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UK STEP TOWARDS A FUSION POWER PLANT PLASMA

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Abstract

STEP is a UK programme to build a prototype fusion power plant targeting 2040 demonstrating fuel self-sufficiency and net electric power output of the order of 100 MW. The plasma scenario is central to the STEP mission. Progress has been made in the understanding of the underlying physics and integration of the scenario components with increasing modelling capability. A first existence demonstration of the flat-top operating point is given using a predictive flux-driven quasilinear model describing the transport in STEP. A recent size change for technical reasons necessitated a redevelopment of the scenario, showing some clear disadvantages of a larger device. An overview of the scenario work is presented.

Introduction

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

- First design base published in 2024 – SPP-1 [1] – ITER volume
- Spherical tokamak $A = 1.8$ with double null divertor(DN) and alternative divertor leg configuration.
- More shielding for TF coils ⇒ size change, SPP-2
- No change in plasma design philosophy
- Volume: ~1.5× ITER, $^1/_2$ × EU-DEMO
- Similar height 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	

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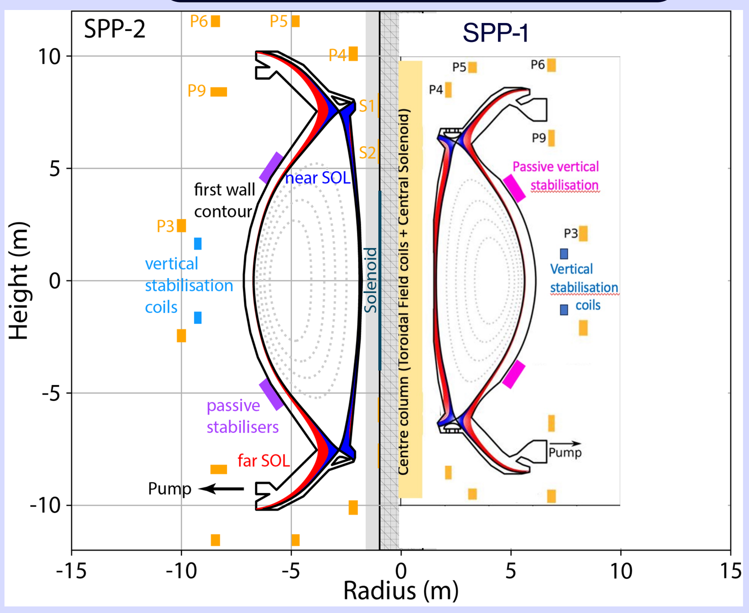
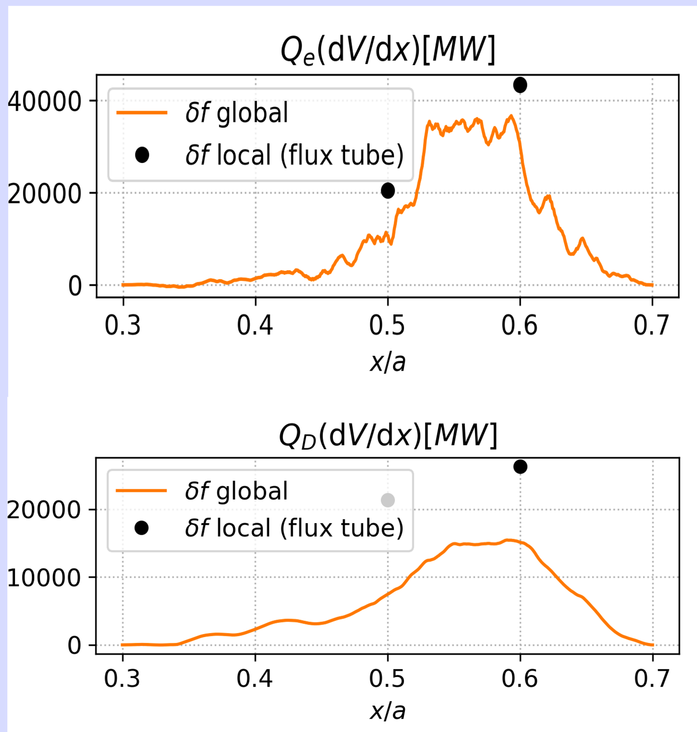


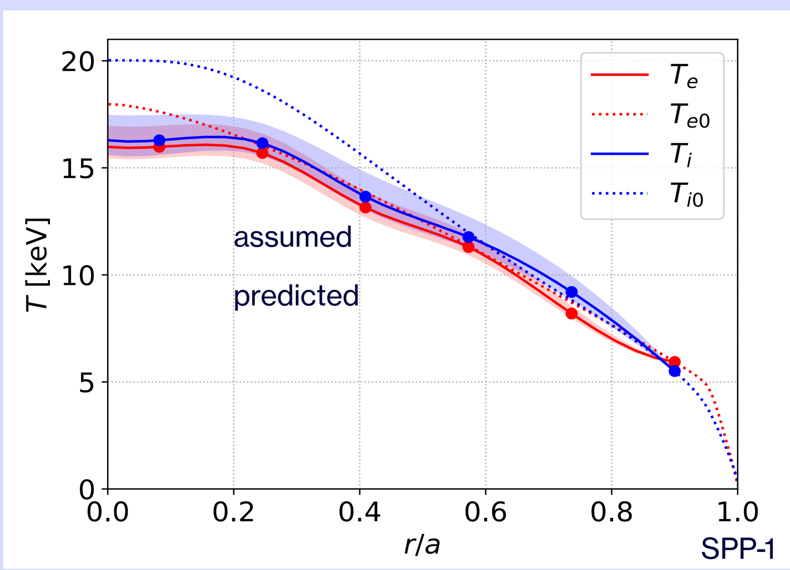
EM turbulence can drive unsustainable transport fluxes

- Transport dominated by hybrid kinetic ballooning mode turbulence (h-KBM).
  - 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 STEPhas no external momentum input except α-particle loss.
- h-KBM also reduced by high pressure gradients β' and negative magnetic shear.

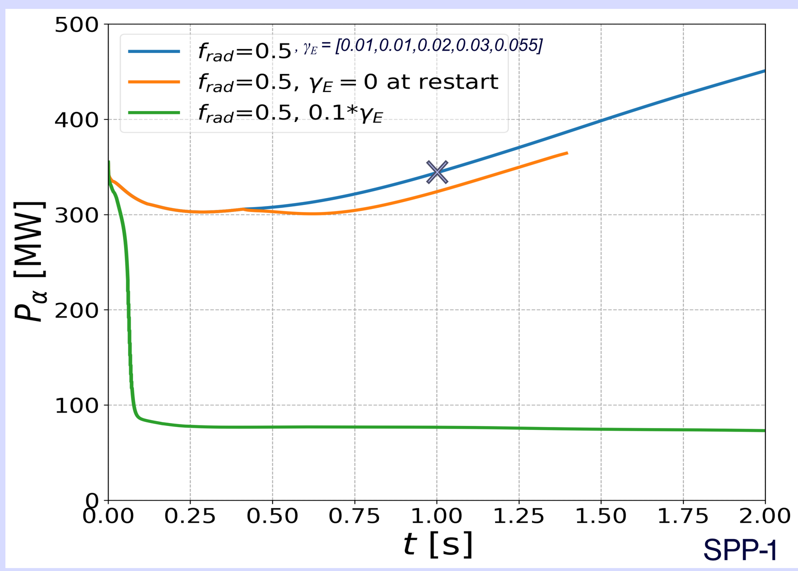


D. Kennedy, C. Roach, B. Patel, H. Dudding, M. Giacomin, D. Dickenson, A. Bokshi

Flux driven calculations show existence of high β state



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

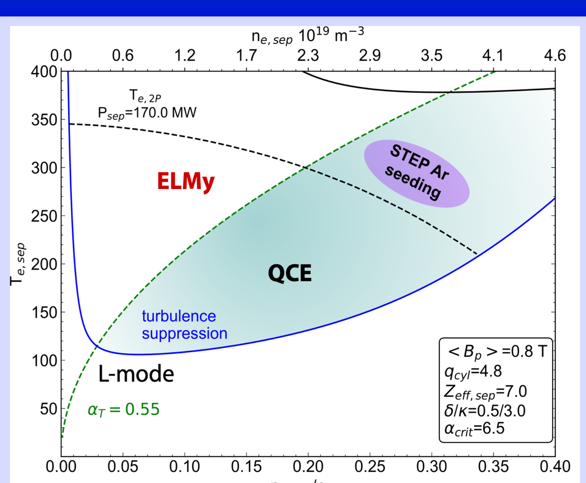


A Bokshi M Abazorius

- 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 ($\gamma_E, f_{rad}, \dots$).

Access from low β_e still unclear as β_e drive must be overcome by $\beta_e{}'$ and flow shear stabilisation.

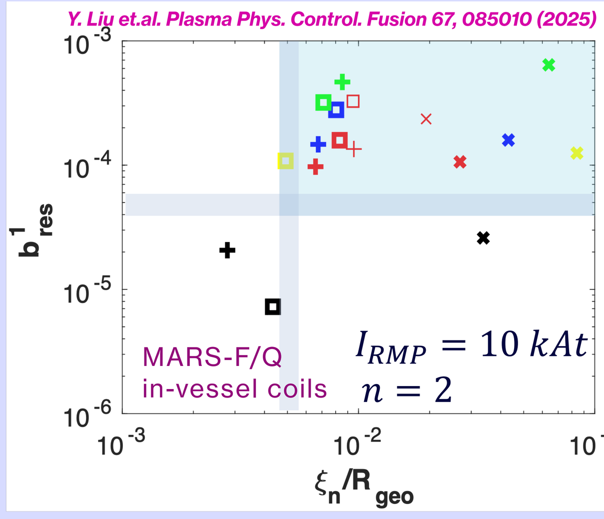
Small ELM (QCE) and RMP ELM suppression seem feasible



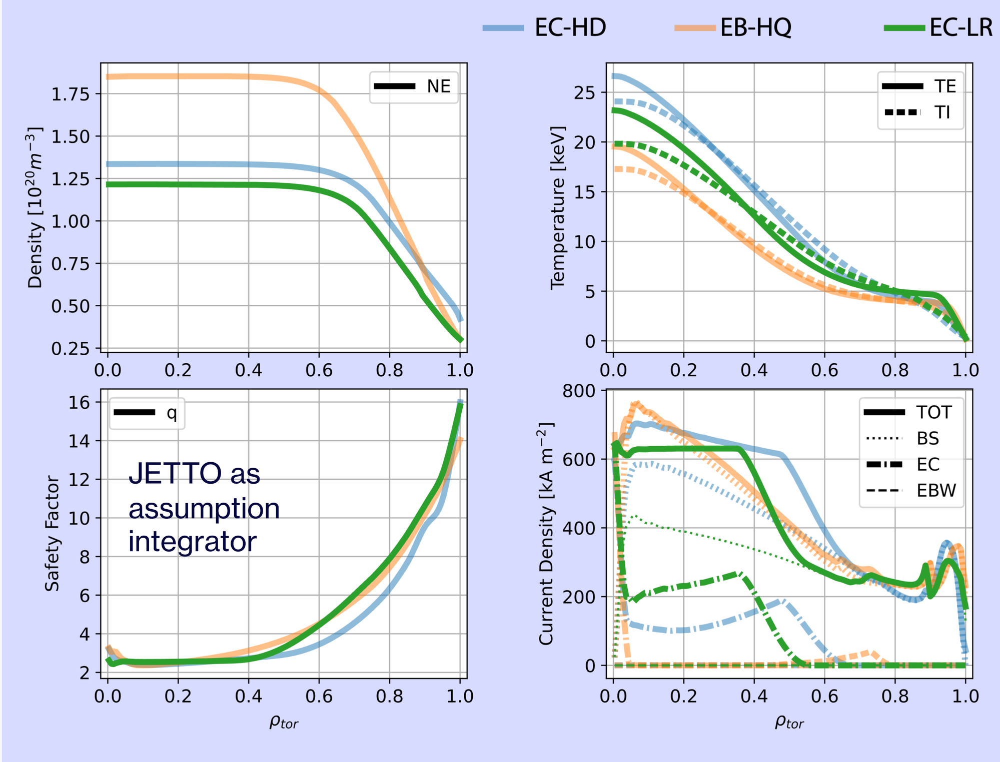
- In the separatrix operating space according to [Eich25] the SPP-2 edge sits in region of quasi continuous exhaust mode (QCE). *[Eich25] T. Eich et al., Nucl. Mat. and Energy 42, 101896 (2025)*
  - $\alpha > \alpha_t^{QCE} = 0.55\alpha_t \approx \nu^*_{e,edge}\hat{q}^2_{cyl}/100$
- Access criteria from [Dun24] also met depending effect of impurities on $\partial T_e/\partial r$. *[Dun24] M. Dunne et.al. the, Nucl. Fusion 64, 124003 (2024).*
  - Unclear if applicable for ST and high Z_{eff}^{sep}~$5-7$.
- Detailed evolution sensitive to initial condition, assumptions (γ_E, f_rad,...)

- 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 up 8 mid, 16 low, SPP-2: 12 up, 12 mid., 12 low.
- 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).

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



Scenario points with three different optimizations



H^*: confinement factor corrected for highly radiating plasmas

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

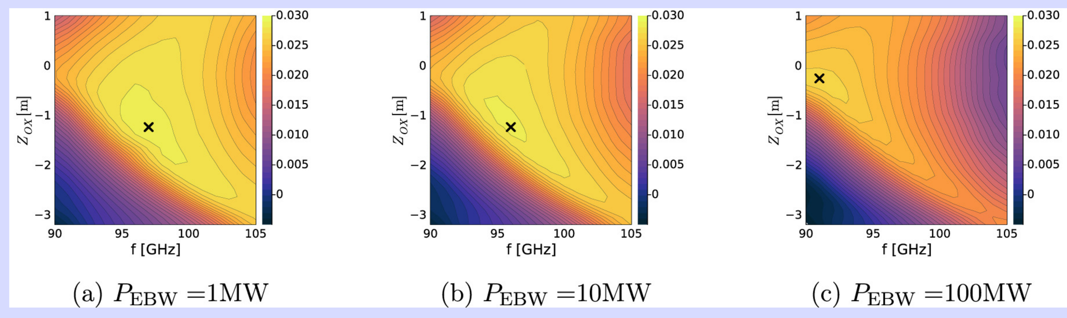
F. Casson, E. Tholerus, C. Olde, S. Marsden, T. Wilson, F. Palermo, P. Fox

- ECCD only f_{GW}~1 – more favourable compared to SPP-1 because of lower density.
- EBW enables way to high $Q \approx 30$ with f_{GW}~1.4.
- Lower f_{rad}~0.4 ⇒ lower P_{fus} and I_p

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		
$\tau_E\ [s]$	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)

Relativistic and non-linear effects are important for EBCD

- 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.



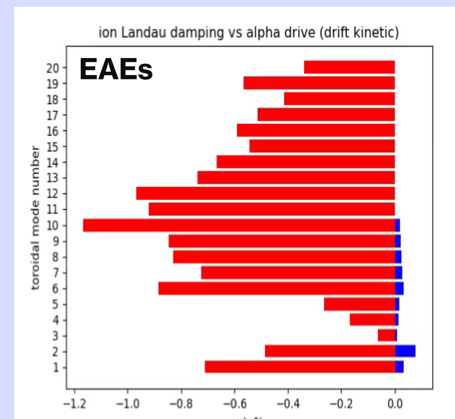
- Shift of optimal launch, η_{CD} and radial location already with $P_{EB} > 10\ MW$
- Mode conversion ⇒ multiple modes + robust ray conversion.

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

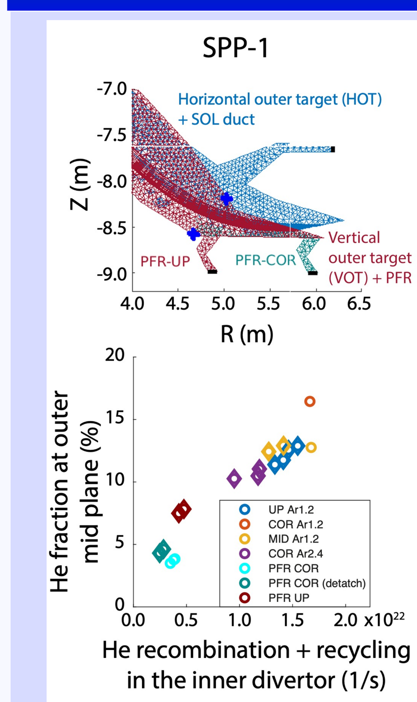
[Wil25]T. Wilson, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

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 $v_\parallel = c_A$
- 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

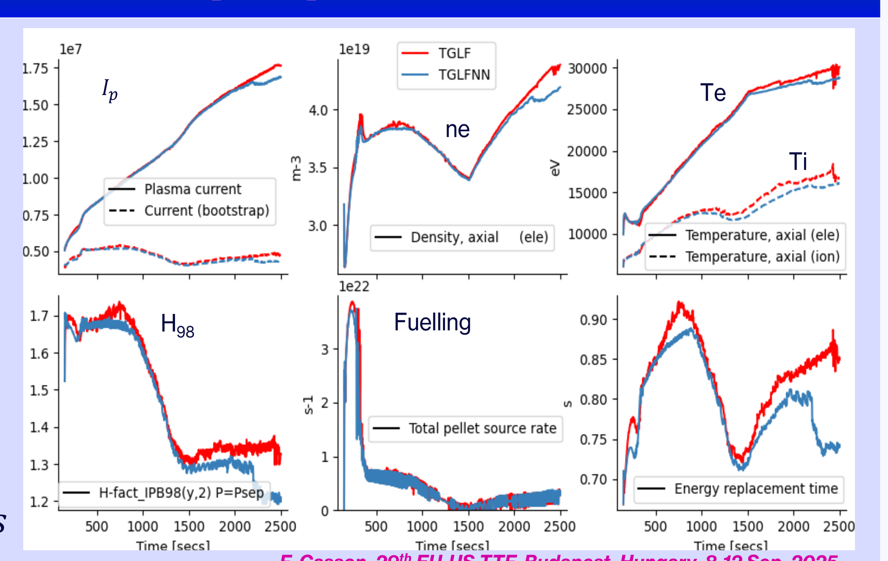


- Optimizing the divertor for detachment access ⇒ insufficient He exhaust (**see E. Tholerus this conf.**)
  - Core requires He concentration of $c_{He}^{sep} < 6\%$.
- Main He source through the X-point from inner divertor recycling.
  - STEP can only pump from the outer divertor!
- Pumping close to 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 c_{He}^{sep}~4% with optim. div..**

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

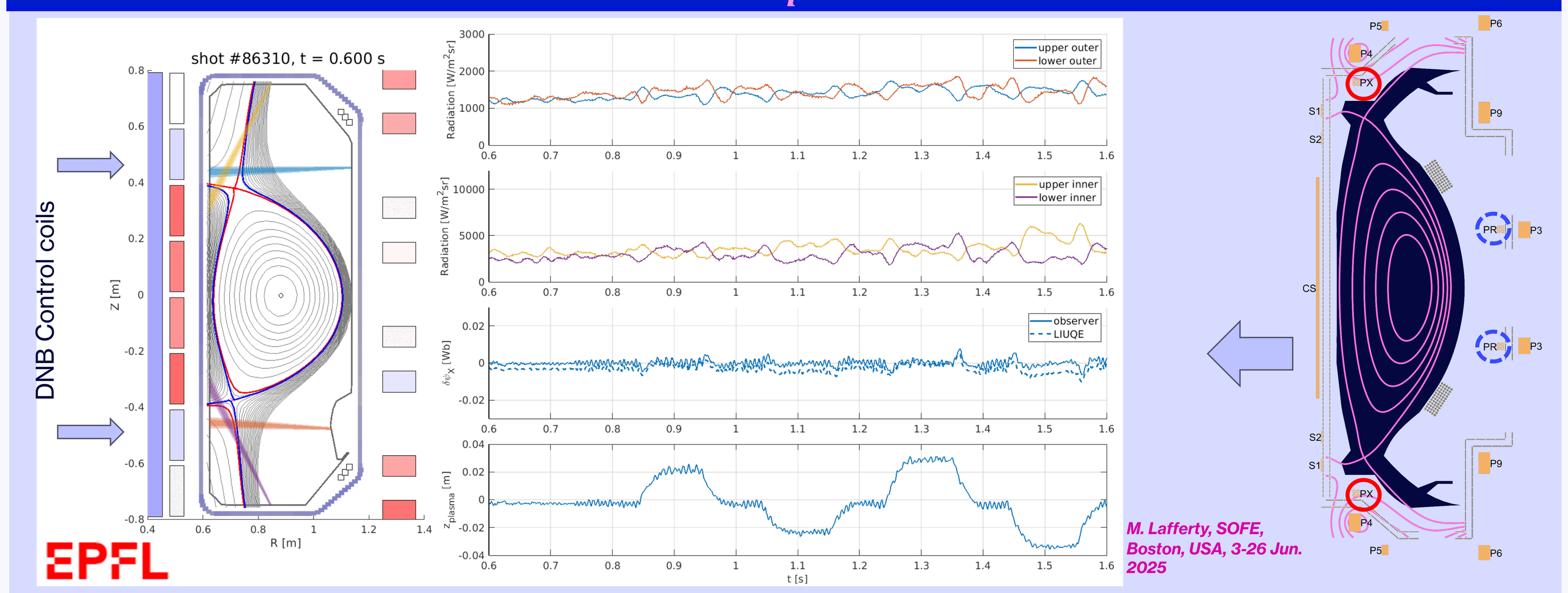
First predictive non inductive ramp-up simulations

- Need to broaden the current profile to avoid current hole.
- Increase density at full current ⇒ Fusion burn.
- Developed surrogate model (TGLFNN) from ST optimized version of TGLF.
- Plasma initiation using resistive solenoid with $\Delta\psi_{CS}$~$5\ Vs$. ($V_{loop} > 15\ V$) – DYON.
- Inductive ramp-up to NI target: $\Delta\psi_{CS}$~$10-15\ Vs$



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

Novel control keeping Δr_{sep}~0 demonstrated on TCV



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

OFFICIAL – 30TH IAEA FUSION ENERGY CONFERENCE, 13 – 18 OCT. 2025, TIANFU INTERNATIONAL CONFERENCE CENTRE, CHENGDU, CHINA

CONCLUSIONS: The plasma scenario and control work continue to reduce the uncertainty of the plasma solution for STEP. Tools and workflows have been developed to re-evaluate efficiently any design changes, and these are progressively being further optimised to increase modelling fidelity. For example, core transport solutions can now be based on predictive modelling though important features are still missing, such as fusion α-particles and impurities. Furthermore, the plasma design is strongly integrated with the engineering effort – a key aspect of successful power plant design.

UK Industrial Fusion Solutions

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