Overview of ASDEX Upgrade Results – Development of integrated operating scenarios for ITER

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Many thanks to our collaborating institutes:

Institute of Atomic Physics, Romania; Consorzio RFX, Padova, Italy; Centro de Fusão Nuclear, IST Lisbon, Portugal; IFP Milano, Italy; University College Cork, Ireland; KFKI Research Institute, Budapest, Hungary; University Stuttgart, Germany; HUT Helsinki, Espoo, Finland; VTT Technical Research Centre, Espoo, Finland; Plasma Physics Laboratory, Brussels, Belgium; Demokritos, Institute of Nuclear Technology, Attiki, Greece; KTH-Alba Nora, University Stockholm, Sweden; UKAEA Culham, GB; CRPP Lausanne, Switzerland; PPPL Princeton, U.S.A.

20th IAEA Fusion Energy Conference, Viamoura, Portugal, 01.-06.11.2004
ASDEX Upgrade programme focuses on ITER

ITER

ASDEX Upgrade

20 MW NBI (on- and off-axis)
< 8 MW ICRH
2 MW ECRH
ASDEX Upgrade programme focuses on ITER

Operation scenarios must be compatible with W as plasma facing material

With C long-term retention of D: 3.5% of input

See poster by M. Mayer, EX-P-5/24, Friday

Step by step towards a C free machine:

• 65% of plasma facing components W coated

See talk by R. Neu, EX-10/5, Saturday

Further hardware upgrades:

• 10 s flat top (~5 current diffusion times)
• higher triangularity: $\delta=0.55$ for $\kappa \leq 1.7$
  (includes ITER shape)
• diagnostic upgrades
Physics understanding ↔ active control

- Particle and energy transport
- Pedestal physics and ELM control
- Plasma wall interaction and impurity transport
- Core MHD stability
- Current profile tailoring

Integrated scenario
Density peaking increases with decreasing collisionality (H-mode and L-mode), consistent with quasi-linear ITG/TEM model. No strong central (electron) heating.
Reaction of the density profile to central electron heating

L-mode, $q_{95} = 4.5$

H-mode

$P_{NBI} = 5\text{MW}, q_{95} = 3$
$P_{NBI} = 5\text{MW}, q_{95} = 4$
$P_{NBI} = 5\text{MW}, q_{95} = 5$

Reaction of density profiles and corresponding time scales again consistent with quasi-linear ITG/TEM model
Control of density profile by central electron heating

Decreased collisionality ⇒ increased anomalous inward pinch

TEM induced thermodiffusion (counteracts anomalous inward pinch)

Increased thermodiffusion ($D \sim \chi$) counteracts neoclassical Ware pinch
Electron heat transport in agreement with the ITG/TEM model.

ECRH in Ohmic discharge:
- constant power
- heat deposition profile varied

Good agreement with quasi-linear GS2 modelling

TEM most unstable ⇒ collisions and density gradient are important
Physics understanding ⇔ active control

- Particle and energy transport
- **Pedestal physics and ELM control**
- Plasma wall interaction and impurity transport
- Core MHD stability
- Current profile tailoring

Integrated scenario
Pedestal physics investigations with improved diagnostics

- Reflectometry for high temporal and spatial resolution density profile measurements (ELM evolution)
  
  See poster by I. Nunes, EX-P-6/20 Friday

- Li-beam CX for ion edge temperatures

- Upgrade of Thomson scattering system
  
  (2.7 mm radial separation, 2 µs burst)

\[ T_{i,\text{ped}} \geq T_{e,\text{ped}} \]

- \( \frac{d \log T_e}{d \log n_e} \sim 2 \) confirmed
- toroidal mode numbers for ELMs: \( n \sim 8-20 \)

See poster by L. Horton, EX-P-3/4, Thursday
Pedestal physics investigations with improved diagnostics

- Fast framing IR camera for structure of heat deposition

  toroidal mode numbers for ELMs

  \[ n \approx 3 \ldots 15 \]

  See talk A. Herrmann, EX-2/4Rb, Tuesday

- Correlation Doppler reflectometry (\( E_r \), \( E_r \) shear, correlation length)

  \[ E_r \text{ shear, QH-mode } \approx 2 \ E_r \text{ shear, H-mode} \]
Quiescent H-mode: an ELM free scenario for ITER?

**QH-mode:**

- stationary, ELM free (at ITER $\nu^*$)
- ELMs replaced by other MHD (EHO, HFO – fast particle driven?)
- $Z_{\text{eff}}$ down to 2.5

See talk by W. Suttrop, EX-1/4, Tuesday
ELM control by pellet pace making

Replace linearly unstable peeling/ballooning mode by local trigger perturbation

See talk by P. Lang, EX-2/6, Tuesday

- only minor confinement degradation with increased ELM frequency compared to, e.g., gas puffing (pedestal temperature reduced!)
- energy loss per ELM for pellet triggered ELMs as for “natural” ELMs
- successful ELM control also by small wobbling (as in TCV)
Physics understanding ⇔ active control

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Integrated scenario
Tungsten as plasma facing material

In most discharges no problem (including W divertor operation)

65% (24.8 m² W covered)

Impurity problems if:
- Density peaking (neoclassical impurity pinch)
- Limiter operation
- ELM free phases in H-mode

See talk by R. Neu, EX-10/5, Saturday
See poster by R. Dux, EX-P-6/14, Friday
Control of impurity accumulation via central heating

Si laser blow-off experiments

Effect of central heating on density peaking (neoclassical inward pinch) and on anomalous particle transport
Replace C by Ar for low divertor temperature ⇒ operation closer to H-L transition without ELM control high radiation, H-L transition
Physics understanding ⇔ active control

- Particle and energy transport
- Pedestal physics and ELM control
- Plasma wall interaction and impurity transport
- **Core MHD stability**
- Current profile tailoring

Integrated scenario
NTM stabilization: optimum launching angle

TORBEAM calculations

optimum launching angle: $5^\circ$, corresponds to 1 cm deposition width

Record values for complete NTM stabilization at given ECCD power:

(3,2) NTM: $\beta_N=2.6$ for $P_{ECCD}=1.0$ MW
(2,1) NTM: $\beta_N=2.3$ for $P_{ECCD}=1.4$ MW
(3,2) NTMs in FIR regime for $\beta_N > 2.3$

FIR regime similar in dimensionless parameters (ASDEX Upgrade and JET)

Active stabilization on ITER only for (2,1) NTM needed?

See talk by M. Maraschek, EX-7/2, Thursday
TAE modes in low density ICRH heated discharges

See talk by D. Borba, EX-P-4/37, Thursday
Physics understanding ⇔ active control

- Particle and energy transport
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Integrated scenario
Current profile modification as predicted by TRANSP (MSE) – thanks to PPPL for support and consistent with shift MHD (shift of $r_{3/2}$)
But it only works at low heating power!

For large heating power:
- CD efficiency well below predictions (ASTRA, TRANSP)
- no change in q-profile

800 kA, 2.5 T, δ=0.15, 5 MW NBI

Δ = \frac{I_{\text{on-axis}}^{\text{ind}} - I_{\text{on-axis}}^{\text{ind}}}{I_{\text{on-axis}}^{\text{ind}}}

exp. (loop voltage)

ASTRA

n_e = 3.2 \ldots 3.6 \times 10^{19} \text{ m}^{-3}

P_{\text{NBI}}

\sim 100 \text{ kA}

no change in q-profile for P_{\text{NBI}} \sim 5\text{MW}

CD efficiency as predicted for low power only
Reduced CD efficiency due to redistribution of fast ions

Fast ion redistribution by Alfvèn waves? excluded:

• no Alfvèn waves observed

• $v_b < v_A$, no difference between experiments with full beam energy ($v_b > v_A /3$) and reduced beam energy ($v_b < v_A /3$)

Current redistribution by MHD? excluded:

• only (1,1) activity observed

• no influence of $q_a/q=1$ surface ($q_a$ varied between 3.9 and 6.2)

Fast ion redistribution, correlated to intensity of thermal transport

Increase in heating power (independent of radial location and pitch angle reduces CD
Physics understanding ⇔ active control

- Particle and energy transport
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Integrated scenario
Improved H-mode: a hybrid scenario for ITER

• attractive ITER scenario: higher Q at $q_a \sim 3$ or longer pulses at $q_a \sim 4.5$ ($Q=10$)
• demonstrated for:
  - ITER relevant $\nu^*$
  - $n=n_{GW}$, (type II ELMs)
  - $T_e=T_i$, (so far only on ASDEX Upgrade)
  - all accessible $\rho^*$ values
  - compatible with W walls
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Tuesday: Wall and divertor heat loads

Wednesday: Integrated exhaust scenarios with ELM control

Thursday: QH mode on ASDEX Upgrade and JET

Wednesday: Improved H-mode - ITER hybrid scenario

Thursday: TAE modes using IRCH

Thursday: Characterisation of H-mode barrier

Wednesday: Active control of MHD instabilities

Friday: Understanding of transport phenomena

Friday: Impurity transport and control

Friday: Electron heat transport

Friday: Carbon deposition and inventory

Friday: Density profile evolution

Saturday: Tungsten for main chamber and PFC
Are there inconsistencies with other experiments?

Slowing down of NBI ions is thought to be classical:

TFTR:
• NBI at r/a=0.5, 2 MW beams with 95 keV, no central heating (nearly no radial diffusion of fast ions: \( D < 0.05 \text{ m}^2/\text{s} \)), Efthimion IAEA 1988

JET, TFTR:
• Slowing down of 1 MeV tritons from d(d,p)t:
  - in low temperature plasmas: classical slowing down
  - for long slowing down time: \( D \approx 0.1 \text{ m}^2/\text{s} \)
    (Conroy EPS 1990, Scott IAEA 1991)

DIII-D:
• anomalous fast ion redistribution needed to match stored energy and neutron rate for NBI heating in TRANSP simulations: \( D \approx 0.3 \text{ m}^2/\text{s} \)
Are there inconsistencies with other experiments?

Slowing down of NBI ions is thought to be local, usually concluded from:

- neutron rates
- heat deposition (mostly in low heat flux discharges)

But beam current particularly susceptible to diffusion:
Slowing down particles contribute substantially longer to beam current than to energy density or fusion rate.
beam current particularly susceptible to diffusion; slowing down particles contribute substantially longer to beam current than to energy density or fusion rate

\[ f(t) = \begin{cases} \beta_1 & \text{for } t < 0.015 \\ \beta_2 & \text{for } t \geq 0.015 \end{cases} \]

fractional contribution \( f \) of fast particles to DD-fusion, \( \beta \), and beam current during first \( t \) seconds of their slowing down history

\[ \text{D}-\text{beam, } E_{\text{beam}} = 92\text{keV}, T_e = 1\text{keV}, n = 5 \times 10^{19}\text{m}^{-3} \]

DIII-D: \( D_b = 0.9\text{m}^2/\text{s} \) induced change:

- \(<20\% \text{ in } f_{\text{DD}}\)
- \(>50\% \text{ in } f_{\text{beam}}\)
Re-direction of neutral beam injection system

- strong off-axis deposition by tilt of injection angle
- significant current drive at half radius expected
Higher beam power possible for higher triangularity

low $\delta$ ($\delta \approx 0.15$)  

high $\delta$ ($\delta \approx 0.4$)