High current RFPs in RFX-mod with induced Locked Mode rotation

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Abstract RFX pulses at at I $\geq$0.9MA were hindered by phase and wall-locking of the MHD dynamo modes. In RFX-mod, thanks to field error reduction by MHD feedback control, well controlled pulses at 1-1.5 MA are routinely obtained. Despite the lower field errors, dynamo modes are still locked, and deteriorate the wall conditioning. Forcing the toroidal rotation of the modes with new control schemes lead to long and reproducible high performance pulses,

Introduction

Core resonating tearing modes provide the dynamo action to sustain the RFP profile (whence the label Dynamo Modes) [1], but they also break the magnetic field symmetry. Their spectrum is made of several core resonating m=1 n $\leq$ -7 modes and a broad spectrum of m=0 modes resonating at the B_φ reversal surface. Due to non-linear coupling, the modes are phase locked and build up an interference pattern, the Slinky or Locked Mode (LM) [2,3]. In the core the LM often result in magnetic field stochastization, except when one mode is dominant, establishing a QSH regime [4]. But the LM also causes a perturbation of the plasma surface [5]: a localized bulge and a kink with amplitudes of a few cm in the radial direction. The Plasma Wall Interaction (PWI) is then localized there, reaching values in the 100 MWm^{-2} range. In the previous RFX this hindered operation at currents $\geq$ 1MA, which were plagued by carbon blooms and short pulses due to impurity contamination [6]. Such problem has been largely solved in RFX-mod with active feedback correction of field errors due to MHD modes [7]. The control is done by 4 poloidal x 48 toroidal saddle coils completely covering the torus and independently controlled by a digital feedback system [8]. With the Virtual Shell (VS) scheme [7, 9], where all the field errors are cancelled at the sensor coils, the perturbation due to the LM is reduced by a factor $\geq$ 3 and high performance plasma pulses at 1-1.2 MA are obtained. In such pulses, although the edge b_r are low, the LM is still present and catalyses PWI [10]. This results in a fast deterioration of the wall conditioning which requires frequent Glow Discharge Cleaning sessions to recover density control. The problem was solved by new techniques [11] which rotate the dynamo modes around the torus.

Virtual Shell + Rotating Perturbations and Mode Control with Complex Gain

Mode rotation is obtained via the direct coupling with external m= 1 perturbations, which occurs thanks to the sheet currents at the resonant layers [12]. In the scheme dubbed VS +

Rotating Perturbation (VS + Rot Pert), field error with helicity m= 1 n = -7÷-13, amplitude of 0.5-0.7 mT rotating toroidally at 10-50 Hz achieves the rotation of the homologous dynamo mode. An example is given in fig.1 where an m=1, n=-7 perturbation rotating at 20Hz is applied. The top frame shows that the radial m=1,n=-7 b_r component is kept close to the preset amplitude (b_r = 0.7 mT at the coil radius) through the pulse and after its end at 0.24 s. On the other hand, the toroidal component b_φ at the coil radius is mainly produced by the plasma dynamo mode, as clearly demonstrated by the sudden drop from 4 mT to 0.5 mT at plasma end. Since both the b_r and b_φ harmonic phases rotate at 20Hz
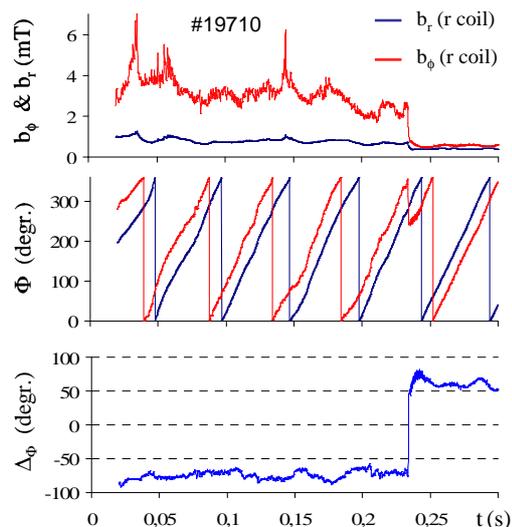

fig.1 Active rotation of an m,n 1,-7 mode: (top) amplitude of radial and toroidal field component at the sensor coil vs time; (middle) phases of same

through the pulse and beyond, not only the external perturbation, but also the dynamo mode rotates toroidally. As a further confirmation of the induced mode rotation, the phase shift between the radial and toroidal components of the m=1, n=-7 harmonics (fig.1 bottom frame) is ~ - 90° during the pulse and not far from 90° afterwards, which are indeed the phase differences corresponding to, respectively, an internal (plasma) mode and to an external perturbation. The rotation of a core dynamo mode by an external perturbation is also independently confirmed [13] by the good agreement with the rotation of the "hot" helical structure associated to the mode in the QSH states [4].

The modes can be rotated also by a different scheme, the Mode Control (MC) with Complex Gain. In this case the regulators of the feedback system are applied to the mode rather than to the coils. Each regulator can be assigned a proper proportional, derivative and integral gain, to optimize its time response and accuracy. Moreover the gain can have an imaginary component, i.e. a phase shift, so that its correction is spatially out-of-phase. In this way a rotating torque proportional to the preset phase is applied to the mode. The MC with Complex Gain should minimize the b_r needed for mode rotation. The main drawback is that the rotation speed is determined by the experimental mode amplitude and braking forces. Hence when one rotates a combination of the main dynamo modes, they tend to stay phase locked and to rotate all at the same speed, resulting in a "Poloidal" rotation of the LM [11] (fig.2 #19299). In other

cases, the modes phases re-adjust so that the LM "jumps" at different angles, rather than showing a regular rotation. Conversely, the VS + Rot Pert accurately controls the absolute phase of each mode and, therefore, several strategies are possible. The most successful ones impose rotation frequencies equally-spaced according to the n-number of the main $m = 1$ modes. For frequencies set to $f_n = n \cdot \Delta f$ (e.g. $\Delta f = 3$, $f_7 = 21$, $f_8 = 24$, $f_9 = 27$, etc.) this results in a toroidal rotation of the LM. Helical rotation around a stationary mode n_0 is instead obtained by imposing $f_n = \Delta f \cdot (n-n_0)$ (e.g. $\Delta f = 10$, $n_0 = 9$, $f_7 = -20$, $f_8 = -10$, $f_9 = 0$, $f_{10} = 10$, $f_{11} = 20$, etc.). In these schemes the relative phase of the modes can also be controlled, since the imposed frequencies entail constant phase differences relative to the LM. For instance, one can minimize the coherent interference of the $m=1$ modes. This reduces the maximum localized plasma perturbation. But the non-linear coupling of the modes acts toward a condition of maximum interference and spoils its reliability, unless relatively high b_r are applied. Conversely, smaller b_r lead to successful LM rotation when phases are set for maximum interference, or equal to the actual values in the plasma before the start of the control. An example is given in fig. 2. The rotation of the controlled modes is good and, as a result, the LM is swept around the torus. The improved PWI given by the VS + Rot Pert lead to reproducible pulses at $I > 1$ MA, where wall condition is maintained. In this way current scaling studies on RFX-mod for the first time showed a linear increase of T and τ_E without saturation beyond 1MA [14].

Figure 2: Control by MC + Complex Gains (#19299) versus VS + Rot Pert (#19279): m,n 1, -7÷-10 modes are rotated. The different rotations produce the LM motion in frame f.

Clean Mode Control and Close Virtual Shell

MHD control has been further improved with the Clean Mode Control (CMC) scheme [13]. With CMC the high order harmonics produced by the coils are subtracted from the measurements to avoid feeding them back as aliasing errors to the control. Moreover the CMC has been integrated with the Close Virtual Shell, where the b_r cancellation is done at the plasma edge, rather than at the measurement radius, thanks to real-time field computations.
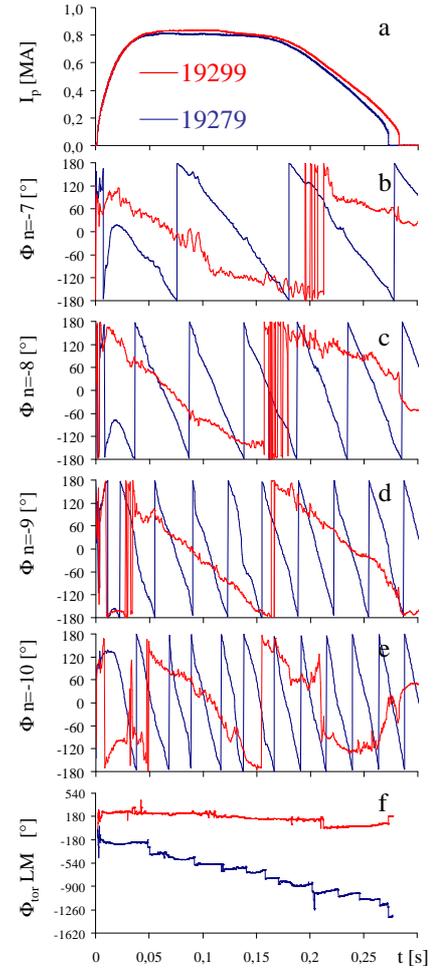
With the CMC the LM perturbation has been reduced by ≥50% [13] relative to VS. The correction is now so good that the modes rotate "spontaneously". Actually the rotation is slow and not due to a complete wall unlocking, but to a combination of the drag by the passive structures around the plasma (liner + shell) and of the feedback delay. As for the MC + Complex Gain, the rotation of the LM is uncontrolled, and reverses or "jumps" during the pulse. Hence the toroidal spread of the LM position is less uniform than that of the VS+ Rot Pert (fig.4). Nonetheless, due to the low residual LM perturbation, this is presently the best scheme to minimize PWI and extend RFX-mod operation towards the 2 MA design. Indeed 1.5 MA pulses lasting >0.45s (fig.3) and with record values of T and confinement have been obtained [13].

Figure 3: High I pulses in RFX-mod VS + Rot Pert (#19700) versus Clean Mode Control + Close VS (#22069) and a RFX pulse (#13130)

Figure 4: Histogram of Φ_{LM} for pulses of fig.3

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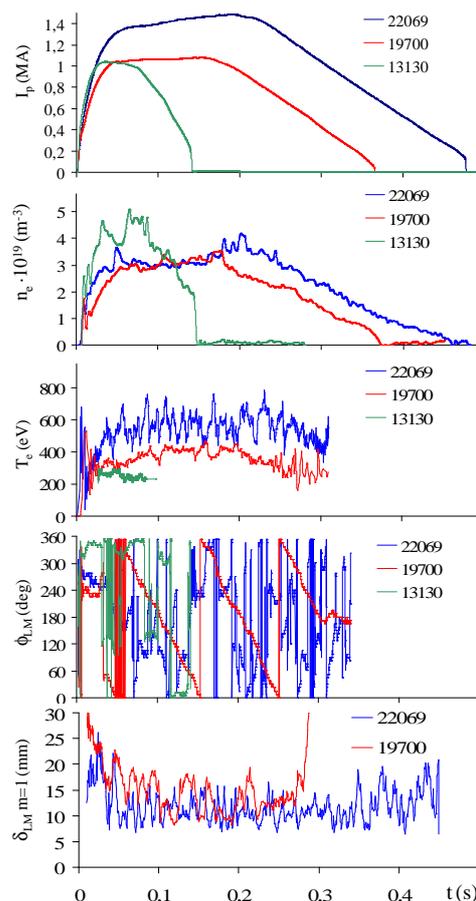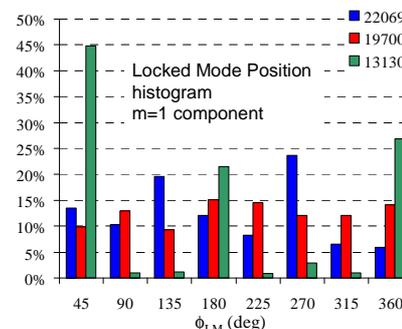[14] Innocente P., et. al., Proc. 21st IAEA Int. Conf. Chengdu, 2006 CD-ROM file EX/P3-10