



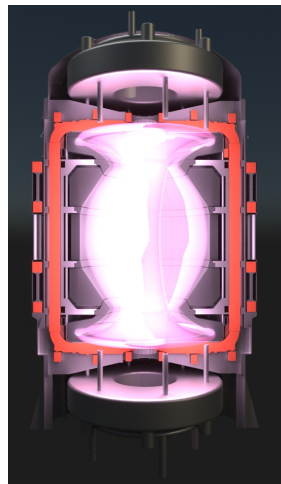
Analysing flat-top operational space of STEP reactor design

The 21st International Spherical Torus Workshop, 02/11/2022

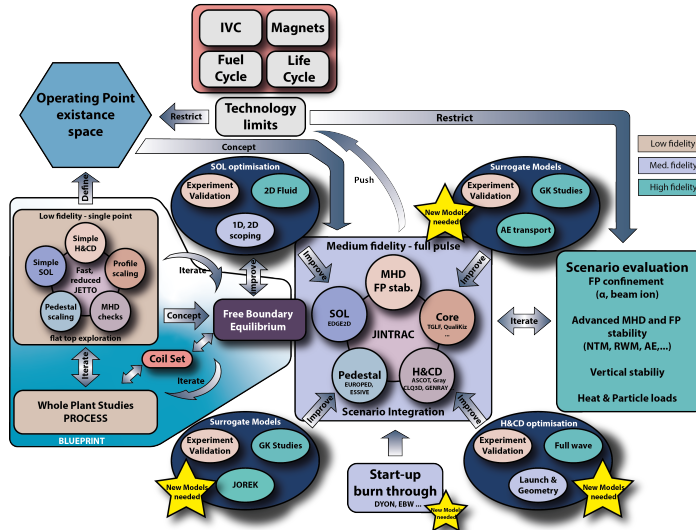
E. Tholerus, F.J. Casson, T. Wilson, S. Marsden, H. Meyer, S. Freethy, and STEP team

STEP: Spherical Tokamak for Energy Production

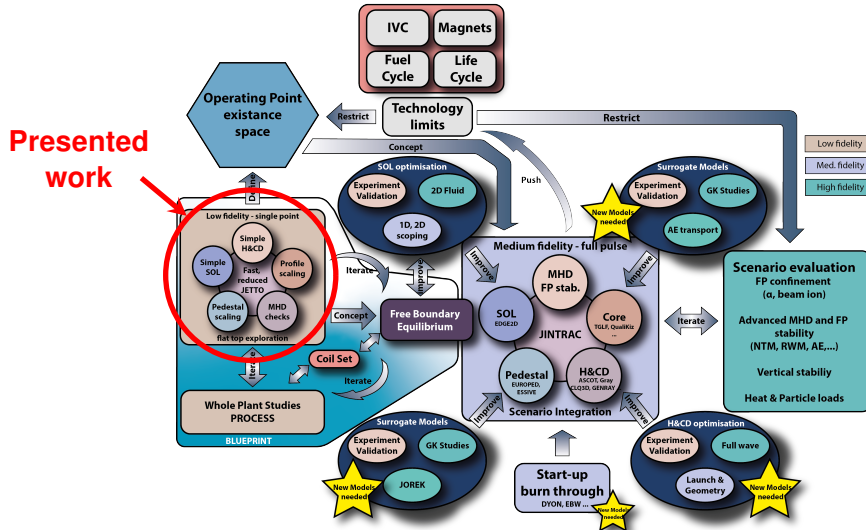
- ▶ Designed to deliver net electric output power
 - A “DEMO” of spherical tokamaks
- ▶ To be built in UK, Nottinghamshire, starting operation in early 2040s
- ▶ $R_{\text{maj}} = 3.6 \text{ m}$, $a_{\text{min}} = 2.0 \text{ m}$, $\kappa = 2.8$, $B_t = 3.2 \text{ T}$, $I_p \gtrsim 20 \text{ MA}$
- ▶ Double null divertor configuration
- ▶ Non-inductive current drive
 - EC and EBW primary auxiliary H&CD systems



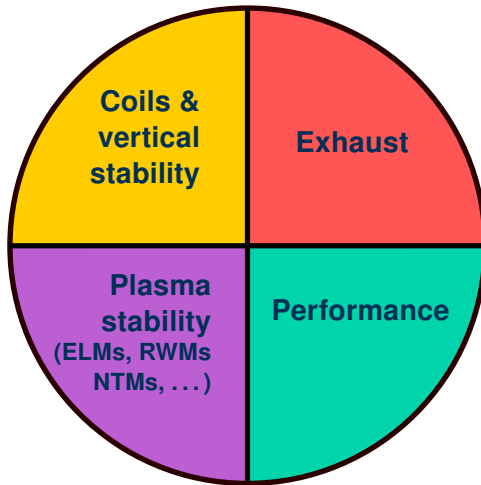
Modelling workflow for STEP design



Modelling workflow for STEP design



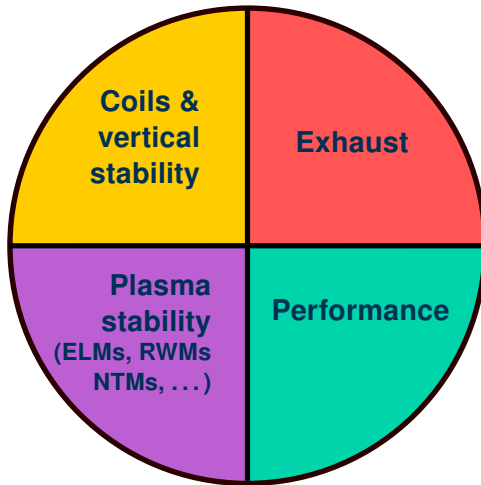
Operational constraints



Operational constraints

- ▶ Plasma current (non-inductive)
- ▶ Internal inductance

- ▶ Plasma β_N
- ▶ Greenwald fraction
- ▶ q -profile



- ▶ Impurity radiation
- ▶ Fusion products

- ▶ Fusion Q
- ▶ H&CD efficiency

JETTO: Integrated core plasma model

Considers key aspects of core plasma physics:

- ▶ Heating and current drive (auxiliary H&CD, ohmic & alpha heating, bootstrap current, . . .)
- ▶ Transport (neoclassical, anomalous transport, ETB)
- ▶ Losses (core impurity radiation, Bremsstrahlung, synchrotron radiation)
- ▶ Equilibrium (fixed boundary solver)
- ▶ MHD instabilities (ELMs, sawteeth)

JETTO: Parameter scans of flat-top scenarios

Main task:

- ▶ Run a set of JETTO simulations in a wide parameter space (varying e.g. heating & fuelling) until they reach stationary conditions
- ▶ Analyse 0D output parameters to understand trends within the operational space
- ▶ Compare outputs against operational limits (e.g. fusion Q , plasma current, internal inductance) to understand limitations of the operational space and identify sweet spots

JETTO: Key parameters

Inputs:

- ▶ Auxiliary power
 - EC
 - EBW
- ▶ Greenwald density fraction
- ▶ β_N
- ▶ Radiation fraction
 $P_{\text{rad}}/(P_{\text{aux}} + P_{\alpha} + P_{\text{ohm}})$

Outputs:

- ▶ Fusion power
- ▶ Fusion Q
- ▶ Plasma current
- ▶ No-wall β_N limit
- ▶ q -profile
- ▶ Internal inductance
- ▶ $P_{\text{sep}}/R_{\text{geo}}$
- ▶ Conf. time τ_E and conf. factor
 $H = \tau_E/\tau_{\text{scaling}}$

JETTO: Anomalous transport assumptions

Anomalous transport is estimated using the Bohm/gyro-Bohm model, rescaled to reach a set target β_N (unless stated otherwise):

- ▶ Electron transport dominates, supported by linear GK modelling and ST experiments
- ▶ Rescaling factors of anomalous diffusivity calculated in feedback loop with β_N , continued until reaching $\beta_{N,target}$

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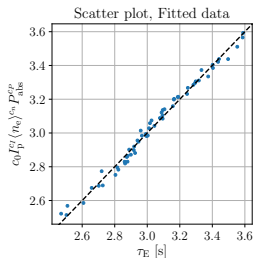
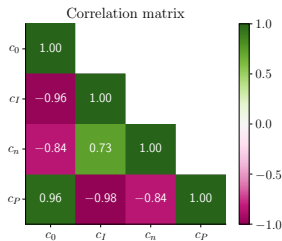
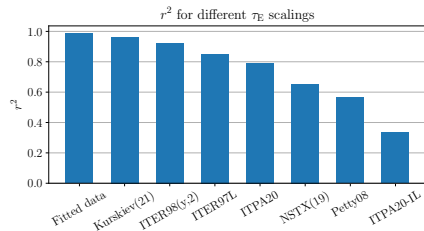
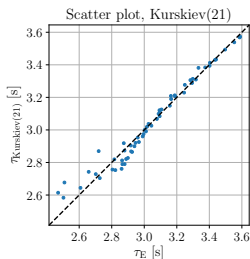
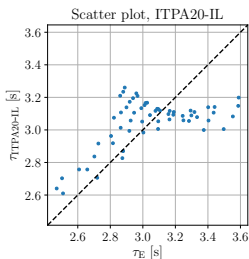
Allows us to study β_N independently of other plasma parameters. *Caveat:*

- ▶ Transport rescaling can drift to unphysical domains
- ▶ Need to monitor confinement factor so that it doesn't grow unreasonably large
 - Ideally $H \lesssim 1.2$
 - Additional study to conclude best scaling laws to use

Additional study: Confinement scaling law

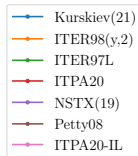
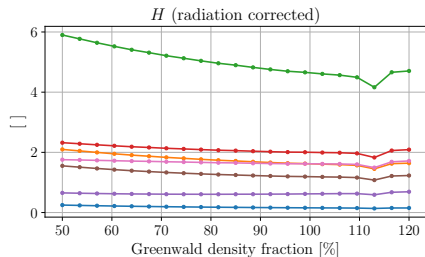
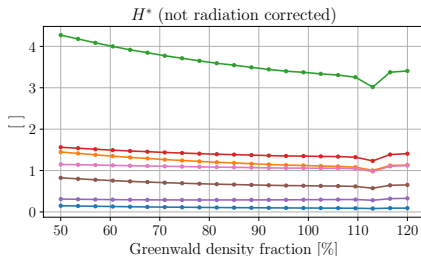
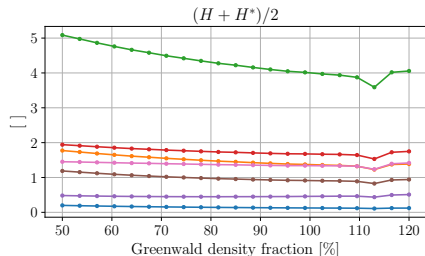
- ▶ Scan of flat-top simulations using *fully predictive* transport assumptions, rather than feedback with β_N
 - Rechester–Rosenbluth: Physics based reduced transport model
- ▶ Find power law $\tau_E = c_0 I_p^{c_I} \langle n_e \rangle^{c_n} P_{\text{abs}}^{c_P}$ that best fits the data
- ▶ Insert power laws of empirical scaling laws to see which ones best capture $\tau_E(I_p, \langle n_e \rangle, P_{\text{abs}})$

Additional study: Confinement scaling law

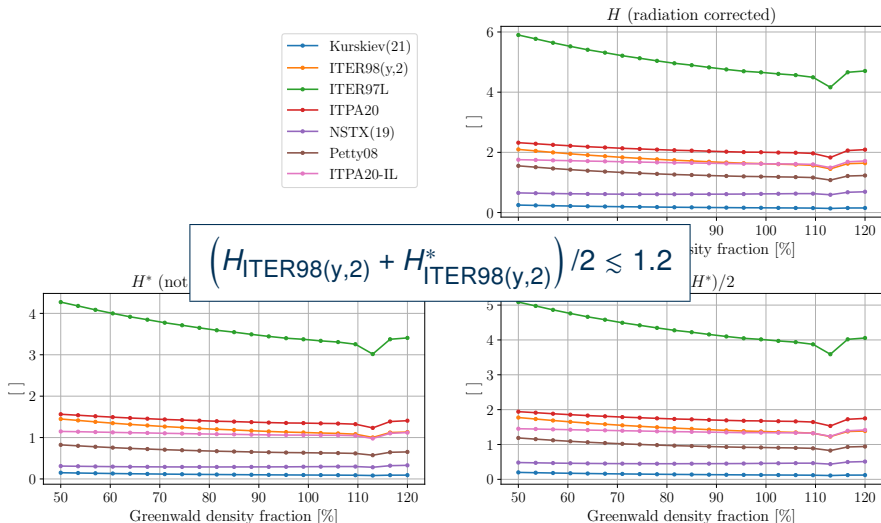


	c_I	c_n	c_P	r^2
Fitted data	0.937	0.661	-0.761	0.987
Kurskiew(21)	0.53	0.65	-0.58	0.964
ITER98(y,2)	0.93	0.41	-0.69	0.924
ITER97L	0.96	0.40	-0.73	0.850
ITPA20	0.98	0.24	-0.669	0.791
NSTX(19)	0.54	-0.05	-0.38	0.655
Petty08	0.75	0.32	-0.47	0.564
ITPA20-IL	1.29	0.147	-0.644	0.334

Additional study: Confinement scaling law



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Summary of scans & limits

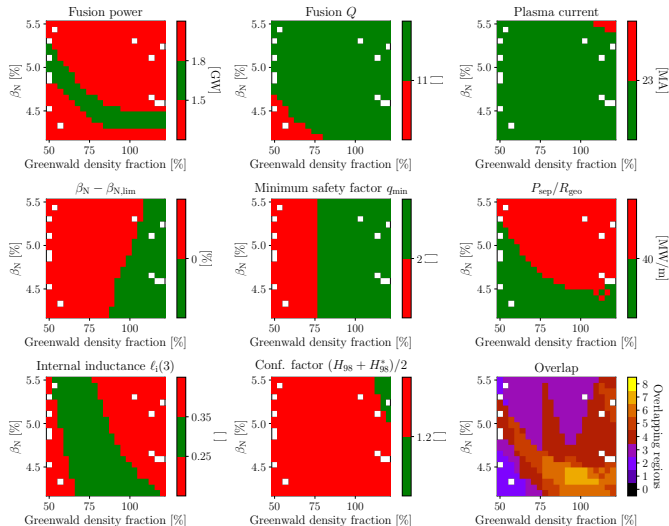
Three 2D scans:

- ▶ Greenwald fraction $\langle n_e \rangle / n_{GW}$ & Normalised beta β_N
 - $P_{EC} = 120 \text{ MW}$ ($P_{EBW} = 0$)
 - $P_{rad} / P_{tot} = 70 \%$
- ▶ EBW power P_{EBW} & EC power P_{EC}
 - $\beta_N = 4.12 \%$
 - $\langle n_e \rangle / n_{GW} = 100 \%$
 - $P_{rad} / P_{tot} = 70 \%$
- ▶ EBW power P_{EBW} & Radiation fraction P_{rad} / P_{tot}
 - $\beta_N = 4.12 \%$
 - $P_{EC} = 55.4 \text{ MW}$
 - $\langle n_e \rangle / n_{GW} = 100 \%$

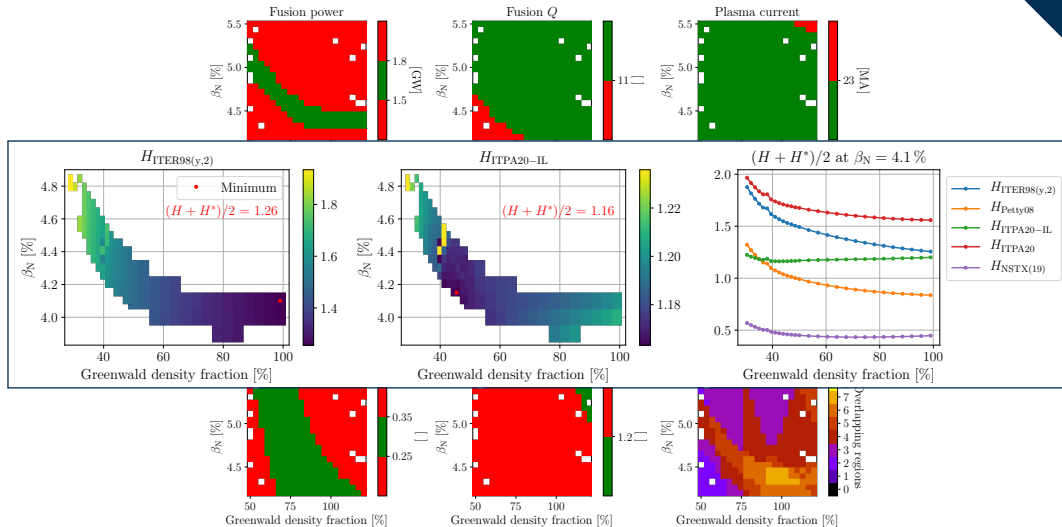
Suggested limits:

- ▶ $1.5 \text{ GW} \leq P_{fus} \leq 1.8 \text{ GW}$
- ▶ $Q_{fus} \geq 11$
- ▶ $I_p \leq 23 \text{ MA}$
- ▶ $\beta_N \leq \beta_{N,lim}$
- ▶ $q_{min} > 2.0$
- ▶ $P_{sep} / R_{geo} \leq 40 \text{ MW/m}$
- ▶ $0.25 \leq \ell_i(3) \leq 0.35$
- ▶ $(H_{98} + H_{98}^*) / 2 \leq 1.2$

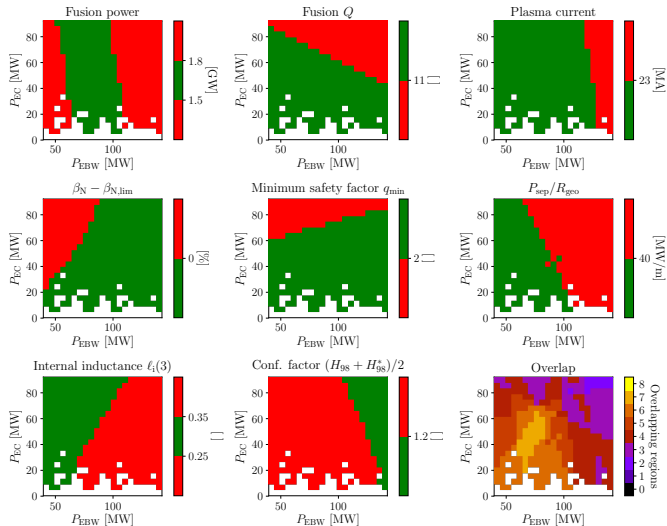
Scan: GW fraction & Normalised beta



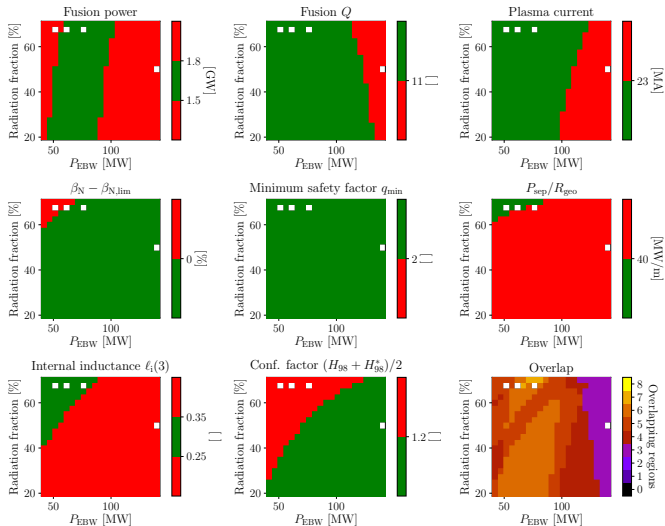
Scan: GW fraction & Normalised beta



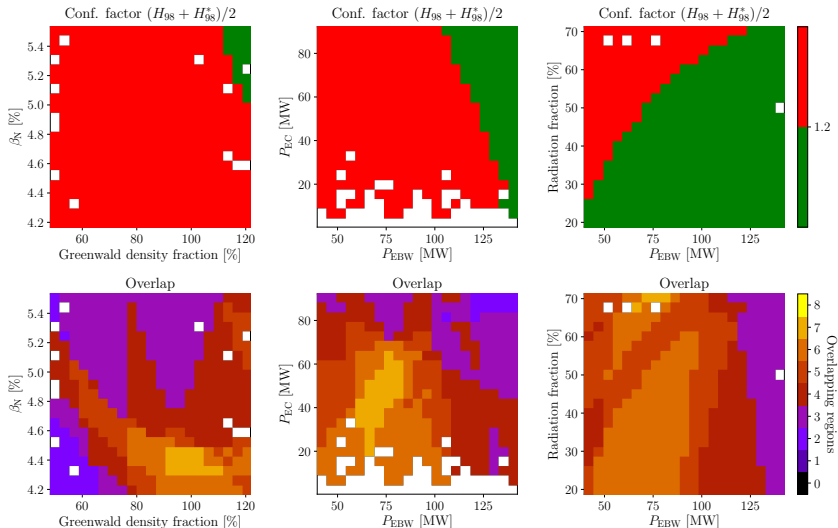
Scan: EBW & EC power



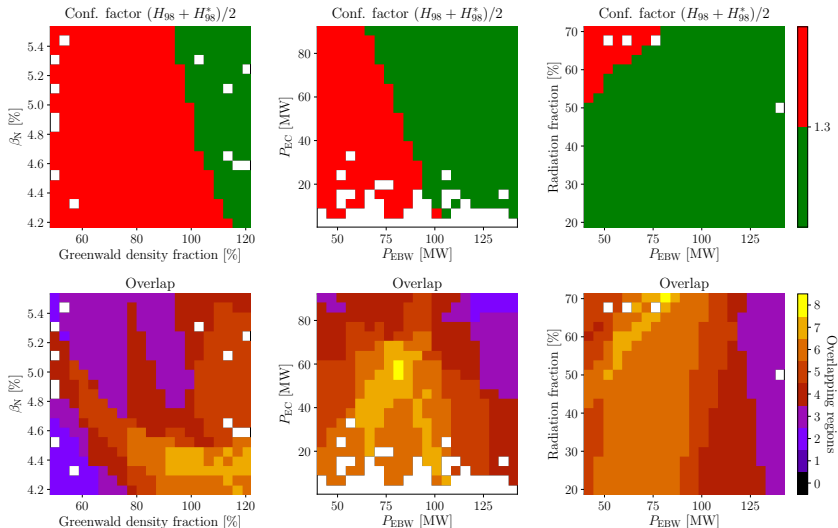
Scan: EBW power & Radiation fraction



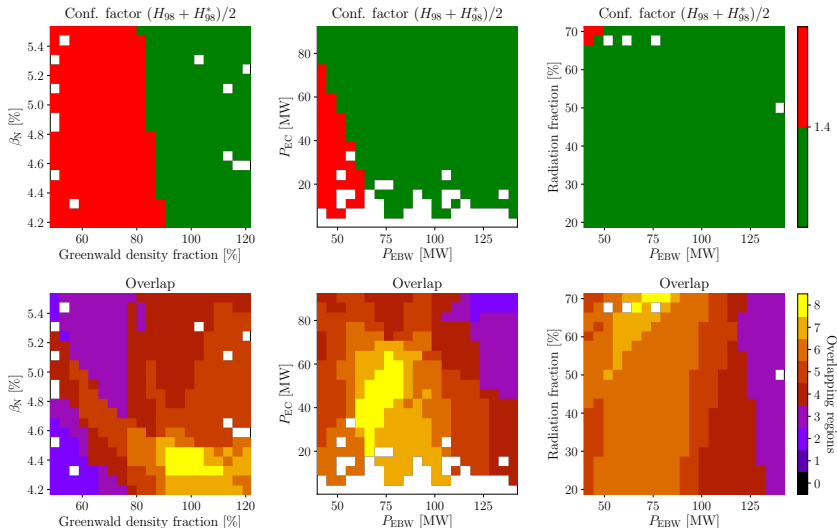
Confinement factor limit



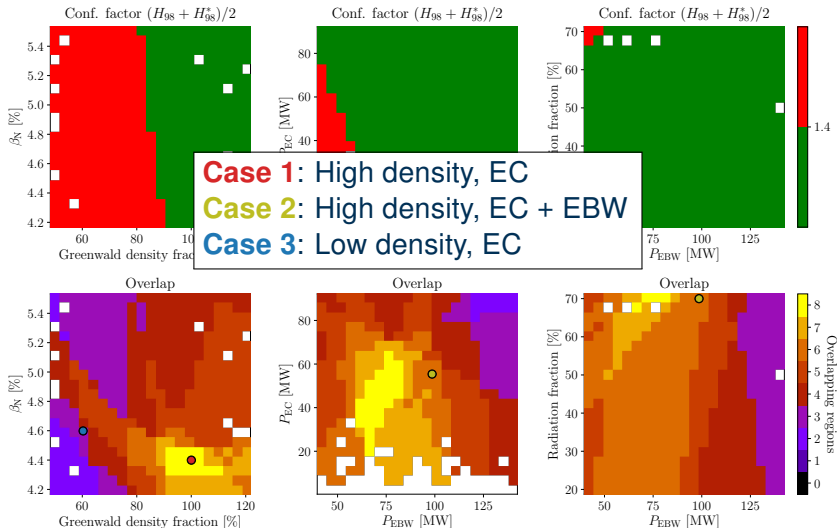
Confinement factor limit



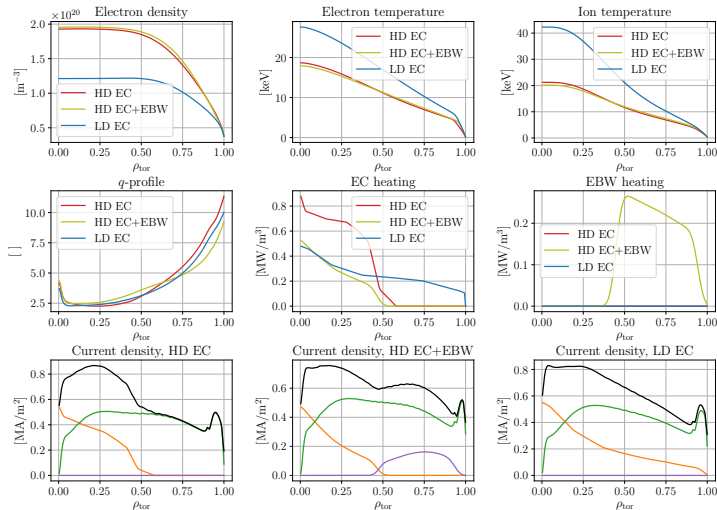
Confinement factor limit



Confinement factor limit



Candidate scenarios



	HD EC	HD EC+EBW	LD EC
P_{fus} [GW]	1.70	1.77	1.63
Q_{fus}	11.23	11.31	10.09
I_p [MA]	20.37	22.00	22.77
I_{BS}/I_p [%]	85.86	77.58	75.94
β_N [%]	4.40	4.12	4.60
$\beta_{N,\text{lim}}$ [%]	4.23	4.54	4.23
q_{min}	2.26	2.45	2.28
q_{95}	9.21	7.57	8.57
$P_{\text{sep}}/R_{\text{geo}}$ [MW/m]	41.12	45.56	40.82
$\ell_i(3)$	0.28	0.25	0.26
$(H_{98} + H_{98}^*)/2$	1.36	1.25	1.59 [†]
P_{EC} [MW]	150.00	55.40	160.00
P_{EBW} [MW]	0.00	98.60	0.00
$I_{\text{aux}}/P_{\text{aux}}$ [kA/MW]	17.52	31.44	33.25
$\langle n_e \rangle / n_{\text{GW}}$ [%]	100.04	93.95	60.30
$P_{\text{rad}}/P_{\text{tot}}$ [%]	70.00	70.00	70.00
P_{rad} [MW]	342.23	355.00	339.30
$\langle n_e \rangle$ [10^{19} m^{-3}]	15.60	15.78	10.63
$\langle T_e \rangle$ [keV]	9.82	9.76	14.65

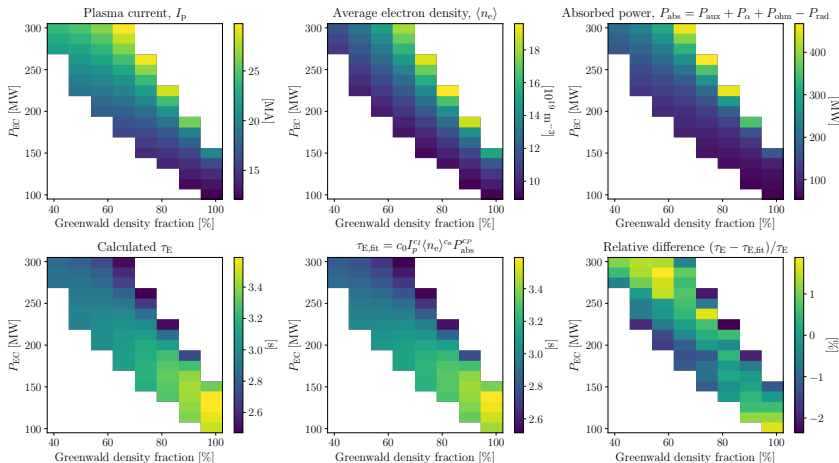
[†] $(H_{\text{ITPA20-IL}} + H_{\text{ITPA20-IL}}^*)/2 = 1.36$

- ▶ Three candidate scenarios have been found:
 - High density, EC heating only
 - High density, EBW + EC heating
 - Low density, EC heating only
- ▶ Physics based reduced transport model showed ITER98(y,2) and Kurskiev(21) provide best scaling law for τ_E w.r.t. I_p , $\langle n_e \rangle$ & P_{abs} variation
- ▶ No scans show domains that satisfy the operation criteria for both power losses P_{sep}/R_{geo} , internal inductance $\ell_i(3)$ and confinement factor $(H + H^*)/2$
 - By increasing the acceptable $(H + H^*)/2$ limit to 1.3, flat-tops with satisfaction of all considered criteria can be found
 - In future studies, reduced transport models will be used fully predictively, rather than rescaled BgB for reaching target β_N

An aerial photograph of a modern, multi-story building with a unique, curved, and somewhat irregular shape. The building features a mix of light-colored panels and darker sections. A large, circular cutaway in the center of the building reveals a bright pink interior space with a large, curved, pink structure that resembles a giant slide or a large piece of machinery. The building is surrounded by lush green trees and a paved area. In the background, there are rolling hills and a body of water. A semi-transparent white box with a blue border is centered over the building, containing the text "Thank you!".

Thank you!

- ▶ τ_E scaling laws
 - ITER98(y,2)/ITER97L: ITER Physics Expert Group on Confinement and Transport *et al.* 1999 *Nucl. Fusion* **39** 2175
 - ITPA20/ITPA20-IL: G. Verdoolaege *et al.* 2021 *Nucl. Fusion* **61** 076006
 - Kurskiev(21): G.S. Kurskiev *et al.* 2021 *Nucl. Fusion* **62** 016011
 - NSTX(19): P.F. Buxton *et al.* 2019 *Plasma Phys. Control. Fusion* **61** 035006
 - Petty08: C.C. Petty 2008 *Phys. Plasmas* **15** 080501
- ▶ JETTO: M. Romanelli *et al.* 2014 *Plasma and Fusion Research* **9** 3204023
- ▶ Anomalous transport
 - Bohm/gyro-Bohm: M. Erba *et al.* 1998 *Nucl. Fusion* **38** 1013
 - Rechester–Rosenbluth: A.B. Rechester and M.N. Rosenbluth 1978 *Phys. Rev. Lett.* **40** 38



Closest fit to data: $c_0 = 1.632$, $c_I = 0.937$, $c_n = 0.661$, $c_P = -0.761$

