Overview of Preparation for SPARC Q>1 and Retiring Physics Risks For ARC

J.C. Hillesheim[1] on behalf of the SPARC and ARC Teams
[1]Commonwealth Fusion Systems, Devens, MA, USA

Commonwealth Fusion Systems is building the SPARC tokamak in Devens, MA, USA, with first plasma planned in 2026. The initial objective of SPARC will be scientific demonstration of Q>1 in a tokamak, with operations then shifting to the goal of retiring physics risks for ARC. The ARC fusion power plant is a tokamak facility designed to generate 400 MW net electric power and is targeting operation by the early 2030's at a site in Chesterfield County, VA, USA.

SPARC (R=1.85 m, a=0.57 m, B=12.2 T, Ip=8.7 MA) is being built with magnets using high temperature superconductor technology, is tritium compatible, will have up to 25 MW ICRH auxiliary power, and is inertially cooled with with tungsten and tungsten alloy plasma facing components. SPARC is designed to produce up to 140 MW fusion power and for 10 s pulse length. Initial design studies for SPARC showed operating points with up to Q=11 and P_{fus}=140 MW may be achieved. Recent work has investigated the physics of scenarios to achieve Q>1 in early operations and developed the control and diagnostic capabilities to execute this goal.

The initial mission of SPARC operations will be the first demonstration of scientific breakeven, Q>1, in a tokamak. Near-breakeven conditions are found for predictions of fusion performance in L-mode plasmas. Q>1 is achievable in L-mode if an edge boundary condition of ~35% of the EPED predicted H-mode temperature pedestal is achieved, when limits on core profile gradients based on gyrokinetic simulations are taken into account, and seeding needed for divertor protection is included. A database scanning parameters using 1000+ ASTRA/EPED/TGLF simulations of SPARC H-modes shows that at 12 T high fusion performance (Q>2, P_{fus}>50 MW) is achievable even with pessimistic assumptions for variations of pedestal top parameters, and Q>1 may also be achievable with H-mode at 8 T operation.

The compact size and high magnetic field in SPARC present challenging and novel regimes for exhaust physics. Boundary and divertor physics for SPARC have informed real-time control models and machine protection, as well as predicted ELM-free operating conditions compatible with boundary physics solutions. Viable operation in the Quasi-Continuous Exhaust regime on SPARC has been identified with n_{sep}=4e20/m^3, $T_{e,sep}$=156 eV, corresponding to α_t=0.7, a value of the collisionality-like variable α_t that has been demonstrated on AUG. SOLPS-ITER modeling of SPARC H-mode operation, for lower separatrix collisionality conditions $\alpha_t \approx 0.2$, has found hysteresis and asymmetry effects driven by parallel currents, informing safe operational regimes. HEAT simulations have been used extensively for final designs of SPARC PFCs. A time-dependent 1D model has been validated against empirical results for detachment access, and is now being used to study time-dependent effects for detachment control.

SPARC will operate at higher plasma current than any previous tokamak, has been designed to be robust to disruptions and will test novel runaway electron mitigation schemes. Disruption simulations of SPARC have shown the runaway electron mitigation coil design prevents the formation of large RE currents and the planned massive gas injection system is sufficient to radiate stored thermal energy, based on non-linear MHD simulations with NIMROD. Within the SPARC control framework, a series of off-normal warning modules for disruption prediction and avoidance have been developed, including radiative collapse and vertical displacement events, which have been tested against Alcator C-mod data.

To rapidly execute SPARC's mission CFS has developed a real-time plasma control system and supporting tools, leveraging modern software and machine learning techniques. Development of modules for use in real-time control and pre-pulse scenario optimization is done in the MOSAIC framework for pulse planning and simulation, already incorporating GSPulse, RAPTOR, TORAX, and POPCON; providing a flexible, collaborative development environment for additional modules, in the IMAS data schema. A real-time PFC temperature model has been developed for machine protection and verified against the higher fidelity HEAT code. A neural network based on TORIC simulations has been developed for a real-time RF module.

To execute the Q>1 mission, quantitative measurement of fusion power with known uncertainty is critical. An initial set of diagnostics for SPARC has been developed, including multiple neutronics measurements to quantify generation of fusion power, and to enable operation and machine protection, as well as to later support retiring risks for ARC.

SPARC is the primary risk retirement platform for ARC. CFS has iterated on variations of the ARC design to assess trade-offs between physics, engineering, economic, and other constraints, and developed the physics basis for ARC, with identification of key physics risks to be retired through SPARC operation, towards completion of a preconceptual design. ARC will be a high field tokamak based on HTS magnet technology, ICRH auxiliary power, tungsten plasma facing components, with a molten FLiBe salt blanket, and with inductive 900 s pulses.

Prediction of fusion performance and identification of key uncertainties and parametric sensitivities are critical for selection of a robust design point for ARC. Transport and fusion performance for ARC have been predicted using a multi-fidelity approach. Low fidelity scoping is done via empirical scaling laws using the open-source POPCONs code to assess broad operational ranges. Medium fidelity simulations are performed using the ASTRA code, with an EPED neural network for the pedestal and TGLF for core transport. High fidelity simulations are performed with CGYRO using the PORTALS framework for full profile gyrokinetic predictions. It is found that core transport for ARC-like parameters is extremely stiff and dominated by ITG turbulence. Design points with P_{fus}≈1 GW, sufficient to deliver the target 400 MW net electric, have been identified. The most robust difference between medium and high fidelity modeling, across various ARC design iterations, is that non-linear gyrokinetic profile predictions have lower density profile peaking than TGLF predictions and empirical scaling laws. To incorporate limitations due to strong ITG stiffness, a reduced semi-empirical model that can be used in low fidelity scoping has been developed.

The ARC operational scenario must deliver sufficient fusion performance, while avoiding erosion from ELMs and providing power exhaust with high radiation fraction. The ARC design includes a double-null, long-legged x-point target divertor, which has been assessed with SOLEDGE2D modeling, showing broad plasma-neutral interaction and strong neutral radiation, with a robust detached operational space, with impurity concentrations similar to existing experiments. Boundary solutions have been investigated for ARC using the SepOS model to assess separatrix operating conditions consistent with detached conditions in the divertor, and provide separatrix values for scoping with the EPED-NN.

Disruption loads have been assessed to inform the structural design of ARC. Vertical forces up to ~70 MN and radial forces up to ~50 MN are found, which are tolerable, based on the SPARC design. These calculations have been performed using analytical estimates, fast calculations with the thin-wall model ThinCurr, and complemented with non-linear VDE simulations with the MHD code M3D-C1. As the high neutron fluence environment precludes in-vessel coils, vertical stability analysis has been important for constraining ARC design. Vertical stability analysis has been performed with Tokamaker and MEQ-FGE, finding robust control of vertical stability Z_0/a~9% with the ARC PF coil set, without any in-vessel coils.

Kinetic analysis of error field correction coils, including NTV effects that limit the maximum correctable error field, have been investigated for a variety of potential 3D coil sets for ARC, identifying optimized coil size, locations, and orientations for robust error field correction requiring only modest coil currents, ~2-4 kAt. Sufficient 3D perturbation amplitude for n=2 ELM control is also feasible with >20 kAt.

As whole, this work addresses a range of gaps important for fusion energy, first through preparation for scientific demonstration of net fusion energy production in a tokamak, then the ARC physics basis informs the current baseline design of ARC and early SPARC campaigns, where after the demonstration of Q>1, the focus will be to retire physics risks for ARC.