**SPARC 3D Field Physics and Support of the Non-Axisymmetric Coil Assessment**

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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 the original application, noting any departures / evolutions from that original application.*

Commonwealth Fusion Systems (CFS) is deploying SPARC, a net-energy tokamak, by 2025. A notable challenge facing all tokamak approaches to fusion energy production is maintaining a stable plasma and thereby steady energy production. "Disruptions" to plasma operation are often encountered in devices when they operate at high normalized pressure, high normalized density, or high normalized current. SPARC is unique in that it is expected to demonstrate Q>=2 in a plasma with low normalized pressure and density, but with a more modest current limit buffer sufficient to avoid disruptions. Due to both the high normalized current and high magnetic field of the SPARC design, it is expected to decrease its relative resilience to instabilities driven by non-axisymmetry in the externally applied magnetic field, termed 'error fields'. To prevent error field driven instabilities, a primary line of defense is strict engineering tolerances in magnet fabrication and installation. A secondary line of defense is a purpose-built set of magnetic coils to correct these errors, termed error field correction coils (EFCCs). The overarching goals of this INFUSE project were to evaluate the effectiveness of the EFCCs in the SPARC design and provide guidance as to how to improve this effectiveness.

The Ideal Perturbed Equilibrium Code (IPEC) code developed and maintained by Princeton Plasma Physics Laboratory (PPPL) scientist Jong-Kyu Park and Lawrence Livermore National Laboratory (LLNL) scientist Nikolas Logan has revolutionized the physical understanding of plasma sensitivity to error fields and was the centerstone of this project. IPEC was used to assess the types of error fields that the plasma is most susceptible to in the various plasma conditions expected during SPARC plasma current ramp-up, the steady fusion production phase, and the plasma current ramp-down. Knowledge of the dominant error fields then allowed the evaluation of a set of EFCCs where the metric is the overlap of the applied correction field with the dominant spectrum. This tool was used to assess and inform CFS' design choices of EFCC placement, geometry, and current level. Additionally, the impact of other sources of non-axisymmetry, such as leads feeding current into nominally symmetric coils, was assessed.

The IPEC code has recently been extended to include other physics including the toroidal torque applied by 3D fields and is now referred to as the Generalized Perturbed Equilibrium Code (GPEC). Although plasma braking by resonant fields is of greatest concern, non-resonant braking reduces the bulk plasma rotation resulting in an increase in the resonant braking in a way analogous to reducing the slip frequency and increasing the torque in a stalled induction motor. GPEC was used to assess the torque applied by the residual field resulting from an imperfect match between the dominant error and the applied error field correction (EFC). Imposing a limit on the braking torque that might be tolerated by the SPARC plasma determines the fidelity with which the EFCCs must correct the dominant error. This requirement helped CFS determine the optimum configuration of coils when deciding between in- and ex-cryostat placement options.

Finally, the baseline operating scenario of the SPARC plasma is expected to have transient instability events at the plasma edge. These events can release significant quantities of energy resulting in potentially damaging heat fluxes at the plasma-wall interface referred to as the divertor. These instabilities are called "edge localized modes" (ELMs) and likely must be suppressed to reduce wall material influx to the plasma and to increase the lifetime of the divertor components. A leading method of ELM suppression uses non-axisymmetric magnetic perturbations that are thought to marginally degrade thermal and particle confinement in the plasma edge thereby reducing the instability drive. The GPEC code was used to assess the ability of the EFCCs to apply magnetic perturbations that are resonant in the plasma edge, thus providing a necessary condition to access a regime without ELMs enabled by the EFCC system.

## 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 DOE's Generalized Perturbed Equilibrium Code (GPEC) [1,2] was used to determine the external fields that are most important for EFC, ELM suppression, and Neoclassical Toroidal Viscosity (NTV) torque in the present SPARC tokamak design. Non-axisymmetric coil array geometries proposed by CFS were assessed in terms of their efficiency in coupling to these dominant field spectra. The ability of the proposed coils to correct expected sources of field errors were also assessed, with a goal of providing input on construction tolerances. This included evaluating the single-mode EFC thresholds as well as multi-mode NTV effects from the proposed coil arrays.

The work leveraged the OMFIT workflow manager for integrated modeling coupling the GPEC [1,2]. Modeling relied on SPARC equilibrium (EFIT g-file), predicted kinetic profiles, and basic machine geometry (R, Z poloidal cross sections of the vessel wall, ports and toroidal field coils) provided by CFS. An iterative process was established, and fast response times of detailed assessments were at pace with CFS needs during quickly evolving design cycles. The INFUSE team, which comprised the CFS team (Alex Creely and subcontractor Ryan Sweeney) and LLNL team (Nik Logan and subcontractor Carlos Paz-Soldan) presented and/or contributed to the following, where the CFS team owned and progressed all coil designs, and the LLNL team evaluated the designs:

- Presented the underlying physics basis of EFCC / RMP at the SPARC physics meeting
- Contributed to resolving technical concerns raised during the EFCC conceptual design review
- Contributed analysis to the EFCC Preliminary Design Review, scheduled for Feb 2022.
- Contributed to the definition of EF requirements in the SPARC General Requirements document.
- Contributed to the decision to maintain ELM function of the EFCC in SPARC
- Presented the project conclusions at the American Physical Society Division of Plasma Physics Annual Meeting, Pittsburg 2021
- Presented the project results at the 3rd Annual INFUSE Workshop on Dec 16, 2021

## 1.3 Results

*Describe the tasks accomplished, results obtained, key deliverables, lessons learned.*
*Do not include proprietary information.*

As planned, the DOE's GPEC was used to determine the dominant driving external fields separately for EFC, ELM suppression, and NTV torque in CFS' projected SPARC tokamak plasma scenarios. Examples are shown in Figure 1. The core EFC dominant mode has long wavelength & high amplitude on the low field side, a structure that comes from toroidicity and pressure driven kink amplification [3]. These characteristics become more extreme with more aggressive $\beta_N$ targets and were used to establish intuition as to where the most efficient coils would need to be positioned.

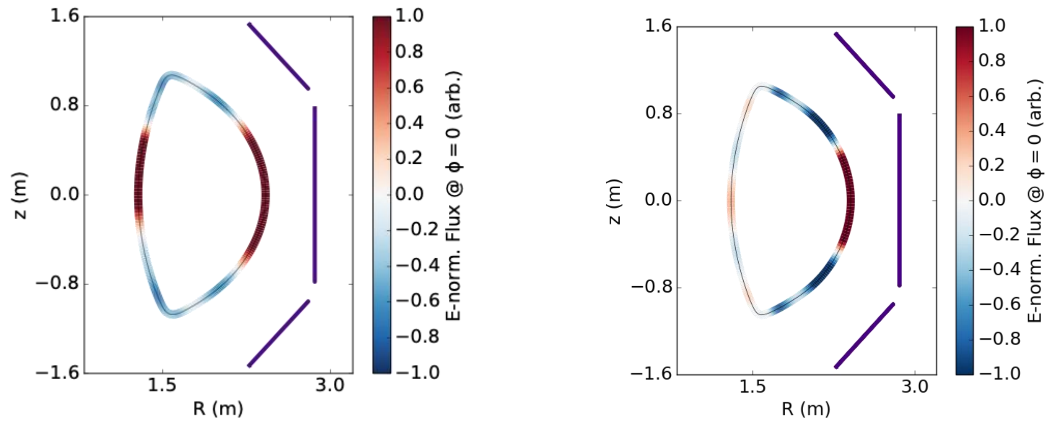


Figure 1: Prediction of EFC dominant mode structure in two possible target equilibrium with different plasma current levels. The overlap of coil spectra with the mode structures that drive significant resonances was used to evaluate coil configurations (purple) as well as various current distributions in the multiple coil arrays.

Nonaxisymmetric coil array geometries, including the most likely coil geometries limited by existing ports as well as more theoretical concepts, were assessed in terms of their efficiency in coupling to these dominant field spectra. Example coil arrays assessed are shown in Figure 2. Here, the low field side (LFS) weighting of the dominant modes was favorably aligned with the engineering constraints that also pushed towards LFS arrays where neutron loads are lower, more room was available, and the ambient toroidal field cross-forces were lower.

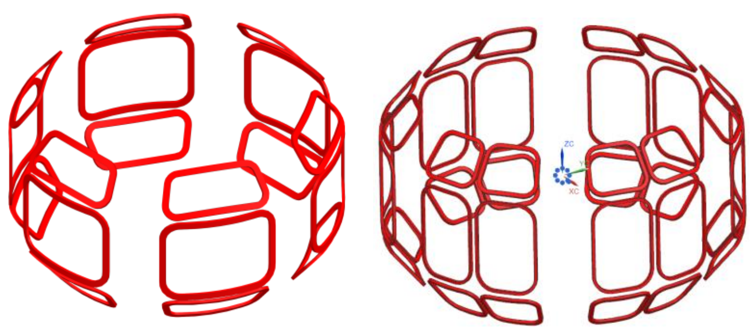

Figure 2: Examples of proposed 3D coil configurations assessed in terms of the GPEC performance metrics to determine their efficiency.

In addition to helping CFS evaluate the efficiency of the coils in terms of their overlap with the most important field structures, finite thresholds in the allowable error field were determined and helped CFS set coil current specifications for various candidate designs. For the allowable core EF, the recently published ITPA database scalings were used to set the allowable compensated EF threshold in terms of the dominant mode overlap metric [4]. This fusion community resource has also been used to project EF thresholds to ITER. Figure 3 shows that SPARC's tolerance is comparable, although perhaps a factor of ~2 lower than ITER owing primarily to the higher toroidal field ($B_T$). It is important to note that the metric used here is the dominant mode overlap normalized by the toroidal field, and it is comforting to see a projected level of robustness within the range of our existing database despite SPARC's uniquely high $B_T$. For RMP ELM suppression, a conservative approach was chosen in using the vacuum island overlap width (VIOW) metric and threshold based on a published database study [5] that was also used for ITER. The threshold of this metric (VIOW = 0.16), however, was translated to alternative edge RMP metrics available from the GPEC model for increased confidence in the projections. Figure 3 shows one such instance of metric comparison, wherein the vacuum Chirikov parameter at the top of a SPARC pedestal reaches 1 at the same current that the VIOW reaches 0.16. More advanced metrics including the plasma response were also considered during the coil assessments, and headroom in EFCC current is available in the design.

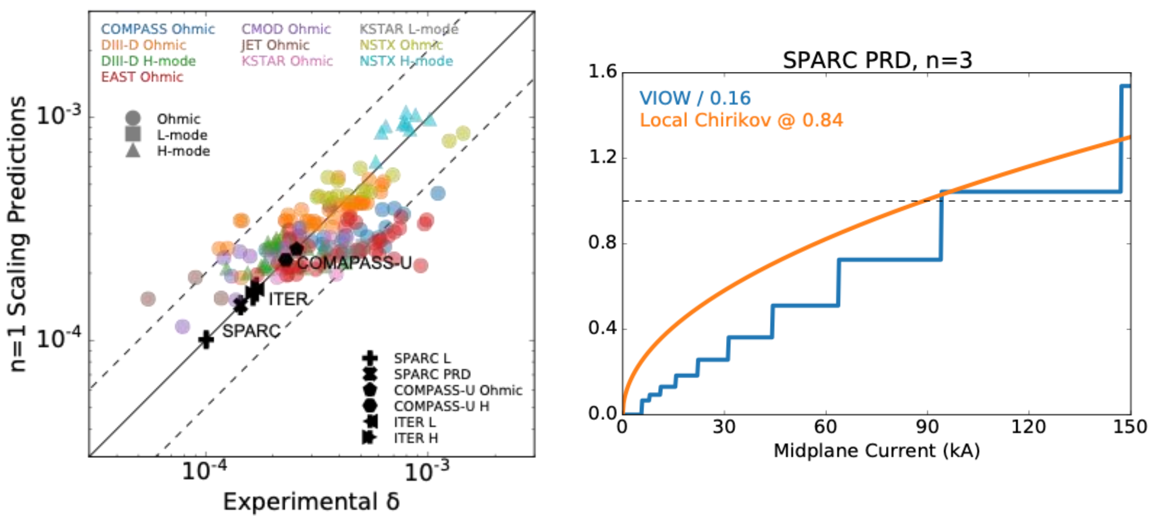


Figure 3: Core (right) and edge (left) 3D field thresholds were established by previously published database scalings. These were used to determine the required current in any proposed coil geometry.

In the case of the tolerable EF and requirements definition, the LLNL team members worked together closely with CFS personnel to form a statistical approach used to identify EF sources and associated correction coil requirements that could quickly adapt to the evolving machine designs. Even nominally axisymmetric coil designs can have significant amounts of non-axisymmetric EFs from finite windings, current leads, or other features. This approach enabled the INFUSE team to guide engineering choices optimizing windings and relative "clocking" of coil assemblies to minimize the nominal design error fields. In addition to this, Monte Carlo analysis of shifts & tilts provides statistical expectation of eventual EF for given tolerances. Figure 4 shows an example of how the relative EF sources compare to the ITPA threshold given one hypothetical tolerancing scheme. These INFUSE tools allowed CFS to confidently balance these statistical expectations, the projected EF threshold limits, and the 3D coil capabilities. Ultimately, this work informed the

SPARC General Requirements on error fields which specify the maximum allowable error resulting from the superposition of all sources.

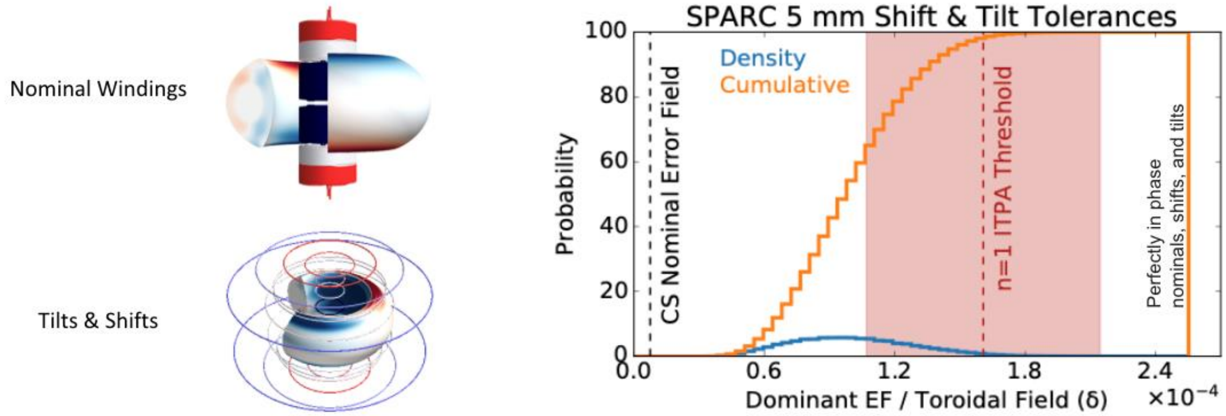


Figure 4: Error field sources accumulated from coil windings as well as Monte Carlo tilts and shifts within a 5mm tolerance for one possible SPARC scenario.

Having established the efficiency of various coil couplings to the plasma as well as the coil current requirements to meet the projected thresholds for EFC and ELM suppression, secondary effects were checked and used to help guide design choice decisions. Figure 5 shows one example of how quickly NTV braking of the plasma rotation might limit the effectiveness of certain coil designs (in this case, a proposed coil array external to the cryostat). This figure was taken from an APS DPP presentation that presented much of the INFUSE work to the fusion community at large and it includes COMPASS-U to highlight the consistency of issues faced by any tokamak design [6].

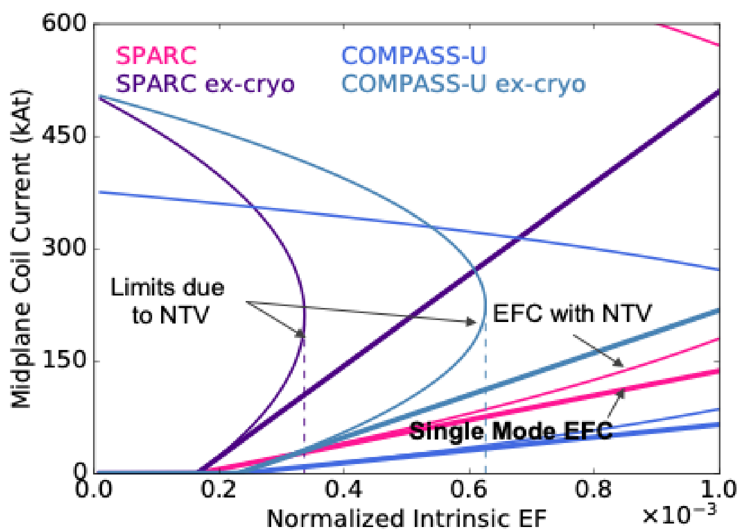


Figure 5: Example of how NTV braking might be expected to increase the current required to correct a given level of EF because the braking decreases the plasma's tolerance to the EF. If the coils couple poorly, the NTV limits the correctable EF by locking the plasma itself (vertical dashed lines of the ex-cryo curves).

[1] J.-K. Park, N.C. Logan, et. al, Computer Software doi:10.11578/GPEC/dc.20190207.1
[2] J.-K. Park, A. H. Boozer, et. al, Phys. Plasmas 16(5) 2009
[3] N.C. Logan, et. al, Nucl. Fusion 61(7) 2021
[4] N.C. Logan, et. al, Ncul. Fusion 60(8) 2020
[5] M. Fenstermacher, et. al, Phys. Plasmas 15(5) 2008
[6] N. Logan et al, Bull Am Phys Soc. APS-DPP

# 2 Impact

## 2.1 Use of Project Results

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

Throughout the course of this project, the CFS team owned and progressed all coil designs, and the LLNL team evaluated the designs. The guidance provided by LLNL team allowed CFS to balance error field risk against the cost of careful magnet tolerancing and EFCC capabilities. Demonstrating net fusion energy on an aggressive timescale requires balancing the risk that error fields challenge and prolong commissioning with the risk that the assembly schedule slips due to unnecessarily tight tolerances. A solution developed by the CFS team and evaluated by the LLNL team was found to provide sufficient margin on the plasma physics uncertainties to have confidence in the operation of SPARC without error field issues while maintaining manufacturing and assembly tolerances that are consistent with the pace of the tokamak construction. An important component of this solution is the EFCC system that effectively loosens the engineering tolerances on all other coils and provides insurance for the error field risk.

The LLNL team also validated the capability of mitigating or suppressing ELMs with CFS' coil set design outside the vacuum vessel, thereby greatly reducing capital cost and engineering complexity. Further, the designed coil set is non-dimensionally similar to a prospective coil set on ARC (the powerplant that follows SPARC), and thereby a successful demonstration of the ELM function in SPARC is expected to map to ARC.

Throughout the design cycle, the LLNL team:

- Quickly delivered guidance to address and resolve concerns raised during the conceptual design review
- Provided detailed design assessments at a pace consistent with CFS needs
  - Prompt responses to quickly evolving design cycles
    - Value engineering, trade-off analysis for close to plasma vs. far from plasma coil designs
  - Provided guidance on:
    - How to formulate the SPARC General Requirements on error fields
    - How to choose the best toroidal periodicity for the RMP
    - Coil wiring schemes and power supply requirements

Figure 6 shows the intersections of CFS' INFUSE programs with the SPARC timeline: this project (top right) will provide data for SPARC's EFCC Preliminary Design Review (PDR).

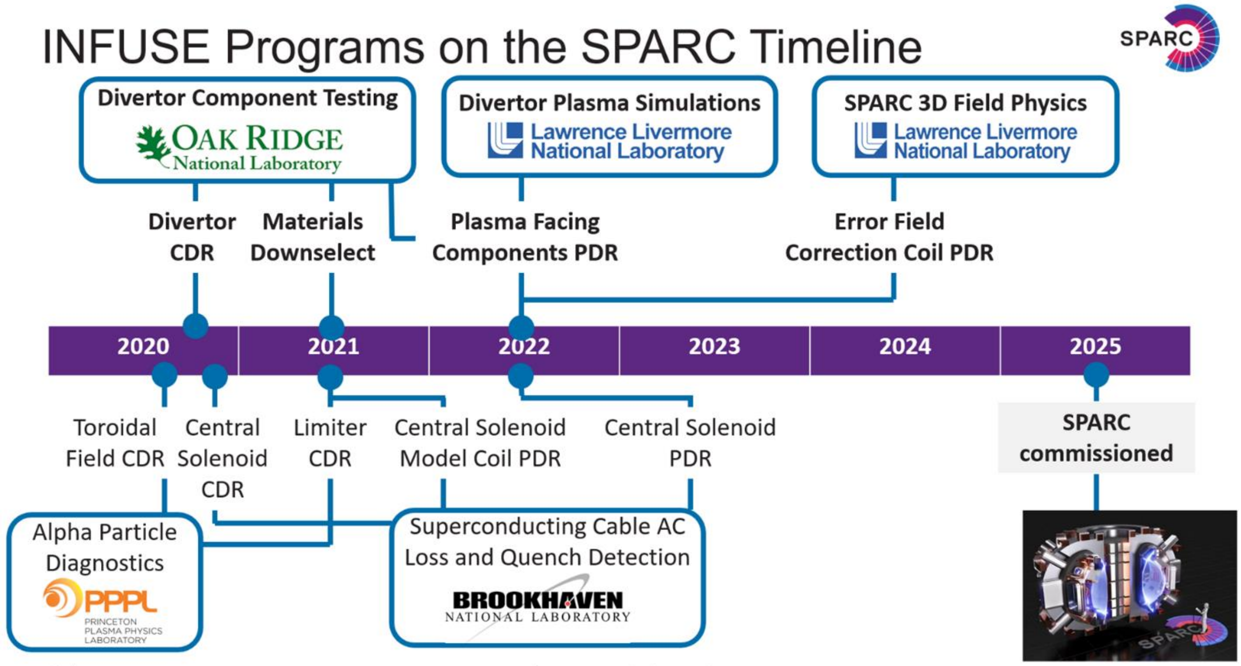


Figure 6. Intersection of CFS' INFUSE programs with the SPARC timeline.

## 2.2 Fusion Energy Impact

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

The results of this study enhanced our community's understanding of optimal 3D field correction by providing a unique high field and low beta case study. The new physics and implications for optimal 3D coil geometry guided the short-term decision making of SPARC while laying a general foundation for future compact, high field, high power density machines such as a future DOE National Tokamak User Facility (NTUF). In fact, the experience gained has already directly translated to other DOE activities. Namely, the DOE Long Pulse Tokamak FOA funded project on 3D fields and ELM control used many of the same general methods of assessment to guide the design of 3D coils in the COMPASS-U machine. This synergy contributed in part to DOE personnel presenting the 3D coil portion of COMPASS-U's final design review and was highlighted in the PI's 2021 APS DPP talk given on the "Common Physics basis for the SPARC and COMPASS-U 3D coil designs". Additional impact towards fusion energy results by improving the robustness of the SPARC design to the issues associated with non-axisymmetric field control - namely the control of error fields and edge localized modes.

## 2.3 Intellectual Property, Publications and Conferences

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

No new IP was generated from this project.

New publications included:

SPARC Team, “SPARC Error Field Correction Coils - Preliminary Design Review”, CFS Internal Document, 2021

Conference presentations included:

N.C. Logan, et. al, “Common Physics basis for the SPARC and COMPASS-U 3D coil designs”, APS DPP Annual Meeting, Pittsburgh USA, 2021

A. Creely, et. al, “SPARC 3D Field Physics and Support of the Non-Axisymmetric Coil Assessment”, 3rd Annual INFUSE Workshop (Virtual), Dec 16 2021