Mode Dynamics and Confinement in the Reversed-field Pinch

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Abstract. Tearing mode dynamics and toroidal plasma flow in the RFP has been experimentally studied in the Extrap T2 device. A toroidally localised, stationary magnetic field perturbation, the "slinky mode" is formed in nearly all discharges. There is a tendency of increased phase alignment of different toroidal Fourier modes, resulting in higher localised mode amplitudes, with higher magnetic fluctuation level. The fluctuation level increases slightly with increasing plasma current and plasma density. The toroidal plasma flow velocity and the ion temperature has been measured with Doppler spectroscopy. Both the toroidal plasma velocity and the ion temperature clearly increase with I/N. Initial, preliminary experimental results obtained very recently after a complete change of the Extrap T2 front-end system (first wall, shell, TF coil), show that an operational window with mode rotation most likely exists in the rebuilt device, in contrast to the earlier case discussed above. A numerical code DEBSP has been developed to simulate the behaviour of RFP confinement in realistic geometry, including essential transport physics. Resulting scaling laws are presented and compared with results from Extrap T2 and other RFP experiments.

1. Introduction

The idealised RFP is surrounded by a perfectly conducting shell that stabilises external, non-resonant kink modes and internally resonant tearing modes. The RFP normally operates close to the marginal stability limit for tearing modes and these tearing mode fluctuations are responsible for the dynamo process and for Taylor relaxation. A problem in RFPs is related to the fact that the internally resonant modes tend to phase align and lock, forming a localised helical perturbation, the "slinky mode", that can be rotating or stationary in the laboratory frame. If the perturbation is stationary, with a resistive shell, the mode amplitude grows on the time scale of the shell penetration time and degrades confinement. The mode locking can occur as a result of field errors or as a direct characteristic result of resistive shell instability. The Extrap T2 device [1] is operated with a resistive shell, and the magnetic fluctuation data have been analysed to determine the dynamics of the mode-locking and the resistive shell effects. The toroidal plasma flow and ion temperature has been measured with Doppler spectroscopy. It was felt that the understanding of transport in RFPs would benefit from the development and use of a numerical code that simulates the behaviour in realistic geometry, including the essential transport physics. A numerical code DEBSP [2] has been developed and the numerical results are compared to measurements from Extrap T2 and other RFP experiments.

2. Tearing mode dynamics and plasma flow

The Extrap T2 experiment is a medium-sized RFP (R/a=1.24m/0.183m). The device was provided with a thin shell with a field penetration time of 1.5 ms, which was about one-tenth of the pulse duration time. (The operation in the mode described here ended in late 1998 and a complete change of the front-end system has taken place since then.) The inside wall was fully covered with graphite tiles. The plasma current was up to I_p=250 kA and the density ranged between n_e=1-10×10^{19} m^{-3}. The MHD mode studies are based on magnetic field measurements from a B_r-array. The two-dimensional array has 4 poloidal positions and 32 toroidal positions resulting in 4×32=128 measurement points of the radial magnetic field. The structure and the dynamics of the modes is obtained from a reconstruction of the last closed flux surface (LCFS) using the radial magnetic field [3].

The "slinky mode" is a toroidally localised, stationary magnetic field perturbation that formed in nearly all discharges in Extrap T2. The helical shape of the mode can be seen in Fig. 1, where the LCFS is reconstructed (the amplitude of the perturbation is enhanced three times for better visibility).

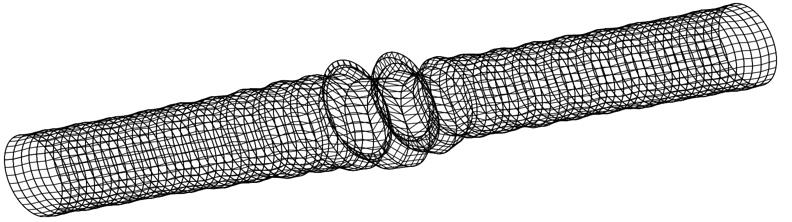
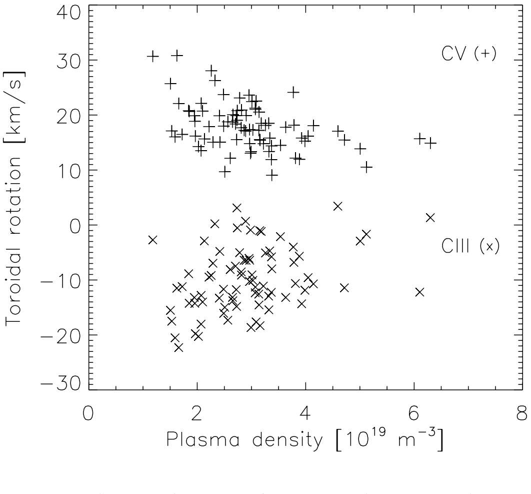


Fig. 1. Perturbed LCFS in Extrap T2 during "slinky mode" (amplified three times for visibility)

The typical perturbation amplitude of the helical LCFS at the position of the toroidally localised mode is about 2 cm. The toroidal distribution of the mode locking position is not completely symmetric, revealing that field errors (mainly due to the OH coil feeders) play a role in the locking process. The Fourier mode spectra show that the dominating modes (m=1, n=-10 to -15) are resonant in the central plasma. External, non-resonant modes are not observed in T2. A higher degree of phase alignment of the internally resonant m=1 modes is observed with increasing r.m.s. fluctuation level. The fluctuation level (1.2-2.3%) increases slightly both with increasing plasma current and increasing plasma density. The scaling of the r. m. s. magnetic fluctuation level with the Lundquist number is $S^{-0.06}$.

In Extrap T2, the toroidal velocity of different impurity ion species have been obtained spectroscopically from the Doppler shifts of CV, OV, OIII and CIII lines emitting from successively larger minor radii.



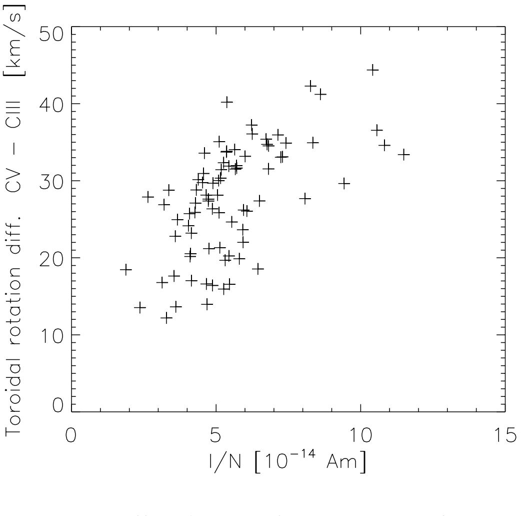


Fig. 2 Flow velocity of CIII and CV vs. density

Fig. 3. Diff. velocity of CV-CIII vs. I/N

Data has been obtained from a large set of discharges with plasma currents in the range I_p=140-190 kA and densities in the range n_e=1-6×10^{19} m^{-3}. The velocity profile is highly sheared [4]. In the core, the toroidal flow velocity is positive, in the direction of the toroidal plasma current, (v_ϕ=10-30 km/s, obtained from CV), and it reverses direction, becoming negative in the edge (v_ϕ=-20-0 km/s, obtained from CIII) (Fig.2). The differential velocity (CV-CIII) increases with the parameter *I/N* (Fig. 3). There is a correlation between the fluid flow and the magnetic fluctuations: As the magnetic fluctuations increase, the mean flow velocity decreases while the flow profile shape apparently is maintained, thus resulting in a increased amplitude of the edge flow in the negative direction (Fig. 4). In the MST device, a similar "down-shift" of the toroidal flow profile has been observed during discrete dynamo events [5].

The ion temperature clearly increases with the parameter *I/N*, as shown in Fig. 5, similar to the differential rotation velocity. (Compare Fig. 3).

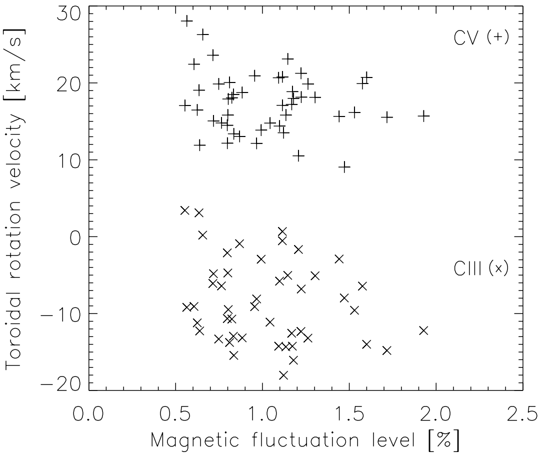


Fig. 4.CV and CIII velocity vs. magnetic fluct.

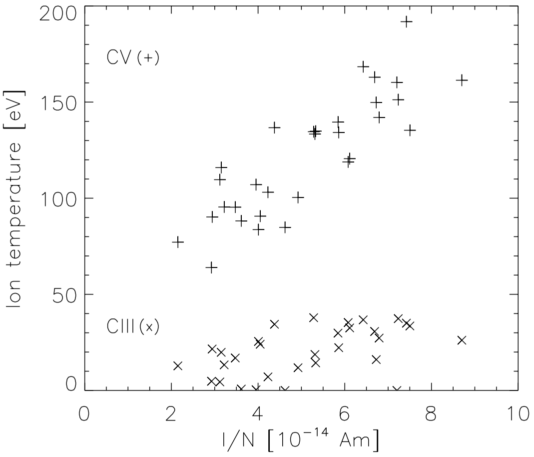


Fig.5. Ion temperature vs. I/N

3. T2 rebuild

The Extrap T2 front-end system, including the first wall, the shell and the toroidal field coil has been completely rebuilt during the last two years. The global dimensions of the vessel are the same as before (minor and major radii). The first wall is now all metal. A total of 180 molybdenum mushroom limiters, installed in the flat sections of the stainless steel vessel, replace the graphite tile armour. A new resistive shell has been installed, consisting of two layers of 0.5 mm thick copper plate with a total vertical field penetration time around 5.5 - 6.5 ms. The poloidal and toroidal gaps of the two copper layers are overlapped in order to reduce the gap error field. A new toroidal field coil with low field ripple is used, consisting of 64 one turn circular coils.

The T2 machine has been re-assembled with the new front-end system and wall conditioning and start-up of RFP operation has recently begun. The vessel has been baked out at a temperature of 250 °C during assembly, and at a temperature of 80° C after installation on the T2 device. The first wall has so far been conditioned with about 4 hrs of hydrogen glow discharge cleaning and 140 RFP pulses. Typical RFP discharge parameters are at present: I_p≈100 kA, V_t≈50 V, n_e≈1-2×10^{19} m^{-3}. The discharge duration is about 10 ms. The toroidal loop voltage and the plasma density are still decreasing shot by shot. The toroidal loop voltage is at present about half of that obtained before the rebuild, suggesting that confinement parameters (not measured yet) most likely have improved. The plasma density behaviour is very different compared to the previous operation: The plasma density has a good shot-to-shot reproducibility and there are no sudden density increases (influx events) during the discharge, as was observed with the graphite first wall.

The MHD mode activity is measured in the same way as before with an array of 128 B_r-flux loops on the vessel surface. Preliminary results indicate that an operational window most likely exists where some core-resonant modes are rotating. An example of this type of discharge is shown in Fig. 6. The m=1,n=-12 mode rotates toroidally in the opposite direction of the plasma current with a phase velocity of $v_\phi \approx -8$ km/s. Indeed, there are also discharges with wall-locked "slinky modes", similar to those obtained before the rebuild. However, the present situation is clearly better than during the previous operation of the device where wall-locked "slinky modes" always were present. The precise reason for the improvement of the conditions in Extrap T2 is not clear at this stage. It is to be noted, however, that the shell field penetration time has increased by a factor of four and that the density control is better with the all metal first wall.

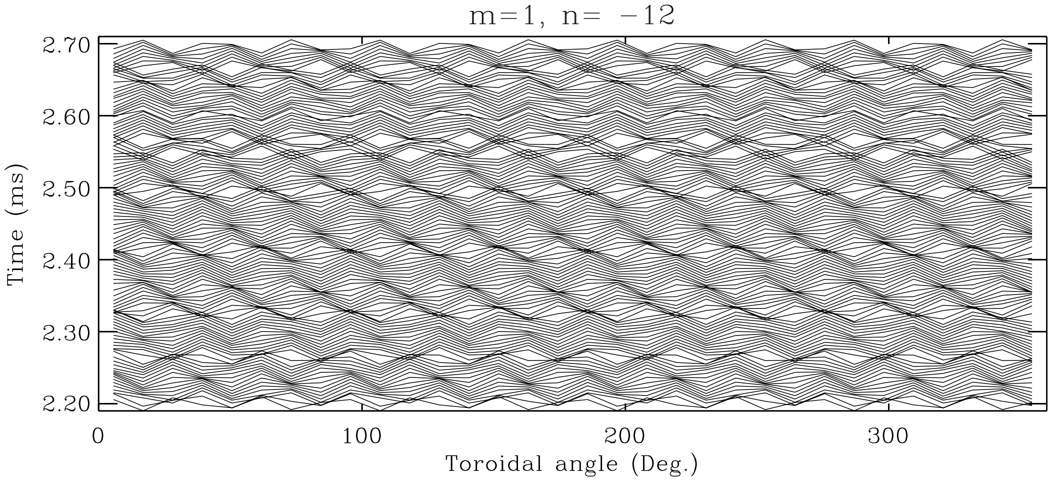


Fig. 6. Sine amplitude of m=1,n=-12 vs time and toroidal angle showing mode rotation.

4. RFP magnetic fluctuations and confinement scaling

A series of high resolution, 3-D, resistive MHD numerical simulations of transport in the conventional RFP is performed. Scaling laws have been obtained for poloidal beta and energy confinement using Lundquist numbers up to record high values of S=10^6. The approach taken is to determine confinement properties of the RFP plasma in the best possible conditions, thereby establishing upper limits for confinement. Optimum plasma conditions are attained by taking the transport coefficients to be classical, and ignoring radiation losses and resistive wall effects. The DEBSP code solves the resistive MHD equations including ohmic heating, convection, and anisotropic heat conduction. Relevant physics such as a realistic beta value, magnetic and velocity fluctuations and transport along stochastic field lines is modelled. A high grid resolution of 300 radial grid points, 42 axial and 5 poloidal modes is found necessary in order to reach to high S numbers.

It is theoretically determined that only two transport parameters mainly determine transport; the initial poloidal beta value and the initial on-axis Lundquist number. After performing a series of time-asymptotic code runs for different sets of these parameters, a linear regression analysis was carried out. The following confinement parameter scalings were obtained for the pinch parameter value $\Theta = 1.8$: poloidal beta $\beta_\theta \propto (I/N)^{-0.40} I^{-0.40}$, energy confinement time $\tau_E \propto (I/N)^{0.34} I^{0.34}$, and on-axis temperature $T(0) \propto (I/N)^{0.56} I^{0.56}$. Here I denotes plasma current and N line density. Experimental results at T2, RFX and MST are consistent with the above numerical results.

We show in Fig. 7 a comparison between DEBSP scalings and results from regression analysis of poloidal beta data from the Extrap T2 experiment [6]. It is assumed that in experiments $T_i = T_e$. The experimental scaling is seen to be very similar to that obtained from simulations. This agreement follows from the fact that core transport in both the experiment and the code is governed by resistive tearing mode fluctuations. The difference in magnitude of poloidal beta between T2 and DEBSP is essentially a constant factor in the scaling law, and is attributed to the fact that there is anomalous cross-field transport in the edge region of the experiment not included in the code simulation. It is further found that the obtained on-axis temperature scaling is close to that observed in T2; $T(0) \propto (I/N)^{0.5} I^{0.5}$. The volume averaged rms radial magnetic field code data yield an $S^{-0.14}$ Lundquist number scaling (Fig.8). The dashed region indicates the fluctuation level required to avoid overlapping m=1 islands. Similar scalings are obtained in major RFP devices; $S^{-0.18}$ (RFX, Padua [7]), $S^{-0.07}$ - $S^{-0.18}$ (MST, Wisconsin [8]) and $S^{-0.06}$ (Extrap T2, Stockholm [3]).

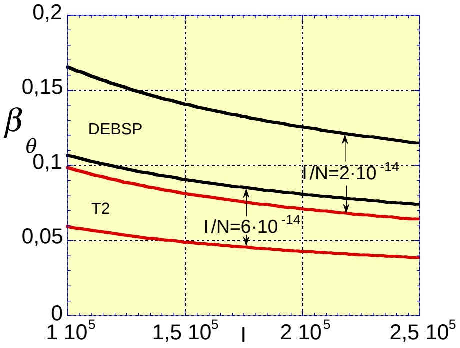


Fig. 7. Poloidal beta vs. plasma current.

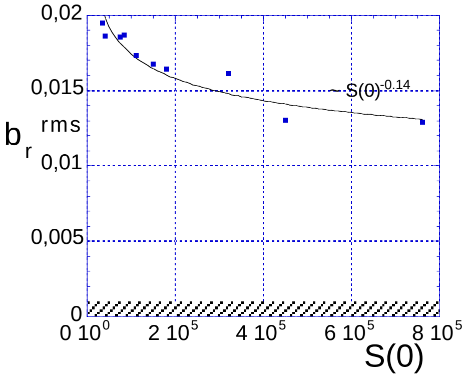


Fig. 8. Fluctuation level vs. Lundquist number

The computer simulations were performed at low aspect ratio (1.25) to save memory and computing time. We show, however, that the results do not depend sensitively on aspect ratio [9]. This is the first numerical magnetic fluctuation scaling that is obtained including finite pressure and transport terms. The results emphasise the importance of controlling the RFP current profile in order to minimise the dynamo fluctuations, reduce the corresponding thermal losses, and improve energy confinement.

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