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A DEMO Relevant Long Leg Divertor with External Poloidal Field Coils

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It is accepted that plasma exhaust is a major challenge for DEMO and future power plants and the reference approach is to use a design similar to JET and ITER. There is not yet full confidence this will extrapolate successfully and be compatible with a maximum power flux of 5-10 MWm-2 on the Plasma Facing Components.
Detachment provides an attractive solution to the power exhaust problem, radiating power across a large area within the divertor and reducing ion energies below the sputtering threshold of the tungsten targets. Extension of the outer target to a large radius reduces power flux flowing along the divertor leg, diluting the detachment threshold to values compatible with the core. The reduction in power flux with increasing radius also provides a stabilising mechanism for the location of the detachment fount.

Scaling the long leg concept up to DEMO relevant machines is often considered impractical due to either excessive loading on coil sets external to the TF or due to the requirement for in-vessel coils. Feasibility of a long leg divertor concept is demonstrated here for a 20.3MA DEMO relevant machine using a set of five PF coils placed external to the TF cage. The outer strike point is extended to 1.5 times the X-point radius without significant modification to the shape of the separatrix. Force, current density and placement constraints are respected across a flat top flux swing of 363Vs.

The long leg concept requires a TF coil with a circumference 22% greater than the reference configuration. The gain in size of the coils and associated structures will undoubtedly increase their cost. However, foreseen ancillary benefits should likewise be considered. These include a reduction in ripple, perhaps enabling a 16 coil configuration, and a reduction in the complexity of remote maintenance schemes.

Keywords: divertor, long leg, detachment, super x, Grad Shafranov, optimization, DEMO

Introduction

The Super-X divertor exploits the dependence of SOL parallel heat flux on toroidal field strength to decrease outer target heat loads. Additional power reduction mechanisms related to increased SOL radiation and detachment may also be assessable by long leg divertors, the experimental conformation of which is anticipated in future MAST-U campaigns.

A configuration study of the Super-X divertor concept applied to a 20.25MA DEMO plasma is presented using a PF coil set placed solely external to the TF coils. Increasing the radius of the outer target reduces SOL heat flux as $1/R_{target}$. It is anticipated that a target expansion $R_{ex}=R_{Xtarget}/R_X$ of at least 1.5 is necessary to offset the increase in the complexity of the Super-X design. The present work aims for an outer target radial expansion of at least $R_{ex}\geq 1.5$ whilst meeting all high level engineering and plasma shape constraints imposed by PMI.

Constraints

The design of a long leg divertor is subject to a number of constraints placed on plasma shape, coil placement and coil loads. These constraints are continually evaluated at the ends of the 363Wb flux swing. Once a viable solution is identified then compliance with the constraints is checked across the whole swing.

1.1 Plasma Shape

Plasma shape parameters are taken from the SN reference created within the DTT1 AC-3 subtask. The target seperatarix is extracted directly from the SN reference equilibrium. A series of 31 colocation points are spaced equidistantly around the normalized 0.9999 Ψ contour. The X-point is located via the specification zero field (B_r=0 and B_z=0) at the desired location. The outboard target is located at a radius of 10.5m where an additional colocation point is placed. Values of Ψ and field line angle are specified at all colocation points to produce the desired seperatarix and divertor leg shape. An extended SF+ topology is maintained via the specification a field line angle of -25° to the horizontal at the outer strike point. A high degree of control over field line angle at the target is important as, for highly angled targets, errors here will lead to large variations in target normal heat flux. The field line angle constrain placed on the outer leg also prevents this leg from 'flicking' downwards through the lower secondary null.

In all 66 constraints are used to define the seperatarix and outer leg shapes. All constraints are weighted by the inverse of the constrained variables field line normal derivative to ensure that error in each constraint translates directly to placement errors in physical space.

1.2 Force Limits

The following force limits imposed by PMI are respected during the optimization the configuration: maximum vertical force acting on each PF coil < 450MN; total vertical force acting on central solenoid < 300MN; and maximum separation force acting on central solenoid pre-compression structure < 350MN

1.3 Coil Placement

All PF coils are placed solely external to the TF coil. Flexibility in PF coil number is retained as a design variable with the preference for viable configurations comprising the least possible number of coils. The curved boundary of the TF coil defines an outer 'track' around which the PF coils may be placed.

The shape of the TF coil is dictated by the position and thickness of internal structures such as the vacuum vessel and blankets. These structures are built outwards, initially normal to the first wall and then normal to the last defined structure. Once constructed, the outer extent of the internal structures form an internal boundary around which the TF coil must wrap. The TF coil is assumed up-down symmetric and is defined by four line segments; one vertical line for the inboard segment and three tangential arcs with poloidal extents of 40, 70 and 65 degrees for the outboard leg. The TF coil geometry is parameterized by the radial and vertical position of the inboard mid-point, the length of the vertical segment and the radii of the three concentric arcs. This parametric description is passed to a Sequential Least SQuares Programing SLSQP optimiser with the objective of minimizing the length of the TF coil.

To ensure compatibility between the TF and PF coil volumes each PF coil is displaced a small distance away from this boundary. The cross-section of each PF coil is sized to respect a 12.5MAm^{-2} current density limit based on the maximum current recorded across the central solenoid swing. The position of each PF coil around the curved sections of the TF coil 'track' is parametrised as a normalised length and passed to the coil placement optimiser as free parameters. An additional compatibility condition on PF placement is applied requiring a minimum separation between each coil to ensure that no two PF coils occupy the same volume.

The central solenoid stack is composed of four independent sections. The stack is specified with a radial thickness of 1.25m. The overall length of the stack, relative lengths of each coil and vertical position of the stack are all passed as free parameters to the coil position optimiser. A current density limit of 12.5MAm^{-2} is enforced via a current limit placed on each CS coil during the optimisation cycle.

Optimization routine

Optimization of both coil currents and coil placement is achieved via a twostep 'nested' procedure. An outer loop optimizes the coil placement using the COstrained BY Linear Approximation method COBYLA whilst an inner loop solves for coil currents using the SLSQP procedure.

The objective of both the coil current and position optimisers is to minimize the weighted least squares error between the specified and returned values. The least squares error is assessed at both ends of the 363Wb flux swing.

Results

The present study demonstrates that a Super-X configuration using a PF coil set placed solely external to the TF coils is feasible. Figure 1 shows the SX configuration at the mid-point of a 363Wb flux swing. Plasma shape and divertor leg positioning is maintained with 5 PF and 5 CS coils.

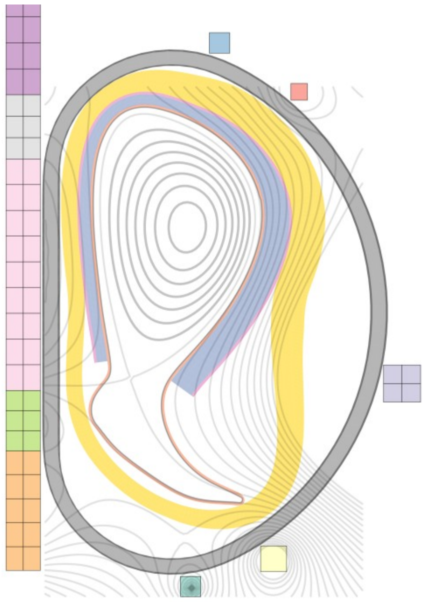

Figure 1 The Super-X configuration at the mid-point of an 363Wb flux swing. Structures shown outwards from the separatrix: the first wall, blankets, vacuum vessel, TF PF and CS coils. Diamonds indicate colocation points.

Maximum vertical loads on the PF coils are maintained well below the PMI limits for the duration of the 363Wb flux swing. Figure 2 illustrates vertical force profiles for the PF coil set along with total and separation forces for the CS. The maximum vertical force in the PF coil set occurs at ~700Wb into the flux swing. This load of 250MN is well within the PMI force limit of 450MN. The maximum CS separation force is observed approximately half way though the swing with a value of 250MN which is again comfortably within the 350MN PMI limit. The largest vertical load observed is the total force acting on the CS stack. This load is constrained to the PMI limit of 300MN.

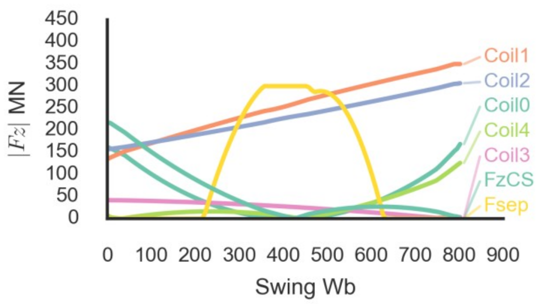

Figure 2 An illustration of vertical loads acting on the PF coils (Coils 0-3) along with the total vertical load on the CS stack FzCS and the CS separation load Fsep.

Figure 3 illustrates current profiles for the PF coil set. A large current of ~20MA is required by Coil1. This is due to the large radial positioning of this equatorial coil dictated by the TF shape (Figure 1). Movement away from a 'Princeton-D' type TF towards a profile more closely conformal to the vacuum vessel could, if necessary, reduce this large current. Currents for the remaining three PF coils are reasonable for a machine of this scale and vary linearly by ~10MA across the swing.

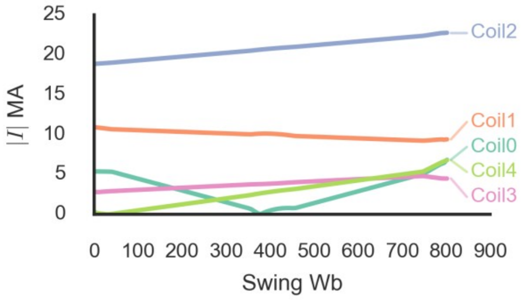

Figure 3 Current profiles for the PF coil set.

The reference separatrix use in this study is extracted from the SN equilibrium. Plasma shape compatibility is therefore judged with respect to this reference rather than the PROCESS shape parameters. A good agreement is demonstrated with all the Super-X plasma shape parameters lying within 5% of their targets. The largest difference is observed for upper triangularly with an error of 4.3%. All the remaining parameters calculated to within 1% of their targets.

Figure 4 demonstrates that a reasonable fit to the reference plasma is maintained across the swing. Further work is however needed in shaping the upper sections of the plasma and first wall as adequate separation is not maintained in this area throughout the swing.

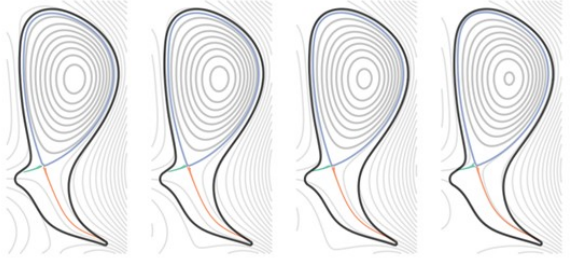

Figure 4 A sequence of equilibrium profiles for the Super-X configuration across an 363Wb flux swing (black: first wall, blue: separatrix, green: inner leg, orange: outer leg). Webber flux values are shown at the top of each subplot.

Whilst the overall shape of the outer leg is maintained a variation of ±0.42m in the placement of the strike point is observed. In addition to translational movement, the poloidal angle of the strike point is also mobile with an error of ±0.05°. At small angles, this error in field line angle would translate proportionally to large fluctuations in target normal heat flux, wiping out any savings realized by radial expansion of the SX divertor.

Conclusions

A configuration study of the Super-X divertor concept demonstrates the feasibility of this topology for a DEMO scale machine using a PF coil set placed exclusively external to the TF coils. The main features of the SX design are summarized as follows: plasma shape maintained throughout an 363Wb flux swing; configuration feasible using 5 PF coils and 5 CS coils; maximum vertical force on PF: 250MN,within 450MN limit; maximum vertical force on CS stack: 300MN, equal to 300MN limit; maximum separation force on CS stack: 250MN, within 350MN limit; the TF coils for the SX divertor are 49.8m long with an enclosed volume of 10013m3; The SX TF coil is 27% longer than the SN reference. The outer target strike point is shown to move by ±0.42m. In addition to translational movement, the poloidal angle of the strike point is also mobile with an error of ±3.5°. Control of the outer target field line angle is considered to be an important design parameter. It is suggested that an additional 'trim' coil placed adjacent to Coil0 could reduce these strike point positioning errors.

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Referances

[1] M. Kotschenreuther, P. Valanju, S. Mahajan, L. J. Zheng, L.D. Pearlstein, R.H. Bulmer, J. Canik, and R. Maingi, Nuclear Fusion, 50, 2010.

[2] P. M. Valanju, M. Kotschenreuther, and S. Mahajan, Fus. Eng. Des., 85, 2010.

[3] R. Albanese, R. Ambrosino, and M. Mattei. PMI TS Ref. No. 7.3.1.1 - Vertical Stability: Final Report 2014

[4] E Havlickova, W Fundamenski, M Wischmeier, G Fishpool and A W Morris, Plasma Physics and Controlled Fusion, Vol.56, No.7, July 2014, p.075008