Characterisation of the BATMAN beam properties by $H_\alpha$-Doppler shift spectroscopy and mini-STRIKE calorimeter

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Abstract

The ITER tokamak is an international project, with the aim of proving the possibility to produce energy by nuclear fusion of deuterium and tritium nuclei in a reactor scale. In order to reach the necessary temperature for fusion, additional heating systems are required, like the injection of a neutral beam. One of the components of the Neutral Beam Injector (NBI) is based on a RF driver source for the production of negative hydrogen or deuterium ions, taking as reference the ion sources developed at Max-Planck Institut für Plasmaphysik (IPP, Garching bei München, Germany).

The activity reported in this thesis has been performed at the IPP BATMAN test facility, which has the target of optimising the source performance, using a small extraction area (63 cm$^2$) and short pulses (4 s). The activity was focused on the BATMAN beam characterisation by means of two different diagnostic tools: Beam Emission Spectroscopy (BES) system and mini-STRIKE calorimeter, both recently installed with a new configuration. The BES system is based on the $\text{H}_\alpha$-Doppler shift spectroscopy, in order to investigate the beamlet divergence and the stripping fraction. In the BATMAN test bed, five telescopes are arranged in a vertical array in order to study the beam vertical inhomogeneity. The second diagnostic system is the mini-STRIKE calorimeter, which consists of two identical one-directional (1D) Carbon Fibre Composite (CFC) tiles, arranged in vertical direction and observed at the rear side by a thermal camera: the measured thermal pattern provides information about the energy flux of the impinging beam. As part of this thesis work, a software for mini-STRIKE data analysis has been developed and various experimental campaigns have been carried exploiting the new layout of the mini-STRIKE calorimeter. The beam properties have been investigated with both diagnostic systems.

In Chapter 1, an introduction to nuclear fusion and ITER experiment is given. Furthermore, the need of external heating systems is explained, focusing on NBI source requirements.

The structure of the IPP prototype negative ion source is described in Chapter 2, together with the already known negative beam properties.

Chapter 3 presents the technical details of the BATMAN test facility and the diagnostic tools present in the BATMAN tank, aiming to characterise the beam: the BES system and the mini-STRIKE calorimeter.

Chapter 4 focuses on the development of the software for mini-STRIKE data analysis.

In Chapter 5 the various experimental campaigns are discussed. The influence of the source parameters on the beam properties has been investigated by means of the BES system and the mini-STRIKE calorimeter.

A comparison of the two diagnostic systems is then carried out, focusing on the investigation of the beam homogeneity, in Chapter 6.

The main results and the future developments are finally presented in Chapter 7.
Sommario

Il tokamak ITER è un progetto internazionale, con lo scopo di dimostrare la possibilità di produrre energia tramite la fusione nucleare di nuclei di deuterio e trizio in una struttura con dimensioni paragonabili a un reattore. Per raggiungere le temperature necessarie per la fusione, sono necessari dei sistemi di riscaldamento addizionali, quale ad esempio l’iniezione di un fascio di neutroni. Un componente dell’iniettore del fascio di neutroni (NBI) si basa su una sorgente a radiofrequenza che crea ioni negativi di idrogeno o deuterio, considerando come riferimento le sorgenti di ioni sviluppate al Max-Planck Institut für Plasmaphysik (IPP, Garching bei München, Germania).

Il lavoro riportato nella presente tesi è stato svolto presso la test facility BATMAN, la quale ha l’obiettivo di ottimizzare le performance della sorgente. La sorgente in BATMAN ha una piccola area di estrazione (63 cm$^2$) e gli impulsi hanno una durata di 4 s. Il lavoro di tesi si è concentrato sulla caratterizzazione del fascio di BATMAN, attraverso l’utilizzo di due diverse diagnostiche: il sistema di spettroscopia di emissione del fascio (Beam Emission Spectroscopy, BES) e il calorimetro mini-STRIKE, entrambi recentemente installati con una nuova configurazione. La prima diagnostica si basa sull’analisi spettroscopica della riga H$_\alpha$ traslata per effetto Doppler, in modo da ricavare la divergenza dei fascetti che compongono il fascio globale e la frazione di particelle prodotte per stripping. Per esaminare la disomogeneità del fascio in direzione verticale, a BATMAN sono impiegati cinque telescopi, disposti l’uno sopra l’altro. Il calorimetro mini-STRIKE invece consiste di due tegole in fibra di carbonio unidirezionale, tra loro identiche, disposte in direzione verticale e osservate sul retro da una camera a infrarossi: il profilo termico misurato fornisce informazioni riguardo il flusso di energia del fascio incidente. Come parte del lavoro di tesi, è stato sviluppato un programma di analisi dati e sono state condotte diverse campagne sperimentali con il nuovo setup di mini-STRIKE. Le proprietà del fascio di BATMAN sono state studiate mediante ambo le diagnostiche.

Nel Capitolo 1 è presente un’introduzione alla fusione nucleare e all’esperimento ITER. Si spiega inoltre la necessità di utilizzare sistemi di riscaldamento esterni, concentrandosi poi sui requisiti della sorgente dell’iniettore del fascio di neutroni.

La struttura del prototipo di sorgente di ioni negativi sviluppato a IPP è descritta nel Capitolo 2, presentando inoltre le già note proprietà del fascio di ioni negativi.

I dettagli tecnici della test facility BATMAN sono esposti nel Capitolo 3. Qui vi è anche una descrizione delle diagnostiche presenti in BATMAN, che hanno lo scopo di caratterizzare il fascio. Queste diagnostiche sono la BES e il calorimetro mini-STRIKE.

Il Capitolo 4 si concentra sullo sviluppo del programma di analisi dati creato per mini-STRIKE.

Nel Capitolo 5 sono discusse le diverse campagne sperimentali: si studia in tal modo l’influenza che possiedono i diversi parametri della sorgente sulle proprietà del fascio attraverso i diversi parametri diagnostici, BES e mini-STRIKE.

Un confronto tra le due diagnostiche è presentata nel Capitolo 6, con particolare riguardo allo studio della disomogeneità del fascio.

Infine, i principali risultati e gli sviluppi futuri sono raccolti nel Capitolo 7.
1 Introduction

In this chapter, an introduction to nuclear fusion and ITER experiment is given, focusing on the neutral beam heating system.

1.1 A solution for energy problem: nuclear fusion and the way to ITER

The energy problem is one of the most discussed topic in the last years: the increasing energy demand due to overpopulation cannot be covered only by burning fossil fuels, hence an alternative energy source has to be found, taking into account the increasing energy demand and the problem of environment pollution. One of the candidates is the nuclear fusion.

1.1.1 Nuclear fusion

The research on nuclear fusion is focused on fusion of deuterium and tritium nuclei, which show the highest cross section compared to other promising fusion reactions, as shown in Fig. 1. Since additionally this reaction has an activation energy lower than the other reactions, a temperature of 15 keV ($\approx 10^8$ K) is enough for fusion to happen with a sufficiently high cross section [1].

![Figure 1: Cross sections of various fusion reactions as a function of the kinetic energy of an incident deuterium atom or proton on a stationary target [1].](image)

The fusion reaction between deuterium and tritium nuclei is the following

$$2^2D + ^3T \rightarrow ^4He \ (3.5 \text{ MeV}) + n \ (14.1 \text{ MeV})$$

While deuterium is available in the water, tritium is not present in a large quantity in nature: it is not a stable isotope and has an half-life time of 12.3 years. It is so necessary to create these nuclei inside the reactor, by means of the following reaction:

$$n + ^6Li \rightarrow ^4He \ (2.05 \text{ MeV}) + ^3T \ (2.75 \text{ MeV})$$

Lithium is widely available in the Earth’s crust and also in the oceans.
1.1.2 Definition of plasma

In a fusion reactor, matter is in the state of plasma: a high-temperature, partly or fully ionised, quasi-neutral gas of charged particles (positive nuclei and negative electrons), showing a collective behaviour. The quasi-neutrality implies the absence of macroscopic concentration of charge, hence the density of positively and negatively charged particles in a plasma is the same. Moreover, if a charge is inserted into the plasma, this charge will be shielded from the rest of the plasma: for example if the charge is positive, in its neighbourhood electrons will be attracted and ions repelled.

The natural scale length \( \lambda_D \), beyond which the shield effect takes place, is called Debye length:

\[
\lambda_D = \left( \frac{\epsilon_0 k_B T_e}{ne^2} \right)^{\frac{1}{2}}
\]

where \( \epsilon_0 \) is the permittivity of free space, \( k_B \) is the Boltzmann constant, \( T_e \) and \( e \) are the electron temperature and charge respectively; \( n \) is the plasma density, corresponding to the negative (and positive) charged particle density.

Inside the Debye sphere of radius \( \lambda_D \), charge neutrality is violated, but outside quasi-neutrality prevails if the number of charged particles \( N_D \) within the Debye sphere satisfies the following equation:

\[
N_D = n \frac{4\pi}{3} \lambda_D^3 \gg 1 \tag{4}
\]

Another important parameter is the plasma frequency \( \omega_{p,e} \), which corresponds to the typical electrostatic oscillation frequency of electrons, in response to a small charge separation:

\[
\omega_{p,e} = \left( \frac{n_e e^2}{\epsilon_0 m_e} \right)^{\frac{1}{2}}
\]

where \( n_e \) and \( m_e \) are the electron density and mass, respectively.

1.1.3 Tokamak and ITER

There are two different methods for producing controlled thermonuclear fusion power. One is based on inertial fusion energy, that is energy released by nuclear fuel when compressed by many high intensity laser beams, irradiating uniformly a spherical shell (for details, see [1]).

The other candidate is represented by magnetic confinement devices. These devices use a magnetic field to confine a plasma in the shape of a torus, in order to reduce the losses of charged particles and trap them away from the inner walls. Charged particles in the plasma in fact feel the magnetic field and gyrate around the magnetic field lines with a radius \( r_g \), called Larmor radius, defined by

\[
r_g = \frac{m v_{\perp}}{|q| B}
\]

where \( v_{\perp} \) is the charged particle velocity perpendicular to the magnetic field \( B \), and \( m \) and \( q \) are the particle mass and charge, respectively.
Two different general experimental designs are used for devices based on magnetic confinement: tokamak and stellarator. In both of them the magnetic field lines wind around the torus in a helical shape, due to the presence of two magnetic fields:

- a toroidal field, produced by coils that surround the torus;
- a poloidal field, in the plane orthogonal to the toroidal field. For a tokamak (a schematic view is shown in Fig. 2 on the left-hand side), this field is created by a toroidal electric current that flows inside the plasma. This current is induced by varying the current in the central solenoid on the axis of symmetry of the torus. For this reason, the tokamak is a pulse device. For a stellarator (a sketch is displayed in Fig. 3 on the right-hand side), the poloidal field is created by external helical coils, which create also the toroidal magnetic field. As there is no induced current, continuous operation is possible.

The poloidal field is necessary, because a purely toroidal magnetic field results in strong particle drifts perpendicular to the magnetic field lines, affecting the plasma confinement.

![Figure 2: Diagram illustrating the tokamak principle: arrangement of magnetic field coils and the resulting magnetic field that confines the plasma [2].](image1)

![Figure 3: Sketch of the electromagnetic coil setup of the Wendelstein 7-X stellarator, under construction in Greifswald (Germany) [3].](image2)

The first reactor-scale nuclear fusion experiment is the ITER tokamak (a sketch is shown in Fig. 4), an international project under construction in Cadarache (France). ITER will be based on deuterium-tritium reaction, in order to produce a plasma with the fusion energy gain factor \((Q \text{ value})\) larger than 10 [4]. The \(Q\) value is the ratio of the fusion power produced by the reactor to the input auxiliary power required to sustain the reaction itself. However, before the D-T experiment, experiments with hydrogen and deuterium separately will be carried out.

The plasma will be confined by the magnetic field inside a vacuum vessel, consisting of a double walled steel container. Outside the vacuum vessel, the toroidal and poloidal field coils lie in the cryostat, where they are cooled and shielded from the neutrons of the fusion reaction. In order to achieve superconductivity, all coils are cooled with supercritical helium around 4 K [4].
The current induced, as already mentioned, by increasing the current in the central solenoid heats the plasma by ohmic heating. However the resistance connected to this current decreases with the increasing temperature [5]. As a consequence, the ohmic heating is limited and external heating methods are necessary to reach the temperature at which fusion can occur.

Furthermore, in order to produce more power by nuclear fusion than the power necessary to heat the plasma, some requirements have to be fulfilled. The Lawson criterion (Eq. 7) establishes a threshold over which this condition occurs:

$$n\tau_E \geq \frac{12}{E_\alpha} \frac{k_B T}{\langle \sigma v \rangle}$$  \hspace{1cm} (7)$$

where $n$, $\tau_E$, $T$, $E_\alpha$ and $\langle \sigma v \rangle$ are respectively the plasma density, the energy confinement time, the plasma temperature, the energy of the alpha particle released by the fusion reaction (for the D-T reaction in Eq. (1) this energy corresponds to 3.5 MeV) and the reaction rate coefficient.

For the D-T reaction of Eq. (1), at the required temperature ($T \approx 15$ keV), the Lawson criterion becomes

$$n\tau_E T \geq 5 \cdot 10^{21} \text{ m}^{-3} \text{ keV s}$$  \hspace{1cm} (8)$$

While sufficient plasma density ($10^{20}$ m$^{-3}$) and plasma temperature (15 keV) can be reached, the energy confinement time in present day fusion experiments is too small (up to around 1 s in JET experiment, in Culham, United Kingdom [2]). The energy confinement time is connected to the size of the tokamak [6] and the ITER machine will be the first to achieve an energy confinement time in the range of 4-6 s, thanks to its large dimensions.

The ITER main parameters are summarised in Tab. 1.
<table>
<thead>
<tr>
<th><strong>ITER specifications</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Fusion power gain ((Q))</td>
<td>(\geq 10)</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3600 s</td>
</tr>
<tr>
<td>Type of plasma</td>
<td>D-T</td>
</tr>
<tr>
<td>Plasma major radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Plasma minor radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Plasma current</td>
<td>15 MA</td>
</tr>
<tr>
<td>Toroidal field at 6.2 m radius</td>
<td>5.3 T</td>
</tr>
<tr>
<td>Installed auxiliary heating:</td>
<td></td>
</tr>
<tr>
<td>- by neutral beam injection</td>
<td>33 MW</td>
</tr>
<tr>
<td>- by radio-frequency waves</td>
<td>40 MW</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>830 m(^3)</td>
</tr>
<tr>
<td>Plasma surface area</td>
<td>680 m(^2)</td>
</tr>
<tr>
<td>Machine height</td>
<td>26 m</td>
</tr>
<tr>
<td>Machine diameter</td>
<td>29 m</td>
</tr>
</tbody>
</table>

Table 1: ITER parameters and operational capabilities [4].

### 1.2 Neutral beam heating

As already mentioned in the previous section, external heating systems are required in order to reach the fusion temperature. These systems introduce also a non-inductive current drive in the torus and this current makes continuous operation possible, sustaining the poloidal field and enhancing the plasma confinement.

The plasma heating can be done in different ways, as shown in Fig. 5: by high-frequency electromagnetic waves or by neutral beam injection.

The electromagnetic waves are generated outside the torus, then coupled into the plasma. Propagating inside the plasma, the RF waves release their energy to the charged

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Figure 5: Sketch of the ohmic heating, the Radio Frequency (RF) heating and the neutral beam injection heating in a tokamak [4].
plasma particles. The two resonance frequencies $\omega$ which will be used for the ITER heating system are [4]:

- the ion cyclotron resonance, $\omega = \frac{eB_{m_i}}{m_i}$, where $e$ is the electron charge, $B$ the magnetic field and $m_i$ the ion mass. This frequency is in the range of 40-55 MHz;
- the electron cyclotron resonance, $\omega = \frac{eB_{m_e}}{m_e}$, where $m_e$ is the electron mass. The electron cyclotron frequency in ITER is 170 GHz.

The second heating method consists in injecting high-energy atoms (hydrogen or deuterium) into the magnetically confined plasma.

To penetrate the magnetic field, these particles have to be neutral, in order to reach the plasma and there be ionised. Considering a hydrogen beam, the possible interactions with the plasma ions are charge exchange reaction, ionisation by ions and ionisation by electrons, respectively [1]:

\begin{align}
    H_{\text{beam}} + H_{\text{plasma}}^+ &\rightarrow H_{\text{beam}}^+ + H_{\text{plasma}} \tag{9} \\
    H_{\text{beam}} + H_{\text{plasma}}^+ &\rightarrow H_{\text{beam}}^+ + H_{\text{plasma}}^+ + e^- \tag{10} \\
    H_{\text{beam}} + e^- &\rightarrow H_{\text{beam}}^+ + 2 e^- \tag{11}
\end{align}

The decay of the neutral beam intensity $I_{\text{beam}}(x)$ inside the plasma is described by the absorption law:

\begin{align}
    \frac{dI_{\text{beam}}}{dx} &= -n \sigma_s I_{\text{beam}} \tag{13} \\
    \sigma_s &= \sigma_{\text{cx}} + \sigma_i + \frac{\langle \sigma_e v_e \rangle}{v_{\text{beam}}} \tag{14}
\end{align}

where $n$, $\sigma_{\text{cx}}$, $\sigma_i$, $\langle \sigma_e v_e \rangle$ and $v_{\text{beam}}$ are the ion density, the charge exchange cross section, the ionisation cross section by ions, the electron ionisation rate coefficient and the beam speed, respectively. The solution of Eq. (13) is given as $I_{\text{beam}} = I_0 \cdot \exp \left( -\frac{x}{\lambda} \right)$, where $I_0$ is the initial intensity of the beam and $\lambda = \frac{1}{n \sigma_s}$ the e-folding length of the beam attenuation.

In order to have a sufficient penetration depth of the beam in the plasma, the beam energy has to be at least in the order of hundreds of keV [1]. The beam energy for ITER is required to be about 1 MeV [7], in order to ensure an high efficiency non-inductive current drive of high-energy particles (the current drive efficiency increases with particle energy) and to supply 33 MW of heating power from two heating beamlines.

The main components of a Neutral Beam Injector (NBI) are displayed in Fig. 6. On the right there is the beam source, where hydrogen or deuterium ions are created in a plasma and then accelerated to the desired energy by an extractor/accelerator system. The ion beam then goes to the drift region (that is the region just downstream the accelerator system), where a fraction of the accelerated ions is neutralised by means of collisions with the dedicated gas cell. A magnetic or electrostatic field (the latter is the case for ITER) is placed after the neutraliser cell, in order to deflect the non-neutralised ions, which are
Figure 6: Sketch of the Neutral Beam Injector for the JT-60U tokamak (Japan) [8]. The main components are the negative ion source (on the right), where ions are created and accelerated by an extractor/accelerator system; the drift region downstream the source, where particles are neutralised, and the Residual Ion Dump (RID), which collects the residual ions deflected by a magnetic field (or electrostatic field in the case of ITER), before the beam reaches the plasma in the tokamak.

dumped by means of the Residual Ion Dump (RID) before reaching the plasma in the tokamak.

The efficiency of the neutralisation process in an ion beam is a critical topic since it determines the efficiency of the whole beam line. The efficiency is different for positive and negative beams, as shown in Fig. 7: at energies higher than 100 keV, the neutralisation efficiency for positive ions decreases rapidly to almost zero. Negative ion beams instead have a neutralisation efficiency of 60% even at higher energies, because of the low binding energy of the electron (0.75 eV). For this reason, the negative ion source is the reference source for the ITER NBI system.

Figure 7: Neutralisation efficiency of positive and negative ions as a function of their kinetic energy [1].

1.3 ITER-relevant ion source parameters

The ITER heating system will consist of two heating neutral beams, injecting 16.5 MW each. These will be based on the acceleration of negative hydrogen or deuterium ions, due to their high neutralisation efficiency discussed in the previous section.

The required accelerated ion currents are 48 A at the energy of 0.87 MeV for $\text{H}^-$ ions and 40 A at the energy of 1 MeV for $\text{D}^-$ ions, with pulse lengths up to one hour [9].
In order to achieve these currents, the source has to deliver extracted negative ion currents of 68 A for H\(^-\) and 58 A for D\(^-\). These current values consider the stripping losses in the accelerator: due to interactions between the negative ion beam and the background gas in the accelerator, some ions are neutralised before reaching the full energy. This process is called *stripping*. For ITER, the stripping losses are calculated to be nearly 30% for a source filling pressure of 0.3 Pa \([10]\). The stripping probability in fact depends strongly on the gas pressure, hence a low filling pressure in the source is required. For ITER, this pressure has to be at most 0.3 Pa, representing a good compromise to have a still high extracted current and a low stripping rate.

The ITER source will have a height of 1.9 m and a width of 0.9 m, and the beam will be created by an acceleration system consisting of seven grids arranged one behind the other. These grids have 1280 apertures each, with an aperture diameter of 14 mm. The corresponding extraction area is 0.2 m\(^2\). This implies a required extracted current density of 340 A/m\(^2\) for H\(^-\) and 290 A/m\(^2\) for D\(^-\).

Since not only negative ions are extracted, but also electrons, deflection magnets in the grid system are used to prevent the full acceleration of the electrons. The deflected co-extracted electrons hit one of the grids (the extraction grid, see Sect. 2.1.2) and the deposition of power onto this grid becomes the real limit of operation and ions extraction. For the ITER extraction system, the ratio between the co-extracted electron current and the negative ion current is required to be one at maximum.

In ITER, the beam must have a divergence (which is an index of the beam opening) of less than 7 mrad and an inhomogeneity of the extracted current density across the large grid of less than 10% in order to minimise transmission losses in the accelerator and in the beam line.

The ITER requirements for NBI are summarised in Tab. 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source dimensions</td>
<td>1.9 × 0.9 m(^2)</td>
</tr>
<tr>
<td>Source pressure</td>
<td>0.3 Pa</td>
</tr>
<tr>
<td>Extraction area</td>
<td>0.2 m(^2)</td>
</tr>
<tr>
<td>Extracted current</td>
<td>58 A for D(^-) beam</td>
</tr>
<tr>
<td>Accelerated current</td>
<td>40 A for D(^-) beam</td>
</tr>
<tr>
<td>Electron content ((j_e/j_{ion}))</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3600 s</td>
</tr>
<tr>
<td>Uniformity</td>
<td>±10%</td>
</tr>
<tr>
<td>Divergence</td>
<td>≤ 7 mrad</td>
</tr>
</tbody>
</table>

Table 2: ITER neutral beam system source requirements and parameters.

The development of negative ion sources is being carried out at Max-Planck Institut für Plasmaphysik (IPP, Garching bei München, Germany). The ITER relevant current densities at the required pressure and electron-to-ion ratio have been achieved in the BATMAN (BAvarian Test MAchine for Negative ions) test facility, equipped with a small extraction area (63 cm\(^2\)) and operating with limited pulse length (4 s). A new test facility has been recently constructed: ELISE (Extraction from a Largely Isolated Source
Experiment) is a half-size ITER-like test bed and represents an intermediate step between the small IPP source and the full size ITER source. ELISE has one of the largest existing negative ion sources and can be operated for one hour.

The next step towards the full size ITER source and injector will be respectively the test beds SPIDER (Source for the Production of Ions of Deuterium Extracted from an RF plasma) [11] and MITICA (Megavolt ITER Injector and Concept Advancement) [12], both under construction at Consorzio RFX (Padova, Italy). Their aim will be respectively to test the full scale ITER-like NBI source, with a beam energy of 100 keV, and the whole system at the required beam energy of 1 MeV.
2 Processes in a negative hydrogen ion source and beam physics

In the following, the structure of the IPP prototype negative ion sources is described and an introduction on the beam physics is given.

2.1 The RF source

The development of the negative hydrogen ion sources for ITER NBI was initially concentrated on filamented arc sources, as described in the ITER reference design in 2002 [13, 14]: electrons are emitted from hot cathodes (usually tungsten filaments) and then accelerated into the source body, where they create a plasma by ionisation of the background gas. Because of sputtering, the tungsten filament lifetime is finite, so these sources require regular maintenance (it is estimated to be about twice a year in the case of ITER).

Taking into account this problem, the RF driven negative ion sources, developed and optimised at IPP in the past years, were suggested as an alternative, and since 2007 the IPP RF source is the reference design for the ITER NBI source [9]. In these sources an oscillating electric field is induced by a RF coil, accelerating free electrons in the source body and creating a plasma by ionisation. Compared to arc sources, RF sources require less maintenance, since no filament is present. Additionally, since the cesium is needed to enhance the source performance (see Sect. 2.1.1), in RF sources the cesium consumption might be less than in the case of arc sources, because no filament material can bury the cesium layer on the walls.

The IPP prototype source for negative ions consists mainly of three parts (shown in Fig. 8):

- the driver, where the RF power is coupled to the plasma;
- the expansion region;
- the extraction region.

![Figure 8: Schematic view of the IPP prototype RF source [15]. It consists of three regions: the driver (on the left), the expansion region and the extraction region (on the right).](image)
The driver is mounted on the back of the source, and consists of a water-cooled RF coil, connected to a 1 MHz oscillator and wound around an aluminum oxide cylinder. An internal water-cooled copper Faraday screen protects the aluminum oxide cylinder from the plasma. The plasma side of the Faraday screen is covered by a thin tungsten layer, in order to reduce the rate of sputtering by the plasma. To ignite the plasma, a starter filament is used, which is switched off around 100 ms after the plasma ignition. Typical electron temperature and density values for hydrogen discharges are $T_e \approx 10$ eV and $n_e \approx 5 \cdot 10^{18}$ m$^{-3}$ in the driver [16].

In the expansion region, the plasma expands into the source body, cooling down the electrons created in the driver to a temperature $T_e \approx 1$ eV near the extraction region, in order to reduce the probability of destruction of negative ions by electron impact (see Sect. 2.1.1) and to limit the amount of electrons ($n_e \approx 5 \cdot 10^{17}$ m$^{-3}$ near the extraction region) [16]. The cooling-down from the expansion region is further assisted by a magnetic filter field, which separates the expansion and the extraction region.

The source is kept at high potential (for the BATMAN test facility, this potential is around $-20$ kV).

The negative ions, $H^-$ and $D^-$, are created in the source by volume and surface processes (described in the next section), and then extracted and accelerated. As already mentioned, the region downstream the ion source is called drift region. Here the ion beam is partially neutralised and several diagnostic systems are mounted in the tank downstream the negative ion source in order to study the beam properties.

Deuterium operation is possible for a limited integrated length pulse because fast deuterium particles can react with deuterium embedded in beam line components and thus produce neutron radiation (for safety reason, a maximum threshold of produced neutrons cannot be overcome).

### 2.1.1 Creation of negative hydrogen ions

Creation of negative hydrogen ions can occur via volume or surface processes.

The volume processes are due to dissociative attachment of electrons to highly vibrationally excited hydrogen molecules in their electronic ground state:

$$
H_2 + e^- \rightarrow H_2(v) + e^- \quad (15)
$$

$$
H_2(v) + e^- \rightarrow H^-_2 \rightarrow H^- + H_0 \quad (16)
$$

where $v$ is the vibrational excitation level and $H_2(v)$ is the vibrationally excited hydrogen molecule, produced by the reaction in Eq. (15).

In the surface processes, instead, atoms or positive hydrogen ions interact with the surface of the first grid of the extraction system and are converted into negative ions:

$$
H, \ H^+ + e^-_{surface} \rightarrow H^- \quad (17)
$$

The reaction rate of this conversion process is strongly increased for a low surface work function. In the negative hydrogen ion source for ITER NBI, the work function of the surface is kept low by coating the surface with cesium.

Volume processes permit to avoid the use of cesium, whose distribution is governed by plasma and is difficult to predict. However, at the required pressure of 0.3 Pa in the
source, the negative ion current due to only volume processes is much below the ITER requirements [15] and the ratio of co-extracted electrons to extracted negative hydrogen ions is consequently high. Thus, the surface process has to be exploited.

Two volume reactions dominate the destruction of negative hydrogen ions, which have a binding energy of the electron of 0.75 eV: mutual neutralisation (Eq. 18) and electron detachment (Eq. 19). The reaction rate for the latter process depends on the temperature of the electrons [17].

\[
\begin{align*}
H^- + H^+ & \rightarrow H + H \\
e^- + H^- & \rightarrow 2 e^- + H
\end{align*}
\]

The latter reaction is dominant above \( T_e \approx 2 \, \text{eV} \). As already mentioned, a magnetic filter field is used to separate the expansion region from the extraction zone near to the plasma grid, as shown in Fig. 8, in order to cool down the electron temperature and to limit the number of co-extracted electrons. Electrons feel the magnetic field and gyrate around the field lines with the Larmor radius given by Eq. (6) (see Sect. 1.1.3); they can pass the magnetic filter field in axial direction by Coulomb collisions with a cross section \( \sigma_{\text{Coul}} \) depending on their velocity. In fact, the collision frequency \( \nu_c \), correlated to the velocity by \( \nu_c \propto v^{-3} \) [18], is given by the following equation:

\[
\nu_c = n \, \sigma_{\text{Coul}} \, v \tag{20}
\]

where \( n \) and \( v \) are respectively the electron density and velocity. As a consequence, \( \sigma_{\text{Coul}} \propto v^{-4} \) and cold electrons are favoured in accessing the extraction region.

The magnetic filter field is of the order of 5-10 mT near the plasma grid, and causes drifts in the plasma. The most relevant one is the \( \vec{E} \times \vec{B} \) drift (where \( \vec{E} \) is the electrical field present in the plasma due to local variation of the plasma potential along the axial axis), and the plasma can become inhomogeneous [19].

Downstream the magnetic filter field, mutual neutralisation becomes the main destruction process of negative ions. The survival length of the negative ions in the source plasma is in the order of a few centimeters, so only ions created in the vicinity of the plasma grid can be extracted. As the electrons in this region have a lower temperature, the mean free path of negative hydrogen ions increases to few tens of centimeters [20]. As already mentioned, to maximise the amount of negative hydrogen atoms, a thin and homogeneous cesium layer covers the first grid of the extraction system, in order to reduce the work function to approximately 2 eV [21].

Cesium is released by an oven mounted in the back side of the source body (as shown in Fig. 8). The oven nozzle penetrates a few centimeters into the source body and cesium is dispensed continuously during and between discharges. The evaporation rate is controlled by the oven temperature (130-150 °C). Cesium appears to accumulate in the source body in those areas where there is less contact between the plasma and the source wall, hence the cesium redistribution is governed by the plasma itself.

For stable operation, the temperature of the source wall is kept typically around 35 °C, above the cesium melting point (28 °C). The temperature of the plasma grid, instead, is above 120 °C, because for such temperatures experimentally higher source performances have been observed [15].
2.1.2 Extraction region

The extraction and acceleration of the negative ions is done at the IPP test facilities using three grids [22]:

- the plasma grid (PG);
- the extraction grid (EG);
- the grounded grid (GG).

Every grid has many apertures, whose diameter is typically in the range of 3-14 mm. The extracted negative ions passing through one plasma grid aperture create a beamlet and the beam consists of all the beamlets exiting from the grid system.

The boundary region between the plasma and where the charged particles feel the extraction voltage is called meniscus. It is defined as the surface with a potential of zero with respect to the source. The shape of the meniscus is a convex lens, which determines the initial beamlet quality.

The grid system currently in use at the BATMAN test facility is the Large Aperture Grid (LAG): the distance between the plasma grid and the extraction grid is about 3 mm and the aperture diameter is 8 mm. These two features are really relevant for the beam optics, as it will be described in Sect. 2.2.

The EG and GG are made of copper, because copper can receive a huge amount of heat when suitably cooled, thanks to its high heat conductivity. The PG instead is made of molybdenum (or is only covered by molybdenum), in order to avoid copper release by sputtering that could contaminate the cesium layer, increasing this way the work function introduced in the previous section.

The plasma grid has more or less the same high potential as the ion source (∼ −20 kV) [23]. The PG apertures are chamfered in order to enhance the extraction rate of negative ions, increasing the area available for surface processes to take place and giving the ions a higher chance to be emitted in the direction of the accelerator downstream the source [24].

As already mentioned, not only negative ions, but also electrons are extracted. In order to decrease the amount of co-extracted electrons, the plasma grid is biased positively against the source body (10-20 V). The beneficial effect is more pronounced by introducing an additional plate (bias plate, BP) in front of the plasma grid in the plasma side, which is electrically connected to the source walls: it decreases the biased area by extending the source potential near the apertures [25]. However, also the amount of extracted negative hydrogen ions is slightly decreased by the bias voltage.

The plasma grid and the bias plate of the BATMAN test facility are displayed in Fig. 9.
The extraction grid is equipped with embedded CoSm magnet rods with alternating magnetisation, in order to deflect the co-extracted electrons out of the accelerated beam. Due to the presence of these magnets, the extraction grid is quite thick (~ 10 mm). The deflection field lines so created are perpendicular to the magnetic filter field ones.

A schematic view of the plasma and the extraction grids and of the magnetic configuration in that region is displayed in Fig. 10. A simulation of negative ion and electron trajectories is then shown in Fig. 11: the electrons hit the extraction grid due to the deflection field, while the negative hydrogen ions are accelerated to the drift region downstream the grounded grid.

The potential difference applied between the plasma grid and the extraction grid (extraction voltage, $U_{ex}$) is typically of 5-10 kV, in order to keep the power deposited by the co-extracted electrons on the extraction grid on an acceptable level (below 25 kW at BATMAN). This is the main technical limitation of negative ion sources, because it limits also the amount of the extracted ion current.

Figure 10: Schematic of the magnetic field structure in the extraction region [24]. The magnetic filter field is perpendicular to the deflection field, created by the embedded magnets in the extraction grid.

Figure 11: Calculated trajectories of electrons and negative hydrogen ions, at 9.6 kV extraction voltage and 16.8 kV acceleration voltage. The geometry system corresponds to the one used in the BATMAN test facility [22].
The grounded grid is at zero potential and the second voltage gap (acceleration voltage, \(U_{acc}\)) between extraction and grounded grid is usually in the BATMAN test facility about 8-15 kV, hence the total voltage is in the range of 15-25 kV.

## 2.2 Beam physics

The optic properties of the beamlets and thus also of the complete beam depend on the space charge distribution and on the electric and magnetic fields in the extraction system [26].

An important parameter to describe the beam optics is the perveance \(\Pi\), defined by the following formula [27]:

\[
\Pi = \frac{I_{ex}}{U_{ex}^{3/2}}
\]

where \(I_{ex}\) is the extracted current and \(U_{ex}\) is the extraction voltage.

It is also possible to define a maximum perveance \(\Pi_0\) (Eq. 23), since the maximum possible extracted current \(I_{ex}^{max}\) is limited by the Child-Langmuir law, because of the space charge of the beamlet [28, 29]:

\[
I_{ex}^{max} = \frac{4}{9} \pi \epsilon_0 \sqrt{\frac{2e}{m}} \left( \frac{r}{d} \right)^2 U_{ex}^{3/2}
\]

\[
\Pi_0 = \frac{I_{ex}^{max}}{U_{ex}^{3/2}} = \frac{4}{9} \pi \epsilon_0 \sqrt{\frac{2e}{m}} \left( \frac{r}{d} \right)^2
\]

where \(\epsilon_0\), \(e\), \(m\), \(r\) and \(d\) are respectively the permittivity of free space, the electron charge, the particle mass, the radius of the aperture and the distance between the plasma grid and the extraction grid. As a consequence, \(\Pi_0\) depends only on the grid characteristics and on the effective mass of the ion species.

To describe the beam optics, as reference parameter the normalised perveance \(\Pi/\Pi_0\) is applied, due to its correlation with the beamlet divergence, which is an index of the beamlet opening caused by the space charge expansion. Assuming that the distribution of the angles between the beam axis and the velocity vector of the beam particles after the extraction system is a Gaussian distribution\(^1\) with standard deviation \(\sigma\), the divergence angle \(\epsilon\) is defined as:

\[
\epsilon = \sqrt{2} \sigma
\]

Generally, the beamlet divergence \(\epsilon\) depends on the perveance (hence on the extracted current and the extraction voltage) and on the ratio of the extraction to the acceleration voltage (Eq. 25) in a three-grids extraction system.

\[
\epsilon = \epsilon \left( \Pi/\Pi_0, \frac{U_{ex}}{U_{acc}} \right)
\]

The optimum normalised perveance condition is reached when the divergence is at its minimum value: with increasing \(\Pi/\Pi_0\), the divergence decreases (this region is called

---

\(^1\)Gaussian distribution: \(\frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-m)^2}{2\sigma^2}}\)
under-perveant region) reaching its minimum (at normalised perveance between 0.1 and 0.2 in the BATMAN test facility), then it increases again (over-perveant region). In the example in Fig. 12, the typical trend of the divergence as a function of the normalised perveance is displayed. Experiments with normalised perveance beyond the optimum value are difficult because of technical limitations which do not allow to obtain a very large extracted ion current, otherwise also the co-extracted electron current would increase too much, overcoming the safety limits on the load of the extraction grid by the co-extracted electrons.

Figure 12: Typical trend of the beamlet divergence as a function of the normalised perveance. The measurements have been carried out in the BATMAN test facility. The divergence has been estimated by the beam emission spectroscopy diagnostics (see Sect. 3.2.1).

As the extraction system can be considered as a system of electrostatic lenses, the normalised perveance is connected to the focus point of the single beamlet. This explains also the dependence of the divergence on the normalised preveance: a bad optics is correlated to a large divergence, as shown in Fig. 13 [30].

The beamlet divergence depends also on the onset of the space charge compensation. The repulsive force caused by the negative space charge of the beamlet leads to a continuous

Figure 13: Sketch of the beamlet shape for three different cases: when the focus point is too close to the plasma grid (a) and when it is downstream the extraction grid (c), the beamlet has a bad optics and shows a big broadening. In (b) the focus point is nearby the extraction grid, and this is correlated to a good optics [30].
increase of the beamlet divergence. This increase is stopped by space charge compensation downstream the extraction system, when the creation of slow positive ions in the drift region occurs mainly due to the interaction between neutrals H\textsubscript{0} or negative ions H\textsuperscript{−} and the background gas:

\begin{align}
\text{H}^0 \text{ ionisation} : \text{H}^0 + \text{H}_2 &\rightarrow \text{H}^+ + \text{e}^- + \text{H}_2 \\
\text{H}_2 \text{ ionisation} : \text{H}^0 + \text{H}_2 &\rightarrow \text{H}^0 + \text{e}^- + \text{H}_2^+ \\
\text{H}^- \text{ double stripping} : \text{H}^- + \text{H}_2 &\rightarrow \text{H}^+ + 2 \text{e}^- + \text{H}_2
\end{align}

(26) \quad (27) \quad (28)

An attractive force is therefore created and the beamlet broadening is reduced [31]. The space charge compensation fully sets in at a certain distance downstream the grounded grid. This distance depends on the tank pressure and simulations show that it is in the range of 10-15 cm [23]. However, this phenomenon is still under investigation.

Since negative hydrogen ions have an electron binding energy of only 0.75 eV, they are easily neutralised by collisions with the residual gas not only in the drift region, but also in the extraction region before reaching their full energy [32]. The stripping depends strongly on the gas pressure. Hence in order to minimise the stripping losses, it is necessary to minimise the pressure, and this is the reason why one requirement for the ITER NBI system is a source filling pressure below 0.3 Pa. At this pressure, the stripping losses for the ITER NBI system are foreseen to be about 30\% [10].

Fig. 14 represents an illustration of the extraction system, with the trajectories of negative ions, stripped particles and neutrals.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure14.png}
\caption{Sketch of the extraction system with trajectories of negative ions, stripped electrons and neutrals [33].}
\end{figure}

For a negative hydrogen ion beam, the stripping reactions are:

\begin{align}
\text{H}^- \text{ stripping} : \text{H}^- + \text{H}_2 &\rightarrow \text{H}^0 + \text{e}^- + \text{H}_2 \\
\text{H}^- \text{ double stripping} : \text{H}^- + \text{H}_2 &\rightarrow \text{H}^+ + 2 \text{e}^- + \text{H}_2
\end{align}

(29) \quad (30)

The fraction of stripped particles can be calculated by a simple 1D model, taking into account the neutral density profile \(n(x)\) obtained from the local pressure and temperature of the gas along the beamlet axis [33]:

\[ f_s(x_{GG}) = 1 - \exp \left( - \int_{x=0}^{x=x_{GG}} n(x) \cdot \sigma_{\text{strip}}(E(x)) \, dx \right) \]

(31)
Figure 15: Cross section for the stripping reaction in Eq. (29) as a function of the H\(^{-}\) energy [34].

where \(x_{GG}\) is the position of the grounded grid (the origin of the beamlet axis corresponds to the plasma grid position) and \(\sigma_{\text{strip}}\) is the cross section of the reaction in Eq. (29) and depends on the local particle energy \(E(x)\), as shown in Fig. 15.

Thus, the amount of stripping losses depends on:

- the particle energy, hence on the extraction and the acceleration voltage;
- the tank and the source pressure, because the stripping losses are correlated to the neutral density profile.
3 IPP test facility: BATMAN

In the following section, the IPP prototype source installed in the BATMAN (BAvarian Test MAchine for Negative ions) test facility and the diagnostic tools mounted in the tank of BATMAN for the beam investigation are described.

3.1 Description of the ion source

BATMAN is a small test bed at IPP, mainly devoted to optimise the IPP prototype RF source with respect to the extracted current density, at pressure and co-extracted electron current density at ITER relevant parameters. The BATMAN test bed is also used for the development of new diagnostic tools and in order to get a better understanding of plasma and beam behaviour.

BATMAN is equipped with an IPP prototype negative ions source, consisting of, as already mentioned, a 150 mm long aluminum oxide cylinder, with an inner diameter of 235 mm and a water-cooled RF coil connected to a 1 MHz oscillator. Typical power of the RF coupled to the plasma is in the range of 20-100 kW. BATMAN is operating with short pulses (∼4 s), because of limitations of the high voltage power supply and the low pumping speed of the titanium-getter pumps in the main vacuum tank [15, 35].

A cesium oven is mounted on the back side of the source and is stored in three capsules. Cesium is introduced into the source continuously at a rate of typically 10 mg/h and the evaporation rate is controlled by the oven temperature (usually this temperature is 160 °C) [15].

The source body has an area of $0.32 \times 0.59$ m$^2$ and is 0.23 m deep, and the typical range of the filling pressure is 0.2-1 Pa. Since by coupling of the RF into the pressure measurement device, the result of the pressure measurement may be disturbed during the pulse, the pressure is calibrated before the operation by means of the gas flow (which is the parameter set for operation) through the pump valve.

As already mentioned, the source is at high potential (∼−20 kV), as well as the plasma grid. The two voltage gaps among the grids are typically in the range of 5-10 kV for the extraction voltage and 8-15 kV for the acceleration voltage. The plasma grid is positively biased of 10-20 V and the bias power supply is current controlled.

The magnetic filter field in BATMAN is created by permanent magnets, which originally were embedded internally in the diagnostic flange near the plasma grid. This way, the axial distance of the center of the magnets (i.e. the maximum of the filter field) from the plasma grid was $z = 3$ cm (where $z$ is the distance from the PG), but this configuration had no flexibility [20]. Hence a new magnet frame, consisting of two magnets boxes, was mounted outside the source body, allowing fast changes of the magnetic filter field configuration.

This frame can be moved continuously along the source body, from the diagnostic flange (corresponding to the closest position to the plasma grid: $z = 9$ cm) up to the driver exit ($z = 19$ cm). The two magnets boxes are attached to the sides of the source body and are filled each with $2 \times 4$ CoSm magnets (with dimensions $9 \times 13 \times 50$ mm$^3$ and a maximum magnetic strength of 1 T). With this configuration, the magnetic filter field is horizontal and its maximum strength (at the centre of the plasma grid) is about 7 mT. Additionally, the magnet boxes can be exchanged, in order to change the horizontal magnetic field direction by 180°. As a consequence, also the drift of the plasma changes.
Figure 16: Horizontal section cut of the IPP prototype source attached to the BATMAN test facility [20]. The magnet positions are indicated. The z-axis starts from the centre of the plasma grid.

its direction (plasma drift can be up or down, accordingly to the right-hand rule) and a different top/bottom asymmetry can be seen in the plasma.

An illustration showing the horizontal section cut of the IPP prototype source in the BATMAN test bed is presented in Fig. 16. The diagnostic flange and the magnet frame for the permanent magnets are indicated too.

Currently, the extraction system used at BATMAN is based on the LAG (Large Area Grid) system, with a distance between plasma and extraction grids of 3.5 mm. The PG is shown in Fig. 9 (in Sect. 2.1.2) and consists of two identical grid halves with 63 chamfered apertures each and inclined by 0.88° for beam focusing reasons. The apertures are displaced in six rows with alternating 11 or 10 apertures, with an aperture diameter of 8 mm; hence the total extraction area is 63.33 cm². The distance between the centres of two apertures in the horizontal direction is 11.6 mm and the vertical distance is 11.9 mm.

The PG is heated by heating wires connected to an external power supply, and the plasma grid temperature is chosen by the user.

In the drift region, the extracted and accelerated ions hit a calorimeter 1.5 m downstream the GG (details in Sect. 3.2.2).

The electrical currents flowing onto the extraction and the grounded grid ($I_{EG}$ and $I_{GG}$, respectively) and the total current flowing back to the High Voltage (HV) power supply ($I_{drain}$) are measured. It can be reasonably well assumed that for good beam optics negative ions do not hit the extraction grid, thus the current measured on the extraction grid $I_{EG}$ is almost completely due to the electron contribution [15]. Analogously, the currents from the grounded grid $I_{GG}$ and from the calorimeter should be carried by the extracted negative ions, with a negligible contribution by electrons. Since the two latter currents are measured separately, the distribution of the negative ions hitting the grounded grid and the calorimeter can be determined: 10-20% of $I_{ion}$ is stopped on the grounded grid, depending on the beam optics (hence on the perveance), and 70-80% hits the calorimeter. The current densities then are calculated by dividing the respective currents by the extraction area.
In order to preserve the safety of the extraction grid, the power deposited by the electrons onto the EG in the BATMAN test bed is limited to 25 kW. As a consequence, also the obtainable ion current density and the source performance are limited. Thus an important operational parameter is the electron-to-ion ratio, given by the ratio of the electron current $I_{\text{EG}}$ and the ion current $I_{\text{ion}}$.

A schematic overview of the electrical circuit of BATMAN is shown in Fig. 17. The currents are also indicated.

The normal duty cycle of the source at BATMAN is one shot every four minutes and, during the shot, the beam is extracted for 4 s. Additionally, there is a delay between RF switching on and the beam extraction of 1500 ms, in order to allow the plasma in the source to stabilise. In order to facilitate spectroscopic measurement there are further 100 ms after the high voltage is removed and before the RF is terminated. The time trace is shown in Fig. 18.

BATMAN achievements are summarised in Tab. 3, together with the ITER requirements: it can be seen that the current densities and the electron-to-ion ratio satisfy the ITER requirements. However, BATMAN can operate only with short pulses, and the
extraction area is only of 63 cm².

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER requirements</th>
<th>BATMAN achievements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction area</td>
<td>0.2 m²</td>
<td>0.0063 m²</td>
</tr>
<tr>
<td>Calorimetric current density</td>
<td>200 A/m² D⁻</td>
<td>230 A/m² D⁻</td>
</tr>
<tr>
<td></td>
<td>280 A/m² H⁻</td>
<td>330 A/m² H⁻</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>9 kV</td>
<td>9 kV</td>
</tr>
<tr>
<td>Source pressure</td>
<td>0.3 Pa</td>
<td>0.3 Pa</td>
</tr>
<tr>
<td>Electron content (jₑ/jₑ⁻)</td>
<td>≤ 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3600 s</td>
<td>4 s</td>
</tr>
<tr>
<td>Source dimensions</td>
<td>1.9 × 0.9 m²</td>
<td>0.32 × 0.59 m²</td>
</tr>
<tr>
<td>Uniformity</td>
<td>± 10%</td>
<td>t.b.d.</td>
</tr>
</tbody>
</table>

Table 3: ITER requirements and achievements of the BATMAN test facility [15].

### 3.2 Beam diagnostics in BATMAN

The BATMAN test facility is equipped with several diagnostic tools in the source and in the vacuum tank to study respectively the plasma and the beam properties. The following sections will focus on the diagnostic systems in the vacuum tank, whose purpose is to investigate the negative ion beam properties (the diagnostics are shown in Fig. 19):

- the Beam Emission Spectroscopy (BES) system;
- the water-cooled copper calorimeter, equipped with thermocouples;
- the mini-STRIKE calorimeter.

The copper calorimeter and mini-STRIKE can not be used simultaneously. Most of the activity described in this thesis has been performed with BES and mini-STRIKE.

Figure 19: Picture inside of the BATMAN tank. The beam diagnostic systems are highlighted in yellow.
3.2.1 Beam Emission Spectroscopy (BES)

For studying the beam properties in BATMAN, the hydrogen Balmer emission line H$_\alpha$ (corresponding to the transition from $n = 3$ to $n = 2$, where $n$ is the principal quantum number) is considered, because of its larger emissivity compared to the other hydrogen emission lines [36].

Excited hydrogen atoms are created by collisions of the ion beam with the residual gas. The main reactions are:

\[ \text{H}^- \text{ excitation} : \text{H}^- + \text{H}_2 \rightarrow \text{H}_0^f(n = 3) + e^- + \text{H}_2 \] (32)

\[ \text{H}_0 \text{ excitation} : \text{H}_0^f + \text{H}_2 \rightarrow \text{H}_0^f(n = 3) + \text{H}_2 \] (33)

\[ \text{Dissociative excitation} : \text{H}_0^f + \text{H}_2 \rightarrow \text{H}_0^f + 2 \text{H}_0^s(n = 3) \] (34)

where the indices $f$ and $s$ denote respectively fast and slow particles.

The subsequent de-excitation of the excited hydrogen by spontaneous emission to $n = 2$ results in the H$_\alpha$ Balmer emission line radiation.

The wavelength $\lambda_0$ of an emission line, from the excited level $a$ to the lower level $b$, depends on the emitted photon energy, hence on the energy gap between the two levels:

\[ \lambda_0 = \frac{h \cdot c}{E_a - E_b} \] (35)

where $h$ is the Planck constant and $c$ is the speed of light in vacuum. This parameter for H$_\alpha$ is 656.28 nm.

Because of the presence of fast particles, the wavelength of the emitted photons for the reactions in Eqs. (32) and (33) can be shifted with respect to the wavelength $\lambda_0$, calculated from Eq. (35). On the contrary, the reaction in Eq. (34) creates slow particles, hence the radiation emitted from these particles is not affected by Doppler effect.

The Doppler wavelength shift $\Delta \lambda$ depends on the velocity $v_0$ of the particles, hence on the energy they gather during the acceleration in the extraction region, and on the observation angle $\theta$, shown in Fig. 20:

\[ \Delta \lambda = \lambda_0 \cdot \frac{v_0}{c} \cdot \cos \theta \] (36)

\[ v_0 = \sqrt{\frac{2 \cdot U \cdot e}{m_{\text{ion}}} \cdot \cos \theta} \] (37)

Figure 20: Illustration of a BES line-of-sight. $\theta$ is the observation angle between beam axis and LOS. Courtesy of B. Ruf (IPP).
where $U$ is the voltage accelerating the particle, $e$ is the electron charge and $m_{\text{ion}}$ is the particle mass [37].

However, not all the particles are fully accelerated. As described in Sect. 2.2, about 30% of the extracted particles are foreseen to be affected by stripping in the NBI system for ITER. In the BATMAN test facility, the stripping fraction is expected to be 8%. This value is different from the ITER one because in the ITER NBI the acceleration length is larger (there will be seven grids instead of three).

Thus, in a BES spectrum taken at a negative hydrogen ion source (an example is shown in Fig. 21), three peaks are seen [33]: the first one (1) is the H$_\alpha$ unshifted peak at $\lambda_0 = 656.28$ nm, due to reaction in Eq. (34). Peak (2) is the Doppler-shifted peak and is due to the fast neutrals having the full accelerated energy $E_0$, corresponding to the total beam energy (15-25 keV for BATMAN). Peak (3) is called stripping peak and represents photons emitted by neutrals that have less than the full energy, so it is always in between the two peaks previously described (typically the position of the maximum corresponds to the particle energy $E_{\text{ex}}$ associated to the extraction voltage, which is in the range of 5-10 kV for BATMAN).

![Figure 21: Typical H$_\alpha$ Doppler-shift spectrum for a negative hydrogen ion beam [33].](image)

The standard evaluation of a BES spectrum allows to estimate the beam divergence and the stripping fraction. The observation angle changes along the line-of-sight, because of the divergence of the beamlets (see Fig. 20); as a consequence, the Doppler-shifted peak has a bell-shaped profile, and its width is correlated to the divergence $\epsilon$ of the beamlets by the formula [33]:

$$
\epsilon = \frac{\lambda_{1/\epsilon}}{\Delta \lambda \tan \theta}
$$

where $\Delta \lambda$ is the Doppler shift calculated via Eq. (36), $\theta$ is the observation angle and $\lambda_{1/\epsilon}$ is the measured half $1/\epsilon$ width of the Doppler peak fitted by a Gaussian (considering only the part of the peak above 30% of the maximum peak value in the case of the standard evaluation technique). This width is corrected from other effects leading to additional broadening, like the apparatus profile of the spectrometer and the aperture angle of the line-of-sight. This divergence estimation represents to an averaged beamlet divergence along the line-of-sight.
The stripping fraction $f_s$ is given as the fraction of neutral atoms in the beam with less than the full energy $E_0$:

$$f_s = \frac{j_{H^0}(E < E_0)}{j_{H^0}(E < E_0) + j_{H^0}(E_0) + j_{H^-}(E_0)}$$

(39)

where $j$ indicates the respective current density and $E$ the particle energy.

The stripping fraction can be estimated experimentally from the ratio of the integral of the stripping peak ($I_{E<E_0}$) to the integral of the fully shifted peak ($I_{E_0}$), properly weighed considering the neutralisation fraction $f_n$ of the fully accelerated beam (which is defined by Eq. 40) and the emission cross sections [38].

$$f_n = \frac{n_{H^-}(E_0)}{n_{H^-}(E_0) + n_{H^0}(E_0)}$$

(40)

where $n_{H^-}$ and $n_{H^0}$ are the negative ion density and the density of the neutral beam particles, respectively.

The stripping peak is broadened due to the divergence of the beamlets and, additionally, due to the energy distribution of the stripped neutrals. However, for the estimation of the stripping fraction, the stripped particles are considered to have the same energy (corresponding to $E_{\text{ex}}$), while the emission cross section for the stripped neutrals is almost constant in the respective energy range (see Fig. 15 in Sect. 2.2). The resulting estimation of the stripping fraction is determined by the following formula [33]:

$$f_s = \frac{I_{E<E_0}}{I_{E<E_0} + \sigma_{0\alpha}(E_{\text{ex}}) I_{E_0} \left( \frac{f_n}{\sigma_{0\alpha}(E_0)} + \frac{1-f_n}{\sigma_{-1\alpha}(E_0)} \right)}$$

(41)

where $\sigma_{-1\alpha}$ is the cross section of reaction in Eq. (32) and $\sigma_{0\alpha}$ is the cross section of reaction in Eq. (33).

However, the estimation of the stripping fraction via BES can be influenced by the negative ion optics: the typical trend of $f_s$ estimated by BES as a function of the normalised perveance is displayed in Fig. 22. The probability that stripped hydrogen atoms can

Figure 22: Typical trend of the stripping fraction estimated by the BES system in perveance scans with hydrogen beams, in the BATMAN test facility.
leave the accelerator depends on the negative ion trajectories at the position at which
the stripping process occurs; if the beam is too broad (low perveance is connected to
high divergence, as seen in Sect. 2.2), the number of stripped atoms being lost in the
acceleration system is high and less stripping losses are measured by BES.

Furthermore, the standard evaluation assumes that the Doppler-shifted peak is due
only to the fully accelerated particles, with no contribution of stripped particles. This is
not true, hence it results in an underestimation of the stripping fraction (of a factor of
two) and an overestimation of the beam divergence [39].

The BATMAN test facility has been recently (end 2013) equipped with five telescopes
for BES measurements in order to investigate the beam vertical profile with a high spatial
resolution. Before then, there were only two telescopes arranged in a vertical array and
installed in front of a flange window. They could not have a symmetrical vertical arrange-
ment with respect to the centre of the plasma grid, covering upper and lower half of the
grid system, because of the titanium compound covering the upper area of the flange win-
dow (due to the titanium-getter pump), thus the two lines-of-sight (LOS) were vertically
arranged at the lower part of the window. Since beamlets of both grid halves contributed
to the divergence measurement of the upper LOS, while for the lower LOS only beamlets
of the lower grid half contributed to the divergence measurement, a deep investigation of
the beam vertical profile could not be possible at that time. The five LOS now installed
in the BATMAN test facility in a symmetrical arrangement could give more information
about this issue.

The optic heads of the BES system consist of lenses of about 20 mm diameter and
with a broadening of about 0.6° [39]. The lenses focus the collected light to optical fibres
connected to a spectrometer and, to protect the lenses from impurities, a 175 mm pipes
are mounted in front of the lenses.

The five telescopes of the BES system are shown in Fig. 23: the lines-of-sight (LOS)
are numbered from the bottom to the top. A portion of the copper calorimeter can be
seen on the left.

Figure 23: Picture of the BES system currently mounted in the tank of the BATMAN test facility.
The five lines-of-sight (LOS) are indicated and numbered from the bottom to the top.
On the left, there is a portion of the copper calorimeter.

The five telescopes are connected to a five-channel ANDOR spectrometer equipped
with a CCD. This spectrometer has a spectral resolution that is sufficient in order to have a well resolution of the peaks and get information about the beamlet divergence and the stripping fraction. The technical details of the spectrometer are summarised in Tab. 4.

The BES system is absolutely calibrated with an Ulbricht sphere, in order to have the possibility to estimate the beam intensity profile from the spectra.

The integration time for an acquisition is 1 s and the observation angle $\theta$ is 147°. The distance between the optic heads and the grounded grid is about 1.2 m.

The LOS are arranged vertically, and the vertical space between two consecutive LOS is 40 mm. Considering the centre of the plasma grid as the origin of a coordinate system, the position of the five LOS tagged by the vertical distance from the centre is given in Tab. 5. The vertical position of the five LOS, with respect to the grid system is indicated in Fig. 24. With this arrangement, it is possible to get information about the vertical beam inhomogeneity.

<table>
<thead>
<tr>
<th>Line-of-sight</th>
<th>Vertical distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS 1 (lower)</td>
<td>-80</td>
</tr>
<tr>
<td>LOS 2</td>
<td>-40</td>
</tr>
<tr>
<td>LOS 3</td>
<td>0</td>
</tr>
<tr>
<td>LOS 4</td>
<td>40</td>
</tr>
<tr>
<td>LOS 5 (upper)</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 5: Vertical position of the LOS of the BES system in the BATMAN test facility. The origin of the coordinate system is the vertical centre of the plasma grid.

Figure 24: Picture of the plasma side of the plasma grid in the BATMAN test facility. The vertical position of the five LOS of the BES system with respect to the grid system is indicated. The optic heads are situated 1.2 m downstream the grounded grid.
3.2.2 Calorimeter with thermocouples

The calorimeter is located at a distance of 1.5 m downstream the grounded grid (as indicated in Fig. 17 in Sect. 3.1). It collects the fast neutrals and the ions accelerated by the source, providing a measurement of the accelerated current density.

The calorimeter is a water-cooled copper panel $60 \times 60 \text{ cm}^2$ (a picture is shown in Fig. 25), equipped with 29 thermally isolated areas (1 cm$^2$ each) where thermocouples provide a temperature measurement. The thermocouples are arranged as a cross and thermally separated by special cuttings and the distance between two consecutive thermocouples is 4 cm.

![Figure 25: Picture of the BATMAN copper calorimeter taken after many shots [39]. The thermocouples are arranged as a cross.](image)

The 2D measured temperature profiles given by means of the thermocouples are related to the beam power deposition on the calorimeter. The 2D beam power profiles obtained are then fitted by a 2D Gaussian, as shown in Fig. 26. Integrating this Gaussian to infinity, it is possible to estimate the total power of the beam, including also the particles not hitting the calorimeter. Dividing this power by the extraction area value and the total beam voltage $U_{\text{HV}}$, a lower limit for the calorimetric current density is obtained, assuming that all the particles have been fully accelerated. As described in Sect. 3.1, this current density contributes to the total ion current density measured.

The calorimeter beam power deposition profile allows to estimate the beamlet divergence by means of an IPP code, the DENSBO [22]. In this code, beamlets are assumed to be

![Figure 26: Comparison between data fitted by a 2D Gaussian and the beam profile given by DENSBO code, for a divergence $\epsilon$ of 2.4° [22].](image)
emitted at the position of the grounded grid with a Gaussian profile. The beamlet width \( \sigma \) is correlated to the divergence by Eq. (24), hence comparing the experimental data with the simulations an estimation of the beamlet divergence is obtained. An example of this comparison is shown in Fig. 26. The measured power density profile is fitted with a 2D Gaussian, in order to compare it to the profile given by the DENS code.

Comparing the horizontal beamlet divergence by the BES system and the divergence derived from the horizontal beam power profile on the copper calorimeter (by means of the DENS code), it can be estimated the difference percentage between these two beamlet divergence estimations. Their correlation is displayed in Fig. 27: the linear fit reveals that this difference percentage is 5%. Thus, as the error associated to the BES estimation of the divergence is about 20%, the two divergence measurements are compatible.

![Figure 27](image.png)

Figure 27: Correlation between the divergence derived from the horizontal beam profile on the copper calorimeter (on the x-axis) and an average of the divergences measured by BES along the five LOS (on the y-axis), at BATMAN test facility. The trend is linear.

This calorimeter is not active when the mini-STRIKE calorimeter (described in detail in the following section) is mounted in the vacuum tank, since the copper calorimeter is partially covered by mini-STRIKE. The activity described in this thesis have been performed with the mini-STRIKE calorimeter, so no further details about the copper calorimeter will be given.

### 3.2.3 Mini-STRIKE calorimeter

STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) is one of the diagnostics of the neutral beam prototype source SPIDER, under construction at Consorzio RFX in Padova (Italy) [11]. The STRIKE calorimeter will characterise the SPIDER negative ion beam profile during short pulse operation (several seconds) [40]. STRIKE is made of 16 one-directional (1D) Carbon Fiber Composite (CFC) tiles, observed at their rear side by an infrared (IR) thermal camera.

A small-scale version (mini-STRIKE) of the STRIKE calorimeter was constructed by Consorzio RFX as a collaboration with IPP and was tested in the BATMAN test bed in 2012, in order to demonstrate and check the applicability of the CFC tiles for STRIKE. In 2014, mini-STRIKE has been installed again in BATMAN in order to characterise in detail
the properties of the beam. Mini-STRIKE is made of two identical $120 \times 90 \times 20 \text{ mm}^3$ CFC tiles$^2$ (a picture of one of the tile is shown in Fig. 28). The tiles are exposed perpendicularly to the beam and are located about 1 m downstream the grounded grid. They are arranged in vertical direction, as shown by Fig. 29, in order to characterise the vertical beam profile. At this distance from the GG, the two tiles are not large enough to completely stop the beam, especially in the horizontal direction, but this layout represents a technical compromise.

The calorimeter is fixed to the side flange of the vacuum tank by a supporting arm, shown in Fig. 30.

An IR thermal camera is mounted on a viewport of the vacuum vessel and observes the rear side of the tiles (not in the front side, because otherwise the presence of the beam would compromise the data) through a zinc selenide window. The angle between the line of sight of the camera and the beam axis is $50^\circ$. The position of the camera with respect to the tiles is shown in Fig. 31. Additionally, to fix the camera to its support, it was necessary to rotate the camera of $90^\circ$.

The thermal behaviour of the tiles have been already bench tested with a CO$_2$ laser (power range: 20-100 W, power density range: 6-32 MW/m$^2$) at Consorzio RFX [41, 42]. As expected, the thermal conductivity in direction parallel to the beam (short side of the tiles) is confirmed to be much larger than in the other two directions. As a consequence, the thermal pattern is slightly distorted during the heat conduction from the front to the rear side of the tiles in the beam-on phase.

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$^2$Mitsubishi MFC 1A

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Figure 28: Picture of a prototype CFC tile. Size: $120 \times 90 \times 20 \text{ mm}^3$.

Figure 29: Picture of the rear side of the mini-STRIKE calorimeter before mounting it in the tank. The tiles are exposed perpendicularly to the beam and are arranged in vertical direction.
The first experimental campaign at the BATMAN test facility has been carried out in 2012, in order to characterise the mini-STRIKE diagnostic properties [43]. During this campaign, an actively water-cooled copper mask with 8 holes (10 mm diameter and 30 mm pitch) was mounted in front of the prototypes at a distance of 10 mm, in order to reproduce a beamlets-like structure on a spatial scale analogous to the one expected in SPIDER. In fact, due to the low total voltage the beamlet divergence in BATMAN is usually greater than 2°: the beamlets strongly overlap each other at the mini-STRIKE position, so without the mask they would create a flat-profile. A picture of the mask used in the 2012 experimental campaign and the experimental setup inside the BATMAN tank are shown in Fig. 32.

The details of the measurements results of the 2012 experimental campaign can be found in Refs. [44, 45, 46, 47]: it was found that the system works quite well and can provide information about the beam properties in different experimental conditions.
In order to better investigate and characterise the ion beam in BATMAN, a new copper mask has been designed [48]. The new arrangement consists of 12 holes with 7 mm diameter and 28 mm pitch and 6 holes along the diagonals for each tile. Hence the BATMAN beam is sampled in 36 points as a whole. This new layout is compatible with the previous arrangement, hence the mask could be re-used closing the old holes with custom screws, as can be seen in Fig. 33.

This mask has been installed in the mini-STRIKE system in April 2014 and has been used for the investigation study described in this thesis.

![Figure 33: Picture of the front side of the new mini-STRIKE mask, currently in use. The mask consists of 36 holes. This mask was used for the previous campaign, whose arrangement consisted of 8 holes, now closed with custom screws.](image)

Furthermore, two thermocouples have been mounted on mini-STRIKE on the rear side of the two tiles, in order to check the tiles temperature.

As already mentioned, the rear side of the two CFC tiles is observed by an IR thermal camera. This camera records with a frequency of 25 frames per second for 20 s (hence 500 frames overall for each pulse) and each frame is saved as a .fpf image, consisting of a matrix \((640 \times 480 \text{ pixel}^2)\) whose elements correspond to temperature measurements.

The thermal camera is already absolutely calibrated, taking into account the emissivity of the CFC tile \((\epsilon = 1)\) and the object distance \((1 \text{ m})\). The error associated to the measured temperature is \(2 \degree \text{C} \text{ or } 2\%\) (the greater error between these two values has to be considered).

The camera is triggered 3.2 s before the beam starts (80th frame), in order to measure the background temperature before the beam-on phase. The pulse lasts 4 s, hence the beam-off phase starts at frame 181. The time trace of the RF, HV and camera triggers is shown in Fig. 34.
During the present thesis, the BATMAN beam properties were studied using the $H_\alpha$-Doppler shift spectroscopy and mini-STRIKE based on the new configuration described above; to this purpose a data analysis software was developed and tested (see Ch. 4). The results of the experimental campaigns are discussed in Ch. 5, analysing first dependencies and comparing mini-STRIKE with BES measurements in Ch. 6.
4 Software for mini-STRIKE data analysis

The programming language used for developing the data analysis software was the Interactive Data Language (IDL) [49]. For each pulse, the program analyses the frames where the beam is present (frame range: 80-180), after having subtracted the background obtained by averaging 25 frames (corresponding to 1 s) taken before the beam starts. This way, the temperature differences $\Delta T$ are considered in the following analysis.

After a perspective correction (necessary because the viewing angle is 50°), the region relevant for the further analysis is selected, i.e. the region corresponding to the two tiles, excluding the shadows of the two thermocouples and the zone between the two tiles. Furthermore, the dimensions of the x-axis and y-axis are scaled from pixels to millimeters.

Three fit procedures are then performed with the aim to obtain the beam profile: the first 2D fit is applied in order to determine the position of the centres of the beamlet-like structures by fitting singularly each peak, in order to treat them as constants (not variable) in the following second 2D fit. This second fit consists in fitting the superposition of 36 2D bell-shaped functions due to the 36 beamlet-like structures. Among all the parameters determined by the second fit, the 36 amplitudes of the 36 structures are the most important ones: they give the amplitude profile of the beam power deposition on the back of the tiles. By fitting again (third fit) these amplitudes, information about the beam profile can be obtained.

In the next sections, the individual procedures of the code will be accurately explained, taking as example the pulse #97364, whose operational parameters are summarised in Tab. 6.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Extraction voltage</td>
<td>4.7 kV</td>
</tr>
<tr>
<td>Acceleration voltage</td>
<td>15.2 kV</td>
</tr>
<tr>
<td>Magnets position</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Source pressure</td>
<td>0.5 Pa</td>
</tr>
<tr>
<td>RF power</td>
<td>51 kW</td>
</tr>
<tr>
<td>Bias current</td>
<td>10 A</td>
</tr>
<tr>
<td>Extracted current density</td>
<td>16.2 mA/cm$^2$</td>
</tr>
<tr>
<td>Normalised perveance</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Table 6: Operational parameters of the reference pulse #97364.

4.1 Background subtraction

The beam-on phase starts at frame 80. The background is calculated doing an average of 25 frames between frame 35 and frame 60. This background is then subtracted from each frame of the beam-on phase. Shown in Fig. 35 are the IR images corresponding to the raw data, the background and the temperature increase (i.e. the difference of the raw data and the background) caused by the beam striking the surface of the CFC tiles for the example pulse.
Figure 35: (a) View from the IR camera (raw data at frame 170, $\Delta t = 3.6$ s after the onset of the beam). The image is rotated of around 90°. The 36 footprints of the beamlets-like structure of the mask are clearly visible. The temperature of the top tile is higher because it is a plasma drift up pulse. The green lines will be used for the perspective correction in the next section.
(b) Background data obtained from the average of 25 frames before the beam starts (from frame 35 to frame 60).
(c) Temperature difference obtained by subtracting the background in (b) from the raw data in (a).

4.2 Perspective correction and data selection

Since the IR camera is not perfectly 90° rotated, a rotation of 0.75° anticlockwise is applied directly to the image.

In order to correct the perspective geometry, present because the thermal camera is looking at the tiles with an angle of 50°, the vanishing point has to be known: this is obtained as the meeting point of the two lines corresponding to the short sides of the back of the tiles. The perspective is then corrected by moving the elements belonging to a line passing through the vanishing point to a vertical line (for which the vanishing point is infinite). The two lines chosen to determine the vanishing point are indicated by the green dashed lines in Fig. 35(a).

The IR image resulting from the perspective correction is displayed in Fig. 36.
After the perspective correction, the pixel to millimeter conversion is performed: the multiplicator factors (horizontal and vertical) are calculated considering the real dimensions of the metallic support of the calorimeter, compared to its dimensions in pixel in the raw image.

Finally, the region of the two tiles is selected, cut and saved, since this is the only relevant zone for the further data analysis. Some areas belonging to the tiles have to be excluded from the following analysis: in correspondence of the two thermocouples and between the two tiles. An example for the final image can be seen in Fig. 37. The dark regions correspond to the thermocouples (TC) and the support in the middle of the two tiles.

The tile on the left is the lower one in the physical space (bottom tile). The tile on the right is the upper tile in the physical space (top tile). The 36 beamlets-like structure (18 for each tile) is clearly visible.
4.3 First fit: 2D single-peak fit

In order to minimise the number of free parameters, the centre of each peak is estimated by a first 2D fit. This procedure is performed at frame 105 (corresponding to 1 s after the pulse beginning), because for this frame usually the overlap of the tails of the different peaks is not strong, hence the centres evaluation is not affected by the nearby peaks. On the contrary, for the next frames the overlapping of the tails can affect the position and the maximum value of the peaks, since each peak receives heat from the closest neighbours.

The procedure consists of taking into consideration only a small area around each peak and fitting the experimental data inside this selected area with a 2D Gaussian function. This procedure is repeated for each peak separately. The Gaussian fit provides 36 \((x, y)\)-coordinates, corresponding to the coordinates \((x_{c,i}, y_{c,i})\) of the centres of the 36 peaks, where \(i\) is the peak index, \(x\) the vertical position and \(y\) the horizontal position. These parameters will be considered as constants for further analyses. Fig. 38 shows the relevant region of the IR image taken at frame 105; an example of the selected area around a peak (green rectangle) and the position of the centres (black crosses) determined by the 2D Gaussian-single peak fit.

![Figure 38: IR image taken at frame 105 (\(\Delta t = 1\) s after the onset of the beam), after background subtraction and perspective correction. The green rectangle indicates the area selected for fitting the peak present inside. The black marks indicate the centres coordinates determined by the 2D Gaussian-single peak fit.](image)

4.4 Second fit: 2D multiple-peak fit

After identifying the position of the centres of the peaks, the next step of the data analysis is to consider the set of experimental data (after background subtraction) at frame 170 (\(\Delta t = 3.6\) s after the onset of the beam). This frame has been selected because represents a good compromise: the recorded temperature differences are enough high, and the beam-off phase is not yet started. The experimental data are fitted with a 2D function, given by the superposition of 36 2D modified Hubbert functions and described by the following equation:

\[
f(x, y) = \sum_{i=0}^{35} a_i \cdot \left[ \cosh \left( \sqrt{\left( (x - x_{c,i}) \cdot w \right)^2 + \left( (y - y_{c,i}) \cdot w \right)^2} \right) \right]^{-q}
\]  
(42)

The fit takes as input the centre coordinates \((x_{c,i}, y_{c,i})\) of the \(i\)-th peak, determined by the first fit (Sect. 4.3), and the errors associated to the experimental data. The modified
Hubbert function has been chosen since, as found in previous tests [50, 51], it reconstructs the mini-STRIKE data better than Gaussian and Lorentz functions (i.e. it gives much smaller residuals).

For this fit, the number of free parameters is 38: the 36 amplitudes \( (a_0, \ldots, a_{35}) \) of the peaks, \( w \) and \( q \), which are related to the width of the peaks.

Firstly, \( w \) is assumed to be identical for all the peaks, because the holes on the mask are identical and the thermal properties of the tiles do not depend on the position where the energy flux impinges on it. The same considerations can be used for \( q \), hence no variation is expected for these two parameters.

The resulting fit is then obtained by minimising the \( \chi^2 \) function and describes quite

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Figure 39: Contour plots of the experimental data (first image) and of the second fit result (second image) for the frame 170 (\( \Delta t = 3.6 \) s after the onset of the beam). The third image represents the residuals, calculated as the difference between fit data and experimental data.

In the experimental data contour, the two white lines are taken as reference for studying 1D profile of the temperature. An example of these profiles is displayed in Fig. 40.
well the experimental data: the experimental data, the fit results and the correspondent residuals, taken at frame 170 of the reference pulse, are shown in Fig. 39, from top to bottom respectively.

In order to facilitate an easy assessment of the quality of the fit, the vertical and horizontal profiles along the two white lines indicated in Fig. 39(top) are plotted in Fig. 40: the fit describes properly the experimental data.

The calculation of the errors associated to the 38 parameters of the fit is performed via the Hessian matrix of the $\chi^2$ function. The Hessian is the square matrix of the second-order partial derivatives of the $\chi^2$ function. The inverse of the Hessian matrix is called error matrix and the elements on the diagonal correspond to the variances of the parameters. The statistical error associated to the amplitudes is usually estimated about 0.2 °C.

It is worth noting that in the beam vertical profile (as shown in Fig. 40, right) a different gradient of the maxima temperatures can be seen for the lower tile (on the left side of the plot) and the upper tile (on the right side of the same plot). Since each of the maxima temperatures is affected by the tails of the nearby peaks, they could give a wrong impression that the beam profile peak is at around $v_{pos}=180$ mm of vertical position. In fact, a peak in the centre of the tiles has more nearby beamlet-like structures than the peaks near the tile sides, hence has more contributions from nearby peaks tails, which increase its temperature.

To avoid this effect, the single 36 amplitudes of the modified Hubbert functions have to be considered, instead of the maxima temperatures in the experimental data. These amplitudes are correlated to the beam power deposition in the different holes of the mask on the front side of the tile. Hence, the 2D profile of the amplitudes provides a profile of the beam.

4.5 Further analysis: 2D fit to the peak amplitudes

In a plot of the 36 amplitudes ($a_0, \ldots, a_{35}$) given by the 2D modified Hubbert functions, the difference in the slope on the vertical profile between the upper and the lower tile is reduced but still clearly visible, as shown in Fig. 41. This figure shows the projection
Figure 41: Amplitudes projection on the "Vertical position" axis (frame 170, $\Delta t = 3.6$ s after the onset of the beam). The horizontal position ($h_{\text{pos}}$) of the peaks is indicated in the legend.

of the 36 amplitudes on the "Vertical position" axis. The respective horizontal positions of the 36 peaks are indicated in the legend.

In order to describe the profile of the 36 amplitudes, an asymmetric fitting function $h(x, y)$ has been chosen, where $x$ and $y$ are the vertical and the horizontal position respectively. This function is the product of a horizontal fit function $p(y)$ and a vertical fit function $g(x)$.

Since the spatial resolution on the horizontal profile is too low to suggest any more complicated function, a parabola $p(y)$ has been chosen (see Eq. 44).

On the contrary, the vertical profile for some pulses shows an asymmetry. To reproduce this effect, an asymmetric function (a skewed-gaussian) has been chosen (see Eq. 45). It has three free parameters: the location parameter $x_0$, a sort of standard deviation $\omega$ and the skewness $\alpha$. When $\alpha$ is zero, the normal symmetric gaussian distribution is recovered. The distribution is right skewed if $\alpha > 0$ and left skewed if $\alpha < 0$.

\[ h(x, y) = g(x) \cdot p(y) \]
\[ p(y) = a \cdot y^2 + b \cdot y + c \]
\[ g(x) = \exp \left[ -\frac{1}{2} \left( \frac{x - x_0}{\omega} \right)^2 \right] \cdot \left[ 1 + \text{erf} \left( \alpha \cdot \frac{x - x_0}{\sqrt{2} \omega} \right) \right] \]

where \( \text{erf} \) is the error function:

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \]

The fitting procedure takes as input the 36 amplitudes of the modified Hubbert functions with their errors, given by the previous fit (described in Sect. 4.4).

The 2D fit of the amplitudes represents the temperature profile due to the beam impinging on the front side of mini-STRIKE.

An example result of the performed 2D fit is shown in Fig. 42(a). The horizontal and vertical profiles along the lines $v_{\text{pos}} = 152$ mm and $h_{\text{pos}} = 45$ mm are compared in Figs. 42(b)
Figure 42: The final 2D fit of the amplitudes (frame 170, $\Delta t = 3.6$ s after the onset of the beam) is displayed in (a). An asymmetry between the right-hand side of the image (top tile) and the left-hand side (bottom tile) can be seen. The two black lines are taken as reference for studying 1D profile of the beam.

The horizontal profile along the line $v_{\text{pos}}=152$ mm is shown in (b).

The vertical profile along the line $h_{\text{pos}}=45$ mm is shown in (c).

and 42(c) with the amplitudes values: it can be seen that the fit describes properly the lateral sides of the 2D profile of the 36 amplitudes.

Furthermore, the fitting function $h(x, y)$ provides a figure-of-merit about the apparent asymmetry between the two tiles (see the following section), recovering a symmetric shape accordingly to the experimental data.

For pulses with small divergence ($< 2^\circ$) a double peak is expected in vertical direction, due to the overlapping beamlets created by the two different halves of the grid system and the presence of the heating wires in the centre, in between the two grid halves; for pulses with larger divergence (between $2^\circ$ and $5^\circ$) a flat top and for even larger divergence ($> 5^\circ$) a single peak. However, the mini-STRIKE system is "blind" in the middle of the two tiles; consequently some information is missing in the centre of the beam so that the fitting function with few parameters like the skewed-gaussian was adopted.
4.6 Relevant fit results

After performing all the fitting procedures, the parameters associated to the final 2D fit (described in Sect. 4.5) that will be taken into account for further and complete data analyses are:

- the position of the maximum point, indicated in Fig. 43(a) with the black star for the reference pulse, keeping in mind that, as described above, mini-STRIKE does not provide information about the central part of the beam;
- the maximum temperature increase;
- the half widths at half maximum on the top and on the bottom of mini-STRIKE, considering the vertical profile along the line passing through the maximum point (as indicated in Fig. 43(a)). The two widths are labelled in Fig. 43(b) as $\text{HWHM}_{\text{top}}$ and $\text{HWHM}_{\text{bottom}}$ respectively;
- the ratio between $\text{HWHM}_{\text{top}}$ and $\text{HWHM}_{\text{bottom}}$, which gives some information about the apparent asymmetry;

![Amplitude fit](image)

![Vertical profile](image)

Figure 43: The final 2D fit of the 36 amplitudes (frame 170, $\Delta t = 3.6$ s after the onset of the beam) is displayed in (a). The black star indicates the maximum position and the black line passing through the maximum is taken as reference for obtaining relevant parameters. The vertical profile, along the line indicated in (a), is shown in (b). Some relevant parameters are also indicated.
• the FWHM, which is given by the sum of the two HWHM (as indicated in Fig. 43(b)). This parameter instead is independent on the position of the peak.

Using these parameters, it is possible to give a description of the beam by means of the mini-STRIKE calorimeter.
5 BATMAN beam properties characterisation by BES and mini-STRIKE

In order to study the beam properties, various dedicated campaigns have been carried out. In this chapter, the main features of the beam related to the source parameters are investigated by means of the BES system and the mini-STRIKE calorimeter. As the experimental data are highly reproducible, some scans in the present chapter have been repeated with and without the mini-STRIKE calorimeter. This reproducibility allows to compare the data of the different diagnostics, since the two calorimeters cannot be operated concurrently. The experimental data presented in this chapter have been collected with all the three diagnostics, focusing on the BES and mini-STRIKE data and using the copper calorimeter data only as reference for the BES measured divergence.

The experimental data have been collected with a normalised perveance in the range 0.05-0.2, that is in the under-perveant region, where the divergence decreases with increasing perveance (see Fig. 12 in Sect. 2.2).

Furthermore, each scan (i.e. each group of shots aiming at studying of the source performance by varying only one source parameter at a time) has been repeated by changing the direction of the magnetic filter field in the source; as a consequence the plasma drift changed. However, pulses with plasma drift up and down are symmetric, as it will be described in Ch. 6, hence in the following sections similar scans with reversed plasma drift are not reported.

For each of the following sections, two scans are described: the first has been performed with the copper calorimeter and the BES diagnostics, in the current and in some past campaigns; the second scan has been carried out with the mini-STRIKE calorimeter and the BES system. In some cases, the two scans have not exactly the same source parameters. However, the purpose of this chapter is to give a complete and exhaustive description of the source performances in different experimental conditions.

In the following, different dependences of the source performance on the source parameters have been analysed: firstly the already known standard dependences are shown, then the results given by the BES system and the mini-STRIKE calorimeter for the current campaign are presented. The following source parameters have been taken into account for studying their influence on the source performance:

- the RF power;
- the bias current;
- the source pressure in two different conditions (in the under-perveant region and at the optimum of the normalised perveance);
- the acceleration voltage;
- the extraction and the acceleration voltage, with constant ratio $U_{ex}/U_{acc}$.
5.1 Influence of the RF power

The first standard dependence analysed in the present thesis has been the relation between the beam performances and the RF power in the source. All the other main source parameters (indicated in Tab. 7) have been kept constant, while RF power has been changed on a shot by shot basis.

<table>
<thead>
<tr>
<th>Source parameters</th>
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<td>Extraction voltage ( (U_{\text{ex}}) )</td>
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<tr>
<td>Acceleration voltage ( (U_{\text{acc}}) )</td>
<td>13 kV</td>
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<tr>
<td>Magnets position ( (z) )</td>
<td>9 cm</td>
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<tr>
<td>Plasma drift</td>
<td>down</td>
</tr>
<tr>
<td>Source pressure ( (p_{\text{source}}) )</td>
<td>0.5 Pa</td>
</tr>
<tr>
<td>Bias current ( (I_{\text{bias}}) )</td>
<td>13 A</td>
</tr>
</tbody>
</table>

Table 7: Source parameters for the RF power scan.

Changing the RF power implies a change in the number of charged particles inside the plasma, as well as the ratio between the densities of atomic and molecular hydrogen \( (n_{H}/n_{H_2}) \). The latter is of relevance for the generation of negative ions since it is known that the conversion of hydrogen atoms (see Eq. 17) is the most effective surface production channel. As a consequence, the electron and ion current densities increase, as shown in Tab. 8. The dependence of the performance on the applied RF power is shown in Fig. 44. The electron-to-ion ratio, in Fig. 44(b), is almost constant for lower values of RF power: some negative ions might have hit the extraction grid, due to the higher divergence (shown in Fig. 45).

In fact, as the perveance depends linearly on the extracted current, the perveance increases with the RF power too, and as a consequence the divergence decreases, as already known. Fig. 45 shows the calorimeter divergence estimated in vertical and in horizontal direction in Fig. 45(a) and the divergence measured by the BES system for the five LOS in Fig. 45(b). The absolute error associated to the calorimeter measurement is 10\% and that one associated to the BES divergence measurement is 20\% [39].

A different behaviour of the divergence measured by BES for different LOS can be detected: it means probably that the beamlets have a different divergence along the vertical profile. This result will be discussed in Sect. 6.1.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>( P_{\text{RF}} ) [kW]</th>
<th>( j_{H^-} ) [mA/cm(^2)]</th>
<th>( j_{e} ) [mA/cm(^2)]</th>
<th>( j_{e}/j_{H^-} )</th>
<th>( \Pi/\Pi_{0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>96500</td>
<td>31</td>
<td>12.7</td>
<td>5.7</td>
<td>0.4</td>
<td>0.031</td>
</tr>
<tr>
<td>96498</td>
<td>40</td>
<td>17.4</td>
<td>7.9</td>
<td>0.5</td>
<td>0.042</td>
</tr>
<tr>
<td>96496</td>
<td>46</td>
<td>18.7</td>
<td>8.5</td>
<td>0.5</td>
<td>0.045</td>
</tr>
<tr>
<td>96495</td>
<td>53</td>
<td>21.4</td>
<td>12.8</td>
<td>0.6</td>
<td>0.052</td>
</tr>
<tr>
<td>96503</td>
<td>61</td>
<td>23.0</td>
<td>16.3</td>
<td>0.7</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Table 8: Measurements results obtained for the RF power.
Figure 44: RF power dependencies: (a) ion and electron current densities; (b) electron-to-ion ratio; (c) normalised perveance.

Figure 45: Divergence as a function of the RF power: image (a) shows the vertical (CalDivV) and horizontal (CalDivH) divergences measured by the copper calorimeter; image (b) the divergences measured by BES for the five LOS.

The stripping fraction estimated by the BES system increases with increasing RF power, as can be seen in Fig. 46. A reason is, as already mentioned, the bad beam optics: if the beam is too broad (high divergence), some of the stripped particles do not leave the accelerator, hence they are not measured by BES. For low values of the RF power,
the divergence increases, hence the measured stripping fraction decreases. However, as already mentioned, the absolute values of the stripping fraction are not correct, because the standard evaluation does not take into account the more energetic stripped particles included in the Doppler-peak, hence only the trend of the stripping fraction is reliable.

Figure 46: Fraction of stripped particles, measured by the BES diagnostics for the five LOS for the RF power scan.

A RF power scan with different source parameters has been carried out with the mini-STRIKE calorimeter mounted in the tank. The main differences in the source parameters with respect to the previous scan is represented by the extraction and the acceleration voltage in the extraction system. The relevant source parameters are reported in Tab. 9, while the current densities and the normalised perveance are listed in Tab. 10 for different values of the RF power.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage ($U_{\text{ex}}$)</td>
<td>4.7 kV</td>
</tr>
<tr>
<td>Acceleration voltage ($U_{\text{acc}}$)</td>
<td>15.2 kV</td>
</tr>
<tr>
<td>Magnets position ($z$)</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Source pressure ($p_{\text{source}}$)</td>
<td>0.5 Pa</td>
</tr>
<tr>
<td>Bias current ($I_{\text{bias}}$)</td>
<td>10 A</td>
</tr>
</tbody>
</table>

Table 9: Source parameters for the RF power scan.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>$P_{\text{RF}}$ [kW]</th>
<th>$j_{\text{H}^{-}}$ [mA/cm²]</th>
<th>$j_{\text{e}}$ [mA/cm²]</th>
<th>$j_{\text{e}}/j_{\text{H}^{-}}$</th>
<th>$\Pi/\Pi_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>98336</td>
<td>20</td>
<td>4.9</td>
<td>2.5</td>
<td>0.5</td>
<td>0.035</td>
</tr>
<tr>
<td>98335</td>
<td>30</td>
<td>9.3</td>
<td>3.3</td>
<td>0.4</td>
<td>0.066</td>
</tr>
<tr>
<td>98334</td>
<td>40</td>
<td>12.1</td>
<td>5.4</td>
<td>0.5</td>
<td>0.086</td>
</tr>
<tr>
<td>98333</td>
<td>51</td>
<td>14.2</td>
<td>8.4</td>
<td>0.6</td>
<td>0.102</td>
</tr>
<tr>
<td>98339</td>
<td>64</td>
<td>16.1</td>
<td>11.5</td>
<td>0.7</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Table 10: Measurements results obtained for the RF power scan.

After the mini-STRIKE data acquisition from the IR camera, the corresponding IR images have been analysed. The vertical profile in the centre of mini-STRIKE of the
amplitude 2D fit is shown for each pulse of the RF power scan in Fig. 47. A different slope of the amplitudes along the beam vertical profile can be clearly seen, especially for higher RF power values.

For each pulse, the relevant parameters associated to the 2D fit of the amplitudes (i.e. the widths calculated as described in Sect. 4.6, the HWHM-ratio, the maximum temperature increase and the position of the peak) have been then evaluated and are shown in Fig. 48.

By considering the widths at half maximum (plotted in Fig. 48(a)), the HWHM_{bottom} (red triangle) is larger than the HWHM_{top}. The difference between the two widths increases with increasing RF power: in fact a top-bottom asymmetry is visible in the thermal images for high powers (≥ 30 kW). Due to the described uncertainty about the position of the peak of the 2D amplitude-fit, the asymmetry might be overestimated by the performed fitting procedure, but anyway present. As a consequence of this difference, the HWHM-ratio is less than one for larger powers, as can be seen in Fig. 48(b).

Fig. 48(a) shows additionally the FWHM (i.e. the sum of the two HWHM), which decreases with increasing RF power (green circles). It is worth noting that the FWHM
shows a similar trend as the averaged beamlet divergence estimated by BES, that was shown in Fig. 45(b). The correlation between the FWHM calculated via mini-STRIKE and the BES divergence measurement will be discussed in more detail in Sect. 6.2.

The maximum temperature difference (indicated as $Max_{sg}$) increases with increasing RF power, as shown in Fig. 48(c), because of the increasing ion current hitting the calorimeter.

The vertical position $x_{\text{max}}$ of the peak can be used as a measure for the beam shift. This depends on the magnetic field and on the particle velocity. For the present scan, these two parameters do not change and $x_{\text{max}}$ (shown in Fig. 48(d)) is almost constant as foreseen. Furthermore, $x_{\text{max}}$ is also an index of the plasma drift: the peak is located on the top or the bottom tile, depending on the plasma drift direction, which can be up or down. In Fig. 48(d), $x_{\text{max}}$ assumes a value greater than 150 mm, hence the peak is located on the top tile, in agreement with the plasma drift up.

Figure 48: Parameters evaluated from the IR camera images of mini-STRIKE, as functions of the RF power: (a) the two HWHM (bottom and top) and the FWHM; (b) the ratio of HWHM$_{\text{top}}$ to HWHM$_{\text{bottom}}$; (c) the maximum temperature increase; (d) the vertical position of the peak.
5.2 Influence of the bias current

For this scan only the bias current has been changed in order to see its effects on the source performance and on the beam. The relevant source parameters are shown in Tab. 11.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage (U_{\text{ex}})</td>
<td>4.7 kV</td>
</tr>
<tr>
<td>Acceleration voltage (U_{\text{acc}})</td>
<td>10.2 kV</td>
</tr>
<tr>
<td>Magnets position (z)</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>down</td>
</tr>
<tr>
<td>Source pressure (p_{\text{source}})</td>
<td>0.7 Pa</td>
</tr>
<tr>
<td>Power (P_{\text{RF}})</td>
<td>60 kW</td>
</tr>
</tbody>
</table>

Table 11: Source parameters for the bias current scan.

The correlation between \(I_{\text{bias}}\) change and the other measurements (like the current densities, the electron-to-ion ratio and the normalised perveance) are shown in Tab. 12 and in Fig. 49.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>(I_{\text{bias}}) [A]</th>
<th>(j_{H^-}) [mA/cm(^2)]</th>
<th>(j_e) [mA/cm(^2)]</th>
<th>(j_e/j_{H^-})</th>
<th>(\Pi/\Pi_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>94147</td>
<td>0</td>
<td>19.6</td>
<td>24.3</td>
<td>1.24</td>
<td>0.122</td>
</tr>
<tr>
<td>94145</td>
<td>6</td>
<td>19.1</td>
<td>14.1</td>
<td>0.74</td>
<td>0.117</td>
</tr>
<tr>
<td>94142</td>
<td>15</td>
<td>18.5</td>
<td>7.3</td>
<td>0.39</td>
<td>0.112</td>
</tr>
<tr>
<td>94149</td>
<td>22</td>
<td>16.9</td>
<td>5.1</td>
<td>0.30</td>
<td>0.102</td>
</tr>
<tr>
<td>94151</td>
<td>26</td>
<td>15.5</td>
<td>4.9</td>
<td>0.32</td>
<td>0.093</td>
</tr>
<tr>
<td>94153</td>
<td>29</td>
<td>14.1</td>
<td>5.1</td>
<td>0.36</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Table 12: Measurements results obtained for the bias current scan.

By increasing the bias current, the electron current density (displayed in Fig. 49(a)) decreases as described in Sect. 2.1.2, and also the ion current density is slightly affected by the bias (as shown in Fig. 49(b)). Usually at BATMAN, for operation with magnets in \(z = 9\) cm position the bias current is set between 10 A and 15 A. In this range the electron current density is already enough suppressed, while the ion current density remains high. Further investigations are needed in order to understand the effect of the bias on the source performance.

The bias current increase affects also the beamlet divergence. This (displayed in Fig. 50) increases with the increase of \(I_{\text{bias}}\) as expected, due to the slight decrease of the perveance with the bias current (shown in Fig. 49(c)). This effect is small for the calorimeter divergence estimation, whereas it seems to be more evident for some LOS in the BES system. The behaviour of the divergence estimated from different lines-of-sight is different: the beamlet divergence is not uniform along the vertical profile of the beam.
Figure 49: Measurements results as a function of the bias current: (a) ion and electron current densities; (b) electron-to-ion ratio; (c) normalised perveance.

Figure 50: Divergence as a function of the bias current: image (a) shows the vertical and horizontal divergences measured by the copper calorimeter; image (b) the divergences measured by BES for the LOS 1, LOS 2, LOS 4 and LOS 5 (LOS 3 was dedicated to other measurements in the source).

Since the optics is modified by $I_{\text{bias}}$ (i.e. the divergence increases with the increasing bias current), a slight decrease is observed in the stripping fraction estimation over the bias scan, as shown in Fig. 51.
Figure 51: Fraction of stripped particles, measured by the BES system for a scan of the bias current.

This scan has been repeated with different source parameters (listed in Tab. 13) with the mini-STRIKE calorimeter mounted in the tank. The source and beam measurements results are shown in Tab. 14.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage ( U_{ex} )</td>
<td>8.5 kV</td>
</tr>
<tr>
<td>Acceleration voltage ( U_{acc} )</td>
<td>13.2 kV</td>
</tr>
<tr>
<td>Magnets position ( z )</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Source pressure ( p_{source} )</td>
<td>0.5 Pa</td>
</tr>
<tr>
<td>Power ( P_{RF} )</td>
<td>50 kW</td>
</tr>
</tbody>
</table>

Table 13: Source parameters for the bias current scan.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>( I_{bias} ) [A]</th>
<th>( j_{H^-} ) [mA/cm(^2)]</th>
<th>( j_e ) [mA/cm(^2)]</th>
<th>( j_e/j_{H^-} )</th>
<th>( \Pi/\Pi_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>97843</td>
<td>1</td>
<td>19.0</td>
<td>34.7</td>
<td>1.8</td>
<td>0.058</td>
</tr>
<tr>
<td>97842</td>
<td>5</td>
<td>18.9</td>
<td>23.8</td>
<td>1.3</td>
<td>0.056</td>
</tr>
<tr>
<td>97841</td>
<td>9</td>
<td>19.0</td>
<td>16.9</td>
<td>0.9</td>
<td>0.056</td>
</tr>
<tr>
<td>97834</td>
<td>12</td>
<td>18.5</td>
<td>13.4</td>
<td>0.7</td>
<td>0.054</td>
</tr>
<tr>
<td>97835</td>
<td>15</td>
<td>18.3</td>
<td>9.7</td>
<td>0.5</td>
<td>0.053</td>
</tr>
<tr>
<td>97838</td>
<td>22</td>
<td>16.7</td>
<td>6.3</td>
<td>0.4</td>
<td>0.048</td>
</tr>
<tr>
<td>97839</td>
<td>26</td>
<td>14.4</td>
<td>6.4</td>
<td>0.5</td>
<td>0.042</td>
</tr>
<tr>
<td>97840</td>
<td>29</td>
<td>13.0</td>
<td>7.2</td>
<td>0.6</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Table 14: Measurements results obtained during the bias current scan.

The IR images of each pulse have been analysed, obtaining the vertical profiles in the centre of mini-STRIKE of the amplitude 2D fit, displayed in the Fig. 52.
Figure 52: Vertical profile in the centre of mini-STRIKE of the 2D fit of the 36 amplitudes. Each image represents a different pulse of the bias current scan, with the bias current, the ion current density and the normalised perveance values indicated. The vertical profile are quite symmetric and the peak position is located between the two tile, in despite of the plasma drift up configuration.

The relevant parameters evaluated from this 2D fit are plotted in Fig. 53 as functions of the bias current.

In Fig. 53(a), the HWHM_{bottom} (red triangles) is larger than the top one (blue triangles) and their ratio is almost constant (Fig. 53(b)). The FWHM (green circles in Fig. 53(a)) increases slightly with increasing bias current, reflecting the similar trend of the divergence estimated by the BES diagnostics.

The maximum of the fitted function decreases, as shown in Fig. 53(c), because of the decreasing ion current density (hence there is less power deposited onto the tiles) and the position of the peak does not change by varying the bias current (Fig. 53(d)). However, the peak is located in between the two tiles (at about 130 mm). Hence mini-STRIKE measurements do not note any shift of the beam towards the top tile (accordingly to the plasma drift up). This topic is currently under investigation.
Figure 53: Parameters evaluated from the IR camera images of mini-STRIKE, during the bias current scan: (a) the two HWHM (bottom and top) and the FWHM; (b) the ratio of $HWHM_{\text{top}}$ to $HWHM_{\text{bottom}}$; (c) the maximum temperature increase; (d) the vertical position of the peak.
5.3 Influence of the source pressure

For the pressure scan, two different source conditions are described in the following: the first scan was performed in the under-perveant region, while the second scan has been done at the optimum of the normalised perveance (between 0.1 and 0.2). The aim is to show the already known source performance by varying the source pressure and with different source conditioning. Since a variation of the source pressure could cause a variation of the beam optics, by means of an increase of the extracted ion current, the scans have been performed checking if the normalised perveance was constant during each scan, in order to describe the effects on the beam properties due only to the pressure, without changing the beam optics (correlated to the normalised perveance, as described in Sect. 2.2). \( \Pi/\Pi_0 \) has been kept constant in the second scan (at the optimum of the normalised perveance) by changing slightly the RF power and the bias current, while for the scan in the under-perveant region this was not necessary.

Before each scan, a calibration of the pressure has been performed, as already mentioned in Sect. 3.1. A different pressure in the source has consequences also on the pressure in the tank due to the limited pumping speed of the titanium-getter pumps in the tank. This dependence is displayed in Fig. 54.

![Pressure scan](image)

Figure 54: Pressure in the tank, correlated to the pressure in the source.

The relevant source parameters for the source pressure scan in the under-perveant region are listed in Tab. 15 and the source performance is summarised in Tab. 16.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage ( (U_{ex}) )</td>
<td>4.6 kV</td>
</tr>
<tr>
<td>Acceleration voltage ( (U_{acc}) )</td>
<td>15.2 kV</td>
</tr>
<tr>
<td>Magnets position ( (z) )</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>down</td>
</tr>
<tr>
<td>RF power ( (P_{RF}) )</td>
<td>50 kW</td>
</tr>
<tr>
<td>Bias current ( (I_{bias}) )</td>
<td>13 A</td>
</tr>
</tbody>
</table>

Table 15: Source parameters for the source pressure scan in the under-perveant region.
Table 16: Measurements results obtained during the pressure scan in the under-perveant region.

In order to compare the source performance with a different optics, a scan at the optimum of the normalised perveance has been performed. The source settings are shown in Tab. 17, and the operational parameters during this pressure scan are summarised in Tab. 18.

Table 17: Source settings for the pressure scan at the optimum of the normalised perveance. The RF power has been varied in order to keep constant the normalised perveance (see Tab. 18).

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage ( (U_{ex}) )</td>
<td>4.7 kV</td>
</tr>
<tr>
<td>Acceleration voltage ( (U_{acc}) )</td>
<td>15.2 kV</td>
</tr>
<tr>
<td>Magnets position ( (z) )</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Bias current ( (I_{bias}) )</td>
<td>10 A</td>
</tr>
</tbody>
</table>

Table 18: Operational parameters for the source pressure scan at the optimum of the normalised perveance.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>( p_{source} ) ( [\text{Pa}] )</th>
<th>( P_{RF} ) ( [\text{kW}] )</th>
<th>( j_{H-} ) ( [\text{mA/cm}^2] )</th>
<th>( j_e ) ( [\text{mA/cm}^2] )</th>
<th>( j_e/j_{H-} )</th>
<th>( \Pi/\Pi_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>96918</td>
<td>0.37</td>
<td>56</td>
<td>16.2</td>
<td>9.2</td>
<td>0.6</td>
<td>0.115</td>
</tr>
<tr>
<td>96914</td>
<td>0.44</td>
<td>58</td>
<td>16.6</td>
<td>7.1</td>
<td>0.4</td>
<td>0.117</td>
</tr>
<tr>
<td>96901</td>
<td>0.51</td>
<td>60</td>
<td>16.8</td>
<td>9.2</td>
<td>0.6</td>
<td>0.119</td>
</tr>
<tr>
<td>96904</td>
<td>0.59</td>
<td>51</td>
<td>16.6</td>
<td>8.7</td>
<td>0.5</td>
<td>0.117</td>
</tr>
<tr>
<td>96906</td>
<td>0.68</td>
<td>49</td>
<td>16.7</td>
<td>8.7</td>
<td>0.5</td>
<td>0.118</td>
</tr>
<tr>
<td>96912</td>
<td>0.76</td>
<td>51</td>
<td>16.5</td>
<td>6.8</td>
<td>0.4</td>
<td>0.116</td>
</tr>
</tbody>
</table>

In Fig. 55, the effects of the pressure increase on the current densities and the normalised perveance are displayed for both pressure scans. As already known, the ion current density (shown in (a)) is almost constant (within the error measurement), and so is perveance (c). However, there is a strong increase in the co-extracted electron current density for low pressure values as expected for the pressure scan in the under-perveant region (red diamonds in Fig. 55(b)), probably due to an increase in the local electron temperature. As a consequence, the electron-to-ion ratio is greater than one for low pressures in the under-perveant scan (red diamonds in Fig. 55(c)).

The difference between the two scans is clearly visible: the ion current density for the under-peaveant scan (red circles in Fig. 55(a)) is lower than the respective current density measured at the optimum of the normalised perveance (magenta circles). The electron
current density and consequently the electron-to-ion ratio drop down at low pressure value for the scan at the optimum of the normalised perveance.

The divergence is plotted vs. the source pressure in Fig. 56 for both scans. It can be seen that the divergence depends slightly on the pressure, though the perveance is not changing. This decrease of the divergence with the increasing source pressure hence is not depending on a different beam optics between one pulse to the other. The divergence decrease might be explained by space charge compensation: the higher the pressure in the drift region, the earlier the space charge compensation might stop the divergence increase (as described in Sect. 2.2). However, this is still an open issue and further investigations are needed.

As expected, the divergence in the case of the optimum of the normalised perveance (Fig. 56(c)) is lower than in the under-perveant region (a).

A difference between the beamlet divergence estimated by the BES diagnostics for the two scans can be seen: the spread of the divergence along the vertical profile is larger for the scan performed in the under-perveant region (Fig. 56(b)) than for the scan at the optimum of the normalised perveance (d). This might be due to the source not-well conditioned, hence there is maybe a not uniform distribution of the ion current density at the plasma grid, leading to a local variation of the normalised perveance.
Figure 56: Divergence as a function of the source pressure for the scan performed in the under-perveant region, (a) and (b), and at the optimum of the normalised perveance, (c) and (d): shown in image (a) and (c) are the vertical and horizontal divergences measured by the copper calorimeter; image (b) and (d) display the divergences measured by the BES system. Image (b) does not show the measured divergence for LOS 3 because it was dedicated to other measurements in the source.

The different plasma drifts are also clearly visible in the Figs. 56(b) and (d): for the scan in the under-perveant region (with plasma drift down) the minimum value of the beamlet divergence is detected for the LOS 1 (hence in the lower half of the grid system), while for the scan at the optimum of the normalised perveance (with plasma drift up) it corresponds to LOS 3 or 4, hence in the upper half of the grid system. This topic will be further discussed in Sect. 6.1.

The stripping fraction, on the contrary, increases with the source pressure, as confirmed in Fig. 57 for both the scans: as described in Sect. 2.2, the stripping fraction depends on the neutral density profile, which is a function of the tank pressure and the source pressure. Since the optics does not change in each of the scans, this trend is a direct consequence of the increasing source pressure, which causes a higher stripping probability rate.

The data in Fig. 57(b) show a large spread along the vertical profile of the beam, revealing a difference between the upper and the lower lines-of-sight. This effect is still under investigation.
Figure 57: Fraction of stripped particles as a function of the source pressure, estimated by the BES system: image (a) refers to the scan performed in the under-perveant region (LOS 3 was dedicated to source measurements); image (b) to the scan at the optimum of the normalised perveance.

A pressure scan at the optimum of the normalised perveance has been carried out by using the mini-STRIKE calorimeter, with the same source parameters listed in Tab. 17. The same measurements have been repeated, obtaining the same results of Tab. 18. For each pulse, the IR images have been analysed and the vertical profiles in the centre of mini-STRIKE of the 2D fit of the amplitudes are displayed in Fig. 58.

The relevant parameters associated to the fit of the 36 amplitudes are displayed in Fig. 59, as functions of the source pressure. In Fig. 59(a), the HWHM\textsubscript{bottom} (red triangles) is larger than the HWHM\textsubscript{top} (blu triangles) and the ratio displayed in Fig. 59(b) is around 0.6. The asymmetry between the top side of IR images and the bottom side in fact is clearly visible in Fig. 58.

Additionally, in Fig. 59(a) a decrease of the FWHM (green circles) with increasing source pressure is observed: the trend is similar to the beamlet divergence measured by the BES system.

The maximum temperature increase is slightly increasing with the increasing source pressure (as shown in Fig. 59(c)), since the power impinging the front side of the mini-STRIKE calorimeter decreases if the divergence increases (as seen in Fig. 56, the divergence is higher for low values of the source pressure).

The peak position displayed in Fig. 59(d) is constant, as it is expected to be, since the shift of the beam depends on the strength of the magnetic field and on the particles velocity. Since for a pressure scan the strength of the magnetic field is kept constant, as well as the voltages applied to the grids, no variation of the shift is expected, as the experimental data confirm.
Figure 58: Vertical profiles in the centre of mini-STRIKE of the 2D fit of the 36 amplitudes. Each image represents a different pulse of the source pressure scan performed at the optimum of the normalised perveance. Each pulse has indicated its source pressure and RF power. The peak position is shifted towards the upper tile (right side of x-axis), accordingly to the drift up configuration.
Figure 59: Parameters evaluated from the IR camera images of mini-STRIKE, during the source pressure scan at the optimum of the normalised perveance: (a) the two HWHM (bottom and top) and the FWHM; (b) the ratio of HWHM_top to HWHM_bottom; (c) the maximum temperature increase; (d) the vertical position of the peak.
5.4 Influence of the acceleration voltage

As seen in Sect. 2.2, the divergence of the beamlets depends not only on the normalised perveance, but also on the ratio of the extraction voltage $U_{ex}$ to the acceleration voltage $U_{acc}$. A scan of the acceleration voltage at constant normalised perveance has been performed, with the extraction voltage value kept constant. With these settings, it is expected that the extracted current density is constant too. BATMAN has been operated in the region of the optimum normalised perveance, in order to ensure a good beam optics.

The source parameters of the pulses during the scan are summarised in Tab. 19. Since only the acceleration voltage is changing pulse by pulse, the current densities and the normalised perveance are foreseen to be constant. This is confirmed, within the error bars (10%), by the measurements results listed in Tab. 20.

### Source parameters

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction voltage ($U_{ex}$)</td>
<td>4.7 kV</td>
</tr>
<tr>
<td>Magnets position ($z$)</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Source pressure ($p_{source}$)</td>
<td>0.5 Pa</td>
</tr>
<tr>
<td>RF power ($P_{RF}$)</td>
<td>51 kW</td>
</tr>
<tr>
<td>Bias current ($I_{bias}$)</td>
<td>10 A</td>
</tr>
</tbody>
</table>

Table 19: Source parameters for the acceleration voltage scan.

<table>
<thead>
<tr>
<th>$U_{acc}$ [kV]</th>
<th>$U_{ex}/U_{acc}$</th>
<th>$j_{H-}$ [mA/cm²]</th>
<th>$j_{e}$ [mA/cm²]</th>
<th>$j_{e}/j_{H-}$</th>
<th>$\Pi/\Pi_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2</td>
<td>0.31</td>
<td>16.4</td>
<td>8.5</td>
<td>0.5</td>
<td>0.116</td>
</tr>
<tr>
<td>14.2</td>
<td>0.32</td>
<td>16.1</td>
<td>8.4</td>
<td>0.5</td>
<td>0.118</td>
</tr>
<tr>
<td>13.3</td>
<td>0.35</td>
<td>16.3</td>
<td>8.5</td>
<td>0.5</td>
<td>0.119</td>
</tr>
<tr>
<td>12.2</td>
<td>0.38</td>
<td>16.2</td>
<td>8.5</td>
<td>0.5</td>
<td>0.118</td>
</tr>
<tr>
<td>11.2</td>
<td>0.41</td>
<td>16.1</td>
<td>8.7</td>
<td>0.5</td>
<td>0.116</td>
</tr>
<tr>
<td>10.2</td>
<td>0.46</td>
<td>15.8</td>
<td>8.7</td>
<td>0.6</td>
<td>0.114</td>
</tr>
<tr>
<td>9.2</td>
<td>0.51</td>
<td>16.0</td>
<td>9.2</td>
<td>0.6</td>
<td>0.114</td>
</tr>
<tr>
<td>8.2</td>
<td>0.57</td>
<td>15.8</td>
<td>9.2</td>
<td>0.6</td>
<td>0.112</td>
</tr>
<tr>
<td>7.2</td>
<td>0.66</td>
<td>15.6</td>
<td>9.2</td>
<td>0.6</td>
<td>0.109</td>
</tr>
<tr>
<td>6.2</td>
<td>0.78</td>
<td>15.4</td>
<td>9.0</td>
<td>0.6</td>
<td>0.106</td>
</tr>
</tbody>
</table>

Table 20: Measurements results in the acceleration voltage scan.

As confirmed in Fig. 60, the beamlet divergence measured with the copper calorimeter (left) and with the BES system (right) increases with increasing the extraction to acceleration voltage ratio, that is with the decrease of the acceleration voltage, as expected.

The stripping fraction dependence on $U_{ex}/U_{acc}$ is displayed in Fig. 61. A decrease of the fraction of stripped particles is expected with increasing extraction to acceleration voltage ratio, because of the worsening optics (as described in Sect. 3.2.1). However, experimentally an increase of $f_{strip}$ with the increasing ratio occurs. This might be due to a wrong estimation of the fraction of stripped particle by means of the standard evaluation of the BES spectra. The increase of the stripping fraction is particularly evident for LOS
Figure 60: Divergence as a function of the extraction to the acceleration voltage ratio $U_{ex}/U_{acc}$: image (a) shows the vertical and horizontal divergences measured by the copper calorimeter; image (b) the divergences measured by BES for the five LOS.

4 and LOS 5 (i.e. in the upper half of the grid system). The previous argument does not explain the difference among the results of different LOS and this issue is still under investigation.

Figure 61: Fraction of stripped particles, measured by the BES system during a scan of the acceleration voltage.

An acceleration voltage scan has been carried out with the mini-STRIKE configuration. The source parameters are kept the same of the previous scan (see Tab. 19), obtaining the same measurements results shown in Tab. 20.

The vertical profiles in the centre of mini-STRIKE of the 2D fit of the 36 amplitudes are shown in Fig. 62.

The relevant parameters associated to the amplitude-fit are plotted in Fig. 63. The HWHM$_{bottom}$ (represented by the red triangles in Fig. 63(a)) is larger than the HWHM$_{top}$ (blue triangles). However, the gap between the two widths decreases with the increase of the extraction to acceleration voltage ratio. In fact, it can be seen clearly that an
Figure 62: Vertical profiles in the centre of mini-STRIKE of the amplitudes 2D fit, during an acceleration voltage scan. Decreasing the acceleration voltage, the maximum temperature difference is decreasing too. The asymmetry is particularly visible for pulses with acceleration voltage larger than 10 kV. The peak position is shifted towards the top tile, accordingly to the drift up configuration.
asymmetry of the temperature gradient occurs between the top tile and the bottom tile for the pulses with high acceleration voltage ($U_{\text{acc}} \geq 10 \text{ kV}$). As a consequence, the ratio between the top HWHM and the bottom one is less than one, as shown in Fig. 63(b).

The FWHM, represented by the green circles in Fig. 63(a), increases with increasing extraction to acceleration voltage ratio, and thus shows a similar trend as the beamlet divergence measured by the copper calorimeter and the BES system, that was shown in Fig. 60.

The maximum temperature difference $\Delta T_{\text{max}}$, displayed in Fig. 63(c), decreases with the increasing voltage ratio, in agreement with what is expected: the higher the acceleration voltage (low ratio values), the higher is the power deposition on the front side of the tiles. The vertical position of the peak $x_{\text{max}}$ is correlated to the beam shift: the higher the total voltage, the larger is the peak shift upwards, as physically expected, since the shift depends on the particle velocity. In Fig. 63(d) the dependence of $x_{\text{max}}$ on the extraction to acceleration voltage ratio is shown: the vertical position decreases with increasing ratio as expected.

![Graphs showing parameter evaluations](image_url)

Figure 63: Parameters evaluated from the IR camera images of mini-STRIKE as functions of $U_{\text{ex}}/U_{\text{acc}}$: (a) the two HWHM (bottom and top) and the FWHM; (b) the ratio of $\text{HWHM}_{\text{top}}$ to $\text{HWHM}_{\text{bottom}}$; (c) the maximum temperature increase; (d) the vertical position of the peak.
5.5 Influence of the perveance

In order to study the dependence of the divergence on the perveance only, a scan of the extraction and acceleration voltages, with constant $U_{\text{ex}}/U_{\text{acc}}$, has been performed. This scan has been performed only with mini-STRIKE mounted in the tank, hence data from the copper calorimeter are not available. The source parameters of the pulses of this scan are summarised in Tab. 21 and the current densities and the normalised perveance measured during this scan are listed in Tab. 22.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets position (z)</td>
<td>9 cm</td>
</tr>
<tr>
<td>Plasma drift</td>
<td>up</td>
</tr>
<tr>
<td>Source pressure ($p_{\text{source}}$)</td>
<td>0.9 Pa</td>
</tr>
<tr>
<td>RF power ($P_{\text{RF}}$)</td>
<td>51 kW</td>
</tr>
<tr>
<td>Bias current ($I_{\text{bias}}$)</td>
<td>11 A</td>
</tr>
</tbody>
</table>

Table 21: Source parameters for the perveance scan with constant $U_{\text{ex}}/U_{\text{acc}}$.

<table>
<thead>
<tr>
<th>$\Pi/\Pi_0$</th>
<th>$U_{\text{ex}}$ [kV]</th>
<th>$U_{\text{acc}}$ [kV]</th>
<th>$j_{H-}$ [mA/cm$^2$]</th>
<th>$j_e$ [mA/cm$^2$]</th>
<th>$j_e/j_{H-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.042</td>
<td>8.5</td>
<td>14.2</td>
<td>14.6</td>
<td>9.0</td>
<td>0.6</td>
</tr>
<tr>
<td>0.046</td>
<td>7.6</td>
<td>12.6</td>
<td>13.5</td>
<td>8.2</td>
<td>0.6</td>
</tr>
<tr>
<td>0.054</td>
<td>6.6</td>
<td>11.1</td>
<td>12.6</td>
<td>7.4</td>
<td>0.6</td>
</tr>
<tr>
<td>0.076</td>
<td>4.7</td>
<td>8.0</td>
<td>10.7</td>
<td>5.7</td>
<td>0.5</td>
</tr>
<tr>
<td>0.095</td>
<td>3.8</td>
<td>6.4</td>
<td>9.9</td>
<td>4.7</td>
<td>0.5</td>
</tr>
<tr>
<td>0.080</td>
<td>2.2</td>
<td>3.3</td>
<td>3.5</td>
<td>3.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 22: Measurements results obtained during the scan of the acceleration and extraction voltage, with constant ratio $U_{\text{ex}}/U_{\text{acc}}$.

The results of the BES divergence measurements are shown in Fig. 64: the divergence decreases with the increasing normalised perveance, as expected.

Figure 64: BES divergence measurements for the perveance scan, with constant $U_{\text{ex}}/U_{\text{acc}}$. 
As concern the IR data analysis, the vertical profile in the centre of mini-STRIKE of the 2D fit of the amplitudes is shown for each pulse in Fig. 65. The profiles are almost symmetric for all the shots.

The dependences of the relevant associated parameters are shown in Fig. 66. The HWHM top and bottom plotted in Fig. 66(a) are quite similar, a small difference is present but this can be smoothed by the uncertainty on the position of the peak. Thus the HWHM-ratio is in most of the cases larger than 0.8, as shown in Fig. 66(b).

The FWHM, represented by the green circles in Fig. 66(a), decreases with increasing normalised perveance, showing again a trend similar to the BES divergence measurement.

The maximum temperature difference shown in Fig. 66(c) is almost constant within the errors, while the maximum position displayed in Fig. 66(d) increases with the increasing perveance.
Figure 66: Parameters evaluated from the IR camera images of mini-STRIKE as functions of the normalised perveance, during a perveance scan with constant $U_{ex}/U_{acc}$: (a) the two HWHM (bottom and top) and the FWHM; (b) the ratio of HWHM$_{top}$ to HWHM$_{bottom}$; (c) the maximum temperature increase; (d) the vertical position of the peak.
5.6 Summary

In the following, the whole data obtained by means of the mini-STRIKE calorimeter are summarised.

The FWHM parameter determined from the mini-STRIKE results follows the divergence trend by BES in all the scans performed. A first benchmark is presented below: Fig. 67 shows the FWHM plotted (for all the pulses during which mini-STRIKE was active) as a function of the normalised perveance. The data are fitted with a parabola. The pattern shown in Fig. 67 reproduces the well-known behaviour of the divergence vs. the normalised perveance, displayed in Fig. 12 in Sect. 2.2.

![Figure 67: FWHM determined from mini-STRIKE as a function of the normalised perveance.](image)

In several operational conditions, the $HWHM_{\text{top}}$ and $HWHM_{\text{bottom}}$ were different and their ratio was not close to one. This means that the vertical temperature profiles exhibit in these situations a different gradient in the top tile and in the bottom tile of mini-STRIKE, resulting in an asymmetric temperature profile with respect to the beam center. This asymmetry moreover is not always present: only pulses with high beam power deposition on mini-STRIKE are characterised by such an asymmetry. A high power deposition corresponds to a normalised perveance close to its optimum (low divergence) and a high acceleration voltage. In all the other conditions $HWHM_{\text{top}}$ and $HWHM_{\text{bottom}}$ are similar (hence the ratio is around one) and the temperature gradients in the two tiles are comparable.

The presence of the asymmetry is thus indicated by the ratio between $HWHM_{\text{top}}$ and $HWHM_{\text{bottom}}$ and its dependence on the normalised perveance is shown in Fig. 68 for pulses with plasma drift up. It can be seen that the ratio decreases with the increasing normalised perveance (hence the asymmetry of the thermal profile is more evident). The large spread of the ratio values for high normalised perveance (around 0.11) is caused by different values of the acceleration voltage.

The maximum temperature increase depends on the power impinging on the front of mini-STRIKE, hence depends on the total voltage accelerating the particles, the ion current density and the divergence. Considering the pulses with the same voltages ($U_{\text{ex}}=4.5$ kV and $U_{\text{acc}}=15$ kV), it can be seen in Fig. 69 the dependence of $Max_{\text{sg}}$ on the ion current density $j_{H^-}$. 
Figure 68: Ratio of HWHM$_{\text{top}}$ to HWHM$_{\text{bottom}}$ determined from mini-STRIKE for plasma drift up pulses as a function of the normalised perveance.

Figure 69: Maximum temperature increase determined from mini-STRIKE as a function of the normalised perveance. The considered pulses have the same extraction voltage ($U_{\text{ex}}=4.5$ kV) and the acceleration voltage ($U_{\text{acc}}=15$ kV).
6 Comparison of BES and mini-STRIKE

In the following, some considerations about the BES system and the mini-STRIKE calorimeter are discussed in order to explain the asymmetry along the beam vertical profile observed in some cases by the mini-STRIKE calorimeter.

6.1 Divergence vertical profile

In all the scans described in the previous chapter, it can be seen that, given a pulse, the beamlet divergence estimated by BES is not the same for all the five lines-of-sight. The divergence spread (i.e. the difference between the maximum and the minimum value of the divergence for a given pulse) reaches values up to 1.5°. The error in the divergences determined by BES (20%) has to be considered in the discussion: such an error might smooth an eventual pattern and the divergence could be compatible with a uniform value. However, there seems to be a reproducible vertical profile of the divergence for pulses with the same drift direction and some particular spatial pattern of the divergence seems to be symmetrically reproduced when the plasma drift is reversed (by reversing the magnetic filter field).

An example is displayed in Fig. 70, where two pulses with similar settings, except the plasma drift direction, are considered (the source parameters for these two pulses are summarised in Tab. 23). The divergence in Fig. 70 seems to be not constant, but shows a minimum value. This minimum is in the lower half of the grid system for plasma drift down pulses (between LOS 1 and LOS 2 in Fig. 70(a)), while the minimum is in the upper half of the grid system for plasma drift up pulses (between LOS 3 and LOS 4 in Fig. 70(b)). Thus, the minimum of the vertical divergence profile measured by BES is found in the part of the beam (bottom or top) where the plasma drift is directed. Similar trends have been seen also in other pulses, and also in that cases the reversal of the plasma drift reverses the divergence pattern.

The divergence pattern in a pulse could be compatible with a uniform value because of the errors in the BES divergence evaluation. However, this is not reasonable as this pattern is well reproduced for every shot and the profile is reversed when the magnetic filter field is reversed, hence the trend is reliable.

<table>
<thead>
<tr>
<th>Source parameters</th>
<th>Pulse #98460</th>
<th>Pulse #97482</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma drift</td>
<td>down</td>
<td>up</td>
</tr>
<tr>
<td>Extraction voltage ( (U_{ex}) ) [kV]</td>
<td>4.6</td>
<td>4.7</td>
</tr>
<tr>
<td>Acceleration voltage ( (U_{acc}) ) [kV]</td>
<td>15.1</td>
<td>15.2</td>
</tr>
<tr>
<td>Magnets position ( (z) ) [cm]</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Source pressure ( (p_{source}) ) [Pa]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>RF power ( (P_{RF}) ) [kW]</td>
<td>51</td>
<td>50</td>
</tr>
<tr>
<td>Bias current ( (I_{bias}) ) [A]</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Extracted current density ( (j_{H^-}) ) [mA/cm²]</td>
<td>15.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Normalised perveance ( (\Pi/\Pi_0) )</td>
<td>0.115</td>
<td>0.112</td>
</tr>
</tbody>
</table>

Table 23: Source parameters of two similar pulses with plasma drift down (pulse #98460) and up (pulse #97482), used for investigation of the vertical divergence profile obtained by the BES divergence estimation.
A vertical divergence profile could be correlated to a local perveance variation, caused by a local variation of the extracted current density \( j_{H^-} \). So far, no indication on that has ever been observed in the BATMAN test facility. Nevertheless, it is reasonable thinking that an imperfect cesium source conditioning or some slight variations in the plasma and particle fluxes in the source due to the presence of the magnetic filter field could affect the extracted current density. This is an open issue for further investigations.

### 6.2 Divergence estimation by mini-STRIKE

It was observed for all mini-STRIKE evaluations that the FWHM of the beam profile in the IR images seems to correlate with the divergence estimated by the BES diagnostics. The average divergence from BES is plotted in Fig. 71 against the FWHM from mini-STRIKE and the correlation is clear.

Since the divergence is not uniform along the vertical profile as seen in the previous

![Figure 71: Average of the beamlet divergence measured along the five BES LOS as a function of the FWHM determined from mini-STRIKE. The trend is linear.](image)
Figure 72: (a) Beamlet divergence estimated by BES for LOS 2 as a function of the HWHM\textsubscript{bottom} determined from mini-STRIKE; (b) Beamlet divergence estimated by BES for LOS 4 as a function of the HWHM\textsubscript{top}.

Hence the FWHM determined from the mini-STRIKE calorimeter could be used as a starting point to estimate the divergence of the beamlets in BATMAN. This can be done by means of an IDL simulation code: the beam total power can be considered to be the result of the overlapping of the beamlets, each with a defined divergence. By varying the power of each beamlet (therefore its divergence according to the normalised perveance variation) it is possible to simulate the power on the mini-STRIKE tiles. The IR data analysis applied to the simulated cases will give the correlation between the FWHM and the divergence of the beamlets. As a consequence, the mini-STRIKE calorimeter will give a direct estimation of the beamlet divergence by the evaluation of the FWHM parameter. However, this topic is beyond the targets of this thesis. This correlation with the divergence is an important result, which confirms that mini-STRIKE can be used as direct diagnostics of the beam properties and it is a further confirmation that the STRIKE calorimeter will work in SPIDER test facility.

### 6.3 Asymmetry on the vertical profile

As shown in Ch. 5, in some cases the vertical temperature profiles are asymmetric, showing a different gradient in the top tile and in the bottom tile of mini-STRIKE. In the present section such different gradients are further investigated.

In order to exclude that the different temperature gradients are an artifact of the IR data analysis, but are related somehow to the beam, pulses with identical parameters and settings apart from the plasma drift (up and down) have been considered. An example is summarised in Tab. 24. The figures-of-merit resulting from the 2D fit of the 36 amplitudes of the IR data analysis are presented in Tab. 25: the HWHM\textsubscript{bottom} and the HWHM\textsubscript{top} values are reversed when the plasma drift is reversed.
<table>
<thead>
<tr>
<th>Parameter and settings</th>
<th>Pulse #97364</th>
<th>Pulse #98462</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma drift</td>
<td>up</td>
<td>down</td>
</tr>
<tr>
<td>Extraction voltage ((U_{ex})) [kV]</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Acceleration voltage ((U_{acc})) [kV]</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Magnets position ((z)) [cm]</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Source pressure ((p_{source})) [Pa]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>RF power ((P_{RF})) [kW]</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>Bias current ((I_{bias})) [A]</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Extracted current density ((j_{H^-})) [mA/cm²]</td>
<td>16.2</td>
<td>15.5</td>
</tr>
<tr>
<td>Normalised perveance ((\Pi /\Pi_0))</td>
<td>0.115</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Table 24: Pulse parameters for shot number #97364 (plasma drift up) and #98462 with (plasma drift down). The source parameters and settings are similar in the two cases.

<table>
<thead>
<tr>
<th>Figure-of-merit</th>
<th>Pulse #97364 (plasma drift up)</th>
<th>Pulse #98462 (plasma drift down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWHM_{bottom} [mm]</td>
<td>58</td>
<td>89</td>
</tr>
<tr>
<td>HWHM_{top} [mm]</td>
<td>87</td>
<td>60</td>
</tr>
<tr>
<td>FWHM [mm]</td>
<td>145</td>
<td>149</td>
</tr>
<tr>
<td>Ratio = HWHM_{top}/HWHM_{bottom}</td>
<td>1.5</td>
<td>0.68</td>
</tr>
<tr>
<td>Max_{sg} [°C]</td>
<td>7</td>
<td>6.9</td>
</tr>
<tr>
<td>x_{max} [mm]</td>
<td>90.4</td>
<td>159.5</td>
</tr>
</tbody>
</table>

Table 25: Figures-of-merit obtained by the 2D fit of the 36 amplitudes for shot number #97364 (plasma drift up) and #98462 (plasma drift down).

Figure 73: Vertical profile of the amplitudes (indicated by the red diamonds) along the centre of mini-STRIKE (along the line \(h_{pos}=45\) mm, shown in the first image of Fig. 39) and of the 2D fit of the amplitudes (represented by the black line), for two similar pulses: (a) the plasma drift up case (pulse #97364); (b) the plasma drift down case (pulse #98462). The red dashed line marks the centre of the image.

The vertical profile of the 2D fit of the amplitudes in the centre of mini-STRIKE for the pulses #97364 and #98462 is displayed in Fig. 73: the IR data are plotted in red and the fit in solid line. The red dashed line marks the centre of the image, in order to better compare the two cases. The two vertical profiles are clearly almost symmetric with respect to the centre of the image, so it can be excluded an intrinsic different property of the two
tiles. Moreover, the two tiles have been tested by a laser, and such differences have been definitively excluded hence the asymmetry of the 2D profile along the vertical direction is not due to a difference between the two tiles.

Moreover, as discussed in Sect. 6.1, the BES system seems to observe a non-constant behaviour of the divergence along the vertical profile. Although the vertical divergence profile given by BES for the five LOS is affected by errors (20%), it is in agreement with the mini-STRIKE results: for the plasma drift up case BES shows a lower divergence in the upper half of the grid systems. This would be correlated to a smaller HWHM on the top than in the bottom, and this is what comes out from the mini-STRIKE data. For the plasma drift down case, the lower divergence is in the bottom half of the grid system and the HWHM_{top} is smaller than HWHM_{bottom}: even in this case the mini-STRIKE data are in agreement with BES.

The divergence vertical profile might be actually due to a gradient pressure in the tank, since the vacuum pump are situated at the bottom of the vacuum vessel. However, the pressure gradient would not explain the reversal of the divergence vertical profile when the plasma drift is reversed.

A possible reason (to be deeply investigated) for the asymmetry could be explained by a current disuniformity, as already mentioned.

So far, the copper calorimeter did not display a clearly asymmetric vertical profile. However, recent IDL simulations show that slight asymmetries in the power density profile of the beam may be observed by mini-STRIKE and not by the calorimeter: Fig. 74 shows the simulated power density profile on the mini-STRIKE calorimeter (1 m downstream the grounded grid) and on the copper calorimeter (1.5 m downstream the GG), considering an assumed power density disuniformity (related to a current density disuniformity) in the vertical direction of 10% and a beamlet divergence of 2° (this first simulation does not consider yet the correlation between the current density disuniformity and the beamlet divergence profile, further developments are needed). The simulated beam is created by the superposition of the 126 beamlets coming out from the grounded grid, each with its

![Figure 74: Vertical 1D profile in the centre of mini-STRIKE of the simulated power density, considering a 10% vertical disuniformity of the current density and 2° beamlet divergence. The x-axis is the vertical coordinate. The red lines represent the two mini-STRIKE tiles. Image (a) shows the power density profile at 1 m distance downstream the grounded grid (mini-STRIKE), image (b) shows the power density profile at 1.5 m distance downstream the GG (copper calorimeter).](image-url)
own divergence related to the power through the normalised perveance. As mentioned before the simulation does not take into account what happens inside the source or the accelerator, hence the simulation does not provide the beam vertical shift due to the magnetic field.

Simulations show that the vertical asymmetry of the beam power is clearly visible in the region where mini-STRIKE is located, while in correspondence of the copper calorimeter it is smoothed so much due to the distance and the overlapping of the beamlets with a quite high divergence that a symmetric curve could fit it well.

Hence, the asymmetry is related to the plasma drift, and might be correlated to a current density disuniformity. This could be due to the conditioning of the source at such high beam power operations.

However, this is still an open issue and will be investigated in the next future.
7 Conclusions

BATMAN (BAvarian Test MAchine for Negative ions) is a RF negative ion source test facility at Max-Planck Institut für Plasmaphysik (IPP, Garching bei München, Germany). The test bed takes part of the international research program for the Neutral Beam Injector (NBI) of the ITER nuclear fusion machine. The purpose of BATMAN is to optimise the performances with short pulses (∼4 s) of the negative ion source provided with a three-grids extraction system, with an extraction area of 63.33 cm².

In order to study the beam properties, BATMAN is equipped with different diagnostics: a Beam Emission Spectroscopy (BES) system and a copper calorimeter; the latter measures the absolute power dumped and, using several thermocouples, the profile of the beam power. The BES system consists of five lines-of-sight (LOS), which observe the beam downstream the grounded grid with an angle of 147°. From the Balmer α emission spectrum, it is possible to estimate the averaged beamlet divergence along the LOS (from the Doppler-shifted peak) and the fraction of stripped particles. The error associated to the divergence measurement is 20%, because of the contribution of the stripped particles in the Doppler peak. The five LOS are arranged vertically in order to investigate the vertical beam homogeneity.

Recently, the mini-STRIKE calorimeter has been installed, which is mutually exclusive with respect to the copper calorimeter, as it partially intercepts the beam. Mini-STRIKE consists of two identical 120 × 90 × 20 mm³ one-dimensional (1D) Carbon Fiber Composite (CFC) tiles, arranged in vertical direction and exposed perpendicularly to the beam, at 1 m downstream the grounded grid. An infrared (IR) thermal camera looks at the rear side of the tiles with an angle of 50°. At BATMAN, the beamlets overlap due to their large divergence (>2°). Thus it is not possible to resolve the single beamlets on the mini-STRIKE calorimeter. Hence, a water-cooled copper mask with 36 holes has been recently mounted in front of the two tiles, in order to sample the BATMAN beam in several positions, reproducing a beamlets-like structure similar to the one expected in ITER beams.

The main goal of the present thesis was to carry out systematic studies on the BATMAN beam properties via the BES system and the mini-STRIKE calorimeter. In order to analyse the IR images, a data analysis software has been developed.

7.1 Main results

In order to investigate the beam properties, the beamlet divergence and the stripping fraction estimated by BES and the IR images have been analysed in various operational conditions. The influence of different source parameters on the beam have been investigated: the power of the RF source, the bias current, the source pressure, the extraction and the acceleration voltage. The diagnostic systems employed in the present work confirmed previous results concerning the correlations between the beam properties and the source parameters (i.e. the effects of the variation of the source parameters on the current densities and the dependence of the divergence on the normalised perveance and on the extraction to acceleration voltage ratio). Moreover, the new investigation of the BATMAN beam provided a deeper characterisation; for instance, a vertical non-uniformity of the beam has been observed: the five LOS of the BES system recently installed on BATMAN
show a vertical divergence profile not flat and related to the plasma drift. The error in the BES divergence estimation could smooth the profiles out, but the fact that when reversing the plasma drift also the divergence profile is reversed suggests that the profile is real. In fact, for the pulses with plasma drift down a minimum value of the beamlet divergence estimated by BES is observed in the bottom part of the beam (lower half of the grid system), while for the pulses with plasma drift up the minimum value occurs in the top part of the beam (upper half of the grid system).

For further investigations of the beam properties, a new software for mini-STRIKE data analysis has been developed: it analyses the frames recorded by the IR camera, considering only the frames where the beam is present and subtracting the background. The perspective is corrected and afterwards the data is fitted by the superposition of 36 2D Hubbert functions. The 36 amplitudes of the Hubbert functions describe a 2D beam temperature (hence power) profile.

Considering the vertical beam profile, different temperature gradients on the top and on the bottom of mini-STRIKE seem to be present. Finally, the 2D profile of the power deposition by the beam is obtained by fitting the 36 amplitudes previously obtained with a 2D function $h(x, y)$ consisting of the product of a parabola for the horizontal direction and a skewed gaussian for the vertical direction (see Sect. 4.5).

The full width at half maximum (FWHM) of the 1D vertical profile of the function $h(x, y)$ reproduces the typical trend of the divergence as a function of the normalised perveance. Therefore, a correlation between the FWHM and the average of the divergence estimated by BES for the five LOS was studied (incidentally, this result confirms the capability of the mini-STRIKE calorimeter to be used as a direct diagnostic of the beam properties).

The fitting function $h(x, y)$ permits to consider separately the temperature gradients in vertical direction. In some operational conditions, with high power deposition on the front of mini-STRIKE (i.e. with normalised perveance close to the optimum condition and high acceleration voltage), the two temperature gradients (at the top and at the bottom of mini-STRIKE) are different and the vertical temperature profile is asymmetric. By reversing the magnetic filter field, the asymmetry is reversed too, suggesting a correlation of the asymmetry with the plasma or the beam as they experience the magnetic filter field.

The results obtained by BES and mini-STRIKE are consistent: where BES estimates a lower divergence (bottom or upper half of the grid system), mini-STRIKE shows a steeper temperature gradient. The divergence profile and the profile of the power impinging on mini-STRIKE in fact are both correlated to the extracted current density profile.

The copper calorimeter did not show such a clearly asymmetric vertical profile of the power impinging on it, but recent simulations show that an asymmetry of the beam power profile would be clearly visible on the mini-STRIKE calorimeter (which is located 1 m downstream the grounded grid), while at the copper calorimeter distance (1.5 m downstream the GG) the power profile would be smoothed out and the beam could appear symmetric due to the greater distance and the overlapping of the beamlets.

In order to explain the cause of the asymmetry, further investigations are needed.
7.2 Future developments

The divergence vertical profile has to be further investigated with a different evaluation of the Gaussian fit for the Doppler peak in the spectra obtained by BES, in order to decrease the error associated to the standard deviation. This should be supported by simulations of the beam which could confirm the presence of a non-uniform beamlet divergence along the vertical profile of the beam.

Further simulations of the beam power (and current) are also needed in order to compare the data of the copper calorimeter and the data from mini-STRIKE, and to confirm that the asymmetry might be not observed on the copper calorimeter because of the higher distance from the source and the large beamlet divergence.

Moreover, it is also possible to modify the mini-STRIKE design, by moving the tiles closer. In this way the centre of the beam would be better investigated and the peak would be better resolved, enhancing the reliability of the function fitting the 2D thermal profile at the back of mini-STRIKE.

In order to better investigate the ion beam by means of the mini-STRIKE calorimeter, it would be worth to enhance the explored portion of the beam using another tile. A similar tile, with the same thermal characteristics as the two tiles currently in use at BATMAN, is available, but it has a different thickness, hence the thermal pattern from the front to the back of the tiles would not be the same for all the tiles. This problem can be solved by performing the inversion of the thermal pattern by means of the transfer function. This method would provide direct information about the power impinging on the front of mini-STRIKE even using different tiles. The development of this method is still at the early stage but promising.

Further experiments are then needed, in order to understand the behaviour of the beam in some operational conditions. Apart from the necessity to investigate more thoroughly the causes of the vertical beam asymmetry (as already mentioned), mini-STRIKE calorimeter together with the BES system are suitable diagnostics for one of the open issues in beam transport, namely space charge compensation. Indeed these diagnostics, somehow complementary, allow to study at which distance from the accelerator a plasma surrounds the beam counterbalancing the electrostatic repulsion of charges and stopping the increase of beam divergence.
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\(^4\)Tests of unidirectional CFC tiles prototypes for the diagnostic calorimeter of SPIDER experiment