Divertor Plasma Simulations

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Note: Report may be posted publicly. Do not include proprietary information.

1 Technical Overview

1.1 Problem Statement

Describe the CFS challenges this program is meant to address. Should be adapted from original application, noting any departures / evolutions from that original application.

CFS in collaboration with MIT and others are working to design a compact, high-field tokamak for the demonstration of net fusion energy. Current empirical scalings indicate that unmitigated parallel heat fluxes in the boundary plasma will exceed 10 GW/m^2, which poses a formidable challenge for the design of the plasma facing components. Successful operation of SPARC will require a detailed understanding of how the boundary plasma performs, and the parameter space within which we can expect to safely operate.

In the original proposal, there was a desire for UEDGE simulation results that would inform concepts of the divertor magnetic field and wall shaping. However, due to the timeline of SPARC design relative to the execution of the CRADA, the design of the SPARC divertor was fixed prior to the start of the project. The original problem statement was thus altered to focus on using UEDGE to perform the first modern, extensive boundary plasma physics simulations of two scenarios: the standard and X-point Target Divertor geometry with the purpose of guiding design assumptions and developing tools for use during early operations to interpret experimental results.

1.2 Work Scope

Describe the approach used to achieve the project goals, including the capabilities at the national laboratory or partner facility, as well as the capabilities at CFS and its subcontractors on this award. Can be informed / adapted from original application, noting departures / evolutions.

The INFUSE project focused on modeling of the SPARC edge plasma and divertor with the UEDGE code. The UEDGE code developed at LLNL in 1990s is one of the most complete and comprehensive models available for describing tokamak boundary plasmas. UEDGE solves time-evolution equations for fluid plasma fields such as density and temperature, in an axisymmetric divertor geometry, with a user-supplied model for the anomalous radial transport to match experimental data, or projections, for the spatial profiles of plasma density and temperature.

Usually a steady-state solution is sought as it is most relevant to the experiment, and in most cases (but not always) UEDGE finds a steady-state solution. The numerical solutions from UEDGE have been validated on experimental tokamak edge plasma measurements (mostly DIII-D, C-Mod, NSTX but also some others), and in many dozens of studies it was shown that UEDGE simulations reproduce edge plasma phenomenology qualitatively and semi-quantitatively, within a factor of ~2, or better.

It is important to note that compared to similar tokamak edge transport codes UEDGE is distinct in its state-of-the-art numerics, allowing large time steps and achievement of exact (to the machine accuracy) steady-state solutions.

UEDGE has a “standard” collisional fluid plasma model built into it, including the dynamic equations for plasma and neutral densities, electron and ion temperatures, ion and neutral parallel velocities, and the electric potential. In the code there are hundreds of switches that allow altering various assumptions and options, both for physics and numerics. However, most of the options are set as default, based on extensive body of theoretical work and on the experience running the code and comparing it with experimental data.

The scope of this work is for LLNL Physicist Maxim Umansky together with MIT graduate student Sean Ballinger to develop and interpret UEDGE simulations results for SPARC. Inclusion of the student on this proposal was desirable as it better leveraged Umansky’s time as well as helped train the next generation of experts in this important tool.

Tasks included:

1. Set-up of UEDGE simulations to align with ‘upstream’ conditions expected in SPARC based on the empirical scalings for a standard divertor geometry
2. Perform scans of input power
3. Perform scans of impurity concentration and species
4. Evaluate sensitivities of the result to input parameters
5. Perform scans of magnetic null balance from single to double-null
6. Develop a similar model of the X-point Target geometry

Note that task 6 was added to replace task 2 of the original proposal (vary divertor geometry to examine divertor plasma performance under standard and various advanced divertor configuration) due to the timeline of SPARC design relative to the start of this INFUSE project.

1.3 Results

Describe the tasks accomplished, results obtained, key deliverables, lessons learned.

<u>Do not include proprietary information</u>.

The UEDGE edge code has been used to examine conditions in the SPARC divertor and edge plasma for various levels of carbon impurity and power from the core. A double-null magnetic configuration was simulated assuming up-down symmetry in both geometry and physics. The anomalous heat and particle transport coefficients are tuned to match empirical predictions for SPARC’s midplane density profiles, target plate heat flux profiles, and inner/outer divertor power sharing. Convective transport is included on the low-field side, while on the high-field side the transport is modeled as purely diffusive. Hydrogen neutrals are modeled as a fluid with inertial effects, and a carbon impurity is included using the fixed-fraction model. It was found that detachment induced by impurity seeding could significantly reduce the heat flux to the divertor surfaces in the SPARC tokamak. At the input power from the code P = 28 MW (the value predicted for SPARC's full-power H-mode scenario) one or both divertor legs can stay detached with 0.3–1.4% carbon impurity fraction, far below Z_{eff} limits for SPARC. When the plasma in a divertor leg is detached, the peak in total normal heat flux to the target plate is below 1 MW/m^2, and electron and ion temperatures are less than 1.5 eV. However, the modeling results are found to be sensitive to the side-wall boundary conditions and the level of neutral pumping, both of which can cause a transition to full attachment or detachment of the outer leg. The results are summarized in a 2021 publication by Ballinger et al. titled 'Simulation of the SPARC plasma boundary with the UEDGE code' that has been accepted by Nuclear Fusion.

The second half of the project was focused on exploration of an advanced divertor configuration with a secondary X-point placed near the end of the outer divertor leg, so-called X-point Target Divertor (XPTD).

XPTD configuration is viewed as one of the options for future SPARC divertor operations (albeit not for the full power), and a set of magnetohydrodynamics equilibria for SPARC was developed, predominantly lower single null but with a secondary X-point in the outer divertor leg. Based on one of those equilibria, a set of computational grids was produced using a new grid generation tool INGRID [Garcia2021]. Next, a set of SPARC UEDGE steady state solutions was obtained for XPTD, for a range of input power and neon impurity ion fraction.

One immediate finding from those UEDGE runs was that using XPTD in the outer divertor leg results in shifting the in-out power split between the divertor legs. With XPTD in the outer leg, a larger fraction of the power is directed to the inner leg, which may compromise the inner divertor target. This result was verified by comparing otherwise similar UEDGE runs, with and without XPTD in the outer leg, it can be explained by a simple analytic model and is consistent with some previous analyses of the TCV tokamak and DEMO reactor studies [Reimerdes2020].

Still, based on those UEDGE runs, using XPTD in the outer divertor leg allows achieving a few times lower peak heat flux on the outer divertor target than on the inner divertor target. This suggests that XPTD may become a practical option for handling the divertor heat exhaust for an up-down symmetric configuration.

The current study of the SPARC XPTD configuration leaves a number of open questions regarding the sensitivity of UEDGE solutions to details of the simulation setup, including details of magnetic equilibrium, impurity fraction and species, neutral gas pumping, radial wall boundary conditions, and effects of currents and drifts. Covering that in a fully comprehensive and detailed study could not be completed within the framework of this one-year INFUSE project. However, the project enabled advancement of the simulation tools and execution of a number of initial UEDGE runs. The groundwork is in place for future development under another INFUSE project or some other funding opportunities.

An important spin-off of the project is training an MIT graduate student (Sean Ballinger) in using the UEDGE code, potentially adding to the future edge plasma modeling workforce. Sean was instrumental in developing a wide range of Python utilities for the UEDGE interface that is being shared across the UEDGE modelling community for other users.

2 Impact

2.1 Use of Project Results

Describe how the results obtained contributes to CFS' roadmap. Include a timeline slide pointing out relationships to other DOE programs and SPARC/ARC milestones.

The main deliverables from this project are two sets of UEDGE converged solutions – standard and X-point Target Divertor geometries, with representative SPARC magnetic geometries and 'upstream' conditions. These two models and their associated scans will be beneficial to CFS to scope out the operational space and develop a set of solutions to compare against as experimental measurements from early operations start to be collected. The combination of the two is expected to improve our ability to interpret experimental results and enable SPARC to accelerate towards high performance operations by reducing the iteration time. This approach is also being taken by ITER as they continue to expand upon the database of divertor simulations that have been run for when operations begin.

Furthermore, the results have also been beneficial during the conceptual design phase of the SPARC divertor. In the divertor heat load specifications, credit was taken for a 50% radiative dissipation of the conducted power entering the divertor to reduce the target peak heat fluxes by spreading the power. The low impurity fraction needed to achieve dissipative divertor conditions found in simulations of the standard divertor geometry supported these assumptions as realistic and likely achievable. Furthermore, results were found to be consistent with simpler empirical models which meant that initial design iterations could be done on a faster time scale using simpler models without the need to run detailed plasma simulations with each cycle. Having these simulations provided the design team with the confidence needed to keep to the SPARC timeline.

The promising XPTD geometry results have also provided the justification for continuing to accommodate it in the technical baseline. Including the XPTD geometry does drive some of the surrounding coil specifications as well as reduce the robustness of the overall divertor design by introducing complexities. The indication from these simulations that an XPTD may indeed reduce peak heat fluxes at the divertor target supported the team's decision to include the alternative divertor geometry into the SPARC divertor design despite these added difficulties. The results suggest that there is indeed the potential for a relevant heat exhaust management solution for ARC to be demonstrated on SPARC.

Figure 1 shows the intersections of CFS' INFUSE programs with the SPARC timeline: this project (top right) aided in expanding the physics basis for the SPARC divertor operations and supported the design of SPARC Plasma Facing Components during conceptual and preliminary design phases.

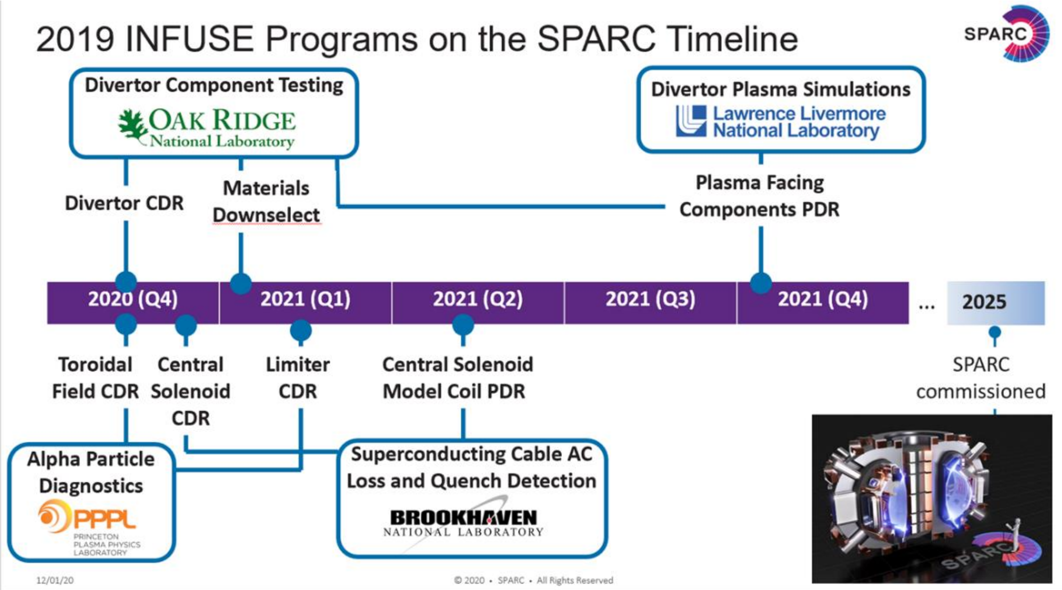

Figure 1 Intersections of CFS' 2019 INFUSE programs with the SPARC timeline

Furthermore, a key focus topic for SPARC is to evaluate X-point Target Divertor geometries for use on ARC. ARC design is scheduled to begin soon after SPARC early operations, as illustrated in **Figure 2**. The X-point Target Divertor geometry and other long-legged divertors can currently only be tested on MAST-Upgrade and TCV, both of which have far lower plasma and power densities than those anticipated for ARC. Extrapolation of results from these devices to ARC has been deemed as carrying too much physics risk that SPARC is meant to retire. Therefore, it is crucial to develop an understanding of the effectiveness of the X-point Target Divertor geometries during early SPARC operations before ARC design begins. As mentioned, having the UEDGE simulations in hand during early operations would aid in the interpretation of measurement data. Furthermore, the simulations have highlighted key sensitivities that would be crucial to test out in SPARC for ARC design.

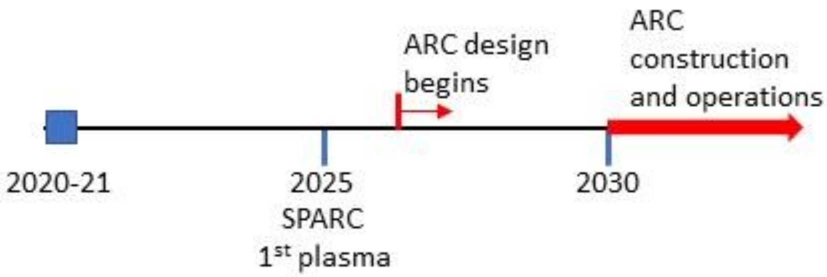

Figure 2 Schematic of CFS' SPARC and ARC timeline. ARC design is scheduled to begin soon after SPARC early operations. A key focus topic for SPARC is to evaluate X-point Target Divertor geometries for use on ARC. And the UEDGE simulation tools developed in this INFUSE project will aid in the interpretation of SPARC measurement data.

Depending on the timeline and final design of the EXCITE device that has been proposed in the FESAC 2020 report – ‘Power the Future: Fusion and Plasmas’, there is potential for it to be highly complementary with the SPARC advanced divertor scoping missions. EXCITE is currently slated to be constructed and in operation by 2030 and includes a core-edge integration mission of finding divertor heat and particle mitigation systems compatible with a high-performance core plasma, and testing out divertor geometries like the X-point Target alongside other options.

2.2 Fusion Energy Impact

Describe how this project will contribute to advancing fusion energy development more generally.

The impact of this project on advancing fusion energy development is two-fold: it advanced the scientific understanding of reactor relevant divertor scenarios and provided training for a new generation of plasma boundary modelers. Developing converged solutions for SPARC has pushed the UEDGE code beyond the typical parameter space that it has been used in the past. Care was taken to ensure sensitivities to the assumed inputs, which were assessed, and comparisons were made to other plasma boundary modelling codes like SOLPS-ITER. The results indicate that full detachment with a reduction of particle fluxes may be more difficult to achieve than in present day devices. Significant target surface power loads are still present even with cold plasmas (T_e<3 eV) due to the high particle fluxes to the target. These results will likely be transferable to other reactor divertor concepts beyond SPARC.

In addition, working with students and training a new generation of plasma boundary modelers was key. New skills and ideas were brought to the project. Sean Ballinger, graduate student at MIT, has been instrumental in developing a wide range of python utilities for the UEDGE interface that is being shared across the UEDGE modelling community for other users.

2.3 Intellectual Property, Publications and Conferences

Identify new IP, publications and conference presentations generated from this project.

Results from this project were summarized in the following publication and conference presentation:

- Ballinger, S., et al. "Simulation of the SPARC plasma boundary with the UEDGE code." Nuclear Fusion (2021); and
- Ballinger, S., et al. "UEDGE Modeling of the Scrape-Off Layer and Divertor in SPARC." Contributed Poster at the 62nd Annual Meeting of the APS Division of Plasma Physics.

In addition, the results were also included as part of a broader publication on the SPARC divertor challenge and design:

- Kuang, A. Q., et al. "Divertor heat flux challenge and mitigation in SPARC." Journal of Plasma Physics 86.5 (2020).

3 References

[Garcia2021] "INGRID: an interactive grid generator for 2D edge plasma modeling" B. M. Garcia, M. V. Umansky, J. Watkins, J. Guterl, O. Izacard, submitted to Comp.Phys.Comm. (2021)

[Reimerdes2020] H. Reimerdes et al. is Nucl. Fusion 60(2020) 066030