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Integrated software for imaging data analysis applied to edge plasma physic and operational safety[☆]

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Abstract

Fusion tokamaks are complex devices requiring many diagnostics for real time control of the plasma and off-line physical analysis. In current tokamaks, imaging diagnostics have become increasingly used for these two purposes. Such systems produce a lot of data encouraging physicists to use shared tools and codes for data access and analysis. If general purpose software programs for data display and analysis are widely spread, a need exists in developing similar applications for quantitative imaging data analysis applied to plasma physic. In this paper, we introduce a new integrated software program, named WOLFF, dedicated to this task. The main contribution of this software is to gather under the same framework different functionalities for (1) data access and display, (2) signal, image, and video processing, and (3) quantitative analysis based on physical models.

After an overview of existing solutions for data processing in the field of plasma data, we present the WOLFF architecture and its currently implemented features. The capabilities of the software are then demonstrated through three applications in the field of physical analysis (heat and particle flux calculations) and tokamak operation (safety operation).

Key words: imaging diagnostic, software design, data analysis, plasma operation, image processing

1. Introduction

In recent years, the use of imaging diagnostics has become increasingly important for plasma physics and tokamak operation [1]. For example, at Tore Supra, the surface temperature of Plasma Facing Component (PFCs) measured by infrared cameras [2] is used for both real-time monitoring to prevent PFCs overheating [3] (plasma control system) and survey (off-line image analysis for overheating study and understanding). Indeed, for physical analysis purposes, temperature is a necessary parameter to calculate the heat flux (see [4]). But extracting quantitative information from images is not a trivial task due to the complexity of the observed infrared scenes. To this end, physicists have to define methods for feature extraction from images and for matching features with physical models [5] or visual references. This requires image processing and programming skills which are not necessarily in their domain of expertise. So a major challenge is to provide a reliable and standard environment to help physicists in the process of imaging data analysis so as to optimize the use of image databases.

Similar issues can be found in medicine where medical imaging has more and more importance. Physicians, together with computer scientists, have then designed and developed software systems [6] useful for both clinical purposes [7, 8] and medical science [9]. We follow the same approach applied to safety tasks and advanced physical analysis in tokamaks.

At Tore Supra, we have developed integrated software dedicated to these quantitative image analysis tasks. WOLFF for *Warping tOoL For Fusion* is open-source and written in *modern* C++. State-of-the-art object-oriented concepts like design patterns have been used to easily adapt and extend WOLFF features to plasma physicists' needs. This high level of abstraction also allows WOLFF to be adapted on other tokamak environment without deep modifications.

After an overview of existing solutions in section 2, the software architecture of the proposed platform, including the object-oriented design is detailed in section 3, image and video processing routines are described in section 4, and some application examples to plasma physics and plasma operation issues

[☆]WOLFF: An object-oriented platform dedicated to off-line quantitative analysis of multi-sensor imaging data

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33 are given in section 5. Finally, future prospects are discussed in conclusion.

34 2. Related Work

35 Traditionally, physics experts working on a domestic fusion device develop
36 their own solutions for data access, display and analysis according to their
37 needs. If some of the solutions discussed below are optimized for general
38 data display through a remote access, existing image-oriented programs are
39 however too *ad hoc* to be interfaced with different data acquisition systems.

40 Among the popular signal-oriented programs shared in the fusion com-
41 munity, we can refer to JETDSP¹. JETDSP is a distributed program to access,
42 display, and analyze JET data in the IDL© environment that contributes
43 to promote standardization [10]. Consequently, using this program for JET
44 data analysis is a good solution to avoid conflicting interpretation of results
45 that may occur when different tools are used. However, this program has a
46 strong focus on signal processing, proposed image processing are very limited
47 and few image/video formats are supported.

48 IRdisp [11] is a graphical user interface written in IDL developed at JET
49 for infrared data display and analysis of recorded films acquired with the
50 wide-angle view IR camera (KL7) and the divertor camera (KL3). This soft-
51 ware has some advanced functionalities as heat flux calculation and image
52 mapping onto 3D geometric model of the vessel inner components. It also
53 provides some image processing functions as image noise filtering and cam-
54 era shaking compensation based on edge detection. The main advantage of
55 IRDisp is its integration into the JET environment. For instance, output
56 files can be written in JET private format (PPF) for further treatments in
57 JETDSP, and 3D model of plasma facing components can be loaded directly
58 from JET CAD files (CATIA), without needing an external tool.

59 At Tore Supra, the acquired data from the six digital IR cameras are
60 monitored so far with a dedicated software named *ShotPlayer*. *ShotPlayer* is
61 multi-frame video player allowing, for one recorded film, a synchronized play
62 of the six IR monitored views. A region analysis tool gives the possibility
63 to extract the maximum temperature time-trace of one area in the image.
64 Further analysis are mostly performed with MATLAB.

65 An alternative to the use of such dedicated software programs is then to
66 develop its own routines using mainly MATLAB© or IDL. One interesting

¹JETDSP for IDL homepage, <http://www.jet.efda.org/expert/jetdsp/jetdsp.shtml>.

67 work based on some MATLAB's functions has been recently applied for in-
68 vessel dust study in Tore Supra [12] by means of automatic image processing
69 from CCD visible cameras. Such programming languages provide plenty of
70 toolboxes (e.g. image processing) and rely on a large community of users
71 and developers. Creation of graphical user interfaces, interfacing with others
72 programs is even made easier with the help of wizards or tutorials. But these
73 software programs raise some important issues. Indeed, a team working with
74 MATLAB cannot reuse programs developed by others teams using IDL and
75 *vice versa*. Moreover, these languages have no standard and the syntax may
76 change and cause some backward compatibility issues. Finally, these inter-
77 preted language are quite slow, which makes heavy calculations taking a long
78 time, thus not always suitable for repeated and automated computations.

79 Pros and cons of the discussed solutions are summarized in Table 1.

Data Analysis Software	Advantages	Weaknesses
interpreted languages with image/signal processing routines (e.g. MATLAB, IDL)	well-spread, available toolboxes, quick learn	licensing policy, evolution issues (version incompatibilities), speed limits
signal & image processing software (e.g. graphics editors)	optimized routines	limited data management possibilities
user-developed programs	do exactly what users need	code-sharing limitations, developed in different languages

Table 1: Comparison table between different data analysis software programs with their main advantages and drawbacks.

80 Solutions deployed in other fusion devices like ASDEX equipped with
81 imaging systems are not discussed here since they are very close to previously
82 described ones or still in an early stage of development.

83 3. WOLFF's software design

84 We need a platform that integrates all analysis tools in the same frame-
85 work and graphical user interface, and allows physicists to develop their own
86 tools inside. First, this prevents from the parallel development of the same

87 analysis code by different people. This would both result in decreasing the
88 code quality and in wasting time. Second, this enables other people to reuse
89 others tools for their own analysis. Finally, the use of common software en-
90 ables all the developed tools to work together and thus to create a reference
91 platform.

92 We also need a program that is reusable, modular and efficient; reusable
93 because the needs may change, sometimes rapidly; modular because those
94 changes must not disturb the structure of the program, and with high per-
95 formance because of the large amount of data to analyze.

96 We decided to write WOLFF in C++, since it is a multi-paradigm language
97 controlled by a standard committee, it is one of the fastest language for
98 complex computation, and also because many compilers are freely available
99 for almost all operating systems [13]. Thus, physicists do not have to pay
100 to get WOLFF working in their own environment. We made WOLFF open-
101 source so that everyone may contribute by adding new modules or proposing
102 changes to an existing one.

103 WOLFF takes advantage of the *multiple paradigms* offered by C++, espe-
104 cially *object-oriented programming* and *generic programming*. On one hand,
105 object-oriented programming allows to use design patterns [14] which en-
106 courage the use of high level abstractions. Those abstractions are crucial
107 because they prevent major changes in the code due to minor modifications
108 of the specifications. Indeed, a design pattern is a general and reusable so-
109 lution to a frequently occurring problem in software design (as the *factory*
110 pattern). Finally, design patterns enable reuse of others programmers' expe-
111 rience, speed up the development process, making the resulting code more
112 robust than *ad hoc* solutions. For instance, the integration of a new data
113 reading module does not affect the global system architecture. As seen in
114 Figure 1, WOLFF is able to read infrared image data from Tore Supra and
115 MAST in a transparent way for the user.

116 On the other hand, generic programming aims at finding abstract rep-
117 resentations of efficient algorithms and data structures. The goal is to ease
118 the re-use and the link of independent features, achieved by the *template*
119 mechanism in C++. As seen in Figure 2, the platform achieves therefore a
120 high level of modularity. The source code makes heavy use of the Standard
121 Template Library (STL), The VIGRA library [15] and the Boost library [16]
122 which provide high performance algorithms that can be applied on both vec-
123 tors and images. Their speed is comparable to a direct RAM access through
124 bit indexing, so the gained modularity has no consequences on the execution

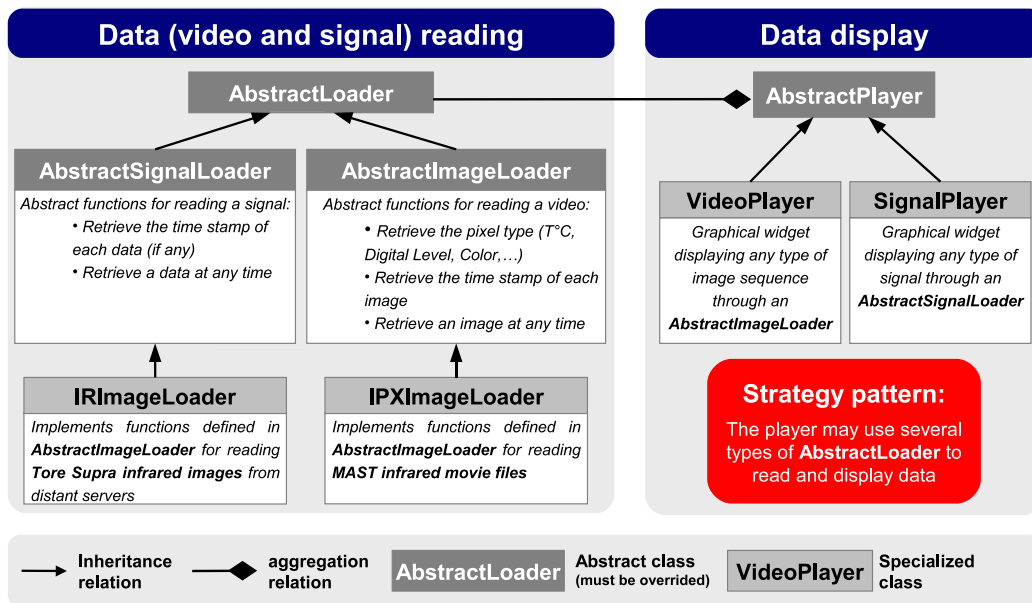


Figure 1: Example of abstraction defined in WOLFF making possible the reading of different types of data sources under the same framework.

125 time.

126 4. WOLFF features

127 The primary goal of this software is to efficiently read and display data
 128 from diagnostic databases in a graphical user interface. Currently, WOLFF
 129 can open several types of multi-sensor data from Tore Supra data bases:

- 130 • image sequences or videos produced by imaging diagnostics (IR, visible)
 131 and stored in distant servers,
- 132 • signals produced by diagnostics or plasma control systems as plasma
 133 parameters, injected power levels, impurity level, etc.,
- 134 • data stored in local hard drives as images, video files, WOLFF files,
 135 predefined Regions of Interest (ROIs), or user scripts.

136 For the Tore Supra environment, WOLFF automatically uses a unique time
 137 base for each opened media (signal, image sequence and video) in order to

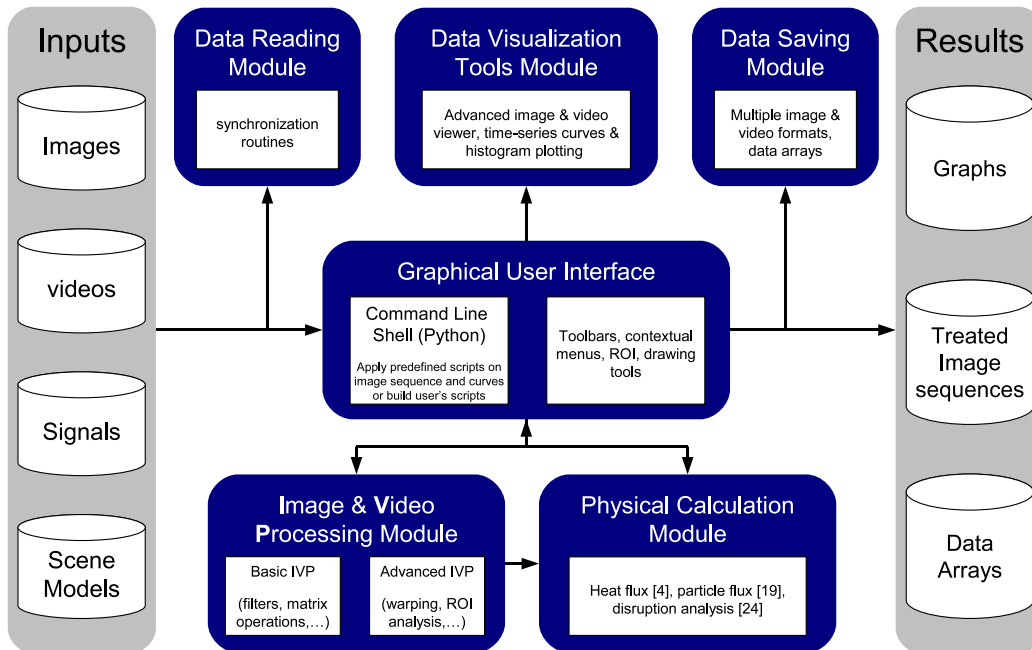


Figure 2: Schema of the modular architecture of WOLFF.

138 synchronize them all together. We can also mention that WOLFF is currently
 139 used at MAST (Mega Ampere Spherical Tokamak) for infrared data display
 140 and analysis.

141 4.1. Data processing functions

142 WOLFF provides an interactive tool for drawing ROI, allowing the user to
 143 create and modify several masks of different shapes (e.g. rectangles, circles,
 144 polygons). These masks are then used to process only interesting zones along
 145 an image sequence. The user can then extract and plot some features inside
 146 the defined ROI like region histograms or temporal evolution of pixel statis-
 147 tics as minimum, maximum, mean and variance values. It is also possible to
 148 extract a temperature profile from a line of pixels. Many image processing
 149 algorithms are implemented in WOLFF, reminding those available in MATLAB
 150 and image processing software programs as listed in Table 2.

From the most used features of WOLFF, we can refer to the warping tool. Digital image warping is a geometric transformation (scaling, rotation, etc.) applied locally or globally to a source image in space (u, v) according to a

functions	applications
arithmetic operators for vector/matrix manipulations	time-series data analysis (e.g. image subtraction)
signal/image filtering, contour detection (e.g., gaussian, sharpen, and Sobel filters)	signal/image de-noising and enhancing
geometric transformations like image translation, reflection, rotation, and morphological deformation [17]	image warping, morphological erosion
image segmentation based on thresholding and background subtraction techniques	object identification, overheating localization

Table 2: Overview of the different basic signal/image processing functions of WOLFF.

destination image in space (x, y) as formalized in equation 1.

$$I' = f(I) \quad \text{with} \quad f: \underset{(u,v)}{\mathbb{R}^2} \mapsto \underset{(x,y)}{\mathbb{R}^2} \quad (1)$$

151 In practice, image warping is used to map two different images into a
152 common geometry. The mapping may be derived given a model of the ge-
153 ometric distortions of a system, but more typically the mapping is inferred
154 from a set of corresponding points (called *control* points) in the source and
155 destination images.

156 The computation of the mapping function f is usually achieved by inter-
157 polation functions. In our approach, we use a weighted linear interpolation
158 based on the k nearest control points from each pixel in the source image.

159 Let (u, v) denote the position of a pixel p in the original image I and
160 (x, y) its position in image I' . Let $\{p_1(u_1, v_1), \dots, p_k(u_k, v_k)\}$ the set of the
161 k nearest control points to p defined by the user on both I and I' . The
162 mapping of the position of p from I to I' is such as:

$$\forall p(u, v) \in I, \begin{cases} x = f_x(u) = u + \frac{1}{SD} \sum_{i=1}^k d(p, p_i) \cdot (u - u_i) \\ y = f_y(v) = v + \frac{1}{SD} \sum_{i=1}^k d(p, p_i) \cdot (v - v_i) \end{cases} \quad (2)$$

where $SD = \sum_{i=1}^k d(p, p_i)$ and $d(., .)$ is the euclidean distance between two points defined by:

$$\forall p, q \in \mathbb{R}^2, \quad d(p, q) = \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2} \quad (3)$$

163 In the field of tokamak application, this technique is very useful to map
164 an image acquired with a visible or IR imaging diagnostic onto the geometry
165 of a real model derived from in-vessel CAD files or represented by *in situ*
166 picture. A good illustration of this technique is given in section 5.1 for heat
167 flux calculation.

168 4.2. User's interface

169 In order to keep the software both user-friendly and flexible, algorithms
170 can be applied in two different ways. Routinely used operations are directly
171 accessible via icons in tool bars or in scrolling/contextual menus. User spe-
172 cific treatments can be loaded, modified, applied and saved via a command
173 line shell. Indeed, WOLFF embeds a PythonTM shell (Python is an interpreted
174 programming language quite similar to IDL) providing all common Python
175 tools and image processing functions. This way, a user can implement its own
176 chain of processes and apply it on a single image or on an image sequence.
177 For example, the set of treatments shown below is used to automate the
178 detection of hot spot observed prior to radiative disruptions on Tore Supra
179 limiter [18] and localized on the high field side of the limiter. extract the
180 boundaries of an image:

```
#define the reference image as the the frame at time t=7s  
im_ref = im_get(1,7)  
#subtract the reference image to the current frame  
this = this - im_ref  
#apply the Canny algorithm to extract edges from the  
#temperature difference image  
this = im_canny(this,6,8)  
#apply a non-maxima suppression algorithm to the resulting  
#edge image  
this = im_nmaximums(this,1)
```

181 As a real live example, figure 3 shows how this image processing chain
182 can be used in a WOLFF session. The lower panel shows the infrared image
183 sequence of the Tore Supra limiter for the plasma discharge #38425 at time
184 t=7s (disruption at 8.38s). The goal is then to automatically extract the hot
185 spot appearing on thick carbon redeposition zones just before the disruption.
186 To this end, the user has defined a small script using the Python shell visible
187 on the right panel. The procedure consists in first subtracting to the current
188 frame a reference image taken few frames before (i.e. during steady-state).
189 The temperature difference image is then filtered with the Canny edge detec-
190 tor [19]. The result is visible on the top panel (white circle) and is directly

191 superimposed on the current frame (time $t=8.2\text{s}$). This procedure can be
 192 easily repeated over several disruptive discharges to automatically extract
 useful information on precise location and shape of such hot spots.

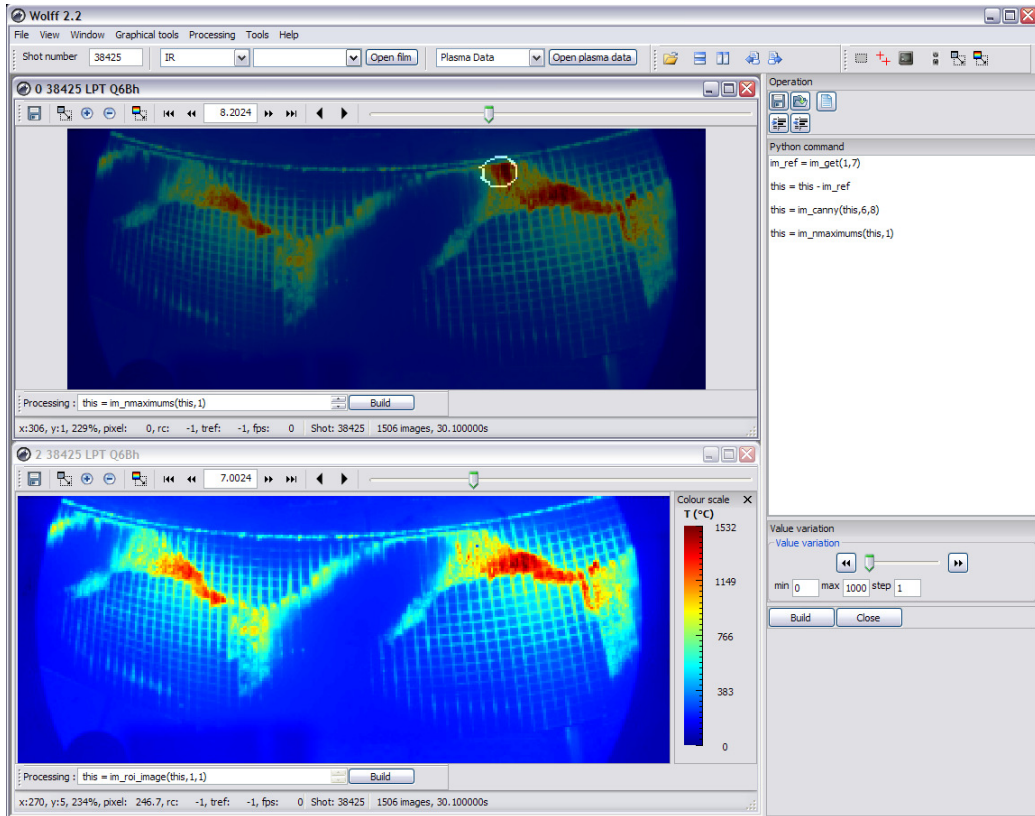


Figure 3: Real live example of using different features of WOLFF (image processing using Python script, image superimposition) for infrared video analysis. Here the goal is to highlight hot spot patterns observed on the limiter just before a radiative disruption (see [18] for details).

193

194 The Python shell also provides algorithms for the analysis of mono-
 195 dimensional signals, and useful functions for I/O operations like opening,
 196 saving and closing any kind of media. Creating and embedding a new filter
 197 or a new algorithm in python syntax thus becomes an easy task for physicists.

198 *4.3. Quantitative analysis using physical models*

199 Currently, the most complex function is a heat flux calculation algorithm
200 based on the quadrupole method using the infrared diagnostic [20]. This
201 functionality gives the possibility to create dynamic heat flux cartographies,
202 useful for physical analysis (see section 5.1 for details).

203 **5. Applications**

204 WOLFF has been successfully used by physicists for different quantitative
205 analysis related to machine protection issues. The two main analysis carried
206 out in Tore Supra are heat flux calculation using infrared imaging and calcu-
207 lation of the carbon erosion (particle flux) on the TPL using visible imaging.
208 PFCs monitoring is also of a crucial help during plasma operation, especially
209 at high power level. The goal is to extract from imaging data three param-
210 eters: localization of the overheating region, identification of the underlying
211 component, and characterization of the thermal event through its temporal
212 evolution. Such information is then used by plasma operators for the esti-
213 mation of the ongoing safeness level. In this section, we relate these three
214 case studies of using WOLFF as an integrated software program for advanced
215 physical analysis and for operational safety.

216 *5.1. Heat flux calculation*

217 WOLFF integrates a heat flux computation tool able to estimate the heat
218 flux deposit on Tore Supra TPL in order to perform a heat balance. This tool
219 uses several functions: morphological deformation of infrared images to work
220 in drawing office geometry (physical components are then well-identified),
221 definition of the regions corresponding to the TPL's tiles, and extraction of
222 the maximum and mean temperatures inside these regions. More precisely,
223 we use the quadrupole model [20] to solve the fundamental heat transfer equa-
224 tion. In our case, the deposited heat flux is supposed to be homogeneous over
225 the tile surface. The heat diffusion is then only in the depth direction mak-
226 ing the problem mono-dimensional. The quadrupole model requires for each
227 tile of the TPL the extraction of the average temperature. To this end, the
228 infrared image (Figure 4(a)) must be mapped onto the real geometry of the
229 TPL represented by a grid (Figure 4(b)) in order to identify each of the TPL
230 tile. Each cell of the grid represents a tile representing a ROI. The mapping
231 is achieved using the warping tool of WOLFF based on elastic deformation

232 algorithms. The user's task consists in setting control points on the two im-
233 ages (Figure 4(c) and Figure 4(d)) by using the footprint of the components
234 (waffle structure) visible in the infrared image. The superimposition of the
235 warped infrared image with the image in the real geometry helps to check
236 the quality of the warping. The poorly attached carbon deposits between
237 tile gaps lead to higher local temperature [21] than the tile surface. In order
238 to eliminate this deleterious effect for heat flux calculation, a morphological
239 erosion is applied to each ROI to take into account only the central pixels
240 of a tile (Figure 4(e)). Finally, temporal evolutions of mean and maximum
241 temperatures are saved for each ROI and given as input to the heat flux
242 algorithm integrated into WOLFF. An illustration of the first steps leading
243 to the heat flux estimation is given in Figure 4.

244 Towards temperature measurement used for heat flux calculation, one
245 may take attention to error bar using image data. This is indeed in an
246 important issue since the estimation of the error bar introduced for each pixel
247 is mainly dependent of the measurement system calibration. Currently, for
248 Tore Supra infrared diagnostic, the calibration function is already taken into
249 account into the temperature conversion function used in WOLFF. Upgraded
250 version of the software could easily integrate this calibration function as a
251 separated module thus enabling further error bar estimation.

252 5.2. Particle flux calculation

253 The second application which takes advantages of the warping tool and
254 the image superimposition tool of WOLFF is the determination of the car-
255 bon erosion [22] using visible imaging. In addition to infrared endoscopes,
256 a visible camera coupled with a set of four optical fibres linked to a spec-
257 trometer looks simultaneously the CD , H_α , and CII emission [23] from the
258 same region of the TPL. This system can be coupled with a high infrared
259 resolution camera in order to superimpose any type of 2D mapping such
260 as atomic/molecular emission on heat load. This multi-spectral approach
261 coupled with infrared thermography diagnostic is carried out for three rea-
262 sons: 1) to de-correlate atomic/molecular photons from Planck emission, 2)
263 to characterize chemical erosion with surface temperature and 3) to study
264 the contribution of gaps in the carbon erosion/migration process. Finally,
265 the particle flux is obtained from the absolutely calibrated brightness using
266 the standard procedure described in [22].

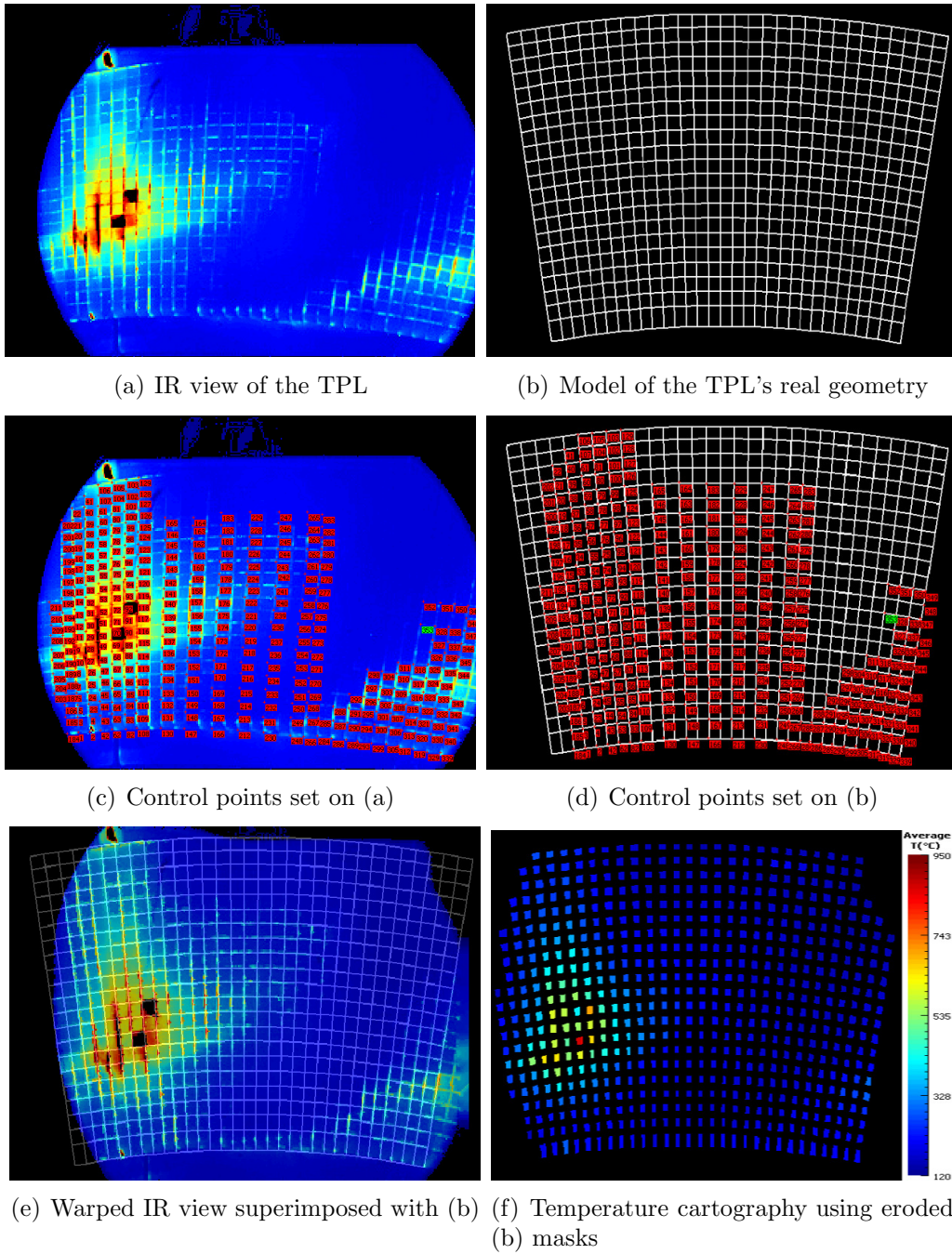


Figure 4: Using WOLFF for temperature cartography of the Tore Supra's TPL tiles without deleterious waffle effect.

267 5.3. Computer-aided infrared image interpretation for plasma safety opera-
268 tion

269 If the quantitative physical analysis of plasma data is mostly achieved
270 after plasma operation, it is sometime necessary to have a quick interpre-
271 tation of data between two plasma discharges. For instance, several plasma
272 parameters as injected power levels must be checked to diagnose an abnormal
273 thermal event observed in the infrared images. As seen in Figure 6, the user
274 interface of WOLFF offers a global view of different signals with synchroniza-
275 tion and temporal marks making easier the abnormal event evidence and so
276 the infrared data interpretation. A second helpful feature is the superim-
277 position between infrared images onto the real geometry of the monitored
278 PFCs allowing an accurate identification of the overheating zones before a
279 physicist interpretation. Finally, WOLFF offers easy and quick functions to
280 plot temporal evolutions of different ROI in order, for instance, to compare
281 suspicious heating zones.

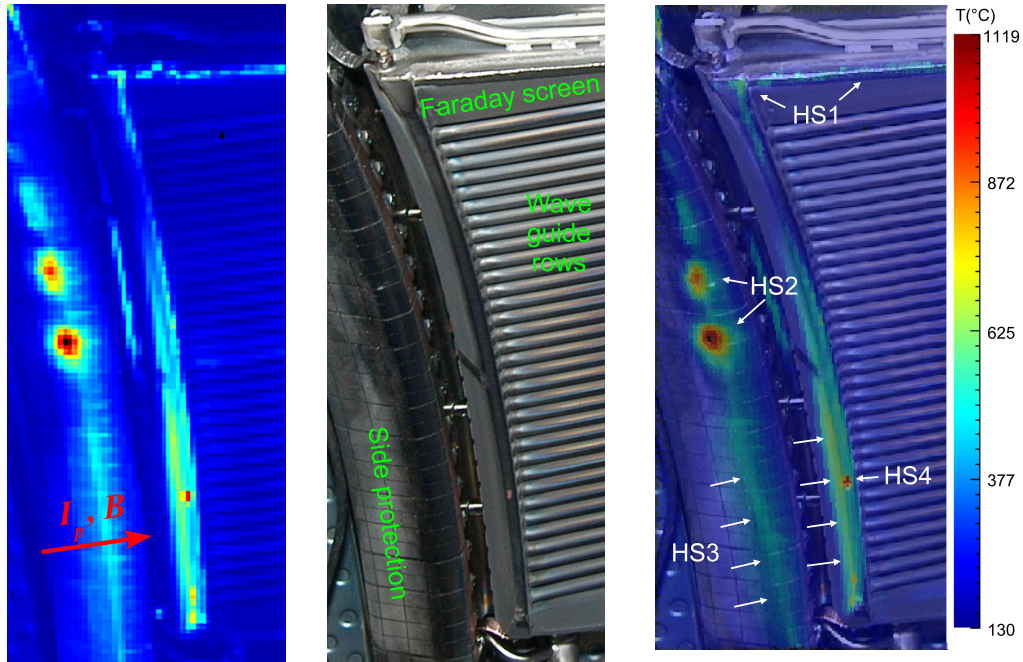
282 Figure 5 shows the localization of four different hot spots identified during
283 previous physical analysis and described below:

284 **HS1 (local RF sheath effect)** : Localized on the top left corner of the
285 Faraday screen (made of stainless steel with B_4C coating), this hot spot
286 is suspected to be due to local RF electrical field carrying an enhanced
287 power onto the antenna as explained in [24]. The deposited power
288 causes hot spots with risk of melting and bursts of metallic impurities.

289 **HS2 (accelerated electrons from lower hybrid)** : This hot spot is lo-
290 calized on the left side protection (made of graphite tiles). It is sus-
291 pected to be due to electrons accelerated in the near field of the lower
292 hybrid launcher which is magnetically connected to the ICRH antenna
293 as explained in [25].

294 **HS3 (fast ion losses)** : This hot spot is localized both on the side protec-
295 tion and the vertical edge of the Faraday screen. It might be caused by
296 fast ions losses created during ICRH hydrogen minority heating scheme
297 as explained in [26]. In Tore Supra these losses are an important cause
298 of concern for the long pulse capability at high RF power levels due to
299 high magnetic ripple (see [27]).

300 **HS4 (B_4C flakes)** : The hot spot has a small size and is localized on the
301 vertical edge of the Faraday screen. It is due to the flaking of the B_4C



(a) Infrared image of the heating antenna (left hand side).

(b) Visible view of the heating antenna (left hand side).

(c) Visible view superimposed with the warped infrared image highlighting Hot Spots (HS) on PFCs.

Figure 5: Using WOLFF during plasma operation to localize precisely the heating areas on PFCs.

302 coating consequently to the heating caused by fast ion losses as shown
 303 in [28]. Temperature may overpass the acceptable threshold without
 304 apparent risk of damage.

305 6. Conclusion

306 In this paper, we have presented a new integrated software program devel-
 307 oped at Tore Supra and dedicated to the quantitative analysis of multi-sensor
 308 data produced by different diagnostics. Compared to existing solutions, the
 309 main advantage of WOLFF is to gather under the same graphical user in-
 310 terface common routines for data access, manipulation, and visualization as
 311 well as specific functions for physic analysis purposes with a strong empha-
 312 sis on image processing. WOLFF is daily used at Tore Supra and MAST by

313 physicists for both quantitative physical analysis and safe plasma operation.
314 Moreover, the modular design of its architecture eases the development and
315 the integration of new algorithms according to the physicist requests.

316 Future long pulse reactors like ITER will produce a very large amount of
317 data at each pulse, and will be the place for new physic experimentations.
318 These two challenges imply new tools for the understanding of plasma-wall
319 interactions. Such computer-aided system might be one part of the solution
320 for the data management and processing issues related to imaging systems.

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