

Article

Simulation and Comparative Analysis of Advanced Scenarios for High- and Low-Temperature Superconducting Tokamaks Using METIS Code

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Abstract

The development of steady-state advanced operation modes with high fusion gain (Q) is a primary objective of magnetic confinement fusion research. The advancement of high-temperature superconducting (HTS) magnet technology has introduced a new development path using devices like SPARC. This path contrasts with the conventional low-temperature superconducting (LTS) approach represented by devices such as BEST. This study utilizes the fast integrated modeling code METIS to compare the physical conditions required for HTS-based (SPARC-like) and LTS-based (BEST-like) devices to achieve an energy gain of $Q \approx 5$. Furthermore, we simulated the achievable fusion power for both devices under an identical set of core physics parameters to isolate the effect of magnetic field strength. Simulation results show that at a similar $Q \approx 5$, the HTS device leverages its high magnetic field to require significantly lower auxiliary heating power (approximately 50–60% less). Additionally, it operates at a lower Greenwald density fraction ($f_{GW} \approx 0.37$) than the LTS device ($f_{GW} \approx 0.87$). This well validates the strong dependence of the fusion triple product on magnetic field strength ($\propto B^3$). Under identical high-density (“BEST-like”) parameters, the HTS device achieves much higher fusion power but faces a drastically increased L-H transition power threshold. This increase may force operation in L-mode. Crucially, even in L-mode, there remains the possibility for high-field HTS devices to achieve $Q > 5$ via high-density operation.

Keywords: tokamak; scenario design; METIS; fusion gain; high-temperature superconductor

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1. Introduction

A low-temperature superconducting (LTS) tokamak is an experimental fusion device that uses superconducting magnets (NbTi/Nb₃Sn) to generate high fields ($B > 5$ T), representing the traditional technology route toward commercial fusion reactors (such as ITER and future power plants). Recently, breakthroughs in rare-earth barium copper oxide (REBCO) high-temperature superconducting (HTS) tape technology have significantly advanced the development of compact, high-field HTS tokamaks such as SPARC and ARC [1,2]. These devices offer a potentially faster and more economical path to fusion energy. A strong magnetic field ($B > 10$ T) can significantly enhance plasma confinement

and fusion reaction rates. Consequently, devices can achieve high fusion gain ($Q = P_{\text{fusion}} / P_{\text{aux}}$) or even ignition with a smaller size and lower auxiliary heating power [3,4].

However, high magnetic fields introduce new physics and engineering challenges. Higher fields typically lead to higher plasma density and pressure, which alter the physics of wave heating and current drive. For example, high fields affect the density cut-off for lower hybrid (LH) waves [5,6] and the absorption location of electron cyclotron (EC) waves [7–9]. Simultaneously, high-power-density operation places extreme demands on first-wall and divertor heat load management. Therefore, it is vital to systematically explore operational scenarios in high-field regimes using integrated modeling tools. Comparing these with conventional LTS device operation modes during the pre-design phase is of great importance.

Traditional high-fidelity 1.5D integrated codes (e.g., TRANSP and CRONOS) offer high accuracy but require long computation times, making extensive parameter scans difficult [10,11]. In contrast, the METIS code employs simplified physics models and empirical scaling laws. It achieves computation speeds far exceeding real-time while maintaining reasonable fidelity for key physical processes [12]. This makes METIS well suited for rapid exploration of operational spaces and sensitivity analysis.

Based on this, this paper employs the METIS code to conduct a comparative study of advanced operation scenarios for an HTS-based device (using SPARC parameters as a reference) and an LTS-based device (using BEST parameters as a reference). We first validate the METIS configuration against published simulation data for SPARC. We then simulate the respective conditions required for each device to reach $Q \approx 5$, comparing their demands on auxiliary heating power, density, and confinement level. Finally, we establish a common set of core physics parameters (aiming to control for the primary variable of magnetic field strength) to compare the ultimate fusion power and operational mode achievable by both devices. This study aims to reveal the impact of magnetic field strength on fusion device performance and provide a reference for the physics design of subsequent high-field tokamaks.

2. Materials and Methods

2.1. METIS Code Introduction

METIS (Minute Embedded Tokamak Integrated Simulator) is a fast integrated modeling code designed to simulate a full tokamak discharge lasting hundreds of seconds within minutes [12]. It adopts a hybrid 0D–1D approach: global 0D equations describe the evolution of integral quantities like plasma stored energy and current, while 1D diffusion equations calculate the transport of profile quantities such as temperature and current density.

Even though METIS employs scaling laws to streamline physical models, its outcomes stay trustworthy and align with 1.5D transport codes [12,13]. The reason lies in METIS's 0D–1D method for characterizing the movement of physical parameters that are heavily impacted by turbulence; moreover, simulations from alternative first-principle codes still exhibit considerable uncertainties regarding these quantities. The energy transport in METIS begins with a time-dependent 0D equation:

$$\frac{dW_{th}}{dt} = -\frac{W_{th}}{\tau_E} + P_{loss} \quad (1)$$

where τ_E is the energy confinement time, W_{th} is the plasma thermal energy content, and P_{loss} represents the total power transported through the plasma separatrix by diffusion or convection mechanisms. Plasma confinement is modified by various processes, resulting in the total thermal energy expression:

$$W_{th} = H_{MHD} H_{li} H_{ref} \tau_E P_{th} + (H_{ITB} - 1) W_{core} \quad (2)$$

where H_{ref} is a prescribed factor, H_{MHD} represents an internally derived confinement factor that accounts for the degradation caused by MHD phenomena—effects omitted from our simulations, i.e., $H_{MHD} = 1$); H_{ITB} denotes an internal confinement factor accounting for enhanced confinement from magnetic shear—this effect is included in our simulations; and H_{li} captures the impact of internal inductance upon energy confinement, but it remains set to 1 as it is excluded from our simulations. τ_E is calculated using the ITER-98P(y,2) scaling law for the H-mode discharges. W_{core} is defined as $\tau_E \times P_{th} - W_{ped}$, where W_{ped} is the thermal energy in the pedestal region predicted by the scaling expression. Next, the radial derivatives of electron and ion temperatures are each solved through diffusion transport equations. Although only the diffusion part is considered in the energy transport equation, the modified diffusion coefficients χ_e and χ_i , or alternatively conductivity coefficients $\kappa_{e,i} = n_{e,i}\chi_{e,i}$, can be expressed by a prescribed analytical equation or theoretical model. In our work, the Current Diffusion Ballooning Mode (CDBM) [14,15] framework describes how the transport coefficient behaves. Consequently, temperature profiles emerge from integrating the solved derivatives within the heat transport equations. The portion of METIS handling current diffusion adopts exactly the same procedure as conventional 1.5D transport codes: it evolves according to poloidal flux, where transport couples a 2D magnetic surface equilibrium with a 1D poloidal flux evolution equation. Multiple source terms appear in the current diffusion equation, each representable by different physical models. Here, the bootstrap current is calculated using the Sauter model [16]. This simplification underpins METIS's fast computation. While it omits certain first-principles details, it has demonstrated reliability when forecasting overall performance trends [12,17].

2.2. Model Validation Based on SPARC H-Mode Simulation Data

To ensure the reliability of the parameter settings and physics models used for the subsequent SPARC and BEST simulations, we first used METIS to reproduce a published full H-mode operational scenario for SPARC. The key parameters for this operating point are from published integrated modeling results [1,18], including: plasma current $I_p = 8.7$ MA, toroidal field $B_t = 12.2$ T, major radius $R = 1.85$ m, minor radius $a = 0.57$ m, Greenwald density fraction ($f_{GW} = \frac{\bar{n}_e}{n_{GW}} = \frac{\pi a^2 \bar{n}_e}{I_p}$, $\bar{n}_e$ is line-averaged electron density; n_{GW} is Greenwald density [19]) $f_{GW} \approx 0.37$, confinement factor $H_{98} = 1.0$, total auxiliary heating power $P_{aux} = 11.1$ MW (of which $P_{ICRH} = 11.1$ MW).

We configured METIS using the data from Table 1 and parameters from the references. The simulation was run for 35 s to reach a steady state. The outputs were compared with reference data for the same scenario, particularly the fusion power P_{fusion} , fusion gain Q , and the current safety factor profile at the 95% flux surface q_{95} . Figure 1 shows the fusion gain Q and a comparison between the METIS simulation results and SPARC reference data for the evolution of safety factors q_0 and q_{95} . It can be seen that the simulated q_0 and q_{95} trends align well with the reference data, with minor numerical differences. In our simulation results, the central electron temperature is close to 25 keV, the central electron density is approximately $3.4 \times 10^{20} \text{ m}^{-3}$, and the fusion gain is $Q \approx 12$. Although the error of the safety factor is not entirely below 10% throughout the entire time period (especially during the current flat-top phase), the overall error still remains around 10%.

Table 1. SPARC design parameters and our simulation parameters.

Parameter	Full-Field H-Mode	Sim. Parameters	Full-Field L-Mode
* Toroidal Field B_t (T)	12.2	12.2	12.2
* Plasma Current I_p (MA)	8.7	8.7	8.7
Safety Factor q_{95}	3.05	3.35	3.05
* Confinement Factor	1.0	1.0	1.0
Energy Confinement Time τ_E (s)	0.77	0.65	0.44
* Total Aux. Power P_{aux} (MW)	11.1	11.1	24.1
* Effective Charge Z_{eff}	1.5	1.48	1.5
Main ion dilution	0.85	0.85	0.85
Volume Avg. $\langle T_e \rangle$ (keV)	7.3	7.58	9.7
Volume Avg. $\langle T_i \rangle$ (keV)	7.3	7.58	9.7
Volume Avg. $\langle n_e \rangle$ ($10^{20} m^{-3}$)	3.1	3.07	1.4
Volume Avg. $\langle n_i \rangle$ ($10^{20} m^{-3}$)	2.7	2.82	1.2
* Greenwald Fraction f_{GW}	0.37	0.37	0.16
Fusion Power P_{fusion} (MW)	140	149	55

Note: Parameter with “*” means that this parameter is METIS input data in our simulation.

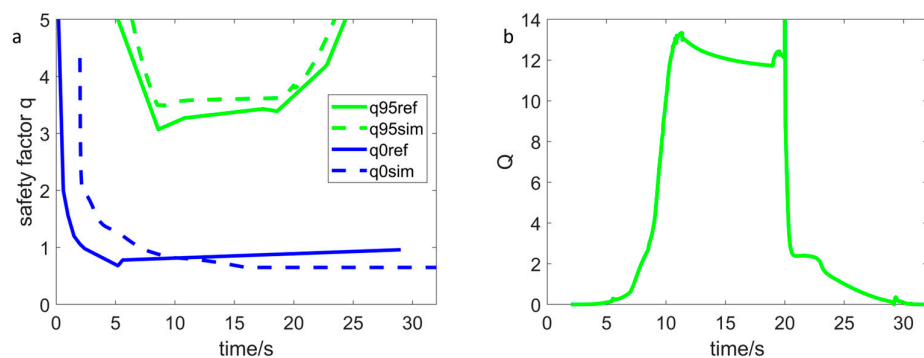


Figure 1. (a) The comparison between our simulation results and SPARC reference data for the evolution of safety factors q_0 and q_{95} . (b) SPARC fusion gain (Q) in our simulation results.

2.3. Simulation Setup for BEST $Q \approx 5$ Scenarios

To explore the differences in parameters, performance, and operational scenarios between high-temperature superconducting (high-field) and low-temperature superconducting devices, we selected the SPARC (representing HTS high-field) and BEST (representing LTS) devices. Through a comparative analysis of these two devices under the same target parameter ($Q \approx 5$) and similar operating scenarios, research conclusions were obtained. Meanwhile, based on the sufficient parameter validation and representativeness of the SPARC and BEST devices, we can, to some extent, extend these conclusions to pulsed HTS and LTS tokamak devices.

Using METIS, we performed parameter scans to find operational scenarios achieving $Q \approx 5$. During the scan, we first fixed some engineering and geometric parameters: BEST references published design parameters ($R = 3.6$ m, $a = 1.1$ m, $B_t = 6.15$ T, $I_p = 7$ MA) [20], and SPARC parameters are as previously described. Secondly, we selected the same energy scaling (ITER-98P(y,2) scaling law and ITER-89P(y,2) scaling law), density model (Angioni) [21,22], and transport model (CDBM). The core variables scanned were: line-averaged density (representing the Greenwald density fraction), impurity fraction, effective nuclear charge number Z_{eff} , and heating power. The scanning process first involves rapidly identifying the operating scenario that achieves the target (this process can be

assisted by a 0D code); then, taking this as the central point, a parameter scan is performed for each key parameter over approximately $\pm 15\%$ with a step size of about 1%. When the output fusion gain is $Q \approx 4.5 - 5.5$, it is considered an acceptable solution. While scanning a particular parameter, the settings of all other parameters remain identical to those in the SPARC or BEST references we cited [1,20] (including heating frequencies, deposition locations and widths, and impurity assumptions).

Table 2 presents the key design parameters for operational scenarios, derived from the central point of the parameter scan. The parameter scan for BEST was conducted based on the $Q \approx 5$ operational scenario outlined in the BEST research plan. Figure 2 shows the METIS simulation results for the high-fusion-gain $Q \approx 5$ scenario in BEST (for the main parameters, see Table 2). The results of the simulation profiles further reveal central electron temperatures T_{e0} of 26 keV and ion temperature T_{i0} of 33 keV at 45 s, accompanied by the formation of an internal transport barrier (ITB). A reversed-shear safety factor profile is also established with $q_0 \approx 2$ and $q_{min} \approx 1$. The parameter scan for SPARC was performed in accordance with the relevant SPARC literature, and the results are presented in Section 3. Table 3 presents the sensitivity analysis of the main parameters, i.e., the variation in fusion gain when each main parameter is individually increased by 1% from the baseline values given in Table 2.

Table 2. Operational scenario design parameters for SPARC and BEST.

Parameter	SPARC $Q \approx 5$	BEST $Q \approx 5$	SPARC $f_{GW} \approx 0.85$
* Major Radius R (m)	1.85	3.6	1.85
* Minor Radius a (m)	0.57	1.1	0.57
* Toroidal Field B_t (T)	12.2	6.15	12.2
* Triangularity δ_{95}	0.43	0.51	0.43
* Elongation κ_{95}	1.72	1.87	1.72
* Confinement Factor	1	1.2	1.2
Fusion Power P_{fusion} (MW)	92	200	420
Fusion Gain Q	5.5	5	27
* Plasma Current I_p (MA)	7.5	7	7
Safety Factor q_{95}	4.05	4.7	4.6
Normalized Beta β_N	1.00	2.7	2.5
Poloidal Beta β_p	0.46	1.3	1.4
Volume Avg./Peak T_e (keV)	6.6/16.6	7.3/26	5.8/24
Volume Avg./Peak n_e ($10^{20}m^{-3}$)	2.6/3.1	1.3/1.8	7.1/7.4
* Greenwald Fraction f_{GW}	0.37	0.87	0.85
L-H transition threshold power P_{LHth} (MW)	35.4	16.2	66.7
* Effective Charge Z_{eff}	1.38	1.53	1.72
* Total Aux. Power P_{aux} (MW)	16.63	40	14
* LHCD Power P_{LHCD} (MW)	0	10	0
* ECCD Power P_{ECCD} (MW)	0	10	0
* ICRF Power P_{LHCD} (MW)	16.63	10	14
* NBI Power P_{NBI} (MW)	0	10	0

Note: Parameter with * means that this parameter is METIS input data in our simulation.

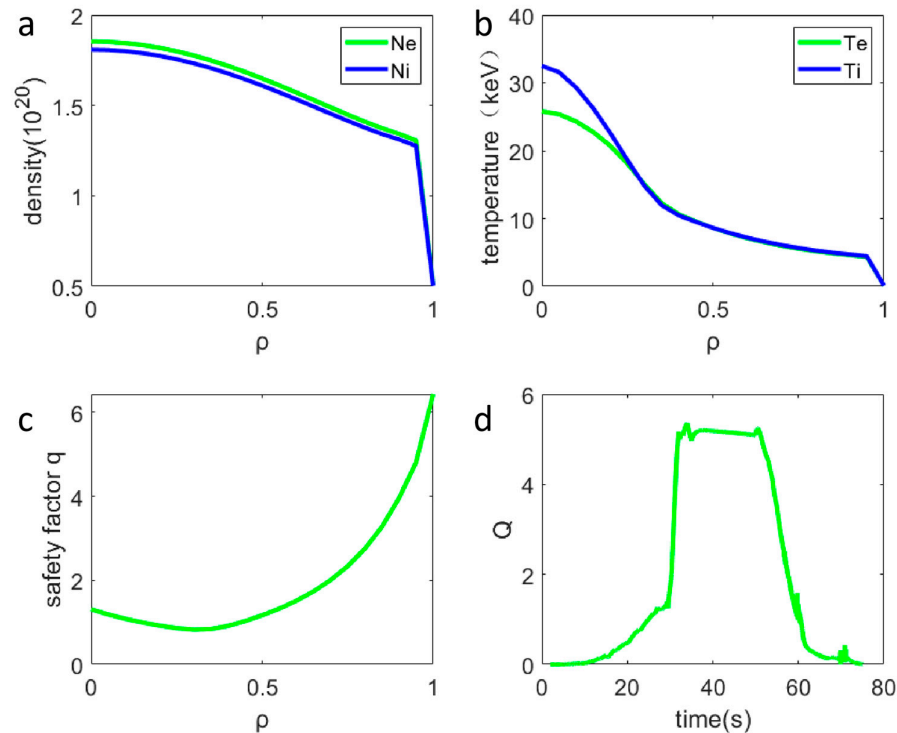


Figure 2. METIS simulation results for the high fusion gain $Q \approx 5$ scenario in BEST. (a) Electron density and ion density profile; (b) electron temperature and ion temperature profile; (c) safety factor profile; (d) fusion gain. All profile data were acquired at 45 s (during the current flat-top phase).

Table 3. Sensitivity of the main parameters in our simulations.

Parameter Sensitivity	$ \frac{\Delta Q}{Q} \times 100\%$ SPARC $Q \approx 5$	$ \frac{\Delta Q}{Q} \times 100\%$ BEST $Q \approx 5$	$ \frac{\Delta Q}{Q} \times 100\%$ SPARC $f_{GW} \approx 0.85$
Major Radius R	0.72	0.73	0.75
Minor Radius a	3.53	3.41	4.22
Toroidal Field B_t	3.81	3.75	3.86
Elongation κ_{95}	0.30	0.29	0.31
Confinement Factor	3.31	3.26	3.43
Plasma Current I_p	0.96	0.94	0.97
Greenwald Fraction f_{GW}	1.21	1.19	1.72
Effective Charge Z_{eff}	0.55	0.49	3.5
Total Aux. Power P_{aux}	0.56	0.55	0.80

Note: Although each parameter was changed individually, the METIS simulation calculation needs to comprehensively consider multiple modules, so the final sensitivity analysis results may deviate to some extent from the theoretical formulas.

3. Results and Discussion

3.1. Simulation Results for HTS Device (SPARC) at $Q \approx 5$

Referring to the SPARC design literature, auxiliary heating of SPARC employs only the ICRH minority ion heating scheme. Under its very high magnetic field (12.2 T) condition, it requires only a relatively low density to achieve a relatively high fusion power. Our scans indicate that SPARC, within the range of $f_{GW} \approx 0.3 - 0.4$, $H_{98} \approx 1.0$, requires only about 15–20 MW of external heating power to achieve $Q \approx 5$. Figure 3 illustrates some key parameters of a $Q \approx 5$ operating scenario ($f_{GW} = 0.37$, $H_{98} = 1.0$, $P_{ICRH} = 16.6$ MW). The results of the simulation profiles further reveal a central electron density n_{e0} of 3.1×10^{20} , electron temperatures T_{e0} of 26 keV and ion temperature T_{i0} of 32 keV at 16 s. Compared with the SPARC $Q = 11$ reference data, this result shows an

increased auxiliary heating power, a slightly reduced electron density; a significantly lower temperature; and consequently, a decreased fusion gain. The reductions in density and temperature diminish the fusion power, thereby lowering the fusion gain, while the increase in auxiliary heating power also contributes to a lower gain. The combined effect of these two factors results in a reduction in SPARC's fusion gain from 11 to 5. This outcome is consistent with the underlying physics and represents a valid scientific result. It can also be seen that even with a confinement factor $H_{98} = 1.0$, which is lower than BEST ($H_{98} = 1.2$), SPARC can still achieve the same $Q \approx 5$ fusion gain target at a lower Greenwald density fraction. This is due to the high plasma pressure and fusion cross-section enabled by the high magnetic field. Unfortunately, a reversed-shear safety factor profile was not achieved in our simulations.

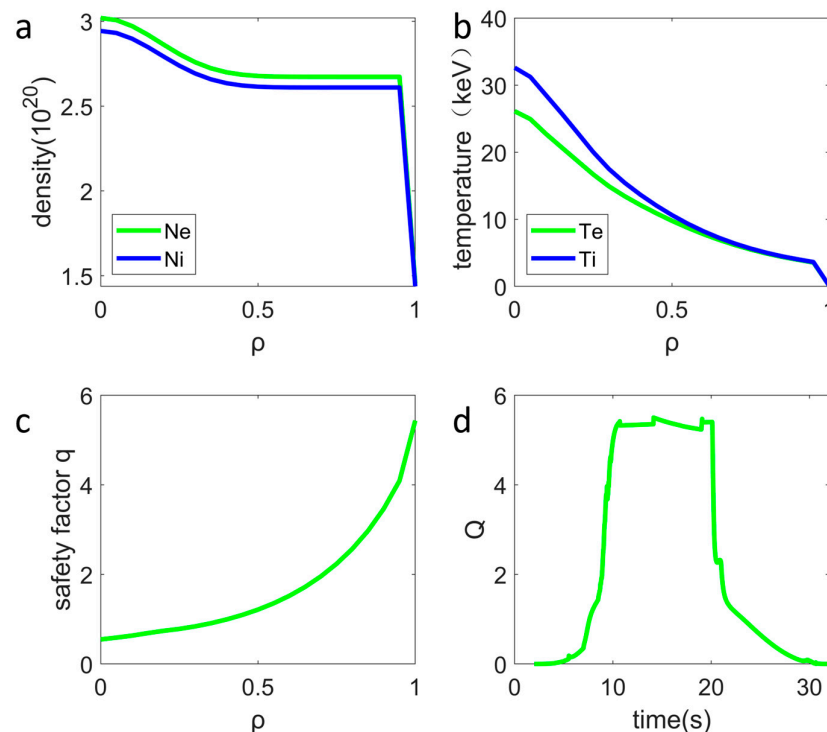


Figure 3. METIS simulation results for the fusion gain $Q \approx 5$ scenario in SPARC. (a) Electron density and ion density profile; (b) electron temperature and ion temperature profile; (c) safety factor profile; (d) fusion gain. All profile data were acquired at 16 s (during the current flat-top phase).

3.2. Comparison of $Q \approx 5$ Results for LTS(BEST) and HTS(SPARC) Devices

As shown in Figure 4, at the same fusion gain, the volume-averaged electron density of SPARC is higher than that of BEST, while its Greenwald density fraction is significantly lower. This is because the high magnetic field generated by SPARC's high-temperature superconductors enables a more compact device with a smaller minor radius and a higher plasma current, meaning that SPARC's Greenwald density limit is substantially higher than that of BEST. This implies that, compared to BEST, SPARC offers a wider operating parameter space—a key advantage of the high-temperature superconducting high-magnetic-field approach.

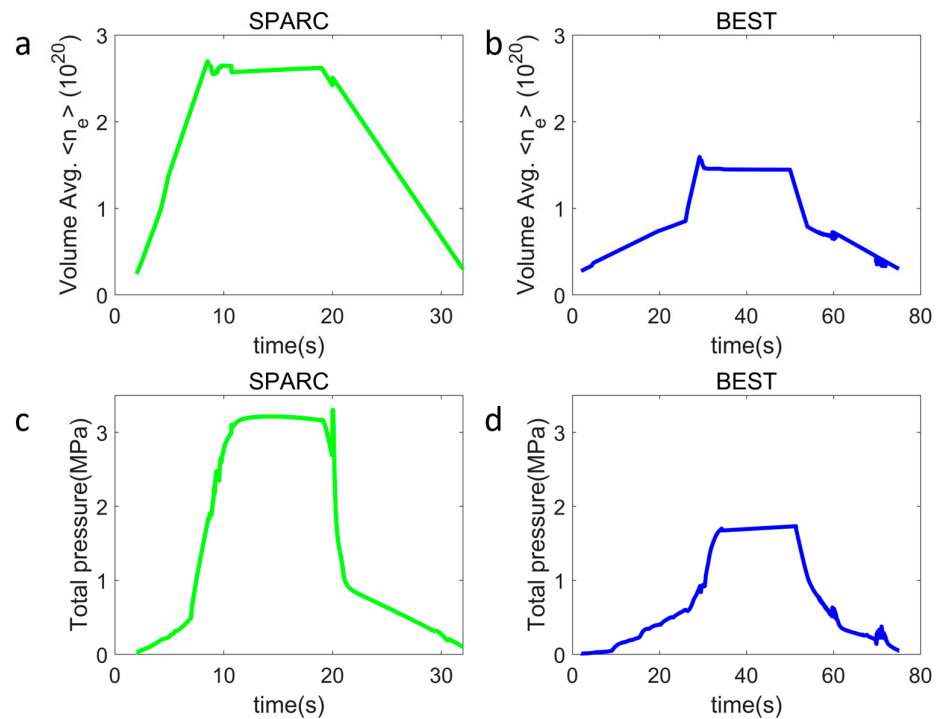


Figure 4. Comparison of $Q \approx 5$ results for LTS (BEST) and HTS (SPARC) devices. (a) SPARC volume-averaged electron density; (b) BEST volume-averaged electron density; (c) SPARC total plasma pressure; (d) BEST total plasma pressure.

Overall, the comparison of simulation results clearly reveals the core advantages of the high-temperature superconducting high-field path:

- (1) Lower auxiliary heating power requirement: SPARC requires about 50–60% less auxiliary heating power ($P_{aux} = 16.6$ MW) than BEST ($P_{aux} = 40$ MW). This directly reduces the cost and complexity of external heating systems.
- (2) Lower operational density: SPARC can operate at $f_{GW} \approx 0.37$, while BEST needs to operate near the Greenwald density limit ($f_{GW} \approx 0.87$). Lower density operation favors wave heating (e.g., EC, LH) coupling and propagation, reduces plasma–wall interaction intensity and may mitigate instabilities like edge-localized modes (ELMs) [23].
- (3) More relaxed requirement on confinement factor: SPARC can achieve its target with $H_{98} \approx 1$, while BEST requires $H_{98} \approx 1.2$. This indicates that HTS high-field devices have higher “tolerance” for plasma confinement performance.

The physical root of these differences lies in the fusion triple product $n\tau_E T \propto \beta_N H_{98} B^3 a^3 / q_{95}^2$ [24]. To achieve a given fusion power (Q), a high magnetic field (B) can “compensate” for stringent requirements on density (n), temperature (T), or confinement time (τ_E , linearly related to H_{98}). Our simulation results offer quantitative support for this fundamental relationship, suggesting that raising the magnetic field strength may be among the more effective ways to improve fusion performance.

3.3. Comparison of Fusion Performance Under Identical Physics Parameters

To further isolate the effect of the magnetic field variable on enhancing fusion device performance, we designed a “fairer” comparison: applying an identical set of core physics parameters to both SPARC and BEST. These parameters include: volume-averaged heating power density (P_{aux}/V_{plasma}), confinement factor H_{98} , Greenwald density fraction

f_{GW} , impurity content (Z_{eff}), transport codes and scalings. This means that both devices operate in “similar” physical states but within different magnetic fields and sizes. We selected a typical high-density operating point from BEST as the parameter set: $H_{98} \approx 1.2$, $f_{GW} \approx 0.87$, $Z_{eff} \approx 1.5$.

3.3.1. Fusion Power and Confinement

The simulation results (see Figure 5) show that under the identical “BEST-like” physics parameters, SPARC, leveraging its 12.2 T field, achieved a very high fusion gain of $Q \approx 27$ ($P_{fusion} \approx 420$ MW), whereas the fusion gain of BEST was $Q \approx 5$ ($P_{fusion} \approx 200$ MW). This result serves as a good illustration of the significant potential of strong magnetic fields in enhancing fusion power. However, it should be noted that this result was obtained under our assumed conditions and thus has certain limitations. Whether it can be directly extended to the design strategy of HTS high-field devices requires further investigation.

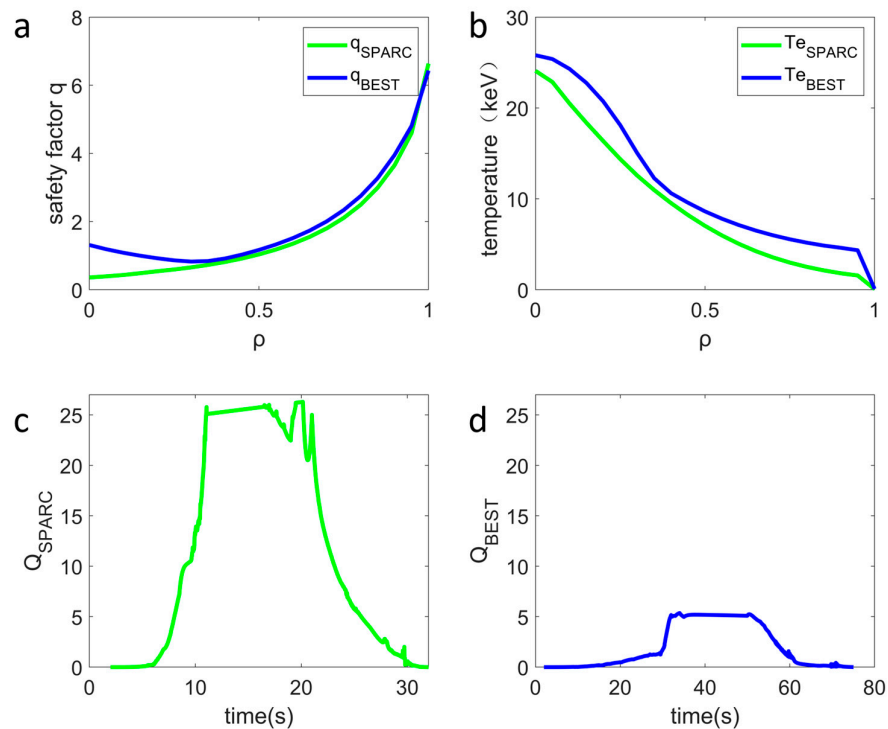


Figure 5. Comparisons of fusion performance of BEST and SPARC under identical physical parameters. (a) Safety factor profile; (b) electron temperature profile; (c) SPARC fusion gain; (d) BEST fusion gain. All profile data were acquired during the current flat-top phase (BEST at 45 s, SPARC at 16 s).

However, high power density also brings challenges. The simulation shows that at such high density and pressure, the L-H transition power threshold P_{LHth} for SPARC increases dramatically. The expression for the L-H transition threshold power is: $P_{LHth} = 0.0488 \bar{n}_e^{0.717} B^{0.803} S_p^{0.941}$, where S_p is the surface area of the plasma [25]. The auxiliary heating power we initially set was insufficient to bring it into H-mode operation; that is, SPARC could only operate in L-mode under the initially set parameters. To better control the variables, we increased the auxiliary heating power of SPARC (P_{ICRH} from 11.1 MW to 14.0 MW) to enable it to enter H-mode.

3.3.2. Discussion on the Feasibility of L-Mode Operation

Our simulations show that under high-field, high-density conditions, SPARC has a higher L-H transition threshold power. This makes entering H-mode more difficult. However, SPARC still achieves decent fusion gain in L-mode. Specifically, under conditions of high density ($f_{GW} = 0.85$), and $H_{89} = 1.0$, the fusion gain reached approximately $Q \approx 5.2$ (see Figure 6). This finding is significant: an operational strategy combining a strong magnetic field and high density can enable a device to achieve decent fusion gain ($Q > 5$) without entering H-mode. However, it should be noted that the current METIS simulation results for the SPARC L-mode are obtained under our assumed conditions and have not yet undergone further comprehensive feasibility analysis (including steady-state current sustainment, MHD stability, acceptable radiative losses, divertor performance, and overall engineering feasibility). The present results can only demonstrate the possibility of a SPARC high-density L-mode operating scenario, and further work is required to validate this possibility.

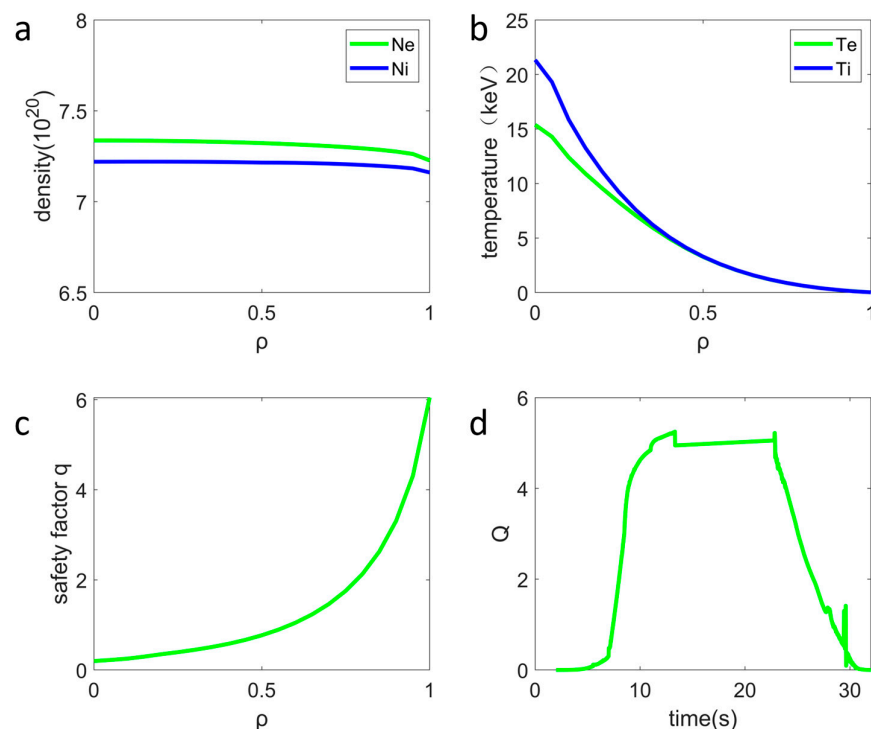


Figure 6. METIS simulation results for L-mode scenario in SPARC. (a) Electron density and ion density profile; (b) electron temperature and ion temperature profile; (c) safety factor profile; (d) fusion gain. All profile data were acquired at 16 s (during the current flat-top phase).

Although the above results have certain limitations, they are still of significant importance for the design of HTS devices. While H-mode offers better confinement, it often involves periodic edge-localized modes (ELMs) [23]. ELMs generate large thermal transients that can damage the first wall and divertor in compact devices like ARC or SPARC [1,26]. Therefore, proactively choosing to operate in an ELM-free L-mode may be a more robust and viable scheme [26]. By appropriately increasing the operational density (f_{GW}), the fusion power loss from poorer L-mode confinement can be compensated for.

3.4. Challenge of Current Drive and Profile Control

Another prominent issue in our simulation process is current profile control. Under high-density ($f_{GW} \approx 1.0$) conditions, EC and LH waves face limitations due to density cut-offs and wave accessibility issues, making it difficult to effectively heat and drive core

plasma current [27]. NBI (neutral beam injection) heating also struggles to heat the core plasma [28,29]. Therefore, the primary method for auxiliary heating of SPARC is ICRH. The ICRH minority ion heating scheme can efficiently heat ions, but its contribution to current drive is limited, and its driven current profile is broad and difficult to tailor flexibly. This makes it difficult for the final current distribution to exhibit an inverse shear configuration, and also hinders the formation of the internal transport barrier (ITB)—resulting in the inability to achieve advanced operating modes.

Because BEST employs four auxiliary heating methods (ECRH, LH, NBI, and ICRH) and has higher total auxiliary heating power, it can drive more current (see Figure 7a) and provide more flexible current profile control. This makes it easier for the final current profile to exhibit a reverse magnetic shear shape (see Figures 5a and 7b).

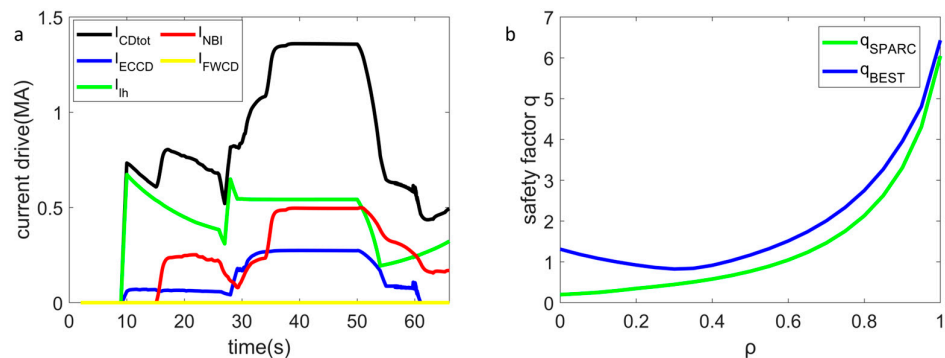


Figure 7. (a) BEST H-mode $Q \approx 5$ scenario auxiliary heating driven current, ICRH (FWCD) generates almost no driven current. (b) Comparison between BEST H-mode $Q \approx 5$ scenario and SPARC L-mode $Q \approx 5$ scenario. All profile data were acquired during the current flat-top phase (BEST at 45 s, SPARC at 16 s).

This highlights a key dilemma: The high-density operational mode pursued by HTS devices for high power density inherently restricts the use of tools most commonly used for fine control of the current profile (e.g., off-axis ECCD, LHCD). In the SPARC simulation, the total current profile is dominated by ohmic and bootstrap currents, with a low fraction of auxiliary-driven current that is difficult to adjust flexibly. This makes it very challenging to actively control the current profile to form and sustain advanced operational modes with reverse magnetic shear [30] or internal transport barriers (ITBs) [31]. Developing effective methods for current profile control under high-density, high-field conditions is a major challenge that must be addressed in the future physics design of HTS devices.

3.5. Overview and Discussion

This study quantitatively demonstrates the performance leverage provided by high magnetic fields in tokamaks. The HTS path (exemplified by SPARC) significantly lowers the entry barriers to high fusion gain by reducing demands on auxiliary heating power, plasma density, and confinement quality compared to the conventional LTS path (exemplified by BEST). The sensitivity analysis of the main parameters and comparison results indicate that the significant fusion performance advantage is brought about by increased magnetic field strength; this well validates the strong dependence of the fusion triple product on magnetic field strength ($\propto B^3$).

However, the pursuit of high-power density through high fields and high densities introduces significant trade-offs. The most critical is the challenge to active current profile control. High densities render common tools like EC and LH waves ineffective, forcing

reliance on ICRH, which is a poor current driver. This limits the ability to establish and sustain advanced, high-performance scenarios like those with reverse magnetic shear or internal transport barriers, which are often desired for steady-state operation.

Furthermore, the increased L-H transition power threshold at high field and density may preclude H-mode operation, forcing the device into L-mode. Although our simulation results show that SPARC can achieve a fusion gain of $Q \approx 5.2$ in a high-density L-mode operating scenario, whether the L-mode can realize a confinement factor of $H_{99} = 1.0$ remains uncertain. Therefore, the L-mode operating scenario for HTS devices may require a higher Greenwald density fraction, which in turn exacerbates the current drive challenges. Therefore, the operational space for compact pulsed high-field devices like SPARC or ARC may involve a complex optimization between confinement mode, density, and current drive capability. The potential benefit of avoiding ELM-induced heat loads by operating in L-mode [26] must be carefully weighed against the confinement penalty and the increased difficulty in controlling the current profile.

4. Conclusions

This study employed the fast integrated modeling code METIS to systematically compare the physical characteristics and requirements for achieving high fusion gain operation in high-temperature superconducting (SPARC) and low-temperature superconducting (BEST) tokamaks, representing different technological paths. The main conclusions are as follows:

The high-field HTS device (SPARC) demonstrates significant advantages in achieving the same fusion gain ($Q \approx 5$): it requires 50–60% less auxiliary heating power, operates at a lower Greenwald density fraction requirement ($f_{GW} \approx 0.37$ vs. ≈ 0.87), and has a more relaxed requirement for the energy confinement factor ($H_{98} \approx 1.0$ vs. ≈ 1.2). This quantitatively validates the strong dependence of fusion performance on magnetic field strength.

Under an identical set of high-density physics parameters, the fusion power potential of SPARC far exceeds that of BEST, but the H-mode transition power threshold of SPARC is also significantly increased, likely forcing operation in L-mode. However, simulations indicate that even in L-mode, SPARC can still achieve $Q > 5$ through high-density operation under our assumed conditions. This might suggest a potential fallback operational strategy for compact HTS devices facing severe first-wall heat load challenges: proactively choosing to operate in an L-mode without large ELM.

However, high-density operation severely limits the application of heating methods such as ECRH and LH, making HTS devices heavily reliant on ICRH. This single auxiliary heating scheme cannot drive sufficient current to adjust the current profile, making it difficult to establish and maintain advanced operating modes such as reverse shearing [30] or ITBs (internal transport barriers) [31]. This poses new challenges for current profile control. Developing efficient, controllable non-inductive current drive methods suitable for high-density, high-field plasmas may be a key point for future research.

Looking ahead, HTS magnet technology opens a new development path for fusion energy characterized by high magnetic fields and compactness. This study reveals the great potential of this new path compared to the previous LTS path in lowering the barriers to fusion (auxiliary heating power and confinement requirements) and also identifies its core physics challenges (current drive and profile control at high density; higher L-H transition threshold power). Follow-up work needs to incorporate more precise wave physics and current drive calculations to explore possible current profile control schemes at high density. Simultaneously, for future higher-parameter steady-state operation devices like ARC and CFEDR, it is necessary to further explore the operational characteristics

and scenarios of HTS and LTS devices to provide guidance for the design of a commercial fusion reactor.

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