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Editorial

Status of the SPARC physics basis

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This special issue provides a snapshot of the physics basis for SPARC, a compact, high-field, deuterium-tritium burning tokamak, currently under design by a team from the Massachusetts Institute of Technology and Commonwealth Fusion Systems. The project builds on a remarkable period of progress in the understanding of magnetically confined plasmas achieved collectively by the world's fusion programs. This progress puts us in a position to take advantage of a technological breakthrough developed outside of our field, namely the emergence of high-temperature superconductors (HTS) as a practical engineering material. By enabling fusion magnets to operate at high magnetic field, the beneficial impact of HTS is clear – the step size of turbulent or collisional transport processes scales with the gyroradius and thus plasma performance improves as a strong function of the number of gyroradii across the plasma ($1/\rho^*$). Further, operational limits for plasma pressure, density and current all increase with magnetic field. For exactly these reasons, the design for the ITER experiment explicitly required the highest possible magnetic field achievable with the niobium-based technology available at the time. The use of a newer, higher field magnet technology enables similar levels of plasma performance in devices of considerably smaller size and thus lower capital cost.

The missions of SPARC are (1) to create and confine a plasma that produces net fusion power; and (2) to retire technological and scientific risks on a high-field path to practical fusion energy. The SPARC design, with $B_T = 12.2$ T, $I_P = 8.7$ MA, $R = 1.85$ m, $a = 0.57$ m and Ion Cyclotron Range of Frequency Heating (ICRF) power up to 25 MW available for heating, targets a minimum fusion gain, $Q > 2$ and fusion power, $P_{\mathrm{FUS}} > 50$ MW. In fact with these parameters, under ITER physics rules, SPARC would attain $Q > 10$ and P_{FUS} up to 140 MW, providing significant margin against assumptions of energy and particle transport or impurity content. Even when operating at somewhat reduced performance, this would place SPARC squarely in the burning plasma regime – whose study is the key science mission for the fusion program. With $\langle T_i \rangle = 8$ keV predicted, the fast alpha physics in SPARC will be similar to that of ITER and would provide essential data on the self-consistent, self-heated state.

Leveraging the broad progress in tokamak physics, the SPARC design has been fundamentally informed and optimized not only by empirical scaling (all data, no physics),

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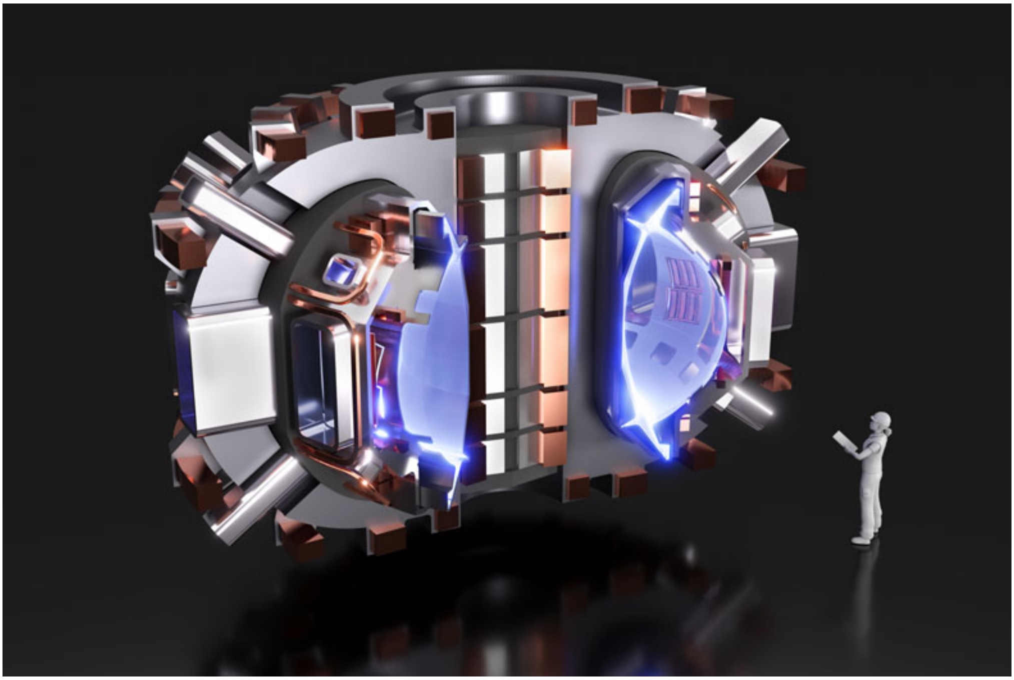

FIGURE 1. Cutaway of SPARC engineering design (image courtesy of CFS/MIT-PSFC, rendering by T. Henderson)

but also by ‘first principles’ modelling (all physics, no data). Both approaches result in essentially the same prediction of overall plasma performance and fusion gain, thereby increasing confidence in the projections. Ongoing work features the use of state-of-the-art codes for calculation of ICRH heating, turbulent transport, pedestal structure, edge profiles, magnetohydrodynamics (MHD) stability and ripple losses of fast alphas.

The SPARC team is keenly aware of the challenges intrinsic to operating an experiment at the proposed levels of performance. In addition to the electro-mechanical and thermal engineering of its high-field superconducting magnets, a device of this class will have enormous power flows that must be managed. The ICRF system will be the largest ever deployed in a fusion experiment and must operate reliably and robustly as it will be the only auxiliary heating method for SPARC plasmas. With an unmitigated parallel heat flux at the plasma midplane, $q_\parallel$ approaching 10 GW m^{-2}, the first wall must survive steady-state and transient heat load without excessive contamination of the core plasma. Nuclear heating of the tokamak components by fusion neutrons and gamma rays will be significant and are being considered in the design. We must also design for mechanical and thermal loads from disruptions and develop strategies to avoid or mitigate the effects of relativistic runaway electron populations. These are all daunting challenges, but they are well known problems, long identified by the fusion community as ones that must be solved if we are to harness fusion as a practical power source. The often quoted lines from President Kennedy has special resonance in this regard ‘*We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone…*’.

The first step in meeting these challenges is to put the SPARC project on the firmest possible physics basis. You will read in the accompanying papers, the current state of that basis. They review the basic parameters of the machine, predictions of core and pedestal performance, RF heating, divertor physics, MHD, disruptions and the confinement of fast particles. Over the coming months and years, the team will seek to refine and elaborate the analysis which has been carried out and documented here. With the basic machine parameters set, the physics team has already begun a deeper level of physics analysis, aimed at informing and confirming design choices, developing a range of operational scenarios and control strategies, defining diagnostic needs and outlining the scientific research program.

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