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STUDY OF MAGNETIC FLUX SHAPED BASE FUNCTIONS FOR TOMOGRAPHY
TCV DIAGNOSTICS – SEMESTRIAL REPORT

Ch. Schlatter

CENTRE DE RECHERCHES EN PHYSIQUE DES PLASMAS (CRPP)
Association EURATOM - Confédération suisse

TCV Diagnostics
Semestrial report

Study of magnetic flux shaped base functions for tomography

Christian Schlatter[1]
CRPP EPFL
PPB
CH-1015 Lausanne

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(1) TP IV in physics, christian.schlatter@epfl.ch

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Chapter 1

Introduction

Ten years ago Zoletnik and Kálvin wrote their basic article about tomography using arbitrary expansions [1]. Several algorithms for Soft X-Ray and bolometry using this technique have been developed, but due to their heavy computational overhead(1) they have never been really employed.

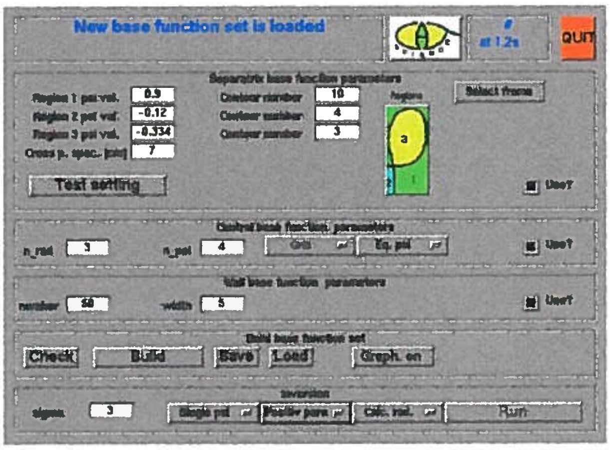

Figure 1.1: GUI extension for BTOMO by Zoletnik and Kálvin. Magnetic flux shaped expansions for tomography using bolometry.

This TP IV aimed to test the existing solution for bolometry and to adapt it for easier use, i.e to control the code with less parameters(2) and to check for possibilities how to make the algorithm faster.

(1) the reconstruction of one single time frame with FLUTO takes about twenty minutes on HAL.

(2) for example the detection of the stable magnetic configuration regime, the determination of the position of the magnetic configuration, the optimal PSI settings etc.

Contrary to all expectations Zoletniks and Kálvins algorithm didn't work on *Matlab 6.1* and therefore a large amount of time was necessary to make it compatible (see section 2.2). Today a working solution exist, so that a few tests were performed.

The next chapter gives an overview about magnetic flux shaped pixels used in tomography, the existing implementations and the new package FLUTO, which has a command line interface and is now able to run under *Matlab 6.1*.

Chapter three deals with problems that came across when the integration for *Matlab 6.1* was established, namely the pixel overlapping problem (which is fixed now) and the pixel truncation at the border of the vessel.

One chapter further some results from specific tests are presented. The PSI value selection shows the effect on how the pixels are scaled in flux values around the LCFS. To ensure the integrity of FLUTO, single time frames of given shots has been processed and compared to inversions obtained with other packages. A section try to analyze the impact of disabled data acquisition channels on the reconstructed image. A last test checks for reliability of the magnetic configuration provided by LIUQE.

Chapter 2

Magnetic FLUx shaped TOmography (FLUTO)

2.1 General description

Surfaces with constant magnetic flux confine the plasma and therefore the emissivity along these surfaces is nearly constant. Hence it would be desirable to have a set of pixels whose shape is given by the magnetic configuration of the plasma. In comparison with completely rectangular grid the number of necessary pixels is smaller to get similar results - this will reduce the effort to calculate the tomographic inversion. Further, the choice of pixels covering almost the whole cross-section of the tokamak permits the reconstruction of localized sources.

A description of a method using arbitrary expansions (given by magnetic flux shaped base functions for example) for tomography can be found in [1].

Kálvin and Zoletnik developed some kind of a plug-in(1) for the bolometry tomography package **BTOMO** [2] (see figure 1.1) for CRPP which is described in [3]. In fact it is a release for bolometry of the older extension of the **TCVXTI** package for soft-X-ray tomography [4].

Since the availability of this diagnostic tool it has been hardly used during daily routine on TCV. In particular a thorough comparison with existing reconstruction techniques was pending.

(1) HAL: `\home\zoletnik\matlab\btomo_final`.

To make testing easier, a GUI-less package called **FLUTO** (magnetic **FLU**x shaped **TO**mography) has been created. It is based essentially on the mentioned **BTOMO** package with Zoletniks and Kálvins flux grid tomography extension. The creation of the base function system and the tomographic inversion is identical to Zoletniks and Kálvins engine.

Before running the package on given shots, the user should check the configuration flags as described in appendix A. The call of **FLUTO** follows the philosophy introduced within **FABCAT** [5], i.e:

- **fluto(shot):**
  treats the specified plasma shot and delivers the reconstruction at the LIUQE times.

- **fluto(shot, t_{min}, t_{max}):**
  loads and treats each time frame located between t_{min} and t_{max} [s] only.

In its present form, **FLUTO** shows the result of the inversion in an special release of the **BTOMOGRAPHICS** window (**BTOMO** package), which makes the analysis of the shot as simple as possible.

Instead of writing directly to the MDS+tree, results are stored to disk in shotxxxxx subfolders, where xxxxx stands for the treated shot number.

2.2 Compatibility with Matlab 6.1

Zoletnik and Kálvin developed their extension to BTOMO on *Matlab Release 5.3*. The use under *Matlab 6.1* (which is available at CRPP since testing began) caused several error and warning messages, preventing a successful execution of the code. The localization of the incompatibility with the new release of Matlab was not an easy job and so a lot of time was necessary to understand how the algorithm works in details and which Matlab built-in functions are used. This effort didn't only reveal the origin of these problems but also uncovered some bugs in the existing code, which are discussed in the following chapter.

Zoletnik and Kálvin use the `delaunay.m` function for the triangularization of the magnetic flux surfaces [6]. It turned out that they integrated the *Matlab 5.3* function `griddata.m` into their package (named as `btgriddata.m`) which was not properly working with the *Matlab 6.1* functions it was invoking. In fact Mathworks implemented a new triangularization algorithm based on the higher dimensional convex hull program (Qhull) [7]. To prevent collisions with other older Matlab functions in Matlabs search path, the full triangularization and interpolation function set has been copied to the local **FLUTO** folder(2).

There still was a persisting error message(3) appearing every time `delaunay.m` called the compiled library file `tsrchmax.mexrs6`, responsible for the selection of the nearest neighboring triangles to a given point. This file was not available in source code format and therefore a fault analysis could not be performed. Mathworks Technical Support finally declared that this is related to truncation errors and can be ignored... Such kind of misleading messages are now disabled by using the `warnings off` command.

The data loading (from MDS) and preprocessing (calibration and smoothing) has been completely replaced by the solution used in the **FABCAT** package. That way the same choice of methods for channel deletion and data calibration is available as in **FABCAT**. The fragmented solution of Zoletnik and Kálvin did calibration at several places, even inside the inversion routine `regulo_2d_flux.m`.

Several command styles which weren't supported any longer by *Matlab 6.1* have been modified(4).

Further modifications and added features are described in the following sections.

(2) `delaunay.m, griddata.m, qhullmx.m, tsearch.m, qhullmx.mexrs6, tsrchmx.mexrs6.`

(3) Warning : one or more points did not converge!

(4) for example the fuzz parameter for `delaunay.m` is obsolete now.

Chapter 3

Problems and modifications of FLUTO

3.1 The pixel overlapping problem

In quest of the error leading to the failure of the inversion the creation of the base function system has been analyzed. It has been found that the superposition of the base functions shows a bad overlapping.

A pixel is given by six base points forming a hexagone at level zero height and a single summit point with height one. The sum over all these pixels should give a uniform surface at level one. Figure 3.1 shows a three dimensional representation of the separatrix base function, i.e. the base function system around the Last Closed Flux Surface (LCFS).

It can clearly be seen that there are at least two regions (in red) where the superposition gives too high levels. This means that emissions originating from these regions would be amplified in the solution, due to an elevated weight of the base function system. For the separatrix a predominance up to 400 % has been observed for other shots!

Another problem causes the interference between the three base function systems themselves. There are some shots where the LCFS is quite near to the border of the cross section and therefore the separatrix base functions overlap with the wall base functions, as this can be seen on figure 3.2, where the wall and center pixel have been added relative to figure 3.1.

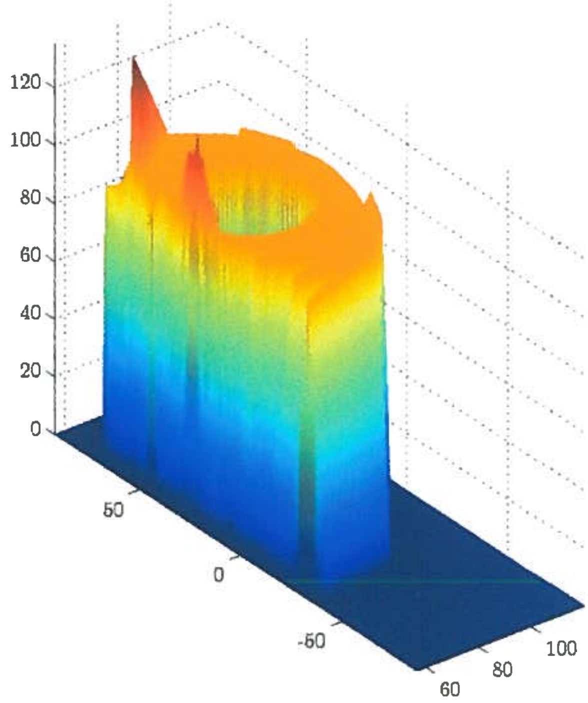

Figure 3.1: TCV shot # 17831 : Separatrix base function superposition bug. The surface in orange represents 100 % coverage of the cross section. The two jagged peak in red are due to a bad arrangement of the base pixel.

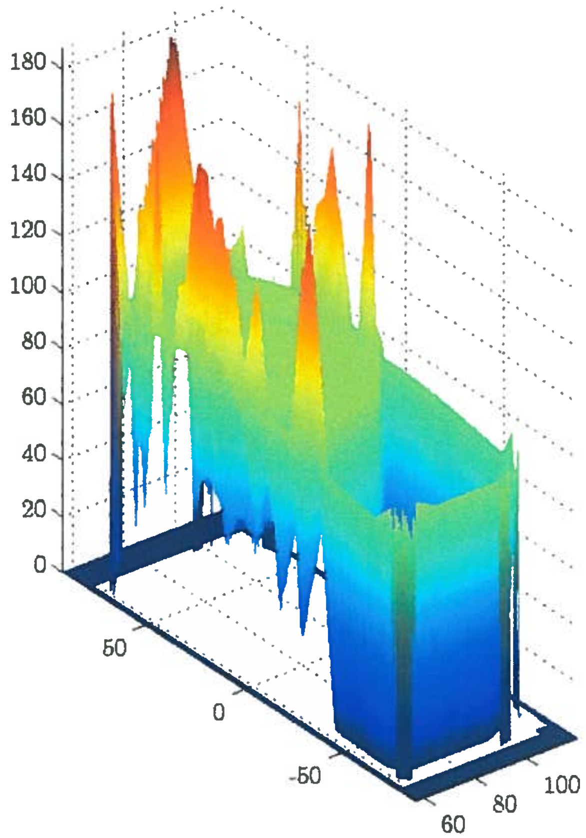

Figure 3.2: TCV shot # 17831 : Separatrix, center and wall base function superposition bug. Emissions from the wall are getting amplified almost up to the double in respect to the rest of the cross section.

The appearance of overweighed pixels inside a single base function system is not easy to understand. A checking of Zoletniks and Kálvins code didn't lead to understanding, there must be further documentation to see what they are doing. A reason may be the pixel truncation at the cross section border as described in the next section.

The overlapping between the different base function systems may be redressed by choosing limiting PSI flux values (see appendix A and section 4.1) closer to the LCFS to isolate them spatially. But this would limit the scope of the covering of the cross section not only where the base systems approach, leading to uncovered zones in the cross section.

In the release at issue the pixels are continuously superposed at creation of the base function systems and any overlapping with already created pixels is subtracted from the recent one. This has been implemented for all three base function systems[(1)]. During creation of the base function systems its construction is drawn on screen. Figure 3.3 shows the results with the modified code for separatrix, center and wall base functions. This type of figures can easily be obtained by using the tool `basetest.m` available in the FLUTO package.

3.2 Pixel truncation at cross section border

For pixels at the border of the cross section of TCV one or more of the base points can occasionally be located outside the vessel. In general the shape of the pixels base points form a hexagone. If a base point lies outside the vessel, this one is replaced by two new base points, determined by the intersections of the vessels limiting curve

(1) see modified sections in `make_function_sep.m` (separatrix), `make_base_function_cent.m` (center) and `make_base_function_wall.m` (wall base function).

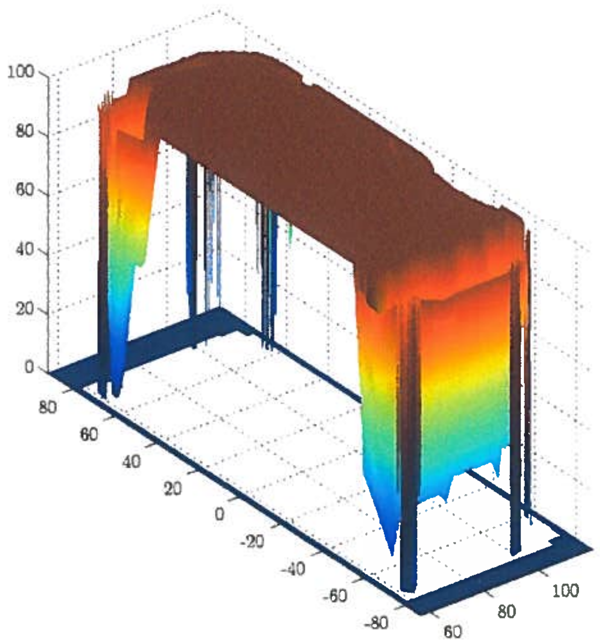

Figure 3.3: **TCV shot # 17831 : Corrected separatrix, center and wall base function superposition.** All regions of the cross section have now uniform weight.

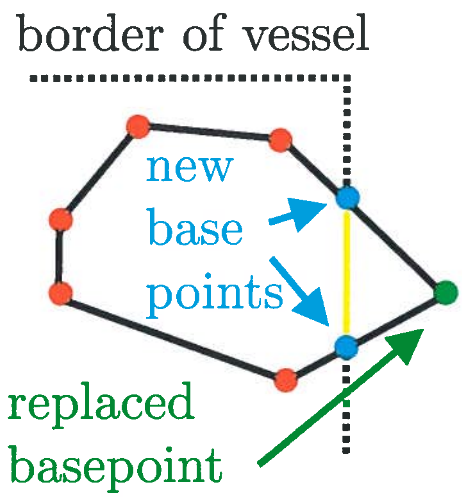

Figure 3.4: Reshaping of hexagonal base area. Red points are base points. The green point outside the vessel is replaced by two new, here drawn in blue.

and the line relying the deleted base point with his neighbors, see figure 3.4.

This procedure is obviously necessary because emissions can only come from inside the vessel ! Nevertheless Zoletnik and Kálvin do linear interpolation through the triangle comprised from these two new base points to the top point. There should rather be interpolation first with the base point lying outside and restriction of the whole pixel to the new base points afterwards, so that the weight at the periphery doesn't decrease to zero. This fact is shown in figure 3.5 where one counts eight base points. This pixel is located at the upper frontier of TCV cross section.

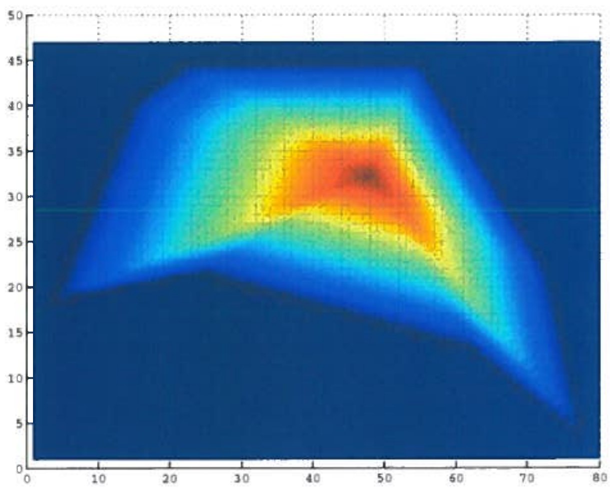

Figure 3.5: Pixel at the upper border of the vessel. The outline is formed of eight base points and the height of the pixel is constrained to zero everywhere on the base shape.

The fact that the discussed pixel overlapping problem occurs only at the outer pixel of the separatrix base function system may be related to the manner how pixels are treated there.

Chapter 4

Testing and application of FLUTO

4.1 The PSI value selection

The creation of the separatrix base function system can essentially be configured through the three PSI value settings(1).

The magnetic flux surface constituting the LCFS has the magnetic flux value zero assigned. See figure 4.1 for the numbering of the adjacent regions.

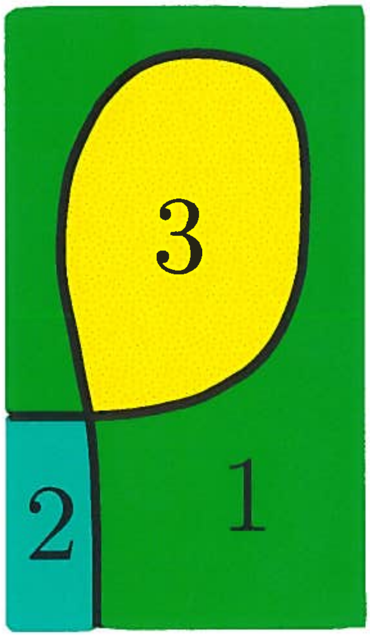

Figure 4.1: LCFS and designation of neighboring regions. 1 : scrape-off layer; 2 : divertor; 3 : inside LCFS.

The settings steer how close (the closer the settings are to zero) the separatrix base function pixels are arranged around LCFS.

In region 1 the value must be positive, in region 2 and 3 negative(2). For region three there is some kind of an automatic determination(3) of the settings value, which in general works well, so that the central and separatrix base function systems fit together. In rare cases there was an only partially covered (weight < 100 %) ring inside LCFS due to malfunction of this feature.

Figures 4.2 to 4.5 shows results for several configurations of these limiting flux settings. The automatic setting for region 3 value has been disabled for these tests.

(1) *gf_para.reg1_val* (region 1), *gf_para.reg2_val* (region 2) and *gf_para.reg3_val* (region 3) in `flutorec.m`

(2) Attention : The indications in Zoletniks and Kálvins documentation [3] are wrong !

(3) `flutrec.m`, line 161

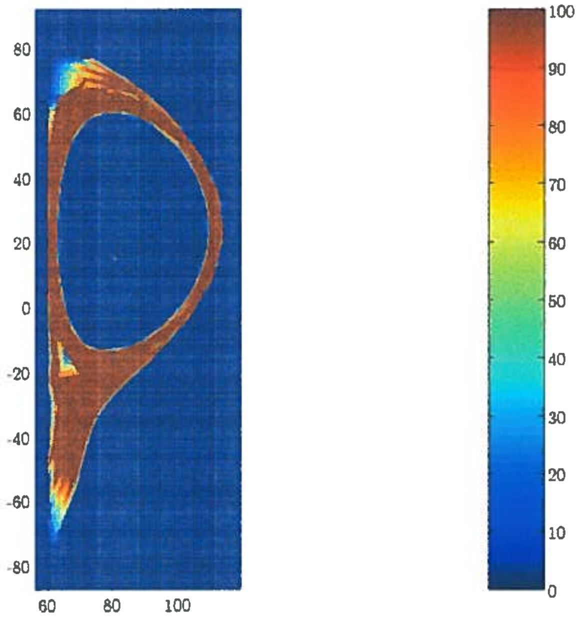

Figure 4.2: Separatrix base function. PSI value configuration in region 1 : + 0.1, 2 : - 0.1, 3 : - 0.1.

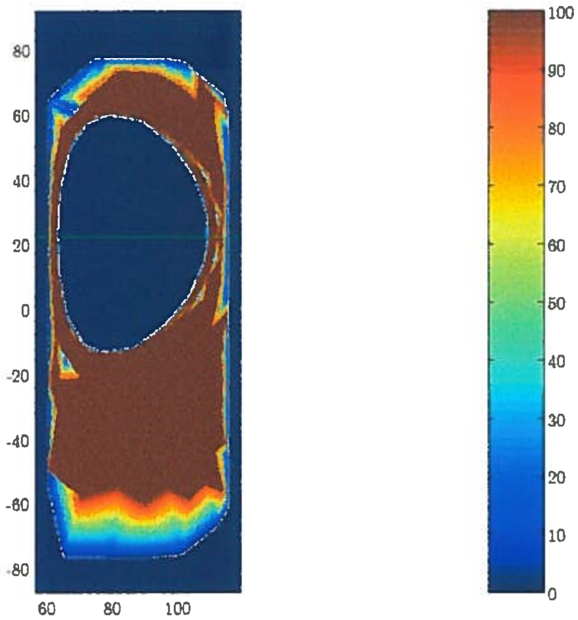

Figure 4.3: Separatrix base function. PSI value configuration in region 1 : + 1.0, 2 : - 0.1, 3 : - 0.1.

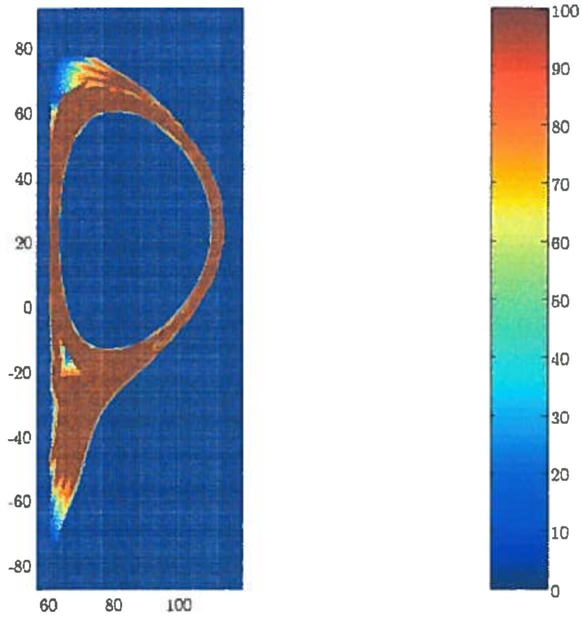

Figure 4.4: Separatrix base function. PSI value configuration in region 1 : + 0.1, 2 : - 1.0, 3 : - 0.1.

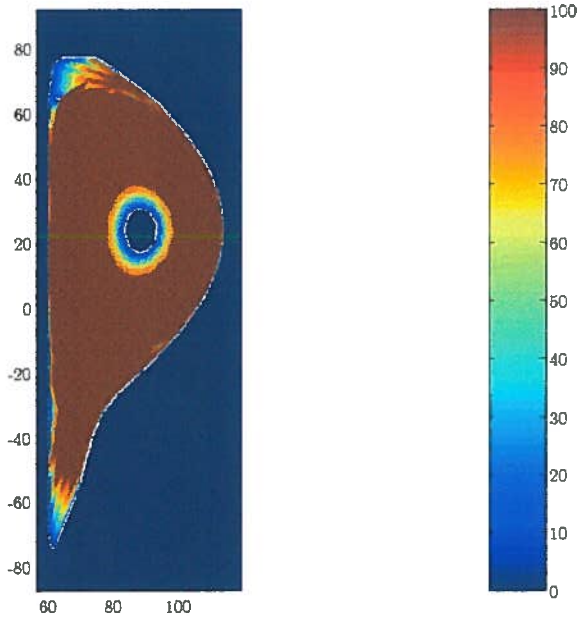

Figure 4.5: Separatrix base function. PSI value configuration in region 1 : + 0.1, 2 : - 0.1, 3 : - 1.0

For most of the analyzed shots the divertor region is so narrow that its associated PSI value doesn't have much implications (you may compare figure 4.4 to 4.2).

For the center region an expansion of the separatrix base function decreases the extent of the center base function. This may only be interesting when choosing different pixel dimensions for these two base function sets.

The choice of the region 1 value is important if emissions appear far from the separatrix : there may be large zones which will not be covered by any of the base functions and therefore will be inaccessible for the inversion.

When enlarging the separatrix coverage one should also increase the resolution, i.e. the number of intermediate poloidal flux values[(4)], so that localized sources still can be traced.

4.2 Single time frame reconstruction

After several modifications of the original code some reconstructions of real shots have been performed.
Especially the question arose, if there is now some difference to Zoletniks and Kálvins results. You may compare figures 4.6 to 4.8 to those given in [3][(5)], where the base function system has been calculated for every fifth time frame.

However, the following figures use the magnetic configuration established only for the single time frame they represent. Further the spatial configuration (resolution and limitation of separatrix base function) of Zoletniks and Kálvins images are unknown.

Please note that this type of images heavily depend on color scaling.

Despite these facts the qualitative coincidence is quite good.

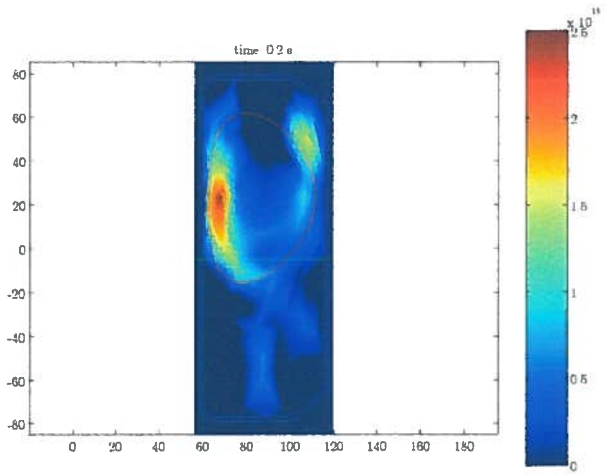

Figure 4.6: Shot # 17831 @ 0.2 s. PSI value configuration in region 1 : + 0.9, 2 : - 0.12, 3 : - 0.2. The red closed line represents the LCFS.

(4) *gf_para.reg1_nu*, region 1 contour number

(5) figure 21 on page 17.

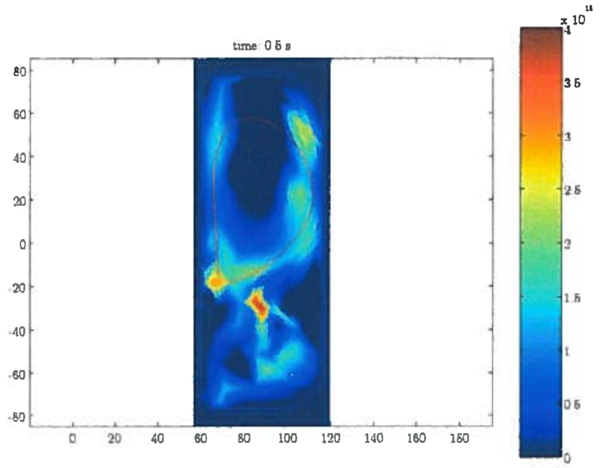

Figure 4.7: Shot # 17831 @ 0.5 s. PSI value configuration in region 1 : + 0.9, 2 : - 0.12, 3 : - 0.2

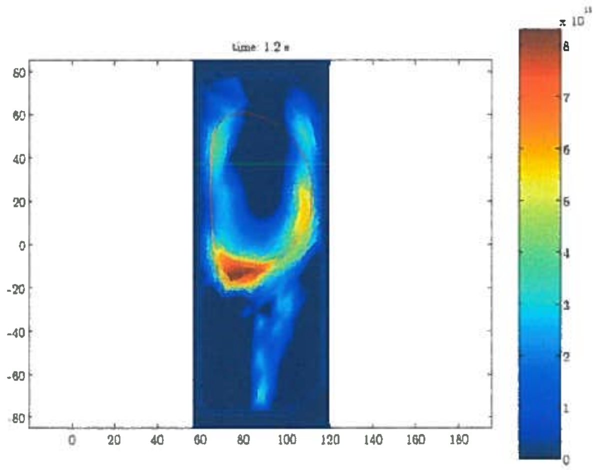

Figure 4.8: Shot # 17831 @ 1.2 s. PSI value configuration in region 1 : + 0.9, 2 : - 0.12, 3 : - 0.2

4.3 The influence of deleted channels

For some shots the inversion didn't succeed when the regularization was executed with the radiation intensity constrained to positive values only(6). All these shots had in common, that an elevated number of channels were not taken into consideration.

To test the code for sensibility to disabled channels a base function system for such a shot has been calculated. To each pixel an imaginary radiation intensity equal to its weight has been assigned. Pixel per pixel, the fictive line integrated radiation collected by each bolometer has been determined followed by a reconstruction of the "filled" pixel. This has been done in respect to disabled channels as well as when all channels were activated. Figure 4.9 shows a fictive radiation source located on the wall (left part of the figure). Even with all 64 bolometer channels enabled this zone is intercepted by none of the central viewing lines. The result (right part of the figure) is quite astonishing : The radiation is assigned to the two narrow zones which are not seen by any of the cameras. Finally, the reconstructed total radiated power is almost 5 times higher.

Figure 4.10 shows a radiating outer pixel of the separatrix without the disabled channels(7). The radiation is therefore only collected by the uppermost lateral pinhole camera. The result is a smeared reconstruction, where radiation is supposed to come from domains exclusively seen by this camera.

(6) configuration flag *gf_para.meth* in `flutorec.m`
(7) 12 channels, namely number 3, 6 - 8, 31 and 58 - 64 were disabled.

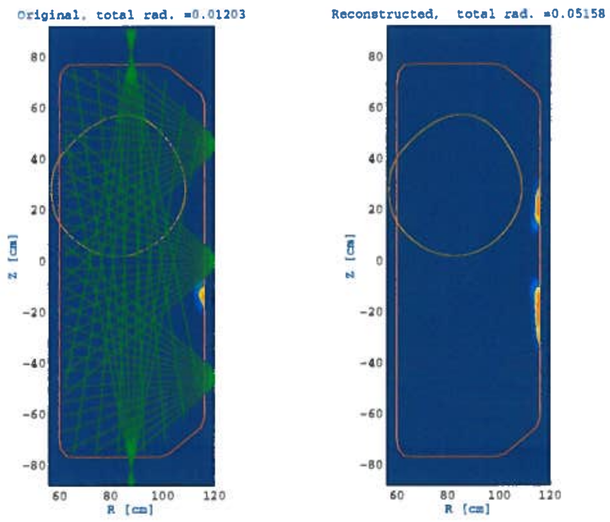

Figure 4.9: Shot # 19780. Reconstruction of pixel 144 using all 64 bolometer channels. The figure on the left shows the initial source distribution. The figure on the right shows the reconstructed sources. The yellow closed line is the LCFS. The green chords represents the viewing lines of the available bolometry detectors.

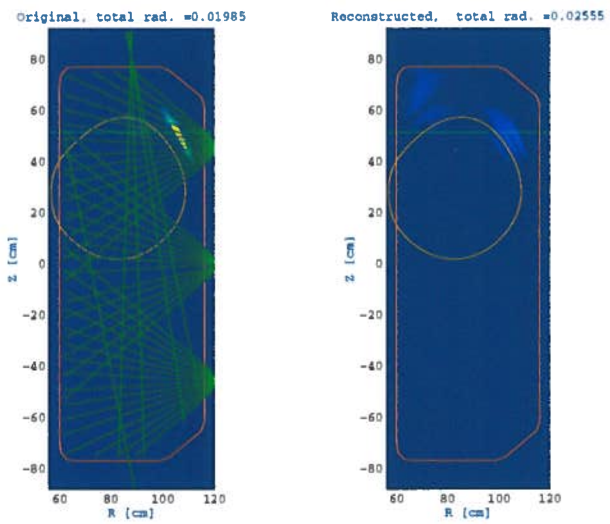

Figure 4.10: Shot # 19780. Reconstruction of pixel 29 without disabled channels. The result is delocalized.

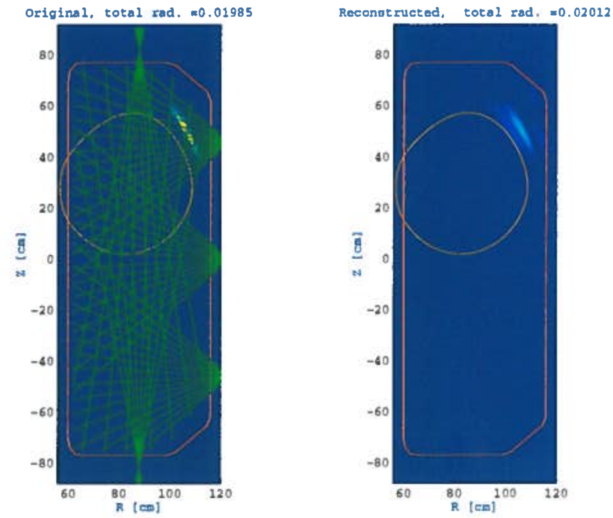

Figure 4.11: Shot # 19780. Reconstruction of pixel 29 using all 64 bolometer channels.

Enabling all 64 bolometer channels, the reconstructed radiation is much better localized (see figure 4.11).

An interesting test is represented by the figures 4.12 and 4.13. Radiating sources have been placed on the pixels lying on the separatrix. With disabled channels(8) the ring oriented to the center of the tokamak is only coated by the lateral channels which see first the exterior part of the separatrix. Hence the radiation is attributed to this outer region only - the inner separatrix share stays empty (figure 4.13). This is not the case when all channels were activated (4.12).

For large source distributions or multiple distribution centers it is important that mainly the top and bottom channels can be used.

(8) 7 of 8 top (1 - 4, 6 - 8) and bottom channels (57 - 63) were out.

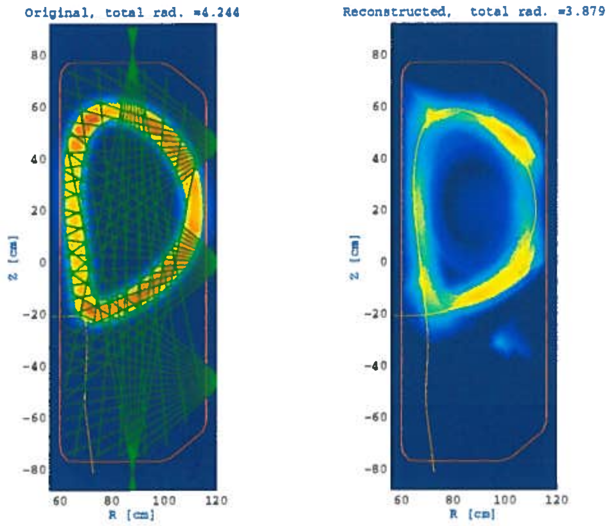

Figure 4.12: Shot # 16197. Reconstruction of a radiating LCFS using all 64 bolometer channels.

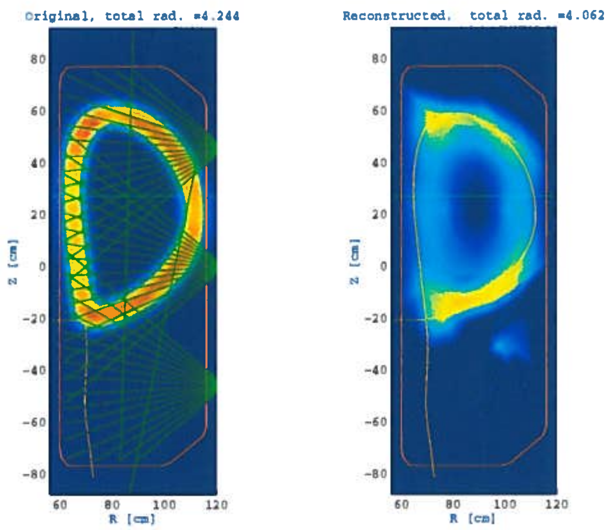

Figure 4.13: Shot # 16197. Reconstruction of a radiating LCFS without disabled channels.

4.4 Location of magnetic axis

Problems with position of the magnetic configuration as provided by LIUQE has been discovered recently using Soft X-Ray tomography measurements. Soft X-Ray gave higher or lower location of the magnetic axis. This could be verified using magnetic flux shaped base functions with bolometry, since the quality of the reconstructed image should be better when correct magnetic position are used. FLUTO has been extended to modify the whole magnetic configuration by moving the flux surfaces vertically(9).

Table 4.1 gives the smoothing parameter κ for the regularization functional(10) for several vertical shifts of LIUQE's magnetic configuration.

shot #	time [s]	Δ z [cm]	κ
16197	1	0	$1.027 \cdot 10^{26}$
16197	**1**	**+ 2**	$\mathbf{9.25 \cdot 10^{25}}$
16197	1	- 2	$9.58 \cdot 10^{25}$
19303	0.9	0	$8.26 \cdot 10^{26}$
19303	**0.9**	**- 1.5**	$\mathbf{7.87 \cdot 10^{26}}$

Table 4.1: Magnetic flux surface postion and smooting parameter κ. The bold lines are the corrections suggested by Soft X-Ray measurements.

A higher κ means a smoother reconstruction. The expectations from SXR measurements have not been confirmed. But additional tests should also verify that there is no misalignment in radial direction, so that a simultaneous displacement in horizontal and vertical direction would maybe give higher κ.

(9) see parameter *vert_shift* in `flutorec.m` (line 45).

(10) it is the Lagrange multiplier for the solution of the PN = LS problem as described in [1].

Chapter 5

Conclusion

With **FLUTO** a working solution using magnetic flux shaped expansions is ready to run on CRPP's server. A first range of tests have already been carried out.

Further tests will be necessary to prove the reliability of flux shaped pixel tomography. Position measurement tests of the magnetic surfaces may be a candidate.

At this stage, the code is not very versatile and quite slow. The added code to prevent wrong superposition of the pixels doesn't cost lot of computation time. Any challenge to make the whole package faster should start with improving the creation of the base function system, since this task takes about 90 % of the necessary time of the whole inversion process. The present implementation is quite arcane, first step would be a better understanding of how this task is done actually.

Improvements of the versatility of the code should aim to reduce the number of settings to choose be the user. All parameters should be moved to the main program `fluto.m`.
The very next step should be the implementation of the stable regime detection of the magnetic configuration, i.e. which time frame is chosen to calculate the base function system and on which time interval it can be used to get good results.

I would like to thank Jan Mlynář who - despite his stay at JET - was ready to accept me as TP IV student.

Christian Schlatter, Prilly, june 2002

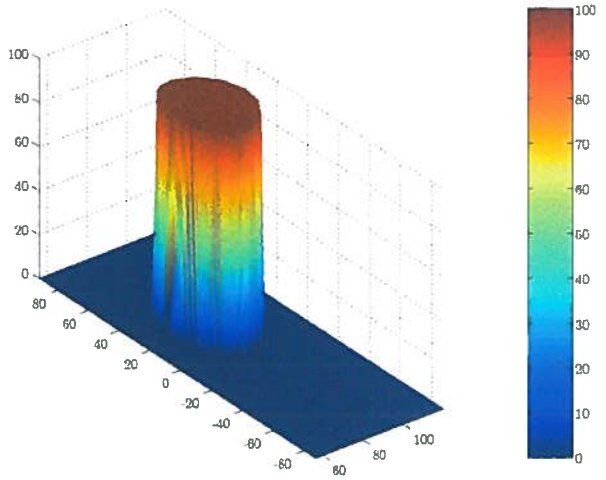

Figure 5.1: Shot # 16197. Superposition of the whole center base function set.

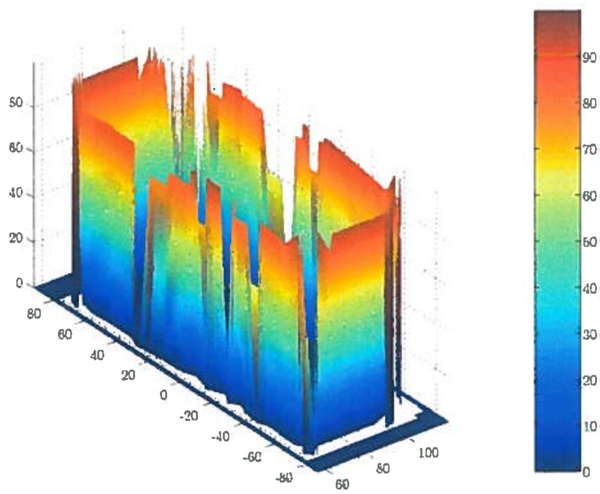

Figure 5.2: Shot # 16197. Superposition of the whole wall base function set.

References

[1] Sandor Zoletnik and Sandor Kálvin; **A method for tomography using arbitrary expansions**, Rev. Sci. Instrum. volume 64, part 5, Budapest 1993.

[2] Iwan Jerjen and Jan Mlynář; **BTOMO: The Software Package used for the Bolometry on TCV Tokamak**, CRPP EPFL Lausanne, INT 197/99.

[3] Sandor Kálvin and Sandor Zoletnik; **Tomographic Reconstruction of Radiation Intensity Profiles from Bolometric Measurements on the TCV Tokamak**, CAT-Science Bt. for CRPP EPFL Lausanne 2000, INT.

[4] Sandor Kálvin and Sandor Zoletnik; **Extension of the TCVXTI software package**, CAT-Science Bt. for CRPP EPFL Lausanne 1999, INT.

[5] Christian Schlatter and Jan Mlynář; **Fast-Algorithm Bolometric Computer Aided Tomography (FABCAT)**; CRPP EPFL Lausanne 2002, INT 205/02.

[6] David E. Watson; **Contouring: A Guide to the Analysis and Display of Spatial Data**, Tarrytown 1992.

[7] **Higher dimensional convex hull program (Qhull)**; The National Science and Technology Research Center for Computation and Visualization of Geometric Structures, University of Minnesota, see http://www.geom.umn.edu/locate/qhull/ for documentation.

Appendix A

User configuration flags

In the header of the main program file `fluto.m` and in the inversion routine `flutorec.m` several flags are specified to control the behavior of the package. When experiencing problems with the execution of the package the first thing to check are these configuration flags and try to run them using the default settings. The settings in `fluto.m` are almost the same as in `fabcat.m` of the **FAB-CAT** package.

A.1 Flags in `fluto.m`

- **f_cam**
  Specifies which pinhole cameras should be used. Each camera gathers eight bolometers looking through the same pinhole of the section.
  Default setting = [1 1 1 1 1 1 1 1], i.e. all eight cameras are activated.

- **chantest**
  The package can itself try to identify bad channels. The following values are admitted :
  0: no automatic testing for bad channels.
  1: Testing using Christian Deschenaux's method (backfiltering).
  2: Testing using Arno Refke's method (consistency check).
  3: Testing using both methods.
  Default setting = 2.

- **smoothmode**
  Specifies the method by which the raw bolometry signals are treated and calibrated.
  0: no data treatment is done.
  1: Processing using Bernard Joye's method (polynomial fitting).
  2: Processing using Christian Deschenaux's method (backfiltering).
  Default setting = 2.

- **delchanuser**
  Allows the specification of channel numbers which will be ignored by the reconstruction. Maybe useful if single bolometers are defective.
  Default setting = [], i.e. no channel excluded.

- **runsigma**
  Provides the global multiplication factor for the error bars. The constants unity is in percent. The variance σ_i will still be divided by the individual channel étendue.
  Default setting = 3.

- **lambda_init**
  Provides the initial λ for the regularization routine, i.e. the balance between fitting and smoothing.
  Default setting = 0.1.

- **chitar**
  Target χ^2, i.e. the reconstruction tries to obtain this final χ^2_{target}.
  Default setting = 1, i.e. a reconstruction image having maximum variance σ_i.

- **errchi**
  Supreme difference between the time averaged final χ^2 and the target χ^2_{target} (see flag **chitar**) which qualifies the shot still as a good one. This parameter was chosen arbitrary.
  Default setting = 0.05.

A.2 Flags in `flutorec.m`

- **gf_para.frame_val**
  Frame value providing the flux shape to calculate the base function system in SINGLE PSI MODE. Set it to **1** if a single time frame is calculated or choose a time frame where the magnetic configuration is stable.

- **vert_shift**
  Permits to shift the magnetic flux surfaces vertically. The offset is given in [cm]. Positive offset moves the magnetic configuration up. This is useful for LIUQE testing purposes.

- **gf_para.sigma**
  SIGMA error bars.
  Default setting = 0.03

- **gf_para.meth**
  Control flag if the radiation should kept positive. Either 1 (no constrain) or 2 (only positive radiation intensity).
  Default setting = 2.

- **gf_para.rmethod**
  Inversion method. Either 1 (single PSI method, i.e. one single base function system is calculated) or 2 (multiple PSI method, i.e. for each time frame a new base function system is calculated).
  Default setting = 1.

- **gf_para.calc_rad**
  If set to 1 then the total radiation intensity and radiation fractions in various regions is calculated.
  Default setting = 1.

- **use_graphic**
  If set to 1 then several graphics showing the creation of the base function systems are printed on screen.
  Default setting = 0.

A.2.1 Separatrix base function system

- **gf_para.use_sb**
  Enables (1) / disables (0) the separatrix base function set.
  Default setting = 1.

- **gf_para.crp_sp**
  Cross point spacing [cm]. This is the spacing of the base points along the flux contours.
  Default setting = 7.

- **gf_para.reg1_val**
  Region 1 PSI value, must be positive. The flux has level zero on the separatrix. The closer you choose the values to zero the narrower the belts are grouped around the separatrix.
  Default setting = 0.9.

- **gf_para.reg1_nu**
  Region 1 contour number. This is the number of flux contours to use in this region. Attention : this includes the separatrix LCFS so this setting has to be greater than 1.
  Default setting = 10.

- **gf_para.reg2_val**
  Region 2 PSI value, must be negative.
  Default setting = -0.12.

- **gf_para.reg2_nu**
  Region 2 contour number.
  Default setting = 6.

- **gf_para.reg3_val**
  Region 3 PSI value, must be negative. This setting gets adjusted automatically.
  Default setting = -0.2.