

Reversed-Field Pinch Experiments in EXTRAP T2R with a Resistive Shell Boundary

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Abstract. The EXTRAP T2R reversed-field pinch has a resistive shell with a magnetic penetration time of 6 ms. This time is intermediate between the dynamo/relaxation cycle time scale (<2 ms) and the pulse length (≈ 20 ms). The resonant tearing modes do not wall-lock. They rotate with angular phase velocities in the range of 20 to 600 krad/s. As a result of the rotation the radial component of the perturbations at the shell from the resonant modes is suppressed. Non-resonant (resistive-wall) kink modes are unstable and their linear growth rates have been measured. The measured growth rates follow the trend expected from theoretical estimates for a range of equilibrium parameters. Furthermore, when the resonant modes are rotating, the loop voltage and confinement parameters have values comparable to those of a conducting-shell RFP. The poloidal beta is around 10% for a range of current and density.

1. Introduction

The reversed-field pinch (RFP) is an axisymmetric toroidal confinement configuration that is akin to the tokamak but with very different current density and magnetic field profiles. As a result the MHD stability differs and there is a higher level of MHD activity in the RFP, which affects confinement. This paper focuses on studies carried out in the EXTRAP T2R RFP in the areas of (i) MHD stability and mode dynamics in an RFP with a resistive wall boundary and (ii) confinement in the presence such MHD activity.

The idealised RFP plasma is surrounded by a perfectly conducting, close-fitting shell that stabilises non-resonant kink modes and affects the stability of internally resonant tearing modes. Theoretical studies and experiments have shown that replacement of the ideal shell by a resistive shell has the following effects:

1. Non-resonant kink modes (resistive wall modes) are unstable with a growth time determined by the shell penetration time (τ_s) [1-3].
2. If the internally-resonant modes are rotating in the laboratory frame with sufficient toroidal phase velocity, the radial perturbation at the resistive shell due to the mode is suppressed [4-7].

3. The radial perturbation of internally resonant tearing modes that become wall-locked grow penetrating the shell with a growth time related to τ_s . Experiments that have been carried out on HBTX-1C [2], OHTE [8] and EXTRAP T2 [9] have demonstrated these effects.

The resonant modes have poloidal mode number $m=0$ (resonant at the reversal surface) and $m=1$ (resonant at $n=-1/q$) and are responsible for the dynamo that modifies the parallel current profile current and sustains the toroidal field. In the resistive shell experiments to date, the internally resonant modes have been wall-locked. This means that the spectra of the radial perturbation at the shell have included strong contributions from the resonant modes as well as contributions from the non-resonant modes (internally non-resonant modes in T2R have $-11 < n < -R/a$, and externally non-resonant modes have $0 < n < R/a$). In the HBTX-1C experiment ($\tau_s \approx 0.5$ ms) unstable resonant and non-resonant modes were both observed. In the OHTE and EXTRAP T2 experiments ($\tau_s \approx 1.5$ ms), the internal modes were phase aligned and wall-locked (slinky mode [5,8,9]). As a result the spectrum of the radial perturbation at the shell was dominated by these resonant modes so that the internally non-resonant modes were not clearly identifiable. Also, for the given equilibria of EXTRAP T2, externally non-resonant modes had slower growth rates and therefore were not evident when the mode spectra were measured.

In the present EXTRAP T2R experiment ($\tau_s \approx 6$ ms), the growth rates of the non-resonant modes have now been measured and are reported here. Because the resonant tearing modes are rotating, their radial perturbation at the conducting boundary is suppressed, as predicted by theory, and it is experimentally possible to resolve the exponential growth of the radial perturbation of the non-resonant modes at very low amplitudes. This enables experimental measurements of the linear growth of the non-resonant modes with different equilibrium conditions that have been compared with theoretical predictions.

The fact that the resonant modes are rotating has also made it possible to carry out detailed studies of global confinement. In previous resistive-shell experiments, large localised magnetic perturbations have existed because the internally resonant modes have been phase-aligned and wall-locked. The localised perturbations grew to large amplitude on the time-scale of the shell penetration time. The confinement was degraded and there were extremely high plasma wall loads at the contact points of the localised perturbation [9]. In the rebuilt T2R experiment with mode rotation, the last closed flux surface maintains a very high degree of axisymmetry for the duration of the pulse [7,10]. With the improved axisymmetry it is possible to make studies of transport based on profile measurements, both at the edge using probes and in the bulk plasma using diagnostics with radial resolution.

The plasma-facing wall is stainless steel vessel with a Mo "mushroom" limiter array providing protection. Without gas-puffing, density pump-out limits the range of operation. Gas puffing at three toroidal points is used to sustain a constant density profile with peak densities in the range $1\text{-}3 \times 10^{19} \text{m}^{-3}$. The confinement in T2R is improved by about a factor of three as compared to confinement in the previous T2 device. Parameters for EXTRAP T2R are shown in Table I.

Table I: EXTRAP T2R PARAMETERS

major radius (R)	1.24 m
minor radius of plasma	0.183 m
minor radius of resistive wall (thin shell)	0.198 m
resistive wall (shell) magnetic penetration time (τ_s)	6 ms
plasma current (I_p)	60 - 120 kA
electron density	$0.5 - 1.5 \times 10^{19} \text{m}^{-3}$
electron temperature (T_e)	100 - 300 eV
ion temperature (T_i)	100 - 250 eV
magnetic fluctuation level $\delta b_{\text{rms}}/B$	0.2-0.5 %
energy confinement time (τ_E)	0.1 - 0.25 ms

2. Mode dynamics in EXTRAP T2R with a resistive shell boundary

The EXTRAP T2R RFP is a rebuilt version of the previous EXTRAP T2 (OHTE) device [6]. In the T2R device, the shell penetration time is intermediate; *dynamo cycle time* $< \tau_s \approx 6 \text{ ms} < \textit{pulse length}$. In this new experiment the internally resonant modes rotate at angular phase velocities, ω , in the range $1/\tau_s \ll 20 \text{ krad/s} < \omega < 600 \text{ krad/s}$. Under these conditions the radial perturbation of the resonant modes is suppressed at the shell; $b_r \approx 10^{-2}$, $b_\theta \approx 10^{-4} B_\theta$. The non-resonant mode growth rates are therefore clearly identifiable even at low amplitudes where estimates of the growth rate based on linear theory are applicable. The evolution of both a non-resonant $(m,n) = (1,-10)$ and a resonant $(m,n) = (1,-13)$ mode is shown in Fig. 1. Note that for this discharge, the resonant mode ($n=-13$) wall-locks at 8-ms and b_r starts to grow. According to linear theory, the growth rate of the RW modes ($n=-10$) is dependent on the shell penetration time and the equilibrium parallel current profile. The current profile is dependent on the RFP pinch (θ) and reversal (F) equilibrium parameters. Typically low θ (shallow reversal) equilibria are more unstable for internally non-resonant resistive wall modes whereas high θ (deep reversal) equilibria are more unstable for externally non-resonant RWs. The T2R experiment has been operated for a range of current profile equilibrium parameters. The

measured linear growth rates (normalised to the shell penetration time) of the non-resonant modes are shown for both an internally ($n = -10$) and an externally ($n = 5$) non-resonant mode in Fig. 2. The trend of the dependence on pinch parameter is consistent with theory.

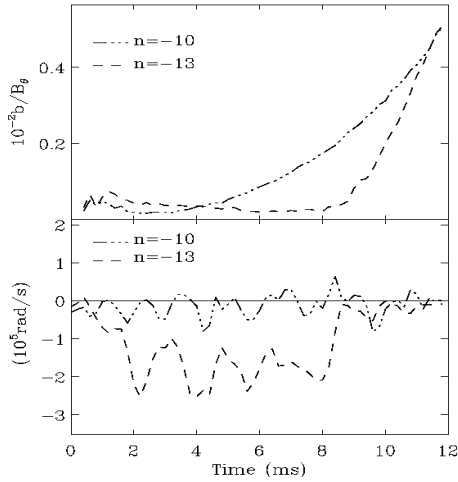


FIG. 1. Time evolution of amplitude and rotation frequency of a non-resonant and a resonant mode.

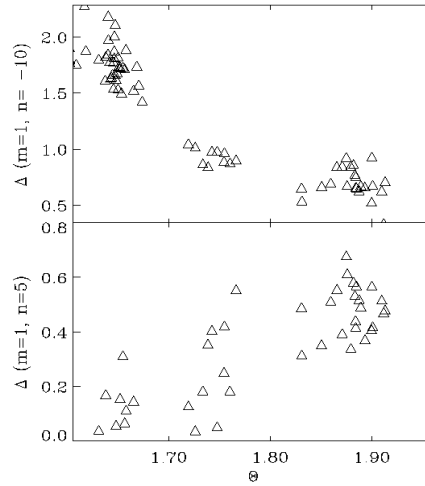


FIG. 2. Measured normalised growth rates for non-resonant modes as a function of pinch parameter θ .

3. Confinement with a resistive shell boundary and rotating resonant modes

Measurements of global confinement have been made in the T2R device under axisymmetric conditions where the internal resonant modes are rotating and the magnetic fluctuation level measured at the edge is low; $0.2\% < \delta b_{\text{rms}}/B < 0.5\%$. The poloidal beta is around 10% for a range of plasma discharge currents and a range of equilibrium conditions. In RFPs the beta typically decreases as the ratio of plasma toroidal current to plasma line density (I/N) increases. Data for EXTRAP T2R is shown in Fig. 3 where this trend is evident. However the beta values are high compared to typical RFP operation and substantially higher than observed in the previous T2 device when the internal modes are wall-locked. This supports the conclusion that beta is limited by transport when the magnetic perturbations are large and that beta can be improved in devices by reducing transport associated with magnetic fluctuations and perturbations. This is also evident when the T2R confinement data is compared with the previous T2 device using the Connor-Taylor scaling law, which is often used in comparing confinement performance in RFP experiments. Confinement data for both devices is shown in Fig. 4. Confinement is improved by a factor of about 4. Under the conditions in T2R with low magnetic fluctuation amplitude, the scaling of confinement with Lundquist number has been determined; the scaling is $\tau_E \propto S^{-0.5 \pm 0.1}$ [10].

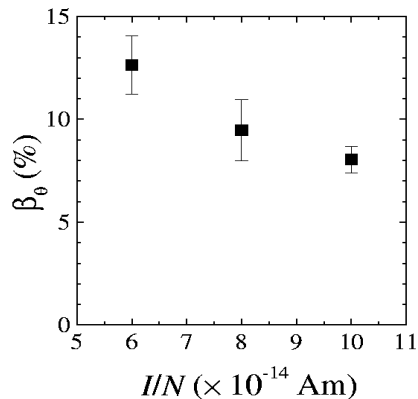


FIG. 3. Scaling of beta for a range of currents and densities.

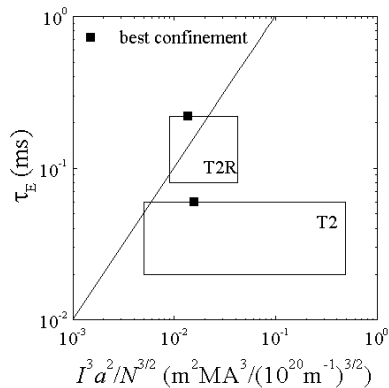


FIG. 4. Comparison of confinement times for T2R ($\tau_s = 6$ ms) and T2 ($\tau_s = 1.5$ ms)

4. Summary

In previous RFP experiments with a resistive shell boundary, the internally resonant modes have been phase-aligned and wall-locked. As a result confinement has been degraded. The EXTRAP T2R RFP was rebuilt with the aim of achieving a configuration where RWM effects could be studied under conditions where the internal resonant modes are not wall-locked. This was achieved by selecting a shell penetration time constant of 6 ms, which is intermediate between the relatively fast time scale of the sawtooth cycles associated the Taylor relaxation phenomena (≤ 2 ms) and the total pulse length (≈ 20 ms). Under these conditions, the internal resonant modes rotate with sufficiently high velocities so that their radial perturbation at the shell is suppressed. The linear RWM growth rates have been measured and compare well with theory. The confinement is comparable to that seen in the best performing conducting shell experiments indicating that as long as internal mode rotation is sustained, the resistive shell does not lead to degraded confinement, at least not until the RWMs have grown to amplitudes where they begin to affect confinement.

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