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Overview of the COMPASS results

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Abstract

The COMPASS tokamak, operated in the Institute of Plasma Physics of the Czech Academy of Sciences in 2009 – 2020, is one of few devices with an ITER-like plasma shape. Its flexibility, extensive set of diagnostics, and NBI heating allow to address key issues in the fusion research in support of ITER and DEMO, such as edge and SOL physics, the L-H transition, runaway electrons and disruption studies, plasma-wall interaction. Recent results related to these fields, obtained in the last two years, till the final COMPASS tokamak shutdown in September 2020, are the subject this contribution.

L-H transition

Extensive sets of experiments have been performed recently in order to study the L-H transition.

The dependence of the L-H power threshold on the X-point height above the divertor P_{LH}(|X-div|) was analyzed in the framework of causal graphical modelling. This motivated the separation (conditioning) of transitions into those with q₉₅~3 and those with higher or lower q₉₅ and also the normalization (counterfactual reasoning) of P_{LH} to a common reference density in order to block confounding effects. The results (see figure) show a clear linear trend where P_{LH} increases by 30-40 kW (~18%) per 1 cm of the X-point height above the divertor. While the trend with |X-div| is similar for all the discharges, those with q₉₅~3 have a base value of P_{LH} larger by 50 kW. This 30% increase in P_{LH} around q₉₅~3 seems to be related to the presence of intrinsic error fields.

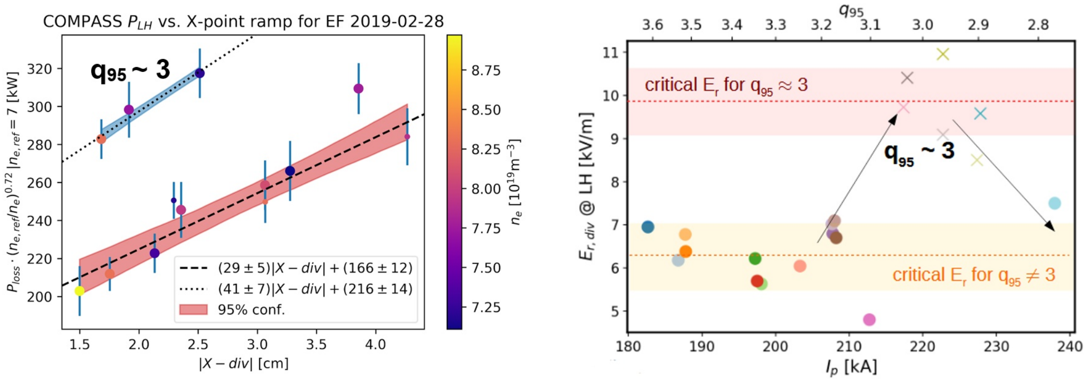

Figure 1: Density-normalized L-H power threshold P_{LH} as a function of the X-point height above the divertor |X-div| (left). Critical radial electric field E_r in the SOL at which the L-H transition occurs (right). In both figures, several outliers are observed for q₉₅ close to 3. [1, 2]

Simultaneous measurements of the radial electric field E_r in the SOL and inside the separatrix shows that E_r increases (in absolute value), both upstream and downstream and inside the separatrix, with decreasing X-point height. This is qualitatively consistent with transport modeling in [3] and also consistent with the idea that the consequent change in the ExB shearing rate could be responsible for the change of P_{LH}.

Furthermore, the effect of controlled HFS error field (EF) on the L-H transition was studied in detail, utilizing the unique COMPASS HFS 3D coils. Using these coils, a displacement of the central solenoid was simulated, while different sets of coils were used to assess the error field correction (EFC) from the LFS and top/bottom of the vessel, which is of high importance for ITER, having in mind the detrimental effects of HFS EF observed on NSTX-U recently [4]. It was shown that the residual EF, after the correction of HFS EF by LFS EFC, can lead to disruptions if present during the L-H transition. While in case of NBI-assisted L-H transitions the disruption rate was around 50% as reported in earlier COMPASS results, in case of purely Ohmic L-H transitions (induced by X-point ramp) the disruptions were inevitable. The critical parameter appears to be the plasma rotation which is very low during Ohmic L-H transitions in COMPASS (and is also expected to be generally low in ITER), but injection of even a small external momentum (P_{NBI} < 100 kW) is sufficient to prevent the disruption.

Run-away electrons (RE) physics

Both experiments and modelling effort contributed significantly to the understanding of crucial topics, such as more efficient mitigation, suppression of RE beam generation, its feedback control, beam detection, transport of RE and their interaction with MHD.

Radial stability of the relativistic RE beam and the role of RE energy was studied and based on this, a new algorithm for the RE beam feedback control was implemented [5]. Vertical electron cyclotron emission (V-ECE) diagnostics has been commissioned [6] and used to monitor RE seed population in the plasma, which is helpful in the mitigation scenarios. The evolution of the RE beam impact and its overall energy was measured using a new dedicated calorimetry head. Studies of low and high Z impurity material impact on the RE beam dynamics showed very promising results thanks to a new vacuum pellet injector system. Besides systematic surveys of the effects of the massive gas injection and impurity seeding, the effect of externally applied resonant magnetic perturbation on the RE dynamics was addressed [7].

A new full orbit particle tracking code taking into account radiation damping and 3D perturbed magnetic field was developed. RE transport model in presence of natural magnetic perturbations based on fractional diffusion theory was developed and qualitative comparison with experiments was made, evaluation of the RE diffusion coefficient with a guiding-center particle code is ongoing. The conditions under which the radiation reaction acting on the charged particle prevails over the collisions were investigated analytically.

Disruptions studies

Disruption studies are focused on electromagnetic loads on the machine. For the first time simultaneous measurements of plasma current asymmetries as well as toroidal and poloidal vessel currents including their poloidal distribution have been performed [8]. New diamagnetic technique for measurements of poloidal current in the wall has been successfully validated in experiments on COMPASS [9]. The disruption forces modelled by CarMa0NL code have been validated against the COMPASS data, and then applied for the design of COMPASS-U vacuum vessel [10].

Two special divertor tiles were installed in COMPASS to directly measure currents flowing between these tiles and the plasma during vertical displacement events (VDEs). They allow better understanding of current pattern distribution within vessel structure and divertor and aim on testing the model of asymmetric toroidal eddy currents (ATEC) [11].

The vacuum vessel motion during disruptions has been studied simultaneously by displacement sensors and accelerometers.

Liquid Metal Divertor (LMD) experiments

Liquid metals are considered as an option to overcome issues related to conventional plasma facing components (PFC), such as melting of leading edges, cracking, morphology and heat capacity deterioration subsequent to neutron irradiation or re-crystallization. One candidate technology is the capillary porous system (CPS) where the liquid metal is impregnated in a metallic mesh and confined against MHD effects by capillary forces. However, this potential solution comes with new issues such as resilience to transients, tritium retention, evaporation, etc. Most of these issues were investigated experimentally for the first time under ELMy H-mode conditions in a tokamak divertor. [12, 13].

A specially designed CPS module filled with liquid Li and with a liquid Sn alloy (LiSn) was installed in the COMPASS divertor for two separate dedicated power exhaust experiments. Good power handling capability of both liquid metals was observed for an averaged deposited, perpendicular heat flux up to 12 MW/m². The CPS module was exposed to ELMs with relative energy ~3% and a local peak energy fluence ~15 kJ/m² locally. No droplets were ejected from the CPS surface and no damage of the CPS mesh was observed, as well as no contamination of the core and SOL plasmas by Sn.

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