Development of the Q=10 Scenario for ITER on ASDEX Upgrade (AUG)

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\textit{25\textsuperscript{th} IAEA Fusion Energy Conference (FEC 2014)
St. Petersburg, Russia, 13-18 October 2014}
Introduction / Motivation

ITER baseline scenario, aims:

- Q~10, producing 500MW of fusion power for 300-500s.

Baseline scenario (BL):

$$15\text{MA}/5.3\text{T}, q_{95}=3, n_e/n_{GW}=f_{GW}=0.85, H_{98}=1, \beta_N \sim 1.8, \text{high } \delta$$

- Working or operation point defined on machines with Carbon wall

- Scenario demonstration at devices with metallic wall like AUG-W (Alcator C-Mod and JET-ILW) in view of ITER is required

- Matching parameters for demonstration on AUG are: $q_{95}$, $f_{GW}$, $H_{98}$, $\beta_N$ (or $P_{\text{heat}}/P_{\text{L-H}}$), $\delta$ and hence NOT $\nu^*$, $\rho^*$
ITER baseline scenario on ASDEX Upgrade (AUG-W)

1.1 MA / 1.8T w. X3 ECRH

- Ramp-up in low $\delta$ configuration
- Stationary discharges as long as enough gas puff and central heating

1.2 MA / 2.0T w. ICRH

FEC 2014, St. Petersburg, Russia, 17 Oct. 2014
J. Schweinzer
Confinement in ITER BL scenario at AUG
(black = AUG-C, low & high δ, coloured = AUG-W, high δ only)

- Existence diagrams for $H_{98y2}$ vs. $f_{GW}$ (left) and $H_{98y2}$ vs. $\beta_N$ (right)
- Rising triangularity improves confinement at higher $n/n_{GW}$
- At low $P_{\text{heat}}$ ($\beta_N \leq 1.8$) confinement $H_{98y2} \leq 0.85$ in AUG-W
Major issue: ELM behaviour

- although significant $D_2$ puff, low $f_{ELM} = 13$ Hz
- $W_{ELM}$ up to 200kJ or 25% of $W_{MHD}$

IR Thermography:
- high heat flux on outer target plate during ELM
Mitigation of ELMs in the ITER BL scenario

ELM mitigation attempts done using:

• pellets for ELM pacing
• nitrogen seeding
• magnetic perturbation (MP) fields
ELM pacing w. pellets in ITER BL scenario in AUG-W

ELM frequency not always elevated by pellets:

- ELM not **reliably triggered**
- ELM size **still very large**
- ELM duration decreased (though ’loss tail’ still present)

Next step: in combination with N-seeding the trigger probablity should go up
Attempt of ELM pacing, with pellets + N-seeding

- N-puff slowly ramped up (t>3.6s) max. level $8 \cdot 10^{21}$ e⁻/s
- 70 Hz Pellets from 4s with reduced D-puff level
- $\Delta W_{\text{ELM}}$ smaller with N
- Pellets increase $f_{\text{ELM}}$
- $c_W$ increase with pellet onset
- Pellets drive discharge towards density limit $f_{\text{GW}} \to 1$

$\Rightarrow$ scenario not stationary yet
Attempt at (R)MP mitigation in ITER Baseline
(MP-coils active in the shaded area)

- ITER BL, MP mitigation not achieved, although \( f_{GW} \sim 1 \)
- low \( q_{95} \) reduces collisionality

ELM mitigation at high density using \( n=2 \), MPs:
- threshold of pedestal top density (or collisionality) has to be exceeded
Demonstration of ITER BL scenario at AUG difficult

Achieved:
• Operation at $q_{95}=3$ demonstrated at $H_{98}=1$, $\beta_N > 2$, $f_{GW} \sim 0.85$

BUT:
• Large ELMs (also observed at JET both JET-C & JET-ILW) - integration of ELM mitigation not achieved until now
• At relevant $P_{\text{heat}} (\sim 1.3 \, P_{L-H})$ confinement $H_{98} \leq 0.85$

$q_{95} = 3$ seems to be a difficult corner in the operational space ->
try to find alternative operational point for $Q=10$
Proposal: Operation could move to higher $q_{95}$ (lower $I_p$)

For scaling (at similar density), keeping $P_{fus}$ and $G$ constant:

(Peeters et al., Nucl. Fusion 47 (2007) 1341–1345)

\[ P_{fus} = 2.77 \left( \frac{\beta_N}{q_{95}} \right)^2 \]

Fusion power normalized to the ITER value

\[ G = \frac{Q}{Q + 5} = 10.8 \frac{H_{98}^3}{\beta_N q_{95}^2} \]

Alternative operation point for $Q = 10$, keeping $P_{fus}$ and $G$ constant

for $q_{95} = 3.6$: $\beta_N \sim 2.2$, $H_{98} = 1.2$ (ITER $I_p \sim 12$ MA)

• Implications for required target density:
  • pedestal $n_e$ as high as possible (for exhaust)
  • higher $n_{e0}/<n_e>$ (w. pellets) to reach $f_{GW} \sim 1$
• Keep high triangularity to reach simultaneously good confinement at high $f_{GW}$
Comparison $q_{95} = 3$ to $q_{95} = 3.6$ at same $P_{\text{heat}}$ (P_{\text{heat}}$ chosen to get $\beta_N \sim 1.8$ for $q_{95} = 3$ case)
Comparison $q_{95} = 3$ to $q_{95} = 3.6$ at same $P_{\text{heat}}$

($P_{\text{heat}}$ chosen to get $\beta_N \sim 1.8$ for $q_{95} = 3$ case)

- same $P_{\text{heat}}$ leads to same $W_{\text{MHD}}$
- $P_{\text{heat}}$ 30% above $P_{L\rightarrow H}$
Comparison $q_{95} = 3$ to $q_{95} = 3.6$ at same $P_{\text{heat}}$

($P_{\text{heat}}$ chosen to get $\beta_N \sim 1.8$ for $q_{95} = 3$ case)

- $q_{95} = 3.6$ scenario allows lower gas puff rate
- $H_{98y2} > 1$
Comparison $q_{95} = 3$ to $q_{95} = 3.6$ at same $P_{\text{heat}}$

($P_{\text{heat}}$ chosen to get $\beta_N \sim 1.8$ for $q_{95} = 3$ case)

- ELM signature similar in both scenarios
- Phase with MP reduces confinement, but does not affect ELMs
Comparison $q_{95} = 3$ to $q_{95} = 3.6$ at same $P_{\text{heat}}$ (\(P_{\text{heat}}\) chosen to get $\beta_N \sim 1.8$ for $q_{95} = 3$ case)

- Same $W_{\text{MHD}}$ confirmed by kinetic profiles
- Same $f_{GW}$, less absolute $n_e$ in $q_{95} = 3.6$ case
- Edge $n_e$ rather similar

Conclusion: Promising performance of 'alternative ITER BL', but ELM behaviour unchanged.
'Alternative ITER BL' plasmas ($q_{95}=3.6$) with and without type-II ELMs

- Closeness to DN configuration (parameter $d_{RXP}$) decisive for switch to type-II ELMs
Alternative ITER BL plasmas \((q_{95}=3.6)\) with and without type-II ELMs

- Parameter \(d_{\text{RXP}}\) changes energy confinement
'Alternative ITER BL' plasmas (q_{95}=3.6)
Nitrogen seeding in phase with type-II ELMs

Nitrogen seeding recovers energy confinement transiently and leads to W accumulation
Type-II ELMs observed in 'alternative ITER BL' plasmas ($q_{95}=3.6$) – typical signature as in the past

- MHD behaviour similar as for the type-II ELMs observed in the past at $q_{95}=5.5$
- Profiles show no significant change in edge gradient
- Type-II ELM pedestal has slightly lower $T_{e,\text{ped}}$ and higher $n_{e,\text{ped}}$

Shape changes are very small:
- Type-I ELMs
- Type-II ELMs

Existence of type-II ELMs extended to $q_{95} = 3.6$ in AUG
Operational range (gas puff level, wall conditions) considerably larger than in $q_{95}=3$ scenario, less prone to W-accumulation.

First results for ‘alternative’ ITER BL (target: $H_{98y2}=1.2$, $\beta_N=2.2$, $f_{GW}>0.9$) promising, but confinement off target by 10%.

Cold divertor operation by N-seeding not yet stationary.
Summary

• $q_{95} = 3$ ITER BL:
  • With 3.8 MW NBI + 1.8 MW ICRH discharge at $\beta_N = 1.8$ established, but $H_{98}$ below 1.

• $q_{95} = 3.6$ ‘alternative ITER BL’:
  • At low $P_{\text{heat}}$ promising performance achieved
  • Extended operational window compared to $q_{95} = 3$
  • Type-II ELMs rediscovered

For both scenarios:

• ELM mitigation techniques still need to be integrated

• Operation with ‘cold divertor’ (by N-seeding) in both scenarios not stationary so far. Attempts with higher puff rates for D and N on the agenda for next experiments
Operation in Helium compared with Deuterium

- **0.8 MA / 1.4 T**, Both discharges performed ~20 days after boronization
- **Deuterium** reference discharge suffers from W-accumulation

Helium discharge shows stable W behaviour
Operation in Helium compared with Deuterium

- **He** plasma has same $n_e$, $T_e$ (and likely same $T_i$, not measured) as D plasma, with 1.5 less particles (both discharges at 0.8 MA / 1.4 T)
- This is consistent with global stored energy ($W_{\text{MHD}}$ in D $\sim$ 1.5 $W_{\text{MHD}}$ in He)
Summary: Helium operation

- A few discharges were performed with the following technical boundary conditions:
  - Helium not pumped by AUG cryo-pumps
  - He-NBI not possible -> D$_2$-NBI used in all discharges
  - Discharges were performed under almost un-boronized wall conditions
- Low current He operation (0.8 MA) even without central wave heating