EFDA–JET–PR(12)24

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Inverse Heat Conduction Problem Using Thermocouple Deconvolution: Application to the Heat Flux Estimation in a Tokamak

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in
Inverse Problems in Science and Engineering

ABSTRACT

Internal components of magnetic confinement fusion machines are subjected to significant hea fluxes. A large part of this power is directed towards plasma facing components. Even if theses components are especially designed to receive about $10MW/m^2$, surface temperature and heat flux measurements are important issues to guarantee safe plasma operation. In the JET tokamak, few embedded thermocouples (TC) located 1 cm below the tile surface are used to measure the bulk temperatures of the Carbon Fiber tiles (coated with about 20μm of tungsten with the ITER-like wall). We propose here to use an inverse thermal calculation based on Thermal Quadrupole method to locally deduce the deposited heat flux. The calculation requires the location of the peak and the normalized 1D-shape of the heat flux deposited on the target.

1. INTRODUCTION

Internal components of magnetic confinement fusion machines are subjected to significant heat fluxes. As an example, in the Joint European Torus (JET), several MW are coupled to plasma facing components for about 10 seconds [1]. A large part of this power is directed towards inertially cooled tungsten tiles or carbon tiles covered with tunsten deposit. In JET experiments, for better understanding and control the heat transfer from the plasma to the surrounding wall, it is very important to measure the surface temperature of the target tiles and to estimate the imposed heat flux. That will be even more important for the protection of the internal components of the International Thermonuclear Experimental Reactor (ITER). In the JET tokamak, an infrared system and several embedded thermocouples are used to measure respectively the surface and bulk temperatures of the carbon composite tiles [2]. Since 2011, in the JET ITER-like wall project, a part of the carbon divertor tiles (1, 3, 4, 6, 7, 8) have been covered with tungsten deposit [3, 4]. The bulk of the Tiles 5 are made of Tunsgten [5]. The upper part of the machine is constituted of Beryllium tiles. As a consequence, all PFC's surfaces are made of metallic materials. In metallic environment, IR imaging thermography, which remains undeniably the major system to monitor the surface temperature on the plasma facing components, becomes more challenging than carbon environment due to high reflection and low emissivity issues (0.2 for the beryllium and 0.4 for the tungsten). In the JET tokamak, few embedded thermocouples (TC) located 10mm below the tile surface are used to measure the bulk temperatures of the vertical CFC tiles (coated with about 20m of tungsten with the ITER-like wall). We propose here to use an inverse thermal calculation based on thermal quadrupoles [6] method to locally deduce the deposited heat flux. The calculation requires the location of the peak (provided by offline magnetic reconstruction, figure 1b) and the normalized 1D-shape of the heat flux deposited on the target provided by empirical scaling of the target heat load profile performed in ASDEX Upgrade and JET [7].

In this paper, the embedded thermocouples measurements are used to estimate the heat flux. In the case of thermocouples, the temperature measurement is distant from the tile surface then heat flux estimation becomes an inverse problem that needs a regularization method to be solved. The associated direct problem is described by the unsteady 2D heat conduction equation [8].

In the first part of the paper, the experimental set-up and the plasma facing components are described. Then, the deconvolution associated to the regularization method and the step response computation with the thermal quadrupoles are presented. Finally, we present experimental results of a shot realised on the last campaign in March 2012.

2. EXPERIMENTAL SET-UP

In JET, most of the plasma facing components are tile-like structures (see Figures 1) made of carbon fiber composite (CFC) covered with a tungsten deposit of about 20m in the divertor and Beryllium in the main vessel. The studied tile in this paper and the thermocouple location are presented in Figure 1b and 1c. The x coordinate represents the poloidal direction, y the toroïdal direction and z the depth in the tile. The tile is located in the divertor, which is the bottom of the machine. Two internal temperatures are measured by two type K thermocouples (Figure 1c). The thermocouple locations are (x = 25mm, z = 10mm) and (x = 125mm, z = 10mm) in the tile [2], which means they are located at 10mm of the tile surface. The thermocouples have been calibrated before their in-vessel installation and provide a temperature difference up to 1200°C between their cold and hot junction (located in the tiles). The temperature of the cold junction, located outside the vessel, is not continuously monitored and assumed at 25°C; the validity of this assumption is established by measurements made after operations and by the monitoring of similar part of the vessel. The acquisition time step of the thermocouple is 50ms. The thermal conductivity in the poloïdal direction x is about a factor 4 lower than in the other directions for the vertical tiles (so $k_y = k_z$ and $k_x \approx k_z = 4$). The heat capacity and the thermal conductivity dependence with respect to the temperature are presented on Figure 2. The density does not depend on temperature and is equal to $1820 kg/m^3$.

3. DESCRIPTION OF THE METHOD

3.1 THE DECONVOLUTION

The carbon tile is modelled with a linear system subjected to a prescribed heat flux Q (x, z = 0, t) having for effect the temperature T (x = 0.125, z = 0.01, t) at the thermocouple location. The linearity assumption is discussed in another paper [9]. This assumption for the duration of the experiment allows to write the following relation between the temperature and the heat flux thanks to the Duhamel's theorem (or convolution method [8]):

$$T(x,z,t) = T(x,z,t=0) + \int_{t_0}^{t} Q(x,z=0,\tau).h(x,z,t-\tau) \qquad (1)$$

h (t) is the impulse response of the system, it is the time derivative of its step response u (x, z, t) (Heaviside function response). So, Eq. 1 can be approximated by finite differences which leads to the expression of the temperature at each time step F in matrix form:

$$
\begin{bmatrix} \Delta T(x,z,1) \\ \Delta T(x,z,2) \\ \Delta T(x,z,3) \\ \vdots \\ \Delta T(x,z,F) \end{bmatrix} = \begin{bmatrix} \Delta u(x,z,1) & 0 & \dots & \dots & 0 \\ \Delta u(x,z,2) & \Delta u(x,z,1) & \cdots & \cdots & 0 \\ \Delta u(x,z,3) & \Delta u(x,z,2) & \Delta u(x,z,1) & \cdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \Delta u(x,z,F) & \Delta u(x,z,F-1) & \cdots & \cdots & \Delta u(x,z,1) \end{bmatrix} \begin{bmatrix} Q(x,z=0,1) \\ Q(x,z=0,2) \\ Q(x,z=0,3) \\ \vdots \\ Q(x,z=0,F) \end{bmatrix} \quad (2)
$$

or

$$\Delta T = X.Q$$

where X is a triangular lower square matrix (of order F) assembled with the components u (x, z, F) = u (x, z, F) Δu (x, z, F – 1) [10].

The deconvolution procedure consists in reversing Eq.2, i.e. expressing surface heat fluxes with measured surface heating:

$$Q = X^{-1}\Delta T \quad (3)$$

In the case of the tiles 3 and 7 of the Tokamak JET, the use of the thermocouples constitutes two major difficulties to estimate the heat flux.

- The first problem is the lake of spatial resolution. Only one thermocouple can be used to estimate a heat flux depending strongly on time and poloïdal direction. Other informations concerning the spatial shape of the heat flux are used to overcome this problem.
- Moreover, the heat flux estimation with an embedded temperature measurement is not directly possible using the deconvolution procedure. Indeed, the matrix X is difficult to inverse because of very low terms in the diagonal. The matrix inversion needs a regularization procedure.

3.2 THE STEP RESPONSE COMPUTATION WITH THE THEORITICAL SPATIAL SHAPE

On the vertical target (tiles 3 and 7) of the JET divertor, the heat flux depends mainly on the poloïdal location (x-direction in Fig.1c) and it is deposited directly at the surface (z = 0). Furthermore, the heat flux presents a symmetry in the toroïdal direction (y- direction in Fig.1c). This direction will therefore be neglected for the modelling of the step response.

3.2.1. Heat flux spatial profile

Since the heat flux is depending on the poloïdal direction x and on time, the use of a temperature measurement in a single location is not sufficient. The calculation requires the 1D-shape of the heat flux deposited on the target (normalized shape) and also the peak position (given by the offline reconstruction of the magnetic equilibrium). The target heat load profile is described with an empiricall expression based on the convolution of the scrapeoff layer (SOL) exponential profile with a Gaussian function representing the diffusion of the heat flux toward the targets (resulting from the parallel and perpendicular transport in the divertor) [7]:

$$q(S) = \frac{Q_0}{2} exp\left[\left(\frac{S}{2\lambda_q fx}\right)^2 - \frac{\bar{S}}{\lambda_q fx}\right] erfc\left(\frac{S}{2\lambda_q fx} - \frac{\bar{S}}{S}\right) + q_{BG} \ and \ \bar{S} = S - S_0 \quad (4)$$

S is the Gaussian Width (m)
S_0 is the strike line position (in m)
fx is the magnetic flux expansion (without unity)
λ_q is the SOL power decay length (in m)
Q_0 is the peak heat load on the strike line position (in W/m^2) (i.e. the parameter that we propose to deduce with the TC data).

All these parameters are depending on the plasma scenario and are computed for each shot. The normalized 1D-shape of the heat flux deposited on the target has been determined with an empirical expression of the target heat load profile found in JET.

3.2.2. Step response computation

The step response has to be computed at the thermocouple location with a prescribed surface heat flux having a Heaviside shape in the time domain and the shape described in eq.4 along the poloïdal direction x. One can note that this step reponse can be easily computed with a Finite Element Modelling or using other semi-analytical methods. In the present case, the heat flux estimation has to be done in few minutes, so the thermal quadrupoles are used. This semi-analytical method is very fast and can be implemented easily. Some geometrical assumptions have to be done. The geometry of the carbon tile is approximated with a rectangular tile with a total mean thickness e = 4cm and a width L = 17.2cm (Fig.3), thus the total area of the tile is respected. The carbon is orthotropic, and $k_x = \frac{kz}{4}$. Surfaces are assumed adiabatic at x = 0 and x = L. The conductive leak due to the tile attachment on its rear face (z = 4cm) is modelled with an equivalent heat exhange coefficient h = 300W=m2K estimated in [2]. The thin surface tungsten layer of about 20m is neglected because of its very short diffusive time (about 6s) compared to the acquisition time of the thermocouple 50 ms. The thermal quadrupoles approach allows to write temperature and flux at z = 0cm as a function of temperature and flux at z = 4cm in the Laplace domain [6]. In our case, the problem is bi-dimensional. This leads to express these fluxes and temperatures in the Fourier–Laplace domain after a cosine transformation along the x variable [11]. To obtain the heating at the thermocouple location z = e_1, the tile of width e = $e_1 + e_2$ is modeled by a bi-layer carbon–carbon of respectively e_1 and e_2 thicknesses:

$$\begin{bmatrix} \bar{\tau}_{in\,1}(\alpha, 0, p) \\ \bar{\phi}_{in\,1}(\alpha, 0, p) \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} \bar{\tau}_{out\,1}(\alpha, e_1, p) \\ \bar{\phi}_{out\,1}(\alpha, e_1, p) \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \bar{\tau}_{out\,1}(\alpha, e_1, p) \\ \bar{\phi}_{out\,1}(\alpha, e_1, p) \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} \bar{\tau}_{out\,2}(\alpha, e, p) \\ \bar{\phi}_{out\,2}(\alpha, e, p) \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} \tau_{out\,2}(\alpha, e, p) \\ \phi_{out\,2}(\alpha, e, p) \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{h} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \bar{\tau}_{amb} \\ \bar{\phi}_{amb} \end{bmatrix} \tag{7}$$

$A_i = D_i = cosh(\sigma e_i)$

$B_i = \frac{1}{k_z \sigma} sinh\,(\sigma e_i)$ σe

$C_i = k_z \sigma sinh\,(\sigma e_i)$

$\sigma = \sqrt{\alpha^2 \frac{k_x}{k_z} + \frac{p}{a_z}}$

$\alpha = \alpha_n = \frac{n\pi}{L}$

$\bar{\tau}$ are the Laplace transform of heatings, i.e. the differences between temperatures at time t and the initial temperature (uniform in the vessel). This is the reason why $\bar{\tau}_{amb} = 0$. According to this assummption, the heating at the thermocouple location can be written as following:

$$\bar{\tau}_{out\,1}(\alpha, e_1, p) = \frac{A_2 + hB_2}{A_2 C_1 + A_1 C_2 + h(C_1 B_2 + A_1 A_2)} \bar{\varphi}_{in\,1}(\alpha, 0, p) \tag{8}$$

Since the spatial shape of the heat flux is not depending on time, it can be written $Q_{in1}(x, 0, t) = H(t)\,.\,f(x)$.

H(t) is the Heaviside function.

$\varphi_{in\,1}(x, 0, p) = \frac{f(x)}{p}$ *is the Laplace Transform (LT) of* $Q_{in\,1}$

$\bar{\phi}_{in\,1}(\alpha, 0, p) = \frac{1}{p}\int_0^L f(x) cos(\alpha x) dx$ *is the Fourier Transform (FT) of* $\varphi_{in\,1}(x, 0, p)$.

After the computation of the step response in the Laplace-Fourier domain, the inverse FT is computed with the following expression [11]:

$$\tau(x, e_1, p) = \frac{1}{L}\bar{\tau}(0, e_1, p) + \frac{2}{L}\sum_{n=1}^{\infty} \bar{\tau}(\alpha = \frac{n\pi}{L}, z, p) cos\left(\frac{n\pi x}{L}\right) \tag{9}$$

The number of terms in the sum is determined with a L-curve, the principle is detailed in the next section. The inverse Laplace Transform is computed using the De Hoog numerical method [12] to obtain the step response u(x; z; t) in the physical domain. Then, the matrix X can be built with the u(x; z; F) = u(x; z; F)−u(x; z; F−1). The inversion of this matrix needs a regularization method to be applied.

3.2.3. The regularization procedure

In the case of in depth measurement inversion, the problem is ill posed and the obtained solution of Eq. (3) is not stable because the matrix X is ill conditioned. The result is that the solution vector Q, is very sensitive to measurement errors contained in vector T. Then, the solution of eq.3 is written in the sense of Ordinary Least Square as following:

$$Q = (X^t X)^{-1} \Delta T \tag{10}$$

It is then possible to apply a regularization procedure to obtain a stable solution. Using the Thikonov regularization [13], a possible regularized solution becomes:

$$\hat{Q}_{reg} = (X^t X + \gamma R^t R)^{-1} T \tag{11}$$

$\hat{Q}_{reg}$ is the regularized solution (an estimation of Q)
γ is the regularization parameter
R is the regularization operator depending on the estimated solution.

In the case of a heat flux estimation, the norm of the solution has to be as minimal as possible (0 order regularization), $R = I_d$. An optimal value of the regularization parameter γ can be found using the "L-curve" technique [14]. This type of representation allows to choose the best compromise—which is located at the bending point of the 'L-curve'—between a stable solution, with a low value of $\|\hat{Q}_{reg}\|$, and an accurate solution, with low residuals $\|X\hat{Q}_{reg} - \Delta T\|$. For lower values of γ, the solution is unstable with low residuals, on the other hand, for strong values of γ, the solution is stable but moves away from the exact solution.

4. EXPERIMENTAL RESULTS

The inverse heat flux calculation has been applied to the H-mode Pulse No:82641 with 2.2 T for the magnetic field and 2MA for ohmic plasma current. Plasma heating has been performed with Neutral Beam Injector (NBI) heating (10MW during 4s). The high-field and low-field sides strike points were on the vertical targets (low triangularity vertical tile configuration, see figure 1-b). The diagnostic set-up is made of four embedded type-K thermocouples (TC) 10mm below the tile surface to measure the bulk temperatures of the inner and outer vertical target plates. The inner and outer strike point (ISP/OSP) positions are given by the magnetic equilibrium: 1cm below the upper thermocouple on the inner side and 0.6cm below upper thermocouple on the outer side. Only the 2 upper thermocouples are used for the heat flux computation, the lower ones are not sensitive enough because of the strike-points locations. The thermocouple measurements for the 2 upper thermocouples on tiles 3 and 7 are presented on figure 4. For this shot the characteristic parameters of the heat flux shape of the equation 4 are: $\lambda_q = 2.5$mm, S = 1mm, $f_x = 8$, $Q_{BG} = 100$kW/m^2 (attributed to plasma radiation). With these parameters and the strike-points positions, the heat flux shape in the poloïdal direction on the two tiles are computed and presented on figure 5. Then, the step responses can be computed allowing the construction of the X matrix in the two cases (outer and inner). The matrix is inverted with a value of the regularization parameter of about 2.10^{-6}.

Peak heat loads are found to be $Q_{ISP} = 3$MW/m^2 and $Q_{OSP} = 5$MW/m^2 with ±15% uncertainties at the inner (ISP) and outer strike points (OSP). This is a normal assymetry between the inner and the outer sides of the divertor. The shot begins at t = 50s with an ohmic heating until t = 59s. The maximum heat fluxes estimated with the thermocouples between t = 59s and t = 64s correspond to the shooting of neutral beam injector. The injected power with the neutral beam is plotted in black, only a part of this power is deposited on the divertor, and particularly on the 2 studied tiles.

CONCLUSION AND DISCUSSION

The combination of the empirical target heat load profiles (mainly constructed with IR thermography during Carbon-wall operation period) with an inverse heat flux calculation using embedded TC data provides a new way to compute heat load on targets. Application to JET data shows satisfactory results even if a lot of assumptions are made to provide this computation: thermal properties constant with temperature, geometrical approximations, modeling of the conductive leak on the rear face with a convective heat exhange coefficient. The errors due to these assumptions are evaluated in [9]and are lower than 20%. On the other hand, the time of calculation is shorter than 1 min and allows to have an heat flux estimation between two discharge during an experimental campaign in JET. In the case of a non linear computation with the exact geometry of the tiles, an estimation with the Conjugate Gradient Method and the adjoint state is possible in 12h.

With this new tool, a complete energy balance in the divertor can be done. Moreover, with another direct computation, the surface temperatures can be estimated and compared to the other temperature diagnostics in the machine (several IR cameras) using the profile done in [7] and the estimated heat flux. This work will be done next in order to evaluate the influences of low emissivities of the observed materials on the IR surface temperature measurements.

ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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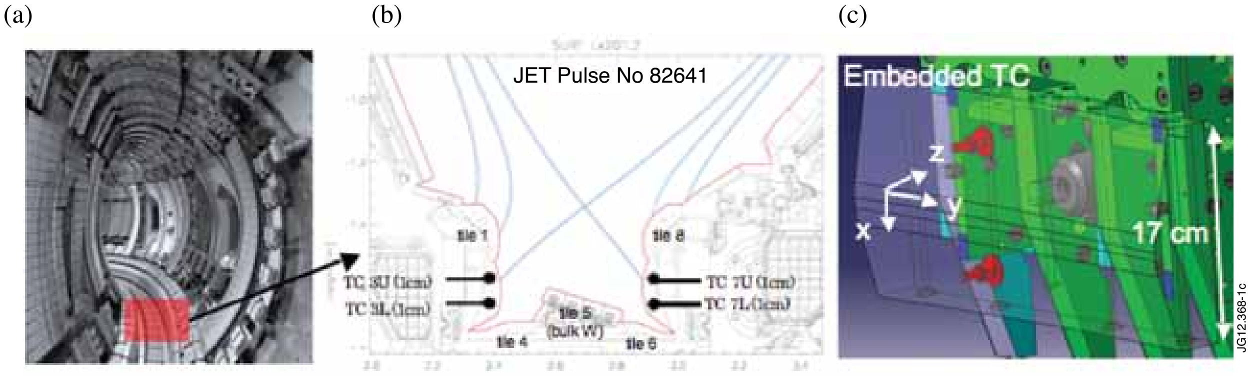

Figure 1: (a) Visible picture of the JET chamber; (b) Poloidal cross-section of the divertor with the magnetic equilibrium of the low triangularity vertical tile configuration. Position of the TCs in the inner (tile 3) and outer target (tile 7) are shown; (c) View of the outer vertical tile with upper and lower embedded TCs.

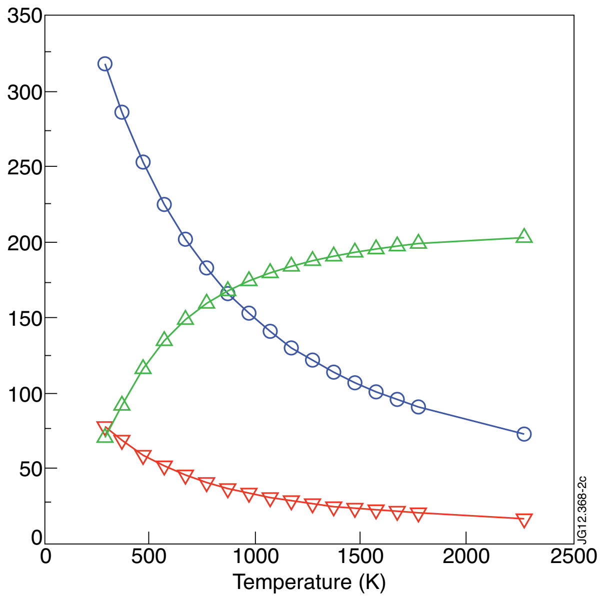

Figure 2: Thermal Properties of the Carbon Fiber Composite vertical Targets of JET. In blue: thermal conductivity in the z direction W/mK, in red: thermal conductivity in the x direction in W/mK, in green: heat capacity10^{-1} in J/kgK.

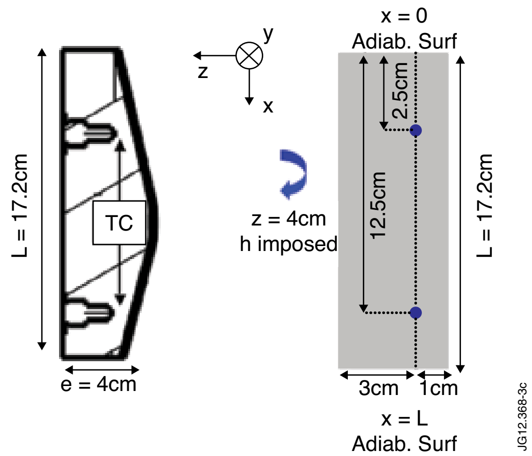

Figure 3: Geometrical approximation of the Tile 7 for the step response computation.

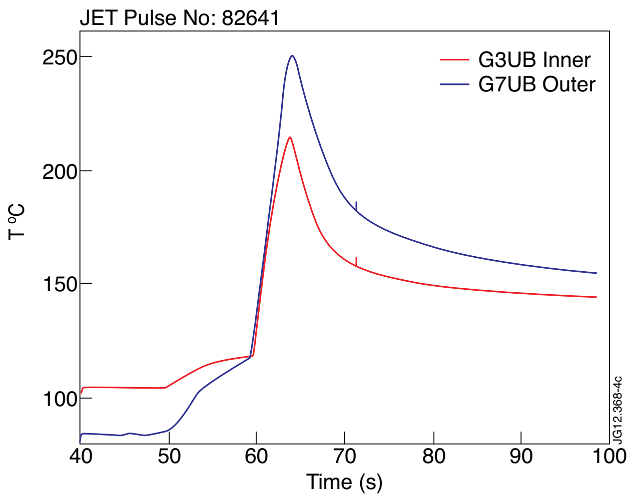

Figure 4: Upper Thermocouples measurements for the Pulse No: 82641 on the tiles 3 and 7.

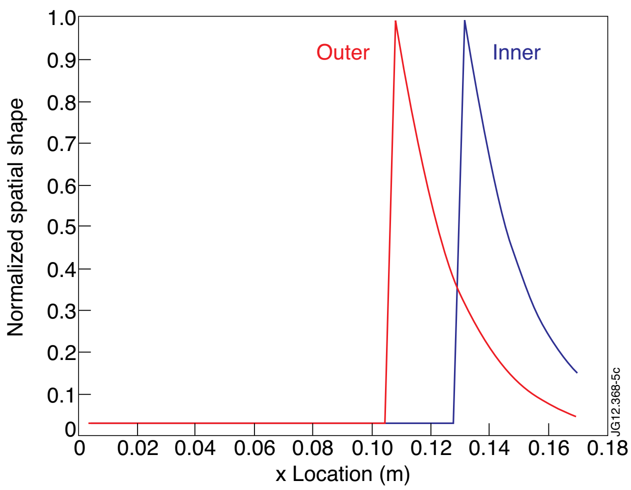

Figure 5: Spatial shape of the heat flux computed with equation 4 for the Pulse No: 82641 on the tiles 3 and 7.

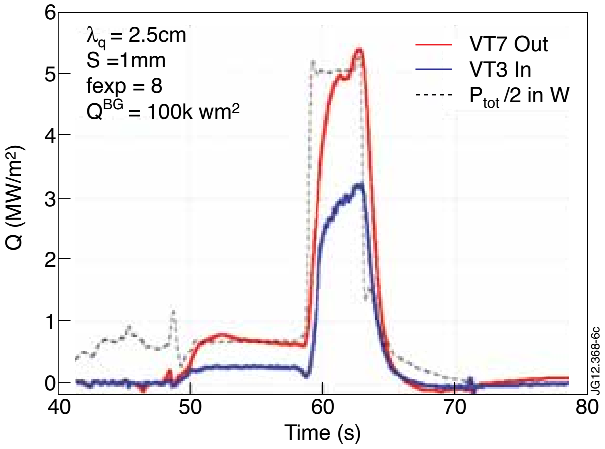

Figure 6: Heat Flux estimation for the Pulse No: 82641 on the tiles 3 and 7 and Total Injected Power in the Tokamak.