

Final report

A THEORETICAL INVESTIGATION OF MODE-LOCKING PHENOMENA IN REVERSED FIELD PINCHES

1. R. Fitzpatrick, *Formation and locking of the “slinky” mode in reversed field pinches*, Phys. Plasmas **6**, 1168 (1999).

This paper investigates the formation and breakup of the “slinky mode” in an RFP using analytic techniques previously employed to examine mode locking phenomena in tokamaks. The slinky mode is a toroidally localized, coherent interference pattern in the magnetic field which co-rotates with the plasma at the reversal surface. This mode forms, as a result of the nonlinear coupling of multiple $m = 1$ core tearing modes, via a bifurcation which is similar to that by which toroidally coupled tearing modes lock together in a tokamak. The slinky mode breaks up via a second bifurcation which is similar to that by which toroidally coupled tearing modes in a tokamak unlock. However, the typical $m = 1$ mode amplitude below which slinky breakup is triggered is much smaller than that above which slinky formation occurs. Analytic expressions for the slinky formation and breakup thresholds are obtained in all regimes of physical interest. The locking of the slinky mode to a static error-field is also investigated analytically. Either the error-field arrests the rotation of the plasma at the reversal surface before the formation of the slinky mode, so that the mode subsequently forms as a non-rotating mode, or the slinky mode forms as a rotating mode and subsequently locks to the error-field. Analytic expressions for the locking and unlocking thresholds are obtained in all regimes of physical interest. The problems associated with a locked slinky mode can be alleviated by canceling out the accidentally produced error-field responsible for locking the slinky mode, using a deliberately created “control” error-field. Alternatively, the locking angle of the slinky mode can be swept toroidally by rotating the control field.

2. R. Fitzpatrick, and E.P. Yu, *Feedback stabilization of resistive shell modes in a reversed field pinch*, Phys. Plasmas **6**, 3536 (1999).

A reactor relevant reversed field pinch (RFP) must be capable of operating successfully when surrounded by a close-fitting resistive shell whose L/R time is much *shorter* than the pulse length. Resonant modes are largely unaffected by the shell resistivity, provided that the plasma rotation is maintained against the breaking effect of non-axisymmetric eddy currents induced in the shell. This may require an auxiliary momentum source, such as a neutral beam injector. Non-resonant modes are largely unaffected by plasma rotation, and are expected to manifest themselves as non-rotating *resistive shell modes* growing on the L/R time of the shell. A general RFP equilibrium is subject to many simultaneously unstable resistive shell modes: the only viable control mechanism for such modes in an RFP reactor is *active feedback*. It is demonstrated that an N -fold toroidally symmetric arrangement of feedback coils, combined with a strictly linear feedback algorithm, is capable of *simultaneously stabilizing* all intrinsically unstable resistive shell modes over a wide range of different RFP equilibria. The number of coils in the toroidal direction N , at any given poloidal angle, must be greater than, or equal to, the range of toroidal mode numbers of the unstable resistive shell modes. However, this range is largely determined by the aspect-ratio of the device. The optimum coil configuration corresponds to one in which each feedback coil slightly overlaps its immediate neighbours in the toroidal direction. The critical current which must be driven around each feedback coils is, at most, a few percent of the equilibrium toroidal plasma current. The feedback scheme is robust to small deviations from pure N -fold toroidal symmetry or a pure linear response of the feedback circuits.

3. R. Fitzpatrick, S.C. Guo, D.J. Den Hartog, and C.C. Hegna, *Effect of a resistive vacuum vessel on dynamo mode rotation in reversed field pinches*, Phys. Plasmas **6**, 3878

(1999).

Locked (*i.e.*, non-rotating) dynamo modes give rise to a serious edge loading problem during the operation of high current reversed field pinches. Rotating dynamo modes generally have a far more benign effect. This paper develops a simple analytic model to investigate the slowing down effect of electromagnetic torques due to eddy currents excited in the vacuum vessel on the rotation of dynamo modes in both the Madison Symmetric Torus (MST) [Fusion Technology **19**, 131 (1991)] and the Reversed Field Experiment (RFX) [Fusion Engineering and Design **25**, 335 (1995)]. This model strongly suggests that vacuum vessel eddy currents are the primary cause of the observed lack of mode rotation in RFX. The eddy currents in MST are found to be too weak to cause a similar problem. The crucial difference between RFX and MST is the presence of a thin, highly resistive vacuum vessel in the former device. The MST vacuum vessel is thick and highly conducting. Various locked mode alleviation methods are discussed.

4. R. Fitzpatrick, and E.P. Yu, *Nonlinear dynamo mode dynamics in reversed field pinches*, Phys. Plasmas **7**, 3610 (2000).

The nonlinear dynamics of a typical dynamo mode in a reversed field pinch, under the action of the braking torque due to eddy currents excited in a resistive vacuum vessel and the locking torque due to a resonant error-field, is investigated. A simple set of phase evolution equations for the mode is derived: these equations represent an important extension of the well-known equations of Zohm, *et al.* [Europhys. Lett. **11**, 745 (1990).] which incorporate a self-consistent calculation of the radial extent of the region of the plasma which co-rotates with the mode; the width of this region being determined by plasma viscosity. Using these newly developed equations, a comprehensive theory of the influence of a resistive vacuum vessel on error-field locking

and unlocking thresholds is developed. Under certain circumstances, a resistive vacuum vessel is found to strongly *catalyze* locked mode formation. Hopefully, the results obtained in this paper will allow experimentalists to achieve a full understanding of why the so-called “slinky mode” locks in some reversed field pinch devices, but not in others. The locking of the slinky mode is currently an issue of outstanding importance in reversed field pinch research.

5. R. Fitzpatrick, and P. Zanca, *Phase-locking of tearing modes in the reversed field experiment*, Phys. Plasmas **9**, 2707 (2002).

In the RFX reversed field pinch experiment [F. Gnesotto, *et al.*, Fusion Engineering and Design **25**, 335 (1995)], the $m = 1$ and $m = 0$ tearing modes present in the plasma are observed to phase-lock together to form a highly peaked, strongly toroidally localized, pattern in the perturbed magnetic field. This pattern, which is commonly known as the “slinky” pattern, gives rise to severe edge loading problems which limit the maximum achievable toroidal current. This paper presents a theory which explains virtually all salient features of the RFX slinky pattern. The central premise of this theory is that at high ambient mode amplitude the various tearing modes occurring in the plasma phase-lock together in a configuration which minimizes the magnitudes of the electromagnetic torques exerted at the various mode rational surfaces. The theory successfully predicts the profiles of the edge radial and toroidal magnetic fields generated by the $m = 0$ and $m = 1$ modes, the phase relations between the various modes, the presence of a small toroidal offset between the peaks of the $m = 0$ and $m = 1$ contributions to the overall slinky pattern, and the response of the pattern to externally generated $m = 0$ and $m = 1$ magnetic perturbations.