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Plasma Scenario Development in the Spherical Tokamak for Energy Production (STEP)

Ken McClements for the STEP Plasma, Control and Heating & Current Drive Team

21st International Spherical Torus Workshop (ISTW 2022), November 1 2022

Thanks to the STEP Plasma team & Collaborators …

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System Engineering
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* STEP Plasma Lead

Site for STEP prototype fusion energy plant selected

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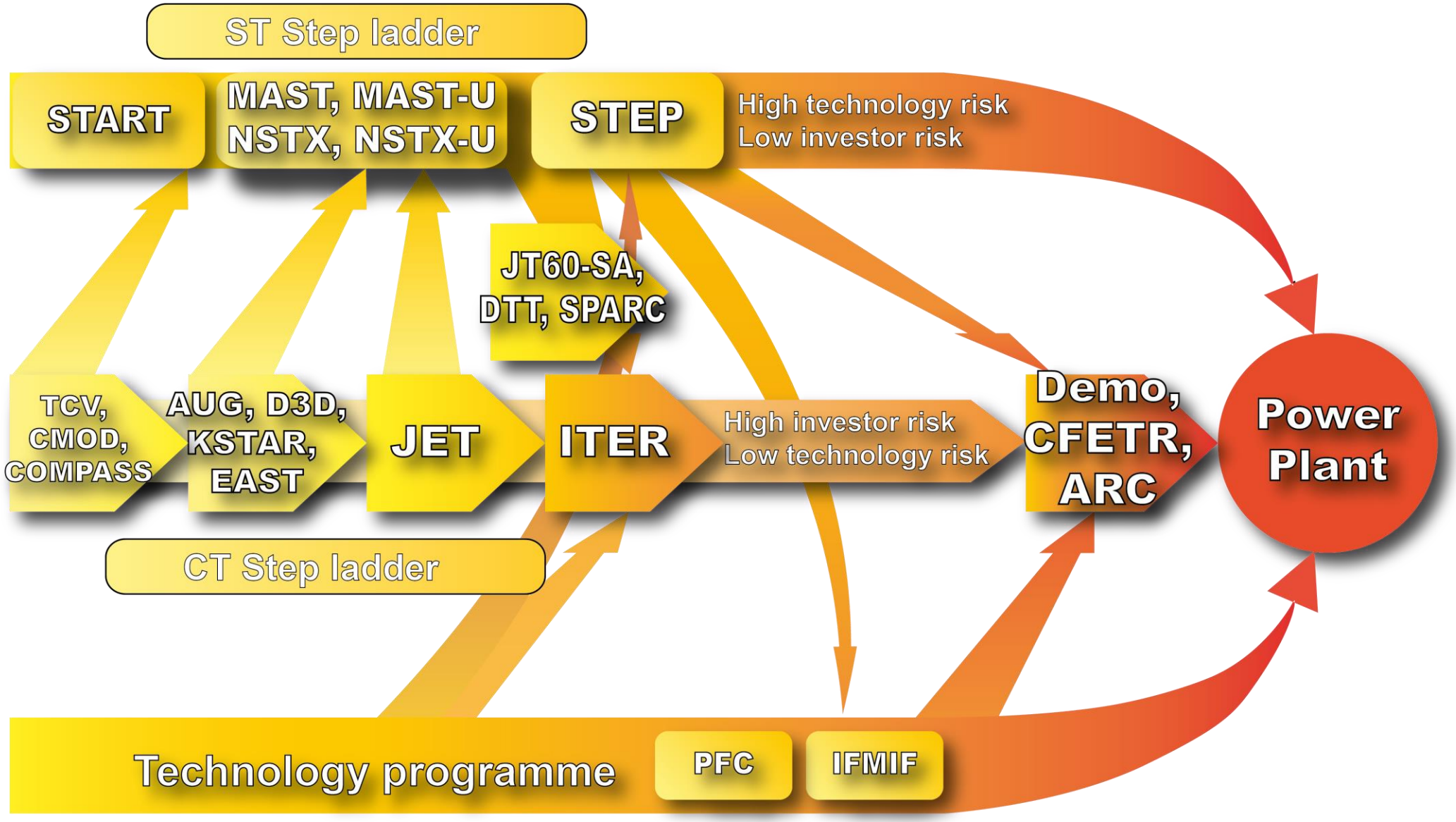
- STEP prototype will be built at West Burton UK, ~200km from Culham Science Centre
- Target completion date: 2040
- Key aims:
  - Fusion power generation on GW scale
  - Net electric power
  - Tritium self-sufficiency

Outline

- Role of STEP in path to power plant
- Plasma modelling workflow
- Flat-top operating points
- Divertor design
- Stability control
- EC & EBW current drive
- Core confinement
- α-particle confinement
- Plasma start-up

Role of STEP in path to power plant



Role of STEP in path to power plant

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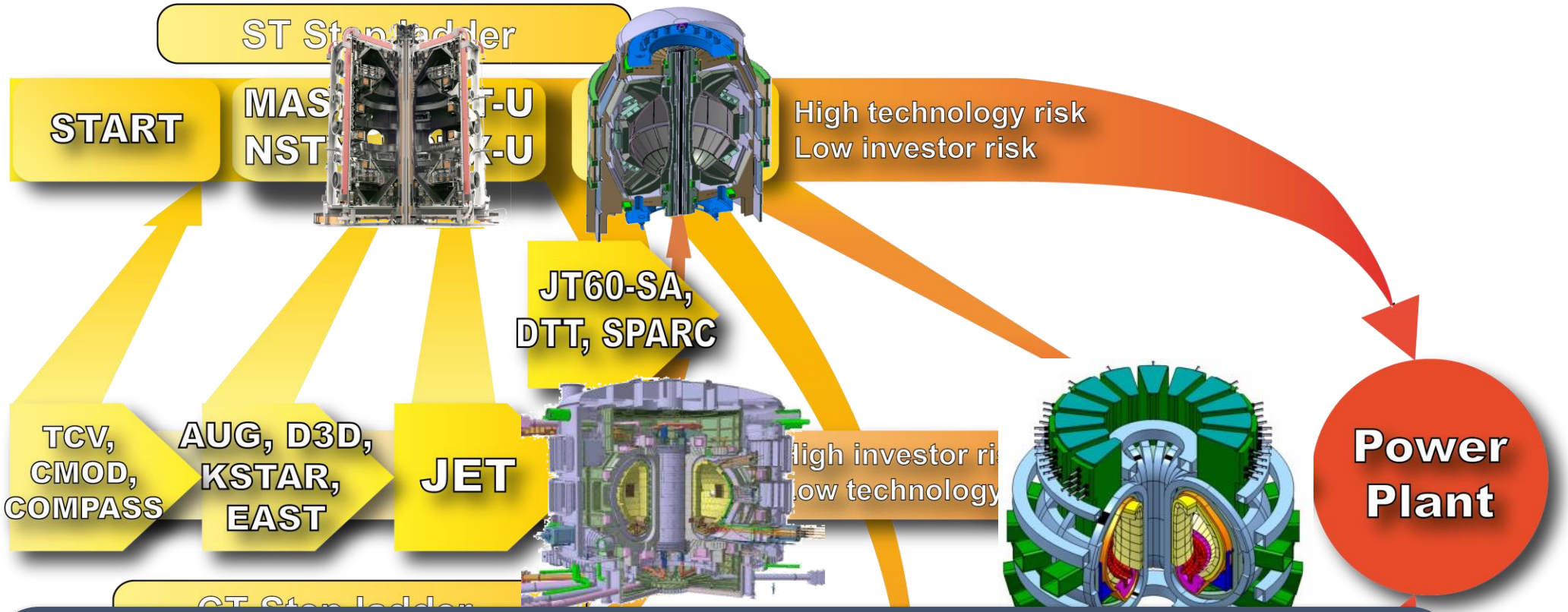

Deliver UK prototype fusion energy plant targeting 2040 & path to commercial viability of fusion

- T1: Concept 2019 - 2024
- Tranche 2: Design 2024 - 2032
- Tranche 3: Build 2032 - 2040

Integrated modelling at centre of modelling workflow

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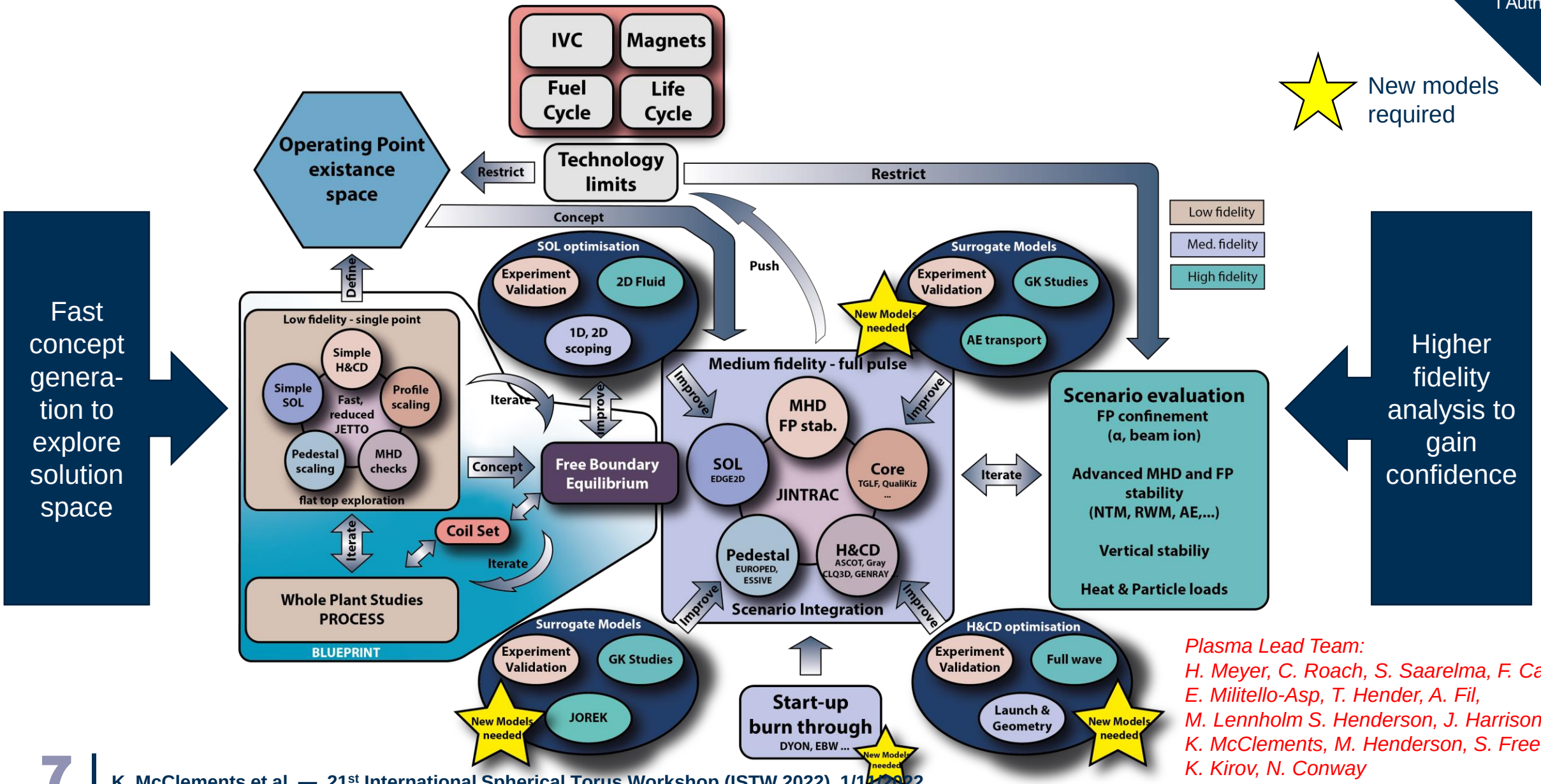

Plasma Lead Team:
H. Meyer, C. Roach, S. Saarelma, F. Casson, E. Militello-Asp, T. Hender, A. Fil, M. Lennholm S. Henderson, J. Harrison, K. McClements, M. Henderson, S. Freethy, K. Kirov, N. Conway

1D transport code (JETTO) used as assumption integrator

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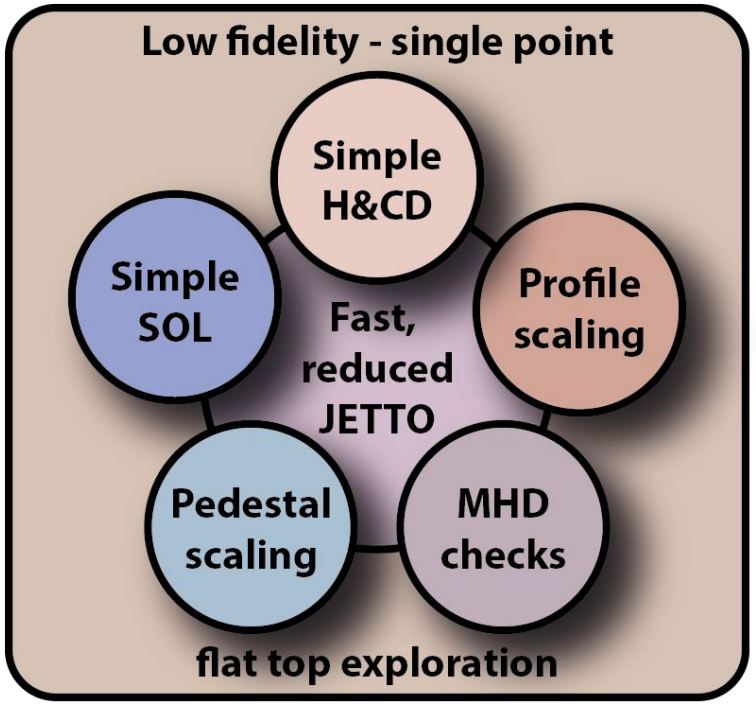
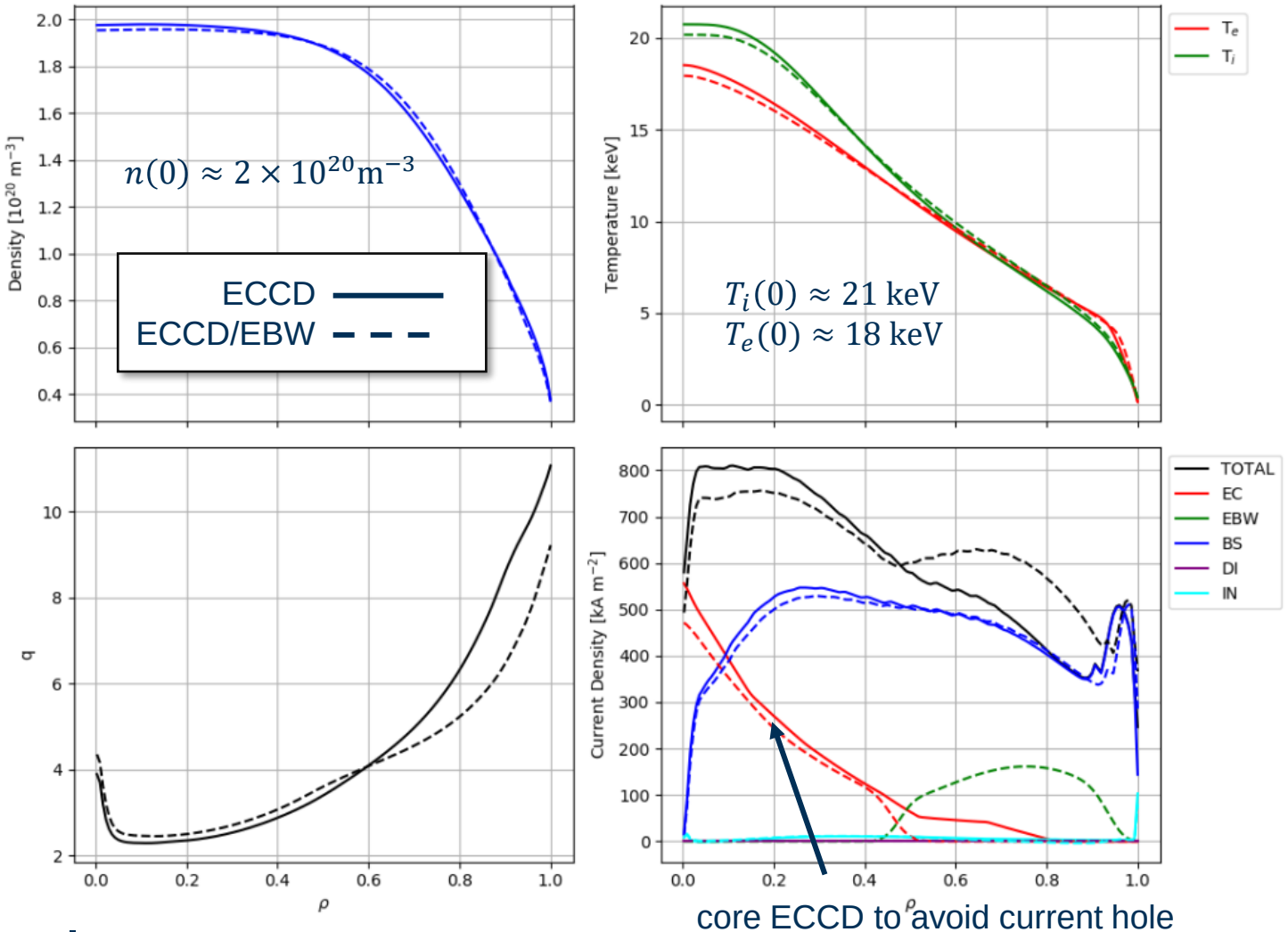
- STEP parameter regime outside validity of reduced transport models developed for present-day conventional tokamaks which don't capture electromagnetic (EM) turbulence expected to prevail in STEP
  - **β_N is input**
  - Other input parameters from systems code PROCESS
- Gyro-Bohm transport model produces profiles consistent with sources & sinks
  - Coefficients adapted to reflect dominant e^- transport as observed in present-day STs & suggested by gyrokinetic calculations
- Simplified heating & current drive models calibrated with higher fidelity calculations



E. Tholerus, *Analysing flat-top operational space of STEP reactor design*, this workshop

Non-inductive flat-top operating points with access to ECCD & EBW $\Rightarrow B_T = 3.2$ T

ECCD: Electron cyclotron heating & current drive
EBW: Electron Bernstein wave heating & current drive

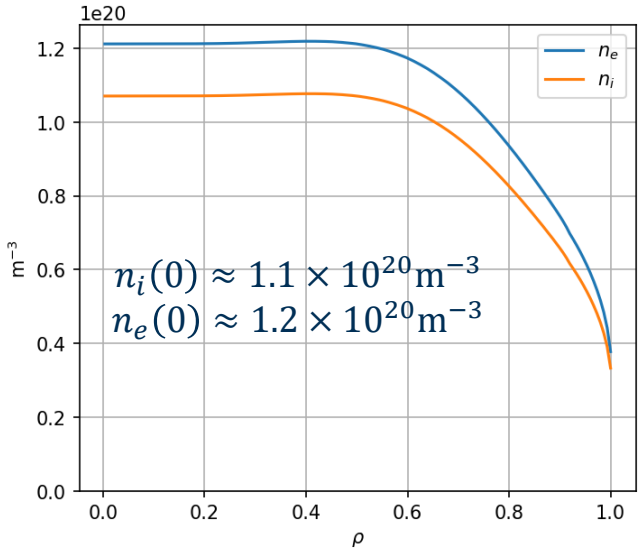


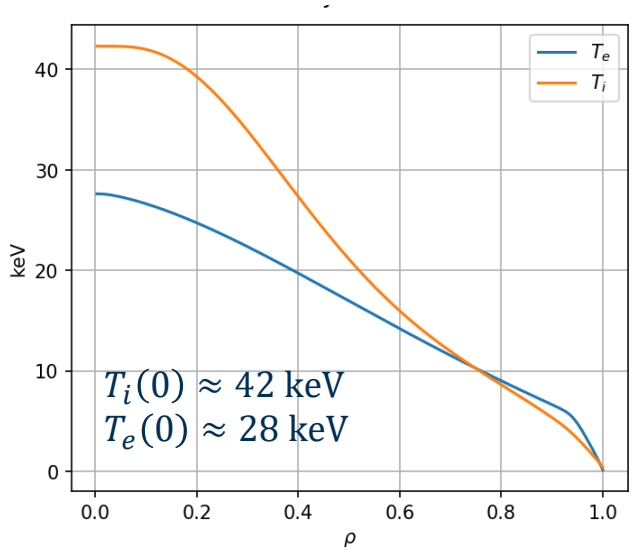
core ECCD to avoid current hole

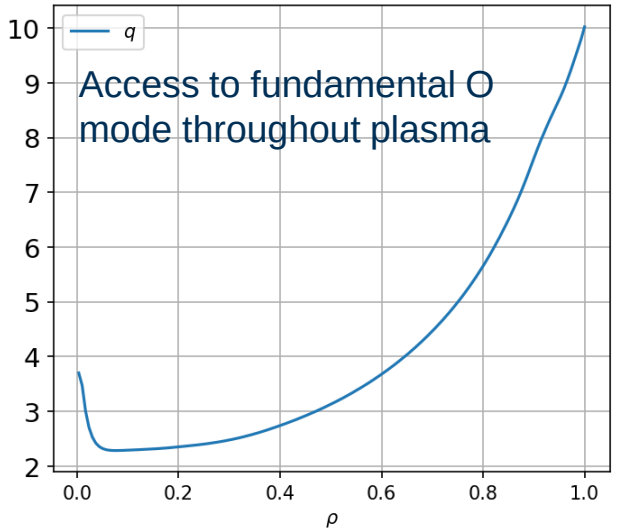
H&CD	EC	EC/EBW
R_{geo} [m]	3.60	
A	1.8	
$B_T\,(R_{geo})$[T]	3.2	
I_p [MA]	20.9	22.0
κ	2.93	
δ	0.59	0.50
P_{fus} [GW]	1.76	1.77
P_{net}^{el} [MW]	188	182
P_{ECCD} [MW]	150	154
P_{rad} [MW]	338	341
Q	11.8	11.5
β_N	4.4	4.1
f_{BS}	0.88	0.78
$\bar{n}/n_{GW}$ [%]	100	94
l_i (3)	0.26	0.25
η_{CD}^{EC} [A/W]	0.016	0.027
η_{CD}^{EBW} [A/W]	N/A	0.034
P_{sep}/R_{geo} [MW/m]	41	
$(H_{98} + H_{98}^{\star})/2$	1.35	1.19

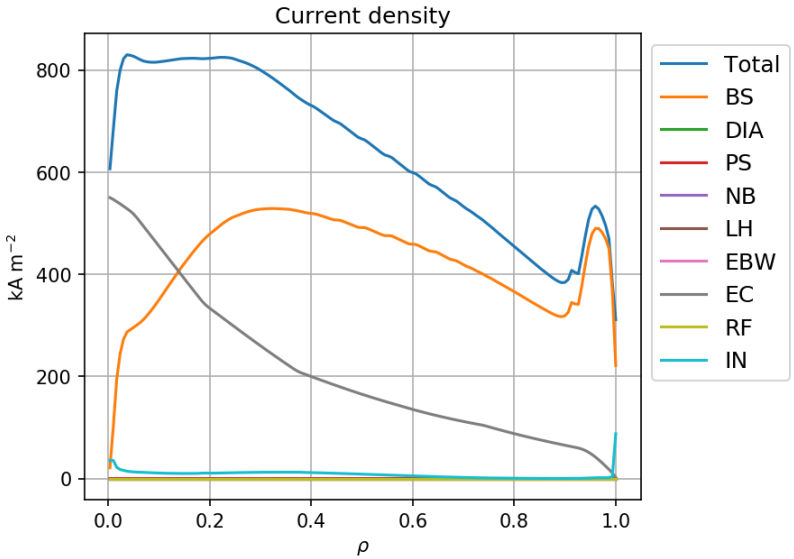
F. Casson, F. Koechl, S. Marsden, G. Szepesi, E. Tholerus, T. Wilson

Low density hot ion flat-top operating point with access to fundamental ECCD







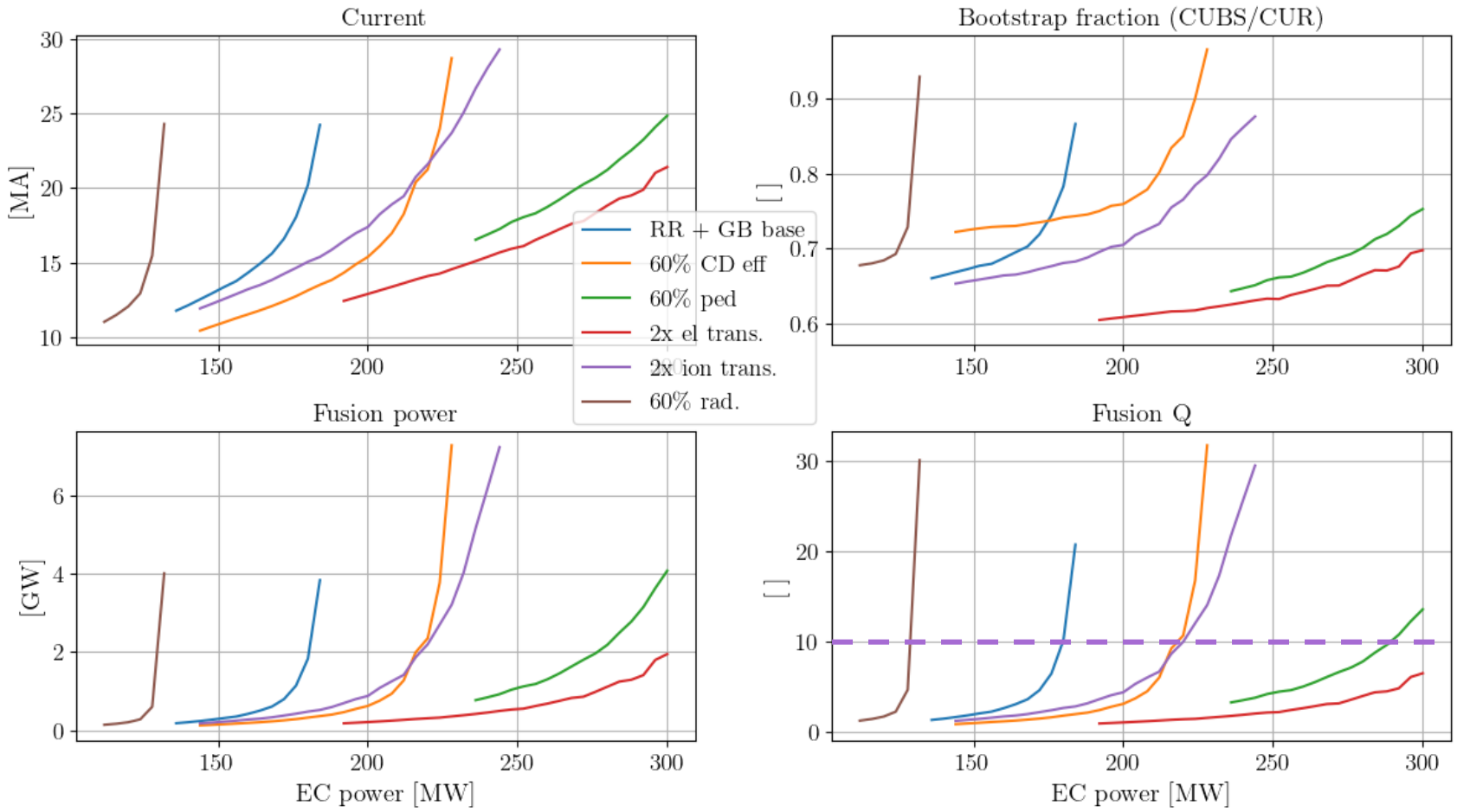


H&CD	EC
R_{geo} [m]	3.6
A	1.8
$B_{\mathrm{T}}(R_{\mathrm{geo}})$[T]	3.2
I_p [MA]	22.8
P_{fus} [GW]	1.62
P_{aux} [MW]	150
P_{rad} [MW]	280
Q	10.1
β_N	4.6
$f_{BS} = I_{BS}/I_p$	0.76
$f_{GW} = \bar{n}/n_{GW}$	0.60
l_i (3)	0.30
η_{CD}^{EC} [A/W]	0.033
P_{sep}/R_{geo} [MW/m]	41

Optimised using ITPA confinement scaling

F. Casson, F. Koechl, S. Marsden, G. Szepesi, E. Tholerus, T. Wilson

"Predictive" uncertainty quantification shows margin in P_{aux} & P_{fus} needed to recover target Q



- Simple predictive setup:
  - Electrons: Rechester Rosenbluth (RR)
    - ➢ collisionless RR with $\delta B/B$ from [1] & connection length from [2]
  - Ions: gyro-Bohm
  - Predict T_i, T_e, n_e, I_p
  - Pedestal: $p_{ped} \propto I_p^{0.8} f_{GW}^{0.45}$ $\Rightarrow P_{fus}$ very sensitive to I_p
- In base case $Q \approx 10$ needs $P_{aux} \sim 180$ MW & $P_{fus} \sim 2$ GW
- Performance sensitive to core radiation fraction

[1] J.F. Drake et al. PRL **44** (1980) 994
[2] K. L. Wong et al. PRL **99** (2007) 135003

Integrated modelling: *F. Casson, F Palermo*
Pedestal scaling: *S. Saarelma*

Non-inductive flat-top operating points with access to ECCD & EBW $\Rightarrow B_T = 3.2$ T

ECCD: Electron cyclotron heating and current drive
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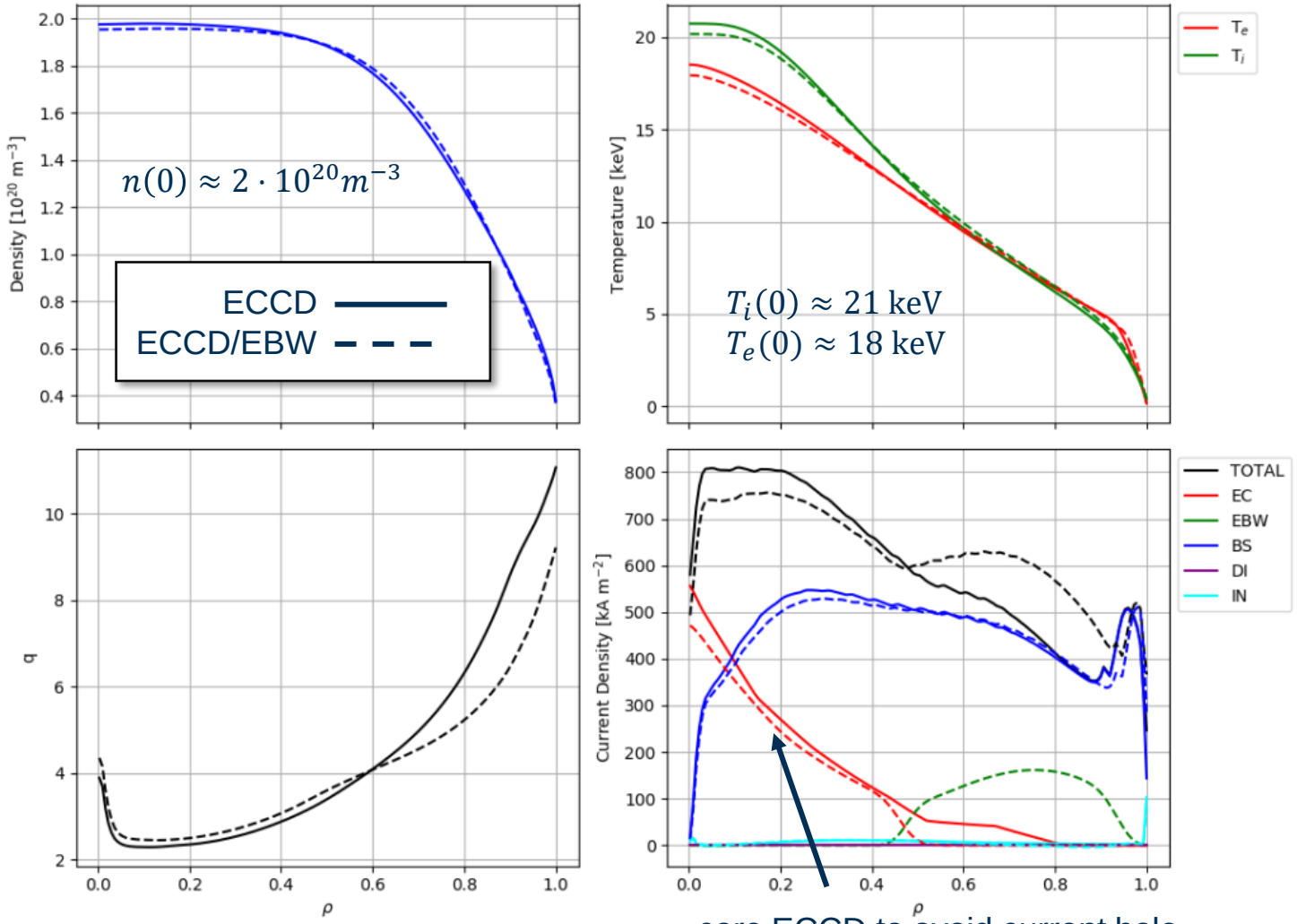
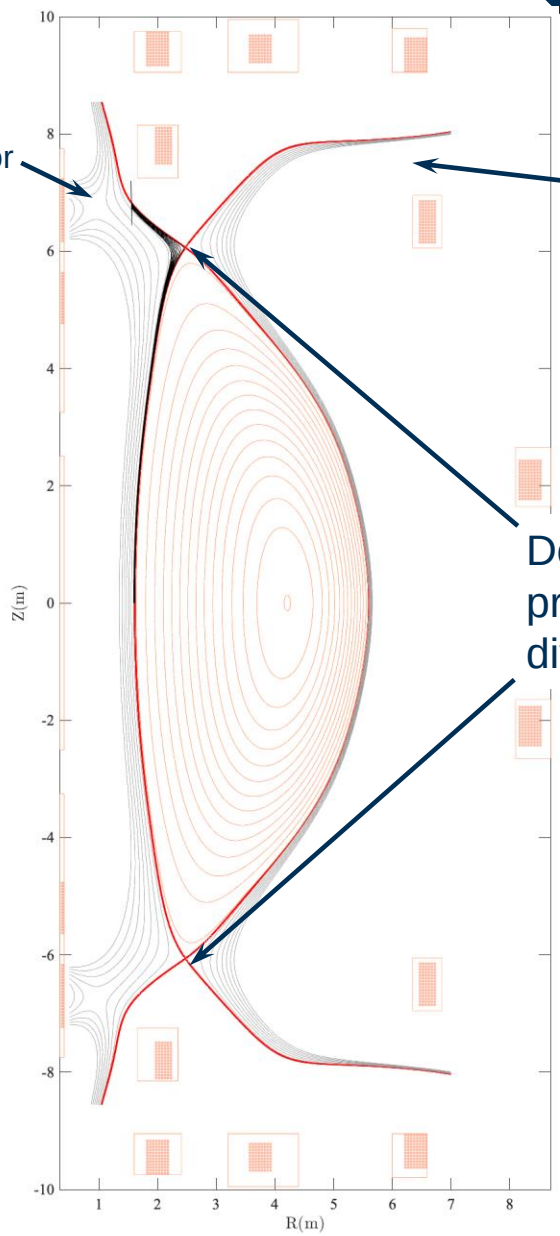


core ECCD to avoid current hole

Preliminary coil-set



inner X-divertor

Outer divertor – extended leg

Double null to protect inner divertor

Further optimisation of inner & outer divertor legs in progress

A. Hudoba, S. Bakes

X-divertor may provide optimum exhaust solution on inboard side

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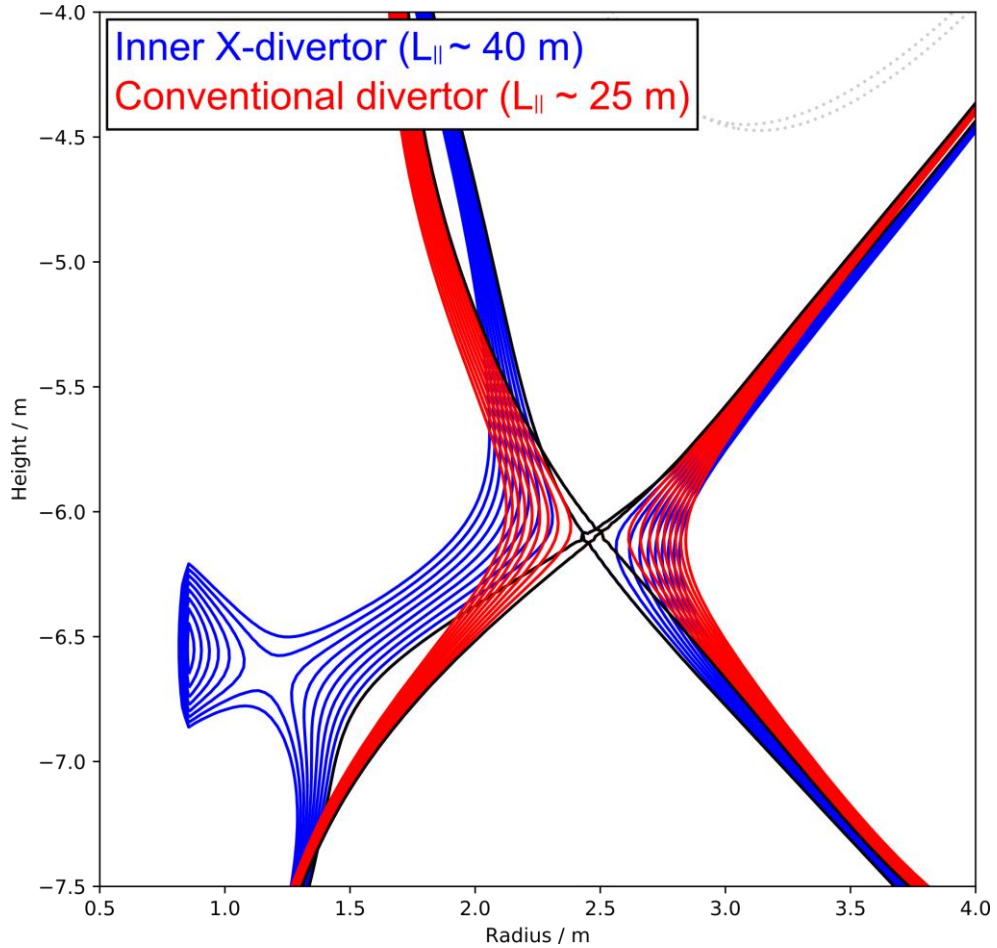
- SOLPS-ITER code used to assess level of detachment & target heat loads in various divertor geometries
- Inboard X-divertor poses engineering challenge but has significant advantages:
  - when strike point radius ~1.7m, connection length $L_{||}$ is nearly doubled
  - offers best performance with fewest compromises in terms of neutral trapping & peak heat loading
  - for details, see talk by S. Henderson, *Physics Drivers of the STEP divertor concept design*, this workshop

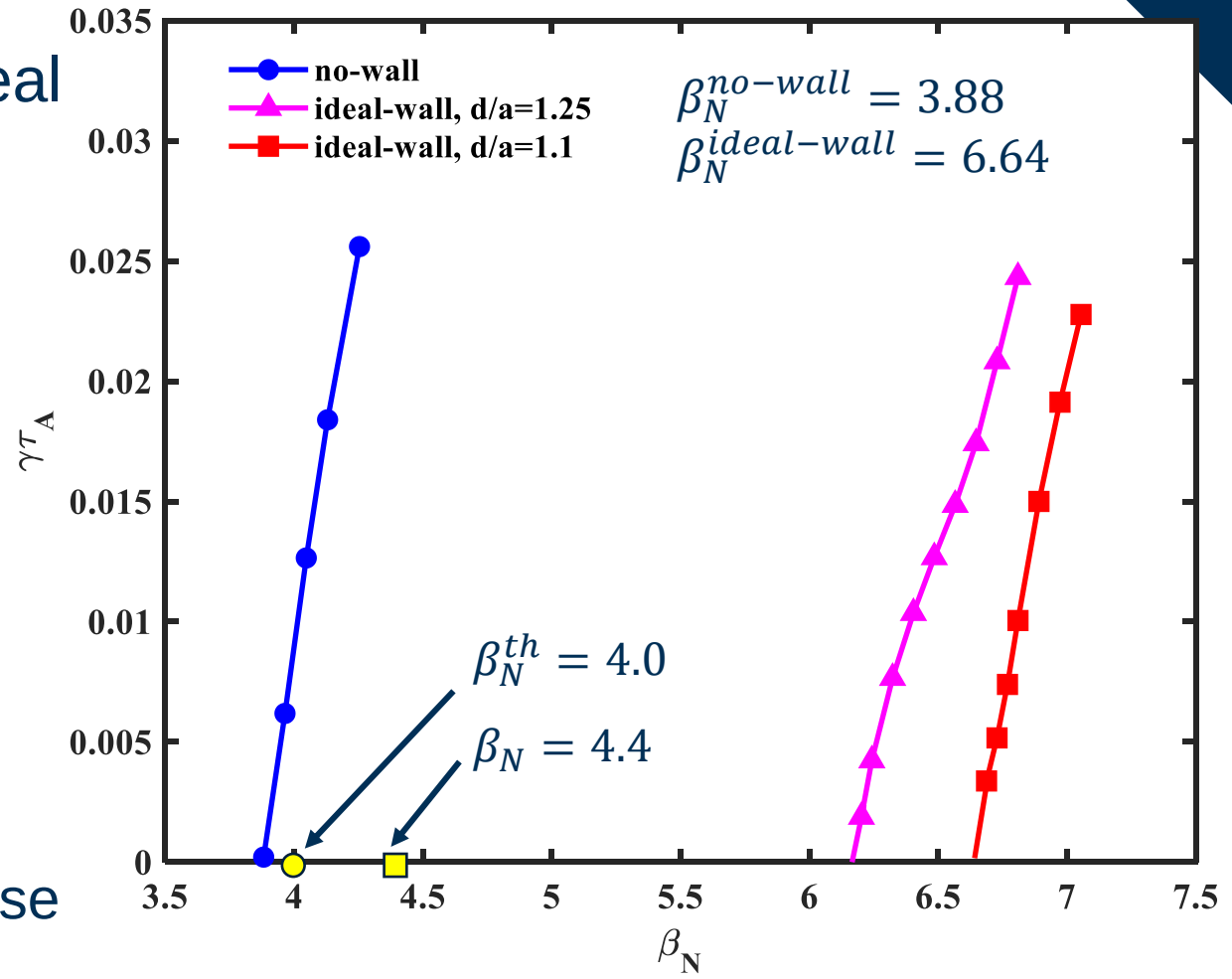


S. Henderson, A. Hudoba

Active control of Resistive Wall Modes (RWMs) allows access to higher β_N

- STEP scenarios are marginally above ideal stability limit without conducting wall:
$$\beta_N > \beta_N^{no-wall}$$
- Conducting wall reduces growth rate to resistive values ⇒ controllable:
$$\beta_N < \beta_N^{ideal-wall}$$
- Active in-vessel coils can keep amplitude of instability well below disruption limit
  - 6 mid-plane picture-frame coils
  - Control system modelled with system noise

EC operating point



G. Xia, T. Hender, Y. Liu (GA)

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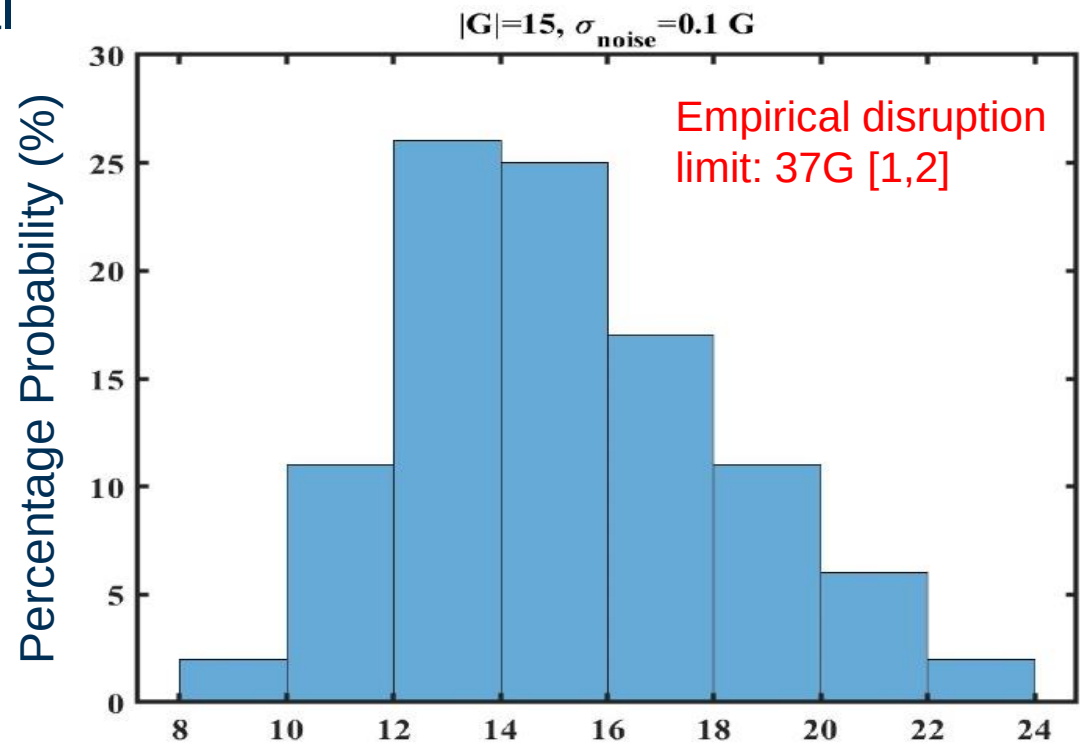
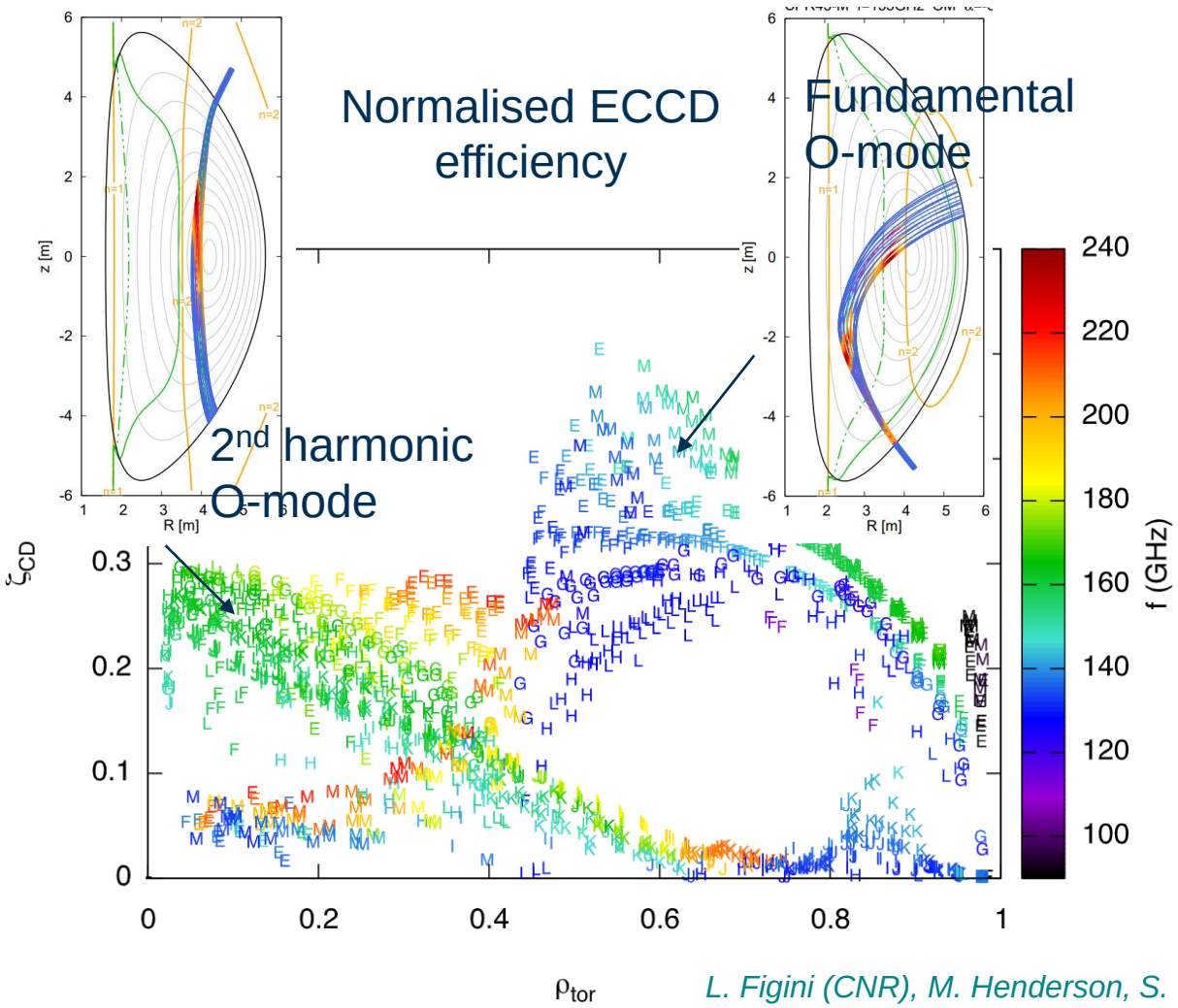


[1] P.C. de Vries et al. Nucl. Fusion **56** (2016) 026007
[2] G. Xia et al. Proc. 48th EPS Plasma Phys. Conf. (2022)

G. Xia, T. Hender, Y. Liu (GA)

ECCD O-mode covers full radius; EBW only covers $\rho > 0.4$ but at 3 - 4 × higher normalised efficiency



$$\zeta_{CD} = 32.7 \frac{\eta[A/W] n_e[10^{20} m^{-3}] R[m]}{T_e[keV]}$$

- ECCD: scan with GRAY code for multiple launch positions
  - Low-field side O-mode launch from above/below midplane allows access through magnetic field well
  - High-field side absorption negates particle trapping degradation for off-axis current drive
- EBW: full wave calculation using GENRAY + CQL3D
  - High central T_e makes $\rho < 0.4$ inaccessible
  - 2nd harmonic with dominant Ohkawa current drive [1]

L. Figini (CNR), M. Henderson, S. Freethy

[1] G. Taylor et al. Phys. Plasmas **11** (2004) 4733

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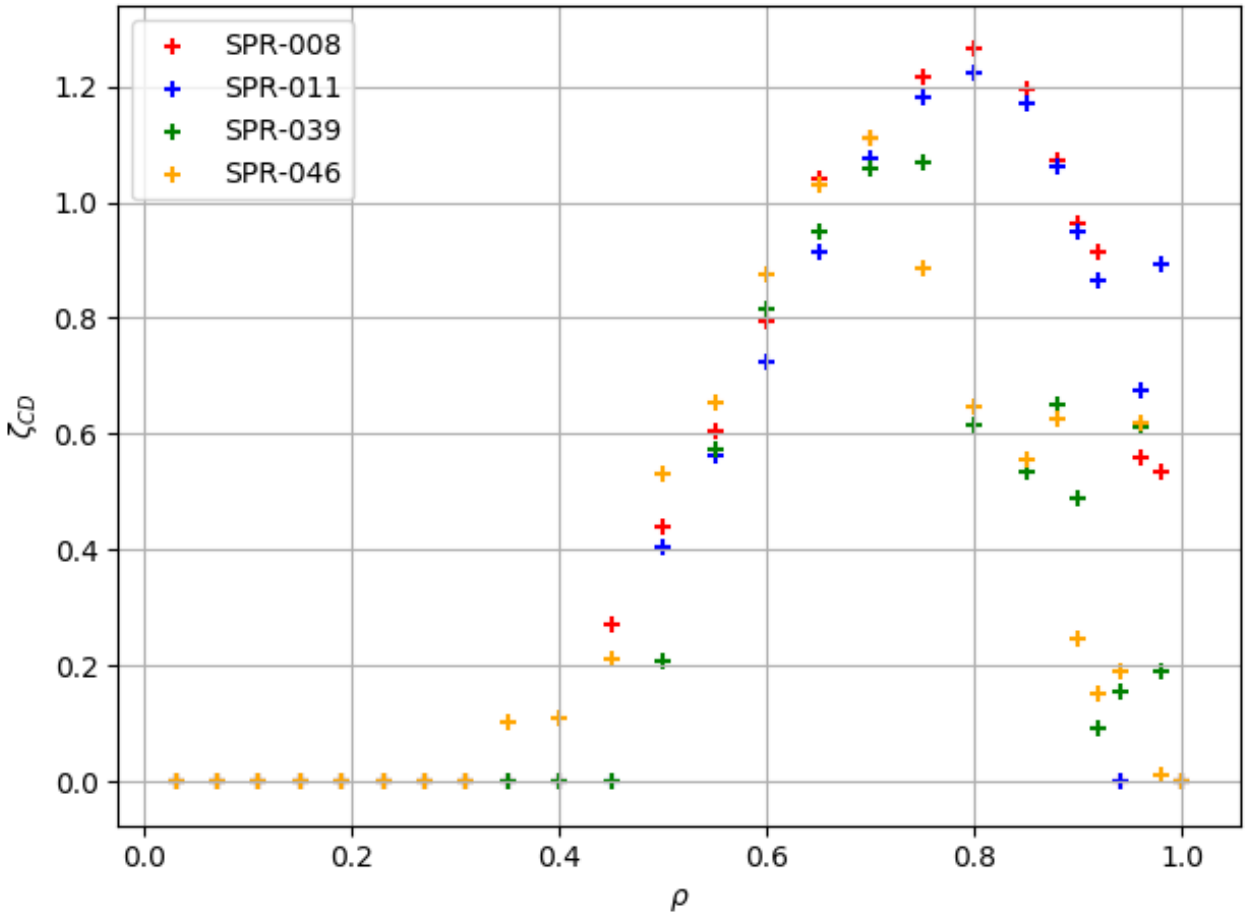
Normalised EBW CD efficiency



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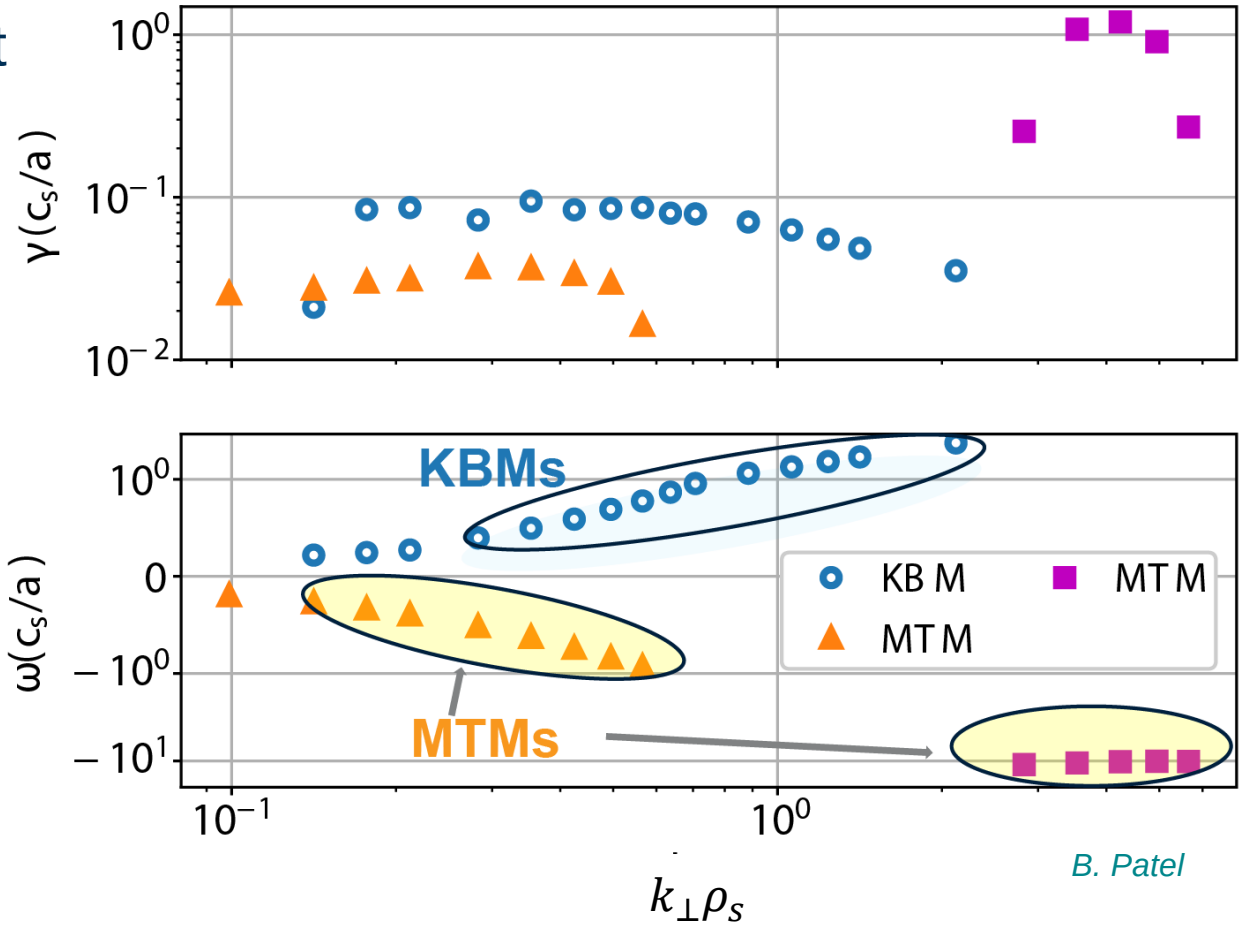
D. Speirs (U. Strathclyde) , T. Wilson, M. Henderson, S. Freethy

[1] G. Taylor et al. Phys. Plasmas **11** (2004) 4733

Microstability in STEP differs significantly from JET, DEMO & ITER

B.S. Patel et al. Nucl. Fusion **62** (2022) 016009

- Electromagnetic turbulence dominates
  - 2 types of micro tearing mode (MTM) at low $k_\perp \rho_s$ (i-MTM) & high $k_\perp \rho_s$ (e-MTM)
  - kinetic ballooning modes (KBMs)
- KBMs have highest growth rates at low $k_\perp \rho_s$ but may be stabilised by flow & β'
- MTMs mainly drive conductive electron heat transport via turbulent radial reconnection of field lines (magnetic flutter [1])



B. Patel

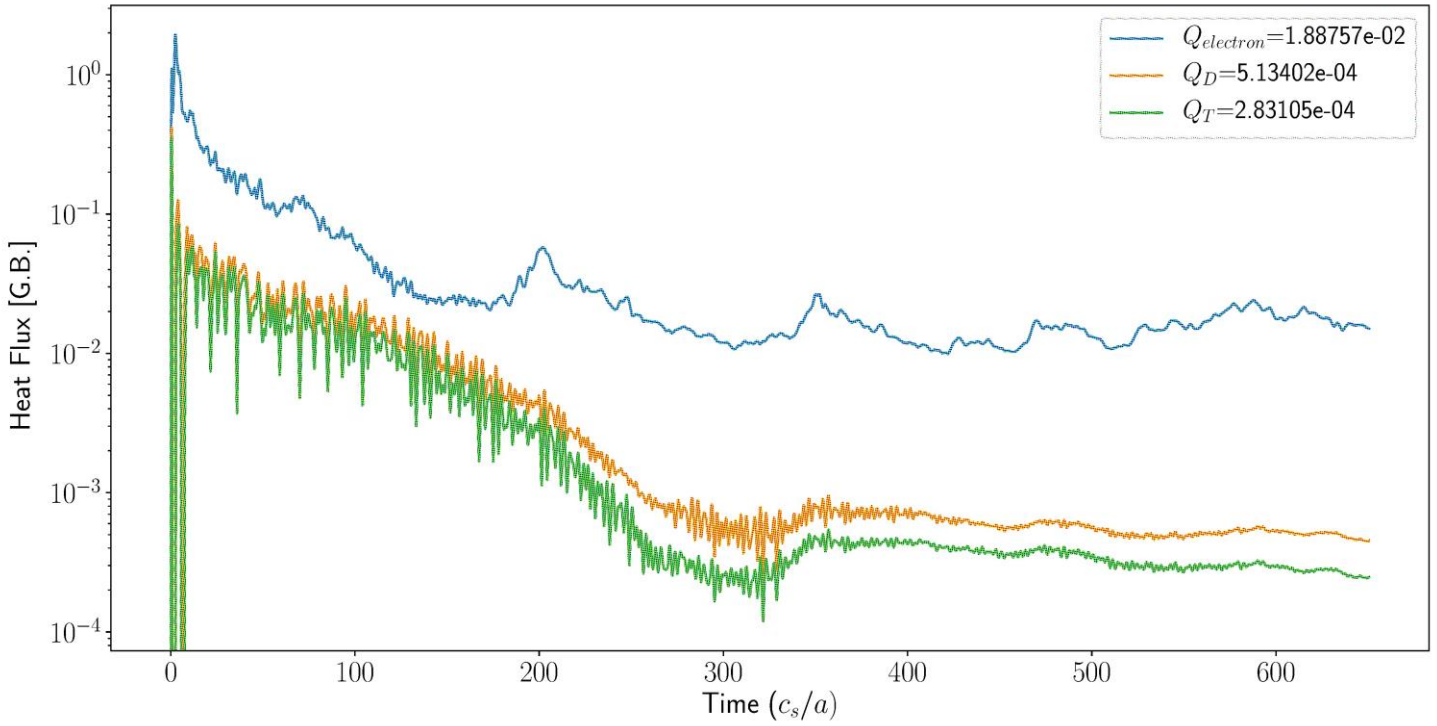
[1] J.D. Callen PRL **39** (1977) 1540

Recent non-linear local gyrokinetic simulations that exclude KBMs show saturation at $Q_e \sim 0.01 Q_{gB}$

- Earlier local nonlinear electromagnetic gyrokinetic simulations for STEP predicted very large magnetic flutter transport from low wavenumber MTMs

  D. Dickinson, Varenna Fusion Theory Conference, 2022

- Recent investigations that exclude KBMs reveal strong sensitivity of heat flux to parallel dissipation
  - GENE simulations with $B_{||} = 0$ (no KBMs) show greatly reduced Q_e & $Q_{D,T} << Q_e$
- i-MTMs & KBMs have different radial scales
  - vastly increases computational cost of nonlinear simulations that include both types of mode



D. Kennedy, B. Patel, C. Roach, D. Dickinson (U. York), M. Giacomin (U. York)

Power loads due to α-particle losses used to constrain parameters of TF & ELM control coils

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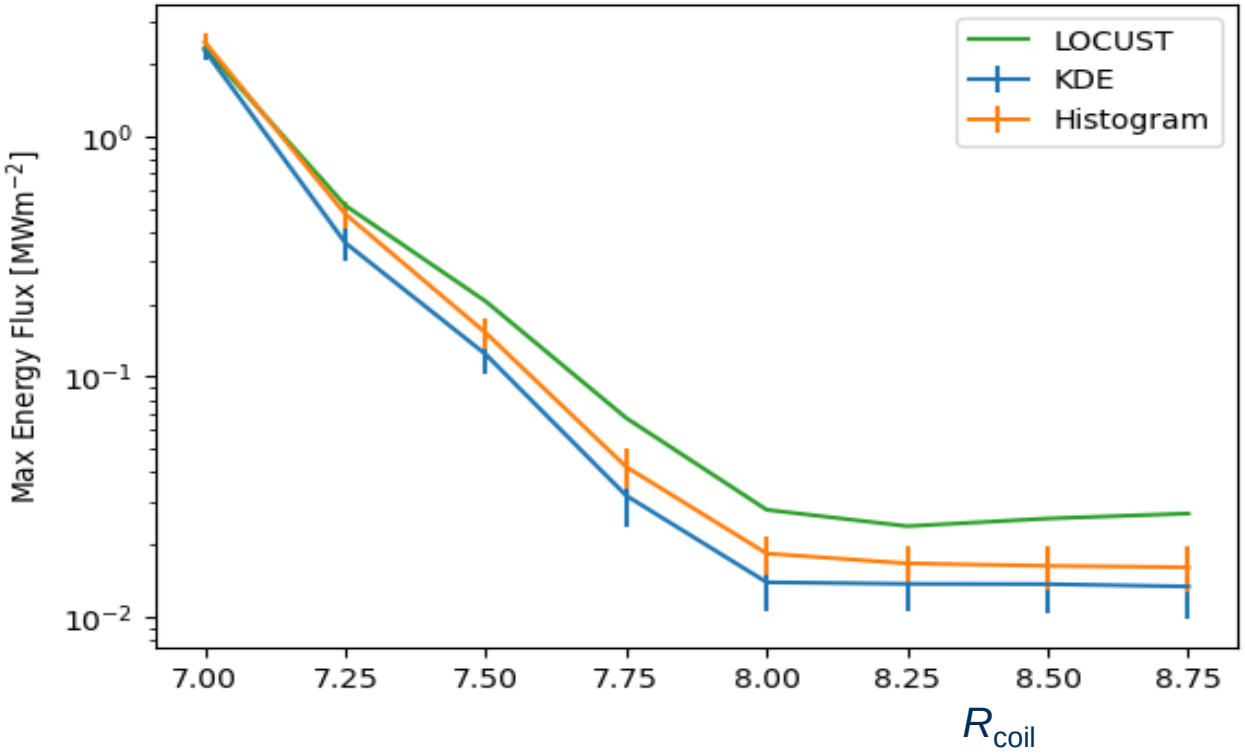
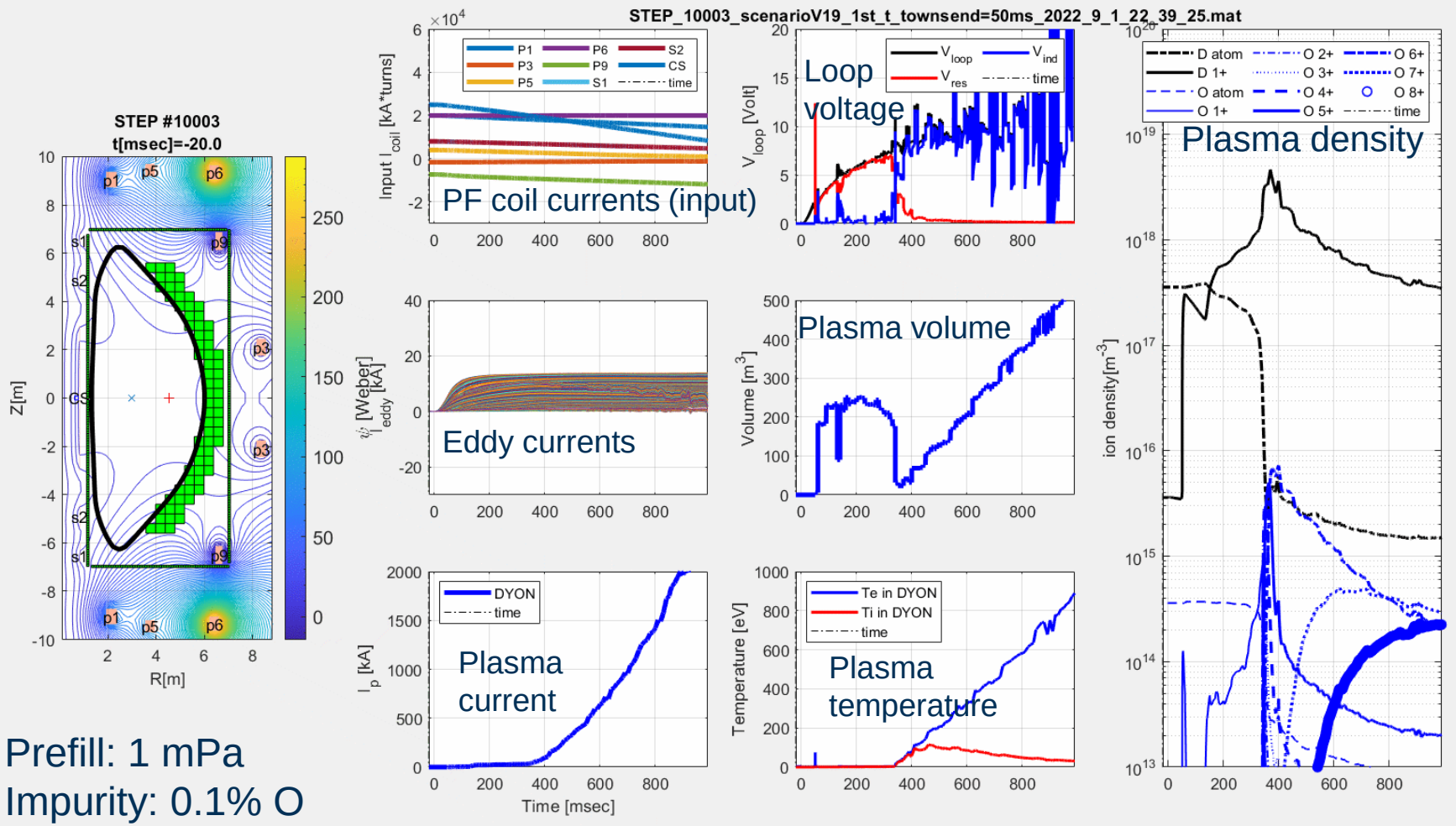
- Full α-particle orbits in 3D fields tracked using LOCUST code
- TF ripple-induced α-particle losses & distribution of associated power loads on 1st wall calculated for N = 16 picture-frame coils with range of outer limb radii R_{coil}
- Maximum loads occur on low field side main chamber wall which can tolerate up to ~1MWm^{-2} in total (including EM radiation)
- Power loads acceptably low for $R_{coil} \geq 8.0$m
- Coils designed for RWM control & error field correction may also be used for ELM control
- α-particle loss & power load calculations for 3D fields needed for ELM control coils underway – significant uncertainty in coil configurations required for suppression of Type I ELMs



A. Prokopyszyn, *Steady-state alpha-particle flux on the walls of the Spherical Tokamak for Energy Production*, this workshop

Burn-through achieved after 350 ms with $V_{loop} \sim 6.5\ V$ using hexapole null at $R = 2.5\ m$



- Small ~9 Vs solenoid used for initiation & target plasma production
- DYON code used to simulate burn-through
  - supported by free boundary equilibrium solver (FIESTA)
  - self-consistent calculation of eddy currents & Townsend break down
- ECRH pre-ionisation & heating expected to lower V_{loop} requirement

H.T. Kim

H.T. Kim et al. Nucl. Fusion **62** (2022) 126012

STEP plasma work improving confidence in feasibility of ST-based fusion power plant

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Fast concept turn-around has made it possible to explore variety of whole plant concepts using 1D transport code & integrated modelling tools

Three flat-top operating points have been defined, trading confinement risk against heating & current drive maturity

Comprehensive tool set for scenario modelling has helped to reduce risks in exhaust, stability, current drive, core plasma & α-particle confinement

Other STEP presentations at this workshop (Wednesday)

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Stuart Henderson – Physics drivers of the STEP divertor concept design (oral)

Emmi Tholerus – Analysing flat-top operational space of STEP reactor design (oral)

Alex Prokopyszyn - Steady-state alpha-particle flux on the walls of the spherical tokamak for energy production (oral)

Alex Fil – Disruption runaway electrons generation & mitigation attempts in STEP preferred concept (poster)

Žiga Štancar – Modelling of the STEP ramp-down phase with JETTO (poster)

Sam Bakes - Free boundary equilibrium modelling of disruption scenarios for STEP (poster)

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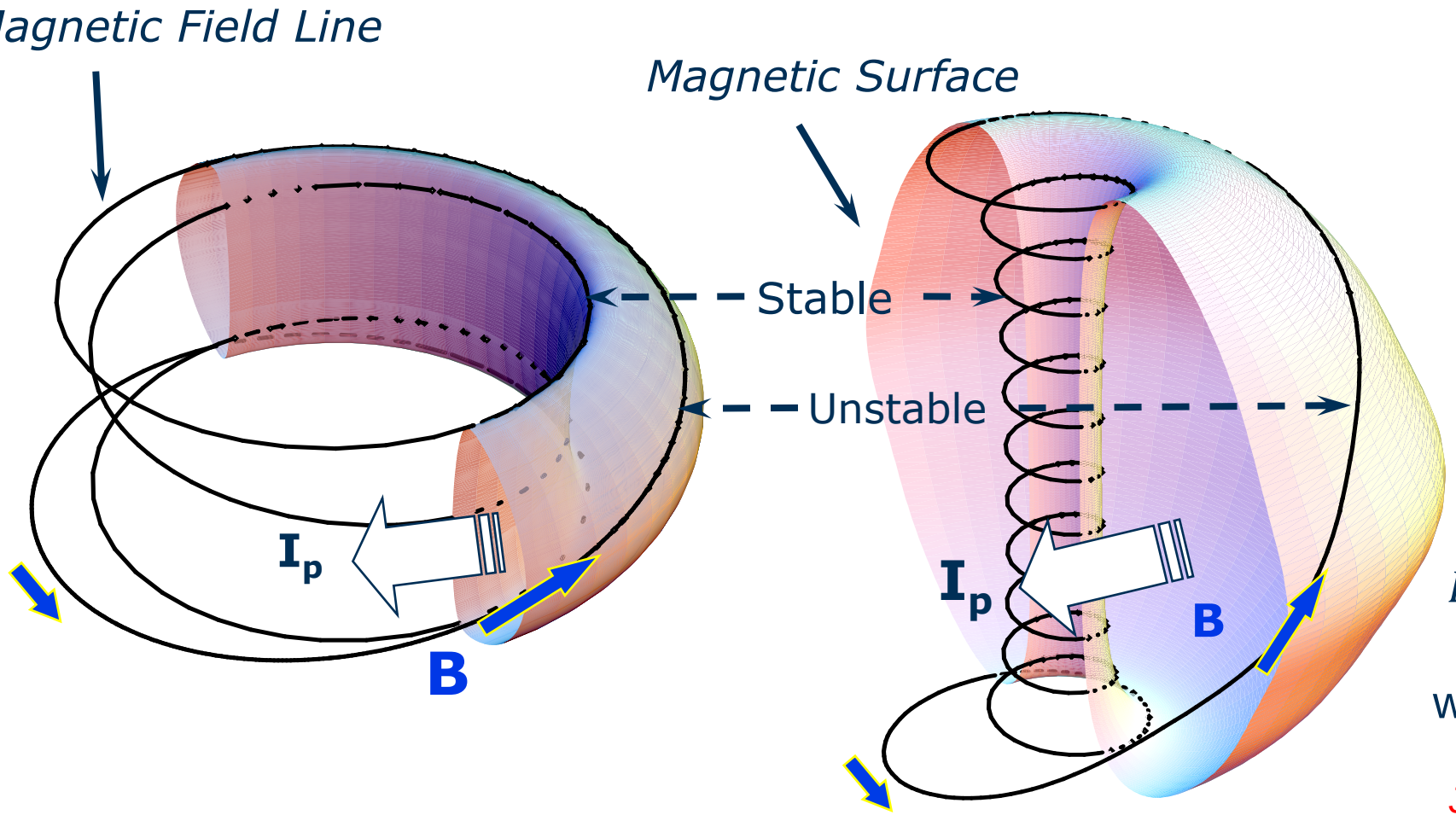
Back-up slides

Why choose ST route to fusion power plant?



Conventional Tokamak *Spherical Tokamak*

cartoon courtesy of Y.M. Peng

- STs allow higher plasma pressure in lower toroidal field ⇒ higher β
- STs operate naturally at higher elongation κ

$$P_{fus} \propto n^2\langle\sigma v\rangle_{DT} \propto p^2 \propto \beta_T^2 B_T^4$$

with $\beta_T \sim A^{-1/2}(1+\kappa^2)\beta_N^2/f_{BS}$

J.E. Menard et al. NF **37** (1997) 595

$$\beta_N = \frac{\beta}{I_p/aB_T} \qquad f_{BS} = I_{BS}/I_p$$

(I_{BS}: bootstrap current)

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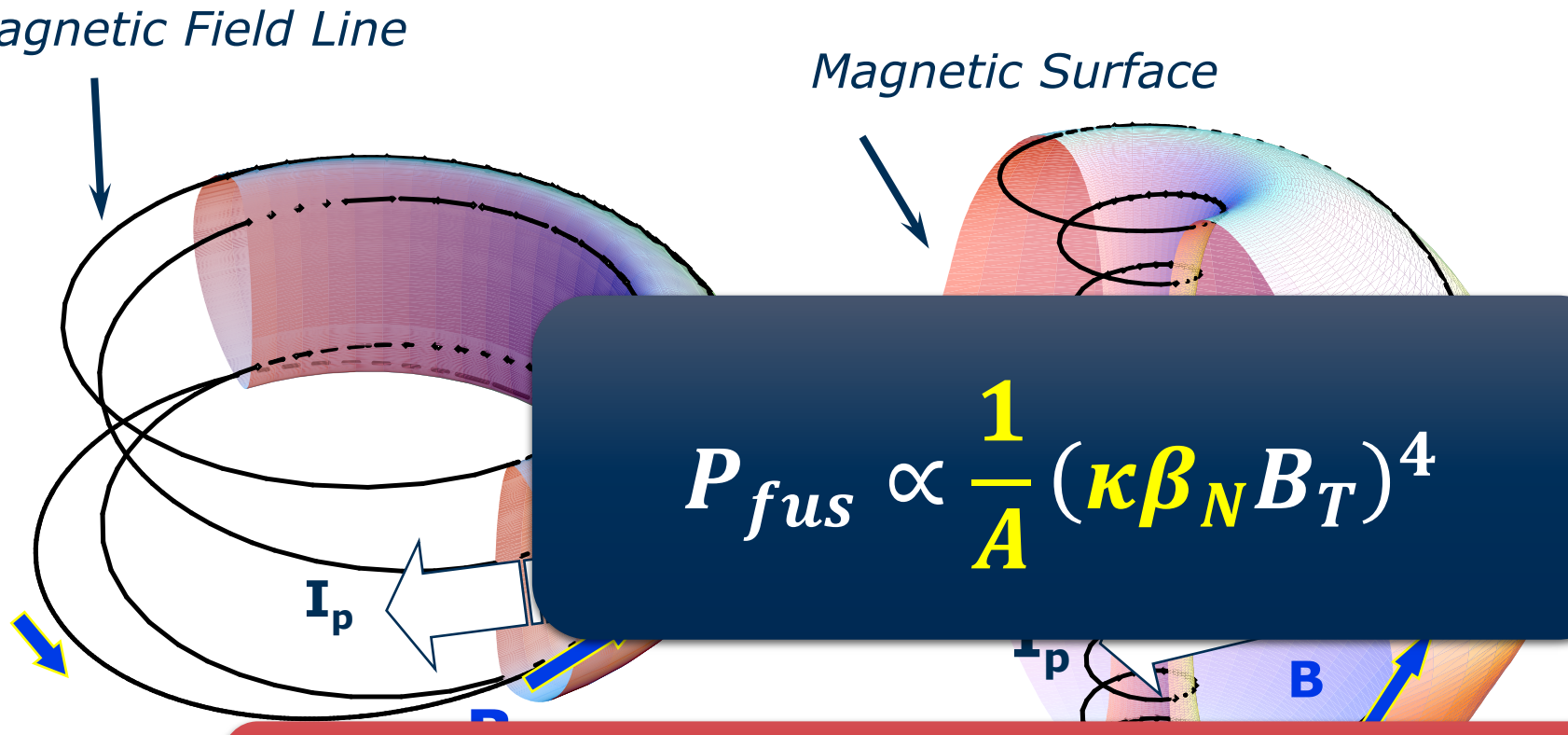

$$P_{fus} \propto \frac{1}{A}(\kappa \beta_N B_T)^4$$

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$$P_{fus} \propto n^2\langle\sigma v\rangle_{DT} \propto p^2 \propto \beta_T^2 B_T^4$$

$$(1+\kappa^2)\beta_N^2/f_{BS}$$

NF **37** (1997) 595

Operation at high β_N and high κ require broad current profile (low l_i) plus robust vertical & resistive wall mode (RWM) control

Conventional Tokamak *Spherical Tokamak*

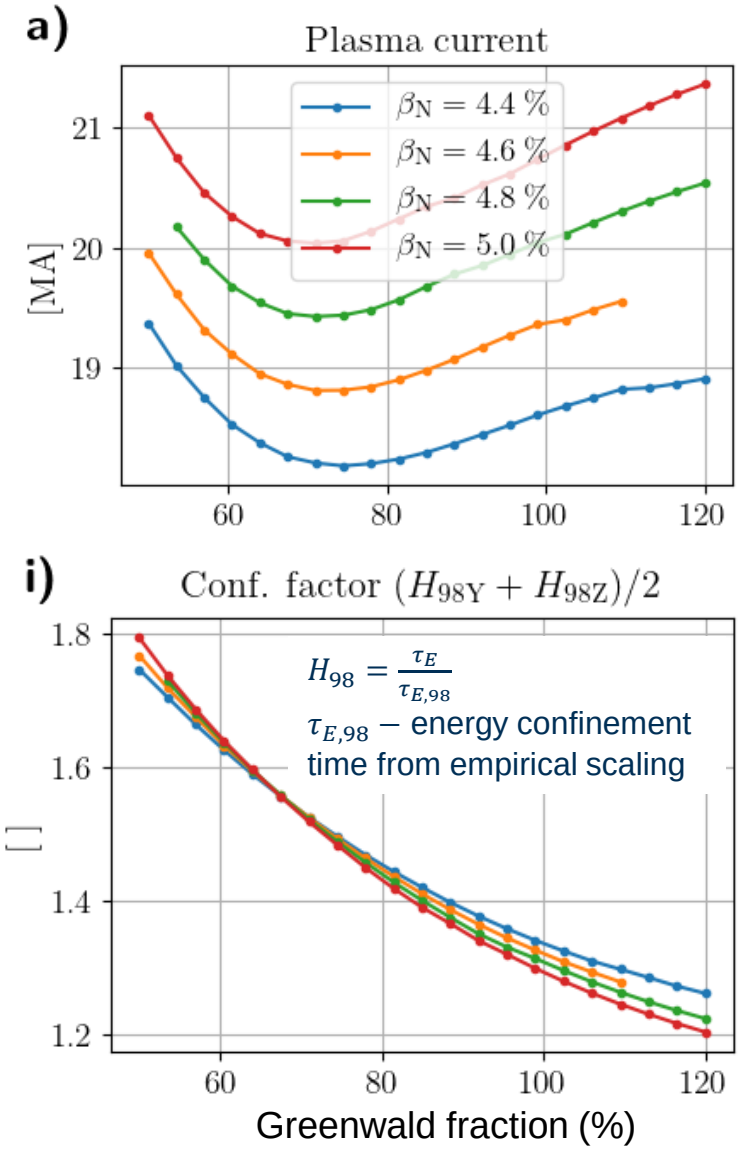
cartoon courtesy of Y.M. Peng

$$\beta_N = \frac{\beta}{I_p/aB_T} \qquad f_{BS} = I_{BS}/I_p$$

(I_{BS}: bootstrap current)

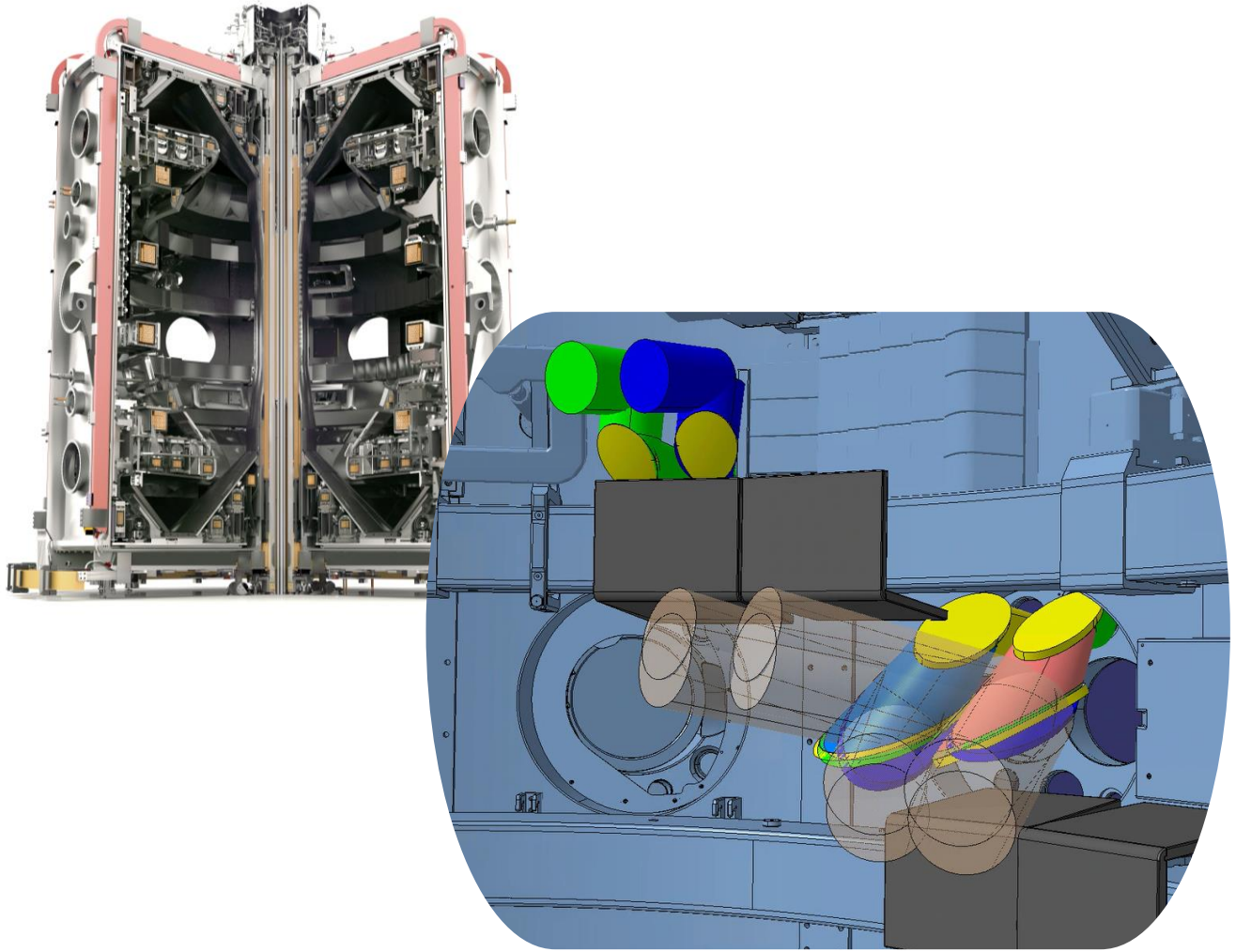
Confinement uncertainty traded against uncertainty in current drive efficiency

- Minimising requirement on plasma confinement at fixed β_N requires operation at high density ⇒ high Greenwald fraction f_{GW}
- Scans performed at fixed P_{aux} with fuelling adjusted to achieve target f_{GW}
- Electron cyclotron current drive (ECCD) efficiency η_{CD} is low at high density ⇒ requires high bootstrap current fraction f_{BS}
- High f_{BS} requires high confinement H_{98} ⇒ no operational point with pure ECCD & $1 \lesssim H_{98} \lesssim 1.2$
  - Lower plot: non-intuitive scaling of $H_{98} \sim \beta_N^{0.14}$
- Electron Bernstein waves (EBWs) expected to provide higher η_{CD}
  - ➢ wider operational space but moves risk to current drive technique with less mature physics basis



E. Tholerus, F. Casson

1.8 MW microwave system will be installed on MAST Upgrade to test EBW performance on ST



- To address open physics questions, two gyrotrons manufactured by Kyoto Fusioneering will be installed in UKAEA MAST Upgrade spherical tokamak:
  - Dual frequency (28 / 34.8 GHz)
  - Up to ~900kW & ~4.5s pulse length
  - In-vessel launcher capable of:
    - on- / off- axis current drive
    - co- / counter- current drive
    - electron heating (no current drive)
    - solenoid-free start-up
- System will be ready for operation in 2024

M. Henderson, S. Freethy

ST-specific challenges for plasma

UK Atomic Energy Authority

- Compact design ⇒
  - Less surface for tritium breeding
  - Less surface for handling heat & particle fluxes ⇒ **alternative divertor design**
  - Less space for solenoid ⇒ **Need to design for largely non-inductive pulse**
    - Non inductive current drive: challenge that all tokamak reactors need to face eventually!

- Optimisation of pressure-driven current fraction (bootstrap) f_{BS} to reduce need for auxiliary current drive
  ⇒ **operation at high normalised pressure β_N & elongation κ**
  - Operation at high β_N ⇒
    - Need to operate at elevated $q_{min} > 2$ ⇒ efficient **off-axis current drive**
      - access to 2nd stability, avoidance of low n/m neoclassical tearing modes (NTM)
    - Need to actively control resistive wall modes (RWM)
  - Operation at high elongation ⇒
    - Need to operate at low internal inductance l_i ⇒ efficient **off axis current drive**

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Other challenges are in common with conventional reactor designs!

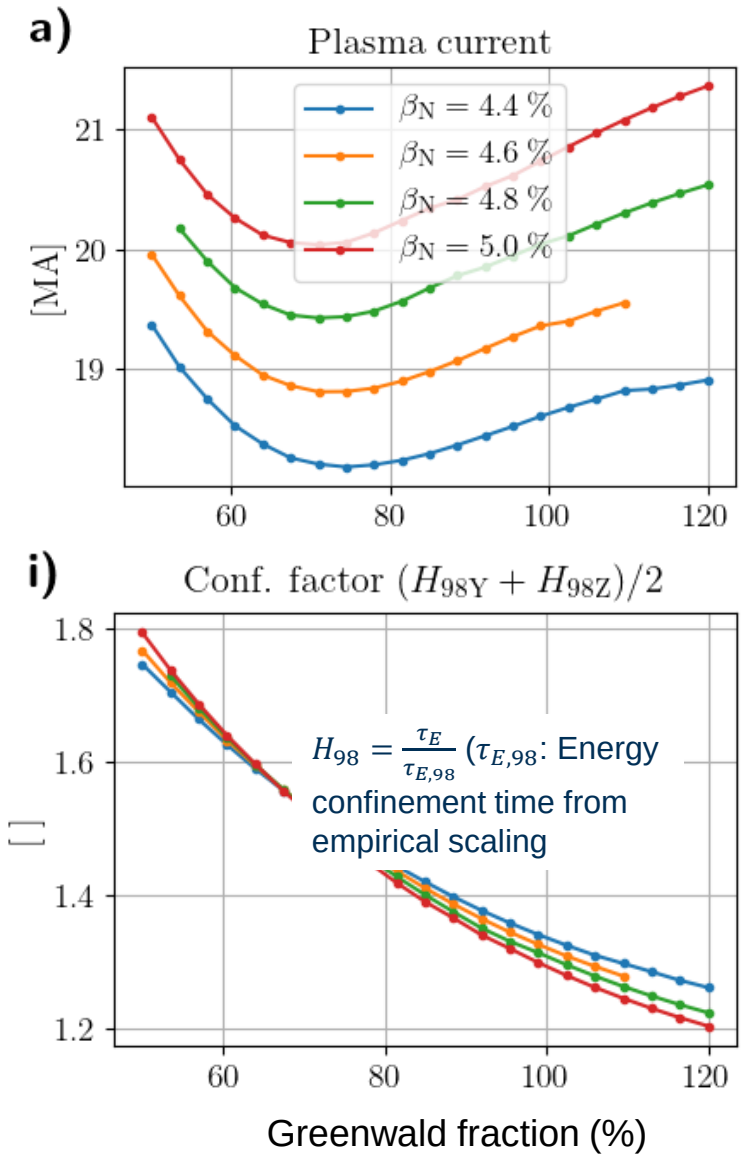
Operation without large edge localised modes (type-I ELMs)

Operation & control of self organised plasma at high radiation & bootstrap fraction

Control with scarce actuators & sensors

Trade uncertainty on confinement against uncertainty of current drive method

- To minimise the requirement on plasma confinement at fixed β_N requires operation at high density ⇒ high Greenwald fraction f_{GW}
- Electron Cyclotron current drive (ECCD) efficiency, η_{CD}, is low at high density ⇒ high bootstrap current fraction f_{BS}
- High f_{BS} requires high confinement assumption H_{98} ⇒ no operational point with low $1 \lesssim H_{98} \lesssim 1.2$ with ECCD
  - At high f_{BS} and Q ⇒ non intuitive scaling of $H_{98} \sim \beta_N^{0.14}$
- Electron Bernstein Wave expected to have much higher η_{CD} ⇒ wider operational space but moves risk to current drive technique with less mature physics basis



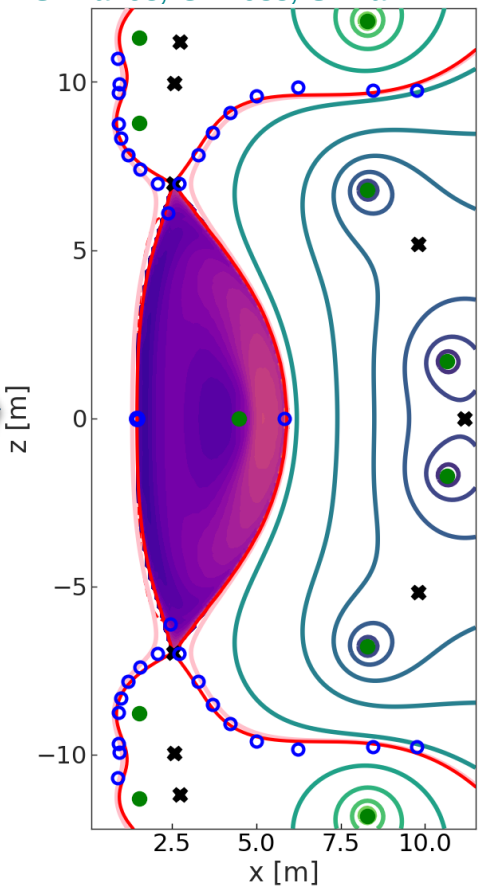
E. Tholerus, F. Casson

Development of an engineering concept optimiser

UK Atomic Energy Authority

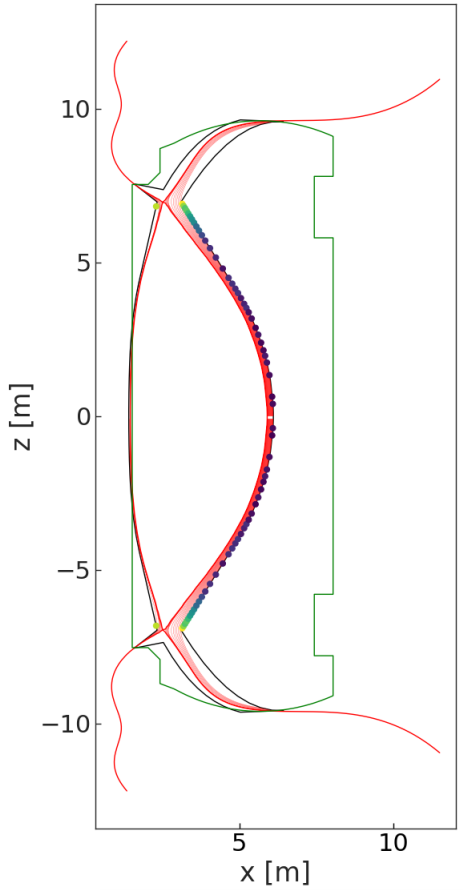
PROCESS
JETTO

PF coil sets optimisation: A. Hudoba, S. Bakes, G. Voss, S. Kahn



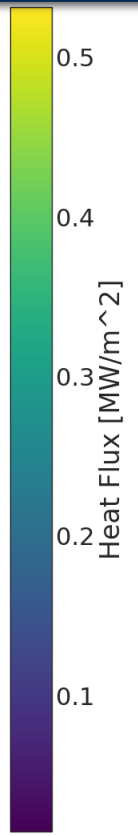
Free boundary Equilibrium

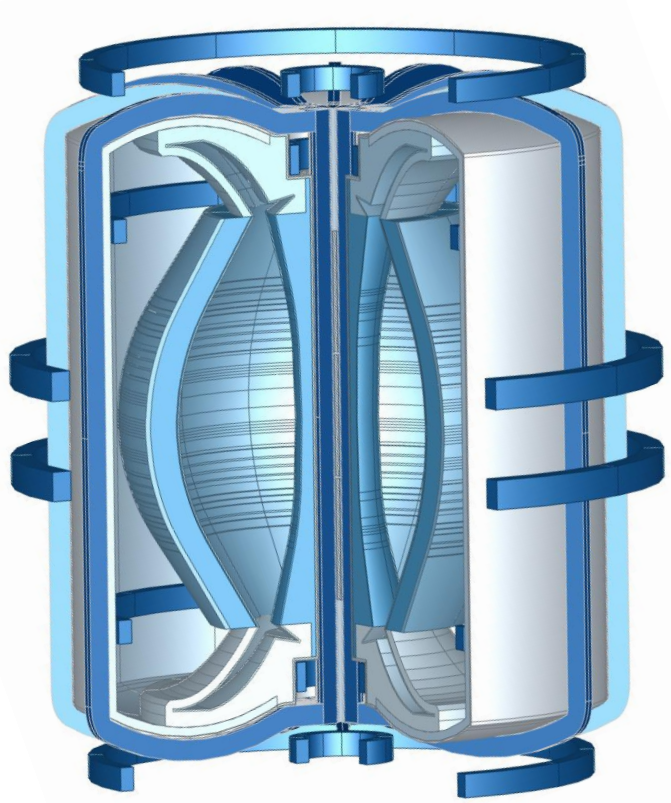
Wall: D. Vaccaro, J. Harrison



First wall

PF coil optimisation in progress
TF optimisation with selected shapes reducing TF ripple





Reduced 3D CAD

BLUEPRINT development: S. Kahn, M. Coleman

STEP will have a small $\psi \sim 9\ Vs$ solenoid to allow break down & initial limited ramp-up

UK Atomic Energy Authority

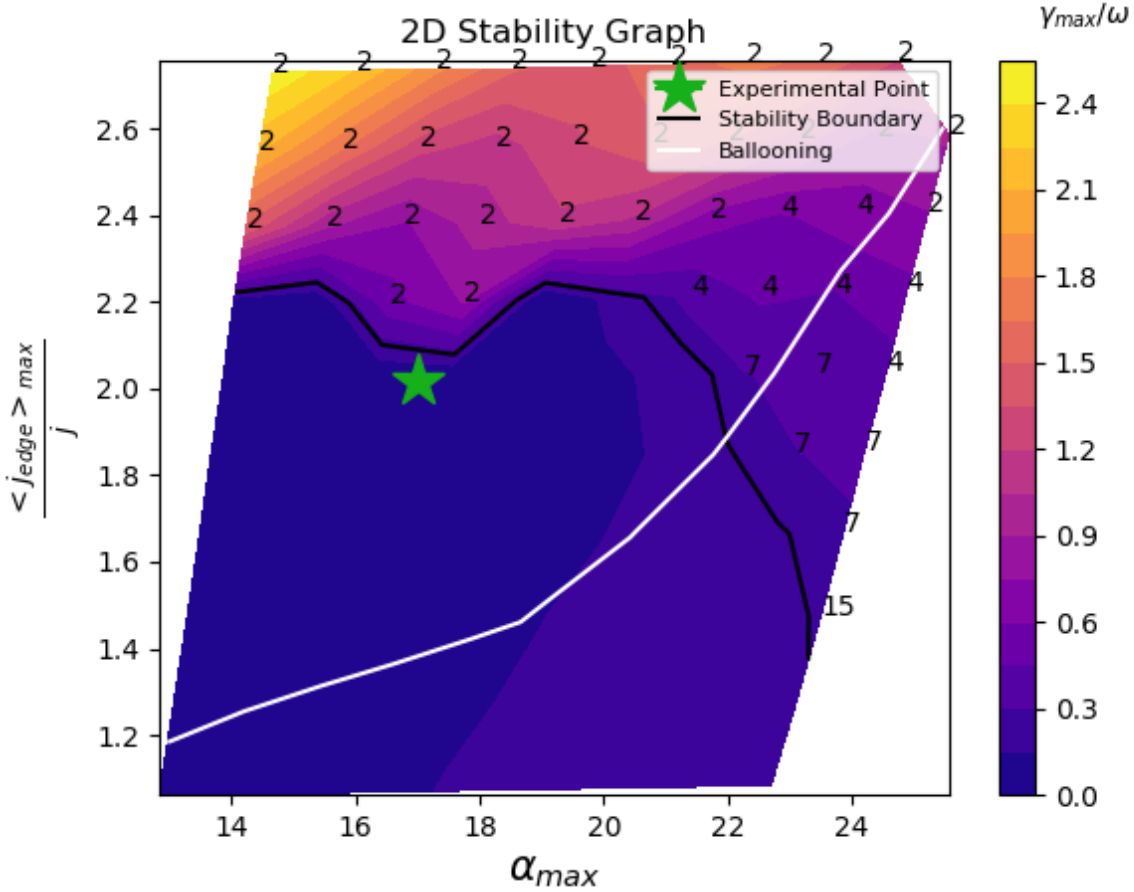
- DYON code used to assess break-down
  - So far pessimistic assumption with no ECRH
  - Field-null evolution included

- First assessment $V_{loop} \sim 20\ V$ and $\psi \sim 1.4\ Vs \Rightarrow I_p \sim 0.4\ MA$
  - ECRH/ECCD assist should make it possible to reduce V_{loop}

- Inductive limiter phase to generate initial target plasma.
  - Modelling shows $I_p \sim 1\ MA$ with $\psi \sim 2\ Vs$
  - Need to increase plasma volume & elongation to allow divertor formation for non-inductive phase.

STEP plasmas fulfil necessary condition to allow access to quiescent H-mode

- Large edge localised modes (type I ELMs) cannot be tolerated in STEP ⟹ **ELM free regimes needed**
  - Energy fluence per ELM much higher than melt limit of W
- Better pedestal performance relieves requirements on core performance.
  - Pedestal pressures that are too high may lead to intolerable α-particle losses
- Pedestal performance found to be insensitive to separatrix density n_{sep} ⟹ **main driver of plasma triangularity δ**



S. Saarelma, S. Smith, B. Chapman-Oplopoiou

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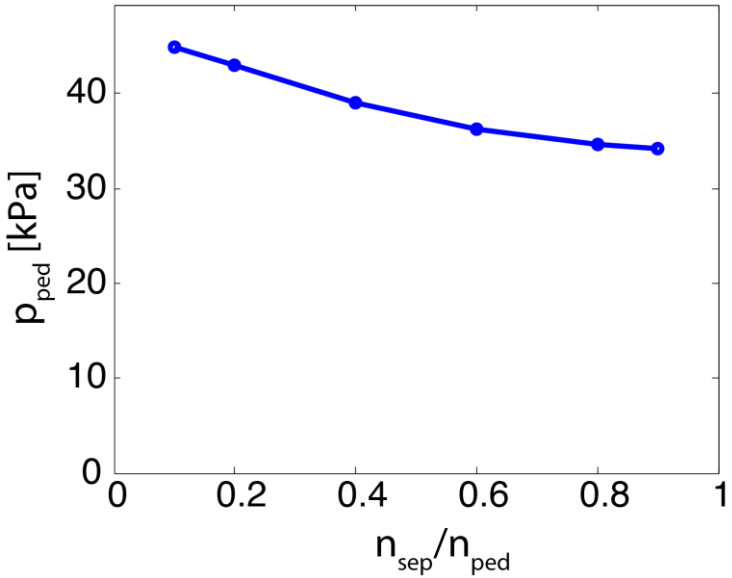
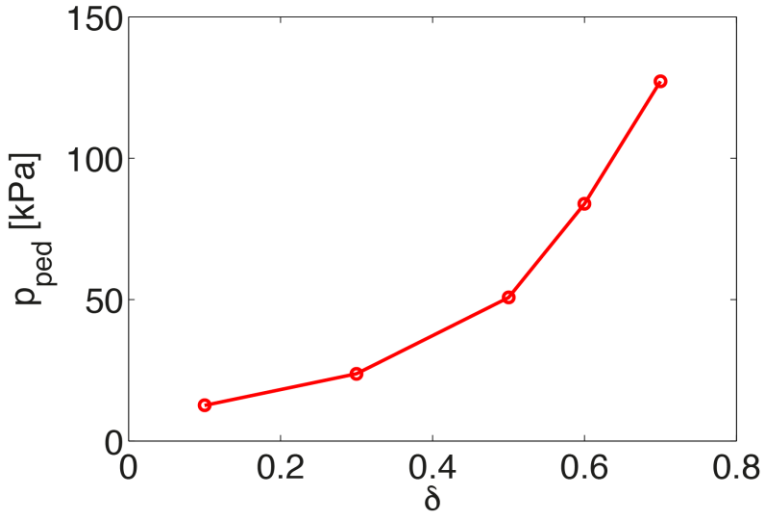


$R_{geo} = 2.5\ m$
$B_t = 2.3\ T$

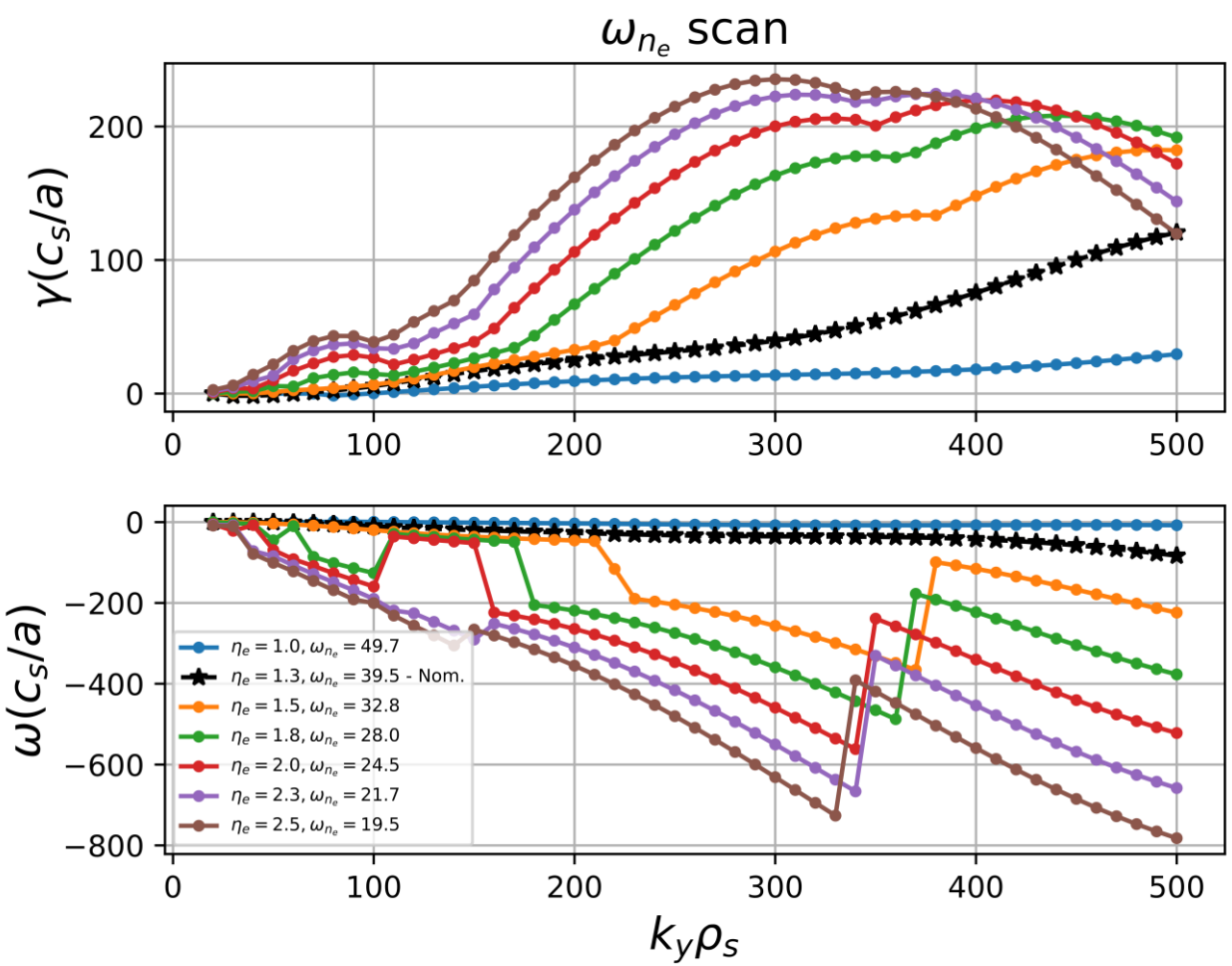


S. Saarelma, S. Smith, B. Chapman-Oplopoiou

Linear gyrokinetic analysis suggests that ETGs could limit pedestal gradients

UK Atomic Energy Authority

- First linear GK analysis for typical STEP pedestal using gyrokinetic code GENE
  - Motivated by findings from JET
- Profiles close to marginal stability for slab-ETGs
  - Increasing $\eta_e = L_{n_e}/L_{T_e}$ by varying density gradient reveals robust slab-ETG modes



ETG: Electrostatic electron temperature gradient driven mode

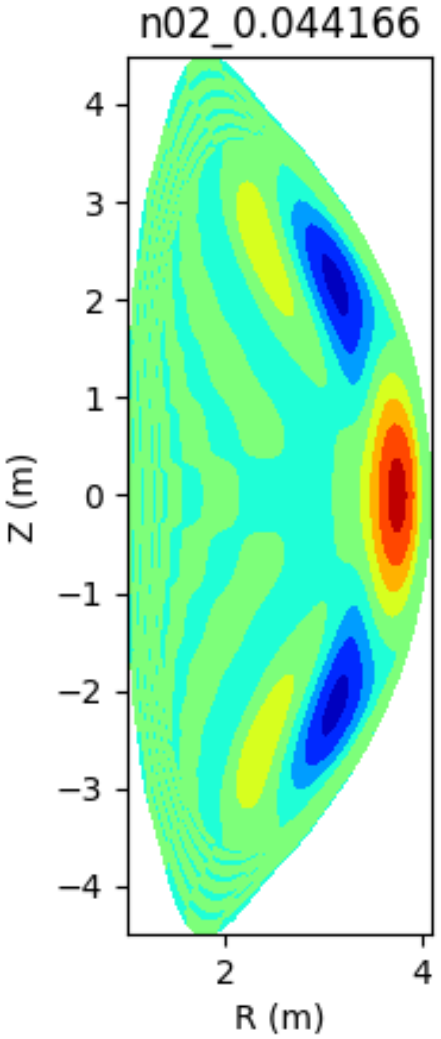
B. Chapman, S. Saarelma

TAE thermal damping stronger than growth

UK Atomic Energy Authority

- STEP equilibria have wide spectrum of toroidal Alfvén Eigenmodes (TAES), some with broad radial structure & relatively high α-particle drive $\frac{\gamma_{TAE}}{\omega} \sim 0.2$
  - ➢ TAEs can degrade α-particle confinement

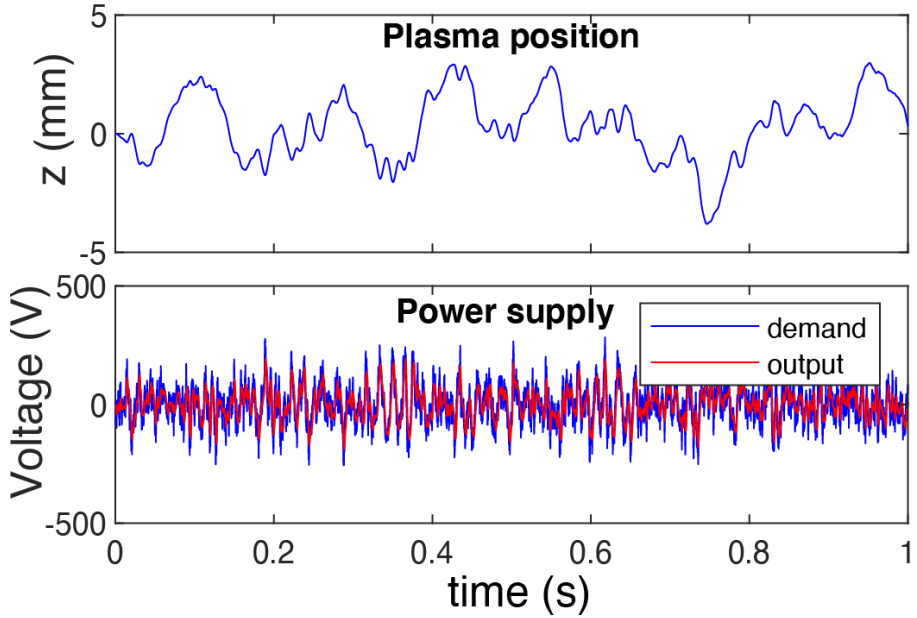
- However TAEs predicted to be stable in flat-top due to high β & consequent strong thermal ion damping
  - May become problematic for phase when current is ramped-up & thermal ion β is low
    - ➢ modes could be driven by hot electrons
  - Higher frequency (ellipticity/triangularity induced) Alfvén eigenmodes also need to be investigated

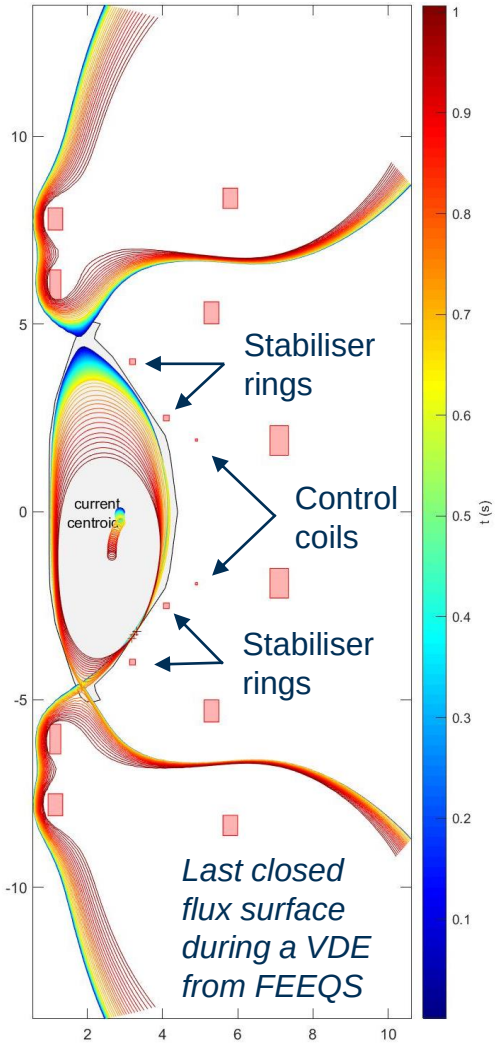


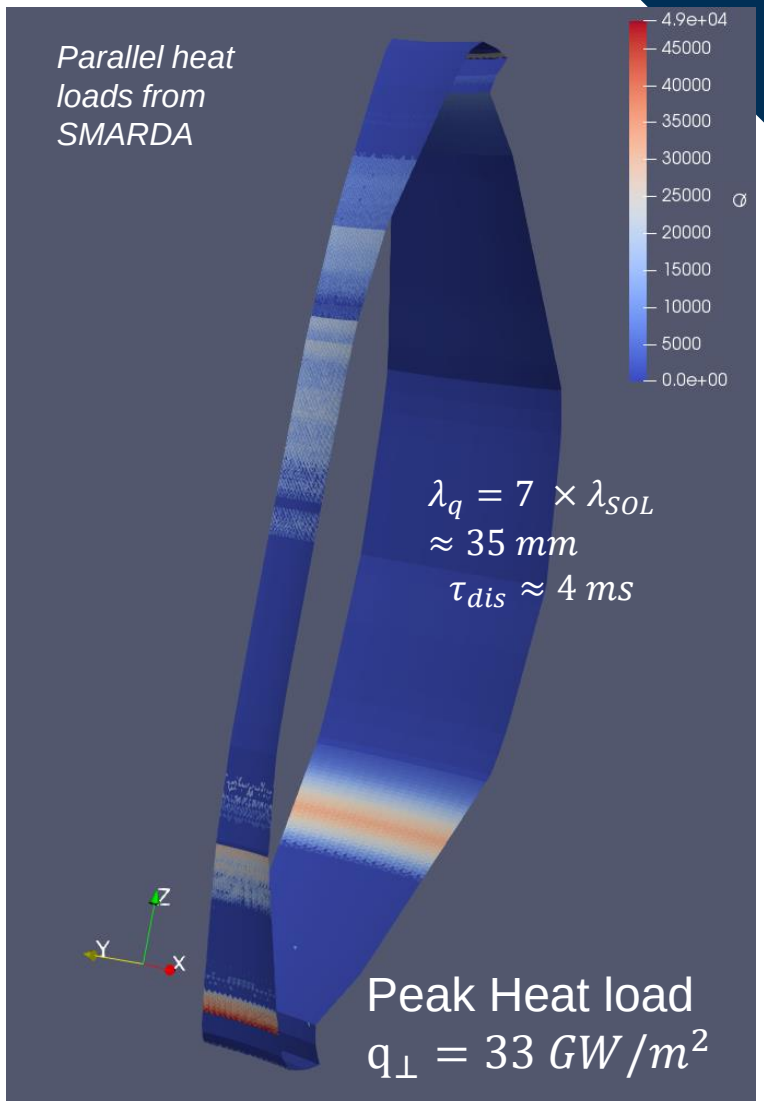
M. Fitzgerald, K. McClements

Passive stabiliser rings and in-vessel coils needed for vertical control

- Loss of vertical control can lead to high disruption heat loads
- High accuracy needed to protect inner divertor
  - achieve $\pm 4\ mm$ with assumed RMS noise of 1 ms^{-1}





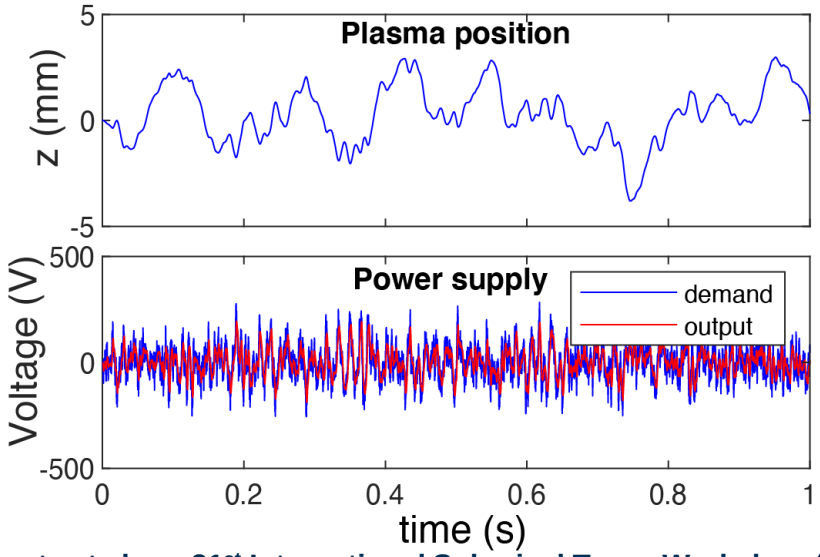


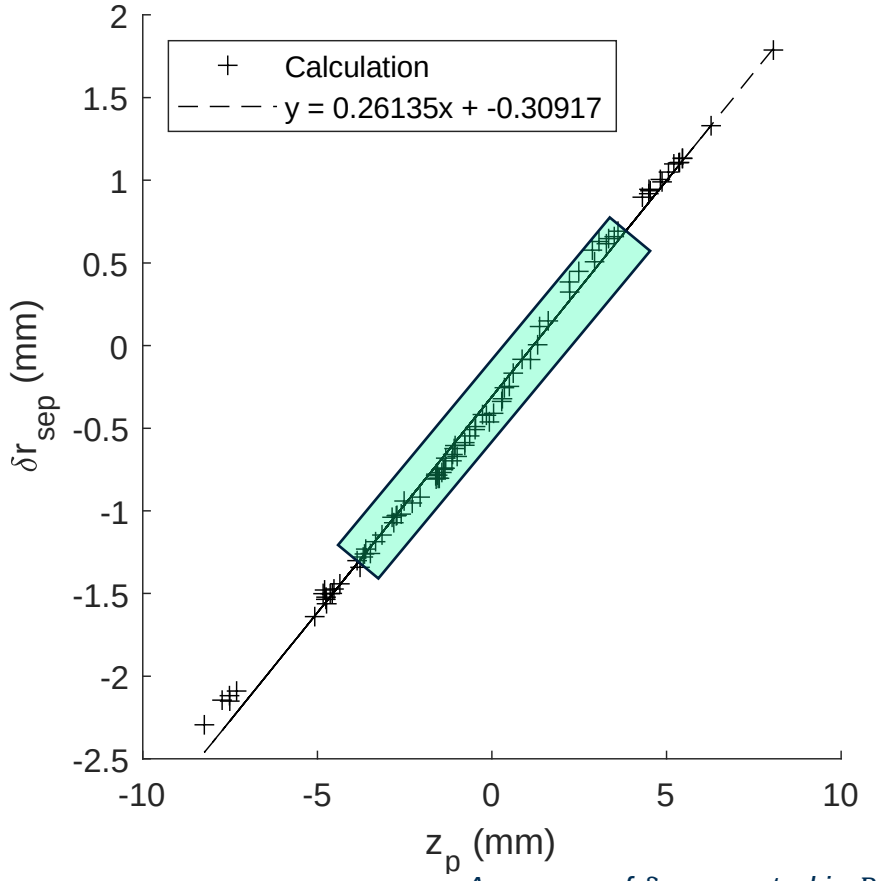
O. Bardsley, S. Bakes, M. Lennholm

W. Arter

Accurate vertical control is needed to protect inner leg by keeping $|\delta r_{sep}| < |\lambda_{SOL}| \sim 1-2\,mm$

- SPP heat loads marginal in single null (SN) ⇒ **dynamic** double null (DN) likely needed for commercial plant
- Power distribution between four divertor legs changes dynamically as the plasma oscillates vertically due to control action
- Initial assessment of vertical control system with *mock RMS noise of 1 m/s* shows promising performance
  - In vessel coils + passive stabilising rings





Accuracy of δr_{sep} control in $R = 2.5\,m$ (SPR-017) device normalised to 1 m/s RMS noise on the vertical velocity measurement.

O. Bardsley, S. Bakes, M. Lennholm

H&CD mix is pure microwave dimensioned for EC but compatible with EBW

UK Atomic Energy Authority

2021 decision:
- Determine HCD mix for STEP ramp-up
- Determine HCD mix for STEP flat-top

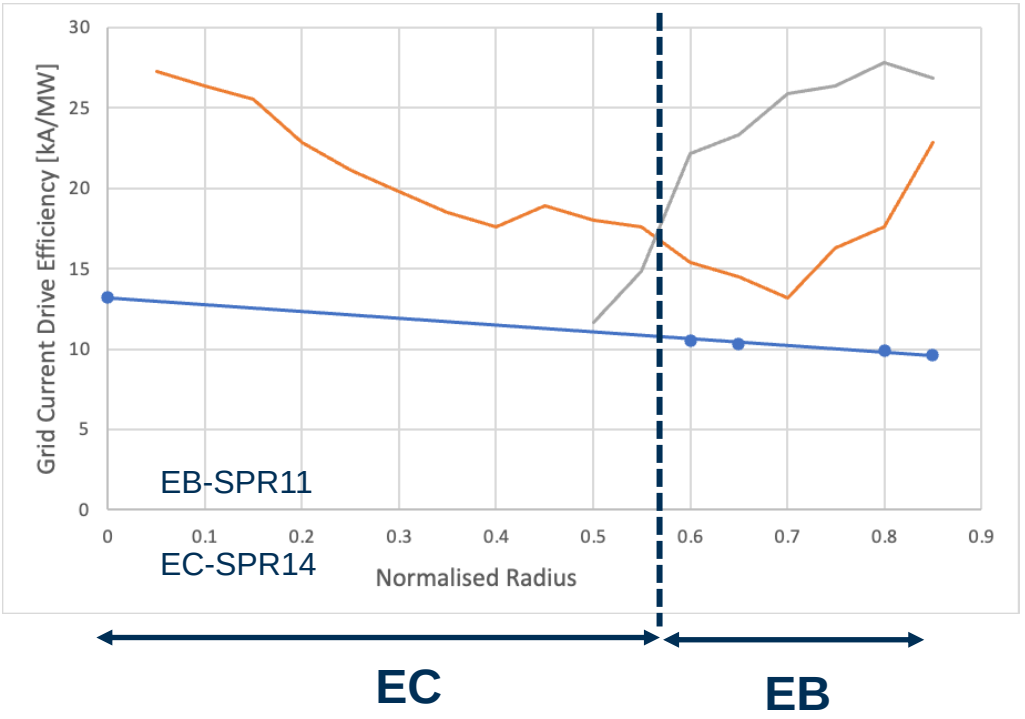
2022 decision:
- Determine HCD mix for STEP ramp-down

Options: NB, IC, LH, HW, EB and EC

Documentation:
- Define Functional Requirements: HCD SRD
- Determine evaluation criteria: HCD Mix Evaluation Criteria
- Evaluation Report: CML3.5 HCD Mix Evaluation Report

	Criteria	NB	EC	EB	HW
1	$\langle\eta_{CD}\rangle$ (0.5 < ρ <0.85) [kA/MW]	~30	~37	~58	TBD
2	Plug-to-Plasma, Target $\eta_{grid} \geq 45\%$	~30%	~44%	~44%	TBD
3	Compatible for Start-up	No	Yes	Partial	No
4	Current Profile Control	Partial	Yes	Partial	TBD
5	VV, Blankets, Magnets Impact	High	Medium	Low	High
6	Building Impact	High	Medium	Medium	TBD
7	System costs	Medium	Low	Low	TBD
8	Impact to STEP Costs	High	Medium	Low	TBD
9	Risks of Technology Level	Medium	Low	High	High
10	RAMI	Low	High	High	Low

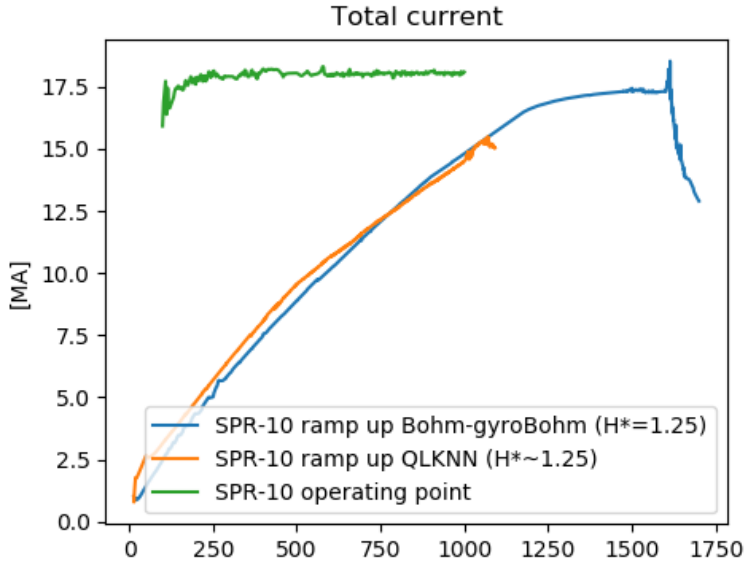
Drive Current [kA] / Grid Power [MW]

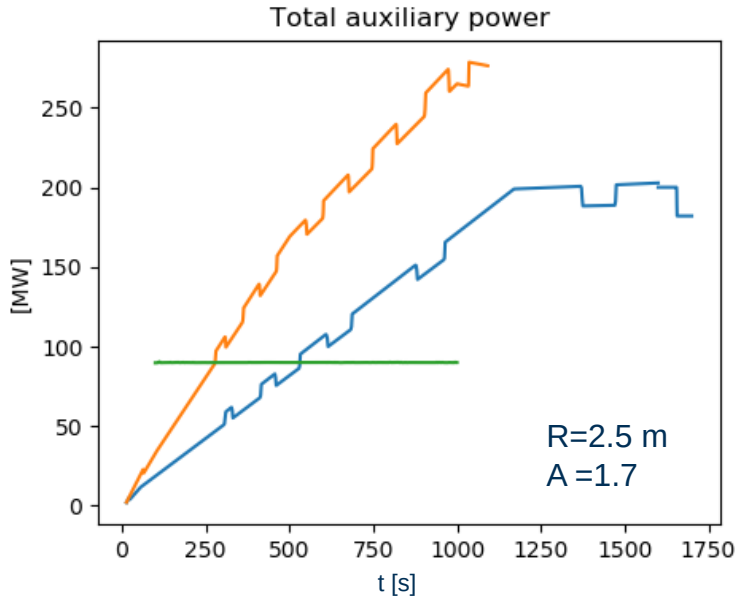


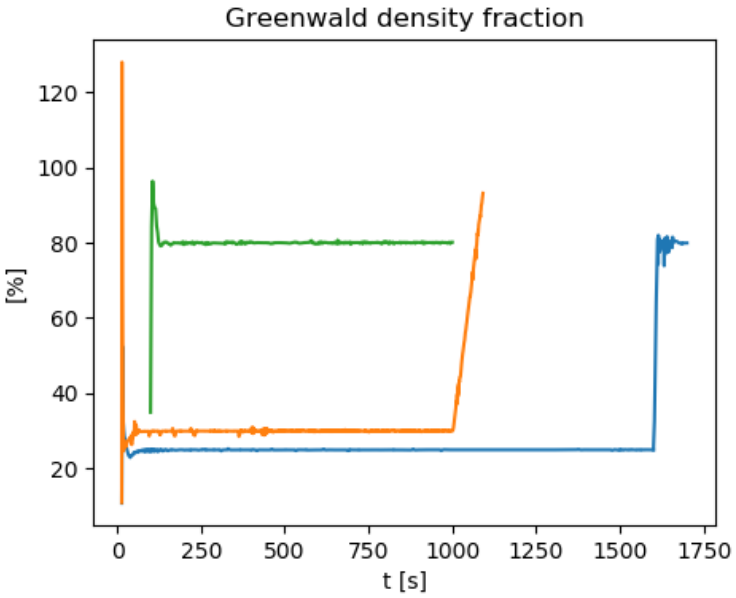
M. Henderson, S. Freethy, I. Konoplev, K. Kirov, R. Sharma

Non inductive ramp-up requires high heating & current drive power, & lasts ~ ½ h

- Limited solenoid flux requires non-inductive ramp-up ⇒ low density for efficient current drive to reduce P_{CD}
- Access to operating point by “fast” density ramp at full current
- $T_e \gg T_i$ during initial low-density phase.
  - May lead to T_i clamping as observed in AUG & W7-X
- Operating point reached with $P_{CD} > 200\ MW$.







F. Casson, F. Eriksson, Y. Baranov,, C.D. Challis, F. Koechl, T. Wilson, S. Marsden, K.K, Kirov, T. Wilson, R. Sharma, L. Figini

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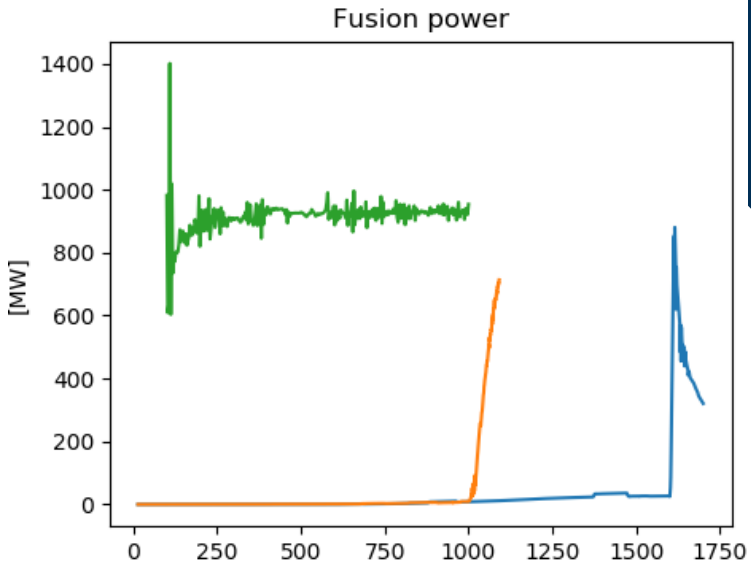

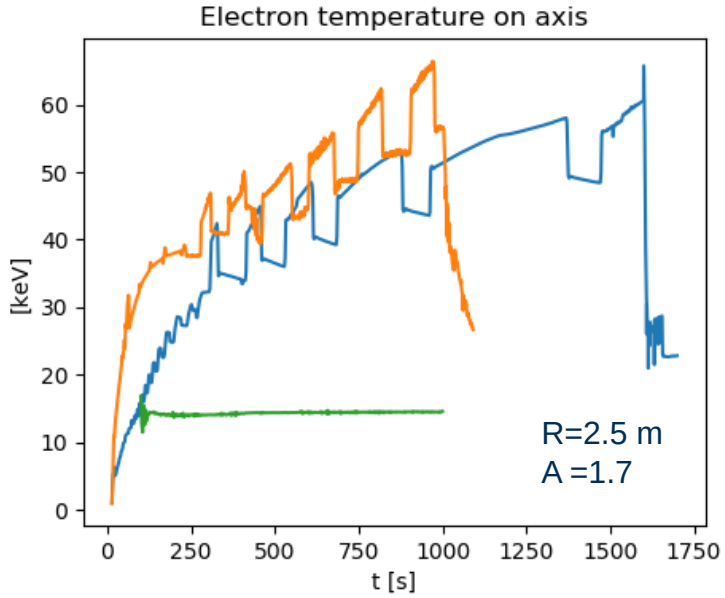

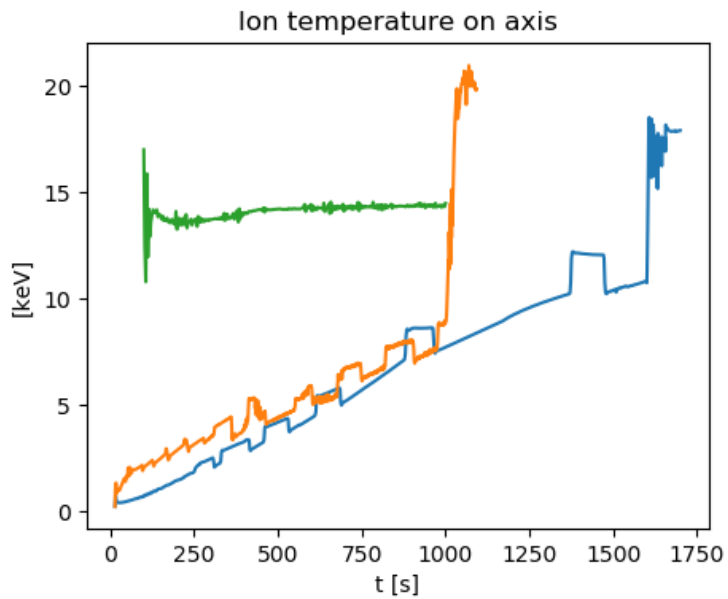

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