ASDEX Upgrade experiments for a physics basis of ITER operation and DEMO scenarios

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Fusion Energy Conference 2021
Total heating power of 27 MW

- NBI: 16 MW
- ECRH: 6.0 MW
- ICRH: 5 MW

Versatile discharge control system

- Enhanced real-time capabilities
- Increasing number of real time sensors
- Coupled with discharge 'flight simulator'

Continuously improved diagnostics

- Imaging Motional Stark Effect (IMSE)
- Microwave fluctuation diag. (DR, CECE)
- He beam for the SOL/edge dynamics
- Divertor Thomson scattering
- Imaging heavy ion beam probe

Tungsten wall and ITER-like magnetic and divertor geometries

$R = 1.65\, \text{m}, \quad a = 0.5\, \text{m}, \quad B = 2.5\, \text{T}$
Ultimate goal: physics based predictive modelling

Present status: workflow for predictive profile modelling of AUG discharges
- Separatrix parameters from an empirical model using gas puff and 2-point model
- Pedestal from peeling-balloonning stability with a critical temperature gradient model
- Core plasma from pedestal top inwards is modelled with TGLF

Outperforms scaling laws in predicting AUG energy confinement

[T. Luda et al., NF 2020]

→ poster by G. Tardini
Outline

- Core transport and confinement
- ELM free discharges scenarios
- Importance of the outer plasma edge
- Elements of power exhaust
Plasma current redistribution by dynamo effect

Prediction by nonlinear MHD code (*MD3D-C1*)
• Current redistribution at high $\beta_N$ related to (1,1) mode can lead to $q(0) > 1$

Experimental confirmation of sawtooth suppression at high $\beta_N$
• At high $\beta_N$ sawteeth vanish
• On-axis co-ECCD makes them reappear
• At high $\beta_N$ more ECCD power can be tolerated without sawteeth

Enables central ECCD in reactor plasmas at high efficiency and flat $q$ profiles

$\rightarrow$ talk by A. Burckhart, Thu. 14:00
Matched edge profiles (by shaping) keeping the source profiles similar

- Low NBI power: core profiles are also similar (no isotope effect)
- High NBI power: reduced ion heat transport in D plasmas

- Interpretation by nonlinear GENE simulations: stabilizing effect of fast ions on turbulence transport and higher fast-ion content in D plasmas (slowing-down time)
- Fast ion effects are also important to explain low-Z impurity transport (B, He)

[Edge isotope effect → poster by P.A. Schneider (P4.1084)]

[10.05.2021]

[P. A. Schneider et al., NF 2021]

[A. Kappatou et al., NF 2018; R. McDermott et al., NF 2020; Manas et al., NF 2020]
Experimental data to compare with global gyro-kinetic simulations (GENE)

- Density fluctuation $k$ spectra
- Electron temperature fluctuation $\omega$ spectra
- Radial correlation lengths
- $n-T$ cross phases
- Turbulent phase velocity
- Zonal flow structure ...

Example: poloidal flow symmetry

- Doppler reflectometer measures poloidally symmetric $ExB$ flows
- Flows agree with CXRS measurements

[K. Höfler et al., NF 2021]
Isotope effect in the L-H power threshold

Important for ITER operation in H, He and D-T

- Small helium content in D plasmas doesn’t change H-mode power threshold
- Continuous increase of the power threshold with H concentration in D plasmas
- Different from JET results and consistent with the critical $E \times B$ shear criterion

[U. Plank et al., NF 2020 & Ph.D.]
Outline

- Core transport and confinement
- Type-I ELM-free discharge scenarios
- Importance of the outer plasma edge
- Elements of power exhaust
ELM suppression by RMP fields

RMP field correlates with 3D pattern in turbulence and transport to the divertor

- Edge turbulence causes "density pump out" which reduces edge density leading to peeling-ballooning stability
- RMP field induced island at pedestal top is not observed

[N. Leuthold, Ph.D. thesis 2020]
I-mode: power window and detachment

β-feedback controlled NBI power ramp

- I-mode operational window is determined by edge pressure
- Pedestal relaxations close to H-mode are harmful for the divertor
- N seeding detaches inner divertor
- Theoretical description [P. Manz et al., NF 2020]

Power window and detachment remain challenges

[D. Silvagni et al., NF 2020 & Ph.D., T. Happel et al., FEC 2018 & NF 2021]
Discharge with full ELM suppression

- Stationary $H_{98} > 1$, $n/n_{GW} = 0.9$, $\beta_N = 2$
- Low tungsten concentration $< 10^{-5}$
- Edge transport by QCM
- N seeding effective for detachment

Power window and low $q_s$ remain challenges

[L. Gil et al., NF 2020 & Ph.D, A. Kallenbach et al., NF 2020]

→ talk by A. Kallenbach
The QCE regime: key elements

Strong gas puff

Closeness to double null configuration

Stability calculations indicate

- Reduced high-$n$ ballooning stability at $\rho \approx 0.99$
- Related transport changes pedestal and stabilizes peeling-ballooning mode

[G. Harrer et al., NF 2018, B. Labitet et al., NF 2019]
An integrated scenario at DEMO relevant separatrix parameters

- High power (15 MW), partially detached divertor, close to H-mode confinement
- Quasi continuous transport by small (type II) ELMs
- Power fall-off length 4 times larger than between ELMs in H-Mode

→ poster by M. Faitsch et al.

[M. Faitsch et al. NME 2020]
Outline

- Core transport and confinement
- Naturally type-I ELM free discharges
- Importance of the outer plasma edge
- Elements of power exhaust
Modes close to the separatrix cause filamentary transport

Edge density fluctuations from a new helium beam diagnostics

[M. Griener et al., PSI 2021, NME 2020]
Boundaries from interchange-drift-Alfvén turbulence without any free parameter

- Density limit at transition from electrostatic to em resistive ballooning turbulence
- L-H transition: turbulence suppression by neoclassical ExB flow shear

[T. Eich & P. Manz, NF subm.]
Separatrix parameters set operational boundaries

Boundaries from interchange-drift-Alfvén turbulence without any free parameter

- Density limit at transition from electrostatic to em resistive ballooning turbulence
- L-H mode: turbulence suppression by neoclassical ExB flow shear

[T. Eich & P. Manz, NF subm]
Core transport and confinement

Naturally type-I ELM free discharges

Importance of the outer plasma edge

Elements of power exhaust
Dense, cold, and strongly radiating plasma above the X-point on AUG and JET

- ELM-free phase: 90 % radiative fraction; $f_{GW} = 0.8$; $H_{98} = 0.95$
- Potential for detachment control and marfe avoidance

[M. Bernert, NME 2017, S. Glöggler, NF 2020]
New upper divertor will be installed in 2022/23

Allows for continuum of configurations between single null and snow-flake

First SOLPS-ITER simulations including drifts of a snowflake divertor plasma

- Increased flux expansion facilitates detachment with nitrogen seeding
- Drifts bring power to additional strike point and increase power on primary strike point

[T. Lunt et al., NME 2019] [Ou Pan et al., PPCF 2018 & 2020]
Progress in physics understanding core and edge transport for improved modelling of future tokamak plasmas

Importance of fast particles for turbulent core transport

Integrated scenarios for naturally ELM-free plasmas. The QCE regime is a promising candidate, combining high power, high confinement, high density with detachment

Plasma parameters close to the separatrix play key role for the operational space and the access to small-ELM regimes

Studies on AUG will be extended to alternative divertor configurations in 2023

Thanks to the AUG and MST1 teams and all external collaborators