# Exploration of long-pulse and steady-state operations in ITER

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# Outline

- ITER Long Pulse (LP) and Steady State (SS) operation goals in Fusion Power Operation (FPO) phase
- ITER Staged Approach with HCD systems and major plasma scenarios
- ITER Q ~ 5 SS target plasma (HCD, MHD stability, divertor power loads, energetic particles)
- ITER Q ~ 5 SS operation scenario including access and exit
- ITER Q ≥ 5 LP operation scenario (e.g ITER hybrid scenario)
- Open issues of ITER LP and SS operation
- A path considered for LP operation in ITER Pre-Fusion Power Operation (PFPO) phase
- Conclusions

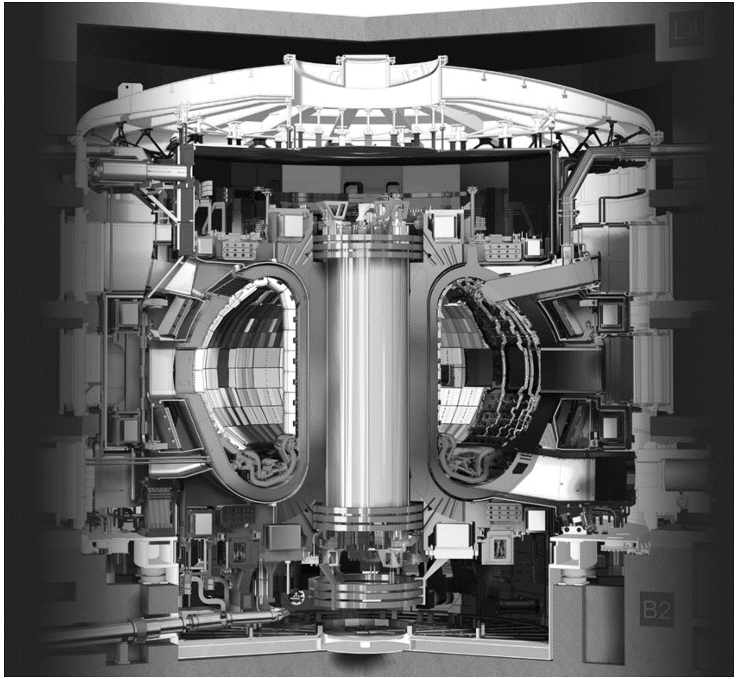
# ITER mission goals

- **ITER shall demonstrate scientific & technological feasibility of fusion energy:**

  - Pulsed inductive operation:
    **Q ≥ 10 for burn lengths of 300-500 s**
    → Baseline scenario ~ 15MA / 5.3T

  - Long pulse operation:
    **Q ≥ 5 for long pulses up to 1000 s**
    → e.g) Hybrid scenario ~ 12.5MA / 5.3T

  - Steady-state operation:
    **Q ~ 5 for long pulses up to 3000 s**
    Fully non-inductive current drive
    → e.g) Steady-state scenario ~ 10MA / 5.3T




- **The ITER Research Plan describes the strategy to achieve these goals**

# Staged approach and H&CD systems

| | 1st Plasma | PFPO-1 | PFPO-2 | FPO | HCD Upgrade |
|---|---|---|---|---|---|
| Electron Cyclotron | 5.8MW,170GHz Upper launcher | 20MW + 10MW * | | | + 20MW ** |
| Ion Cyclotron | | | 20MW | | + 20MW ** |
| Neutral Beam | | | 33MW, H-beam | 33MW, D-beam | + 16.5MW **, D-beam |
| Key Scenarios | First plasma | 5MA/1.8T H-mode, 10MA/5.3T L-mode | 7.5MA/2.65T H-mode, 15MA/5.3T L-mode | 15MA/5.3T DT H-mode (baseline), Long pulse (hybrid) explorations | Long pulse (hybrid) and steady-state |

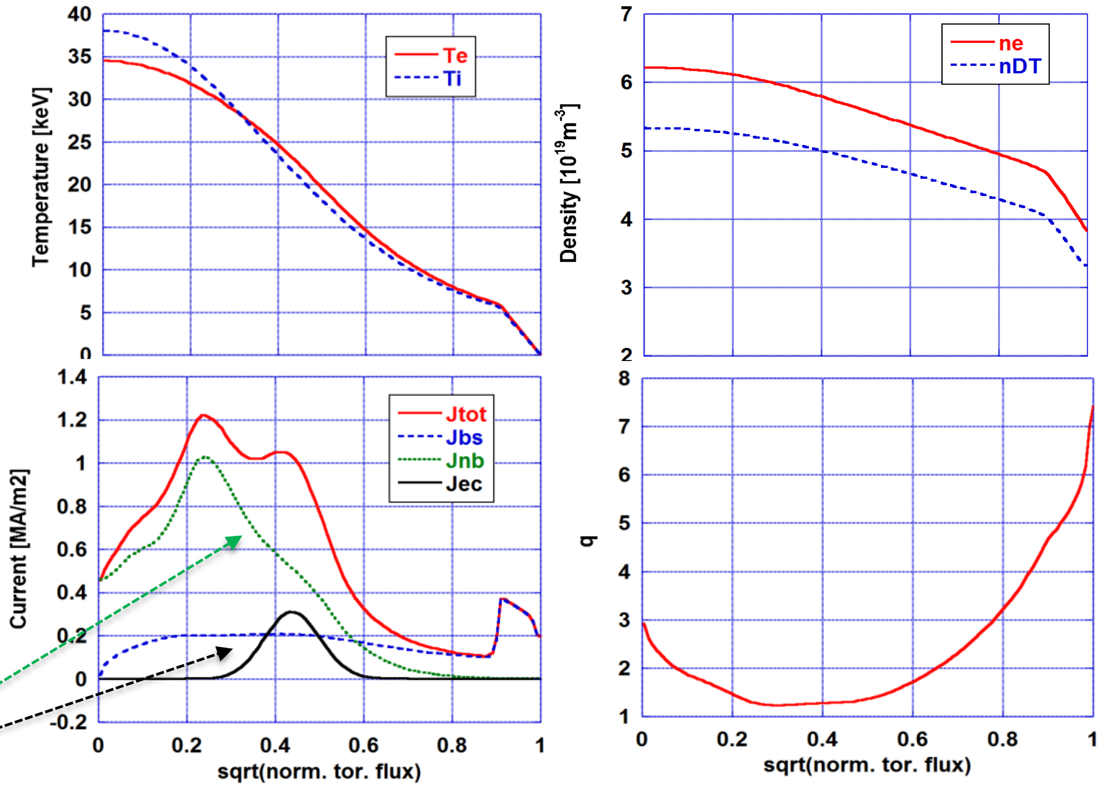
* To be confirmed
** HCD upgrade options

# ITER Q~5 SS target plasma

# Q ~ 5 target steady-state plasma at 10 MA

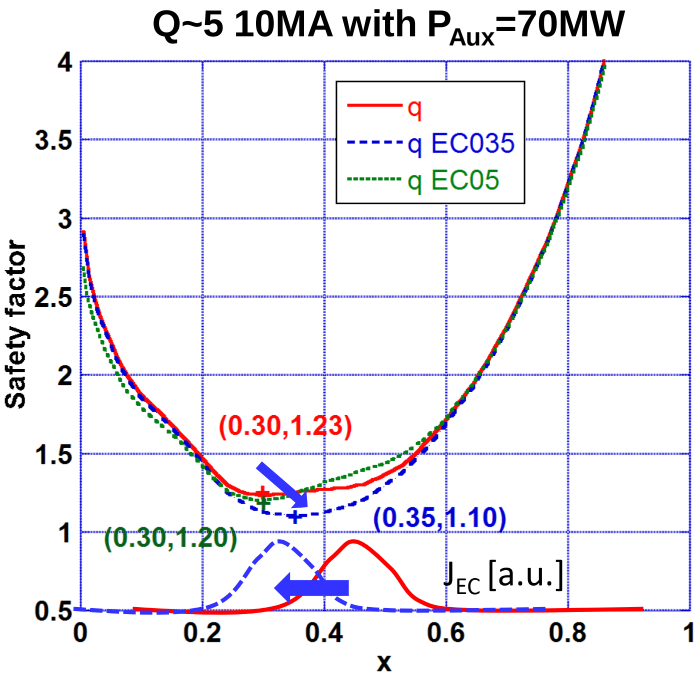
- Conditions identified by multiple integrated modelling activities including 1.5-D ASTRA modelling
  - EPED1+SOLPS used for pedestal and boundary → high $n_{sep}$, low $\Delta n_{ped}$
  - $Q=5.02$, $f_{GW}=0.69$
  - $\beta_N=3.02$ , $q_{min}=1.23$
  - $H_{98}=1.52$ (Improved confinement essential)
  - $l_i(3)\sim0.87$ - relatively high mainly due to near on-axis 50 MW NBI (20-30 MW off-axis ECCD)

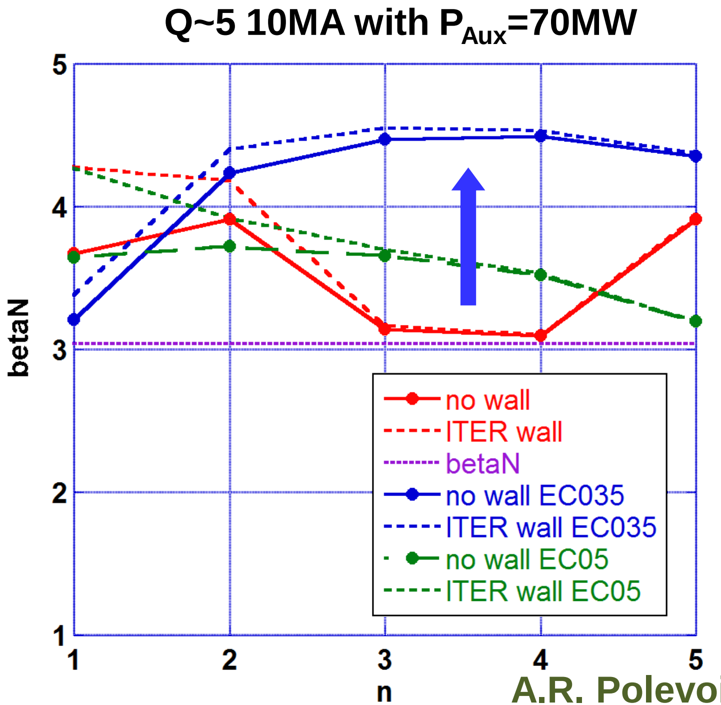
A.R. Polevoi – NF 2020



# Stability optimization with ECCD

- KINX stability analysis shows that low-n (=1-5) ideal MHD modes ($\beta_N < \beta_{N,limit}$) by varying the ECCD location ($\rho_{ECCD}$=0.35 was good)

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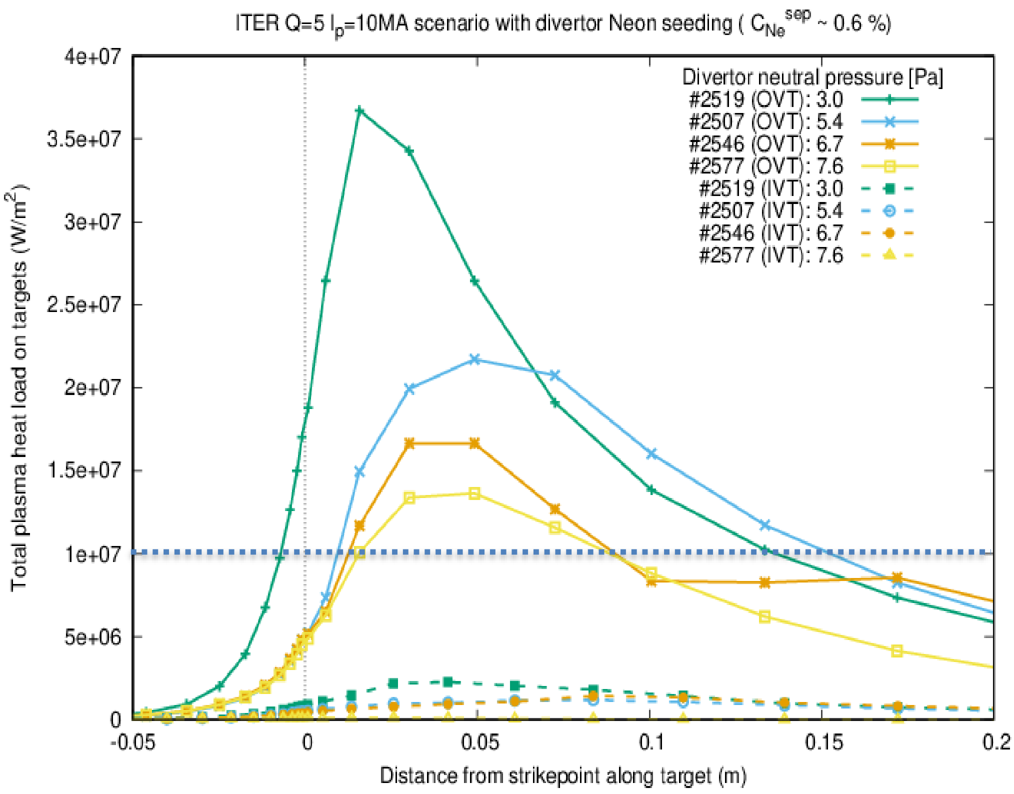
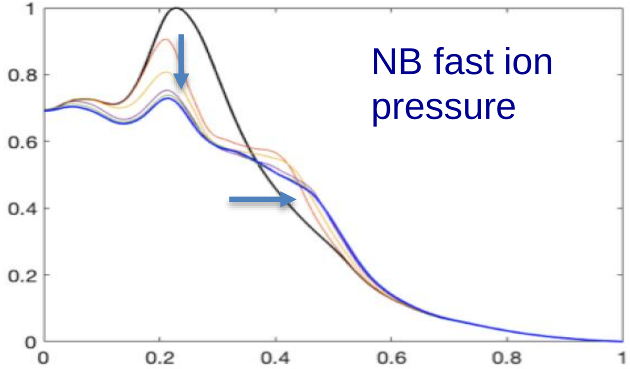
# Divertor power loads in Q~5 steady-state operation

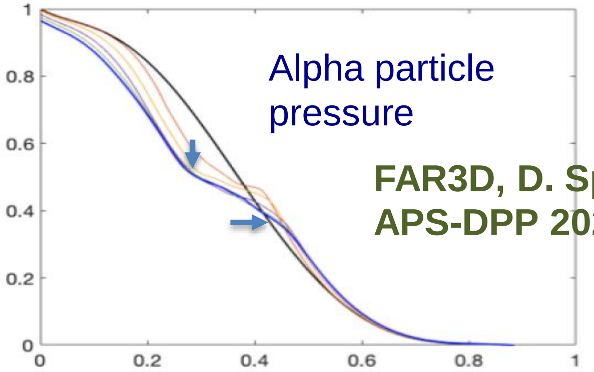
- SOLPS-ITER analysis – Simulations performed at IFERC Computational Simulation Center (JA-EU)
- $P_{SOL}$ ~ 120MW with $P_{Aux}$ ~ 70MW
- Ne seeding injected below the divertor ($C_{ne}^{sep}$ ~0.6%) and divertor neutral pressure varied with fuel gas puff
- Divertor power loads decreased along with the divertor neutral pressure (not yet <10MW/m$^2$, also note large in/out asymmetry)
  ➔ Scans on Ne seeding rate & location, and gas puff rate are on-going



# Energetic particles in Q~5 steady-state operation

- SciDAC ISEP + ITPA-EP modelling (Z. Lin et al.) using gyrokinetic (GTC, ORB5), kinetic-MHD (FAR3D, M3D-C1, MEGA, XTOR-K, GAM-Solver, NOVA-K), & reduced models (CGM, RBQ, Kick)
- Macroscopic MHD mode – gyrokinetic & kinetic-MHD
  - n=1 fishbone and kink modes driven by energetic particles are stable
- Meso-scale Alfvén Eigenmode - gyrokinetic, kinetic-MHD, & reduced models
  - NB fast ion and alpha particle profiles can be flattened near $q_{min}$, at $\rho$=0.3-0.4
- Cross-scale coupling of AE with microturbulence and MHD: further studies are on-going



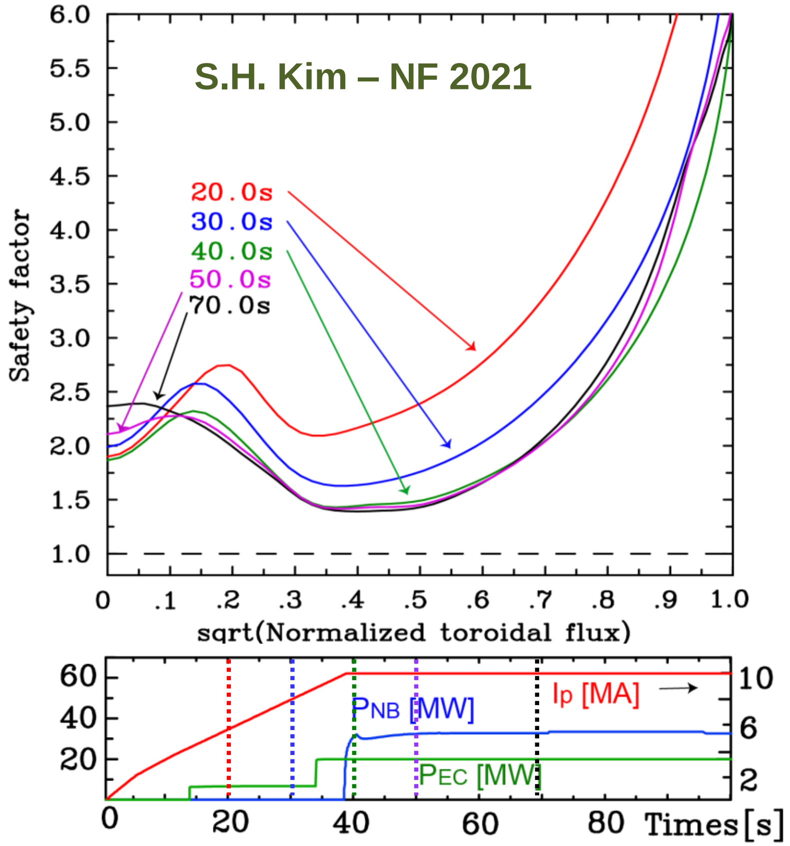




**FAR3D, D. Spong**
**APS-DPP 2022**

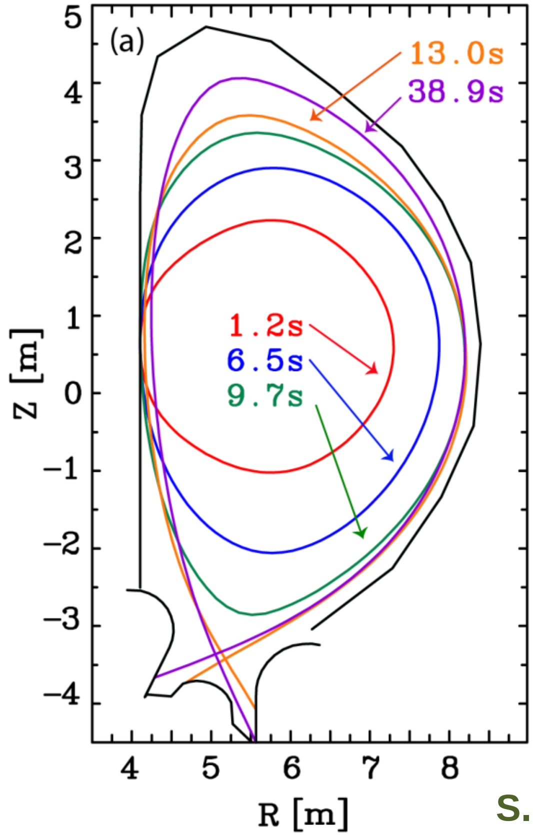
# ITER SS and LP operation scenarios

# Access to the target steady-state plasma

- Tailoring q profile using ECCD during the L-mode ramp-up to be close to the target profile at SOF (~40s)
- Access to a high-β H-mode minimizing the perturbation on the target q profile
- Step increase of NBI power during the initial flat-top phase to reduce the excursion of q at the core region

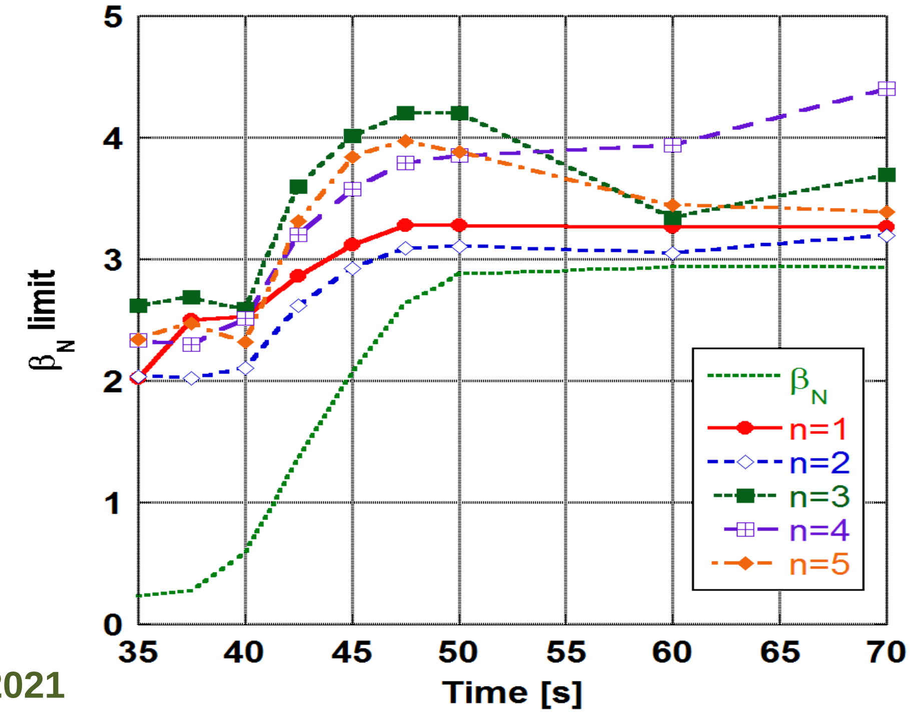


# Plasma stability during access to steady-state operation

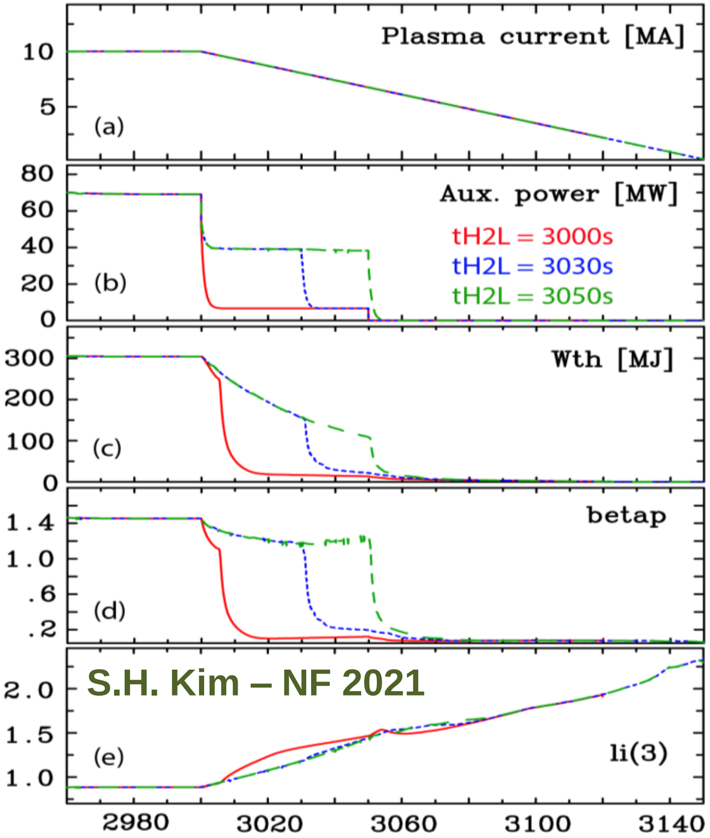



S.H. Kim – NF 2021

- The HCD waveform designed to avoid ideal MHD limits during the ramp-up and access to SSO



# Exit from high Q H-mode conditions




- H-L transition designed at $I_p$=7-10MA
  - To avoid the density limit
  - To avoiding impurity accumulation and excessive divertor power flux by varying $W_{th}$ and $<n_e>$ slowly [F. Kochl, PPCF2018]
  - To delay $\beta_p$ drop and $l_i$ increase to imporve vertical stability during H-mode

# ITER Q ~ 5 steady-state scenario

- Stationary q profile (q > 1) with enhanced confinement ($H_{98} > 1.5$)
- Obtained with $P_{aux} = P_{NBI} + P_{ECH} \geq 70$ MW with non-inductively driven current ~ 100%
- Flat-top length limited to 3000s by hardware design (removal of deposited energy)

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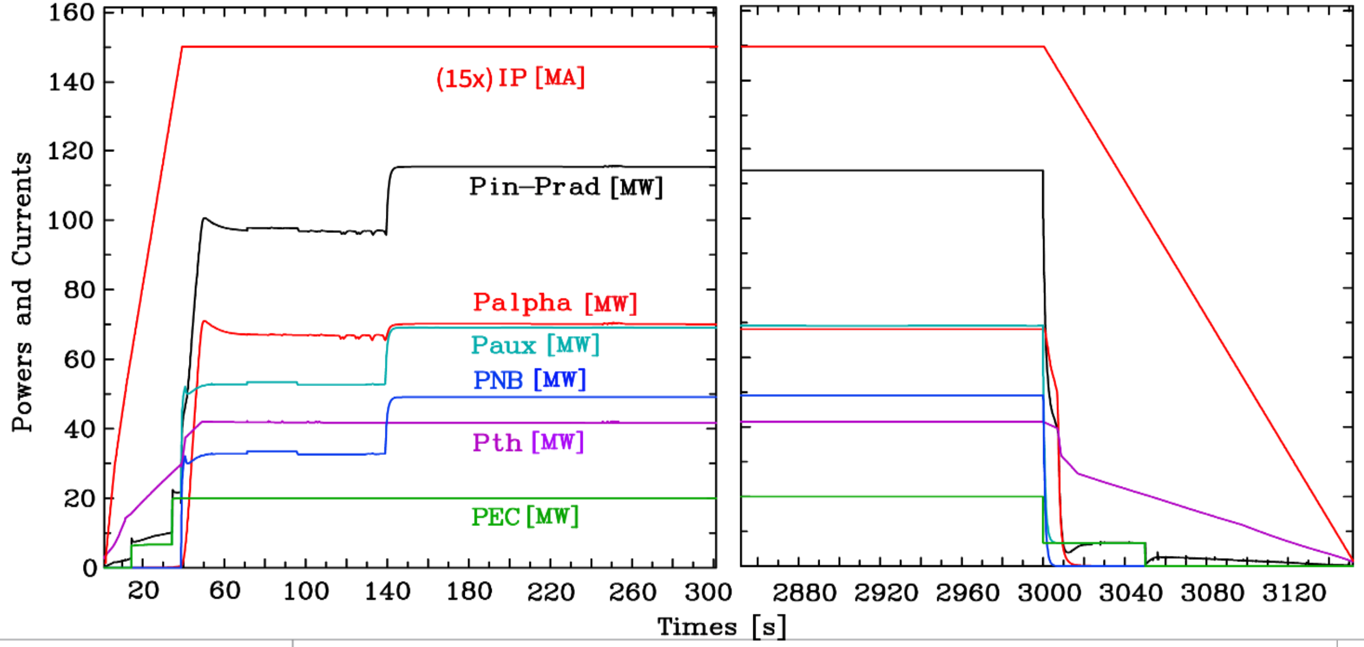
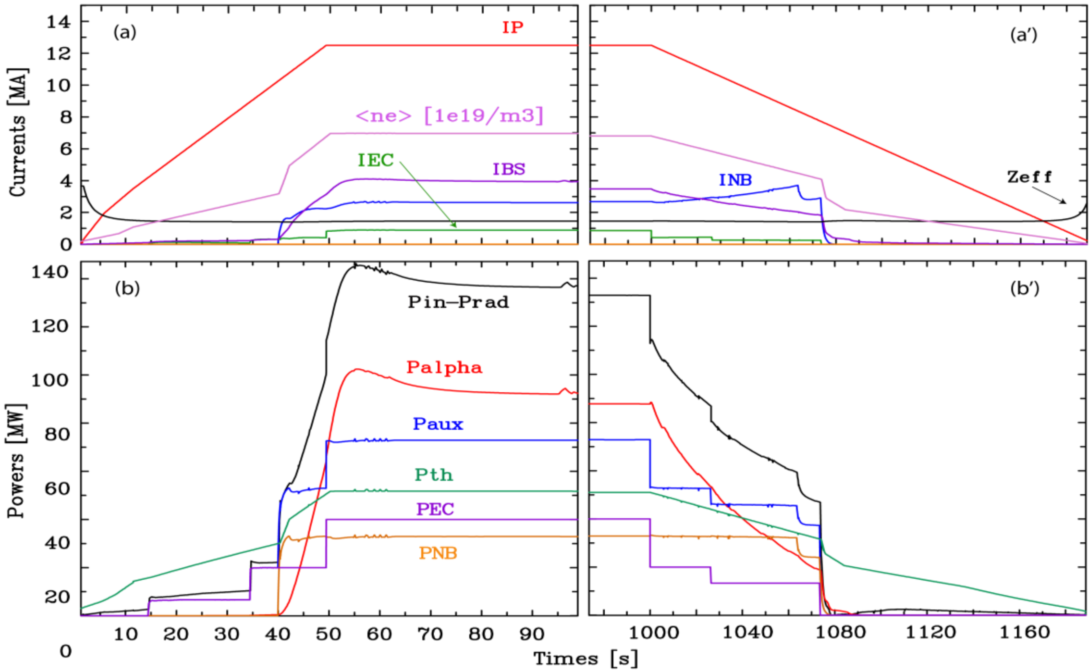
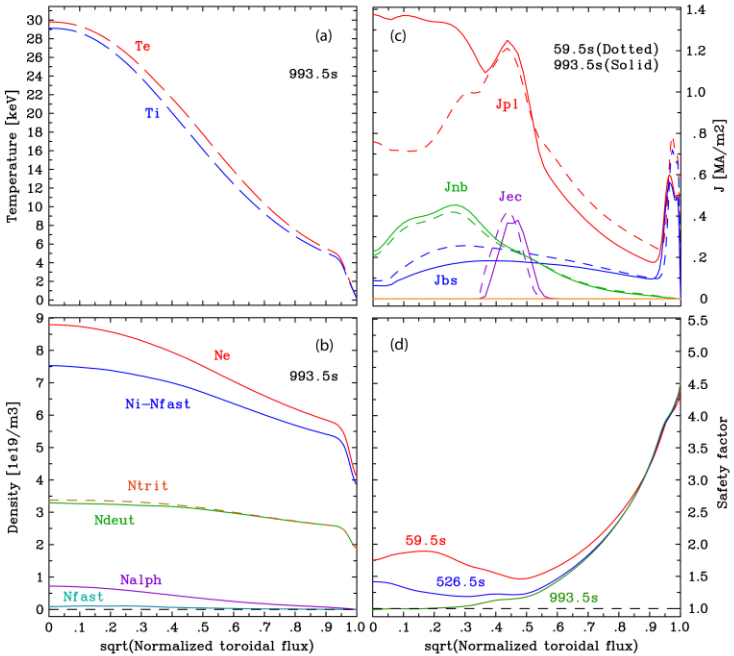


# ITER Q ≥ 5 long pulse (hybrid) scenario

- q(0)>1 for ~900s flat-top (limited by current diffusion) with $H_{98}$ ~ 1.2 in 12.5 MA/5.3 T
- Obtained with 33MW $P_{NBI}$ + 40MW $P_{ECH}$ with non-inductively driven current ~ 50%
- Alternative LPO options based on low density H-mode ($q_{95}$~3)

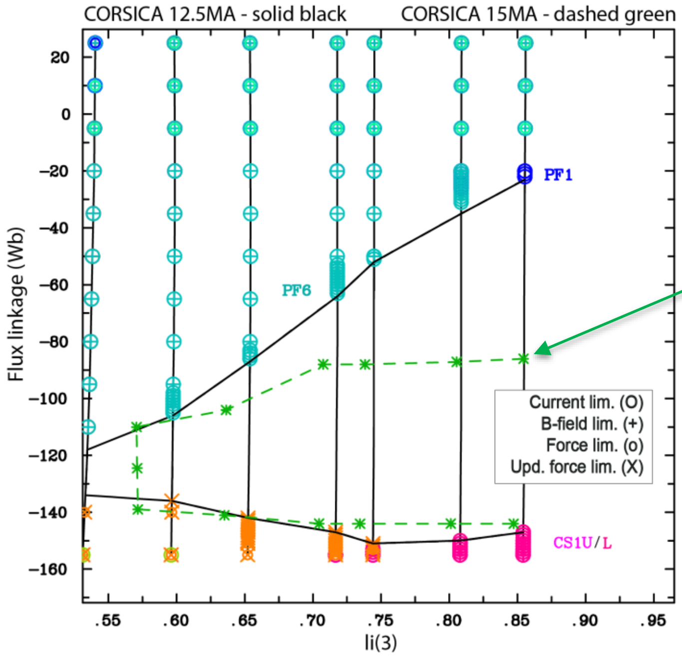


# 12.5MA LP & 10MA SS operational spaces

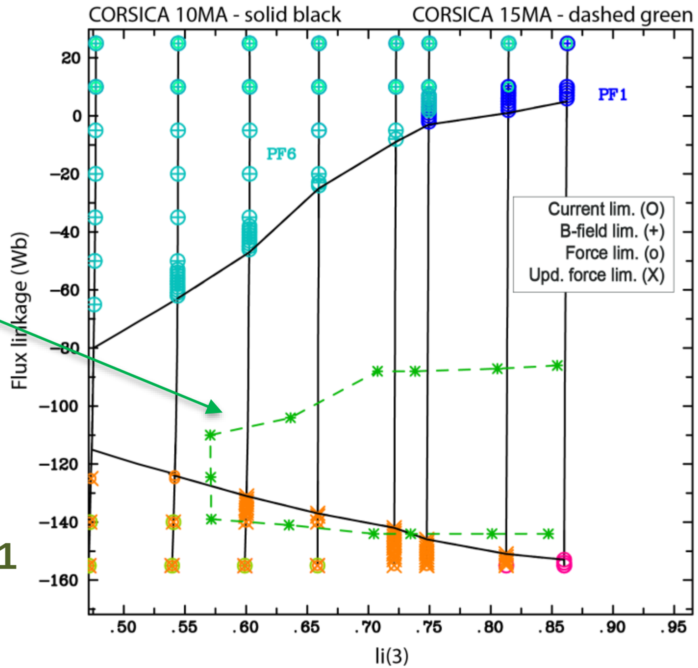
- Operational space with as-built properties of ITER CS modules (CORSICA Constrained EQ)
- OSs extended from 15MA baseline – mainly due to reduced $I_p$

**12.5MA hybrid**




15MA Baseline

**10MA steady-state**

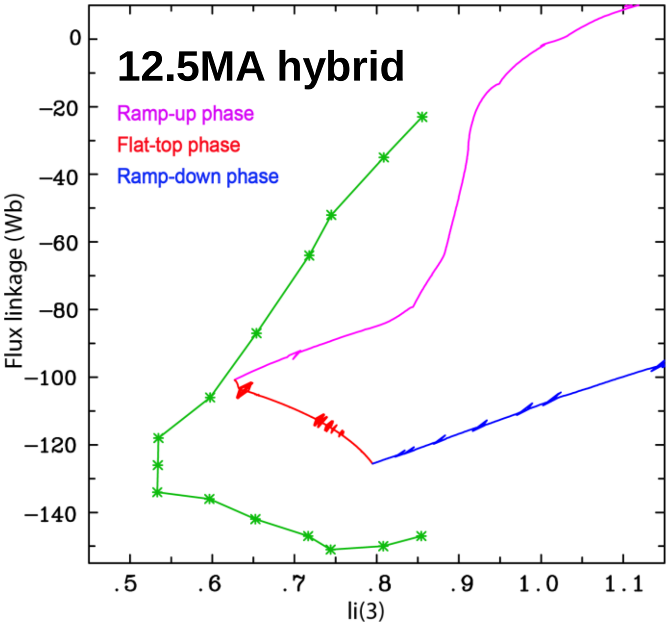


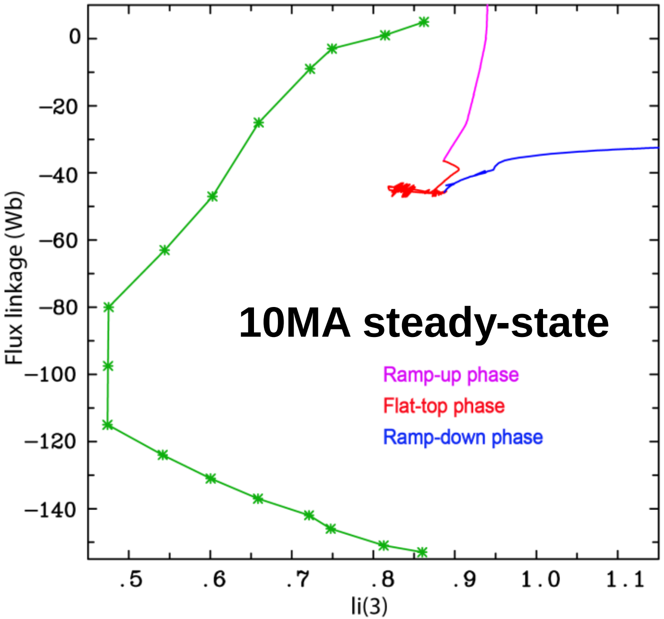

S.H. Kim – APS 2021

# Plasma evolution within the operational spaces

- Flat-top plasmas are well within the extended operating space
- Initial magnetization can be further optimized for 12.5MA hybrid scenario
- Significant margins in 10MA steady-state scenario

**S.H. Kim – APS 2021**



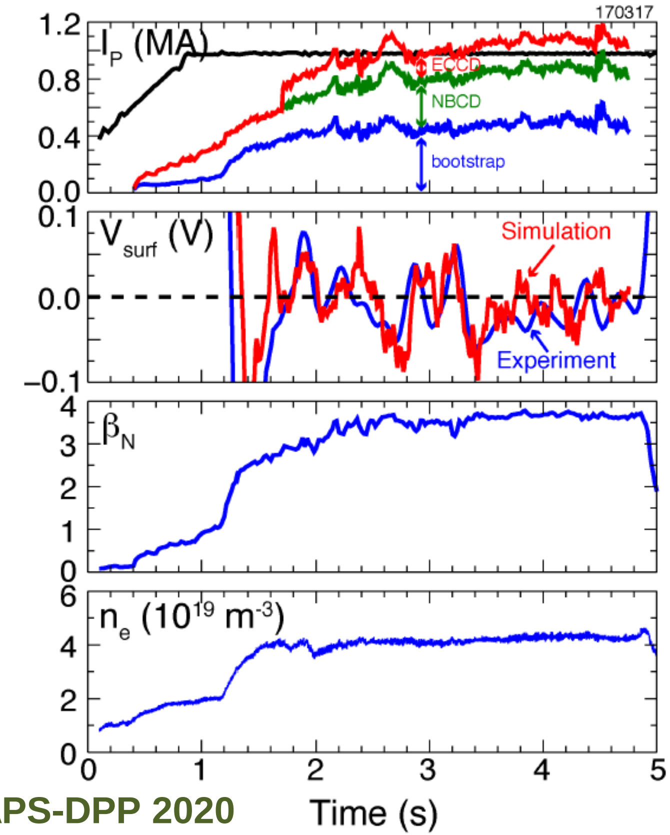



# Open issues of ITER LP and SS operation

# Access to higher confinement beyond H-mode

- DIII-D steady-state hybrid discharges achieved a good confinement ($H_{98}$=1.5-1.6) at similar HCD configuration with the ITER SS target plasma
  - NBCD + off-axis ECCD (rho~0.2-0.45)
  - $q_{min}$=1.0~1.5

- Uncertainties in extrapolating the results from present experiments – access to high confinement, CD efficiencies, plasma rotation, ion heating, core NBI fueling, etc

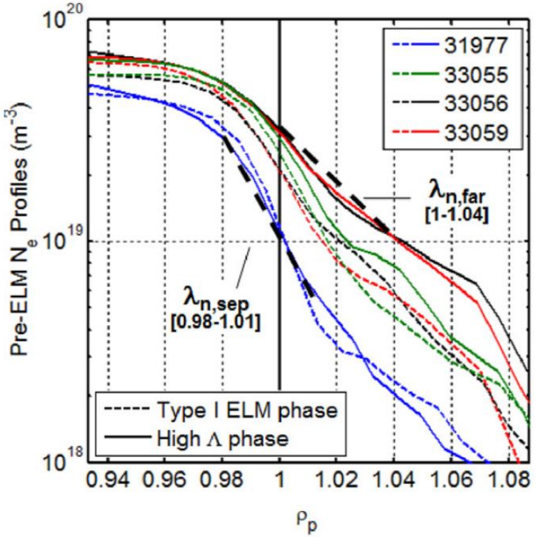


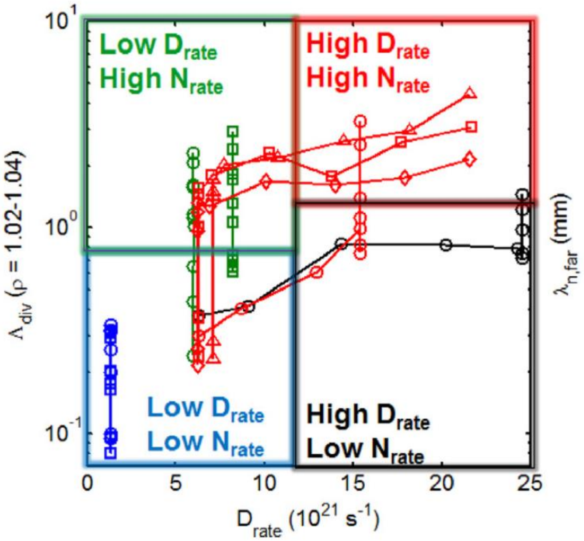

C.C. Petty – APS-DPP 2020

# Uncertainties in the SOL transport

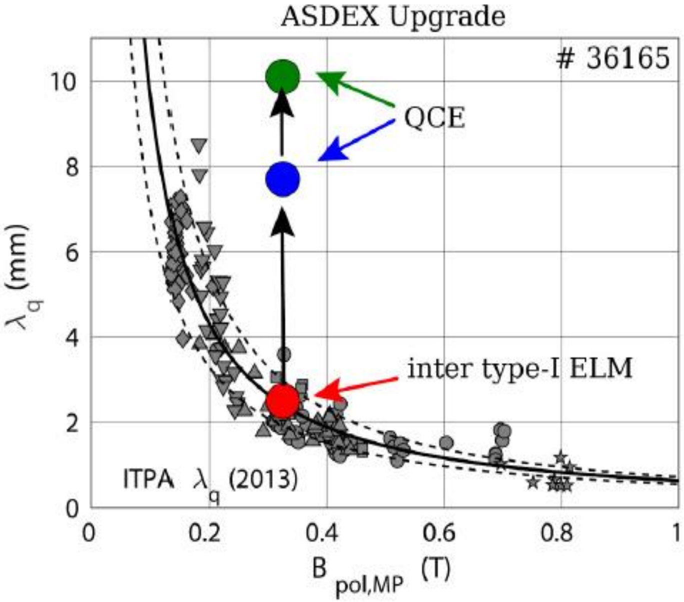
- Plasma transport in the H-mode far SOL linked to divertor conditions and neutral recycling dynamics (D. Carralero, NME 2017)
- $\lambda_q$ broadening by gas puffing - ASDEX QCE regime (M. Faitsch, NME 2021)
- Impact of drifts on in-out asymmetries

D. Carralero – NME 2017



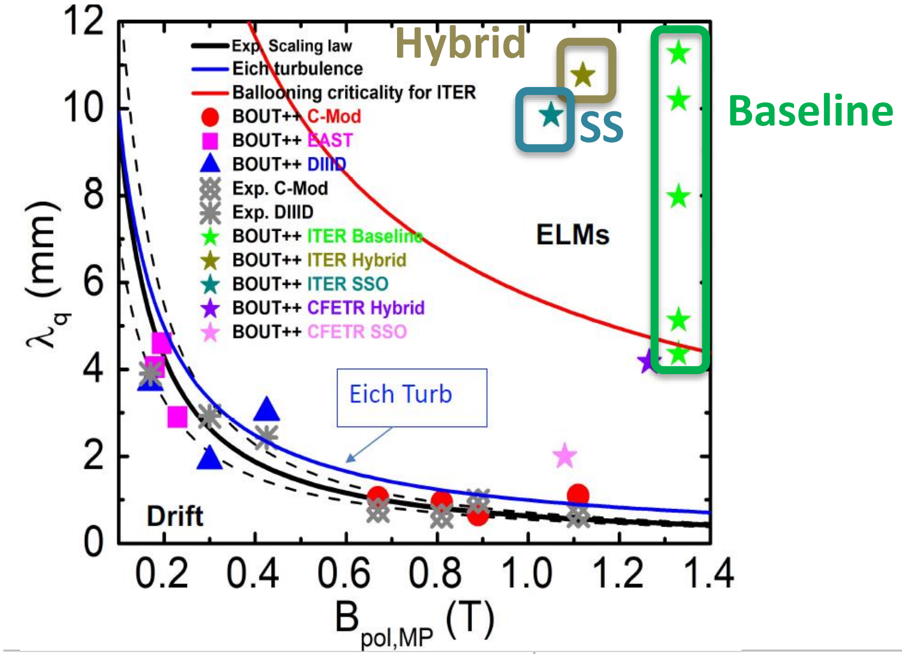

M. Faitsch – NME 2021



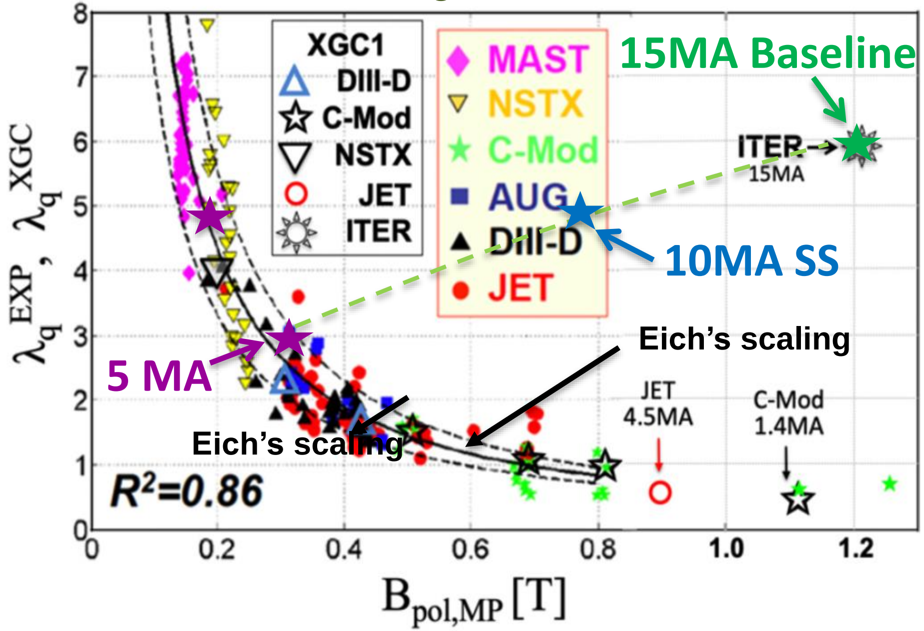
# $\lambda_q$ in ITER high Q (incl. LP and SS) operation

- BOUT++ and XGC1 modelling predicted that edge transport in ITER may be different (more turbulent) at high Q (high $I_p$) operation

**X.Q. Xu – NF 2019, ITPA-PEP 2022**




**C.S. Chang – PoP 2021**



# Other open issues in FPO

- Fuelling - neutral penetration ineffective in ITER
  - Separated control of $n_{sep}$ (gas puffing & impurity) and $n_{ped}$ (pellets)
- ELM and W impurity control
  - Plasma response to 3D fields and pellet injections
- MHD control at different (or varying) $q_{95}$
  - Optimization of actuators, control methods and strategies
- Disruption mitigation – Large amount material from multiple locations
  - Optimization for runaway electrons and thermal loads
- EP modes - ITER first wall can only tolerate losses of a few % fast ions
  - Optimization towards benign saturation of modes
- First wall erosion, dust production, T retention and W divertor lifetime

# A path for LPO at ITER Pre-Fusion Power Operation Phase

# Exploration of long pulse operation in PFPO

- In FPO, **low density Baseline H-mode ($q_{95}$~3)** can be an intermediate step towards long-pulse operation development – utilizing well-established operational capabilities at $q_{95}$~3

- In PFPO, **low current H-mode, 5MA/1.8T and 7.5MA/2.65T ($q_{95}$~3),** can be used for testing long-pulse development – thanks to the reduced poloidal flux consumption at low $I_p$

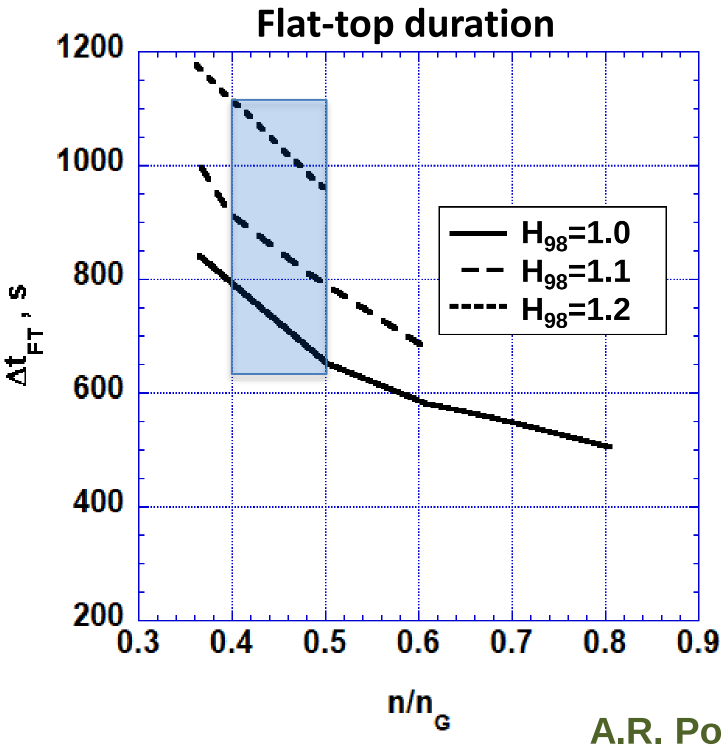
- If the CS coils are charged less (< 30kA/turn), it is foreseen that the **fatigue lifetime of CS coils** is not consumed

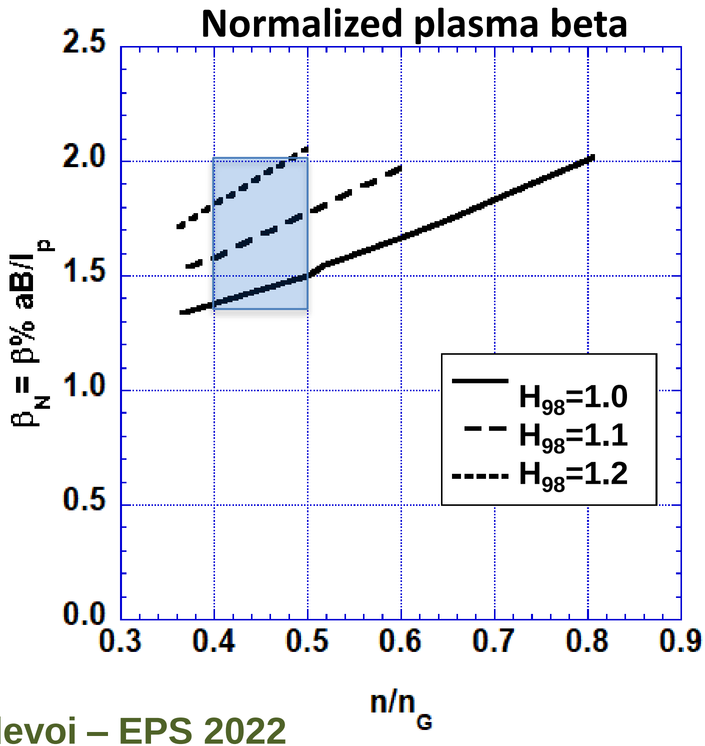
- $q_{95}$=4~5 paths in PFPO are not yet fully investigated (probably limited by NBI shine-through)

# Low density Baseline H-mode LPO capability

- Reduced poloidal flux consumption at low density 15MA/5.3T Baseline DT H-mode

- 600-1100s flat-top operation may be allowed at
  - $n/n_G$ = 0.4-0.5
  - $H_{98}$=1.0-1.2

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# LPO capability in PFPO-2

- 5MA/1.8T Hydrogen (PFPO-2)
  - 10MW NBI + 20MW EC
- 7.5MA/2.65T Hydrogen (PFPO-2)
  - 33MW NBI + 20MW EC (Ne-seeding)
- 15MA/5.3T low density DT(FPO)
  - 33MW NBI + 20MW EC

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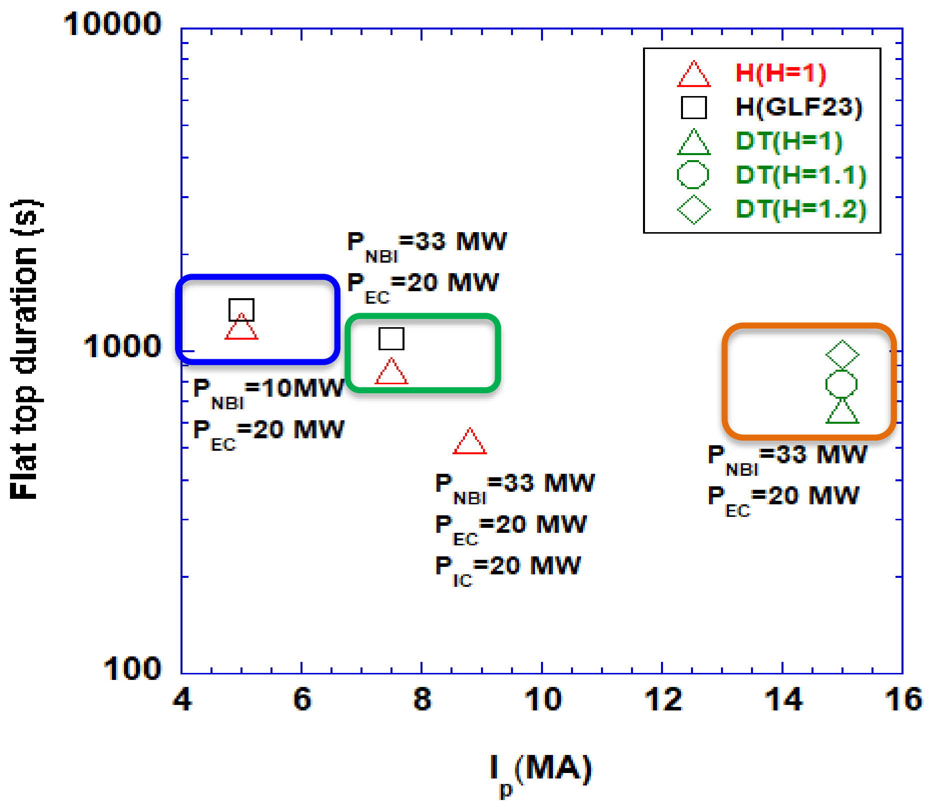
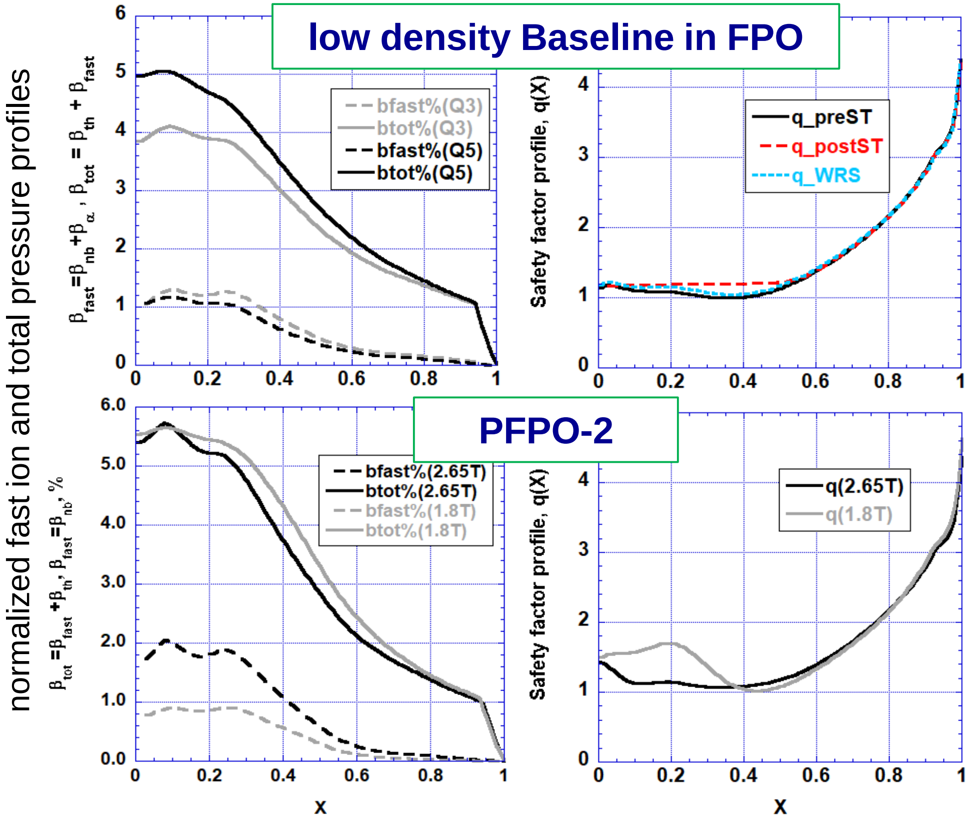


# Similarity between LPOs in PFPO-2 and FPO

- Heating power close to the H-mode power threshold ($P_{tot} < 2P_{LH}$)
- High toroidal rotation mainly due to lower density or better confinement, $V_{tor}(0) > 200$ km/s
- Moderate Mach number for the fuel, $V_{tor}/C_S < 0.25$;
- High fast particle pressure, $\beta_{fast}/\beta_{th} > 0.1$
- Low or weak reversed shear profile with $q_{min} \sim 1$
- Relatively high $n_{sep}/n_{ped} > 0.25$
- These similarities will support and drive LPO studies (e.g. CD validation, energetic particle stability) in PFPO-2 prior to FPO

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# ITER LP and SS candidates in IMAS scenario DB

This list will be continuously extended

## ASTRA

| Pulse | Run | Database | Reference | Ip[MA] | B0[T] | Fuelling | Confinement | Workflow | Date |
|---|---|---|---|---|---|---|---|---|---|
| 101000 | 50 | ITER | PFPO-2 tf=tE,2NBI,highTped,postST | -7.5 | -2.65 | H | H-mode | ASTRA | 2021-08-02 14:40:57 |
| 101001 | 50 | ITER | PFPO-2 tf=tE,2NBI,highTped,preST | -7.5 | -2.65 | H | H-mode | ASTRA | 2021-08-02 14:40:57 |
| 101002 | 50 | ITER | PFPO-2 tf=tE,2NBI,lowTped,postST | -7.5 | -2.65 | H | H-mode | ASTRA | 2021-08-02 14:40:57 |
| 101003 | 50 | ITER | PFPO-2 tf=tE,2NBI,lowTped,preST | -7.5 | -2.65 | H | H-mode | ASTRA | 2021-08-02 14:40:57 |
| 101004 | 60 | ITER | PFPO-2 tf=2tE,2NBI | -7.5 | -2.65 | H | H-mode | ASTRA | 2021-08-25 09:48:55 |
| 101005 | 60 | ITER | | | | | | | |
| 101006 | 60 | ITER | | | | | | | |
| 101007 | 40 | ITER | | | | | | | |
| 101007 | 41 | ITER | | | | | | | |
| 101007 | 42 | ITER | | | | | | | |
| 101010 | 0 | ITER | | | | | | | |
| 101010 | 1 | ITER | | | | | | | |
| 101014 | 0 | ITER | | | | | | | |
| 101014 | 1 | ITER | | | | | | | |
| 101015 | 0 | ITER | | | | | | | |
| 101015 | 1 | ITER | | | | | | | |
| 101019 | 0 | ITER | | | | | | | |
| 101019 | 1 | ITER | | | | | | | |
| 101020 | 0 | ITER | | | | | | | |
| 111000 | 50 | ITER | | | | | | | |
| 111001 | 50 | ITER | | | | | | | |
| 131000 | 50 | ITER | | | | | | | |
| 131001 | 50 | ITER | | | | | | | |
| 131002 | 50 | ITER | | | | | | | |
| 131015 | 50 | ITER | | | | | | | |
| 131016 | 50 | ITER | | | | | | | |
| 131017 | 50 | ITER | | | | | | | |
| 131035 | 40 | ITER | | | | | | | |
| 131035 | 41 | ITER | | | | | | | |
| 131035 | 42 | ITER | | | | | | | |
| 131035 | 43 | ITER | | | | | | | |
| 131035 | 44 | ITER | | | | | | | |
| 131035 | 45 | ITER | | | | | | | |
| 131036 | 40 | ITER | | | | | | | |
| 131036 | 41 | ITER | | | | | | | |
| 131036 | 42 | ITER | | | | | | | |
| 131036 | 43 | ITER | | | | | | | |
| 131036 | 44 | ITER | | | | | | | |
| 131036 | 45 | ITER | | | | | | | |
| 131039 | 10 | ITER | | | | | | | |
| 131039 | 11 | ITER | | | | | | | |
| 131041 | 0 | ITER | | | | | | | |

## SOLPS-ITER

| Pulse | Run | Database | Reference | Ip[MA] | B0[T] | Fuelling | Confinement | Workflow | Date |
|---|---|---|---|---|---|---|---|---|---|
| 123163 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=1.76e21_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:22:54 |
| 123164 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=4.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:30:00 |
| 123165 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=7.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:35:51 |
| 123166 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=1.06e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:42:23 |
| 123167 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=1.32e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:48:28 |
| 123168 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=1.58e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:54:27 |
| 123169 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.3%_Dtpt=1.85e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:59:39 |
| 123170 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=1.76e21_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:24:31 |
| 123171 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=4.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:30:59 |
| 123172 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=7.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:37:24 |
| 123173 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=1.06e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:43:23 |
| 123174 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=1.32e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:49:19 |
| 123175 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=1.58e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:55:19 |
| 123176 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.4%_Dtpt=1.85e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 18:00:28 |
| 123177 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=1.76e21_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:25:33 |
| 123178 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=4.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:31:48 |
| 123179 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=7.80e22_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:38:20 |
| 123180 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=1.06e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:44:28 |
| 123181 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=1.32e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:50:10 |
| 123182 | 2 | ITER | D+He+Ne_130MW_Be-top_cNe=0.6%_Dtpt=1.58e23_f/4 | -10.05 | -5.3 | D | tbd | SOLPS-ITER | 2022-06-10 17:56:09 |
| 123183 | 2 | | | | | | | | |
| 123184 | 2 | | | | | | | | |
| 123185 | 2 | | | | | | | | |
| 123186 | 2 | | | | | | | | |
| 123187 | 2 | | | | | | | | |
| 123188 | 2 | | | | | | | | |
| 123189 | 2 | | | | | | | | |
| 123190 | 2 | | | | | | | | |
| 123191 | 2 | | | | | | | | |
| 123192 | 2 | | | | | | | | |
| 123193 | 2 | | | | | | | | |
| 123194 | 2 | | | | | | | | |
| 123195 | 2 | | | | | | | | |
| 123196 | 2 | | | | | | | | |
| 123197 | 2 | | | | | | | | |
| 123198 | 2 | | | | | | | | |
| 123199 | 2 | | | | | | | | |
| 123200 | 2 | | | | | | | | |
| 123201 | 2 | | | | | | | | |
| 123202 | 2 | | | | | | | | |
| 123203 | 2 | | | | | | | | |
| 123204 | 2 | | | | | | | | |

## CORSICA

| Pulse | Run | Database | Reference | Ip[MA] | B0[T] | Fuelling | Confinement | Workflow | Date |
|---|---|---|---|---|---|---|---|---|---|
| 130502 | 3 | ITER | Hybrid-DT, 12.5MA 5.3T L-H-L, 53.0MW Paux, Be/Ar | -12.5 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:01:26 |
| 130503 | 3 | ITER | Hybrid-DT, 12.5MA 5.3T L-H-L, 73.0MW Paux, Be/Ar | -12.5 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:01:34 |
| 130507 | 3 | ITER | Hybrid-DT, 11.5MA 5.3T L-H-L, 73.0MW Paux, Be/W | -11.5 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:02:24 |
| 130509 | 3 | ITER | Hybrid-DT, 12.5MA 5.3T L-H-L, 73.0MW Paux, Be/W | -12.5 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:02:36 |
| 130504 | 3 | ITER | Steady-DT, 9MA 5.3T L-H-L, 56.5MW Paux, Be/Ar | -9.0 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:01:42 |
| 130505 | 3 | ITER | Steady-DT, 8.5MA 5.3T L-H-L, 58.0MW Paux, Be/Ar | -8.5 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:01:48 |
| 130508 | 3 | ITER | Steady-DT, 10.0MA 5.3T L-H-L, 79.5MW Paux, Be/W | -10.0 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:02:29 |
| 130510 | 3 | ITER | Steady-DT, 10.0MA 5.3T L-H-L, 69.5MW Paux, Be/W | -10.0 | -5.3 | D-T | L-H-L | CORSICA | 2022-06-23 10:02:43 |

## DINA

| Pulse | Run | Database | Reference | Ip[MA] | B0[T] | Fuelling | Confinement | Workflow | Date |
|---|---|---|---|---|---|---|---|---|---|
| 105027 | 1 | ITER | 5MA H-DINA2022 PFPO1-4b | -5 | -1.8 | H | H-mode | DINA-IMAS | 2022-08-29 16:25:16 |
| 115001 | 4 | ITER | 5MA 1.8T He-DINA2018-01 | -5.18 | -1.8 | He | H-mode | DINA | 2021-04-09 19:11:28 |
| 115002 | 4 | ITER | 5MA 1.8T He-DINA2018-02 | -5.13 | -1.8 | He | H-mode | DINA | 2021-04-09 19:36:17 |

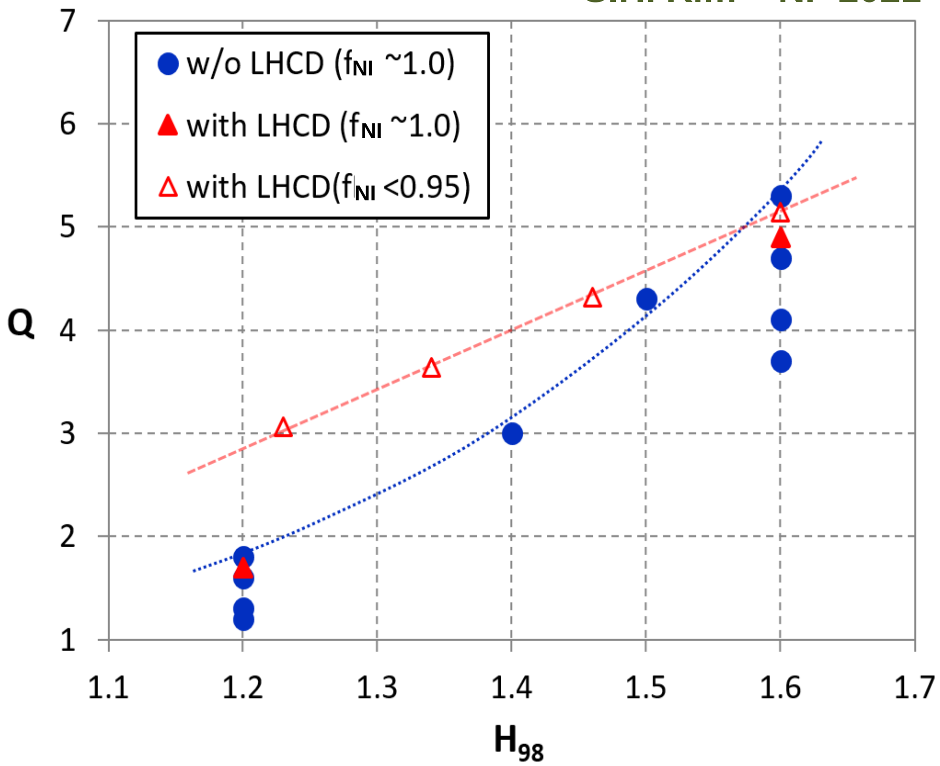
# Conclusions

- ITER high Q scenarios are based on extensive modelling studies and the developed scenarios are available in the ITER scenario database
- Open issues remain regarding physics assumptions that can impact ITER scenarios
- Development of long pulse operation in PFPO will focus on identifying reliable paths (in terms of $q_{95}$, current drive, fast ions, etc) for extrapolation to FPO LPOs
- Targeted experiments and integrated modelling are required to strengthen basis of ITER scenarios
- IO High Fidelity Plasma Simulator (HFPS), which is under development by combining DINA and JINTRAC, will be used to further improve ITER scenarios and to identify other candidate paths

# Back-up Slides

# Non-inductive scenarios with or w/o LHCD

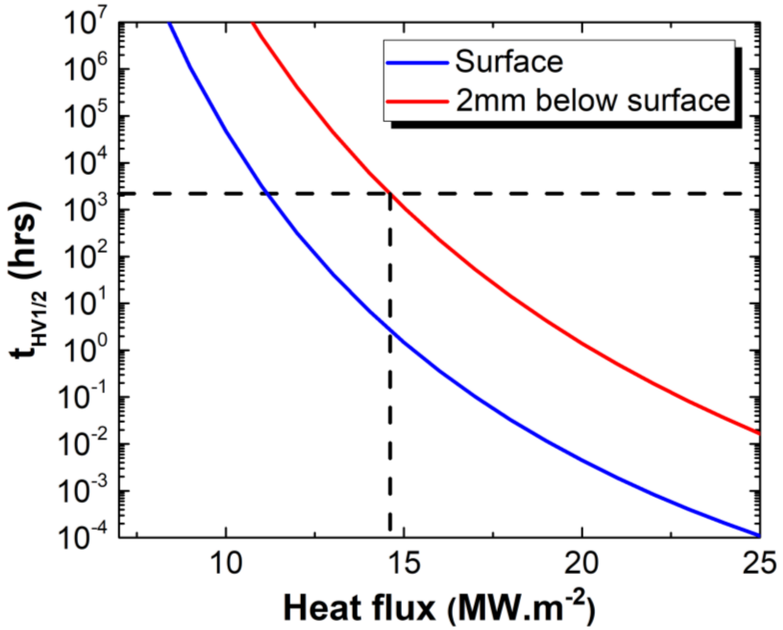
S.H. Kim – NF 2021




- ITER research plan (IRP) with the staged approach required early decision on HCD upgrade, in particular for **LHCD system**
- Q~5 fully non-inductive scenarios at $H_{98}$~1.6 using HCD upgrade options **with or without including LHCD**
- ASTRA/KINX stability analysis shows that the plasma stability was **equivalent or better** in the case **without LHCD**

# Power fluxes and divertor lifetime

- High $q_{div}$ leads to W divertor cracks due to stresses in material (typically ~2mm at 20MW/m$^2$)
- Permissible stationary heat loads estimated reflecting W material recrystallization and monoblock self-castellation can be ~50% higher [R. Pitts, NME 2019] ➔ ~15 MW/m$^2$ (~10MW/m$^2$ toroidally averaged)
- Lifetime of ITER divertor is determined by the W recrystallization dynamics in the absence of large transients
- Time required for W hardness to drop by 50% is estimated as 2000-3000 hours (from FPO-1 to FPO-3)




**G. de Temmerman – PPCF 2018**
**R. Pitts – NME 2019**

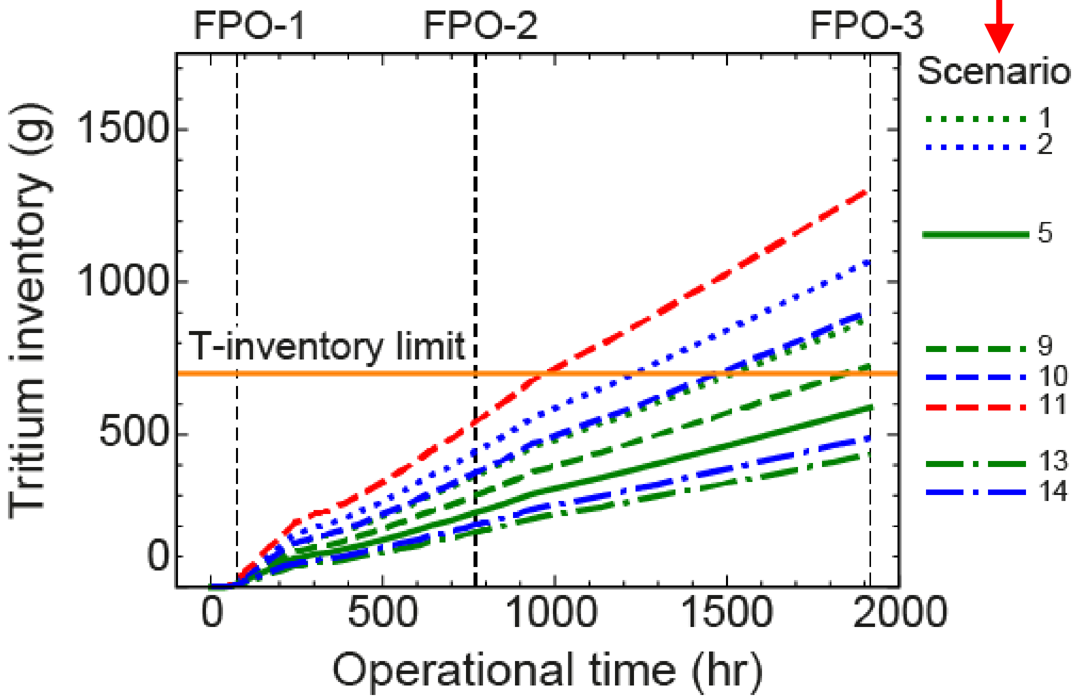
# Stationary power exhaust

- Basic assumptions
  - Narrow near separatrix e-folding length → 80 – 100 % of $P_{SOL}$ power arrives divertor
  - Broad far SOL e-folding length (+ ELMs) → 20 - 0 % $P_{SOL}$ arrives at first wall
- Most studies done for 15 MA/5.3 T Q = 10 plasmas
  - Q = 5 plasmas have lower densities → unfavourable for divertor dissipation → Radiative divertor studies in advanced plasmas required

# T retention and budget

- Cases for which peak FWP stationary erosion < 4 mm
  - Several cases above in-vessel T-limit already in FPO-2, if no T removal action implemented
  - Will require well developed inventory control strategy

Different plasma backgrounds

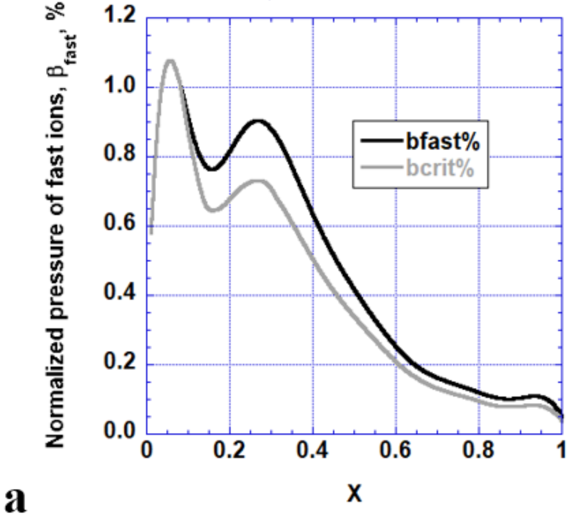



R. Pitts – PSI 2022

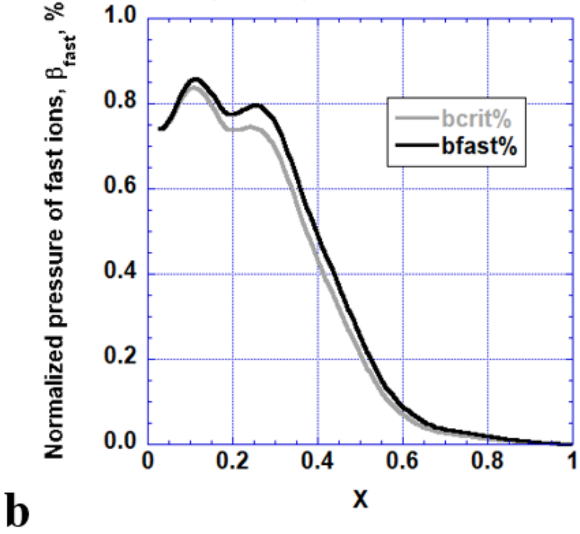
# HINST EP analysis LPOs in PFPO-2 and FPO

- Non-perturbative critical gradient model, HINST, is applied to study AE mode driven fast ion transport

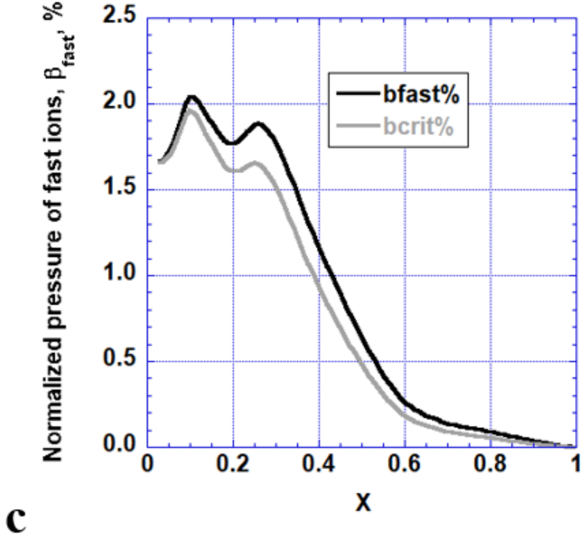
15MA/5.3T low density DT H-mode




5MA/1.8T Hydrogen H-mode

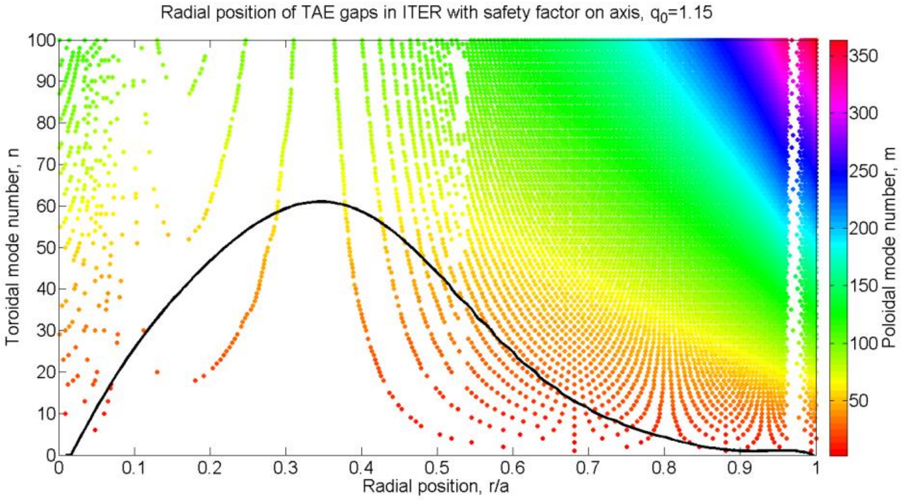



7.5MA/2.65T Hydrogen H-mode



# Energetic particles in 15 MA / 5.3 T baseline scenario

- Consequences of EP-driven AE modes range from
  - Benign saturation → significant high-amplitude bursting and transport
- Extrapolation from present machines difficult due to small $\rho_\alpha / a \cong 10^{-2}$
  - ITER first wall can only tolerate losses of a few %
  - Max power transfer from alphas occurs when drift orbit width ~ mode width → n~30
  - Many overlapping AE




Radial localisation of TAE gaps in ITER