Energy Balance for Ohmic Plasmas on Golem

Mathieu Debongnie, Ekaterina Matveeva

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Abstract

This paper reports the results of an investigation on global energy balance on tokamak Golem[1]. Measurements of interferometer diagnostics, rogowski coil, loop voltage are analysed to calculate power losses and energy confinement time. Discharges with various plasma densities and electron temperatures are compared.

Golem, Power Balance

1 Introduction

A tokamak plasma is subjected to power loss through various channels so it is crucial to understand the balance between inputs and losses to improve tokamak operation. One of the most important parameters of fusion plasma is the energy confinement time which can be derived using the global power balance. The global energy balance can be expressed as[2]:

$$\frac{dW}{dt} = P_\alpha + P_{Ext} - P_{Rad} - P_{Loss}, \tag{1}$$

where P_α is the heating from alpha particules, P_{Ext} is the external power coupled to the plasma, P_{Rad} is the energy loss through radiative processes (e.g. line radiation, bremsstrahlung) and P_{Loss} is the loss of energy through transport to the wall.

The confinement time can then be calculated using:

$$\tau_E = \frac{W}{P_{Loss}}. \tag{2}$$

In the golem tokamak there is no fusion reactions which means that $P_\alpha = 0$. So the only additional heating is provided by ohmic heating from the current induced in the plasma of finite resistance ($P_{Ext} = P_{OH}$).

To evaluate the impact of the radiation loss, two different assumptions can be compared. The first hypothesis is that the radiation power and the variation of internal energy are negligible with respect to ohmic heating power. Equation 2 can then be expressed as:

$$\tau_E^{OH} = \frac{W}{P_{OH}}. \tag{3}$$

The second assumption is that the radiation losses and the variation of energy can not be neglected so that equation 2 becomes:

$$\tau_E^{tot} = \frac{W}{P_{OH} - P_{Rad} - \frac{dW}{dt}}. \tag{4}$$

2 Description of the experimental campaign

A number of experiments were carried out to investigate the relations between the different power sinks and to determine the energy confinement time. The discharge parameters that were used are described in Table 1. For each set of parameters the discharge was repeated three times in order to estimate error bars. Every discharge has been initiated through pre ionization by a heated tungsten filament and with no delay between the two sets of capacitors.

discharge number	20885 20884 20868	20909 20908 20864	20888 20886 20863	20907 20906 20905	20890 20889 20861
P [mPa]	16	18	22	26	30
U_{CD} [V]	700	700	700	700	700
U_{Bd} [V]	1100	1100	1100	1100	1100

Table 1: *Parameters of the analysed discharges. P is the requested pressure in the chamber before the discharge, U_{CD} controls the electric field during the discharge and U_{Bd} controls the electric field during the breakdown.*

3 Experimental data analysis

Plasma current and plasma resistance

The plasma current I_p and the plasma resistance R_p can be determined from the loop voltage U_{loop} and the Rogowski coil measurements I_{Rog}:

$$U_{loop} = I_{ch}(t)R_{ch} + R_p(t)I_p(t), \tag{5}$$

with $I_{ch}(t) + I_p(t) = I_{Rog}(t)$ and where $I_{ch}(t)$ and R_{ch} are the current and the resistance in the chamber walls respectively and are determined through a vacuum discharge ($I_p = 0$). By using these relations, the effect of the inductance of the plasma and the walls is neglected (valid for $\frac{dI_{Rog}}{dt} \approx 0$).

Ohmic heating and electron temperature

From the plasma current and resistance, the ohmic heating generated can be simply expressed as:

$$P_{OH}(t) = R_{pl}(t)I_{pl}^2(t). \tag{6}$$

And the electron temperature at the center of the plasma is given by the Spitzer's formula:

$$T_e(0,t) = T_{e0}(t) = \left(0.7\frac{I_p(t)}{U_{loop}}\right)^{2/3}. \tag{7}$$

Energy content and density profiles

From the ideal gas law and assuming the temperature profile to be $T_e(r,t) = T_{e0}\left(1 - \left(\frac{r}{a}\right)^2\right)^2$, the total energy content is simply given by:

$$W_{pl}(t) = V\frac{\bar{n}_{pl}(t)k_B T_{e0}(t)}{3}, \tag{8}$$

where V is the volume of the plasma ($= 2\pi^2 Ra^2$ for a toroidal shape), $\bar{n}(t)$ is the average density, k_B is the Boltzmann constant and $T_{e0}(t)$ is the electron temperature calculated with the Spitzer's formula (eq. 7).

In the majority of analysed discharges, the interferometer density measurements were not reliable. So two different assumptions were considered in order to derive the average density of the plasma. The first consist to assume that all the gas in the chamber is ionized during the discharge. Therefore, using the ideal gas law and taking into account that for each hydrogen molecule there are two electrons produced through ionization, the average density is given by:

$$\bar{n}_{pl}^{ideal} = \frac{2P_{ch}}{k_B T_{ch}}, \tag{9}$$

where P_{ch} and T_{ch} are respectively the pressure and the temperature in the chamber just before the discharge.

The second assumption is that the average density of the plasma is a constant fraction χ of the Greenwald limit:

$$\bar{n}_{pl}^G = \chi n_G = \chi\frac{I_{pl}}{\pi a^2}. \tag{10}$$

The merit of the first assumption is its simplicity but it provides a constant value which is not realistic. The second assumptions however provides a value that evolves with the plasma properties but requires to fit χ for each discharges. In the present work, χ is assumed to be equal to 0.3.

In both cases, the density profile is assumed to follow a bell shape given by:

$$n_{pl}(r,t) = n_{pl0}(1 - \left(\frac{r}{a}\right)^2), \tag{11}$$

where $n_{pl0} = 1.5\bar{n}_{pl}$. Considering the quasi-neutrality of the plasma, the ion density simply follows the same density profile ($n_e(r,t) =$

$n_i(r,t) = n_{pl}(r,t)$. And so as a first approximation the neutral density profile can be taken as the complementary of the ion density profile:

$$n_H(r,t) = n_{pl0} - n_{pl}(r,t). \tag{12}$$

Radiation losses

The radiation losses include bremsstrahlung radiations, impurity and hydrogen line radiations and synchrotron radiations. However, only the bremsstrahlung radiations and the hydrogen line radiations are considered in the present work.

The bremsstrahlung radiations is calculated using:

$$P_{brem} = 2.10^{-38} V Z_{eff} \bar{n}_{pl}^2(t) T_e^{0.65}(r,t), \tag{13}$$

where $Z_{eff} = 2$ is assumed and is the effective charge of the plasma.

The golem spectrometer and photodiodes are not calibrated so to do an estimation of the hydrogen line radiation it is necessary to use a model. Here, the following model is considered:

$$P_{Hrad}(r,t) = n_{pl}(r,t) n_H(r,t) f(T_e(r,t)), \tag{14}$$

where $n_H(r,t)$ is the density of the neutral hydrogens and $f(T_e(r,t))$ is the radiation function provided by Dr. R. Guirlet. The radiated power calculated with this model include all the different hydrogen lines.

4 Results

A typical time evolution of the terms in the power balance (eq. 1) is shown in Fig. 1. The energy loss through bremsstrahlung radiations is shown to be of the order of 0.1 to 1 W which is negligible in regards to the ohmic heating. Except for the first and last moments of the plasma, the variation in internal energy is also negligible in the power balance. Finally, the H line radiations is shown to be an important part of the balance for most of the plasma lifetime. This case is of particular interest as a high radiation at the edges of the plasma is preferable in order to decrease the thermal load on the walls and the divertor.

From the previous consideration, it becomes clear that H line radiations strongly affect the energy confinement time. In particular Fig. 2 shows that τ_E^{OH} underestimates the confinement time by a factor 2 to 10.

In order to compare confinement time for different plasma densities and electron temperatures it was assumed that the power loss is equal to the ohmic heating (eq. 3). The reason for that lies in the observation that calculating the confinement time using radiation power (eq. 2) gives significant fluctuations, making the comparison between discharges difficult.

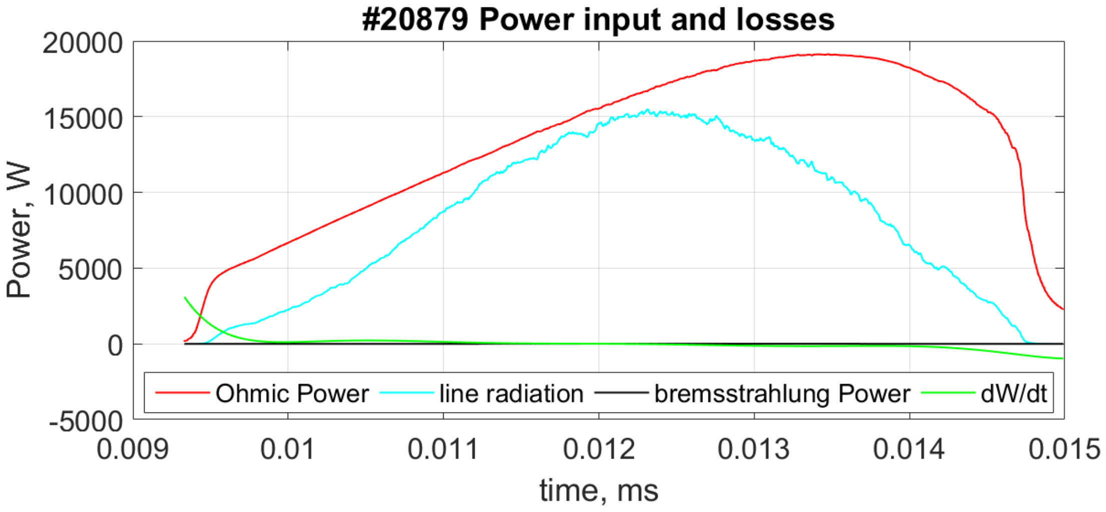

Figure 1: Time evolution of the power balance terms.

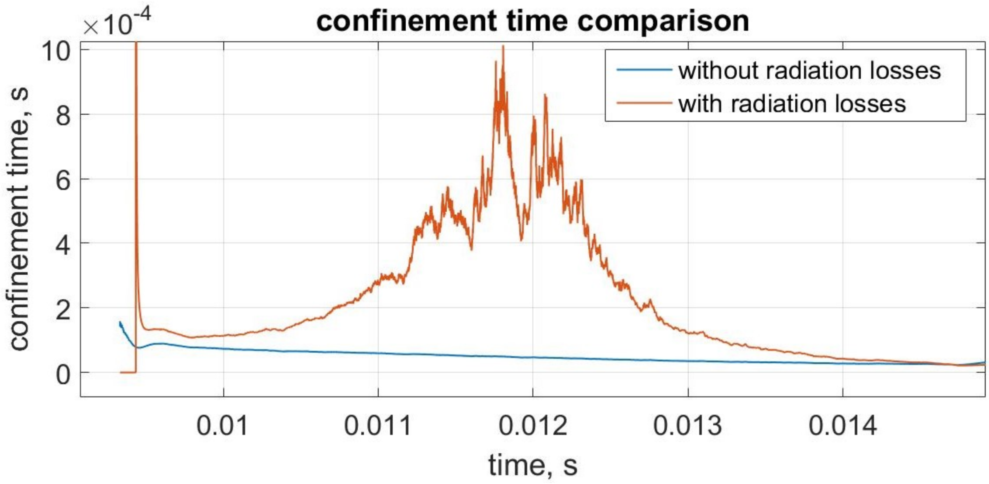

Figure 2: Time evolution of the confinement time with and without the radiation losses.

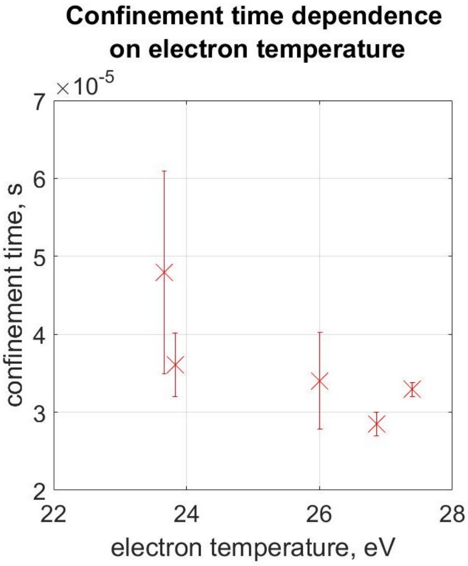

Figure 3: Energy confinement time in dependence on electron temperature in the plasma center.

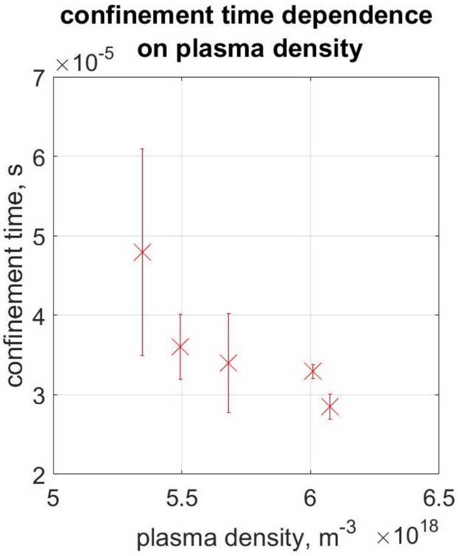

Figure 4: Energy confinement time in dependence on average plasma density.

A time point in the middle of the discharge (where $\frac{dI_{pl}}{dt} \approx 0$) was chosen to investigate confinement time dependence on electron temperature and plasma density. Fig. 3 and 4 show the energy confinement time in dependence on electron temperature in the plasma center and on the average plasma density respectively. In both cases confinement time tends to decrease with increasing plasma density and electron temperature, however the dependence is not clear due to the large error bars.

The standard deviation of the profiles were evaluated for the maximum values of the ohmic power and the H line radiation losses. This makes the comparison between discharges more accurate.

Fig. 5 shows that the error is negligible in regard to the amplitude of the discussed parameters. Which allows the comparison between power input and losses.

5 Conclusion

A number of discharges with various plasma densities and electron temperatures were considered to investigate the global power balance on the tokamak Golem. It was shown that bremsstrahlung radiations and the derivative of the energy content can be neglected in comparison with ohmic heating and the H lines radiations. Also significant change in confinement time is observed when including the radiation power in the calculations.

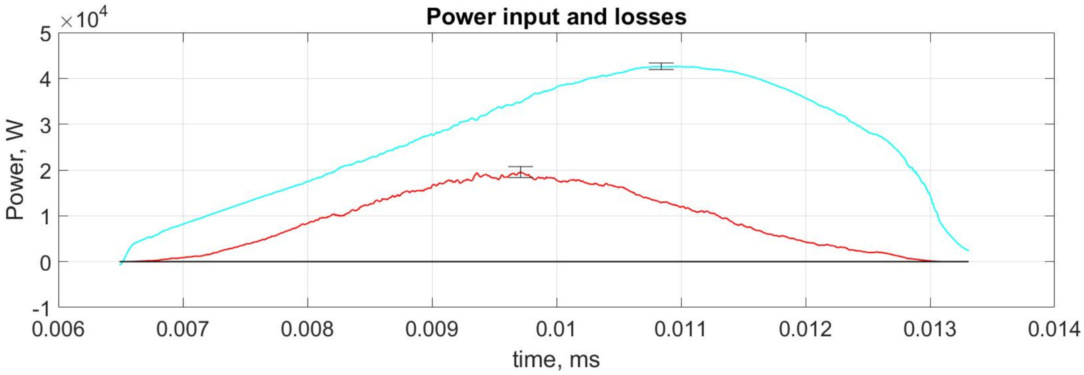

Figure 5: Time dependence of the ohmic power (teal) and the H line radiation loss (red). Error bars were determined at the maximum of both curves.

In addition to this confinement time dependence on the electron temperature and the plasma density was investigated. Results strongly depend on the way the plasma density is estimated. It was shown that calculation of plasma density with ideal gas law (using neutral pressure and chamber temperature) gives an overestimated density which leads to radiation losses higher than ohmic heating. Also only "bell" shaped radial profile of density was used. The effect of different profile configurations such as triangular and flat might be studied in future.

References

[1] E. Bromova et al. The golem tokamak for fusion education. In *Europhysics Conference Abstracts, 38th EPS Conference on Plasma Physics*, volume 35G, page 1, 2011.

[2] J. Wesson and J. W. Connor. *Tokamaks*. Clarendon Press, 1987.