Engineering integration constraints for advanced magnetic divertor configurations in DEMO

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Abstract:

The divertor configuration defines the power exhaust capabilities of DEMO as one of the major key design parameters and sets a number of requirements on the tokamak layout, including port sizes, PF coil positions, and size of TF coils. It also requires a corresponding configuration of plasma-facing components and a remote handling scheme to be able to handle the cassettes and associated in-vessel components the configuration requires.

Alternative magnetic configurations to that baseline ITER-like single-null (SN) – double-null, snowflake, X-, and super-X – exist and potentially offer power-handling solutions to the limits imposed by plasma-facing component technology and first-wall protection whilst maintaining good core plasma performance. But these options impose significant changes on machine architecture, increase the machine complexity and affect remote handling and plasma physics and so an integrated approach must be taken to assessing the feasibility of these options.

In this contribution we describe the engineering and physics limitations which must be respected in assessing the impact of incorporating these alternative configurations into DEMO, including requirements on remote handling access, forces on coils, plasma control and performance, etc.

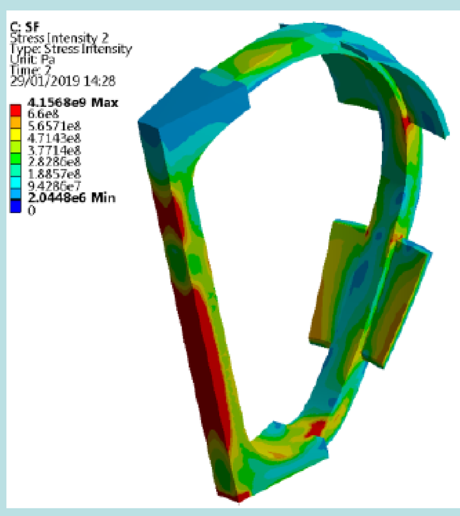
Keywords: DEMO, system modelling, fusion power plant, technology choices

Mechanical requirements:

The steels used for superconducting magnets must be compatible with cryogenic operation, and the PF coils (and the forces on them) must be supported by structures which cannot be arbitrarily large. This means that the forces and stresses in these components are limited, and their positioning must be compatible with access for the removal and replacement of the in-vessel components.

Therefore the following limits apply:

- < 400 MN force on PF coils
- < 300 MN separation force in the CS
- < 660 MPa membrane stress in the TF inner limb
- < 500 Mpa membrance stress in the TF outer limb
- Target flux swing from CS = 320 Vs



Port access:

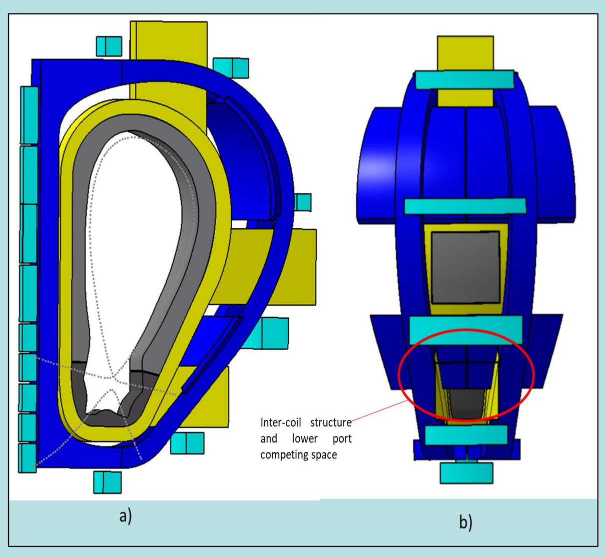
There must be space for a mid-plane port and upper and lower ports. The midplane port is 3m in poloidal extent. The upper port (for single-null) needs to be able to see all blanket segments for pipe connections and lift, and be large enough to extract blanket segments. The lower port must have access to divertor cassette for direct removal.

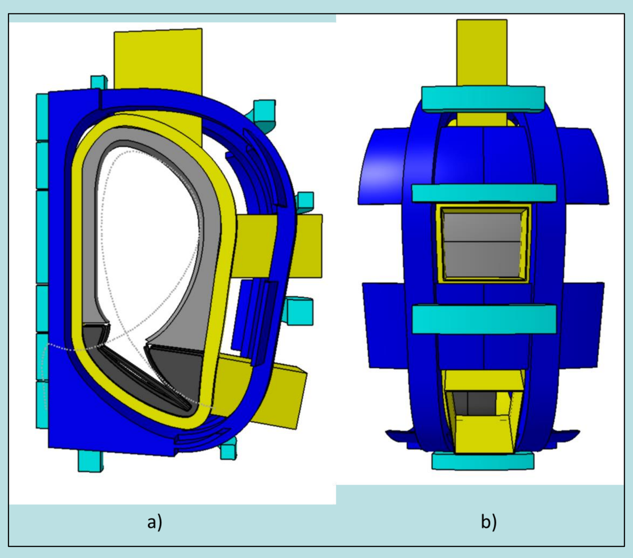
In double-null vertical removal of upper and lower divertors must be considered subject of PPPT KDII4), although alternative strategies can also be considered. Is there a reasonable and obvious unobstructed path to the components?

TF intercoil structures also cannot obstruct port access. However they are critical to the stress modelling in the coils.

In-vessel coils:

In-vessel coils can be considered, based on small advances in ITER technology, up to 400kA per coil. These must be shielded by the blanket or divertor and supported by the vacuum vessel. They must not obstruct ports or component removal paths. In-vessel coils are undesirable but if they make the difference between an impossible configuration and a possible one they can be considered.





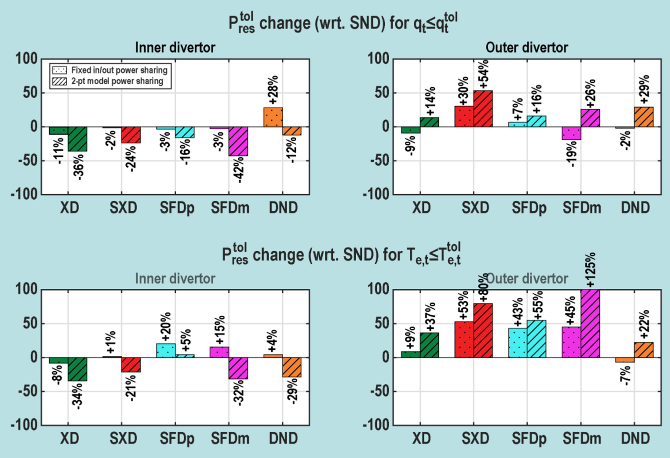
Inner limb heat loading:

An advanced divertor configuration that reduces loads on the outer limb but does not improve performance at the inner limb may not provide benefits to machine design.

$T_e \leq 5$ eV (for sputtering)
$q_\perp \leq 20$ MW m^{-2}

And assuming that

$$q_{||,in}/q_{||,out} = L_{||,out}/L_{||,in}$$



where q is the parallel heat flux, and L is the connection length, shows that increasing the connection length on the low field side would cause a larger fraction of the power crossing the separatrix to be directed onto the high field side target. This penalises various configurations unless overall more power can be stably radiated away in the scrape-off layer.

In any event the heat flux to the inner plate should not be greater than that to to the outer plate.

For double-null there is the possibility of incorporating the divertor inner plate into the blanket (also KDII4):

However this means aligning the lifetimes of the divertor and blanket, which changes the available materials and thus heat-removal capabilities. A conventional divertor using CuCrZr should be able to handle 10 MWm^{-2} but with Eurofer the limit is ~1 MWm^{-2}. If this option is pursued further assessment of critical heat flux and consequences of reattachment need to be considered.

Dust considerations for DN:

In normal (ELM-free) operation tungsten evaporated from the divertor is usually promptly redeposited in forms which adhere well and do not lead to dust formation. Experimental results showing significant dust production are almost always associated with either transients, co-deposition with other materials, e.g. Be droplets, or due to disruption of W layers and therefore should not apply to the bulk W PFCs expected in DEMO.

In the case of transients (or divertor reattachment) significant enough to erode significant quantities of W DEMO would be immediately shutdown for component replacement. In the case of really significant damage and tungsten "showering", much of the machine interior may be replaced. However this is off-normal operation.

Open questions and conclusions:

- **Can there be "small" transient events which may cause damage/erosion to a single component** leading to its replacement while leaving enough W dust in the rest of the device to cause a potential issue for the future? In other words, can we expect feedback control fast enough to keep us in this range or is the expected behaviour binary between no damage at all and replacement damage?
- **DEMO divertor considerations are driven by off-normal events** such as the risk of reattachment, or limits imposed by stable impurity radiation. Do ADCs provide benefits which sidestep these limitations by, for example, allowing highly stable X-point radiation which limits the risks of reattachment and helps prevent impurities diffusing to the plasma core?
- **Guidelines for the development and assessment of Advanced Divertor Configurations (ADCs) for integration into DEMO have been developed** in discussion between WPADC and PPPT. These are intended to permit a more rapid development cycle without onerous full modelling overheads, whilst still allowing successful outcomes to be integrable into DEMO.
- **It is unlikely that all the configurations are power-plant relevant**.

For results of the concept development, see:

Fulvio Militello: *Assessing Alternative Divertors for DEMO – strategy and first results*

Roberto Ambrosino: *Electromagnetic and mechanical analysis of alternative magnetic divertor configurations for DEMO*

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