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Interpretation and Tomography of SXR Data
with the Codes VISO and DIRO

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Abstract

Two codes are described: VISO and DIRO. With VISO it is possible to plot and print SXR data from different sets of channels. Features of this code are: plots of emissivity versus time, band bass filtering, colored contour plots, 3D plots, FFT calculations, profiles in time and frequency space versus channel number, q, ρ_{pol} and R, plots of FFT phase versus channel angle, (p, ϕ)-diagram, error profiles. Furthermore, it is possible to calculate and to correlate data of other diagnostics with the SXR data, e. g. the FFT frequencies of the Mirnov coils. VISO also prepares input data for the DIRO code.

DIRO calculates the differential rotational tomography. The reconstructed radial mode amplitudes and the two dimensional emissivity image are plotted and printed. Finally, a temporal animation of emissivity contours can be created.

The differential rotational tomography is an innovative tomography method, which — for the first time — is able to reconstruct the soft X-ray emissivity of coupled MHD modes [9]. The principles of this method are described.

Contents

Chapter 1

User's Guide to VISO

1.1 About VISO

VISO stands for view and interpret SXR and others. It means especially data of the soft X-ray diagnostic and further data of other diagnostics at ASDEX Upgrade. VISO is primary written in IDL (Interactive Data Language, [1]), but it uses also Fortran and C++ routines. It provides the standard investigation methods for soft x-rays and is an interface for the tomography code DIRO.

1.2 Preparing Unix Environment

In order to use most of VISO features, you need a special directory tree. Create these directories by typing `viso⎵install` at the operation system prompt. This creates also the necessary files and directories for the code DIRO. The top directory is `~/idl/viso/`, where ~ means the user's home directory. There you can find the default startup file `viso_ini_user.pro` for your VISO sessions. This file includes the idl procedure `viso_ini_user`, which is executed at the beginning of each VISO session. Here you can write your default settings, e. g. the default printer name (cf. section 1.6). In the directory `~/idl/viso/data/` there are different data files, which you will get to know later.

1.3 Starting and Exiting VISO

To run VISO, enter `viso` at the operation system prompt. The control window named 'viso [control window]' will appear, see figure 1.1. You see buttons, pull down menus, slider and text widgets. The applications are organized line by line
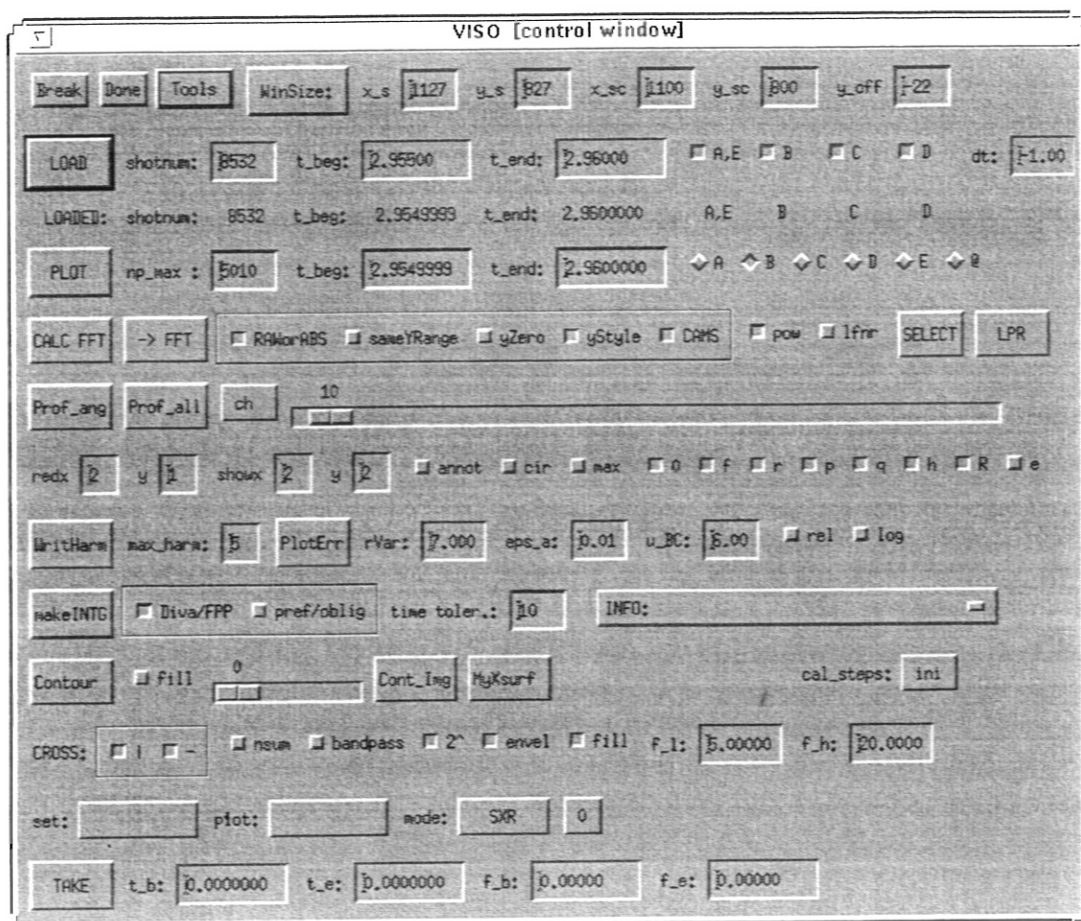
Figure 1.1: Control window for the VISO program.

and are described in the following sections.

To exit VISO press the button **Done**.

For the interactive use of IDL, press the button **Break**. Then all VISO windows are iconified and in your shell window IDL prompts with the string IDL>. To reenter VISO type viso.

1.4   Loading a SXR Shotfile

The philosophy for dealing with SXR data is first to load all desired data into the memory and then to work with them. To do that look at the second line of the control window (figure 1.1). Fill the text widgets with the shot number, the beginning time **t_beg** and the end time **t_end** of the desired time interval. Illogical settings, i. e. **t_beg** > **t_end**, cause a load of the largest possible time

interval. Then select the cameras of which you want to load the data. For normal use you can skip the last text widget with the label **dt:**. However, if you look at data sampled with high constant frequency, you can reduce this frequency by typing the new sample time interval in microseconds into the last text widget. This number must be positive. A negative number will be ignored. The data in each time interval will be averaged. Finally press the button **LOAD**. When loading is completed, the parameters of loaded data will appear in the third line (figure 1.2).
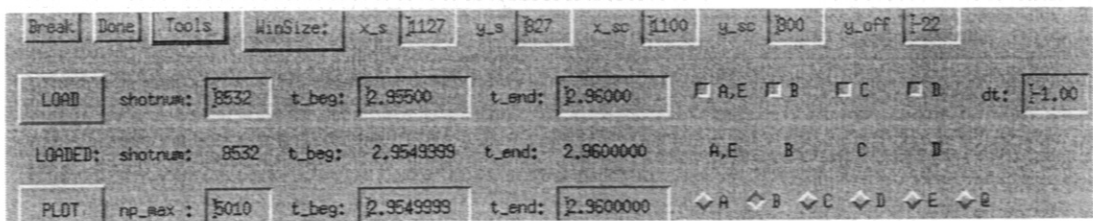
Figure 1.2: Parameters of loaded data appear in the third line.

1.5 Plotting SXR Data

1.5.1 Plotting SXR Data of One Camera

To plot SXR data of one camera, look at the second line of the control window and fill the text widgets with the beginning time **t_beg** and the end time **t_end** of the desired time interval. Ignore the field with the label **np_max**. It will be described in section 1.5.6. Then select the camera of which you want to plot the data. The symbol @ stands for both cameras A and E. Finally press the button **PLOT**. The plot window named 'viso plot [plot window]' will appear, see figure 1.3. It shows up to 32 graphs with SXR emissivity and a control panel on top of it. The graphs are labeled on the right side with camera name and channel number. At the bottom the time axis is depicted. The graphs show either the raw SXR data in bits or the calibrated SXR data in kWm^{-2}, depending on the state of the **RAWorABS** switch, see section 1.5.6. On the left side the minimum and maximum emissivity value for each graph are shown. For an example see figure 1.4. Here the emissivity ranges from 45 bits to 61 bits.

The function of the control panel are described in the following section.
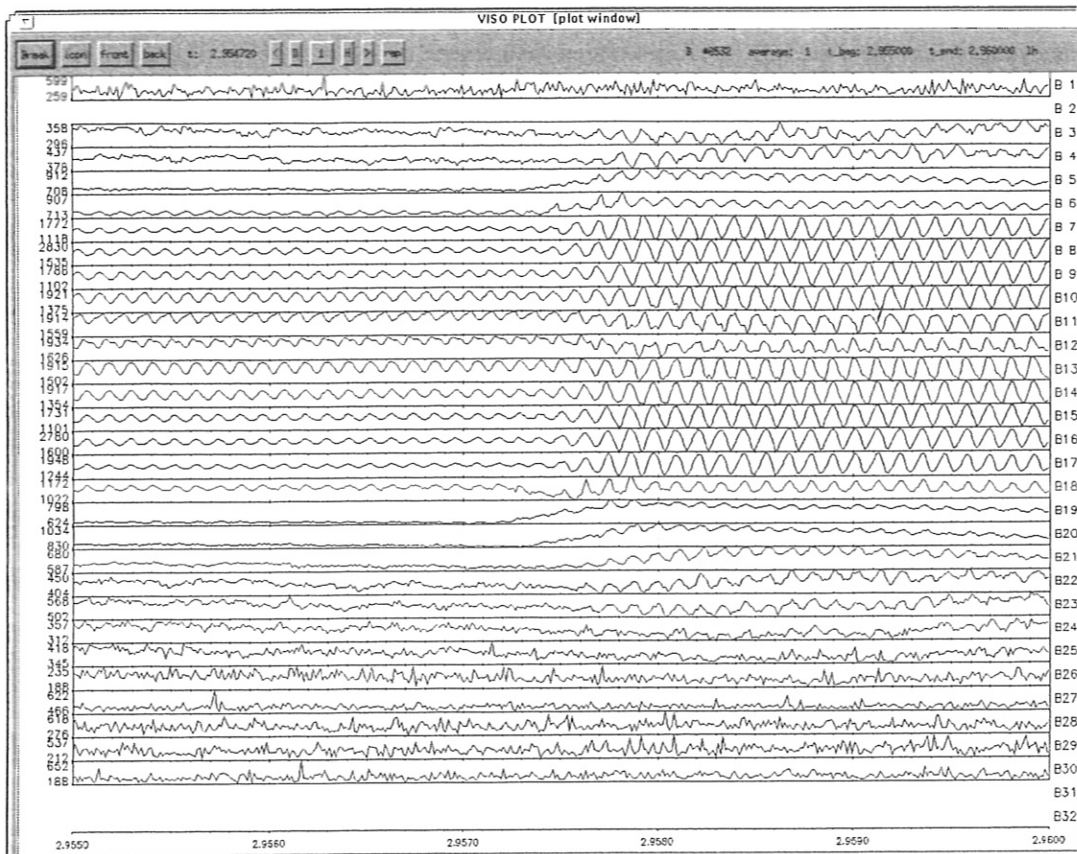
Figure 1.3: *Plot window of the VISO program.*
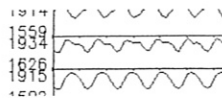
Figure 1.4: *Minimum and maximum emissivity values.*

1.5.2   Control Panel of the Plot Window

The buttons on the control panel of the plot window have different functions. The button **Break** allows interactive use of IDL like the same button on the control window (cf. section 1.3). To iconify the whole plot window press the button **icon**. The buttons **front** and **back** switch the control window to the front and to the back, respectively.

Directly to the right the time in seconds at the location of the hair cross is shown. The next five widgets control the range of the x-axis. The buttons **<** and **>** shift the shown time interval by its own width to the left and right, respectively, so that the adjacent interval will appear. The buttons **D** and **H** double and half the shown time interval range as many times as it is selected on the pull down menu

in between. There the hexadecimal code is used, e. g. F means 15 times.

The button **rep** means 'repeat plot', i. e. it causes the same effect as pressing the **PLOT** button on the control window. In the middle of the control panel, free space is left for selecting a new time interval by mouse clicking, see section 1.5.3. On the right there are further informations: the camera name, the shot number, the number of averaged points for one plotting point (cf. section 1.5.6) and the time range of the plotted time interval (**t_beg** and **t_end**). Finally, there are two signs, which will be described in the following section.

1.5.3 Plot Control by Mouse

The mouse has three buttons. The VISO program reacts on the release of the buttons.

With the left and right button you can specify the border of a new time interval. The selected time points will appear in the middle of the control panel after the labels **t_beg_new** and **t_end_new**. To clear a time point release the left or right mouse button while the hair cross is located below the time axis.

When both the left and right mouse buttons are released at the same time the data of the new time interval will be plotted. If an interval border was not specified the old one will be used. Illogical settings, i. e. **t_beg_new > t_end_new**, cause a plot of the largest loaded time interval.

To shift the plotted time range so that the mouse position becomes the middle of the interval, release all three mouse buttons. To do the same with an additional three times halving of the interval release only the right and the middle mouse button. For the reverse use the left and the middle mouse button.

The middle mouse button handles quick changes between a large time interval for an overview and short time intervals for details. The usual procedure is as follows: Plot a large time interval for an overview, e. g. from 2.0 s to 3.0 s. Save this interval by clicking the middle mouse button below the right half of the x-axis. The penultimate sign on the control panel of the plot window is the letter l, which indicates that you should be looking at the large time interval. Now point with the mouse to an interesting detail in the data above the x-axis and release the middle mouse button. The letter l changes to letter s, standing for short time interval, and you see the selected data in an interval with the default width of 16 ms. Now correct the short interval to the desired width and save this interval width by clicking the middle mouse button below the left half of the x-axis. Clicking the middle mouse button above the x-axis allows to change between the selected overview plot and plots of details with the selected and saved interval width.

Now have a look at the logic of the middle mouse button functions. By clicking with the mouse below the x-axis different settings are made. Below the left half of the x-axis the width of the current (short) interval is saved. Below the right half of the x-axis the borders of the current (large) interval are saved. Outside the x-axis on the left (bottom left corner), you switch between the letters l and s. Outside the x-axis on the right (bottom right corner), you switch between the signs h (for hold) and - at the end of the control panel. By clicking with the mouse above the x-axis at the time position t, you plot different time intervals: If before clicking the letter l is shown, the plotted interval is centered around the position t with the saved interval width. In case of letter s there are two possibilities. If the last sign on the control panel is an h, an interval with the saved borders will be plotted, but if this sign is a -, an interval centered around the position t with a width determined from the saved borders will be plotted.

1.5.4   Selecting Functioning Channels

To switch off channels, which are out of order, press the **SELECT** button on the control window. The select window named 'VISO SELECT [select window]' will appear, see figure 1.5. The second to sixth column depict the cameras A to E. You can switch on and off each channel by clicking the square buttons. The buttons of the first column have special functions. With the buttons **load M1**, **load M2**, **load M3**, **save M1**, **save M2** and **save M3** you can load and save the current channel selection state to one of three temporary memories. These memories are cleared when exiting IDL. The buttons **on all**, **on A**, **on B**, **on C**, **on D**, **on E**, **off all**, **off A**, **off B**, **off C**, **off D**, **off E**, **swap all**, **swap A**, **swap B**, **swap C**, **swap D** and **swap E** allow to switch on, switch off and swap the states of all channels in one camera or in the whole SXR diagnostic. By pressing the button **save chan** the selected channel states will be accepted for the rest of the IDL session. To save these states to the hard disc for use in further IDL sessions press the button **save HD**. To load them from hard disc press the button **load HD**. If present on the hard disc, the states will be loaded automatically upon loading a new SXR shotfile.

Normally, it is not possible to switch on a channel, which was already off. To allow this, switch on the square button **slcBeg**.

To iconify the select window press the button **icon**. To dismiss it press the button **SlcDone**.

In VISO, it is possible to plot the data for any set of channels. First select the desired channels as described above and save them by clicking the **save plot** button. Pressing the **load plot** button shows the already selected channels. To plot these channels see next section.

Figure 1.5: *Select window for the VISO program.*

1.5.5   Plotting SXR Data for Selected Channels

To plot a set of channels select them in the select window (cf. section 1.5.4). Then switch off the square button **CAMS** in the fifth line of the control window (cf. figure 1.1) and press **PLOT**.

1.5.6   Plot Parameters

The y-ranges of the graphs are calculated automatically (cf. IDL, [1]). The properties of that calculations are controlled by a few square buttons in the fifth line of the control window.

Switch on the button **sameYRange** for selecting the same range of emissivity for each plotted graph. Switch on the button **yZero** to force all lower borders of the y-axes to be not larger than zero (cf. the contrary of the IDL keyword: ynozero). Switch on the button **yStyle** to force the y-range to be exactly $[\min(data), \max(data)]$ (cf. the IDL keyword: ystyle=1).

When the button **RAWorABS** is switched on, the raw SXR data will be plotted instead of calibrated data. In case of plotting FFT data (cf. section 1.7) absolute values will be plotted instead of phase values.

By switching on the button **lfnr** the running number of the data points will be shown on the plot window instead of the time value.

In order to save the plotting time, it is possible to specify the maximum number of plotted points for a graph. Do that using the field named **np_max** in the fourth line of the control window. The default value of 5010 is a recommended number. To reduce the plotted data points VISO takes only every n-th point, where $n =$ number of data points / np_max. By switching on the button **nsum** in the 11th line, VISO uses the IDL keyword 'nsum' to average every group of n points. But this procedure takes more time. For the rest the number n is shown in the control panel of the plot window after the keyword 'average' (cf. section 1.5.2).

With the two cross buttons in the 11th line, you can switch between a long and a short cross line for the vertical and horizontal dimension.

1.5.7   Band Pass Filtering

To the right from the button **nsum** there are a few widget for calculation of the band pass filtered data. Switch on the button **bandpass** to pass the data through a band pass filter with the low and high filter frequency read from the fields **f_l** and **f_l**. In order to make the FFT calculation much more faster switch on the button **2^**. This causes an extension of the data number to a power of 2.

Now press **PLOT** for plotting the filtered data. To plot only the envelop of the filtered data switch on the button **envelop**. To fill this envelop with yellow color switch on the button **fill**, see figure 1.6.
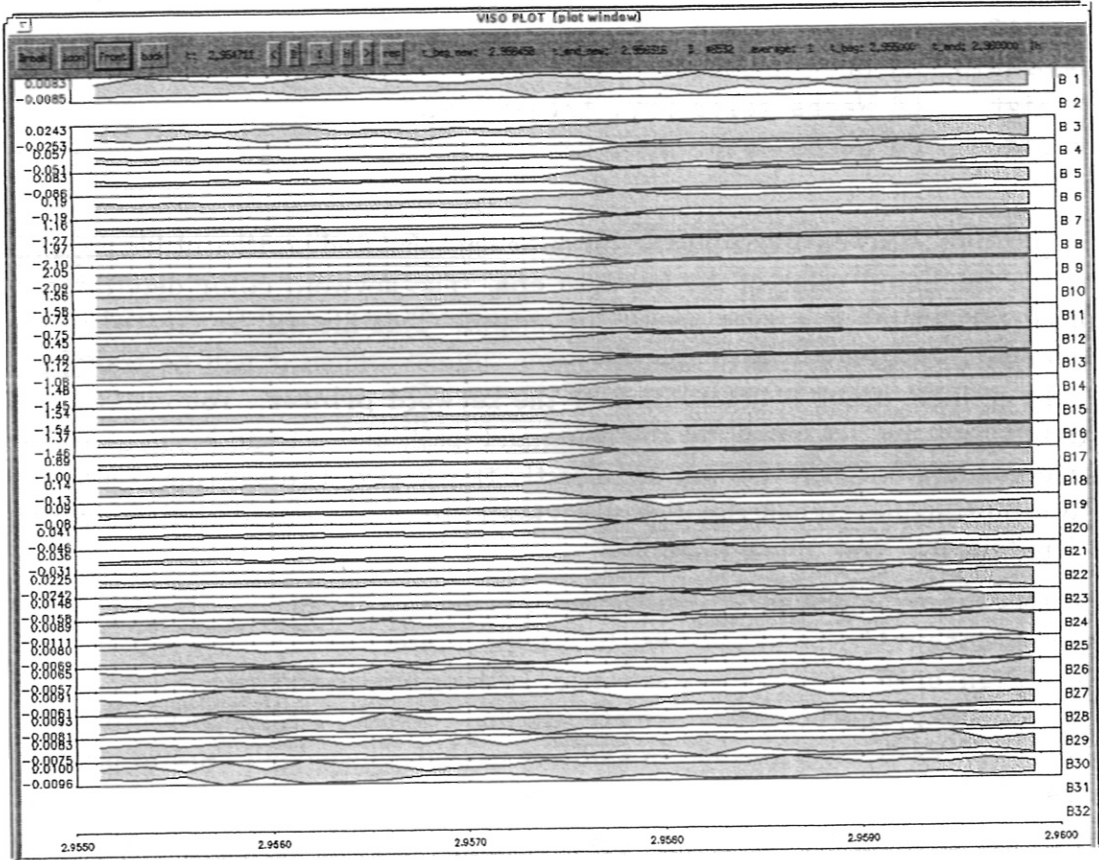
Figure 1.6: *Envelop of the band pass filtered data.*

1.6 Printing

To print graphs from the plot window press the button **LPR** in the fifth line of the control window. To change printer settings use the procedure 'pss' after pressing **Break** for an interactive use of IDL (section 1.3). Type 'pss' without arguments and you will get a list about current settings.

```
printer    = spdoc
color      =          0
lpr        =          1
rm         =          1
eps        =          0
```

```
----- Printer List -----
0          default printer
1 spdoc    Doktorandenzimmer
2 psl6n2   L6 oben Treppe
3 psdpl6   L6 oben Raum 241
4 ojgt     L6 Wachs color prt, transparency
5 ojg      L6 Wachs color prt, paper
```

For printing VISO creates a postScript or an encapsulated postScript file depending on the digital value of the keyword **eps**. The keyword **color** determines a 'black and white' or a color postScript output. This file will be created in the directory ~/idl/viso/ with the file name 'idl.ps'. Then it will be transfered to the printer, which is determined by the keyword **printer**. You can select a printer from the list, made by the command 'pss', and set the keyword to the corresponding number. Or you set directly this keyword to a string containing the printer name. When the digital keyword **rm** is set, the file 'idl.ps' will be deleted finally. Now follow examples:

`pss,printer='s20scan'`	set printer name to s20scan
`pss,printer=''`	set to default printer
`pss,printer=5`	set to the fifth printer in the list
`pss,color=1,eps=0,rm=0`	create and don't remove a color postScript file
`pss,c=1,lpr=0,rm=0,eps=0`	in addition to that above don't send to printer
`pss,1000`	abbreviation for that above

To fix all settings for the future VISO sessions add the commands described above to the procedure `viso_ini_user` in the startup file `viso_ini_user.pro` (cf. section 1.2).

1.7   Calculating and Plotting Fast Fourier Transform

To calculate a FFT (Fast Fourier Transform) of the SXR data specify a time interval by plotting it. Then press the button **CALC FFT** in the fifth line of the control window. The FFT will be calculated for all loaded data and VISO changes to the frequency space and plots FFT data versus frequency, see figure 1.7. The button **PLOT** changed to the button **PLOT FFT**. Now you can use all features described in section 1.5 for diagram FFT data. To switch between the frequency and the time space use the second button in the fifth line with the name **-> TIM** or **-> FFT**, respectively (cf. figure 1.8). For plotting the power spectrum instead of the absolute values switch on the button **pow** in the fifth line.
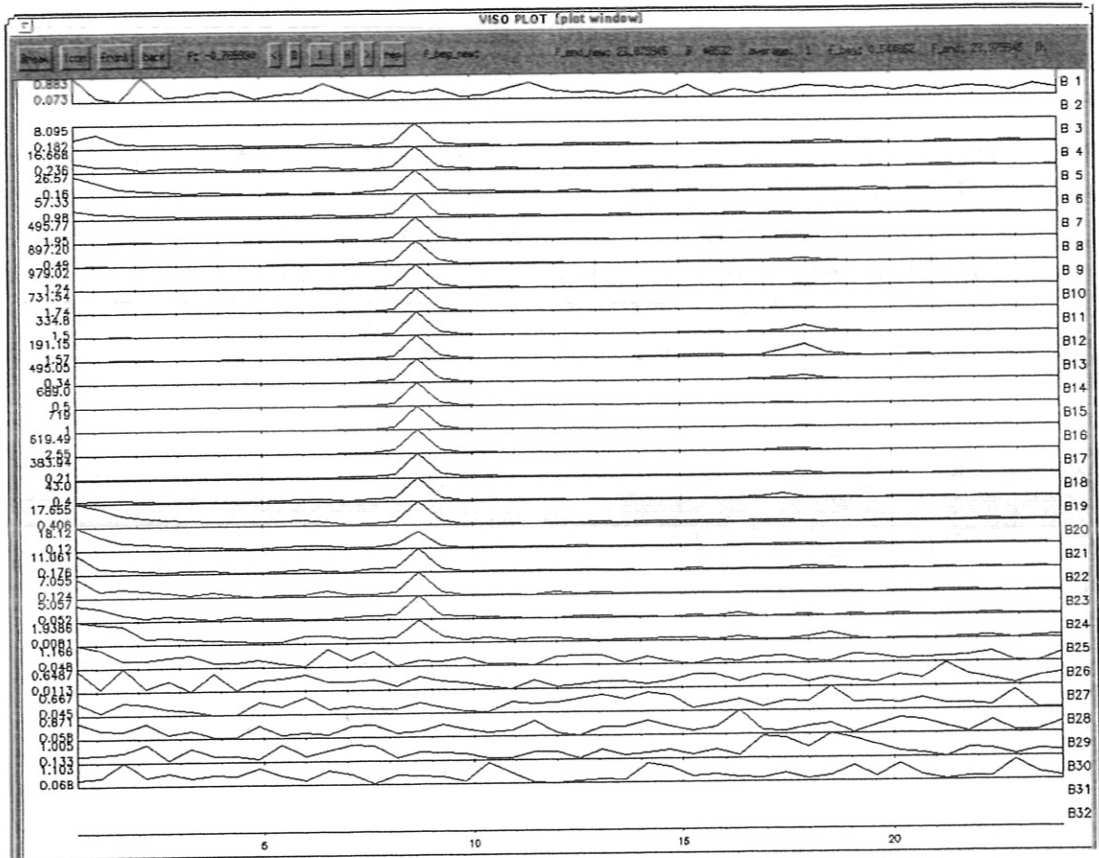
Figure 1.7: *Plot window of the VISO program with plotted FFT data.*

1.8   Plotting SXR Profiles

SXR profiles mean different SXR data plotted versus the channel number for one
time point or interval. The SXR data can be averaged emissivity in time space,
the FFT absolute value or the FFT phase. VISO is in time space mode if the
second button in the fifth line of the control window names -> **FFT** and it is in
frequency space mode if this button names -> **TIM** (cf. figure 1.8).
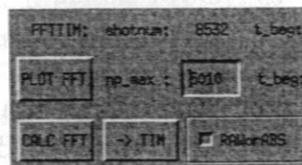
Figure 1.8: *A cutting from control window with active frequency space.*

1.8.1   Profiles in Time Space

The button **Prof_ang** causes a plot of averaged SXR emissivity for the selected
camera. This function is obsolete. So, it is better to use the button **Prof_all**.
First at all, choose, whether raw or calibrated data should be plotted (cf. sec-
tion 1.5.6). Then, mark the time interval for averaging by use of the left and right
mouse button as described in section 1.5.3. Finally, press the button **Prof_all**.
You will get something like figure 1.9. The x-axis at the bottom shows the channel
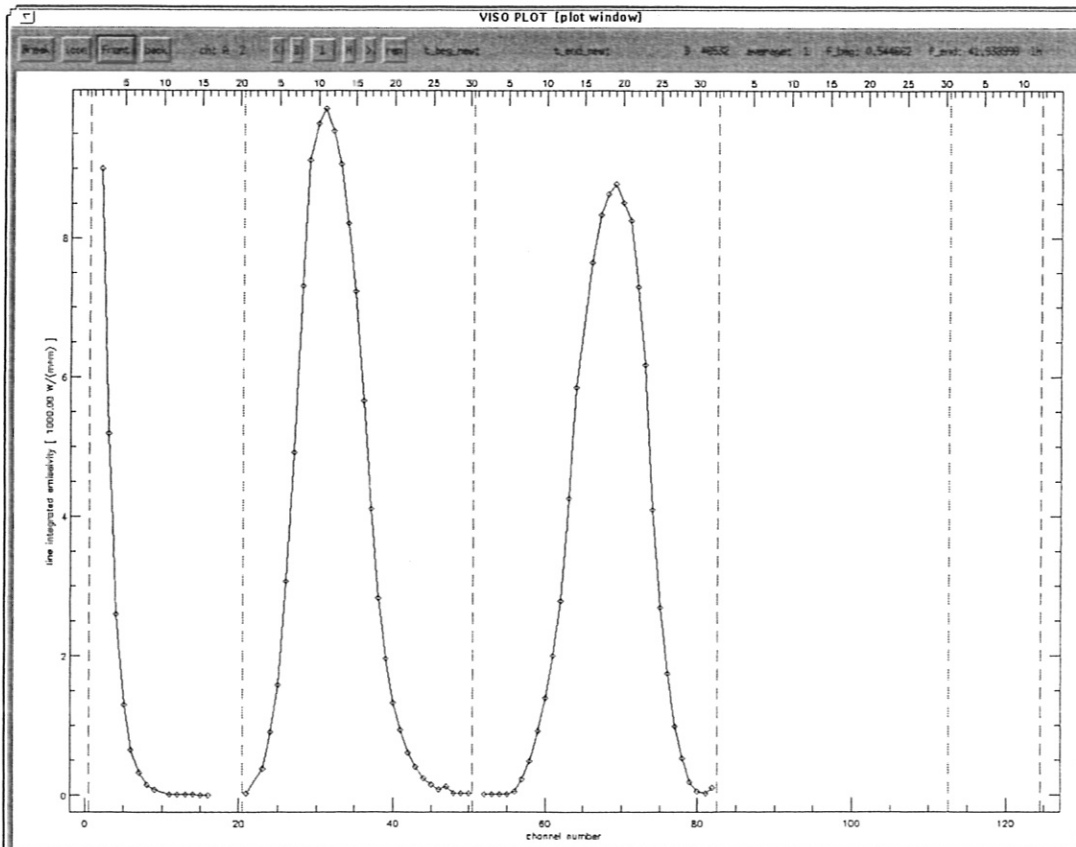
Figure 1.9: *Profiles of SXR emissivity in time space.*

numbers, numbered for the whole diagnostic, while the x-axis at the top shows
the channel numbers, numbered for each camera. The y-axis shows the line inte-
grated emissivity. The vertical dashed lines separate the cameras. By using the
left and right mouse button, as described in section 1.5.3, it is possible to select
the x-axis range.

1.8.2   Profiles in Fourier Space

In order to work in Fourier space, the FFT has to be calculated before. After
that, specify on the plot like in figure 1.7 a new frequency range by using the
left and right mouse button, as described in section 1.5.3. Often, this range is
only one point. In case of more points, they will be reduced to one point by a
special way: The absolute values will be add geometrically (power spectrum).
The averaged phase is determined by the weighted sum of the complex FFT
values. The weights are the absolute values. By pressing the button **Prof_all**
a few profiles will be plotted, see figure 1.10. The meaning and the control of
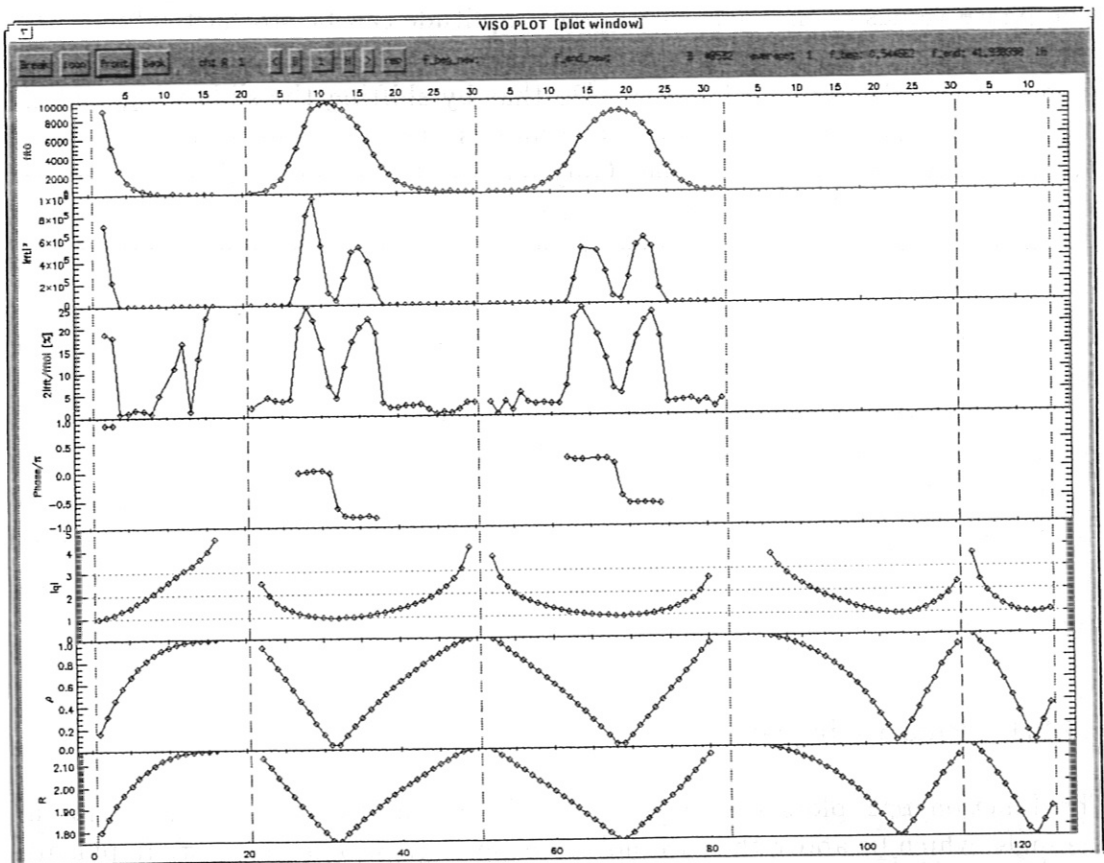
Figure 1.10: *Profiles of SXR emissivity in Fourier Space.*

the x-axis is as described in previous subsection. The y-axes are different for
each profile. `fft0` (short hand: `0`) means the FFT value at the frequency 0, i. e.
the profile in time space for the time interval used by the FFT. $|fft|^2$ (short
hand: `f`) is the value from the power spectrum. $2|fft/fft0|$ (short hand: `r`)
is the relative absolute value of the FFT, i. e. it is the relative amplitude of the
oscillation. `Phase` (short hand: `p`) is the phase in units of π. $|q|$ (short hand: `q`)
is the absolute value of the safety factor q for the flux surface, which is tangent

by the line of sight. ρ (short hand: h) means the normalized poloidal flux radius belonging to the safety factor. R (short hand: R) is the radial coordinate, where the above flux surface cross the mid plane outside of the torus. Error (short hand: e) means the absolute statistical error of the real and imaginary part of the FFT value (cf. section 1.10). The values q, ρ and R are determined from the function parametrisation FPP [2].

Each of the profiles, you can switch on and off by the buttons at the end of the seventh line in the control window. These buttons are labeled with the short hands.

The phase values of channels with small amplitude can be stochastically distributed. To switch off such channels in the phase profile adjust a threshold for the square of the absolute FFT values. Do that by shifting the slide widget in the sixth line of the control window. The unit is one thousandth of the maximal square of the absolute FFT value. Only phases of channels, which lie above the threshold, will be plotted. Instead of selecting a high threshold you can switch on the button **max** in the seventh line. Then only phases of channels, which have a local maximum in the $|fft|^2$ profile, will be plotted.

It is also possible to plot the profiles with different x-axes. Instead of channel numbers the x-axis can be q, ρ and R. These modes are controlled by the third widget in the sixth line on the control window. The profiles for different cameras are depicted in different colors. The symbols are annotated if the button **annot** in the seventh line is switched on. Two samples for ρ as x-axis are depicted in figure 1.11 and figure 1.12.

With the same widget you can select three further functions: mp1, mp2 and pph. Here use also the button **annot** for annotation.

1.8.2.1   Phase Diagram

The function mp1 plots the angle ϕ (x-axis) versus the phase (y-axis) for all channels, which lie above the threshold, see figure 1.13. The unit is π. In plasmas with circular shape, ϕ is the slope angle of the distance line between the magnetic axis and the line of sight for each channel. In plasmas with noncircular shape, ϕ is the slope angle of the line between the magnetic axis and the touching point of the line of sight and a flux surface. The button **cir** in the seventh line allows to toggle between the two definitions of ϕ.

In the control panel is written the name of the nearest channel and the coordinates of the hair cross. In the plot window you can roll over the x-axis by releasing all three mouse buttons. This marked position will be the new border of the x-axis. Further, it is possible to test the slope in the plotted plane. First, press left mouse button to mark a point. Now a line between that point and the hair
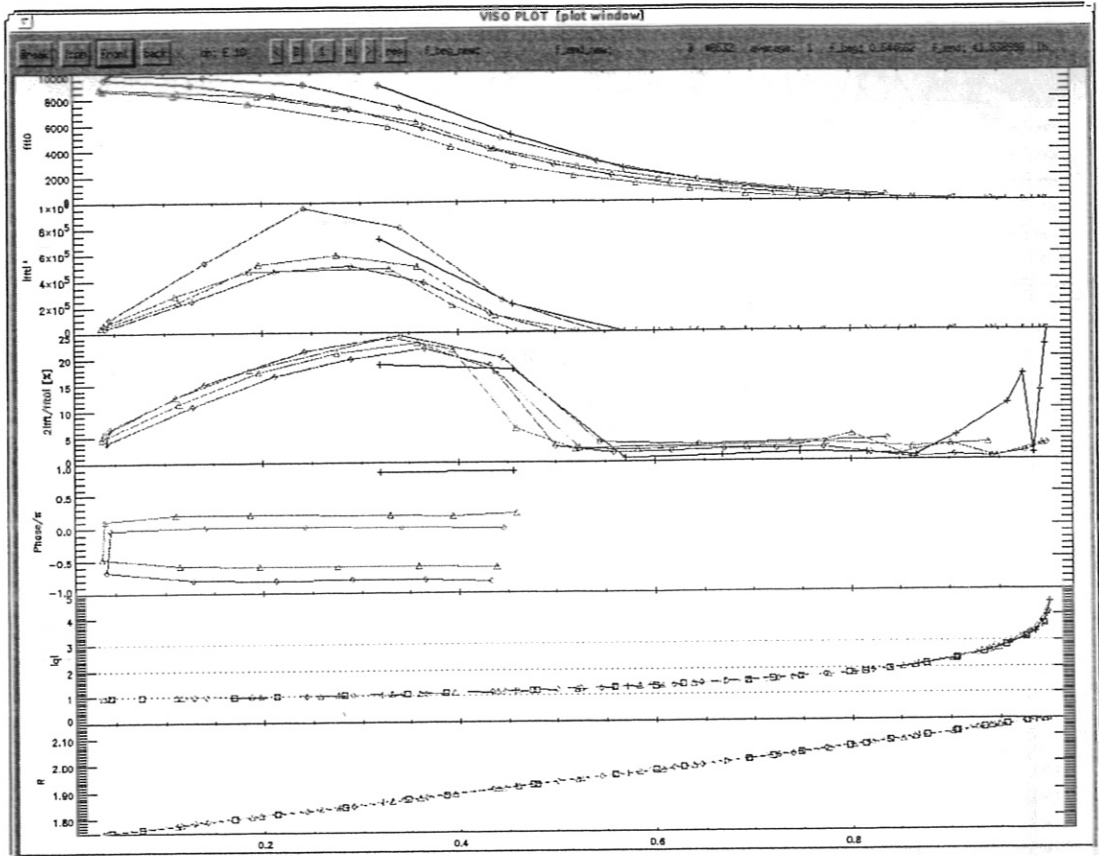
Figure 1.11: *Profiles of SXR emissivity in Fourier Space versus ρ. without annotation.*

cross is plotted. Then mark a second point with the right mouse button. The slope of the line is now written behind the label 'f_end_new'. You can change the slope by renewed pressing of the right mouse button. If you want to fix these lines press the middle mouse button. These lines will not appear on a printout. On some workstations the lines cannot be seen because they are white. So, try another workstation.

The function mp2 cause the same as the function mp1, but in addition it is possible to select the length of the axes and to produce copies of the channels: In the two fields behind the label 'showx' in the seventh line you can specify the length of the x- or y-axis in units of π. In the two fields behind the label 'redx' you can specify the reduction number m (1 or 2) for each axis, i. e. the coordinates are changed by calculating the *modulom* function. So, all symbols are in an interval like $[x_0, x_0 + m\pi]$. The data for all other intervals $[x_0 + im\pi, x_0 + m\pi + im\pi]$, $i \neq 0$ are created by copying from the first interval.
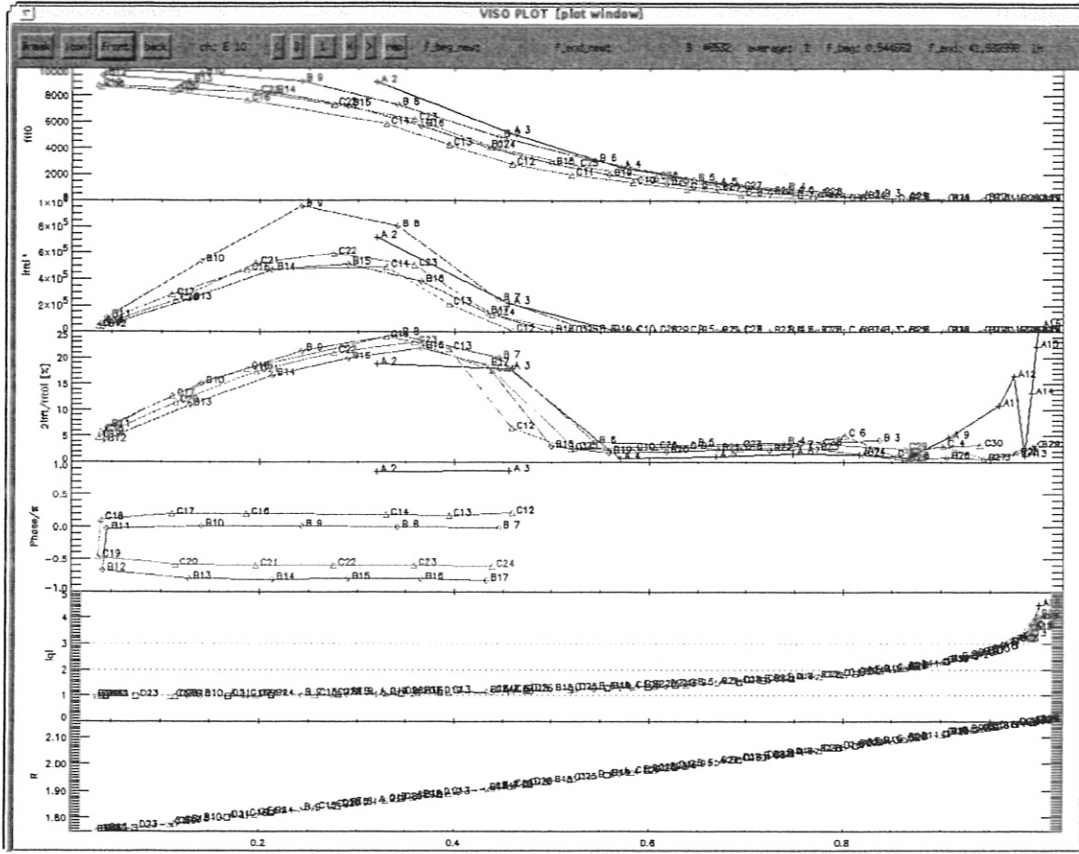
Figure 1.12: *Profiles of SXR emissivity in Fourier Space versus ρ with annotation.*

1.8.2.2 (p, ϕ) Diagram

The function pph plots the angle ϕ (x-axis) versus the value p (y-axis) for all channels, see figure 1.14. The unit is π. In plasmas with circular shape, p is the distance between the magnetic axis and the line of sight. In plasmas with noncircular shape, p is the normalized poloidal flux radius ρ of this magnetic surface, which touches the line of sight. The button **cir** in the seventh line allows to toggle between the two definitions of p. Here use also the button **annot** for annotation.

1.9 Preparing Data for DIRO

The Code DIRO, which calculates the differential rotational tomography, needs as input data the SXR profiles and a few integrals calculated from the SXR geometry and from the magnetic equilibrium at the desired time point. VISO
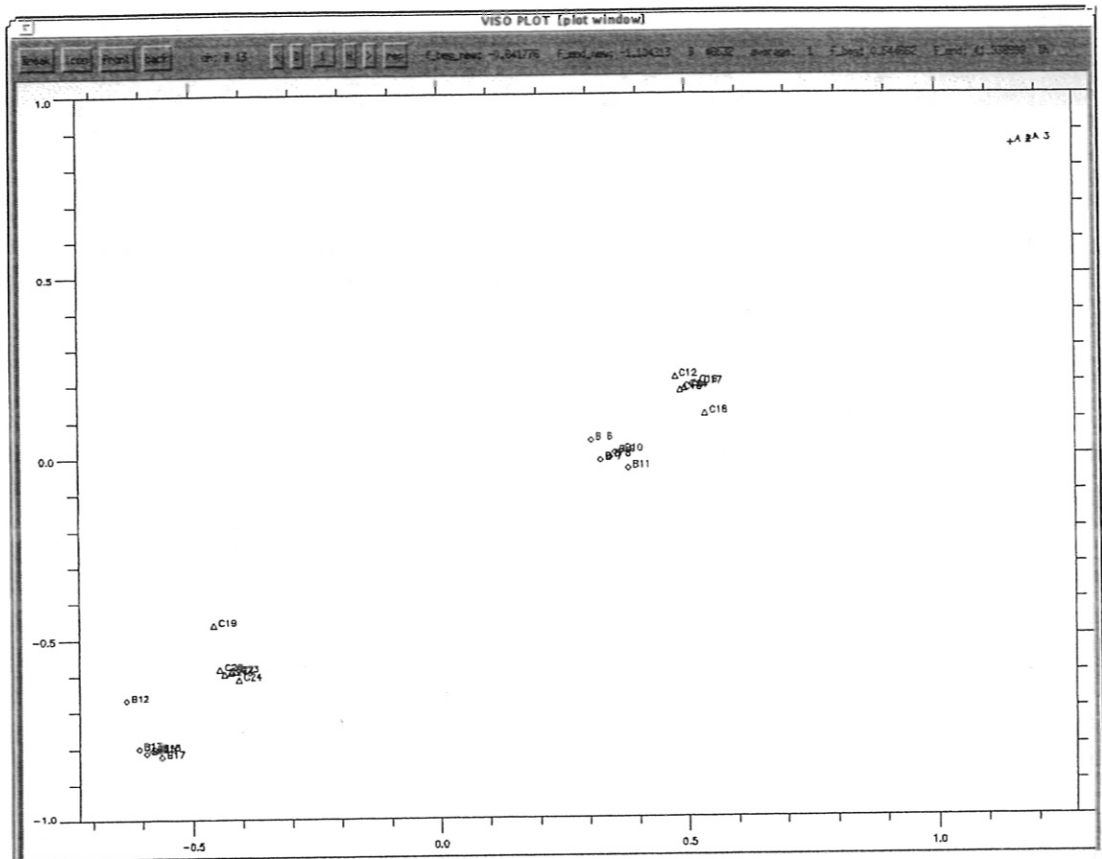
Figure 1.13: *prof mpl annot*

helps to prepare these input data.

1.9.1 Writing Harmonics

For writing harmonics choose a time interval by calculating the FFT. Then, select a small frequency range around the ground frequency as if you would like to plot a SXR profile. Now determine the maximal number of harmonics you like to save by using the field 'max_harm' in the eighth line of the control window. Finally, press the button **WritHarm** in the eighth line. A file, which file name starts with 'harmonics.dat.' is saved in the directory `~/idl/viso/data/harmonics/`. To calculate the tomography you must later insert this file name into the file 'diro.in' (section 2.4).
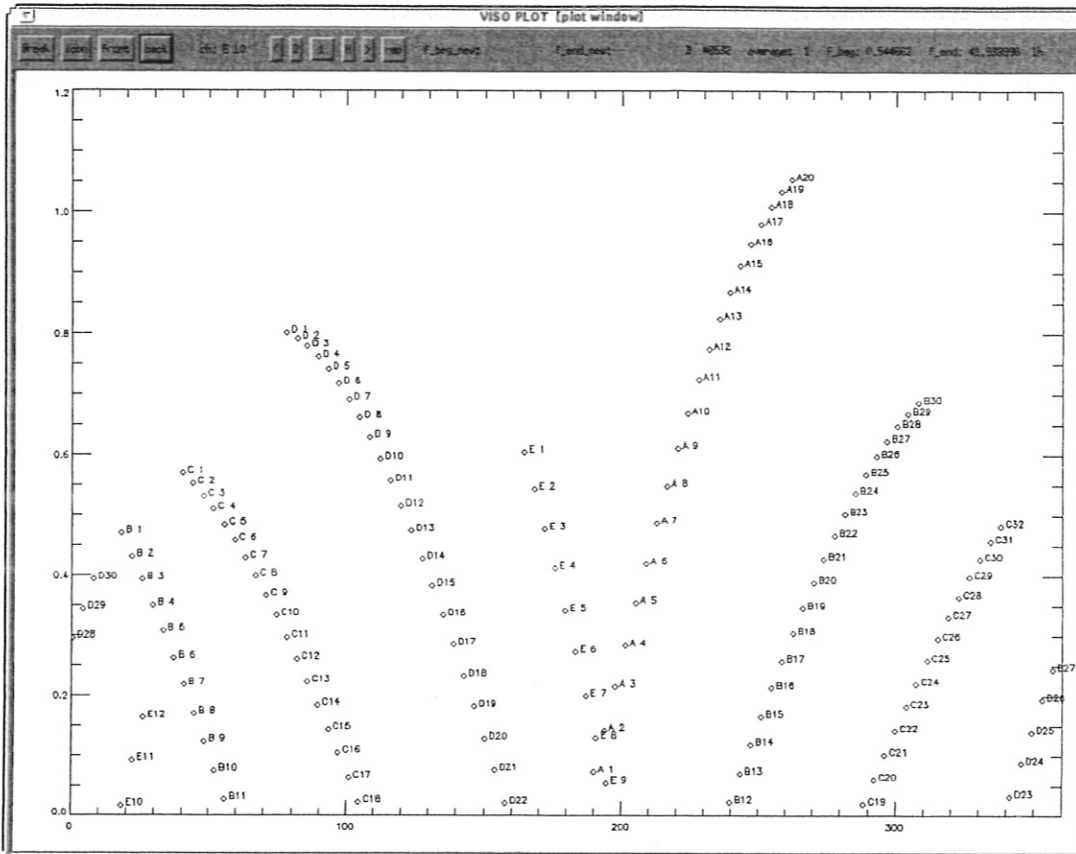
Figure 1.14: (p, ϕ) *Diagram for circular case.*

1.9.2   Calculating Equilibrium and Integrals

To calculate the equilibrium and the integrals, which you need for tomography first plot the related time interval in the time space. By pressing **makeINTG** in the ninth line of the control window all calculations are done for the average time point of the interval. This procedure is executed in the background. When it is finished a message appears in the **INFO**-window at the end of the line nine. A file with the extension '.intg' is saved into the directory ˜/idl/viso/data/equilibrium/data/#/, where # stands for the shot number. To calculate the tomography you must later insert this file name into the file 'diro.in' (section 2.4). Pressing on the **INFO**-widget (i. e. on the first item of this pull down menu) at the end of the ninth line you will get the file names of the last saved harmonics and the calculated integrals in the shell window related with the current IDL session.

Before pressing **makeINTG** decide whether the equilibrium should be obtained from Diva [3] or from FPP [2] by selecting the button **Diva/FPP** (Diva=button unset). The button **pref/oblig** determines whether your decision is only a pref-

erence or obligatory. Furthermore, edit the time tolerance, i.e. the maximal deviation between your selected time point and the time which the equilibrium is calculated for.

The **INFO** pull down menu contains a list of files with the extension '.intg', which were calculated earlier and correspond to the conditions described in the previous paragraph. Clicking one of them you get a list of knots, from which this file is created. The format of the lines in that list corresponds to that which you need to create a new '.intg'-file by the procedure 'intg' of the DIRO code, see section 2.8.

1.10 Plotting Error Profiles

The code VISO creates (and saves in the file 'harmonics.dat....' for use in DIRO) statistical errors for each channel. They are calculated from the three variables eps_a, u_BC and $rVar$ in the eighth line of the control window. eps_a is the relative error for the electronical components (1%), u_BC (6bits) is the absolute mean standard deviation of noise in the measured signals and $rVar$ is the mean variance for low frequencies (5kHz–30kHz). To make a plot of error profiles adjust these variables and press the button **PlotErr**. The switches **rel** and **log** in the same line decide whether the relative or absolute errors are depicted logarithmic or not. This procedure was changed a lot of times. Thus be careful using it.

1.11 Contour Plots of SXR Data

The tenth line of the control window contains buttons for contour plotting. Switch off the button **fill** and press **Contour** (IDL procedure) to get a conventional contour plot for the time interval you selected with the left and right mouse button before, see figure 1.15. This plot represents the data of one camera. With the slider right to the button **fill** you can specify the number of contour levels. 0 means the default value of 5 Switch on the button **fill** to color the space between contour lines (fill is an IDL keyword), see figure 1.16.

In contrast to the filled contour plot there is the button **Cont_Img** corresponding to the modified IDL procedure 'image_cont' Here, you get a conventional contour plot over-plotted with a color coded image, where each color corresponds to a small range of values, see figure 1.17.

Finally, you can press the button **MyXsurf** to get a 3D-plot of the SXR data, confer figure 1.18. This corresponds to the slightly modified procedure 'xsurface' of IDL.
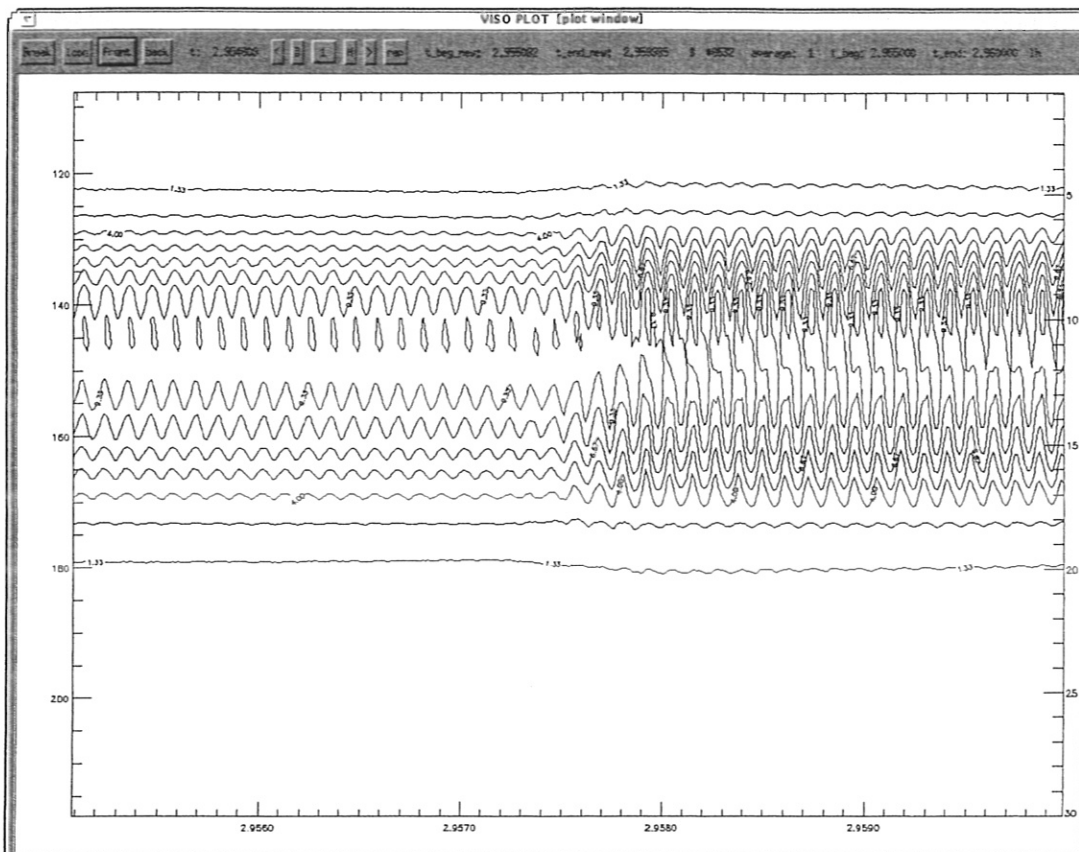
Figure 1.15: *Conventional contour plot of SXR data for one camera.*

1.12   Loading Partial Calibrating data

In a shotfile the data are calibrated step by step. Usually VISO loads entirely calibrated data. But you have the possibility to load only partial calibrating data. The pull down menu 'cal_steps:' at the end of the tenth line in the control window allows to select the number of calibration steps you like to execute during the load procedure. Negative numbers $-i$ mean entirely calibration with the exception of the last i steps. The keywords 'all' and 'ini' mean the complete calibration.

1.13   Environment: Tools and Window Size

In the first line there is the pull down menu **Tools**. Here, you can start the following IDL tools [1]: XLoadct, XPalette and XManagerTool.

Furthermore, you can adjust the size of the plot window in the fields **x_sc** and **y_sc**, the size of the plot inside that window in the fields **x_s** and **y_s** and the
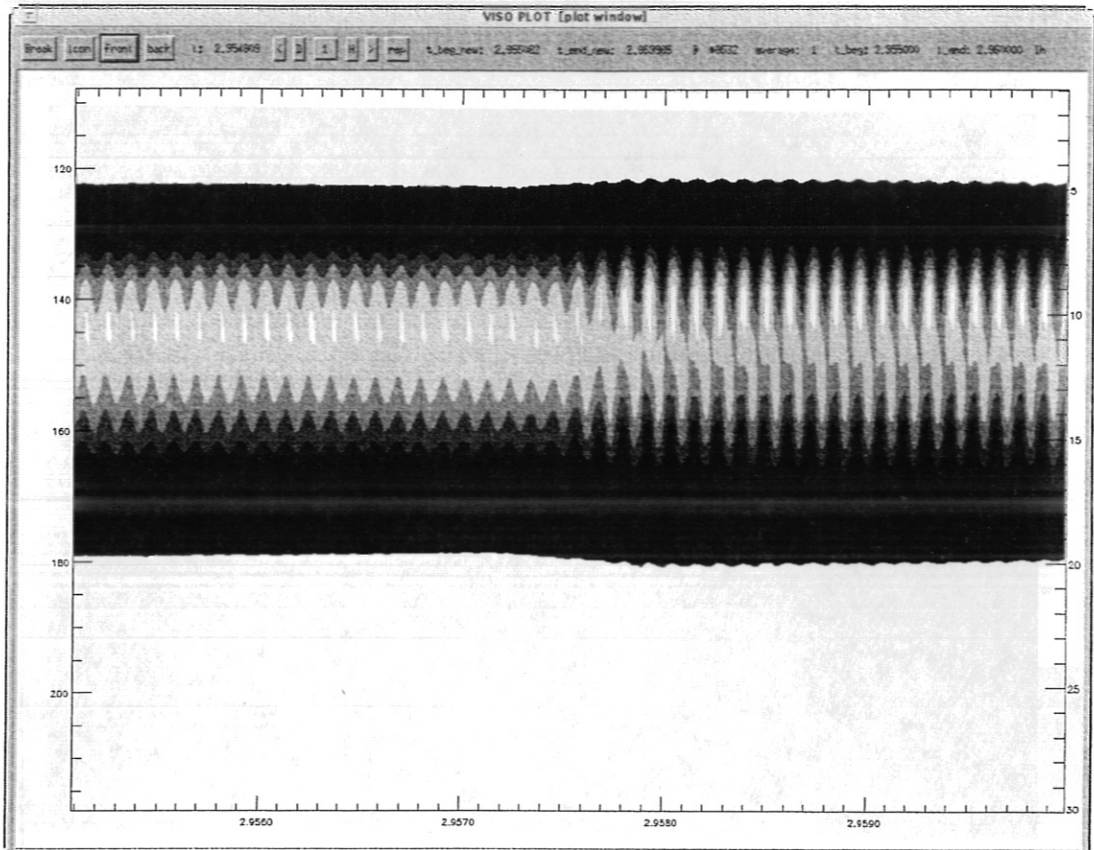
Figure 1.16: *Colored contour plot of SXR data for one camera.*

vertical offset of the plot window in the field **y_off**. If necessary the plot will get scroll bars. Press the button **WinSize** to realize the changed size settings.

1.14   Plotting Other Shotfiles

VISO allows also to plot data from other shotfiles than SXR. It is comparable with the Code OSIRIS. To control this feature use the 12th and 13th line in the control window. The philosophy of loading data changes now. The data will be loaded only when they are needed.

First, select a file containing a set of diagnostics you want to plot by using the pull down menu **set:** in the 12th line. Then, select a file containing the plot properties by using the pull down menu **plot:** in the 12th line. Both lists of files are saved in your configuration file `~/idl/viso/data/config/config`. If you do not have such a file the default configuration file from the author of VISO is used (`/u/mcs/idl/viso/data/config/config`). It looks like listed below:
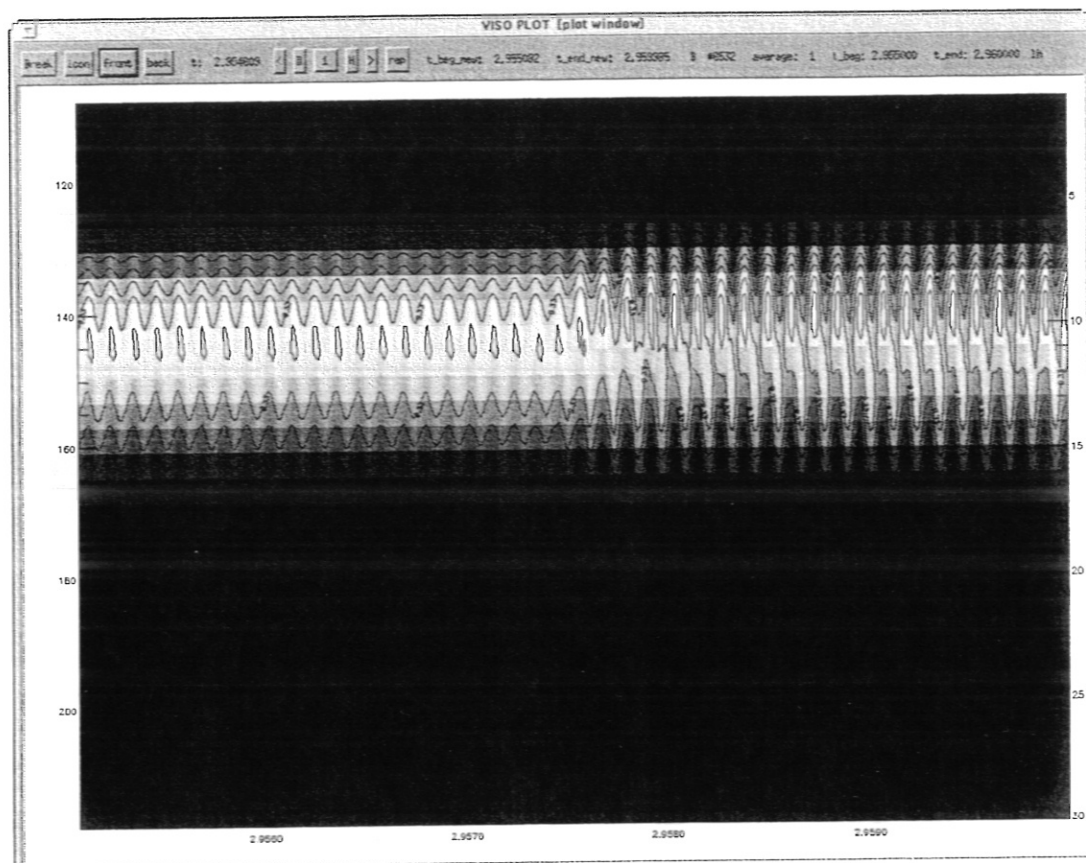
Figure 1.17: *Conventional contour plot over-plotted with a color coded image.*

```
/begin{set_files}
all
load.in
std   // this is a sample for comments
zw    /* this is a sample for comments */
tb_sxr
test7nAB67
mtr_n_10
mtr_m_32
SXRB
SXRB11
/end

/begin{plot_files}
zw
halpha
all
```
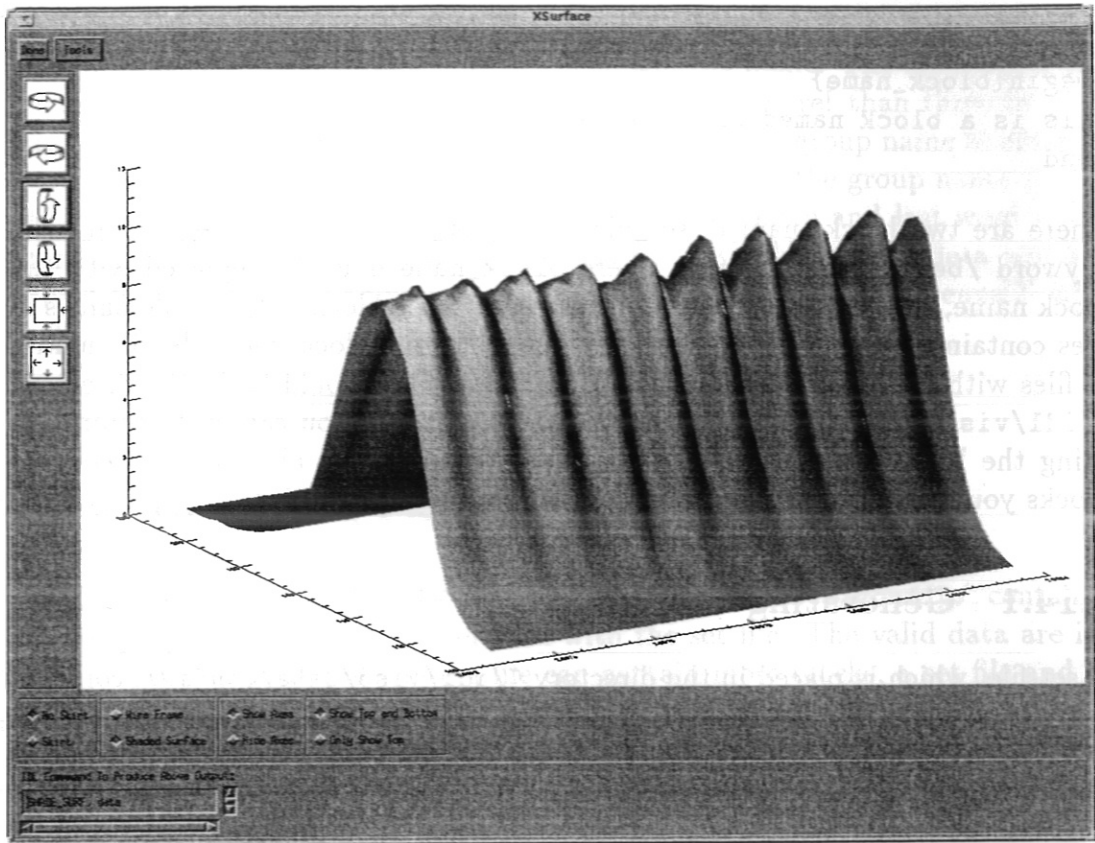
Figure 1.18: *3D-plot of SXR data for one camera.*

```
load.in
std
tb_sxr
betadoku
mtr_for_n
test7nAB67
mtr_n_10
mtr_m_32
SXRB
SXRB11
/end

this is a comment
// this is a comment line
/*
   this is a comment area
   this is a comment area
```

```
*/
/begin{block_name}
this is a block named block_name
/end
```

There are two blocks named 'set_file' and 'plot_file'. A block begins with the keyword `/begin{block_name}`, where `block_name` must be replaced with the block name, and ends with the keyword `/end`. In the block 'set_file' file names of files containing a set of diagnostics are listed. In the block 'plot_file' file names of files with plot properties are listed. All these files should be in the directory `~/idl/viso/data/config/`. At any place in that files you can write comments using the 'C++'-comment-conventions (see the examples above). Between the blocks you can also put any comments without any conventions.

1.14.1   Generating Set File

A set file, which is placed in the directory `~/idl/viso/data/config/`, contains a set of diagnostics you want to plot. The valid data are in the block named 'set'. For an example see the file `/u/mcs/idl/viso/data/config/all`. At the end of this file there is a description of the syntax. An entry for one diagnostic is a series of words separated by an arbitrary number of blanks or tabs. A '.' or a missing word means the default value of this word. For example consider the entry for the total power of the neutral beam injection

```
. NIP . PNI
```

The first word is an arbitrary name for this entry (group name). The default group name is the second word, which is the diagnostic name (NIP). The third word is the signal text, which will be seen on the plot. The default value is the fourth word, which is the signal name (PNI). The fifth word is the signal base, i. e. an arbitrary value, which you can use as a value of an special x-axis. The next words are: a flag for using doubles for the time base (default: 0B), a flag for reading calibrated data (default: 1B), the edition number of the shotfile (default: 0L), the experiment name (default: 'AUGD'), the shot number (default: -1L, i. e. will be taken from the second line in the control window), the beginning time (default: -1.) and finally the end time (default: -2.). The third to fifth word can be repeated by enclosing it between the 'begin' and 'end' keyword as it is shown below:

```
FPGW FPG begin
. Wmhd
. betpol
end
```

Often one like to plot derived data like: sample frequency, FFT, envelop of the data. In that case use a special keyword as diagnostic name. The difference to a conventional diagnostic name is that this keyword has more! than three letters. Here, the entry has a different format: the first word is the group name as defined above, the second word is that keyword, the third word is the group name of the entry, which the new data will be derived from. The fourth and last word is an extension for the signal text defined in the entry, which the new data will be derived from. For an example see the 'diagnostic names 'tbase', 'tenvel2' and 'fft_' in the file /u/mcs/idl/viso/data/config/all.

1.14.2   Generating Plot File

A plot file, which is placed in the directory ~/idl/viso/data/config/, contains the plot properties for the data selected with the set file. The valid data are in the block named 'plot'. Because a file can contain more blocks, a set file and a plot file can be identical, confer the file /u/mcs/idl/viso/data/config/all as an example. One entry corresponds to one plot. In order to correlate a plot with an diagnostic the first two words are the signal text and the group name. The third word is a hexadecimal code for the plot properties. The bit 0 of the nibble 0 (i. e. the four lowest bits) controls the plotting itself: if it is set, then plot, else do not plot. The other bits of that nibble have only a special meaning for plotting FFT, see the file /u/mcs/idl/viso/data/config/all. The bits 0 and 1 of the nibble 1 correspond directly to the bits 0 and 1 of the 'ystyle'-keyword in IDL [1]. If bit 2 is set, then the y-axis will start at $y = 0$. If bit 3 is set, then the IDL keyword 'nsum' will be set to 0. The fourth word is a factor, which the data will be multiplied with (default: 1.). The next and last two words correspond to the IDL keyword vector 'yrange' and specify an automatic or an specific range determination for the y-axis.

1.14.3   Plotting

With the pull down menu **mode:** in the 12th line you can select the plotting mode: 'SXR' means that, if you press **PLOT** only the SXR data will be plotted. The mode 'other' means that only the other data defined in the set and plot file will be plotted. 'both' plots first the SXR data and then the other. 'xaxis' plots an example of the x-axis in order to test the functions of the mouse. 'special' is reserved for future use as well as the last pull down menu in the 12th line.

1.14.4   Marking Ranges in Time and Fourier Space

In order to calculate the FFT you must specify a time range. Do that by using the left and right mouse buttons followed by pressing the button **TAKE** in the 13th line. Then the new time range is written into the fields **t_b** and **t_e** in the 13th line. Use the same procedure to mark the frequency range, which will be written into the fields **f_b** and **f_e**.

Chapter 2

User's Guide to DIRO

2.1 About DIRO

DIRO stands for **di**fferential **ro**tational tomography (chapter 3). It is a tomography code, which uses data written by the code VISO for input. The output are reconstructed radial amplitude functions of modes and contour plots of emissivity (chapter 3). DIRO is primary written in IDL (Interactive Data Language, [1]), but it uses also C++ routines.

2.2 Preparing Unix Environment

For using DIRO you need a special directory tree. Create these directories by typing `viso⎵install` as described in section 1.2. The top directory is `~/idl/viso/`, where ~ means the user's home directory. There you can find the default startup file `diro_ini_user.pro` for your DIRO sessions. This file includes the idl procedure `diro_ini_user`, which is executed at the beginning of each DIRO session. Here you can write your default settings, e. g. the default printer name (cf. section 1.6). The next file is `diro.in`. It controls which reconstruction DIRO will calculate (cf. section 2.4). In the directory `~/idl/viso/data/` there are different data files, which you will get to know later.

2.3 Starting and Exiting DIRO

To run DIRO, enter `diro` at the operation system prompt. The IDL program prompts with the string `IDL>`, you are in the interactive mode of IDL and you can use the DIRO procedures described in the following sections.

To exit DIRO and IDL type exit or ^D at the IDL prompt.

2.4   Editing the Control File diro.in

The control file ~/idl/viso/diro.in is organized in blocks as described in section 1.14. You can also use the 'C++'-comment-conventions. There are two significant blocks named 'modes' and 'intg'. The first of them is used to define the input files and the set of modes for the calculation of reconstruction. The second defines the calculated equilibrium and new knots for recalculation of the line integrals I_{jklD} (see equation (3.7), chapter 3).

In the first line of the block named 'modes' you have to specify the variables Harm_max, Harm_fak and Harm_fname separated by one or more blanks. These variables have the following meaning:

Harm_max	if it is greater or equal than 0, DIRO considers only harmonics, which are not higher than Harm_max. If Harm_max is lower than 0, then there is no limit.
Harm_fak	an integer, which is the ground frequency of the saved harmonics divided by the toroidal plasma rotational frequency (normally = 1). If Harm_fak = 0, then DIRO sets Harm_fak to the greatest common divisor of all toroidal mode numbers n.
Harm_fname	name of file containing the harmonics data (cf. section 1.9.1). Either it is with an absolute path (it starts with a slash) or the default path ~mcs/idl/viso/data/harmonics/ will be used.

In each of the next lines specify a mode with its harmonics by defining the variables m, n, numb_harm and intg_fname:

m	is the poloidal mode number
n	is the toroidal mode number
numb_harm	is the number of harmonics, e. g. the entry 2 1 3 means the modes (2,1), (4,2) and (6,3). If numb_harm = -1, then this mode is switched off, but not the following variable intg_fname. numb_harm = 0 takes as much as possible of harmonics.
intg_fname	name of file containing the data of calculated integrals (cf. section 1.9.2). Either it is with an absolute path (it starts with a slash) or the default path ~mcs/idl/viso/data/equilibrium/data/ will be used. If you leave out this entry, then the file name from the line above will be used.

Thus, this block is ready for calculation (see section 2.5).

In the first line of the block named 'intg' you have to specify the equilibrium by editing the name of file containing the data of calculated integrals. It is the same entry as for the variable `intg_fname` described above. Instead of this file name you can also edit the keyword 'last' in order to specify the equilibrium used in the last calculation. The second and last line begins with the keyword 'intg_all_chReff' and ends with 'end'. In between there are a lot of numbers. First of them — the second entry in that line — is the number of knots for the radial functions. If it is positive, then the knots are equidistant, else the knots are listed beginning with 0. and ending with 1.. The last number — the penultimate entry in that line — is the maximal poloidal number m_{jk} of the integrals I_{jklD} (see equation (3.7), chapter 3), which the recalculation will be done for (see section 2.8).

2.5 Starting Calculation

After preparing the block named 'modes' in the file `diro.in` (section 2.4) start the procedure 'calc' by typing `calc` at the IDL prompt. The results of the calculation appear in a plot of radial functions with different kinds of figures of merit. This plot is described in section 2.9.

You can force DIRO to calculate with a specified set of channels by setting the variable 'indall_def' to a vector of desired channel numbers before executing the procedure 'calc'. For example, type `indall_def=indgen(64)+32` for a calculation with only the camera B and C, or type `indall_def=indgen(160)` for a calculation with all cameras.

The procedure 'calc' can be invoked with a few different keywords: Set the keyword 'change_rot_dir' (type: `calc,/change_rot_dir`) to force a calculation for changed rotation direction (in ASDEX Upgrade with NBI modes rotate clockwise in the poloidal plane). The figure of merit helps to decide in which direction the modes rotate. Set the keyword 'svd' (type: `calc,/svd`) to see the results of the fitting procedures (done by singular value decomposition) for each harmonic separately. In that case the program stops after each fitting and shows the input data in black and the recalculated input data, which should be approximately the same, in red (see figure 2.1). The x-axis is the channel number and the y-axes are the absolute value, the phase, the real part and the imaginary part.

2.6 Saving Calculated Reconstruction Data

After a calculation you can save the calculated data to a file by typing `save_e`. The new created file name is printed to the shell window, where IDL is running.
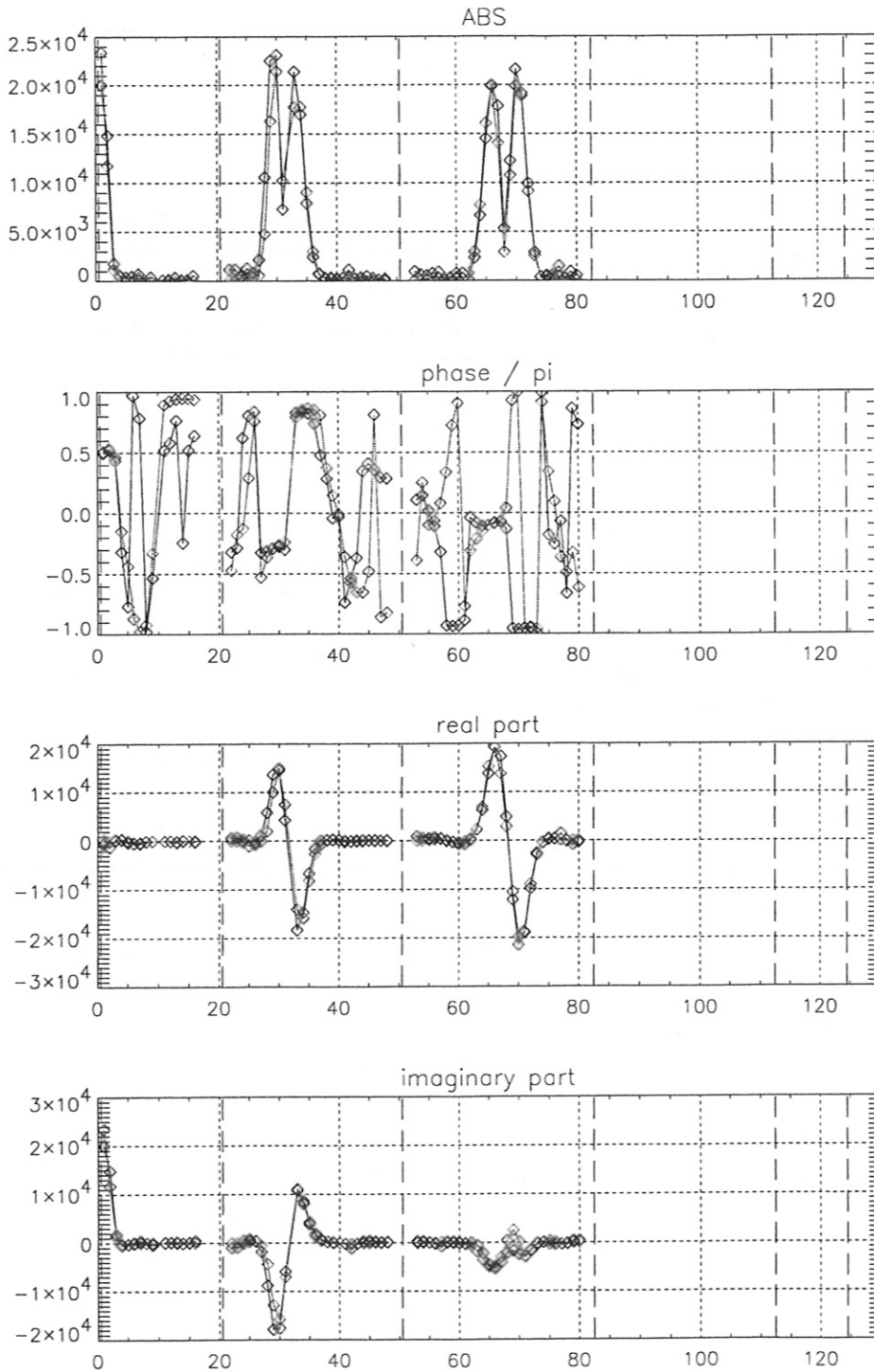
Figure 2.1: *Results of a fitting procedure for one harmonic: input data and recalculated input data. The x-axis is the channel number and the y-axes are the absolute value, the phase, the real part and the imaginary part.*

This file is saved into the directory ~mcs/idl/viso/data/diro_results/. Its
name is coded and contains the shot number, the time in microseconds, the fre-
quency in Hz, the number of periods of the related interval, the number of the
highest used harmonic, a key letter for the used equilibrium (F=FPP, D=Diva),
a special string code for related q-values, the sign + for clockwise rotation or the
sign - for counter clockwise rotation, and finally the version number. The special
string for q-values is coded as follows: The sign '0' stands for the (0,0) mode. Af-
ter that follow the codes for all q-values in ascending order. The sign codes mean:

q-value	1/1	2/1	...	3/2	4/2	...	4/3	5/3	...	5/4	6/5	...
sign code	1	2	...	d	e	...	E	F	...	5=4	6=5	...

2.7 Loading Calculated Reconstruction Data

To load reconstruction data, which were calculated earlier, type load at the IDL
prompt. A menu with file names appears, where you can choose one of them.
You can also use this file name directly as argument, e. g. type:
load,'7694.1887166.11029.24.2.F.0b1d2+000'.

2.8 Recalculation of Integrals

For tomography with a different set of knots you have to recalculate the integrals
by using the procedure intg. First, edit the block named 'intg' in the control file
'diro.in' as described in section 2.4. Then, save the already calculated integral file
with the extension '.intg' in the directory ~/idl/viso/data/equilibrium/data/#/
(# stands for the shot number) by moving it to another file name. After that,
start the procedure intg at the IDL prompt. Finally, rename the new integral
file and rename the old file back.

2.9 Plotting and Printing Radial Functions

For plotting and printing radial functions use the procedure 'pla'. It has a lot of
keywords.

The keyword 'plot' controls which plots will be plotted. Each bit of this keyword
corresponds to one plot. Bit 0 corresponds to the plot of the amplitude versus
ρ, bit 1 corresponds to the phase versus ρ, bit 2 corresponds to the polar plot of
the phase with additional information about the figure of merit (see below), bit

3 corresponds to the plot of the real part versus ρ and bit 4 corresponds to the plot of the imaginary part versus ρ.

The modes in the plots are coded by colors. On the right site the mode numbers are printed in the same colors. To each of them corresponds a running number starting with 1. You can select only a few modes for plotting by setting the keyword 'ind_m' to a vector of the desired running numbers. Negative numbers mean select all modes with the exception of those, e. g. `pla,ind_m=[-1]` plots all modes accept the (0,0) mode.

Set the keyword 'shiftphase' to a phase, which will be added to all phases.

Switch the keyword 'knots' off (`pla,knots=0`), if you do not like the plotted knots.

Set the keyword 'tit' to the title of the first plot.

Set the keyword 'lpr' for an output to a printer instead to the screen.

Set the keyword 'num_sigma' to a number a, if you like to plot confidence belts with a width of $a\sigma$.

For plotting only the error values set the keyword 'onlyerr'.

Set the keyword 'fak' to an arbitrary factor number for the data (example: fak=1.e-3).

Unset the keyword 'small0' to force the same y-axis for all modes.

Additional keywords for the plot of the amplitude versus ρ: Set the keywords 'ma_' and 'ma0' to the maximal value of the left and right y-axis, respectively. Set these keywords to variables containing zero in order to get the maximal values of the two y-axes. The relation between these two values is calculated and printed (in percent) into the title of the x-axis.

Right to the polar plot of the phase there are listed a few numbers of figure of merit for each mode (one line = one mode). First, there are two numbers written like: 'a of b'. a is the rank and b is the dimension of the matrix used for the least square fit. The next number is χ^2 of the fit. The last four numbers let us call d, e, f and g. The least square fit is calculated with the help of singular value decomposition. Thus, the number e is the minimum relative singular value in percent (relative to the largest singular value). The fit problem can be described as follows:

$$\| \overset{\leftrightarrow}{A} \cdot \vec{v} - \vec{w} \|_2 = \chi^2 \tag{2.1}$$

The Matrix $\overset{\leftrightarrow}{A}$ and the vector $\vec{w}$ are input data. χ^2 is minimized and the vector $\vec{v}$ is the solution. Thus, the number d is the relative error in percent defined by $d = \sqrt{\chi^2/v^2}$, the number f is the square of the relative error in percent ($f = d^2$) and the number g is the angle between the vectors $\vec{w}$ and $\vec{v}$. This means: the fit

is good for small numbers d, f and g.

The procedure 'calc' (section 2.5) invokes at the end of calculation the procedure 'pla' without arguments. The output is depicted in figure 2.2.

2.10 Plotting and Printing Emissivity Contours

For plotting of emissivity contours triangulation for the coordinate transformation has to be calculated first. If you have just calculated the tomography, as described in section 2.5, then start the procedure load_e for triangulation. But if you have loaded the earlier calculated tomography, as described in section 2.7, then the triangulation was already started automatically and there is nothing to do.

For plotting and printing emissivity contours use the procedure 'pl'. It has a lot of keywords and three arguments: flagRz, flagplot and af0t. flagRz specifies the coordinate system for the plot: 0 for (ρ, θ^*) coordinates and 1 for Euclidean coordinates. flagplot specifies the kind of plot: 0 for contour lines, 1 for contour image, 2 for 3D plot, 3 for stopping inside the procedure (forget this option), 4 for making sections through the poloidal plane (see below) and 5 for starting a program for depiction of more dimensional data fields written by S. de Peña Hempel [4]. af0t is an additional normalized time delay: it is the time delay t multiplied by the ground frequency $|f_0|$. If you omit the last argument a value of zero will be assumed.

For an output to a printer start first the procedure 'psa', then the contour procedure 'pl' and finally the procedure 'psp', e. g. psa & pl,0,1,/ac & psp. For color printing or creating of an postscript file set these properties by using the procedure 'pss' before. This procedure is described in section 1.6.

Use the keywords 'xmin', 'xmax', 'ymin' and 'ymax' to force a specific range of the x- and y-axis.

Set the keyword 'fak' to a factor by which the data will be multiplied.

The meaning of the keywords 'ind_m' and 'num_sigma' is already described in the previous section.

To see the mode structures it is often useful to subtract a background emissivity, which is constant on magnetic surfaces, from the data. To do that use the keyword 'ac'. Set $ac = 1$ to force the minimum emissivity on each magnetic surface to become zero, or set $ac = 2$ to force the maximum emissivity on each magnetic surface to become zero, or set $ac = 1.5$ to force the maximum emissivity on each magnetic surface to become the absolute value of the minimum emissivity. ac can be set to all values between 1 and 2. If ac is negative, then the emissivity will be calculated for $-ac$ and finally it will be multiplied by (-1). If ac is 0, then the
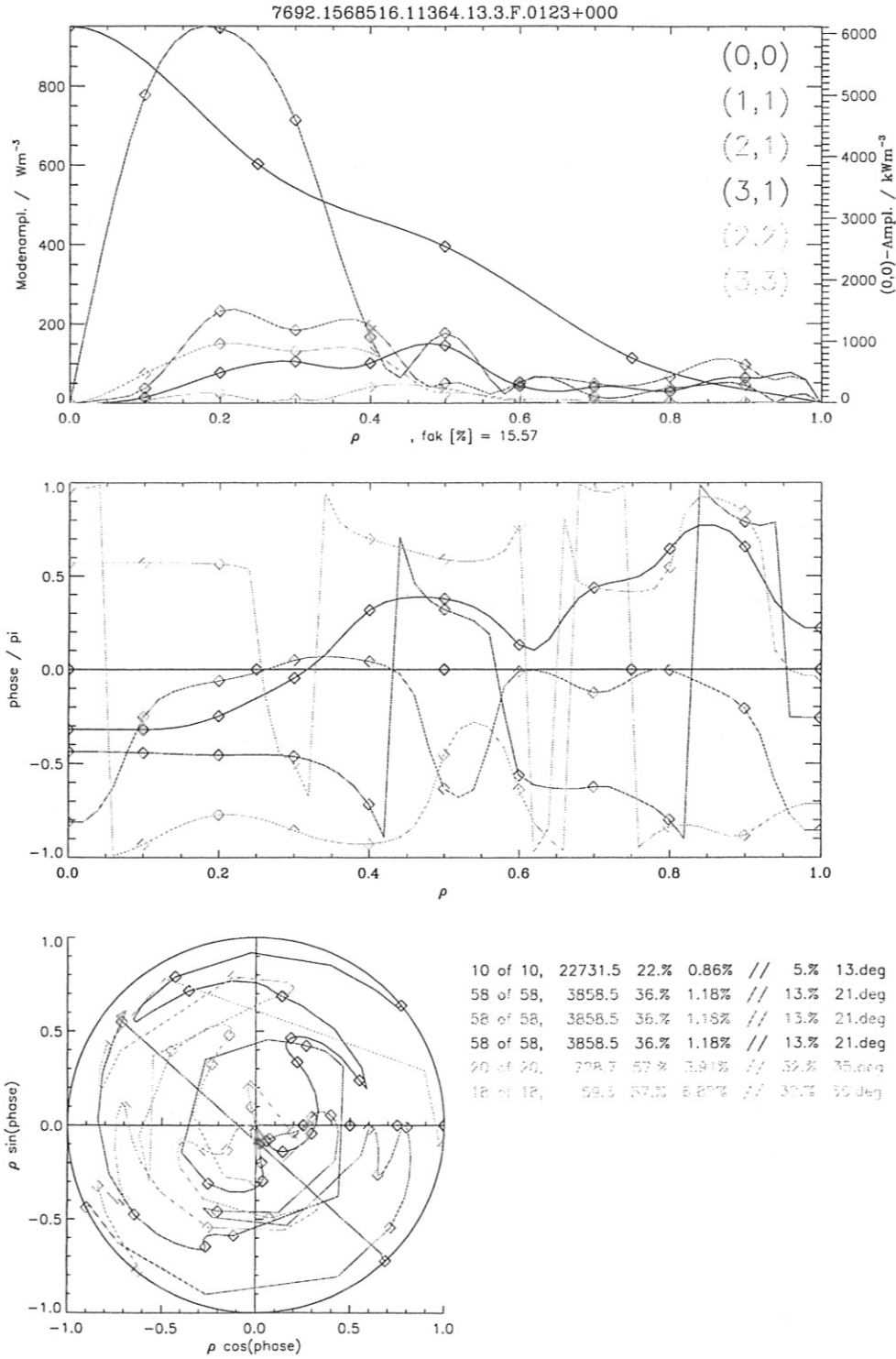
Figure 2.2: *The output after executing the procedure 'pla' without arguments.*

average of the resulting emissivity on each magnetic surface is 0. To see only the background emissivity without any modes set the keyword 'dc'.

If you are plotting contours, you are able to fill the space between the contour lines with color by setting the keyword 'fill'.

It is also possible to use the most of keywords for the standard IDL procedure 'plot'.

To set the character size for the plots use the procedure 'setcharsize' with the character size as argument, e. g. type: `setcharsize, 1.5`.

At work with colors use also the modified IDL procedure 'xloadct' in order to change the properties of the color palette.

For example, figure 2.3 and figure 2.4 show the output after typing the following lines:

```
setcharsize,1.5
!p.charsize=1.5
fak=1.e-3
xtitt = '!7q!6 cos(!7h!6!E*!N)'
ytitt = '!7q!6 sin(!7h!6!E*!N)'
xtitR = '!8R!6 [m]'
ytitR = '!8z!6 [m]'
ma     = .7
tic    = [-.5,0.,.5]
load,'7694.1887166.11029.24.2.F.0b1d2+000'
xs = 9.5 & ys = 8.5 & psap,ys=ys,xs=xs
pl,0,1,/ac,tit=' ',sthick=2,xst=8,yst=8,xmax=ma,xmin=-ma $
,ymax=ma,ymin=-ma,ticklen=-.005,/fill $
,xticks=n_elements(tic)-1,xtickv=tic  $
,yticks=n_elements(tic)-1,ytickv=tic,fak=fak,follow=0    $
,xtit=xtitt,ytit=ytitt
psp
wait,2
xs = 11.6 & ys = 16.5 & psap,ys=ys,xs=xs
pl,1,1,/ac,tit=' ',sthick=2,xst=8,yst=8,fak=fak,follow=0 $
,xtit=xtitR,ytit=ytitR,ticklen=-.005,/fill
psp
```
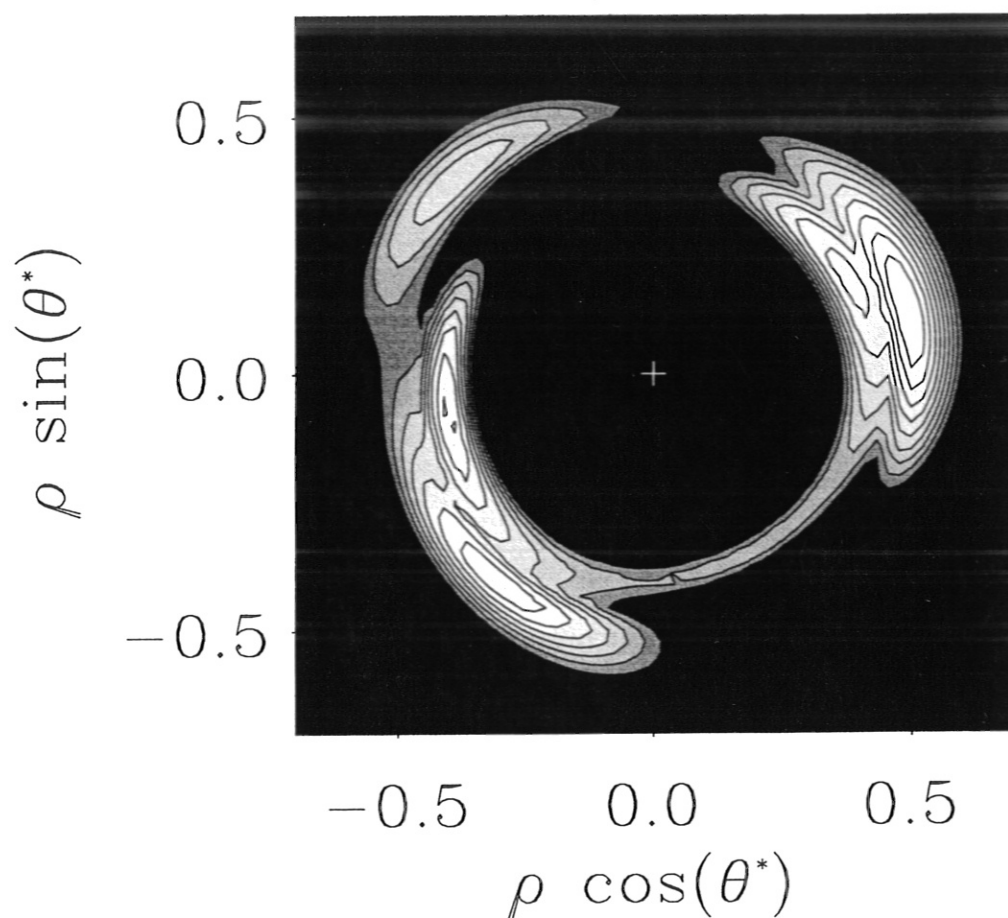
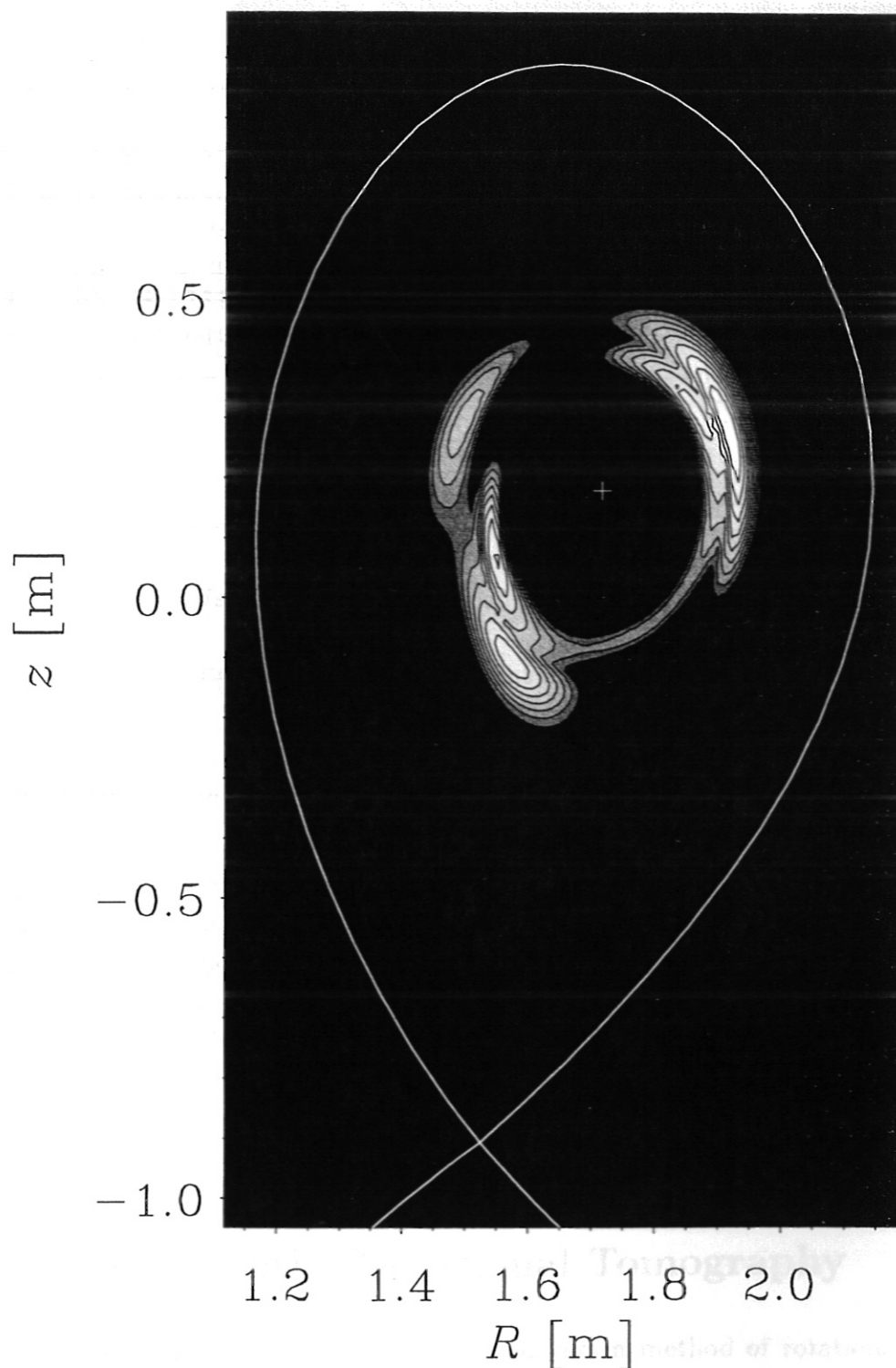**Figure 2.3:** *Example for the output of the procedure 'pl'.*

Figure 2.4: *Example for the output of the procedure 'pl'.*

2.11   Temporal Animation of Emissivity Contours

If you are ready to make a contour plot, you are also able to create an animation of
temporal development of the modes. To do that use the procedure 'anim' with the
same keywords as for the procedure 'pl' and with the arguments: flagRz, flagplot,
anz and af0t, or flagRz, flagplot, beg, fin and step. The arguments flagRz, flagplot
and af0t are described in the previous section. Which set of arguments is valid
depends on their number. In the first case the animation is created for a number
of anz plots for one rotation period f_0^{-1}. af0t can be omitted. In the second case
the animation starts with a plot at the normalized delay time of beg and ends
at the normalized delay time of fin. The variable step defines the step width in
normalized time between two plots.

A few examples follow:

```
; *** create : anim,0,1,5,ac=1,/invert,c_labels=0
; *** restart: anim
; *** close   : anim,0
; *** more.. : anim,0,1,0.,200.,10.,ac=1,/invert,c_labels=0
```

To save an animation use the procedure: anim_save,'filename'. To load an
animation use the procedure: anim_load,'filename'.

2.12   Different Uncoupled Modes

Uncoupled modes have more than one ground frequency in the Fourier space. For
each ground frequency you have to calculate the tomography separetely. After
that you can create a common contour plot with all uncoupled modes. To do
that load the first reconstructed data set as described in section 2.7, but with the
keyword 'first': load,/first. Then load the next reconstructed data sets with
the keyword 'next': load,/next. After loading all reconstructed data sets use
the procedure 'pl' as described in section 2.10.

To list all you have already loaded use the procedures 'listf' and 'listm'. Please,
try it out.

Chapter 3

Differential Rotational Tomography

3.1 Introduction

Soft X-rays (SXR) emitted from a fusion plasma can be used to diagnose and interpret magnetohydrodynamic (MHD) plasma activities and their structure. At the tokamak ASDEX Upgrade the soft X-radiation is measured by 5 pinhole cameras with a total of 124 detectors. The detected signals are integrals along lines-of-sight, which lie in one poloidal cross-section of the tokamak. Thus, a tomographic reconstruction is a very important tool for the interpretation of the data.

For investigation of complex mode structures (higher poloidal mode number, several modes) the spatial resolution is too poor due to the low number of detectors ($\sim 10^2$), because of restricted space. On the other hand in the medical tomography some 10^5 chords are available [5].

To obtain sufficient spatial resolution tomography methods are adapted to the conditions in fusion plasmas. The method presented here is unique in its ability to reconstruct the soft X-ray emissivity of coupled MHD modes with high spatial resolution.

3.2 Differential Rotational Tomography

To improve the spatial resolution the well known method of rotational tomography can be used [6, 7]. Here, time information is transformed into spatial information. Because of the toroidal and/or poloidal plasma rotation the mode

rotates in the observation plane. Assuming a circular, rigid and concentric rotation of a stationary mode with constant angular velocity it is easy to correlate the data for one chord at different time points with the data for different chords at one time point.

To analyse noncircular and nonconcentric plasma shapes the rotational tomography was expanded by using an adaptive coordinate system $(\rho, \varphi, \theta^*)$. ρ is the radial poloidal flux coordinate. The toroidal coordinate φ is the Euclidean toroidal angle. The poloidal coordinate θ^* is the straight field line angle, i. e., the magnetic field lines are straight in the plane (φ, θ^*). The definitions are as follows:

$$\rho = \sqrt{\frac{\psi - \psi_A}{\psi_S - \psi_A}}, \quad \theta^* \sim \int_0^\theta d\theta' \frac{1}{R} \frac{\partial(R, z)}{\partial(\psi, \theta')} \quad \text{for } \rho = const. \tag{3.1}$$

θ^* is normalized to 2π. R and z are the Cartesian coordinates in the poloidal plane. θ is the Euclidean poloidal angle. ψ is the poloidal flux obtained from equilibrium calculations. It takes the value ψ_S on the separatrix and ψ_A on the magnetic axis. All lines-of-sight lie in the plane (ρ, θ^*) (or (R, z)) at one toroidal location $(\varphi = 0)$. The advantage of the coordinate system (ρ, θ^*) is that the motion of one mode is represented as a rigid, uniform, circular and concentric rotation. This simple properties are offset by complex representation of the lines-of-sight in these coordinates, confer figure 3.1.

Conventional rotational tomography fails if more than one mode is present. To deal with this difficulty we developed two complementary strategies. First, if the modes are uncoupled, i. e. if they correspond to different frequencies in the measured signal, we separate them in the Fourier space using the fast Fourier transform (FFT). Second, if they are coupled, we apply an ansatz which takes into account the corresponding different rotational velocities in the observation plane (ρ, θ^*). This will be developed step by step in the following paragraphs.

First, look at the ansatz for the soft X-ray emissivity of a pure harmonic mode (m, n):

$$g(\rho, \varphi, \theta^*) = A(\rho) \, e^{i(m\theta^* - n\varphi)} \tag{3.2}$$

Here, $A(\rho)$ is the complex radial function of this mode. Its absolute part corresponds to the radial amplitude function. Next, assume a rigid plasma rotation with the frequency ω and consider the time dependent ansatz at the toroidal location of the SXR diagnostic:

$$g(\rho, t, \theta^*) = A(\rho) \, e^{i(m\theta^* + n\omega t)} \tag{3.3}$$

The frequency $\omega = \omega_{tor} - \frac{m}{n} \omega_{pol}$ is composed of the toroidal and poloidal plasma rotation. Now, expand this ansatz to different frequencies ω_k and suppose for each of them a set of modes (m_{jk}, n_{jk}):

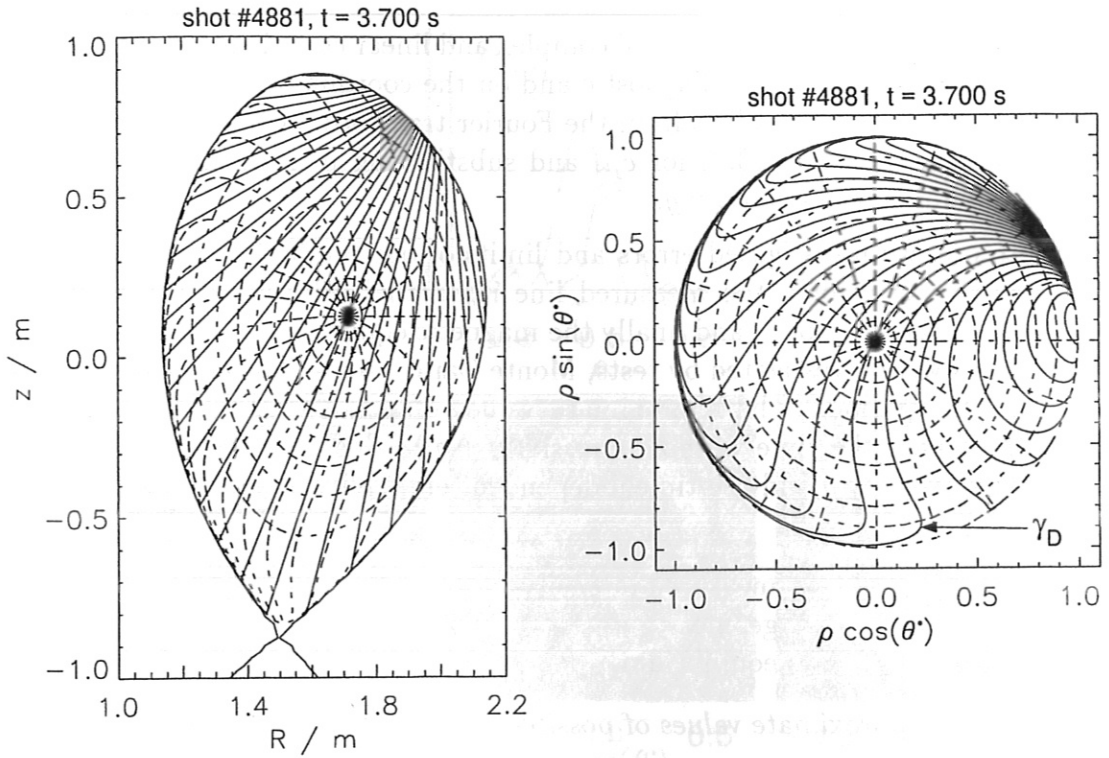$$g(\rho, t, \theta^*) = \sum_{jk} A_{jk}(\rho) \, e^{i(m_{jk}\theta^* + n_{jk}\omega_k t)} \tag{3.4}$$

Figure 3.1: *Lines of constant ρ and θ^* (dashed), and lines-of-sight for camera D (solid), depicted in Euclidean (left) and adaptive (right) coordinates.*

For each mode there is one radial function $A_{jk}(\rho)$. It is defined as an arbitrary cubic spline with h internal knots. Thus, it can be represented as a linear combination of real and well defined cubic B-splines [8]:

$$A_{jk}(\rho) = \sum_{l=1}^{h+4} c_{jkl} N_{jkl}(\rho) \tag{3.5}$$

Equations 3.4 and 3.5 give the total ansatz

$$g(\rho, t, \theta^*) = \sum_{jkl} c_{jkl} N_{jkl}(\rho)\, e^{i(m_{jk}\theta^* + n_{jk}\omega_k t)} \tag{3.6}$$

The measured signal $f_D(t)$ of a detector D is a line integral along a line-of-sight described by the curve γ_D (see figure 3.1):

$$f_D(t) = \sum_{jkl} c_{jkl} \left[\int_{\gamma_D} ds\, N_{jkl}(\rho)\, e^{i\,m_{jk}\theta^*} \right] e^{i\,n_{jk}\omega_k t} =: \sum_{jkl} c_{jkl}\, I_{jklD}\, e^{i\,n_{jk}\omega_k t} \tag{3.7}$$

This set of equations separates in the Fourier space with respect to $\omega := n_{jk}\omega_k$:

$$\tilde{f}_D(\omega) = \sum_{jkl} c_{jkl}\, I_{jklD}\, \delta(n_{jk}\omega_k - \omega) \tag{3.8}$$

Thus, for each ω we obtain one set of complex and linear equations. I_{jklD} depends only on the geometry of the diagnostic and on the coordinates ρ and θ^*. c_{jkl} are unknown and $\tilde{f}_D(\omega)$ are values from the Fourier transform of the measured SXR data. Solving equations (3.8) for c_{jkl} and substituting it in equation (3.6) one obtain the unknown emissivity g.

Furthermore, we investigated errors and limits of our method. There are three main sources of errors: the measured line integrated intensities, the assumed geometry of the diagnostic and finally the magnetic equilibrium. The influence of these errors were investigated by tests, Monte Carlo simulations and calculations of error propagation. The approximate values of possible errors are listed in table 3.1, where the time variable emissivity Δg means the difference between the total emissivity g and the time independent emissivity, i. e. the (0,0) mode.

	g	Δg
measured intensity	1%	1%
geometry	0.5%	2%
equilibrium	2%	9%

Table 3.1: *Approximate values of possible errors of the emissivity g and Δg.*

For the splines we use mostly 11 knots ($\rho = 0.0, 0.1, 0.2, \ldots, 1.0$). It corresponds to a radial resolution of about $5\,\text{cm}$ ($\Delta\rho = 0.1$) for each mode. The poloidal resolution is limited by the number of harmonics, i. e. by the band width of the data acquisition system. This is large enough, so that the poloidal resolution is limited only by the spatial extension of the lines-of-sight, which corresponds to a resolution of about $4\,\text{cm}$.

3.3   Results

With this new high resolution method we investigated the internal kink, the evolution of the sawtooth crash, the growth of the tungsten snake and coupled modes. An example for the studies of coupled mode structures in ASDEX Upgrade high-β discharges is shown in figure 3.2. Tomographic reconstructions of three phases of the discharge are depicted. In the first phase (left plots) the plasma does not reach the β-limit yet and a (1,1) mode is unstable. The radial mode amplitude and the contour plot of the time variable emissivity Δg can be seen. The next phase is at the beginning of the β-collapse. Here, we discovered a (4,3) mode with a toroidally coupled (3,3) mode. Finally, in the last phase during the β-collapse we reconstructed a (3,2) mode with a toroidally coupled (2,2) mode. The tomography procedure yields the m numbers while the n numbers are determined by the relations of the frequencies and by the Mirnov signals.
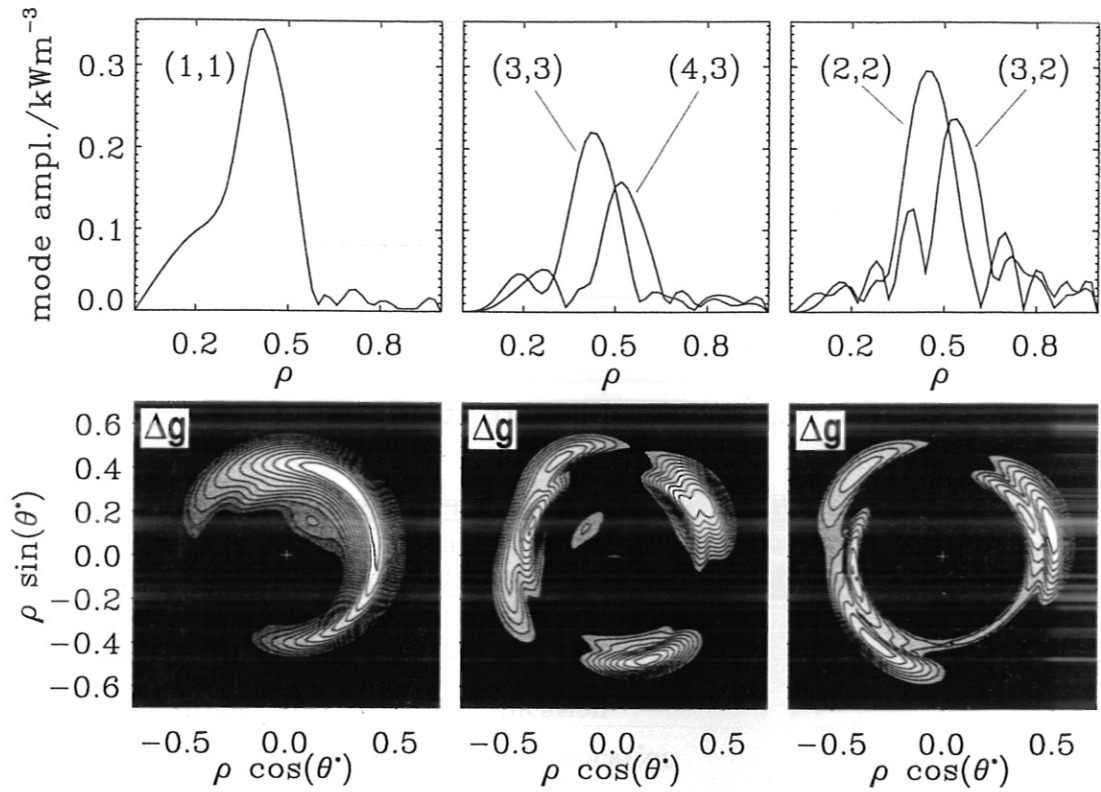
Figure 3.2: *Tomographic reconstruction of an high-β discharge in ASDEX Upgrade (shot #7694). Top: radial mode amplitudes. Bottom: contour plots of the time variable emissivity Δg. Left (t = 1.831 s): (1,1) mode before the β-collapse. Middle (t = 1.844 s): coupling of (4,3) and (3,3) modes at the beginning of the β-collapse. Right (t = 1.887 s): coupling of (3,2) and (2,2) modes at the end of the β-collapse.*

3.4 Summary

An innovative tomography method was developed for interpretation of the soft X-ray data. It has high spatial resolution. For the first time, it is possible to reconstruct the soft X-ray emissivity of coupled MHD modes. The necessary assumption is a stationary mode structure on the time scale of one plasma rotation period (in ASDEX Upgrade: $\sim 100\,\mu s$). The main features are the use of rotational tomography in an adaptive coordinate system, an ansatz for coupled modes with the help of cubic splines and calculation in the Fourier space. Thereby the mode structures in high-β discharges have been clarified in detail.

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