Introduction

- Plasma startup on ITER will be in limiter configuration on the inner wall (IW) [1]
- TF ripple on lower HFS
- Lower 3D fields due to eddy currents induced in UV
- Plasma better located in EC-assist resonance location
- Typical time to reach $i_b \sim 3.0$ MA for X-point formation $\sim 10$ s
- Happens on every shot
- Important that IW beryllium First Wall Panels (FWP) can tolerate the peak surface power fluxes ($q_{\text{peak}}$)
- $q_{\text{peak}}$ very sensitive to FWP alignment

Blanket alignment fundamentals

- Two main FW misalignments:
  - Shortwave (SW) \rightarrow between neighbouring FWPs
  - Longwave (LW) \rightarrow between circle of FWPs and toroidal field (TF)
- ITER IW Blanket alignment requirement:
  \[ \Delta R \leq 5 \text{ mm} \]
- Key assembly alignment target:
  - Provide most uniform possible distribution of gaps between TF coil (TFC) inner legs
  - Target is 2 mm gap

5-step assembly process:
1. Machine datum (MD) starts from the Site Datum (SD).
2. SD transfers to Tokamak Global Coordinate System (TGCS).
3. TGCS transfers to Crystall base Datum (CBD), based on as-built position of the Crystall base.
4. CBD transfers to the Tokamak Assembly Datum (TAD) based on the geometrical equivalent axis of as-assembled TFCC. All other components aligned to TAD.
5. Blanket Shield Modules (BSM) are accurately aligned to the MD defined by TAD, together with magnetic field measurements to be made during the First Plasma (FP) phase.
- Anticipate assembled machine configuration as component and assembly data become available \rightarrow use Reverse Engineering simulations to control the full chain of tolerances during final assembly

FWP heat loads: SW and LW misalignment

- ITER Blanket Heat Load Spec. \rightarrow IW FWPs in start-up region must allow $I_p \leq 5$ MA and $P_{\text{SOL}} \leq 5$ MW [4]
- Use SMITER field line tracing code [5] to assess FWP surface heat loads for specified $q(r)$ at outer midplane

SW misalignment:
- For $R_{\text{q,peak}}$ increasing $\lambda_{\text{SW}}$ increases wetted area of misaligned panel \rightarrow $q_{\text{peak}}$ constant but total power to FWP increases by factor $\sim 3.5$ for $\Delta R \leq 5$ mm
- For fixed $\lambda_{\text{SW}} \leq 5$ mm, narrow heat flux channel plays bigger role but $q_{\text{peak}}$ still tolerable even for $R_{\text{q,peak}} = 8$

LW misalignment ($n = 1$):
- $q(r)$ formula may be modified to satisfy power balance:
  \[ q \sim \frac{1}{\left(1 - \frac{r}{a}\right)^n} \]
  \[ \frac{q_{\text{near}}}{q_{\text{near},\text{FWP}}} \sim \frac{1}{\left(1 - \frac{r}{a}\right)^n} \frac{1}{\left(1 - \frac{r}{a}\right)^n} \]
- Since $\lambda_{\text{SW}} \sim \lambda_{\text{SW},\text{midplane}} \sim \lambda_{\text{SW},\text{FWP}} \ll \lambda_{\text{LW}}$, LW misalignment amplifies heat flux mainly in the narrow channel
- For $R_{\text{q,peak}} = 4$, $q_{\text{peak}} \sim 4.8$ MWm$^{-2}$ at $\lambda_{\text{LW}} = 5$ mm \rightarrow exceeds FWP power handling (\sim 25% faceting penalty)
- $\lambda_{\text{LW}} \sim 3$ mm more prudent alignment target
- If $\lambda_{\text{LW}} = 0$, $q_{\text{peak}}$ insensitive to $\lambda_{\text{LW}}$, but for max. allowed $\lambda_{\text{LW}}$, $q_{\text{peak}}$ increases rapidly for $\lambda_{\text{LW}} \sim \lambda_{\text{LW},\text{midplane}}$ gets worse if $R_{\text{q,peak}} >$ design value (4)
- SW misalignment not an issue for $q_{\text{peak}}$ even if $\lambda_{\text{LW}} > 0$

Measuring the TF structure

- What if TF inner leg gap distribution is not perfectly uniform?
- Radial TFC displacement will vary from coil to coil after energization
- Use FE simulations of a full 18 TFC model with different example gap distributions, including pre-compression and energization
- Final TFC coil radial positions into KLONDIKE code [6] with Coil Centre Line approximation and compute toroidal variation of field line deviation from ideal circle
- Field structure no longer $n = 1$ \rightarrow need measurement to guide final IW Blanket alignment
- Planned on ITER before FP using array of custom built Nuclear Magnetic Resonance (NMR) sensors
- Analytic model developed to assess TF Mapping diagnostic \rightarrow Fourier decomposition of perturbed field into M toroidal harmonics \rightarrow gives radial deviation of field lines at IW FWP location ($r = a_s$) based on measurements at 18 sensors located at $r = a_s$:

18 TFC FE model

KLONDIKE code

TF Mapping diagnostic:
- 27 NMR probes, 18 near IW midplane (centre of FWP #4), 9 at centre of FWP #5 \rightarrow toroidally at TFC centres
- Prototype glycercol Pulse Wave sensor already demonstrated:
  - Field range: 3.5 \rightarrow 5.5 T
  - Field gradient: 12.3 mTcm$^{-1}$
  - Accuracy: 5% T
- Operation at 100°C, tolerant to 200°C
- Target measurement at FP with $B_T = 2.65$ T (4.5 T at sensor)

Conclusion

- Inner wall limiter plasma ramp-up the default on ITER \rightarrow power fluxes on shaped IW FWPs will be particularly sensitive to SW misalignments between FWP ring and $B_T$
- Depending on parameters describing SOL $q(r)$, baseline LW ($n = 1$) alignment requirement is marginal for FWP heat fluxes \rightarrow target should be tightened to $\Delta r_{\text{FWP}} \leq 3$ mm
- If toroidal field coil inner leg gaps not uniform after assembly, final TF will have harmonic structure and LW alignment target will have to be modified
- An NMR-based TF Mapping diagnostic is in preparation to measure inboard field structure at First Plasma and support metrology estimates of VV to TF alignment.

References