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OPTIMIZATION OF THE RFX-MOD PERFORMANCE AT HIGH CURRENT

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1. Introduction. The RFX-mod Reversed Field Pinch is a very flexible machine that allows a rich variety of operational scenarios. The main power supply circuits are designed to allow a great degree of customization in the magnetic setting-up of the discharge and in the control of the horizontal equilibrium. In addition, the experiment can rely on a MHD feedback control system, based on an extended set of 48x4 saddle coils individually fed by current controlled power amplifiers. During the last year, the particular features of the machine were exploited to optimise the plasma discharge at high current (>= 1.5MA). The optimisation process had two final targets: the improvement of both machine operation efficiency at high current and and the physics performance of the experiment. Concerning machine operation, the main issue is to demonstrate the capability of the machine to produce plasma current higher than 1.5MA in a safe, efficient, repeatable and controlled way, up to the design limit (2MA). This means on one side maximizing the number of shots per day without losing the first wall conditioning, and on the other side finding the best start-up to maximize the value of the plasma current. The optimisation is also aimed at improving the physics performance in terms of energy confinement time and temperature, mainly by creating a plasma scenario where reproducible shots are possible and various advanced techniques for performance improvement can be tested. The optimisation is basically a trade-off between the efficiency in exploiting the available magnetic energy for plasma current building-up and the necessity of mitigating the localized plasma-wall interaction, which is a key issue for achieving good performances. This is done through a good control of the equilibrium, of the error fields and of the MHD modes. A first campaign at plasma current higher than 1.5MA was carried out to test some optimisation schemes and to explore the behaviour of the plasma. In this paper we describe the integrated optimisation carried out and the first preliminary results achieved beyond 1.5MA. We focus on the choice of the start-up and on the analysis of the recent database, showing which setting-up parameters are best suited and promising to obtain good plasma at high current.

2. Start-up style. The RFP configuration is obtained increasing the plasma current in a bias toroidal field, starting with a tokamak like configuration, through a succession of low-q states inside a conductive shell, until the toroidal field at the edge reverses its direction. During this process, the plasma equilibrium follows quite closely the F-Theta diagram [1]. In this framework, the state of RFP discharge is determined by the equilibrium point in the F-Theta diagram and by the plasma current or, equivalently, the toroidal magnetic flux. Different start-up styles are possible. The “ramped” start-up [2] is characterized by a weak bias toroidal field, with very early field reversal, current growth mostly in the RFP state, peaked current density profiles and self-generation of the toroidal magnetic flux. The “matched” start-up consists instead in a start-up with a stronger bias toroidal field, giving the toroidal flux expected in the final state. In principle, the advantage should consist in avoiding the self-generation of flux, with a flatter toroidal current density profile and consequently a lower inductance, ending up with a higher plasma current value for the same expense of poloidal flux. Finally, the “aided” start-up is obtained at an even higher bias toroidal field. However, in the “matched” and “aided” cases, the low-q states, characterized by strong ideal MHD unstable modes [3] are slowly passed through, giving time to the modes to grow [4]. The net effect is an increase of effective start-up resistivity that, during this phase dissipates most of the toroidal flux. The case for RFX-mod is reported in fig. 1. The final current is increased only slightly with respect to the “ramped” start-up. In addition, the unstable phase exhibits a poor particle confinement, which requires an increased initial filling or robust gas puffing to be sustained. This in turn increases the Hydrogen trapped shot by shot on the graphite first wall, requiring time consuming glow-discharge wall treatments during experimental sessions to recover the density control. In RFX-mod high current operation, the above consideration led to choose a “ramped” start-up with a bias toroidal field as low as possible. A satisfactory value has been found between 30 and 50 mT.

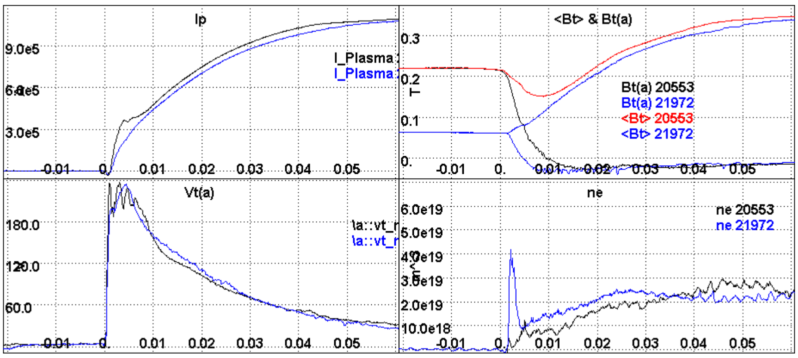
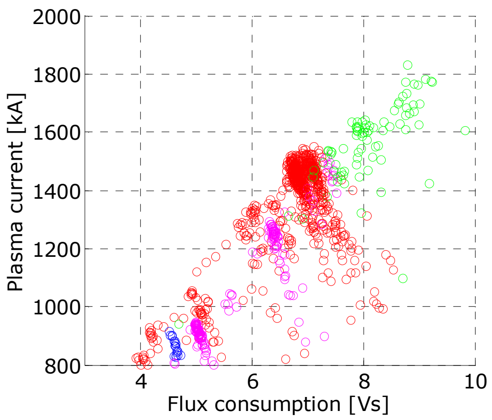
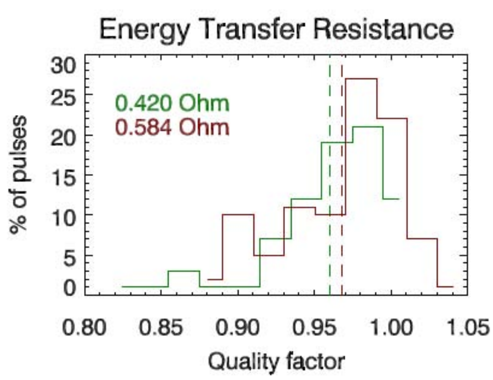


Fig.1. Start-ups with different initial toroidal bias field. Despite the large increase of the bias toroidal field, the final current is comparable.



3. Optimisation of the start-up efficiency. Once the start-up style and the bias toroidal are defined, the plasma current value is basically determined by the amount of magnetic flux stored on the primary winding. The flux is transferred to the plasma by diverting the freewheeling current circulating in the primary winding into the so-called transfer resistors. The applied loop voltage and thus the plasma current rise time can be modulated by changing the resistor values. The choice is basically a trade-off between two conflicting requirements: while a higher resistance maximizes the overall energy transferred to the plasma, on the other hand it increases the power, driving instabilities which increase the energy dissipation, leading to a worse plasma wall-interaction. Since the optimal value was not known, for the sake of safety the initial exploration of RFP at plasma currents higher than 1.5MA was carried out using a rather low transfer resistance (0.420 Ω), which guaranteed a slow ramp-up of the plasma current. Other values of resistance have been tested at 1.5MA to quantify their effect



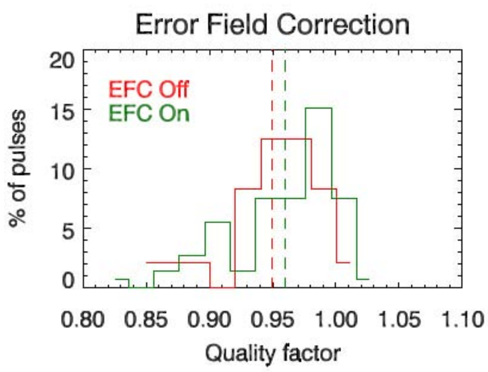


Fig. 3. Quality Factor associated with flat-top current for two transfer resistance.

Fig. 4. Quality Factor distribution with and without error field correction for the same transfer resistance.

on the efficiency. Fig. 2 shows the flux consumption as a function of the flat-top plasma current for different values of transfer resistor. It is clear that the higher is the transfer resistance, the higher is the efficiency of the energy transfer. However, in order to verify whether the slow ramp-up is actually beneficial as supposed to limit the interaction with the wall, the effect of the different transfer resistance on the efficiency has been decoupled using a simplified electrical model of the power supply circuit coupled with the plasma, which gives the typical maximum plasma current expected for different magnetizing currents and transfer resistances. A quality index has been defined by normalizing the experimental plasma current with the model output value and with the magnetizing current. The results are reported in fig. 3 for different transfer resistances. It comes out that there is a slight increase in effective performance with a higher transfer resistance. This effect mainly can be ascribed to the fact that the plasma-wall interaction, associated with the MHD modes during the ramp-up phase, persists for a shorter time, being the mode control system only marginally effective in controlling MHD modes during current ramping.

During the start-up phase the passive metallic structures of the machine gives rise to a non-uniform magnetic boundary with localized error fields. The MHD control system has been used to compensate for such errors, using both feed-forward and feedback compensation [6]. The effectiveness of this compensation scheme has been tested with the same method as before, this time comparing shots with the same transfer resistance and with and without error field correction. The result (fig. 4) shows a slight improvement in the distribution of the calculated quality index.

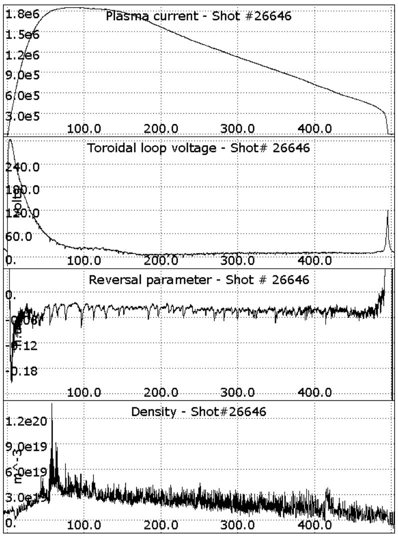


Fig. 5 – Example of plasma shot at 1.8MA.

4. First operation above 1.5MA. The optimisation allowed performing the first RFX-mod discharges beyond 1.5MA. Fig. 5 shows a plasma shot at 1.8MA. A first assessment of the performance has been tried. Optimisation in terms of plasma parameters has not been done, yet. However, good performance has been obtained on some shots, where electron temperature profiles showed high gradients corresponding to a well identified transport barrier. Temperatures as high as 1.2keV have been measured, with density significantly higher than that observed with spontaneous QSH. As a result of the optimisation process, the total number of shots per day above 1.5MA has nearly reached the limit given by the maximum allowed temperature of the magnetizing winding (on the order of ten per day).

The optimisation process carried out so far gave the clear indication that the control of the plasma-wall interaction is the key to improve efficiency and performance. The improvent of the control of the MHD modes at start-up can be an option to further optimise the discharge.

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