Overview of Physics Research on TCV

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The *Tokamak à Configuration Variable TCV*

Mission: contribute to physics basis for ITER scenarios
DEMO design
tokamak concept improvement

- $R = 0.88\text{m}$; $a = 0.25\text{m}$
- $B_T \leq 1.5\text{T}$; $I_p \leq 1.2\text{MA}$
Unique TCV feature: flexible plasma shapes

- $R = 0.88\text{m}; \ a = 0.25\text{m}$
- $B_T \leq 1.5\text{T}; \ I_p \leq 1.2\text{MA}$
- $0.9 < \text{elongation } \kappa < 2.8$
- $-0.6 < \text{triangularity } \delta < 0.9$
- Internal $n=0$ coils
  (as in ITER)
Unique TCV feature: Electron Cyclotron systems

2nd harmonic (82.7GHz)

- 6 x 0.5MW, 2s
- Side launch ECH, ECCD
- $n_{cut-off} \approx 4 \times 10^{19} \text{ m}^{-3}$

3rd harmonic X3 (118GHz)

- 3 x 0.5MW, 2s
- Top launch ECH
- $n_{cut-off} \approx 1 \times 10^{20} \text{ m}^{-3}$
Advanced real time control using EC waves

- New digital systems operational; actuators include EC power, deposition location
  - Ex.: sawtooth period control by local modification of current profile
    - Adaptive algorithm for highly nonlinear plasma response
    - Proof-of-principle for real time instability control e.g. for ITER

J. Paley et al., EX/P6-16
Lay-out of the talk

- Review of recent results based on TCV unique flexibility in shape, heating and control
  - Identification of edge flows for material migration
  - Effect of plasma triangularity on stability, transport and rotation
  - Physics of advanced scenarios
    - Role of magnetic shear on internal transport barriers
  - Elements for steady-state tokamak operation
    - Control of global plasma relaxations
    - Demonstration of 100% bootstrap current in steady-state discharges

Outlook

- TCV upgrades under discussion
Parallel Scrape Off Layer ion flows

- Major contributor to transport of impurities from source to destination
  - Material migration and T-retention (e.g. for ITER and DEMO)

- Two main flow components
  - Magnetic field sign dependent
    - Neo-classical, strong at plasma midplane
  - Magnetic field sign independent
    - Turbulence driven and possible divertor sink

- TCV shape flexibility provides an ideal tool to isolate and understand these flows
Parallel SOL ion flows: methodology

- Reciprocating Mach probe on machine midplane
- Move plasma, change shape and reverse $B_T$ to probe above and below plasma midplane
- Mean of FWD-$B_T$ and REV-$B_T$ flows to isolate field independent components

- Ohmic L-mode
  ($I_p = 260kA$)
- Density scans
  $2.5 \times 10^{19} - 8 \times 10^{19} \text{ m}^{-3}$

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R.A.Pitts et al., EX/P4-20
SOL flow components

- Mean of $FWD-B_T$ and $REV-B_T$ flows to isolate field independent components

- Below plasma midplane
  - Offset towards outer divertor (sink + turbulence)

\[ \bar{n}_e(10^{19}\text{m}^{-3}) \quad 1.7 \quad 2.5 \quad 4.2 \quad 6.5 \quad 7.3 \]

\[ M|| = v||/c_s \]

\[ Connected\ SOL \]

\[ Midplane\ separatrix\ distance\ (\text{mm}) \]

R.A.Pitts et al., EX/P4-20
SOL flow components

- Mean of $FWD-B_T$ and $REV-B_T$ flows to isolate field independent components

- Below plasma midplane
  - Offset towards outer divertor (sink + turbulence)

- Above plasma midplane
  - Offset towards inner divertor (turbulence) – divertor sink not important

\[ M_{||} = \frac{v_{||}}{c_s} \]

R.A. Pitts et al., EX/P4-20
SOL flow components

- Mean of FWD-\(B_T\) and REV-\(B_T\) flows to isolate field independent components

- Below plasma midplane
  - Offset towards outer divertor (sink + turbulence)

- Above plasma midplane
  - Offset towards inner divertor (turbulence) – divertor sink not important

- At plasma midplane
  - No offset within exp. error, strong ballooning character

\[ M_{||} = \frac{\nu_{||}}{c_s} \]

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R.A.Pitts et al., EX/P4-20
SOL flow components

- Field independent offset
  - Well reproduced by model of interchange driven convective filaments (blobs)

- Field dependent component
  - Good agreement with neo-classical Pfirsch-Schlüter return ion flows

\[ M_{||}^{PS} = \frac{2q \cos \theta}{c_s} \left( \frac{E_r - \nabla p}{en_r} \right) \frac{B}{B^2} \]

R.A. Pitts et al., EX/P4-20
Influence of plasma triangularity on stability

- Measured sawtooth period is minimum for negative $\delta$ (-0.4 < $\delta$ < -0.2)

- Similar $\delta$ range predicted to be the most unstable to ideal MHD internal kink mode (m=n=1)

A. Pochelon et al., EX/P5-15
Influence of plasma triangularity on transport

- L-mode, large $T_e$ gradient: $R/L_{Te}>10$
- $\chi_e$ decreases for increasing $\nu_{eff}$ and for decreasing $\delta$
  - $\tau$ doubles from $\delta=+0.4$ to $\delta=-0.4$

Y. Camenen et al., IAEA 2006 EX/P3-20
A. Fasoli et al., IAEA 2006 OV/3-3
Influence of plasma triangularity on transport

- Negative triangularity
  - Reduces matching between the toroidal drift frequency of electrons and the TEM frequency ⇒ smaller growth rate γ
  - Enhances the local magnetic shear ⇒ larger $k_{\perp}$
  ⇒ Smaller heat diffusivity from mixing length estimate: $\chi_e = \gamma / k_{\perp}^2$

- Trend confirmed by nonlinear local gyro-kinetic simulations

- Do other regimes (e.g. H-mode) show same reduction of transport for negative $\delta$?

A. Pochelon et al., EX/P5-15
Influence of triangularity on intrinsic rotation

- Diagnostic NBI: 50kV, $P_{\text{dep}} < 20$ kW, negligible induced rotation <2 km/s

- $\delta > 0$ (L-mode)
  - Bifurcation in toroidal rotation profile from counter to co-current as density increases

- $\delta < 0$ (L-mode)
  - Continuous transition from co-to counter-current, no clear bifurcation

- A clue to role of TEM turbulence in momentum transport?

B.P. Duval et al., PoP '08
Electron Internal Transport Barriers on TCV

- Obtained routinely with strong ECH/ECCD

- eITB operational control tools
  - OH (≤10kW, pure current source)
  - X2 ECCD power (≤3MW), location

- Steady-state
  - $V_{\text{loop}} = 0$, stationary ($>100\tau_E$, $\sim10\tau_{\text{CRT}}$)

- Peaked density profiles explained by linear gyrokinetic model in terms of turbulence-driven thermo-diffusive pinch

- Fundamental questions
  - *Transport barrier physics, steady-state with large bootstrap current*
eITB physics: role of magnetic shear

- **Experiment**
  - Small perturbations to core current profile by ohmic transformer

- **Simulations**
  - q-profile and magnetic shear in steady-state conditions
    - Confinement improves linearly with increasingly negative shear

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\begin{align*}
q_{\text{profiles}} & \quad q_{\text{from}} \quad q_{\text{kinetic}} \\
q_{\text{min}} = 3.06; \quad I_{\text{tot}} = 91 \text{ kA} \\
q_{\text{min}} = 2.84; \quad I_{\text{tot}} = 92 \text{ kA} \\
q_{\text{min}} = 2.67; \quad I_{\text{tot}} = 78 \text{ kA} \\
q_{\text{min}} = 2.37; \quad I_{\text{tot}} = 83 \text{ kA} \\
q_{\text{min}} = 1.97; \quad I_{\text{tot}} = 91 \text{ kA} \\
q_{q} = q_{\text{min}} = 1.44; \quad I_{\text{tot}} = 102 \text{ kA} \\
q_{q} = q_{\text{min}} = 1.66; \quad I_{\text{tot}} = 92 \text{ kA}
\end{align*}
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C. Zucca et al., PPCF '08

Confined vs. shear

HRLW

\begin{align*}
\rho \quad \tau_E / \tau_L \\
25952 (-60 \text{mV}) \\
29866 (-30 \text{mV}) \\
25953 (-30 \text{mV}) \\
29867 (0 \text{mV}) \\
25956 (0 \text{mV}) \\
25957 (+30 \text{mV}) \\
29863 (+90 \text{mV})
\end{align*}
Steady-state potential of advanced scenarios  
Periodic plasma relaxations in eITBs

- Global \((m=n=0)\) plasma relaxations, due to non-linear interaction between \(j\), \(\nabla p\) and MHD stability, may prevent stationary ITB discharges

  - Different types of relaxations occur close to ideal (infernal mode) stability limit

  - ‘Resistive’
    - Triggered by resistive MHD modes \((m/n=3/1)\)

  - ‘Ideal’
    - Fast crashes with no clear MHD precursors

G.Turri et al., EX/P3-6
Suppression of plasma relaxations

- For all types of relaxations: need to restore MHD stability by affecting $j(r)$, $\nabla p(r)$
  - Demonstrated on TCV using OH current density perturbations or ECH/ECCD
- Ex. of suppression of slow relaxations by modifying ECCD
  - $q$-profile is affected by reducing off-axis co-ECCD
  - Oscillations are suppressed
  - High performance transport barrier is fully recovered

G.Turri et al., EX/P3-6
Steady-state potential of advanced scenarios
Large bootstrap current fractions in eITB

- High confinement obtained with high bootstrap current fraction and $\beta_{pol}$

- Can a tokamak plasma be sustained with no externally driven current?
100% bootstrap current fraction reached on TCV

- 100% bootstrap current needs exact, stable alignment between $j(r)$ and $\nabla p(r)$
  - Alignment is governed by relation between current and transport

- 100% bootstrap demonstrated first on TCV in steady-state
  - *With exactly balanced co- and counter- ECCD on pre-existing steady-state eITBs in reverse shear*
  - With pure ECH (perpendicular injection) in eITBs during current ramps ⇒

*S.Coda et al., EX/2-3*
100% bootstrap with pure ECH (perp injection)

- eITBs formed during current ramps evolve into self-sustained equilibrium state

- Steady-state over full TCV pulse (~1s)
  - $\tau_{CRT} > 150-300$ ms
  - $\tau_E > 3-6$ ms

S. Coda et al., EX/2-3
Summary and outlook

- The flexibility of TCV and its EC systems allowed us to address basic questions important for ITER scenarios, DEMO and tokamak concept improvements.

- After 2007-2008 shutdown, operation with clean wall, improved diagnostics, and full X2 and X3 EC plant availability has started, with focus on:
  - Advanced plasma and EC control
  - Transport, toroidal and poloidal rotation
  - H-mode physics (e.g. ELM-free with strong X3 heating, ELM fast dynamics)
  - ECH and ECCD physics
  - eITBs, steady-state and large bootstrap current fractions
  - New plasma shapes and configurations (e.g. doublets, snowflake divertor)

- On medium term, major upgrades are envisaged to adapt spectrum of studies to ITER and DEMO and increase reactor relevance of results:
  - In-vessel coils and low field side wall
  - Heating systems
TCV in-vessel upgrades

- Ergodisation coils
  - Physics of ELM control
    - $3 \times 8$ coils, $n = 2$ or $4$
  - Also for $n=1$ error field correction, $n=0$ vertical control, mode rotation control

- LFS power handling CFC tiles
  - Divertor at negative triangularity

- Alfvén wave antennas
  - AE and burning plasma physics in shaped plasmas
TCV heating upgrades

- Increase in X3 power (up to 3 new 1MW gyrotrons using existing infrastructure)
  - Optimum density \( \sim 10^{20} \text{ m}^{-3} \), frequency (140) 129, 126, 121 GHz
  - High density, high power electron-heated plasmas

- Neutral beam heating (up to 3MW)
  - 3x1MW D injectors, \( 25\text{keV} < E_b < 35\text{keV} \)
  - Heat deposition and shine-through compatible with inductive scenarios and advanced scenarios
  - High \( \beta \) and MHD control, rotation, fast ion physics
  - Mixed electron/ion heating with ECH, ECCD over wide range of \( T_e/T_i \) (0.5 < \( T_e/T_i < 10 \))

Example:
1 cntr normal
2 co normal
3 co tangential
CRPP presentations

- **TCV**
  - **EX/2-3:** S.Coda et al., *Full Bootstrap Discharge Sustainment in Steady State in the TCV Tokamak*
  - **EX/P6-16:** J.I.Paley et al., *Real Time Control of Plasmas and ECRH Systems on TCV*
  - **EX/P4-20:** R.A.Pitts et al., *SOL Transport in TCV*
  - **EX/P5-15:** A.Pochelon et al., *Physics Insight and Performance Benefits in MHD and Energy transport from Plasma Shaping Experiments in the TCV Tokamak*
  - **EX/P3-6:** G.Turri et al., *Global Plasma Oscillations in TCV*

- **Theory**
  - **TH/P8-30:** S.Jolliet et al., *Global Nonlinear Simulations of Ion and Electron Turbulence Using a Particle-In-Cell Approach*

- **Basic plasma physics**
  - **EX/P5-41:** I.Furno for the TORPEX team, *Turbulence and Transport in Simple Magnetized Toroidal Plasmas*

- **Fusion Technology**
  - **FT/P2-3:** Z.Oksiuta et al., *Optimisation of the Chemical Composition and Manufacturing Route for ODS RAF Steels for Fusion Reactor Application*

- **ITER**
  - **IT/P7-13:** P.Bruzzone, *Qualification Tests and Facilities for the ITER Superconductors*

- **JET**
  - **EX/P5-20:** M.Maslov et al., *Density Profile Behaviour in JET H-mode Plasmas*