Contribution ID: **936** Type: **Regular Poster**

Leveraging 3D magnetic topologies in support of long-pulse high performance plasma operation

Thursday, May 13, 2021 6:25 PM (20 minutes)

Long-pulse high performance plasma operation of future fusion power plants requires a solution for tolerable plasma exhaust, including steady-state and transient heat- and particle-fluxes on plasma-facing components. Recently, applications of three-dimensional (3D) magnetic topologies for controlling the edge plasma transport, stability, and plasma-wall interactions (PWIs) have attracted much attention in fusion research, especially the use of resonant magnetic perturbations (RMP) in tokamaks [1] and an intrinsic 3D magnetic topology concept in stellarator devices [2]. To leverage 3D magnetic topologies in support of long-pulse high performance plasma operation, the synergy between 3D magnetic topology and edge plasma transport, and its profound impacts on the divertor heat load pattern have been investigated by international joint experiments on several major superconducting devices, including the Experimental Advanced Superconducting Tokamak (EAST), the Large Helical Device (LHD) and the Wendelstein 7-X (W7-X) Stellarator.

- ***Equilibrium effects on the intrinsic 3D magnetic topology and its impacts on the divertor heat load pattern for high-performance long-pulse discharges on LHD and W7-X***

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  Due to the self-consistent equilibrium solution of interactions between plasmas with a finite beta and magnetic fields induced by the external coils and the plasma current, so called equilibrium effects, the structure of the magnetic field at high-performance operation can differ significantly from the vacuum assumption. On LHD, 3D magnetohydrodynamic (MHD) modelling using the code HINT predicts the expansion of the edge stochastic region in high beta plasmas [3]. To investigate an indication of transport modification by plasma-beta related edge topology changes, an EU-JP joint experiment has been performed on LHD. For perturbation of the plasma, modulated electron cyclotron resonance heating (ECRH) was applied in the plasmas heated with different levels of the total neutral beam injection (NBI) power. A variation in the edge responses to the applied modulated ECRH was observed, and is consistent with the expected "short-cut" in transport delay for higher beta scenarios. This variation could also be observed together with a significant change in both the amplitude and the phase of the m/n=1/1 magnetic component. Here, the m and n are the poloidal and toroidal mode numbers of the magnetic field. Additionally, edge topology changes show up as a modification in strike-pattern on the divertor Langmuir probes as well as a change in impulse response to the ECRH modulation.

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  To develop a high-performance long-pulse plasma operation scenario on W7-X with an island divertor configuration in the upcoming campaign OP2, the impact of the toroidal current and the plasma beta on the magnetic topology, the scrape-off layer (SOL) plasma profiles and divertor power depositions have been investigated during the second divertor campaign OP 1.2. The measurements of the divertor heat loads showed a shift and spread of the strike-line due to the evolving toroidal current in agreement with the topology calculation [4]. Consistency was also found between the calculated evolving magnetic topology and the plasma profiles measured by the multi-purpose manipulator (MPM) system [5-6]. Finite-beta (up to 5%) 3D equilibria for the three most important configurations of W7-X ("Standard", "High-Iota", "Low-Iota") were obtained with the code HINT. The configurations were seen to have varying responses to finite beta, with high-iota showing large degrees of edge stochastization and low-iota showing a reduction of the island widths and an eventual transition to a limiter-like edge topology. The standard configuration (5/5 edge islands) is the most stable of the three analyzed configurations. The only observable modification of the heat-load distribution at moderate plasma beta is a toroidal shift of the heat-load inside the strike-line pattern on the vertical divertor plate. Only in the highest-beta scenarios (flat core, axis beta of 5%), approaching a volume-average beta of >3.5%, does a faint second strike-line structure appear on the divertor, as shown in figure 1. No significant heat-loads on PFCs outside the main divertor plate were observed in OP2-relevant configurations.

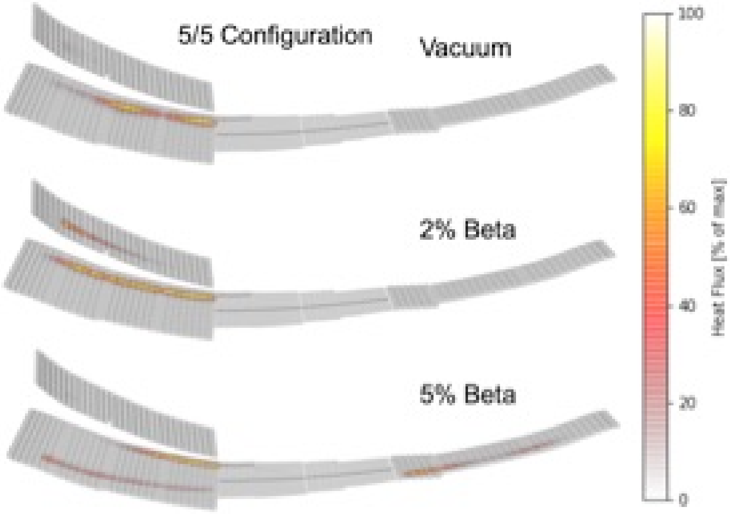

Figure 1: Heat-flux predictions onto the divertor plates of W7-X for its standard island divertor configuration at different plasma betas

- ***Active control of the redistribution of the divertor flux by the synergy of the supersonic-molecular-beam-injection (SMBI) and the 3D magnetic topology induced by the LHWs on EAST***

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  The magnetic topology change induced by lower hybrid waves (LHWs) and its profound effects on the edge transport and stability has been investigated on EAST [8]. Transport enhancement at the plasma edge during the application of LHWs has been identified during the ECRH modulation experiment. The time delay of the ECRH heat pulse propagating to the divertor plate decreased from 70 ms to 40 ms when the 2.45 GHz LHW was applied, and it dropped further to 20 ms when the 4.6 GHz LHW was switched on. The impact of the LHW-induced magnetic topology change on the heat flux distribution has been simulated by utilizing a self-consistent fluid 3D edge plasma Monte-Carlo code coupled to a kinetic neutral particle transport code (EMC3-EIRENE), and it agrees well with experimental observations [9]. Furthermore, active control of the redistribution of the divertor flux has been developed by exploiting the synergy of the SMBI and the magnetic perturbations induced by the LHWs on EAST. To reveal the underlying physical mechanism, first simulations using the EMC3-EIRENE with good agreements to the experimental findings were performed [10]. These simulations show that the ions and electrons originating from the ionization of injected neutral particles in the plasma edge flow along the magnetic flux tube towards the divertor, thus directly increasing the divertor flux on the split strike lines in the footprint. Combining this with the multi-lobe structure of the edge magnetic topology, active control of the divertor flux can be realized by adjusting the SMBI position or the phase of the magnetic perturbations.

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Session Classification: P6 Posters 6

Track Classification: Magnetic Fusion Experiments