Study of avalanche phase on GOLEM tokamak

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Introduction

As the energetical needs of the human population increases, it is necessary to find new ways to produce energy in a near futur. One of the, if not the only, solution for backbone energy seems to be nuclear fusion especially thanks to the high abundance of the fuel (which is virutally unlimited), the absence of pollution during operation and the very limited radioactivity (contained in the reactor anyway). Fusion also allows local huge energy production, the fuel being easy to obtain ias long as you have water., thus removing a geopolitical pressure on fuels but increasing the already existing tensions on water sources. This is the reason why many highly developed countries like EU, Japan, China, USA, Russia, India and South Korea decided to build ITER, an experimental nuclear fusion reactor that should lead to final fusion power plants. Fusion research in Europe is very developed and one of the most advanced in the world, thus leading to high demand for fusion scientists and technicians. Some universities decided to open courses related to fusion, like the Erasmus Mundus master of Sciences of Fusion from the Ghent university, or the Physics and Technology of Thermonuclear Fusion curriculum for FNSPE, which posses its own tokamak, GOLEM. Nowadays GOLEM is only used for educational purposes, giving students the possibility to work on a real tokamak even with remote control and allowing them to do their own shots.

The aim of this report is to study the start-up phase and more exactly what happens during the avalanche phase. Indeed, it is interesting to study plasma breakdown to better understand it and so to be able to chose optimal parameters for a discharge.

1 GOLEM

1.1 History

The TM-1 (Tokamak Malyj, which means "small tokamak number 1") tokamak was built in Moscow in 1960, being the third tokamak after T-1 (which never achieved to produce tokamak plasma) and T-2 and the oldest tokamak still in activity. The nowadays Kurhatov Institue offered TM-1 for free to the IPP in Prague so the scientists there could test their theories. The machine was reinstalled in Prague in 1977 as TM1-MH and later completely refurbished and started as Castor in 1984, especially to get good diagnostics ports and modifiy the copper stabilising wall, to allow more ports and to install a feedback system for plasma equilibrium.

It was operating in IPP Prague until 2007, when the Culham research center gave the COMPASS tokamak for free which was more suited for ITER-relevant research thanks to his bigger size and his D-shaped divertor plasma. The TM-1 MH, then called CASTOR (Czech Academy of Sciences TORus) was given to the Technical University in Prague. It took some time to make CASTOR operational but nowadays it serves as an edcational tokamak and is also used for the GOMTRAIC (and also SUMTRAIC) event. The CASTOR tokamak got renamed GOLEM because of his proximity to the place where Rabi Loew, which is the builder of the Golem in the legend, is burried.

One of the interesting feature of GOLEM is the possibility to totally operate it remotely with an internet access.

1.2 Description

GOLEM is a small toroidal tokamak with a circular cross section and a limiter configuration. The parameters of the tokamak are shown in the following tab.

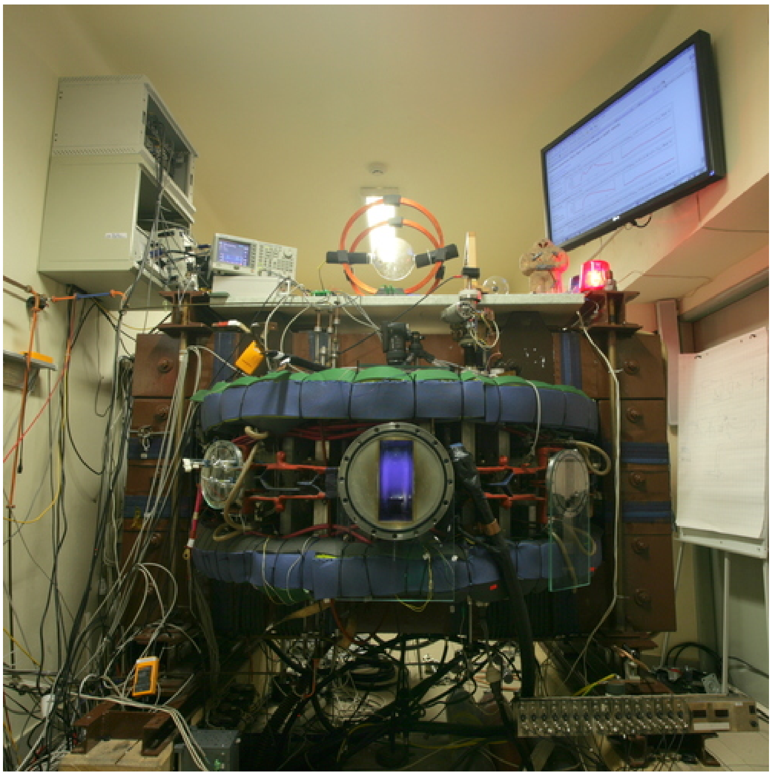

Figure 1: Picture of GOLEM in action [1].

GOLEM Parameters	
Major radius R (m)	0.4 m
Minor radius a (m)	0.1 m
Limiter radius	0.085 m
Material	Bellows Stainless Steel
Conducting in Toroidal direction	Yes
Diagnostic ports	6×3
I_p (max) (kA)	< 8
B_T (max) (T)	< 0.8
Discharge duration	13 ms
Central electron temperature	80 eV
Safety factor at plasma edge	15
Background pressure of vacuum	10-200 mPa
Work gas	H_2
Liner resistivity	5 mΩ

Table 1: Golem central toroid and operation parameters.

2 Avalanches

2.1 Before a discharge

Before a discharge the tokamak has to be pumped down to a pressure of 0.1 mPa to 1 mPa and then the vessel has to be baked to $150-250°C$ with a glow discharge cleaning being required. Then the tokamak vessel is filled by a working gas, H_2 at a pressure around 0.2 to 2 mPa. Some free electrons have to be generated inside the wessel by some external source. Thris process is called pre-ionization and is done, in the shots this article will cover, by an electron gun or a microwave gun. At least to capacitor banks need to be charged to drive the current in the toroidal magnetic field coils and the current in primary winding of the transformer.

2.2 Start-up of a tokamak discharge

The start-up phase is always the same and is the following :

Step 1 A trigger pulse is applied to start the data acquisition system ⇒ Experimental data are collected.

Step 2 A trigger pulse is applied to discharge the capacitor bank of the toroidal field to the toroidal field coils ⇒ Toroidal magnetic field is generated inside the vessel.

Step 3 Wait until a reasonable level of the toroidal magnetic field is reached, on GOLEM a typical time delay is around 1 to 4 ms.

Step 4 A trigger pulse is applied to discharge the ohmic heating capacitor bank to the primary winding of the transformer ⇒ Time-deoendent current in the primary winding generates the toroidal electric field inside the vessel.

The plasma start-up can be divided into two phases with different underlying physics.

1. **Avalanche phase :** The degree of ionization is low, dominant collision process is between electrons and hydrogen molecules. Electrons obey a drift velocity, which is higher than their thermal velocity, and is parallel to the electrical toroidal field. The rotational transform is negligible and the plasma current is still low.

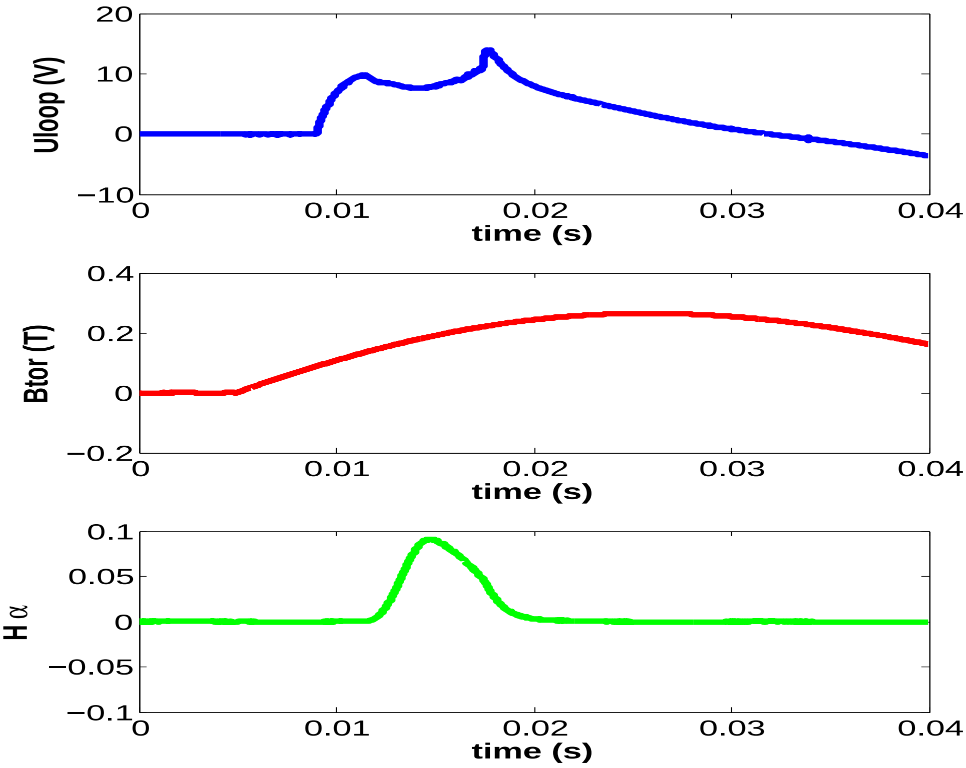

Figure 2: Example of a discharge.

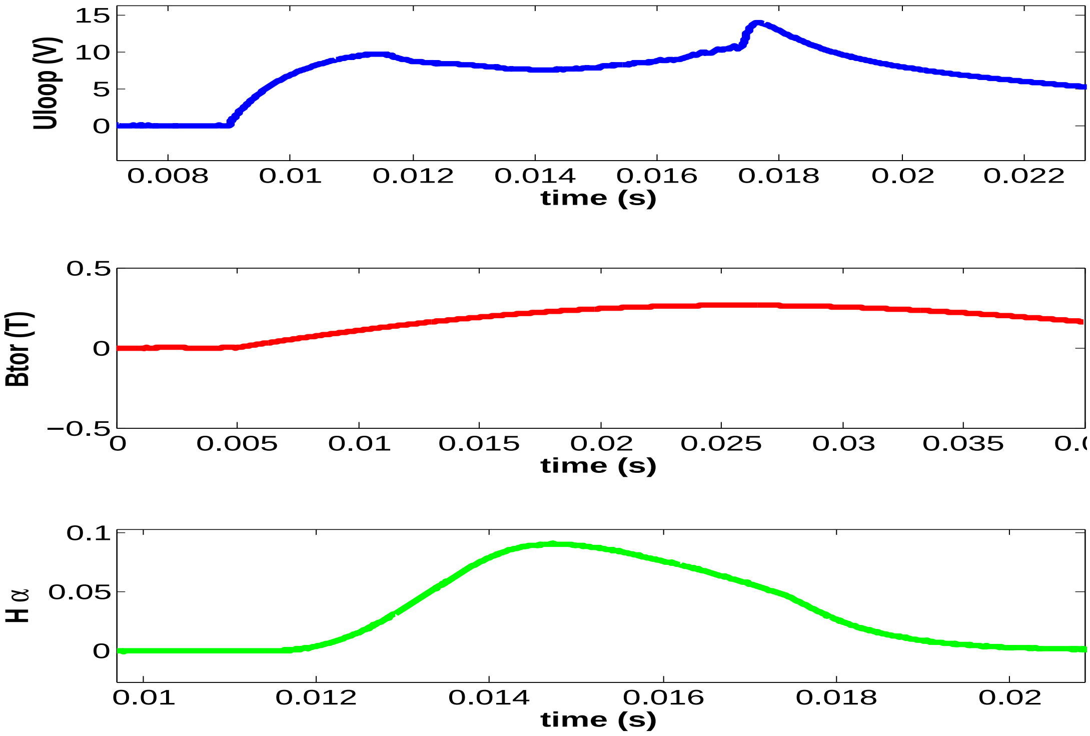

Figure 3: Example of a discharge, zoomed version, which one is best ?

2. **Coulomb phase :** In this case the collisions between charged particles dominate. Plasma current is sufficiently high and magnetic surfaces as well as the confinement are expected to increase significantly.

The transition between these two phases occurs when we have :

$$\frac{\gamma}{1-\gamma} \approx 5 \times 10^{-5} T_e^{\frac{3}{2}} \ (eV)$$

with γ the degree of ionization.
Typically this transition occurs in tokamaks at 5% ionization at $T_e \sim 5\ eV$. This article is going to focus on the avalanche phase, and more precisely on the particle loss due to the perpendicular component $B_\perp$ of the toroidal magnetic field as seen in figure 4.

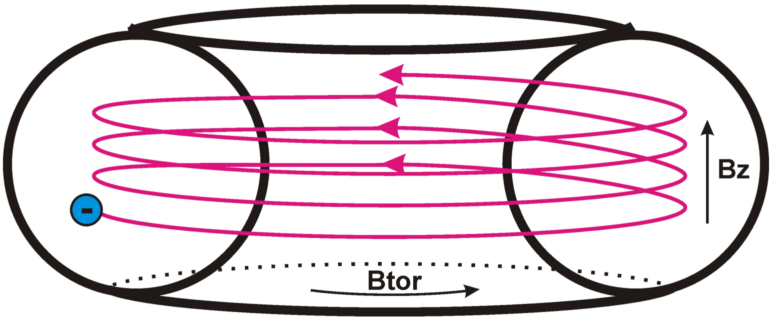

Figure 4: Shifting of the toroidal magnetic field [2].

We see that the particle will hit the wall after a certain amount of time and we want to increase this time as much as possible. A connection length can then be defined as $L_{con} \sim a\frac{B_T}{B_\perp}$ and an effective loss time $\tau_{loss} \sim \frac{L_{con}}{v_D}$. We then have the following rate of the density increase :

$$\frac{n(t)}{n_0} = \exp\left(\frac{1}{t_i} - \frac{1}{t_{loss}}\right) t = \exp\left(\frac{1}{L_i} - \frac{1}{L_{con}}\right) v_D t \tag{1}$$

Where the ionization length is equal to the inverse of the first townsend coefficient.

$$L_{ion} = \alpha^{-1} = Ap_0 \exp\left(\frac{-Bp_0}{E}\right) \ (m) \quad \text{where} \quad E = \frac{U_{loop}}{2\pi R}$$

It is then possible that the breakdown doesn't occur when $L_{ion} \sim L_{con}$ so in practice the condition $L_{ion} \sim 10 \times L_{con}$ should be fulfilled.

During the avalanche electrons obtain a drift velocity $v_D = 6.9 \times 10^4 \sqrt{\frac{E}{p}}$ with

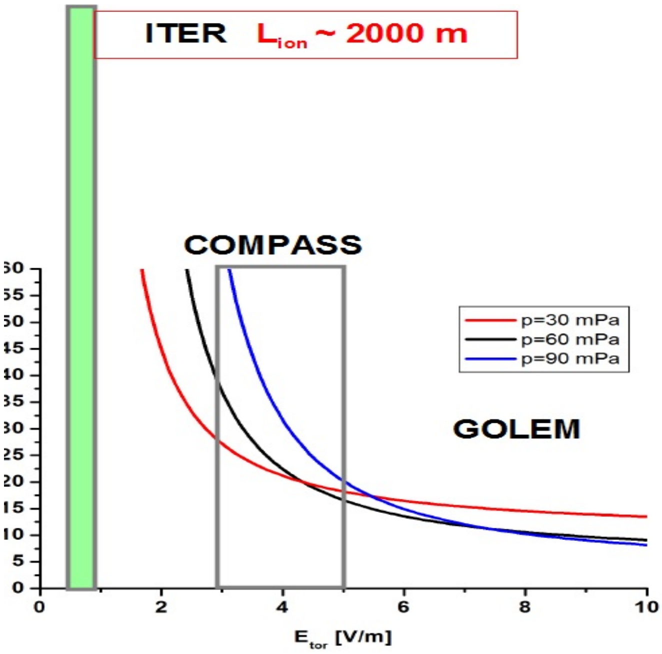

Figure 5: Ionization lengths for different pressures and tokamaks [2].

E the toroidal electric field and p the pressure of molecular hydrogen. Typically we have $\frac{E}{p} = 80 - 800$[1] so $v_D \sim 0.55 - 2 \times 10^6 m.s^{-1}$.
During the avalanche the plasma current grows exponentially with approximately the same rate as the plasma density as seen in the following equation :

$$I_{plasma} = S \times e \times n_e(t) \times v_D(t)$$

where S is the cross section of the current channel, $S \sim 0.02m^{-2}$
$e = 1.6 \times 10^{-19}$
We take the average of the drift velocity, so $v_D(t) = const \sim 10^6 m.s^{-1}$ (for E_{Tor} around 3 to 4 $V.m^{-1}$)
At the end of the avalanche phase, the plasma density is $\gamma \times n_{max}$ with the degree of ionization $\gamma = 0.05$ and $n_{max} = 10^{19} m^{-3}$. The plasma current at the end of the avalanche phase should be I_{plasma}(end of avalanche)$\sim 1.6kA$.

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[1] Beware, for $\frac{E}{p} > 500$ the electron distribution function becomes strongly non-Maxwellian and a significant fractin of electron can run-away.

3 Results and discussion

3.1 Results

We focused on shot 10789 (preionization by electron gun) and shot 10805 (microwave preionization) and wrote a matlab program to compare both. Both these shots had a loop voltage triggered 4 ms after the toroidal magnetic field and had the following parameters :

Shot #	10789	10805	10704	11237	10742	10745
Preionizaion	Electron gun	Microwave	Electron gun	Microwave	Electron gun	Microwave
Chamber pressure (mPa)	0.51 → 20.35	0.49 → 20.43	0.86 → 11.98	0.49 → 9.85	0.51 → 12.17	0.50 → 12.17
C_{B_T} capacitors (81,0 mF) (Charged to / triggered at)	600 V / 5.0 ms	600 V / 5.0 ms	600 V / 5.0 ms	600 V / 5.0 ms	600 V / 5.0 ms	600 V / 5.0 ms
C_{CD} capacitors (11.2 mF) (Charged to / triggered at)	400 V / 9.0 ms	400 V / 9.0 ms	400 V / 9.0 ms	400 V / 9.0 ms	400 V / 9.0 ms	400 V / 9.0 ms
Plasma life time (ms)	6.8 (from 11.2 to 18.0)	7.4 (from 10.9 to 18.3)	7.6 (from 10.8 to 18.4)	8.1 (from 10.6 to 18.7)	7.5 (from 10.8 to 18.3)	8.0 (from 10.5 to 18.5)
Mean toroidal magnetic field B_T (T)	0.18	0.18	0.18	0.18	0.18	0.18
Mean plasma current (kA)	0.73	0.82	1.11	1.35	1.12	1.18
Mean loop voltage (V)	8.57	8.42	8.04	7.54	8.05	7.78
Breakdown voltage (V)	9.9	9.5	8.7	8.3	8.7	8.1
Ohmic heating power (kW)	6.22	6.93	8.90	10.17	9.02	9.17
Q edge	11.3	9.9	7.4	6.1	7.3	6.8
Central electron temperature (eV)	11.0	12.1	15.3	18.2	15.4	16.3

Table 2: Golem central toroid and operation parameters [1].

On the figures 6 and 7 it seems that the line for the shot 10805, with microwave preionization, grows faster so breakdown occurs at a slightly lower loop voltage and therefore slightly earlier compared to shot 10789 which is preionised

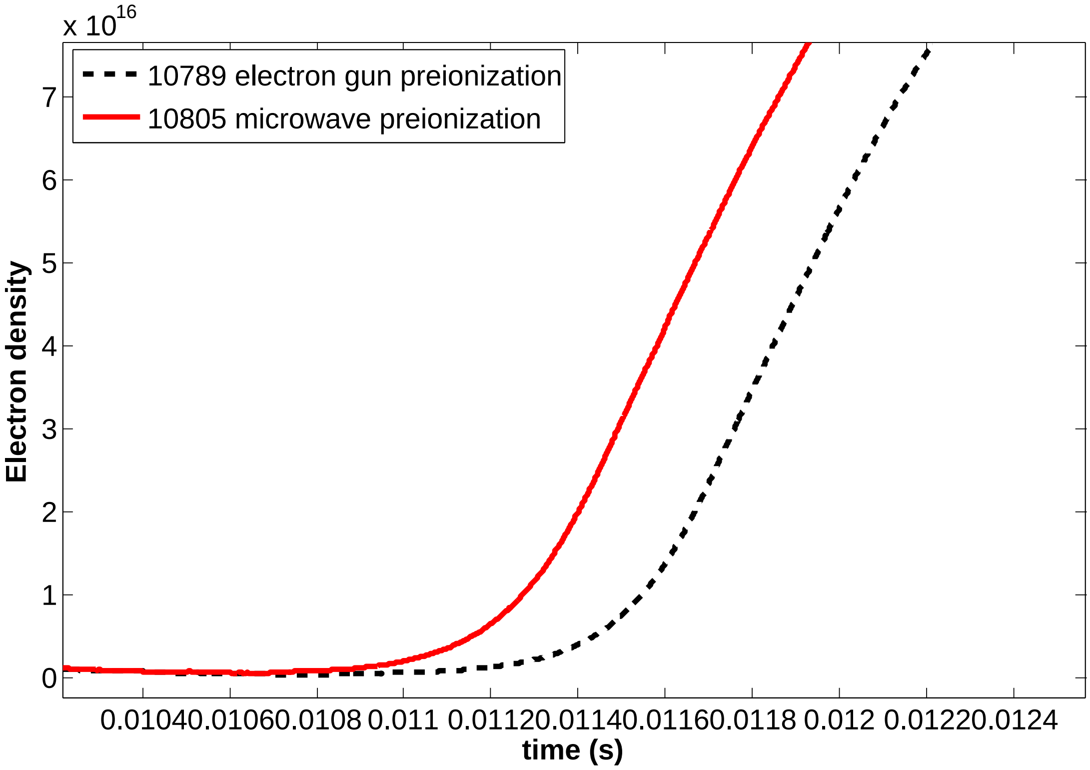

Figure 6: Electron density versus time using a linear scale zoomed on the avalanche phase.

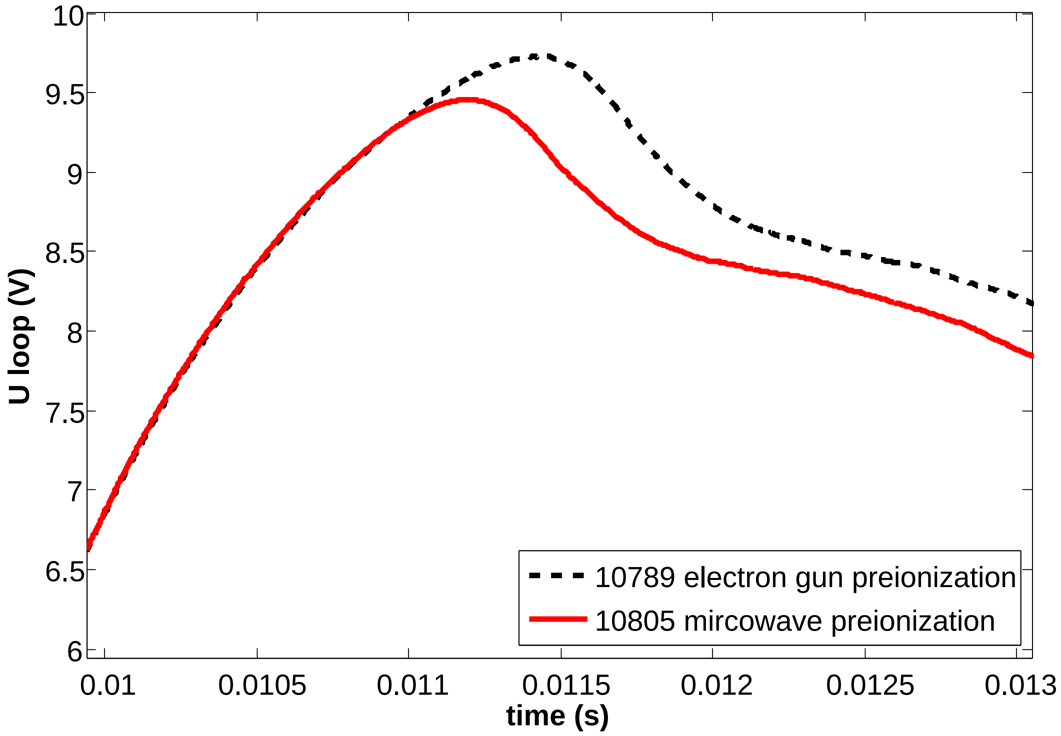

Figure 7: Loop voltage versus time using a linear scale zoomed on the avalanche phase.

with an electron gun.

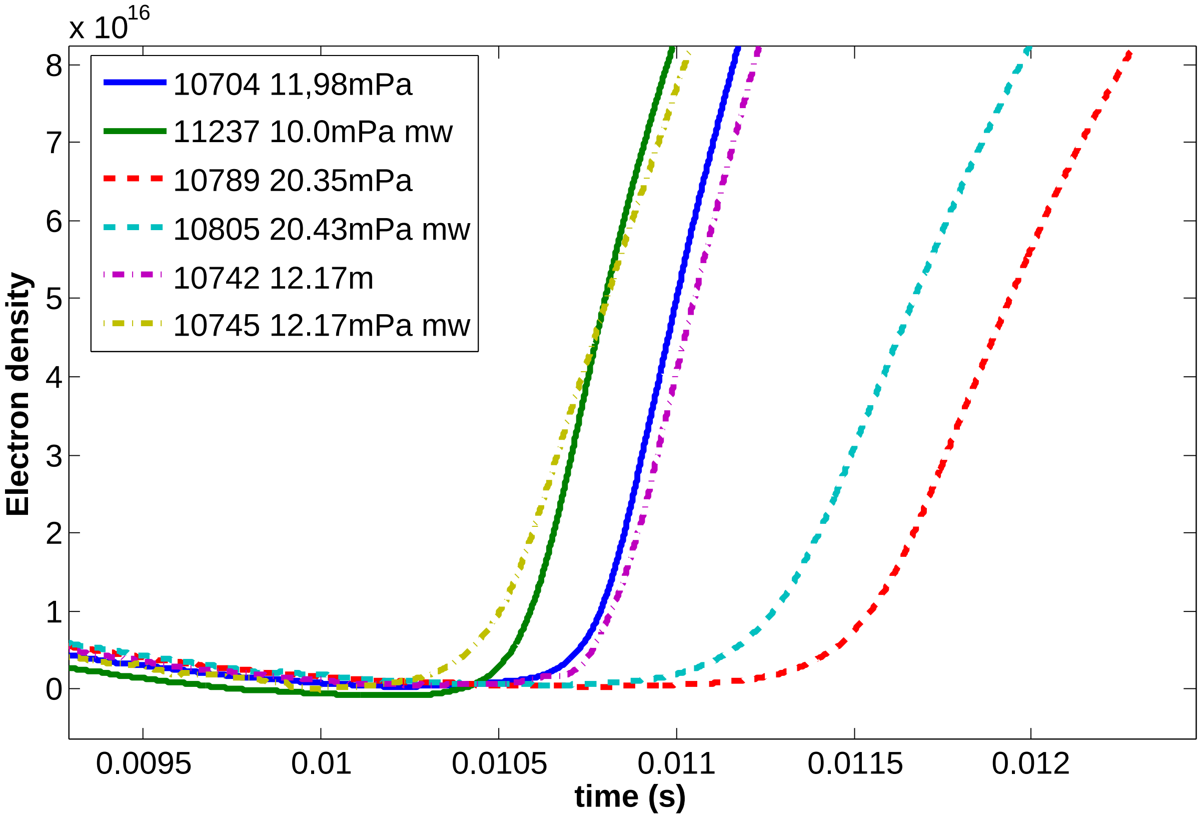

Figure 8: Comparison of electron density versus time using a linear scale zoomed on the avalanche phase for different shots.

On figure 8 we can see that the lower the plasma pressure is, the faster the increase of electron density is and the lower the loop voltage at breakdown is as seen on figure 9. Between two shots with the same pressure (the second shot in the legend always being the one with microwave preionization) we can see that the ohmic heating (indicated in kilowatts in the legend) has a huge influence on the time of the breakdown and also lowers the loop voltage at breakdwon. For now we don't understand why breakdowns occus so much earlier for shot 10745.

Figure 10 looks like a graph of $\frac{1}{x}$ versus x, with x being B_{Tor} in this case, which would mean that the loop voltage at breakdown is constant (the indicated

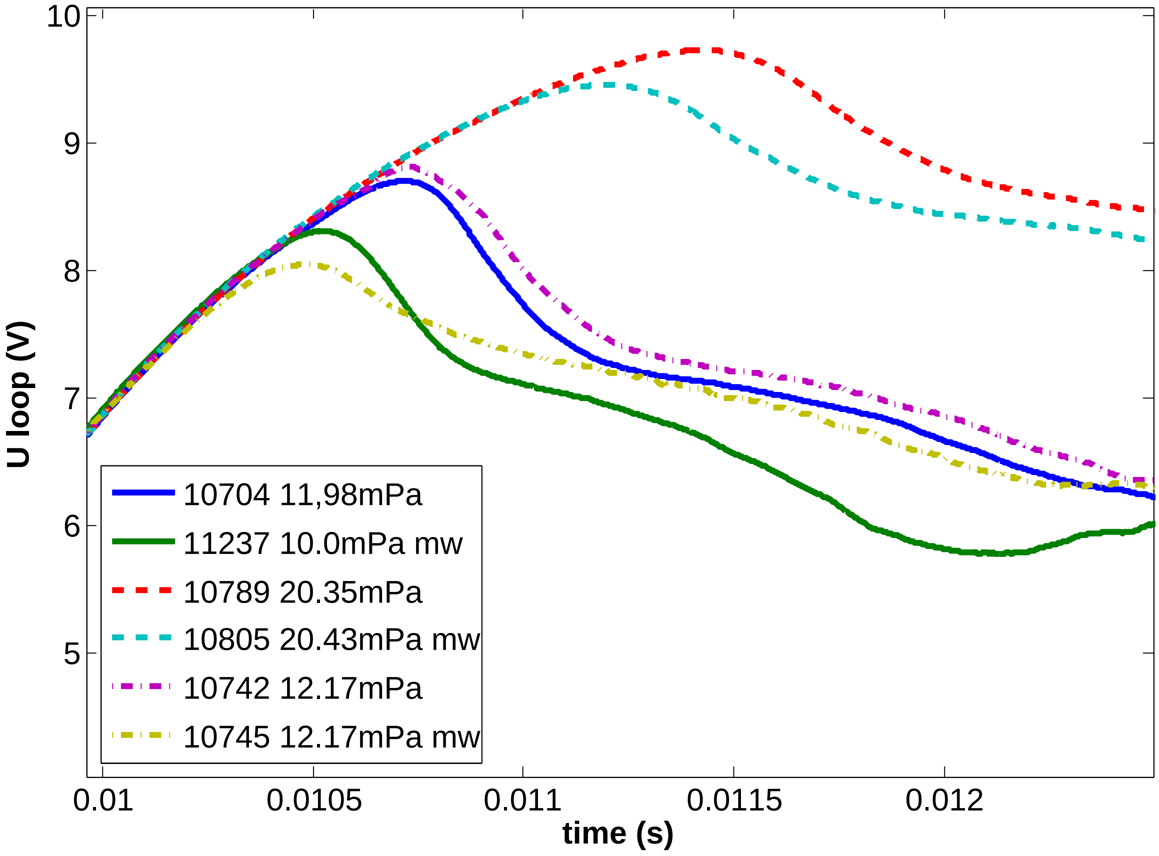

Figure 9: Comparison of loop voltage versus time using a linear scale zoomed on the avalanche phase for different shots.

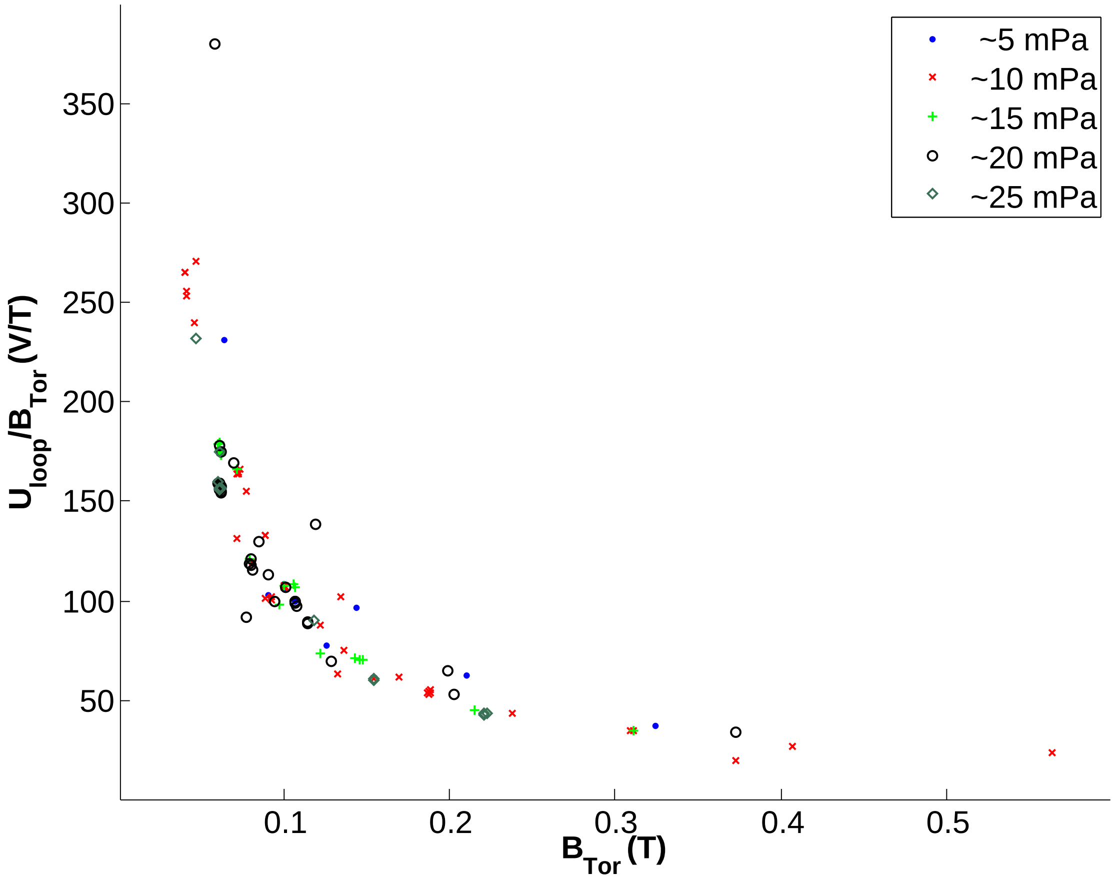

Figure 10: Loop voltage at breakdown divided by toroidal magnetic field at breakdown versus toroidal magnetic field at breakdown for numerous shots with different pressures.

pressure has an error of 2 mPa).

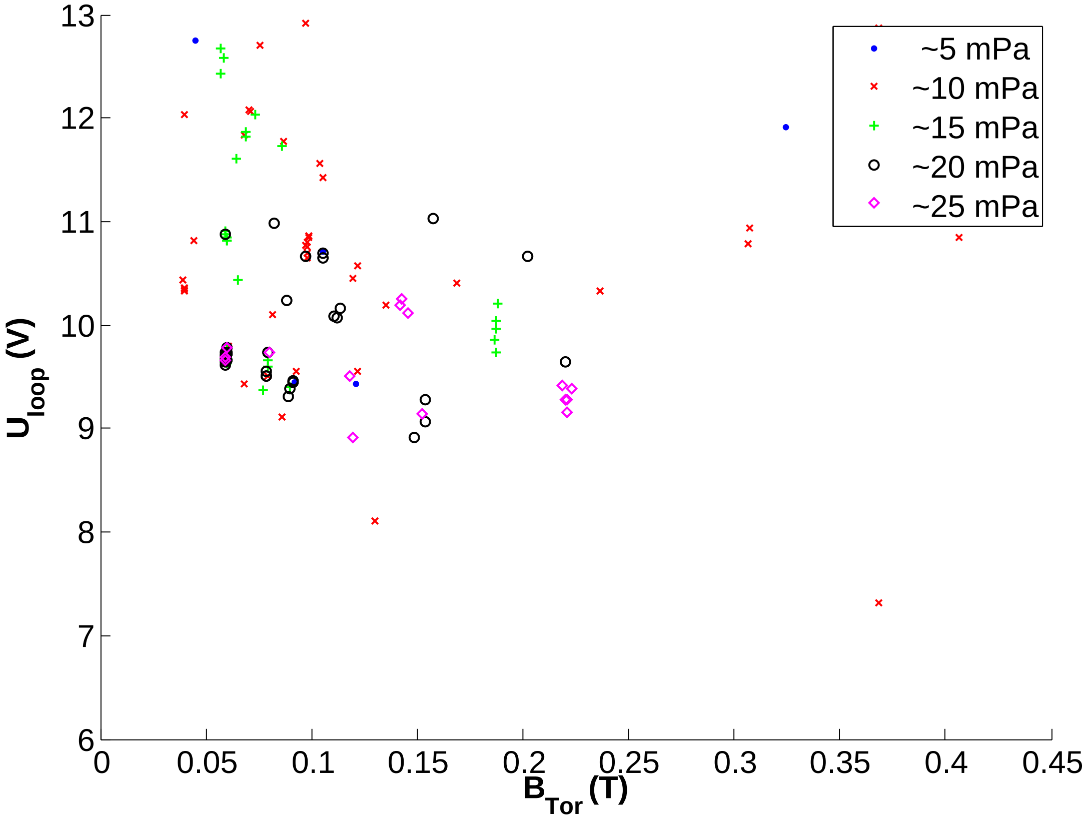

Figure 11: Loop voltage at breakdown versus toroidal magnetic field at breakdown for different pressures.

Figure 11 shows us that the loop voltage at breakdown isn't really constant for a given breakdown toroidal magnetic field. The error on the pressure is the same as for the previous graph.
Figure 12 seems to show a "bowl shaped" trend for the electron gun preionization and we see that for microwave preionization we only have one value of loop voltage at breakdown per toroidal magnetic field at breakdown which is something that we expect.
On figure 13 we can see that for a given pressure the breakdown voltage for microwave preionization is ever the same whatever the toroidal magnetic field at breakdown. For electron gun preionization we see a "bowl shaped" curve for the breakdown voltage versus toiroidal magnetic field at breakdown.

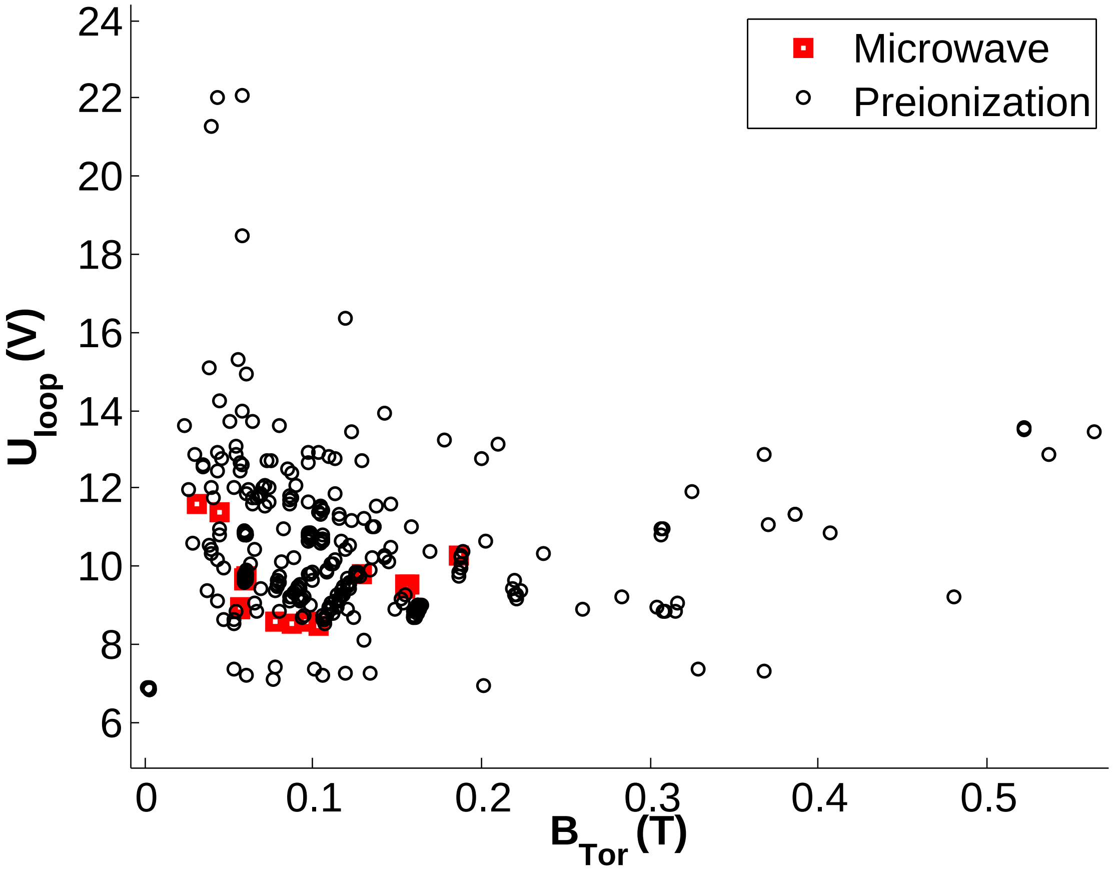

Figure 12: Loop voltage at breakdown versus toroidal magnetic field at breakdown for every shot with plasma. Sadly Only a few microwave shots are presents and are very close to each other so they look like one big point. There are 49 microwave preionization shots for 604 electron gun preionization shots in this graph.

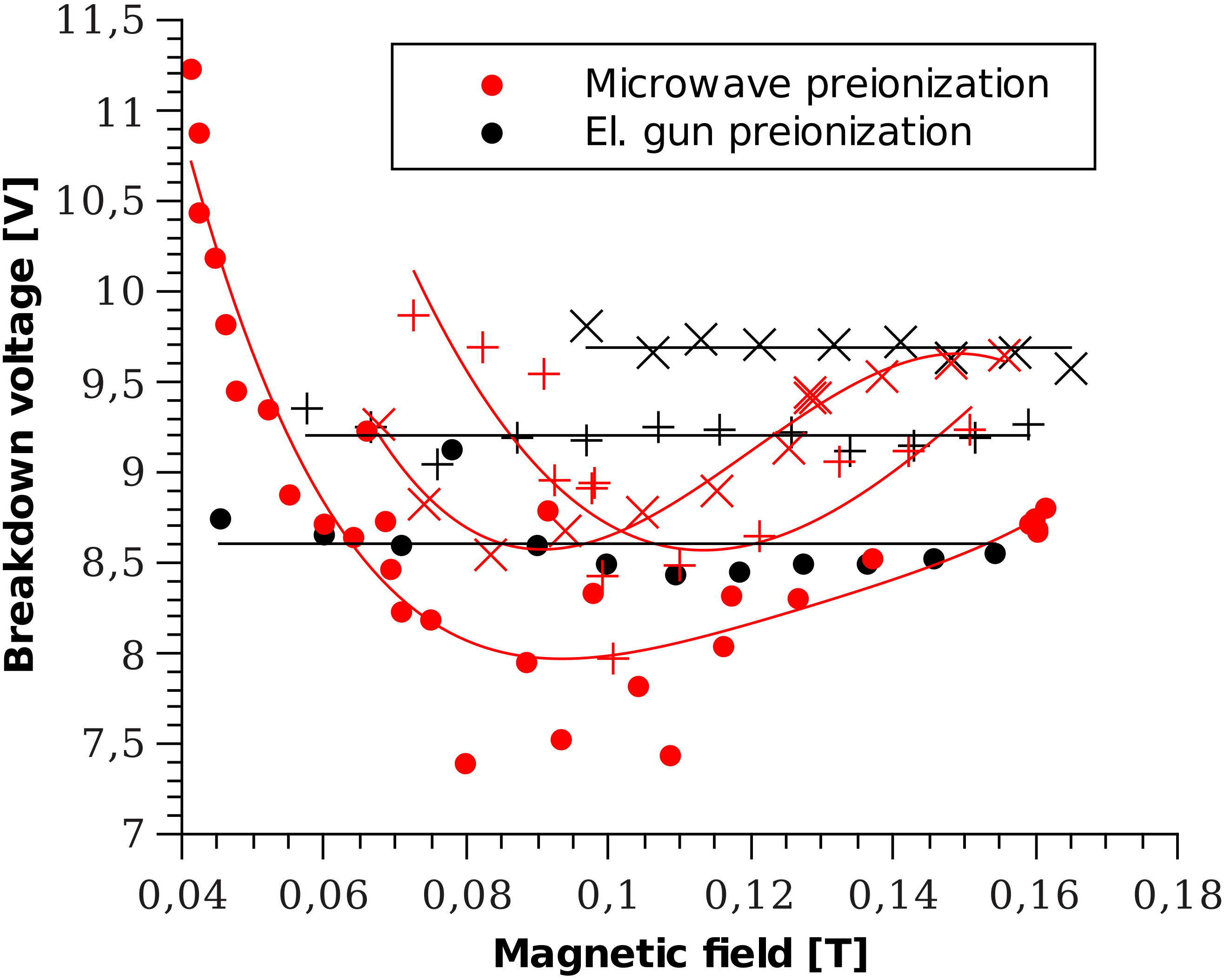

Figure 13: Loop voltage at breakdown versus toroidal magnetic field at breakdown for different pressures and both preionization methods.

3.2 Discussion

It seems that pressure has the biggest influence on the start of the avalanche and the breakdown voltage. No minimal limit was found (mainly by lack of relatively similar shots) but it seems logical that for a lower pressure the breakdown occurs at a lower voltage and so earlier. It also seems that the breakdown and the avalanche phase start earlier with microwave preionization rather than electron gun preionization.

References

[1]

[2] Stockel J. Plasma start-up in tokamaks.