MHD stability and symmetry breaking

The minimum energy state is obtained in the range $ \beta = 0.5\% - 5.6\%$. The initial guesses for the $\beta$ that yield the minimum energy states at each $\beta$ are identified in the figure. At $\beta = 0.5\%$ corresponds to the difference between $r_{\text{P}}(\theta) = 0$ evaluated at finite $\beta$, and $\beta = 0$. The ordinate values $D$ indicating that the volume averaged total plasma energy is lower at finite values of $\beta$ (on the range of $\beta$: explored).

For $\beta = 5\%$, the most stable values appear for finite values of $\beta = 0.28\%$ and $0.3\%$. Eddy currents in the vacuum chamber produce periodicity-breaking perturbations that can be enhanced by linear MHD instability dynamics (the system investigated is unstable to linear ideal MHD modes when $\beta > 0.6\%$). This justifies increasing $\beta$ with $\beta$.

Properties of the new configuration

In current-free stellarators, MHD instabilities driven by the interaction of the pressure gradient with the magnetic field line curvature. The relevant function is $2\nu_{\text{g}}(\nu_{\text{s}})$. $2\nu_{\text{g}}(\nu_{\text{s}})$ calculated for $\beta = 0.5\%$ Top row: perturbed configuration ($n=1$ distortion). Bottom row: periodic configuration.

Structure of $2\nu_{\text{g}}(\nu_{\text{s}})$: $\nu_{\text{s}}$ on flux surfaces close to LCSFs:

- Strong change from the periodic to the perturbed configuration.

- The most destabilising contribution (most negative) concentrates near the outside edge of one of the bean-shaped cross sections indicating an important $n = 1$ distortion.

- The structure when the 4-fold periodicity is relaxed is more closely magnetic field aligned.

- The range of values for $2\nu_{\text{g}}(\nu_{\text{s}})$ is neutral (with respect to positive and negative values) when the periodicity constraint is relaxed indicating marginal stability. However, it tends to be more negative when the 4-fold periodicity is enforced suggesting that this configuration is linearly unstable to ideal MHD, a condition we have confirmed with the TERRIICORE code [6].

- The periodicity-breaking deformations constitute a saturated ideal MHD instability state.

The Helias reactor configuration examined approaches conditions of quasi-isodynamicity [7]. The poloidal closure of the contours of the 2nd adiabatic invariant $J$ in a polar plot for trapped particles imply the good NC confinement of fast and bulk ions.

The estimated rotational transform profiles (h) for the Helias reactor configuration for $\beta = 0.5\%$ and $\beta = 5\%$. $i = 3$ is outside the plasma, the main low order resonances that break the 4-fold periodicity of the coils are n=m=10/11, 9/10, 7/8, 6/7 and 5/6. Shapes of the LCSFs for the Helias reactor at each of the eggplant cross sections throughout one toroidal transit for $\beta = 0.5\%$, 2\% and 4\%. There are small but visible deformations. The LCSFs at the bean, eggplant and triangular cross sections over 1 toroidal transit at $\beta = 5\%$. A small corrugation of the edge surface appears.

The mid plane pressure distribution for $0.5 \leq \phi \leq 2\pi$ at $\beta = 5\%$. The bulk plasma retains the underlying 4-fold periodicity of the system, while a small $n = 1$ modulation is visible close to the edge.

MHD activity can alter the symmetry properties of magnetic plasmas. The 3D equilibrium solver VMEC [1] has been applied to model the breaking of the axisymmetry in RFPs [2] and tokamaks [3]. In stellarator experiments, very-long-lasting oscillations characterized by low $n$ and $m$, which break the periodic symmetry, have been detected in many devices like the T-J-II Helias [4] and the Large Helical Device (LHD) [5].

**SYMMEtRY BREAKING BY MHD**

**MHD STABILITY AND SYMMETRY BREAKING**

**PROPERTIES OF THE NEW CONFIGURATION**

**CONCLUSIONS**

Long-lived low frequency oscillations with $n$ smaller than the machine periodicity detected in stellarators such as T-JII. We report, for the first time, free boundary VMEC stellarator equilibria with 3D distortions to the LCSFs that break the ORIGINAL periodicity.

- The Fourier spectrum of $R$ and $Z$ at the LCSFs is dominantly $m = n = 1$ at $\beta = 5\%$. The $m/n = 1/\pm 1$ structures are nonresonant as $\alpha_{\text{res}} < 0.95$.

- We contend that these geometric deformations correspond to saturated ideal MHD interchanges.

- The $2\nu_{\text{g}}(\nu_{\text{s}})$ structure confirms a $n = 1$ modulation around the torus.

- The quasi-isodynamic properties of the Helias configurations are not significantly altered.

- FAVOURABLE conditions for the Helias stellarator as reactor.

The relaxation of the periodicity does not modify significantly the contours of the $J$ for different particle pitch angles ($\beta$ = 5\%). Energetic particle confinement and NC transport should not be seriously impacted when periodicity is broken.

**We contend that the deformations observed constitute nonlinear saturated ideal MHD interchange structures with low n driven by the interaction of the pressure gradient with the magnetic field line curvature.**

**3D free boundary ideal MHD VMEC-equilibrium calculations in a nominally 4-field period Helias reactor including edge distortions that break the periodicity imposed by the coil system.**

**FINDING: Configurations with broken symmetry are more stable than the symmetric ones.**

**MHD CALCULATIONS**

Computation of 3D MHD equilibrium states with the VMEC code imposes nested magnetic flux surfaces [1] without magnetic field lines breaking and reconnecting // ideal MHD. A 4-fold periodic Helias reactor configuration has been chosen because the spectrum of modes required is much narrower than that of T-JII Helias. Furthermore, the Helias configuration represents one of the most attractive concepts for stellarator reactor. The plasma energy is given by

$E = \int \delta \beta \; d^3 \mathbf{r}.$

The equilibrium state is obtained by varying the energy functional with respect to an artificial time variable employing a steepest descent energy minimization scheme. We allow the 4-fold periodicity breaking by including two toroidal mode numbers in the range $-20 \leq n \leq 20$ and poloidal mode numbers $0 \leq m \leq 11$. The 4-fold periodic Fourier components of $R$ and $Z$ at the LCSFs are $R_{\text{C}}(n,m) = 17.7\beta$, $\delta_{R_{\text{C}}} = 0.72\beta$, $\delta_{\beta_{\text{R}}} = 2.15\beta$, $\beta_{\text{C}} = 0.99\beta$, $\delta_{\beta_{\text{C}}} = 0.33\beta$, $R_{\text{g}} = 2.44\beta$, $\delta_{R_{\text{g}}} = 1.33\beta$ (all in $\beta$).

**Edge periodicity-breaking introduced through $\delta_{R_{\text{C}}} = \delta_{\beta_{\text{C}}} = 0$, and $\delta_{R_{\text{g}}} = \delta_{\beta_{\text{g}}} = -\delta_{g}$.**

**Null toroidal current ($\delta_{g} = 0$ and plasma profile $\beta(\phi) = \beta(0)[1-2/(1+\phi^4)]$.**

- $\nu_{\text{res}}(h) = 1.25\%$, $\nu_{\text{res}}(g) = 0.8\%$, $\nu_{\text{res}}(\text{c}) = 0.4\%$.

Shapes of the LCSFs for the Helias reactor at each of the eggplant cross sections throughout one toroidal transit for $\beta = 0.5\%$, 2\% and 4\%. There are small but visible deformations. The LCSFs at the bean, eggplant and triangular cross sections over 1 toroidal transit at $\beta = 5\%$. A small corrugation of the edge surface appears.