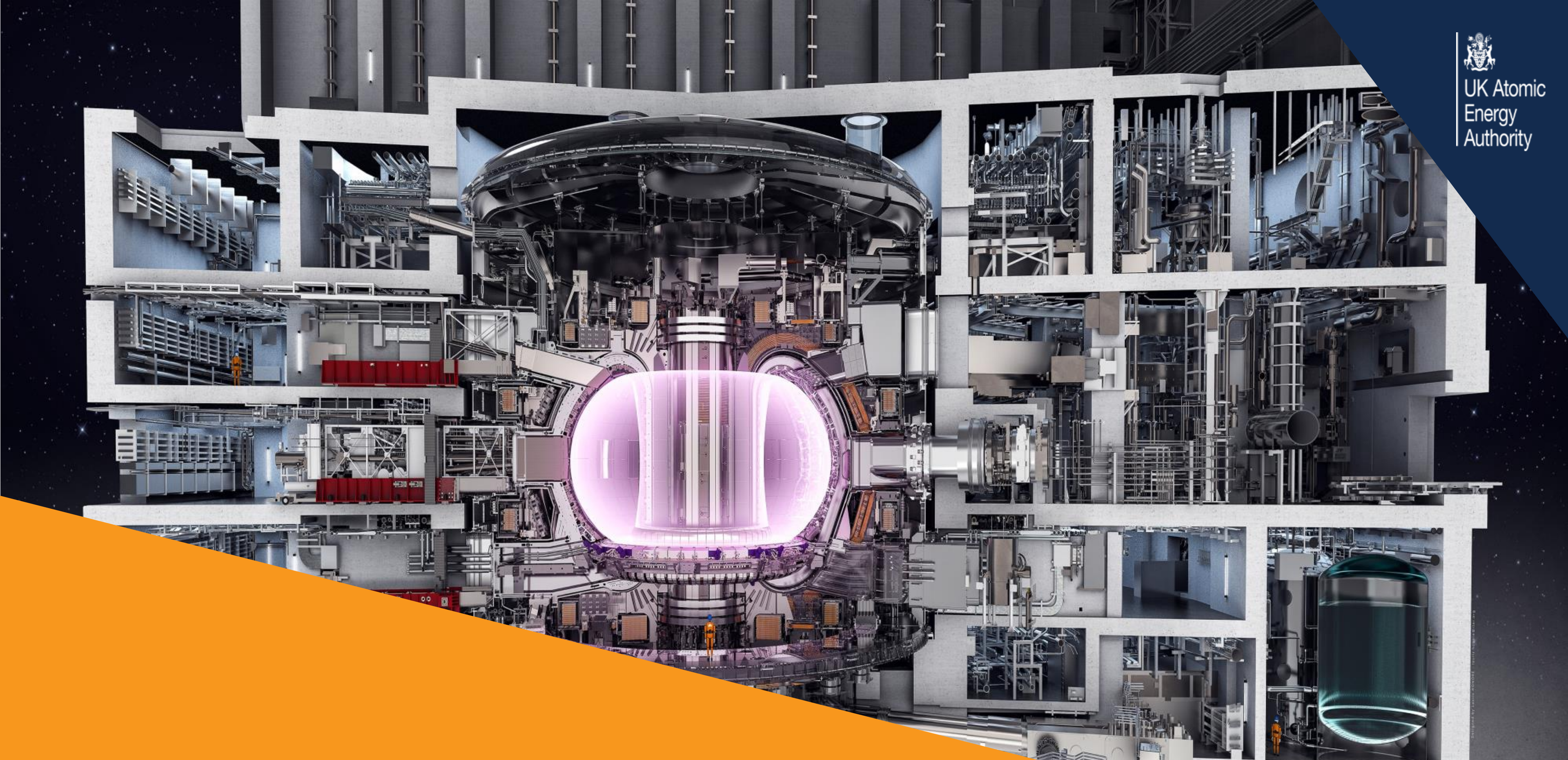

# Global Plasma Simulations for ITER Scenario Development

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# ITER Research Plan: From first plasma to producing 500MW of fusion power

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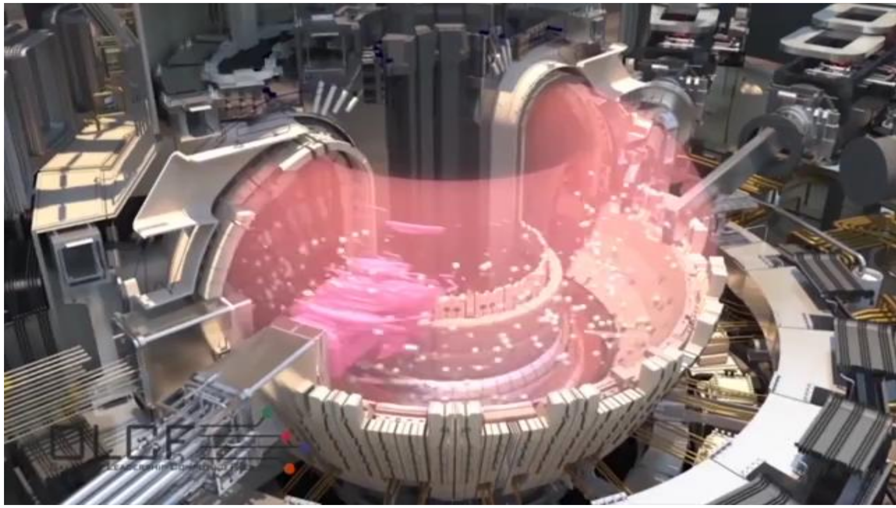
| Dec 2025 | Dec 2028 – Jun 2030 | June 2032 – March 2034 | Dec 2035 |
|---|---|---|---|
| First plasma | Pre-Fusion Power Operation (PFPO) Phase 1 & 2<br>Hydrogen and Helium plasmas | | Fusion Power Operation (FPO)<br>Aim: DT Q=10 plasmas |

The ultimate aim of ITER is to produce 500MW of fusion power from 50MW of input heating power for 500s.

- PFPO goals:
  - Commission ITER systems.
  - Exploration of operational space and plasma scenario development to achieve best possible plasma performance in FPO.
- Main priorities:
  - Longevity of the divertor
    - ➢ Divertor power loads <10MWm$^{-2}$
    - ➢ Minimise W sputtering
  - Limit W transport into the core plasma



**Available actuators:**
**Heating, fuelling and Ne seeding.**

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# JINTRAC – A state-of-the-art tool for integrated modelling of the whole plasma

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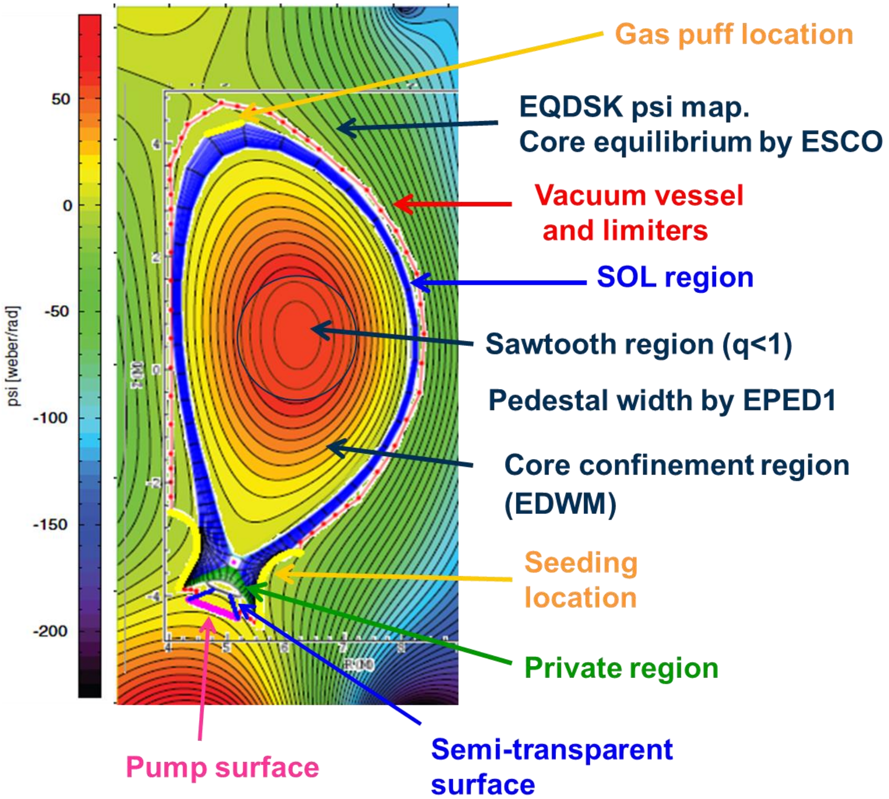
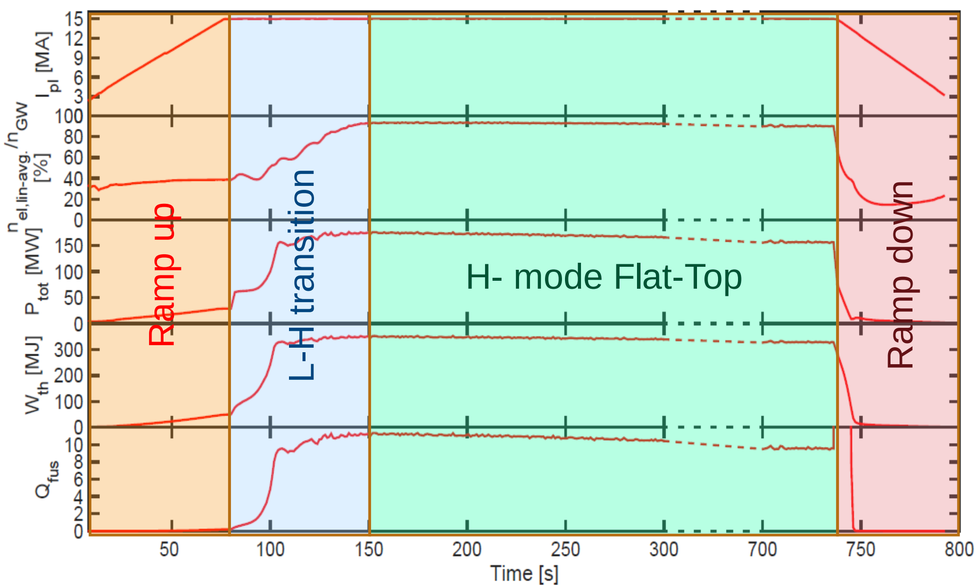
- JINTRAC can perform core/edge/SOL/divertor integrated simulations across all phases of a discharge.




- LH power threshold for $f_{GW}$>40%
  - $P_{\mathrm{LH}}^{\mathrm{D}} \propto n_{\mathrm{e}20}^{0.8} B_{\mathrm{T}}^{0.8} S^{0.9} M^{-1}$
  - $P_{\mathrm{LH}}^{\mathrm{H}} = 2 \times P_{\mathrm{LH}}^{\mathrm{D}}$
  - $P_{\mathrm{LH}}^{\mathrm{He}} = 1.4 \times P_{\mathrm{LH}}^{\mathrm{D}}$
  - $P_{\mathrm{LH}}^{\mathrm{H+He}} = 0.85 \times P_{\mathrm{LH}}^{\mathrm{H}}$

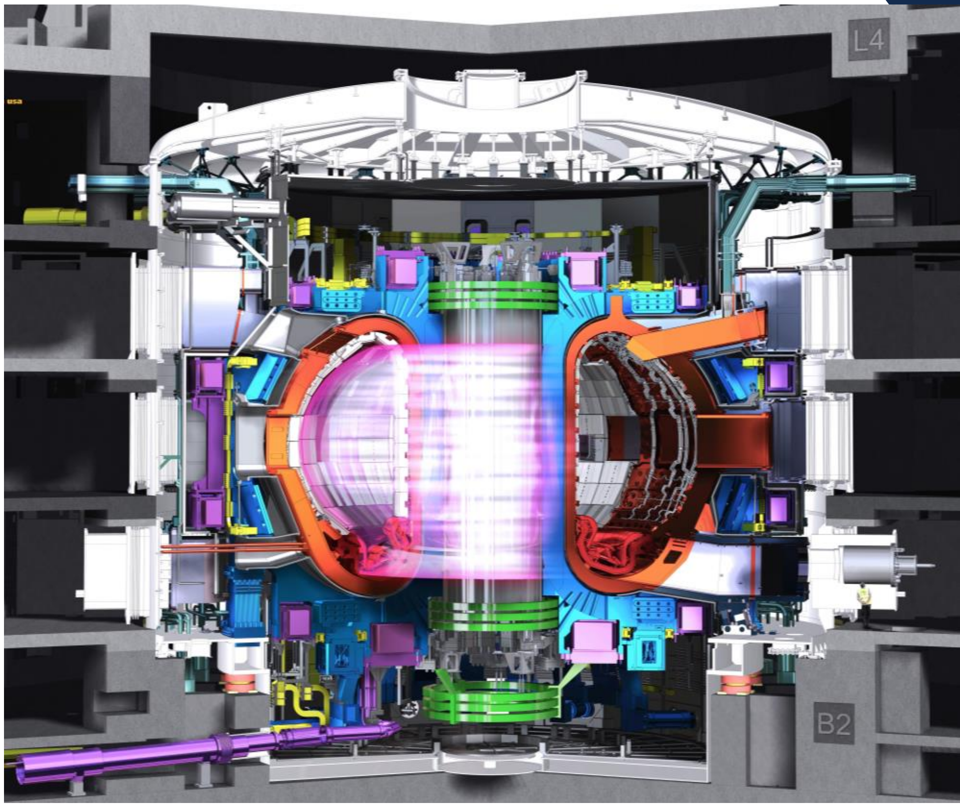

Martin Y. R. et al. 2008 *Journal of Physics: Conference Series* **123** 012033, Righi E. et al. 1999 *Nucl. Fusion* **39** 309, Ryter F. et al. 2009 *Nucl. Fusion* **49** 062003,Gohil P. et al. 2011 *Nucl. Fusion* **51** 103020, McDonald D.C. et al. 2011 *EFDA-JET report* No. EFDA–JET–CP(10)08/24, Maggi et al 2014 Nucl. Fusion 54 023007, J.C. Hillesheim IAEA FEC 2018


F. Köchl, IAEA FEC 2018 EX/P7-25

# PFPO-1:
# Initial H-mode plasmas at 5MA/1.8T

- Hydrogen & Helium discharges at 5MA/1.8T
  - 20-30 MW ECRH heating.
- Assess feasibility to sustain robust type-I ELMy H-modes
- Low density - just above the minimum density for H-mode access.

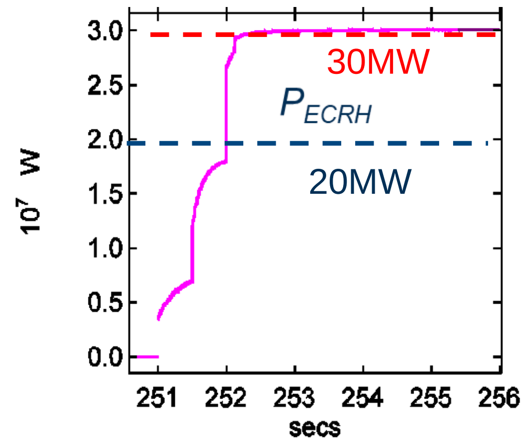


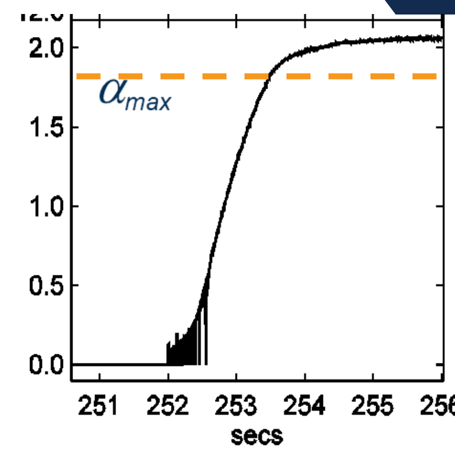

- Problem with divertor power loads?
- Problem with ECRH absorption?
- Problem with core impurity accumulation?

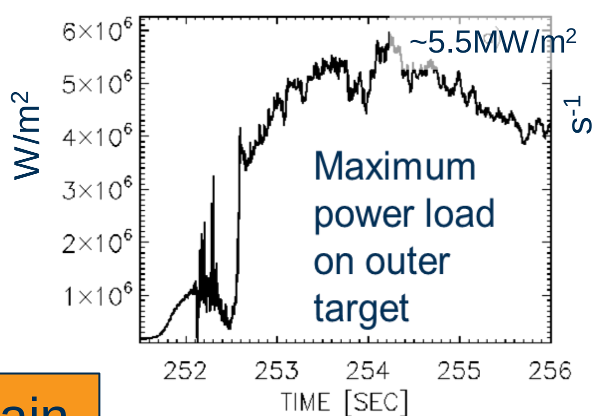
# H-mode access in ITER 5MA/1.8T Hydrogen plasma with 30MW ECRH

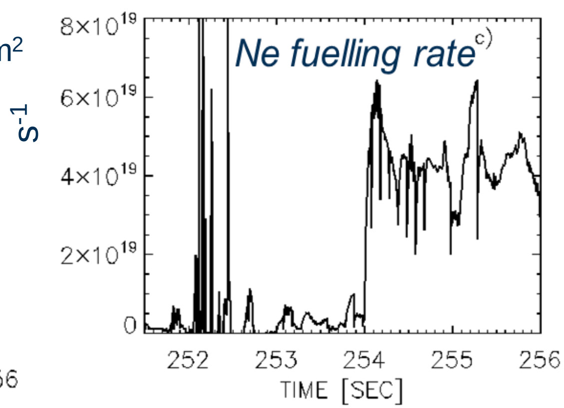


- Low density: $n_{el}$= 1.2-1.9x$10^{19}$$m^{-3}$
  - Thermal decoupling of electrons and ions
    - Te > 10keV
    - Full ECRH absorption!
- Ne seeding
  - Keeps maximum power load acceptable
  - 1.5MW core radiation
- W @256s:
  - sputtering yield minimal
  - Core $\langle n_W/n_H \rangle \sim 1\text{x}10^{-6}$
  - 1MW core radiation



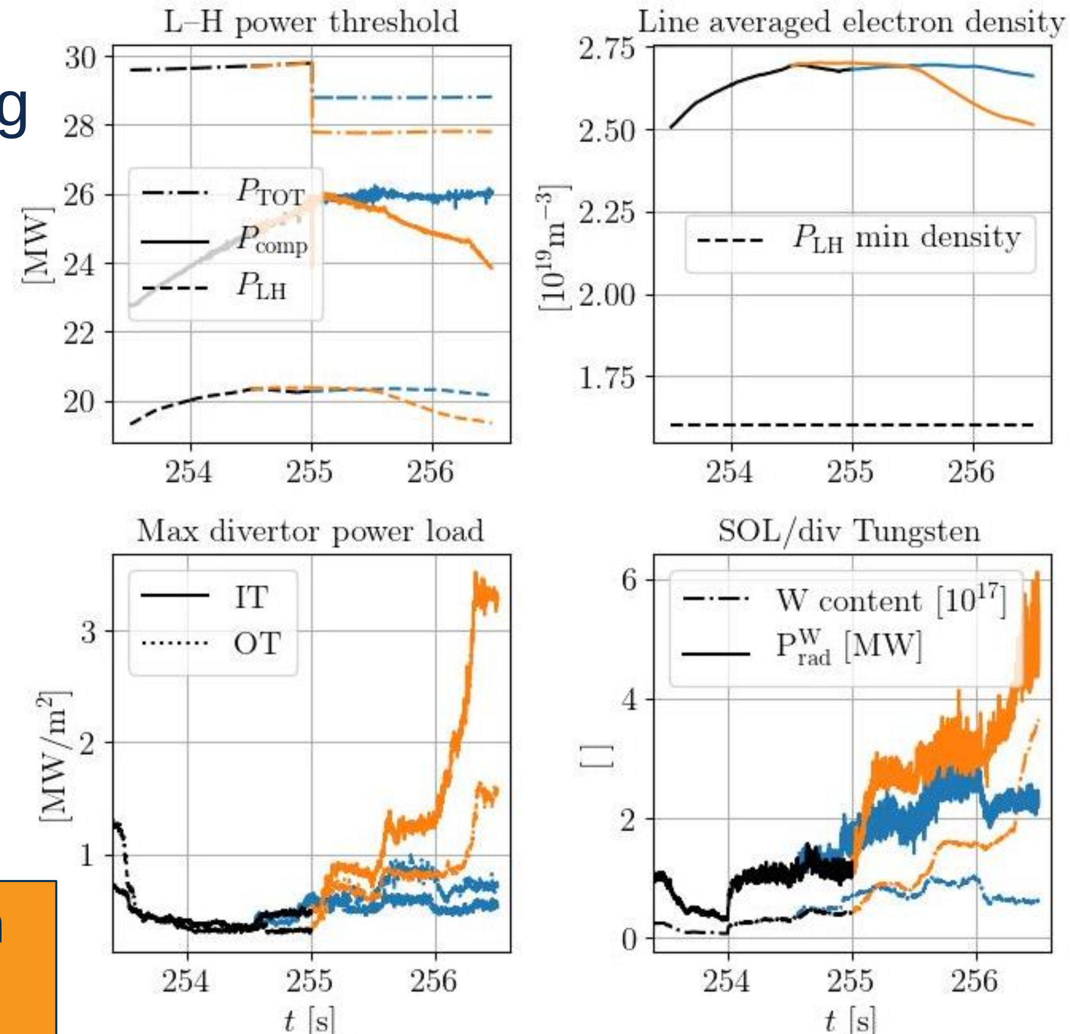




**30MW ECRH allows to sustain a robust type-I ELMy H-mode in 5MA/1.8T Hydrogen plasma**

- 251<t<252s: L-mode
- 252-252.6s: L-H transition
- t>254s: ELMy H-mode

# H-mode access in 5MA/1.8T Helium plasma with 30 MW ECRH

- At low density W sputtering a problem
  - Higher He density required.
  - ➢ Trade off between between higher $P_{LH}$ and lower W plasma contamination.
- Scan He gas rate:
  - For 30MW ECRH
    - ➢ Optimal rate: >$0.3 \times 10^{22} s^{-1}$
    - ➢ Final core $P_{rad,W}$ <1MW
    - ➢ Divertor fluxes < $1 MWm^{-2}$

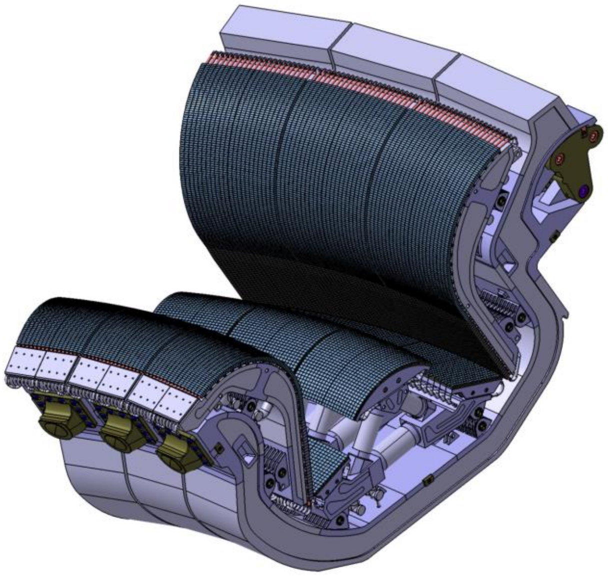



30MW ECRH allows to sustain type-I ELMy H-mode in 5MA/1.8T Helium plasma

# PFPO-2:
# H-mode plasmas at 7.5MA/2.65T

- Hydrogen & Helium discharges at 7.5MA/2.65T with
  - 20-30 MW ECRH heating
  - 33MW Hydrogen Neutral Beam ($H^0$-NB) Heating
- ➢ Not enough to get pure H plasma into H-mode! Options:
  1. Low density H plasma
     - ➢ Add Ne to get NB absorption up
  2. High density H plasma
     - ➢ Add 10% He to lower $P_{LH}$
- Assess feasibility to access robust ELMy H-modes!

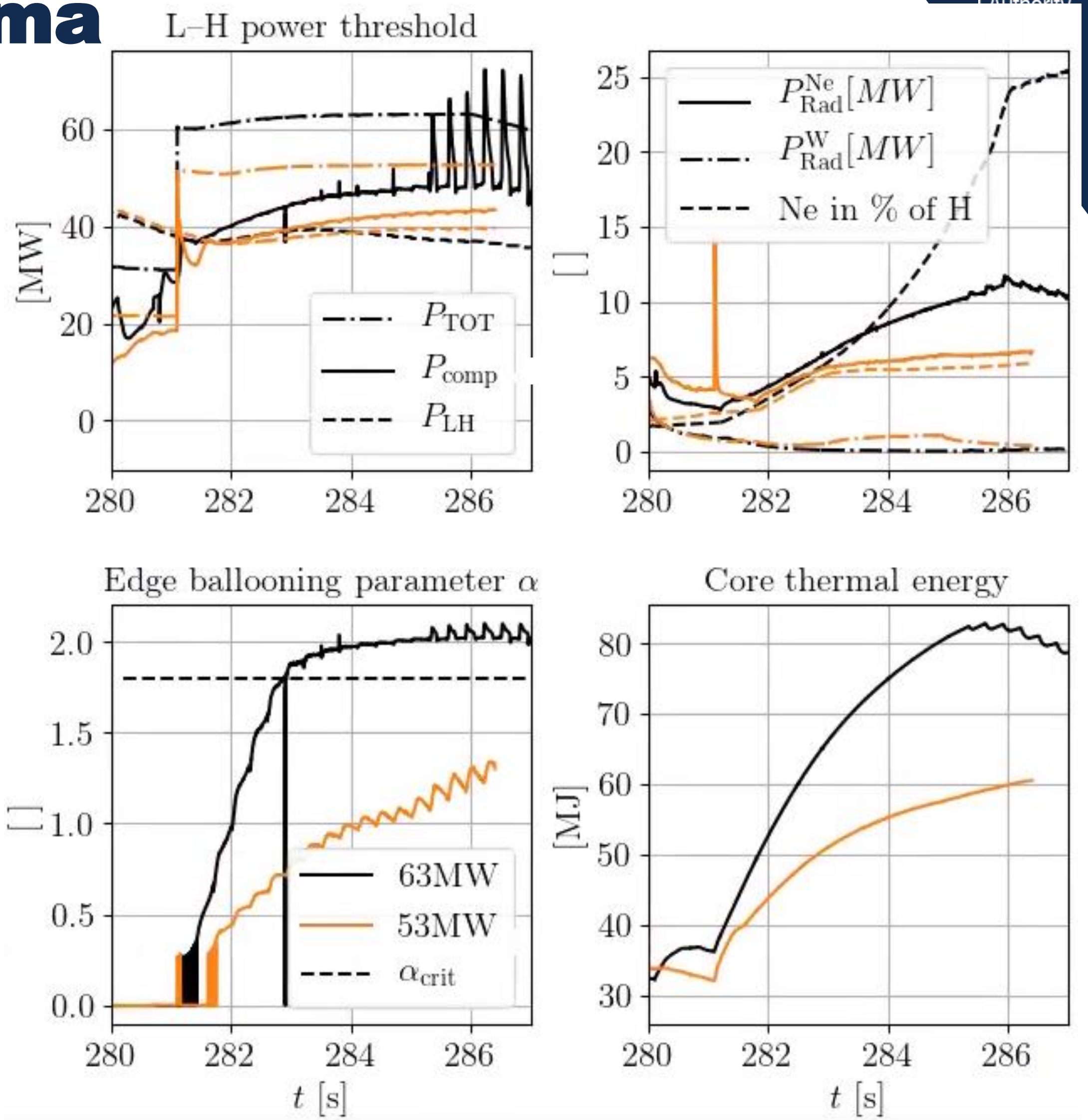
- Problem with divertor power loads?
- Problem with NB absorption?
- Problem with core impurity accumulation?



The ITER Divertor
Surface material:
Tungsten tiles

# H-mode operation in 7.5MA/2.65T Ne rich Hydrogen plasma

- Low plasma density
  - $n_{el}$~2.5-3x$10^{19}m^{-3}$ / $f_{GW}$~45%
- L-mode: Max 2% Ne to avoid full divertor detatchment
- H-mode: 6% of Ne give low NB shine-through
- 20MW ECRH + 33MW NB
  - ➢ Type-III ELMy H-mode



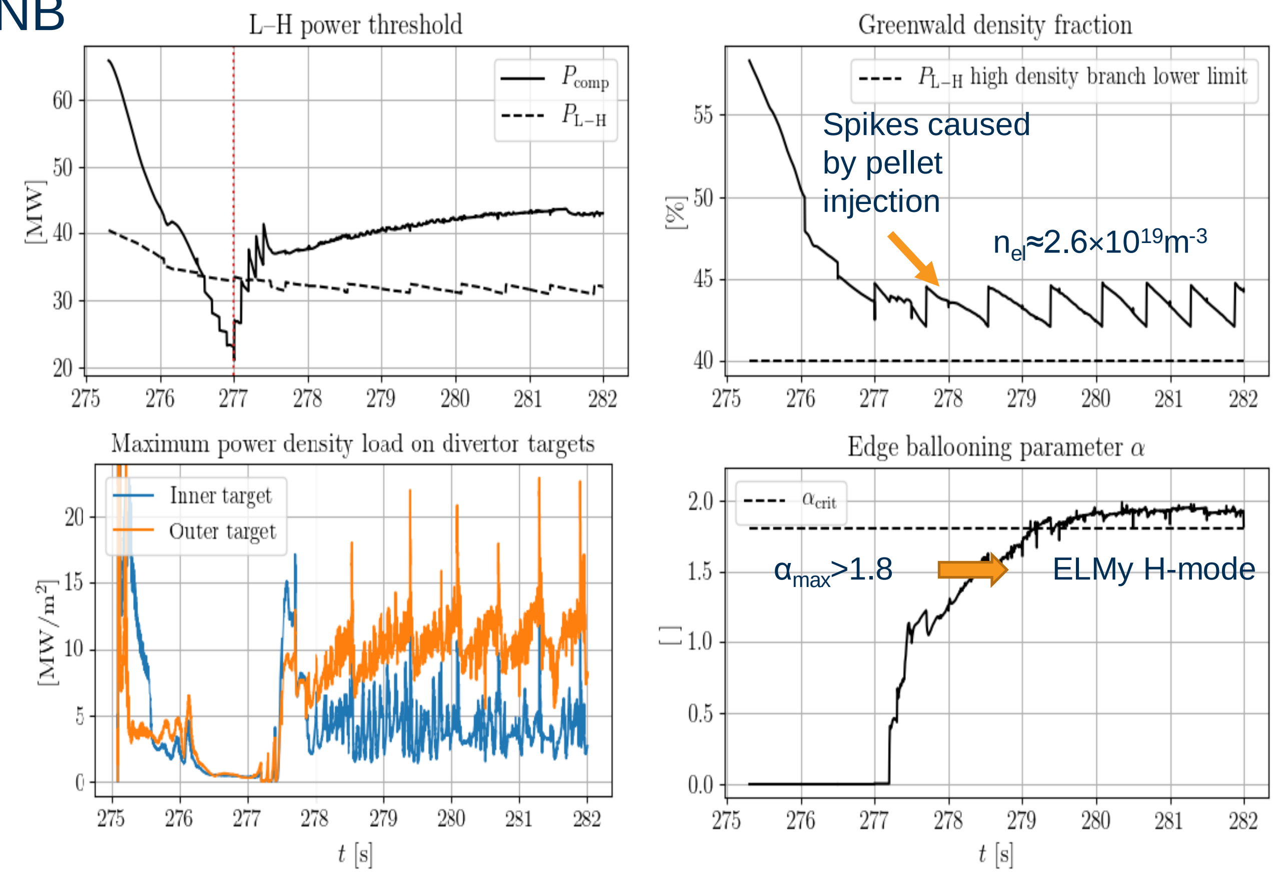

30MW ECRH + 33 MW NB allows to sustain a stable type–I ELMy H-mode in 7.5MA/2.65T Ne rich H plasma

E. Tholerus APS-DPP 2020 CO07.00009

# H-mode access in 7.5MA/2.65T Hydrogen plasma with ~11% Helium



- **20MW ECRH** + 33 MW NB
- $n_{He}/n_e$~11%
- $n_{Ne}/n_H$~10%
  - ➢ NB shine-through: 1MW <1.8MW
- Divertor loads too high
- 6.4 MW core radiation:
  - Ne: 5.8MW
  - W: 0.8MW

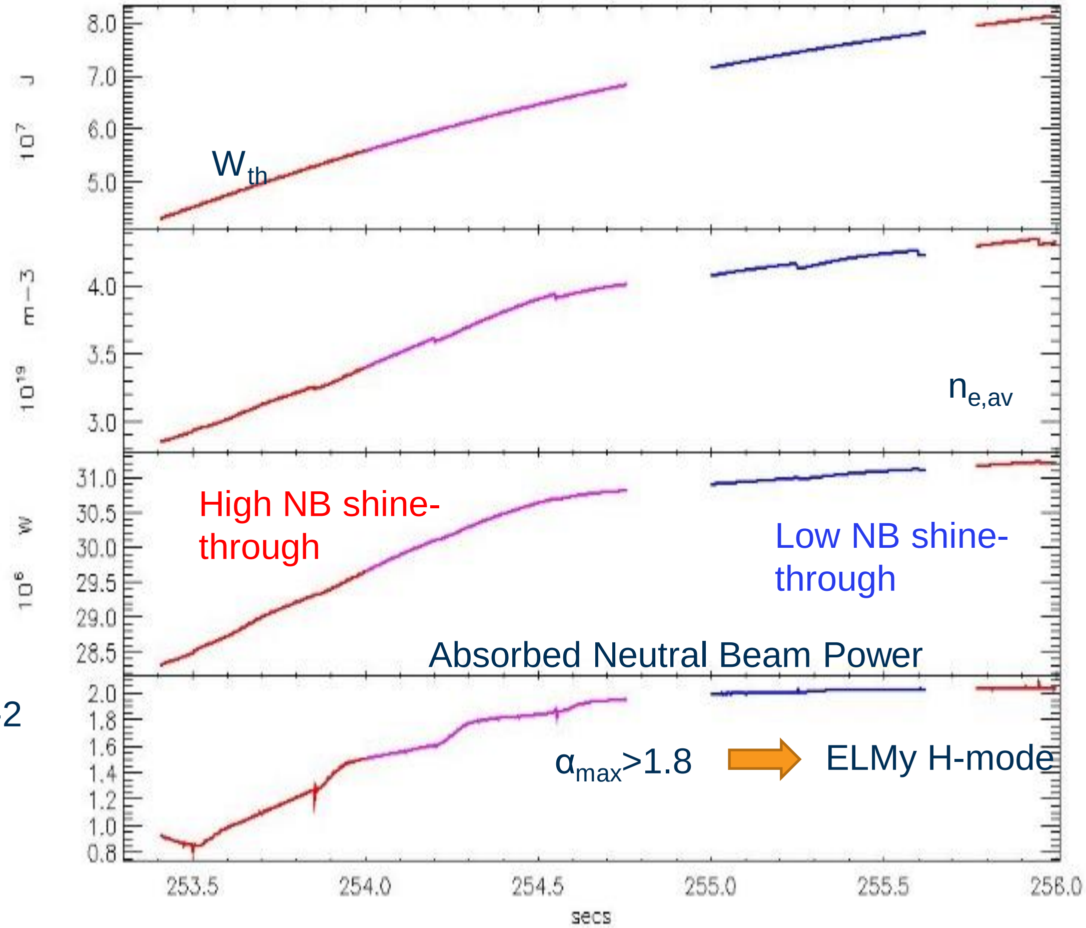



20MW ECRH + 33 MW NB allows to sustain type-I ELMy H-mode in 7.5MA/2.65T H plasma with ~11% He and 10% Ne

. Tholerus APS-DPP 2020 CO07.00009

# H-mode access in 7.5MA/2.65T Helium plasma

- **20MW ECRH** + 33 MW NB
- High initial NB shine-through rapidly decreased by increasing density.
    - Max He gas rate $2 \times 10^{22}$ el/s
    - Any higher leads to full detachment.
- W core:
    - concentration ~$1 \times 10^{-4}$% of He
    - radiation ~0.25MW
- Divertor power fluxes < $1 MWm^{-2}$
    - No Ne in these simulations!




20MW RF + 33 MW NB allows to enter a stable type-I ELMy H-mode in 7.5MA/2.65T He plasma.

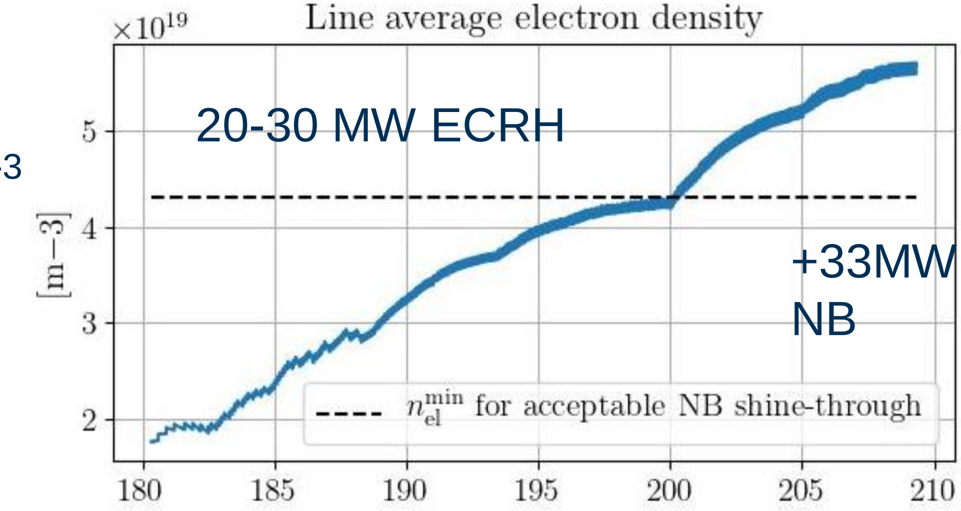
# PFPO-2: First plasma at 15MA/5.3T - Hydrogen L-mode

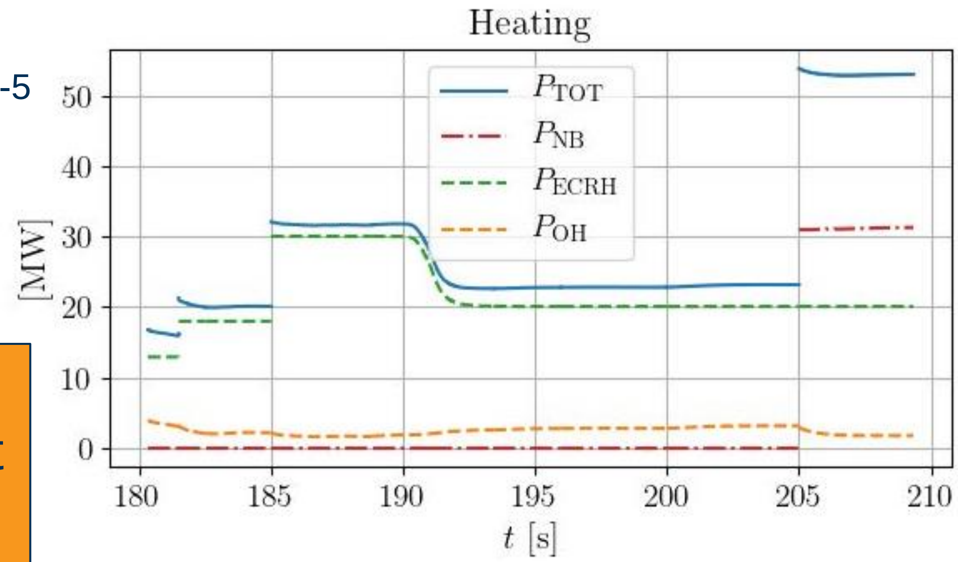
First plasma at current, field and NB power required for DT Q=10!

- Important proof-of-concept!
- $P_{LH} \propto B^{0.8}\ Z^{3/2} M^{-1}$ > 100MW for 15MA/5.3T Hydrogen plasma!
  - Only up to 73MW available auxiliary heating
  - ➢ H-mode operation not possible
  - ➢ ELM control not needed!
  - ➢ Possibility of commissioning the hydrogen neutral beams at full energy (1MeV)!
    - H plasma need very high density > $4.3 \times 10^{19} m^{-3}$ for permissible neutral beam shine-through.
    - ECRH heating to sustain plasma

# First plasma at 15MA/5.3T: Hydrogen L-mode

- Final average density > $5.0 \times 10^{19} m^{-3}$
  - Pellet fuelling essential
- Full NB power (33MW) injected.
- Divertor power loads < $5 MWm^{-2}$
- Levels of Ne, Be & W very low
  - W sputtering increases when NB applied
    - W sputtering yield < $1.2 \times 10^{-5}$
  - Be Sputtering yield < $2.5 \times 10^{-5}$
  - Final W core radiation: 7kW




**Commissioning of Hydrogen Neutral Beam Heating at full power possible in 15MA/5.3T Hydrogen L-mode.**

# Summary and conclusions

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- With state-of-the-art integrated modelling tool JINTRAC we have developed integrated core/pedestal/SOL/divertor scenarios for ITER PFPO respecting operational and technical constraints.
- The ITER Research Plan: initial power of 20MW ECRH in PFPO-1.
  - Upgrade by 10MW to 30MW ECRH for PFPO-1 under discussion.

Our study support this upgrade and suggest that robust type-I ELMy H-mode operation for 5MA/1.8T H, He and H- He minority plasmas requires 30MW ECRH in PFPO-1.

- PFPO-2: Type-I ELMy H-mode operation at 7.5MA/2.65T requires:
  - 20MW RF & 33MW NB in He plasma
  - 20MW ECRH & 33MW NB in H plasma with a He/Ne minority mix
    - More robust H-mode with 30MW ECRH
    - Caveat: Benefits from a 15% lower $P_{LH}$ as observed on JET.
  - 30MW ECRH & 33MW NB in H with Ne minority
    - 20MW ECRH & 33MW NB not yet ruled out but will likely be more marginal.

PFPO-2 key milestone for DT Q=10: fully developed 15MA/5.3T integrated H L-mode scenario allowing for 33MW/1MeV NB.



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# Thank you for your attention!

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ITER site, Provence, France, Nov 2020



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