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A MIRNOV LOOP ARRAY FOR FIELD-REVERSED CONFIGURATIONS

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ABSTRACT

An array of 64 magnetic pick-up loops has been used for stability studies of large field-reversed configurations in the FRX-C/LSM device. This array proved reliable, could resolve signals of a few Gauss, and allowed the detection of several plasma instabilities.

PACS numbers: 52.55 Hc, 52.35 Py, 52.30 Gz

INTRODUCTION

Field-reversed configurations (FRC) are elongated compact toroids formed in theta pinches with a reversed bias magnetic field.¹ Cross stability has recently emerged as a key issue for large-size FRCs and there is a need for a non-perturbing diagnostic technique that could detect possible low- n (toroidal mode number) instabilities. Mirnov loop arrays are routinely used in many toroidal plasma experiments to detect coherent modes but such a measurement has only now been attempted on FRC experiments. This is because the FRC plasma is relatively far from the wall of the vacuum chamber and also because some instabilities such as the theoretically predicted tilt mode¹ are believed to be largely internal to the FRC separatrix. A Mirnov loop array installed on the FRX-C/LSM device² is described in this paper. This array performed well in the high-voltage theta-pinch environment and could resolve signals of a few Gauss. Several plasma instabilities detected with this diagnostic are briefly presented.

I. THE MIRNOV LOOP ARRAY

The system consists of 64 B_θ pick-up loops located between the coil and quartz tube of the FRX-C/LSM device sketched in Fig. 1. Further details concerning the device, diagnostics, typical FRC plasma parameters and formation method are described elsewhere.² B_θ is chosen over B_r because an axisymmetric FRC has no B_θ , so that instabilities can be easily detected as a departure from zero signals. In addition, B_θ provides increased sensitivity over B_r for a non-perturbing array located near the straight conducting boundary. The B_θ pick-up loops are mounted at 8 axial locations

($z = \pm 0.1, \pm 0.3, \pm 0.5, \text{ and } \pm 0.7 \text{ m}$) as shown in Fig. 1(a). At each axial position, 3 loops are mounted at equal $45^\circ \theta$ intervals as shown in Fig. 1(b). The array provides near complete coverage of a typical FRC (sketched in Fig. 1) with axial and toroidal spacings ($\sim 0.2 \text{ m}$) comparable to the distance from the probes to the FRC separatrix. Each B_θ loop is inserted radially through a coil slot and is mounted on a rotary stage (see Fig. 2) to null B_z pick-up within a few Gauss. This requires angular adjustments down to a few milliradian since typical B_z fields are of order 1 kG. A probe typically remains aligned for hundreds of discharges, so that the array is quite reliable and relatively maintenance-free.

The B_θ probes have a coaxial design with Kapton film and epoxy casting for high voltage insulation (induced voltages around the theta-pinch coil are up to 100 kV). A pick-up loop consists of 16 square turns (total area of about 20 cm^2) wound on an acrylic form and surrounded by a stainless steel electrical shield ($0.2 \mu\text{s}$ penetration time). This shield is extended by a copper tubing and the outer braid of a triax cable to protect the twisted leads and provide essentially noise-free signals. The B_θ signals are integrated passively ($RC = 200 \mu\text{s}$) and have a resultant sensitivity of 1 mV/G. The signals are digitized at $1\text{-}\mu\text{s}$ intervals on 12-bit LeCroy 6810 recorders (0.1 mV resolution). Simultaneous sample digitization at 0.2, 0.5 and $1\text{-}\mu\text{s}$ intervals established that a 1 MHz sampling rate is adequate and that most of the signal information lies in the range 30-500 kHz.

II. OFF-LINE ANALYSIS

Once the B_θ signals are digitized, a numerical procedure is used to remove the residual B_z pick-up and to provide toroidal Fourier analysis at each z location. This procedure is illustrated in Fig. 3 for a typical 3-mtorr FRC discharge. The integrated signals of the 8 loops located at $z = -0.5$ m are shown as functions of time in Fig. 3(a). The FRC is formed a few μ s after the main theta-pinch discharge ($t = 0$) and has a lifetime of about 160 μ s. The fluctuating signals between -20 and 0 μ s are associated with the ionization of the neutral gas fill. The steady signals before -20 μ s are residual pick-up of the 0.7 kG B_z bias field applied at -160 μ s. Such pick-up is removed by comparison with a B_z probe at the same axial location and with similar digitization. The differences $B_\theta - \alpha B_z$ are shown in Fig. 3(b), where the values of α are determined numerically such that these differences are zero between -30 and -20 μ s.

The signals of Fig. 3(b) are now Fourier analyzed for the $n = 0, 1, 2$, and 3 toroidal symmetries. At each time step and for each value of n , $s_n = \sum_k B_{\theta k} \sin(n\theta_k)$ and $c_n = \sum_k B_{\theta k} \cos(n\theta_k)$ are summed over the loop toroidal locations (θ_k , $k = 1, 8$) and the Fourier amplitudes $A_n = \sqrt{s_n^2 + c_n^2}/4$ and phases $\phi_n = \tan^{-1}(s_n/c_n)$ are computed ($-\pi < \phi_n \leq \pi$). The results from this analysis are shown in Fig. 3(c). The top trace is a reference line-integrated density at $z = 0$. Below it, the Fourier amplitudes ($n = 0, 1, 2$, and 3) and phases ($n = 1, 2$, and 3) are plotted as functions of time.

The numerical analysis program has many options, one of which is separation of axially even and odd components. This is achieved before Fourier analysis by forming half sums and differences of the B_θ signals at given $\pm z$. Even and odd refer to the axial symmetry of flux surfaces. Note that the axial parity of B_θ is opposite to that of flux surface displacement (i.e. an even mode has odd B_θ and vice-versa) because B_θ signals at the pick-up loops arise from distortions of B_r at the separatrix. This option is important because the most virulent instabilities predicted theoretically for large FRCs are axially-odd tilt modes.

III. SAMPLE ANALYSIS

Some instabilities detected with the Mirnov loop array are briefly presented to illustrate the usefulness of this diagnostic in FRC studies. First, the example in Fig. 3 shows that an $n = 1$ component is present during most of the FRC lifetime and that an $n = 2$ component starts to grow from around 70 μs . The latter is the familiar rotational mode¹ (also visible on the density trace) which causes an elliptical deformation of the plasma cross section. The plasma contacts the tube at around 140 μs and the discharge terminates soon after. Analysis to be detailed elsewhere shows that the $n = 1$ component is also a rotational instability which saturates at low amplitude and merely appears as a small (1-2 cm) rigid radial displacement. Both rotational instabilities are even modes (axially-odd B_θ signals are less than 2-3 Gauss up to 120 μs) that are fairly uniform along the FRC length.

Second, $n = 1$ axially-odd asymmetries have been observed soon after FRC formation whenever the FRC confinement is poor. An example of such an asymmetry is given in Fig. 4 with time histories of (a) line-integrated density and (b) amplitude of the odd $n = 1$ component. The asymmetry starts to grow at around $3 \mu\text{s}$, peaks, and abruptly collapses at around $20 \mu\text{s}$ in coincidence with a drop in plasma density. Then, a smaller FRC survives up to $120 \mu\text{s}$. These asymmetries occur for more MHD-like FRCs formed with either high bias fields (1 kG for the example of Fig. 4) or fill pressures greater than 4 mtorr. Preliminary comparisons with 3-D MHD numerical simulations³ suggest that the initial growth, magnitude, and spatial distribution of these asymmetries are consistent with those calculated for internal tilt instabilities.

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FIGURE CAPTIONS

Fig. 1 The FRX-C/LSM device and the B_θ Mirnov loop array. Sketched are partial (a) side-on, and (b) end-on views. The apparatus is symmetric around the $z = 0$ and $\theta = 0$ planes.

Fig. 2 Photograph of one of the B_θ pick-up loops. The epoxy cast, rotary stage and mount, and triax cable are visible from left to right.

Fig. 3 A 3-mtorr FRC example showing for the 8 loops at $z = -0.5$ m (a) the B_θ signals, (b) the B_θ signals with B_z pick-up removed, and (c) toroidal Fourier analysis as functions of time.

Fig. 4 Time histories of (a) line-integrated density at $z = -0.2$ m and (b) axially-odd $n = 1$ amplitude at $z = \pm 0.3$ m for a 3-mtorr FRC with poor confinement.

Fig. 1

Fig. 2

Fig. 3

Fig. 4