Developing plasma scenarios for the updated STEP design point

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Introduction

The Spherical Tokamak for Energy Production (STEP) is a UK programme aiming to design a prototype fusion powerplant with the goal of demonstrating net electricity production [1]. For plasma scenario development, the integrated core plasma model JETTO is used to find viable operational spaces for the different phases of operation [2]. A series of technical reviews of the STEP prototype powerplant (SPP) design concluded that an increase to the machine size was necessary to provide more space within the inboard build. This change provides more space for shielding which improves the protection of the inboard coils from neutrons. After deciding on a larger major radius R_{geo} of 4.3m for the SPP-002 design (previously R_{geo} = 3.6m for SPP-001), the plasma scenarios for the different phases of operation all require re-optimisation for the updated design point.

	SPP-001, EC-HD	SPP-002, EC
I_P [MA]	21.23	21.67
B_T [T]	3.2	3.0
P_{FUS} [GW]	1.68	1.79
f_{BS} [%]	89.5	85.2
P_{EC} [MW]	150.0	150.0
η_{ECCD} [kA/MW]	12.5	18.4
Q	11.2	11.9
$<n_e>$ [$10^{20} m^{-3}$]	1.51	1.16
f_{GW} [%]	94.8	100.0
$<T_e>$ [keV]	10.99	10.54
$<T_i>$ [keV]	11.72	10.86
Zeff	2.72	3.28
f_{rad} [%]	70.38	71.10
P_{sep}/R [MW/m]	39.01	33.45
q_{min}	2.50	2.39
q_0	2.86	3.20
β_N [%]	4.50	4.20
β_e	0.07	0.06
β_{tor}	0.15	0.13
Li(3)	0.27	0.32
H98 Avg	1.42	1.38
p_0/<p>	2.28	2.73

Table 1: *Comparison of key plasma parameters between SPP-002 (R_{geo} = 4.3m) and SPP-001 (R_{geo} = 3.6m). q-profile only partially optimised to reach desired q_{min} value [2].*

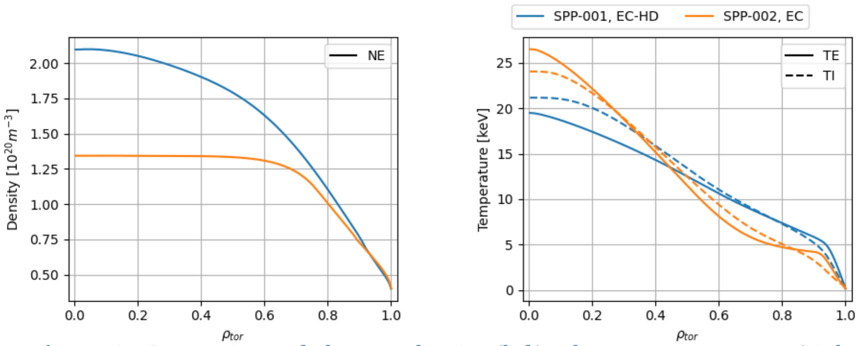


Figure 1: *Comparison of electron density (left), electron temperature (right, solid) and ion temperature (right, dashed) profiles between SPP-002 (orange, R_{geo} = 4.3m) and SPP-001 (blue, R_{geo} = 3.6m).*

Flat-top scenarios

Initial scans of operational spaces for the larger SPP-002 design aimed to keep key plasma parameters fixed from SPP-001, such as fusion gain $Q \geq 11$, radiation fraction f_{rad} = 70%, Greenwald density fraction f_{GW} = 100% and aspect ratio A = 1.8. These scans highlighted a significant impact to the flat-top scenarios: changes to the Electron Cyclotron (EC) and Electron Bernstein Wave

(EBW) current drive (CD) efficiencies η_{CD}. The main factor alongside the larger R_{geo} affecting η_{CD} in SPP-002 is a revised set of transport assumptions informed by gyrokinetic (GK) analysis of SPP-001 [3]. The Bohm/gyro-Bohm anomalous transport coefficients were changed to reduce $\frac{\chi_e}{\chi_i}$ to ~ 3, where χ is heat diffusivity. This is more in line with hybrid Kinetic Ballooning Mode (h-KBM) transport that is expected to dominate in STEP. Also, the inward particle pinch described in [2] was removed, which flattens the electron density n_e profile and better matches the results of the GK analysis. In the JETTO simulations, a target f_{GW} is reached by a feedback loop on the fuelling rate. Keeping f_{GW} = 100% in the SPP-002 design causes $< n_e >$ to drop due to the Greenwald density $n_{GW} \propto a^{-2}$ where a is minor radius. Consequently, the electron temperature T_e in the core has increased to keep the same Q at fixed auxiliary power P_{aux} and reduced $\frac{\chi_e}{\chi_i}$, but the pedestal temperature height has dropped in SPP-002 due to the updated χ_e, χ_i profiles. These changes to T_e and n_e profiles can be seen in Figure 1. Since $\eta_{CD} \propto \frac{T_e}{n_e}$, Figure 2 shows how the on-axis ECCD has benefited from the larger design size whereas the off-axis EBWCD has suffered. Hence the EBW flat-top scenario requires further development to reach the plasma performance seen in the SPP-001 design. One potential option is to explore operating points above the Greenwald limit, which has been previously demonstrated on tokamaks such as AUG [4] and DIII-D [5]. ECCD has a limitation in operational plasma density above which access is cutoff, whereas EBWCD does not have this restriction, allowing this system to take advantage of higher density scenarios [6]. However, the flatter density profiles in SPP-002 seen in Figure 1 could increase the chances of encountering an edge density limit at higher density. Another potential challenge of operating above the Greenwald limit is the weaker impurity screening over the pedestal gradient region

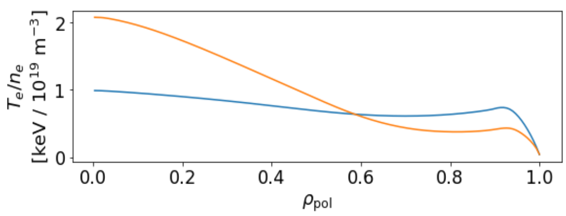
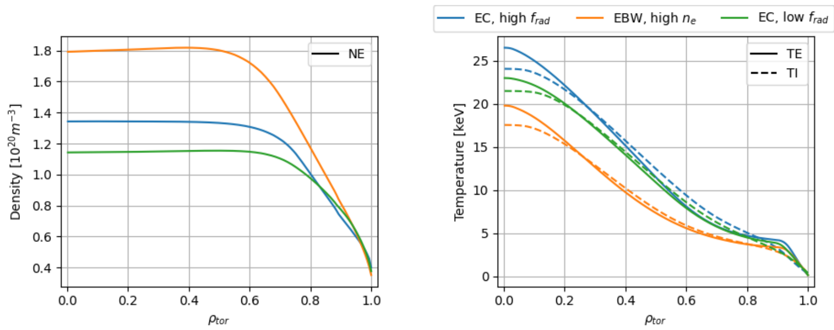


Figure 2: *Comparison of T_e/n_e for the SPP-001 design (blue) and the SPP-002 design (orange).*



	EC, high f_{rad}	EBW, high n_e	EC, low f_{rad}
I_P [MA]	21.67	20.02	19.25
B_T [T]	3.0	3.0	3.0
P_{FUS} [GW]	1.79	1.69	1.08
f_{BS} [%]	85.2	95.6	88.5
P_{EC} [MW]	150.0	0.9	95.0
P_{EBW} [MW]	0.0	30.0	0.0
η_{ECCD} [kA/MW]	18.4	22.7	20.0
η_{EBWCD} [kA/MW]	0.0	13.7	0.0
η_{CD} [kA/MW]	18.4	14.0	20.0
Q	11.9	54.8	11.4
$<n_e>$ [$10^{20}m^{-3}$]	1.16	1.50	1.04
f_{GW} [%]	100.0	140.0	100.0
$<T_e>$ [keV]	10.54	7.44	9.81
$<T_i>$ [keV]	10.86	7.49	9.96
Zeff	3.28	2.30	2.80
f_{rad} [%]	71.10	69.75	39.86
P_{sep}/R [MW/m]	33.45	25.73	43.30
q_{min}	2.39	2.35	3.20
q_0	3.20	2.98	6.00
β_N [%]	4.20	4.10	3.78
β_e	0.06	0.06	0.05
β_{tor}	0.13	0.11	0.10
Li(3)	0.32	0.30	0.29
H98 Avg	1.38	1.38	1.35
p_0/<p>	2.73	2.90	2.49

Figure 3: *Comparison of plasma parameters for different SPP-002 flat-top scenarios: EC high f_{rad} (blue), EBW high density (orange) and EC low f_{rad} (green). Impurities are not self-consistent in EBW and EC low f_{rad} cases.*

due to strong density gradients. Pedestal optimisation would be necessary to keep impurities out of the core plasma that could otherwise lead to excessive radiation losses. Another alternative scenario that is being explored is operating at lower f_{rad}, which allows lower fusion power P_{fus}, plasma current I_p and EC power P_{EC} whilst still producing net electric power $P_{net,elec} > 100$MW. The main consequence of lower f_{rad} is an increase in the demands on the exhaust as the separatrix power P_{sep} is higher. Despite $\frac{P_{sep}}{R_{geo}}$ decreasing in the SPP-002 design, further investigations are needed to quantify the exhaust limits. A comparison of flat-top scenarios at approximately the same confinement factor $H_{98,avg}$ assumption can be seen in Figure 3, showing potential EC scenarios at high and low f_{rad}, as well as an EBW scenario at f_{GW} =140% optimising for high Q. An important challenge for the plasma scenarios is vertical stability, particularly due to the high elongation ($\kappa \sim 3.0$) of STEP. A recent study explored whether the SPP-002 design could tolerate a reduction in κ to improve vertical control, as well as having other potential benefits like increasing the tritium breeding ratio (TBR) and reducing the complexity of passive stabilising conductors (PSCs). Figure 4 shows results of an elongation scan performed at fixed plasma volume V_{pl}, P_{fus}, f_{GW} and A. At fixed V_{pl} and A, as κ decreases the radii increase. Since f_{GW} is also fixed, the increase in a results in lower n_e. The main consequence of lower κ is the need for significantly higher normalised beta β_N and confinement factor $H_{98,y}$ to remain at the same P_{fus}. This, combined with the lower bootstrap current I_{BS}, would create considerable problems for a non-inductive flat-top scenario, which is why the decision was ultimately to keep $\kappa \sim 3.0$ for the flat-top scenarios.

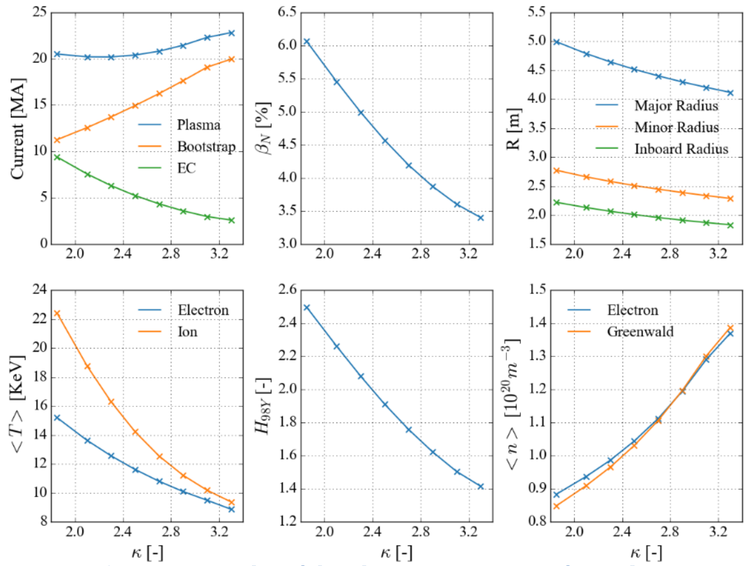


Figure 4: Results of the elongation scan performed on SPP-002 at fixed P_{fus}, f_{GW}, V_{pl} and A.

Ramp-up and ramp-down phases

As expected, there are many similarities between the challenges of the ramp-up and ramp-down scenarios. STEP aims to have a small central solenoid which will only be used for the initial start-up and inductive current ramp-up to ~2MA. Therefore, non-inductive scenarios for ramping up to flat-top conditions and subsequently ramping down towards plasma termination require careful optimisation of the available plasma actuators to create a viable pathway for these transient operational phases. Vertical stability is a key challenge for both phases, and the vertical control target is to keep internal inductance $l_i(3) < 0.4$ based on an estimated upper limit of the controllable elongation in a spherical tokamak $\kappa = 3.4 - l_i(3)$ [7]. Minimising $l_i(3)$ is made more difficult by the back-EMF which is induced in the core during both phases. Due to low resistivity in the core, there is a long current diffusion time where the on-axis ECCD is injected. If the ECCD is driven or removed too quickly from the plasma, this generates a back-EMF current to oppose this change. This also makes it difficult to avoid a current hole in the core, and there is uncertainty in whether a current hole is tolerable for STEP. To avoid excessive back-EMF current, which peaks the current density profile and hence increases $l_i(3)$, the duration of both the ramp-up and ramp-down must be at least 20 minutes. Progress has been made to create a non-inductive current ramp-up scenario that demonstrates flat-top access in 0D quantities [8], and future work aims to utilise improved transport models and controllers to show that a controlled pathway to the 1D profiles of the flat-top is possible. For the ramp-down phase, it is vital that disruptions at $I_p > 2$MA are avoided as they could inflict severe damage to the plasma facing components, since disruption force $\propto {I_p}^2$. Figure 5 shows that optimising the 0D parameters of the ramp-down scenario to stay below the vertical control target of $l_i(3) < 0.4$ is possible. But as with the ramp-up, further work needs to be done to optimise the 1D profiles of these scenarios whilst also exploring the use of improved transport models.

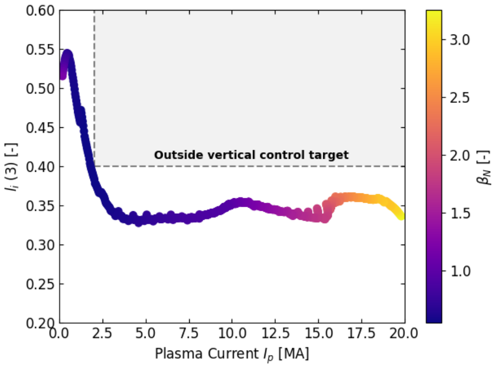


Figure 5: *Plot of $l_i(3)$ vs I_p for a SPP-002 ramp-down scenario. The grey area indicates the vertical control target to keep below until I_p is sufficiently small.*

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