HANDS ON PROJECT : EXPERIMENT ON GOLEM

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During this session of experiments on the tokamak GOLEM, we want study some characteristics of the plasma discharge. In a first time, we measure the Paschen curve of the discharge to determine the smallest breakdown voltage. In a second time, we determine the energy confinement time and try to verify the Neo Alcator scaling law established in 1984 by Goldston. With the values of this time, we compute some characteristics of the transport in GOLEM.

I. MEASURING PLASMA CURRENT IN GOLEM

To compute plasma parameters (electron temperature, electron density,…) we need to measure the plasma current. A Rogowski coil around the vessel is used to measure indirectly the total current I_{tot}, which is the sum of the plasma current (I_p) and the current through the metallic vessel (I_{ch}). The Rogowski coil measures a voltage U from which we can deduce the total current : $U = \mu n S \dot{I}_{tot}$ where μ is the magnetic permeability of the coil, n is the loop number by unit length and S is the coil's section. To obtain I_{tot} we need to integrate U over the time.

We must determine I_{ch} to obtain I_p. For this, we model the system by the following electrical circuit :

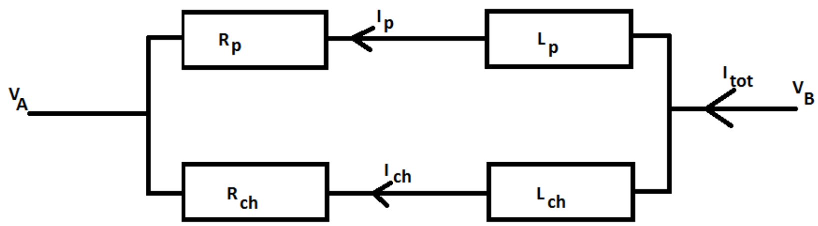


Figure 1 :

Equivalent electrical circuit of the system.

Neglecting all mutual induction effect, we have the following system of equations :

$$U_{loop}(t) = R_{ch} I_{ch} + L_{ch}\frac{dI_{ch}}{dt} = R_p(t) I_p + L_p(t)\frac{dI_p}{dt}$$

$U_{loop} = V_A - V_B$ is measured by a coil around the transformer core. The loop voltage is generated by induction (because of the variation of the magnetic flux in the transformer) and it is connected to the toroidal electric field which creates the plasma. The main difficulty is that the plasma resistance and the plasma inductance are not constant in the time. If we know the chamber features : chamber resistance R_{ch} and chamber inductance L_{ch}, we can determine I_{ch}, and we have :

$$I_P = I_{tot} - I_{ch}$$

We do a shot without creation of plasma. As the chamber characteristics are constant, we can deduce R_{ch} from the curve of $I_{ch}(t)$ when its time derivative is zero. Knowing R_{ch}, we deduce L_{ch} but it's quite difficulte because of the noise. We obtain the following results :

$$L_{ch} = 0.91\ \mu H \pm 5\% \quad \text{et} \quad R_{ch} = 0.0100\ \Omega \pm 2\%$$

With the plasma current, it is possible to compute the plasma inductance, if we suppose for example that the resistivity obey to the Spitzer equation and if we have the time dependance of the temperature, but we don't make this calculus.

The value of the plasma current allows us to compute the electron temperature, which is necessary to access to some discharge parameters : details are given in the third section.

II. THE PASCHEN CURVE OF GOLEM

In this section we want to obtain the Paschen curve of the GOLEM discharge, that is to say a representation of the breakdown voltage (the value of the loop voltage measured when the plasma is created) in function of the neutral gas pressure (measured by a Pfeiffer gauge). The main objective of this experiment is to determinate the "minimum of Paschen" : the value of pressure which minimizes the breakdown voltage. In a second time, we investigate briefly the influence of the toroidal magnetic field on the breakdown voltage.

During this experiment, we make a serie of discharges varying the neutral gas pressure and maintaining constant the magnetic field and the current drive. As we can see on the first figure, the minimal breakdown voltage seems to be between 4 mPa and 6 mPa.

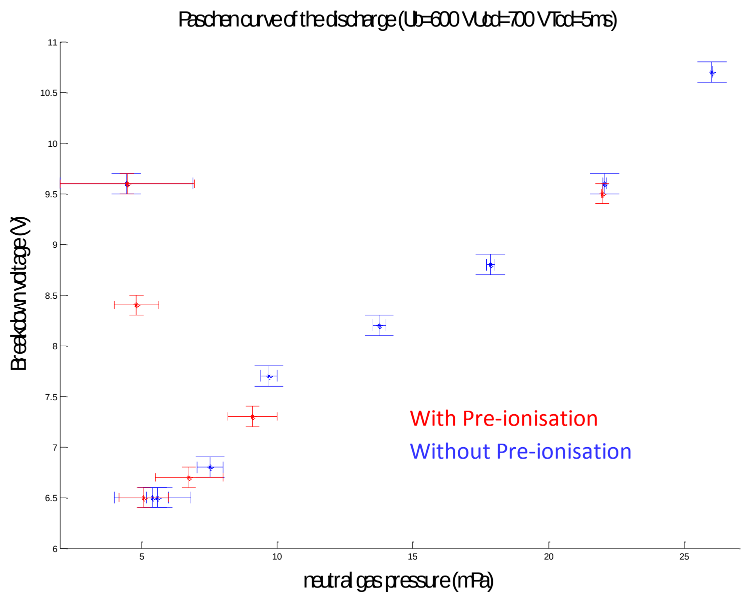


Figure 2 :

Paschen curves with and without pre-ionisation

It seems that the pre-ionisation has no effect on the breakdown voltage, which can seems to be a little bit strange because pre-ionisation has to make easier the breakdown. A new serie of measures it's necessary to confirm this result. We also remark that the lifetime of the plasma decreases when the breakdown voltage increases. It should be interesting to make new experiments to show if it's repeatable.

We fix the pressure around the minimum of Paschen to see the evolution of the minimal breakdown voltage in function of the toroidal magnetic field. It is important to know if the minimal breakdown voltage is associated to the same value of the gas pressure for any value of the magnetic field. The following result show that the magnetic field has not influence on the value of the breakdown voltage if the pressure remains constant, that seems logical.

Toroidal Magnetic Field Voltage U_B (V)	Breakdown Voltage (V)
900	8.8
1000	8.9
1100	8.9
1200	9

For others values of Ub, we can see some unexepcted differences on the breakdown voltage. This can be explained by the deficiency of the pressure regulation system of GOLEM during the experiment. It should be interesting to make an other Paschen curve for an other value of the magnetic field to see if the curve is modified or not.

III. ENERGY CONFINEMENT TIME

In this section, we compute the energy confinement time τ_E of two series of GOLEM discharges, the first at constant magnetic field, the second at constant pressure. We compare our experimental values with the Neo-Alcator confinement scaling law [Goldston, Plasma Phys. Control. Fusion 26 (1984) 87].

The standard definition of τ_E is the characteristic decay time of the plasma thermal energy when the heating sources are cut. But, the GOLEM plasma is only heated by ohmic heating : cut the ohmic heating means kill the plasma, so it is impossible to use this definition. Also, GOLEM plasma is not in a steady state. We have to use an other definition of τ_E :

$$\tau_E = \frac{3\bar{n}_e k_B \overline{T_e}}{P_\Omega},$$

where P_Ω is the ohmic power absorbed by the plasma, $\overline{n_e}$ is the mean density and $\overline{T_e}$ the mean temperature of the plasma. The plasma is mainly composed of hydrogene (we neglect the impurities), so, if we suppose quasi-neutrality, ion density is equal to the electron density. Because we have not a diagnostic able to measure the ion temperature we suppose that this temperature is equal to the electron temperature, but it is a priori a crude approximation. However, if the rate of electron-ion collisions is high, this hypothesis can be justified.

1) Mean electron temperature

We can deduce the electron temperature from the plasma current and the loop voltage by using the Spitzer resistivity which gives us this formula :

$$I_P = 1.13 \times 10^3 \times \frac{U_{loop}}{2\pi R_0} \frac{1}{Z_{eff}} \int_0^a 2\pi r T_e(r)^{3/2} dr,$$

where R_0 is the major radius of the plasma (supposed constant, a quite reasonable approximation), Zeff is the effective charge of the plasma, supposed equal to 1, 'a' is the minor radius of the plasma (supposed constant, but it is probably not the case). U_{loop} is the loop voltage and I_p the plasma current calculated in the first section. It's necessary to know the temperature profile, but no diagnostic in GOLEM is able to measure it. So, we suppose a quadratic profile. T_0 the core temperature, is equal to :

$$T_0 = \left(\frac{R_0 Z_{eff} I_P}{U_{loop} a^2 \times 129.14}\right)^{2/3} \text{ in eV.}$$

We calculte $\overline{T_e}$ by using the formula : $\overline{T_e} \approx \frac{1}{V}\int_0^a T_e(r) r dr d\theta R_0 d\varphi = \frac{T_0}{2}$, where θ and φ are respectively the poloidal and toroidal angle, V is the volume of the plasma chamber (because the plasma shape is not well known).

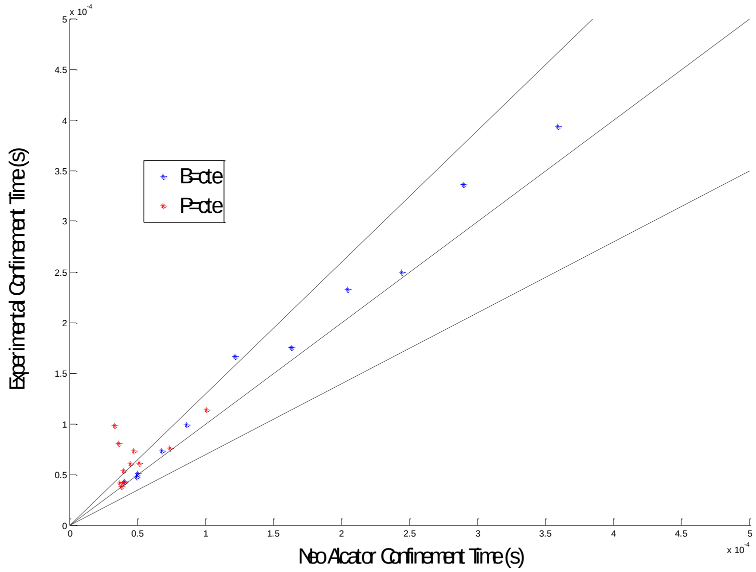
2) Mean electron density

As there is no specific diagnostic for measuring the density, we do the perfect gas approximation to compute the mean electron density. So, we have : $n_e = \frac{2P_{H_2}}{k_B T_{H_2}(K)}$ where T_{H2} = 300 K. The factor 2 comes from the fact that the neutral gas is dihydrogene which is supposed to be fully ionized. A typical value of $\overline{T_e}$ is around 20 eV, that means the neutral gas is probably not fully ionized.

3) Safety factor

The goal of our experiment is to verify the Neo-Alcator scaling law : $\tau_E = 7.1 \times 10^{-22} \overline{n_e} a^{1.04} R^{2.04} \sqrt{q(a)}$, where q(a) is the safety factor at the edge, given by this formula : $q(a) = \frac{2\pi a^2}{\mu_0 I_p} \frac{B_\varphi}{R_0}$ (because a<<R0).

We do two series of measures : the first at constant magnetic field (with U_B fixed), the second at constant pressure.



We can remark that GOLEM seems to follow the Neo Alcator scaling law for the confinement time. The split lines with the greatest and the lowest slopes represent a deviation of 30% to the Neo Alcator law. The red points correspond to the experiment at constant pressure: it has been difficult to maintain the pressure, probable because of a bad regulation of it on GOLEM. This can explain the gap between these points and the law. The values of the confinement time are much lesser than the lifetime of the plasma in every case.

As we have τ_E , we can evaluate the thermal diffusivity of ions χ_i with this formula : $\chi_i = \frac{a^2}{\tau_E}$. Doing this, we suppose that the ions are responsible of the majority of the heat transport. We find diffusivity values between 18 m²/s and 190 m²/s. These values are very important (for comparison, the prevision obtained with ITER parameters is $\chi_i = 1\ m^2/s$. Nevertheless, GOLEM plasma is far to be a steady state plasma, so it is necessary to consider these values with caution.

We can also use the values for temperature and density we have computed to determine the electron-ion collision frequency : $\upsilon_{ei} = \frac{n_i Z^2 e^4 \ln \Lambda}{4\pi\varepsilon_0{}^2 m_e{}^2 v_e{}^3}$. The classical ion thermal diffusivity is given by $\chi_{ii} = \sqrt{\frac{m_i}{m_e}} \upsilon_{ei} r_{Le}{}^2$: a typical order of magnitude for this transport is around 1 m^2/s, it's weak compared to the experimental values.

We can use a neoclassical approach and take into account the effects of the toroidal geometry (mainly due to the trapped particles). For this purpose, we compute the collisionnality : the ratio between the so-called detrapping frequency ($\upsilon_{detrapping} = \frac{\upsilon_{ii}}{2\varepsilon}$, which is the inverse of the mean time needed by a trapped particle to become a passing particle, and where $\upsilon_{ii} = \frac{m_e}{m_i}\upsilon_{ei}$ as we suppose that the ion temperature is equal to the electron temperature and that we have an hydrogene plasma) and the bounce frequency, linked to the "banana motion". Collisionnality is found around 10^1 and 10^2 in GOLEM plasma : this is the boundary between the intermediate regime and the Pfirch-Schlütter regime. Here again, the values computed are too weak. A possible conclusion is that the anomalous transport plays an important part in the thermal diffusivity in GOLEM.