STEP FUSION

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STEP
FUSION

AN UPDATED PLASMA SCENARIO FOR THE SPHERICAL TOKAMAK FOR ENERGY PRODUCTION

30 Jun. 2026 – Hendrik Meyer
For the STEP Plasma Team

UKFE – Head of Plasma Development

TEAM LIST

Thanks to the STEP Plasma, Control and HCD team…

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G Hodgson, Z. Johnson,
G. Keech
…

The UK STEP programme aims to deliver a tritium self-sufficient prototype power plant ~2040 with $P_{net}^{el} \sim 100\ MW$

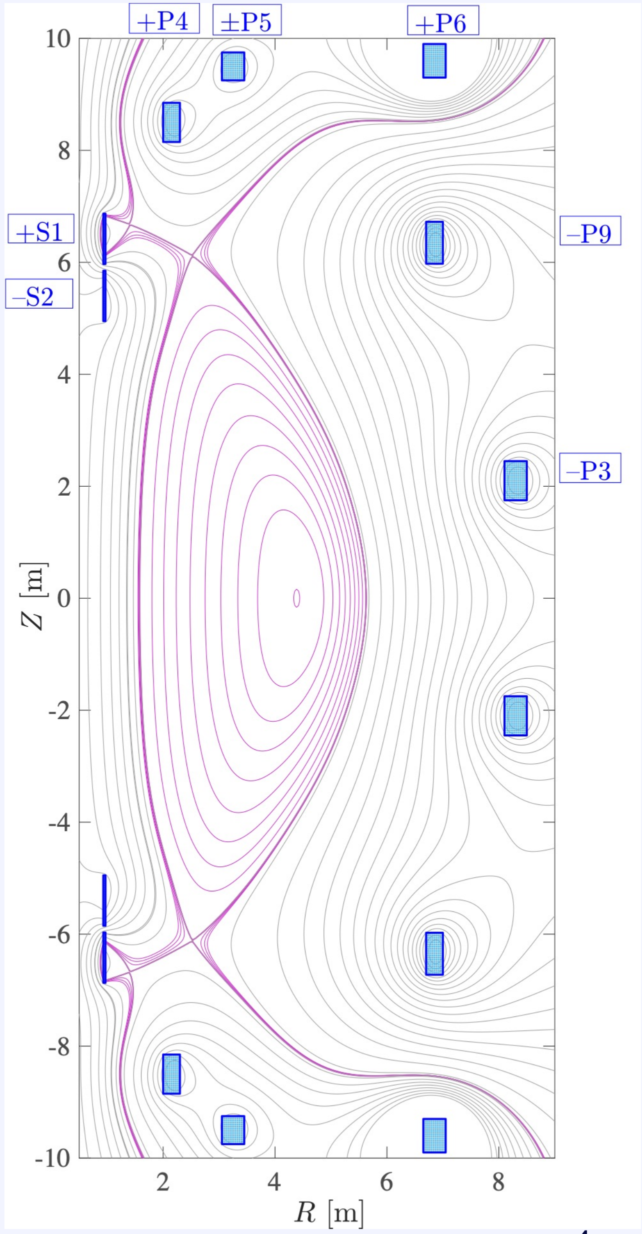
- First design base published in 2024 – SPP-1
  - *see Phil. Trans. R. Soc. A. Vol 382, issue 2280*
  - ***Plasma**: H Meyer et.al. Phil. Trans. R. Soc. A.382 20230406*
  - ***Plasma Control**: M. Lennholm et.al. Phil. Trans. R. Soc. A.38220230403*
- Based on a highly elongated and spherical tokamak

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

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

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

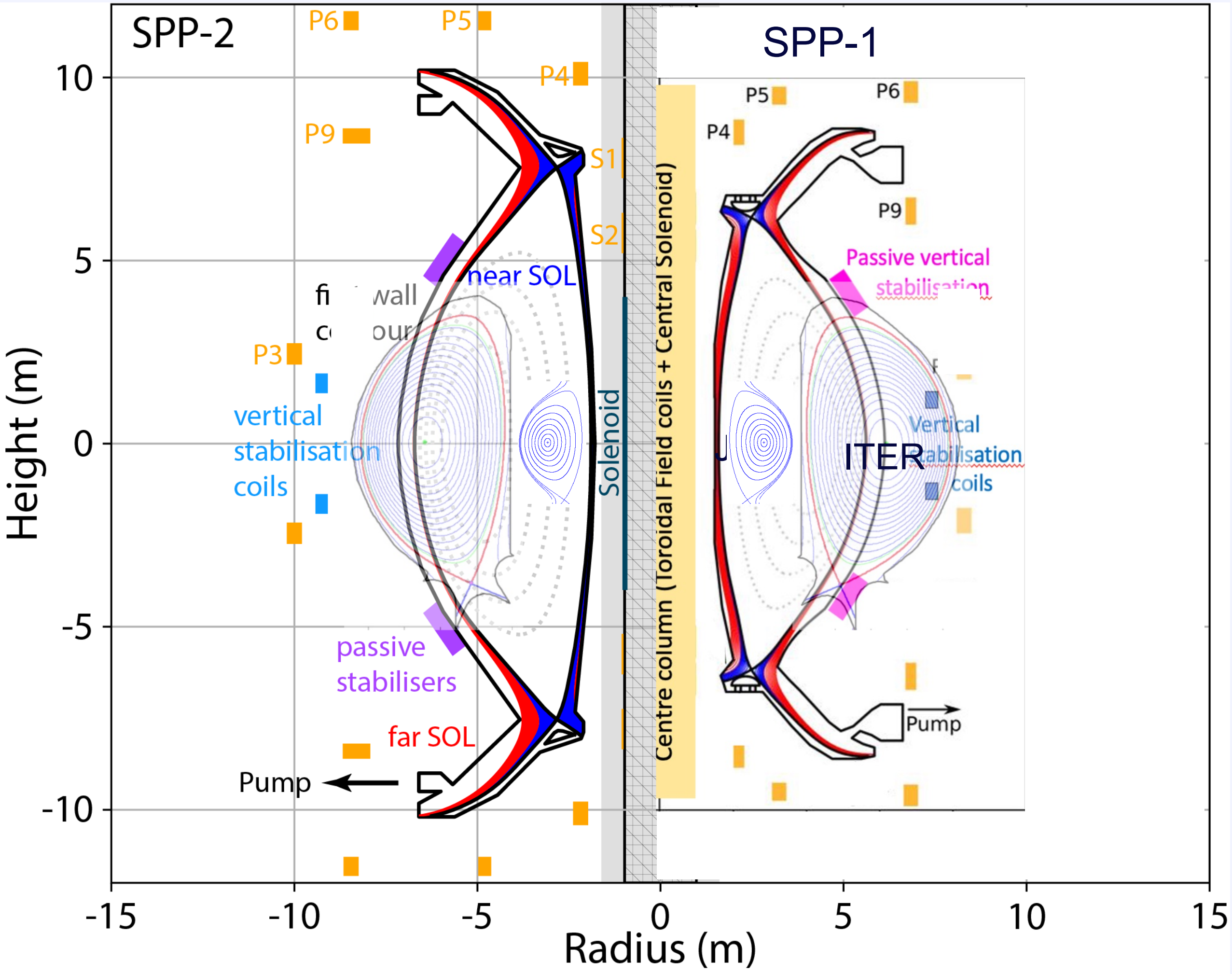
https://github.com/ukaea/OpenSTEP



Essential to the STEP plasma design:
steady state operation ⇒ fully non-inductive flat top

For technical reasons the 2024 baseline pivoted to a larger major radius of $R_{geo} = 4.3\ m$ at same A

- **Plasma design philosophy not changed.**
- Volume $\sim 1.5\times$ 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}	$714\ \mathrm{m}^3$	$1250\ \mathrm{m}^3$
B_t	$3.2\ \mathrm{T}$	$3.0\ \mathrm{T}$
κ	3	
δ	0.5	$0.5-0.6$
β_N	$4.5-5.3$	~ 4.8
P_{fus}	$1.5\ -1.8\ \mathrm{GW}$	
P_{net}	$130\ MW$	$270\ MW$

P_{net} for scenario with only electron cyclotron heating and current drive

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

Explored ways to reduce the recirculating power ⇒ Updated assumption set

- The plasma solution was constrained by the target range in fusion power ($1.5\ GW \leq P_{fus} \leq 1.8\ GW$).

$$P_{net}^{el} \sim (0.4 - 1.4/Q_{fus})\, P_{fus} - 63\ MW$$

- Increased understanding of the balance of plant has questioned the lower limit ⇒ *opens space to explore more efficient plasma solutions*.

- Increasing the electrical (wall plug) efficiency of the heating and current drive HCD system from $\eta_{HCD} = 0.41$ to $\eta_{HCD} \approx 0.6$ [1] ⇒ *achieves net electrical power output with less P_{fus} and lower fusion gain Q_{fus}.*

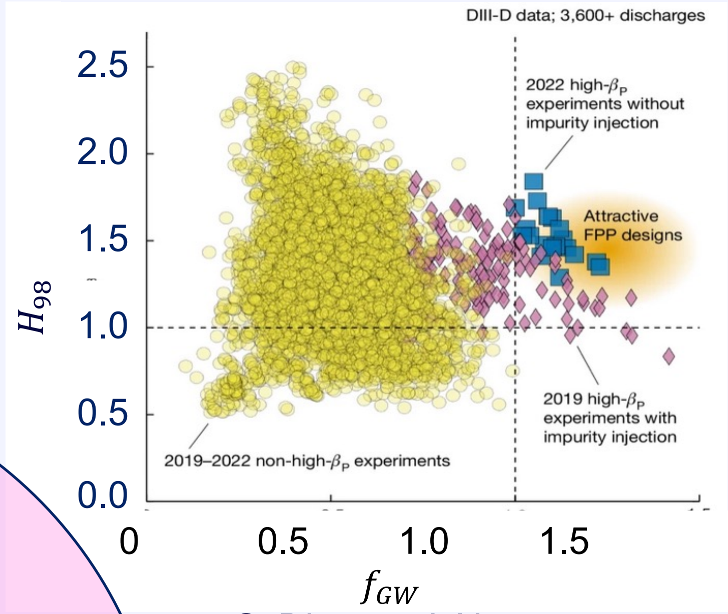
[1] *Louksha, O.I. et.al. IEEE Electron Device Letters (2024) Issue 9 p. 1638-1641*

Increased plasma density $f_{GW} > 1$

Reduced P_{fus}, I_p, P_{aux}

Reduced core radiation fraction f_{rad}

Increased current drive efficiency η_{CD} (EBW)



*S. Ding et.al. Nature **629** (2024), p.555–560*

***AUG:** P. Lang et.al. Nucl. Fusion 52 (2012) 023017*

EBW kept as opportunity

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Increased plasma density

Reduced
P_{fus}, I_p, P_{aux}

Reduced core radiation fraction f_{rad}

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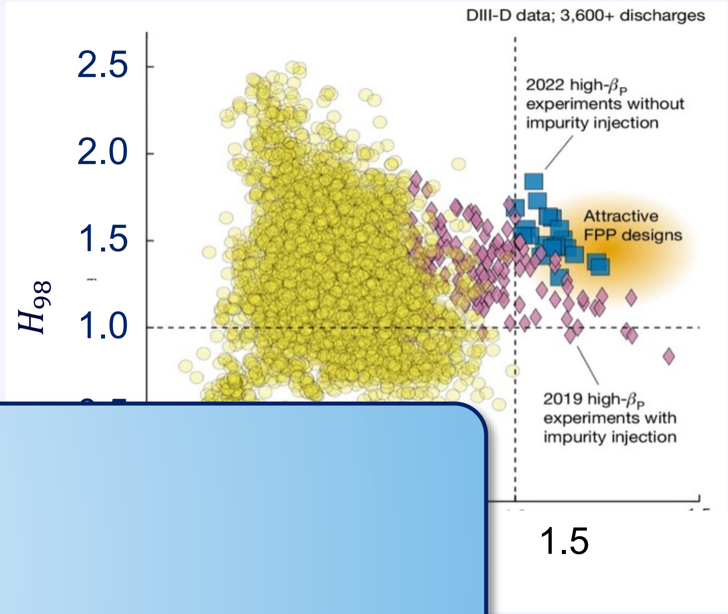


ature ***629***
560
Add.: *F. Lang et.al. Nucl. Fusion 52 (2012) 023017*

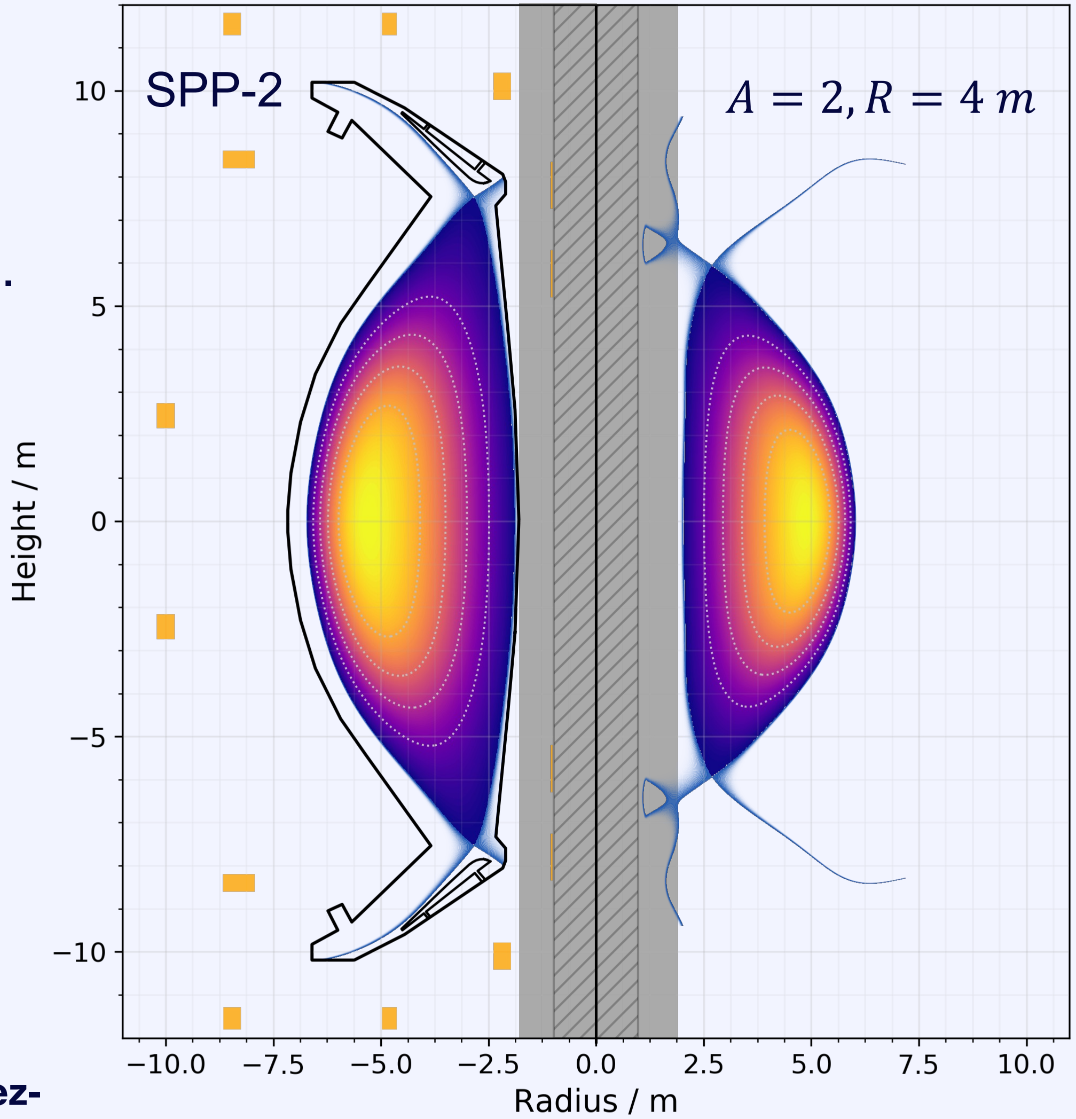
EBW kept as opportunity

Lower P_{fus} and lower I_p

⇒ explore if a smaller device size is more attractive

Explore higher $A = 2$ point ⇒ compromise between magnets, size and plasma

- New assumptions: $f_{rad} = 0.5, f_{GW} = 1.1$ ⇒ lower P_{fus}, I_p, P_{aux}.
- Enables tolerable exhaust solution at $f_{rad} \sim 0.5$.
- Core radiation from Ar alone¹⁾ ⇒ higher $p_{div} \lesssim 20\ Pa$



	SPP-2 A=1.8	A=2
R_{geo}	$4.3\ m$	$4.0\ m$
R_{in}	$1.9\ m$	$2.0\ m$
B_t	3.0 T	3.2 T
I_p	$20\ MA$	$16\ MA$
P_{fus}	$1.9\ GW$	$1.0\ GW$
P_{net}	$270\ MW$	$110\ MW$
P_{aux}	$150\ MW$	$120\ MW$
V_{pl}	$1250\ \mathrm{m}^3$	$800\ \mathrm{m}^3$
f_{GW}	100%	**110%**
f_{rad}	0.7 (Ar, Xe)	**0.5 (Ar)**
f_{BS}	0.82	0.85
κ, δ	3.0, 0.55	2.9, 0.65
β_N	4.8	~4.3
β_p	3.5	3.8
P_{sep}/R	$32\ MW/m$	$38\ MW/m$
$\langle H_{98} \rangle$	1.5	1.4
$\langle H_{Petty08} \rangle$	1.0	1.0

1) see also poster by G. Suarez-Lopez on Ar shielding

First flux-driven calculations increase confidence in the existence of a flat-top operating point

- Competition between Reynolds (ES) and Maxwell (EM) stresses on zonal flow
  ⇒ **onset of large transport fluxes.**

$$q^2\beta_e = f(\hat{s},\gamma_E) \propto \beta_p\, {}^{a}/_{R}$$

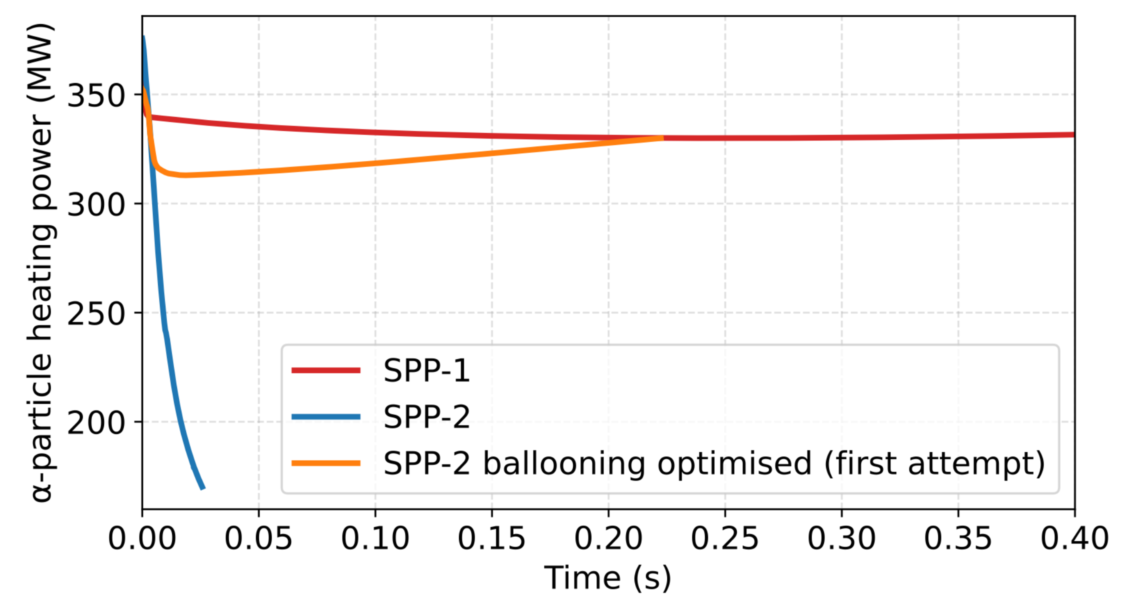
$\hat{s}$: magnetic shear
γ_E: flow shear

- Ideal ballooning physics ⇒ β' stabilisation
  ⇒ access to high performance regime.

- 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 $\beta_e{}'$ and flow shear stabilisation.

EC-HD



D. Kennedy et al, Thu 9am

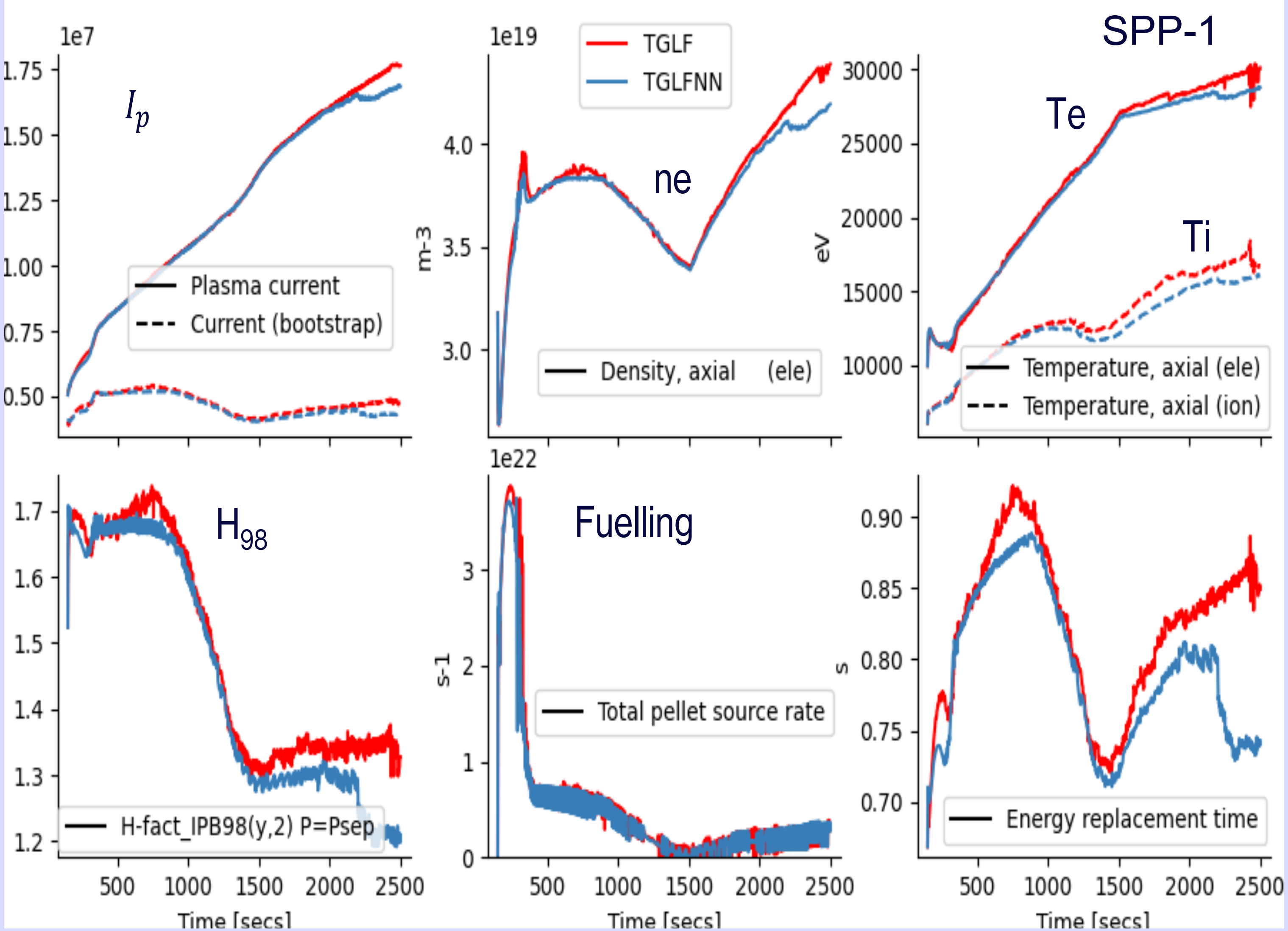
Model: M Giacomin et. al. J. Plas. Phys. 91 (2025) pE16

quasi-linear model capturing hybrid KBM driven turbulent transport – no impurities, no α-particles, no equilibrium

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

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.
- Coupled an advance control framework to JETTO/TGLF ⇒ prove that slow access to fusion burn is possible.



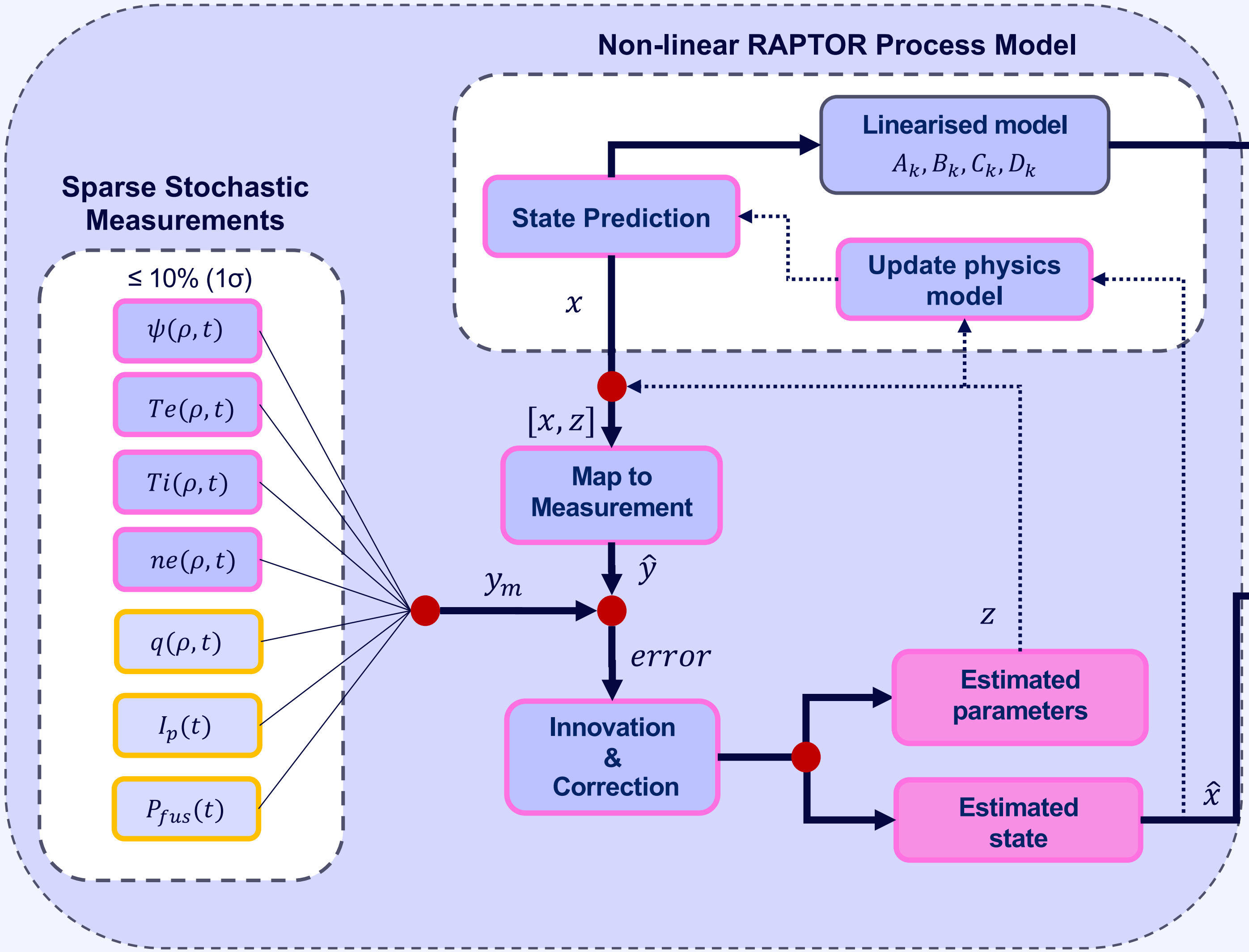
see also posters by S. Gabriellini (Tue, 14:00) and F. Watts (Tue, 14:00)

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

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

Burning plasma control requires novel control techniques ⇒ Adaptive Observer and adaptive model predictive controller

Adaptive Observer



Non-linear RAPTOR Process Model

Sparse Stochastic Measurements

≤ 10% (1σ)

$\psi(\rho,t)$

$Te(\rho,t)$

$Ti(\rho,t)$

$ne(\rho,t)$

$q(\rho,t)$

$I_p(t)$

$P_{fus}(t)$

State Prediction

Linearised model A_k, B_k, C_k, D_k

Update physics model

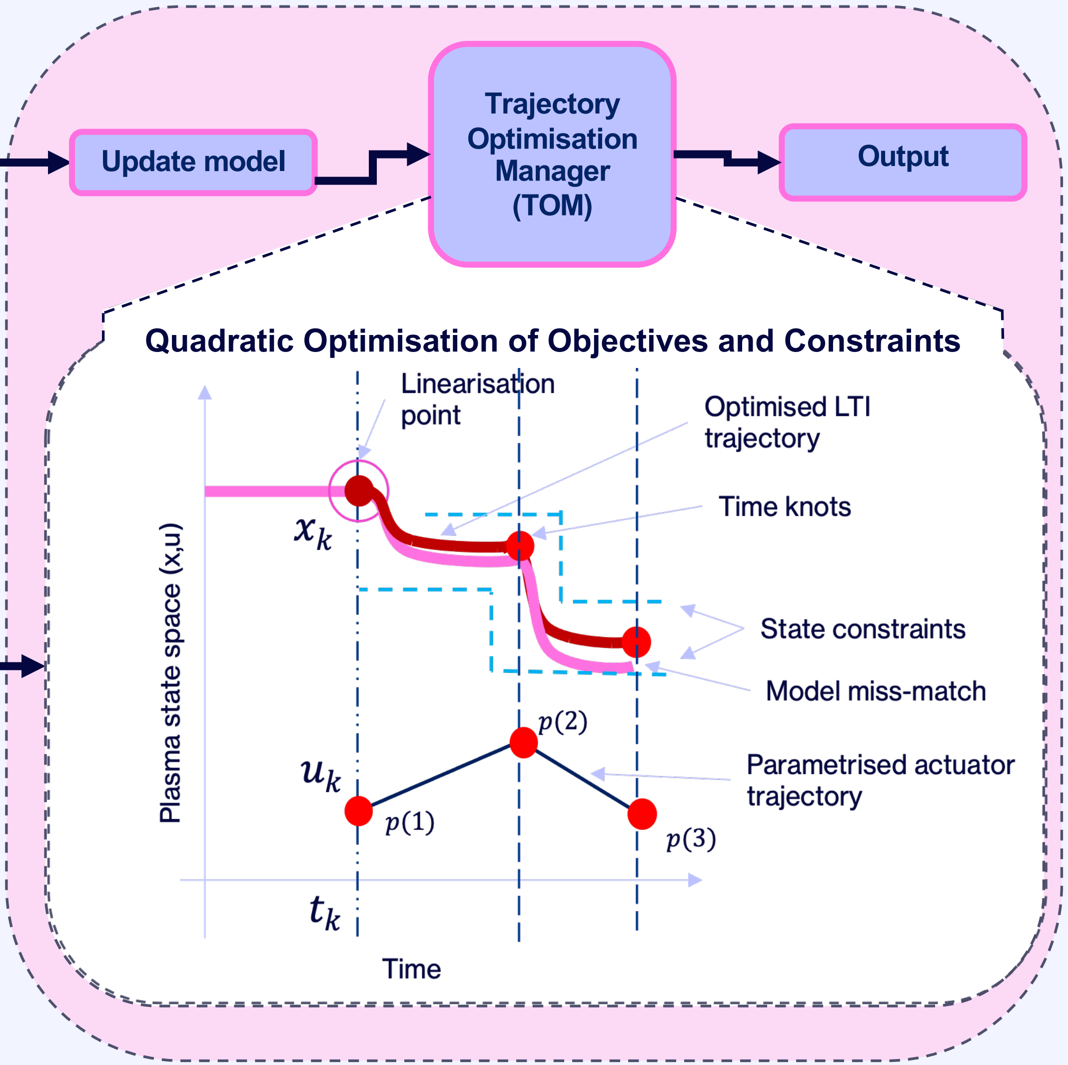
Map to Measurement

Innovation & Correction

Estimated parameters

Estimated state

Adaptive - MPC



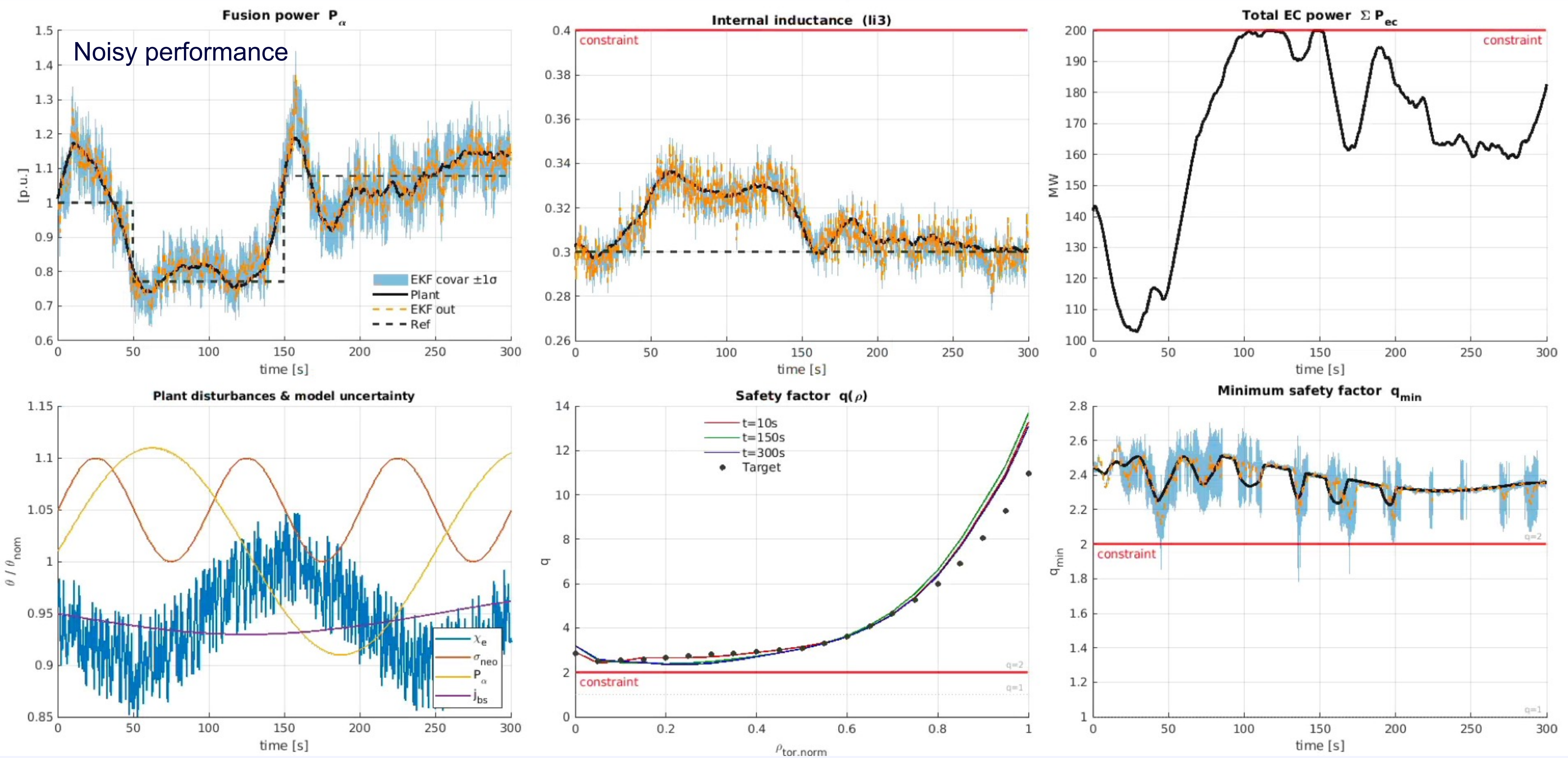
Update model

Trajectory Optimisation Manager (TOM)

Output

Quadratic Optimisation of Objectives and Constraints

Kinetic controller performs well despite noise, model uncertainty and model disturbance



Noisy performance

J. Mitchell, IAEA TM, 18 – 22 May 2026, Oxford

HELIUM particle exhaust improved through divertor design

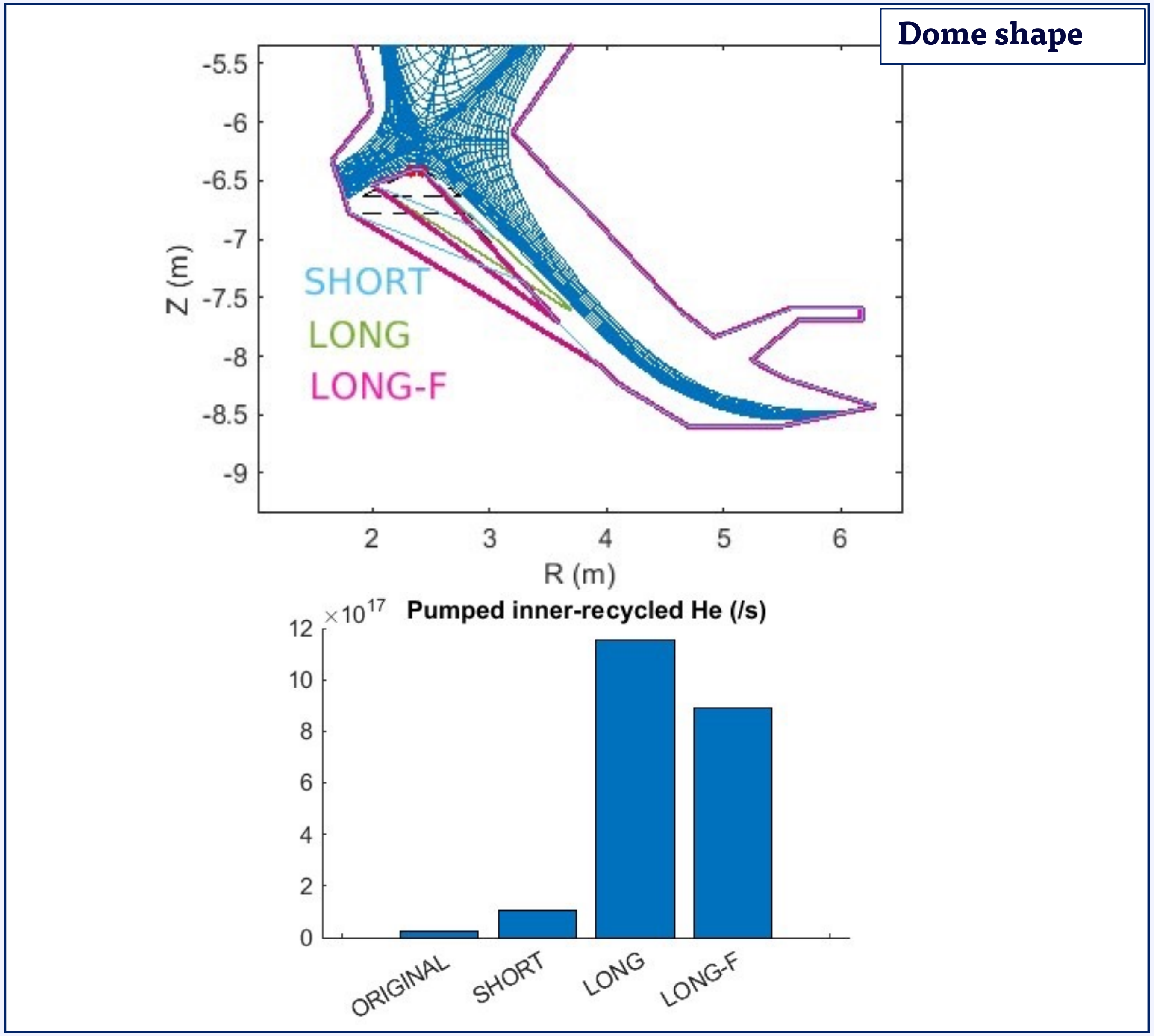
- Three key design features have been identified that significantly alter the He particle exhaust:
    - Divertor to sub-divertor duct location
    - Dome shape
    - Strike-point geometry

- Including state-of-the-art impurity closure models in SOLPS-ITER improved confidence in the absolute predictions of He transport and pumping

Improved confidence of He exhaust

Design optimisation for both detachment onset and He exhaust

see posters by: O. Myatra (Mon 14:30) and
L. Aho-Mantila (Tue 14:00)



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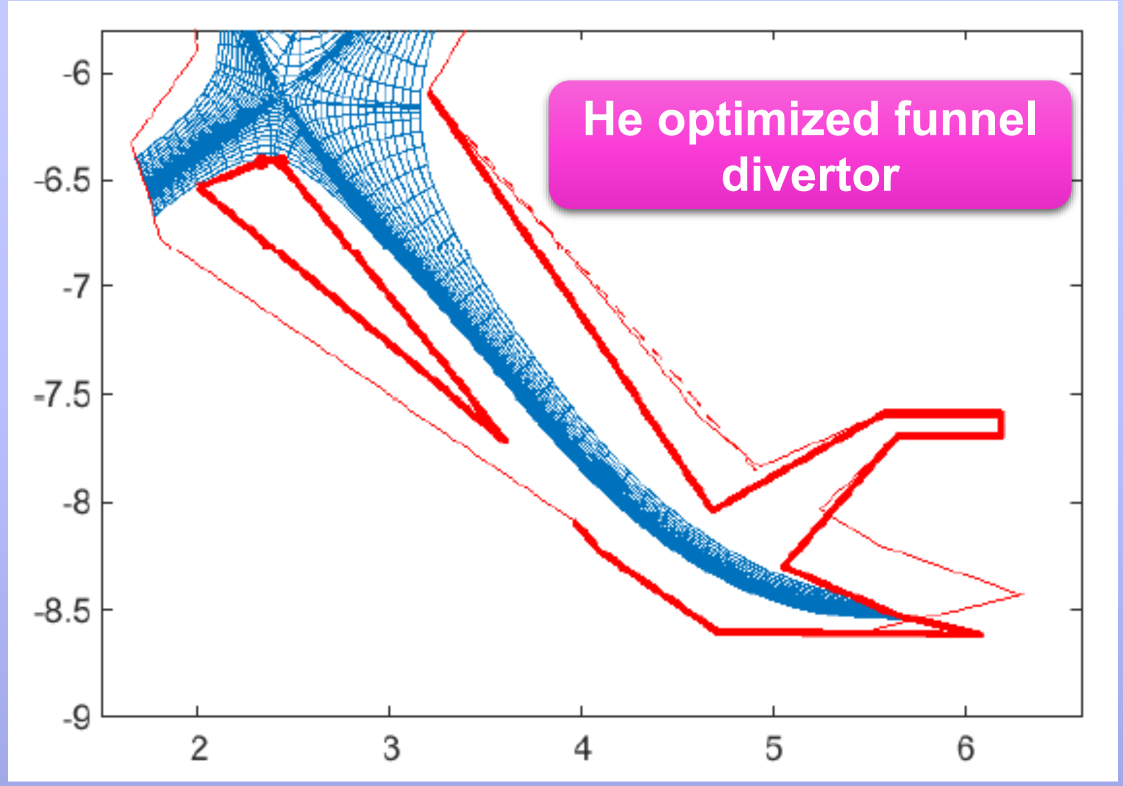
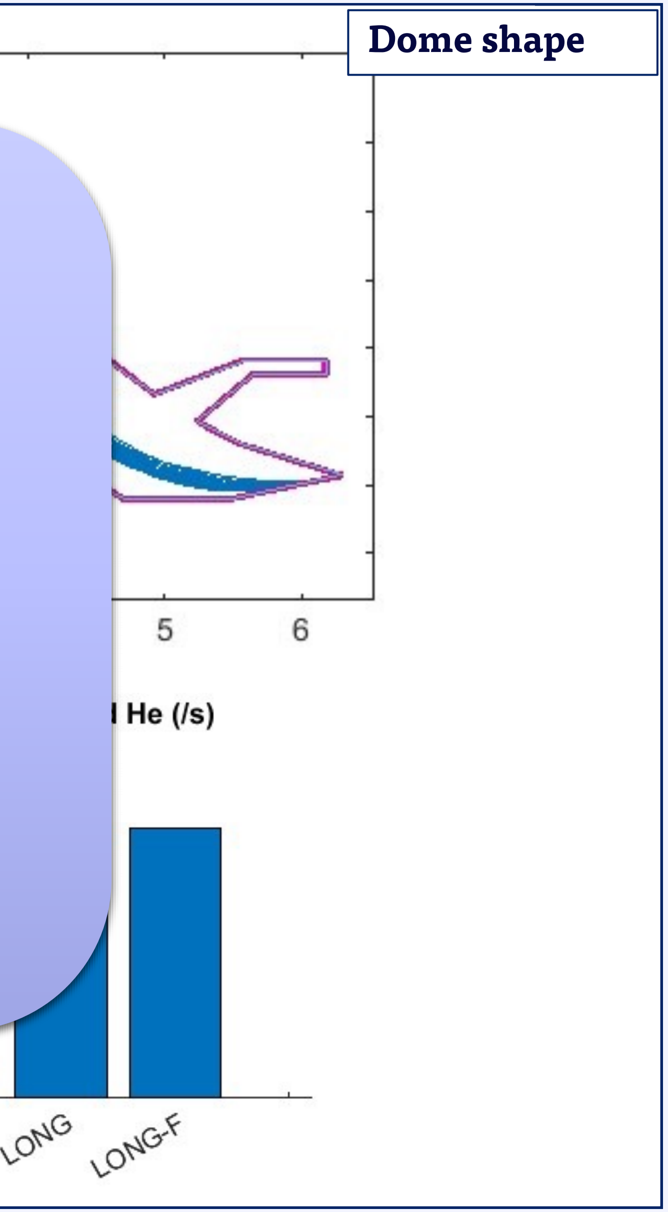


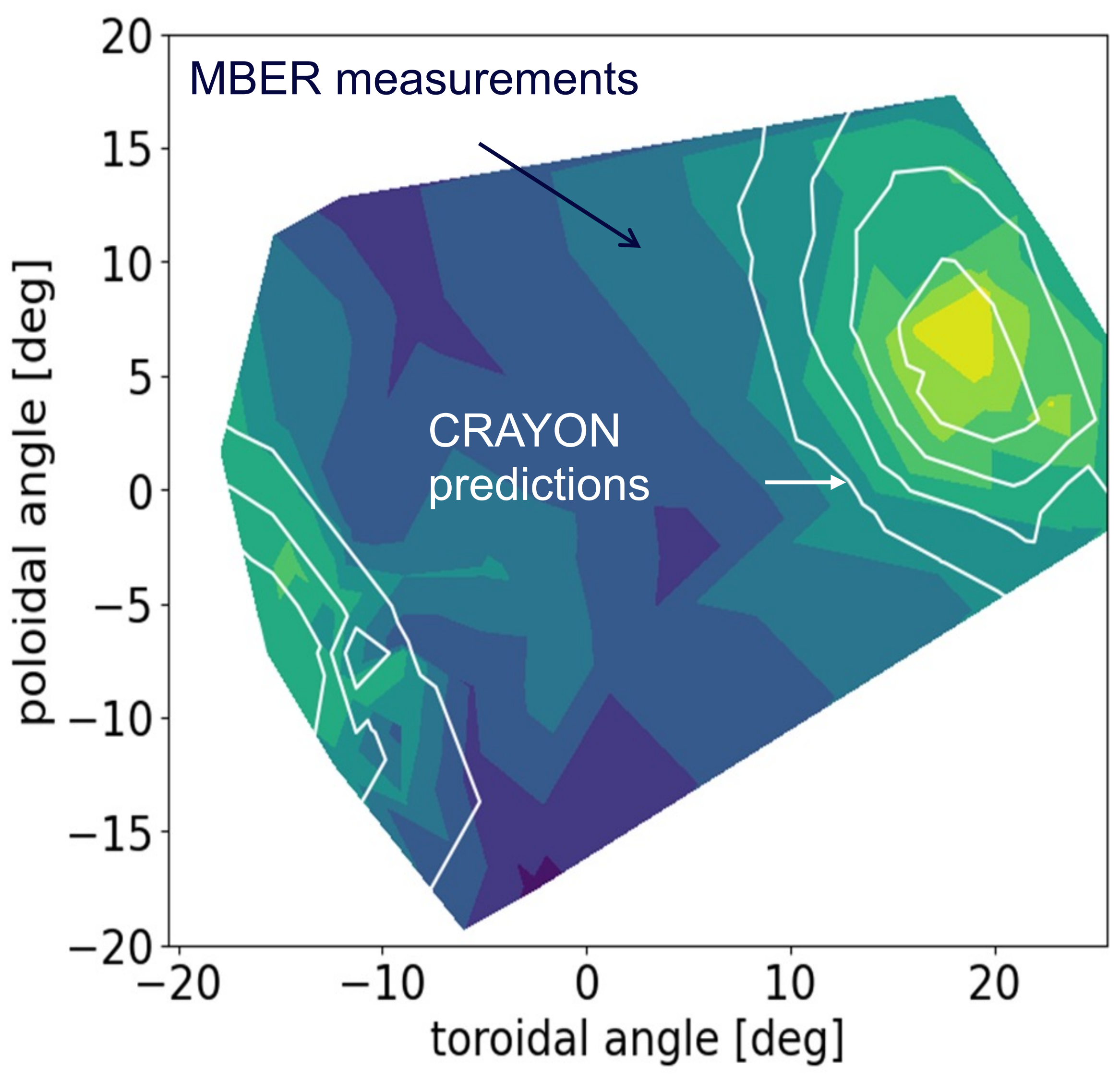
He optimized funnel divertor



Dome shape

see posters by: O. Myatra (Mon 14:30) and
L. Aho-Mantila (Tue 14:00)

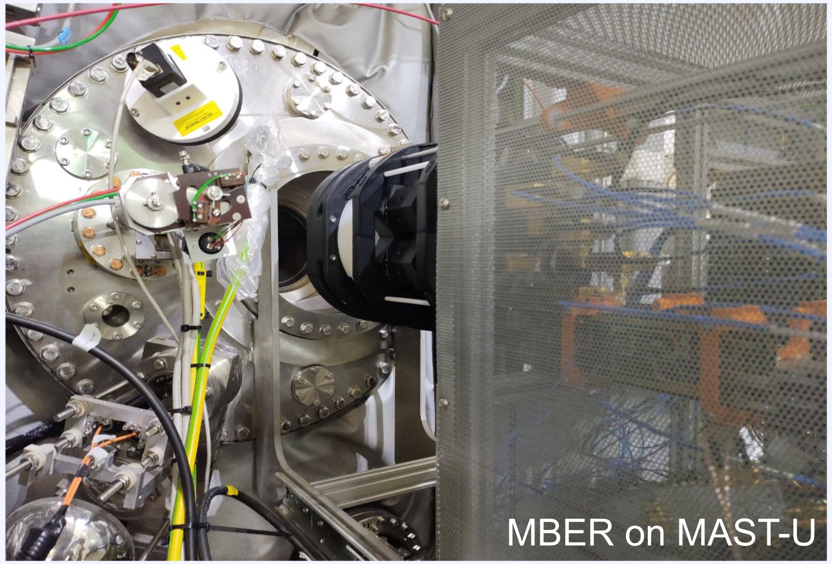
Demonstrated good linear coupling in ELM-free regimes and good agreement of CRAYON with observations on MAST-U



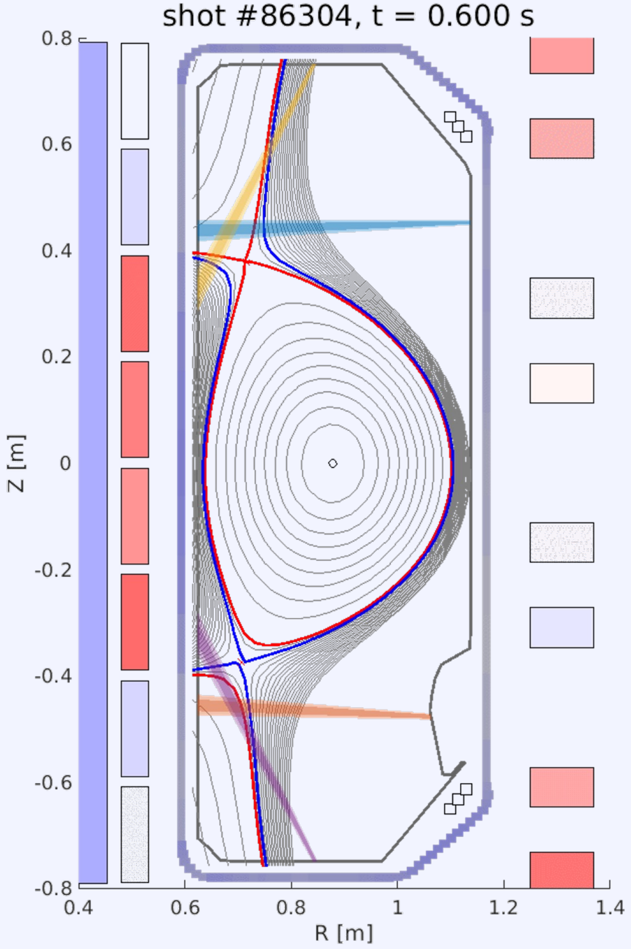
- UKAEA and Univ. of York built a microwave camera to visualise EBW coupling on MAST-U
- Detailed measurements confirm location and size of coupling windows
- Verified some key design assumptions for the MAST-U system
- Provided validation for elements of CRAYON code ⇒ STEP predictions

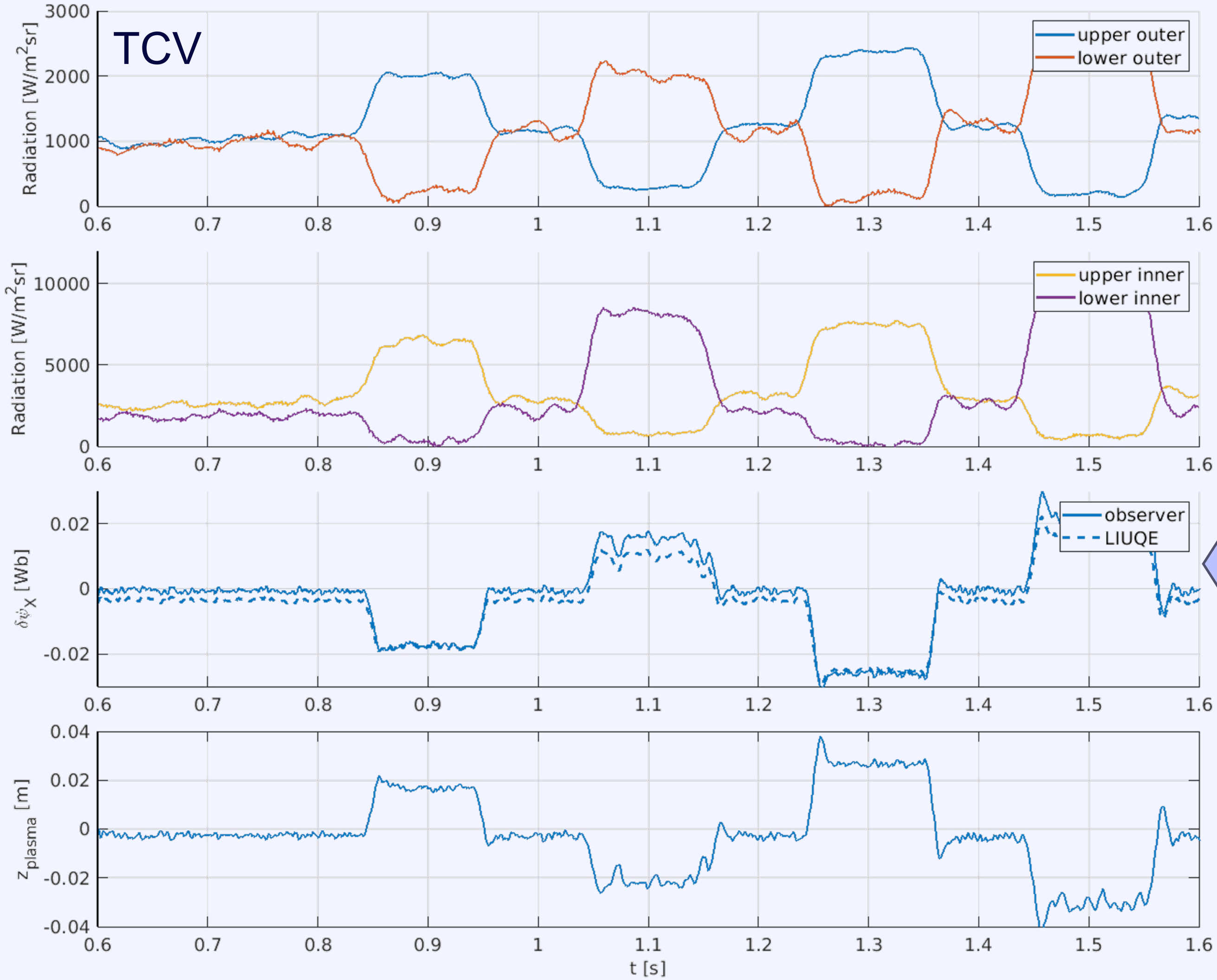
S. Freethy, EC-23, Barcelona, Spain, 18-22 May 2026

C. Hopkins, EC-23, Barcelona, Spain, 18-22 May 2026


MBER on MAST-U

Standard vertical control will require extreme accuracy to keep $\delta r_{sep} < 1 - 2\ mm$





Power distributions in the divertor

X-point flux separation

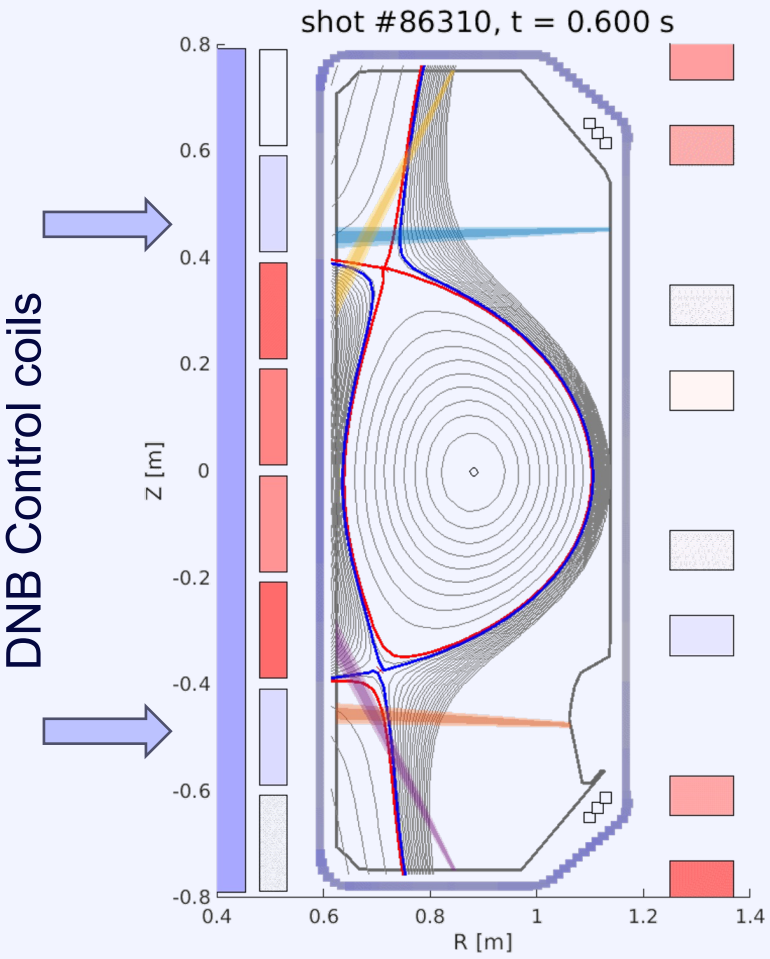
Vertical displacement

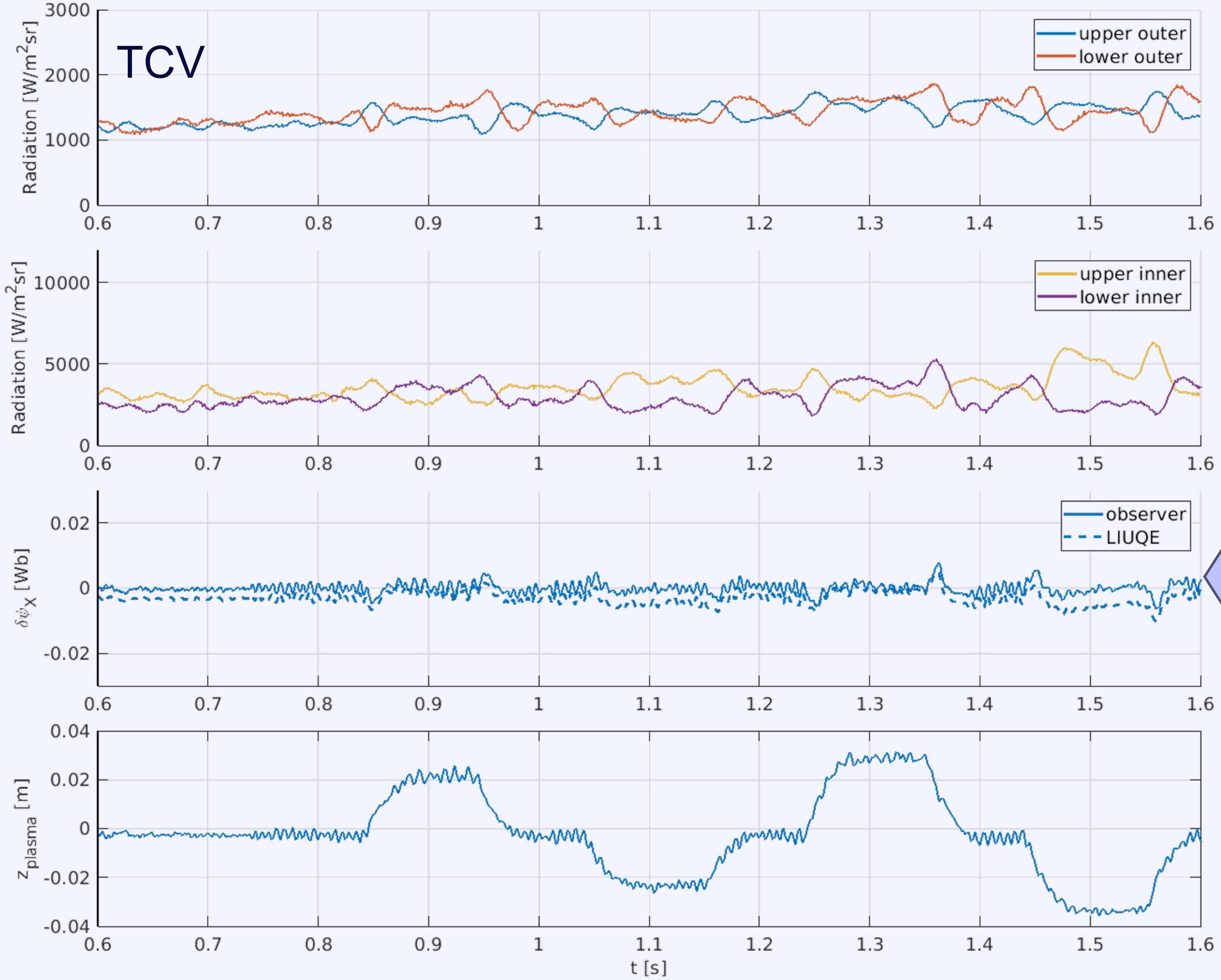
TCV experiment with standard vertical control shifting the plasma up and down by 2 cm

M. Lafferty et.al., IEEE Trans. on Plasma Science 54 (2026) no 6 p. 2640

Advanced vertical control will keep Double null configuration

DNB Control coils





Power distributions in the divertor

X-point flux separation

Vertical displacement

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

M. Lafferty et.al., IEEE Trans. on Plasma Science 54 (2026) no 6 p. 2640

Considerable progress in understanding and de-risking the STEP plasma

Improved scenario performance:

- Changed assumption set ($f_{rad}\sim 0.5,\ f_{GW} > 1,$) has led to more attractive scenarios at lower $P_{fus}\sim 1\ GW$ and lower I_p ⇒ **possible way to a smaller plasma**.

Increased scenario confidence:

- Onset and regulation large fluxes due to KBM turbulence understood.
- Predictive capability for scenario modelling achieved.
- Advanced/novel control techniques for kinetic and vertical control developed.

Novel divertor geometry to optimise He pumping and detachment:

- Improved confidence that He can be exhausted fast enough whilst maintaining good detachment.

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

Thank You for your attention