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Design of in-vessel saddle coils for MHD control in ASDEX Upgrade

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Introduction

The likely requirement to control MHD instabilities in ITER is leading to increased effort to investigate techniques for mitigation of Edge Localised Modes (ELMs) [1, 2], stabilisation of Neoclassical Tearing Modes (NTM) and Resistive Wall Modes (RWM) [3]. Non-axisymmetric error fields have been found to reduce the ELM energy loss or fully suppress ELMs in COMPASS-D [4], DIII-D [5] and JET [6]. A highly flexible set of error field coils (see Fig. 1) is proposed for ASDEX Upgrade [7] that consists of three poloidally separated rings of eight toroidally distributed in-vessel saddle coils. These coils can produce fields with up to $n = 4$ toroidal mode number, which results in fast radial decay of the error field and avoidance of triggering parasitic core islands while the achieved field strength is 20 times larger than needed for ergodisation of the H-mode pedestal in a non-rotating plasma. The upper and lower coils are designed to allow operation with AC currents up to $f = 1$ kHz for RWM feedback stabilisation. The middle coil ring will allow up to $f = 3$ kHz to produce a rotating field to prevent mode-locking to the ASDEX Upgrade intrinsic error field, useful to delay and mitigate pending beta limit disruptions. While the suitability of the proposed coil set for the purposes of ELM mitigation and RWM control is discussed in Ref. [7], we focus here on the technical design and verification of the coils and current feeds.

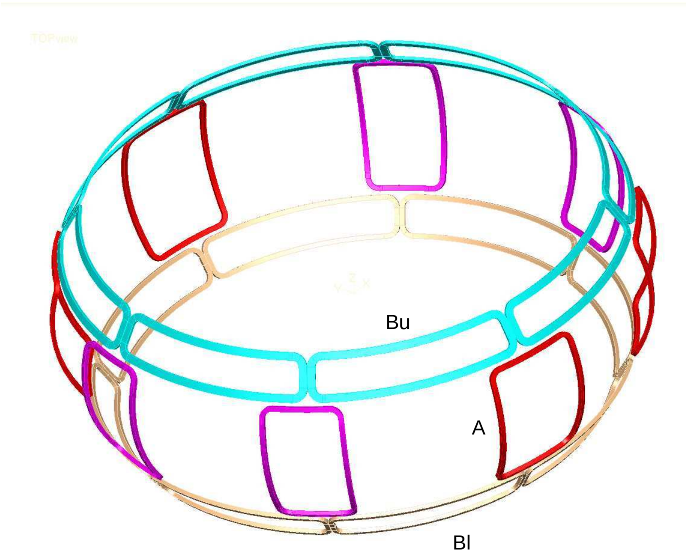

Figure 1: 3D view of active in-vessel saddle coils for ASDEX Upgrade

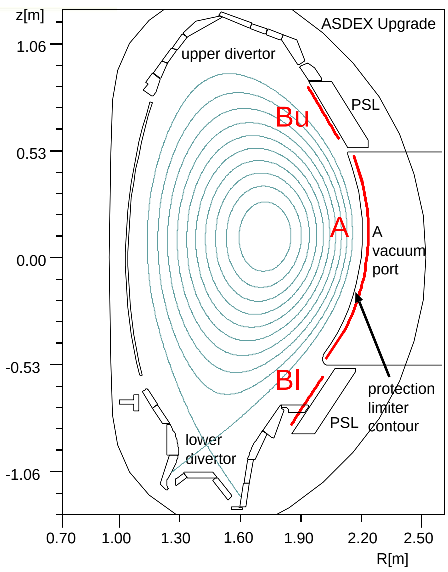

Figure 2: Location of coils shown in a poloidal cross section

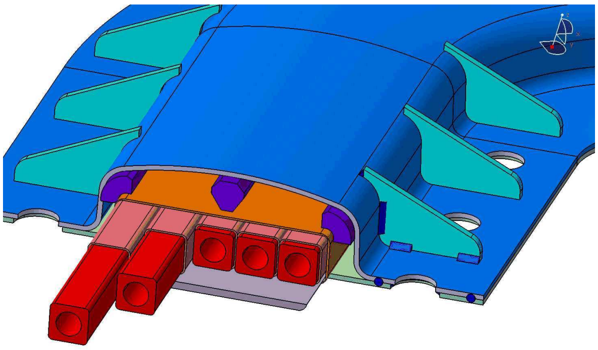

Figure 3: 3D cut view of B-coil with 5-turn winding (red) and thin inconel housing (blue).

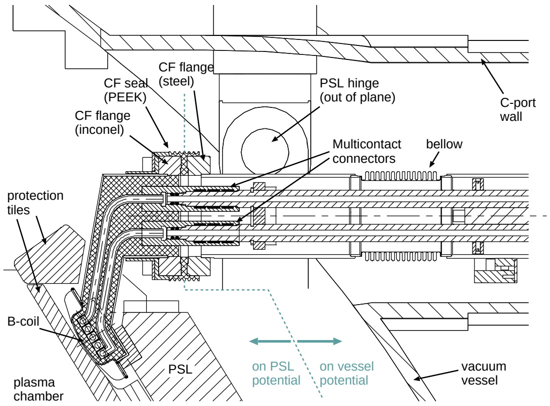

Figure 4: Feedthrough of upper B-coil (poloidal section)

Design of active coils and feedthrough

The coils are located inside the ASDEX Upgrade vessel on the low field side, cf. Fig. 2. The distance between conductors to the plasma depends on the plasma shape and position and is typically 10 cm. Narrow upper (Bu-) and lower (Bl-) coils are mounted at 10 mm and 30 mm distance, respectively, on the passive stabilising loop (PSL). Induced currents in this copper conductor produce $n = 0$ radial fields which reduce the vertical growth rate. The middle (A-) coils are mounted around the eight large midplane vacuum vessel ports.

The design of B-coils is shown in Fig. 3. A five-turn copper winding (rectangular cross section with cooling water bore) is embedded in an inconel casing (thickness 1.2 mm). The winding is wrapped with glass fibre, positioned with insulating spacers and immersed in cast epoxy. The casing is composed of a flat base sheet and a deep-drawn cover which are laser-welded with two joints that independently ensure mechanical strength and vacuum tightness. The casing is stiffened with inconel ribs against bending stress arising from electromagnetic forces pulling the winding away from the PSL. The coil is mounted with narrowly spaced bolts under pre-stress to avoid fatigue by rapidly alternating stress directions during AC operation.

A cross section of the B-coil feed connection is shown in Fig. 4. The winding ends are guided out of the coils into a break-out box with micro-contact connectors. These are plugged into a feedthrough tube with two parallel copper conductors through the upper and lower radial ports of the ASDEX Upgrade vessel. The feedthrough tube is pumped separately from the vessel. Relative displacements between coil and outer feedthrough tube are taken up by a bellow. Lateral motion of the conductors is accommodated by their support structure inside the tube while radial motion is taken up by two sliding gaskets in the outer flange of the feedthrough.

Design verification

The design is verified by computer simulations and hardware tests. A maximum coil current of $I_{\text{coil}} = 1$ kA is sufficient to meet the physics requirements [7]. The electrical and thermal properties of B-coils are calculated with the `Quickfield` 2D Finite Element code (`www.quickfield.com`). The normal field at a distance of 10 cm from the middle of the coil is shown in Fig. 5 as a function of frequency for Bu- and Bl- coils and is above $B_n = 2.7(5.1)$ mT, respectively, for frequencies below 1 kHz. The maximum coil voltage at these parameters is 120 (200) V. The field rolls over above $f = 1.2$ kHz due to eddy currents in-

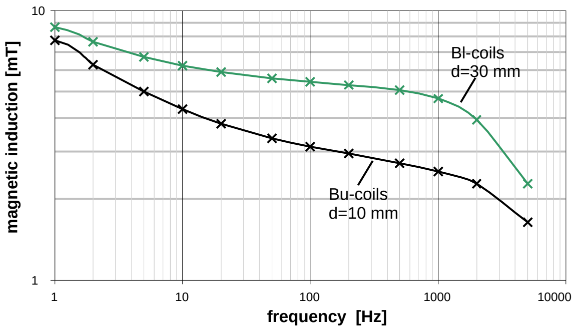

Figure 5: Normal field at reference point vs. frequency at $I_{\text{coil,peak}} = 1$ kA for Bu- and Bl-coils.

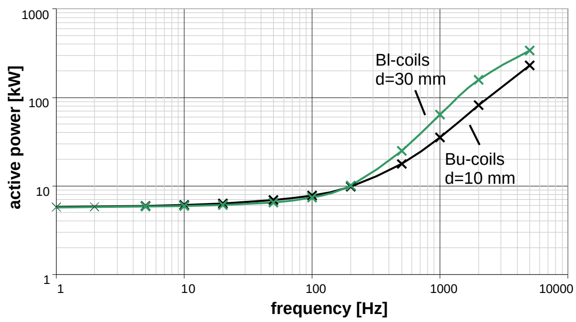

Figure 6: Frequency dependence of active power at $I_{\text{coil,peak}} = 1$ kA for Bu- and Bl-coils.

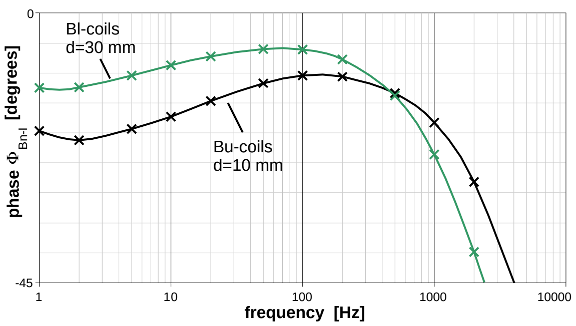

Figure 7: Relative phase between B_n and coil current vs. frequency.

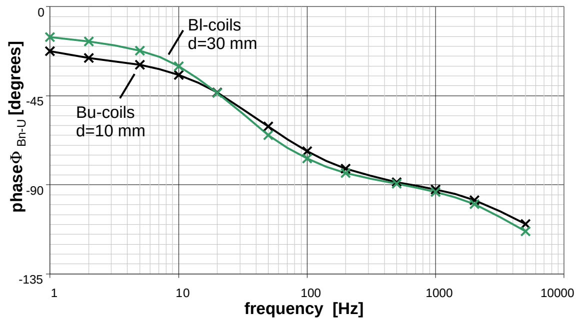

Figure 8: Relative phase between B_n and coil voltage vs. frequency.

duced in the inconel casing, which also lead to rapid increase of the dissipated active power at high frequencies (Fig. 6). The phase lag between B_n and coil current (Fig. 7), relevant for controlled coil current (non-saturated amplifier voltage, i.e. small signal response) is below 25 degrees for $f = 0 \ldots 1$ kHz. The phase between B_n and coil voltage (Fig. 8, large signal response) reaches 95 degrees at 1 kHz. This behaviour leaves phase margin for closed loop control provided the pick-up coils, controller and amplifiers are sufficiently fast.

The heating and re-cooling of the coil casing is also simulated with `Quickfield`. The casing heats up fastest at the top center of the lid. Fig. 9 shows the heating rate at maximum coil current, $I_{\text{coil,peak}} = 1$ kA, vs. frequency. The operation pulse length is limited by the maximum tolerable casing temperature (90 degrees C). For a temperature swing of 40K, the tolerable pulse duration at $f = 500$ Hz is 12.5 s, more than the typical duration of ASDEX Upgrade plasmas. Inter-pulse cool-down is simulated assuming only heat conduction through the epoxy cast into the water-cooled copper conductor (Fig. 10). Within 2 minutes, all parts of the coil casing cool down below 323K, to allow for a new pulse.

The mechanical strength of the coil casing is verified with 2D and 3D `Ansys` finite element calculations using “cement” elements for purely compressive forces between the epoxy cast winding block and the casing and “gap” elements to simulate frictional shear at the bolt and washer and the bottom coil support. Upward electromagnetic forces on the conductor lead to bending stress on the casing lid near the inner weld which are effectively reduced by the stiffening ribs. The combination of bolt pre-stress, stiffener and PSL support achieves an overall low stress level as long as the electromagnetic force stays below the pre-stress force (600 N per bolt), which gives a factor of 3 margin over maximum electromagnetic forces,

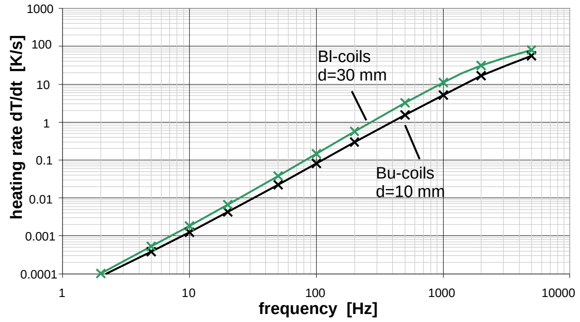

Figure 9: Heating rate of coil casing at fixed coil current, $I_{coil,peak} = 1$ kA, vs. frequency.

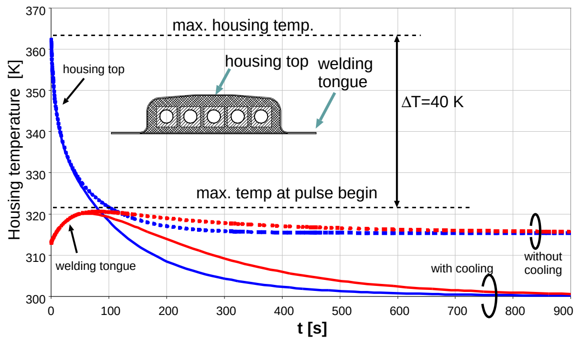

Figure 10: Simulation of cool down after pulse.

17 kN/m at vertical and 3.7 kN/m for horizontal coil branches. Fatigue life with dynamic stresses has been tested with a shorter straight coil mock-up for the full estimated lifetime, 10^7 load cycles at maximum stress amplitude. Extensive welding tests have been performed to verify the welded joints between the inconel top and baseplate sheets.

During disruptions, halo currents can flow through protecting tiles into the PSL. The coils are grounded at PSL potential only at one point. However, the fast flux change from vertical displacement and plasma current quench can induce a terminal voltage causing, at low source impedance, a large additional coil current. `Quickfield` simulations show that the PSL effectively blocks flux penetration on the disruption time scale and the induced maximum coil voltage is only about 35V. In the worst case (short circuit outside coil) this leads to 1.2 kA peak coil current, well within the margins of the mechanical design.

Conclusion and outlook

The proposed coil set for ASDEX Upgrade is capable of DC and AC operation (`B`-coils, up to $f = 1$ kHz) for ELM suppression, NTM rotation control and RWM stabilisation. It is planned to install the first set (`B`-coils) during the 2009 and 2010 shutdowns in ASDEX Upgrade (2×4 coils during each shutdown) and midplane coils (`A`-coils) in 2011. The design of `A`-coils will differ from that of the `B`-coils to achieve higher bandwidth ($f_{max} = 3$ kHz for mode rotation control). In parallel, independent AC amplifiers are prepared. Afterwards, the system will be complemented with a conducting wall for slowing down the growth rate for external modes and a feedback control system for RWM stabilisation.

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