

ABSTRACT

The interplay between pump and core plasma in tokamaks is a highly integrated problem, requiring consistent plasma solutions from the magnetic axis all the way to the pump via the scrape-off layer (SOL). This is a crucial problem for any DEMO-class reactor, such as the Spherical Tokamak for Energy Production (STEP), which requires efficient pumping of helium ash to avoid degradation of fusion power performance due to impurity dilution. STEP is intended to demonstrate net electric output power ~100 MW during steady-state flat-top operation, which means that the total fusion power will need to significantly exceed the power required for heating, fuelling and coil systems to account for various loss mechanisms [1]. JINTRAC, which is a unique tool for integrated core, edge, SOL, pump and divertor modelling at run-time, has been used in this work to model α -particle generation, thermalisation and transport to the pump surfaces. The benefits of running a core/SOL/pump integrated model as opposed to a core-only plasma model are that self-consistent boundary conditions can be applied at the last closed flux surface, and quantitative pump parameters, such as the pumping speed, can be directly correlated with core plasma performance. Complementary studies has been done with core-only JETTO simulations to account for uncertainties in the confinement and pedestal assumptions. Based on the most recent set of confinement and pedestal assumptions for STEP, the presented modelling indicates a minimum required helium pumping speed of around 50 m³/s. While this value is significantly larger than in any present-day experiment, it is in line with the assumption for ITER [2].

MODELLING RESULTS: SCAN IN CONFINEMENT AND PEDESTAL ASSUMPTIONS WITH JETTO

- As $n_{\text{He,sep}}$ is increased, the core averaged n_{He}/n_e also increases in stationary conditions (Fig. 2.c)
- Increased pedestal height (α_{max}) also reduces core He concentration for a given $n_{\text{He,sep}}$, as density & temperature profiles become less peaked $\Rightarrow$ more off-axis He source and shorter He confinement time
- Confinement factor H_{98}^* increases with increased helium dilution at fixed $P_{\text{fus}} = 1.5$ GW and fixed $\langle n_e \rangle = 1.6 \times 10^{20} \text{ m}^{-3}$ (Fig. 2.a)
- Scan output has been filtered to only include points where the final output deviates less than 1 % of time averaged value over the last 10 s (Figs. 3.a – 3.d)
- Filtered H_{98}^* data has been fitted to linear function in $n_{\text{He,sep}}$ and α_{max} (Figs. 3.e & 3.f):

$$H_{98}^* = C_0 + C_n n_{\text{He,sep}} + C_\alpha \alpha_{\text{max}}$$

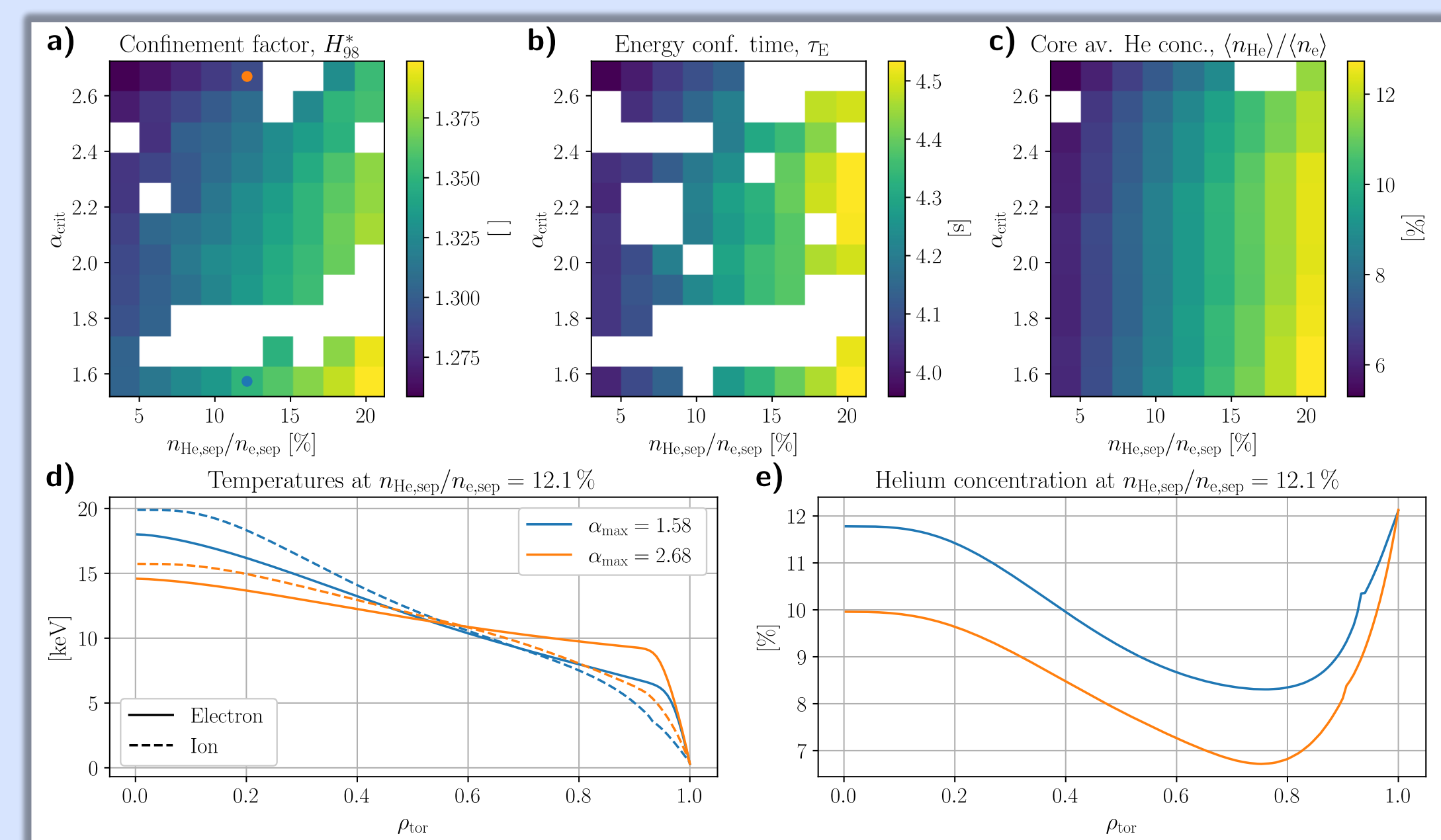


FIGURE 2. JETTO scan results and selected profile data.

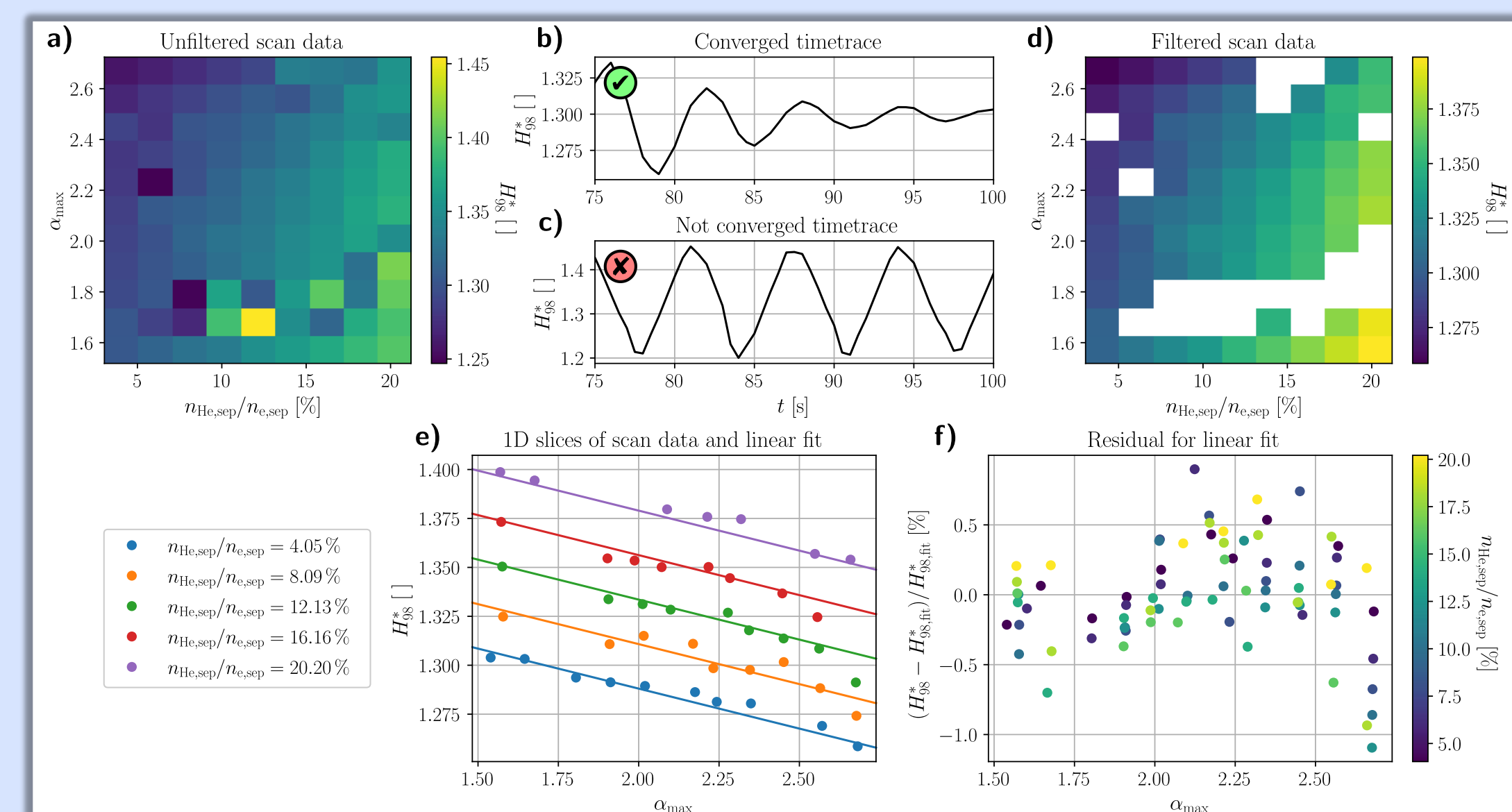


FIGURE 3. Filtering of scan data and linear fit to H_{98}^* output.

CONCLUSIONS

The presented studies have shown how important the pumping efficiency of helium ash is for fusion power performance for the STEP prototype power plant, using integrated core/SOL/divertor/pump modelling with JINTRAC. The lower limit of the helium pumping speed largely depends on the confinement and pedestal assumptions, which have been assessed quantitatively using the confinement factor and maximum edge ballooning parameter as proxies for these assumptions. The latest iteration of the flat-top scenario for the presented configuration predicts a minimum pumping speed of ~50 m³/s, with uncertainties ~20 m³/s in either direction. This value is similar to what has been suggested for ITER helium pumps. With increased understanding of the confinement and pedestal for STEP-relevant scenarios, the pumping requirements can be further specified.

REFERENCES

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- PEARCE, R., *et al.*, ITER Technical Report ITR-24-12 (2024).
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MODELLING ASSUMPTIONS

JINTRAC is a tokamak modelling framework that consists of core plasma modelling (JETTO) and plasma/neutrals modelling in the SOL, gas puffing and pumping, and sputtering/recycling from the divertor and first wall (EDGE2D/EIRENE). The presented modelling explores the helium pumping operational space with two sets of parameter scans:

SCAN IN HELIUM PUMPING SPEED WITH JINTRAC

- JETTO and EDGE2D/EIRENE are integrated at run-time with boundary conditions at the last closed flux surface (LCFS)
- Core plasma modelling assumptions are largely the same as for the EC-HD scenario in [3]
 - Xenon impurity seeding is excluded for computational efficiency. Core radiation is set to 70% of total heating power
- Separate pump systems for helium and other species $\Rightarrow$ pumping system designs can be optimized separately
 - Helium pumping speed takes the values {12, 48, 192, 768} m³/s. Fixed albedo for remaining species.
- Rescaled Bohm/gyro-Bohm transport for core plasma (described in [3]), with diffusivities scaled on feedback against a target β_N
 - Allows for more stability and faster convergence of scenario. $H_{98}^* = H_{1P98}(y,z)$ with 60% P_{rad} used as a proxy for confinement assumption

SCAN IN CONFINEMENT AND PEDESTAL ASSUMPTIONS WITH JETTO

- Core-only simulations with boundary conditions at the LCFS
- Transport scaled on feedback against fusion power
 - Target value (1.5 GW) is the assumed lower limit for sufficient fusion power performance
- 2D parameter scan
 - Varying the boundary helium density changes the helium dilution in stationary conditions. Combining with fixed fusion power and fixed $\langle n_e \rangle = 1.6 \times 10^{20} \text{ m}^{-3}$ ($\approx n_{\text{GW}}$) effectively varies the confinement.
 - Continuous ELM model with varying maximum edge ballooning parameter (α_{max}) varies the pedestal height
- Each simulation is run until stationary conditions are met (100 s)

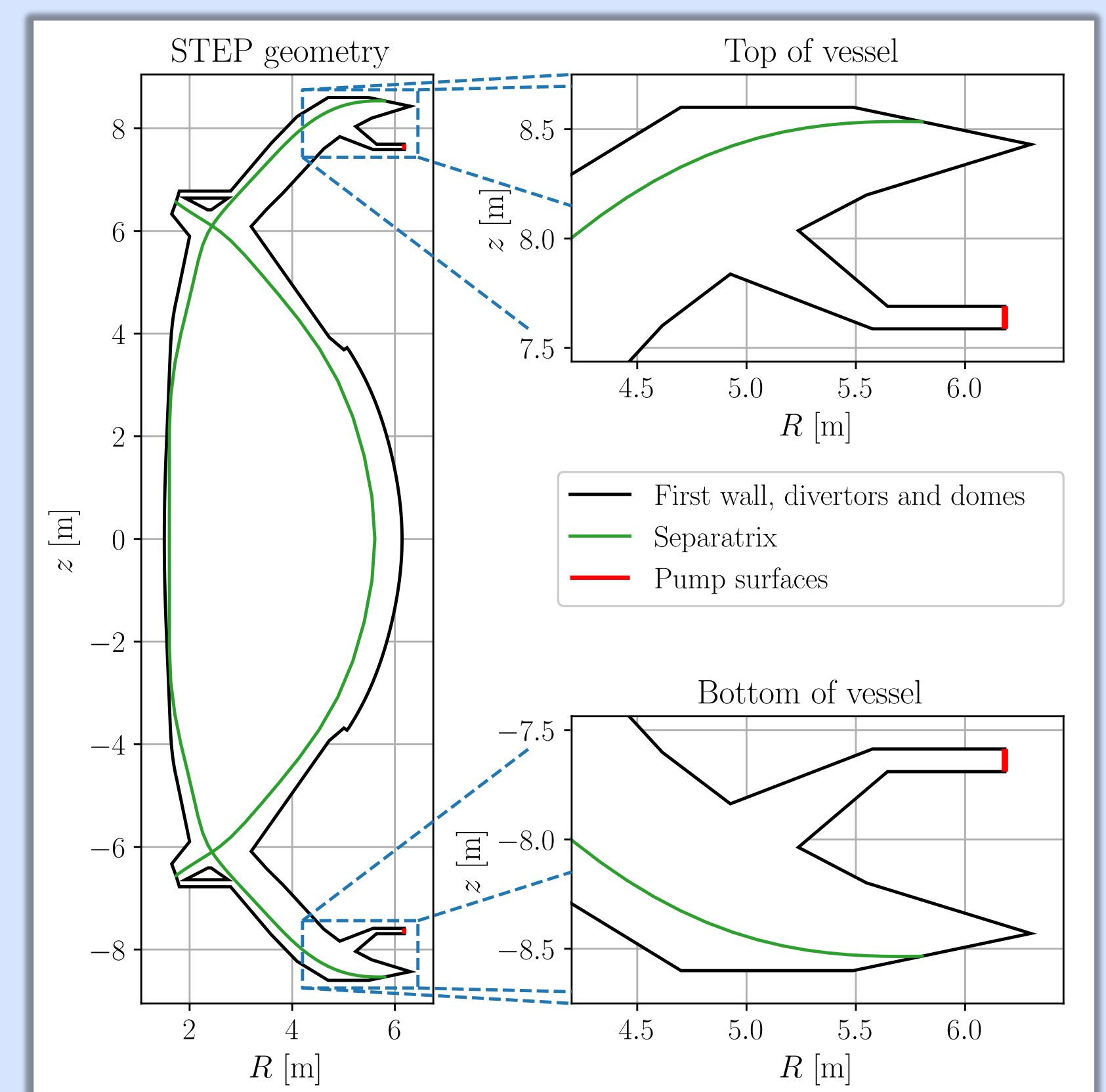


FIGURE 1. Vacuum vessel geometry and pump locations as assumed in the JINTRAC simulations. The geometry matches the latest iteration of designs as presented in [4].

$$S_{\text{He}} = \Sigma_{\text{pump}} (1 - A_{\text{He}}) v_{\text{th,He}^0} / \sqrt{2\pi}$$

$$\Gamma_{\text{pump}} = S_{\text{He}} n_{\text{He}^0, \text{pump}}$$

S_{He} (m³/s): Pumping speed $v_{\text{th,He}^0} = \sqrt{T_0/m_{\text{He}}}$ (m/s): Helium atom thermal velocity
 Γ_{pump} (s⁻¹): Pumped flux
 Σ_{pump} (m²): Pumped surface area $n_{\text{He}^0, \text{pump}}$ (m⁻³): Average helium atom density at pump surfaces
 A_{He} (): Pump helium albedo

MODELLING RESULTS: SCAN IN HELIUM PUMPING SPEED WITH JINTRAC

- Clear separation in helium concentration and total helium content for different S_{He} (Figs. 4.a and 4.b)
- Less clear separation in fusion power (Fig. 4.d), likely a consequence of fixed β_N
- Large oscillations in H_{98}^* $\Rightarrow$ difficult to tell if low S_{He} cases have higher confinement (Fig. 4.f)
- Last 3 s of $n_{\text{He}^0, \text{pump}}$ and $n_{\text{He,sep}}$ time traces have been highlighted for each S_{He} case in Figs. 5.a – 5.c
 - Indication of oscillation around stable points in $(n_{\text{He}^0, \text{pump}}, n_{\text{He,sep}})$ -space (Fig. 5.c)
- Suggested stable points assumed to satisfy $n_{\text{He,sep}} \approx n_{\text{He}^0, \text{pump}}^\beta$ (shaded area: uncertainty)
- Using $n_{\text{He,sep}} \approx n_{\text{He}^0, \text{pump}}^\beta$, we can derive $n_{\text{He,sep}}$ as a function of S_{He} at a fixed pumped flux ($\Gamma_{\text{pump}} = \Gamma_{\text{min}}$ matching reaction rate of $P_{\text{fus}} = 1.5$ GW in Fig. 5.d)
- Combining with $H_{98}^* = C_0 + C_n n_{\text{He,sep}} + C_\alpha \alpha_{\text{max}} \Rightarrow$

$$S_{\text{He}} = \Gamma_{\text{min}} \left(\frac{AC_n}{H_{98}^* - C_0 - C_\alpha \alpha_{\text{max}}} \right)^{1/\beta}$$
as shown in Fig. 5.f for two different α_{max} , which is the **minimum required pumping speed as a function of confinement and pedestal assumption**
 - Suggested practical limit of $S_{\text{He}} \approx 50 \text{ m}^3/\text{s}$ (dotted line in Fig. 5.f)
 - Cyan error bar: Confinement and pedestal of EC-HD flat-top [3]
 - Unknown if there is a viable pumping operating point

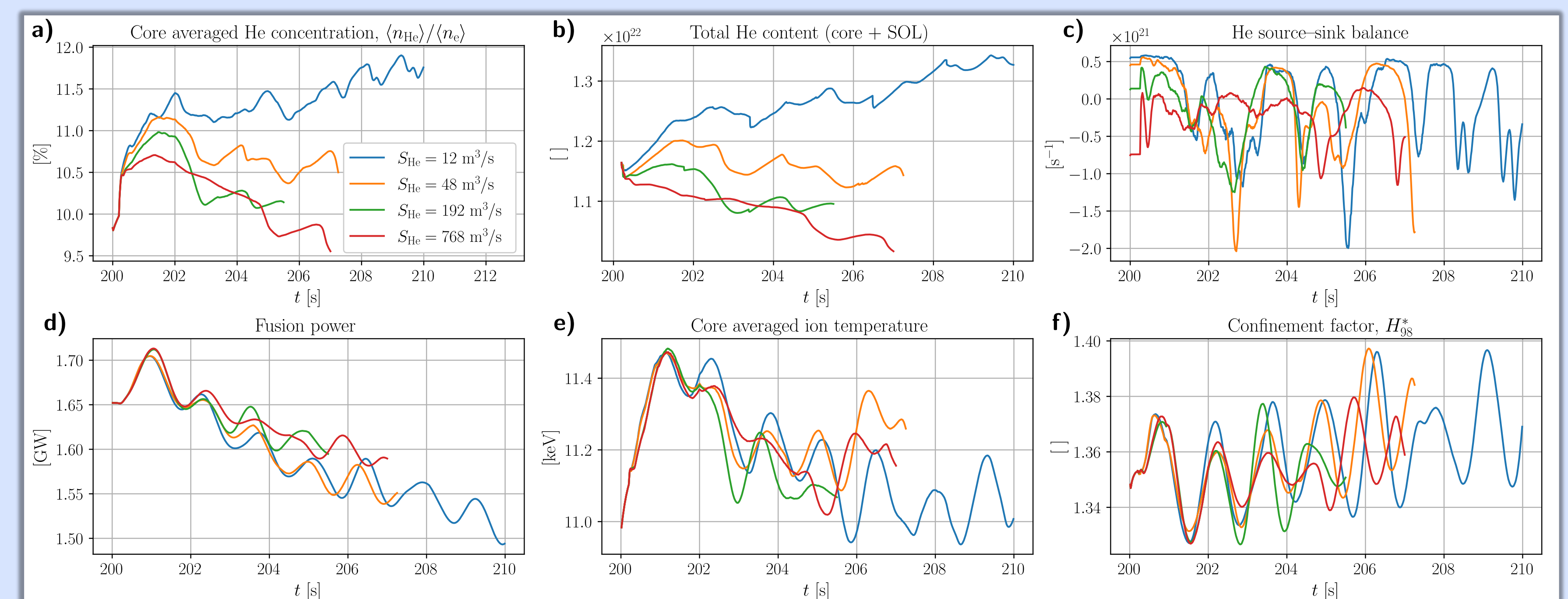


FIGURE 4. Time trace data for scan in helium pumping speed with JINTRAC.

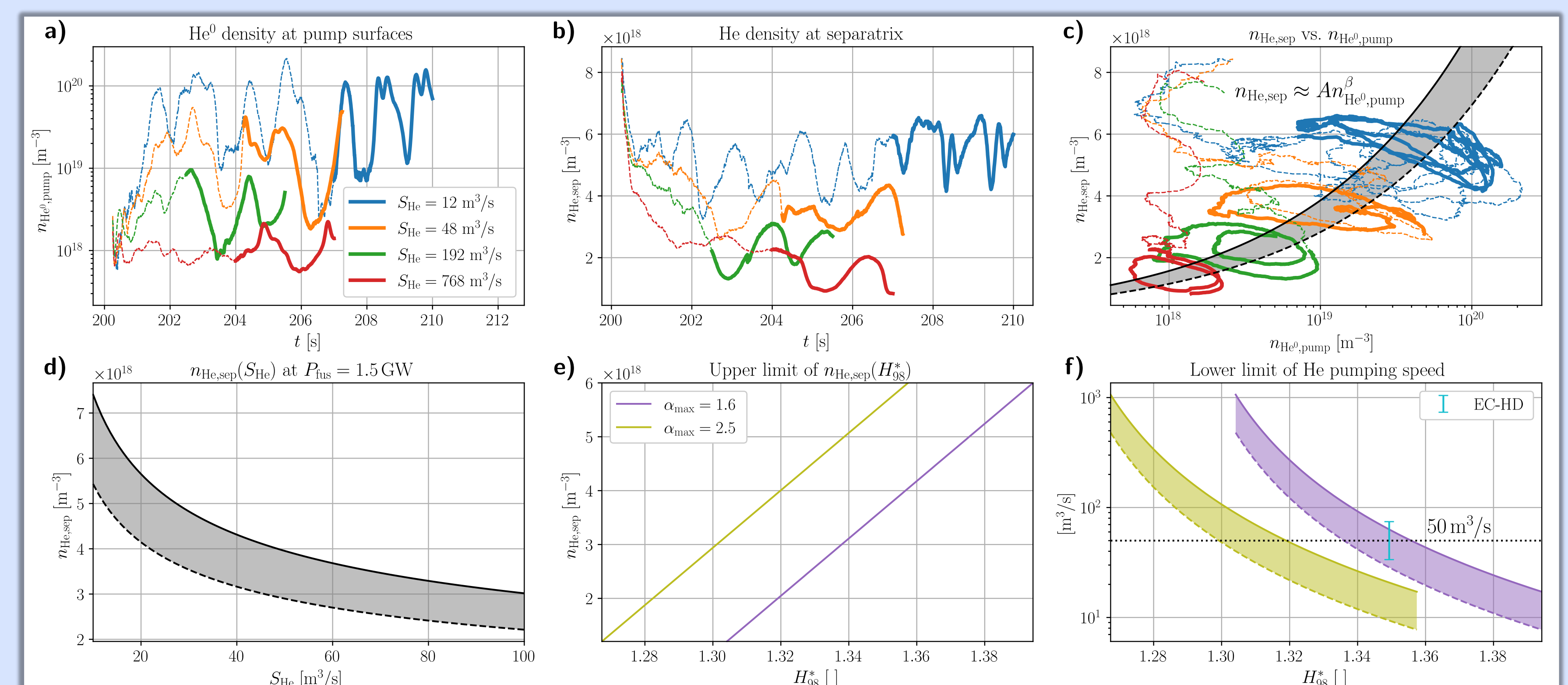


FIGURE 5. Demonstrating the correlation between $n_{\text{He}^0, \text{pump}}$ and $n_{\text{He,sep}}$. Used together with scans of Figs. 2 & 3 shows a relationship between S_{He} , H_{98}^* and α_{max} (f). Separate limits of $n_{\text{He,sep}}(n_{\text{He}^0, \text{pump}})$ are shown with solid & dashed curves in c), d) and f).