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A flux control tool to perform single discharge magnetic configuration sweeping at the TJ-II heliac.

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I. INTRODUCTION

One of the aims of the TJ-II flexible Heliac is to study the influence of magnetic configurations on confinement and stability in a wide range of rotational transform values. This requires numerous discharges with different sets of configuration coil currents being established during the heating/fuelling phase. Plasma discharges are not always easy to reproduce, and the comparison between different types of discharges with different kinetic and magnetic parameters is always cumbersome. A alternative approach is to establish a route in the configuration space that can be swept in a single discharge. This has associated induced currents that change rotational transform profiles on a resistive time scale. To avoid this, a set of poloidal field coils arranged to maximize vector potential and minimize magnetic field in the plasma area (the ohmic coils) are used to counteract the flux variation produced by the configuration coils, so the configuration sweeping is performed minimising the induced currents in the plasma [1] [2] . Previous configuration sweeping experiments at TJ-II [2] could only be performed by establishing ramp rates and flat-tops in the configuration and ohmic coils [3] . The control system has been recently upgraded to accommodate arbitrary waveforms in all the coils, giving a full range of new possibilities. This work presents a computational tool to design arbitrary configuration sweeps with minimum induced ohmic current and its application to the design of the latest experiments performed by the newly commissioned system

II. COMPUTATIONAL METHOD

The TJ-II device has 7 coil systems. The coil arrangement and geometry is described in [4] . Six of them are devoted to shape the vacuum magnetic configuration, namely the TF (toroidal) , VF (vertical,) RF (radial) , CC (central) and HX (comprising 2 Helical systems) .

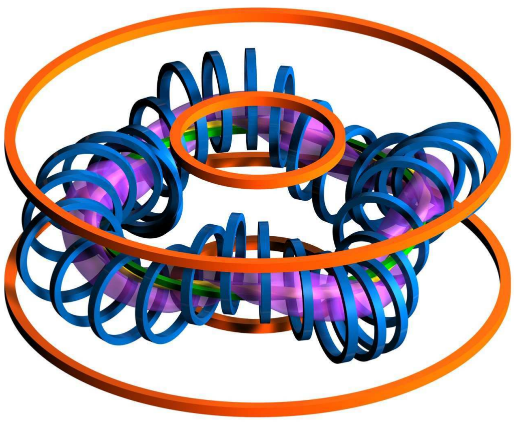

Fig.1 TJ-II coil system. Orange: Ohmic coils. Blue: Toroidal field coils. Yellow: Helical coil. Green central coil. Vertical and radial coil systems sit on the same frame as the ohmic coils.

The seventh system is the OH (ohmic), designed to maximize vector potential and minimize magnetic field perturbation in the plasma region, so its field doesn't perturb the vacuum configuration. The ohmic coil is the primary of a transformer where the plasma is the secondary, and can used to induce ohmic currents in the plasma [5] ,[6] or to compensate voltages in the plasma during configuration sweeps [2] , which is the subject of this work.

All the systems have independent power supplies. Fig.1 shows just 4 sets of coils for simplicity.

At the limit when a three-dimensional current density is reduced to a current flowing in a closed or opened circuit the A,B fields created by these coils are expressed as

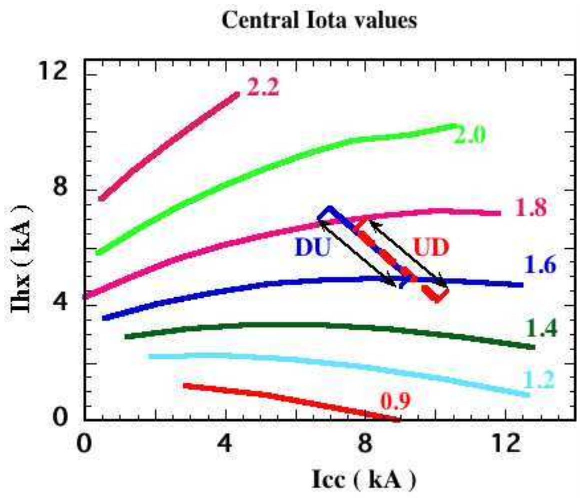

Fig 2 Experimentally tested configuration sweep in the operational diagram. Color curves are iso-iota values at the magnetic axis as function of the configuration currents in the helical (Ihx) and central (Icc) conductors. The blue straight lines labeled DU is the seeping down in iota and then back up again. The red line labeled UD goes up in iota and then down.

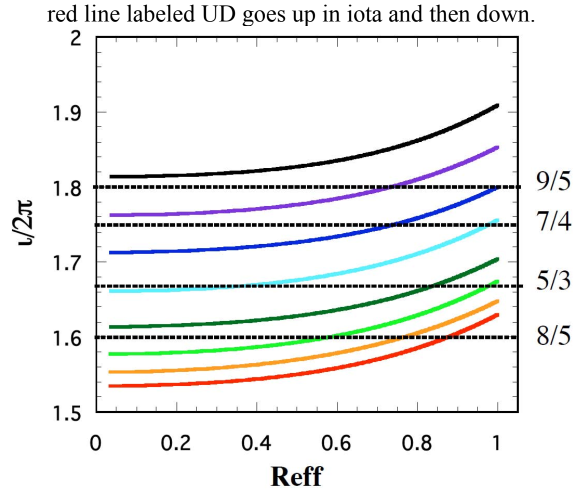

Fig 3 Iota profiles for some of the configuration along the path. Iota values at the center can be compared with those of Fig 2 to associate the profiles to the sweeping trajectory.

$$\vec{A} = \frac{\mu_0 I}{4\pi}\int \frac{d\vec{l}}{r} \qquad \vec{B} = \frac{\mu_0 I}{4\pi}\int r \times \frac{d\vec{l}}{r^3}$$

For the circular coils, the formulae are reduced to expressions in terms of elliptical integrals of the first and second kind [7] . Coils of arbitrary geometry, such as the helical conductor are described by filaments made of hundreds of segments, and a numerically sound Biot-Savart method is used to calculate the fields [8] and from here field lines are obtained by integration of

$$\left(\frac{d\phi}{dl} \quad \frac{dR}{dl} \quad \frac{dz}{dl} \right) = \left(\frac{B_\phi}{RB} \quad \frac{B_R}{B} \quad \frac{B_z}{B} \right)$$

as function of the arc length. A magnetic field line is finally defined by a number "m" of segments of variable length determined by the integration algorithm. The final field line goes N times around the machine axis . The external magnetic flux generated at a magnetic flux surface by the coil system k is obtained from the curl of A as

$$\Phi_j^{ext} = \frac{1}{N}\int \vec{A}_k^{ext} d\vec{l} \cong \frac{1}{N}\sum_1^m \vec{A}_k^{ext} d\vec{l}_j$$

The number of turns N around the machine axis is chosen to be large enough to achieve convergence, typically around 30.
The flux at a given flux surface j produced by the internal current distribution along a magnetic field line i is expressed in a similar way as

$$\Phi_{i,j}^{\text{int}} = \frac{1}{N}\int \vec{A}_i d\vec{l}_j \cong \frac{1}{N}\sum_1^m \vec{A}_i d\vec{l}_j$$

now the magnetic field lines are considered to be filamentary conductors carrying an unknown current , which can be bootstrap, ECCD, ohmic etc.

The surface loop voltage is $V = -\frac{d\Phi}{dt} = -\frac{d\Phi^{\text{int}}}{dt} - \frac{d\Phi^{ext}}{dt}$ In an static configuration,

$V = -\frac{d\Phi^{\text{int}}}{dt} = 0$ as soon as the bootstrap current reaches steady state. In configuration sweeping experiments without compensation, the external flux change due to the configuration coils current sweep will drive a significant voltage, capable of driving a few kA of plasma current. To avoid ohmic current in the plasma, we should try to compensate internal and external flux changes to give a zero voltage profile across the plasma. Being the voltage zero, there is no possibility for ohmic current to develop. Ideally, we should manage

$$\frac{d\Phi^{\text{int}}}{dt} = -\frac{d\Phi^{ext}}{dt}$$

In compensated configuration sweeps, the ohmic coil current is pre-programmed to drive a voltage with similar magnitude and opposite sign to the voltage drive due to the configuration sweep. This can only be attained approximately. If we don't consider the back e.m.f. from the plasma, the voltage profile due to the ohmic coil as function of the flux surface label is almost constant, while the transient voltage profile due to configuration sweep is a parabolic shaped profile with a factor of two difference between axis and boundary (see Fig 4). Then, the criteria for compensation is not exactly defined. Should we aim for compensation at the axis, at the LCFS, or somewhere in between? . To simplify the calculations the mutual inductance between the kth coil system and the ith flux surface is calculated as

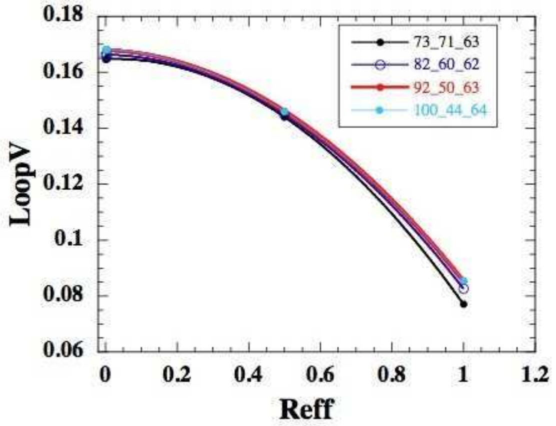

Fig 4 Surface voltage profiles induced by a configuration sweep for several configurations along the sweeping trajectory.

$$M_{k,j} = \frac{\Phi_k^{ext}}{I_j}$$

Typical values for the mutual inductances between the all coil systems and the magnetic axis for an standard configuration are shown in the table below .

	Toroidal	Central	Helical	Vertical	Ohmic	Radial
M (μH)	6	87	105	58	28	0

The actual algorithm is in fact quite simple. Given a ramp rate variation for all the coil systems, the ramp in the OH system (index as k=1) is calculated as

$$\frac{dI_1}{dt} = -\frac{1}{M_{1,axis}} \sum_{k=2}^{7} M_{k,axis} \frac{dI_k}{dt}$$

For a discrete number of configurations along the configuration sweep, the mutual inductance between the coil systems and the plasma is calculated as function of the flux surfaces. From here, a current waveform for the ohmic coil is generated by time integration of the OH ramp rates. Given the uncertainty on the internal flux provided by bootstrap current, mutual inductance values at the axis are sufficient to design the ohmic coil drive.

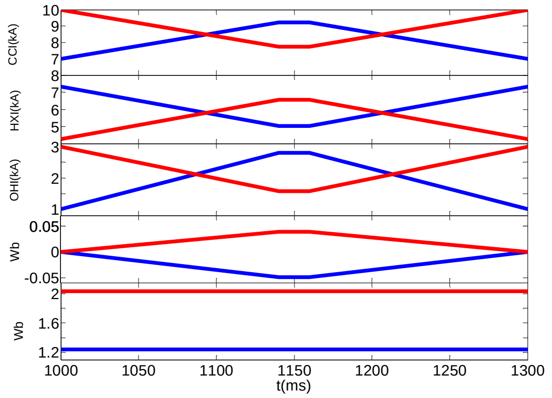

Fig 5 Pre-programmed currents for the configuration sweep and resulting fluxes. From top-down are shown the central conductor current, the helical conductor current and the ohmic coils current, the flux change introduced by the sweep and the total flux after compensation with the ohmic coil. Blue and red traces are the DU and UD sweeps.

III. FAST CONFIGURATION SWEEP DESIGN

Two symmetrical configuration sweeps with large coil current variations are designed. The down-up (DU) sweep goes from iota values of 1.9 at the LCFS to 1.65 in 100ms. Then, stay at a fixed configuration for 20ms, and back to high iota in another 100 ms. The up-down (UD) sweep is the exact symmetrical of the former. All this is done while maintaining a constant plasma volume of $1m^3$. The location of the sweep in the operation diagram is shown in Fig 2 . Sweeps are started some time earlier to give time to the plasma density to settle. The

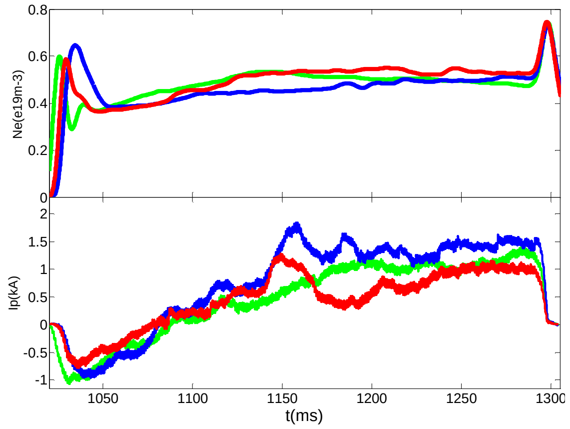

Fig 6 Density and plasma current for reference (green) , DU scan (blue) and UD scan (red) .

overlapping region is the region of interest. The associated iota profiles for some of the configurations along this sweeping trajectory are show in Fig 3. The currents in the configuration coils change at rates of 10 kA/s , enough to drive plasma currents in excess of 5 kA if no compensation is used. Fig 4 shows a typical voltage profile induced in a typical configuration sweep for several configuration transits. The voltage at the axis is typically a factor of two the voltage at the LCFS. In contrast, the ohmic coil induces an almost constant voltage profile. Fig 5 shows the calculation for the DU and UD scans. Compensation at the magnetic axis is not completely symmetrical as intuitively expected. This is due to the fact that the ohmic coil introduces an small field component, which modifies slightly the vacuum configuration.

IV. EXPERIMENTAL RESULTS

To test the capabilities of the newly commissioned sweeping system a series of discharges along the DU and UD trajectories were performed. Using the flux control tool, the ohmic coil current ramp rate was estimated between 10-12kA/s to achieve compensation at the magnetic axis. The final OH ramp rate (9kA/s) was fine tuned to give a plasma current similar to the reference discharge in both DU and UD scans (see Fig 6). Being this ramp rate slightly lower that the necessary to achieve null voltage at the magnetic axis, we conclude that the compensation criteria should be established for some flux surface inside the plasma (see Fig 4) , but close to the magnetic axis. The resulting net ohmic current estimated from the difference with reference case, appears to be negligible during the first cycle of the sweep (1000ms-1150ms) , and at the end of the second (1250-1300), but there is evidence of small ohmic current transients due to the sweep inversion.

V. CONCLUSIONS

A computational tool to design configuration sweeping experiments have been developed. Given a set of coil current waveforms, it generates coil currents for the ohmic coil to cancel the surface loop voltage at any desired flux surface. With this tool, the design of sweeping experiments is greatly simplified. The TJ-II control system has been recently upgraded to accommodate arbitrary waveforms in all the coils. A fast direct-reversed sweeping experiment changing iota profiles by 0.2 in 100 ms has been successfully designed and carried out to have negligible net ohmic current. This demonstrates the robustness of the technique.

VI. REFERENCES

[1] Blackwell B. D. et al.14th International Stellarator Workshop, Greifswald, Germany, September 2003, P.We21
[2] D.Lopez-Bruna et.al. 22nd IAEA Fusion Energy Conference. Geneva, Switzerland 2008.
[3] A. de la Peña et al. 25th Symposium on fusion technology. Rostock, Germany 2008.
[4] C. Alejaldre. et.al. Fusion Technology 17,131(1990)
[5] J.Romero et al. Nuclear Fusion 43 386 (2003)
[6] D.Lopez-Bruna et.al. Nucl. Fusion 44 645 (2004)
[7] K. Miyamoto. Plasma physics for nuclear Fusion. MIT press 1980.
[8] S.Hanson, P. Hirshman, Phys. Plasmas 6, 1532 (1999)