The science program of the TCV tokamak: exploring fusion reactor and power plant concepts

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Outline

• Scientific mission of the TCV program
• Present and future capabilities of TCV
• Scientific results
  □ Heat exhaust: conventional and advanced concepts
  □ H-mode threshold
  □ MHD and integrated instability control
  □ Turbulence and zonal flows
  □ Turbulence-driven spontaneous rotation
  □ New insights into confinement and a new I-mode
• Summary and outlook
TCV mission

• Investigating fusion science and control techniques for reactor and power plant
  □ versatile control tools
  □ wide range of scenarios and parameters

• Furthering high-temperature plasma science
  □ agile program to respond to new ideas and theoretical challenges

*Run from 2015 partly as a European facility within Medium-Size Tokamak (MST) Task Force in EUROfusion program*
Overview of TCV science

- $R/a = 0.88/0.25 \text{ m}$
- $I_p < 1 \text{ MA}$
- $B_T < 1.54 \text{ T}$
- $n_e = 1-20 \times 10^{19} \text{ m}^{-3}$
- $\kappa < 2.8$
- $-0.6 < \delta < 0.9$
- graphite wall
TCV

2014: 2.5 MW ECRH power, 6 steerable launchers
Overview of TCV science

2014: 2.5 MW ECRH
2015: + 1 MW NBI
   + diagnostic upgrades
2016: 4 MW ECRH
2018: 5 MW ECRH

20??: additional NBI, vessel modifications to test exhaust concepts,

⇒ $\beta_N = 2.4$, $T_e \sim T_i = 2.5\text{ keV}$
⇒ $\beta_N = 2.8$

see also A. Fasoli et al, FIP/P7-7 (Friday morning)
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Snowflake vs conventional divertor: reduced peak heat flux, enhanced transport into private region

Overview of TCV science
Power channeled to extra strike points is substantial even for "imperfect" SF

**Infrared Langmuir probes**

H. Reimerdes et al, PPCF 55, 124027 (2013)
Simulations greatly underestimate transport into private SF region

ExB drifts are a good candidate to explain extra transport

see also B.P. Duval et al, EX/P3-56 (Wednesday morning)
SOL not broadened in today’s devices but could broaden in DEMO-sized SF

TCV L-mode

DEMO H-mode
Further exotic shapes prototyped in TCV for future studies

X-divertor (high flux expansion)

Triple-null

W. Vijvers et al, 55th APS, PP8.00047 (2013)
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Ohmic H-mode power threshold in hydrogen is lower than expected

Ohmic H-mode threshold increases with divertor leg length

Scaling refinements required by ITER

Ohmic H-mode threshold is independent of $dl_p/dt$

Scaling refinements required by ITER

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Integrated control

- New r/t version of equilibrium reconstruction code LIUQE runs in 200 μs

⇒ used for new generalized shape/position controller
⇒ used to improve NTM control by ECRH through r/t knowledge of rational surface location

Sinusoidal dither improves reliability of NTM control, in both pre-emption and stabilization schemes

MHD and integrated control: additional work

- Study of neoclassical toroidal viscosity and interplay with sawtoothless NTM excitation and spontaneous rotation

*see also S. Nowak et al, EX/P2-54 (Tuesday afternoon)*
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Edge triangularity (which affects global $\tau_E$) also influences core turbulence.

A conundrum:

1. Core triangularity ~ 0
2. Accordingly, flux-tube gyrokinetics find no core effects
3. Core gradients independent of $\delta$

$\alpha$ global nonlinear simulations + synthetic diagnostics hold the key.

Correlation ECE

$\rho = 0.4$

$\delta_{\text{edge}} = 0.34$

$\delta_{\text{edge}} = -0.34$

Frequency (kHz)

$\delta T_e$ (dB)
Geodesic acoustic mode observed at low $q$ as a global eigenmode

$\delta n_e$ by phase contrast imaging
GAM seen simultaneously by four diagnostics

- Phase contrast imaging ($\delta n_e$), correlation ECE ($\delta T_e$), Doppler backscattering (flow), magnetics ($\delta B$)
- All quantities ($\omega$, $k$, location, etc.) derived through multi-diagnostic coverage

see also L. Porte et al, EX/P3-57 (Wednesday morning)
GAM structure

- Magnetics confirm axisymmetry and find predicted $m=2$ structure
- Spatially extended eigenmode or dispersive mode depending on parameters (esp. safety factor)
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Edge rotation driven by turbulence and co/counter-ion orbit asymmetry

- A new theoretical proposal
- Testable on TCV: predicts linear dependence of toroidal rotation on X-point major radius, with sign inversion for sufficiently outward location
Predicted turbulence-driven edge rotation confirmed in TCV

$v_{0.85}$ (km/s) vs. $v_{\text{theory}}$ (km/s)
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Study of edge role in global confinement: e.g. $I_p$ scan with high-resolution measurements
Global confinement scalings largely regulated by extended edge region ($\rho \sim 0.8-1$), not by plasma boundary.

Stiff core profiles: uniform, $I_p$-independent gradient scale length.

Global confinement scalings largely regulated by extended edge region ($r \sim 0.8-1$), not by plasma boundary.

Similar dependence on density, power (standard scalings), triangularity.

See also A. Merle et al, EX/P3-55 (Wednesday morning).
Density limit

- Density rise causes positive feedback loop: density peaking, core cooling, sawtooth stabilization $\Rightarrow$ ultimately 2/1 mode and disruption
- $n_{\text{max}}$ is close to Greenwald density at low current, well below at higher current

\[
\frac{n_{\text{lim}}}{n_{\text{Gw}}} = \frac{10^{19}}{m^{-3}} \text{ vs. } I_p, \text{ kA}
\]

\[
\begin{align*}
\text{d > 0} & \quad \text{d < 0} \\
\text{d = 0} & \quad \\
\end{align*}
\]

see also N. Kirneva et al, EX/P3-54 (Wednesday morning)
IN-mode: raised edge density gradient, L-mode-like edge temperature

Obtained by early gas puffing or by marginal entry into H-mode followed by H-L transition (low internal-inductance trajectories)
IN-mode: H-mode-like confinement

H-factor profile

see also A. Merle et al, EX/P3-55 (Wednesday morning)
Summary of highlights

• Enhanced transport to private region in snowflake greatly underestimated by modeling thus far
• Lower than expected H-mode threshold in hydrogen
• Improved MHD control through real-time equilibrium reconstruction
• Complete multi-diagnostic characterization of GAM
• Confirmation of new theory of turbulence-driven edge rotation
• Determination of regulatory role of edge plasma in global confinement
• New high-particle-confinement regime (IN-mode) discovered
The immediate future

Europe-wide call for proposals in November for TCV and ASDEX Upgrade in 2015

International collaborations always welcome
Overview of TCV science

CRPP contributions

• TCV
  - EX/P2-54: S. Nowak, "(N)TM onset by central EC power deposition in FTU and TCV tokamaks", Tue pm
  - EX/P3-54: N. Kirneva, "High density regime in Ohmic TCV discharges with positive and negative triangularity", Wed am
  - EX/P3-55: A. Merle, "From edge non-stiffness to improved IN-mode: a new perspective on global tokamak radial transport", Wed am
  - EX/P3-56: B.P. Duval, "Progress in snowflake divertor studies in TCV", Wed am
  - EX/P3-57: L. Porte, "Multi-diagnostic study of core turbulence and geodesic acoustic modes in the TCV tokamak", Wed am
  - FIP/P7-7: A. Fasoli, "TCV heating and in-vessel upgrades for addressing DEMO physics issues", Fri am

• Fusion technology
  - FIP/1-4Ra: B. Stepanov, "Summary of the test results of ITER conductors in SULTAN", Mon pm

• Basic plasma physics
  - EX/P3-59: I. Furno, "Basic investigations of turbulence and interactions with plasma and suprathermal ions in the TORPEX device with open and closed field lines", Wed am

• Theory
  - TH/3-2: P. Ricci, "First-principle theory-based scaling of the SOL width in limited tokamak plasmas, experimental validation, and implications for the ITER start-up", Wed pm
  - TH/P7-13: W. Cooper, "Equilibrium and fast particle confinement in 3D tokamaks with toroidal rotation", Fri am
SOL not broadened in today’s devices but could broaden in DEMO-sized SF

TCV L-mode

DEMO H-mode

S. Coda, 25th IAEA Fusion Energy Conference, OV/4-2, St. Petersburg, 14 October 2014
Neon radiates more in SF, carbon radiates more in SND

Likely due to different radiative properties of species, appears consistent with relevant divertor volume ratios
L-mode limiter: double decay length for parallel heat flux

Up to ~10% extra power from narrow feature
Global confinement scalings largely regulated by extended edge region ($\rho \sim 0.8-1$), *not* by plasma boundary.

Similar dependence on density, power (standard scalings), triangularity.

See also A. Merle et al, EX/P3-55 (Wednesday morning)
Edge physics and exhaust concepts: additional results

- Characterization of limiter heat flux in L-mode
- Comparison of radiation properties of SF and SND
- Study of blobs in SF and SND
- Control optimization to increase maximum SF current

see overview paper and references therein
H-mode and ELMs: additional results

• Study of magnetic structure of type-I ELMs: nonlinear phase dominated by $n=1$ component

see overview paper and references therein
MHD and integrated control: additional work

- Study of neoclassical toroidal viscosity and interplay with sawtoothless NTM excitation and spontaneous rotation
- Study of effect of MHD on suprathermal electrons
- Possible 3D helical equilibrium state found
- Position control through visible boundary images
- Improved vertical stability of high-$\kappa$ plasmas by bang-bang control
- Exact sawtooth period control used for diagnostic purposes (coherent averaging over s.t.)
- Iterative Learning Control helped to improve internal inductance control over several shots

see overview paper and references therein
Spontaneous rotation: additional results

- 2D poloidal map of carbon density, temperature, flow; poloidal asymmetries under analysis

*see overview paper and references therein*