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STEP

UK STEP TOWARDS A FUSION POWER PLANT PLASMA

17/10/25 – HENDRIK MEYER

Head of Plasma Development

FOR THE STEP PLASMA TEAM

THANKS TO THE STEP PLASMA, CONTROL AND HCD TEAM...

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Andrew Turner
Anthony Field
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T. Todd, (G. Fishpool), F. Militello

System Engineering
G Hodgson, P. Curson, Z. Johnson,
F. Chaudry
...

Names in **bold** are coordinating specific STEP areas

OVERVIEW

THE STEP PROGRAMME AIMS TO DELIVER A TRITIUM SELF–SUFFICIENT PROTOTYPE POWER PLANT ~2040 WITH P_{net}^{el}~100 MW

- First design base published in 2024 – SPP-1
  - *see Phil. Trans. R. Soc. A. Vol 382, issue 2280*
  - ***Plasma**: H Meyer et.al. Phil. Trans. R. Soc. A.382 20230406*
  - ***Plasma Control**: M. Lennholm et.al. Phil. Trans. R. Soc. A.38220230403*

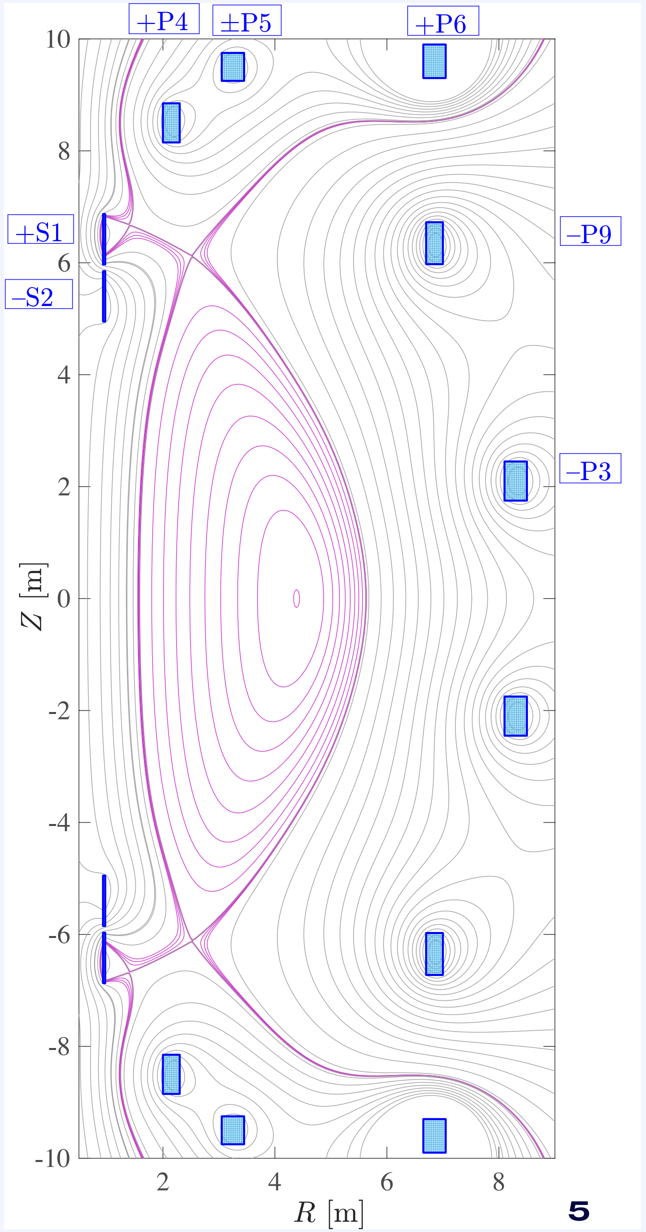
SPP-1	
R_{geo}	3.6 m
A	1.8
V_{pl}	714 m^3
B_t	3.2 T
κ	3
δ	0.5
P_{fus}	1.5 – 1.8 GW

- Based on a highly elongated and spherical tokamak

$$P_{fus} \propto (\beta_N B_t)^4 \kappa^5 \frac{R^3}{A^3}$$

- Double null configuration to protect the inner divertor.
- Alternative magnetic configurations in all divertor legs.

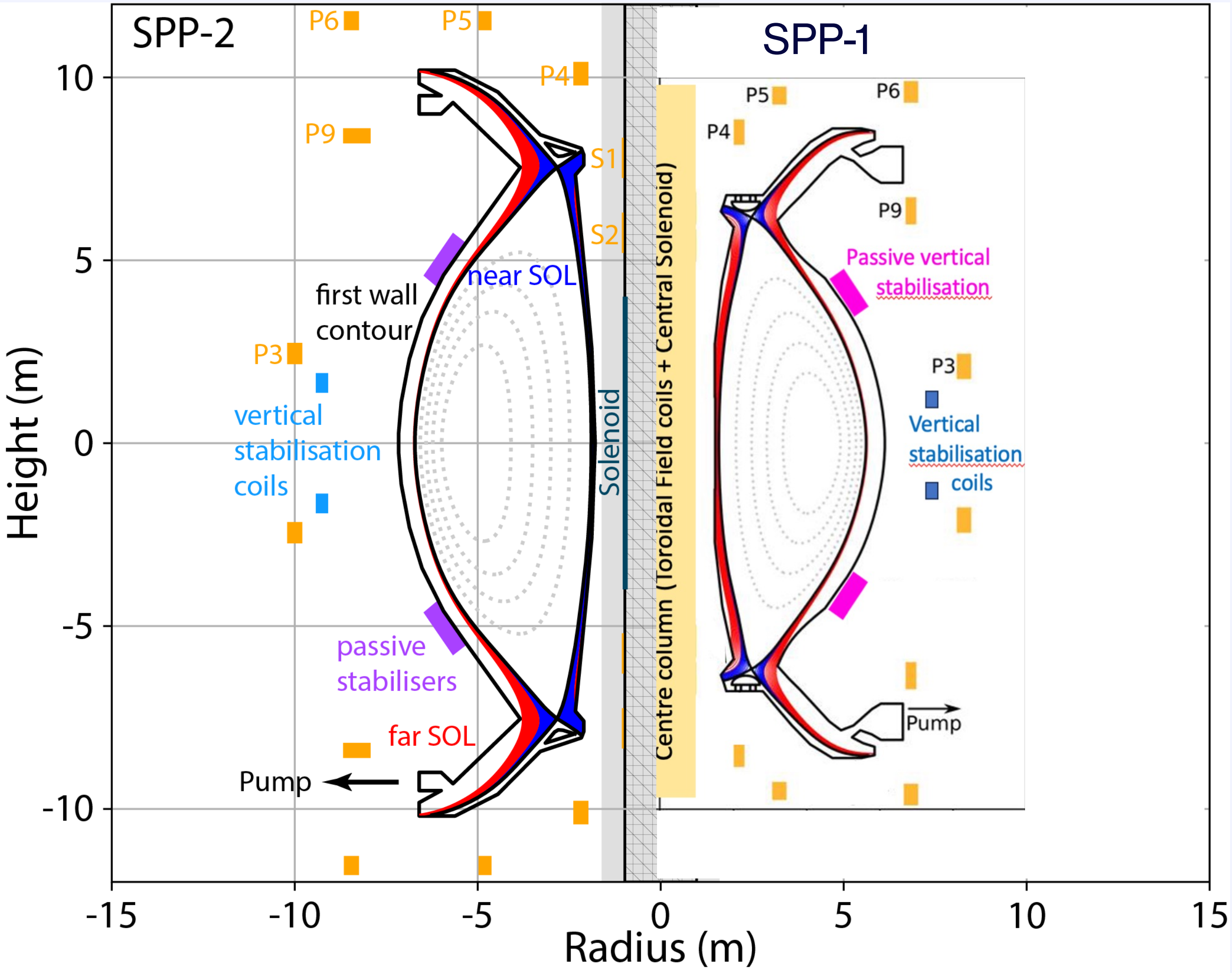
https://github.com/ukaea/OpenSTEP



Overview over the STEP Programme: H. Wilson tomorrow 14:40

FOR TECHNICAL REASONS THE BASELINE PIVOTED TO A LARGER MAJOR RADIUS OF $R_{geo} = 4.3\ m$ AT SAME A

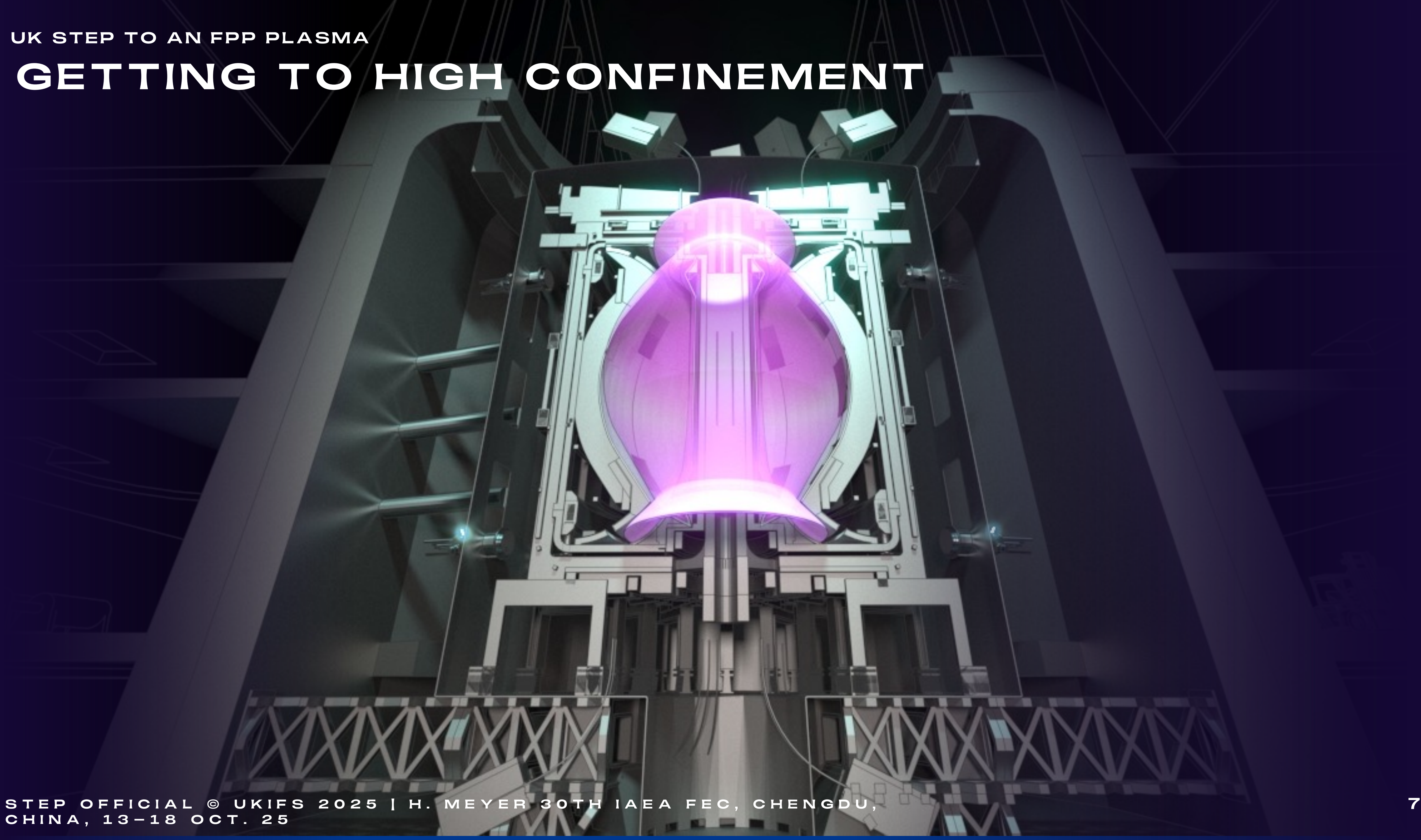
- **Plasma design philosophy not changed.**
- Volume ~1.5× ITER, but only ½ of EU-DEMO
- Height similar to EU-DEMO



	SPP-1	SPP-2
R_{geo}	$3.6\ m$	$4.3\ m$
R_{in}	$1.6\ m$	$1.9\ m$
A	1.8	
V_{pl}	$714\ m^3$	$1250\ m^3$
B_t	3.2 T	3.0 T
κ	3	
δ	0.5	0.5 – 0.6
β_N	4.5 – 5.3	~4.2
P_{fus}	1.5 – 1.8 GW	

Baseline Concept SPP-1 see:
Phil. Trans. R. Soc. A. Vol 382, issue 2280

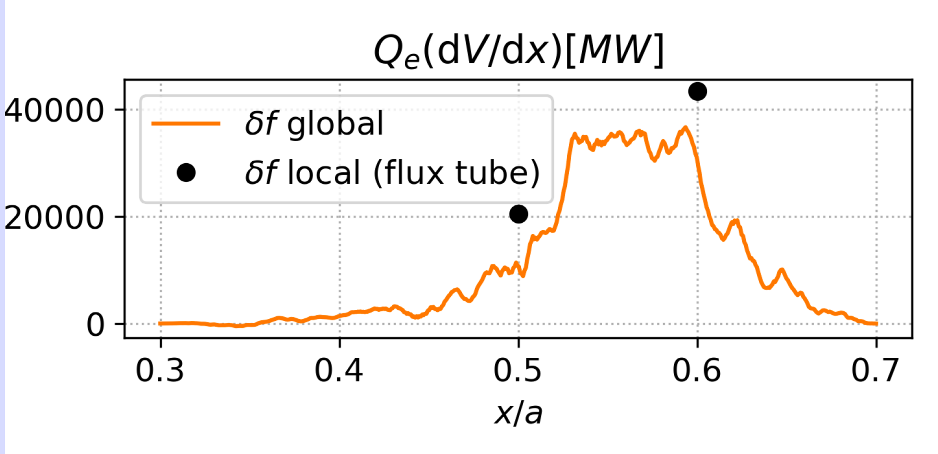
GETTING TO HIGH CONFINEMENT

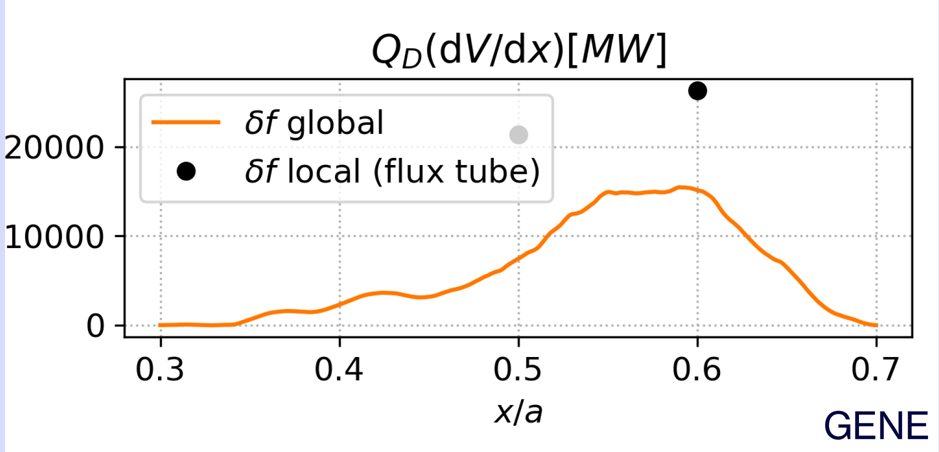


EM TURBULENCE IN STEP CAN DRIVE UNSUSTAINABLE TRANSPORT FLUXES

- Transport dominated by hybrid kinetic ballooning mode turbulence (h-KBM). – ***See next talk D. Kennedy!***
  - Subdominant: Micro-tearing mode turbulence (MTM).
- Good agreement between global and local nonlinear gyrokinetic simulations.
  - Fixed gradient not flux driven!
  - MTMs suppressed.
- h-KBM turbulence strongly reduced by flow shear, but STEP has no external momentum input except α-particle loss.
- h-KBM also reduced by high pressure gradients β' and negative magnetic shear.

SPP-1: EC-HD





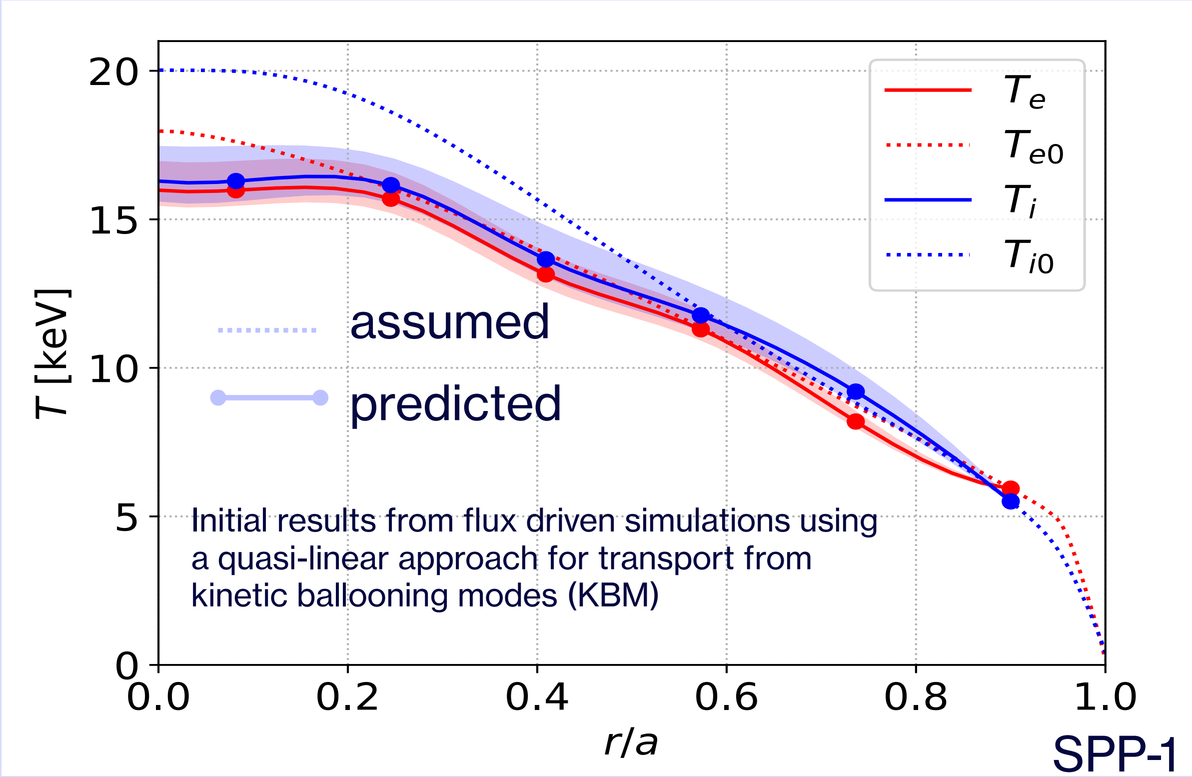
D. Kennedy et al in preparation

D. Kennedy, C. Roach, B. Patel, H. Dudding, M. Giacomin, *D. Dickenson, A. Bokshi*

FIRST FLUX–DRIVEN CALCULATIONS INCREASE CONFIDENCE IN THE EXISTENCE OF THE FLAT–TOP OPERATING POINT

- New quasi-linear model for hybrid kinetic ballooning mode (h-KBM) transport *neglecting fast ions and impurities.*
  - Benchmarked with local NL GK simulations.
- Strong transport at SPP1 reference, but transport relaxes profiles to a nearby marginal state.
  - Flux driven calculations weakly sensitive to flow shear.
- Detailed evolution sensitive to initial condition, assumptions ($\gamma_E, f_{rad}, \ldots$).

Access from low β_e still unclear as β_e drive must be overcome by β_e' and flow shear stabilisation.



Flattening of predicted profiles reduces P_{fus} by 10%

M Giacomin et. al. J. Plas. Phys. ***91*** *(2025) pE16*

D. Kennedy, C. Roach, B. Patel, H. Dudding, *M. Giacomin, D. Dickenson, A. Bokshi*

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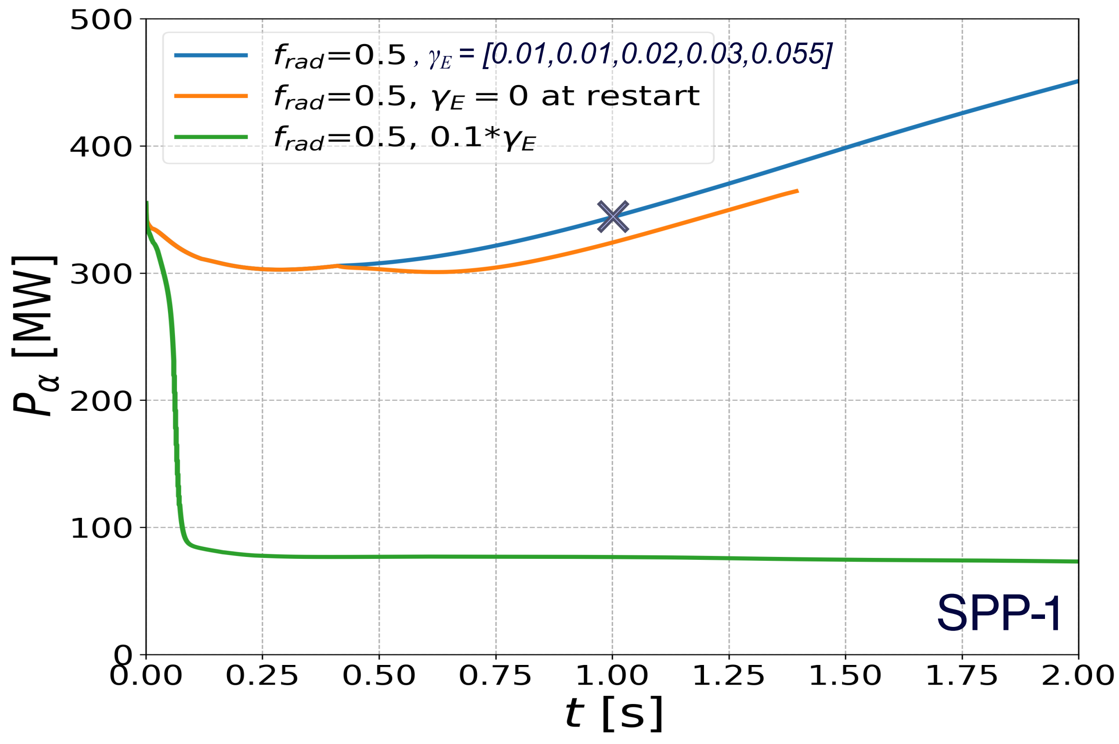
EC-HD



Access from low β_e still unclear as β_e drive must be overcome by β_e' and flow shear stabilisation.

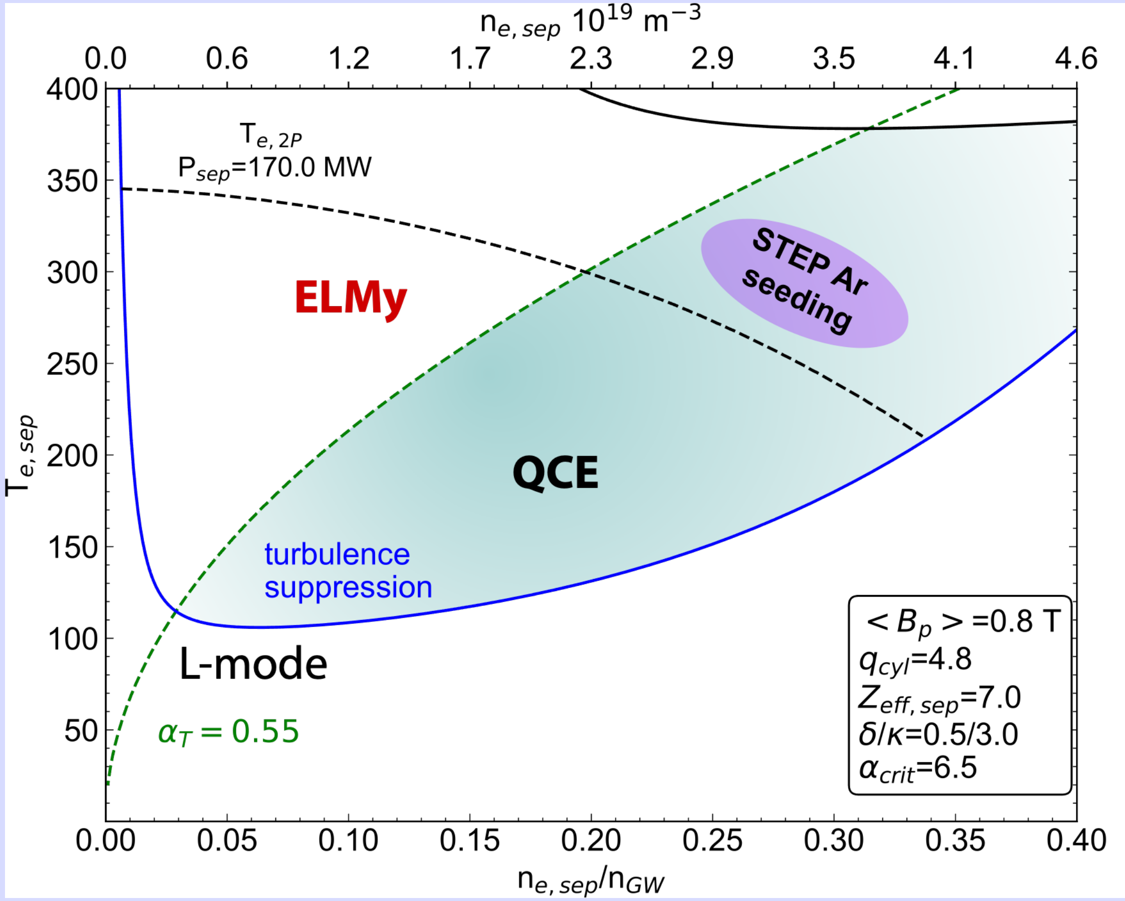
A Bokshi
M Abazorius

D. Kennedy, C. Roach, B. Patel, H. Dudding, *M. Giacomin, D. Dickenson, A. Bokshi*

EVIDENCE OF ACCESS TO QCE IN STEP IS GROWING

- In the separatrix operating space according to [Eich25] the SPP-2 edge sits in region of quasi continuous exhaust mode (QCE).
  - $\alpha > \alpha_t^{QCE} = 0.55\alpha_t \approx \nu_{e,edge}^{\star}\hat{q}_{cyl}^2/100$
- Access criteria from [Dun24] also met depending effect of impurities on $\partial T_e/\partial r$.
  - Unclear if applicable for ST and high Z_{eff}^{sep}~$5-7$.

QCE recently observed on MAST-U ⇒ better understanding for STEP.



[Dun24] M. Dunne et.al. the, Nucl. Fusion **64**, 124003 (2024).
[Eich25] T. Eich et al., Nucl. Mat. and Energy **42**, 101896 (2025)

S. Saarelma, S. Henderson

FALL BACK: ACTIVE RMP ELM SUPPRESSION SEEMS FEASIBLE WITH $n = 1 - 4$

Y. Liu et.al. Plasma Phys. Control. Fusion **67,** 085010 (2025)

- In- and ex-vessel coils for resonant magnetic perturbations (RMP) included in the design.
  - Studied 5 cases (4 SPP-1, 1 SPP-2) with MARS-F/Q for in-vessel coil set.
  - SPP-1: 16 upper 8 middle, 16 lower, SPP-2: 12 upper, 12 middle, 12 lower.

- Figure of merits derived from SN conventional aspect ratio can be exceeded with $I_{RMP} = 10 - 20\ kAt$ (n = 1,2) or $I_{RMP} = 100 - 200\ kAt$ (n = 3, 4).

MAST-U: RMP ELM suppression achieved for the first time in an ST (SN)
see J. Harrison – this confernece

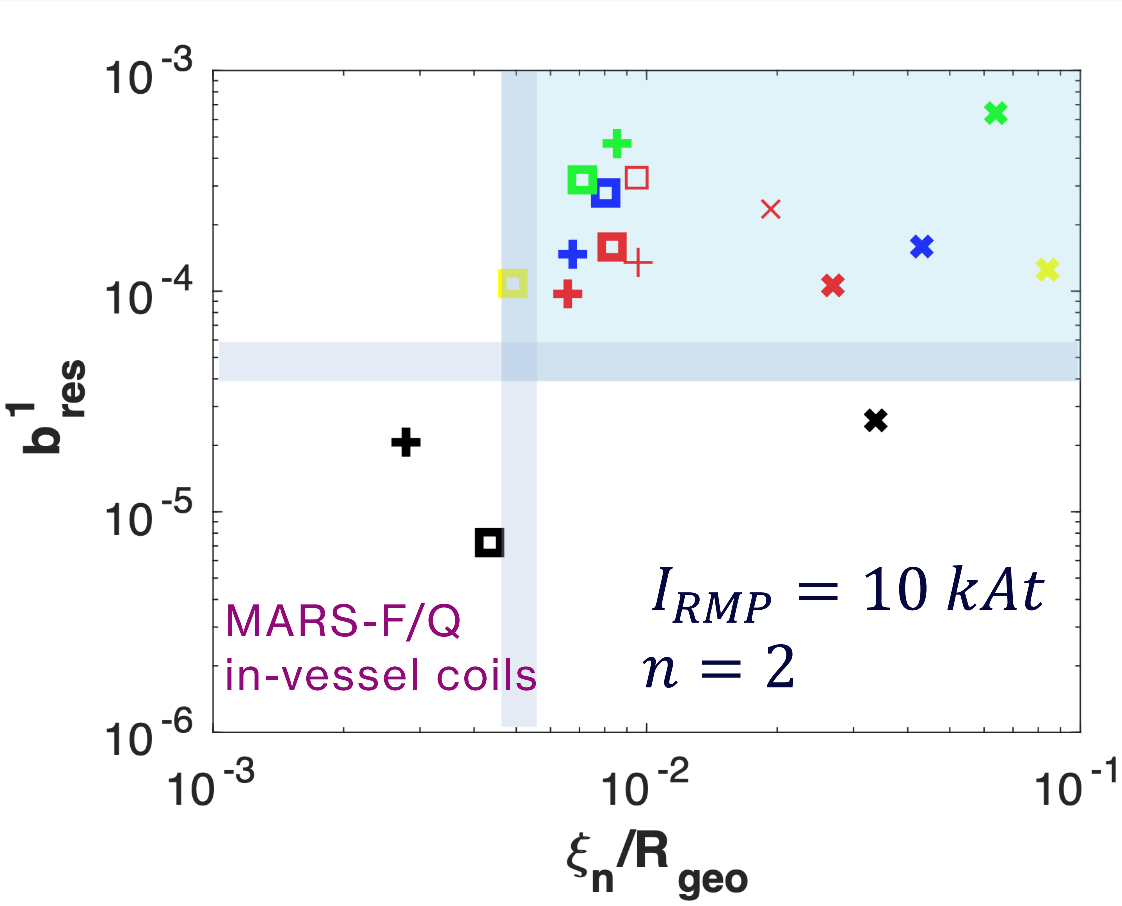
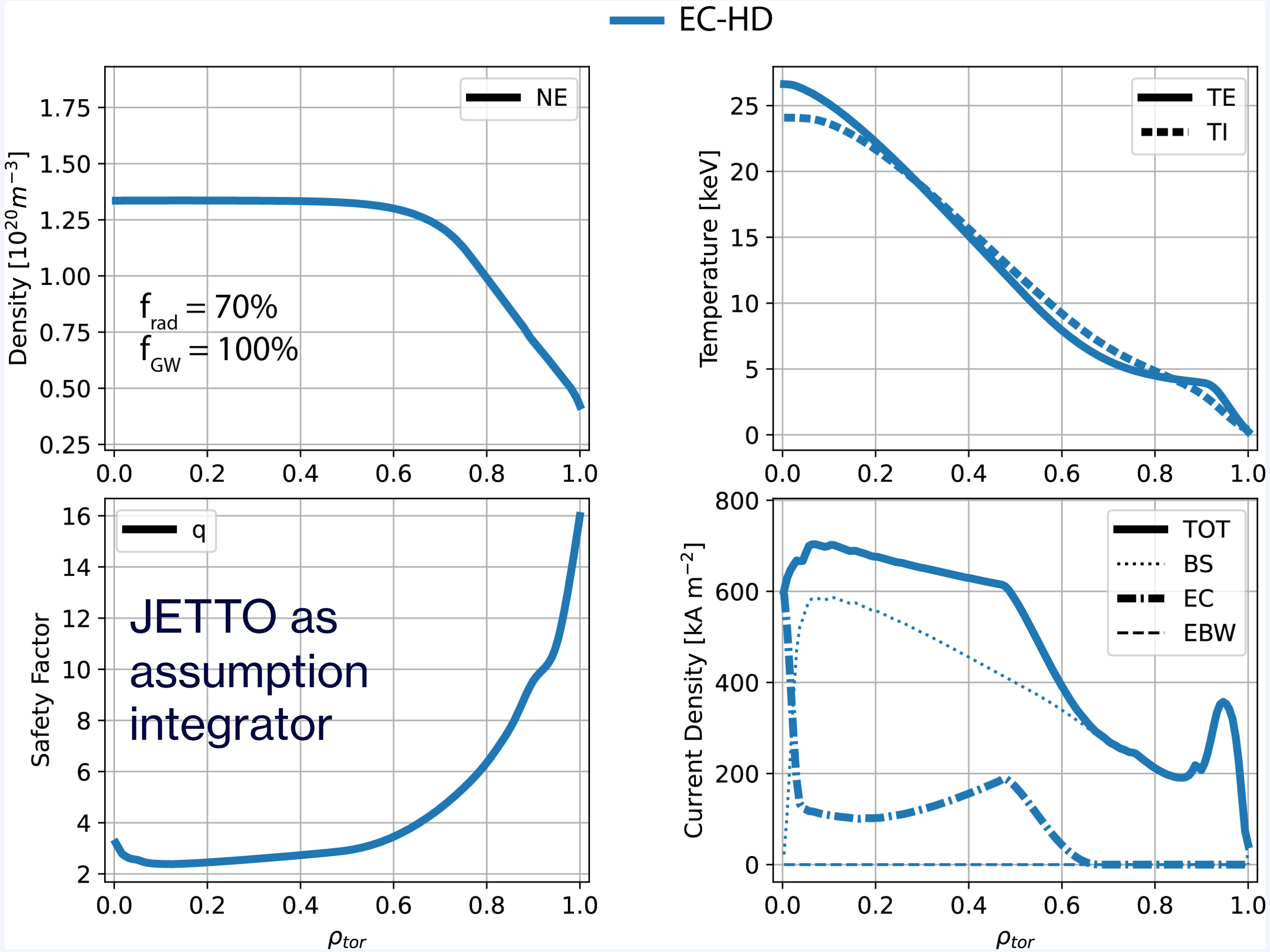


Figure of merits for ELM suppression for 4 SPP-1 (●●●●) and one SPP-2 (●) scenario with $n = 2$ and $I_{RMP} = 10\ kAt$ (shaded region indicates the thresholds.). The symbols are different flow assumptions Ω_0/ω_A.

Y. Liu (GA), G. Xia, X. Chen (GA), Z. Li (GA), T. Tang (GA), S. Saarelma

THE SCENARIO

COMPARED TO SPP–1 LARGER MINOR RADIUS ⇒ LOWER DENSITY ⇒ HIGHER ECCD EFFICIENCY



Name	EC-HD	EB-HQ	EC-LR
f_{rad}^{core}	0.7	0.7	0.4
I_p $[MA]$, f_{BS}	22, 0.9	20, 0.9	19, 0.8
P_{fus} [GW]	1.8	1.8	1.3
Q	10	**30**	12
P_{net}^{el} $[MW]$	230	460	180
P_{EC}, $P_{EBW}[MW]$ 1)	174, 0	0.7, **60**	104, 0
$f_{GW} = \bar{n}_e/n_{GW}$	1	1.4	1
β_N **(input)**	4.2	4.1	3.8
$l_i(3)$	0.3		
τ_E $[s]$	5.6	6.3	3.0
P_{sep}/R_{geo} $[MW/m]$	32	25	45
$(H + H^*)/2$	**1.4** 2) (1.4) 3)	**1.3** 1) (1.4) 2)	1.3 2) (1.3)

H^*: confinement factor corrected for highly radiating plasmas

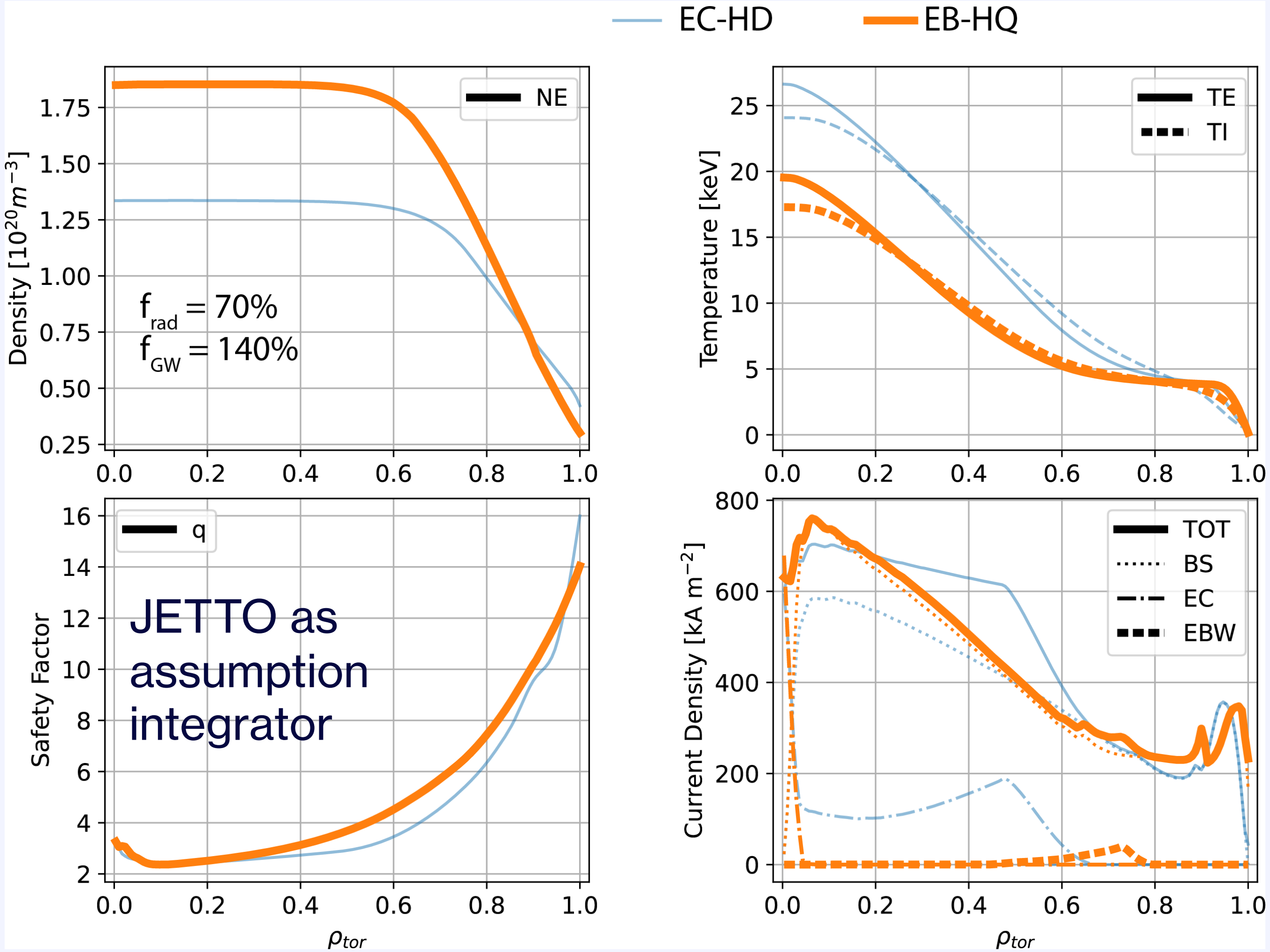
1) Values corrected for residual "inductive" current.
2) IPB98(y,2), 3) ITPA20-IL

Electron Bernstein Wave (EBW) heating and current drive enables either reduced confinement assumption or access to high Q

C. Olde, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

F. Casson, E. Tholerus, C. Olde, S. Marsden, T. Wilson, F. Palermo, P. Fox

EBCD ENABLES ACCESS TO HIGH Q BUT AT $f_{GW} > 1$



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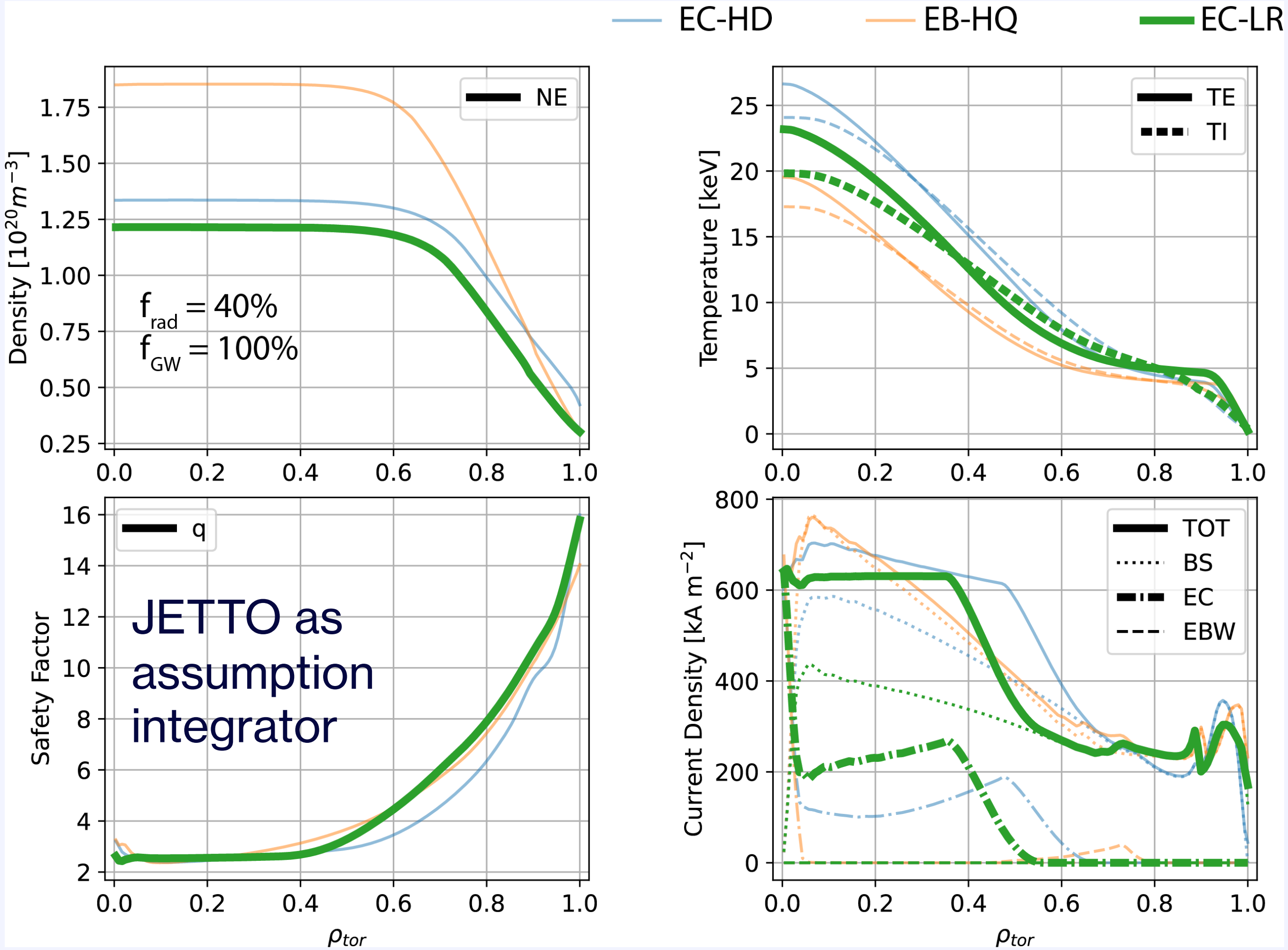
F. Casson, E. Tholerus, C. Olde, S. Marsden, T. Wilson, F. Palermo, P. Fox

LOWER f_{rad} WOULD ENABLE ROUTE TO LOWER $P_{fus}\sim 1.3\ GW$ BUT IS MORE CHALLENGING FOR THE DIVERTOR



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$P_{sep}/R_{geo}\ [MW/m]$	32	25	45
$(H + H^*)/2$	**1.4**[2] (1.4)[3]	**1.3**[1] (1.4)[2]	1.3[2] (1.3)

H^*: confinement factor corrected for highly radiating plasmas

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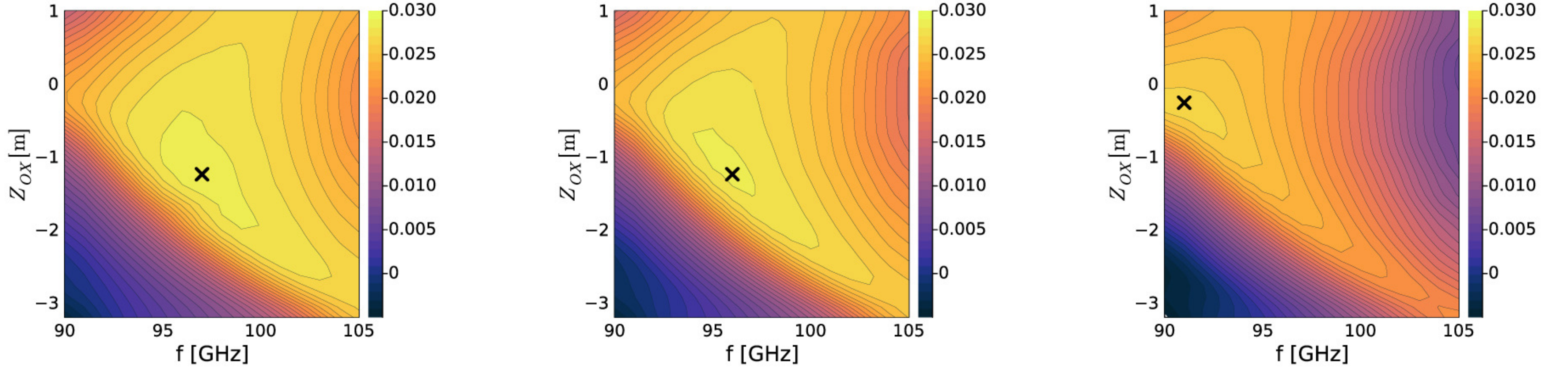
C. Olde, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

F. Casson, E. Tholerus, C. Olde, S. Marsden, T. Wilson, F. Palermo, P. Fox

EBCD MODELLING REQUIRES INCLUSION OF RELATIVISTIC AND NON–LINEAR EFFECTS

*B. Biswas, Nucl. Fusion **65**, 016010 (2025)*



(a) P_{EBW} =1MW (b) P_{EBW} =10MW (c) P_{EBW} =100MW

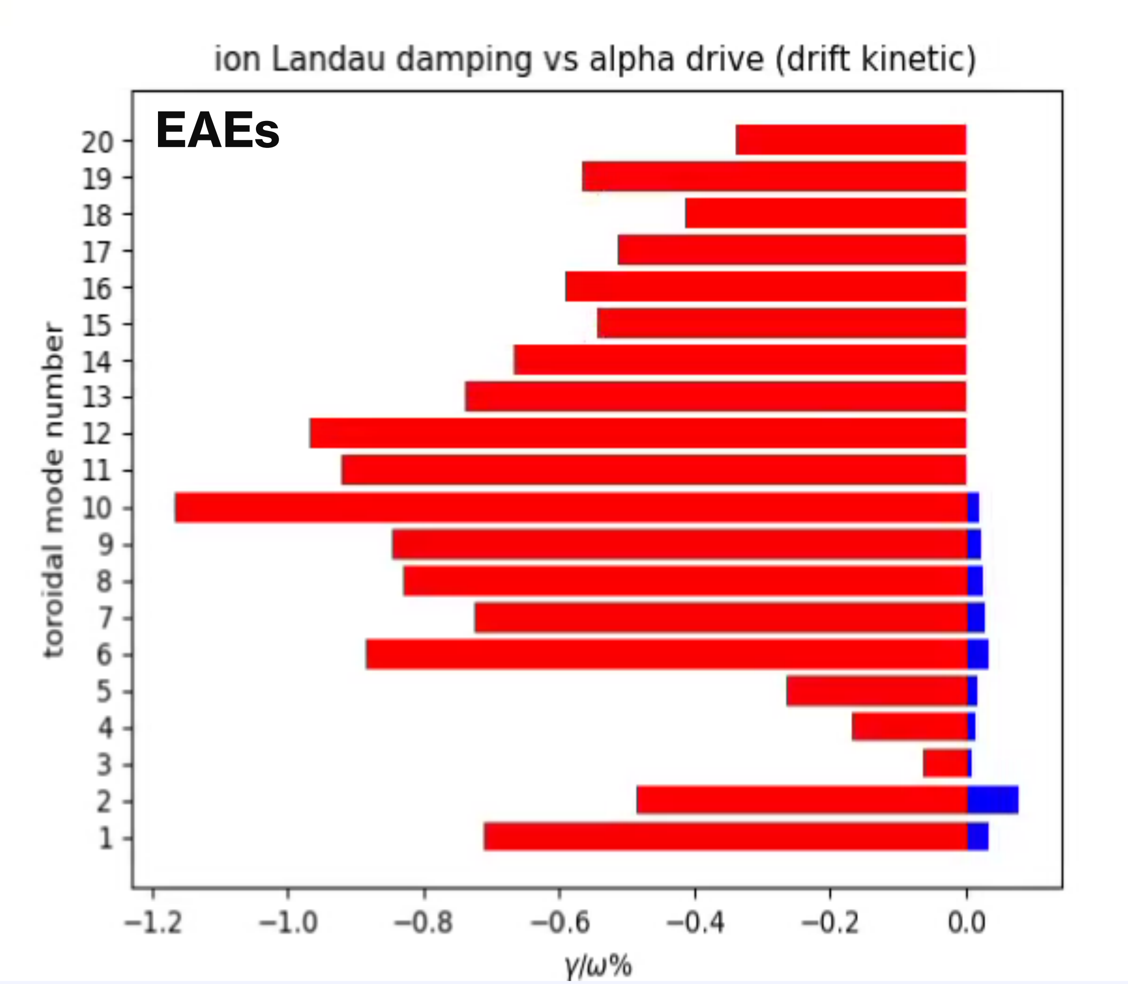
- New robust fast ray-tracing tool for scenario modelling of EBCD ⇒ CRAYON [Wil25].
- Coupling to high energy tail ⇒ Relativistic ray tracing + non-linear power absorption.
- Shift of optimal launch, η_{CD} and radial location already with $P_{EB} > 10\ MW$
- Mode conversion ⇒ multiple modes + robust ray conversion.

S. Freethy, T. Wilson, B. Biswas, A. Köhn, R. Sharma, B. Eliasson, D. Speirs, R. Vann

[Wil25]T. Wilson, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

ALFVÉNIC INSTABILITIES ARE DAMPED BY BULK ION LANDAU DAMPING

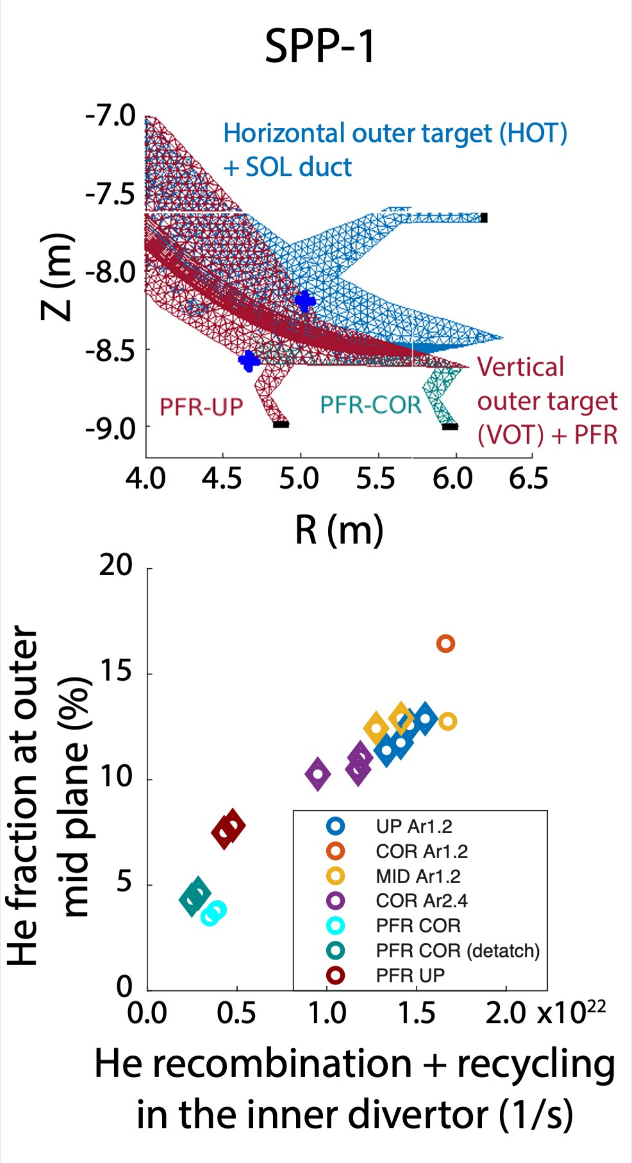
- Toroidicity & ellipticity induced Alfvén eigenmodes (TAEs & EAEs) propagate at Alfvén speed c_A & are resonantly driven by alpha-particles with $v_{\|} = c_A$
- Due to high β, Alfvén speed & ion thermal speed are closer in STEP than in conventional tokamak burning plasmas
- Bulk ion Landau damping suppresses all TAEs & EAEs in flat-top



PUMPING FROM THE PRIVATE FLUX IMPROVES HE EXHAUST

- Optimizing the divertor for detachment access ⇒ insufficient He exhaust (**see E. Tholerus Mi 10:10**)
  - Core requires He concentration of $c_{He}^{sep} < 6\%$.
- Main He source through the X-point from inner divertor recycling.
  - STEP can only pump from the outer divertor!
- Pumping close to the strike-point (corner) optimal for He but detrimental for DT.
  - Inventory limit on DT puff from fuel cycle!
- **Improved light impurity transport** in SOLPS-ITER [Mak23] reduces c_{He}^{sep} by a factor of 2 (sim. to ITER mod.) ⇒ **SPP-2** $\boldsymbol{c_{He}^{sep} \sim 4\%}$ **with optim. div..**

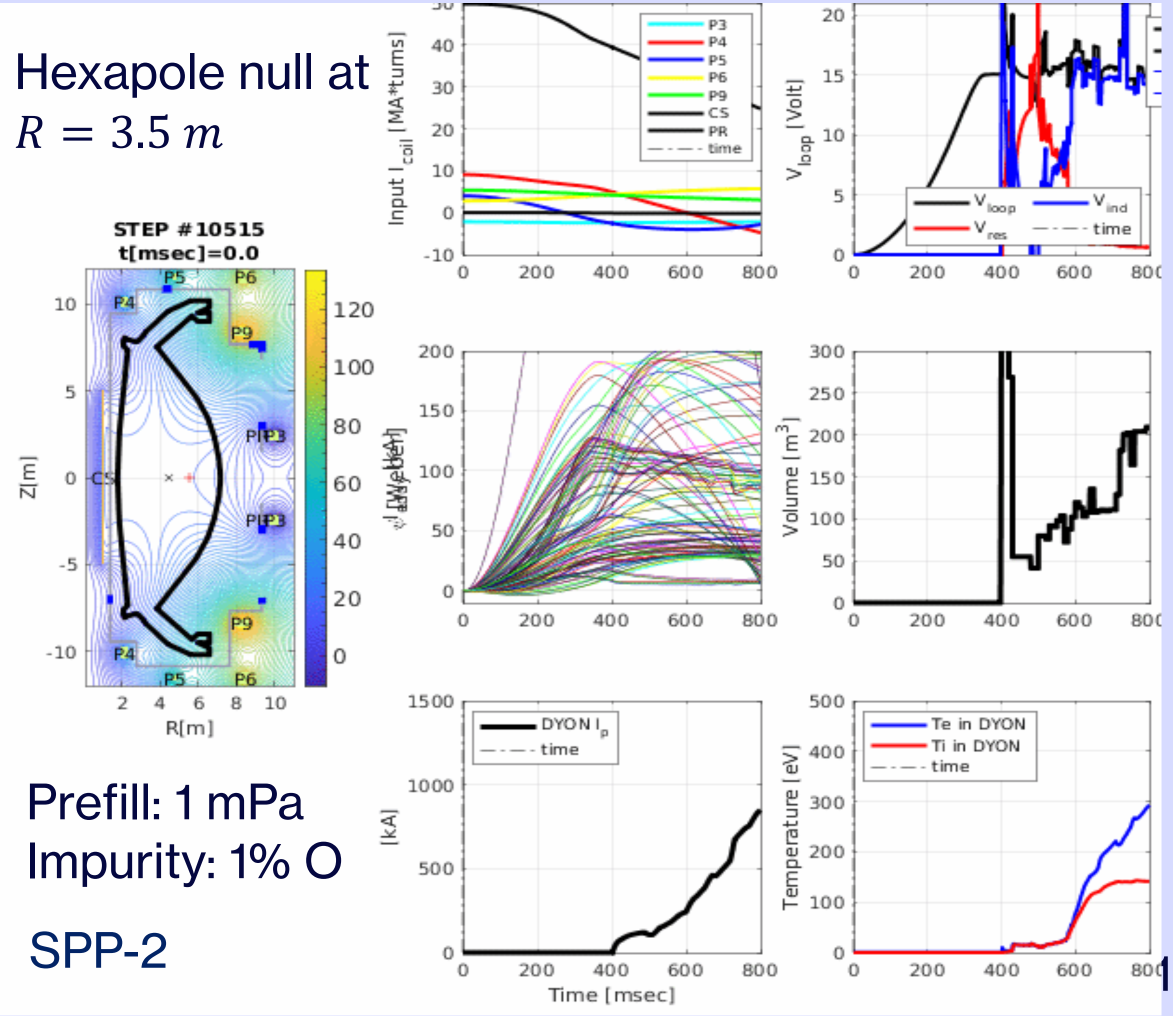
[Mak23] S. O. Makarov et al., Nucl. Fusion ***63****, 026014 (2023)*



R. Osawa, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

SMALL SOLENOID FACILITATES GENERATION OF DIVERTED TARGET PLASMA FOR THE NI RAMP–UP

- Resistive solenoid with $\Delta\psi_{CS} \approx 20\ Vs$.
- Break down and burn through from small solenoid: $\Delta\psi_{CS} \sim 5\ Vs$. ($V_{loop} > 15\ V$) - DYON
- Inductive ramp-up in limiter phase to create a full-bore target plasma with $I_p \approx 1 - 2\ MA$ $\Delta\psi_{CS} \sim 10 - 15\ Vs$

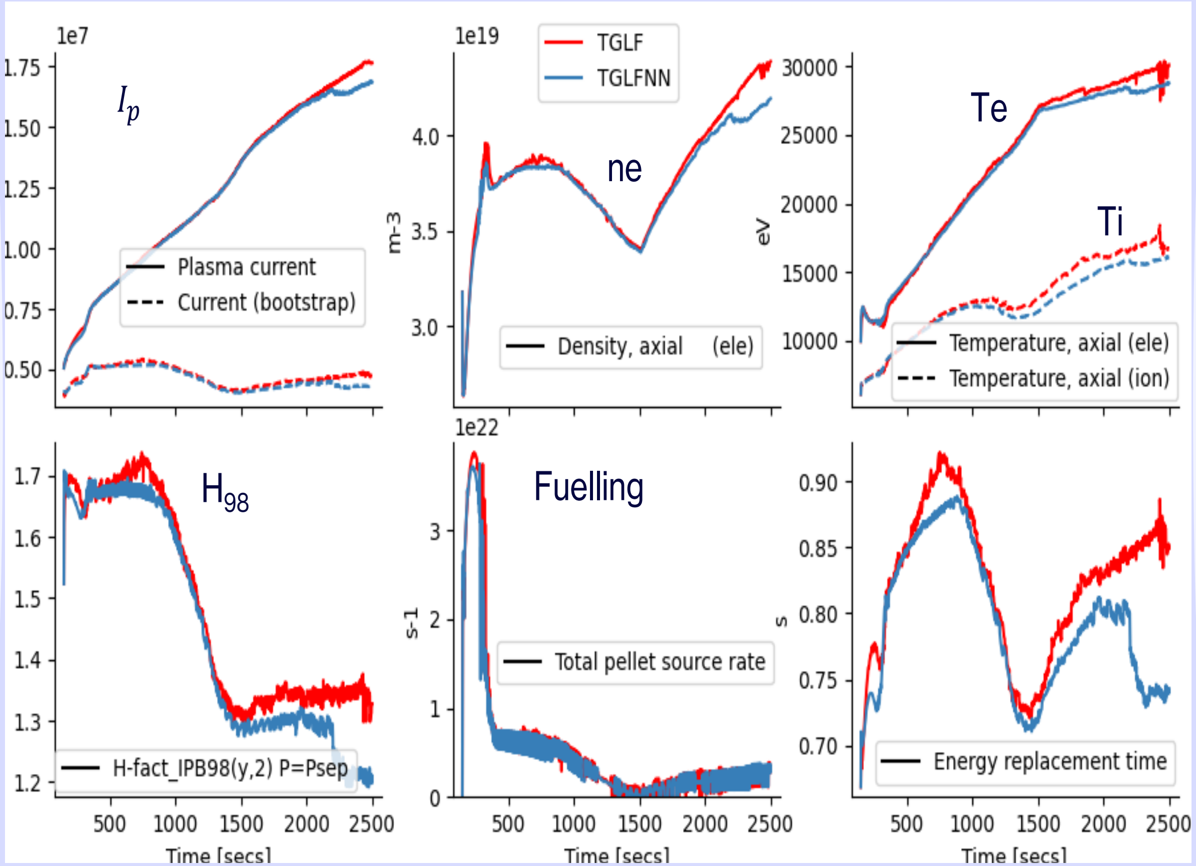


DYON: H.-T. Kim Fr 11:00

H.-T. Kim, O. Bardsley

FIRST PREDICTIVE NON INDUCTIVE RAMP–UP SIMULATIONS WITH FAST TGLFNN SURROGATE

- Need to broaden the current profile to avoid current hole.
- Increase density at full current ⇒ Fusion burn.
- Developed surrogate model (TGLFNN) from ST optimised version of TGLF.

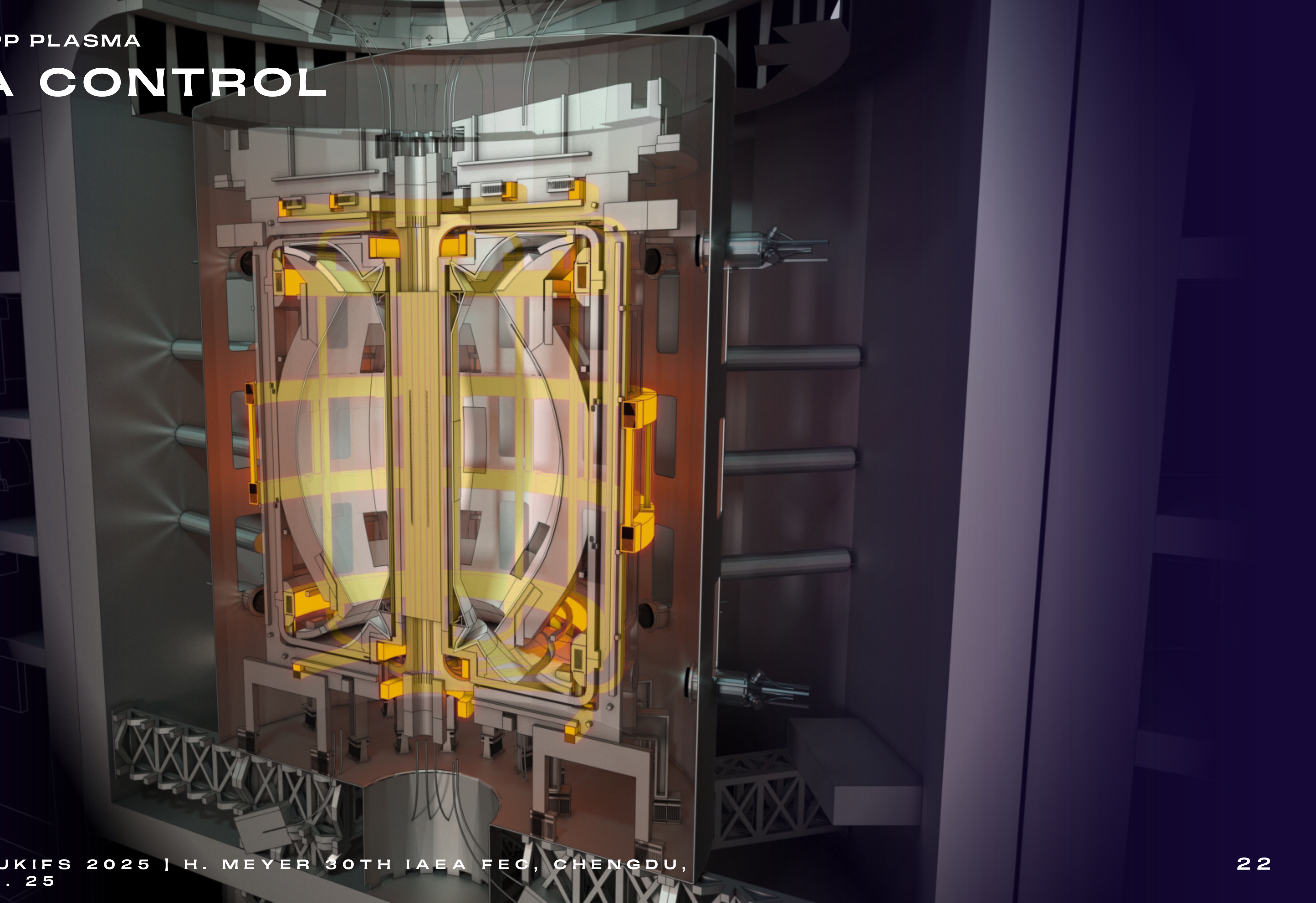


SPP-1

F. Casson, 29th EU-US TTF, Budapest, Hungary, 8-12 Sep. 2025

F. Eriksson, C. Olde, J. Mitchell, F. Casson, K. Kirov, C. Challis

PLASMA CONTROL

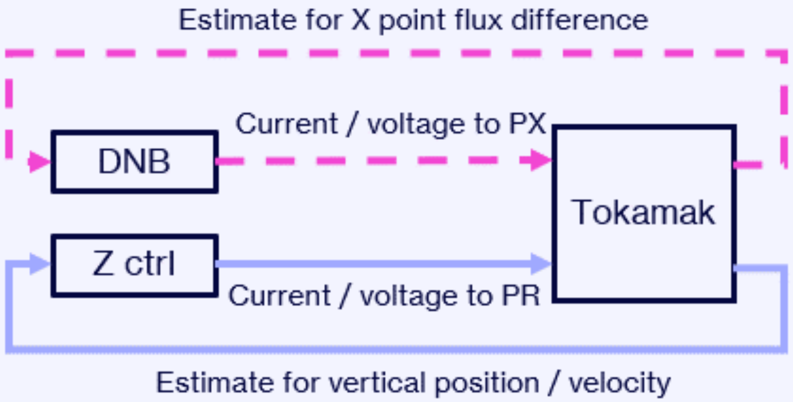


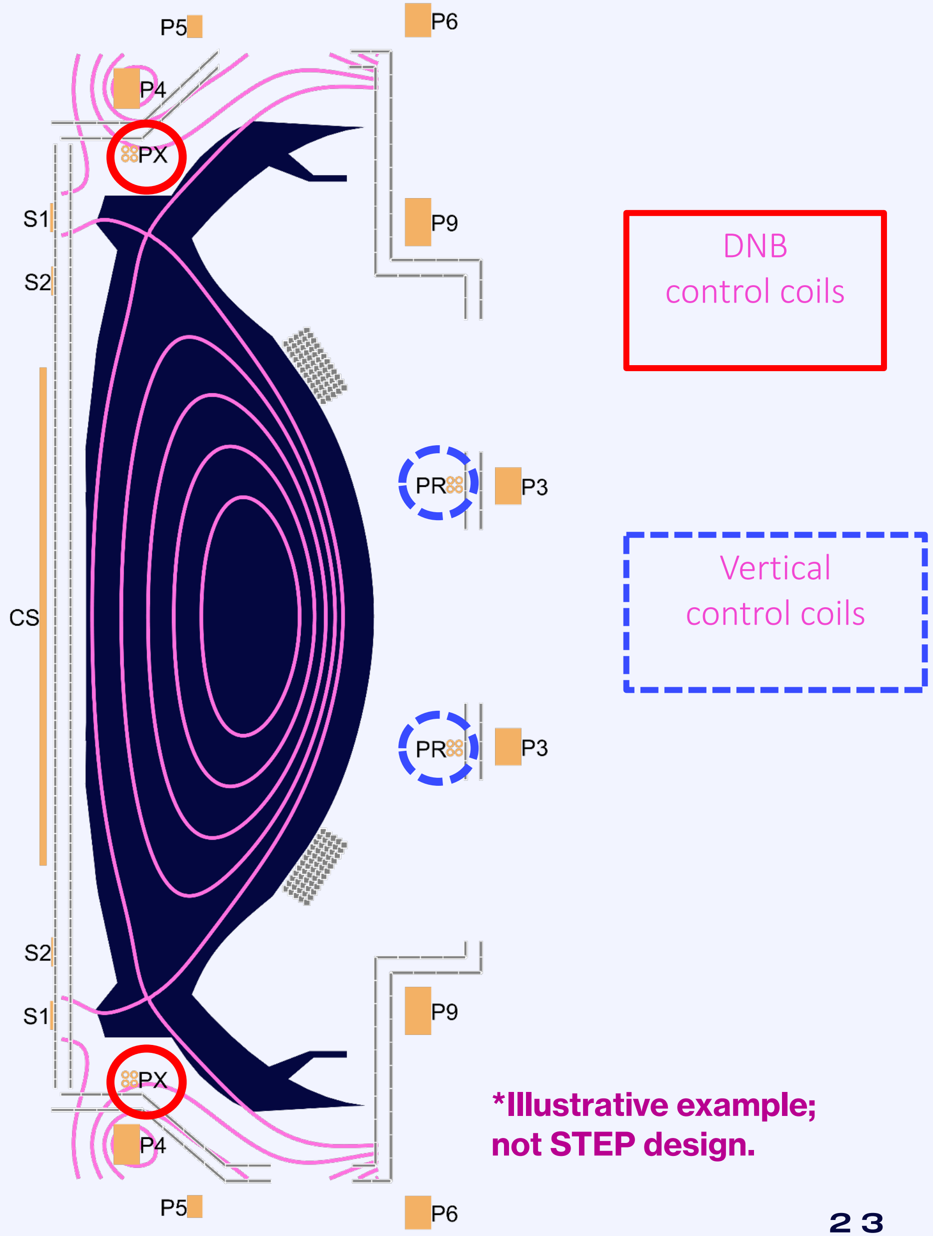
ACCURATE DOUBLE NULL CONTROL WITH A NOVEL CONTROLER

This mitigates a key risk on the vertical position accuracy for H-mode access and divertor protection!

Combination of…

1. Flux difference between x-points being observed and controlled.
2. Dedicated, **fast, in-vessel coils** controlling x-point fluxes.
3. Feedback control on a timescale **equal or faster than vertical control.**

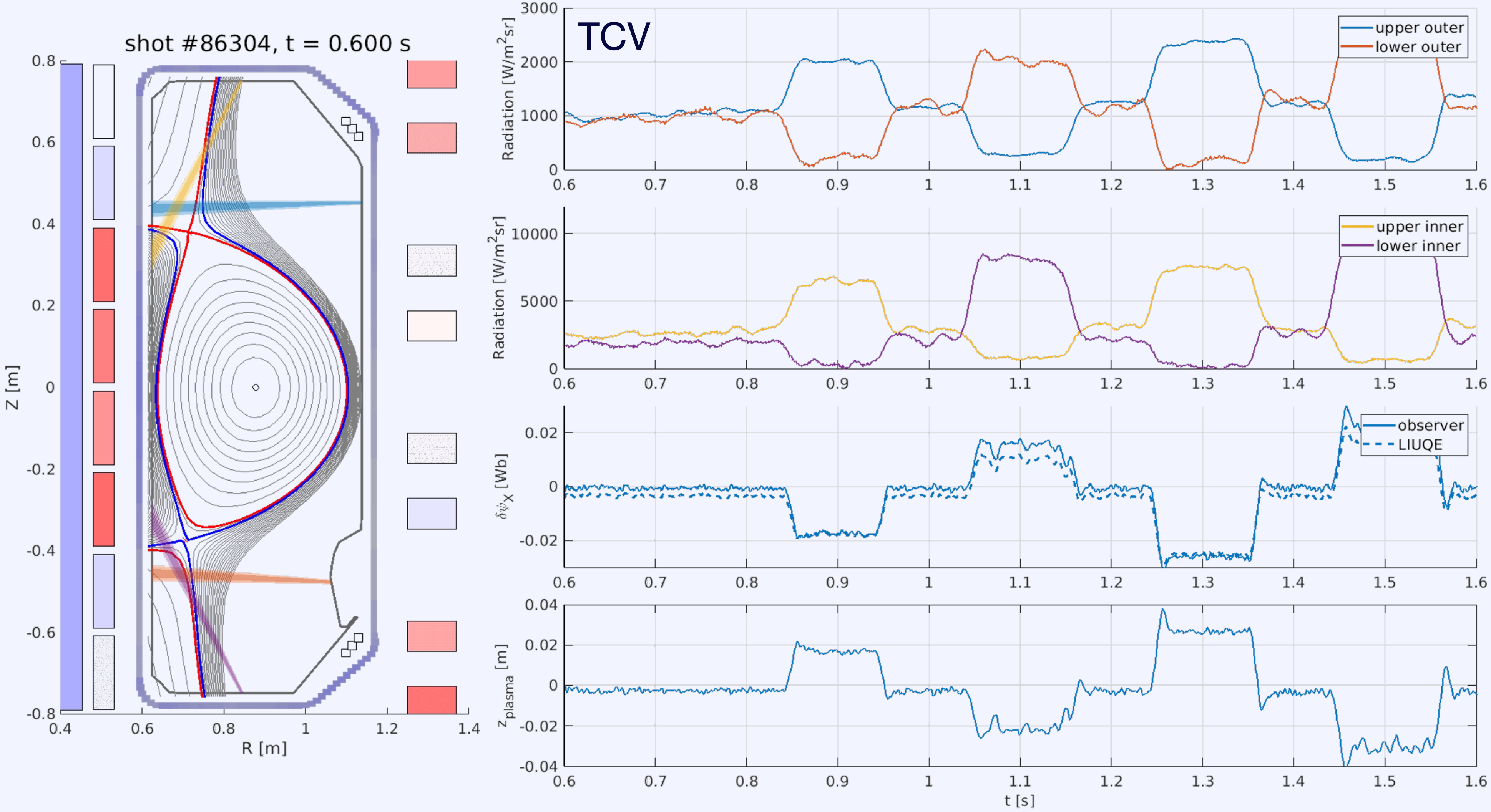




***Illustrative example; not STEP design.**

M. Lafferty, SOFE, Boston, USA, 3-26 Jun. 2025

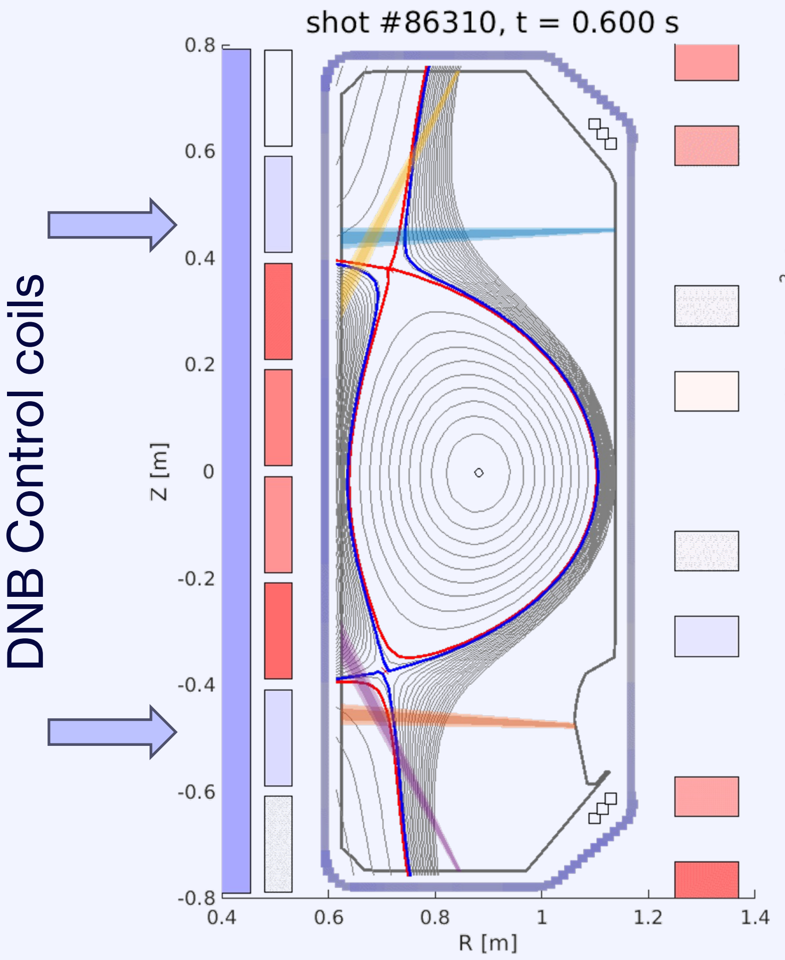
STANDARD VERTICAL CONTROL WILL REQUIRE EXTREME ACCURACY TO KEEP $\delta r_{sep} < 1 - 2\ mm$

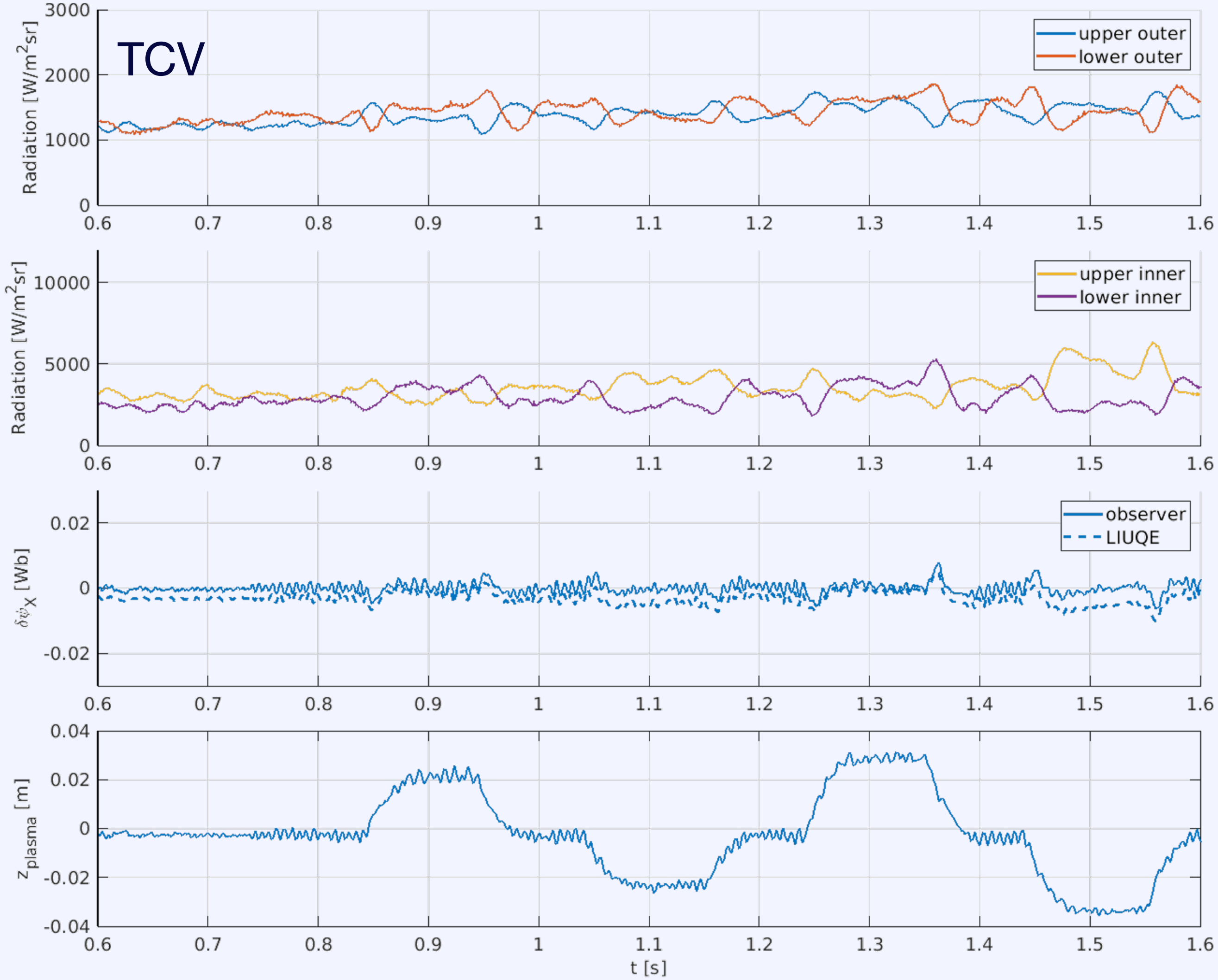


M. Lafferty, SOFE, Boston, USA, 3-26 Jun. 2025

TCV experiment with standard vertical control shifting the plasma up and down by 2 cm

ADVANCED VERTICAL CONTROL WILL KEEP DOUBLE NULL CONFIGURATION

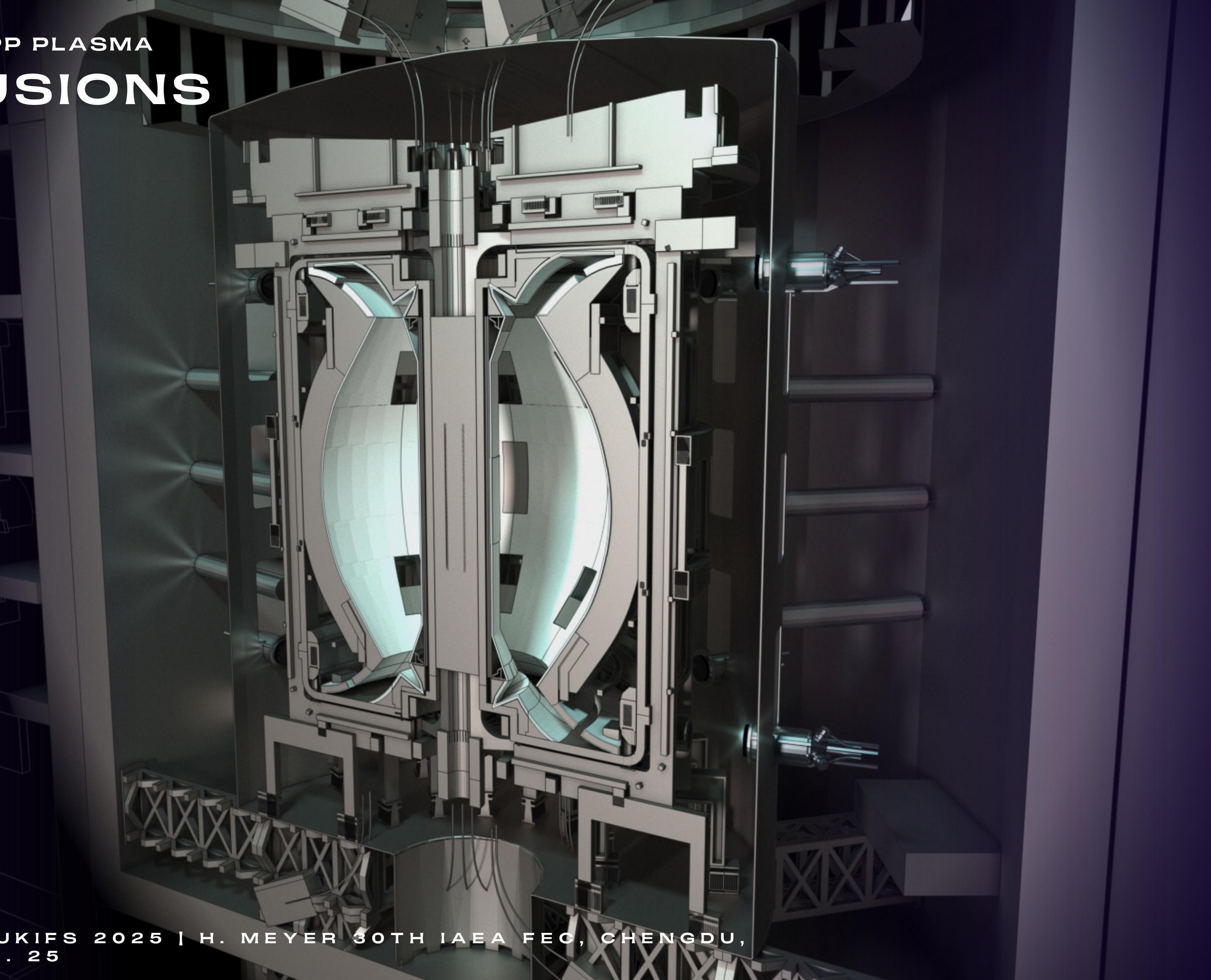




M. Lafferty, SOFE, Boston, USA, 3-26 Jun. 2025

TCV experiment with novel vertical control shifting the plasma up and down by 2 cm

CONCLUSIONS



CONSIDERABLE PROGRESS IN UNDERSTANDING AND DE-RISKING THE STEP PLASMA

- Tackling of scenario design challenges with increased physics capability and understanding ⇒ **uncertainty reduction**.
- Pivot to a larger design has uncovered new challenges ⇒ **improved physics understanding**.
- The compatible exhaust solution requires a physics driven optimised divertor design and magnetic configuration.
- Novel control schema increases confidence that operation in double null at high elongation is feasible.

Key plasma challenges remain but STEP has developed a strong team and efficient design tools.