Tomography in the ISTTOK tokamak

Summary of Master Degree Thesis in Physical Engineering
Instituto Superior Técnico, October 2015

Francisco Maria Lampreia Burnay
Supervisor: Prof. Horácio João Matos Fernandes

Abstract: In this work a set of tomography cameras for the ISTTOK tokamak was developed, aiming to improve a non-magnetic diagnostic used in magnetized plasma experiments. Starting from the preceding work done at IPFN, and using newly available integrated circuits, the design was optimized hoping to achieve better SNR as well as resolution, in order to adapt the current tomographic diagnostic system to the spectral band of soft X-rays.
Keywords: tomography, Cormack, plasma, SXR, tokamak, ISTTOK.

Introduction

Work has been proceeding in Instituto de Plasmas e Fusão Nuclear (IPFN) in order to devise a tomographic diagnostic system that could inform the plasma's repositioning control system during a current inversion. The ISTTOK tokamak is one of the few tokamaks that operates both in AC as well as DC mode. The AC mode avoids the limitations imposed by the saturation of the tokamak's iron core, and this allows for longer periods. On this account, the ISTTOK tokamak has extended its discharges from 35 ms to 1 s. However, during a plasma current inversion, the magnetic diagnostics are not trustworthy. Radiation-based diagnostics do not have this problem, and tomography can be used as a way of determining the plasma's position. Such a diagnostic would take advantage of the soft X-ray spectral band, since the plasma's emissivity profile in this region is approximately constant along the magnetic surfaces [1].

In the past[2][3], a set of three tomographic pinhole cameras was installed in the ISTTOK tokamak (see Tab. 1). Each camera had a column of 8 photodiodes, each of which was part of a transimpedance amplifier. The three cameras were originally distributed around a section of the torus in poloidal angles of +90°, 0° and -90° for the top, equatorial and bottom views, respectively. The original idea was to cover the pinhole with a CVD aluminum pellicule. However, this filter proved opaque for the SXR radiation, and the remaining signal was too weak for the tomographic system to work. As such, no filter was used and the reconstruction algorithm accounted for the full spectre signal. The current work is a new attempt at limiting the radiation spectral band to the SXR region, while improving both SNR and resolution.

Parameter	**Value**
Major radius	0,46 m
Minor radius	85 mm
Toroidal field	0,5 T (nom.)
Plasma current	3 – 5 kA
Average plasma density	3 – 5×10^{18} m^{-3}
Electron temperature	100 eV
Discharge length	25 ms – 1 s
Confinement time	0,3 ms
Security factor	5 – 9 (típ.)

Table 1: The ISTTOK tokamak's main parameters. From [2] and `http://www.ipfn.ist.utl.pt`

1 Tomography algorithm 101

Tomography is the technique by which the cross section of an object is mapped without the need to cut it open. This technique was devised by Cormack and Hounsfield[4][5] in the sixties as a new medical diagnostic tool, and was a precursor to the modern CAT scan. In essence, the object in study is irradiated in a given direction by some form of radiation, and the non-absorbed radiation level is measured at the opposite side. Repeating the process for several lines of sight allows for a computerized reconstruction of the internal structure of the object in study. This is achieved by resorting to Cormack's method. Cormack's method for tomography makes use of an aproximation of the Radon transform. A simple implementation of this method is as follows:

1) A set of base-functions is chosen that can appropriately represent a function $f(x,y) : \Re^2 \rightarrow \Re$, that describes the inner structure of a given body;

2) The representation series is then truncated following Nyquist's sampling criteria, in respect of the number of cameras and photodiodes;

3) Each of the remaining base-function is then integrated in the xy domain for the viewing angles of each of the K photodiodes used.

4) The resulting $(2N \times L - 1) \times K$ matrix of contibutions C is then used to fit[1] an array of weights $\mathbf{a}$ in order to reproduce the measured light levels $\mathbf{f}$, obeying to $\mathbf{f} = C\mathbf{a}$.

5) Taking the thus obtained weights, and making use the chosen base functions, one can now reconstruct the body's inner structure. The choice of the base functions will obviously have implications to the accuracy of the tomographic reconstruction, and those that produce the least amount of artefacts should be preferred.

2 New circuit and cameras

Fig. 2 shows the schematic of the transimpedance amplifier circuit used. Since the previous circuit could not work with an optical filter, the first thing to do was to raise the transimpedance gain R_G. The greater transimpedance gain alone has a positive effect in the signal quality, since a transimpedance amplifier circuit's SNR follows $\sqrt{R_G}$ in regard of the Johnson-Nyquist noise[6]. However, most noise comes from interference. Reducing the conducting tracks' length would reduce this interference, and a decision was taken to put all the signal amplification and voltage regulation circuits inside the vessel. Since the photodiode array now has 20 units, fitting everything to the ∼36 mm wide cross section of the brass tube that composes the pinhole camera proved difficult. As such, the 4 outermost photodiodes were left out, keeping the remaining 16. This still represents the double of the radial resolution of the previous tomographic system. In order to make room for all the parts, feedback capacitors were also left out at an initial stage, allowing for a greater bandwidth even if risking oscillating behaviour.

The result of all the choices made is the PCB board of Fig. 3. This board is comprised of two different PCB boards: a rectangular shaped board for voltage regulation, and a circular shaped board for amplification circuits, which were then soldered together. Each of the boards are directly coupled to the vaccum flange's DB-25 data feedthrough. The cameras were then connected to 48 ADC modules in either one of two ATCA boards. This connection was made through three 8 m cable, one for each camera. Each cable is composed of 4 insulated ethernet cables each with 4 twisted pairs, for a total of 16 signals. In order to avoid interference even further, the 4-fold cable is also twisted. The inside wall of the pinhole camera was covered with a graphite colloid, in order to avoid internal reflections that could induce distortions in the tomographic reconstruction. One of the cameras didn't receive this finishing at an initial stage (top view), in order to observe the difference in the results.

The three new cameras are currently installed in port 8 of the ISTTOK tokamak, instead of port 6 (see Fig. 1). According to Nyquist's sampling criteria, having three cameras with 16 photodiodes each limits the tomographic reconstruction's angular resolution to the 2nd order, and the radial resolution to the 7th order.

3 Calibration and results

The output signals of each photodiode are not the same for a given reference input. This happens because not only the radiation intensity falls with r^{-2} for a distance r, each photodiode having a different distance from the pinhole, but also because each resistor has a variability of 1% around its face value. Being so, there is need for a callibration that normalizes this effect. This was made by using a standard light source and a diffuser plate. For the tomographic algorithm to work properly it is also necessary to know the viewing angles of each photodiode. Once more, a callibration is in order, this time using a collimated light source. The outcome of the two callibrations is shown in Figs. 6 and 7. These results show that the graphite colloid does have a positive effect, and the viewing angles are more well-defined in those cameras

[1] For example, in a least squares sense.

that have this finishing. During callibration, no signs of oscillatory behaviour were observed.

Once installed, data samples were retrieved from the cameras, with an ADC callibrated for a 0-10 volt range taken at a rate of 10 kSPS. All the signals were saturated, and some seem to have some wiring issues. The saturation was an expected result, since there was no way to estimate the SXR intensity from previous results. An SNR of 66,7 dB was also measured.

4 Conclusion

Once the wiring issues mentioned above are corrected, the tomographic system will be ready for testing with a new CVD alluminum filter. If the measured signal is large enough, the tomographic algorithm will then have to be ajusted for the larger number of photodiodes. If not, other options are available for the full spectral range that might avoid saturation, namely:
1) Using slits to minimize the light intensity, as well as toroidal aperture;
2) Using smaller pinholes
3) Using a log amplifier.

References

[1] J. Wesson, *Tokamaks*. Clarendon Press - Oxford, 3rd ed., 2004.

[2] P. Carvalho, *Tomography Algorithms for Real-Time Control in ISTTOK*. PhD thesis, Instituto Superior Técnico, 2009.

[3] P. Carvalho, H. Thomsen, S. Gori, U. Toussaint, A. Weller, R. Coelho, A. Neto, T. Pereira, C. Silva, and H. Fernandes, "Fast tomographic methods for the tokamak ISTTOK," *AIP Conference Proceedings*, vol. 996, pp. 199–206, 2008.

[4] A. Cormack, "Representation of a function by its line integrals, with some radiological applications," *Journal of Applied Physics*, vol. 34, pp. 2722–2727, 9 1963.

[5] A. Cormack, "Representation of a function by its line integrals, with some radiological applications. ii," *Journal of Applied Physics*, vol. 35, pp. 2908–2913, 10 1964.

[6] Burr-Brown, "Designing photodiode amplifier circuits with opa128," 2000.

5 Figures

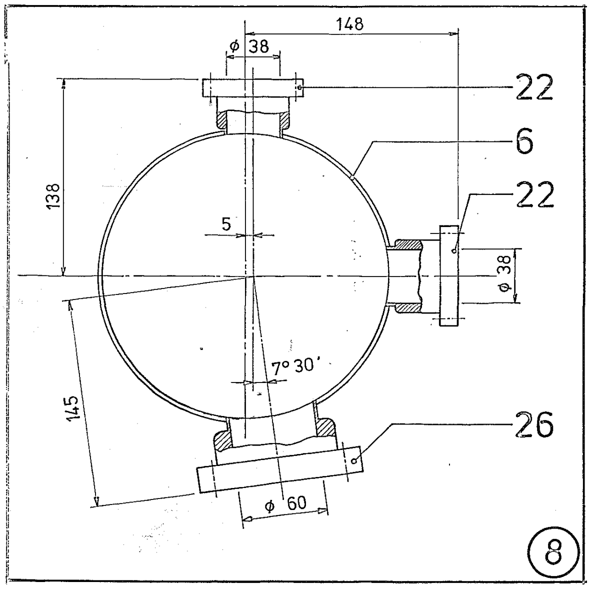

Figure 1: Tokamak ISTTOK's port 8, where the pin-hole cameras are installed. Note the LFS deviation of the bottom view.

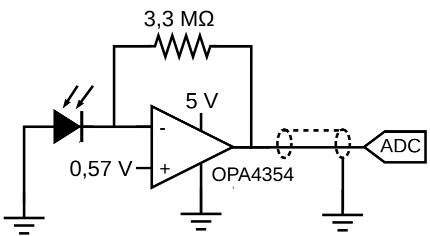

Figure 2: The implemented transimpedance amplifier circuit.

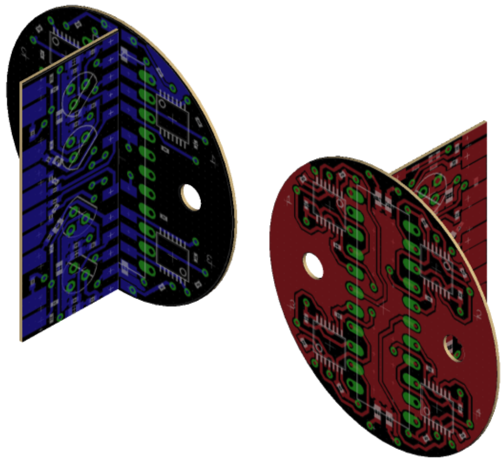

Figure 3: The resulting PCB board, back (left) and front (right). The two holes are for the two M4 screws fixture. These boards are kept in the vacuum vessel.

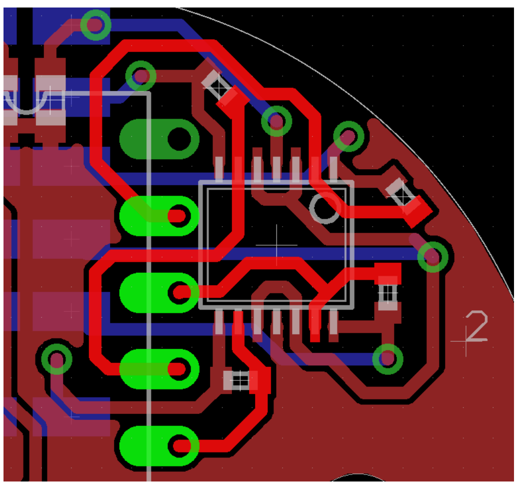

Figure 4: Detail of the PCB board, highlighting the tracks whose lenght was minimized. At the center, a OPA4354 SMD integrated circuit is visible, surrounded by four 0402 resistors.

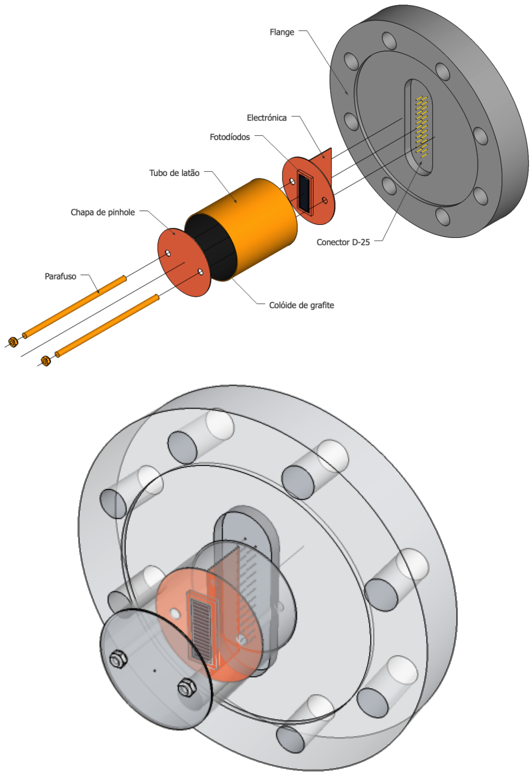

Figure 5: How it all fits together. Top: Exploded view of the tomographic cameras, showing from right to left: vaccum flange with DB-25 data feedthrough, PCB with photodiode array, brass tube with graphite colloid, pinhole and supporting screws and nuts. Bottom: compact transparent display of the camera.

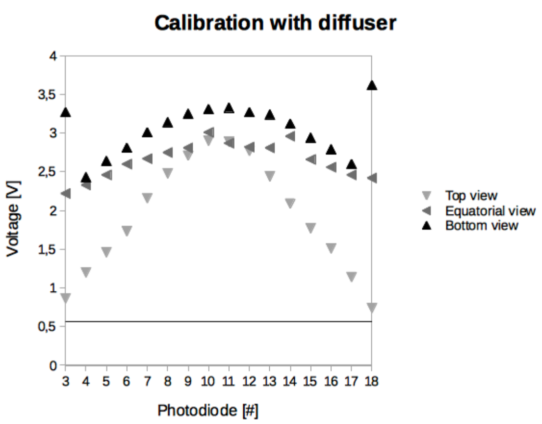

Figure 6: Results for the diffuser callibration.

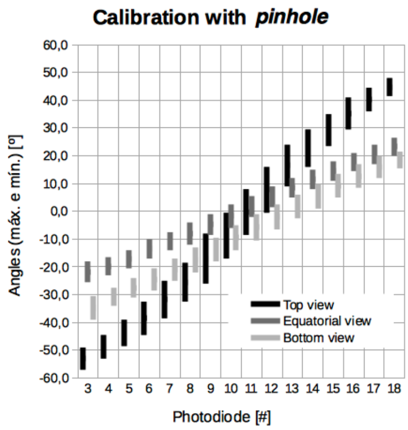

Figure 7: Results for the pinhole callibration, in which the role of the graphite colloid is visible in those cameras that have this finishing (equatorial and bottom views).

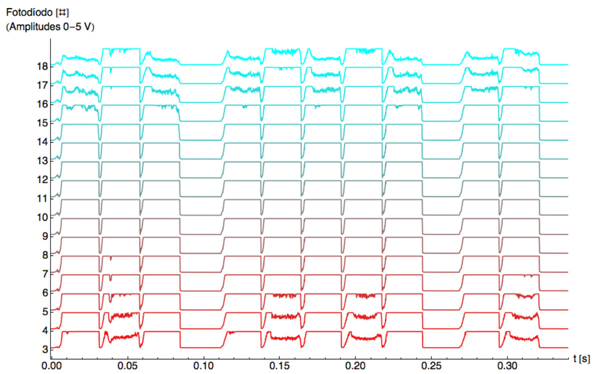

Figure 8: Example results for shot #38234 (equatorial view) showing overall signal saturation.