Measurements of the SOL heat flux width on Globus-M


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Introduction. A SOL heat flux width \( \lambda_q \) at the upstream point (normally at outer middle plane) is a principal parameter which determines heat loads onto the divertor plates at the given geometry and magnetic configuration. Since no first principles model exists for \( \lambda_q \), a variety of rather different scaling laws are being established from experiments [1, 2]. A heat balance of both confined and divertor regions has demonstrated that an essential part of plasma energy (up to 30% at NSTX) is not deposited onto the divertor plates. These problems prevent a clear choice of the design parameters for a compact machine, which are being considered as fusion neutron source [3]. Further divertor studies are required.

Experimental setup. To measure SOL plasma parameters several techniques were used on Globus M. The heat flux distribution at the divertor plate was measured using an infrared camera working in the spectral range of 8-14 \( \mu m \) with spatial resolution of about 2 mm, 30-120 frames per second frequency, and 50 \( \mu s \) exposure time. The heat flux density onto the divertor plates made out of graphite was determined from the temperature rise at the plate surfaces. This procedure is based on the one-dimensional half-infinite solid state model [4] for heat transport in divertor plates. The model links the surface temperature \( T(t) \) of the divertor plates with heat flux density \( q(t) \) at the same spatial position by the following equation:

\[
T(t) = \frac{1}{\sqrt{K\pi\rho c}} \int_0^t \frac{q(\tau)}{\sqrt{t - \tau}} d\tau. \tag{1}
\]

Where \( K \) is the heat conductivity, \( \rho = (2026 - 2220) kg/m^3 \) is the density and \( c = 700 J/(kg \cdot K) \) is the heat capacity of the divertor material according to reference [5].

Graphite has a rather asymmetric heat conductivity, namely \( K_{||} = (850 - 1050) W/(m \cdot K) \) along a base plane and \( K_{\perp} = (130 - 190) W/(m \cdot K) \) in the direction normal to it.

The base plane was oriented in the direction normal to the divertor plate surface [5] during its manufacturing. Therefore, \( \sqrt{K_{||}\pi\rho c} = 6.6 \times 10^4 J/(m^2 \cdot K \cdot s^{1/2}) \) should be used for the
derivation of the heat flux using equation (1). We should note that the value \( \sqrt{K \pi \rho c} = 2.7 \times 10^4 J/(m^2 \cdot K \cdot s^{1/2}) \) was used improperly in our previous work [6]. This caused the underestimation of the heat flux density by up to a factor of 2.5.

Besides, a procedure of experimental data processing of IR data was improved in comparison the one employed in Ref. [6]. It allowed to subtract the systematic IR camera noise which was the main cause for the signal background far from the SOL region. In addition to the improvement of the signal to noise ratio, the IR data along the toroidal direction were averaged.

Spatial distributions of density and electron temperature at the divertor plates were measured by means of a set of 10 embedded Langmuir probes with 8 mm diameter and a temporal resolution of about 2 ms. At a given sheath transmission coefficient of 7, the heat flux density was evaluated using the density and temperature measured by probes.

*Table 1. Parameters of Globus-M discharges studied.*

<table>
<thead>
<tr>
<th>Type</th>
<th>( B_n, T )</th>
<th>( I_p, \text{kA} )</th>
<th>( \bar{n}_e, 10^{19} \text{m}^{-3} )</th>
<th>( P_{Oh}/P_{NBI}, \text{kW} )</th>
<th>( P_{div} )</th>
<th>Shot numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>0.35</td>
<td>170</td>
<td>4</td>
<td>270</td>
<td>120 kW</td>
<td>###30088-30095</td>
</tr>
<tr>
<td>OH</td>
<td>0.35</td>
<td>170</td>
<td>4</td>
<td>270</td>
<td>60 a.u.</td>
<td>###32041-32042</td>
</tr>
<tr>
<td>OH+NBI</td>
<td>0.35</td>
<td>180</td>
<td>4</td>
<td>290/500(^1)</td>
<td>80 a.u.</td>
<td>###31514-31521</td>
</tr>
</tbody>
</table>

\(^1\) The output power of the neutral beam injector, \(^2\) Just after the cleaning procedure of the divertor plates.

\(^3\) After one year of machine running.

**Ohmically heated plasmas.** First results had been obtained during the 2012 campaign in OH plasmas (parameters are shown in the first row of Table 1) and were published in Ref. [6]. These IR data were re-processed as described above and are shown by blue line in Fig. 1 together with data of Langmuir probes depicted by dots. One can see that the maximal heat flux density is up to 2.3 MW/m\(^2\) and that the Langmuir probe yields lower values at the right wing of the IR curve. We should also note that the new analysis approach does not change the heat flux width. For the Ohmically heated regime shown in Fig. 1 the measured heat flux width is 15 mm corresponding to 3 mm heat flux width at the mid-plane. This value is in fair agreement with 5 mm width estimated using Goldstone scaling [2].

The heat flux density profile integrated over the divertor plate reveals 120 kW of total divertor heat load at outer leg that is \(~45\%\) of the heating power of about 270 kW. The later value was deduced from measured values of loop voltage (1.6 V) and plasma current (170 kA). Radiation losses can be assumed less than 10% according to Ref. [8]. Therefore, one can conclude that about 40% of the power entering the SOL goes to the divertor plates.
fraction of power deposited on the outer leg is in fairly agreement with those observed in other spherical tokamaks [9].

Results of theoretical simulations of the heat flux density using the B2SOLPS5.2 code from Ref. [7] are also shown in the Fig. 1. The shape of the profiles are similar but the IR experimental data are about 1.8 times higher than the computed ones. We should note, however, that in the modeling of this OH discharge [7] the power crossing the separatrix was calculated under the assumption of $Z_{\text{eff}}(r)=1.5$ yielding 150 kW. This is about 1.9 times lower than the measured value and might be the reason of the discrepancy between experimental and theoretical heat flux profiles. Independent measurements of $Z_{\text{eff}}$ using the visible continuum radiation will elucidate these discrepancies in near future.

**OH+NBI heated plasmas.** Recently, the divertor heat flux density profile was measured during either OH or OH+auxiliary NBI using the IR camera. Parameters of these shots are presented in Table 1 (rows 2 and 3). The heat flux profiles in arbitrary units are shown in Fig. 2. For comparison, the data of Fig. 1 from an OH shots with similar parameters but taken a year ago are also shown (blue thin line). It is not clear at present, what caused the changes in profile height and width between these two ohmic discharges of similar setting (up to 2 times).

During the summer 2013 shutdown of Globus-M we will control the surface of the divertor plate for additional layers not accounted for and will inspect the IR optical system.
Therefore, only a qualitative analysis is possible at present. The divertor heat flux density profile is more narrow in the OH+NBI than during the OH phase. The total divertor heat load increases by a factor of 1.5 with beam heating. The shrinking of the SOL heat flux profile with increasing input power has also been observed at NSTX [1]. This variation is, however not in agreement with the latest multi-machine scaling law [2]. Because of the above mentioned problems for the ohmic phase and as the absorbed beam power is not sufficiently well defined owing to large orbit losses of fast ions [10] we have not yet tried a power balance calculation.

Summary. The processing algorithm of IR data of SOL heat flux measurements by an IR camera was improved. Heating flux profile measured by Langmuir probes demonstrate lower values than those based on IR measurements. The measured power fraction onto the divertor plate confirms the typical observations on spherical tokamaks. Goldstone scaling applies fairly well to the SOL heat flux width measured in OH discharges but does not explain the findings with beam heating. Modeling by means of the B2SOLPS5.2 code reproduces the shape of the heat flux profile in SOL. The absolute values of the divertor heat load is lower at, however, also a lower input power.

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References.
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