Impact of current density profile on quasi single helicity equilibria in RFX-mod

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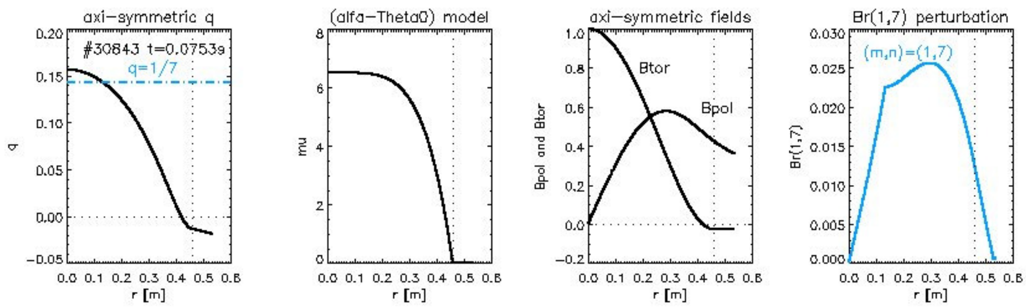
SHAX states and *laminar* dynamo. SHAx (Single Helical Axis) states are the self-organized helical states developing during high plasma current Reversed Field Pinch (RFP) discharges. The helical deformation arises due to the dominance in the MHD spectra of the innermost resonant mode, which in RFX-mod is the m=1/n=7 mode (where m is used for the poloidal mode number and n for the toroidal one) [1]. A dynamo process is always acting in Reversed Field Pinch (RFP) plasmas, in order to provide the reversal of the toroidal magnetic field through a velocity field **v**. In the standard view of the RFP configuration the dynamo term is the non-linear (**v**×**B**) term in the averaged parallel Ohm's law, understood as the effect of perturbations to the axi-symmetric fields. One mode of the perturbation could be enough to sustain the dynamo: in this case the necessity of a dynamo can be understood as the necessity of a helical deformation of the whole plasma column, and the flow **v** can be thought as an electrostatic drift due to a current density modulation along the helical magnetic field lines (electrostatic view) [2]. We call laminar or Single Helicity (SH) states plasma configurations where just one mode of the perturbation is present, in contrast to Multiple Helicity (MH) states where many MHD modes are present in the perturbation. In any case, the field reversal is a consequence of the loss of the axi-symmetry of the system: this is known (in astrophysics) as the Cowling's theorem, for which no dynamo can sustain an axi-symmetric RFP.

The SHEq code. The SHEq code is an equilibrium code used to model plasma quantities in helical states [3]. It adopts a perturbative approach, superposing to an axi-symmetric equilibrium a single Fourier mode resulting from the solution of a Newcomb-like equation consistently with experimental boundary conditions. We therefore use pure SH states to model SHAx states, neglecting the so-called secondary modes which are still present in the configuration with small but non-zero amplitude. By default the axi-symmetric (force free) equilibrium reconstruction assumes a $\mu = J_{//}/B$ profile given by a two parameters model, $\mu = 2\Theta_0\left(1 - x^{\alpha}\right)/a$, where α and Θ_0 are adjusted as to match the experimental pinch and reversal parameters, and x stands for the radius normalized to a=0.459m. As an example of the axi-symmetric equilibrium field reconstruction see the curves in fig.1. In the Newcomb-like equations (for the reconstruction of the MHD eigenfunctions) the force free condition is considered, together with a curvilinear metrics [4]. In fig.1d the reconstructed profile of the dominant mode (m=1/n=7) is plotted, as a perturbation of the equilibrium in fig.1a-1c. The discontinuity in its shape is in correspondence of the resonance of the mode. Using a perturbative approach in order to model helical states we are in particular able to reconstruct the safety factor profile during the helical SHAx states. This is done using action-angle coordinates following a Hamiltonian approach, and the typical shape of the helical safety factor can be seen in fig.2a: differently from the axi-symmetric q-profile (fig.1a) it is not monotonic, featuring a maximum in correspondence to an Internal Transport Barrier (ITB), [5]. The origin of the axis in the figure corresponds to the helical axis, and we use the symbol ρ to label the helical flux surfaces.

Fig.1 #30843 t=0.753s . Axi-symmetric equilibrium quantities



The ohmic constraint. The equilibrium system of equation that is solved for SHEq does not account for Ohm's law. Considering SHAx states as stationary equilibria one can derive the ohmic constraint: $V_t\langle B^{\varphi}\rangle/(2\pi)=\eta\langle J\cdot B\rangle=\eta\mu\langle B^2\rangle$, where the Spitzer resistivity η is considered as a flux function and the loop voltage V_t is constant; both the magnetic field and the current density are made of an axi-symmetric part plus the m=1/n=7 perturbation and the averages are done over the helical magnetic flux surfaces. If the modelled equilibrium is consistent with Ohm's law, this relation must be valid on each flux surface: as one can see in fig.2c, this is not the case for SHEq equilibria. Using the definition $\mu=J_{//}/B=\langle J\cdot B\rangle/\langle B^2\rangle$ it is possible to compute the non-ohmic helical μ profile, plotted in black in fig.2b, from the SHEq code. On the other hand one can assume the ohmic constraint to be valid and therefore compute the ohmic helical μ profile as: $\mu\_ohm=V_t\langle B^{\varphi}\rangle/(2\pi\eta\langle B^2\rangle)$. This is plotted in orange in the same fig.2b. As one can see the ohmic profile exhibits a steep gradient in correspondence of the thermal ITB (fig.2d), which is not the case for the non-ohmic profile: the SHEq code reconstructs the magnetic topology of helical states without any information on the temperature profile, but starting from the α-Θ_0 model assumed for the axi-symmetric zeroth-order parallel current density profile (fig.1b). An extended version of the code allows the use of any μ profile to model the axi-symmetric equilibrium. We therefore explore the effect of different current density profiles on the resulting helical magnetic topology.

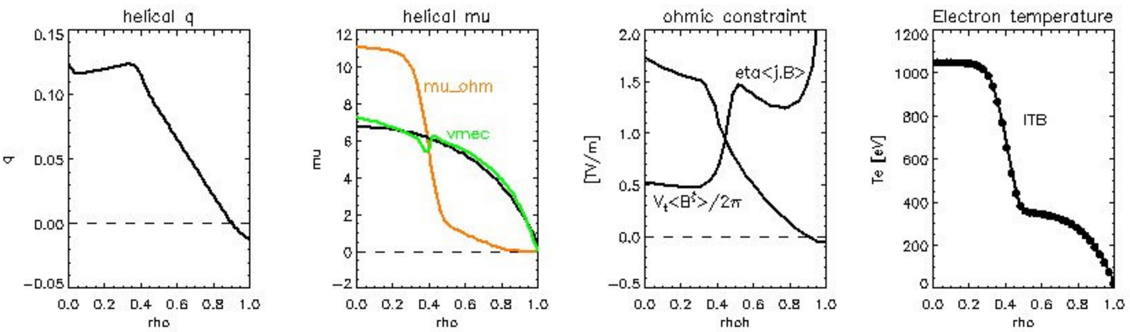
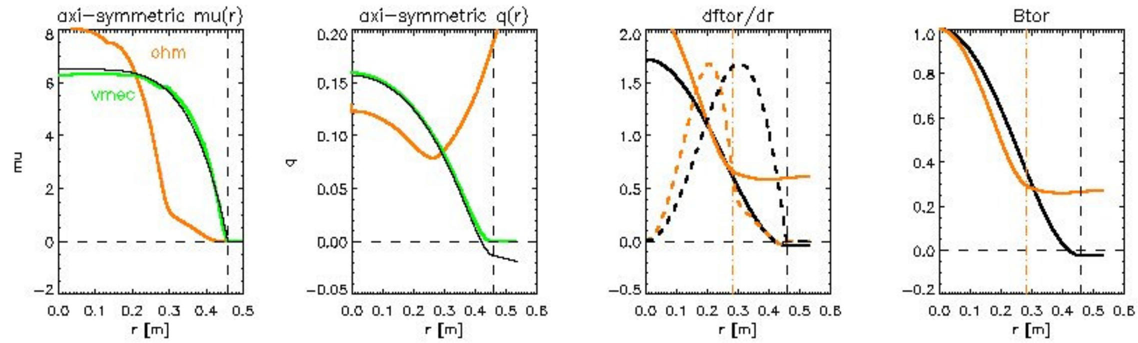


Fig.2. Helical equilibrium quantities computed by the SHEq code. Temperature profile from Thomson scattering

Axi-symmetric current density profiles. Using the helical q-profile computed with the SHEq code (fig.2a) as an input it is possible to run the VMEC code for RFP equilibria. VMEC does not account for the Ohm's law, and it converges very close to SHEq equilibria even if a non-zero pressure gradient compatible with temperature measurements is set. The non-ohmic helical μ profile from the VMEC code is plotted in green in fig.2b. In order to choose an axi-symmetric μ profile related to the helical geometry of the SHAx state (instead of the one coming from the α-Θ_0 model), we can use this helical μ profile averaged on the circular cross-section of the shifted axi-symmetric equilibrium. The remapped profile can be seen in green in fig.3a, together with the remapped ohmic μ profile, in orange. 1. VMEC equilibria. To model the axi-symmetric equilibrium we use the green parallel current density profile in fig.3a, which is related to the helical equilibrium obtained from VMEC. The black curves in fig.3a-3b are related to the α-Θ_0 model of the axi-symetric equilibrium (also plotted in fig.1a-1b). As one can see, the green curves are very similar to the black ones, with the difference that we obtain just a marginal reversal of the q-profile (green in fig.3b): even in an iterative way we are not going to peak the current density profile in order to approach the ohmic profile. 2. Ohmic equilibria. In order to look for an ohmic equilibrium, we start from the ohmic helical μ profile, remapped and averaged on the circular flux surfaces of the axi-symmetric equilibrium (ohmic equilibria always in orange in the figures). As one can see in fig.3b the related equilibrium does not reverse and this is due to the steep gradient in the μ profile. In fig.3c are plotted the two components of the equation for the radial derivative of the toroidal flux (see eq.(A.50) in [4], which comes from the force-free force balance equation together with the Ampere's law): in order to have the reversal of the toroidal field at the edge (fig.3d) the dashed line in fig.3c should always be over the solid one at the edge. While this is true for the α-Θ_0 model (in black), it is not for the not-reversed 'orange' equilibrium. 3. Some more parametrization. Some parametrizations of the μ profile between the VMEC (green lines) and the ohmic one (orange lines) have been tried. In order to have the reversal of the axi-symmetric equilibrium (in agreement with experimental value) we need to have a less steep gradient and/or to higher the value of the current on the axis. But this leads to the loss the resonance of the dominant m=1/n=7 mode in reversed configurations.

Fig.3. #30843 t=0.753. Study of the effect of different current density profiles on the equilibria



Conclusions. In order to comply with the ohmic constraint the improved confinement properties of SHAx states must be associated to peaked current density profiles, with respect to the Multiple Helicity (chaotic) states. But we could not find any current density profile which is in agreement with both the ohmic constraint (assuming a Spitzer resistivity) and the experimental reversal parameter (that indicates a reversed axi-symmetric equilibrium). A limitation in this study is the fact that VMEC cannot work using the (peaked) current density profile in input. Further work can use V3FIT instead of VMEC in order to take into account the temperature profile. At this moment we can just conclude that a dynamo process is still acting in our plasma during SHAx states, and we are not able to extract more information on the shape of the current density profile in pure SH ohmic states. Reminding that the ohmic constraint is true only for stationary equilibria, we can conclude that an inductive term in the electric field must be present, and probably due to the presence of non saturated MHD modes.

References

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