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...

Adam Parrott
Agnieszka Hudoba
Alistair McShee
Alex Tilley
Alexandru Boboc
Andy Meigs
Andrew Turner
Anthony Field
Arka Bokshi
Ashwin Patel
Bhavin Patel
Brian Lloyd
Cameron Olde
Christopher Bowman
Colin Roach
Daniel Kennedy
Daniel Valcarcel
David Moulton
David Ryan
David Taylor
Emmy Tholerus
Evelyn Litherland-Smith
Fabio Camillo de Souza
Fernanda Rimini

Francesco Palermo
Francis Casson
Frida Eriksson
Guoliang Xia
Harry Dudding
Hendrik Meyer
Hongjuan Sun
Hyun-Tae Kim
Igor Monakhov
Ivan Konoplev
Ivor Coffey
James McDonald
James Oliver
James Simpson
John Morris
Joshua Mitchell
Kamaran Pentland
Ken McClements
Kerry Lawson
Klaus Dieter Zastrow
Krassimir Kirov
Lingyan Xiang
Luca Spinicci
Lynton Appel

Mark Henderson
Mark Lafferty
Martin Cox
Martin O'Mullane
Matthias Brix
Michael Fitzgerald
Mikhail Maslov
Morten Lennholm
Neil Conway
Nickolas Hawkes
Nico Amorisco
Oliver Bardsley
Omkar Myatra
Patrick Carolan
Plamen Ivanov
Rennan Morales Gomez
Ridhima Sharma
Romain Futtersack
Ruben Otin
Ryoko Osawa
Samuel Bakes
Samuli Saarelma
Scott Silburn
Sean Conroy
Sergei Gerassimov

Sheena Menmuir
Simon Freethy
Slava Kachkanov
Spyridon Aleiferis
Stephano Gabriellini
Stephen Marsden
Steven Craig
Stuart Henderson
Terry Thompson
Thomas Wilson
Tim Hender
Vasily Kiptily
Zamir Ghani

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

University of York

(H. Wilson)
D. Dickinson
R. Vann
(B. Dudson)
B. Lipschultz
C. Ridgers
(M. Anastopoulos)
L. Holland
F. Maiden
(M. Giacomin)
M. Kryjak
M. Khan
Žiga Štancar

University of Strathclyde Glasgow

B. Eliasson
A. Cross
K. Ronald
D. Speirs
M. Higgens

Universität Stuttgart

A. Köhn-Seeman

VTT

J. Karhunen
A. Järvinnen
A. Snicker
L. Aho Mantilla
M. Arilia

Consiglio Nazionale Ricerche

L. Figini

Create

R. Albanese
R. Ambrosino
A. Castaldo
M. Mattai

cea, EPFL, DTU, IPP, CHALMERS, KTH

GENERAL ATOMICS

D. Humphreys
A. Himak
J. Barr
A. Pajares
M. Walker
A. Welander
X. Zichuan
Y. Liu

DIFFER

B. Kool
M. van Berkel
M. de Baar
A. Ho
E. Westerhof

Project Support
D. Livingstone, E. Burt,

Scientific Advice
W. Morris, A. Kirk, M. Cox,
T. Todd, (G. Fishpool), F. Militello

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

STEP

OVERVIEW

INTRODUCTION

GETTING TO HIGH CONFINEMENT

THE SCENARIO

PLASMA CONTROL

CONCLUSIONS

THE STEP PROGRAMME AIMS TO DELIVER A TRITIUM SELF–SUFFICIENT PROTOTYPE POWER PLANT ~2040 WITH $P_{net}^{el}\sim100\ MW$

- 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*

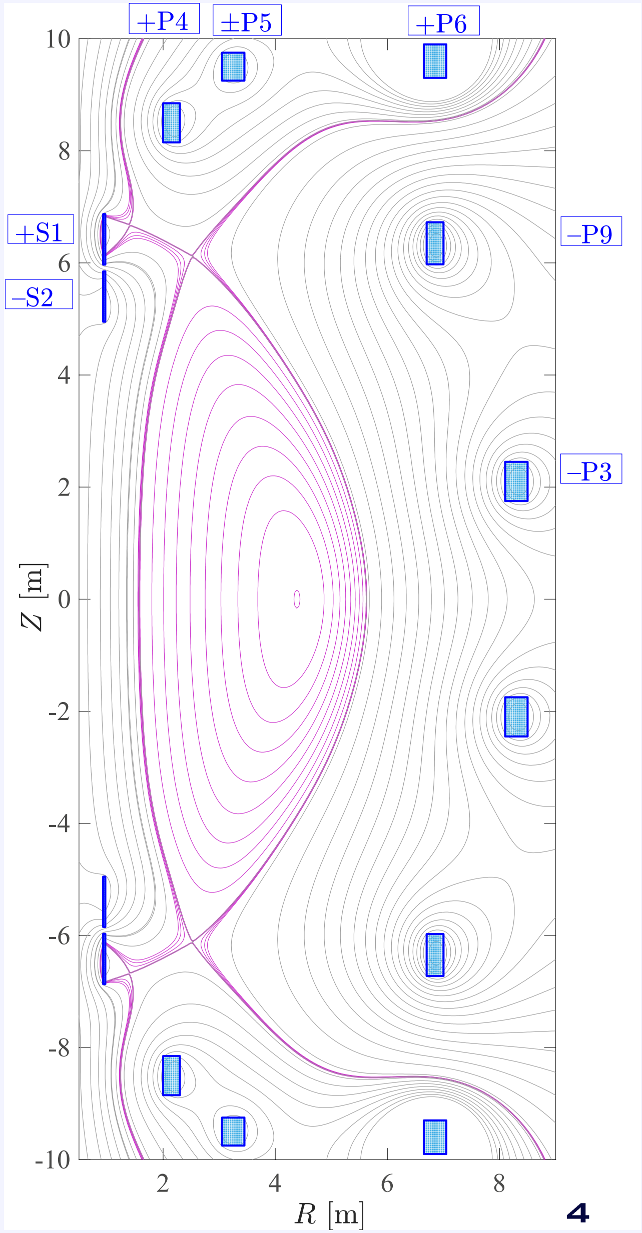
SPP-1	
R_{geo}	$3.6\ m$
A	1.8
V_{pl}	$714\ \mathrm{m}^3$
B_t	$3.2\ T$
κ	3
δ	0.5
P_{fus}	$1.5\ -1.8\ GW$

- 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.

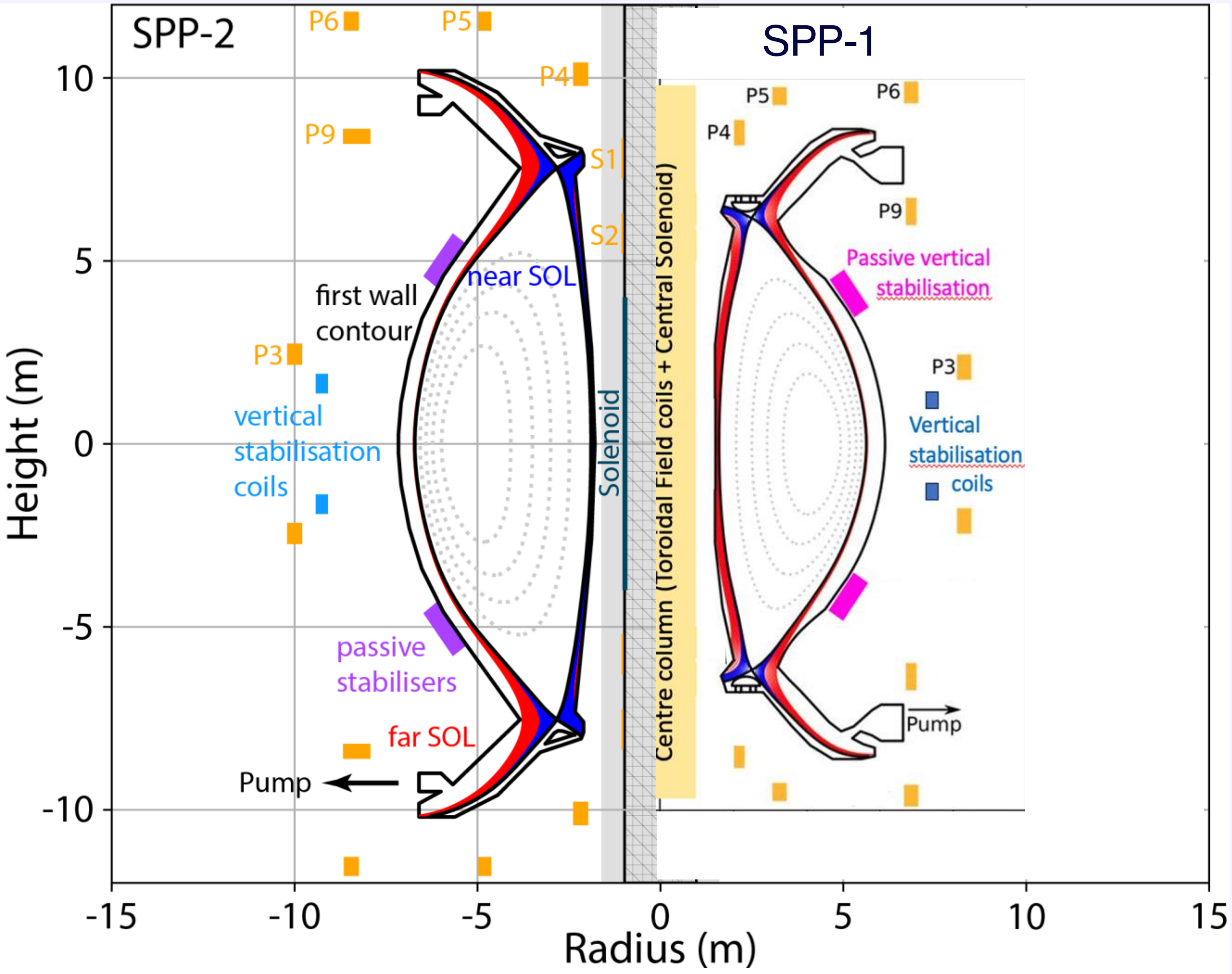
https://github.com/ukaea/OpenSTEP



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

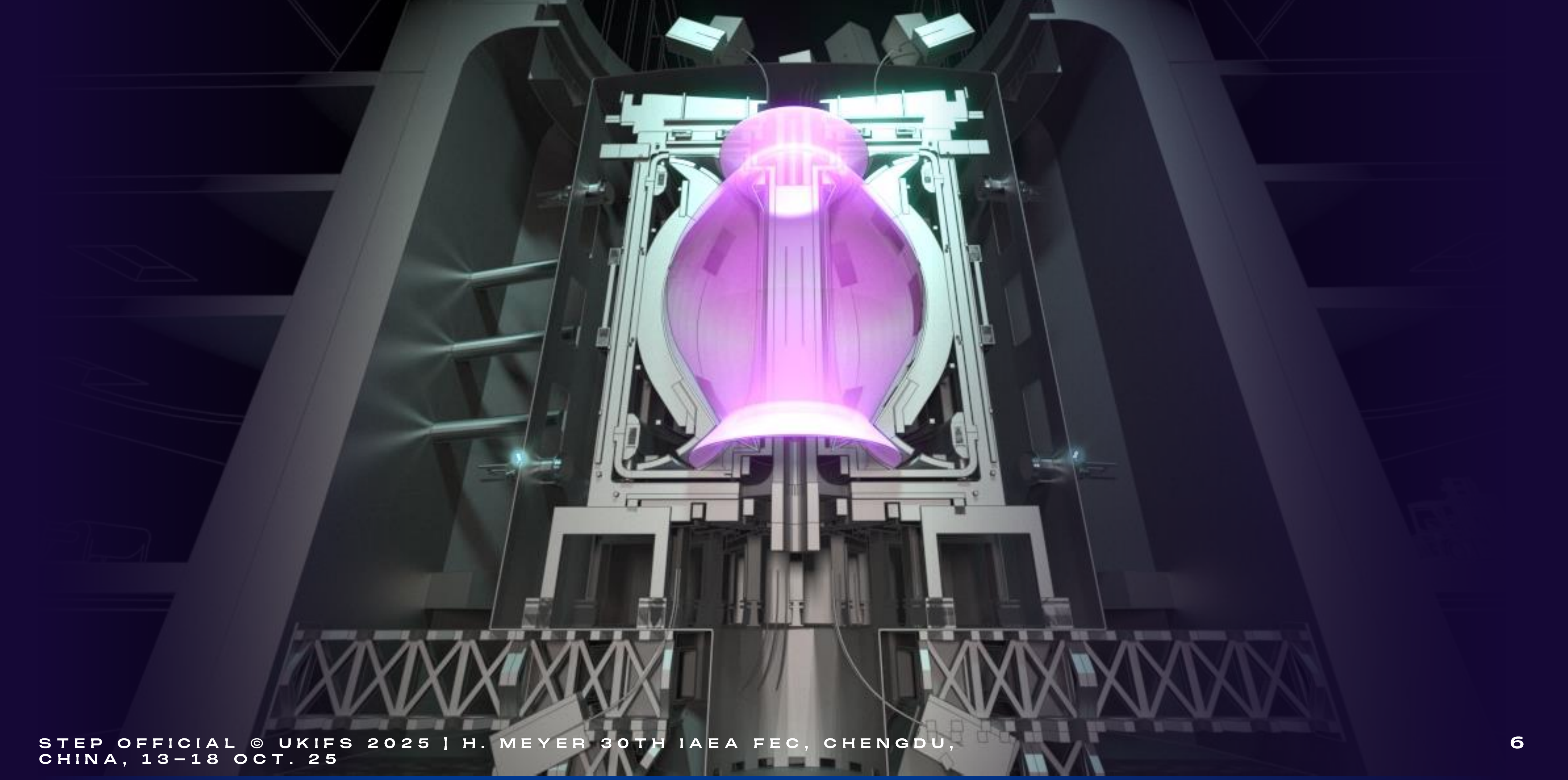
- **Plasma design philosophy not changed.**
- Volume ~1.5 × ITER, but only ½ of EU-DEMO
- Height similar to EU-DEMO



	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}	$714\ \mathrm{m}^3$	$1250\ \mathrm{m}^3$
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

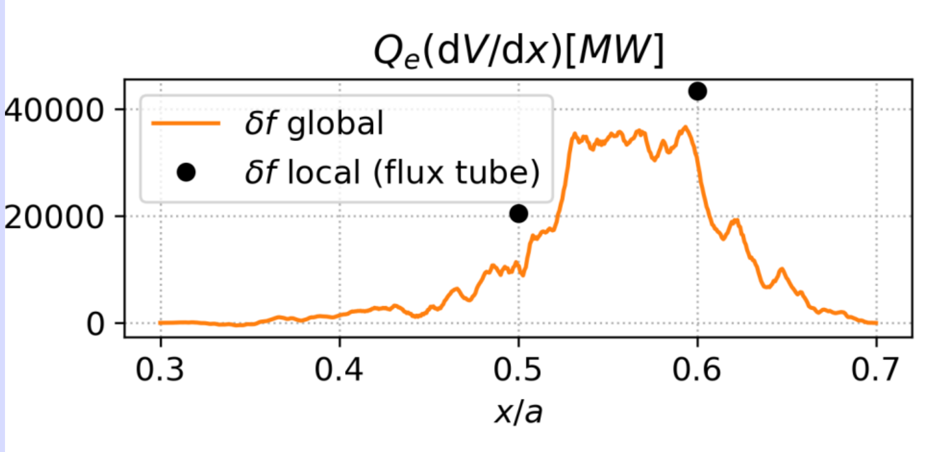
GETTING TO HIGH CONFINEMENT

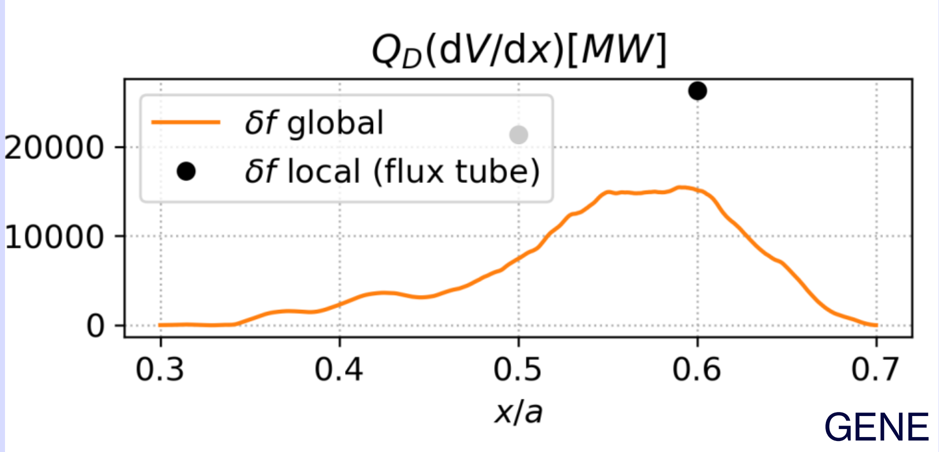


EM TURBULENCE IN STEP CAN DRIVE UNSUSTAINABLE TRANSPORT FLUXES

- 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





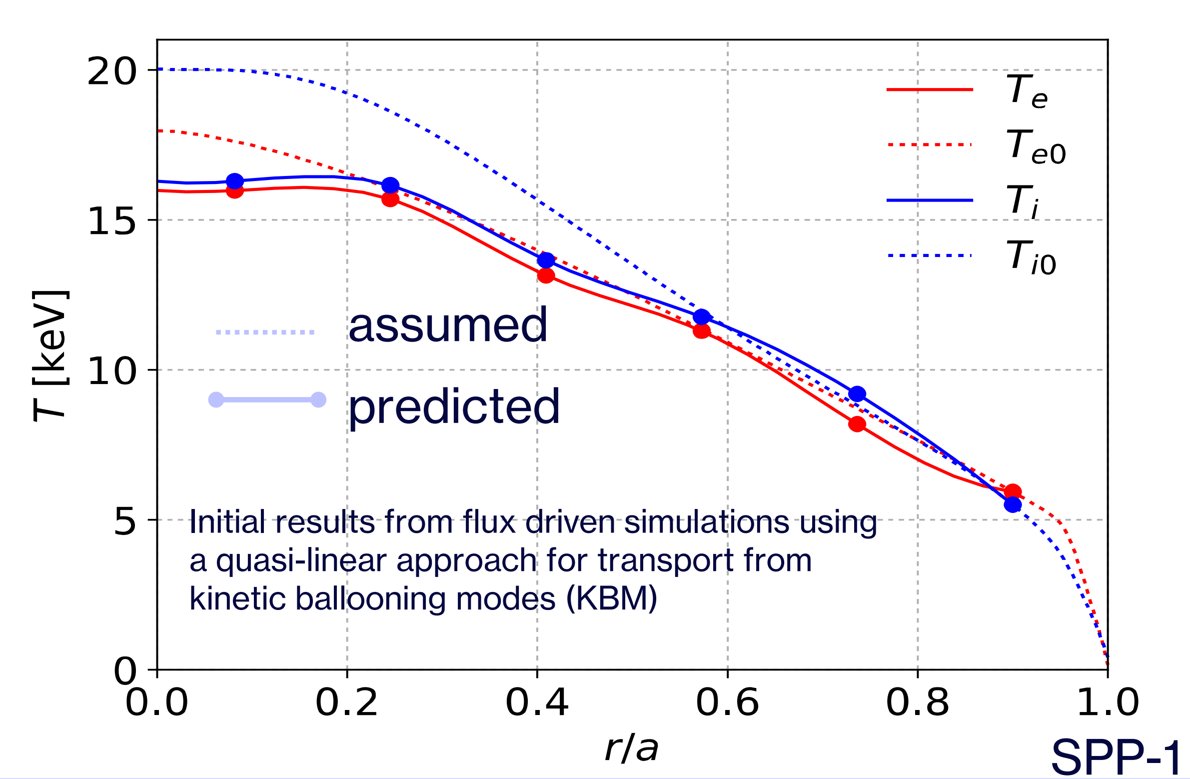
D. Kennedy et al in preparation

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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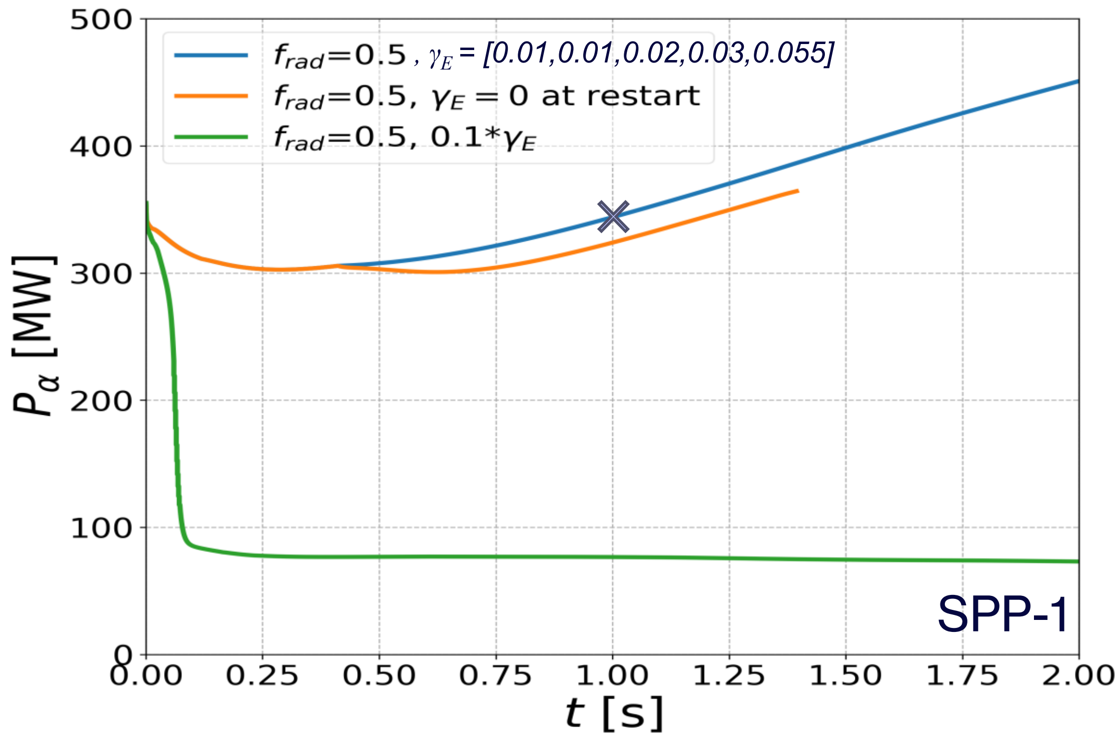
EC-HD



A Bokshi
M Abazorius

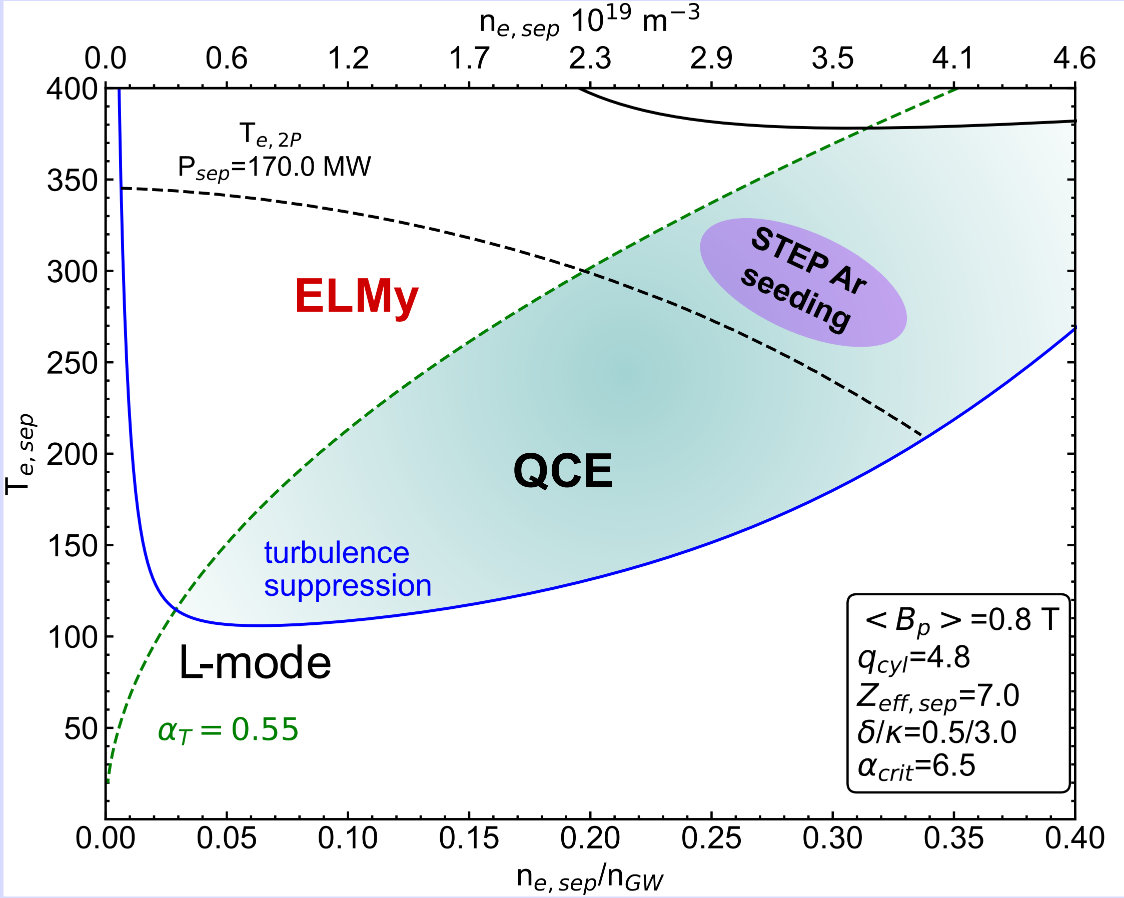
D. Kennedy, C. Roach, B. Patel, H. Dudding, *M. Giacomin, D. Dickenson, A. Bokshi*

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 $Z_{eff}^{sep} \sim 5 - 7$.

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 $n = 1 - 4$

- 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

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

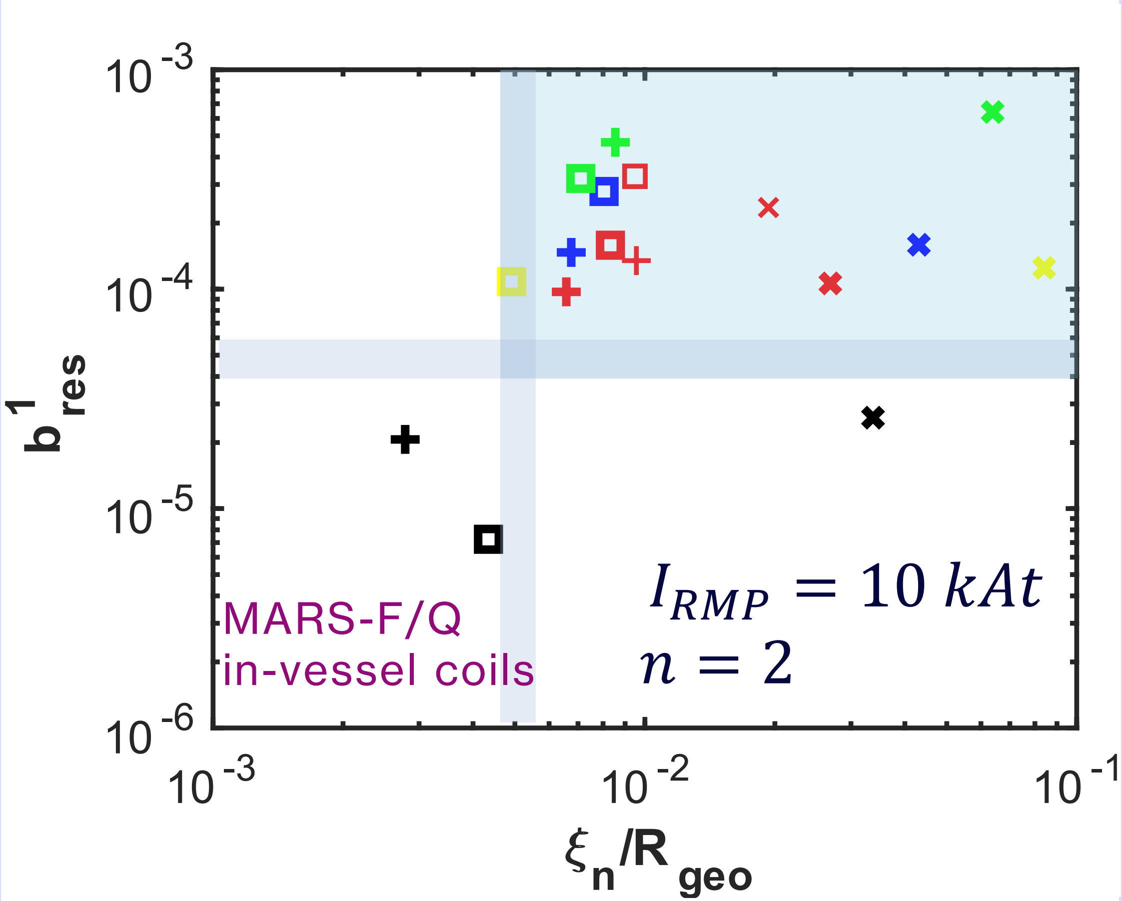
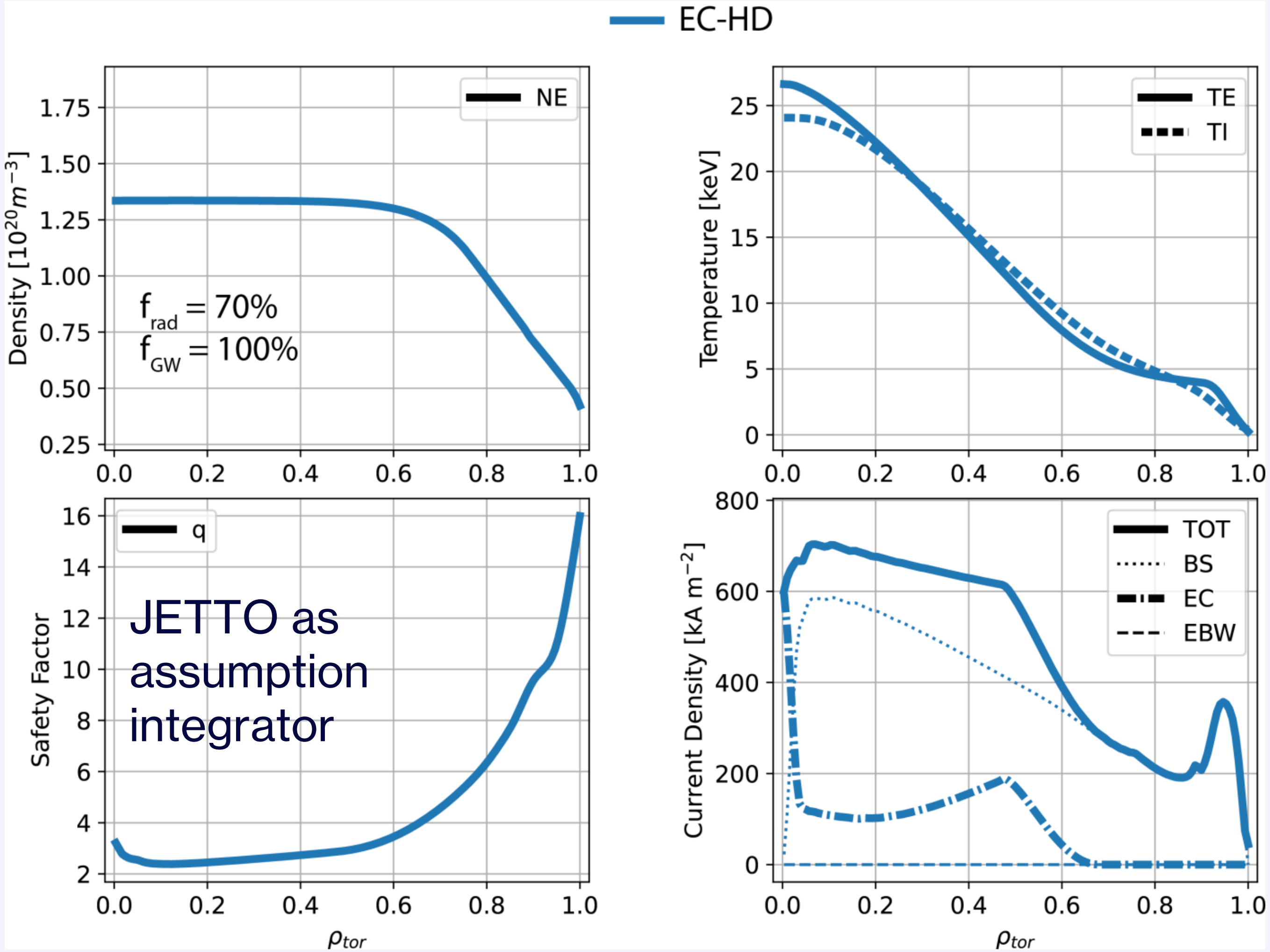


Figure of merits for ELM suppression for 4 SPP-1 (●●●●) and one SPP-2 (●) scenario with $n = 2$ and $I_{RMP} = 10\ kAt$ (shaded region indicates the thresholds.). The symbols are different flow assumptions Ω_0/ω_A.

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

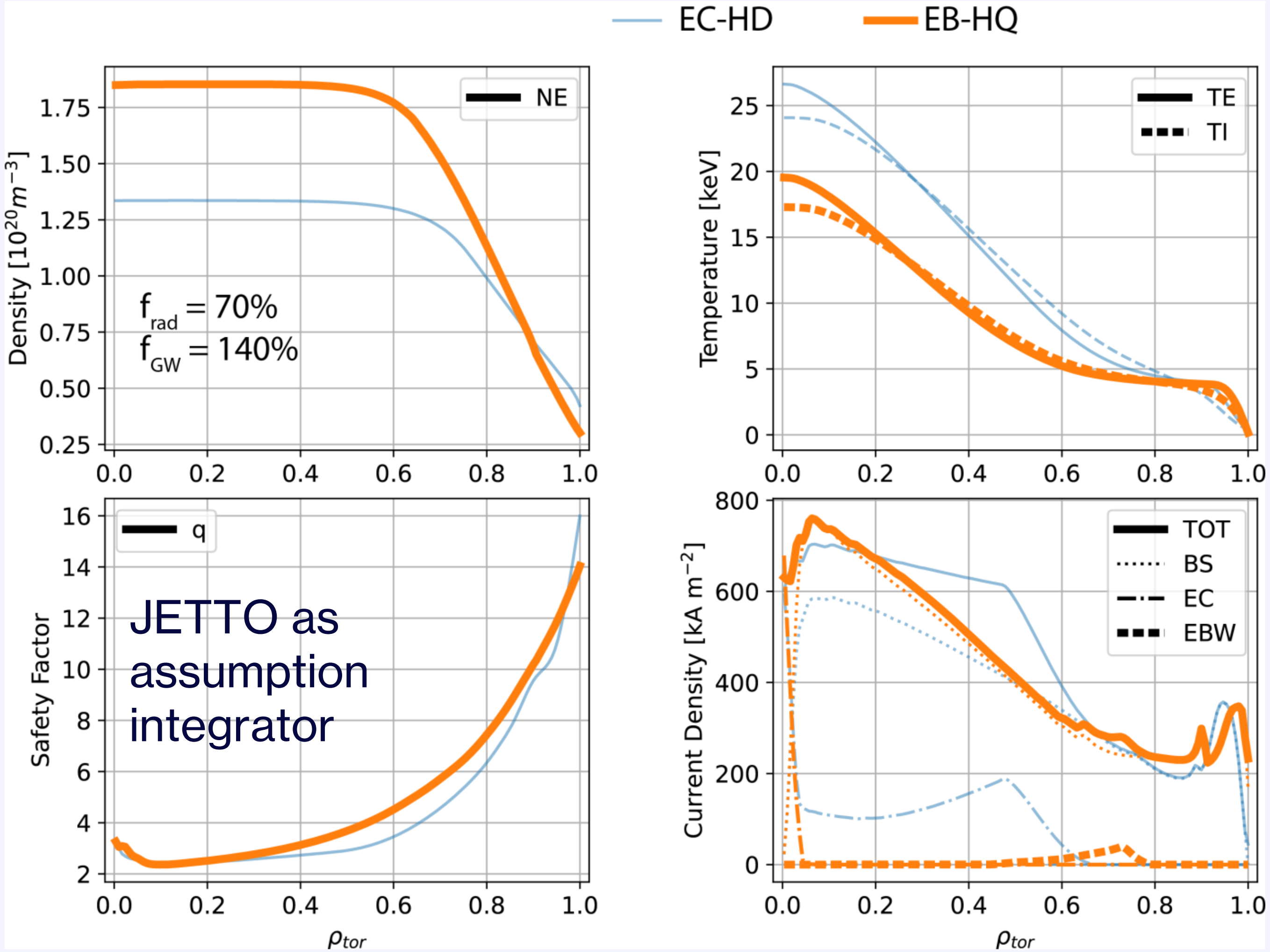
[1] Values corrected for residual "inductive" current.
[2] IPB98(y,2), [3] ITPA20-IL

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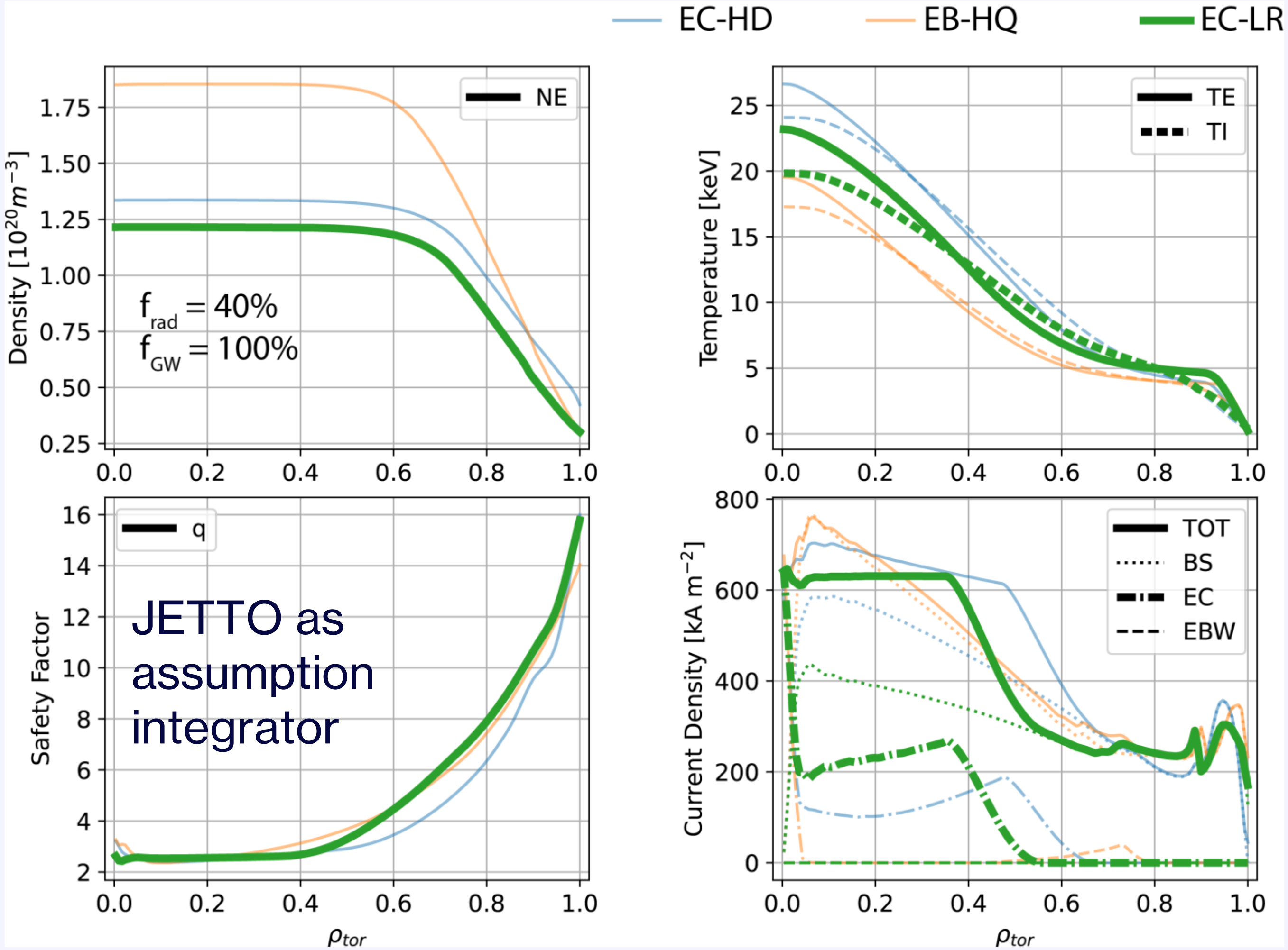
C. Olde, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

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

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



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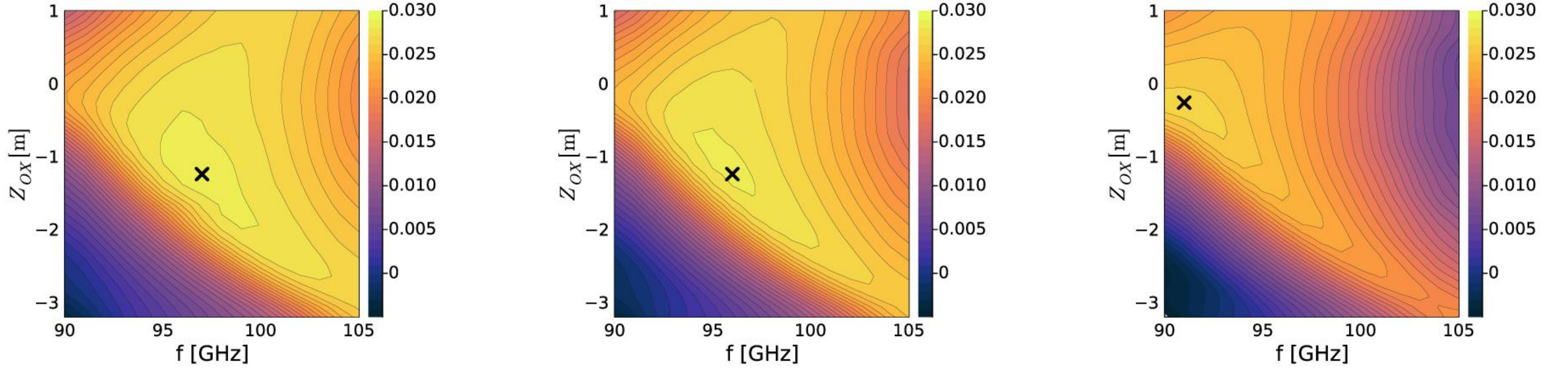
C. Olde, 51st EPS, Vilnius, Lithuania, 7-11 Jul. 2025

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

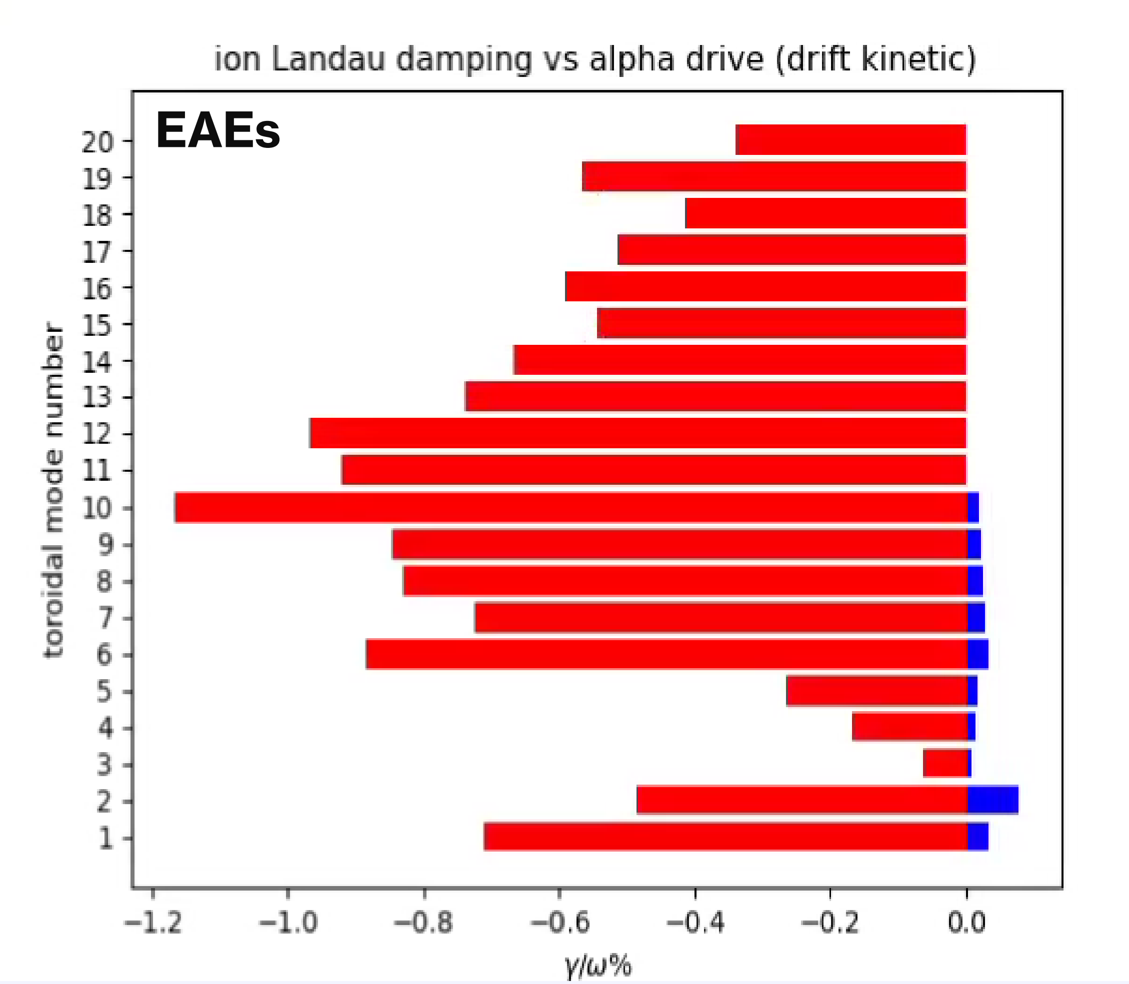
- New robust fast ray-tracing tool for scenario modelling of EBCD ⇒ CRAYON [Wil25].
- Coupling to high energy tail ⇒ Relativistic ray tracing + non-linear power absorption.
- Shift of optimal launch, η_{CD} and radial location already with $P_{EB} > 10\ MW$
- Mode conversion ⇒ multiple modes + robust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

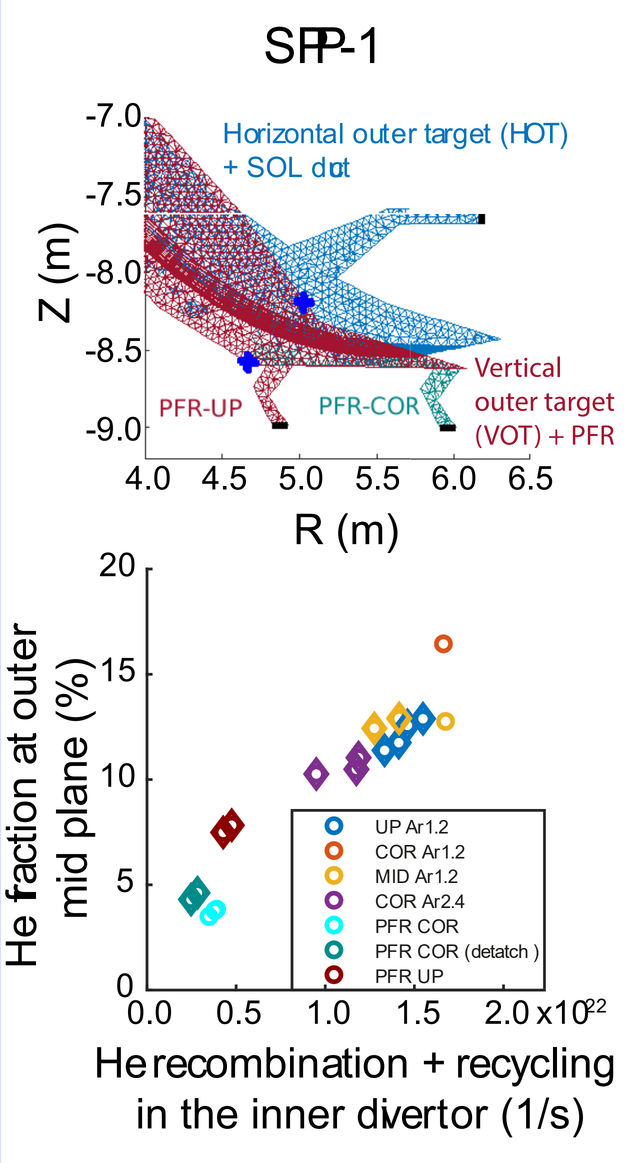
- Toroidicity & ellipticity induced Alfvén eigenmodes (TAEs & EAEs) propagate at Alfvén speed c_A & are resonantly driven by alpha-particles with $v_\parallel = c_A$
- Due to high β, Alfvén speed & ion thermal speed are closer in STEP than in conventional tokamak burning plasmas
- Bulk ion Landau damping 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 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 $c_{He}^{sep} \sim 4\%$ with optim. div..**

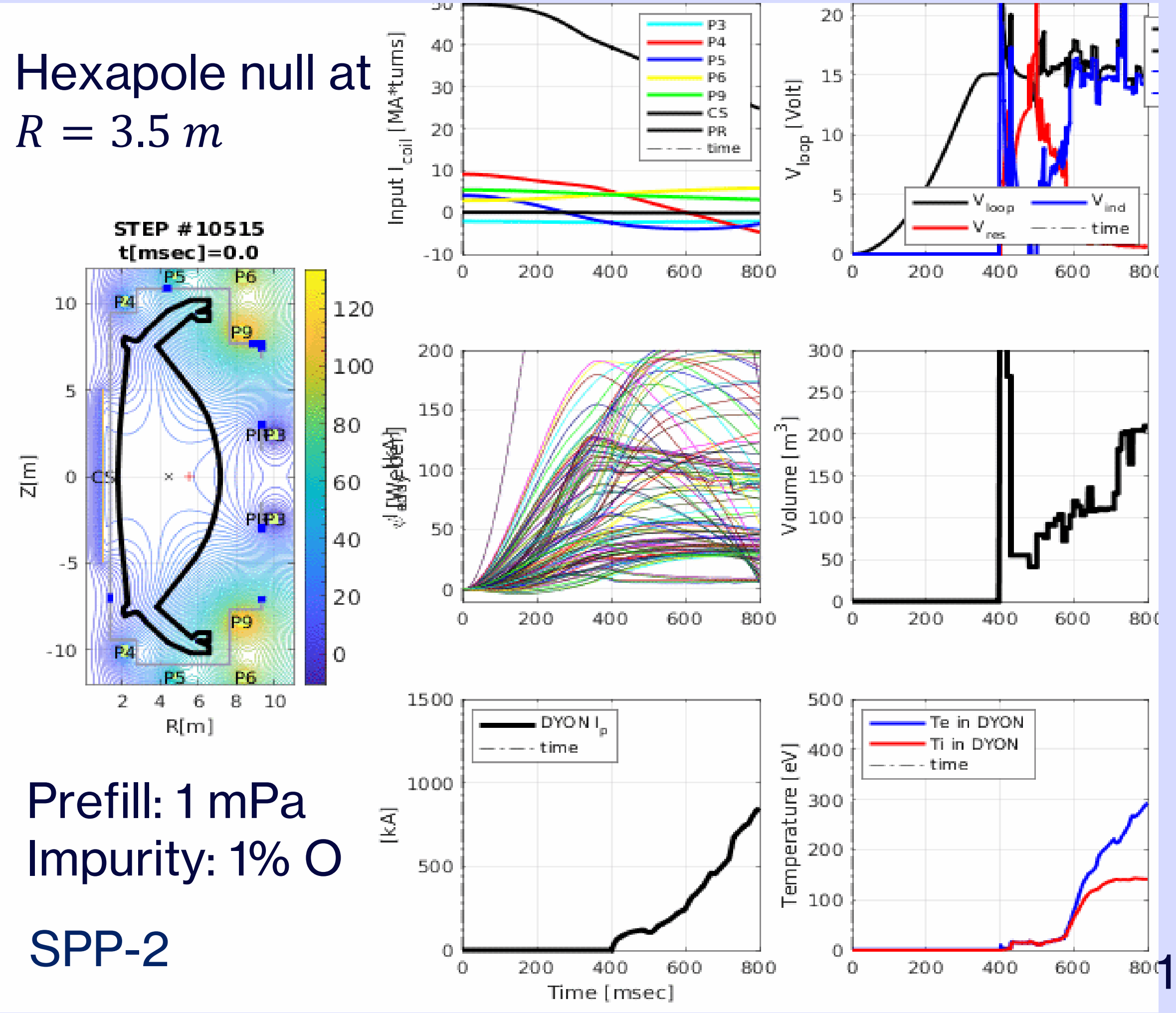
*[Mak23] S. O. Makarov et al., Nucl. Fusion **63**, 026014 (2023)*



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 $I_p \approx 1 - 2\ MA$ $\Delta\psi_{CS} \sim 10 - 15\ Vs$

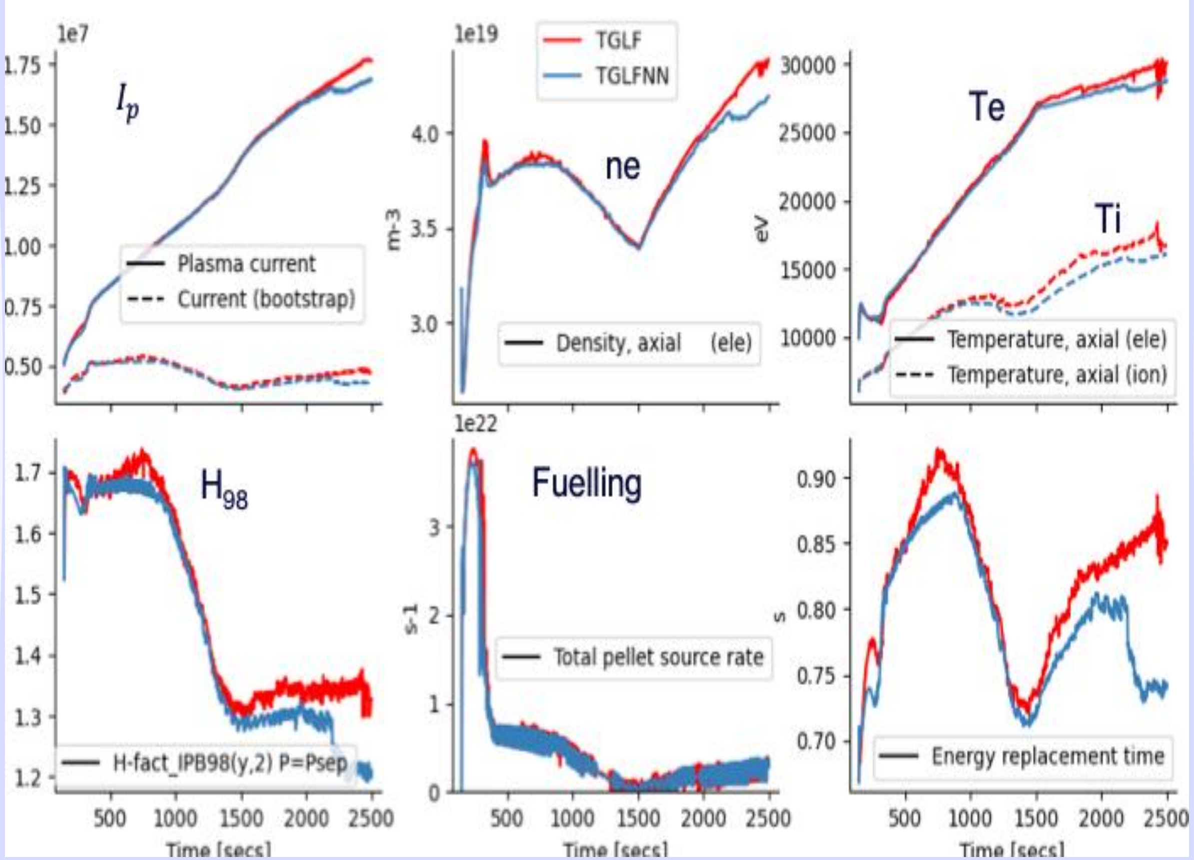


DYON: H.-T. Kim Fr 11:00

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.

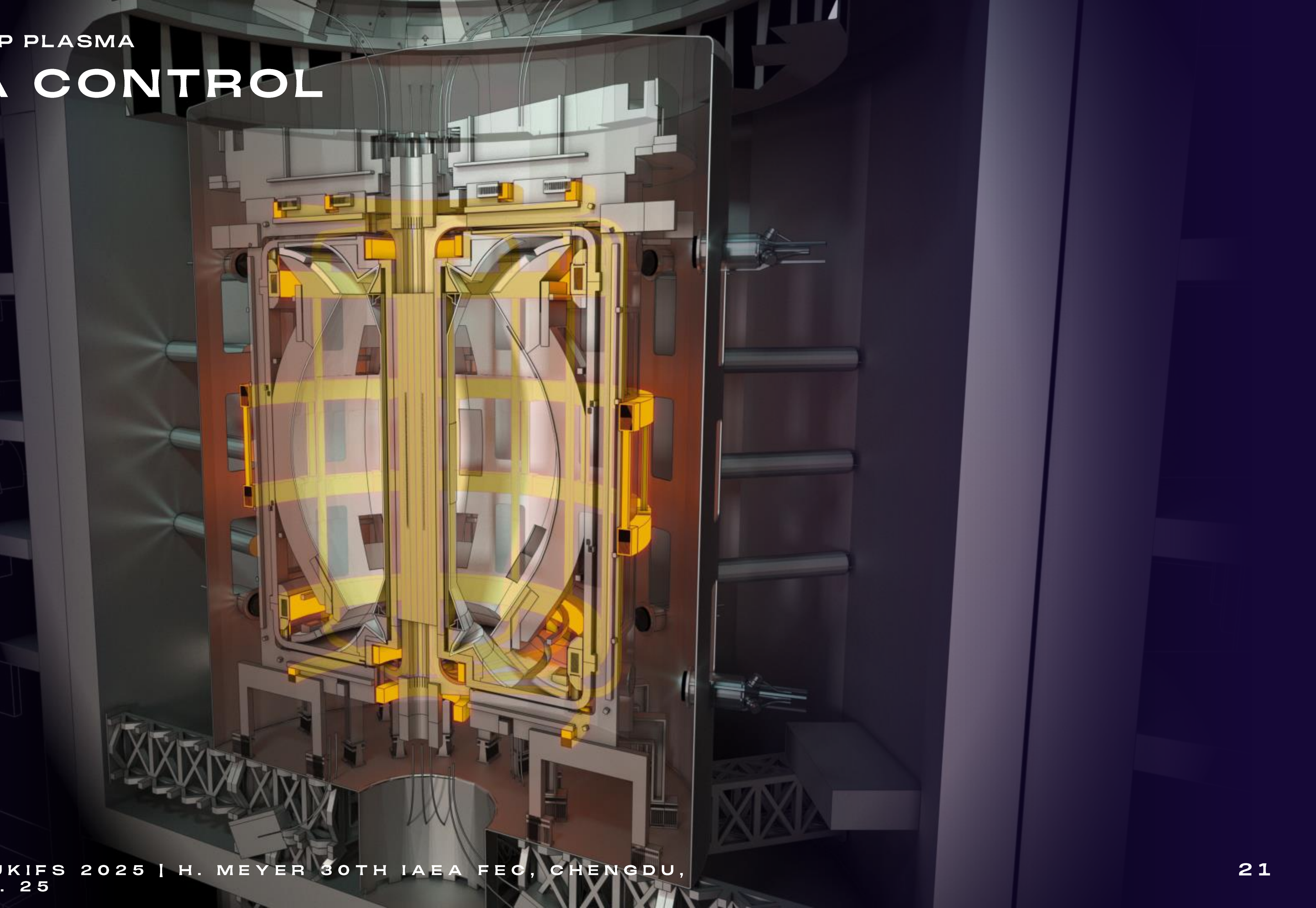


SPP-1

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

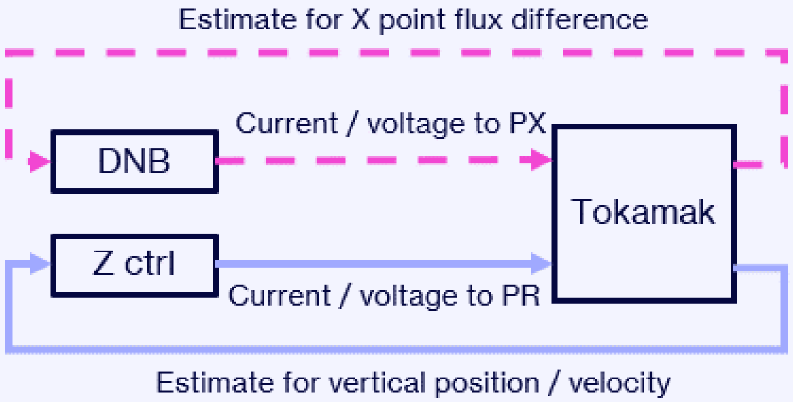


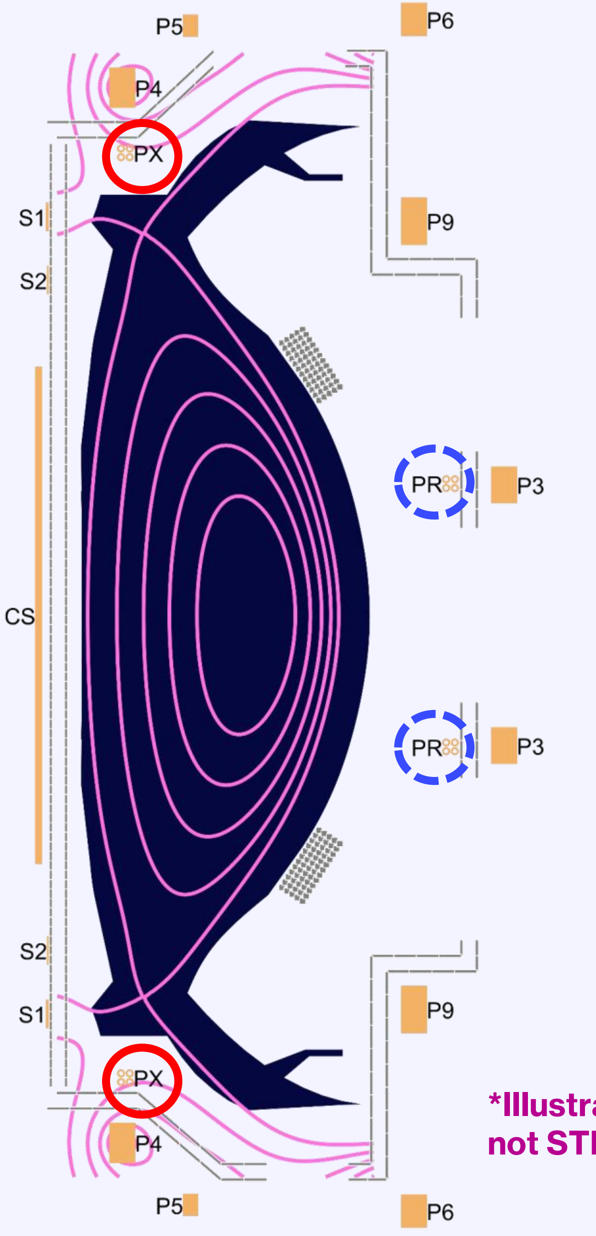
ACCURATE DOUBLE NULL CONTROL WITH A NOVEL CONTROLER

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.**





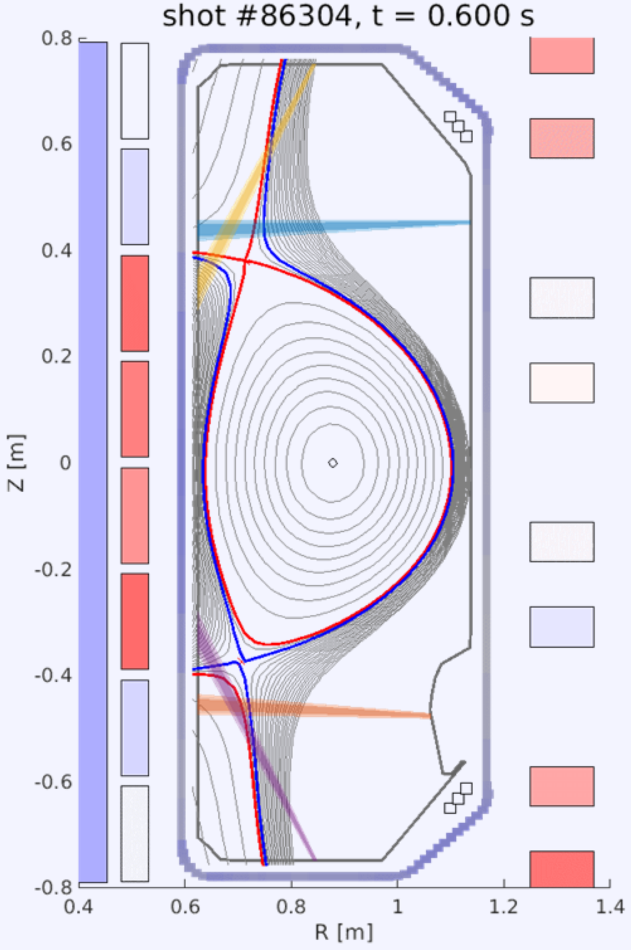
DNB control coils

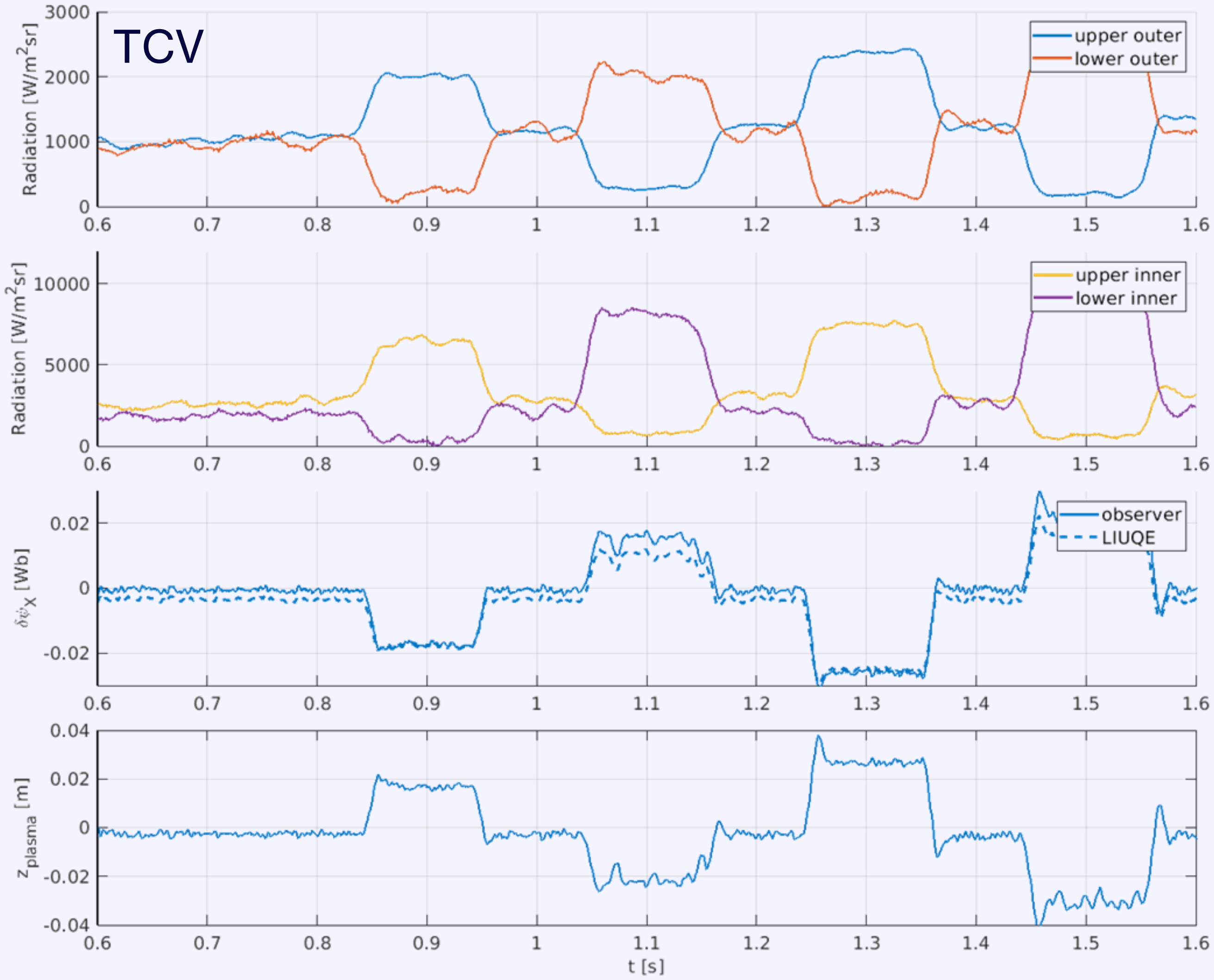
Vertical control coils

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

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

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

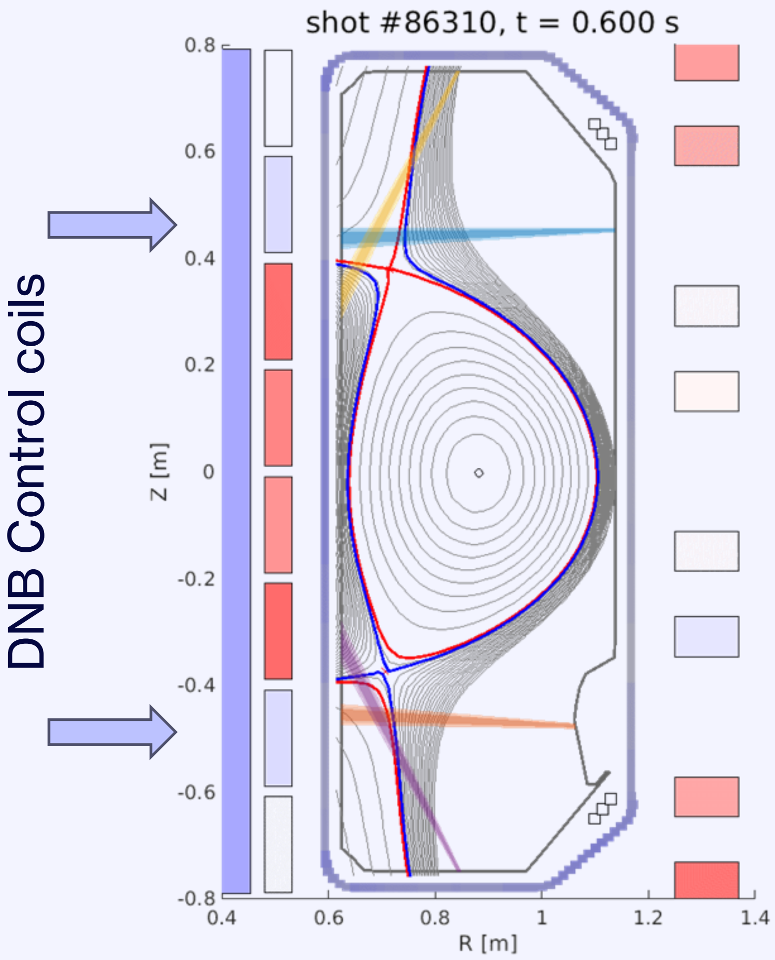


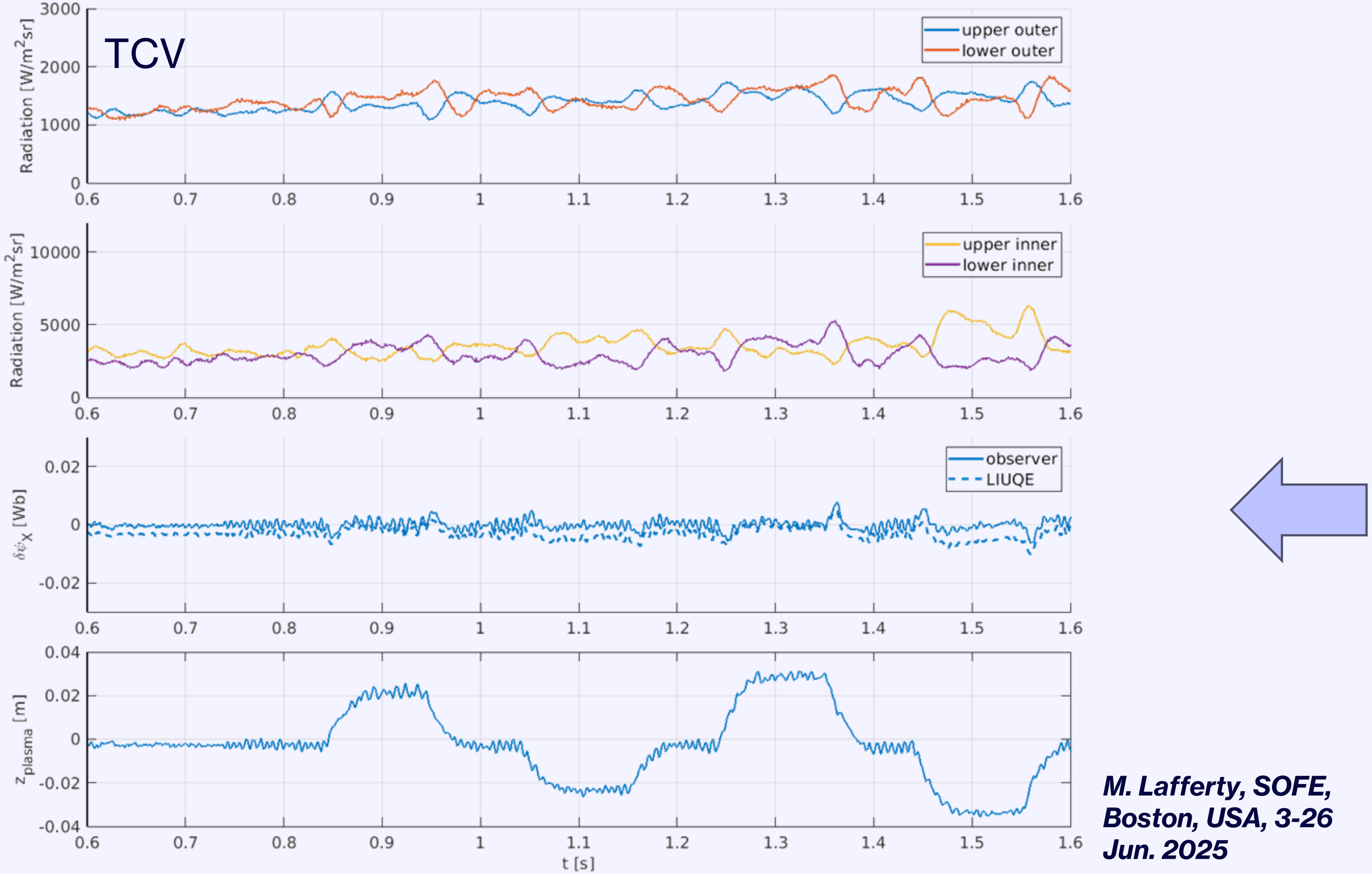


M. Lafferty, SOFE, Boston, USA, 3-26 Jun. 2025

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

ADVANCED VERTICAL CONTROL WILL KEEP DOUBLE NULL CONFIGURATION

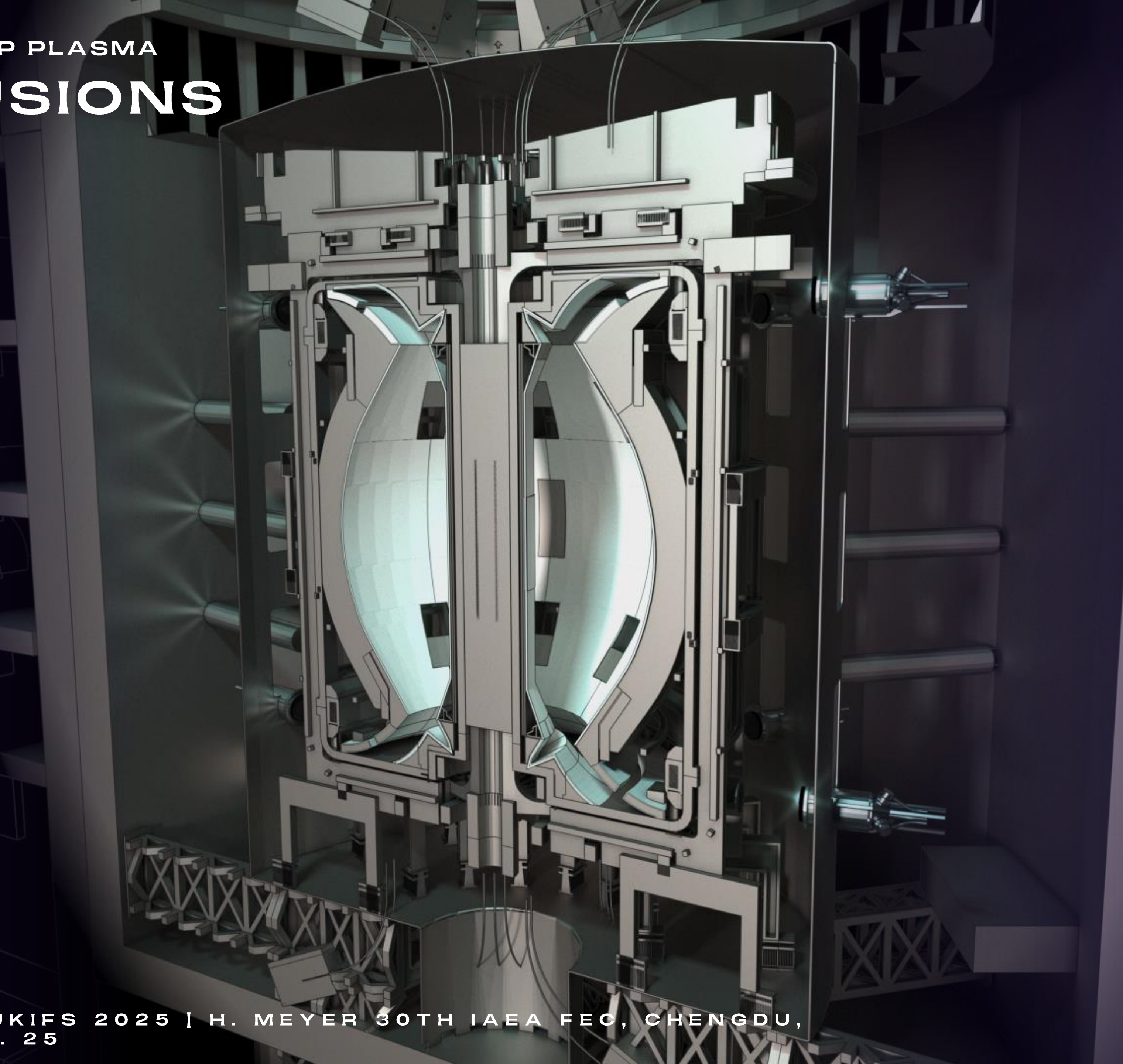




M. Lafferty, SOFE, Boston, USA, 3-26 Jun. 2025

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.

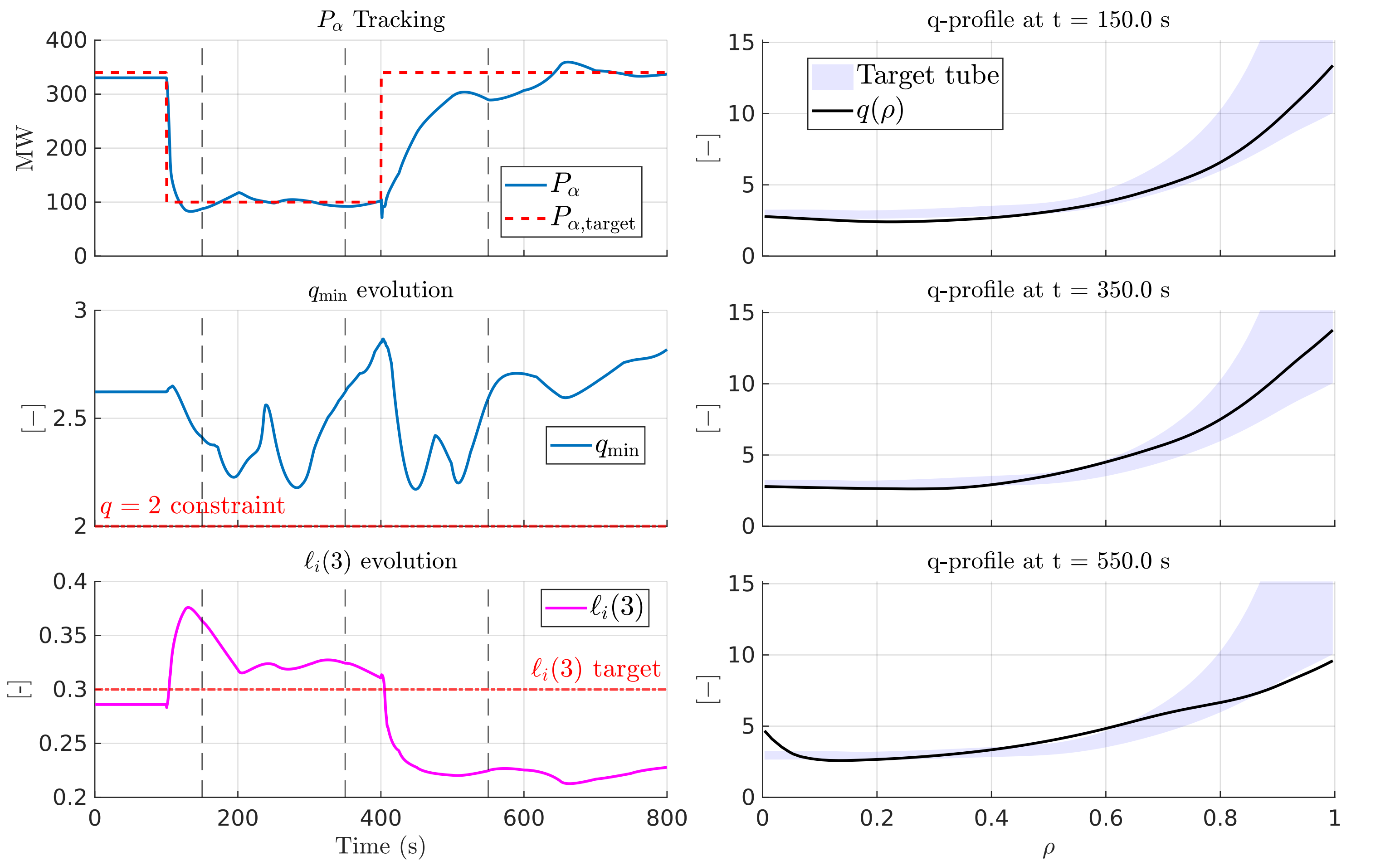
Key plasma challenges remain but STEP has developed a strong team and efficient design tools.

STEP

BACK-UP

MULTI-OBJECTIVE CONTROL DEVELOPED FOR STEP BURN CONTROL

- Burn control is a key function for an FPP
  ⇒ multi objective control needed.
- First time: simultaneous control of $P_\alpha, q(r)$ and $l_i(3)$ in a fully NI scenario.
- Unrealistic $\Delta P_\alpha \sim 240\ MW$ step down for 300s to test response.
  - Recovery worse due to accumulated errors.
- Good control of $q(r)$ and $l_i(3)$ not possible, but $l_i(3) < l_i^{lim} = 0.4$ and $q_{min} > q_{min}^{lim}$

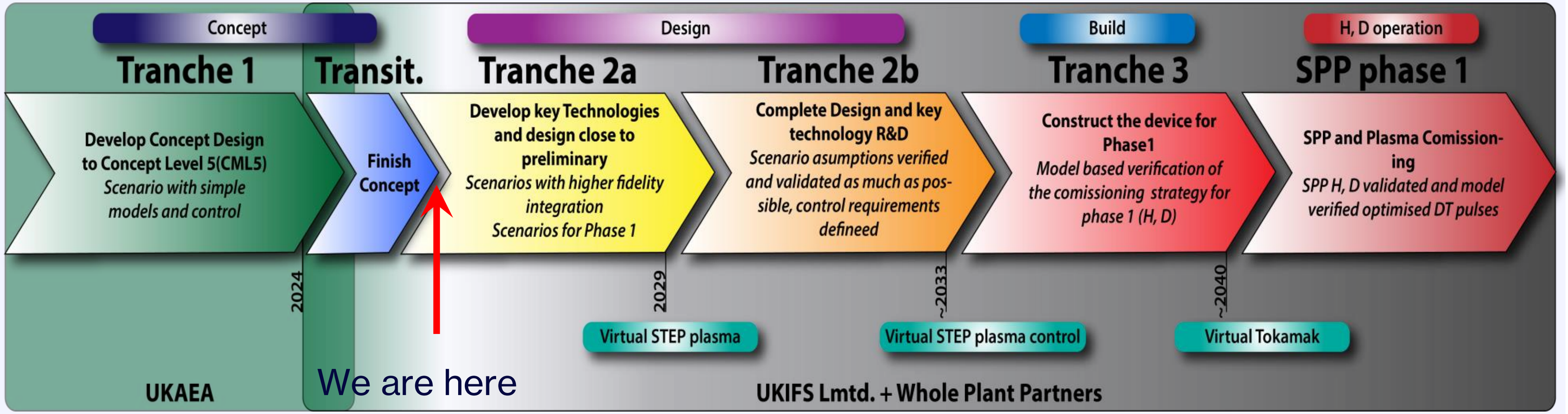


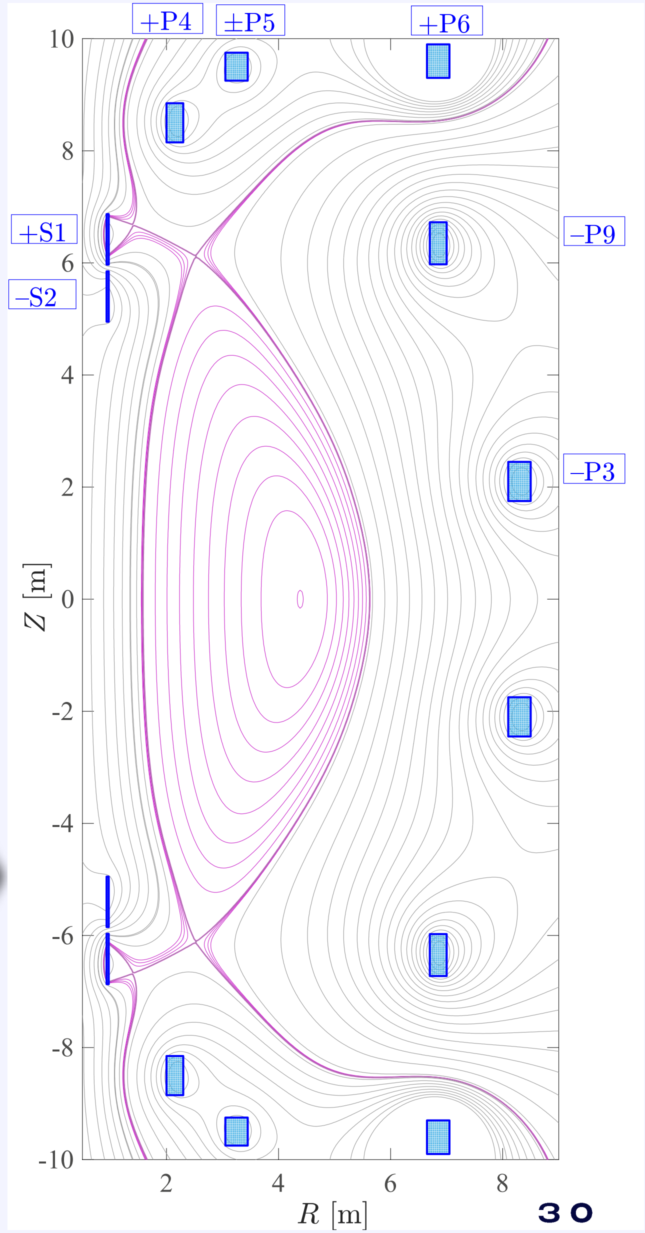
J. Mitchell et al., *Fusion Engineering and Design* 219, 115202 (2025)

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

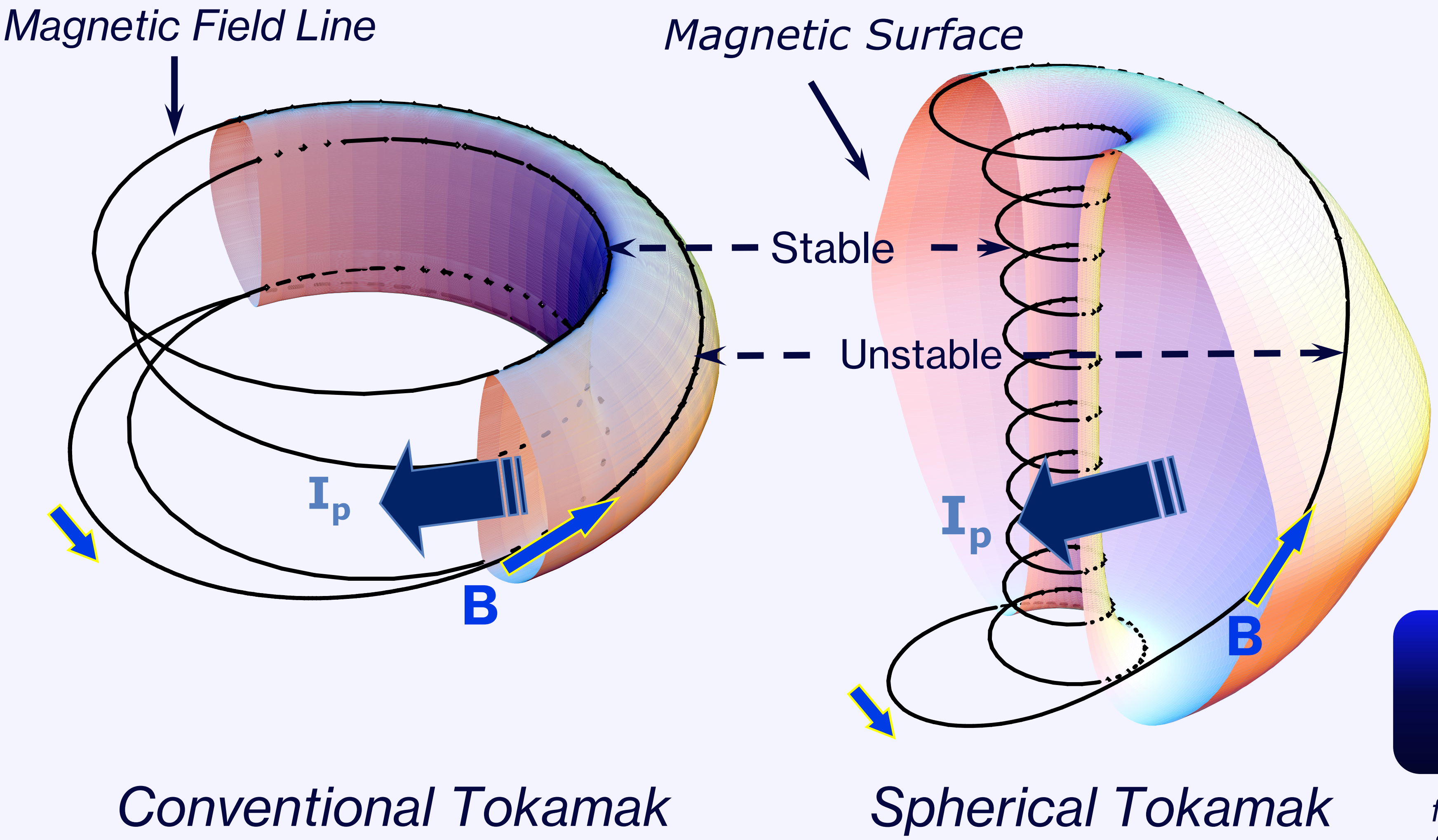
- First design base published in 2024 – SPP-1
  - *see Phil. Trans. R. Soc. A. Vol 382, issue 2280*
  - ***Plasma**: H Meyer et.al. Phil. Trans. R. Soc. A.382 20230406*
  - ***Plasma Control**: M. Lennholm et.al. Phil. Trans. R. Soc. A.38220230403*

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}	$1.5\ -1.8\ GW$





THE SPHERICAL TOKAMAK PROVIDES A ROUTE TO A STEADY STATE COMPACT FPP



cartoon courtesy of Y.M. Peng

- STs allow higher plasma pressure in lower toroidal field ⇒ higher β
- STs operate naturally at higher triangularity δ (⇒ improved pedestal) & elongation κ

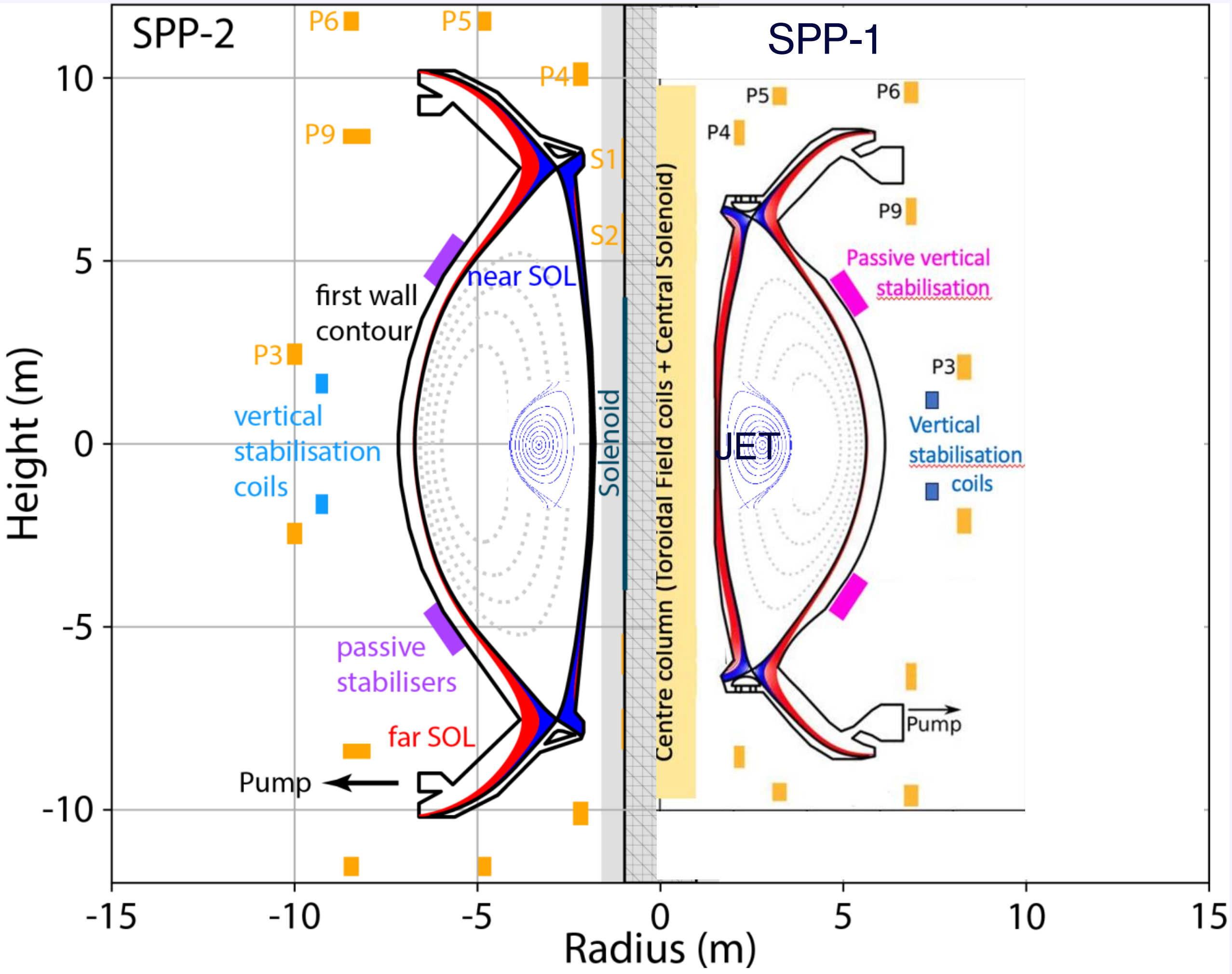
$$P_{fus} \propto (\beta_N B_t)^4 \kappa^5 \frac{R^3}{A^3}$$

for a constant (high) bootstrap fraction and $\kappa^2 \gg 1$

E. Tholerus et.al. Nucl. Fusion **64** 106030

FOR TECHNICAL REASONS THE BASELINE PIVOTED TO A LARGER MAJOR RADIUS

- Plasma design philosophy not changed.
- Elongation is maximised $\kappa \sim 3$
- Volume $\sim 1.5 \times$ ITER, but oly ½ of DEMO
- Height similar to 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 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

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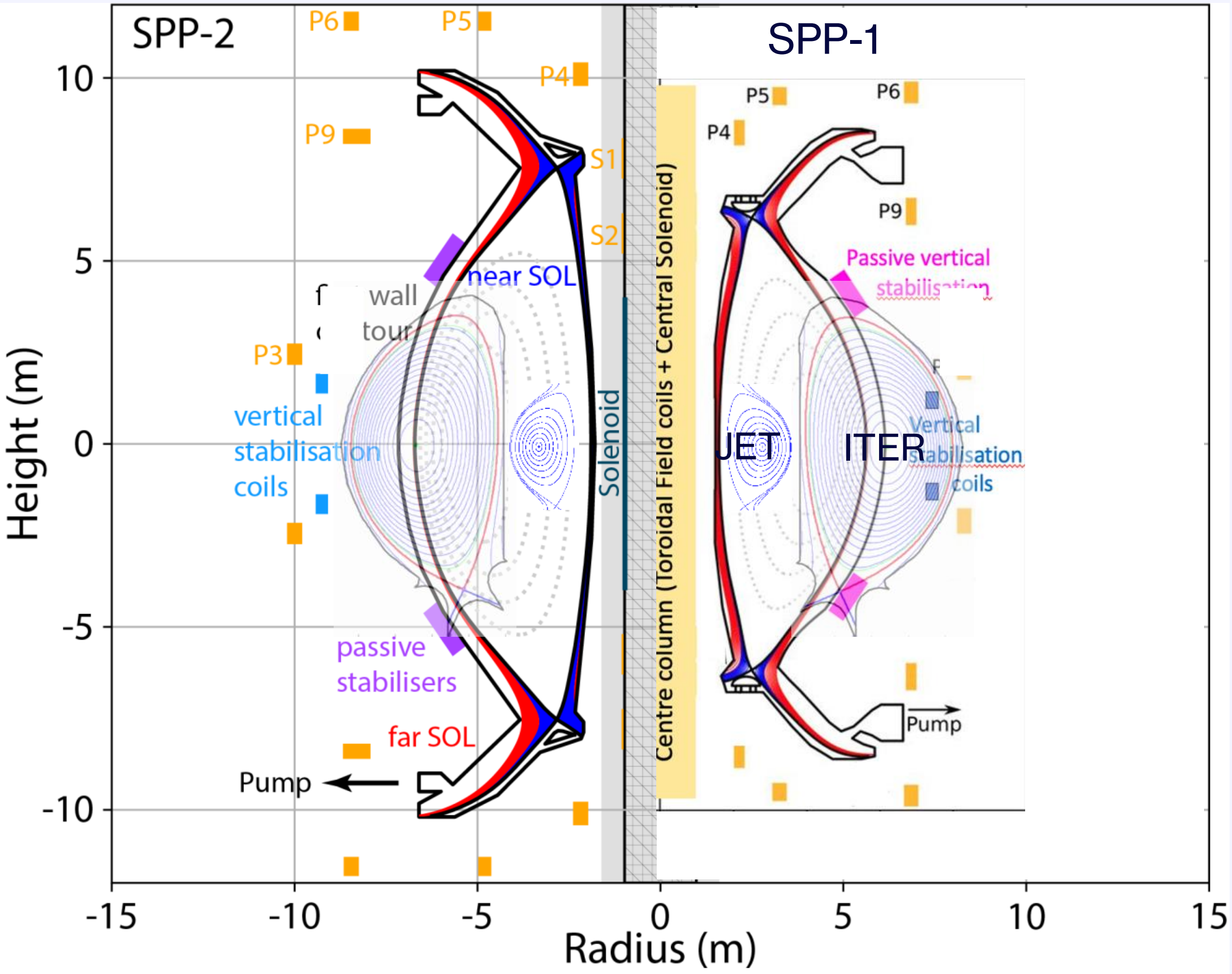

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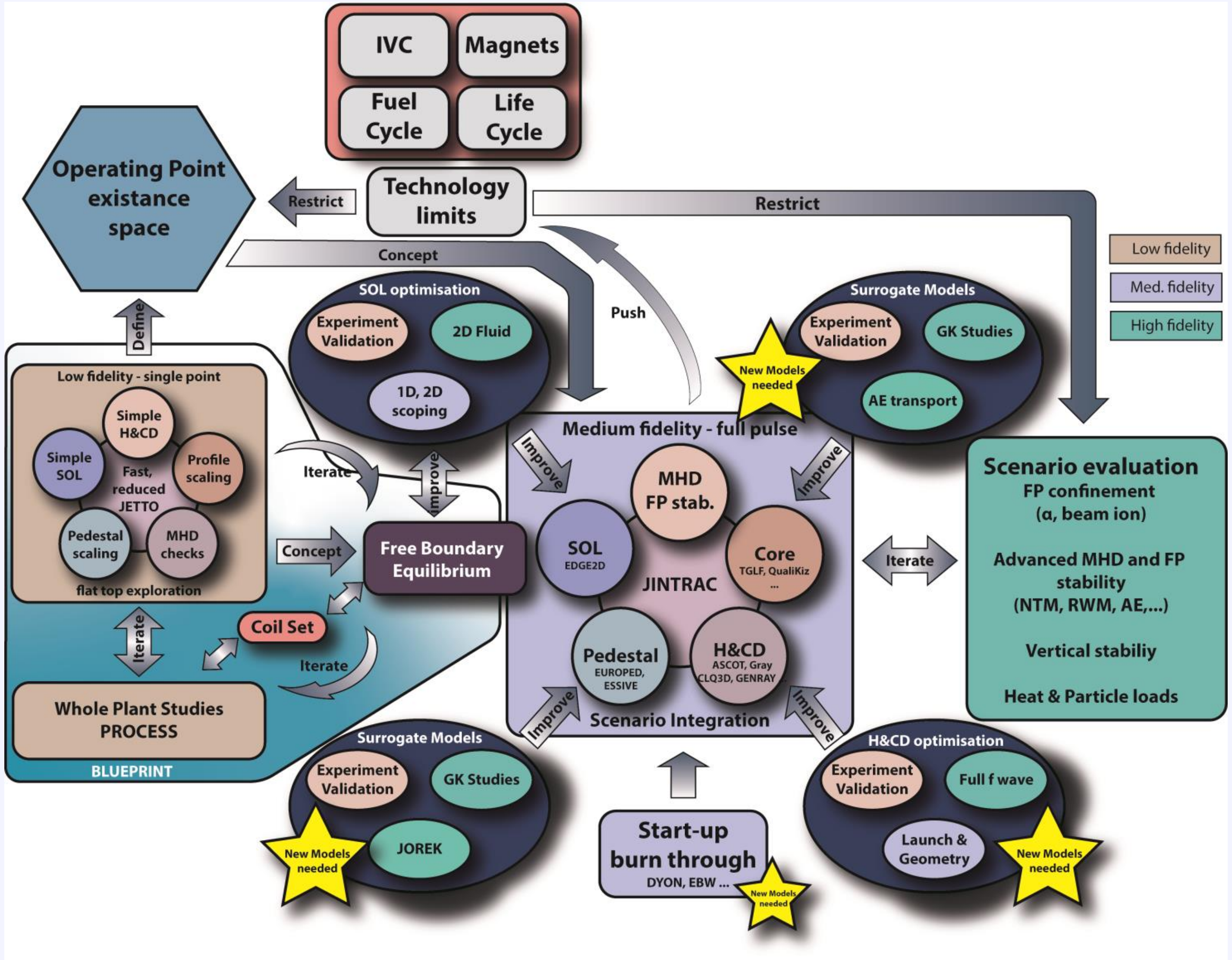
Baseline Concept SPP-1 see:
Phil. Trans. R. Soc. A. Vol 382, issue 2280

INTEGRATED PLASMA SCENARIO DESIGN ALLOWING FOR DIFFERENT LEVELS OF FIDELITY

- System code + fast transport modelling for concept space exploration.
- JINTRAC integrated modelling framework for scenario refinement.
- Stand-alone modelling and model development for uncertainty reduction.



H Meyer et.al. Phil. Trans. R. Soc. A.382 20230406

STEP

CONTRIBUTIONS AT THE 22ND ISTW

Monday		
13:20	F. Casson	*A non-inductive ramp-up scenario for STEP*
13:20	M. Lafferty	*Vertical Stability of Transient Plasma Scenarios for STEP*
15:40	C. Roach	*Recent Progress in our Understanding of Electromagnetic Turbulence in a Conceptual Spherical Tokamak FPP (STEP)*
Tuesday		
15:00	K. McClements	Confinement of fusion alpha-particles and Alfvén eigenmode stability in the Spherical Tokamak for Energy Production (STEP) – 15:00
Thursday		
11:40	L. Xiang	Physics Studies for STEP Divertor Design
12:00	C. Olde	Optimising the STEP current ramp-down phase with JINTRAC

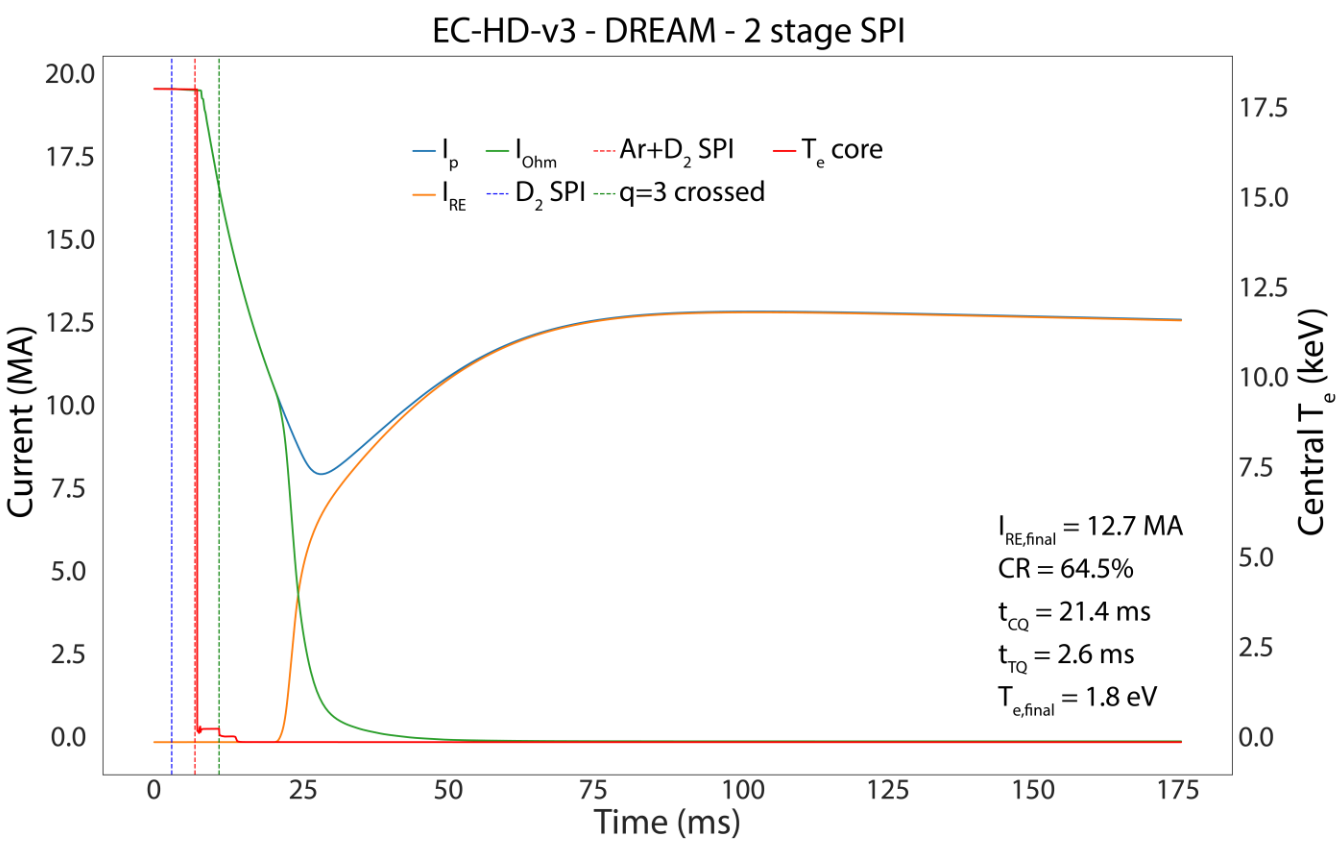
Recent STEP Publications

E. Tholerus et al., Nuclear Fusion (2024).
R. T. Osawa et.al., Nuclear Fusion 64, 106007 (2024).
H. Meyer et.al., Philosophical Transactions of the Royal Society A 382, 20230406 (2024).
M. Lennholm et al., Philosophical Transactions of the Royal Society A 382, 20230403 (2024).
M. Lennholm et al., Nuclear Fusion 64, 096036 (2024).
D. Kennedy et al., Nuclear Fusion 64, 086049 (2024).
J. Karhunen et.al., Nuclear Fusion 64, 096021 (2024).
A. Hudoba et.al., Nuclear Fusion 64, 086055 (2024).
W. A. Hornsby et al., Physics of Plasmas 31, 012303 (2024).
M. Giacomin et.al., Plasma Physics and Controlled Fusion 66, 055010 (2024).
M. Giacomin et al., accepted in Journal of Plasma Physics. arXiv preprint arXiv:2404.17453 (2024).
S. Freethy et.al., Nuclear Fusion 64, 126035 (2024).
A. Fil et.al., Nuclear Fusion 64, 106049 (2024).
G. Xia et.al., Nuclear Fusion 63, 026021 (2023).
T. Wilson et.al., EPJ Web Conf. 277 (2023).
R. T. Osawa et.al., Nuclear Fusion 63, 076032 (2023).
J. Mitchell et.al., Fusion Engineering and Design 192, 113777 (2023).
A. Kirschner et al., Nuclear Fusion 63, 126055 (2023).
D. Kennedy et.al., Nuclear Fusion 63, 126061 (2023).
A. Hudoba et.al., Nuclear Materials and Energy 35, 101410 (2023).
A. Hudoba et al., Fusion Engineering and Design 191, 113704 (2023).
M. Giacomin et.al., Plasma Physics and Controlled Fusion 65, 095019 (2023).
S. Freethy et al., EPJ Web Conf. 277 (2023).
B. Biswas et.al., Nuclear Fusion (2023).
H. Anand et al., Fusion Engineering and Design 194, 113724 (2023).
B. S. Patel et.al., Nuclear Fusion 62, 016009 (2022).
H.-T. Kim et al., Nuclear Fusion 62, 126012 (2022).

MITIGATION OF RUNAWAY ELECTRON (RE) BEAM STILL INSUFFICIENT

Planned injected quantities able to radiate all thermal energy (mitigates thermal quench heat loads) with current quench time ~ 20ms

- Multiple shattered pellet injections still leave an intolerable RE beam current of $\mathrm{I_{RE}} \sim 13\ MA$
  - 2 stage: D_2 then Ar + D_2
- Could lead to loss of coolant accident (LOCA)
- Try to reach benign termination (D_2+MHD) regime ⇒ improved modelling



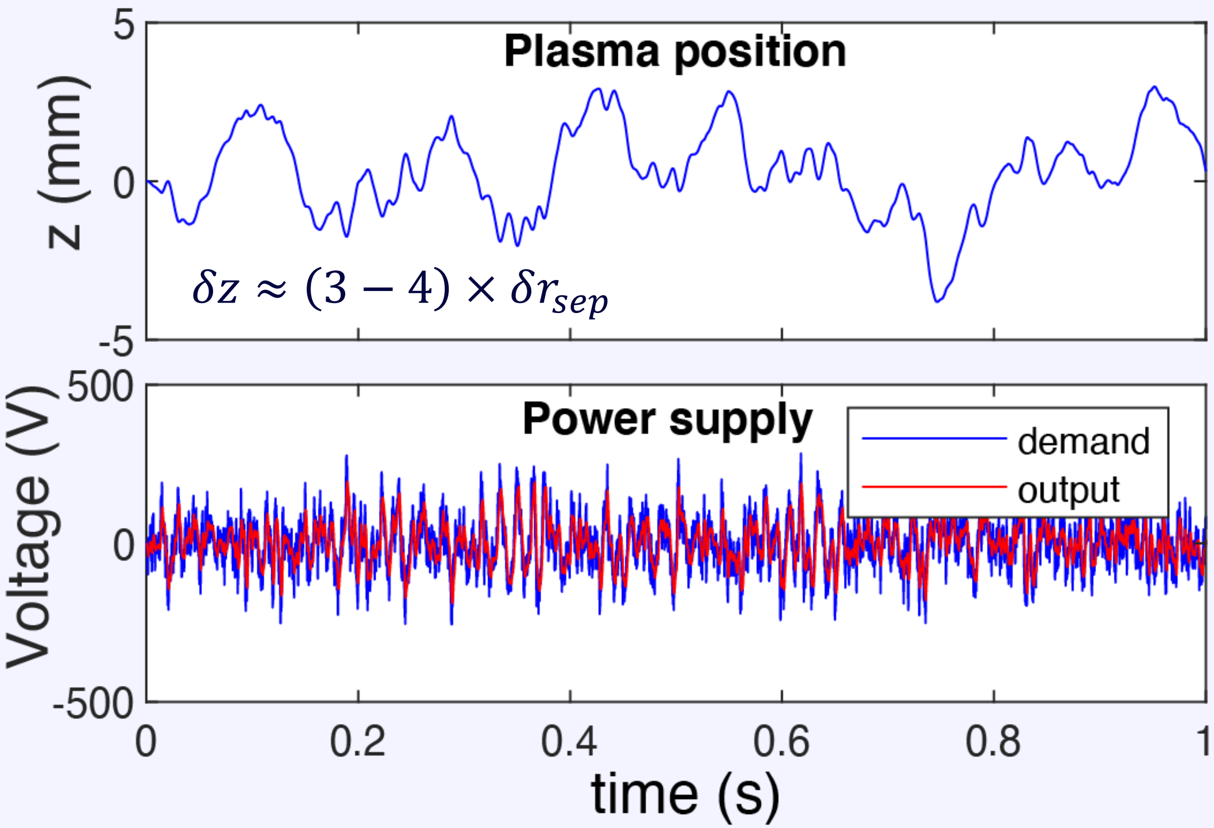
A Fil et al 2024 Nucl. Fusion 2024 **64** 106049

LOCA due to RE beam remains a very high risk ⇒ exploring RE mitigation by 3D fields

J. Morris, T. Hender, (A. Fil), (L. Henden), M. Hoppe, E. Trier, S. Newton, O. Valhagen

ACCURATE VERTICAL CONTROL NEEDED TO PROTECT INNER LEG BY KEEPING $|\delta r_{sep}| < |\lambda_{SOL}| \sim 1-2$ mm

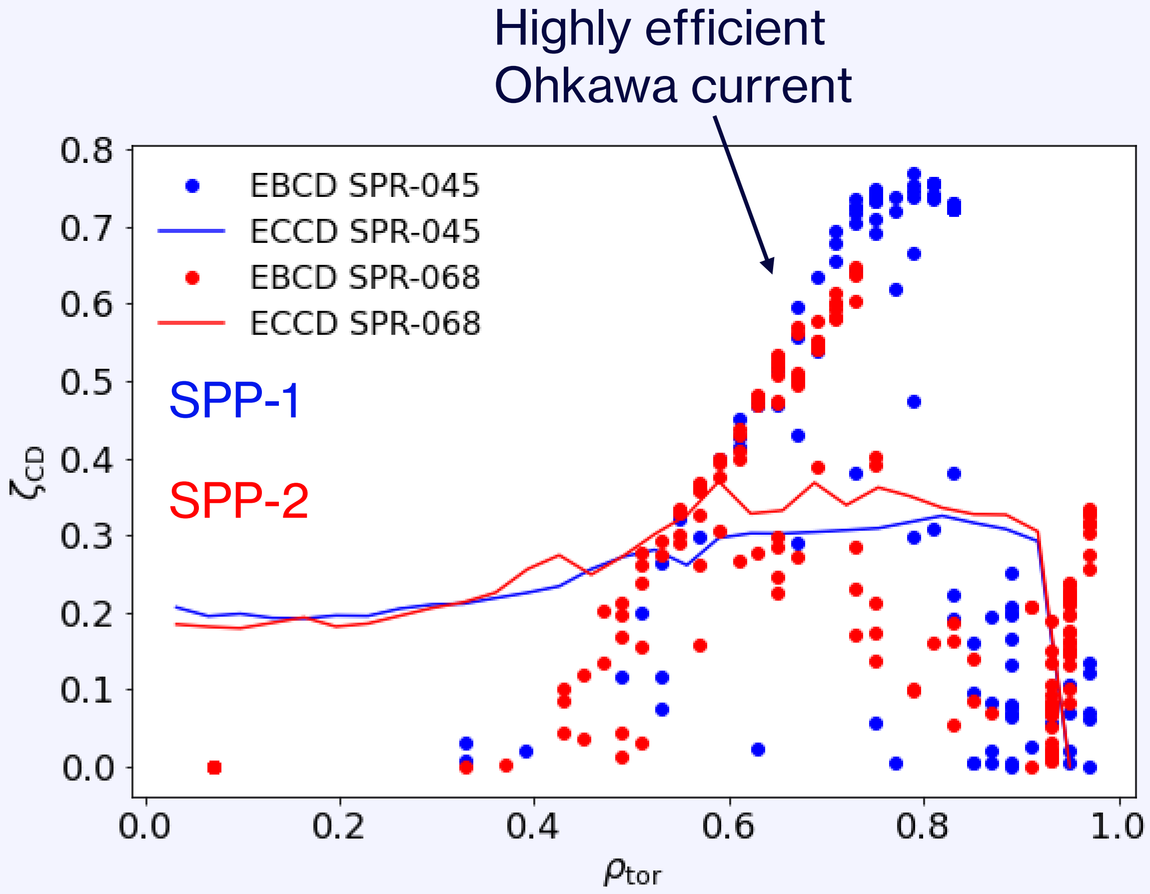
- Power distribution between four divertor legs changes dynamically as plasma fluctuates vertically due to control action
  - Dynamic double null
- Initial assessment of vertical control system with RMS noise of 1 ms^{-1} shows promising performance
  - Achievable with in-vessel coils and passive stabilising rings.
  - Assessment with "full" conducting structures in progress



M. Lafferty poster Mon 13:20-15:00

O. Bardsley, S. Bakes, M. Lennholm

PROFILE CHANGES FAVOUR ECCD CURRENT DRIVE IN THE LARGER SIZE DEVICE



ECCD using GRAY
EBCD using CQL3D/GENRAY

- **Normalised** current drive efficiency, ζ_{CD}, is not affected by the size pivot.
- New transport assumption (h-KBM), lower $n_{GW} = I_p/\pi a^2$ and lower p_{ped}. ⇒ **different profiles!**
- Change in **absolute** efficiencies:

  $\eta_{EBW} = 2\,\eta_{EC}$ ➔ $\eta_{EBW} = 0.77\,\eta_{EC}$

  SPP-1 SPP-2
- Optimisation of pedestal stability and pellet injection ⇒ some EBCD performance can be recovered.
- High-Q EBW scenario harder due to decrease in $T_{e,\mathrm{ped}}$

S. Freethy, M. Henderson, I. Konoplev, T. Wilson, R. Sharma, B. Lloyd, *R. Vann, B. Biswas, F. Maiden, L. Holland, M. Kahn, B. Eliasson, , A. Köhn, A. Cross, K. Ronald, D. Speirs, M. Higgens, L. Figini*

S Freethy et.al. Nucl. Fusion 2024 ***64*** 126035

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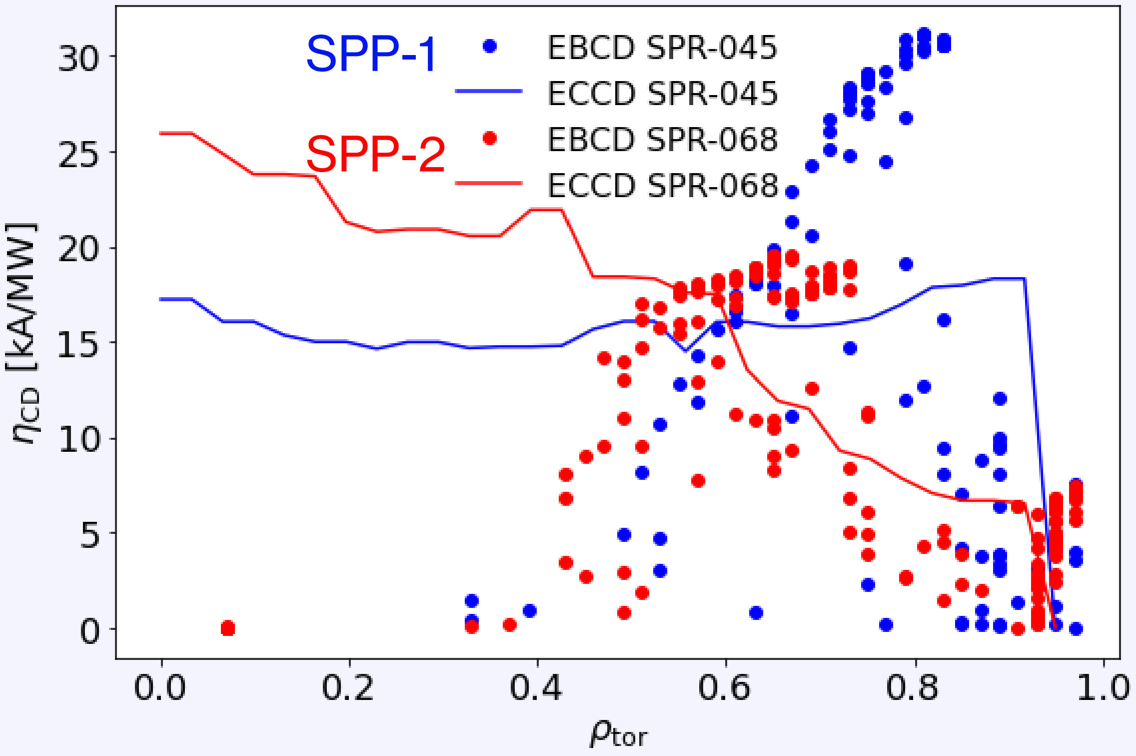

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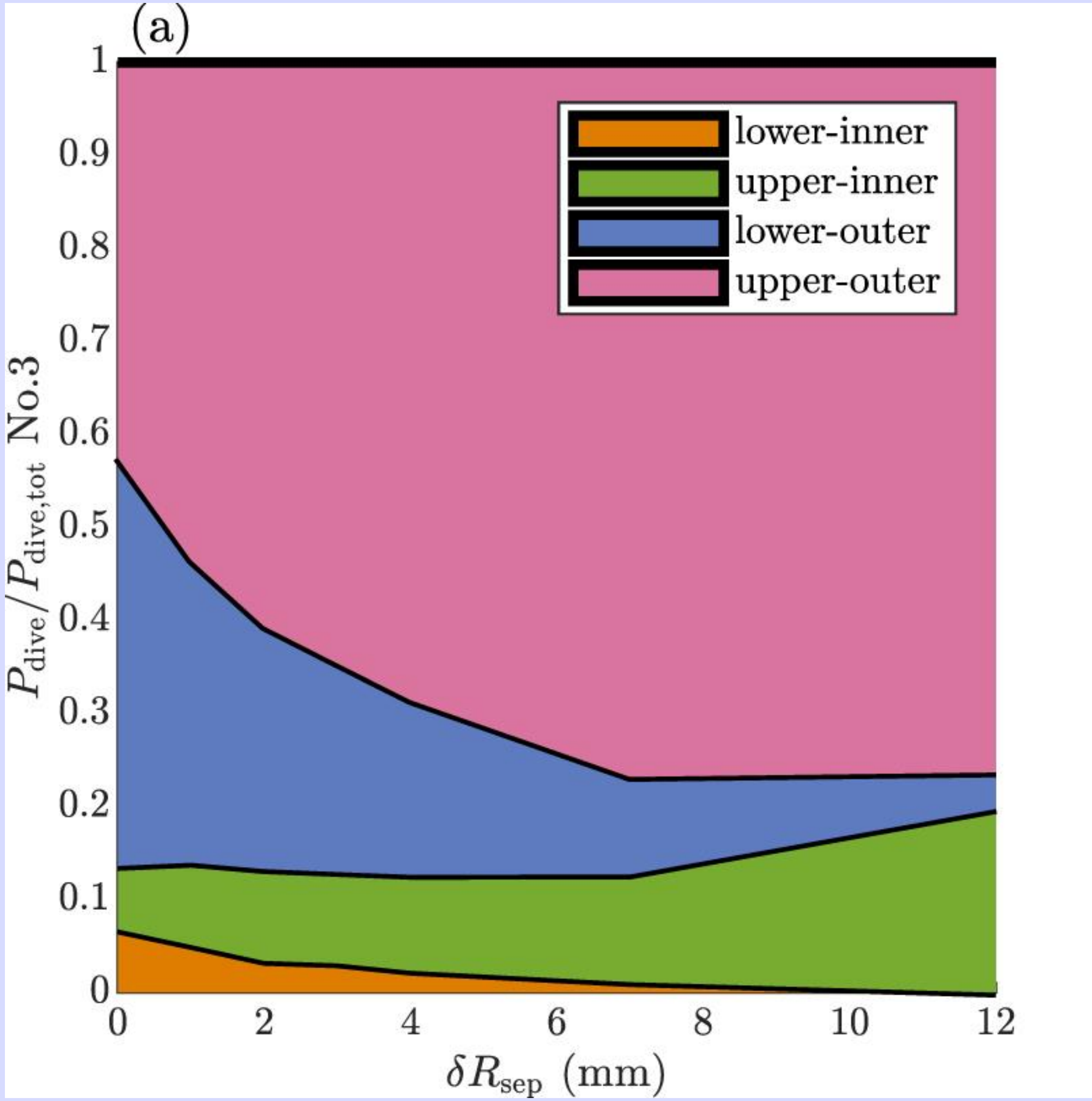
S Freethy et.al. Nucl. Fusion 2024 ***64*** 126035

DOUBLE NULL (DN) OPERATION TO SHIELD THE INNER DIVERTOR

- Alternative configurations needed to handle heat loads and erosion ($T_i < 5\ eV$).
  - Outer legs: Extended (Super-X)
  - Inner legs: Expanded flux (X-divertor)

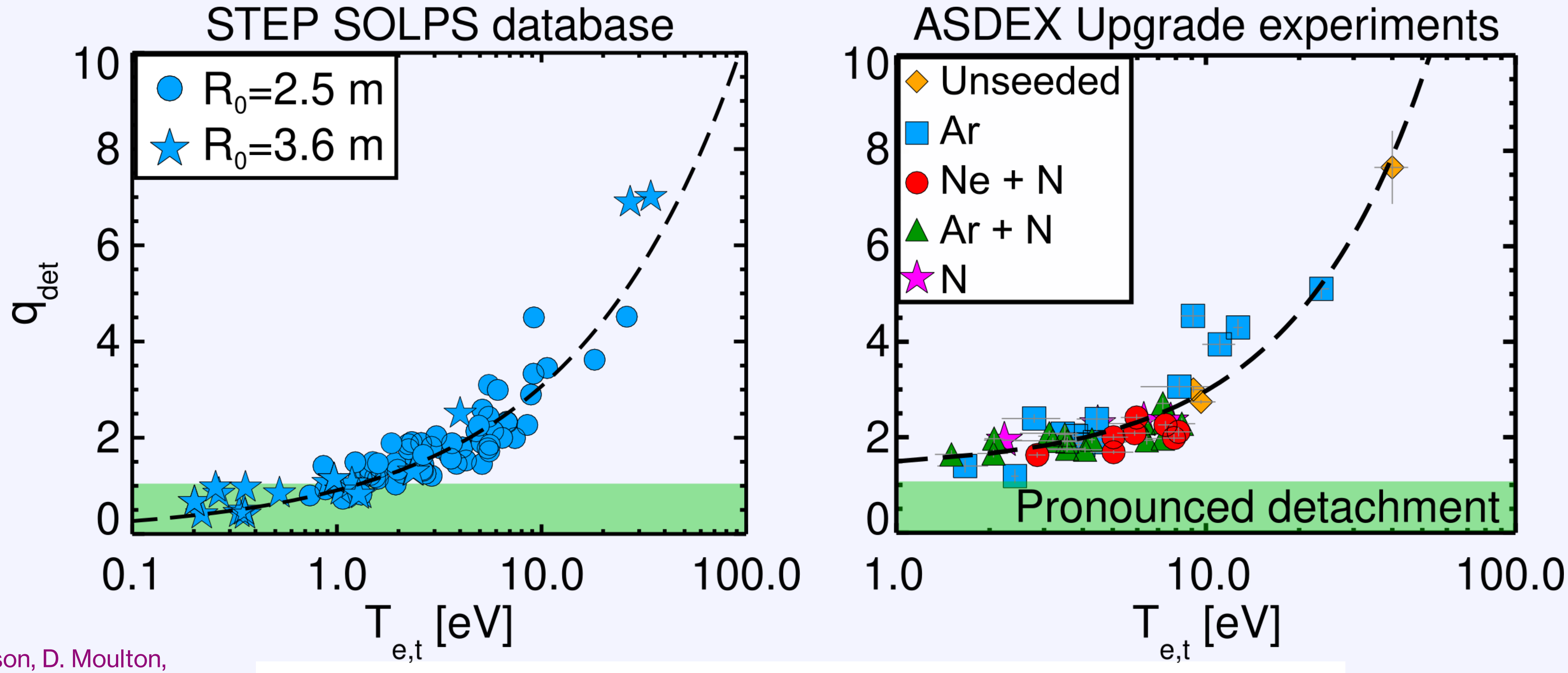
- STEP may marginally work in single null but a commercial ST power plant likely requires DN



S. Henderson, D. Moulton, R. Osawa, L. Xiang, A. Hudoba, S. Newton, *J. Karhunen, A. Järvinnen, M Kryjak, B. Lipschultz, C. Ridgers*

R.T. Osawa et al 2023 Nucl. Fusion 63 076032

SIMPLE ANALYTICAL MODEL CAN BE USED TO PREDICT DETACHMENT ONSET



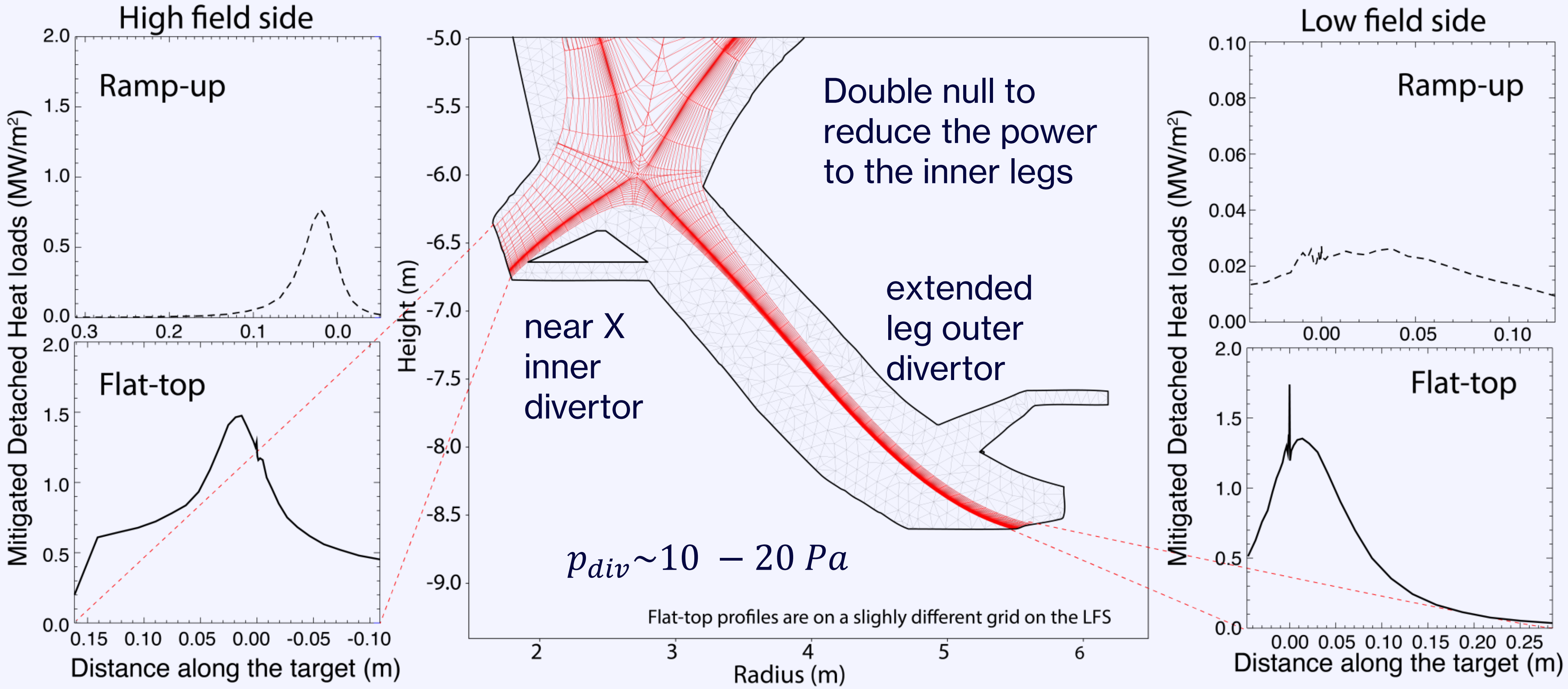
S. Henderson, D. Moulton, R. Osawa, L. Xiang, A. Hudoba, S. Newton, *J. Karhunen, A. Järvinnen, M Kryjak, B. Lipschultz, C. Ridgers*

$$q_{\mathrm{det}} = \left(\frac{P_{\mathrm{sep}} f_{\mathrm{div}}}{R_{\mathrm{t}}}\right)\left((1 + f_Z c_Z) p_0\right)^{-1}\left(\frac{2.5}{\lambda_{\mathrm{q,u}}}\mathrm{mm}\right)\left(\frac{5}{L_X}\mathrm{m}\right)^{0.04} \times 2.54\ [\mathrm{Pa\ MW\ m^{-1}}]$$

UNIVERSITY of York

Simple model can be used to predict detachment based on known engineering parameter

FULLY DETACHED OPERATION IS FEASIBLE WITH $c_{Ar} \sim 3\%$ DURING RAMP–UP AND FLAT–TOP



Here SPP-1 but similar for SPP-2

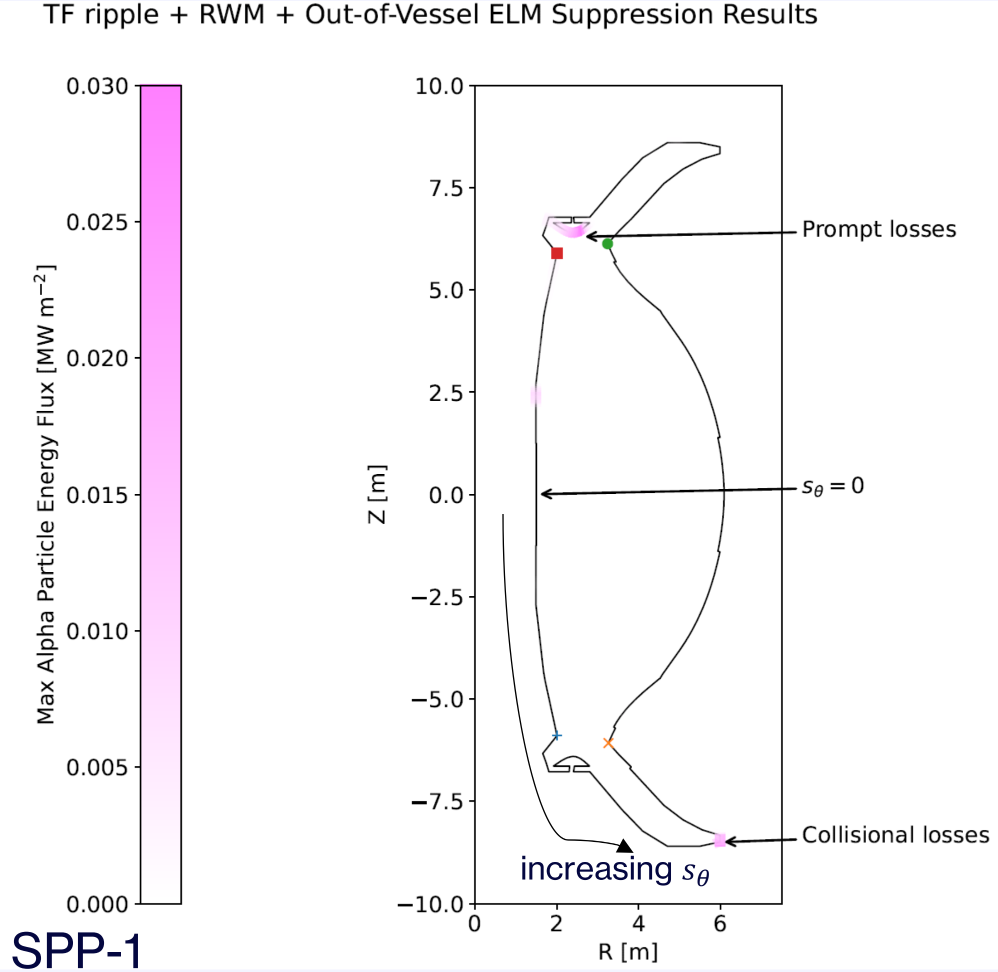
- Worst case point during ramp-up – High current $I_p \sim 10\ MA$, “low” density.
- Realistic wall structure may increase heat loads by a factor 2-3.

S Henderson et.al. Nucl. Fusion accepted

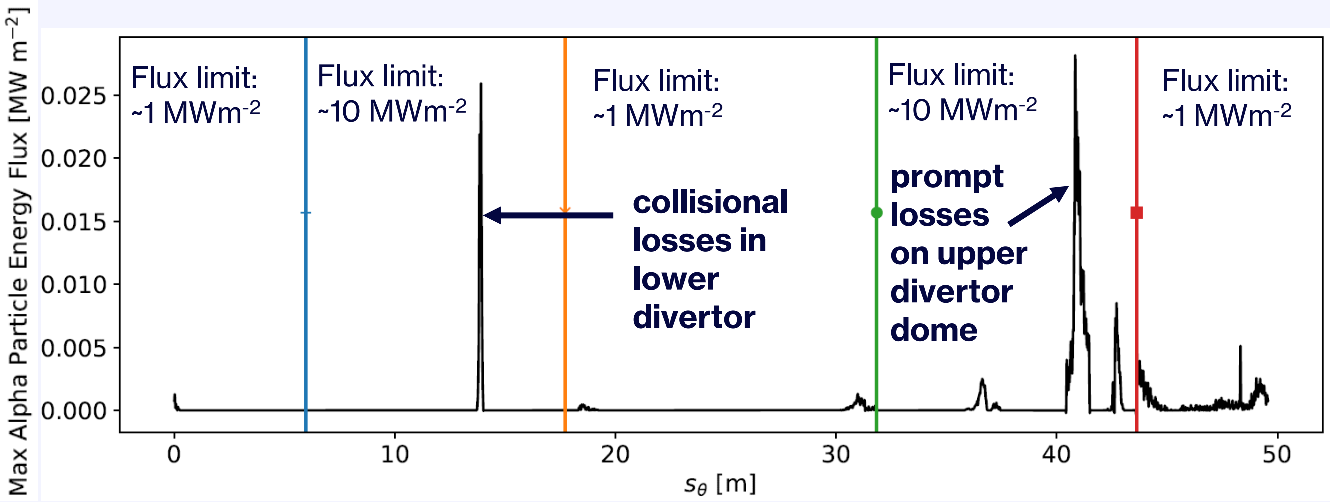
S. Henderson, D. Moulton, R. Osawa, L. Xiang, A. Hudoba, S. Newton, *J. Karhunen, A. Järvinnen, M Kryjak, B. Lipschultz, C. Ridgers*

Developed coil-set allows good optimisation of the inner and outer divertor geometry

WALL LOADING DUE TO EXTERNAL FIELD–INDUCED ALPHA–PARTICLE LOSSES ARE WELL WITHIN MATERIAL LIMITS



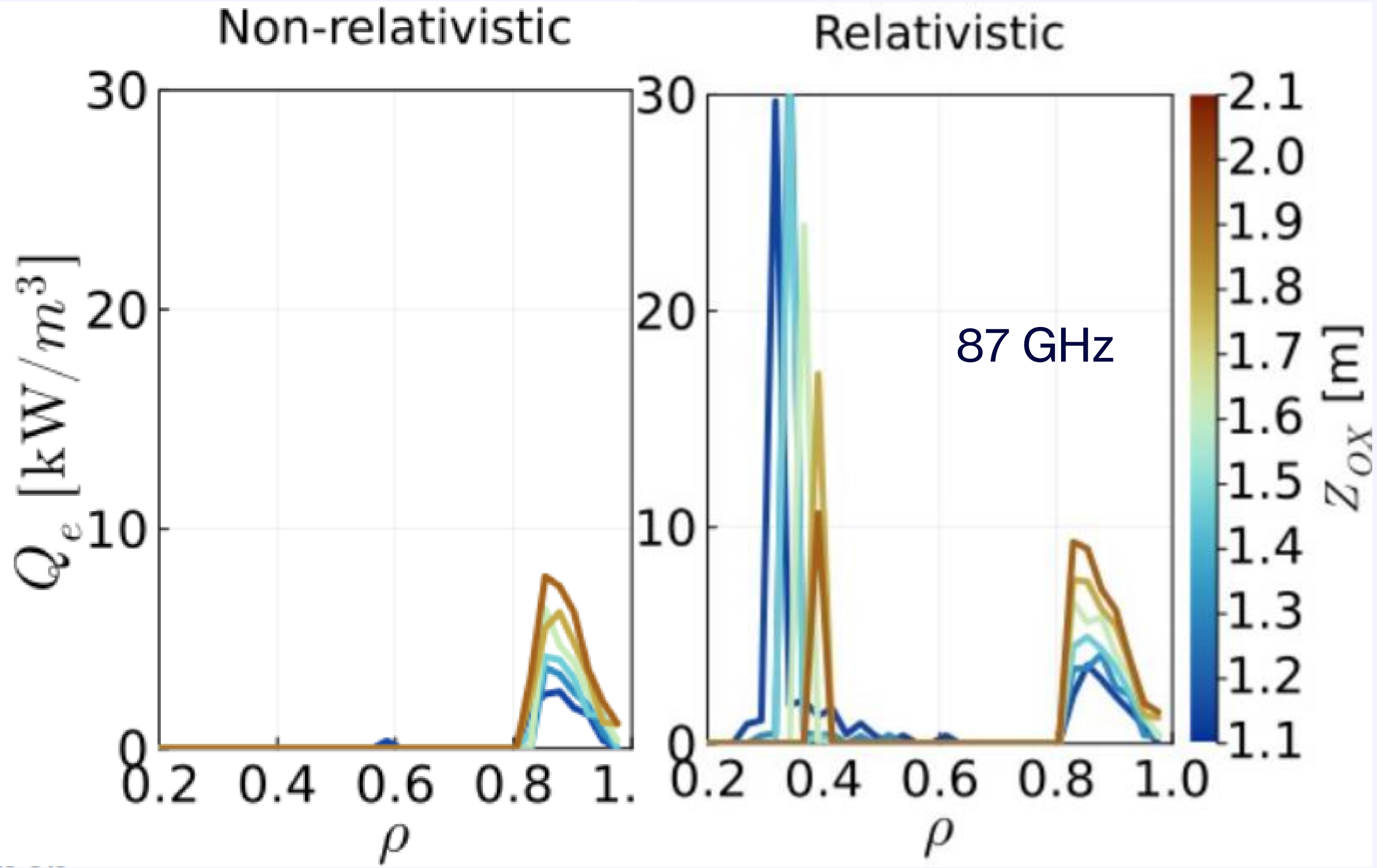
- Losses & wall loads calculated for $R_{geo} = 3.6\text{m}$ device due to TF ripple, resonant magnetic perturbations & controlled resistive wall modes
- Loads highly localised, with strongest peaks in outer leg of lower divertor (collisionally-delayed losses) & upper divertor dome (prompt losses)
- Divertor loads well within 10 MWm^{-2} limit



A. Prokopyszyn, J. Oliver, K. McClements, M. Fitzgerald

K. McClements (oral) Tue 15:00

RELATIVISTIC EFFECTS MAY GIVE ACCESS TO EBW ONLY SCENARIO



B. Biswas subm. to NF

- Non-inductive flat-top operating points need core ECCD ⇒ restricted range in $(\boldsymbol{B_t}, \boldsymbol{n_e})$ for access.
- A novel fast relativistic ray-tracing tool (CRAYON) has unlocked a class of EBW rays that can propagate to near the core

CRAYON is planned to be used in integrated modelling of EBW in JINTRAC

S. Freethy, M. Henderson, I. Konoplev, T. Wilson, R. Sharma, B. Lloyd, *R. Vann, B. Biswas, F. Maiden, L. Holland, M. Kahn, B. Eliasson, , A. Köhn, A. Cross, K. Ronald, D. Speirs, M. Higgins, L. Figini*

Consiglio Nazionale Ricerche

University of York

Universität Stuttgart

University of Strathclyde Glasgow

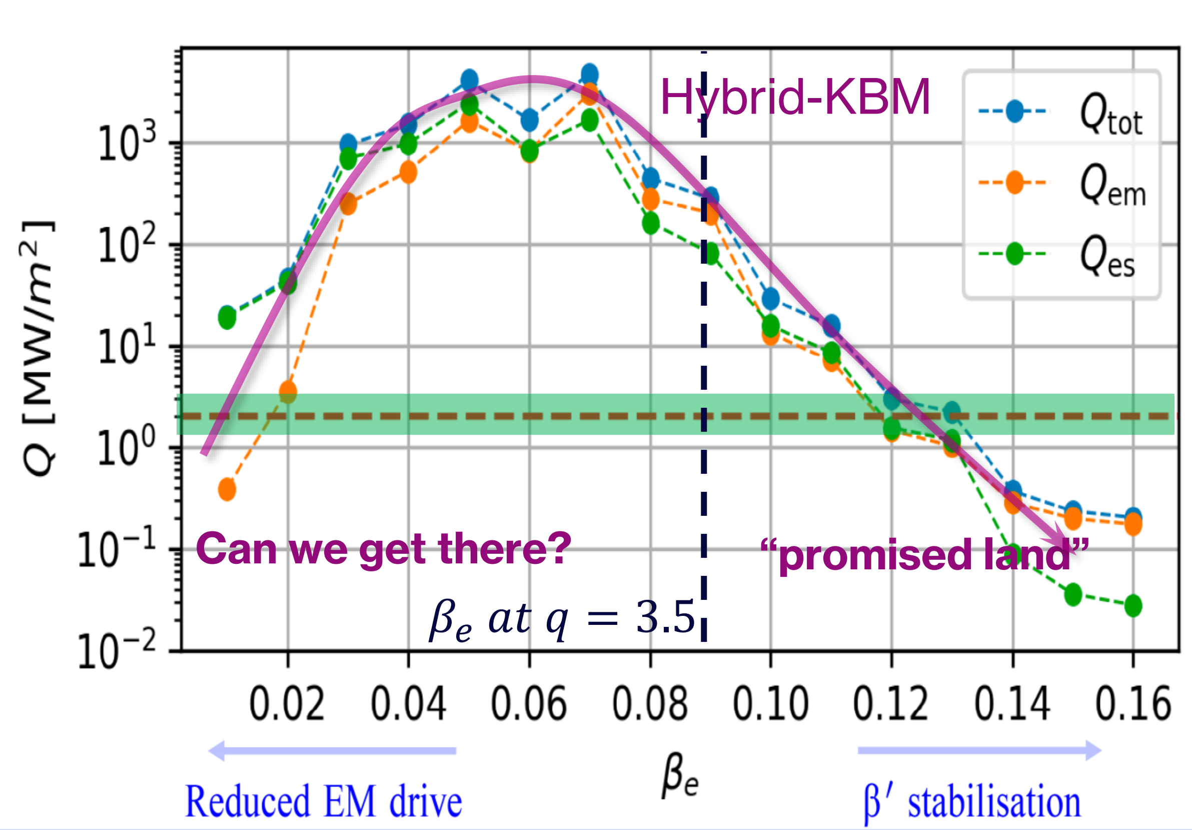
C. Roach oral Mon 15:40

MAY NEED TO OVERCOME HIGH HYBRID–KBM TRANSPORT REGION AS β_e EM DRIVE COMPETES WITH β'_e STABILISATION

- Transport dominated by hybrid kinetic ballooning mode (h-KBM)
- β scan on reference surface ($\gamma_E = 0$)
  - β′ set consistently ∝ β
- Flow shear becomes essential as this reduces the h-KBM transport strongly.

$$\gamma_E^{dia} = \frac{1}{B}\left(\frac{\partial\psi}{\partial\rho}\right)^2 \left[\frac{1}{p_i n_i e\left(1+\frac{L_n}{L_{T_i}}\right)}\left(\frac{\partial p_i}{\partial\psi}\right)^2 - \frac{1}{n_i e}\frac{\partial^2 p_i}{\partial\psi^2}\right]$$

α-particle losses provide a small torque input (TF ripple, 3D fields)



M Giacomin et al 2024 PPCF **66** 055010
D. Kennedy et al 2023 Nucl. Fusion 63 126061
D. Kennedy et al 2024 Nucl. Fusion 64 086049

UNIVERSITY of York

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

C. Roach oral Mon 15:40

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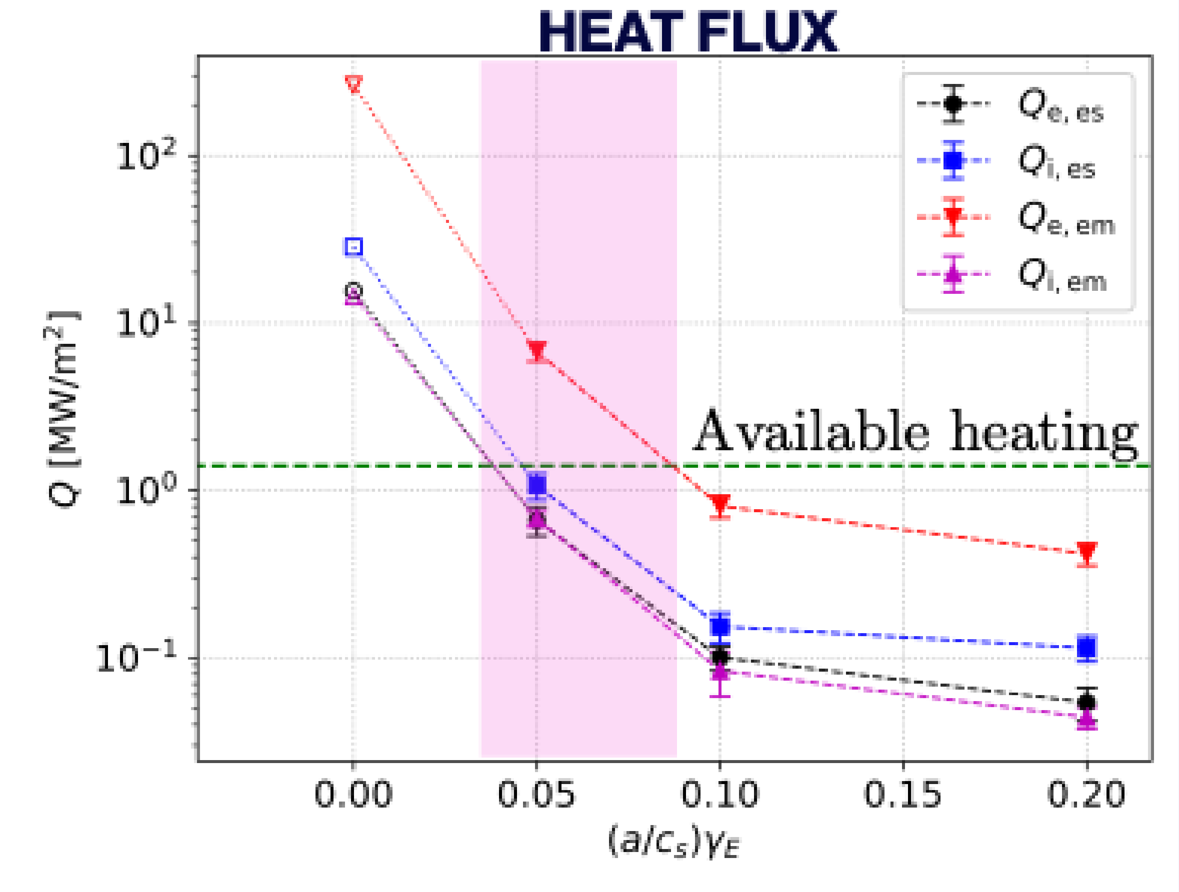


M Giacomin et al 2024 PPCF **66** 055010
D. Kennedy et al 2023 Nucl. Fusion 63 126061
D. Kennedy et al 2024 Nucl. Fusion 64 086049

UNIVERSITY of York

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

MHD RESISTIVE WALL MODE CONTROL

EASIER IN SPP–2

- RWM analysis with MARS-F indicates RWM control should be easier than in SPR-045
  - n = 1 almost passively stable
  - n = 2,3 stable

Ideal ballooning MHD
- n = infinity stable after q optimisation

TD-0020612

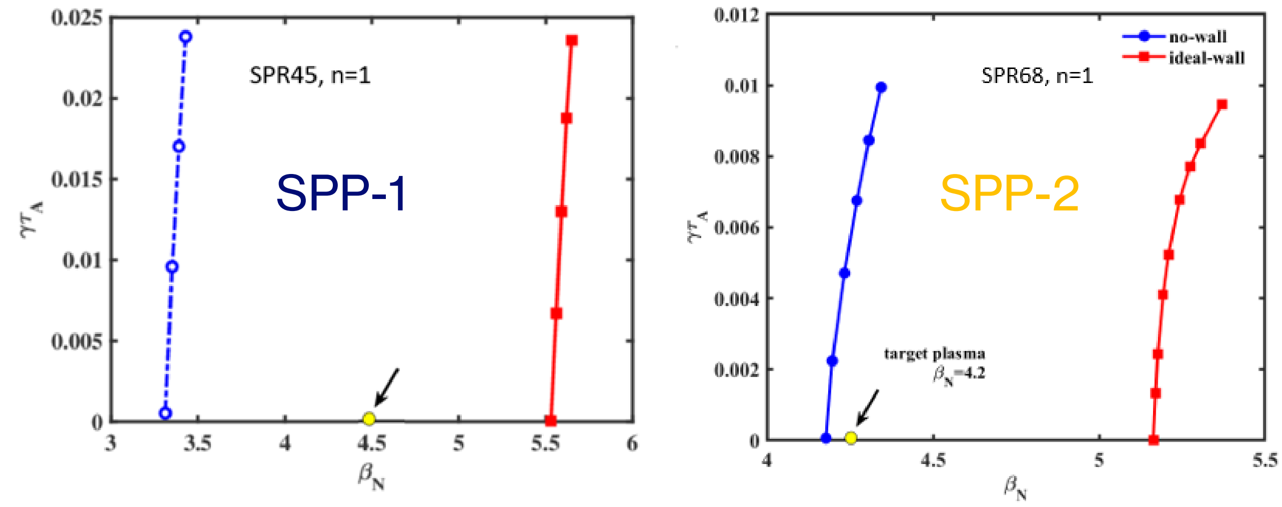


Figure 7 - RWM analysis with MARS-F for SPR-45 (left $C_\beta = 0.54$) compared to SPR-68 v4 (right $C_\beta = 0.02$) candidate operating point indicating RWM control may be easier than SPR-45.

Table 1: n=1 RWM n=1 betaN limits evaluated with MARS-F. The no-wall limit is increased relative to the smaller device, but the with-wall limit is decreased relative to the smaller device due to increased pressure peaking. The required βN for the desired fusion power is lower, the overall stability is improved in the larger device.

	FTOP	β_N	R_0	β_N(no-wall)	β_N(ideal-wall)	$C_\beta = \frac{\beta_N - \beta_{N,IW}}{\{\beta_{N,NW} - \beta_{N,IW}\}}$ (<0 stable, >1 uncontrollable)
SPP-1	SPR-45 v20-2-55	4.5	3.6	3.31	5.52	0.54
SPP-2	SPR-68 v4	**4.2**	**4.3**	**4.18**	**5.16**	**0.02**

FTOP PERPENDICULAR ELM ENERGY FLUENCE ESTIMATES $0.2\,\frac{MJ}{m^2} \lesssim \varepsilon_\perp \lesssim 0.3\,\frac{MJ}{m^2} \Rightarrow$ COULD BE MARGINALLY ACCEPTABLE

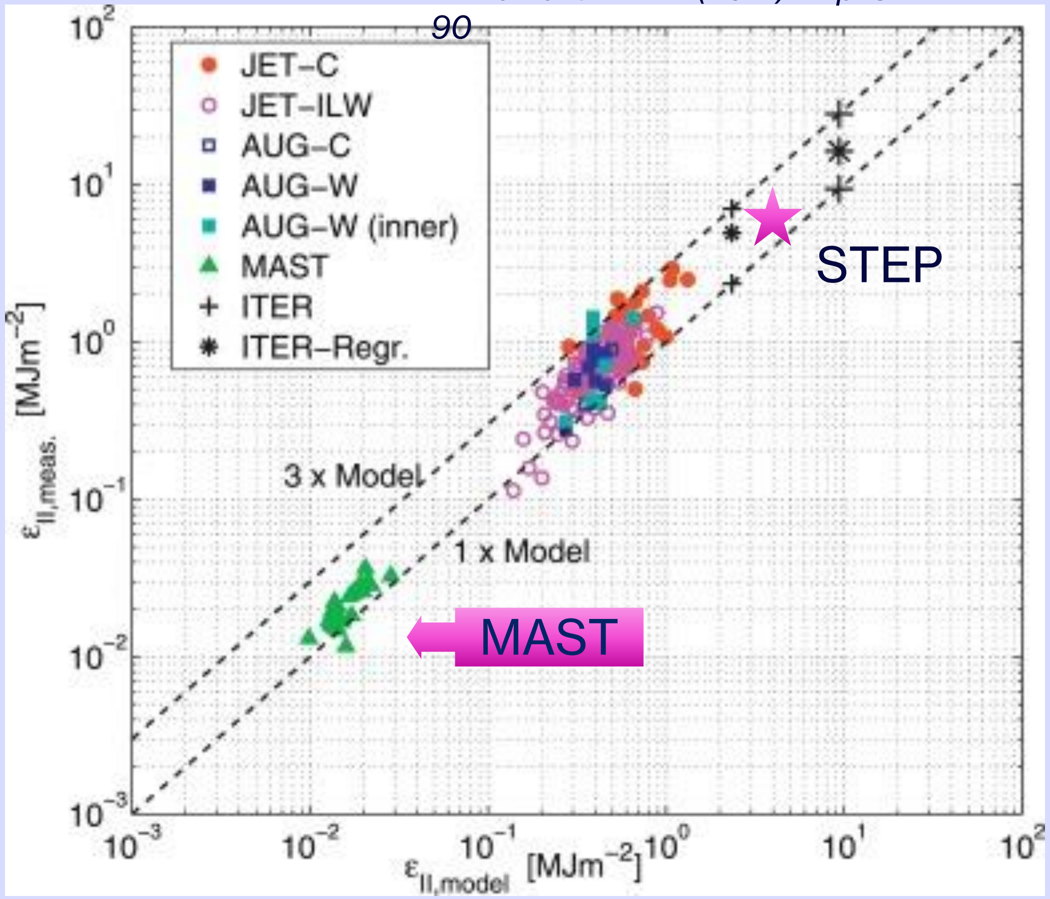
T. Eich: $\varepsilon_\parallel = \Delta_{equi} \cdot 2\pi a_{geo}\sqrt{\frac{1+\kappa^2}{2}} \cdot \frac{3}{2} \cdot n_e^{ped} \cdot k_B \cdot T_e^{ped} \cdot \frac{B_t}{B_p}$

The parameters that need to be predicted:

- n_e^{ped}, T_e^{ped} from Europed at pedestal top
- Equilibrium quantities (B_t, B_p) from self-consistent equilibrium of the Europed profiles
  - Δ_{equi} calculated
  - $\alpha = 4°$ ($\varepsilon_\perp = \varepsilon_\parallel \cdot \sin\alpha$)
- ELM buffering expected with Ar seeding (observed on JET and AUG)

JOREK ELM modelling needed to confirm estimates

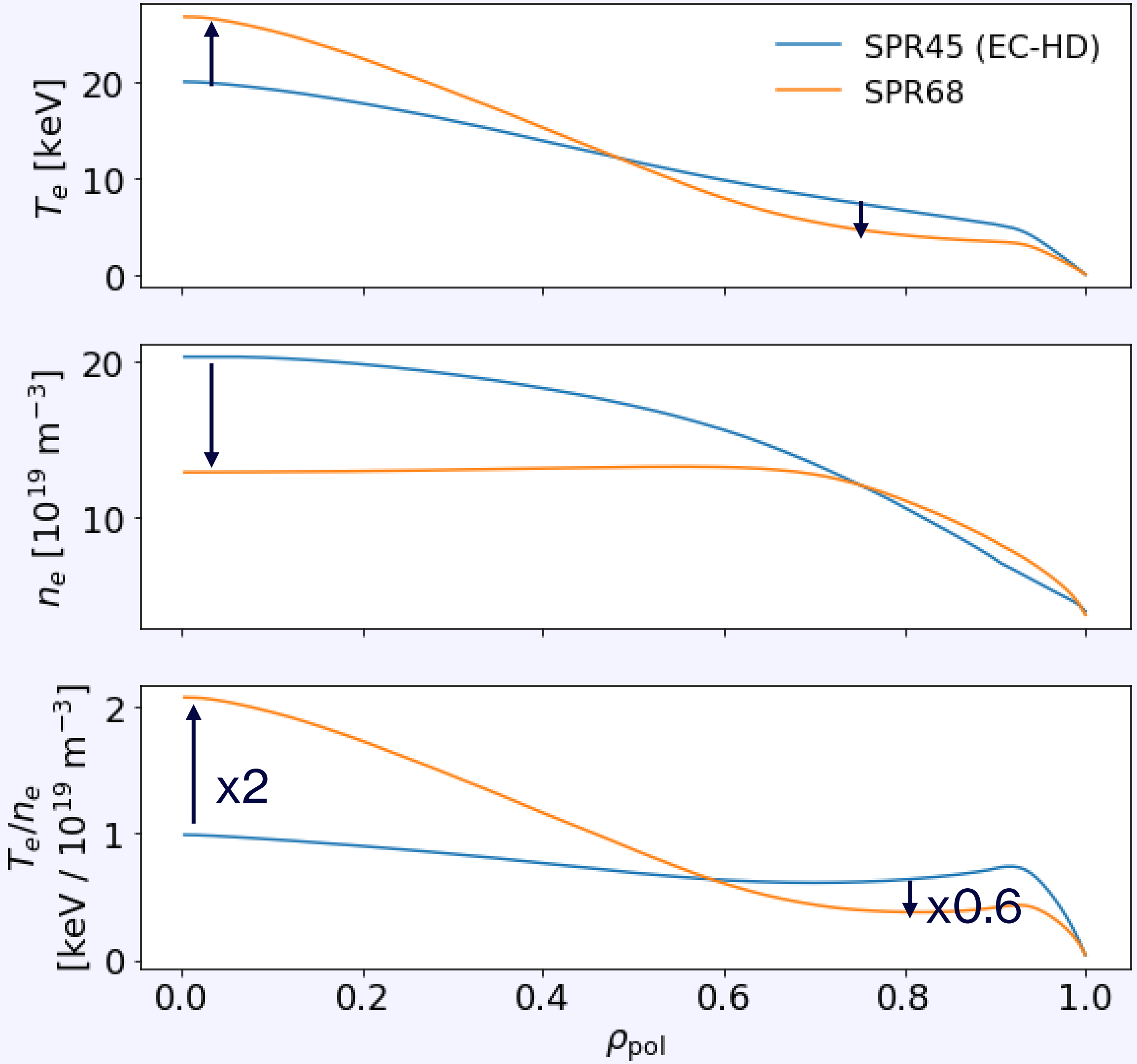
T. Eich et.al. NME (2017) **12** p. 84-90



Eich projection for ITER:	**0.7 MJ/m²**
Material limit (Eich):	**0.5 MJ/m²**
Cracking limit :	**0.1 MJ/m²**

SPP-1

RADIUS CHANGE HAS DIFFERENT IMPACTS ON ON-AXIS & OFF-AXIS CURRENT DRIVE



Approx. constant
(much higher for EBW off-axis)

Increases efficiency

$$\frac{I}{P} = \frac{\zeta_{\mathrm{CD}}\, T_{\mathrm{keV}}}{n_{20}\, R_{\mathrm{m}}}$$

efficiency

Decreases efficiency

Key changes:

1. Major radius has increased
2. Core density decreased
3. Core temperature has increased
4. Temperature pedestal height decreased

Consequences:

1. Net increase in ECCD efficiency inside mid-radius
2. Net decrease in EBCD efficiency (off-axis)

50% REDUCTION OF P_{fus} WITH GOOD PROFILE CONTROL SEEMS FEASIBLE

RAPTOR simulation of controlled step down in alpha power:

Optimised control to try to maintain:

- q-profile,

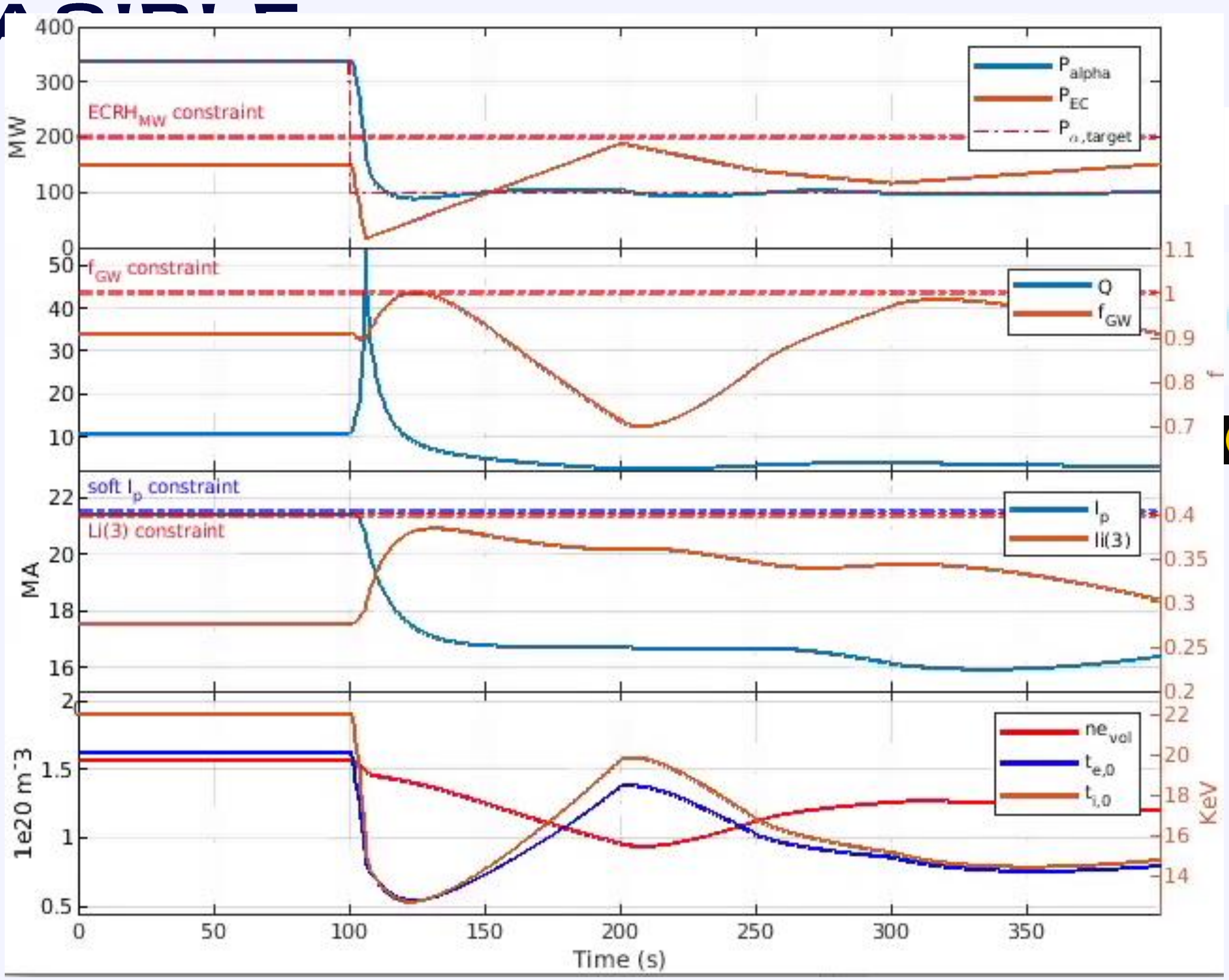
While assuring:

- Greenwald Fraction <1

Main actuators:

- Plasma current (ECCD power)
- Density (Pellet fuelling)

Good burn-control seems feasible with time constant ~50s



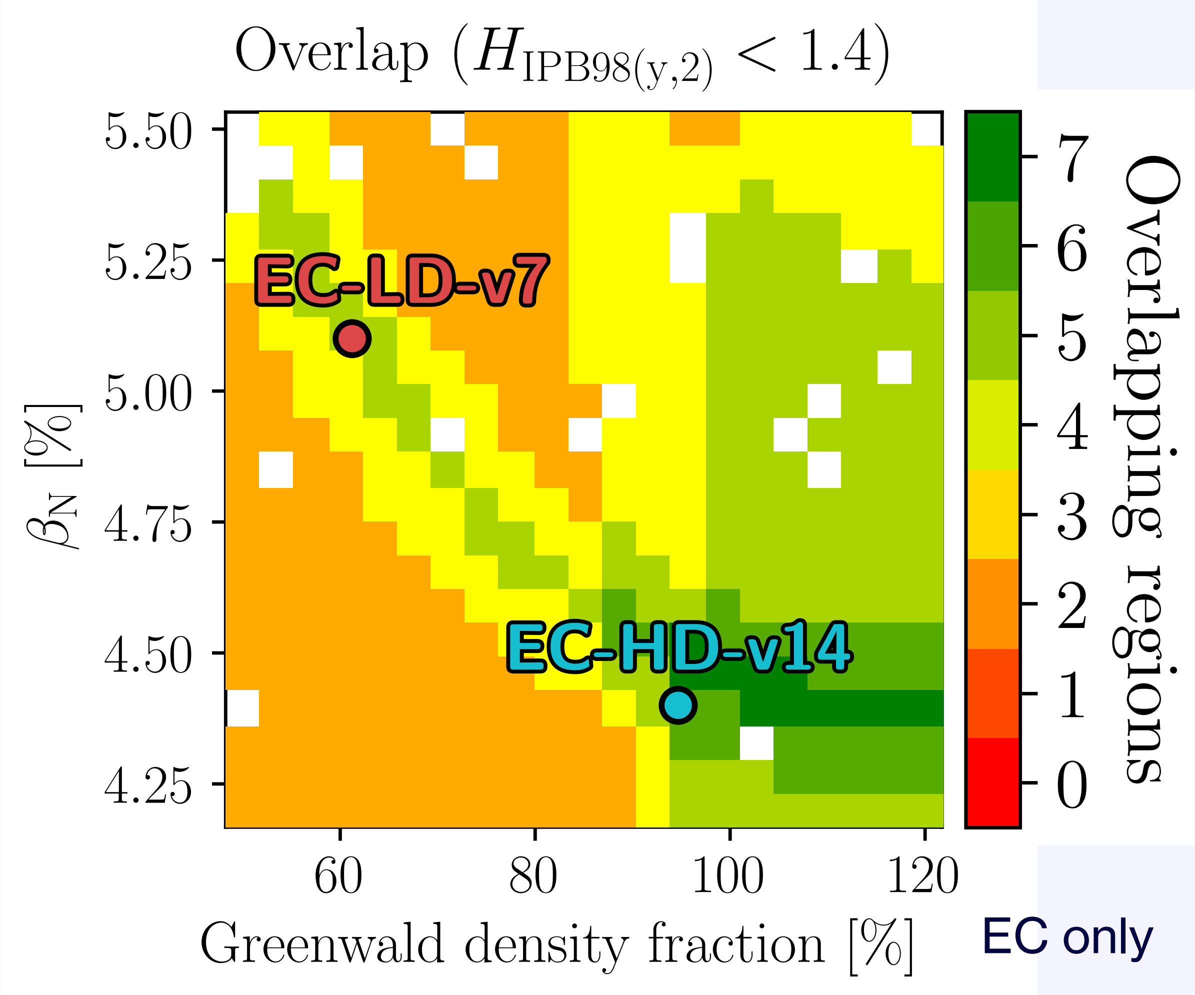
M. Lennholm, D. Valcarcel, J. Mitchell, O. Bardsley, M. Lafferty, *B. Kool, M. van Berkel, M. de Baar, A. Ho, E. Westerhof, R. Albanese, R. Ambrosino, A. Castaldo, M. Matta, D. Humphreys, A. Himak, J. Barr, A. Pajares, M. Walker, A. Welander, X. Zichuan*

ADDING EBCD AND REDUCING THE REQUIREMENT FOR f_{rad}^{core} OPENS THE POSSIBLE OPERATIONAL SPACE

- Operating space explored to match set of constraints using JETTO with simplified models.
- EC only FTOP requires $1.2 < H_{98} < 1.4$
- EC+EBW scenarios viable with "conservative" confinement assumption

7 Constraints:

1. $1.5\ GW < P_{fus} < 1.8\ GW$
2. $I_p \leq 25\ MA$
3. $Q_{fus} \geq 11$
4. $\frac{\beta_N - \beta_N^{NW}}{\beta_N^{IW} - \beta_N^{NW}} \leq 0.5$
5. $P_{sep}/R_{geo} \leq 45\ MW/m$
6. EC access (yes/no)
7. $H_{98}^{\star} < 1.2$ or $H_{98}^{\star} < 1.4$

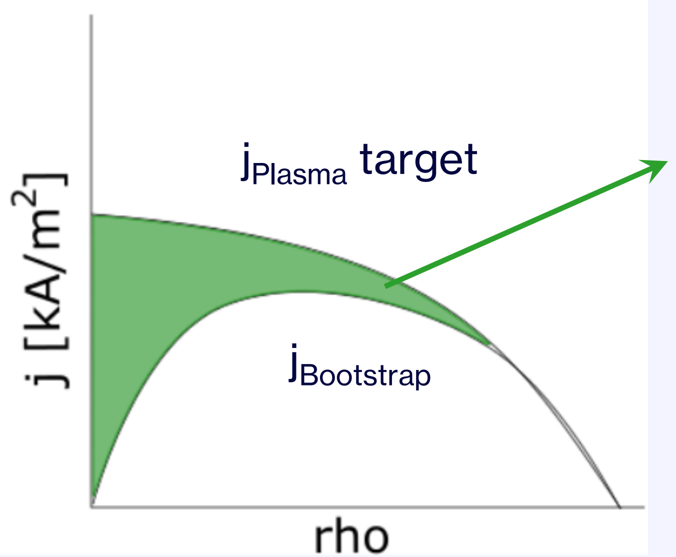


EC only

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

E. Tholerus et.al. Nucl. Fusion ***64*** *106030*

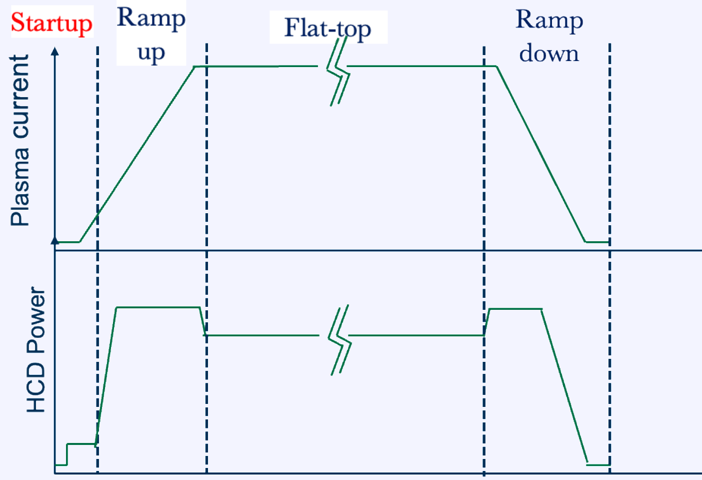
HCD SYSTEM DESIGN: MODULAR & ADAPTABLE



HCD shall provide

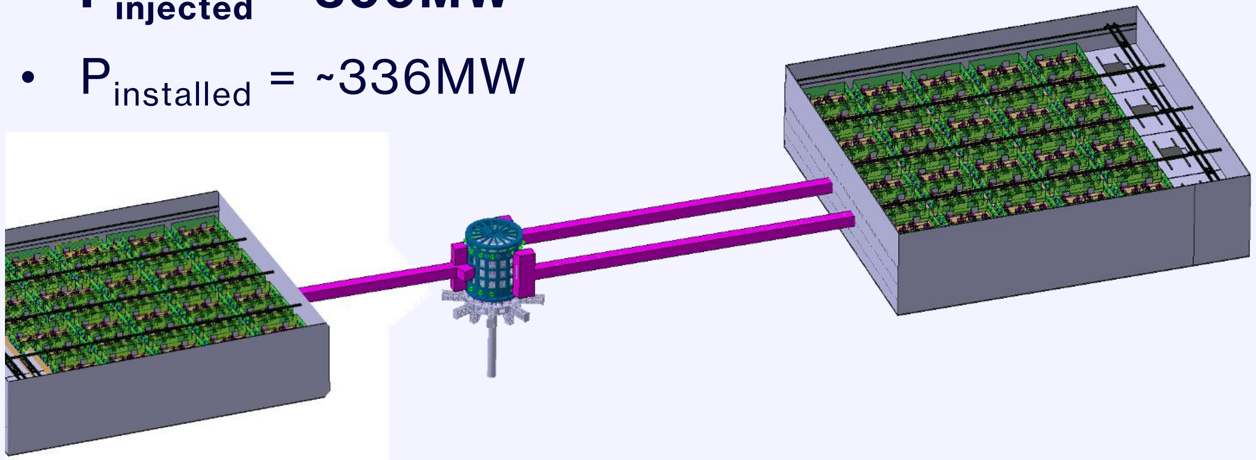
$$j_{HCD}(r,t) = j_{Plasma}(r,t) - j_{bootstrap}(r,t)$$

- Cover all 5 phases of the pulse
- Support EC and EC+EBW operating scenarios
- Adapt to variations in n_e and T_e (cloud of operating points)



SPP-1 Design Proposal:

- **$P_{injected}$ = 300MW**
- $P_{installed}$ = ~336MW



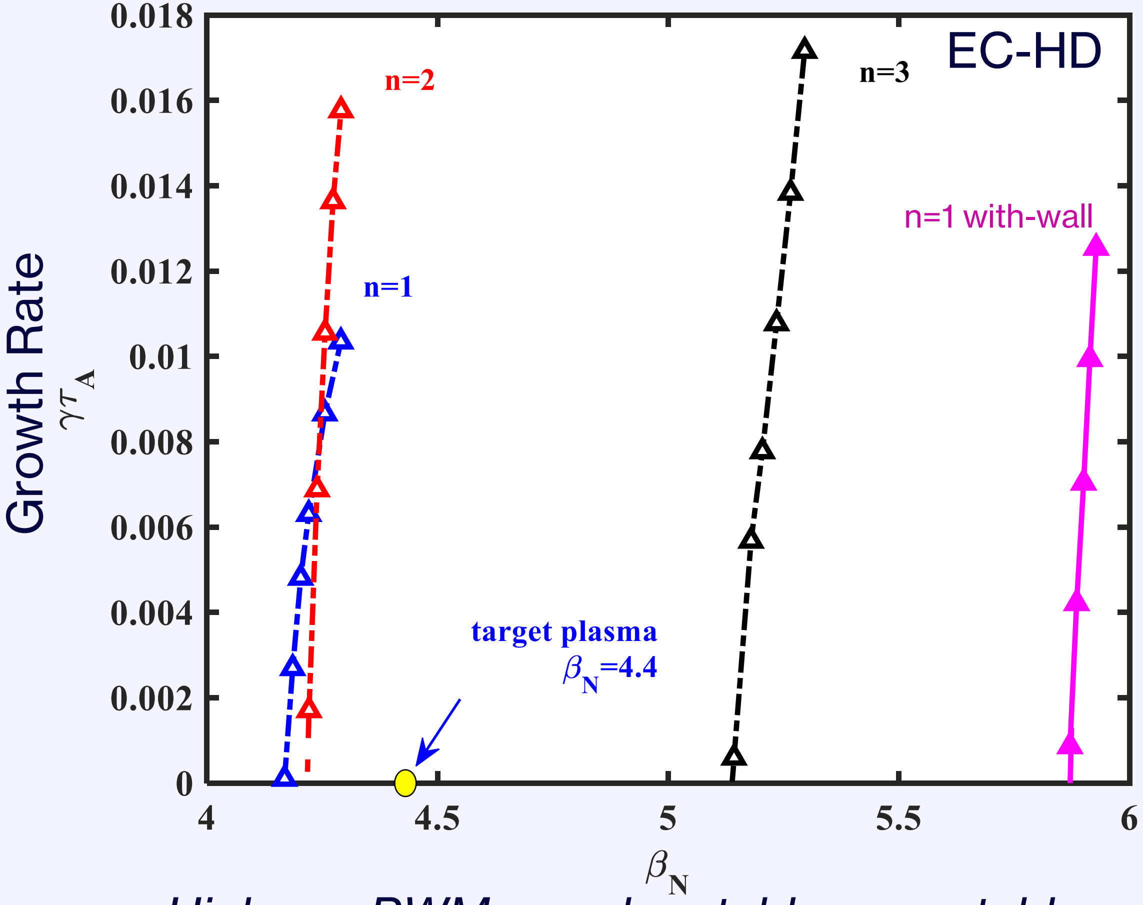
Design Achieves:

- **P_{EC} = ~170MW** with 30% reserve
- **P_{EC+EBW} = ~150MW** with 30% reserve
- **$P_{heating}$ = 50MW**
- 10% redundancy for component failure (not active)

The HCD system design is well-advanced and achieves all currently-set requirements

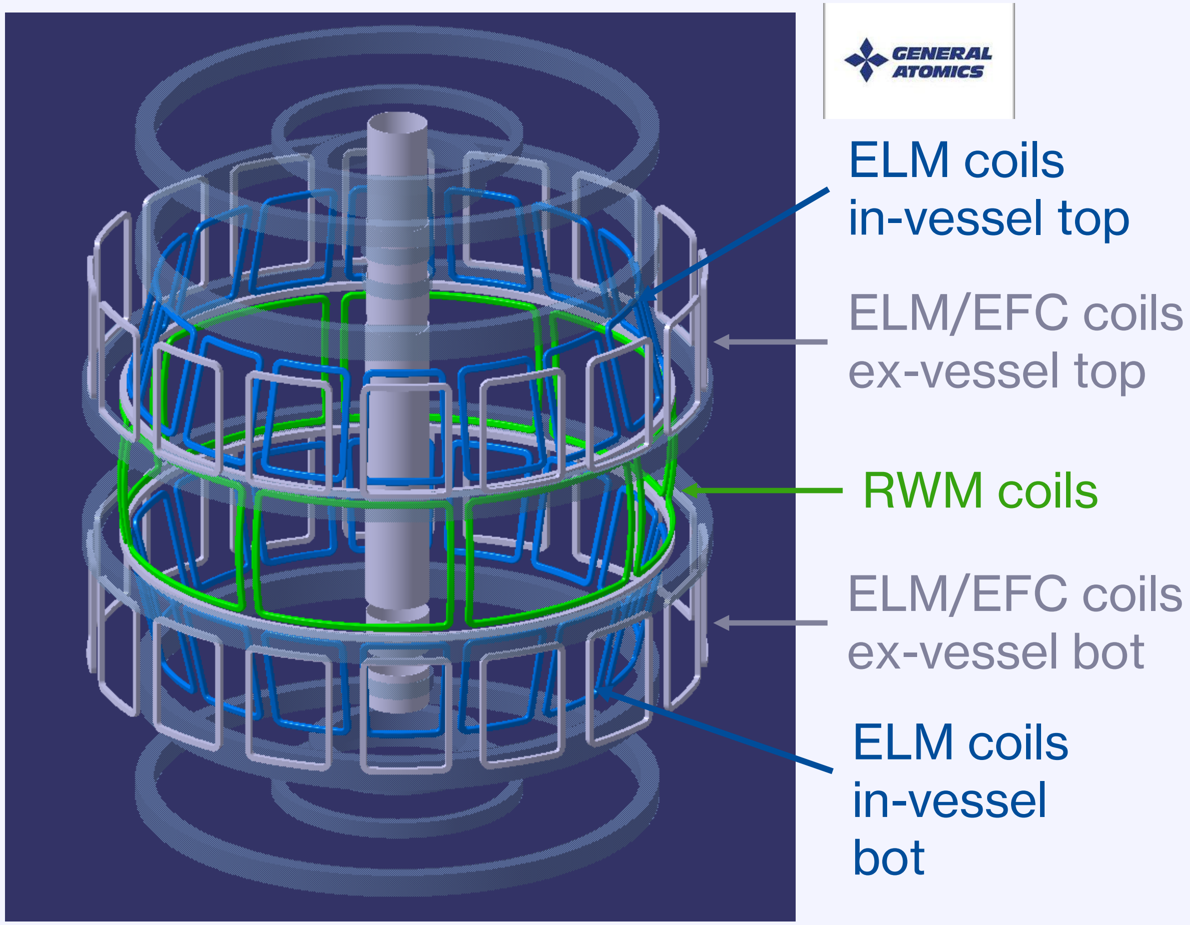
S. Freethy, M. Henderson, B. Lloyd, M. Nightingale, S. Craig ...

$n = 1, 2$ RWMS CAN BE UNSTABLE ⇒ NEED 8 COILS



Higher-n RWMs can be stable or unstable

Guoliang Xia et al 2023 Nucl. Fusion 63 026021



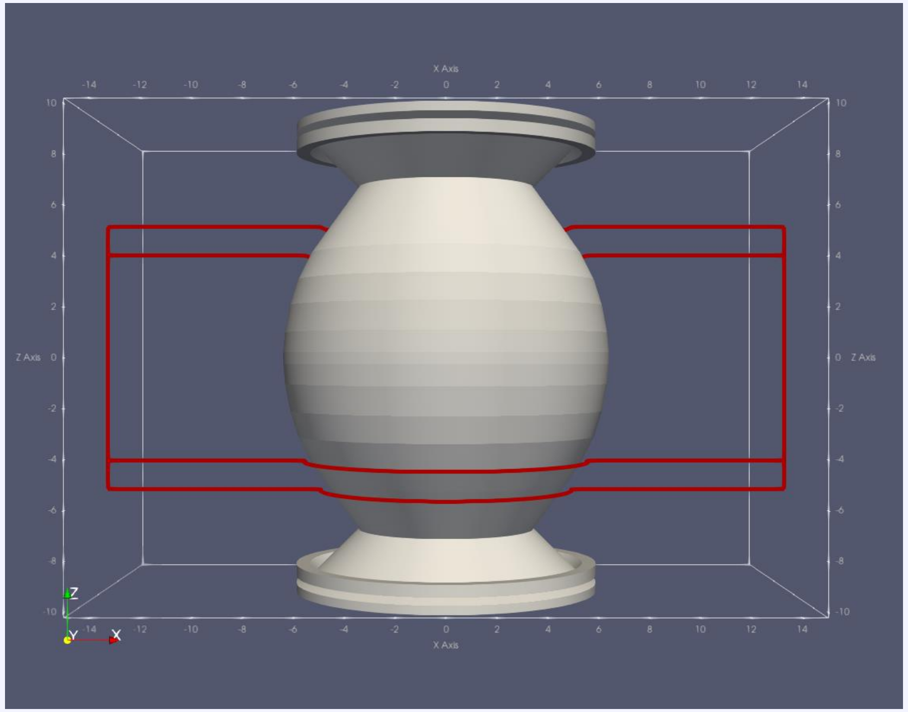
8 RWM control coils to allow n=1 and 2 feedback

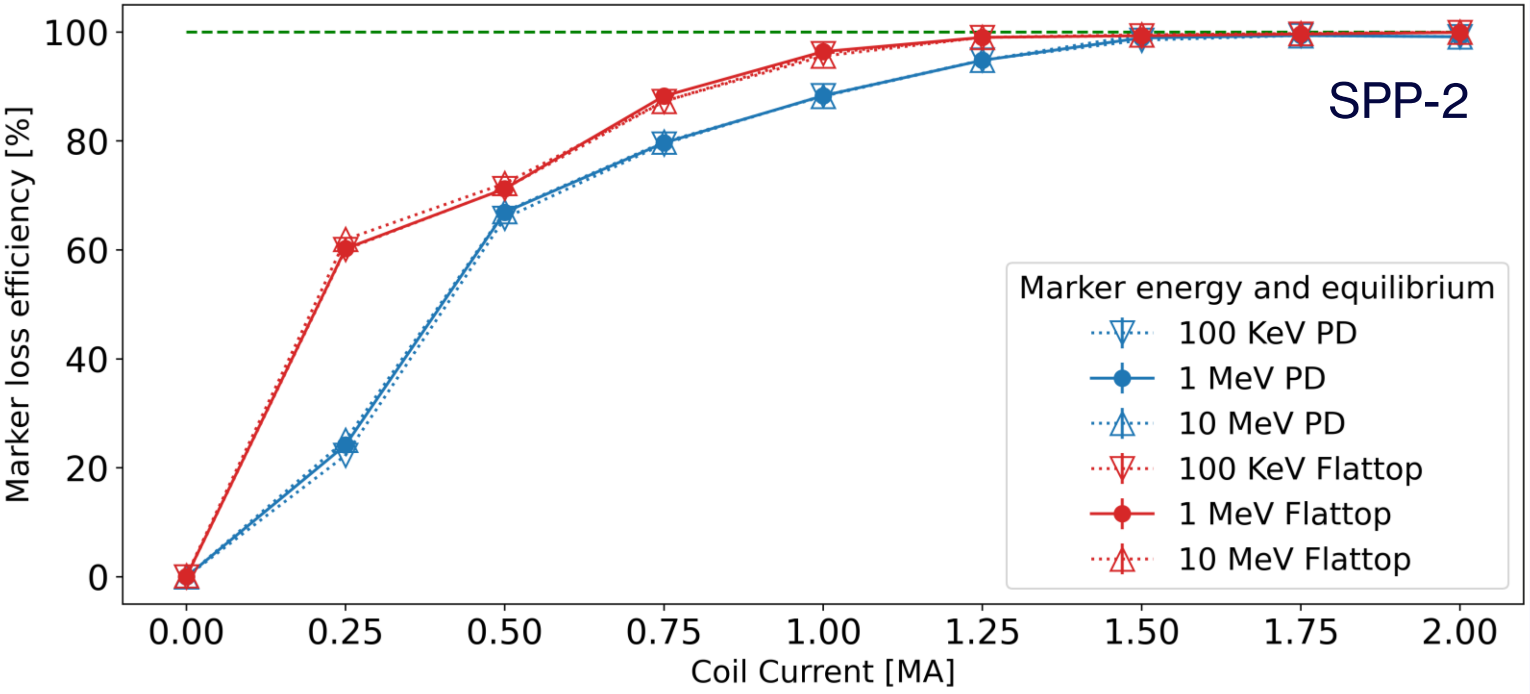
Feedback modelling with noise ⇒ Control of $n = 1$ and $n = 2$ RWMs seems feasible

Effect of conducting structures on $n = 1, 2$ control not yet fully assessed

J. Morris, T. Hender, G. Xia, E. Trier, A. Hudoba, S. Bakes, D. Ryan, (A. Fil, L. Henden), *Y. Liu*

MITIGATING RUNAWAY ELECTRONS USING AN $n = 1$ PERTURBATION SEEMS FEASIBLE



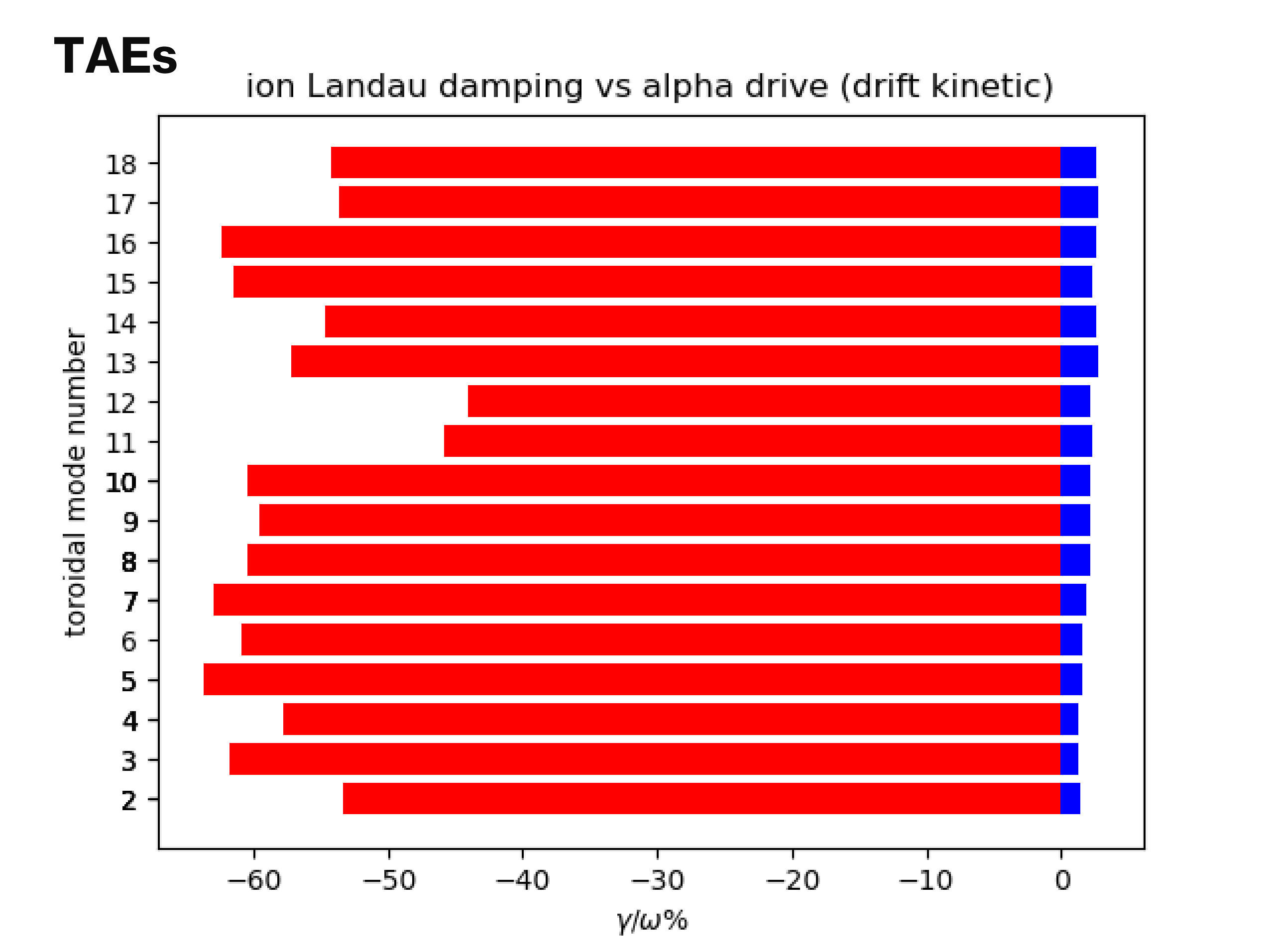


- LOCUST modeling of RE shows 100% deconfinement with $I_{REMC} > 1.5\ MA$ ⇒ **large EM forces**
  - 100% deconfinement ⇒ no runaway electron beam can form
  - Needs to be balanced against high heat loads (rapid deconfinement) and EM forces (large REMC current)
- Initial uncertainty quantification provided by 2 different equilibria: Flat-top and pseudo disruption

J. Morris, RE Physics Meeting, Lausanne, Switzerland, Sep. 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

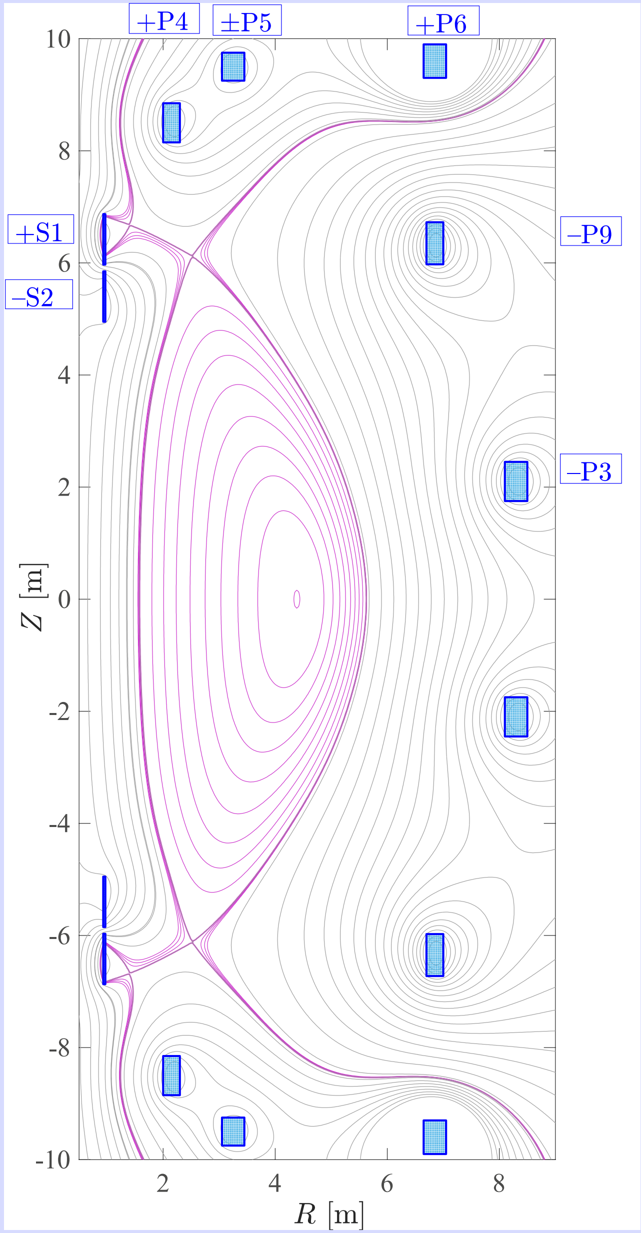


DOUBLE NULL (DN) OPERATION TO SHIELD THE INNER DIVERTOR

- Alternative configurations needed to handle heat loads and erosion ($T_i < 5\ eV$).
  - Outer legs: Extended (Super-X)
  - Inner legs: Expanded flux (X-divertor)

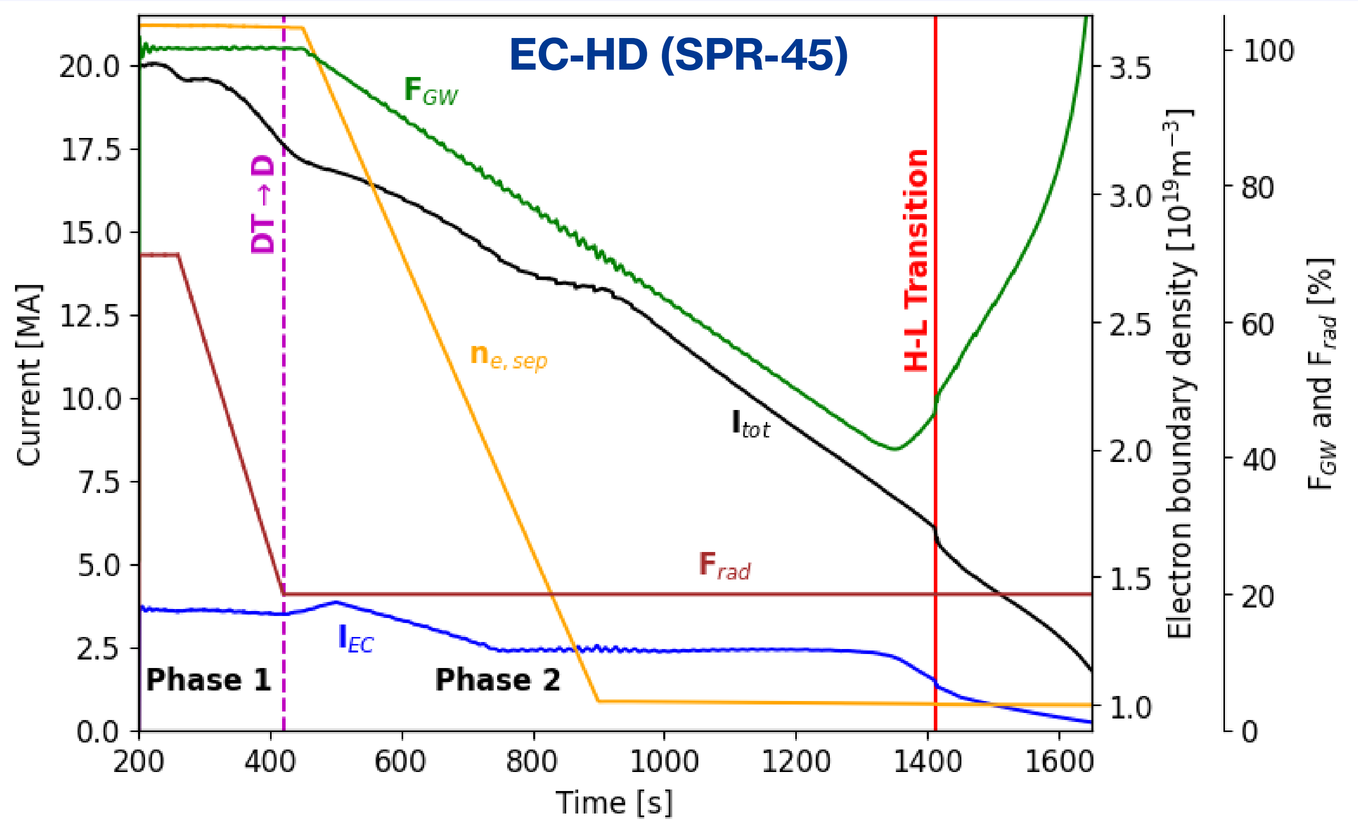
- STEP may marginally work in single null but a commercial ST power plant likely requires DN

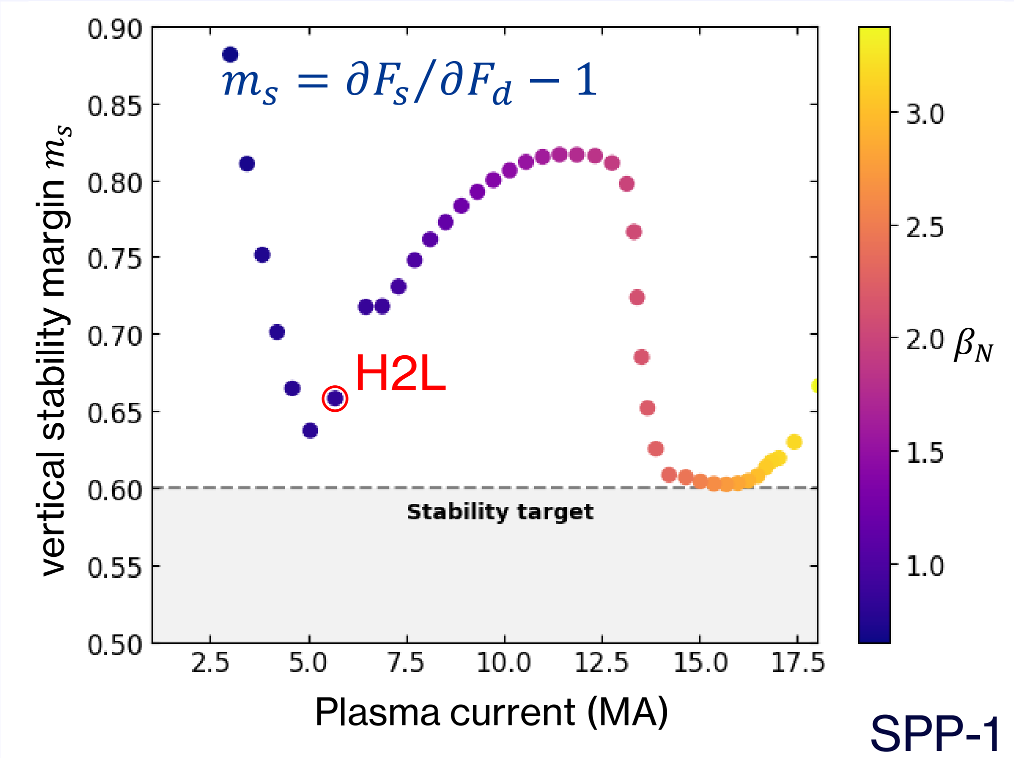
S. Henderson, D. Moulton, R. Osawa, L. Xiang, A. Hudoba, S. Newton, *J. Karhunen, A. Järvinnen, M Kryjak, B. Lipschultz, C. Ridgers*



A Hudoba et.al. Nucl. Fusion 2024 ***64*** *086055*

A POSSIBLE RAMP–DOWN PATH HAS BEEN IDENTIFIED BY TAILORING THE ECCD CURRENT DRIVE PROFILE





SPP-1

H2L transition is the most critical phase as l_i increases, β decreases and the plasma needs to maintain high $\kappa \Rightarrow$ vertical control hard $\Rightarrow$ Driven current profile needs to be tailored.

Flat-top boundary conditions	Fixed equilibrium at full bore

Martin scaling for H2L mode transition

$$P_{L-H} = 0.0488\, n_{e,20}^{0.717}\, B_t^{0.803}\, S^{0.941}\, \frac{2}{M}$$

K. Kirov F. Eriksson, Z. Stancar, C. Olde, C. Challis, M. Lafferty

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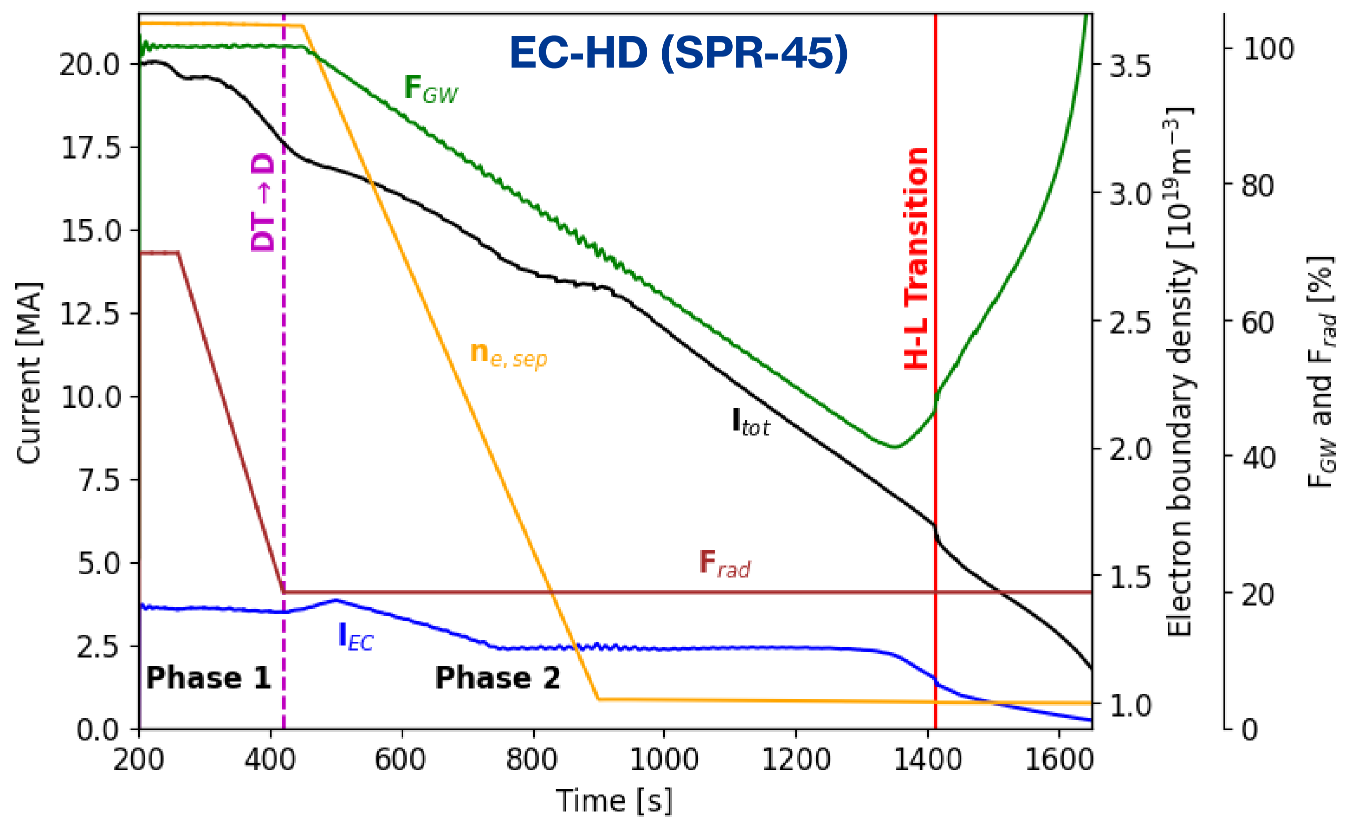

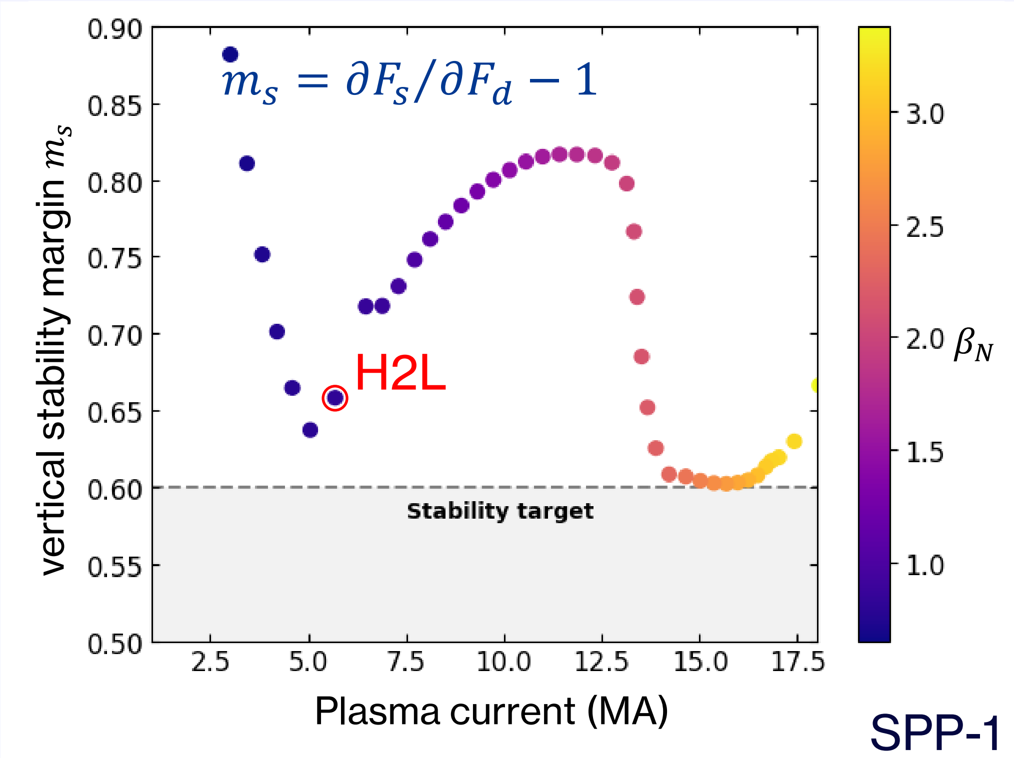

SPP-1

Flat-top boundary conditions

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K. Kirov F. Eriksson, Z. Stancar, C. Olde, C. Challis, M. Lafferty

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

- 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

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

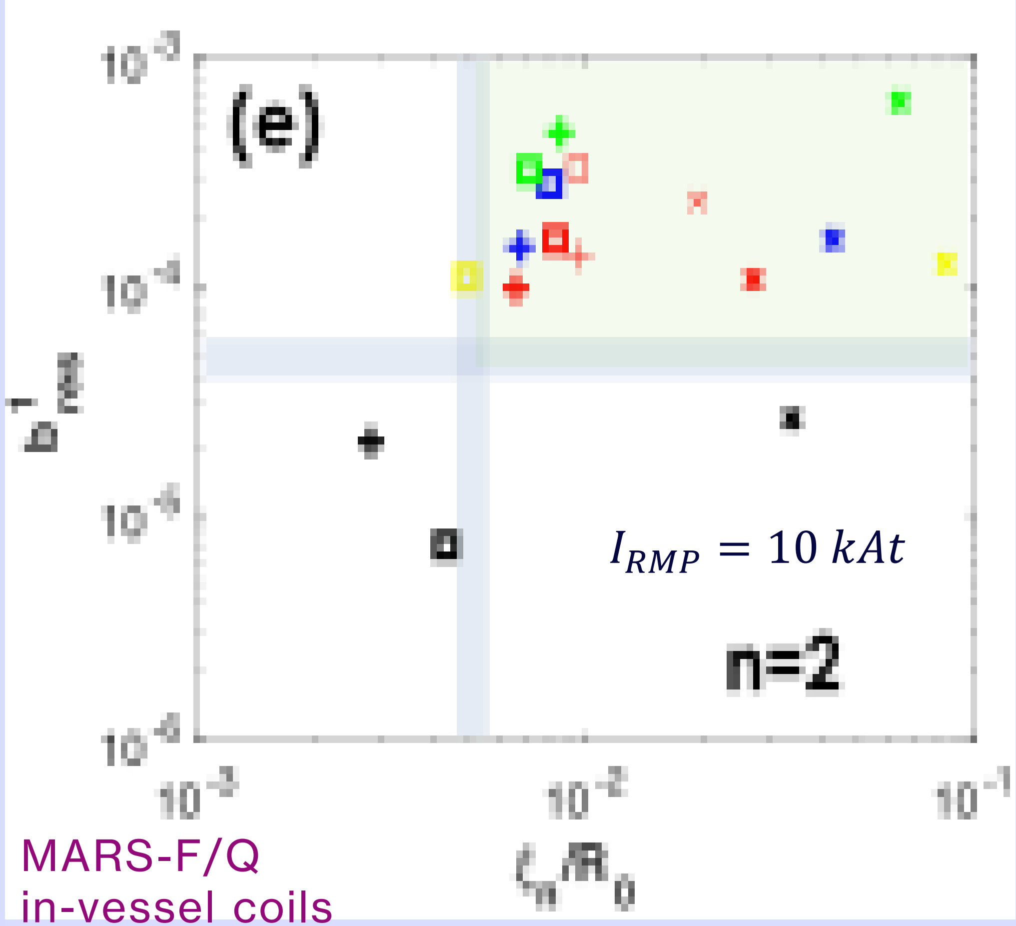

Figure of merits for ELM suppression for 4 SPP-1 (●●●●) and one SPP-2 (●) scenario with $n = 2$ and $I_{RMP} = 10\ kAt$ (shaded region indicates the thresholds.). The symbols are different flow assumptions Ω_0/ω_A.

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