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** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

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ABSTRACT

The aim of the PFX Operating Early Task (POET) was to obtain a highly shaped plasma and X-point formation in the early phases of the discharge. The PFX is an amplifier which feeds the central pancakes of the JET primary circuit. In the past it was possible to energize the PFX circuit only when the PFGC current, which feeds all the coils of the primary circuit, was already flowing in the same direction as the PFX current would have flowed, to avoid repulsive vertical forces which would tend to lift the top pancakes of the central solenoid, balanced only by the net weight of the upper part of the JET machine. In this paper the modeling activity performed to provide a more accurate estimate of the ejection forces acting on the upper coils in order to safely widen the operational space, by using two dimensional finite element electromagnetic models and the simulation of the performances of the actual controller algorithm on tracking the desired references of current are described. Finally the results of the implemented POET system, routinely used in JET, in the 2011/12 experimental campaigns, will be presented.

1. INTRODUCTION

The aim of the PFX Operating Early Task (POET) was to obtain a highly shaped plasma and x-point formation (point of zero poloidal field where the separatrix crosses itself) in the early phases of the discharge. This would enable a better exploitation of the machine by increasing the duration of relevant operational scenarios. PFX is a two quadrant amplifier that feeds the six central of the ten pancakes of the JET primary circuit, named P1 central (Fig.1). The remaining two upper and two lower pancakes are named P1 external. Power diodes allow one-directional current flow in the PFX amplifier within the range [0, +35kA], while the whole primary is fed by the Poloidal Flywheel Generator Converter (PFGC) which can drive a current within the range [–40, +40] kA. In the past it was possible to energize the PFX circuit only when the PFGC current was greater than +3kA, delaying the time at which relevant plasma configurations could be formed. This protection was in place to avoid the flow of the currents in opposite direction in the central and external pancakes which would create repulsive vertical forces lifting the top pancakes. The forces on the upper pancakes are overcome only by the net weight of the upper part of JET machine which sits on top of them, estimated to be ≈450 tons. In order to safely enlarge the allowed operational space modeling activity has been carried out to provide a more accurate estimate of the ejection forces acting on the upper coils. For this task the 2D finite element method (FEM) CREATE [1] and ANSYS electromagnetic models of JET have been compared and validated. A series of static reconstructions have been run to assess all the force contributions acting on the components of the magnetic and electric circuits. Fully non linear CREATE models have been employed to run dynamic simulations to take into account the effects of the eddy currents flowing in the passive structures at different iron saturation levels. Finally, simulation evaluated the performances in simulation of the actual JET current controller algorithm on tracking a series of desired curves. A simulator facility, built in the actual JET current controller, was used for this task, which permitted to use the linearized CREATE L state space models of the plant.

2. MODELLING ACTIVITY

The aim of the modeling activity was to obtain an accurate evaluation of the vertical force acting on the primary stack in case of reverse current in the six central pancakes, in order to allow an early energization of the PFX circuit. In a large portion of the achievable current operational space these forces are sufficient to lift the upper part of the stack and magnetic circuit. Two different electromagnetic models have been to quantify the lifting forces with the purpose of establishing a safe operational space: The 2D FEM CREATE [1] model, validated at JET in several years of operations and currently used for plasma shape control and vertical stabilization, and an ANSYS electromagnetic model, developed specifically for this activity Both models can include different non-linear ferromagnetic curves for each part of the magnetic circuit [2]. The force on coils and magnetic circuit were calculated using the Maxwell magnetic stress tensor $\ddot{\sigma}$:

$$F = \oint_S \ddot{\sigma} \cdot dS.$$

In cylindrical coordinates the Maxwell stress tensor can be written as:

$$\sigma_{rz} = \frac{B_r B_z}{\mu_0} - \frac{B^2 \delta_{rz}}{2\mu_0};$$

with B_r and B_Z representing respectively the flux density in the radial and vertical direction, and δ_{rz} the Kronecker delta. Being interested only in the vertical forces, the relation becomes:

$$F_z = \oint_S [n_r \; n_z] \cdot \begin{bmatrix} \frac{B_r B_z}{\mu_0} \\ \frac{B_z^2}{\mu_0} - \frac{B^2}{2\mu_0} \end{bmatrix} dS.$$

The forces acting on the central stack were also validated using the Lorentz force relation

$$F = \int_V J \times B \, dV.$$

Figure 2 shows the components of the magnetic and electric circuits taken into account in the ejection force calculation. For symmetry reasons the vertical forces are evaluated at the interface between the P1 central and external pancakes with the respective magnetic supporting rings. In the magnetic circuit have been considered only the vertical forces acting on the horizontal limb, collar, central piece and supporting ring, while in the electric circuit are considered the P1 external upper pancakes. The vertical force on the horizontal limb is shared between the central core and the outer vertical limb, thus the force is considered to be shared inversely with the area.

3. STATIC RECONSTRUCTION IN POET DOMAIN

Static plasmaless reconstructions have been calculated for the whole POET operational space. The results are shown in the Fig. 3the x-axis representing the current flowing in the P1 external pancakes (IP1E) and the yaxis representing the current in the central pancakes (IP1C = IP1E + IPFX). The vertical force acting on each element of interest have been evaluated and validated using the CREATE and ANSYS models, with the methods described in the paragraph 2, finding a good agreement. A sensitivity analysis was run to take into account model uncertainties, such as the air gaps in the central stack, and the magnetic properties of the materials (for instance the effect of the flux density saturation levels and the collar filling factor due to the presence of cavities). The largest discrepancies were found at low currents (with the iron core not fully saturated) in a safe region of the operational space.

The overall accuracy due to the uncertainties was evaluated within the 5-10%. The worst total ejection force case was chosen to leave a safety margin (Fig.3). A speculative series of plasma equilibria was run to evaluate the effect of the plasma on the vertical force. The ejection force is reduced by the plasma current. The magnitude of the reduction depends on the plasma position and other plasma parameters, such as current magnitude and poloidal field coil configuration. Because the plasmaless case is more demanding in terms of ejection force, it was set as the reference force map. This was done to consider a possible sudden loss the plasma during a disruption event. It was decided to take the 3MN line as safe POET limit.

4. POET DYNAMIC RECONSTRUCTIONS

A fully non linear CREATE model was used to run dynamic open loop simulations to assess the effect of the different iron magnetization levels and the dynamic effects of the eddy currents flowing in the passive structures [3]. The current driven simulations assessed the capability of the non linear model to reproduce the experimental magnetic flux signals when the JET iron is not fully saturated, for a series of specifically designed plasmaless experiments, where only the primary current was energized.

5. CONTROL ANALYSIS

A control analysis on tracking the desired current references was run to evaluate the performances achievable by the actual JET controller of the poloidal field currents, named Shape Controller. This was done by using a built in facility of the Shape Controller system, which allows using a CREATE L [1] linear state space model of the plant. For each simulation several state space models were used; they were obtained linearizing the original non linear problem around relevant point of equilibrium where high non linearity were found, linked to the different iron saturation levels. The control performances have been tested on a list of designed POET relevant plasma and plasmaless current trajectories in the IP1E and IP1C space. These results were used to estimate the safety margin needed due to control error close to the POET ejection force limits. The larger tacking errors were obtained where the iron is not fully saturated. This is due to the fact that the controller matrices used at JET are optimized for the operation with fully saturated iron, which is the normal regime when the high plasma current is present. These errors are mainly due to the strong inductive coupling between P1E and PFX circuit. Finally a fault analysis was run on a fully comprehensive list of possible amplifiers trips, i.e. considering the actual or conservative estimation of the crowbar firing delay and transition time. A safety margin of 10% was judged to be sufficient to take into account the discrepancies for typical IP1E and IPFX current rates around POET limits.

6. POET LOGIC IMPLEMENTATION AND EXPERIMENTAL RESULTS

The implementation of the new control logic that allows opening the POET operational space has been performed within the Plasma Position and Current Control (PPCC) system [4]. The modification had to be within the following conditions:

- the upgrade shall not imply any changes to the current hardware;
- the upgrade shall be designed within the existing code and framework;
- the upgrade shall minimize the changes to current code logic.

The main reasons were that the changes shall not jeopardize the current P1 protection logic and shall maintain the current capability of operating PPCC for negative and positive plasma current. The previous logic included a unique limit, which could assume only nonnegative values, named IP1E_LOWER_LIMIT, which would allow the enabling of the PFX circuit only once the value of the IP1E current was larger than this value, that was typically set to +3kA. In the Fig.4 the POET parameters are shown for a negative plasma current configuration. The new IP1E_LOWER_LIMIT was modified in order to allow a positive or negative sign, to permit to anticipate the tracking of the limit before the primary current has changed sign. A new signed parameter IP1E_ENABLE_POET allows the PFX circuit to be energized after the primary current has crossed the line left to right. If the parameter is set non-negative and equal to IP1E_LOWER_LIMIT the old operational window is obtained. In order to avoid the red POET ejection force limit, the PFX current is restricted between IP1E_ENABLE_POET and IP1E_LOWER_LIMIT to IPFX_POET_LIM.

After the commissioning phase, occurred in 2011during the JET restart program, the new POET operational space has been routinely used allowing for an optimized operation of the machine. Positive results have been achieved in the anticipation of the x-point formation, for typical values up to ≈5s for low triangularity plasmas, increasing the duration of relevant operational scenarios and allowing the earlier achievement of the desired final configurations. A further benefit introduced was the possibility to reduce the initial limiter phase of the pulses, decreasing the heat load limits of the new JET metallic ITER Like Wall. Some of the experimental proposal that took advantage the most of the new POET domain are the fuel retention studies [5], varying durations ratios of divertor-to-limiter configuration, were used for fuel retention experiments and the long term sample retrieval experiment, with a series of 151 identical pulses using POET domain to reduce the initial limiter phase.

CONCLUSIONS

This paper presents the modeling and control analysis for the implementation of the PFX Operating Early Task (POET), aiming at achieving highly shaped plasmas and x-point formation in the early phases of the JET discharge. The modeling activity has been performed to estimate the vertical forces acting on the magnetic and electric circuits to safely open the new operational space. Two different FEM models, the CREATE [1] and an ANSYS model have been employed to estimate these vertical forces. Good agreement of the two models and a sensitivity analysis on the uncertainties of the geometric and magnetic properties of the magnetic circuit allowed to define a safe operational region, which takes into account also the possible faults and relative delays of the corrective actions required by the circuits. A control analysis was run in order to evaluate the actual JET current controller performances using the CREATE model of the plant. The final POET operational space and logic have been implemented and fully commissioned during the restart activity of JET 2011 experimental campaign. Several experiments have used so far the new POET operational space in the 2011/2012 JET campaign, i.e. exploiting the possibility to safely achieve an early x-point formation and allowing to vary with more flexibility the ratio between limited and diverted configurations.

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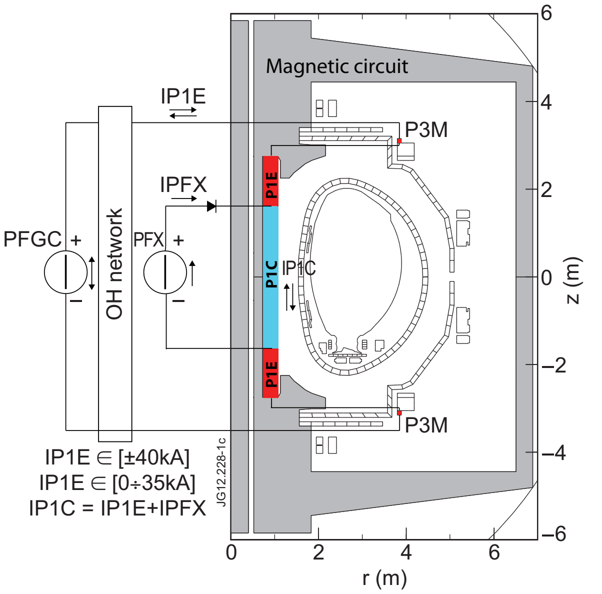

Figure 1: The Poloidal Flywheel Generator Converter (PFGC) feeds the whole primary circuit, while the PFX amplifier only feeds the central pancakes of P1. In light grey it is highlighted a model of the magnetic circuit.

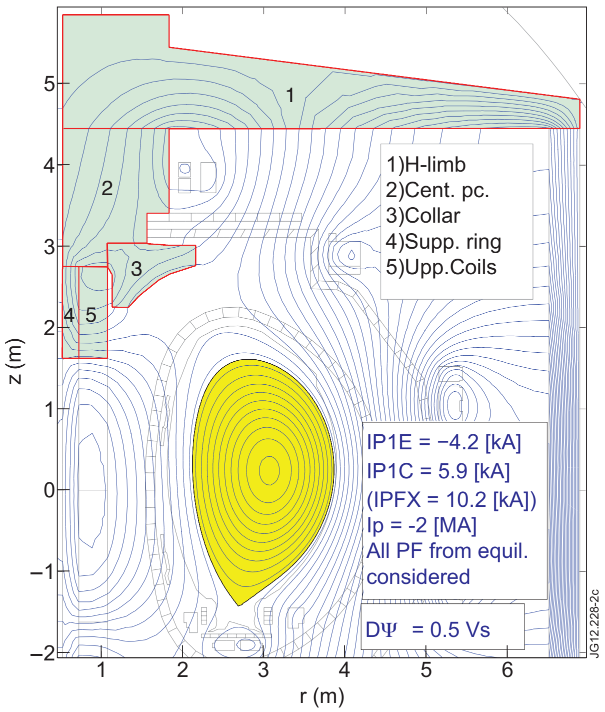

Figure 2: Magnetic flux map reconstruction of a synthetic plasma equilibrium showing the elements taken into account for the vertical force calculation: horizontal limb, collar, central piece and supporting ring (magnetic circuit), and P1 external upper pancakes (electric circuit).

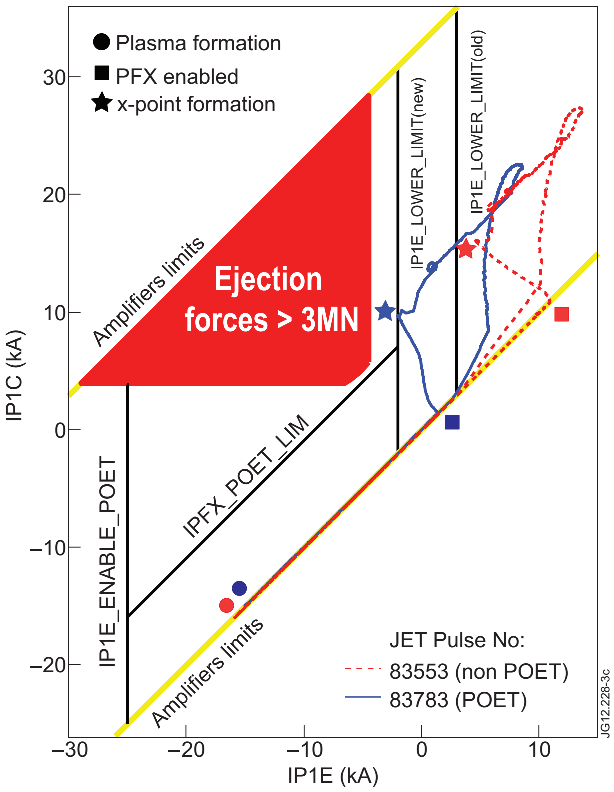

Figure 3: Vertical force map expressed in MN. In the picture are shown also the IP1E and IP1C (=IP1E + IPFX) amplifier limits for positive (red solid) and negative (red dashed) plasma current configurations.

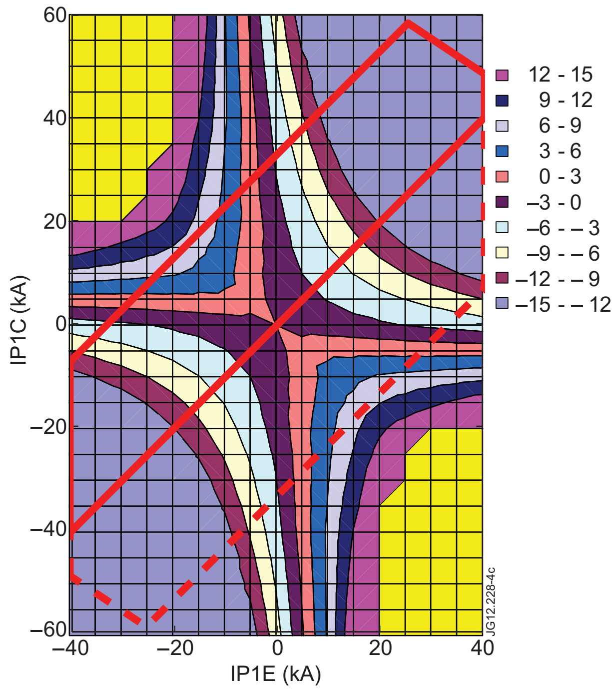

Figure 4: POET logic implementation superimposed on experimental Pulse No's: 83553, and a POET Pulse No's: 83783 traces. In the latter the IP1E_LOWER_LIMIT (new) was set to –2kA and it was possible to anticipate the x-point formation by ~5s.