Progress and innovations in the TCV tokamak research programme OV

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TCV is a highly flexible, medium-sized tokamak at the Swiss Plasma Center at EPFL, featuring unique magnetic shaping, excellent diagnostics, a modern control system, and versatile heating (2.6 MW NBI, 3.75 MW X2/X3 ECRH). Operated partly as a EUROfusion facility, TCV research tackles key challenges for ITER and fusion power plants while contributing strongly to the education of young researchers. Following a complete overhaul of neutron and gamma-ray shielding in early 2023, TCV now operates without radiation-imposed limits. The 2023-2024 campaigns were highly productive, featuring four different divertor closures and attaining a record of 3,517 successful plasma discharges in 2024, while simultaneously preparing for various upgrades.

NBI and ECRH-heated ITER Base-Line (IBL) scenarios were developed, showing good performance (H_{98}~1.2, β_N~1.6) before NTM onset. NTM avoidance with X3 heating succeeded at medium β_N and high q_{95} but was constrained at ITER q_{95} due to density peaking and weak X3 absorption. Integrated modeling identified ITGs as the dominant core instability, reproducing turbulence-driven density peaking. New scenarios with up to 90% X3 absorption featured large, regular ELMs and avoided NTMs but at lower q_{95} than the IBL. Pedestal studies were extended to D_2 fuelling and N_2 seeding scans at reactor-relevant, low ν*, showing no pedestal pressure degradation with increasing $n_{e,sep}/n_{e,ped}$ (consistent with Europed) but a reduction with seeding[1]. H-mode access with NBI heating was analysed across different n_e, I_p, and ion species/mixes. While generally aligning with the ITPA scaling law, P_{LH} decreased with I_p, consistent with the idea that good L-mode confinement eases the L-H transition.

Guided by Astra modeling, different heating and current drive recipes were developed for advanced, high-bootstrap, high-beta scenarios aimed at steady-state operation[2]. Non-inductive ITB scenarios transiently reached record core T_e of 11 keV and β_N~1.85, but T_e>>T_i. With more ion heating power, this evolved into a fully non-inductive semi-stationary scenario with partial signatures of both an ITB and ETB, at similar β_N with T_i~T_e.

Plasma pedestal/edge studies on TCV greatly benefited from new or enhanced diagnostics (short-pulse reflectometry, thermal helium beam, parametric decay instability radiometry, DBS, and GPI) and improved modeling. Limit cycle oscillations in the I-phase and periodic profile flattening due to a high-frequency edge mode were detailed, along with the resulting bursty SOL 2D filamentary transport. DBS measurements showed deeper E_r wells with favourable ∇B drift, with stronger effects from NBI than ECRH, and emphasizing the inner-well shear's role in the L-H transition. First gyrokinetic GENE simulations of the TCV pedestal indicate that at high gas puffing, ETG-driven electron heat fluxes match experimental values, suggesting ETG modes limit pedestal formation.

Alternative, high-confinement scenarios remained a key focus on TCV[3]. In high-density H-modes, increasing upper triangularity from 0.0 to 0.6 resulted in the transition from a Type-I ELMy to a Quasi-Continuous Exhaust (QCE) regime. SOL power and density fall-off lengths increased 2.5-fold, correlating with the α_t turbulence control parameter, suggesting resistive ballooning-dominated SOL turbulence. Negative triangularity (NT) plasmas were further developed as a promising high-confinement, ELM-free regime. Stable, high-performance (β_N ~1.8, H_{98}~1), NBI-heated NT plasmas were achieved, showing higher central ion and electron temperatures than equivalent positive triangularity (PT) L- and H-modes[4]. Divertor detachment proved more challenging in Ohmic NT density ramps than in PT, at least partly due to a narrower λ_q, an effect understood theoretically and confirmed experimentally. Nevertheless, in high-performance NBI scenarios, divertor detachment with an X-point radiator was achieved via nitrogen seeding, highlighting NT's core-edge integration potential. Experimental and numerical studies of NT in view of DTT showed promise despite its limited NT shaping capabilities.

TAE and Fast Ion (FI) studies have greatly advanced due to improvements in NBI and diagnostic capabilities. TAEs, destabilized by counter NBI, could be stabilized with on-axis ECRH[5]. Flux-tube gyrokinetic simulations underscored the need for a global approach on TCV due to TAE-TEM turbulence coupling and radially elongated streamers. FI loss studies in low-collisionality peeling-limited and high-collisionality IBL scenarios, supported by

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improvements in the FILD hardware and related modeling, revealed distinct inter- and intra-ELM transport. Significant inter-ELM FI losses were linked to TAEs and NTMs, respectively, in each regime. The first microsecond velocity-space (E, pitch) resolved measurements of FI dynamics during ELMs allowed recovering the filamentary and burst-like velocity-space dynamics of the FI losses, exhibiting different pitch and energy values before, during and after the ELM onset. NBI-generated fast ions also drove EGAMs at sufficiently high fast particle pressure and low q, with the EGAM's detailed structure and non-rotating character identified via multichannel SXR and AXUV.

To mitigate startup and post-disruption Runaway Electron (RE) beam formation, central ECRH reduced RE seed populations by up to three orders of magnitude, attributed to enhanced RE transport and reduced loop voltage. Direct experimental evidence of RE momentum-space engineering, via toroidal magnetic field ripple inducing RE pitch angle scattering, was demonstrated to limit RE energy. For safe post-disruption RE beam termination, Benign Termination (BT) has emerged as a promising method[6]. BT requires a low-density, recombined companion plasma, achieved in a specific neutral pressure range, with immediate consequences for ITER. Its lower limit is prescribed by neutral energy conduction and explored for the first time with SOLPS-ITER. Its upper limit is linked to RE-induced ionization, resulting in increased companion plasma density, thereby reducing mitigation efficacy.

For plasma exhaust studies and reactor extrapolation via validated modeling, TCV's divertor baffles remained central. Extensive datasets, including divertor closure scans and T_i, parallel flow, and 2D kinetic electron profile measurements, challenge SOLPS-ITER predictions. Improved core-edge coupling with JINTRAC and kinetic corrections in the SOL yielded significant improvements over previous simulations[7], which predicted overly dense and cold target conditions. SOLPS-ITER comparisons with TCV also revealed strong underprediction of molecular processes, reconciled by corrected molecular charge-exchange rates. Synergetic benefits of impurity seeding and baffling were demonstrated experimentally and in SOLPS-ITER, identifying the key physics behind enhanced divertor impurity retention. The interplay of turbulence and kinetic neutrals in detachment was studied using GBS turbulence simulations for the first time[8], with experimental validation of filamentary structures showing agreement in motion but a 2× size overestimation.

Alternative divertor configuration studies confirmed strong exhaust benefits from an extended divertor leg but find no significant impact from enhanced poloidal flux expansion on divertor cooling, in both experiments and SOLPS-ITER simulations. H-mode X-Point Radiator (XPR) operation, with a narrow operational window in SN as predicted for C-wall machines, was reliably achieved by positioning a secondary X-point near the separatrix, enabling fully ELM-suppressed, stable XPR operation. With the secondary X-point placed near the target, a stable XPR was achieved remote from the primary X-point and without notable edge cooling, providing a first proof-of-principle of the X-point target divertor concept[9]. Demonstrated in Ohmic and high-power L-modes, this scenario offers TCV's most favourable exhaust performance, significantly reducing parallel target heat fluxes and thermal front sensitivity, promising excellent detachment control.

Towards fully integrated plasma control, TCV's flexible digital distributed control system underwent major hardware and software upgrades, with most of its real-time codes implemented and real-time diagnostic and actuator capabilities steadily expanding. A versatile supervisory control framework, SAMONE, was developed to manage multiple plasma control objectives, demonstrating beta control in high-performance NT plasmas and advanced density, shape, NTM, and detachment control. ML/AI enhancements gained traction, enabling real-time event detection, plasma trajectory optimization, latent variable models for plasma state monitoring, and real-time neutron rate detection[10].

Looking forward, several TCV upgrades are in progress, including a novel, Tightly-Baffled, Long-Legged Divertor[11], combining key divertor benefits with minimal added engineering complexity, a runaway electron mitigation coil, and an additional 2MW of dual-frequency X2/X3 gyrotron power.

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