Strategy for first wall power flux management during plasma current ramp-up on ITER

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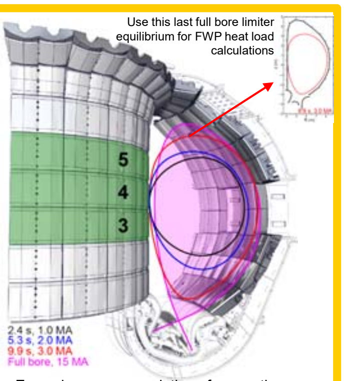
Introduction

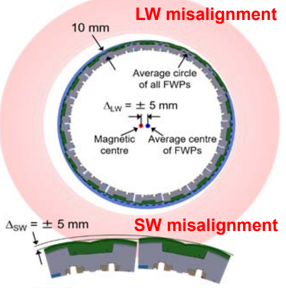
- Plasma start-up on ITER will be in **limiter configuration on the inner wall (IW)** [1]
  - TF ripple lower on HFS
  - Lower 3D fields due to eddy currents induced in VV
  - Plasma better located in EC-assist resonance location
- Typical time to reach I_p ~3.0 MA for X-point formation ~10 s
- Happens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



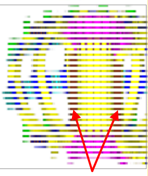
Example ramp-up evolution of magnetic equilibrium from DINA code [2]

Blanket alignment fundamentals

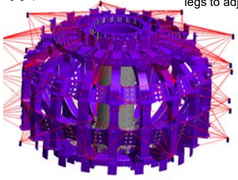
- Two main FW misalignments:
  - Shortwave (SW) → between neighbouring FWPs
  - Longwave (LW) → between circle of FWPs and toroidal field (TF)
- ITER IW Blanket alignment requirement:
  - $\Delta_{SW} \leq \pm$ **5 mm**
  - $\Delta_{LW} \leq \pm$ **5 mm** → assumes n = 1 displacement between TF and central column (admits existence of a "magnetic centerline")
- **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 Cryostat Base Datum (CBD), based on as-built position of the Cryostat Base.
  4. CBD transfers to the Tokamak Assembly Datum (TAD) based on the geometrical equivalent axis of as-assembled TFC. 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 → use Reverse Engineering simulations [2] to control the full chain of tolerances during final assembly



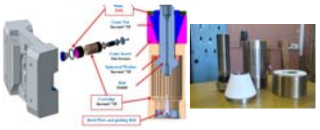
Total accumulated TFC inner leg gaps must = 36 mm



Shims used on inner legs to adjust spacing



TAD reference datum based on as-built TFC torus



4 flexible cartridges attached each shield block to VV wall and can be custom adjusted over a 15 mm range to allow blanket alignment [3]

IW FWP toroidal shaping

- Optimized for double exponential parallel SOL heat flux profile → narrow near-SOL feature expected for IW limiter plasmas [1]:

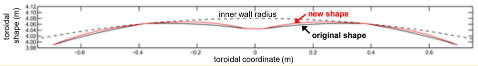
$$q_{||}(r) = q_{||0,near}e^{-\Delta r_{LCFS}/\lambda_{q,near}} + q_{||0,main}e^{-\Delta r_{LCFS}/\lambda_{q,main}}$$

$$q_{||0,main} = \frac{P_{SOL}}{4\pi R_{OMP}(\lambda_{q,main} + R_q\lambda_{q,near})\left(\frac{B_{pol}}{B_{tot}}\right)_{OMP}}$$

$$\boldsymbol{R_q \equiv q_{||0,near}/q_{||0,main}}$$

OMP=outer midplane

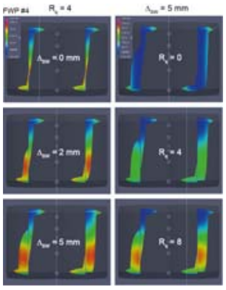
  - Experimental scalings give R_q = 4, $\lambda_{q,near,IW}$ = 4 mm, $\lambda_{q,main,IW}$ = 50 mm for ITER → IW FWP shape is a double logarithmic contour
  - Shaping re-designed in 2014 after narrow feature discovered
  - Max. stationary power flux = 4.7 MWm^{-2} for IW FWPs



Complexities of designing an actively cooled component means that real FWP shape is an approximation to the analytic contour → surface is "facetted" → heat flux penalties

FWP heat loads: SW and LW misalignment

- ITER Blanket Heat Load Spec. → IW FWPs in start-up region must allow $I_p \leq$ 5 MA and $P_{SOL} \leq$ 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 fixed R_q, increasing Δ_{SW} increases wetted area of misaligned panel → $q_{\perp,peak}$ ~constant but total power to FWP increases by factor ~3.5 for Δ_{SW} = 5 mm
  - For fixed Δ_{SW} = 5 mm, narrow heat flux channel plays bigger role but $q_{\perp,peak}$ still tolerable even for R_q = 8



$\lambda_{q,near,IW}$ = 4 mm, $\lambda_{q,main,IW}$ = 50 mm, I_p = 5 MA, B_φ = 5.3 T, P_{SOL} = 5 MW, Δ_{LW} = 0

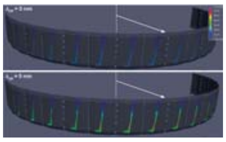
- **LW misalignment (n = 1):**
  - $q_{||}(r)$ formula must be modified to satisfy power balance:

$$q_{||0,near}^{misalign} = \frac{\pi e^{\Delta_{LW}/\lambda_{q,near}}}{I(\Delta_{LW}/\lambda_{q,near})} q_{||0,near}^{align}$$

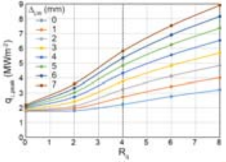
$$q_{||0,main}^{misalign} = \frac{\pi e^{\Delta_{LW}/\lambda_{q,main}}}{I(\Delta_{LW}/\lambda_{q,main})} q_{||0,main}^{align}$$

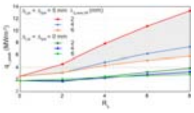
$$I(\Delta_{LW}/\lambda_q) = \int_0^{\pi} e^{\Delta_{LW}cos\varphi/\lambda_q}\, d\varphi$$

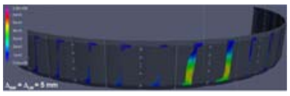
  - Since $\Delta_{LW} \approx \lambda_{q,near} \approx$ mm << $\lambda_{q,main}$, LW misalignment amplifies heat flux mainly in the narrow channel
  - For R_q = 4, $q_{\perp,peak}$ ~4.8 MWm^{-2} at Δ_{LW} = 5 mm → exceeds FWP power handling (+ ~25% faceting penalty)
  - Δ_{LW} ~ 3 mm more prudent alignment target
  - If Δ_{LW} ~ 0, $q_{\perp,peak}$ ~insensitive to $\lambda_{q,near}$ but for max. allowed Δ_{LW}, $q_{\perp,peak}$ increases rapidly for $\lambda_{q,near}$ < design value (4 mm) → gets worse if R_q > design value (4)
  - SW misalignment not an issue for $q_{\perp,}$ even if Δ_{LW} > 0



$\lambda_{q,near,IW}$ = 4 mm, $\lambda_{q,main,IW}$ = 50 mm, I_p = 5 MA, B_φ = 5.3 T, P_{SOL} = 5 MW, Δ_{SW} = 0







Measuring the TF structure

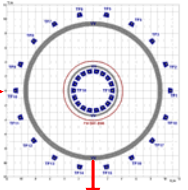
- What if TFC inner leg gap distribution is not perfectly uniform?
  - Radial TFC displacement will vary from coil to coil after energization
  - Use FE simulations of a full 18 TFC model with different example gap distributions, including pre-compression and energization
  - Final TFC coil radial positions into KLONDIKE code [6] with Coil Centre Line approximation and compute toroidal variation of field line deviation from ideal circle

V0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
V1	1	1	2	1	1	7	4	1	1	3	1	0	10	1	0	1	0	1
V2	1	2	3	4	5	6	7	0	0	0	1	1	1	1	1	1	1	1
V3	0	0	0	0	0	0	2	2	2	2	2	2	4	4	4	4	4	4

4 cases (V0-V3) of 18 TFC inner leg gap distributions (in mm) used in the FE coil locking simulations. Case V0 is the ideal situation in which assembly leads to a perfectly uniform gap distribution.

18 TFC FE model

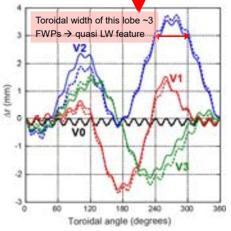
KLONDIKE code



- Field structure no longer n = 1 → 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 → Fourier decomposition of perturbed field into M toroidal harmonics → gives radial deviation of field lines at IW FWP location ($r = a_{fw}$) based on measurements at 18 sensors located (at $r = a_s$):

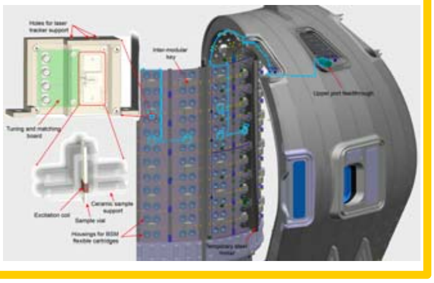
$$\Delta r(\varphi) = \frac{a_{fw}}{B_0(a_{fw})}\left\{\frac{B_N(a_{fw})}{N}[cos(N\varphi) - 1] + \sum_{m=1}^{M}\frac{B_m(a_{fw})}{m}[cos[m(\varphi - \varphi_m)] - cos(m\varphi_m)]\right\}$$

$$B_0(a_{fw}) = \frac{\mu_0 N I_{TFC}}{2\pi a_{fw}} = \frac{B_{max}(a_{fw}) + B_{min}(a_{fw})}{2}, B_N(a_{fw}) = \frac{B_{max}(a_{fw}) - B_{min}(a_{fw})}{2}, B_m(a_{fw}) = B_m(a_s)\left(\frac{a_s}{a_{fw}}\right)^{m+1}$$



Dashed lines → reconstructed radial deviations of field lines using analytic model → differences are ≲ 0.5 mm

- **TF Mapping diagnostic:**
  - 27 NMR probes, 18 near IW midplane (centre of FWP #4), 9 at centre of FWP #5 → toroidally at TFC centres
  - Prototype glycerol Pulse Wave sensor already demonstrated:
    B field range: 3.5 → 5.5 T
    Field gradient: 12.3 mTcm^{-1}
    Accuracy: 5x10^{-5} T
  - Operation at 100°C, tolerant to 200°C
  - Target measurement is at FP with B_φ = 2.65 T (= 4.5 T at sensor)



Conclusion

- Inner wall limiter plasma ramp-up the default on ITER → power fluxes on shaped IW FWPs will be particularly sensitive to LW misalignments between FWP ring and B_φ.
- Depending on parameters describing SOL q||(r), baseline LW (n=1) alignment requirement is marginal for FWP heat fluxes → target should be tightened to $\Delta_{LW} \leq \pm$ 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

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