Advances in the high bootstrap fraction regime on DIII-D towards the Q=5 mission of ITER steady state

By
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Q=5 of ITER steady state is addressed based on the extended DIII-D high bootstrap fraction scenario

\[ f_{\text{bootstrap}} \sim \beta_P \sqrt{\varepsilon} \]

- High bootstrap current fraction addresses key challenge for steady-state operation: minimizes need for external current drive
Previous EAST/DIII-D joint experiment has demonstrated high bootstrap fraction regime with good confinement for

\[ I_p \text{ (MA)} \]

\[ \beta_N \]

\[ \beta_T \% \]

\[ H_{\psi y2} \]

\[ T_{i,p-0.5} \text{ (keV)} \]

\[ T_{e,p-0.5} \text{ (keV)} \]

\[ P_{\text{NBI}} \text{ (MW)} \]

\[ P_{\text{ECCD}} \text{ (MW)} \]

\[ \Omega \left(10^4 \text{ rad/s}\right) \]

\[ 0 \leq \rho \leq 1 \]

\[ T_i \text{ (keV)} \]

\[ T_e \text{ (keV)} \]

\[ \text{Shot 154406 time: 5200.000±10.} \]

\[ \text{Garofalo et al., IAEA FEC 2014} \]

\[ \text{Gong et al., IAEA FEC 2014} \]

\[ \text{Ren et al., APS 2015} \]

\[ \text{Pan et al., TTF 2016} \]

\[ \checkmark \text{ Excellent confinement quality associated with formation of ITB at large minor radius} \]
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- **DIII-D high \( \beta_P \) scenario**
  - High bootstrap current (~80%)
  - High confinement with large radius ITB

- **ITER steady state requires:**
  - Good confinement at low torque
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![Graph showing Scaled Fusion Power Versus Self-Driven Current Fraction with curves for different qₗ₉ values and markers for ITER, ITER SS, ARIES ACT-1, DIII-D 2014, and DIII-D 2016.]
Recent experiment shows large radius ITB, good confinement can be maintained at extended operational regime

- Extension of DIII-D high $\beta_p$ scenario to low rotation near ITER NBI equivalent torque
- Shafranov shift has key stabilizing effect on turbulence transport
- Investigation on lower $q_{95}$ confirmed shafranov shift effect
- Extrapolation of DIII-D high $\beta_p$ scenario to ITER steady state
Recent experiment confirmed high confinement can be achieved near ITER NBI equivalent torque

- **High $\beta_p$ scenario**
  - $q_{95} \sim 12$
  - High $f_{bs} \sim 80\%$
  - Nearly fully non-inductive

- **High confinement**
  - $H_{98y2} \sim 1.8$

- **Low toroidal rotation**
  - Reduced torque $T_{\text{inj}} \sim 1.5\,\text{Nm}$
  - Close to DIII-D ITER equivalent NBI torque

- **No strong impurity accumulation**
Large radius ITB is maintained at low toroidal rotation

- Similar $T_e$ profiles with large radius ITB in high and low toroidal rotation
- High rotation shear does not align with $T_e$ ITB
- Toroidal rotation is not the dominant effect on the formation of the ITB
Large radius ITB is maintained at low toroidal rotation
No ion turbulence near ITB at high and low toroidal rotation

- Ion scale turbulence measurements from Beam Emission Spectroscopy
Ion energy transport is dominantly neoclassical

- Evolving just the ion temperature predicted from TGLF + NEO
- Neoclassical transport is the dominant ion energy flux
- Small change in predicted Ti with/without EXB

Energy flux is not sensitive to EXB shear

![Graph showing energy flux comparison with and without EXB shear at BC rho=0.8](image-url)
Modeling shows shafranov shift stabilize ion turbulence

- EFIT creates a series of equilibria with scaled pressure profiles
- Calculations focus on ITB region, rho~0.63 with TGLF and NEO
- Turbulent ion energy fluxes by TGLF decrease with the increasing $\beta_P$

\[
\text{Shafranov shift} \propto \beta_P + \frac{l_i}{2}
\]
Recent $\beta_P$ Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization

- Ramp down of $\beta_P$ obtained with feedback control of the NBI heating power
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- Ramp down of $\beta_p$ obtained with feedback control of the NBI heating power
- ITB becomes weaker and disappears when lowering $\beta_p$
- Ion-scale fluctuations increase as $\beta_p$ reduced
To achieve $Q=5$ Mission of ITER-SS requires lower $q_{95}$

- **Using GA 0-D model**
  - $H_{98y2}=1.6, f_{BS}=80\%$
  - $P_{aux}=73$ MW, $B_T=5.3$ T

- **Reducing $q_{95}$ increases the fusion power**

- **Question:** lower $q_{95}\rightarrow$ lower betaP$\rightarrow$lower shafranov shift
  - Can $H_{98y2}>>1.0$ be maintained?
Good confinement plasmas are also achieved when lowering $q_{95}$

- **Second Ip ramp-up**
  - $I_p$ 0.6MA $\rightarrow$ 1MA
  - $q_{95}$ 11 $\rightarrow$ 6.5
- **Good confinement**
  - $H_{98y2}$ > 1.5 at $q_{95}$ > 7.0
  - Confinement decreases due to weaker ITB
Large radius ITBs can be maintained at reduced $q_{95}$

- A broad current profile was achieved at reduced $q_{95}$
- $T_e$ profiles with large radius ITB are produced at high and low $q_{95}$
- Higher plasma current has a higher core $T_e$
Large radius ITBs can be maintained with sufficient shafranov shift stabilization effect

- Higher $\beta$ or higher $q_{95}$ $\rightarrow$ stronger shafranov shift $\rightarrow$ better for ITB formation
DIII-D high $\beta_p$ scenario profiles are scaled to ITER according to 0D modeling results

0D modeling (assuming $H_{98y2}=1.6$):

$\rightarrow I_P, T_e(0), T_i(0), n_e(0)$
TGLF indicates Shafranov shift is not sufficient for ITB in ITER

- Evolved $T_i$ is much lower than the scaled temperature
- ITB disappears
TGLF indicates Shafranov shift is not sufficient for ITB in ITER. Larger negative magnetic shear recovers ITB, enables Q=5.

- Increase $q(0)$ to 7 at constant pressure
- Improved confinement with turbulence suppressed
- Q=5 achieved with high $T_e$ and $T_i$
Summary: DIII-D high $\beta_p$ scenario shows promising path for long pulse fully non-inductive scenario on ITER

- Large radius ITB and excellent confinement maintained at reduced rotation or $q_{95}$

- Transport analyses suggest that EXB shear has little contribution to turbulence suppression, while Shafranov shift has the stabilizing effect on the turbulence.

- 0-D and 1.5-D modeling analyses indicate high bootstrap scenario can be a candidate for $Q=5$ of ITER steady state.