ANALYSIS OF THE DIAGNOSTIC CALORIMETER MEASUREMENTS AND CHARACTERISATION OF THE PARTICLE BEAM OF THE BATMAN EXPERIMENT

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1 Introduction

The world energy demand is rapidly increasing and by the end of this century it will at least double. Nevertheless this demand can not be fulfilled completely by the present portfolio of options, also because the most important of them (such as coal and oil) are environmentally unfriendly: the production of greenhouse gases must be reduced not to create an unliveable climate for future generations. There is not a single energy path for the future, but a new green and powerful energy option must be found, a source able to be the major contributor in the world energy production: nuclear fusion is one of the possibilities.

Nuclear fusion has many attractive features in terms of safety, fuel reserves, minimal impact on the environment and it will provide large quantity of energy; its actual main disadvantages are the very difficult scientific and engineering challenges in creating an operating and secure fusion reactor. The world fusion research programme aims at overcoming, one by one, all these problems, to create an economically competitive power plant to fulfill world energy demand.

As it will be thoroughly explained in the next chapters, an experimental nuclear-fusion reactor is under construction thanks to an international collaboration, ITER. One of its components is a neutral-beam injector, containing a negative-ion source (SPIDER): an important SPIDER diagnostic is a calorimeter named STRIKE, and to evaluate its capabilities a smaller version (named mini-STRIKE) has been created and subjected to a negative-ion beam (experimental campaign performed in the autumn 2012).

The present thesis work contains the first, full-scale and extensive data analysis on mini-STRIKE.

After a brief introduction to nuclear fusion and to the plans for the near future, a description of the diagnostic mini-STRIKE is given. Chapter 3 is devoted to the numerical codes, which have been used for data analysis during the present work, as described in chapter 4. Some open issues and the conclusions of the thesis are discussed in chapter 5.

1.1 Nuclear fusion

Fusion is a form of nuclear energy as fission, but they are quite different: fission involves the splitting of heavy nuclei to lighter ones (as the $^{235}\text{U}$ fission) while fusion occurs when light elements are merging. The light elements involved in fusion are mainly hydrogen (H) and its isotopes deuterium ($^2\text{H}$, denoted as $D$) and tritium ($^3\text{H}$, denoted as $T$). This kind of fuel is not rare unlike Uranium: deuterium occurs naturally in ocean water (there is one atom of deuterium for every 6700 atoms of hydrogen) and can be easily extracted. \[ \text{H} \]

The D-T reaction produces more energy than a pure deuterium (D-D) reaction and moreover it has a larger cross section (it occurs at a faster rate): consequently all first generation fusion reactors (as ITER) will use D-T.

1.1.1 D-T fusion cross section and energy release

The D-T cross section can not be calculated using only classical physics but it includes nuclear quantum mechanics effects (the tunneling effect for example): indeed the nuclear interactions occur on the scale lenght of the nucleus, where classical physics does not apply. The cross sections are anyway determined experimentally and, as seen in Fig.1.1 (left-hand plot), D-T fusion has the highest cross section.
The D-T reaction has the largest cross section (about 5 barns) when the deuteron kinetic energy is about 120 keV. Using a Maxwellian distribution for the particles it is possible to calculate the reaction rate of the fusion process \( R = n_1 n_2 \langle \sigma v \rangle \) (\( n_1 \) and \( n_2 \) denote the densities of the two fusion reagents): the latter factor, known as "velocity averaged cross section", has a peak value for \( T = 70 \text{keV} \) (Fig.1.1, right-hand plot). This temperature maximizes fusion power density.

The large amount of energy released in the fusion becomes kinetic energy of the products; the energy is apportioned between the two end products differently because of their different mass. Computations show the following subdivision:

\[
D + T \rightarrow \alpha + n + 17.6 \text{MeV} = \alpha(3.5 \text{MeV}) + n(14.1 \text{MeV})
\]

The flux of high-energy neutrons to reactor walls is intense: to sustain such a stress the walls are covered by a specific blanket.

### 1.1.2 Power balance in a fusion reactor

At the temperatures nuclear fusion requires to take place (about \( 10^6 K \), that is thermal energies of the \( \text{keV} \)) the matter is not solid or liquid or gas but it becomes a "plasma", a high-temperature, partially-ionized and nearly-neutral gas which shows a collective behaviour under magnetic and electric fields; the plasma is confined in the reactor by particular configurations of magnetic fields.

In order to house in the reactor a plasma in a steady state, power balance must be reached between losses and power heating. A fusion reactor is indeed affected by several losses; among them the main are radiation (Bremsstrahlung radiation due to Coulomb collisions) and thermal conduction losses.

The power balance condition for a fusion reactor can be obtained with the analysis of the law of conservation of energy from fluid dynamics; more detailed considerations lead to the fundamental outcome \( \Pi \):

\[
p \tau_E = \frac{24}{E_\alpha} \frac{T^2}{\langle \sigma v \rangle}
\]

\( p \) and \( \tau_E \) denote respectively the plasma pressure and the 'energy confinement time' (the relaxation time of the plasma energy due to heat conduction). Observing Fig.1.2, the product \( p \tau_E \) must exceed a certain minimum value for ignition to occur, corresponding to a plasma temperature of \( T_{\text{min}} = 15 \text{keV} \). For a higher temperature a larger value of \( p \tau_E \) must be reached in the reactor to start the nuclear fusion. Increasing \( p \) or energy confinement time \( \tau_E \) requires an increase in the device size or in the magnetic field, both of them leading to an increase in the cost of the reactor.
1.2 ITER - the way to new energy

Figure 1.2: Critical $p\tau_E$ as a function of temperature

So the plasma temperature must be of about 15 keV; a hotter plasma (70 keV) would have a larger amount of fusion reactions ($\langle \sigma v \rangle$ is maximum at this temperature) but the reactor would be too difficult and expensive to realize. With this choice, only the plasma particles belonging to the tail of the Maxwellian distribution are involved in nuclear reactions.

1.1.3 Heating the fusion plasma with neutral beams

In a self-operating fusion reactor, as seen before, the operational plasma temperature must be 15 keV; the procedure to reach this temperature consists in two stages. First, external heating brings plasma temperature to 5–7 keV: in this phase alpha ($^4$He nuclei) power is too weak to compete with radiation losses, so the external heating must alone overcome all the losses. Above 5–7 keV nuclear reactions are more intense, and alpha power heats the plasma to its final temperature.

To heat the plasma in the first stage various methods exist. Ohmic heating, that is using a toroidal current to heat the plasma, is surely the simplest way; however the resistivity of a fusion (full-ionized) plasma decreases with temperature, making it more and more difficult to heat the plasma as its temperature is raising. A second technique is radiation, using radio frequency (RF) waves; if the wave frequency is matched to one of the resonant frequencies of the plasma (i.e. electron and ion cyclotron frequencies), there is a strong absorption of energy. Heating at electron/ion cyclotron frequency is known as ECH/ICH.

A third method of heating the fusion plasma, quite successful, is neutral beam heating: a high-energy neutral beam (of D or T) is injected into the plasma, the neutral atoms propagate in straight line (not affected by magnetic fields) until a collision with the plasma particles occurs. In the collision the energetic neutral particle is ionized, remaining confined in the plasma and gradually losing its energy through collisions with other ions.

1.2 ITER - the way to new energy

ITER is the major fusion experiment in the world fusion programme; it is based on the 'tokamak' concept of magnetic confinement.

1.2.1 ITER history

In the late 1970s an international collaboration, named INTOR (INternational TOkamak Reactor) was established to design the first large-scale nuclear fusion experiment; this reactor was never constructed but it was the start for other international collaborations. Indeed in the 1985 Geneva Summit Meeting, a worldwide collaboration to design and build a fusion ignition experiment was born: USA, URSS, EU and Japan joined. The project name was ITER. A two-years work (1989–1991) produced a successful conceptual design of the reactor (CDA - Conceptual Design Activity); few years later (in 1998) also a detailed engineering design for ITER was ready (EDA - Engineering Design Activity). The 1998-ITER design was ambitious: a 20MA tokamak with a major radius of 8.1m, a cost of $9B and 10 years to construct. The high cost for ITER and the fact that
energy in those years was not expensive lead to the decision to realize a smaller ITER: the most important difference between the old and new version is that the latter is not expected to achieve full ignition ($Q = 10$ instead of $Q = \infty$). The new design for ITER, ready in 2001, can be seen in Fig. 1.3 (left-hand image); the cost is smaller ($\$4\text{B}$) but the project remains ambitious and gigantic. The energy price increase made this project extremely attractive: nowadays ITER members are USA, Russia, EU, India, China, North Korea, Japan. After an arduous period of negotiations, the building site was decided: the French site of Cadarache, where ITER buildings are currently under construction. [1] Fusion experiments are planned to begin in November 2020. [2]

The future after ITER  Assuming that ITER will show itself successful in achieving its objectives, the next step is a full-scale demonstration power plant, DEMO: this will be the last step before commercialization.

1.2.2 ITER physics mission and technical details

The primary physics mission of ITER is to "produce a stable, well-confined, $Q=10$ plasma lasting for a sufficiently long duration to reach quasi-steady-state operation". [1]

ITER experimental fusion reactor will use as a fuel a mixture of deuterium and tritium as a hot plasma; superconducting magnets will generate a strong magnetic field (at the center of the plasma) of 5.3 T in order to control the plasma. The major and minor radius of the doughnut-shaped vacuum vessel are 6.2m and 2m, and the current flowing in the plasma will be of 15 MA. ITER will operate for pulse duration of $\tau_{pulse} = 400\text{s}$ and it will be provided with three sources of auxiliary power: 33 MW of neutral beam, 20 MW of ICH and 20 MW of ECH.

To efficiently heat the plasma, the injected neutral beam must have a temperature higher than the plasma; ITER requires 1 MeV beams. The process of neutral beam injection consists of two steps. First a negative ion source provides a negative-ion beam; then this beam is neutralized by passing a gas, as ions would not reach the plasma core because of the high magnetic field.
Two neutral beam injectors are currently being developed: one of these involves the SPIDER and MITICA projects, to whom Consorzio RFX participate.

1.3 MITICA, SPIDER and STRIKE

Negative ions as the accelerated species As outlined, to realize a high-power neutral beam a negative-ion beam is accelerated and later neutralized. Both accelerated negative and positive hydrogen ions can be neutralized by collisions with hydrogen molecules; Fig. 1.4 shows that the neutralization efficiency of positive ions decreases as the beam energy increases, becoming very low at the energies required by ITER (MeV). On the contrary negative-ion neutralization efficiency remains high even at the megaelectronvolt level: for this reason \( H^- \) are the choice as the primary ion species for the neutral beam system \[3\].

Figure 1.4: Neutralization efficiency of the ions, analyzed by the authors utilizing cross section data in \[4\]

The 33MW of NBI (Neutral Beam Injectors) power will be provided to ITER by two-three injectors; the required voltage, negative ion current density and stationary conditions have never been obtained simultaneously, so a thorough demonstration activity has been endorsed by ITER.

To this purpose PRIMA (Padova Research on ITER Megavolt Accelerator) facility is under construction at Consorzio RFX (in Padova, Italy) in the CNR research area; it includes the full power injector MITICA (Megavolt ITER Injector & Concept Advancement) and the negative ion source SPIDER (Source for Production of Ion of Deuterium Extracted from RF Plasma) \[12\]. The neutral beam provided by MITICA will be injected directly into the plasma: a precise knowledge of the beam composition and of its energy flux profile is of extreme importance.

This task will be performed by STRIKE.

STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) is one of the diagnostics of SPIDER, shown in Fig. 1.5.
It is a calorimeter composed mainly by 16 Carbon Fibre Composite (CFC) tiles and observed by two thermal cameras; they are displaced in the device in order to provide a top-bottom view of all the tiles together (Fig. 1.6). The beam inevitably interacts with the neutral particles in the vacuum and with the graphite dust emitted from tiles surface, producing radiation in front of the calorimeter: to avoid this background the thermal cameras observe the rear side of the tiles. The side-to-side (front to back) thermal conductivity must be at least ten times the conductivity in the other directions: in this way the heat rapidly reaches the rear side of the tiles and the beam pattern alterations are minimized. Carbon Fibre Composite have the required anisotropy in heat conduction, even up to 2000 Celsius degrees \[9\].
Negative ions): this device consists of only two CFC tiles, in contact with three thermocouples and observed by a thermocamera. The present thesis work will expose the results of some experimental campaigns performed with mini-STRIKE in BATMAN ion source and the methods adopted in data analysis.

2 Mini-STRIKE in BATMAN

The first experimental test campaign on mini-STRIKE tiles was carried out at BATMAN facility at IPP (Max-Planck-Institut, Garching, Germany), during the months of October-November 2012.

2.1 BATMAN facility at IPP-Garching (D)

The experiment BATMAN was built at IPP Garching for the development of a RF negative ion source able to meet the ITER negative ion source requirements; this work began at the end of 2002.

2.1.1 BATMAN negative ion source

The IPP RF negative ion source scheme is reported (Fig.2.1).

![Figure 2.1: IPP RF negative ion source](image)

It consists of:

1. a driver, where the RF is coupled to the filling gas ($H_2$) and the plasma is generated by the RF power supply.

2. the expansion region, where the plasma expands into the source body. The survival length for negative hydrogen ions is typically of few cm, because of different destruction processes (mutual neutralization with other $H^-$ or with energetic electrons). The formation of negative ions near the first accelerating grid (plasma grid) is favored by 'surface processes', i.e. the interaction of hydrogen atoms or ions with a low-work-function material, as Caesium. Caesium, continuously dispensed, covers by layers the plasma grid: high-kinetic-energy neutrals hit the grid and become negatively charged ($H^-$), as well as $H^+$ are produced. A caesiated source, compared with Cs-free ones, provides higher current densities and a lower electron-to-ion ratio in the beam. Between the expansion and extraction regions a quite strong magnetic field is located, the "filter field", in order to deflect the so-called 'hot electrons': these electrons, having energies higher than 2 eV, efficiently destroy negative hydrogen ions by collisions.

3. the extraction region. BATMAN houses a three-grid system to extract negative ions from the expansion region: the plasma grid (PG), extraction grid (EG) and grounded grid (GG).
(a) plasma grid $\rightarrow$ extraction grid: under a 5kV voltage negative ions and co-extracted electrons are accelerated. Strong magnets inserted into the extraction grid deflect the majority of these electrons: they collide with this grid, they are collected and, as a measured electrical current, flow back to the HV power supply. There is clear evidence that 95% of the EG current is composed by electrons and 95% of current flowing from the ground potential consists in negative ions. Due to the magnets, the extraction grid is quite thick (approx 10mm): consequently the beamlet, moving in this potential free volume, naturally expands because of its space charge.

(b) extraction grid $\rightarrow$ grounded grid: 15kV strongly accelerate the beam. Some ions happen to hit the grid: a current flowing back to HV devices is then measured. BATMAN measurements show that about 10-20% of the ion current is intercepted by GG: more than 80% of the ion current flows into the vacuum chamber.

The grid geometry is quite important as it shapes the final beam profile: known as LAG (Large Area Grid), it features 126 holes 8 mm in diameter, resulting in an extraction area of $63 \text{ cm}^2$ (Fig. 2.2).

Figure 2.2: The Large Area Grid in BATMAN
2.2 Mini-STRIKE

2.2.1 The mask: creation of a SPIDER-like configuration

The expected BATMAN beam energy flux profile, 10 cm downstream from the Large Area Grid (LAG), can be seen in Fig.2.3 (left-hand plot), in the case of a beamlet divergence of 2 degrees.

Figure 2.3: Simulation of beam energy flux profile on the two tiles at 10cm and 1.5m from the source

To avoid graphite contamination of the source, mini-STRIKE had to been installed at 1m from the source; at that distance, because of divergence due to space charge, the beam pattern is quite flat and the footprint of the single beamlets can not be resolved (Fig.2.3, right-hand plot). In SPIDER, on the contrary, the calorimeter position will guarantee a resolvable beamlet pattern (see Fig.1.5, right-hand image), closer to that at 10 cm; in order to test the diagnostic in a SPIDER-like situation, a 8-apertures mask in front of the prototype had to be realized and installed.

The mask consists in a 10mm-copper slab with 8 holes, six positioned in the vertical direction to study the vertical beam profile (the mask is visible in Fig.2.4); active cooling (behind the mask) is provided.

2.2.2 Mini-STRIKE housing in BATMAN vessel

In the final design, mini-STRIKE (two CFC tiles, three thermocouple and the mask) was housed in a dedicated frame connected to a supporting arm attached to BATMAN vacuum flange; the rear side of the tiles was observed by a thermal camera attached on a viewport. Because of its periferic housing, the angle between the beam trajectory and the camera is 50 degrees; a second porthole is used for the extraction of thermocouple cables and copper-mask-cooling tubes.
When the beam reaches the mask, a 8-beamlets geometry is created, which simulates the grounded grid beam-pattern.

### 2.3 Negative ion source varied parameters

The experimental campaigns for mini-STRIKE in BATMAN were performed by varying several source parameters, in order to study the behaviour of beam profile in multiple situations. A scheme of the HV power supply is reported.

![Fig. 2.5: BATMAN ion source HV power supply](image)

The involved parameters are enumerated as follows:

1. $U_{bias}$ and $I_{bias}$. The plasma grid (PG) is biased against the source body: a voltage is applied between the grid and the wall of the source volume: this biasing was found to enhance the negative ion yield and to decrease the number of co-extracted electrons. 

2. $U_{extr}$ and $U_{acc}$: these are respectively the difference of potential between PG and EG and between EG and GG. The extraction voltage accelerates both negative ions and electrons (those not stopped by the filter field); because the volume between PG and EG has a strong magnetic field, the values of $U_{extr}$ condition the total beam deflection by modifying the Larmor radius of each negative charge ($r_L = \frac{m v}{q B}$).
3. \( P_{\text{fill}} \) and \( P_{HF} \): \( P_{\text{fill}} \) is the source pressure (measured in the source body), while \( P_{HF} \) is the radio-frequency-source power.

4. \( P/P_0 \) (Normalized Perveance). The "perveance" is a fundamental parameter in describing the beam optics. The beam emerges in the vacuum chamber through a grid; each aperture generates a long narrow beam. As a consequence of negative space charge, the ions will not continue to travel all in a straight line, but the beam will diverge. In the hypotheses that the spreading angle is small, the lateral field due to the strong space charge can be analytically obtained by Gauss’ law; some integration yields the so called “Child Equation”

\[
J_0 = \chi \cdot \frac{V^{3/2}}{a}
\]

where \( J_0 \) is the injected current density, \( \chi \) is a constant, \( V \) is the accelerating potential and \( a \) is the smaller of the two aperture sides.

Perveance is defined starting from this equation as

\[
P = \frac{I}{V^{3/2}}
\]

it represents all the repulsive effects of space charge on the optics of the beam. [10]

**Perveance-Divergence Correlation** BATMAN facility researchers investigated the functional dependence of beam divergence on perveance; their conclusion was that the best fitting function is a parabola: 

\[
\text{divergence} = a \cdot (P/P_0)^2 + b \cdot (P/P_0) + c \quad \text{with} \quad a = 715.15, \ b = -189.73 \text{ and } c = 15.39
\]

(Fig. 2.6, left-hand plot).

![Figure 2.6: (Left-hand plot) Divergence-normalized perveance dependence; (right-hand plot) the horizontal magnetic field strength variation in the z direction. The zero of the reference was taken at the centre of the PG.](image)

**Magnetic field configurations** The magnetic filter field is often changed between the experimental campaigns: indeed it is possible to vary its position (moving the magnet bars), intensity (using 2x3 or 2x4 bars) or its polarity (see Fig. 2.6, right-hand plot).

2.4 Data collection at IPP-Garching

The BATMAN negative ion source usually operates with sequences of 5s pulses, one every 3 minutes; during the pulse the thermal-camera (featuring 3 thermocouples) observes the tiles and a video is recorded. The video consists of 420 frames (images), one every 40 ms.

Data collection in BATMAN facility was organized in 30 campaigns, each campaign consisting in a set of shots, performed by varying mainly (but not exclusively) one parameter; each campaign takes its name from the main varied parameter. The experimental campaigns lasted about 24 days, for a total amount of 2300 shots; out all these shots, those acquired in optimal conditions (with the source and all other diagnostics working properly) have been selected.
The source was filled with $H_2$ in all the campaigns, except the last seven, when deuterium was used.

Before the begin of data analysis, video-to-image conversion was executed: video frames were extracted and saved in a proprietary format (FPF) by the programme of the thermocamera.
3 Software development

3.1 Software for first-level data analysis

An IDL programme was written to analyse iteratively each frame of each shot for each campaign: a frame consists in a FPF image that is a 2D array of pixel temperatures. This IDL programme is a combination of 3 nested cycles and it is structured as follows:

1. **frame acquisition and background subtraction**: the background is obtained by averaging the first 45 frames of that shot: indeed in the first 60-70 frames of each shot the beam is not activated yet and the image of the tiles is pure background. The background is subtracted from all the following frames (see Fig. 3.1).

![Figure 3.1](image)

Figure 3.1: (Left-hand side) Raw data; (centre) background; (right-hand side) image resulting from subtraction of the background from raw data (actual signal)

2. **search of the beam-start frame**: a IDL-written procedure determines the frame of beam-start. As already reported, the thermal camera observed the rear side of the tiles with a significant angulation, approximately 50 degrees: in every IR image a part of the copper mask, lying behind the tiles, can be seen. When the plasma pulse is activated, it hits first the front side of the tile: only some frames later the beamlet is visible also at the rear side of the tile. When the beamlet hits the front side of the tile (not visible by the thermocamera), the tile temperature increase can be seen thanks to reflection on the rear side of the copper mask: a 'spot' of light appears in the image (Fig. 3.2).

![Figure 3.2](image)
Before pulse, the temperature of the mask and of the tile is quite uniform and background oscillations are far smaller than 1K. Starting from this considerations, the IDL procedure determines at what frame the maximum temperature of this 'spot' increases at least of 1K with respect to the background: this is the beam-start frame. From data analysis on the first frames after beam-start it emerged that signal on the rear side of the tiles was sufficiently strong to be distinguished by background only 10 frames (i.e. 400ms) after beam-start; consequently data analysis begins always 10 frames after beam-start.

3. **single peak analysis**: the following procedure is iterated for each peak (eight peaks are visible because the mask has 8 apertures). A rectangular zone is selected all around the peak excluding the shadow (if present) of a thermocouple; then a 1-D gaussian fit is performed on the peak both along the x and y directions.

On the peak several 2-D fits are performed (Gaussian, Hubbert and Mod-Hubbert) by the IDL "powell" procedure: this pro minimizes the fit function with the Powell method, using as starting point a 5-element vector created from the parameters of the two previous Gaussian fits. In general it was found out that the best 2D-fitting-function was the Mod-Hubbert (see next paragraph).

**Hubbert and Mod-Hubbert functions** Several investigations and studies had been performed to find a good and precise fitting function for the single beamlet temperature...
profile; the result of this extensive research ([8]) was the discovery of the "Mod-Hubbert" function. The 1D (Eq. 2) and 2D (Eq. 3) "Mod-Hubbert" functions are the Hubbert function (Eq. 1) with three and five degrees of freedom respectively.

\[ f_{\text{hub}}(x) = \frac{e^{-x}}{(1 + e^{-x})^2} = \frac{1}{(\cosh(x))^2} \]  

(1)

\[ f_{\text{mHub1D}}(x) = \frac{a_0}{(\cosh(\frac{|x-a_1|}{a_2}))^{a_3}} \]  

(2)

\[ f_{\text{mHub2D}}(x, y) = \frac{a_0}{(\cosh(\sqrt{(\frac{x-a_1}{a_3})^2 + (\frac{y-a_2}{a_4})^2}))^{a_5}} \]  

(3)

4. beam profile reconstruction (on the rear side of the tile). The software developed during the present work was applied to the temperature profile on the rear side of the tiles. At present this thermal pattern is the best approximation to the beam profile and will be improperly referred to as "beam" in the following.

The beam profile is reconstructed starting from the amplitudes of the six-vertically-aligned beamlets obtained previously with 2D fittings (Gaussian, Hubbert and Mod-Hubbert): three Gaussian fits are performed over these three groups of values (see Fig. 4.1, left-hand image). In the following only the results coming from the last fit (that performed on Mod-Hubbert parameters) are presented.

The programme analysis of a single frame produces 19 png images: two images of the tiles (raw frame data, signal after background subtraction), three Gaussian profiles of the beam and 2 images for each of the 8 beamlets (IR image and vertical-horizontal temperature fits). The whole process is iterated for all the frames (after beam ignition) and for all shots. Moreover fit parameters are recorded into various files; these files are the starting point for second-level data analysis.
3.2 Software for second-level data analysis: GUI creation

The first scope of second-level data analysis is to have a tool to access easily and efficiently the huge amount of data produced by first-level data analysis. For example, it is requested to study the time evolution of a beam-parameter for a specified shot or the dependence between two parameters (of the beam and/or of the ion source) for one or more campaigns at a given instant of the shot; the same can be done as regards one or more mask beamlets, for one or more campaigns. The number of possible plot combinations is huge. So the tool should be at the same time able to access agiley the ten of thousands of results, to retrieve data as queried by the user and to be user-friendly: the choice was to develop a Graphical User Interface (GUI), connected to various IDL procedures.

A GUI provides a graphical mean to perform simple and complex operations or procedures: the graphical interface developed provides a simple and intuitive mask for search parameter insertion; once confermed, an IDL routine inspects data files and retrieve the requested values, plotting them on screen and in case also writing them to disk. The code writing process is structured as follows:

1. Reading of files with first-level-data-analysis results. The outcomes of first-level data analysis programme are saved as tables in text files. Each line contains data of different types (string, double precision numbers, integers etc..); for this reason special IDL procedures have been written. These routines use structures of array to read data and store them in an efficient way, one array for each column; when invoked by the top-level routine, a structure with the whole file content is return. The same is performed on BATMAN-parameters. For this task 3 routines were written.

2. Database-filtering according to user-inserted parameters. These procedures are the core of second-level data analysis, since they access results-database and return values as asked; a short scheme follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Search parameters</th>
<th>Values returned</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProCampaign</td>
<td>CampaignName, frame No, xpar, ypar</td>
<td>three data arrays (x,y,ey)</td>
</tr>
<tr>
<td>TimeEvolution</td>
<td>shot No, one beam parameter</td>
<td>three data arrays (x,y,ey)</td>
</tr>
<tr>
<td>ProCampaignBatVsBat</td>
<td>CampaignName, xpar, ypar</td>
<td>two data arrays (x,y)</td>
</tr>
</tbody>
</table>

Table 2: Overview of some IDL procedures developed for data analysis

As its name suggests, CampaignName is specific for a single-campaign research and TimeEvolution provides the time evolution of a beam parameter; ProCampaignBatVsBat permits to recover and plot two source parameters during a complete campaign. A pro similar to ProCampaign, named ‘ProCampaignPeak’, was also developed: its task is to retrieve data regarding not the beam parameters but the single beamlets (created by the copper mask) parameters.
3. Development of GUI widgets. The writing of GUI code proceeded in parallel to that of data-recovery programmes; several widgets were written to create a constructive dialog between graphical tools (windows, menus...) and the already written data-recovery routines. The details of this part of programming are contained in the next subsections.

3.2.1 Plot of a beam parameter for one or more campaigns

First a parameters-selection interface was developed: the user insert the parameters for database filtering (Fig. 3.5, left-hand image). One click on ‘View’ button will activate the call to the proper data-recovery procedure: the resulting arrays are plotted on the right-side part of the main window (Fig. 3.4). It is possible to study one or more beamlets, as well as one or more campaigns: in the case of more campaigns a dialog window opens (Fig. 3.5, right-hand image), where the user can easily select the desired campaigns.

3.2.2 Time evolution of a parameter of the beam

In the time-evolution interface the user can select the desired shot (an external selection window opens) and one beam parameter; clicking on ‘View’ the time evolution of that parameter is plotted (Fig. 3.6).

Figure 3.5: (Left-hand image) Menu for search-parameters insertion; (centre) selection of the abscissa parameter; (right-hand image) window for multiple campaigns selection.

Figure 3.6: Time evolution of beam peak
All plots visualised on screen can be saved to disk; clicking the button 'Save Graph to file' the save-to-file widget is activated. This window shows the destination directory and the filename of the plot (Fig. 3.7).

In total, as regards both first and second level data analysis, about 5300 lines of IDL code have been written.

Figure 3.7: Saving-to-file window
4 Data Analysis

The procedure of data analysis consists of two stages: a first-level data analysis, in which the data of the total temperature pattern on the rear side of the tile are obtained from single peaks, and a second-level, in which these data are plotted as functions of operational parameters.

4.1 First-level data analysis

First-level data analysis provides a complete beam profile reconstruction (on the rear side of the tiles), at every instant during beam on time. As anticipated, the temperature profile is reconstructed starting from the peaks of the six vertically aligned beamlets; a Gaussian fit on parameters from former Mod-Hubbert fits shows a very good accordance with data (Fig.4.1).

![Figure 4.1: Fitting of peaks: reconstruction of beam profile (left-hand plot). Beam profile obtained by BATMAN researchers with another calorimeter (right-hand plot).](image)

Typical beam profiles had already been obtained by BATMAN-facility researchers (Fig.4.1, right-hand plot) using another calorimeter located at about 1.5 m downstream the ground grid [6]. As it can be observed, both vertical and horizontal profiles are approximately Gaussian; the beam is vertically deflected because of the vertical shift due to the magnetic field in the extraction grid. The study of width, height and center of the vertical beam profile while varying several operational parameters is the main aim of the present work.

Tile-image-pixels numbering: centre of the beam The first image on the left of Fig.3.2 shows the pixel-numbering order: the zero of vertical position is at the top of the tile. So if the centre of the beam moves up/down during a campaign, the beam position coming from data will respectively show a decrease/increase. This aspect must be always kept in mind in order to interpret correctly the plots regarding the centre of the beam.

4.2 Second-level data analysis

4.2.1 Time evolution of beam parameters

For each shot of the experimental campaigns an analysis of the time evolution of beam centre, peak and width have been performed; an example plot is reported in Fig.4.2.
The first frame plotted is number 10, corresponding to 0.4 s, because, as already explained, the tenth frame after beam-start is the first frame with a signal sufficiently strong to permit good fits to the tile temperature. Beam width and center, after a short initial transient, appear to be stationary while the peak temperature increases; the beam end corresponds to a decrease of peak (there is no more an incoming power), a weak increase of the width and no appreciable variation of the centre.

### 4.2.2 Perveance Campaigns

Some perveance campaigns were performed by varying the axial distance of the magnets from the plasma grid (z=9 cm, z=14 cm), their number (2x3-2x4) and the drift direction (up-down) (see Table 1).

**Operational parameters trends** The main varied parameter is $U_{extr}$: as it can be seen in Fig.4.3 (left-hand plot) a $U_{extr}$ increase corresponds to an increase in the negative ion current (it can be seen that the same happens for electron current and electron-to-negative-ion-currents ratio). Moreover the perveance decreases because its denominator grows ($U_{extr}^3/2$) faster that the numerator ($jH^-$ is approximately linearly proportional to $U_{extr}$) (Fig.4.3, right-hand plot).
4.2 Second-level data analysis

Figure 4.4: Comparison of $H^-$ current and perveance between drift-down campaigns.

**2x4 configuration: beam peak** The beam peak temperature decrease as a function of $U_{extr}$ is shown in Fig.4.5 (left-hand plot) for all four magnetic configurations: as the perveance decreases the beam divergence increases because of the already-cited parabolic dependence divergence-perveance. Upon assuming that the power associated to the beam is not strongly dependent on the divergence, the local beam energy flux decreases as the divergence increases, explaining the behaviour of the peak temperature shown in Fig.4.5 (left-hand plot).

Comparing different campaigns the beam peak seems to have a weak dependence on the magnetic configuration: actually this dependence is only apparent, as can be discovered by normalizing peak values to the negative ions currents. As shown by the right-hand plot of Fig.4.5, the peak dependence on the magnetic configuration is essentially lost, meaning that the peak trends of Fig.4.5 (left-hand plot) seemed different only because of different $H^-$ currents (see Fig.4.3, left-hand plot).

Figure 4.5: Beam peak trend before and after normalization on $H^-$ current

**2x4 configuration: beam centre** The following graph (Fig.4.6) compares beam centre trends with strong/weak magnetic field at the plasma grid ($z=9$ cm, $z=14$ cm respectively) and up/down drifts. When the negative ions and the electrons reach the plasma grid, the strong magnetic filter field bends their trajectories: the resulting deflection depends on the ratio $\frac{v}{B_{ion}}$ according to the Larmor-radius formula, and the direction of deviation depends on the sign of $B$.

Concentrating the attention on drift-up campaigns it emerged that, at the same extraction potential, a higher filter field ($z=9$ cm) gives a higher deviation of the beam from the horizontal direction with respect to the case $z=14$ cm (Fig.4.6, left-hand plot); the same consideration concerns the drift down campaigns.
A higher extraction potential means a more rigid particle and hence a lower deviation of beam centre from the horizontal and the direction of deviation changes with drift direction: all experimental results are in accordance with theory expectations (Fig.4.6 left-hand plot).

For evident symmetry reasons, at very low $U_{\text{extr}}$ two trends with same value of B should converge at the condition of nearly-zero beam deviation, that is a unique horizontal value in the plot; on the contrary data show a kind of ‘offset’ between the drift up and drift down campaigns (B is fixed). This offset has already been detected by BATMAN researchers at IPP-Garching, and this matter is still under investigation.

Figure 4.6: Beam centre as a function of $U_{\text{extr}}$ (left-hand plot) and of normalized perveance (right-hand plot)

**beam centre: comparison of 2x3 and 2x4 campaigns** It is now performed a comparison between the two magnetic configurations with different number of magnets (2x3 vs 2x4) but same positioning and drift direction (Fig.4.7). It emerges that centre dependence on normalized perveance seems to be sensible to the number of magnets used. If we consider only a couple of campaigns, for example the two campaigns with z=9 cm and drift down but with different number of magnets (2x3 and 2x4), the plot suggests that between the two groups of data a simple horizontal shift exists: if this shift is removed the two of them belong to the same curve.

This reasoning is actually correct because investigations evidenced that between the two campaigns a ion current density spread persisted (Fig.4.4 left-hand plot); removing this $jH^-$ spread corresponds to remove a perveance shift (Fig.4.4 right-hand plot), so a horizontal shift in Fig.4.7.

This argument however can not be applied to the couple of campaigns with z=14 cm; the centre trends are distinct even after the $jH^-$ shift removal. Moreover, once removed all these ion current spreads, the order of the groups of data from the lowest to the highest deviation is as follows: ‘2x3 z=18 cm’, ‘2x4 z=14 cm’, ‘2x3 z=14 cm’, and ‘2x3 z=9 cm’ together with ‘2x4 z=9 cm’. This sequence is correct if we compare the 2x3 campaigns or the 2x4 campaigns (a higher magnetic field, z=9 cm, correspond to a higher deviation of beam centre); though if we consider only the z=14 cm campaigns, a lower magnetic field (2x3) seems to provoke a higher deviation, an unexpected behaviour which must be investigated.

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1P.Franzen, private communication
4.2 Second-level data analysis

Figure 4.7: Centre as a function of $P/P_0$ in different magnetic configurations

2x4 campaigns: beam width  Fig. 4.8 (right-hand plot) shows approximately the same parabolic dependence that was found by BATMAN researchers between divergence and perveance: comparing different magnetic configurations no significant difference is visible. If the same graph is plotted with $U_{\text{extr}}$ as x-axis, the four groups of data can on the contrary be more clearly distinguished as linear dependences with different slopes. Fixed $U_{\text{extr}}$, the negative ion current of different magnetic configurations is different (see Fig. 4.3, left-hand plot): this affects the beam width through the causal chain $H^-$ current $\rightarrow$ perveance $\rightarrow$ divergence $\rightarrow$ width.

Figure 4.8: Beam width dependence on extraction potential and on normalized perveance
4.2.3 Bias Campaigns

Several bias campaigns have been performed by varying the axial distance of the magnets from the plasma grid (z=9 cm and z=14 cm), the number of magnets (2x3 or 2x4) and other operational parameters.

Operational parameters trends The main operational parameter varied in this campaign is $U_{bias}$, the voltage applied between the plasma grid (PG) and the walls of the source. The negative-ion current trend with respect to $U_{bias}$ is quite different if the magnets are near (z=9 cm) or far (z=14 cm) from the plasma grid (Fig.4.9); this aspect is currently under investigation by BATMAN researchers.

![Figure 4.9: H⁻ current trends in z=9 cm (left-hand plot) and z=14 cm (right-hand plot) magnetic configurations.](image)

The extraction and acceleration voltages, according to data, remain constant during all the campaigns ($U_{extr} = 5kV$ and $U_{acc} = 15kV$, see Table1).

2x3 configuration: beam centre Observing Fig.4.10, data show the same ‘offset’ that emerged in Fig.4.6, so the points of drift-down campaigns must be shifted upwards (at least of 70÷80 mm).

Starting from the top, the order of the groups of data becomes: z=9 cm (drift down), z=14 cm (drift down), z=14 cm (drift up) and z=9 cm (drift up) (green-cyan-red-black).

Correctly, fixed $U_{bias}$, a more intense magnetic field (z=9 cm) means a higher deviation from the horizontal; indeed the z=9 configuration is, according to this ordering, always more deviated that the z=14.

However, for increasing values of $U_{bias}$, the four centre trends stabilize on four different values instead of converging together to the nearly-zero deviation (as happened in Fig.4.6), the reason for this fact is still under investigation.

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2P. Franzen, private communication
4.2 Second-level data analysis

Figure 4.10: Beam centre as a function of $U_{bias}$ in different magnetic configurations with 2x3 magnets.

**2x4 configuration: beam centre**  Beam centre dependence on $U_{bias}$ is reported for all the possible magnetic configurations (Fig. 4.11); the same considerations done for the 2x3 campaigns can be applied to this plot.

The general dynamics of beam centre in all the bias campaigns are at the moment not completely understood; it is possible that more subtle phenomena, as the dielectric current or the inhomogeneity of the beam, are involved. Moreover the full comprehension of $jH^-$ behaviour could help finding an explanation.

Figure 4.11: Beam centre plotted as a function of $U_{bias}$ (left-hand plot) and of $P/P_0$ (right-hand plot)

**2x4 configuration: beam peak**  As previously reported, $U_{extr}$ is steady; if the beam peaks are normalized on $jH^-$ all the shots of a campaign will have the same perveance, since $P/P_0$ is a function of the negative-ion current and of the extraction potential. Following these considerations, beam peak normalized on $jH^-$ is expected to be constant during each campaign.

Beam peak normalized on $jH^-$ is approximately constant for the $z=14$ cm campaigns (magnets distant for the PG) but it decreases with $U_{bias}$ if the magnets are near the grid ($z=9$ cm) (Fig. 4.12); a dependence on magnets position (but not on drift verse) seems to exist.
Figure 4.12: Beam peak normalised on negative ion current and plotted as a function of $U_{bias}$ (left-hand plot) or of $P/P_0$ (right-hand plot) for 2x4 campaigns.

It can be seen that the same trends characterize the beam peak for the bias campaigns with 2x3 magnets (see Fig. 4.13).

Figure 4.13: Beam peak normalised on negative ion current and plotted as a function of $U_{bias}$ (left-hand plot) or of $P/P_0$ (right-hand plot) for 2x3 campaigns.

**2x4 and 2x3 configurations: beam width** For the campaigns with $z=14$ cm, the $jH^-$ increase should correspond to an increase in $P/P_0$ and a reduction of beam width; this trend however is not clear from data (Fig. 4.14) because of relevant error bars affecting both the 2x3 and 2x4 campaigns.
4.2 Second-level data analysis

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4.2.4 Power Campaign

Power campaign was performed with a unique magnetic configuration: 2x4 magnets at the nearest position with respect to plasma grid (z=9 cm). RF power alterations condition directly the plasma creation rate; indeed the mechanism of plasma creation is structured as follows.

First RF oscillations create the plasma from neutral \( \text{H}_2 \), injected into the source; the \( \text{H}_2 \) molecules which are not ionized gain kinetic energy by collisions with high-speed plasma electrons. These neutrals then enter the expansion region, go straight on towards the plasma grid (they are not affected by magnetic or electric fields), hit the grid and, by surface processes, generate both \( \text{H}^- \) and \( \text{H}^+ \).

Operational parameters trends As the RF power increases, plasma-electron temperature goes up: the flux of energetic \( \text{H}_2 \) increases and negative-ions creation rate at the PG goes up as well. Data response shows that both ion current density and electron current density (the latter measured on the extraction grid) increase with \( P_{HF} \), in accordance with our expectations (Fig.4.15): a clear linear dependence is visible for \( jH^- \).

Beam width and peak It can be seen that the extraction voltage is steady during this campaign \( (U_{extr} = 5kV, \text{see Table I}) \) and that perveance values lie on the left part of the divergence-perveance parabole; the \( jH^- \) increase leads consequently to a perveance increase and a divergence and width decrease (Fig.4.16).
The increase of $iH^-$ corresponds also to a rise of the power associated to the beam (Fig. 4.15, left-hand plot); because at the same time the beam width is lowering, the beam temperature must increase (Fig. 4.17).

Beam centre trend is less clear because of significant error bars affecting the points at the lowest values of $P_{HF}$ (under 50 kW). Fig. 4.18 compares the profile of the beam for the first and last point of the campaign (lowest and highest value of $P_{HF}$); the Gaussian function interpolates well data in both shots, but only in the latter the fitting is really precise.
4.2 Second-level data analysis

Figure 4.18: Beam profile of the shots with lowest (left-hand plot) and highest (right-hand plot) value of $P_{HF}$.

These error bars prevent a deeper inspection on center dynamics; still data suggest that a real center-to-$P_{HF}$ dependence is only apparent.

Figure 4.19: Beam centre as a function of $P_{HF}$ and normalized perveance

4.2.5 Pressure Campaign

The magnetic configuration for the pressure campaign is $z=9$ cm and drift up (high magnetic filter field); the main varied parameter is the pressure of the source, $P_{fill}$.

Operational parameters trends A source pressure ($P_{fill}$) increase corresponds to an increase in $H_2$ injection rate; at the same time, because $P_{HF}$ is constant, the creation rate of high-energy electrons is constant. This combination leads to a reduction of plasma density (indeed $H^-$ density decreases in Fig.4.20 right-hand plot): the electrons, shot from the source into the expansion region, lose kinetic energy colliding with more and more neutrals and when they hit the PG surface they are slower, so their capability of $H^-$ creation is reduced.
The biasing potential ($U_{bias}$) steadily decreases, for a total spread of 10 Ampere (Fig.4.20 left-hand plot); furthermore $I_{bias}$ is fixed. Since $I_{bias}$ generally depends both on plasma potential and $U_{bias}$ (they together determine the flux of particles hitting the plasma grid) and $U_{bias}$ changes during the campaign, it means that the plasma potential is changing too: $P_{s\text{fill}}$ variations indeed modify the density of the plasma.

**Beam width and peak** The experimental $jH^{-}$ decrease (Fig.4.20 right-hand plot) provokes a lowering of perveance (it can be seen (Table 1) that the extraction potential remains constant during this campaign). Beam divergence and beam width should consequently increase; because of significant error bars the rise of beam width, corresponding to the increase of $P_{s\text{fill}}$, is visible but not very clear (Fig.4.21 left-hand plot).

Since $jH^{-}$ decreases and the beam enlarges, the beam peak must decrease (Fig.4.22).
4.2 Second-level data analysis

Figure 4.22: Peak centre plotted as a function of source pressure (left-hand plot) and of $P/P_0$ (right-hand plot).

**Beam centre** Because of the high error bars affecting data, no clear dependence of beam centre on $P_{s\text{fill}}$ or on $P/P_0$ can be distinguished; the monotone trend of Fig. 4.23 is indeed compatible with stationarity.

Figure 4.23: Beam centre as a function of $P_{s\text{fill}}$ (left-hand plot) and of $P/P_0$ (right-hand plot).

Nonetheless, if the error bars were smaller and data points the same, the centre decrease in Fig. 4.23 (left-hand plot), corresponding to an increasing vertical deviation of the beam, could be correlated to the decreasing $H^-$ speed due to the lowering of $U_{bias}$.
5 Future work for mini-STRIKE

This thesis-work produced hundreds of plots; many of them must still be analysed and several trends must still be completely interpreted and understood.

The full comprehension of the results is consequently an important immediate-future work for the mini-STRIKE project; this task could be performed with the help of a new data analysis procedure (see subsection 5.1), and it will be useful for the planning of the next experimental campaign in BATMAN (see subsection 5.2).

5.1 New data analysis procedure

A new automatic fitting procedure, similar to that applied in the analysis of laser-pulses on the CFC tiles [14], is currently under development, in preparation for data analysis in SPIDER; a brief description follows.

The coordinates of the beamlets are determined by preliminary considerations on the thermal-images of the tiles; they are fixed. A 2D-Mod-Hubbert fit (Eq. 3, four d.o.f.) is singly performed on each beamlet; starting from the parameters just obtained a 1D-Mod-Hubbert fit is executed both along the horizontal (fitting function is the sum of two Mod-Hubberts) and vertical (fitting function is the sum of four Mod-Hubberts) direction. Hence a 2D-Mod-Hubbert fit is done on the entire tile (fitting function is the sum of six 2D-Mod-Hubberts, six d.o.f.): Fig 5.1 shows the 1-D and 2-D fitting curves along the vertical direction (the shadows of the thermocouples are visible).

![Figure 5.1: Fittings of the six vertically aligned beamlets with 1D-Mod-Hubberts (red) and a 2D-Mod-Hubberts (green).](image)

Finally the amplitudes of the six beamlets (from 2D-Mod-Hubbert fittings) are fitted with a Gaussian as done in the first level data analysis (Fig 4.1, left-hand plot); the three parameters of the beam (peak, centre, width) are obtained.

This new data analysis procedure is still on going and it has been tested only on two campaigns, PowerScan1029 and PerveanceScan1018: the plots reported are a simple preview of this new work.

Anyway it seems that, as regards these campaigns, only small differences exist between the previous and this new method because the results are in general very similar and compatible in the error bars. For example, in the perveance campaign, peak values with the new procedure are slightly smaller that those from the previous one (Fig 5.2, left-hand plot); in the power campaign the beam is generally wider (Fig 5.4, right-hand plot).
Figure 5.2: (Left-hand plot) Beam peak as a function of normalized perveance in PerveanceScan1018; (right-hand plot) beam peak as a function of $P_{HF}$ in PowerScan1029.

Figure 5.3: (Left-hand plot) Beam centre as a function of normalized perveance in PerveanceScan1018; (right-hand plot) beam centre as a function of $P_{HF}$ in PowerScan1029.

Figure 5.4: (Left-hand plot) Beam width as a function of normalized perveance in PerveanceScan1018; (right-hand plot) beam width as a function of $P_{HF}$ in PowerScan1029.
5.2 New experimental campaign at IPP

A new experimental campaign for mini-STRIKE is already planned for autumn 2013 at IPP-Garching. A new version of the copper mask will be used, with a distance between the beamlets more similar to the beam pattern that STRIKE will have to resolve in SPIDER (Fig. 1.5, right-side image); the new design consists in 18 holes with 7 mm diameter. In Fig. 5.5 are presented the design of the mask (left-hand image) and the expected temperature profile on the rear side of the tile after a 5s pulse; the holes of the current version of the mask, visible in the first image, will be plugged.

![Design of the mask and temperature profile](image.png)

Figure 5.5: The new design of the mask (left-hand image) and the expected temperature profile on the rear side of the tile after a 5s pulse (right-hand image).

5.3 Conclusions

The optimisation of the negative ion source for ITER Neutral Beam Injectors will be carried out in the facility SPIDER.

In the present thesis work the first, full-scale and extensive analysis of the data measured by a small-scale diagnostics of the beam properties (mini-STRIKE) has been performed in the beam source BATMAN (at IPP, Munich, Germany). The software developed, several IDL routines and Graphical User Interfaces, worked properly: many different experimental beam conditions have been analysed and the double-level data analysis procedure allowed the visualisation of results and the corresponding production of summary graphs.

This work demonstrated that the diagnostic calorimeter mini-STRIKE, in conjunction with the software developed, reached completely its goals: the plots produced by the data analysis procedure permitted to understand the beam dynamics and to obtain a good characterization of the particle beam of the BATMAN experiment. A more detailed campaign, planned for autumn 2013, will clarify few issues that emerged during the analysis.

The success of the first test campaign by mini-STRIKE suggests that the entire calorimeter, STRIKE, once in SPIDER will similarly be capable of characterising the particle beam in terms of resolution and reliability of the results; the software for STRIKE data analysis will be based on the one presented in this thesis work.
References


Tests Of Unidirectional CFC Tiles Prototypes For The Diagnostic Calorimeter Of SPIDER Experiment

Numeric and Experimental Characterisation Of CFC Tiles Subjected To Power Laser Pulses