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Oscillating Field Current Drive experiments in RFX-mod

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Introduction Oscillating Field Current Drive (OFCD), also known as F-Θ pumping or ac magnetic helicity injection is a technique originally proposed for plasma current sustainment in the Reversed Field Pinch (RFP) configuration. It was first tested in the ZT-40 RFP device [1]. Recently the MST device in Madison (Wisconsin, US) showed evidences of counter- and co- current generation (up to 10% in low current, ≈250 kA) discharges) with respect to the toroidal current induced by the main transformer [2]. OFCD can also be seen as a tool for current profile control in a “hybrid” current sustainment scenario where steady induction is combined with partial OFCD to study configurations with minimum E// [3]. As for other non-inductive current drive mechanisms, one of the major challenges of OFCD is to understand and to optimise the coupling between the power systems ad the plasma. In this paper the first tests of OFCD operations on RFX-mod [4] are presented. Testing OFCD on RFX-mod is of particular interest because of its unique possibility to operate under a large range of plasma current values and to investigate in this way the favourable OFCD efficiency scaling with the Lundquist number S foreseen by numerical simulations.

Experimental setup RFX-mod is a large Reversed Field Pinch device (a=0.46 m, R=2.0 m), with high plasma current capabilities (present maximum plasma current Ip = 1 MA). Its toroidal and poloidal power supply systems allow the operator to add modulations to the mean loop voltage values and to choose easily modulation shape, amplitude, frequency and initial shift. This is an approach to OFCD operations alternative to the MST one, where circuit oscillations are induced by coupling two resonating circuits to the main toroidal and poloidal power systems.

RFX-mod now is equipped with a redesigned toroidal power supply system [5]: in the new system, each of the twelve toroidal coil sectors has its own power supply based on Integrated Gate Commutated Thyristor (IGCT) switching converters that allow fully programmable current/voltage waveforms for each sector. Allowed frequencies vary up to 250 Hz, while amplitudes can reach ± 40 V, though they limited to lower values during usual plasma operations. Similarly, the poloidal power supply system can be pre-programmed, with a similar frequency limit and with the limitation on the amplitude that the applied toroidal voltage (typically between 20 and 30 V during the flat top phase of the pulse) cannot reverse sign. Non-sinusoidal (e.g. square wave) waveforms are possible as well. An example of OFCD oscillations in a vacuum shot is shown in Fig.1. In that case the frequency is 100 Hz and the amplitudes of toroidal and poloidal loop voltage oscillations are 4 and 12 V respectively; oscillations start at 50 ms.

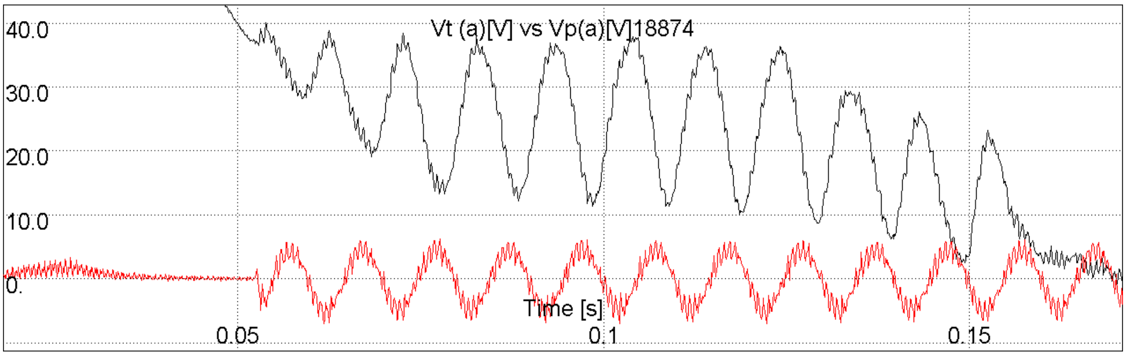

Figure 1: Time evolutions of toroidal (black) and poloidal (red) loop voltage oscillations during a vacuum test of OFCD operations at 100 Hz.

Experimental results In the experiments shown in this paper, OFCD is applied to I_p≈800 kA RFP plasmas, ≈250 ms discharge duration, with electron plasma density n_e=2-3 10^{19} m^{-3}, and different values of the toroidal field at the edge, $B_t(a)$. The main aim of these first experiments is the exploration of the flexibility offered by the power supply systems in terms of frequency and shaping of the voltage oscillations, keeping limited the power injected into the plasma.

In these experiments, the full compatibility of OFCD operations with the new active control of the magnetic boundary [4] was demonstrated. This is important because it permits the repetition of the OFCD cycle many times during the discharge (discharge duration is up to 330 ms plasma with 100-150 ms of flat-top).

By inducing loop voltage oscillations with amplitudes of the order of 10 Volts in the toroidal and poloidal directions, the influence of different phase shifts has been systematically studied for a modulation frequency of 100 Hz. In Fig.2 the main results (average toroidal field, toroidal and poloidal loop voltages) of a phase scan at 100 Hz are shown. In these experiments only the initial phase of the toroidal loop voltage oscillations was changed. It is possible to notice that the amplitude of the V_ϕ modulation changes according to the relative phase between the oscillations and this is probably due to an electro-magnetic coupling between the two systems. The faster peaks that appear on the poloidal loop voltage are not due to a plasma response, but to the poloidal power supply switching operations. Independent measurements with coils placed inside the vacuum vessel confirm that these peaks are strongly filtered by the vessel (1 kHz cut frequency) and do not affect plasma behaviour.

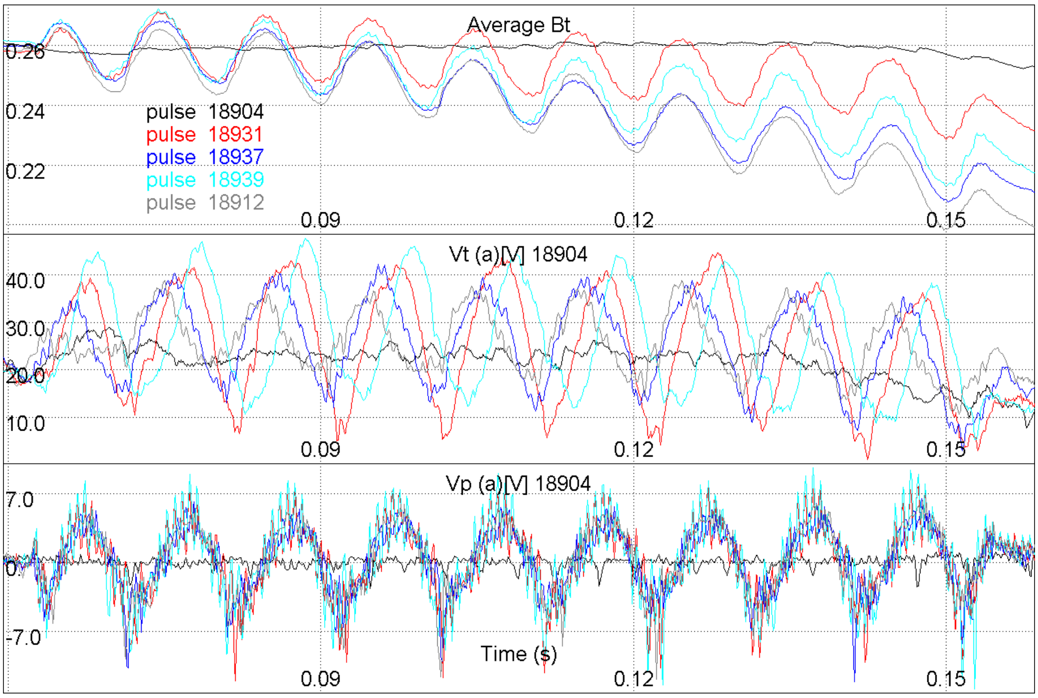

Figure 2: Example of phase scan for oscillations of about ± 12 V in the toroidal loop voltage (second window) and 6 V in the poloidal loop voltage (third window). Resulting toroidal flux is shown in the first window. Black (18904): reference; red (18931): $\delta\approx 0$; blue (18937): $\delta\approx\pi/4$; cyan (18939): $\delta\approx -\pi/2$; grey (18912): $\delta\approx\pi/2$.

When studying MHD dynamics in OFCD plasmas spurious V_θ peaks appear as fast oscillations in the m=0 mode amplitudes. Again, we believe this is an artificial effect measured by the main magnetic diagnostic system (placed between vessel and shell), but strongly reduced at the plasma radius. Nevertheless, dynamo properties are affected and modified by the oscillating fields, as confirmed by the fact that discrete relaxation events are often triggered when the poloidal loop voltage goes close to its minimum values. Finally, as for the current drive effect, as is discussed below at this low amplitude level of the oscillations no measurable net additional current is expected.

RFX-mod OFCD simulation To study OFCD experiments, a one-dimensional rigid profile model is used. The model is described extensively in [3] where it is applied to model MST experiments and its results are compared to the ones of a full 3-dimensional code. The code has been adapted to run with RFX-mod typical parameters. The results for two oscillation amplitudes are shown in Fig.3 and confirm that at low injected power the expected induced current is negligible (few kA over 800 kA or ≈0.5 %). For comparison these results are shown together with the induced current predicted for oscillations close to the maximum nominal amplitudes of the present power systems.

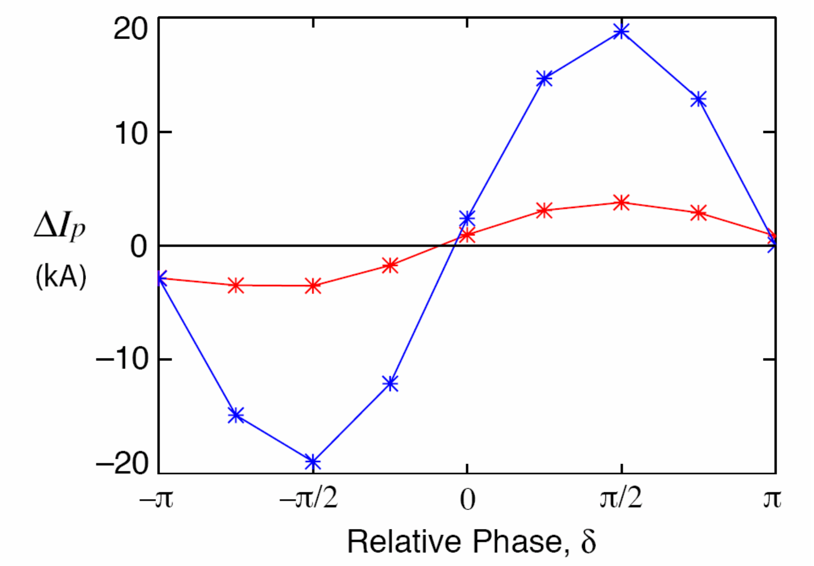

Figure 3: RFX-mod simulation of OFCD induced current versus relative phase for 2 cases. Red line: oscillation amplitudes as in the experiments described in the paper V_ϕ=+-12V and V_θ=+-6V; blue line: possible result with values close to the maximum power available in the present system V_ϕ=+-30V and V_θ=+-15V.

Conclusions First OFCD experiments in RFX-mod confirmed the flexibility of both poloidal and toroidal power supply systems. The main present limitation for current drive experiments seems to be the maximum oscillation amplitude, especially in the poloidal system. Even if a net current drive effect is not detectable in the experiments presented, MHD behaviour suggests that this kind of operations indeed affects, at least locally, the plasma current profiles. Further experiments will aim at maximising the power delivered to the plasma, by increasing the oscillation amplitude and by testing the effect of non-symmetric waveforms; on the other hand the use of OFCD for MHD spectroscopy will be further investigated.

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