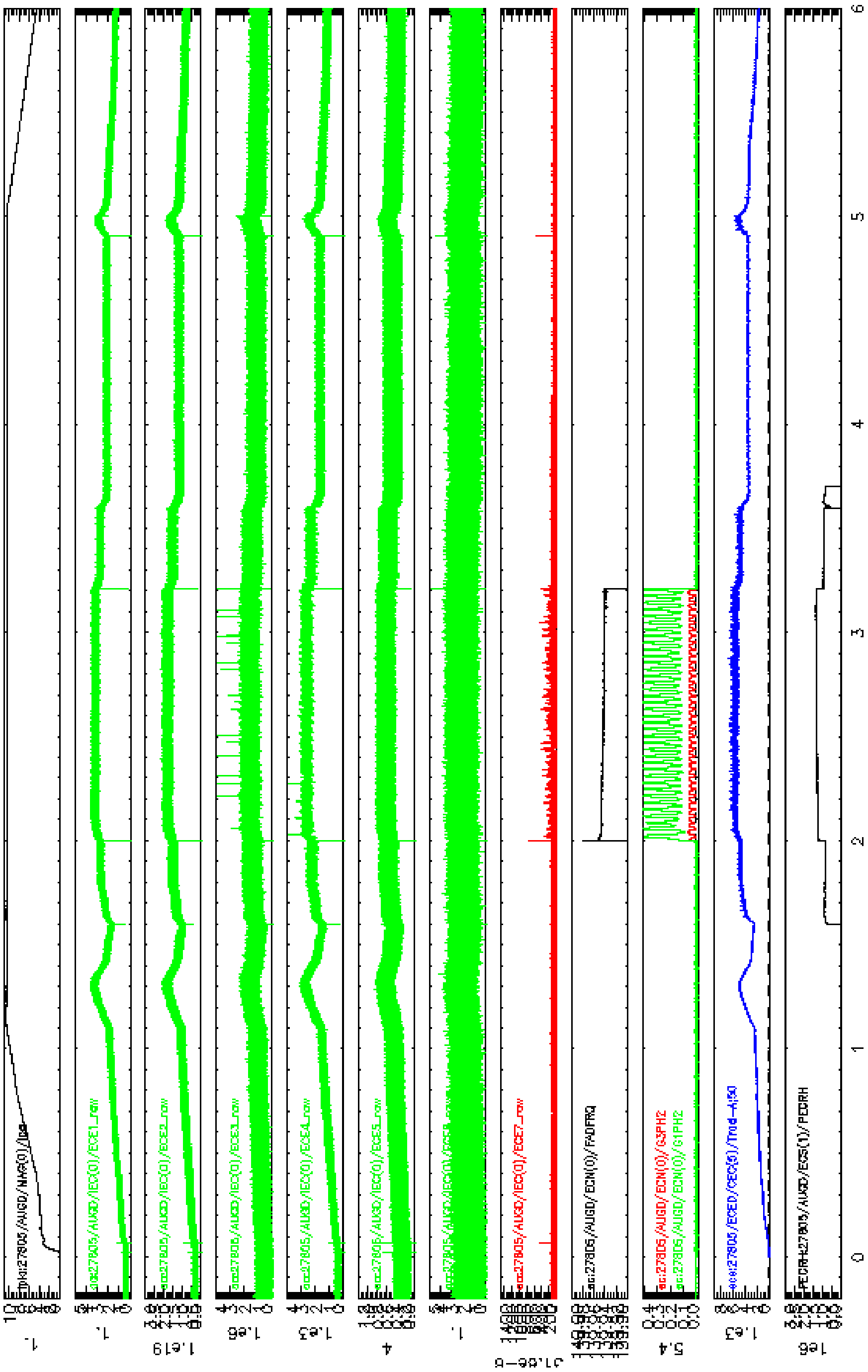

Figure B.1: Scan ECE27805, in this measurement FADIS is fast-sweeped.
The graphs show:
1. The current in the Plasma. **2.** Line-of-sight ECE channel 1. **3.** Line-of-sight ECE channel 2. **4.** Line-of-sight ECE channel 3. **5.** Line-of-sight ECE channel 4. **6.** Line-of-sight ECE channel 5. **7.** Line-of-sight ECE channel 6. **8.** Detector on the mach-zehnder load. **9.** Frequency used for FADIS control. **10.** Resonant(green) and non-resonant(red) FADIS outputs. **11.** Conventional ECE signal. **12.** Powers of different gyrotrons.

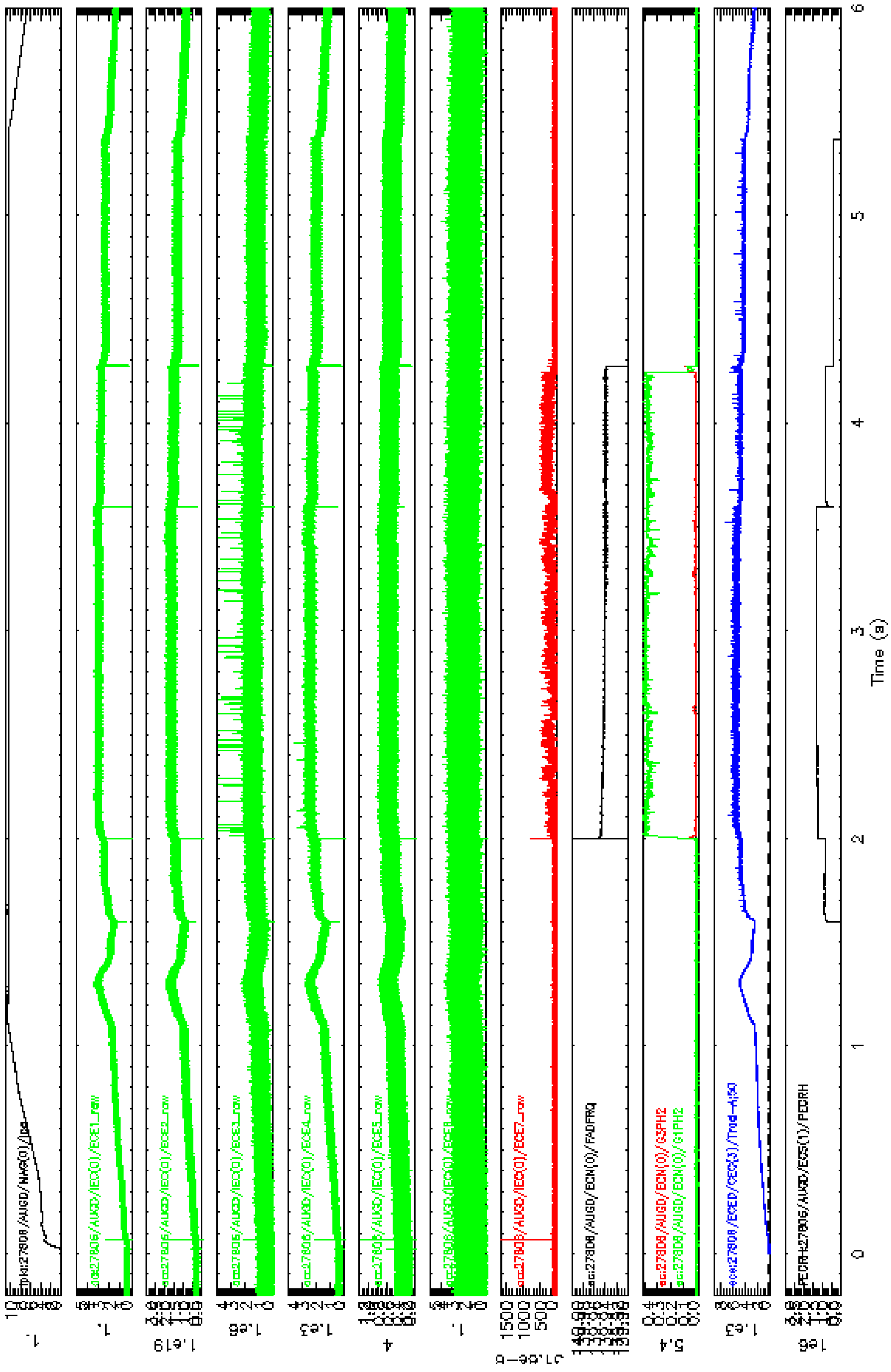

Figure B.2: Scan ECE27806, Mechanical switching: Control to resonance: on - off . Manually ECRH L-mode, 2 sec
The graphs show:
1. The current in the Plasma. **2.** Line-of-sight ECE channel 1. **3.** Line-of-sight ECE channel 2. **4.** Line-of-sight ECE channel 3. **5.** Line-of-sight ECE channel 4. **6.** Line-of-sight ECE channel 5. **7.** Line-of-sight ECE channel 6. **8.** Detector on the mach-zehnder load. **9.** Frequency used for FADIS control. **10.** Resonant(green) and non-resonant(red) FADIS outputs. **11.** Conventional ECE signal. **12.** Powers of different gyrotrons.

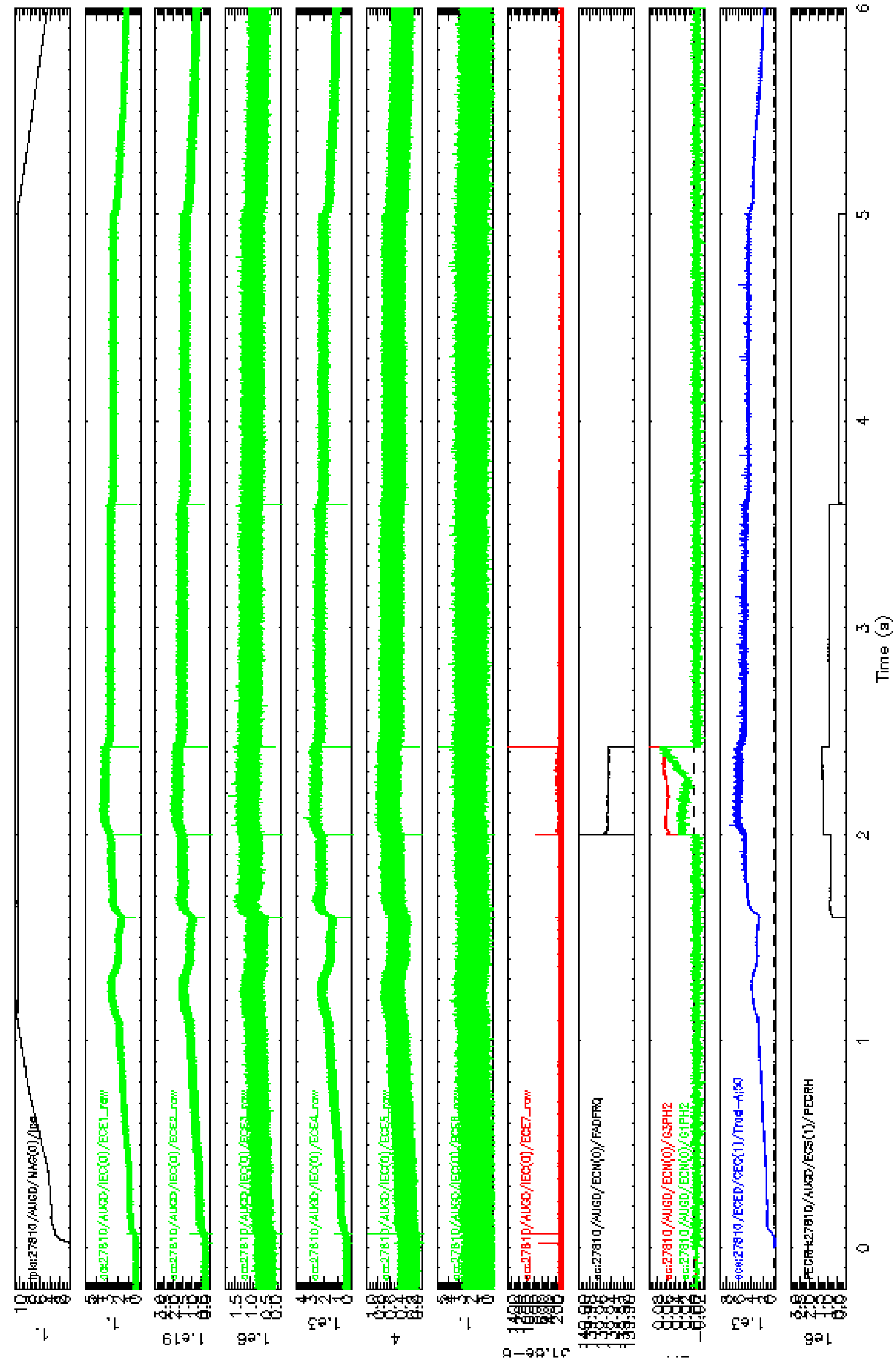

Figure B.3: Scan ECE27810, Mechanical scanning of resonator mirror 800 m/s .arc
The graphs show:
1. The current in the Plasma. **2.** Line-of-sight ECE channel 1. **3.** Line-of-sight ECE channel 2. **4.** Line-of-sight ECE channel 3. **5.** Line-of-sight ECE channel 4. **6.** Line-of-sight ECE channel 5. **7.** Line-of-sight ECE channel 6. **8.** Detector on the mach-zehnder load. **9.** Frequency used for FADIS control. **10.** Resonant(green) and non-resonant(red) FADIS outputs. **11.** Conventional ECE signal. **12.** Powers of different gyrotrons.

Appendix C

Project ITER

In 1985 the President of France, Mitterand, the Prime Minister of the United Kingdom, Thatcher, and General Secretary of the Soviet Union, Gorbachev, proposed to U.S. President an international project aimed at development of a fusion energy reactor. Later also Japan, the People's Republic of China, the Republic of Korea and India joined the project. This project is now known as the ITER (International Thermonuclear Experimental Reactor).

Already in 1988 the first designs were made and in 2001 the final design was approved by the members, see also figure C.1. ITER is an example of big international collaboration and in all the member states parts for the Tokomak Fusion Reactor are developed. In 2019 ITER hopes to make the first plasma and in the years following research will continue to archive the first productive fusion.

FOM DIFFFER, formerly known as FOM Rijnhuizen, is the leading institute in the Netherland for plasma research. The institute contributes with research on different parts of the Tokomak Fusion Reactor constructed in Cadarache, France, by the ITER Organization. [7]

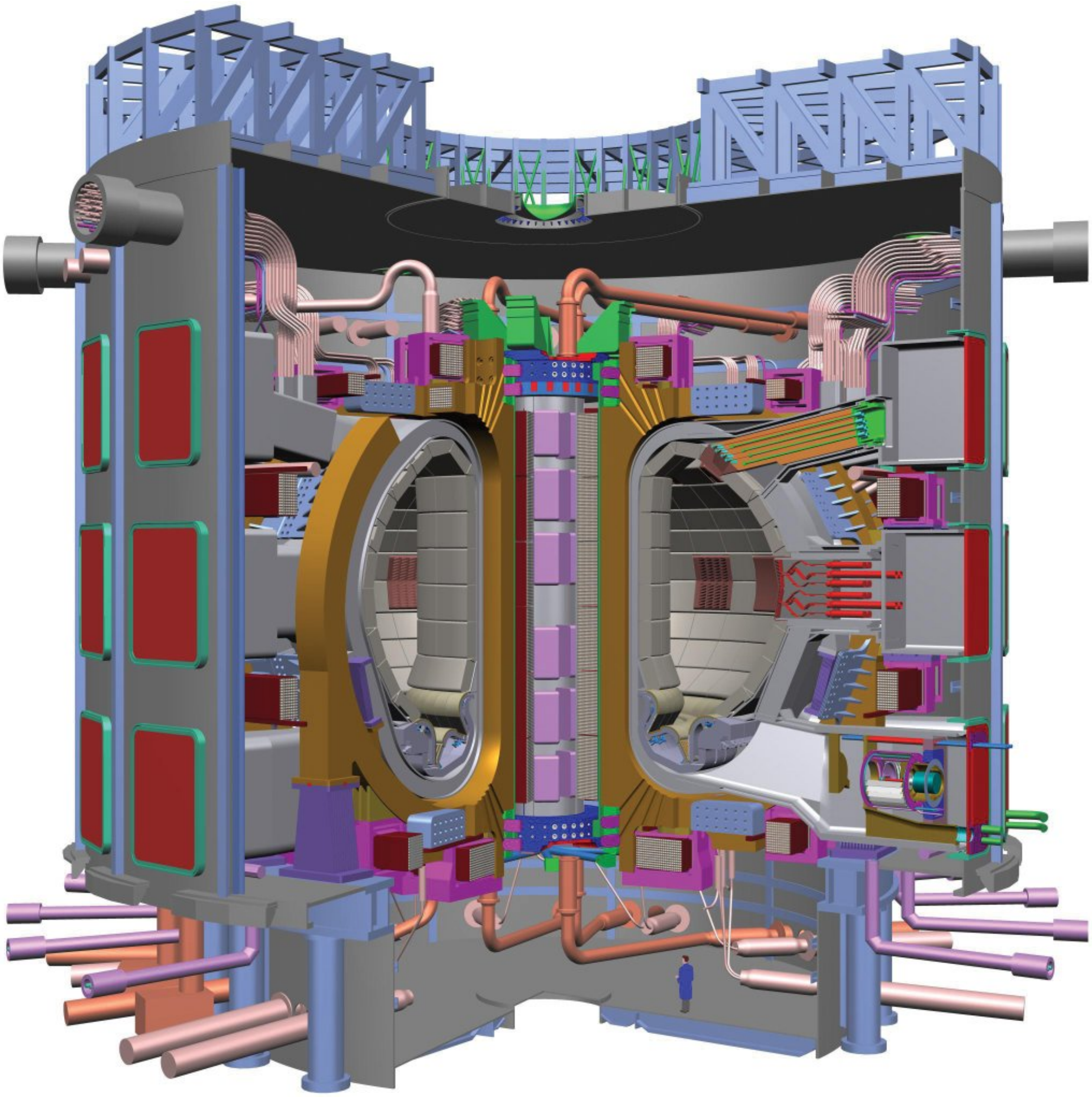

Figure C.1: Concept design of ITER, currently contstructed in Cadarache, France.