Quantitative access to Neutral Beam Current Drive Experiments on ASDEX Upgrade

9th IAEA TM on SSO 2017 – Vienna, Austria
21.03.2017

Motivation non-inductive current drive

• Non-inductive current drive is necessary for the extension of Tokamak pulse length
  • ITER from 400 s pulse duration to 3600 s
• Power plant:
  • Increase $\frac{\text{Pulse length}}{\text{Down Time}} \rightarrow$ Increase mean output power
  • Reduce of number of thermal cycles $\rightarrow$ reduce fatigue due thermal stress
• Completely non-inductive current drive $\rightarrow$ stationary Tokamak

• Common non-inductive current drivers:
  • intrinsic Bootstrap current
  • ECCD
  • NBCD
Outline

• ASDEX Upgrade NBI

• Off-axis neutral beam current drive

• Highly non-inductive current scenario

• Conclusion
Beam 6 and 7 are more tangential than the other beams → Higher NBCD efficiency

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<tr>
<th>In Deuterium</th>
<th>NBI Box 1</th>
<th>NBI Box 2</th>
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<tr>
<td>Beam Power</td>
<td>4 x 2.5 MW</td>
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<td>60 keV</td>
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Beam 6 and 7 are more tangential than the other beams → Higher NBCD efficiency

Beam 6 and 7 deposit their energy more off-axis

Beam 3 is used by many diagnostics (e.g. MSE, FIDA)

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Off-axis NBCD experiments on ASDEX Upgrade

- Discrepancy between measured MSE angles and neoclassical TRANSP predictions in earlier NBCD studies
- Better match assuming anomalous fast ion diffusion

Günter S. at al, 2007 Nucl. Fusion 47 920
History of off-axis NBCD experiments on AUG

- Discrepancy between measured MSE angles and neoclassical TRANSP predictions in earlier NBCD studies
- Better match assuming anomalous fast ion diffusion
  Günter S. et al., 2007 Nucl. Fusion 47 920

- FIDA data in good agreement with neoclassical TRANSP predictions
- Anomalous diffusion underestimate FIDA data
Off-axis NBCD: Experimental Setup

Power

On Axis

Off Axis

On Axis

NBI 6 & 7

NBI 5 & 8

NBI 6 & 7

NBI 3 (MSE, FIDA)

ECRH preemptive NTM control

ECRH central ECCD (ST control/avoid W accumulation)

Basic Parameter Set

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$I_p$</td>
<td>800 kA</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$\sim 6 \cdot 10^{19} \frac{1}{m^3}$</td>
</tr>
<tr>
<td>$B_T$</td>
<td>-2.6 T</td>
</tr>
<tr>
<td>$P_{NBI}$</td>
<td>7.5 MW</td>
</tr>
<tr>
<td>$P_{ECRH}$</td>
<td>2.5 MW</td>
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MSE and FIDA measurements

- Small disagreement in offset corrected MSE angles
  - Offset correction to match between 5-6 s value <1° (polarized background)
  - MSE measurement close to absolute calibrate
- FIDA measurement disagree centrally with on-axis NBI deposition
- Maximum positon disagrees during off-axis deposition
NBI Geometry

- Review of the NBI geometry with small changes (IR thermography)
  → Small correction in cm range slightly more off-axis for beam 6 and 7
NBI Geometry

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  → Small correction in cm range slightly more off-axis for beam 6 and 7
Further improvements

- Effective charge of the plasma corrected
  - Measured of main impurities with CXRS
- Mixed up sign for the radial electric field in TRANSP used only for the MSE
  - Error fixed in the TRANSP code
- Still systematic deviation in FIDA during on-axis NBI deposition
MHD activity

- Off-axis phase MHD quiescent
- Fishbone activity during on-axis phase
  ➢ Assumption of anomalous fast ion diffusion at $q<1$ with $0.3 \text{ m}^2/\text{s}$
MHD activity

- Off-axis phase MHD quiescent
- Fishbone activity during on-axis phase
  - Assumption of anomalous fast ion diffusion at $q<1$ with $0.3 \, m^2/s$

#32148

![Graphs showing MHD activity measurements and simulations](image_url)
Alternative anomalous fast ion diffusion model

- Anomalous fast ion diffusion ($\rho$, $t$, $E$) due to electrostatic and electromagnetic micro turbulence
- Assumptions from GENE based calculations in comparable regimes
  
  \[ M.J. \text{ Pueschel et al., NF 52 (2012)} \]

  \[ 103018 \]

- Diffusion value in same order of magnitude

- Not jet clear if diffusion came from fishbones or em/es-micro turbulence

- Central anomalous fast ion diffusion does not effect the overall amount of NBCD
Highly non-inductive Scenario

- Feedback controlled $\beta_{\text{pol}}$-ramp 2-3.5 s by NBI
- Off-axis NBCD/ECCD $\rightarrow$ hollow current profile
- High $T_e$ ($\sim$5-6 keV)
  $\rightarrow$ High NBCD and bootstrap efficiency
- From 4.5s fixed current in central solenoid

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Highly non-inductive Scenario

Feedback controlled $\beta_{pol}$-ramp 2-3.5 s by NBI
Off-axis NBCD/ECCD $\rightarrow$ hollow current profile
High Te (~5-6 keV)
$\rightarrow$ High NBCD and bootstrap efficiency
From 4.5s fixed current in central solenoid
TRANSP underestimate the loop voltage

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Review of the TRANSP simulation

- Corrected NBI geometry
- Correction in mapping of the kinetic profiles
Review of the TRANSP simulation

- Corrected NBI geometry
- Correction in mapping of the kinetic profiles
- Additional NBI with constant $\beta$?

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Current [kA]

800
600
400
200
0

Time [s]

1 2 3 4 5 6 7 8

Power [MW]

14
12
10
8
6
4
2
0

Time [s]

1 2 3 4 5 6 7 8

$\beta_{pol}$

3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
MHD activity

- From 4.5 s on a 3/2 NTM appears
- $\beta_{\text{pol}}$ decrease compensated by NBI
- deviation from neoclassical TRANSP predictions
Anomalous fast ion diffusion

- Assumption of anomalous fast ion diffusion
  local transport does not force fast ion losses
  → Better agreement in FIDA
  → MSE comparison slightly better
Anomalous fast ion diffusion

- Predicted non-inductive current fraction decrease assuming anomalous fast ion diffusion
- Disagreement in diamagnetic flux measurement disappear
- Loop voltage comparison not very conclusive
The 3/2 NTM leads to fast ion losses, in TRANSP modeled by assuming anomalous fast ion diffusion (as a tool). Fast ion losses contribute to the non-inductive driven current decrease:

- $H_{98}$ decrease below 1
- Increasing NBI compensates fast ion losses
- NBCD efficiency decrease
- Bootstrap current fraction decrease

NTM degrading confinement and the non-inductive driven current
Conclusion

• Overall driven NBCD not affected by central fast ion redistribution
  • Modeled by assumption of anomalous fast ion diffusion
  • Measurable with the FIDA diagnostic
  • MSE diagnostic not very sensitive to fast ion redistribution
    • Changes in profile of the total current are small
• Small NBI geometry changes lead to changes in the overall NBCD
  • NBCD is very sensitive to minor changes in the NBI geometry especially
    the tangential off-axis sources
• NTMs degrade confinement and non-inductive current drive
  • Degradation of the confinement and kinetic profiles
  • Fast ion losses forced by orbit stochastisation
  • Non-inductive driven current is strongly reduced

➤ NTM induced confinement degradation and non-inductive current reduction could be a major issue for steady state tokamak operation
BACK UP SLIDES
### Further off-axis NBCD Investigations

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<tr>
<th>Experiment</th>
<th>Result investigation of off-axis NBCD</th>
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<tr>
<td>MAST</td>
<td>Non neoclassical current profile broadening due to off-axis NBCD</td>
</tr>
<tr>
<td>JT60U</td>
<td>NBCD in good agreement for current profile reconstruction with neoclassical predictions for wide beam energy range</td>
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<td>For high NBI power: Assumption of anomalous fast ion diffusion is the best prediction</td>
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<tr>
<td>ASDEX Upgrade</td>
<td>Anomalous fast ion diffusion for high power and low triangularity</td>
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<tr>
<td>ASDEX Upgrade</td>
<td>Neoclassical for high triangularity</td>
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Quantitative estimate of anomalous fast ion diffusion due to electrostatic and electromagnetic micro-turbulent transport

Based on gyrokinetic (GENE) simulations

Energy-averaged above 20 keV

\( \chi_{\text{eff}} \): effective heat diffusivity, \( \eta \): fast ion pitch angle, \( E \): fast ion energy, \( \beta \): Plasma beta, \( \beta_{\text{crit}} \): critical beta w.r.t. KBMs, \( T_e \): Electron Temperature

\[
D_{\text{fi,p}}^{es} \approx \frac{\sigma_{\text{es,p}} \cdot \chi_{\text{eff}}}{\eta^2} \cdot \left( \frac{E}{T_e} \right)^{-1}
\]

\[
D_{\text{fi,p-FLR}}^{es} \approx \frac{\sigma_{\text{es,p-FLR}} \cdot \chi_{\text{eff}}}{\eta^2 \cdot (1 - \eta^2)^{1/2} \cdot \left( \frac{E}{T_e} \right)} \cdot \left( \frac{E}{T_e} \right)^{-3/2}
\]

\[
D_{\text{fi,p}}^{em} \approx \frac{\sigma_{\text{em,p}} \cdot \chi_{\text{eff}} \cdot \left( \frac{\beta}{\beta_{\text{crit}}} \right)^2}{(1 - \eta^2)^{1/2}}
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\]
Infrared Measurement