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Mitigation and control of the particle pinch in the Electric Tokamak

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Abstract

The Electric Tokamak [R. J. Taylor, T. A. Carter, J.-L. Gauvreau *et al.*, Nucl. Fusion **45**, 1634 (2005)] operates at high plasma density (one and a half times the Greenwald limit) due to a strong particle pinch. However, particle accumulation causes several problems. The operation of the machine can suffer several violent disruptions which hinder the study of many plasma phenomena. Plasma motion and large density swings are undesirable because they alter continuous processes, leaving only transient regimes to study. Particle source and local temperature control can defeat the fundamental mechanisms of this electric pinch. If edge fueling feedback is not sufficient to induce quiescent behavior, the fast ion loss caused by second harmonic ion-cyclotron radio-frequency injection functions as a particle sink deep within the outer plasma cross-section. By linking these strong effects to the fueling feedback, stable medium density ($2\text{x}10^{18}$ particles/m^3) plasmas can be sustained for several seconds. This new regime yields surprisingly long and calm discharges.

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I. Introduction

Atypical inward diffusion processes are known to feed particles into the core of edge fuelled machines[1,2]. The Electric Tokamak[3] (ET) has run for many years with exceptional confinement[4] times due to its large size and relatively high densities (one and a half time the Greenwald limit). The density limit (due to a 2/1 tearing mode) at $2.5\text{x}10^{18}$ particles/m^3 can be reached without any central fueling. The only possible mechanism for obtaining such densities in Ohmic edge fueled plasmas is via a pinch mechanism. Regrettably, this "efficient" pinch comes with a large drawback; it exacerbates run away behavior, making density control almost impossible.

The pinch observed in ET is quite pronounced and generates significant density accumulation. It occurs only when there is little magneto-hydrodynamics (MHD) activity and when current profiles are peaked. The density rise time is strongly dependant on the gas puff rate. On the other hand, the density rise itself follows a digital principle. Below a certain threshold, the density build up does not occur. Above this limit, density accumulates until a disruption triggered by a 2/1 tearing mode terminates the rise. This phenomenon is observed even when the gas puff is turned off.

Figure 1 shows a typical medium density rise. Up to three consecutive rises can be obtained with successive density limits increasing with time, as Figure 2 illustrates. The line average density of Figure 1-a highlights a typical density rise, where its acceleration takes place for constant gas puff levels. Figure 1-b shows the undisturbed plasma current at 50 kA, not affected by the violent disruption due to the destabilizing 2/1 mode.

The physical mechanism of the pinch has been uncovered recently and is attributed to inward ion mobility due to a radial negative electric field[3]. Successful mitigation of this pinch is possible when the local electric field is physically reversed by using a positively biased electrode. While sound for physics understanding and underlying mechanism identification, this mitigation method stays limited. Typically, the runaway nature of this phenomenon indicates a pernicious process which remains difficult to manage. This article presents a practical mitigation scheme that efficiently controls this particle pinch.

Ion cyclotron radio frequency (ICRF) heating should switch the Ohmic confinement to a degraded state, called L-mode. Degraded confinement solved the runaway pinch problem, and high power rf heating was rapidly successful. However, a series of experiments demonstrated that low power ICRF was also extremely efficient in mitigating the pinch while largely preserving the Ohmic confinement scaling. Because the necessary injected power to control the pinch increases with the density one whishes to mitigate, we opted to run medium density plasmas. Consequently, low power ICRF can be used and there is a clear separation between the mitigation effects from the low confinement mode (L-mode).

The remainder of this exposé follows the subsequent outline. After this introduction, Sec. II summarizes the characteristics of the electric pinch transport. Sec. III details the mitigation mechanism using feedback edge fueling and second harmonic ICRF heating schemes to produce a successful control of the pinch. Finally, a conclusion regroups the major results presented in this paper.

II. Pinch Transport

To appreciate the pinch mitigation process, we first examine the pinch transport properties. The major governing equation of the density time evolution in the cylindrical one-fluid plasma model is the simple continuity equation,

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma\right) + S_0 . \tag{1}$$

The radius r ranges from 0, at the magnetic axis, to a, the plasma minor radius, at the edge. The density time evolution accounts for particle sources or sinks S_0. The particle flux Γ is given by,

$$\Gamma = -D\frac{\partial n}{\partial r} + V_{pinch}n . \tag{2}$$

The flux has two distinct parts. The "diffusive" contribution involves the first term of the RHS in Eq. (2), where D is the diffusivity. The second term corresponds to the pinch velocity V_{pinch}[5,6],

$$V_{pinch} = V_{pinch}^{Ware} + \gamma D\frac{1}{T}\frac{\partial T}{\partial r} + D\frac{eE_r}{kT} . \tag{3}$$

where V_{pinch}^{Ware} is the Ware pinch velocity due to the toroidal electric field[7]. The second term is turbulent thermo-diffusion pinch, γ is a scaling factor which depends upon fluctuation levels and collisionality regimes. Ion temperature gradients (ITG) and trapped electron modes (TEM)[8,9] usually trigger this pinch. The last term corresponds to the inward ion mobility[10] due to the radial electric field[11]. This term drives the pinch in ET[3].

Consequently, the mitigation of the pinch can happen in the three following ways. From Eq. (1), the control of the sources and sink of particles should influence the accumulation in the core. Eq. (3) indicates that the electric field and the temperature are also major parameters in the pinch strength. As mentioned before, increasing D by switching to an L-mode is not an option.

Clearly, the application of density feedback is the first logical step toward controlling the phenomenon. Alternatively, second harmonic ICRF heating could also be applied to mitigate the pinch. Avoiding L-mode effects by injecting low power levels, fast ion loss and temperature rise should also reduce the pinch velocity. Using this insight, the next section discusses which of these techniques were successfully implemented on ET.

III.Pinch Mitigation and Control

The raison-d'être of the particle pinch led to mitigation using a positively biased electrode. Electron extraction triggered ion loss to enforce ambipolarity. However, the limitations of this biasing technique precluded the development of a practical density control apparatus. The undesirable effects of plasma pollution from electrode etching militated for the exploration of other techniques. It is worth noting that the principles discussed herein ultimately function on the same pinch mitigation as the bias electrode, i.e. particle loss.

A. Edge fueling control

Despite low recycling materials in ET's vessel, edge fueling control remains difficult due to the presence of gas reservoirs in several locations in the machine. The different attempts used a feedback system based on soft x-ray emission or line average density signals. The level of control is remarkably efficient at low densities. When the density level is increased, the particle accumulation takes place. Figure 3 shows the line average density for three different gas feedback levels. Density flattops can only be produced at extremely low levels. Unfortunately the maximum attained densities are well below the levels that the pinch develops. If the feedback level is increased, the uncontrollable accumulation starts to resurface. The run away behavior is not present, as the feedback is regulating the particle count. Nevertheless disruptions still occur, giving evidence for a peaked density profile as the pinch forces the edge particles toward the center of the plasma.

Used alone, this technique is bound to fail. The control of edge sources is not sufficient to achieve mitigation if reasonable plasma density is sought. As a result we will set it aside for now to focus on the other mitigation technique discussed in this paper.

B. ICRF

By using second harmonic ICRF, the heated ion population is promptly deconfined. Due to fast ion loss, ICRF creates a sink of particles inside the plasma. The frequency launched was the second harmonic of ion cyclotron frequency on the magnetic axis. A single antenna was used, localizing toroidally the effects of the extraction. Several attempts yielded remarkable mitigation results.

1. Mitigation

To prevent the strong deconfinement accompanying ICRF heating, i.e. L-mode, low power (300 kW) was injected inside the plasma. To underline the ICRF effects a pulsed mode was adopted instead of the usual continuous injection. This technique highlights the difference between the standard particle accumulation shots and the mitigated shots.

Figure 4-a shows the line average densities of a standard shot superimposed over a shot where ICRF was applied in a series of three pulses. The mitigation is quite clear. The rf absorption in the plasma is high enough to generate a sizable number of fast ions. As they leave the plasma, the density stops increasing (and even diminishes) during the third pulse. Furthermore, the density rise between ICRF pulses matches the density rise of the standard shot. This does indicate Ohmic confinement during ICRF heating because

several energy confinement times are required to transition between confinement modes. Thus the instantaneous change in between rf pulses rules out L-mode confinement. The soft x-ray data from Figure 4-b corroborate the core heating remains relatively low, also supporting that the confinement follows an Ohmic scaling. Also soft x-ray signals show the absence of impurity in the plasma core during ICRF pulses. These noteworthy points support the theory of ion sinking through fast ion loss rather than confinement reduction. Finally, the evidence of fast ion loss was demonstrated by repeating the experiments in deuterium plasmas. No mitigation was visible when the ICRF pulses were applied. A detailed investigation was conducted using density profile data to identify which part of the plasma was the most susceptible to ion loss.

2. Profile Modification

The experimental data hitherto presented utilized line average density signals from microwave interferometry. Using Thomson scattering density profiles, it is possible to identify which region of the plasma is affected by the ICRF heating processes. The frequency was tuned for the resonance layer intersecting the plasma core. Interestingly, Figure 5 shows no central density profile modification during rf pulses, where the biggest losses would be expected. Only the mantle (r > 50 cm) was depleted during ICRF injection because the resonance layer crosses this region in the top and bottom part of the cross section. At the power levels used, the core fast ions do not have enough energy to overcome the strong radial electric field and get back in. Transport studies and experimental data suggest the negative electric field peaks around half the plasma radius[3]. Thus, core particles are trapped in the potential well and cannot escape easily. Higher power levels are required to bootstrap particle loss in the core. Because our objective was to study mitigation effects due to ion loss, we kept the injected power low to avoid confinement degradation which would mask the sought effect of the rf on the ions.

However, loss mechanisms in the outer regions of the plasma do exist due to trapped particles, which bounce off the resonance layer in the top and bottom part of the banana trajectory[12]. When trapped ions have their turning point near the cyclotron resonance, they can transfer the energy absorbed at the resonance layer to other particles via collisions along their orbits. The negative radial electric field decreases (i.e. less negative) in the outer region of the plasmas and the energetic trapped particles walk outward each time they acquire energy at the resonance layer. Collisions with slower ions also favor diffusion of the latter. The asymmetric wave spectrum injected in ET gives rise to a net drift of the turning points across the flux surfaces. Because the particles drift differently (outwards or inwards) depending of the toroidal direction of the interactive wave[13], the toroidal angular momentum transfer gives rise locally to an induced ICRF spatial diffusion[14] of the fast trapped ions. The same kind of process also acts on collisional populations in the edge plasma region as they become energized when they pass through the resonance layer. In both collisional and trapped regimes, the edge gets depleted as the fast particles leave the plasma, as Figure 5 shows. The density reduction in turn mitigates the pinch velocity and the process reverses.

C. Pinch Control

The reversal of density accumulation happening during the third ICRF pulse of Figure 4 suggests that control over the pinch can be achieved using edge fueling feedback. Figure 6 shows the density flattop during ICRF injection. The pinch effect is gone and appears only when the ICRF stops slightly before the end of the shot. We obtained several discharges without any observable pinch in time evolution or profiles for a density level of $1\text{x}10^{18}$ particles/m^3. This level is four times higher than the stable level reached without ICRF injection. Yet it is lower than the high density shots usually obtained. Nonetheless, the attained density remains acceptable for plasma research, 30% below the Greenwald density limit.

Figure 7 illustrates a stepped approach to feedback control, establishing the critical threshold beyond which a run-away pinch occurs. For the ICRF power levels discussed, a maximum of $1.2\text{x}10^{18}$ particles/m^3 can be realized. Lower power does not yield significant pinch mitigation. Higher levels improve the pinch control at the risk of inducing L-mode confinement. It seems necessary to increase the number of injection locations to obtain a smooth power deposition in the machine to prevent further L-mode behaviors while enforcing mitigation.

IV. Conclusion

In this article, we explored the particle accumulation in the core of ET. After presenting the particulars of this pinch, directing the reader to other ET publications for a more detailed picture[3], the basic transport mechanisms were developed to demonstrate how edge fueling feedback and ICRF can influence the pinch properties. Unfortunately, edge fueling feedback is localized and this method maintains only low density flattops. If the feedback level increases, so does the pinch velocity. Once the system becomes unstable, a run-away behavior develops and a disruption occurs. Another procedure utilizing ICRF power injection has yielded compelling results. By using the ICRF at levels below the L-mode confinement threshold, successful pinch mitigation was achieved. Mitigation is accomplished on a wider spatial range by increased temperature and fast ion loss in the outer layer of the plasma cross section, where the negative radial electric field is weaker. The reduction of the pinch velocity and the particle sink are sufficient to develop low density regions which prevent the formation of the pinch. By coupling this technique with the gas puff feedback, flattops in the time evolution of the line average density become possible. The obtained densities are three to four times higher than the stable density reached by using edge fueling feedback alone. The highest densities attained using these scenarios are far from the pinch outstanding performances. However stability is the major tradeoff and physics studies can be carried out in a quiescent environment, as long as the ICRF effects do not impede the conducted experiment. Although ICRF may be an extra perturbation for small scale studies, the absence of disruptions is a major advantage in the operations of ET.

Acknowledgments

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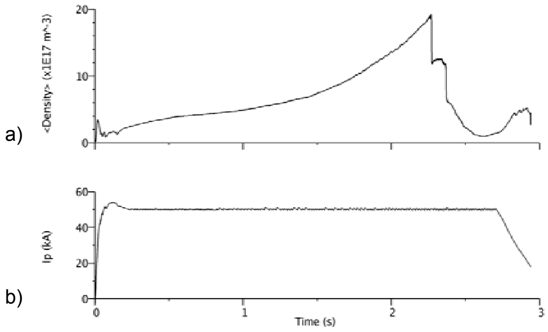

Figure 1. Typical medium density shot in the Electric Tokamak. A constant gas puff fuels this discharge. The density accumulates in the center of the machine due to a strong pinch. As the density peaks, MHD activity increases and forces a violent disruption when all density is lost. a) The line average density shows the density rise, its acceleration and sudden fall. b) The plasma current is unaffected by the density dump and the discharge survives. If the fuelling rate is increased, many density accumulations happen.

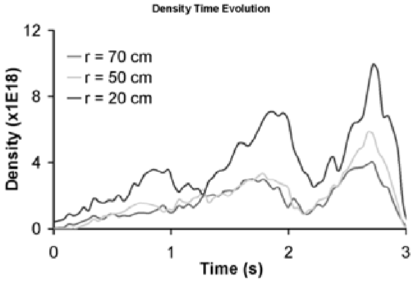

Figure 2. Thomson scattering density evolution for three different plasma radii. The pinch profile changes from one accretion to the next. While the first two accumulations have peaked profiles, the last one is broader. The increase in density for each ramp shows the previous disruption rearranges profiles in such a way that disruptions occur at higher densities.

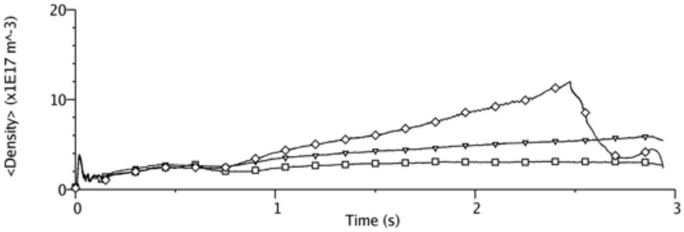

Figure 3. Pinch control using gas puff feedback. The control signal is the line average density from the interferometer. Three gas puff feedback levels have been used. The lowest (squares) and medium levels (triangles) give almost flat densities. The plasma falls into a pinch mode when a higher level (diamonds) is used. Error bars were not plotted to improve the readability of the figure.

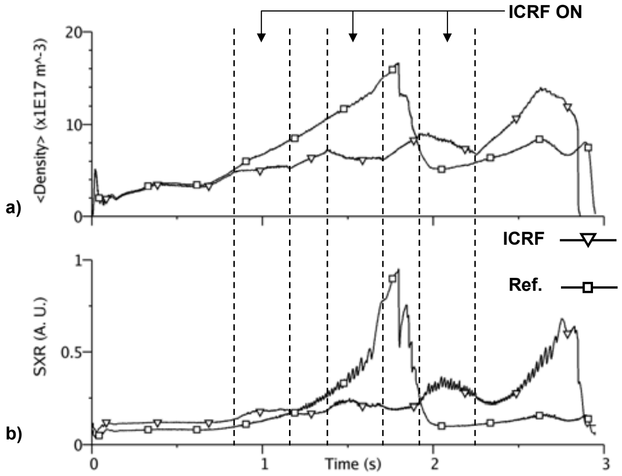

Figure 4. Pinch mitigation using low power (300 kW) ICRF only. The gas feedback was disabled during this series of shots. A reference shot (Ref.) is shown on the same figure as the ICRF shot (ICRF) to highlight the different plasma behaviors in both cases. a) The ICRF effects on the line average density are quasi instantaneous. The third ICRF pulse reverses the density rise completely. b) The soft x-ray increase during pulses is an indicator of some temperature changes. The density rise in between ICRF pulses is the same as the reference shot's. This indicates that ICRF is not changing dramatically the confinement regime of the plasma.

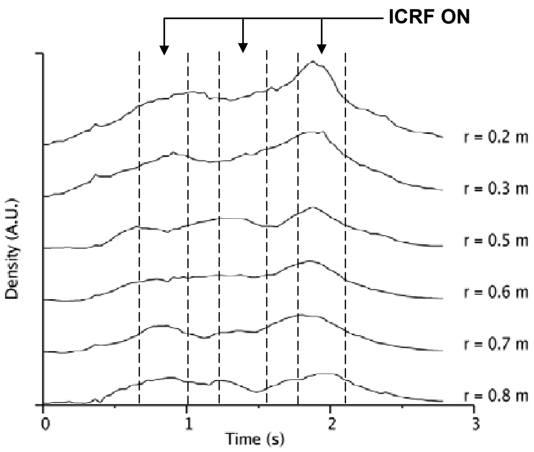

Figure 5. Density depletion from ICRF in the Thomson scattering data. The density loss is visible only in the plasma mantle (0.8 < r < 0.5 m), the core density is not affected by the ICRF. The Thomson data is taken at 20 Hz and time averaging does smooth out the density depletion when the rf is pulsed.

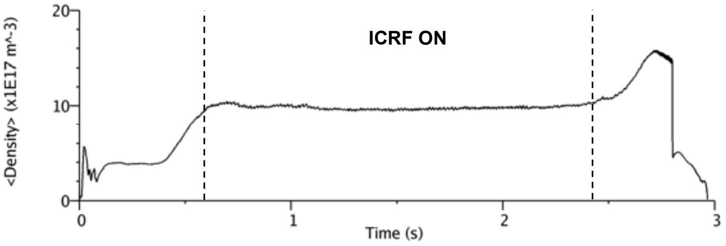

Figure 6. Density feedback using gas puff control and ICRF injection. The density flattop lasts for nearly 2 seconds. The density is stabilized by the ICRF. As soon as the ICRF is stopped the density takes off and a crash occurs.

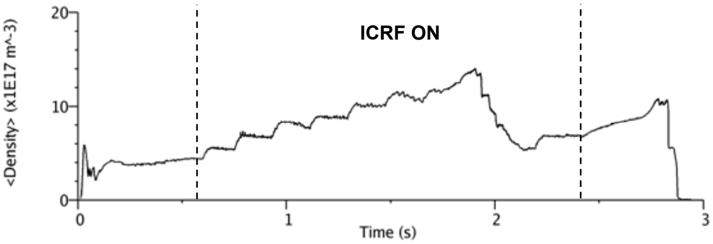

Figure 7. Stepped feedback control leading to a disruption. A level of no return is found at 1.2x10^{18} particles/m^3 when a crash occurs just before the 2 s mark.