Helical structures and improved confinement in the MST RFP*

B.E. Chapman 1), A.F. Almagri 1), W.F. Bergerson 2), F. Bonomo 3), D.L. Brower 2), D.R. Burke 1), D.J. Clayton 1), D.J. Den Hartog 1), W.X. Ding 2), C.B. Forest 1), P. Franz 3), M. Gobbin 3), J.A. Goetz 1), C.C. Hegna 1), M.C. Kaufman 1), P. Piovesan 3), J.A. Reusch 1), J.S. Sarff 1), and H.D. Stephens 1)

1) UW-Madison and the CMSO, Madison, Wisconsin, USA
2) UCLA, Los Angeles, California, USA
3) Consorzio RFX, Padova, Italy

Email address of first author: bchapman@wisc.edu

Abstract. There are two cases in MST where a central helical magnetic structure emerges and produces a region of improved confinement. One case is due to a single tearing mode dominating the core-resonant $m = 1$ mode spectrum. Here, runaway electrons are observed with energies > 100 keV [1], a feature normally absent in standard, stochastic RFP plasmas. These electrons are deduced to be confined in a locally non-stochastic region inside the dominant mode's magnetic island. The other case corresponds to an additional mode that emerges following global reconnection events. In this case, the $m = 1$ spectrum is fairly flat, but the electron temperature profile exhibits a local peaking corresponding to a substantially reduced electron thermal diffusivity [2]. While neither of these cases corresponds to a substantial improvement in global confinement, recent discharges near MST's maximum toroidal plasma current exhibit very peaked tearing mode spectra. These spectra bear a striking similarity to those in the RFX-mod RFP which produce a several-fold improvement in global confinement [3]. Helical structures in the RFP are of interest not only for their contribution to confinement improvement, but also for their connection to 3D physics in other configurations.

Due to the growth and spatial overlap of multiple internally resonant $m = 1$ tearing modes in standard RFP plasmas, the internal magnetic field is stochastic, and energy confinement is relatively poor. These modes are driven by a gradient in the current profile, and previous work demonstrated tearing mode reduction and globally improved confinement with a modification of this profile. Another potential route to improved RFP confinement, the quasi-single-helicity (QSH) state, was identified about one decade ago [4]. Here, the $m = 1$ spectrum is dominated by one large mode, nearly always that resonant closest to the magnetic axis, and the large helical island associated with this mode can contain healed flux surfaces. QSH has been readily achieved in MST, RFX-mod, and other RFP's, but the impact on global energy confinement has been modest. The electron temperature inside the dominant helical stucture is sometimes enhanced, but the plasma volume encompassed by this structure is typically small. Recently, by pushing to large toroidal plasma current (> 1 MA) in RFX-mod, QSH was extended to the so-called Single Helical Axis (SHAx) state, wherein the helical structure grows to the point that it envelops the magnetic axis, increasing substantially the structure's volume [3]. Simultaneously, the other (secondary) $m = 1$ modes are somewhat diminished. This has resulted in a several-fold improvement in global energy confinement and has heightened interest in helical structures in the RFP.

In MST plasmas with a single dominant $m = 1$ mode, runaway electrons are confined with energies > 100 keV [1]. This is illustrated in Fig. 1, which contains hxr emission from the runaways and the amplitudes of two tearing modes. A modest neutron flux is also observed, indicative of a fast ion population. The $n = 5$ mode in Fig. 1 ranges from weakly to strongly dominant, the latter corresponding to QSH. The $n > 5$ modes, resonant further out in the plasma, remain relatively small. The helical structure associated with the $n = 5$ mode is observed with soft-x-ray tomography. Previously, runaway electrons in the RFP had only been observed during current profile control and reduced stochasticity in MST. In the

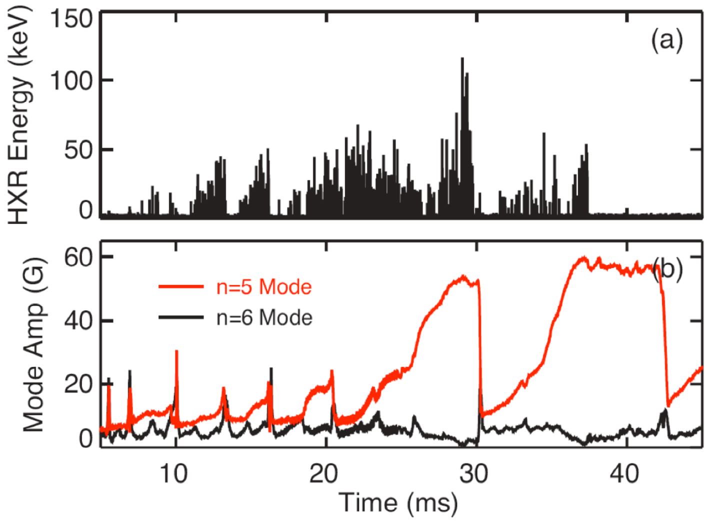

FIG. 1. Temporal evolution of (a) hard-x-ray energy along a central chord, (b) amplitudes of the two innermost-resonant m = 1 tearing modes.

discharge in Fig. 1, the region of reduced stochasticity is localized to the n = 5 island. The data later in time in Fig. 1 also reveal that a large dominant mode is not always sufficient for confinement of runaway electrons. The local magnetic topology, and particle confinement, can also be affected by variations in the smaller secondary modes.

In RFX-mod, the broadened SHAx T_e structure emerges only with a sufficiently large dominant mode and sufficiently small secondary modes, normalizing the mode amplitudes to $B(a)$. In MST plasmas with QSH such as that in Fig. 1, the secondary modes are usually not sufficiently small for SHAx. However, near MST's maximum toroidal current (0.6 MA), QSH plasmas have now been achieved that easily satisfy both SHAx criteria. Data from one such plasma is shown in Fig. 2. The dominant mode is shown in red, while the root-mean-square sum of the secondary modes are shown in black. The pairs of red and black dashed horizontal lines indicates the range of dominant and secondary mode amplitudes that are associated with SHAx in RFX-mod. For this MST data, the same number of secondary modes is used for the sum as has been used in RFX-mod. The dominant mode in MST is nearly twice the amplitude achieved in RFX-mod, while the summed amplitude of the secondary modes lies at the bottom end of the range of the RFX-mod data.

The global energy confinement time has not yet been measured in these plasmas, but MST's advanced diagnostics are already revealing details of the 3D structure. Laser polarimetry has identified a strong perturbation to the central magnetic topology when the dominant mode is present. Laser interferometry has also identified a possible structure in the density profile associated with this large mode. Additional diagnostics that will soon be brought to bear on these plasmas are Thomson scattering and soft-x-ray tomography.

Another type of helical structure emerges in MST, again associated with the n = 5 mode but with a fairly flat m = 1 spectrum [2]. This mode comes into resonance near the magnetic axis following global reconnection events, which cause a sudden alteration of the magnetic equilibrium. A high-rep-rate (25 kHz) Thomson scattering diagnostic reveals a localized, off-

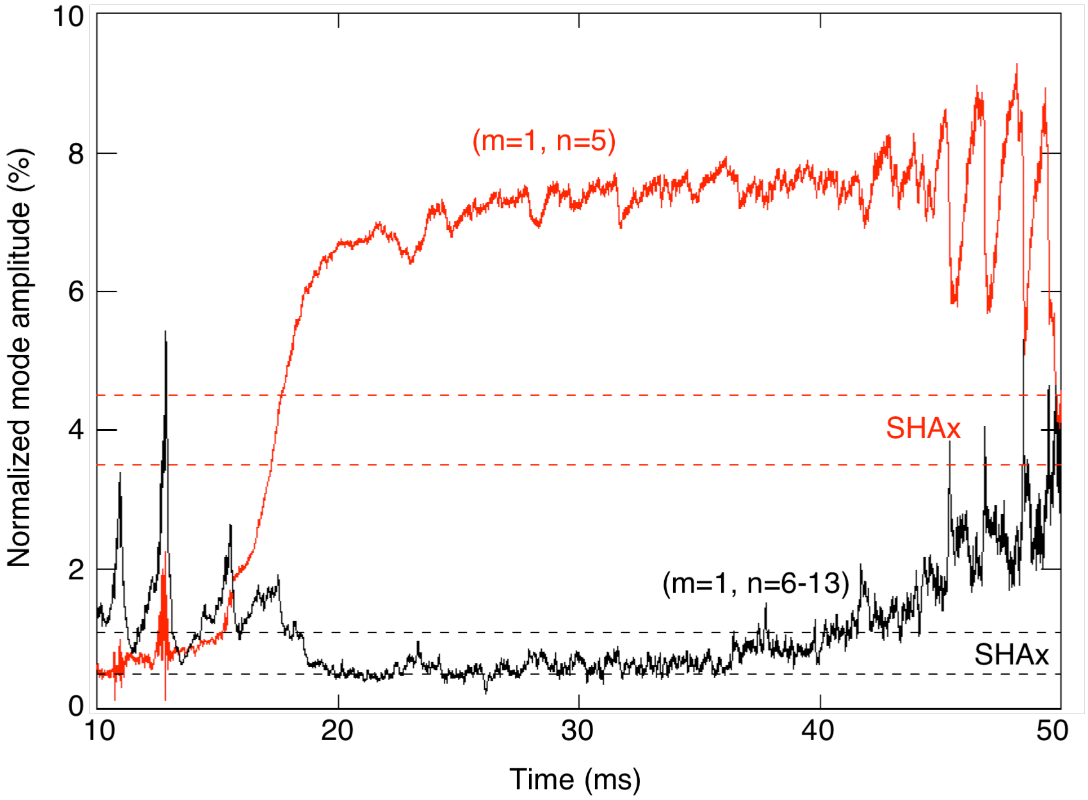

FIG. 2. *Temporal waveforms of the dominant n = 5 mode (red) and secondary n = 6-13 modes (black) normalized to the equilibrium magnetic field at the plasma boundary. Mode amplitudes derived from toroidal magnetic fluctuations. Range of the dominant and secondary mode amplitudes corresponding to SHAx in RFX-mod indicated by dashed lines, red for the dominant modes, black for the secondary modes.*

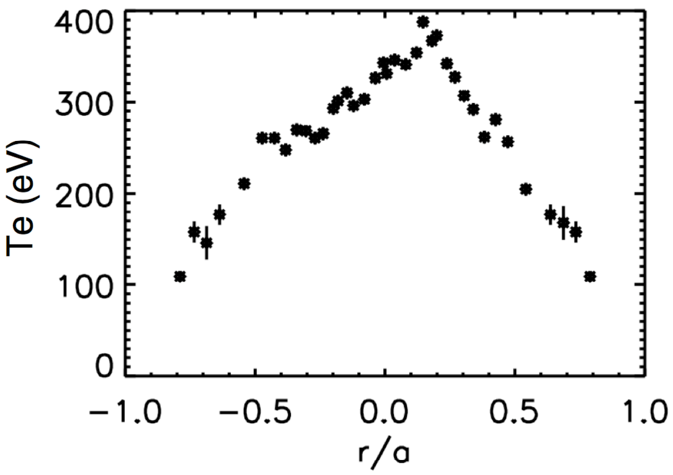

FIG. 3. Electron temperature profile showing off-axis peak associated with n = 5 helical structure.

axis peak in the T_e profile corresponding to the rotating n = 5 helical structure. This is illustrated in Fig. 3, which shows a composite profile of the electron temperature. The Thomson scattering diagnostic measures the temperature profile over the plasma minor radius, but because the helical structure rotates, the diagnostic is able to measure the profile with the structure's O-point at different locations in the poloidal plane. With this temperature profile, and a rough estimate of Z_{eff}, the electron thermal diffusivity inside the structure is estimated to be about 30 m^2/s, reduced substantially from the normal stochastic value.

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