ED2245 Project in Fusion Physics

Project 1

Plasma flow velocity from spectroscopic measurement of Doppler line shifts

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

The plasma in the EXTRAP T2R device contains small traces of impurity atoms, e. g. oxygen originating from atmosphere, present inside the vacuum vessel even under the normal ultra-high vacuum state in the device. The impurity atoms are typically not completely ionized in the plasma, and the oxygen ions appear in different charge states. This ions emit line radiation which can be observed and spectrally analyzed with spectroscopy. Since the ions interact with the main hydrogen ions, the information obtained about their velocity and temperature is indicative of the main plasma.

The purpose of this project is to estimate the plasma flow velocity from spectroscopic measurement of the Doppler line wavelength shift. The Doppler wavelength shift of spectral lines occur when the plasma source emitting the line radiation is moving away (red-shift) or moving towards (blue-shift) the observer. The plasma diagnostic method includes:

- Setup of spectroscopic measurement with optical fibre on EXTRAP T2R
- Measurement of the Doppler broadened line profile for a selected spectral line using a high resolution spectrometer.
- Fitting of the line profile with a gaussian profile.
- Estimation of the line wavelength shift due to plasma flow.

2 Spectroscopy diagnostic

The spectroscopic measurement determines the velocity of partially ionized impurity ions with bound electrons emitting line radiation. Typically the oxygen impurity O^{+4} ion line at $\lambda = 2781$ A is used. The ion velocity is estimated from the Doppler wavelength shift of the spectral line. In order to evaluate the Doppler shift also a reference zero-velocity (unshifted) wavelength measurement of the spectral line is required. The spectroscopic measurements are made through a horizontal port on EXTRAP T2R, viewing the plasma along the tangential, toroidal direction, see Fig.1 . The reference, zero-velocity measurement is obtained through a vertical port viewing

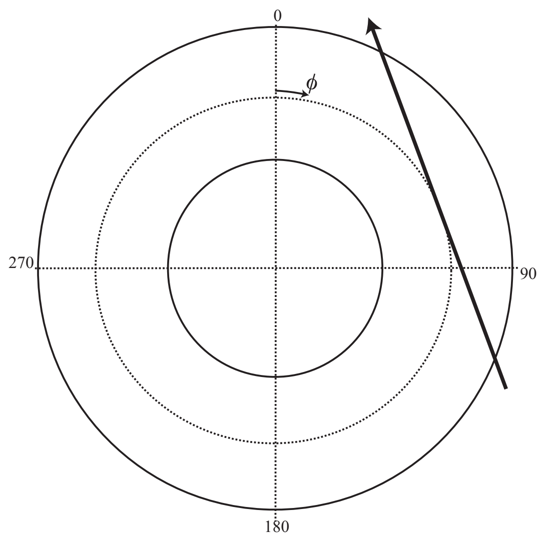


Figure 1: Viewing line for Doppler spectroscopy for toroidal flow measurement at 81 degrees horizontal port. View from top.

through the centre of the plasma column. By selecting a vertical port that is off-center, the poloidal plasma flow is measured, see Fig. 2.

The plasma is viewed using collection optics that consist of a lens focusing the plasma light onto the end surface of an optical fibre. The collection optics can be moved at the plasma device to a position that suits the measurement requirements:

- Reference (zero-velocity) measurement: Vertical lower central port at 78 degrees viewing along a vertical line-of-sight through the plasma center. The av
- Toroidal velocity measurement: Horizontal port at machine angle 81 degrees viewing in the negative toroidal direction. degrees. erage plasma velocity along this transverse line-of-sight is zero.
- Poloidal velocity measurement: Vertical lower inner port at 78 degrees viewing along a vertical line-of-sight, in the negative poloidal direction.

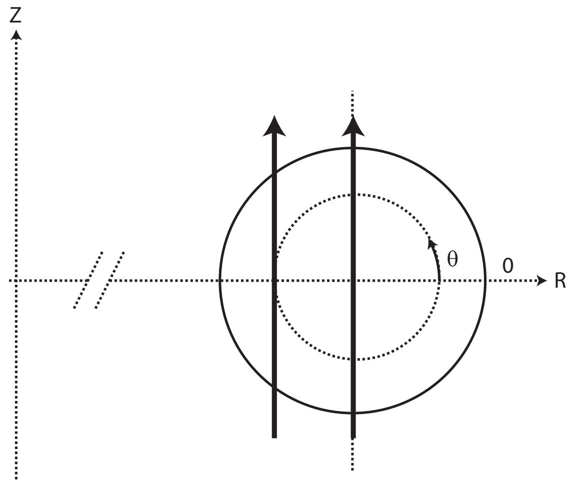


Figure 2: Viewing line for Doppler spectroscopy for poloidal flow measurement and zero-velocity measurement at 78 degrees ports. View from side.

Parameter	Value
Focal length	1000 mm
Grating ruling	2400 lines/mm
Lateral dispersion	4.1 Angstrom/mm
OMA detector element spacing	25μm per pixel
Array dispersion	0.10 Angstrom/pixel
OMA detector diode array (full)	1028 channels
Multi-scan reduced range	50 channels
Number of scans	29
Instrumental function width $\Delta\lambda_{FWHM}^{instr}$	0.96 Angstrom

Table 1: Spectrometer parameters.

Light is transmitted from the plasma to a spectrometer using an optical fibre. At the spectrometer end the optical fibre has a fixed position in front of the spectrometer entrance slit. The spectrometer is Model Monospek 1000 (manufacturer Hilger & Watts). It is a plane grating,

Item	Specification
Port 81 deg horizontal, window type	Quartz
Port 78 deg vertical, window type	Quartz
Optical fibre label F02, type	UV graded
Fibre label F02, diameter	600 microns

Table 2: Experimental setup parameters

symmetrical Czerny-Turner spectrometer. Radiation transmitted through the entrance slit is collimated and directed towards the diffraction grating by a collimating mirror. The diffraction grating disperses the incident radiation and part of it falls on to a focusing mirror which directs and focuses a spectrum at the exit slit. The focal length of the mirrors is 1000 mm. A grating with 2400 lines/mm is used. The nominal reciprocal dispersion at the detector with this grating is 4.1 Angstrom/mm.

The spectrometer has an external dial for changing the wavelength band passing the exit slit by manually rotating the diffraction grating. The the dial setting should be two times the wavelength measured in unit Angstrom. (The dial is marked for a 1200 lines/mm grating while a 2400 lines/mm grating is actually used.) The following formula is used for calculating the desired setting for the central wavelength:

$$N_{dial} = 2 \times \lambda - 5$$

The wavelength spectrum is obtained with an optical multi-channel analyser (OMA) Model 1461 system (manufacturer EG&G Princeton Applied Research). The light detector consists of an intensified silicon photodiode array (EG&G PARC Model 1421). The detector uses a photodiode array coupled to a microchannel plate intensifier. Photons from the plasma are incident on a photocathode that emits electrons when struck by photons. The photosensitive material in the photocathode has a high quantum efficiency in the wavelength region 2000-6500 Angstrom. The detector pixel size is $25\mu\text{m} \times 2.5$ mm with 25μm distance between pixel centers. The dispersion is thus $d = 25\mu\text{m} \times 4.1$ Angstrom $= 0.10$ Angstrom per pixel.

The wavelength resolution for the whole system is characterized by the value of the full-width at half-maximum of the measured instrumental function. The measured value is $\Delta\lambda_{FWHM}^{instr} = 0.96$ Angstrom at the wavelengths presently used.

The electrons emitted from the photocathode are accelerated along the MCP channels and as the electron collide with the channel wall, the walls act as electron multipliers liberating additional electrons. The electrons packets emerging from the MCP hit a phosphor screen causing it to emit photons which are detected by the silicon photodiodes. The diode array has a total of 1024 diodes. Each diode provides one channel of information corresponding to a measurement of the spectrum The integration time of the photon flux is set by a gate pulse generated by the detection system timing unit and pulse amplifier (EG&G PARC Model 1304). The OMA system has provides the possibility to scan the diode array at short time intervals to measure multiple wavelength spectra during the plasma discharge. The minimum time between subsequent spectra is limited by the read-out time of the photo diode array, which depends on the number of channels read. The read-out can be done in two modes:

- Normal scanning: The full array diode (pixel) range is used. The scanning time is 16 μs per pixel.
- Fast scanning: A reduced pixel range used. This range is scanned at 16 μs per pixel, the unused pixels outside this range are scanned at 0.5 μs per pixel.

Typically fast scanning readout is used with at reduced range of 50 pixel (wavelength range of 5 Angstrom) allowing a maximum repetition rate of about 2.5 ms. Data for the spectrometer diagnostic at EXTRAP T2R are summarized in Tables 1 and 2.

3 Estimation of plasma flow velocity from Doppler line shift

The wavelength shift of the emitted line radiation due to the Doppler effect is

$$\Delta\lambda = \pm\frac{v}{c}\lambda_0$$

where λ_0 is the unshifted wavelength, v the velocity of the ion, and c the velocity of light. The plus sign indicates velocity away from the observer (red-shift) and the minus sign indicates velocity towards the observer (blue-shift). The plasma ion velocity distribution is assumed to be shifted Maxwellian distribution characterized by a thermal velocity v_T and a flow plasma velocity v_0. The number of ions dN moving in the line of sight with velocity in the range $[v, v + dv]$ is

$$dN = \frac{N}{\sqrt{\pi}v_T}\exp\left\{-\left(\frac{v - v_0}{v_T}\right)^2\right\}dv$$

where N is the total number of emitting ions. The thermal velocity v_T is given by the ion temperature as

$$v_T = \sqrt{\frac{2eT_i}{m_i}}$$

where the temperature is in units electron Volt (eV). Define the Doppler 1/e-width characterizing the line broadening as

$$\Delta\lambda_D = \frac{v_T}{c}\lambda_0$$

and introduce the wavelength shift λ_s due to the plasma flow velocity as

$$\Delta\lambda_s = \frac{v_0}{c}\lambda_0.$$

By substituting v with $\Delta\lambda$, the velocity distribution is written as

$$dN = \frac{N}{\sqrt{\pi}\Delta\lambda_D}\exp\left\{-\left(\frac{\Delta\lambda - \lambda_s}{\Delta\lambda_D}\right)^2\right\}d(\Delta\lambda)$$

Assuming further that the plasma is optically thin, the intensity $Id(\Delta\lambda)$ of emitted light from the plasma is proportional to the number dN of emitting ions, giving the line intensity distribution the same Gaussian shape:

$$I(\Delta\lambda) = \frac{I_t}{\sqrt{\pi}\Delta\lambda_D}\exp\left\{-\left(\frac{\Delta\lambda - \lambda_s}{\Delta\lambda_D}\right)^2\right\}$$

Here I_t is the total intensity of the line. It is useful to calculate the full-width at half-maximum (FWHM) value $\Delta\lambda_{FWHM}$ for the line intensity distribution.

$$\Delta\lambda_{FWHM} = 2\sqrt{\ln 2}\,\Delta\lambda_D.$$

This value is used for calculating the ion temperature as

$$T_i = \frac{1}{8\ln 2}\frac{m_i c^2}{e}\left(\frac{\Delta\lambda_{FWHM}}{\lambda_0}\right)^2 \text{ [eV]}.$$

When estimating the ion temperature, it is important to correct the measured value $\Delta\lambda_{FWHM}^{meas}$ for the instrumental broadening in the spectrometer $\Delta\lambda_{FWHM}^{instr}$,

$$\Delta\lambda_{FWHM} = \sqrt{\left(\Delta\lambda_{FWHM}^{meas}\right)^2 - \left(\Delta\lambda_{FWHM}^{instr}\right)^2}.$$

4 Software

The software packages IDL from Research Systems for graph plotting, and MDS from MIT for data acquisition is used. More detailed information about how to write, compile and run IDL programs will be given at the time of the laboratory project. Some useful IDL library functions and system variables are listed below:

- `DATA` Function that reads MDS signals into an IDL data vector.
- `GAUSSFIT` Function that fits paired data $[x_i, y_i]$ to a gaussian function $\mathbf{y} = f([a_j], \mathbf{x})$ by least squares minimization. The gaussian function $f([a_j], \mathbf{x})$ has a number of unknown parameters $[a_j]$, which are determined in the fitting process.

Use the `!p.multi` parameter to stack graphs in one plotting window. The `WINDOW` statement opens a new plotting window on the screen. Use the `OPLOT` function and `LINESTYLE` keyword to over-plot several curves on the same graph with different line styles. The `!P.CHARSIZE` system variable to used for setting character size in graph labels. Information about the syntax of these functions and other IDL routines are found in the IDL on-line help pages.

5 EXTRAP T2R

The geometry of the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Plasma minor radius $a = 0.183$ m

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). The time vector is stored with the ending "TM" to the name as shown below. Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the IDL program using the signal names which are as follows:

`GBL_ITOR_PLA, GBL_ITOR_PLA_TM`

The plasma current signal is scaled to unit kA.

6 Stored spectrometer signal

The multiple wavelength spectra measured with the OMA detections system are stored sequentially in one signal, that is available for the data analysis, and called from IDL by using the signal name;

`OMA_01`

The number of data stored in the signal is the number of scans (typically 29) times the number of pixels in each scan (typically 50) giving $N_{data} = 29 \times 50 = 1450$ stored data values.

7 Data analysis

- Separate the data for the individual scans in the signal.
- Estimate the parameters for the measured line intensity distribution by performing a non-linear fit using the IDL `GAUSSFIT` routine.

ED2245 Project in Fusion Physics

Project 2

Measurement of plasma magnetic field fluctuations with arrays of pick-up coils

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

Plasma in the fusion device EXTRAP T2R is confined partly by a magnetic field from an external magnetic field coil, and partly by an internal magnetic field produced by electric currents flowing in the plasma. This internal magnetic field has variations in time and spaced due to magneto-hydrodynamic (MHD) unstable modes. Measurement of the fluctuations give information of the modes; the spatial structure can be used to identify the physical plasma eigenmode. Measurement of the mode propagation can give information on the bulk plasma flow. The project work includes

- Measurement of magnetic field fluctuations at the plasma boundary with an array of pick-up coils.
- Data analysis involving decomposition of the perturbation into the spatial Fourier mode spectrum.
- Identification of eigenmodes and calculation of their propagation velocities.

One goal of the present project is to provide information about the plasma flow by studying the propagation MHD modes, and compare with flow estimates obtained in other projects by different methods.

2 Two-dimensional array of magnetic field pick-up coils

A two-dimensional array of magnetic field pick-up coils with $M = 4$ coils in the poloidal direction and $N = 64$ coils in the toroidal direction is used on EXTRAP T2R. The coils are small

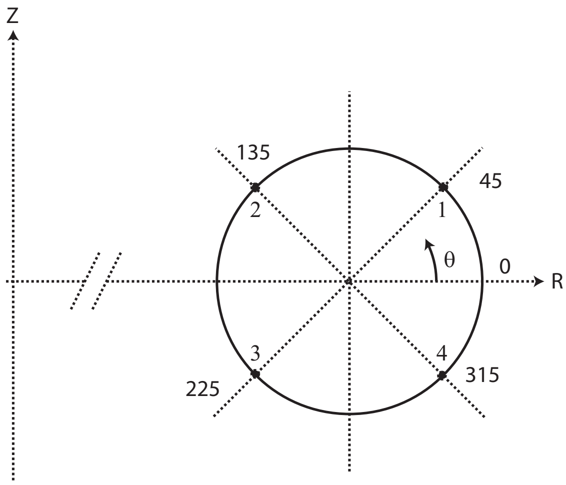


Figure 1: Two-dimensional pick-up coil array used on EXTRAP T2R with 4 coils in the poloidal direction and 64 coils in the toroidal direction. View from side.

solenoids that measure the poloidal magnetic field component at the plasma boundary. The coils are equally distributed over the torus surface, with coils at poloidal and toroidal positions

$$\theta_j = \frac{\pi}{4} + (j-1)\Delta\theta, \quad j = 1, 2, 3, 4$$

$$\phi_k = \frac{\pi}{128} + (k-1)\Delta\phi, \quad k = 1, 2, \ldots, 64.$$

The parameters of the array are as follows

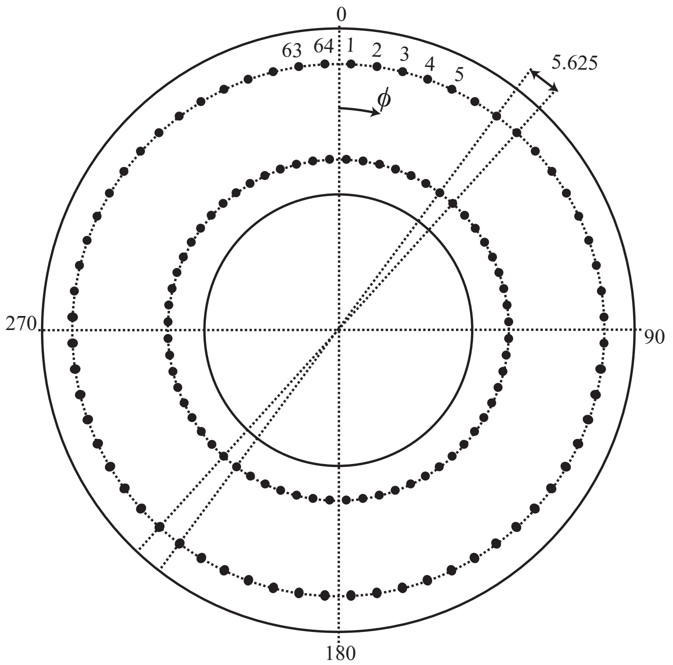


Figure 2: Two-dimensional pick-up coil array used on EXTRAP T2R with 4 coils in the poloidal direction and 64 coils in the toroidal direction. View from top.

- Poloidal spacing between coils $\Delta\theta = 2\pi/4$
- Toroidal spacing between coils $\Delta\phi = 2\pi/64$
- Minor radius of coil array $r_s = 0.1895$ m
- Solenoid coil cross section area $A = 3.14$ mm^2
- Number of turns $N = 200$

3 Fourier mode decomposition

The poloidal magnetic field vector component $b_p(\theta, \phi)$ at the plasma boundary is measured. It can be decomposed into spatial poloidal (or toroidal) Fourier harmonics. Introduce the shifted angular coordinates

$$\theta' = \theta - \frac{\pi}{4}$$
$$\phi' = \phi - \frac{\pi}{128}$$

In the present measurement only poloidal mode $m = 1$ is used. The field can be expressed in terms of the $m = 1$ Fourier coefficients $b_c(\phi')$ and $b_s(\phi')$ as follows:

$$b_p(\theta', \phi') = b_c(\phi') \cos\theta' + b_s(\phi') \sin\theta'$$

The Fourier coefficients $b_c(\phi')$ and $b_s(\phi')$ are functions of the toroidal angle ϕ'. They are in principle obtained from the measured field through the relations

$$b_c(\phi') = \frac{1}{\pi}\int_0^{2\pi} b_p(\theta',\phi')\cos\theta'\,d\theta'$$
$$b_s(\phi') = \frac{1}{\pi}\int_0^{2\pi} b_p(\theta',\phi')\sin\theta'\,d\theta'$$

The measurement with a $M \times N$ two-dimensional array of pick-up coils would correspond to a spatial sampling of the field yielding a two-dimensional sequence of data points $b(j,k), j = 1,2,...,M, k = 1,2,3,...,N$:

$$b(j,k) = b_p(\theta'_j,\phi'_k)$$

In order to reduce the number of required data acquisition channels from 256 to 128, the magnetic coil outputs are series connected in pairs at each toroidal position. Through the series connection, the *difference* of two poloidally opposite coils are obtained:

- Coil A output = coil '1' output - coil '3' output
- Coil B output = coil '2' output - coil '4' output

The series connection gives as output two one-dimensional sequences of measurement data $b_c(k)$ and $b_s(k)$, that corresponds to the poloidal $m = 1$ Discrete Fourier Series coefficients:

$$b_c(k) = \frac{1}{2}\left(b(1,k) - b(3,k)\right) = \frac{2}{M}\sum_{j=1}^{M} b_p(\theta'_j,\phi'_k)\cos\theta'_j \sim b_c(\phi'_k)$$
$$b_s(k) = \frac{1}{2}(b(2,k) - b(4,k)) = \frac{2}{M}\sum_{j=1}^{M} b_p(\theta'_j,\phi'_k)\sin\theta'_j \sim b_s(\phi'_k)$$

The first step in the data analysis of the pick-up signal is to perform a spatial two-dimensional Discrete Fourier Transform (DFT) of the a two-dimensional sequence of coil array signals:

$$B_{m,n} = \frac{1}{MN}\sum_{j=1}^{M}\sum_{k}^{N} b(j,k)e^{-i(m\theta'_j+n\phi'_k)}$$

with the inverse transform

$$b(j,k) = \sum_{m=-M/2+1}^{M/2}\ \sum_{n=-N/2+1}^{N/2} B_{m,n}e^{i(m\theta'_j+n\phi'_k)}$$

The mode spectrum $B_{m,n}$ is the obtained from the two-dimensional DFT of the sequence $b_{j,k}$, using the Fast Fourier Transform routine `FFT2` in `MATLAB`. In order to use the 2-D FFT routine, it is necessary to reconstruct the individual coil signals at all 4 poloidal angles, considering only the $m = 1$ part of the field:

$$b(0,k) = b_c(k)$$
$$b(1,k) = b_s(k)$$
$$b(2,k) = -b_c(k)$$
$$b(3,k) = -b_s(k)$$

4 Software

The measurement data from the MHD control system is acquired from the experiment using the `MDS-Plus` data acquisition software. The `MDS-Plus` software, mainly developed at MIT, is interfaced with the `MATLAB` software. Data manipulation and plotting is performed by writing `MATLAB` scripts. More detailed information how to use `MDS-Plus` and `MATLAB` will be available in the lab. For the analysis of the magnetic data, the following `MATLAB` functions are available:

- `mdsopen` Connect to the MDS-Plus database server and open the MDS-Plus database pulse file for a given plasma pulse.
- `mdsvalue` Read a named signal stored in the pulse file into a MATLAB array.
- `mdsclose` Close the MDS-Plus pulse file, and disconnect from the server.
- `fft2` Perform a 2-D Discrete Fourier Transform
- `fftshift` Shift Fourier coefficients.

Information about these routines and other `MATLAB` routines are found in the on-line help pages. Note that `mdsopen`, `mdsvalue` and `mdsclose` are not part of the standard library, they are specific to the `MDS-plus MATLAB` interface.

5 EXTRAP T2R

he toroidal plasma in the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Minor radius $a = 0.183$ m

The main equilibrium magnetic field components (assumed axisymmetric) are obtained from data stored in the `MDS-Plus` database. Global magnetic data describing the equilibrium includes the toroidal plasma current (from which the poloidal magnetic field component is obtained using Amperes law) and the toroidal magnetic field component.

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the `MATLAB` arrays using the signal names. The plasma current signal name is:

`GBL_ITOR_PLA`

The plasma current signal is scaled to unit kA and the time is in unit ms. The other global data signal needed for the analysis is the toroidal magnetic field at the plasma boundary. The toroidal field outside the plasma is given by the magnetic field produced by the toroidal field coil (TFC) enclosing the plasma column. The plasma edge toroidal field signal name is

`PFM_BTEDGE`

The following is an example of a `MATLAB` script that reads the plasma current data into a two arrays:

```
% connect to database server, open the T2R database containing global signals
mdsopen( '130.237.45.71:T2R, shot_number'); %shot_number selects pulse file

% read the current signal into array 'curr'
curr = mdsvalue( '\gbl_itor_pla'); % current in unit kA

% read the sample times into array 'tm'
tm = mdsvalue( 'dim _of( \gbl_itor_pla)'); %time in unit ms

% close the T2R database
mdsclose
```

6 Magnetic pick-up coil signals

The signal names used by MDS-Plus are obtained from the coil positions of the full array of 64 coils in the toroidal direction.

Cosine component array ($V_A(\phi_k)$):

```
MHD_BP_1A
MHD_BP_2A
MHD_BP_3A
...
MHD_BP_64A
```

Sine component array ($V_B(\phi_k)$):

```
MHD_BP_1B
MHD_BP_2B
MHD_BP_3B
...
MHD_BP_64B
```

The MATLAB script to read a pick-up coil signal and the time vector into two arrays are:

```
% read the coil voltage signal into array 'volt'
volt = mdsvalue( 'signal name')

% read the sample times into array 'tm'
tm = mdsvalue( 'dim _of(signal name)'); %time in unit seconds
```

Each signal contains 60k sample data. The time vectors for the magnetic coil signals is in unit seconds. The stored pick-up coil signal outputs are in unit Volt. The signals plotted should be scaled to magnetic field per unit time. The recorded coil signals $V_A(k)$ and $V_B(k)$ are scaled from Volt using the coil area A, number of turns N:

$$b_c(k) = \frac{1}{NA} V_A(k) \quad (1)$$
$$b_s(k) = \frac{1}{NA} V_B(k)$$

Note the in the following b_c and b_s actually denote the time-derivative of the magnetic field. It turns out that it is more convenient to work with non-integrated signals when studying the mode propagation which involves the fast fluctuating part of the signal.

7 Fast Fourier Transform

The fft2 function is used for the computation of the two-dimensional DFT. It is important to pay attention to the ordering the routine uses for the Fourier mode coefficients that are stored in the output array. Consider e. g., a transform of a one-dimensional sequence of data points $b(i), i = 1, 2, \ldots, 64$ of length $N = 64$. The fft function outputs the mode coefficients $B(n)$ for $-31 \leq n \leq 32$ in a one-dimensional array of length $N = 64$ in the order $n = 0, 1, 2, \ldots, 31, 32, -31, \ldots, -2, -1$. Use the function fftshift in order to change to ordering $n = -31, -30, \ldots, -1, 0, 1, \ldots, 31, 32$. For the two-dimensional function fft2, the sequence of the poloidal mode numbers m is stored in a similar way as the toroidal mode numbers: The output array stores the poloidal modes in the order $m = 0, 1, 2, -1$, which has to be shifted to get the usual ordering $m = -1, 0, 1, 2$.

8 Total mode power, Parseval's theorem

The total MHD mode power is obtained as the sum of all $M \times N$ mode amplitudes squared. According to Parseval's theorem, this sum equals the sum of all $M \times N$ field values squared, divided by the number of field values $M \times N$. Parsevals's theorem thus gives the following relation:

$$\frac{1}{MN}\sum_{j=1}^{M}\sum_{k=1}^{N} b_{j,k}^2 = \sum_{m=-M/2+1}^{M/2}\sum_{n=-N/2+1}^{N/2} B_{m,n}^2$$

Parseval's theorem is useful for checking that the scaling of the Fourier transform has been correctly done.

9 Mode propagation velocities

The mode phase is computed as the argument of the complex Fourier coefficient.

$$\alpha_{m,n} = \arctan\left(\frac{\Im\{B_{m,n}\}}{\Re\{B_{m,n}\}}\right)$$

Then the mode angular frequency is obtained by taking the time derivative of the mode phase:

$$\Omega_{m,n} = -\frac{d\alpha_{m,n}}{dt}$$

This is the helical angular frequency that is the sum of the poloidal angular frequency ω_θ and the toroidal angular frequency ω_ϕ through the relation

$$\Omega_{m,n} = m\omega_\theta + n\omega_\phi$$

These angular frequencies can then finally be related to the mode poloidal and toroidal propagation velocities through

$$v_\theta = r\omega_\theta$$

and

$$v_\phi = R\omega_\phi.$$

ED2245 Project in Fusion Physics

Project 3

Edge plasma flow from electric field measurement with probes

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

The aim of this project is to estimate the plasma flow velocity at the edge from measurements of the radial electric field with inserted probes. The toroidal component of the plasma $\mathbf{E} \times \mathbf{B}$ drift velocity is estimated from the radial electric field and the poloidal magnetic field. The project work includes:

- Building and testing a small electric circuit for a triple-tip probe measurement (actually two identical circuits for two probes are to be built and tested.
- Setup and calibration of the probe data acquisition.
- Measurements in EXTRAP T2R plasma discharges with two radially separated triple-tip probes.
- Analysis of probe data involving the calculation of the plasma potential at two radial locations.

The measured radial electric field is useful for estimating the toroidal plasma flow due to the $\mathbf{E} \times \mathbf{B}$ plasma drift.

2 Probe diagnostic

The probe is inserted into the plasma with a simple vacuum feed through at one of the available ports on the device:

- Horizontal port at machine angle 256 degrees.

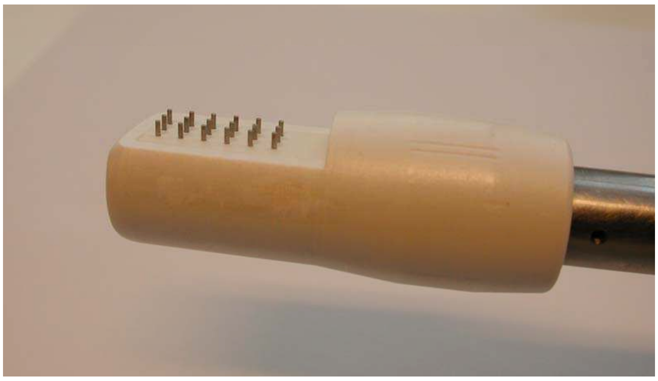


Figure 1: Probe head with 3x6=18 pins

The probe head, shown in Fig. 1 has an array of $3 \times 6 = 18$ pins, placed in 6 rows perpendicular to the probe axis. Each row has 3 pins which can be electrically interconnected for a triple-probe measurement. In principle, the probe can be used as 6 independent triple probes. However, in this project only two probes will be used, requiring in total 6 data acquisition channels. The distanced between a pin and the adjacent pin in a row is 3 mm. The distance between the rows is 3 mm, allowing triple-probe measurements to be performed at radial positions with 3 mm separation. The distance from the first row to the probe holder front edge is 5 mm. In summary, the insertion radius r_k of the k:th row of tips is calculated from the formula:

$$r_k = r_{holder} + 5 + 3(k-1) \text{ [mm]}$$

where r_{holder} is the insertion minor radius of the probe holder front edge and $k = 1, 2, \ldots, 6$ is the row index. The probe insertion is selected using specially prepared distance rods of different length. The insertion minor radius of the probe holder front edge is related to the distance rod length l_{rod} as follows

$$r_{holder} = 58 + l_{rod} \text{ [mm]}$$

For example, insertion of the probe holder front edge to the plasma limiter minor radius $a = 183$ mm, requires a distance rod of length $l_{rod} = 125$ mm. Insertion of the probe holder front edge insider the limiter radius must be done with great care, with the probe position changed in small steps, observing the probe signals and the global plasma behavior for each position. The probe has an unavoidable degrading effect on the plasma which increases with the insertion depth. The minimum holder front edge minor radius possible is around $r_{holder} = 175$ mm ($l_{rod} = 117$ mm) which corresponds to an insertion of the probe head 8 mm inside the plasma, thus aligning the second row of probe tips with the plasma limiter minor radius.

The probe tips are cylindrical with a diameter of 0.5 mm and a length of 2 mm. The probe tips are metal, made of molybdenum. They are mounted into an non-conducting insulator holder made of boron nitride. The probe tips are placed on a plane surface of the holder. The probe should be rotated around the axis so that the plane surface is horizontal and facing downward. In this way the curved back side of the probe holder is facing upward, blocking the downward fast electron flux which otherwise perturbs the probe measurement.

The probe tips are connected with wires to a feed-through vacuum flange. On the outside of the flange coaxial cables are connected providing the probe signals. The cables are labeled as follows:

- Row 1: 11, 12, 13
- Row 2: 21, 22, 23
- ...
- Row 6: 61, 62, 63

Data for the probe diagnostic are summarized in Table 1.

Parameter	Value
Number of tips in array	3×6
Number perpendicular rows in array	6
Number of tips in row	3
Distance of first row to holder front edge	5 mm
Distance between rows	3 mm
Distance between tips in row	3 mm
Diameter of cylindrical tip	0.5 mm
Length of cylindrical tip	2 mm

Table 1: Probe head geometrical parameters.

The available probe pins are used to set up two triple probes, using two rows of pins as shown in Fig. 2 The first triple-probe uses pins 11, 12, 13, and the second triple-probe uses pins 31, 32, 33.

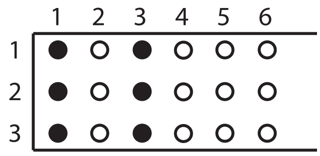


Figure 2: Probe pins used for the two triple-probes.

3 Triple-probe technique

The electric current flowing into a probe tip from the plasma is the sum of the electron current I_e and the ion current I_i due to the thermal motion of the particles. Typically, the electrons moves faster than the ions, and a floating probe tip will accumulate negative charge which gives the probe a negative potential relative to the plasma space potential V_s. At the probe floating potential V_f, the electrons are repelled by the negative probe voltage $V_f - V_s$, which reduces the electron current so that the net probe current is zero ($I_i + I_e = 0$). When the probe tip is biased at a potential V (which is still negative relative to the plasma space potential), the electron current into the probe tip is given by

$$I_e = -\frac{1}{4} e A n_e \exp\left(\frac{e(V - V_s)}{kT_e}\right) \sqrt{\frac{8kT_e}{\pi m_e}} \tag{1}$$

This current is dependent on the probe voltage V, while the ion current into the probe at a negative potential is the ion saturation current

$$I_i = I_s = e A n_e \exp\left(-\frac{1}{2}\right) \sqrt{\frac{kT_e}{m_i}} \tag{2}$$

independent of the probe voltage. Here, A is the area of the probe tip. The electron charge is e,the electron mass m_e, the ion mass m_i, the electron density n_e and the electron temperature T_e.

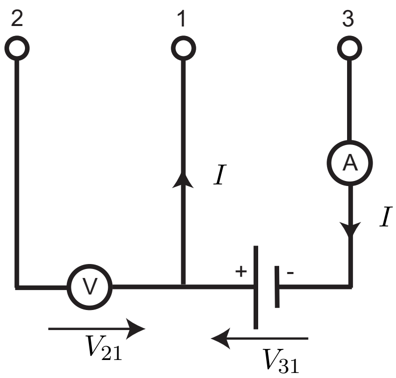


Figure 3: Triple-probe schematic circuit diagram

The aim of the triple-probe technique is to measure plasma potential, electron density and temperature simultaneously. The triple-probe is floating, connected through a high resistance to the vacuum vessel, which is grounded. The probe circuit is shown schematically in Fig. 3. One tip (2) is at the floating potential V_f, while two tips (1) and (3) are biased at a fixed voltage differing from the floating potential. The tips (1) and (3) are interconnected via a battery that drives a probe current I between the two tips. The ion saturation current I_s, the electron temperature T_e and the floating potential V_f are obtained from the probe current I and the probe tip potential differences V_{21} and V_{31}. The probe circuit can be easily analyzed by writing the equations for the current into each probe tip:

$$-I = I_s - I_e \exp\left(\frac{e(V_1 - V_s)}{kT_e}\right) \tag{3}$$

$$0 = I_s - I_e \exp\left(\frac{e(V_2 - V_s)}{kT_e}\right) \tag{4}$$

$$I = I_s - I_e \exp\left(\frac{e(V_3 - V_s)}{kT_e}\right) \tag{5}$$

Introduce

$$\psi_{21} = \frac{e(V_2 - V_1)}{kT_e} \tag{6}$$

$$\psi_{31} = \frac{e(V_3 - V_1)}{kT_e}. \tag{7}$$

Typically $\psi_{21} < 0$ and $\psi_{31} < 0$. It is straightforward to show that

$$I_s = I \frac{\exp(\psi_{21})}{1 - \exp(\psi_{21})} \tag{8}$$

and

$$\exp(\psi_{21}) = \frac{1}{2}(1 + \exp(\psi_{31})). \tag{9}$$

The battery voltage is selected sufficiently large compared to the electron temperature so that

$$|\psi_{31}| \gtrsim 2. \tag{10}$$

The following approximate relations are then obtained

$$\psi_{21} \approx -\ln 2 \tag{11}$$

giving

$$\frac{kT_e}{e} \approx -\frac{V_2 - V_1}{\ln 2} \tag{12}$$

and

$$I_s \approx I. \tag{13}$$

The floating potential is obtained directly as

$$V_f = V_2. \tag{14}$$

The electrical circuit required for the triple-probe measurement is contained in a metal box close to the probe, shown in Fig. 4. The output signals are transferred via optical links to the data acquisition modules. The input voltages to the optical links must be in the range ±10 V. The electrical circuit consists mainly of two resistive voltage dividers, measuring the probe voltages V_1 and V_2. The battery voltage gives the probe voltage difference $V_{31} = -V_{bat}$. The voltage source consists of 20 series connected 9-volt batteries giving a voltage of approximately $V_{bat} = 20 \times 9 = 180$ V. Finally, the voltage measured over a small series resistance gives the current I. The three probe tips are connected at the inputs $P1$, $P2$, $P3$, and output voltage signals are labeled $V13$, $V23$, $V43$, and the current output is labeled $I31$. The probe voltages V_1, V_2, V_3 and the probe current I are easily obtained from the output signals using the component values shown in the circuit diagram.

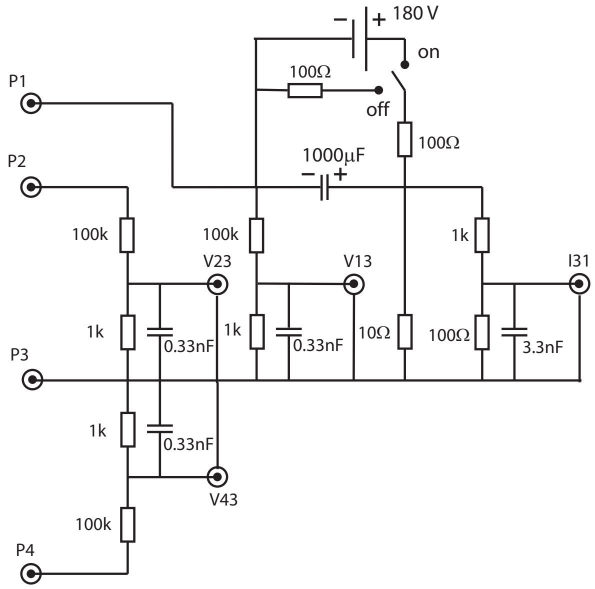


Figure 4: Triple-probe electric circuit. The circuit is in metal shielding box with BNC connectors for three probe input signals (P1,P2,P3), one input P4 for a grounding wire to the vacuum vessel and four output signals (V13, V23, V43, I13)

4 Software

The software packages IDL from Research Systems for graph plotting, and MDS from MIT for data acquisition is used. More detailed information about how to write, compile and run IDL programs will be given at the time of the laboratory project. Some useful IDL library functions and system variables are listed below:

- `SET_SHOT` Sets shot number to read
- `DATA` Function that reads MDS signals into an IDL data vector.

Use the `!p.multi` parameter to stack graphs in one plotting window. The `WINDOW` statement opens a new plotting window on the screen. Use the `OPLOT` function and `LINESTYLE` keyword to over-plot several curves on the same graph with different line styles. The `!P.CHARSIZE` system variable to used for setting character size in graph labels. Information about the syntax of these functions and other IDL routines are found in the IDL on-line help pages.

5 EXTRAP T2R

The geometry of the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Plasma minor radius $a = 0.183$ m

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). The time vector is stored with the ending "TM" to the name as shown below. Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the IDL program using the signal names which are as follows:

```
GBL_ITOR_PLA, GBL_ITOR_PLA_TM
```

The plasma current signal is scaled to unit kA.

6 Stored probe signals

There are six data channels available, allowing simultaneous measurements with two triple-probes. The signals are labeled

```
PROBE_01
PROBE_02
...
PROBE_06
```

Data are typically sampled at a sampling frequency of 1 MHz.

7 Data analysis

The relation between the plasma space potential and the floating potential is obtained from the condition $I_i + I_e = 0$,

$$\frac{1}{4} e A n_e \exp\left(\frac{e(V_f - V_s)}{kT_e}\right) \sqrt{\frac{8kT_e}{\pi m_e}} = e A n_e \exp\left(-\frac{1}{2}\right) \sqrt{\frac{kT_e}{m_i}} \tag{15}$$

which gives

$$\frac{e(V_f - V_s)}{kT_e} = \frac{1}{2}\left(\ln\left(\frac{2\pi m_e}{m_i}\right) - 1\right) \tag{16}$$

For hydrogen, the relation is approximately

$$V_s \approx V_f + 3.3\frac{kT_e}{e} \tag{17}$$

The radial electric field is obtained from the plasma space potentials measured with two sets of triple-probes as

$$E_r \approx \frac{V_{s1} - V_{s2}}{d} \tag{18}$$

where $d = 6$ mm is the radial separation of the probes. The poloidal magnetic field is obtained from the plasma current measurement using Ampere's law in integral form:

$$B_\theta \approx \frac{\mu_0 I_p}{2\pi a} \tag{19}$$

and finally the toroidal plasma velocity is estimated as

$$v_\phi \approx \frac{E_r}{B_\theta} \tag{20}$$

ED2245 Project in Fusion Physics

Project 4

Determination of plasma column shape from the external magnetic field

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

The aim of this project is to determine the shape of the plasma column from measurements of the external magnetic field. The shape of the boundary of the plasma column is determined by the shape of the outermost closed magnetic flux surface. The magnetic flux surface is the toroidal surface formed by the magnetic field lines winding around the torus. Measurement of the magnetic field intensity outside the plasma followed by some calculations on the magnetic field data then provides the plasma column shape.

It is particularly important to determine the shape of the plasma in experiments where external control coils are used to produced a non-axisymmetric perturbation of the plasma column. Such non-axisymmetric perturbations are used in order to study the effect of plasma non- axisymmetry on the plasma toroidal and poloidal flow (the plasma rotation). Specifically, non-axisymmetry has been shown to cause a braking of the plasma rotation.

The project involves mainly work on the MHD mode control system installed at EXTRAP T2R, which is described in a separate note. The project work includes the following tasks:

- Spatially resolved measurements of radial (normal) magnetic field component at the plasma boundary using an array of 4x32 magnetic flux loops.
- Decomposition of the radial magnetic field into the spatial Fourier mode spectrum.
- Calculation of the local displacement of the plasma boundary from the ideal axisymmetric shape.
- Development of a MATLAB routine that plots the plasma shape in a 3-D graph as a function of time, allowing the visualization of the plasma shape evolution.
- Perform experiments using the MHD control system at EXTRAP T2R with applied non-axisymmetric external fields as part of a study on plasma rotation braking.

2 Software

The measurement data from the MHD control system is acquired from the experiment using the MDS-Plus data acquistion software. The MDS-Plus software, mainly developed at MIT, is interfaced with the MATLAB software. Data manipulation and plotting is performed by writing MATLAB scripts. More detailed information how to use MDS-Plus and MATLAB will be available in the lab. For the analysis of the magnetic data, the following MATLAB functions are available:

- `mdsopen` Connect to the MDS-Plus database server and open the MDS-Plus database pulse file for a given plasma pulse.
- `mdsvalue` Read a named signal stored in the pulse file into a MATLAB array.
- `mdsclose` Close the MDS-Plus pulse file, and disconnect from the server.
- `fft2` Perform a 2-D Discrete Fourier Transform
- `fftshift` Shift Fourier coefficients.

Information about these routines and other MATLAB routines are found in the MATLAB on-line help pages. Note that `mdsopen`, `mdsvalue` and `mdsclose` are not part of the standard MATLAB library, they are specific to the MDS-plus MATLAB interface.

3 EXTRAP T2R global magnetic data

The toroidal plasma in the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Minor radius $a = 0.183$ m

The main equilibrium magnetic field components (assumed axisymmetric) are obtained from data stored in the MDS-Plus database. Global magnetic data describing the equilibrium includes the toroidal plasma current (from which the poloidal magnetic field component is obtained using Amperes law) and the toroidal magnetic field component.

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the MATLAB program using the signal names. The plasma current signal name is:

```
GBL_ITOR_PLA
```

The plasma current signal is scaled to unit kA and the time is in unit ms. The other global data signal needed for the analysis is the toroidal magnetic field at the plasma boundary. The toroidal field outside the plasma is given by the magnetic field produced by the toroidal field coil (TFC) enclosing the plasma column. The plasma edge toroidal field signal name is

```
PFM_BTEDGE
```

The following is an example of a MATLAB script that reads the plasma current data into a two MATLAB arrays:

```
% connect to database server, open the T2R database containing global signals
mdsopen( '130.237.45.71:T2R, shot_number'); %shot_number selects pulse file

% read the current signal into array 'curr'
curr = mdsvalue( '\gbl_itor_pla'); % current in unit kA

% read the sample times into array 'tm'
tm = mdsvalue( 'dim _of( \gbl_itor_pla)'); %time in unit ms

% close the T2R database
mdsclose
```

4 Magnetic flux loop array

A two-dimensional array of magnetic field flux loops with $M = 4$ loops in the poloidal direction and $N = 32$ loops in the toroidal direction is used. The loops have an approximately rectangular shape and are placed on the surface of the toroidal vacuum vessel in order to measure the magnetic field normal to the plasma boundary (the radial field component). The flux loop array used is a subset of the full array of 4x32=128 loops installed on the vessel.
The parameters of the array are as follows

- Poloidal spacing between coils $\Delta\theta = 2\pi/4$

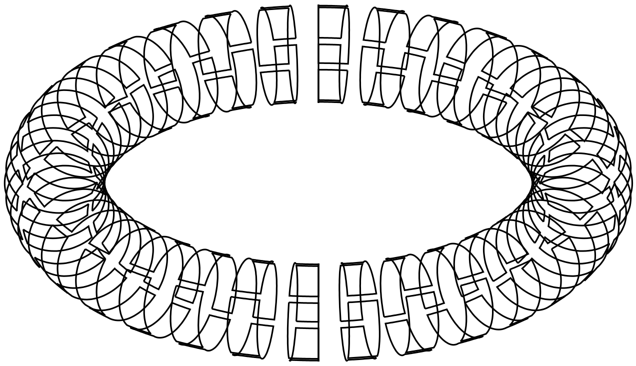


Figure 1: Two-dimensional flux loop array used on EXTRAP T2R with 4 loops in the poloidal direction and 32 loops in the toroidal direction.

- Toroidal spacing between coils $\Delta\phi = 2\pi/64$
- Minor radius of coil array $r_s = 0.1965$ m
- Flux loop area $A = 3.70 \times 10^{-2}$ m^2
- Number of turns $N = 1$
- Integration time constant $RC = 0.625$ ms
- Preamplifier gains $G = 10$ or $G = 25$ (see separate note)

The flux loops are equally distributed over the torus surface. The loops centres are at poloidal and toroidal positions

$$\theta_j = (j-1)\Delta\theta, \;\; j = 1,2,3,4$$
$$\phi_k = (2k-1)\Delta\phi, \;\; k = 1,2,3\ldots,32.$$

The flux loop signals are scaled to magnetic flux density (T) using the coil area A, the integrator time constant RC and the preamplifier gain G:

$$b_c(k) = \frac{RC}{G\,A} V_A(k) \tag{1}$$
$$b_s(k) = \frac{RC}{G\,A} V_B(k)$$

5 Fourier modes

The radial magnetic field vector component $b_r(\theta,\phi)$ at the plasma boundary can be decomposed into spatial poloidal (m) and toroidal (n) Fourier harmonics. The poloidal harmonic $m = 1$ field can be expressed in terms of the cosine and sine Fourier coefficients $b_c(\phi)$ and $b_s(\phi)$ as follows:

$$b_p(\theta,\phi) = b_c(\phi)\cos\theta + b_s(\phi)\sin\theta$$

The Fourier coefficients $b_c(\phi)$ and $b_s(\phi)$ are functions of the toroidal angle ϕ. They are in principle obtained from the measured field through the relations

$$b_c(\phi) = \frac{1}{\pi}\int_0^{2\pi} b_p(\theta,\phi)\cos\theta\,d\theta$$
$$b_s(\phi) = \frac{1}{\pi}\int_0^{2\pi} b_p(\theta,\phi)\sin\theta\,d\theta$$

The coil measurement can be viewed as a spatial sampling of the continuous field, resulting in a two-dimensional sequence of data points:

$$b(j,k) = b_p(\theta_j, \phi_k)$$

In order to reduce the number of required data acquisition channels (from 256 channels to 128 channels), the magnetic coil outputs are series connected in pairs. This is possible since only the $m = 1$ component (not the $m = 0$) is of interest in the present experiment. Through the series connection, the *difference* of two poloidally opposite coils are obtained:

- Coil A output = coil '1' output - coil '3' output
- Coil B output = coil '2' output - coil '4' output

The series connection gives as output two one-dimensional sequences of measurement data $b_c(k)$ and $b_s(k)$, that corresponds to the poloidal $m = 1$ Discrete Fourier Series coefficients:

$$b_c(k) = \frac{1}{2}\left(b(1,k) - b(3,k)\right) = \frac{1}{2}\left(b_p(0,\phi_k) - b_p(\pi,\phi_k)\right) = \frac{2}{M}\sum_{j=1}^{M} b_p(\theta_j,\phi_k)\cos\theta_j \sim b_c(\phi_k)$$

$$b_s(k) = \frac{1}{2}(b(2,k) - b(4,k)) = \frac{1}{2}(b_p(\pi/2,\phi_k) - b_p(3\pi/2,\phi_k)) = \frac{2}{M}\sum_{j=1}^{M} b_p(\theta_j,\phi_k)\sin\theta_j \sim b_s(\phi_k)$$

The goal is to obtain the helical mode spectrum by performing a two-dimensional Fourier mode analysis, using a two-dimensional DFT, defined as

$$B_{m,n} = \frac{1}{MN}\sum_{j=1}^{M}\sum_{k=1}^{N} b(j,k)e^{-i(m\theta_j + n\phi_k)}$$

with the inverse transform

$$b(j,k) = \sum_{m=-M/2+1}^{M/2}\ \sum_{n=-N/2+1}^{N/2} B_{m,n}e^{i(m\theta_j + n\phi_k)}$$

The helical mode spectrum $B_{m,n}$ is the obtained from the two-dimensional DFT of the sequence $b_{j,k}$, using the Fast Fourier Transform MATLAB function `fft2`. In order to use the 2-D fft2 function, it is necessary to construct the individual coil signals at all 4 poloidal angles as follows:

$$\begin{aligned} b(1,k) &= b_c(k) \\ b(2,k) &= b_s(k) \\ b(3,k) &= -b_c(k) \\ b(4,k) &= -b_s(k) \end{aligned}$$

6 Signals stored in the MDS-plus database

The signals from the flux loops are stored in a separate MDS-plus database tree (T2R), different from the global magnetic signals. The mapping of the signal names to the flux loops are shown in a separate note. There are 64 flux loop signals stored in the MDS-plus database (32 A-sensors and 32 B-sensors). The signal names in the MDS-plus are:

Cosine component array ($V_A(\phi_k)$) (odd number signals):

```
\t2:input_1 (sensor 2A)
\t2:input_3 (sensor 4A)
...
\t2:input_63 (sensor 64A)
```

Sine component array ($V_B(\phi_k)$) (even number signals):

```
\t2:input_2 (sensor 2B)
\t2:input_4 (sensor 4B)
...
\t2:input_64 (sensor 64B)
```

Each signal contains 2k sample data. The stored magnetic are unscaled, in unit Volt. The time vectors for the magnetic signals is in unit seconds. The time vector is read from MATLAB using the expression below:

```
dim_of( signal_name)
```

(see the script for reading plasma current shown earlier).

The MHD control system includes a set of 64 active saddle coils (see the separate note "Overview of the MHD mode control system"). The 64 coil currents are stored in the MDS-Plus database. The signal mapping to coil current is different from the magnetic sensor mapping.

Cosine component array ($V_A(\phi_k)$) (odd number signals):

```
\t2:current_1 (coil 2A)
\t2:current_3 (coil 6A)
...
\t2:current_31 (coil 62A)
\t2:current_33 (coil 4A)
\t2:current_35 (coil 8A)
...
\t2:current_63 (coil 64A)
```

Sine component array ($V_B(\phi_k)$) (even number signals):

```
\t2:current_2 (coil 2B)
\t2:current_4 (coil 6B)
...
\t2:current_32 (coil 62B)
\t2:current_34 (coil 4B)
\t2:current_36 (coil 8B)
...
\t2:current_64 (coil 64B)
```

Each signal contains 2k sample data. The stored magnetic are unscaled, in unit Volt. The conversion factor for the current signal is -20 A/V. Again, the time vectors are in unit seconds.

7 Fast Fourier Transform

The MATLAB `fft2` function is used for the computation of the two-dimensional DFT. It is important to pay attention to the ordering of the Fourier mode coefficients that are stored in the output array. Consider e. g., a transform of a one-dimensional sequence of data points $b(i), i = 1, 2, \ldots, 64$ of length $N = 64$. The MATLAB `fft` functions outputs the mode coefficients $B(n)$ for $-31 \leq n \leq 32$ in a one-dimensional array of length $N = 64$ in the order $n = 0, 1, 2, \ldots, 31, 32, -31, \ldots, -2, -1$. Use the MATLAB function `fftshift` in order to change to ordering $n = -31, -30, \ldots, -1, 0, 1, \ldots, 31, 32$. For the two-dimensional FFT, the sequence of the poloidal mode numbers m is stored in a similar way as the toroidal mode numbers: The output array stores the poloidal modes in the order $m = 0, 1, 2, -1$, which has to be shifted to get the usual ordering $m = -1, 0, 1, 2$. More details about the FFT routine is found in the MATLAB help pages.

8 Total mode power, Parseval's theorem

The total MHD mode power is obtained as the sum of all $M \times N$ mode amplitudes squared. According to Parseval's theorem, this sum equals the sum of all $M \times N$ field values squared, divided by the number of field values $M \times N$. Parsevals's theorem thus gives the following relation:

$$\frac{1}{MN} \sum_{j=1}^{M} \sum_{k=1}^{N} b_{j,k}^2 = \sum_{m=-M/2+1}^{M/2} \sum_{n=-N/2+1}^{N/2} B_{m,n}^2$$

Parseval's theorem is useful for checking that the scaling of the Fourier transform has been correctly done.

9 Magnetic flux surface displacement

The magnetic flux surface at the plasma boundary defines the plasma column shape. The radial displacement of the magnetic flux surface is obtained from the Fourier decomposition of the radial magnetic field. One can compute the radial surface shift, r_s, which is a measure of how much a flux surface is displaced. Assume that r_s and the radial magnetic field, B_r, are dependent of the poloidal (θ) and toroidal (ϕ) positions.

Consider the triangles shown in Figure 2. An infinitesimal difference in the radial displacement can the be written:

$$dr_s = \frac{\partial r_s}{\partial \theta} d\theta + \frac{\partial r_s}{\partial \phi} d\phi \tag{2}$$

By using the similarity of the triangles, the following relations can be computed:

$$\frac{B_\theta}{B_r} = \frac{a d\theta}{dr_s} \tag{3}$$

$$\frac{B_\phi}{B_p} = \frac{R d\phi}{dl_p} \tag{4}$$

Figure 2: The triangles show the relation between the magnetic field vectors and the flux surface displacement.

$$\frac{B_p}{B_r} = \frac{dl_p}{dr_s} \tag{5}$$

These last two equations can be reduced into the following equation by eliminating l_p:

$$\frac{B_\phi}{B_r} = \frac{Rd\phi}{dr_s} \tag{6}$$

Multiply with a both in the numerator and denominator and divide by dr_s.

$$1 = \frac{1}{a}\frac{\partial r_s}{\partial \theta}\frac{ad\theta}{dr_s} + \frac{1}{R}\frac{\partial r_s}{\partial \phi}\frac{Rd\phi}{dr_s} \tag{7}$$

Then B_r can be written:

$$B_r = \frac{B_\theta}{a}\frac{\partial r_s}{\partial \theta} + \frac{B_\phi}{R}\frac{\partial r_s}{\partial \phi} \tag{8}$$

Then we got expressions for dr_s and B_r as functions of the differentials $\partial r_s/\partial\theta$ and $\partial r_s/\partial\phi$. By using Fourier decomposition B_r and r_s can be written:

$$B_r = \sum_m \sum_n C_{mn} e^{i(m\theta + n\phi)} \tag{9}$$

$$r_s = \sum_m \sum_n S_{mn} e^{i(m\theta + n\phi)} \tag{10}$$

Here m and n are the toroidal and poloidal mode numbers respectively. Differentiation with respect to θ and ϕ gives the following expressions:

$$\frac{\partial r_s}{\partial \theta} = \sum_m \sum_n S_{mn} im e^{i(m\theta + n\phi)} \tag{11}$$

$$\frac{\partial r_s}{\partial \phi} = \sum_m \sum_n S_{mn} in e^{i(m\theta + n\phi)} \tag{12}$$

Here C_{mn} is known from the measurements of B_r, on the other hand S_{mn} is unknown. A relation between C_{mn} and S_{mn} can be computed.

$$C_{mn} = i\left(m\frac{B_\theta}{a} + n\frac{B_\phi}{R}\right)S_{mn} \tag{13}$$

The local flux surface displacement as a function the poloidal and toroidal angles can then be obtained by an inverse Fourier transform. Using MATLAB, the displacement can then be plotted in a 3-D plot using cylindrical or toroidal geometry.

ED2245 Project in Fusion Physics

Project 5

Plasma temperature measurement using soft X-ray detectors

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

The aim of the project is to obtain the plasma electron temperature by the measurement of electromagnetic bremsstrahlung emission from the plasma. The bremsstrahlung intensity emitted from the plasma decays exponentially with photon energy, with the rate of the decay dependent on the plasma electron temperature. The method is based on measurement of soft X-ray radiation with detectors that view the plasma through absorbing foils of varying thickness. The foils allow different portions of the emitted spectrum to be measured with each detector, thereby providing a method to estimate the plasma temperature. The project includes

- Setup of the soft X-ray detectors on the EXTRAP T2R device.
- Plasma measurements on EXTRAP T2R using detectors with identical foils for calibration and with different foils for temperature measurement
- Data analysis to obtain the plasma temperature.

The plasma electron temperature is an important basic parameter for a fusion plasma. Information on the electron temperature is useful for estimating the so called ambipolar radial electric field in the plasma that drives poloidal and toroidal plasma flows.

2 Soft X-ray absorbing foil method for temperature measurement

The electromagnetic radiation due to bremsstrahlung emission from the plasma depends on plasma parameters and photon energy as

$$I_b(E) \sim n_e n_i Z_i^2 T_e^{-1/2} \exp\left\{-\frac{E}{kT_e}\right\}$$

where E is the photon energy, T_e is the plasma electron temperature, n_e is the plasma electron density, n_i is the plasma ion density, and Z_i is the ion charge number. From the expression it is clear that the intensity decays exponentially with photon energy, and that the decay rate is determined by the electron temperature. The plasma electron temperature is obtained from measurements using two (or more) detectors that view the same plasma volume through absorbing foils with different thicknesses. The intensity measured by the detector is given by the detector response function $R(E)$. For a single absorption foil (neglecting for the moment the response function of the detector itself) the response function is written

$$R(E) = \exp\{-\mu(E)\, t\}$$

where E is the photon energy and $\mu(E)$ is foil absorption coefficient and t is the thickness of the foil. The total radiated power reaching the detector is then obtained by integration over energy:

$$P = C \int R(E) \exp\left\{-\frac{E}{kT_e}\right\} dE$$

where C is a constant dependent on plasma parameters, detector area, viewing solid angle and so on. The foil absorption coefficient $\mu(E)$, which is a function of the photon energy, is specific for the material selected for the foil. Different materials can in principle be used. A common choice is Beryllium (Be). The foil absorption coefficient $\mu(E)$ increases with decreasing photon energy in the soft X-ray region, and this provides an energy cutoff at the low energy end of the measured photon energy spectrum. Since the bremsstrahlung intensity decreases at the high end of the energy spectrum, the power transmitted to the detector is dominated by the low photon energy range near the cutoff. The low end energy cutoff will depend on the thickness of the foil, and by selecting foils with two different thicknesses, the ratio of the measured intensity on the two detectors will be determined by the emitted radiation in a well defined energy range between the two cutoff energies. By a suitable combination of foils, it is possible to select an energy range where line radiation from the plasma is small. (Line radiation will otherwise disturb the measurement of the continuum bremsstrahlung emission.) The ratio of the radiation power on the two detectors with response functions R_1 and R_2 is

$$\frac{P_1}{P_2} = \frac{C_1 \int R_1(E) \exp\left\{-\frac{E}{kT_e}\right\} dE}{C_2 \int R_2(E) \exp\left\{-\frac{E}{kT_e}\right\} dE}.$$

The technique does require a separate plasma measurement for calibration prior to the temperature measurement. The calibration determines the ratio C_1/C_2 in a plasma measurement with identical foils ($t_1 = t_2$) mounted on the detectors. The plasma temperature measurement is performed with different foils ($t_1 \neq t_2$). For a given set of foil thicknesses t_1, t_2, with the ratio C_1/C_2 and the response functions $R_1(E), R_2(E)$ known, the plasma temperature T_e is determined from the measured ratio P_1/P_2 using the expression above.

3 Soft X-ray Surface Barrier Detectors

The detector used for measurement of the soft X-ray radiation is a type of semi-conductor radiation detector known as the Surface Barrier Detector (SBD). A rectifying junction, the barrier, is formed by evaporating a metal on an oxydized silicon wafer. Two types are common, gold (Au) on N-type silicon or aluminium (Al) on P-type silicon. A reverse bias voltage is usually applied across the junction creating a so called depletion layer inside the semi-conductor. In this layer electron-hole pairs are formed by the incident radiation, typically one pair is formed per 3.76 eV of photon energy. The charges drifts in the applied electric field resulting in an electrical current proportional to the incident radiated power. The current is converted to voltage and amplified by a low-noise pre-amplifier. The parameters of the SBD are shown in Table 1. The

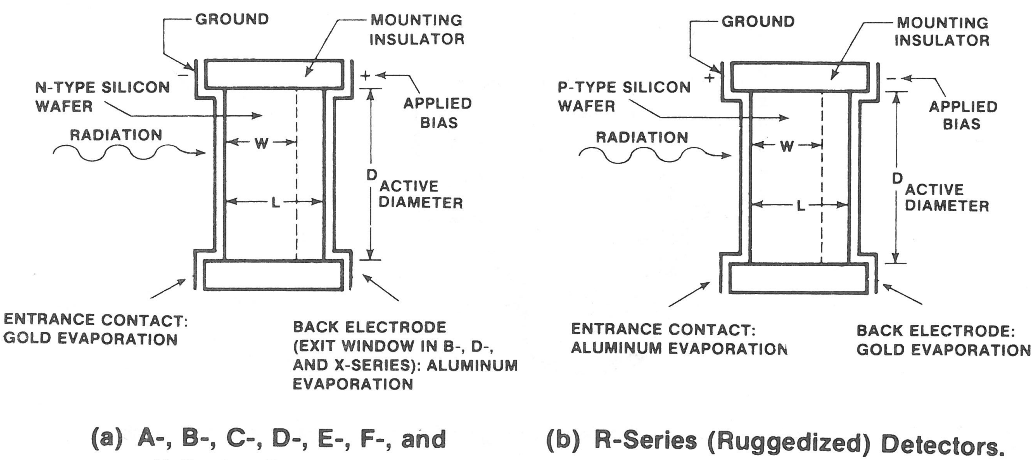
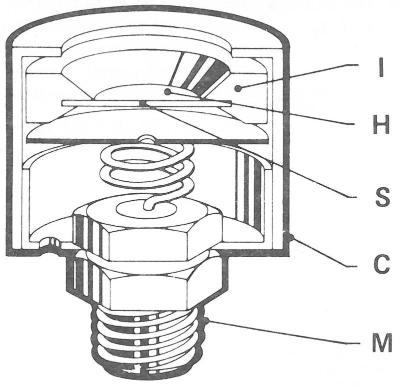


Figure 1: Two common types of Surface Barrier Detectors. EG&G ORTEC Silicon Charged Particle Radiation Detectors Instruction Manual)

finite thickness of the active depletion layers gives a high energy limit for the detector response,



Cross Section of an A-Series Charged Particle Detector in a B Mount.

Figure 2: The sensitive surface (H) is evaporated with a thin layer of gold. The circular silicon wafer (S) is mounted in an insulating ring (I) whose back and front surfaces are metallized. The front surface of the ring is grounded to the metal case (C) and thereby connected to the shield of the BNC or Microdot contact (M). The back surface of the insulating ring is connected to the center electrode of the connector which serves as the signal output and bias voltage connection. (EG&G ORTEC Silicon Charged Particle Radiation Detectors Instruction Manual)

since high energy photons will simply pass through the detector without creating any electron-hole pairs. This fall-off at high energy is taken into account by multiplying the response function with the factor

$$R_{Si}(E) = 1 - \exp\{-\mu_{Si}(E)\, t_{Si}\}$$

where $\mu_{Si}(E)$ is the absorption coefficient in Silicon, and t_{Si} is the thickness of the active depletion layer. Further, absorption in the gold surface layer may also be taken into account, giving another attenuation factor

$$R_{Au}(E) = \exp\{-\mu_{Au}(E)\, t_{Au}\}$$

where t_{Au} is the thickness of the gold electrode layer. Finally, the detector has a so called dead layer close to the Si surface in which electron-hole pairs created quickly recombine and do not contribute to the detector current. Including this region gives a factor

$$R_{dl}(E) = \exp\{-\mu_{Si}(E)\, t_{dl}\}$$

where t_{dl} is the thickness of the dead layer.

Parameter	Value
Diode structure	Au - N-type Si - Al
Active area [mm^2]	50
Electrode Au thickness [Angstrom]	200
Dead layer Si thickness [Angstrom]	800
Active layer Si thickness @ 15 V bias [μm]	65

Table 1: SBD parameters.

4 Detector response function

The total response function is mainly determined by the Beryllium absorption foil in front of the detector. The Be absorption foil mounted on the detector is typically very thin, with a thickness of the order of 10 μm. The absorption coefficient for the foil $\mu(E)$ from experimental data is available in the literature. From the tabulated Be absorption coefficients, the Be foil response function for a given foil thickness t_{Be} can readily be calculated, and including the detector response functions it is written:

$$R(E) = R_{Si}(E) R_{Au}(E) R_{dl}(E) \exp\{-\mu_{Be}(E)\, t_{Be}\}.$$

The response function for Beryllium foils with different thicknesses are shown in Fig. 3, where the dependence of the low energy cutoff with foil thickness is evident, as well as the high energy fall-off due to the finite thickness of the active layer. Also the absorption in the detector gold surface layer (Au) and the so called dead layer has been included. However, with a relatively thick foil these corrections are small, as is also clear from the figure.

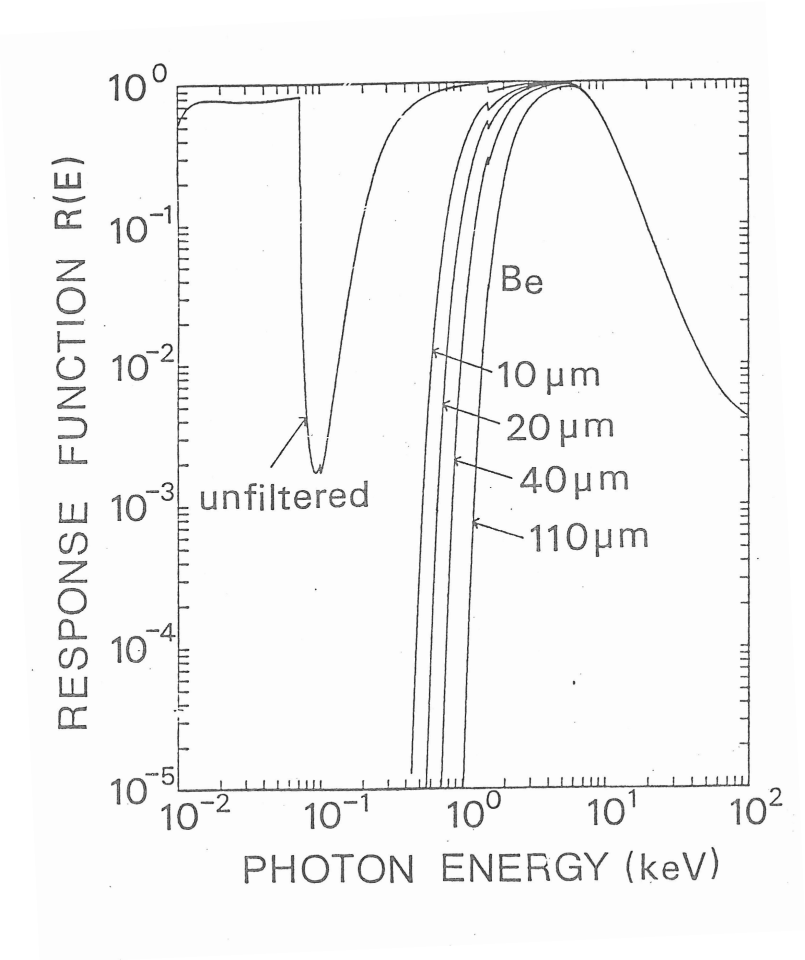


Figure 3: Response functions for SBD with Beryllium foils of 10, 20 40 and 110 μm thickness. The low energy cutoff increases from about 500 to 1000 eV with increasing thickness. The response function includes also the SBD detector response functions.

5 Software

The software packages IDL from Research Systems for graph plotting, and MDS from MIT for data acquisition is used. More detailed information about how to write, compile and run IDL programs will be given at the time of the laboratory project. Some useful IDL library functions and system variables are listed below:

- `SET_SHOT` Selects plasma shot number
- `DATA` Function that reads MDS signals into an IDL data vector.

Use the `!p.multi` parameter to stack graphs in one plotting window. The `WINDOW` statement opens a new plotting window on the screen. Use the `OPLOT` function and `LINESTYLE` keyword to over-plot several curves on the same graph with different line styles. The `!P.CHARSIZE` system variable to used for setting character size in graph labels. Information about the syntax of these functions and other IDL routines are found in the IDL on-line help pages.

6 EXTRAP T2R

The geometry of the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Plasma minor radius $a = 0.183$ m

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). The time vector is stored with the ending "TM" to the name as shown below. Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the IDL program using the signal names which are as follows:

```
GBL_ITOR_PLA, GBL_ITOR_PLA_TM
```

The plasma current signal is scaled to unit kA.

7 SBD signal data acquistion

The two SBD detectors are connected to pre-amplifiers. The outputs of the pre-amplifers are connected to transient recorders. The signals in MDS database are

```
SXR_1, SXR_1_TM
SXR_2, SXR_2_TM
```

The signals are recorded with 12 bit resolution, and sampling frequency can be set to 1 MHz or optionally to 3 MHz.

8 Data analysis

- Calculate response functions for the two detectors
- Calculate the theoretical detector power ratio function (P_1/P_2) as function of electron temperature T_e
- Fit experimental power ratio data to find T_e time evolution in the plasma pulse.

ED2245 Project in Fusion Physics

Project 6

Measurement of plasma fluctuations with electric probe pairs

March, 2011

EES/Fusion Plasma Physics
KTH

1 Aim

The project aim is the measurement of plasma fluctuations with inserted electric probes and analysis of the data using statistical methods. The characteristic local plasma parameters such as the temperature, density and potential have variations in time and space, which are referred to as fluctuations. The fluctuations are due to various waves and instabilities in the plasma, and often broad band fluctuation signals characteristic of a fully developed turbulent state is seen.

The method is based on using two fixed probes separated by a small distance in the toroidal direction. Since the fluctuating plasma typically is propagating in the toroidal direction, cross-correlation analysis of the probe data from the two probes allows estimation of the wave number spectra as well as the local plasma flow velocity. The project work includes:

- Measurements on EXTRAP T2R with pairs of electric probes.
- Developing computer codes for statistical analysis of probe data
- Analysis of probe data for estimates of wave number spectra and local plasma flow velocity.

2 Probe diagnostic

The probe is inserted into the plasma with a simple vacuum feed through at one of the available ports on the device:

- Horizontal port at machine angle 256 degrees.

Data for the probe diagnostic are summarized in Table 1. The probe head has an array of $3 \times 6 = 18$ pins, placed in 6 rows perpendicular to the probe axis. Each row has 3 pins. The

Figure 1: Electric probe head with 18 pins.

distance between a pin and the adjacent pin in a row is 3 mm. The distance between the rows is 3 mm. The distance from the first row to the probe holder front edge is 5 mm. In summary, the insertion radius r_k of the k:th row of tips is calculated from the formula:

$$r_k = r_{holder} + 5 + 3(k-1) \text{ [mm]}$$

where r_{holder} is the insertion minor radius of the probe holder front edge and $k = 1, 2, \ldots, 6$ is the row index. The probe insertion is selected using specially prepared distance rods of different length. The insertion minor radius of the probe holder front edge is related to the distance rod length l_{rod} as follows

$$r_{holder} = 58 + l_{rod} \text{ [mm]}$$

Parameter	Value
Number of tips in array	3×6
Number perpendicular rows in array	6
Number of tips in row	3
Distance of first row to holder front edge	5 mm
Distance between rows	3 mm
Distance between tips in row	3 mm
Diameter of cylindrical tip	0.5 mm
Length of cylindrical tip	2 mm

Table 1: Probe head geometrical parameters.

For example, insertion of the probe holder front edge to the plasma limiter minor radius $a = 183$ mm, requires a distance rod of length $l_{rod} = 125$ mm. Insertion of the probe holder front edge insider the limiter radius must be done with great care, with the probe position changed in small steps, observing the probe signals and the global plasma behavior for each position. The probe has an unavoidable degrading effect on the plasma which increases with the insertion depth. The minimum holder front edge minor radius possible is around $r_{holder} = 175$ mm ($l_{rod} = 117$ mm) which corresponds to an insertion of the probe head 8 mm inside the plasma, thus aligning the second row of probe tips with the plasma limiter minor radius.

The probe tips are cylindrical with a diameter of 0.5 mm and a length of 2 mm. The probe tips are metal, made of molybdenum. They are mounted into an non-conducting insulator holder made of boron nitride. The probe tips are placed on a plane surface of the holder. The probe should be rotated around the axis so that the plane surface is horizontal and facing downward. In this way the curved back side of the probe holder is facing upward, blocking the downward fast electron flux which otherwise perturbs the probe measurement.

The probe tips are connected with wires to a feed-through vacuum flange. On the outside of the flange coaxial cables are connected providing the probe signals. The cables are labeled as follows:

- Row 1: 11, 12, 13
- Row 2: 21, 22, 23
- ...
- Row 6: 61, 62, 63

The basic idea of the measurement is to use two probes separated by a small distance in a given direction. The measurement will be performed using the no 21 and no 23 pins in row 2 as a first and second probe to measure fluctuations propagating in the toroidal direction. Further a third probe using pin no 43 in row 4 will be used to measure fluctuations propagating in the radial direction from the second and third probe. The probe pins used is shown in Fig. 2. The separation distance of the selected pins is $X = 6$ mm in both directions.

3 Electric probe measurement

The electric current flowing into a probe tip from the plasma is the sum of the electron current I_e and the ion current I_i due to the thermal motion of the particles. Typically, the electrons moves faster than the ions, and a floating probe tip will accumulate negative charge which gives

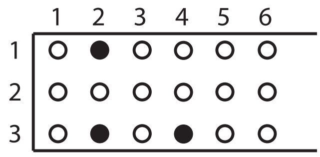


Figure 2: Probe pins used for two-probe measurement of plasma potential fluctuations propagating in toroidal and radial directions.

the probe a negative potential relative to the plasma space potential V_s. At the probe floating potential V_f, the electrons are repelled by the negative probe voltage $V_f - V_s$, which reduces the electron current so that the net probe current is zero ($I_i + I_e = 0$). This floating potential is used in the present project as an estimate for the local plasma potential. The electric probe measurement setup is shown schematically in Fig. 3. The probe signal is routed to a voltage divider that measures the potential on the probe tip relative to the vacuum vessel.

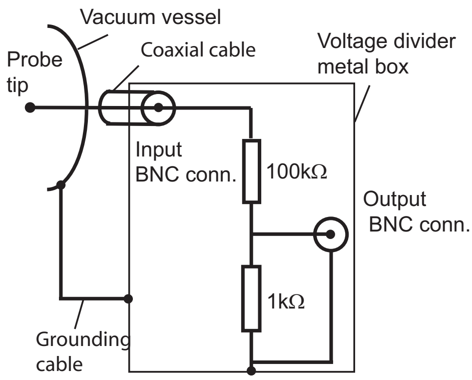


Figure 3: Floating probe measurement.

The electrical circuit required for the voltage divider is contained in a metal box close to the probe. The box has BNC connectors for three probe input signals and three output signals. The output signals are transferred via optical links to the data acquisition modules. The input voltages to the optical links must be in the range ±10 V.

4 Statistical data analysis

The basic quantity describing the fluctuations is the frequency resolved auto-power spectrum $S(\omega)$ where $\omega = 2\pi f$ is the angular frequency. However, knowledge of the wave number resolved spectrum $S(k)$ is also important. The plasma fluctuations are usually not described by a single dispersion relation $k(\omega)$ since the plasma is in a turbulent state and the fluctuations are broadly distributed in wave number space. The fluctuations are in this case described by the combined frequency and wave number spectrum $S(k, \omega)$. The spectrum $S(k, \omega)$ can be estimated using two probes separated a distance X. The underlying basic idea is that the spectrum can be approximated with the local spectrum $S_l(K, \omega)$, where K is the local wave number, which is obtained from the phase difference between the signals from the two probes $\theta(\omega)$ as

$$K(\omega) = \frac{\theta(\omega)}{X}.$$

The data analysis is carried out as follows: In the first step, the two probe signals to be analyzed are divided into N time records $\Phi_1^{(j)}(t)$, $\Phi_2^{(j)}(t)$, of length T,where $j = 1, 2, 3, ..., N$. The Fourier transforms of each time record $\Phi_1^{(j)}(\omega)$, $\Phi_2^{(j)}(\omega)$ are

$$\Phi_1^{(j)}(\omega) = \frac{1}{2\pi}\int_{-T/2}^{T/2} \Phi_1^{(j)}(t)\exp(i\omega t)dt,$$

$$\Phi_2^{(j)}(\omega) = \frac{1}{2\pi}\int_{-T/2}^{T/2} \Phi_2^{(j)}(t)\exp(i\omega t)dt.$$

The power spectra are

$$S_1^{(j)}(\omega) = \Phi_1^{(j)}(\omega)\left(\Phi_1^{(j)}(\omega)\right)^*,$$

$$S_2^{(j)}(\omega) = \Phi_2^{(j)}(\omega)\left(\Phi_2^{(j)}(\omega)\right)^*,$$

and the cross-spectrum is computed as

$$H^{(j)}(\omega) = \Phi_1^{(j)}(\omega)\left(\Phi_2^{(j)}(\omega)\right)^*.$$

where * denotes the complex conjugate. The phase difference between the probes is then obtained as the argument of the complex cross-spectrum

$$\theta^{(j)}(\omega) = \arg H^{(j)}(\omega) = \arctan\left[\frac{\Im\left(H^{(j)}(\omega)\right)}{\Re\left(H^{(j)}(\omega)\right)}\right],$$

the local wave number is

$$K^{(j)}(\omega) = \frac{\theta^{(j)}(\omega)}{X},$$

and the average power spectrum is

$$S^{(j)}(\omega) = \frac{1}{2}\left(S_1^{(j)}(\omega) + S_2^{(j)}(\omega)\right).$$

The wave number range is divided in M intervals $[K_m, K_m + \Delta K]$ where $m = -M/2 + 1 \ldots - 1, 0, 1, \ldots M/2.$ and $K_m = m\Delta K$. The wave number resolution ΔK will then be

$$\Delta K = \frac{2\pi}{MX}.$$

In the second step of the data analysis, ensemble averages over the set of time records is performed. The local wave number and frequency spectrum ensemble average is

$$S_l(K_m, \omega) = \frac{1}{N}\sum_{j=1}^{N} S^{(j)}(\omega)\delta\left(K_m - K^{(j)}(\omega)\right),$$

where

$$\delta(k) = \begin{cases} 1 & \text{if } |k| < \Delta K/2, \\ 0 & \text{otherwise} \end{cases}$$

The power spectrum estimate is

$$S(\omega) = \frac{1}{N}\sum_{j=1}^{N} S^{(j)}(\omega).$$

Define the conditional wave number and frequency spectrum as

$$s_l(K_m, \omega) = \frac{S_l(K_m, \omega)}{S(\omega)}$$

The first moment of $s_l(K_m, \omega)$ is the average power weighted wave number $\bar{k}(\omega)$

$$\bar{k}(\omega) = \sum_{m=-M/2+1}^{M/2} K_m s_l(K_m, \omega)$$

The second moment of $s_l(K_m, \omega)$ is the wave number width $\sigma_k(\omega)$:

$$\sigma_k^2(\omega) = \sum_{m=-M/2+1}^{M/2} \left(K_m - \bar{k}(\omega)\right)^2 s_l(K_m, \omega)$$

The average power weighted wave number is an estimate of the dispersion relation $\bar{k}(\omega)$ from which the propagation of the perturbations is obtained as the group velocity v:

$$v \approx \frac{d\omega}{d\bar{k}}$$

5 Software

The software packages IDL from Research Systems for graph plotting, and MDS from MIT for data acquisition is used. More detailed information about how to write, compile and run IDL programs will be given at the time of the laboratory project. Some useful IDL library functions and system variables are listed below:

- `SET_SHOT` Set plasma shot number
- `DATA` Function that reads MDS signals into an IDL data vector.
- `FFT` Compute Discrete Fourier Transform

Use the `!p.multi` parameter to stack graphs in one plotting window. The `WINDOW` statement opens a new plotting window on the screen. Use the `OPLOT` function and `LINESTYLE` keyword to over-plot several curves on the same graph with different line styles. The `!P.CHARSIZE` system variable to used for setting character size in graph labels. Information about the syntax of these functions and other IDL routines are found in the IDL on-line help pages.

6 EXTRAP T2R

The geometry of the EXTRAP T2R device is given by the two parameters:

- Major radius $R_0 = 1.24$ m
- Plasma minor radius $a = 0.183$ m

A stored signal for the plasma current is available. (The signal contains processed data, for which the primary Rogowski coil signal has been corrected for the toroidal liner current). The time vector is stored with the ending "TM" to the name as shown below. Note that the unit of the time vector for the plasma current is milliseconds.

The stored signals are read into the IDL program using the signal names which are as follows:

```
GBL_ITOR_PLA, GBL_ITOR_PLA_TM
```

The plasma current signal is scaled to unit kA.

7 Data acquisition for probes

There are a number of data channels available, allowing simultaneous sampling of the floating potential signals from all three probes. Signals are typically sampled at a sampling frequency of 1 MHz or optionally 3 MHz. The signals are accessed form IDL using signal names such as

```
PROBE_01, PROBE_01_TM
PROBE_02, PROBE_02_TM
PROBE_03, PROBE_03_TM
```

or similar.