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Hands-on project : Experiment on GOLEM
Group 3 – Report

2. How to determine the main physical quantities ?

2.1 Total current :

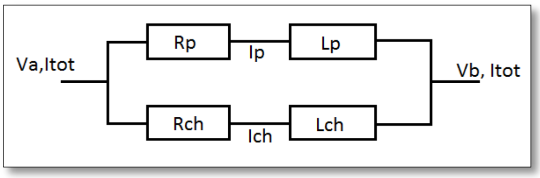
The Rogowski coil measurement is U_{rog} and has an offset. Since it is a coil, we can write :

$$U_{rog} = L_{rog}.dI_{tot}/dt + U_{offset}$$

So, in order to obtain I_{tot}, we have to remove the offset : $U_{rog} - U_{offset} = L_{rog}.dI_{tot}/dt$,then we have to multiply by $1/L_{rog} = C_I = 5000$: $dI_{rog}/dt = C_I.(U_{rog} - U_{offset})$, and finally, we have to integrate over time : $\boxed{I_{tot} = \int(U_{rog} - U_{offset}).C_I.dt}$

2.2 Plasma current :

We can represent the chamber and the plasma like this :



So, thanks to Kirchhoff's circuit laws, we obtain :

$$\begin{cases} I_{tot} = I_p + I_{ch} \\ V_b - V_a = U_{loop} = R_p.I_p + L_p.dI_p/dt = R_{ch}.I_{ch} + L_{ch}.dI_{ch}/dt \end{cases}$$

From the previous equations and the measurements, we can deduce I_p.
In order to determine the plasma resistivity, we can use the relation $U_{loop} = R_p.I_p + L_p.dI_p/dt$ when I_p is maximum, so that $dI_p/dt = 0$. If we call t_{max} the time at which I_p is maximum, we have $U_{loop}(t_{max}) = R_p.I_{pmax}$, so $\boxed{R_p = U_{loop}(t_{max})/I_{pmax} \text{ (some } m\Omega)}$

2.3 Toroidal magnetic field :

We can write : $U_B = d/dt.\int\int B_t.dS + U_{offset}$, so by removing the offset and integrating over the time, we obtain : $\int(U_B - U_{offset}).dt = B_t.S$ (assuming B_t is constant)
And, by multipling by $1/S = C_B = 170$, we obtain B_t :

$$\boxed{B_t = \int(U_B - U_{offset}).C_B.dt}$$

2.4 Injected power :

The injected power in the plasma is simply : $\boxed{P_{inj} = U_{loop}.I_p}$

2.5 Electron temperature :

We have : $I_p = 1.13.10^3.(U_{loop}/2\pi R_0 Z_{eff})\int_0^a T_e(r)^{3/2}.2\pi r.dr$

Let us assume that $T_e(r) = T_{e0}(1 - r^2/a^2)$, with T_{e0} the central temperature, thus :

$$\int_0^a T_e(r)^{3/2}.2\pi r.dr = \int_0^a T_{e0}(1 - r^2/a^2)^{3/2}.2\pi r.dr = 2\pi T_{e0}{}^{3/2}.(\frac{-a^2}{2})\int_0^a(1 - r^2/a^2)^{3/2}.(\frac{-2r}{a^2}).dr$$

Which is of the form : $\alpha \int u^n.u'$, so we obtain :

$$I_p = 1.13.10^3\,.(U_{loop}/2\pi R_0 Z_{eff}).2\pi {T_{e0}}^{3/2}.\frac{a^2}{5}, with\ a = 8{,}5.10^{-2}m$$

Thus : $\boxed{T_{e0} = (6.12.10^{-1}.\frac{Z_{eff}.I_p}{U_{loop}})^{2/3}, \quad (\sim 10eV)}$

2.6 Electron density :

Let us consider a complete ionization so that H_2 dissociates in $2H^+ + 2e^-$, thus $\overline{n_e} = 2\overline{n_{H_2}}$, and a collisional plasma since the electron density is pretty important with respect to the electron temperature. Let us assume T_{room} is the room temperature ($\cong 300K$).

So we have : $\overline{P_{H_2}} = \frac{3}{2}.\overline{n_{H_2}}.k_b.T_{room} = \frac{3}{2}.\frac{\overline{n_e}}{2}.k_b.T_{room}$

Thus : $\boxed{\overline{n_e} = \frac{4P_{H_2}}{3k_b T_{room}} \cong 3.22.10^{17}.\overline{P_{H_2}}, \quad (with\ \overline{P_{H_2}} = [mPa])}$

2.7 Safety factor :

According to the definition of the safety factor : $q(r) = \frac{r}{R}.\frac{B_t}{B_p}$. So, at the last closed flux surface, $q(a) = \frac{a}{R}.\frac{B_t}{B_p}$. By using Maxwell-Ampere's law, we have :

$$2\pi a B_p = \mu_0 I_p$$

So, $B_p = \mu_0 I_p / 2\pi a$ and $q(a) = \frac{a}{R}.\frac{B_t}{\mu_0 I_p}.2\pi a = \frac{2\pi a^2 B_t}{R.\mu_0 I_p}$,

Thus, we obtain : $\boxed{q(a) = 90.\frac{B_t}{I_p}, \quad with\ B_t = [T], and\ I_p = [kA]}$

2.8 Plasma energy content :

The plasma energy content can be either determined by integrating the pressure over the torus volume, or by considering the pressure equilibrium $\overrightarrow{grad}P = \overrightarrow{J_{dia}} \times \overrightarrow{B_t}$

We can consider $P = P_e + P_i$ and since the plasma is collisional, we have $T_e = T_i$, and $n_e = n_i$ (electroneutrality), so $P_e = P_i$, and $P = 2P_e$. Thus : $W = \iiint P.dV = \iiint 2P_e.dV$

By using $P_e = \overline{n_e}.k_b.T_e$, we can obtain W.

$$W = 2\overline{n_e} \iiint k_b.T_e.dV \cong 6.44.10^{17}.\overline{P_{H_2}}(mPa).2\pi R_0 \int_0^a k_b.T_e(r).2\pi r.dr$$

With $T_e(r) = T_{e0}(1 - r^2/a^2)$, we obtain : $\boxed{W \cong 1.84.10^{16}.\overline{P_{H_2}}(mPa).T_{e0}}$

Thus, this is the first way to determine W.

The second way of determining W is by using the relation : $\overrightarrow{grad}P = \overrightarrow{J_{dia}} \times \overrightarrow{B_t}$.

$\overrightarrow{J_{dia}}$ is obtained thanks to the diamagnetic loop voltage $U_{dia} = L_{dia}.\frac{d}{dt}\iint \overrightarrow{J_{dia}}.\overrightarrow{dS} + U_{offset}$, so :

$$\overrightarrow{J_{dia}} = \int \frac{(U_{dia} - U_{offset})}{L_{dia}.S}.dt$$

And B_t is obtained thanks to U_B (see 2.3). So we obtain $\overrightarrow{grad}P$ that we have to integrate over r in order to determine P, and finally we integrate P over the space to obtain :

$$\boxed{W = \iiint P.dV.S = \iiint (\int j_{dia}.B_t)}$$

Processing and interpreting results

Golem is the oldest tokamak in the world, settled in the Czech Technical University since 2006, it is continuously upgraded with the aim of training students by organizing remote experiments. The subject of our work is to experiment situations in the tokamak in order to see how it reacts, with the objective of maximizing the plasma duration. For this, we will adjust some parameters such as : the presence of preionization, the toroidal field, the current drive, the H_2 pressure, and the time delay between the launch of the toroidal field and the current drive.
Our action plan was to make modifications on one of these parameters with the other parameters set to a constant value and to observe the evolution of the plasma duration. The fixed parameters are chosen with respect to the idea of maximizing the plasma duration.

3.1 Chamber resistivity and inductance :

We have $U_{loop} = L_{ch}.\frac{dI_{ch}}{dt} + R_{ch}I_{ch}$, so when $I_{ch} = I_{chmax}$, we have $R_{ch} = \frac{U_{loop}(t_{max})}{I_{chmax}}$ ($\sim 10m\Omega$), and then : $L_{ch} = \frac{U_{loop}(t) - R_{ch}I_{ch}(t)}{\frac{dI_{ch}}{dt}(t)}$ $(\sim some\ mH)$

3.2 Processing – Set of values :

$Preion : Preionization\ with\ bottom\ electron\ gun$
$U_B: Toroidal\ magnetic\ field\ [Volt] - U_{CD}: Current\ drive [Volt] - P_{H_2}: Pressure\ of\ H_2\ [mPa] - T_{CD}: Time\ delay\ between\ U_B\ and\ U_{CD} [\mu s]$

For the different set of values, we will use this notation : $(from)x \rightarrow (to)y : (step)[z]$

Measures :

$$T_{CD} = 1000;\ U_{CD} = 500;\ U_B = 600; \begin{cases} with\ Preion;\ P_{H_2} = 10 \rightarrow 20: [2]; 30 \\ without\ Preion;\ P_{H_2} = 10 \rightarrow 20: [2]; 30 \end{cases}$$

$$P_{H_2} = 10; with\ Preion;\ T_{CD} = 1000;\ U_{CD} = 500;\ \ U_B = 0 \rightarrow 1100: [100]$$

$$P_{H_2} = 10; with\ Preion;\ T_{CD} = 1000;\ U_B = 600;\ \ U_{CD} = 100 \rightarrow 700: [100]$$

<u>Tests with knowledge of previous results (in order to increase the plasma duration) :</u>

$$P_{H_2} = 10; with\ Preion;\ T_{CD} = 1000; \begin{cases} U_B = 1100;\ U_{CD} = 300 \\ U_B = 1300;\ U_{CD} = 300 \rightarrow 500: [100] \end{cases}$$

$$P_{H_2} = 10; with\ Preion;\ U_B = 1300;\ \ U_{CD} = 400; \begin{cases} T_{CD} = 15000 \\ T_{CD} = 5000 \end{cases}$$

We observed after these experiments that the plasma duration was increasing with :

$$\boxed{Low\ values\ of\ U_{CD} -\ High\ values\ of\ U_B -\ Low\ values\ of\ P_{H_2} -\ Preionization}$$

However it exists operational limits, and for some values, plasma is not created. Preionization has an impact on the plasma duration, plasma begins earlier but also finish later. We assume that preionization decreases the threshold of plasma creation.
<u>To sum up our operational results :</u>

$$4\ mPa < P_{H_2} < 20mPa -\ U_B > 200V -\ U_{CD} > 200$$

However it exists a correlation between U_B and U_{CD}, and the operational limit of U_B is obsreved for $U_{CD} = 600V$. The operational limit of U_{CD} is for $U_B = 500V$.

The different experiments gave us an overview of the possible plasma durations in this tokamak :

$$6.14ms \leq T_{plasma\ duration} \leq 10.78ms$$

The minimum value is for :
$U_{CD} = 500V; U_B = 300V; P_{H_2} = 10\ mPa;\ T_{CD} = 1000\ \mu s; Preion$
The maximum value is for :
$U_{CD} = 400V; U_B = 1300V; P_{H_2} = 10\ mPa;\ T_{CD} = 1000\ \mu s; Preion$

Thanks to a Matlab script, we have determined the dissipated energy of the longest plasma and the one of the shortest plasma (in time), and it appears that they have dissipated almost the same enrgy (12.5% more for the shortest). The injected energy is directly linked to the value of U_{CD}(500V for the shortest, and 400V for the longest). That means that the ohmic power dissipated is greater for the shortest plasma. Another set of experiments would have enabled to draw the dissipated ohmic power as a function of the plasma duration (this curve might be decreasing).

<u>**Conclusion :**</u>

The maximization of the plasma duration is not a simple task because of the correlation between the different parameters. Even if a wide variation of plasma duration (6,14ms to 10,78ms) and the general influence of these parameters have been observed, we could increase in a small extent the value of the plasma duration with some accurate values.

<u>**Opening :**</u>

We have noticed a correlation between the increase of the electronic temperature and the derivative of the toroidal magnetic field. It would be interesting to confirm this idea with another set of experiment (when the derivative of B_t is finite, we have an increase of the temperature)

$$\frac{\partial B_t}{\partial t} > 0 \rightarrow E_\theta \neq 0 \rightarrow v_e = \frac{\overrightarrow{E_\theta} \times \overrightarrow{B_t}}{{B_t}^2}$$

With E_θ, the poloidal electric field.
The drift velocity v_e is oriented towards the center, so the particles will drift towards the center too. This confinement might lead to an increase of the electronic temperature, it would be interesting to develop this idea with experiments.