REPORT OF PRACTICAL WORK

Speciality :

Physique et Technologie de la Fusion et des Plasmas

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About Hands :

Experiment on GOLEM

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0.1 Purpose of practical work

These tutorials are aimed firstly to study the variation of the confinement time (τ_E) measured on the GOLEM experience depending on the electron density (n_{e0}) and plasma current (I_p) measured on the same experience and secondly to compare the confinement time (τ_E) to scaling law that obtained on experience Neo-Alcator (τ_S).

To achieve this goal, we diagnosed the different plasma obtained on GOLEM and subsequently calculate the different parameters of these plasma, thanks to Matlab code we took care to write.

We will present initially a brief discussion of the experience GOLEM then we will present the various parameters we had to calculate, after we present the variation of τ_E (n_{e0}, I_p) and we compare it with τ_S and finally we will make a conclusion.

0.2 State of the art

Tokamak GOLEM is a small tokamak operating at the Faculty of Nuclear Sciences and Physical Engineering at the Czech Technical University in Prague. It is an educational device which contribute to the training of students in fusion research. One of the key features of this device is the possibility of a fully functioning remote so it is suitable for international experiences with broad participation.

The main parameters are GOLEM :

The large plasma radius : $R_0 = 40$ cm ; The small plasma radius : $a_0 = 8{,}5$ cm
The maximum toroidal magnetic field : $B_{tor.max} = 0.8$ T
The current maximum plasma : $I_{P.max} = 10$kA
The typical duration of the plasma : 15 ms ; The gas used : H_2

0.3 Calculation of the physical parameters of the plasma

Parameters that will be presented below have been calculated using 14 plasma discharges performed on the GOLEM tokamak. Our goal is to see how τ_E varies depending on n_{e0} and I_p as an adjustable parameters of the tokamak (the pressure of the gas injected into the chamber of the tokamak therefore the gas density and voltage U_{CD} therefore the plasma current) and the results were read directly online on the website of Tokamak GOLEM. On the plasma discharge 14, the first discharge was vacuum without gas injection, the other 13 were made with injection of gas and among these 13, 10 were generated plasma and 3 were not able to produce the plasma.

The GOLEM tokamak can be considered an electrical circuit with two resistors in parallel and two inductors (see Figure 1)

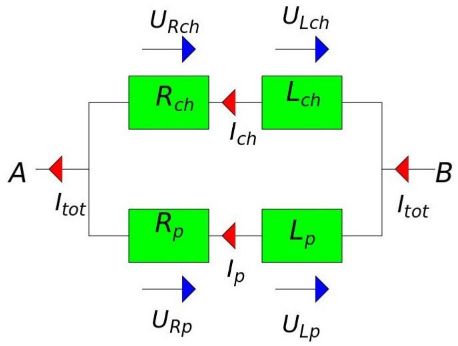

FIGURE 1 – Equivalent electrical circuit of the tokamak GOLEM

0.3.1 Calculating total current and plasma current

To calculate the total current, we have considered measurements made on the coils also call Rogowski coil.

For this we have recouped the file called IROGs online. This file provides the voltage Us (U_{rog}) versus time (t) measured by the Rogowski coil. This voltage may be represented as follows :

$$U_{rod} = \frac{1}{C_1}.\frac{\mathrm{d}I_{tot}}{\mathrm{d}t} \Longrightarrow \int \mathrm{d}I_{tot} = \int U_{rog}.C_1.\mathrm{d}t \tag{1}$$

Where $C_1 = 5000$ is the calibration factor.

After calculating the offset, it was subtracted from the voltage U.

To calculate the plasma current, we first calculate the resistance R_{ch} andL_{ch} inductances of the vacuum chamber. Discharge was performed without gas injection and the current I_{tot} and voltage U_{loop} measured, which means we have the plasma current $I_p = 0$ and the plasma inductance $L_p = 0$ (see Figure 1)

We therefore obtain the following equation :

$$U_{loop} = R_{ch}I_{ch} + L_{ch}\frac{\mathrm{d}I_{ch}}{\mathrm{d}t} \tag{2}$$

With $I_{tot} = I_{ch} + I_p \Longrightarrow I_{tot} = I_{ch}$ for $I_p = 0$ and for $I_{ch} = I_{ch.max}$ was $\frac{\mathrm{d}I_{ch}}{\mathrm{d}t} = 0$

With the Matlab code we programmed, it was found $R_{ch} = 0.0101\ \Omega$ and $L_{ch} = 1.21{\times}10^{-6}$ H.

These parameters calculated above have allowed us to calculate I_p, L_p and R_p.

To calculate I_p, was replaced by his I_{ch}, I_{ch} value = I_{tot} - I_p and through Matlab code, we found Ip (t) (the average value will be given in the following).

L_p was then calculated by the formula :

$$L_p = \mu_0 R_0 \left(\ln \left(\frac{8R_0}{a_0} - \frac{7}{8} \right) \right) \tag{3}$$

Found $L_p = 9.4{\times}10^{-7}$, we assume here that Lp is constant because we set $a_0 = 8.5$ cm.

R_p is thus deduced that varies with temperature and therefore the time T_{e0}

$$R_p = \left(U_{loop} - L_p \frac{\mathrm{d}I_p}{\mathrm{d}t} \right) \frac{1}{I_p} \tag{4}$$

We give the average value of R_p in the following.

0.3.2 Calculation of the toroidal magnetic field and the power injected

To calculate B_{tor} was recouped btor the file online. This file provides the voltage Us (U_{tor}) versus time (t)

$$U_{tor} = \frac{1}{C_b}.\frac{\mathrm{d}B_{tor}}{\mathrm{d}t} \Longrightarrow \int \mathrm{d}B_{tor} = \int U_{tor}.C_b.\mathrm{d}t \tag{5}$$

Where $C_b = 170$ is the calibration factor.

The injected power is simply

$$P_{ohm} = U_{loop}I_p \tag{6}$$

0.3.3 Calculation of the temperature (T_{e0}) and density (n_{e0}) Electronic

To calculate T_{e0}(eV) and $n_{e0}(m^{-3})$ in the center of the plasma, it was assumed that the temperature and the electronic density has a parabolic profile can therefore be written as :

$$x = x_0 \left(1 - \left(\frac{r}{a_0} \right)^2 \right) \tag{7}$$

After considering Ohm's law gives us Ip I_p ($U_{loop}, T_e(r)$ and by assuming that $Z_{eff} = 1$ are :

$$T_{eo} = \left(\frac{5R_0 I_p}{1.13 * 10^3 {a_0}^2 U_{loop}} \right)^{\frac{2}{3}} \tag{8}$$

n_{e0} the power density is obtained by considering that the H_2 gas injected into the tokamak is a perfect gas, in this case we have :

$$n_{e0} = \left(\frac{6 P_n \alpha_{ion}}{K_b T_n} \right) \tag{9}$$

Where $T_n = 300$ K is the temperature of the room, P_n is the pressure of inert gas, $\alpha_{ion} = 1 - \exp\left(-\frac{T_{e0}}{13.6}\right)$ is the ionization ratio of plasma.
We give the values found in the sequel.

0.3.4 Calculation of the safety factor and energy contained in the plasma

To calculate the safety factor, we used the formula :

$$Q_{cycl} = \frac{a_0 B_{tor}}{R_0 B_\theta} = \frac{2\pi {a_0}^2 B_{tor}}{\mu_0 I_p R_0} \tag{10}$$

With $B_\theta = \frac{\mu_0 I_p}{2\pi a_0}$
The energy of the plasma is obtained by integrating the pressure of the electronic volume of the tokamak. we have :
$P_e = \frac{3}{2} n_e T_e, \qquad T_e = T_{e0}\left(1 - \left(\frac{r}{a_0}\right)^2\right), \qquad n_e = n_{e0}\left(1 - \left(\frac{r}{a_0}\right)^2\right)$
This allowed us to write :

$$E_{th} = \int P_e \mathrm{d}V = \pi^2 R_0 {a_0}^2 n_{e0} T_{e0} e \tag{11}$$

Where T_{e0} is Kelvin and e is the electron charge

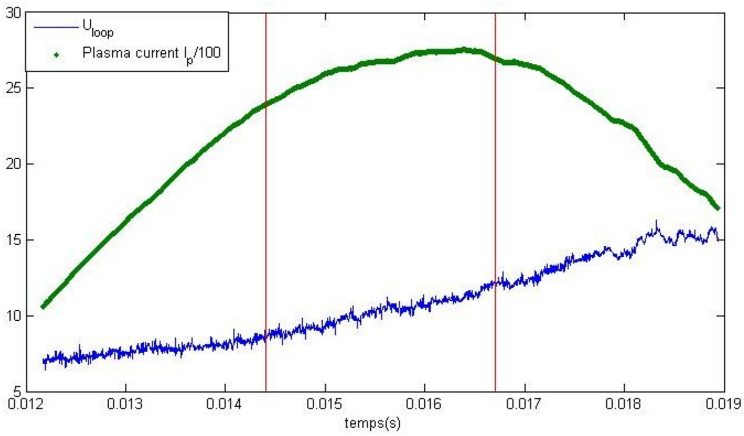

FIGURE 2 – Curve representing U_{loop} and $\frac{I_p}{100}$ versus time. The time gap between the two vertical lines represents the space in which we calculated the average of all physical parameters

The mean values obtained for a plasma discharge with $P_n = 5.1295$ mPa and $U_{CD} = 700$ V are :
$I_{tot} = 3639.4664$ A ; $U_{loop} = 10.1987$ V ; $R_c = 0.0101\ \Omega$; $L_c = 1.21 \times 10^{-6}$ H ; $I_p = 2646.816$ A ; $L_p = 9.4411 \times 10^{-7}$; $R_p = 0.0038\ \Omega$; $B_{tor} = 0.15836$ T ; $P_{ohm} = 27076.6017$ W ; $n_{e0} = 5.14 \times 10^{+18}\ m^{-3}$; $T_{e0} = 15.977$ eV ; $Q_{cycl} = 5.4027$; $E_{th} = 0.37474$ J

0.4 Variation τ_E (n_{e0}, I_p) and its comparison with τ_S

Confinement time is a very important characteristic for the area of fusion. It is evaluated by :

$$\tau_E = \frac{E_{th}}{P_{out}} = 1.416 \times 10^{-005} s \Longrightarrow \tau_E \propto \frac{n_{e0}}{I_p} \tag{12}$$

We have $P_{out} = P_{ohm} - \frac{\mathrm{d}E_{th}}{\mathrm{d}t}$, we have neglected the second term $\Longrightarrow P_{out} = P_{ohm}$
The figure below shows how τ_E varies depending on the electron density and function of plasma current I_p.

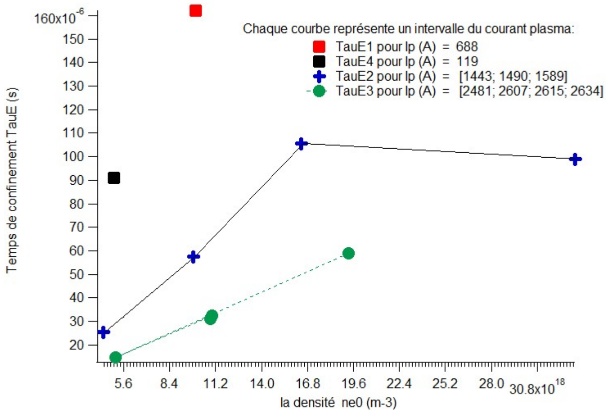

FIGURE 3 – Variation as a function of τ_E n_{e0} and I_p
. Uncertainties have been minimized because very low.

The values of τ_E , n_{e0} and I_p are noted in Figure 3 are average values. It is seen that, when the density increases n_{e0}, τ_E also increases in accordance with Equation 12 and τ_E decreases when I_p increases , which is also verified by our experiments on the tokamak GOLEM

($n_{e0} \approx$ cte, $\tau_E \nearrow I_p \searrow$ and for $I_p \approx$ cte, $\tau_E \nearrow n_{e0} \nearrow$).

We were then compared to the confinement time τ_E given by the scaling law τ_S obtained on the Neo-Alcator tokamak.

$$\tau_S = 7.1 \times 10^{-22} \overline{n_{e0}} {a_0}^{1.04} {R_0}^{2.04} \sqrt{Q_{cycl}} \tag{13}$$

In comparison, we has obtained the graph below :

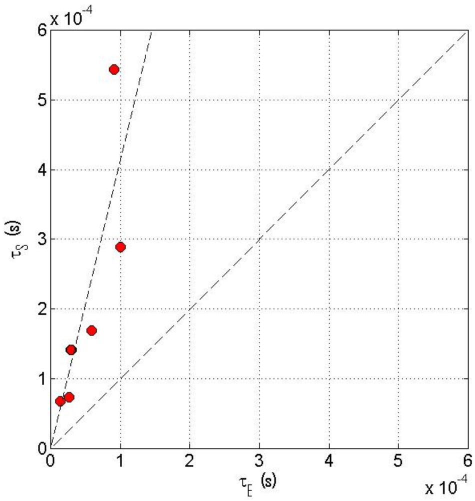

FIGURE 4 – Comparaison entre τ_E et τ_S

We noticed we $\tau_S \approx 5 \times \tau_E$, but there is still a nearly linear relationship between the two confinement time.

0.5 Conclusion

The purpose of these experiences was to see how varied the confinement time of the tokamak (τ_E) based n_{e0} and I_p,, which has been highlighted, but should nonetheless be noted that there is a correlation between n_{e0} et I_p, it is not enough to increase I_p for more τ_E.

We also saw that there is an almost linear relationship between τ_E and τ_S. The observed difference is probably due to assumptions that we had to do to simplify our calculations, for example the constant a_0 or on account of gas H_2 gas as a perfect gas, etc..

The experiments we performed on the tokamak GOLEM was a unique opportunity for us to put into practice the theoretical baggage that we were to receive throughout our mileage.