A Stable Toroidal Magnetized Plasma Created by Electron Cyclotron Resonance with Twisted Magnetic Field Lines

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Abstract.

A toroidal magnetized plasma is created by electron cyclotron resonance (ECR) at 300 MHz. High quality confinement is obtained by adding a poloidal magnetic field created by a central conductor (Pierre T 2013 *Rev. Sci. Instrum.* **84** 013504). The decay time of the ECR plasma is measured and found similar to the decay time obtained in the case of a thermionic discharge. The efficient ECR ionization and the high quality of the confinement lead to the production of a large volume magnetized plasma injecting only a watt-level power at UHF frequencies.

1. Introduction

Anomalous transport induced by turbulent structures in magnetized plasmas has been extensively studied during the past 30 years. However, it was not possible to investigate the evolution of the dynamical system starting from a stable toroidal magnetized plasma and progressively evolving toward a turbulent toroidal plasma. As a consequence, it is of major interest to be able to produce a toroidal magnetized plasma exhibiting no instability and a very good confinement of the particles as a reference system. We have recently shown [1] that a stable and dense toroidal thermionic plasma can be produced when a poloidal magnetic field is superimposed to the toroidal magnetic field. The magnetic field lines exhibits then a torsion. We have shown that the shear of the magnetic field lines is stabilizing the plasma in this configuration. During the last forty years, many papers have reported that simple magnetized toroidal plasma devices exhibit most often turbulent regimes with a poor confinement /Blaaman,Torix, Thorello, Torpex/. Turbulence and transport have been studied in toroidal device with sheared magnetic field lines[2] but the transition between the stable plasma and the turbulent regime has not yet been studied in that device.

The presence of a spontaneous radial electric field existing when the magnetic field lines are circular is a destabilizing parameter. This is the case in the simple toroidal configuration of a SMT (Simple magnetized Torus). The density gradient is also a free energy source for various instabilities for instance gradient drift waves, ExB drift instability, interchange instability, drift interchange instability, Simon-Hoh instability i.e. the collisional slow-ion-drift instability [11, 12, 13, 14].

It has been understood early [3] that the torsion of the field lines cancels the instabilities induced by the inhomogeneity of the magnetic field and by the radial density gradient. The global drift of the charged particles is canceled when the torsion of the field lines is present and this leads to the reduction of the anomalous transport. For instance, Chen *et al.* [3] (1967) have shown that a linear magnetized plasma column produced in a Q-machine is stabilized by twisting the magnetic field lines. In this pioneering experiment, a central conductor with high current was inserted on the axis of the device creating a poloidal magnetic field. In that configuration, the equilibrium radial electric field was reduced and the density fluctuations were strongly damped. In the case of a toroidal device without end-losses, it is important to counterbalance the destabilizing effect of the curvature of the field lines in the bad-curvature part of the plasma. Indeed, when instabilities are controlled and damped, the toroidal configuration is clearly the most efficient way to produce a dense magnetized plasma due to the absence of end-losses.

2. The Electron Cyclotron Resonance Sheared-Magnetized Toroidal plasma (ECR-SMT)

As mentioned here upon, we have shown recently that a laboratory toroidal plasma with twisted field lines exhibits an increase of the confinement time [1] compared to a classical simple magnetized torus. Consequently, a high density plasma can be created in this magnetic configuration with a low injected ionizing energy. The experiment is conducted inside the MISTOR device described previously. It consists in a toroidal vessel with major radius 60 cm and minor radius 20 cm. The toroidal magnetic field is created by 55 coils. During the measurements described in this paper, the typical B-field strength on the secondary axis is lower than 0.03 Tesla. Helium gas is used at a pressure 0.2 Pa.

The radial profile of the pitch angle of the field line is an important parameter. At a given radial position, the parameter q is the number of turns a field line orbits around the principal axis of the torus for one complete orbit around the minor axis. Given the toroidal magnetic field B_T and poloidal field Bp, at radial position R (major radius) and minor radius position r, q=(r/R)(B_T/B_p). Figure 1 displays the evolution of the safety factor q across a section of the torus.

For typical conditions with 750 A in the toroidal conductor and with a toroidal B-field strength of 0.010 T, the q value at the plasma edge is larger than 3 and for radii lower than r = 9 cm, the safety factor is below q=1. This means that close to the internal conductor, the field lines make several turns around the secondary axis during one turn around the principal axis. As will be seen below, this strong shear of the field lines in typical conditions induces a good homogeneity and a high density of the plasma.

The density and temperature of the electrons are analyzed using several radially movable Langmuir probes located around the torus. Choke coils are inserted in the measurement circuits in order to eliminate UHF signals.

3. Experimental results: stability and confinement time

At working pressure 0.1 Pa in Helium, the density is in the range 10^{15} to $10^{17} m^{-3}$.

As will be seen below, the density and the stability of the plasma can be largely enhanced by establishing the poloidal confinement. The plasma potential is estimated from the probe voltage at which the electron collection by the biased probe is no longer maxwellian. The radial electric field is evaluated from the radial profile of the plasma potential.

In this way, it is possible to measure the ExB drift experienced by the charged particles. The decay time of the plasma density is evaluated using a fast switch of the UHF source feeding the high frequency amplifier.

When no toroidal current is present (SMT configuration), we observe that is is not possible to create the plasma. The toroidal current flowing in the internal circular conductor is set to 320 A.

Using a radially movable plane Langmuir probe whose collecting area is oriented facing the field lines, the density profile across a poloidal section of the plasma torus and the averaged electric field deduced from the radial profile of the plasma potential are compared in two different situations. In this situation, the ionization is more homogeneous across the poloidal section and this contributes to a low radial electric field inside the plasma torus. It is suspected that the anomalous transport associated with the turbulence is suppressed in this situation, allowing a stable and quiet plasma to be created.

The quality of the confinement is investigated by measuring the decay time of the plasma density after the UHF is switched-off (external input of a gate signal on the UHF wobulator). At location r = 8 cm in the equatorial plane the low field side, the decay time is recorded in two typical situations: without toroidal current (curve a) and with a security factor q = 1 established at radius r = 8 cm (curve b). In the first case, a turbulent decay of the plasma is recorded with a decay time about 100 μs, as shown in Fig. 3. In the sheared field situation, the decay time is much longer, and the decay curve exhibits three different phases that more accurately analyzed with a log-lin plot of the data. During the first 50 μs, a rapid decrease of the density is recorded and a second phase is established over the next 400 μs with a slightly slower decrease of the density and a decay time of 0.4 ms. Finally, an exponential decay is present with a longer decay time of 1.8 ms. The exact decay law during the first phase is difficult to characterize as an exponential decay in a diffusing plasma or as a reciprocal decay in a recombining plasma.

Further detailed measurements will allow to decide about the mechanisms for the decay of the plasma density, for instance electron-ion recombination, loss of particles on collecting surfaces, or radial diffusion of the particles. In the latter case, it is important to investigate whether classical diffusion, Bohm diffusion, or neoclassical diffusion is the leading mechanism [16, 17, 18, 19, 20]. A rough estimate of the classical diffusion time can be obtained using typical value of the collision time and typical plasma parameters. The decay can be computed assuming a decay due to the sole radial diffusion without convection radial velocity. In this device, the electron temperature is low (4 eV) compared to the ionization potential of Helium so a source term for plasma sustainment during the plasma decay has not to be considered here. For simplicity, it is possible to use a model of plasma decay inside a cylinder of radius r = 20 cm. The transport coefficient of the electrons will determine the decay of the plasma if ambipolar diffusion is assumed. This is a correct hypothesis only if no conductive surface is collecting the charges and canceling the radial electric field induced by the difference in perpendicular mobility of ions and electrons (Simon short-circuit [21]). Assuming the decay inside a cylinder of radius 20 cm, this gives a measured value $D_{exp.} = 9m^2/s$.

The diffusion coefficient is calculated in the classical way by evaluating the random-walk process inducing the diffusion using an elementary step equal to the electron Larmor radius and a time interval equal to the electron-neutral collision time Considering the typical plasma parameters and the working pressure in Helium, this transport coefficient for the electrons is close to $0.01m^2/s$ giving a very long decay time of 1.5 s. On the other hand, the diffusion coefficient of the ions indhttps://fr.overleaf.com/project/5bc9a17224f85304d932a4f7uced by the collisions with neutral is about $= 1m^2/s$. It is larger than $D_{\perp e}$ mainly due to the low magnetization of the ions. It would give a decay time close to 15 ms indeed very long compared to the measured value.

In toroidal plasmas with sheared field lines, the trapping of particles inside banana orbits modifies the diffusion coefficient if the trapping time is long compared to the collision time. This induces the so-called neoclassical effects. In our device, it is easily shown that the ions are not efficiently trapped inside the magnetic mirrors due to the high collisionality. However, a significant part of the electron distribution function is actually trapped inside the banana orbits. In this situation, the neoclassical diffusion takes into account the poloidal Larmor radius and the local aspect ratio of the magnetic surface in order to evaluate the random-walk process of diffusion. This gives a neoclassical decay time about 10 times shorter than the decay time evaluated without trapping of the electrons but still too long compared to the measured value.
In conclusion, the classical diffusion and the neoclassical diffusion for ions and electrons, assuming ambipolar diffusion or not, are not compatible with the decay time measured in the experiment.

Finally, the decay time has to be compared with the value predicted by the Bohm diffusion coefficient. Assuming an electronic temperature of 4 eV, the Bohm diffusion coefficient is $D_B = 17\ m^2$/s corresponding to a decay time of 1 ms calculated over a decay radius of 20 cm. This value is half the measured value. If the decay time is calculated over a smaller radius, it is found in the range 0.1 to 0.5 ms. It is important to note that an agreement with the measured value can be obtained if the electron temperature is about 2 eV in the final stage of the decay.

It would be interesting to modulate slightly the plasma density during the decay in order to track the transverse diffusion coefficient, for instance by imposing a modulated localized thermionic ionization on the major axis of the device.

The volume recombination mechanism must be excluded because the plasma density is rather low. As a concluding remark about the efficiency of the confinement of the thermal plasma particles, we can assert that the escape time of about 20 times longer when the poloidal magnetic field is properly adjusted.

4. Conclusion

We have presented a new toroidal magnetized plasma laboratory device including a circular internal conductor establishing a stabilizing and confining poloidal magnetic field. A high quality of the confinement is obtained and beyond a critical safety factor, the plasma is found free of low-frequency instabilities. The radial transport is suspected to be in agreement with the Bohm diffusion, higher than the classical radial transport of electron and ions even taking into account the partial trapping of the electrons inside internal magnetic mirrors. This radial transport is considerably lower than the so-called anomalous radial transport observed in classical simple magnetized torii with circular field lines that are intrinsically turbulent laboratory devices.

The key parameter for the achievement of this stable toroidally confined plasma is the obtained low value of the radial electric field, but the effective parameter is the profile of the safety factor. More precisely, the torsion of the magnetic field lines has to be sufficient to produce an efficient mixing of the trajectories of the ionizing electrons and of the plasma electrons in order to get an equipotential volume of plasma.

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References

[1] Pierre T 2013 *Rev. Sci. Instrum.* **84** 013504
[2] Podestà M *et al* 2005 *Plasma Phys. Controlled Fusion* **47** 1989
[3] Chen F F and Mosher D 1967 *Phys. Rev. Lett.* **18** 639
[4] Garnier D T *et al* 2008 *J. Plasma Physics* **74** 733
[5] Wong K L *et al* 1982 *Rev. Sci. Instrum.* **53** 409
[6] Bora D 1989 *Phys. Lett. A* **139** 308
[7] Rypdal K *et al* 1994 *Plasma Phys. Controlled Fusion* **36** 1099
[8] Riccardi C *et al* 1997 *Phys. Plasmas* **4** 3749
[9] Lemoine N and Grésillon D 2005 *Phys. Plasmas* **12** 092301
[10] Theiler C *et al* 2008 *Phys. Plasmas* **15** 042303
[11] Simon A *et al* 1963 *Phys. Fluids.* **6** 382
[12] Hoh h C 1963 *Phys. Fluids* **6** 1184
[13] Kaur R *et al* 2011 *Phys. Plasmas* **18** 012109
[14] Pierre T 2016 *Phys. Plasmas* **15** 042110
[15] Pierre T *et al* 2004 *Phys. Rev. Lett.* **92** 065004
[16] Maggs J E *et al* 2007 *Phys. Plasmas* **14** 052507
[17] Simon A 2008 *Phys. Plasmas* **15** 022507
[18] Maggs J E *et al* 2008 *Phys. Plasmas* **15** 074701
[19] Simon A 2008 *Phys. Plasmas* **15** 074702
[20] Fruchtman A 2009 *Plasma Sources Sci. Technol.* **18** 025033
[21] Simon A 1955 *Phys. Rev.* **98** 317