อิทธิพลของสนามแม่เหล็กกับการทะลุทะลวงของเชื้อเพลิงแช่แข็งในเครื่องปฏิกรณ์นิวเคลียร์แบบฟิวชันทอร์ซูพรา

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บทคัดย่อ

งานวิจัยนี้ ได้มุ่งศึกษาเกี่ยวกับผลกระทบของสนามแม่เหล็ก กับค่าการทะลุทะลวงของเชื้อเพลิงแช่แข็งในเครื่องปฏิกรณ์นิวเคลียร์ฟิวชันแบบโทคาแมคทอร์ซูพรา ประเทศฝรั่งเศส โดยใช้โปรแกรมจำลองแบบทำนายผลโครโนสโดยใช้ข้อมูลจากการทดลองที่ 45072 ถึง 45085 และ 45716 ถึง 45734 โดยการทดลองเหล่านี้ได้ใช้ค่าความหนาแน่นฟลักซ์แม่เหล็กจาก 1.9 ถึง 3.8 เทสลา และการยิงเชื้อเพลิงแช่แข็งต่อเนื่องประมาณ 4-6 เม็ดต่อการทดลอง การทะลุทะลวงของเชื้อเพลิงแช่แข็ง และการเลื่อนตำแหน่งสามารถวัดได้จากอินเตอร์เฟอโรมิเตอร์และกล้อง CCD โปรแกรมจำลองแบบทำนายผลโครโนสพร้อมด้วยโมดูลเชื้อเพลิงแช่แข็งได้รับการนำมาใช้ เพื่อทำนายผลจากการทดลอง ในการจำลองแบบจากผลการทดลองการส่งผ่านอนุภาคและพลังงานองพลาสมาได้ใช้แบบจำลองในการเคลื่อนที่แบบไม่ปกติ GLF23 และแบบจำลองการส่งผ่านอนุภาคและพลังงานแบบนีโอคลาสสิก NLCASS การเสียดกร่อนของเชื้อเพลิงแช่แข็งในพลาสมาใช้แบบจำลองแบบการปกคลุมด้วยแก๊สและพลาสมา ซึ่งพบว่าการทะลุทะลวงของเชื้อเพลิงแช่แข็งที่ได้จากการทำนายผลมีค่าใกล้เคียงกับค่าจากการทดลองโดยภาพจากกล้อง CCD ยิ่งกว่านั้น ผลจากการปรับเปลี่ยนค่าความหนาแน่นฟลักซ์แม่เหล็กในแนวทอรอยดัล ไม่ได้ส่งผลกับการทะลุทะลวงของเชื้อเพลิงแช่แข็งมากนัก

คำสำคัญ : โทคาแมค เชื้อเพลิงแช่แข็ง พลาสมา

Effect of Magnetic Field on Pellet Penetration in Tore Supra

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Abstract

In this work, we aim to study the effect of magnetic field on pellet penetration in Tore Supra Tokamak using CRONOS integrated predictive modeling code. The Tore Supra plasma discharges with LFS pellet injection (discharges 45072-45085 and 45716-45734) are simulated. In these discharges, the toroidal magnetic field varies from 1.9 to 3.8 tesla. Consecutively, 4 to 6 pellets per discharge are applied. The experimental pellet deposition and penetration can be measured by using CCD camera and interferometer. The CRONOS code with pellet module is used to simulate these experimental results. In these simulations, the core transport is calculated using a combination of the GLF23 anomalous core transport model and the NLCASS neoclassical transport model. The pellet ablation in the hot plasma is described using NGPS pellet ablation model. It is found that the simulation results of pellet penetration agree well with experimental data obtained from the CCD camera. In addition, the result shows that the toroidal magnetic field does not have strong influence on pellet penetration.

Keywords: Tokamak, pellet, plasma

1. Introduction

During the last few years, both theoretical and experimental works on pellet penetration and deposition in the tokamak have been carried out by many research teams in various countries. When a pellet is injected into hot plasma, it is exposed to the energy fluxes carried by the plasma (both electrons and ions). That results in an ablation of the pellet, at which the rate is defined by the balance between the energy flux available and the flux that is required to remove the particles from the pellet surface and dissociate, ionize and accelerate them. As a result, the plasma density can increase. An excellent review for pellet studies can be found in Ref[1]. Scaling penetration pellets HFS in AUG[2] shows that pellet penetration λ_p vary with toroidal magnetic field $B_\varphi^{-0.4}$. Incomprehensible according to physics as currently understood due to[3] was shown that λ_p vary with $B_\varphi^{0.02}$. Then LFS with B vary from 1.9 to 3.8 T per stage of ~ 0.12 T with 4 to 6 pellets per discharge was experimented in Tore Supra (discharge 45072-45085 and discharge 45716-45734).

By observed with ccd camera, then pellet deposition and penetration was investigate. The pellet creates a zone with positive density gradient and increased temperature gradient. In additional for clarify the pellet behavior the simulations with CRONOS code[4] was shown, with effect grad-B drift after pellet ablation then plasmoid form another peak of density toward LFS. Effect of magnetic field B and rational q-values on the pellet penetration and deposition were simulate and compare with experiment data to demonstration influence of magnetic field B and rational q with penetration and deposition effect. The structure of the paper is the following: section 2 pellet ablation and deposition process are shown, section 3 describes the experimental set-up, the geometry of pellet injection in Tore Supra and the system of diagnostics used to measure the pellet trajectory, ablation and deposition, section 4 gives a quantitative analysis of the pellet behaviors. An estimate of the drift average displacement of the ablation profile and penetrate are investigate then the observations are compared with the predictions of simulation codes, the results of the simulations are discussed in more detail and conclusions are given in section 5.

2. Pellet ablation and pellet drift models

The pellet injection module is integrated with the core transport code on CRONOSCRONOS[5] suite of code to calculate pellet ablation rates and drift displacements in the major-radius direction with model of a neutral gas and plasma shielding with grad-B drift[6].In this model the drift occurs and stops due to the rotational transform and the potential distribution associated with the cloud polarization propagates along field lines and fills up on the very short time scale the whole toroidal shell in which the plasmoid has been deposited. After a time much shorter than the drift time, a connection appears along the field lines, in the plasma, between the positive and negative parts of the cloud. The parallel (resistive) current (see Fig. 1.) which flows along these relatively short field lines significantly reduces the polarization of the plasmoid and thus the drift velocity. It follows that, after an initial phase of rapid acceleration, the plasmoid drift slows down dramatically. The full stop of the drift arises at pressure equilibration is shown in equation below.

$$\frac{dV_d}{dt} = \frac{2(n_0 T_0 - n_\infty T_\infty)}{n_0 m_0 R} - V_d \left[\frac{(1-P_{con})B_\infty^2}{\mu_0 C_A n_0 m_0 Z_0} + \sigma_{//} \frac{P_{con} B_\infty^2 R_0^2}{L_{con} Z_0 n_0 m_0} \right] \quad (1)$$

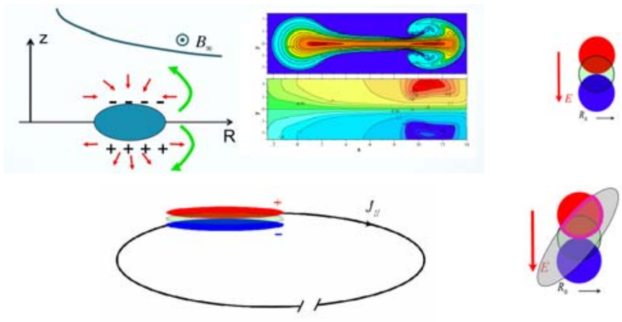


Fig. 1 Effect of Grad-B drift on pellet[7] and parallel current process for reduces the polarization of the plasmoid and thus the drift velocity[6].

3. Experimental Set-up

For the Tore Supra pellet experiments are described here, in 2003, a new continuous pellet injector was installed [8]. It is based on a screw extruder, cooled by liquid He. This injector can inject cylindrical pellets (diameter 1.7 or 2 mm) continuously at a frequency of up to 10 Hz and a velocity between 100 and 900 m s^{-1}, with a very high reliability (99%). The length of the pellets can be varied from 1.5 to 3.5 mm. The pellet content can therefore be varied between 1.5 and 6 × 10^{20} D atoms by changing its diameter and length. Pellets can be injected from four different poloidal locations regularly distributed from the low field side (LFS) to the high field side (HFS). A fast selector and a set of guide tubes (stainless steel, diameter 6 mm, length 12–14 m) are used to convey the pellets to the HFS to take advantage of the expected favorable ∇B induced drift[6]. This system is also used for studying particle transport and the complex interplay between pellet ablation, current profile and MHD instabilities. So far most of the experiments have been carried out in the LFS and HFS configurations. The propagation of ablated matter during pellet ablation is measured with a five-chord interferometer toroidally located at $\pi/3$ rad of the pellet injector in the countercurrent direction ≈ 2.5 m along the discharge axis. The distance between two chords is 16.5 cm and their 1/e total width 1.7 cm. The time resolution is 16 μs and the sensitivity in line integrated density better than 3×10^{17} m^{2}. The beginning of the fast acquisition is triggered by the pellet itself (nevertheless, due to the uncertainty on the pellet velocity, the time at which the pellet enters the discharge, t_0, is only known with an accuracy of 100 μs), and its maximum duration is 20 ms the ccd camera also used in this experiments. For the high speed pellet injection experiments carried out in Tore Supra, the penetration depth and the D_α emission evolution are directly measured using a high dynamic range charged coupled device (CCD) camera. A standard CCD camera was used to measure the penetration depth when the centrifugal pellet injector was used and the D_α emission is measured, like on the other devices, by photodiodes that view the ablation light emission with a suitable D_α filter. The mass of the pellets is in general measured by a microwave cavity in the injection line. The Q of the cavity changes in proportion to the dielectric change introduced by the pellet and thus with proper calibration can yield an accurate measure of the mass. Images taken with the fast camera are dominated by the D_α line emission from the neutral atoms in the partially ionized plasmoid surrounding the pellet, which, due to the high density of the plasmoid (10^{23}–10^{24} m^{-3}), are collisionally coupled with the ions so that the ionized and the neutral part of the plasmoid move together across the background plasma. The images taken during the pellet ablation process is shown in Fig. 2.

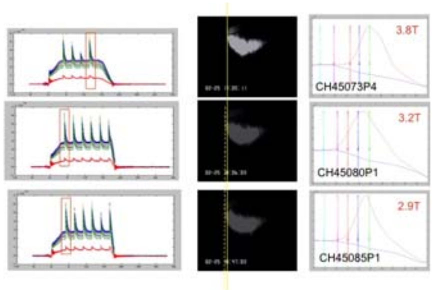


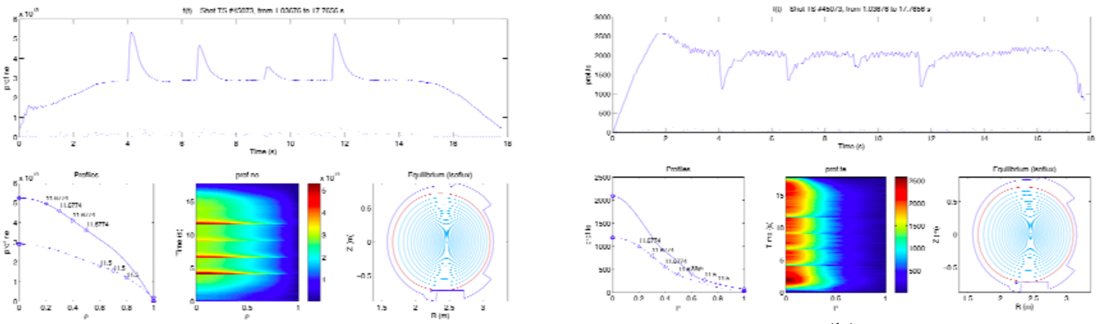
Fig. 2 show the plasma density at pellet ablation process occur measurement by interferometer and the images taken with CCD camera.

4. Simulation and Experimental Result

In this section the simulation result of pellet injection was shown and analysis in order to understand of plasma behavior, then the simulation result is compare with experiment data parameter to clarify effect of magnetic field *B* on the pellet penetration.

4.1 plasma behavior during pellet injection

Fig. 3a shows the electron density evolution and density profile when pellet is injected. Noting that pellet is injected at time of about 4, 6.5, 9, 11.5 sec respectively. During ablation process plasma density increasing rapidly and form another peak of density and then stop when pressure is equilibrium, The pellet deposition could also be affected by changes in micro-turbulence induced by the pellet itself. Fig. 3b shows the electron temperature evolution and temperature profiles when pellet is injected temperature drop rapidly. Fig. 4 and Fig. 5 show the density profile and time derivative of electron density profile before and after pellet injection. Fig. 6 shows the gradient of electron density profile that the pellet creates a distinct zone with positive density gradient. Fig. 7 and fig. 8 show the electron temperature profile and electron temperature gradient respectively, the electron temperature decreased rapidly relative to the value before pellet injection.



(a) (b)

Fig 3 (a) Electron density evolution when pellet is injected (b) Electron temperature evolution when pellet is injected.

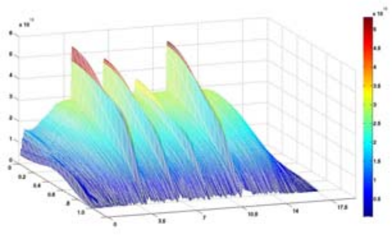


Fig. 4 The electron density profile during pellet injection.

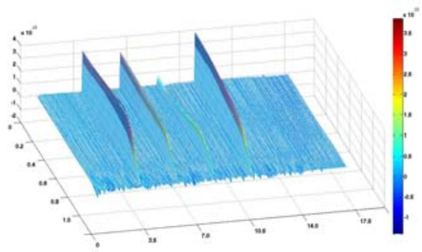


Fig. 5 Time derivative of the electron density profile during pellet injection.

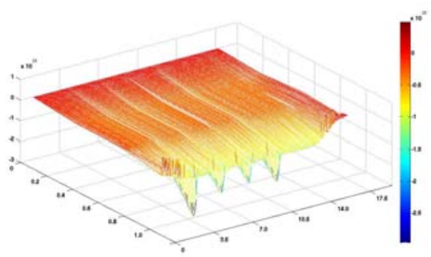


Fig. 6 The gradient of electron density profile during pellet injection.

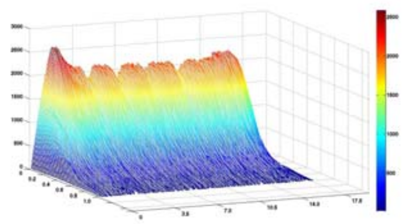


Fig. 7 The electron temperature profile during pellet injection.

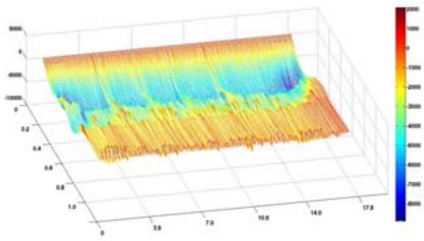


Fig. 8 Gradient of electron temperature profile during pellet injection.

4.2 Effect of magnetic field B on pellet penetration

By varying magnetic field from 1.9 to 3.8 T, then the pellet penetrate from LFS is investigate with image from ccd camera and recalculate by CRONOS suite of code to clarify relation about magnetic field B on pellet penetration. Fig. 9 shows the temperature profile before pellet injection with various values of *B*. when the magnetic field is increased the gradient of temperature is increased due to $\omega_c = \dfrac{qB}{m}$ and $\chi = \dfrac{-q_r}{n\nabla T}$ then pellet would be ablate rapidly when compare with low magnetic field but the influent of magnetic shield from the increased of magnetic flux $\varphi = \dfrac{B}{A}$ is dominate thus the increased of magnetic file is not take a strong influent to pellet penetration which see in Figure 10. The pellet penetration that measurement by the image from ccd camera is shown in Fig. 11 then are plot with the various of *B* 1.7 – 3.9 T in Fig. 12, the penetration from simulation with effect of grad– B drift and without drift is also shown.

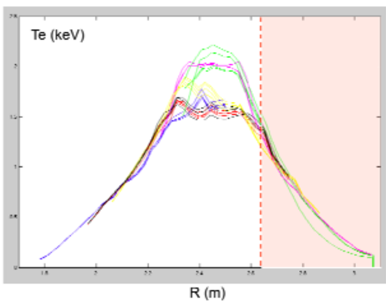


Fig. 9 The various colors correspond to the various values of *B* the orange zone corresponds to the zone of penetration of the pellet (note: all these profiles are profiles of pre- pellet).

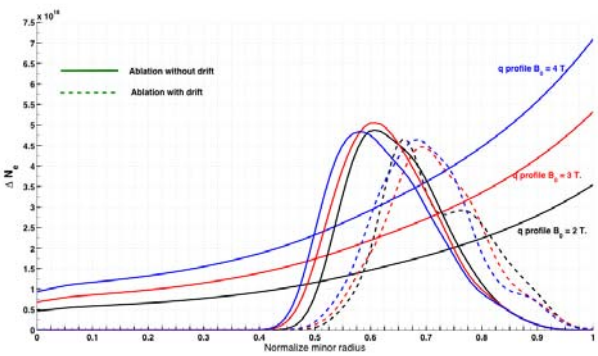


Fig. 10 Relation of pellet penetrate with magnetic fieldBT = 4.0, 3.0 and 2.0 T.

Fig. 11 pellet penetration measurement with image by ccd camera.

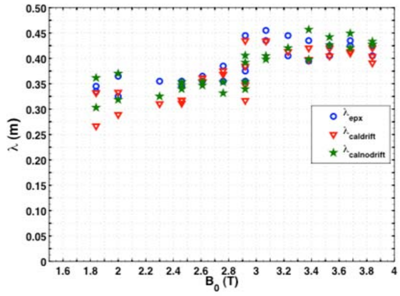


Fig. 12 Pellet penetration is simulated with CRONOS vs. Experimental data for study effect of *B*

5. Conclusions

The simulation of pellet injection from LFS Tore Supra with CRONOS suite of code show that when the magnetic field is increased the pellet can penetrate deeply due to the effect of magnetic shield but not strong effect due to the increase of temperature gradient make the ablation rate higher than low magnetic. Finally the contribution of Tore Supra data to the characterization of Effect of magnetic field B on the pellet penetration phenomenon should be complemented with data from experiments performed on different machines for validation of existing ablation/deposition codes in order to extrapolation of the results to ITER.

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