ALPHA PARTICLE DIAGNOSTICS SIMULATION

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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.

A key design decision for SPARC, in common with the design of all DT tokamaks, is the allowable toroidal field (TF) ripple. TF ripple breaks the toroidal symmetry of the magnetic field geometry, leading to potential loss of some classes of fast banana-trapped ions (Goldston1981) and `ripple-trapped’ ions (Stringer1972) , i.e. those with very small parallel velocity that become trapped in the local magnetic well between two TF coils. SPARC’s conceptual design envisions heating by up to 25 MW of ICRF which sustains a plasma that generates up to 28 MW of alpha power. This combination yields a total of potentially ~50 MW of energetic ions, of which > 30 MW will be banana trapped. Loss of a significant fraction of that power in a compact machine the size of SPARC (R=1.85 m) would lead to excessive first-wall or limiter heating and material failure. More importantly, numerical calculations of ripple-induced losses for ITER (Kurki-Suonio2009) indicate that the lost ions do not deposit uniformly on the first wall, but concentrate heavily in a poloidal band near the outer midplane; this behavior is expected to prevail in SPARC also. Consequently, (1) we can tolerate only a very small fractional loss of fast-ion power – a few percent, and (2) understanding the detailed power ‘footprint’ of the lost power is very important for the design of limiters and first-wall shape.

The TF ripple from a set of identical, uniformly-spaced TF coils is typically very small at the plasma center but rises rapidly near the edge, ~ $(R/R_c)^N$ where R_c is the major radius of the outer leg of the TF coils and N is the number of coils. This circumstance is beneficial to minimizing ripple-induced alpha losses, because the alpha source rate is largest on-axis where the ripple, and hence the ripple loss rate, is small. Unfortunately it raises the possibility of an unfavorable synergy between magnetohydrodynamics (MHD)-induced radial displacements of fast ions (TAEs, sawteeth, etc.) and ripple: MHD can move the alphas from the center out to a radius where the ripple is larger, from which the alphas can then be lost due to ripple. It is important that the guidance regarding the maximum tolerable TF ripple account for possible synergy between MHD and ripple losses. As a definitive evaluation of the interaction of the large known ‘zoo’ of energetic-ion driven MHD instabilities fast ion confinement with TF ripple is beyond a 1-year work scope, the goals of this project are to qualitatively or semi-quantitatively characterize the synergy between sawteeth and ripple in terms of enhancing the loss of energetic ions and develop the beginning of a workflow to compute the synergy between a variety of MHD modes, including TAEs, and ripple. This workflow will then result in a maximum permissible intrinsic ripple due to the finite number of TF coils.

In addition, all real tokamaks have finite misalignments between toroidal field coils, resulting in larger than the ideal ripple. This work will be used to guide the maximum permissible misalignments between coils, as tight requirements generally have both monetary and schedule cost.

Finally, orbit-following codes that simulate the behavior of fast ions in tokamaks are computationally intensive, which limits the number of scenarios that can be evaluated. A capability to perform faster simulations of ripple loss using so-called ‘reduced’ models, which will allow time-dependent ripple-loss simulations using the TRANSP code is desirable. This project also used some of these optimizations to enable evaluation of many different limiter placements and shaping in order to minimize localized alpha heating.

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 full orbit following SPIRAL code was extended with the envisioned SPARC wall geometry and input files for the equilibrium and toroidal ripple fields were generated and used to calculate ripple-induced alpha particle losses to the wall. These alpha losses were than used to calculate heat loads on the SPARC wall.

At CFS a different code, ASCOT, was also used for the calculation of ripple-induced alpha losses and a careful benchmark between the two codes was performed. Some discrepancies between the two codes were found and the origins of these discrepancies were traced back and corrected in either ASCOT or SPIRAL. Both codes now give results that are identical within their statistical accuracy. Both codes are now able and well suited to be used in the further design of the SPARC plasma-facing wall and especially, the placement and shaping of limiter structures. In addition, the corrections made to both codes significantly increase their validity and usefulness for broader applications beyond SPARC.

At PPPL, the guiding-center code ORBIT has been updated to include information on the toroidal field ripple expected on SPARC. Initial tests have demonstrated the possibility to transfer information from ORBIT on the expected alpha particle response to ripple to TRANSP for time-dependent simulations.

1.3 Results

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

The main results of the studies mentioned in section 1.2 were reported in:
“Fast ion physics in SPARC”
S.D. Scott, G.J. Kramer, E.A. Tolman, A. Snicker, J. Varje, K. Sarkimaki, J.C. Wright, and P. Rodriguez-Fernandez
J. Plasma Phys. 86 (2020) 865860508

As a summary of the results, as reported in the above publication by Dr. S. Scott, it was found that ripple-induced alpha power loss to the last-closed flux surface is negligible (~0.25%) for the *SPARC V1E* design that includes 18 “perfectly aligned” TF coils. The ripple-induced power loss is sub-dominant with respect to first-orbit loss (2.8%). Only few alpha particles born at $\rho_{pol}<0.8$ are lost because of ripple, where ρ_{pol} is the square root of the normalized poloidal flux. There is modest concentration of the alpha loss poloidally and minimal concentration toroidally. The computed alpha loss naturally increases as the TF coils are assumed to be more and more poorly aligned in the simulations. In addition, losses become more concentrated toroidally, so the peak surface power density increases rapidly with coil misalignment.

A specific recommendation for the maximum allowable coil misalignment awaits an optimization study of candidate first-wall shapes. The results of this study suggest that coil misalignments greater than 0.7 cm may be problematic, though alignments better than this should be readily achievable on SPARC.

In addition to the ripple-induced alpha studies reported above, the ORBIT guiding-center code has been updated to include a parametrization of the TF ripple field as provided by Dr. Scott. Further enhancements to the code include the possibility of initializing markers based on realistic fast ion distributions from the NUBEAM module of TRANSP, and the extension of the code beyond the last-closed flux surface with a realistic wall geometry (e.g. as read from EFIT equilibrium files).
Initial tests have been performed to compute alpha transport induced by TF ripple and cast the results into “transport matrices” that can be used as input for the energetic particle transport *kick model* in TRANSP/NUBEAM. Test runs with TRANSP/kick model, limited to losses up to the last-closed flux surface, show negligible increase in the alpha loss rate, which is in qualitative agreement with the SPIRAL and ASCOT results. More extensive scans (e.g. of the ripple amplitude) will be required to quantify alpha losses through TRANSP.

The ORBIT code has also been recently updated to include a self-contained model that mimics energetic particle transport by a sawtooth instability. The model can be used for further studies to assess the possible synergy between the two transport mechanisms.

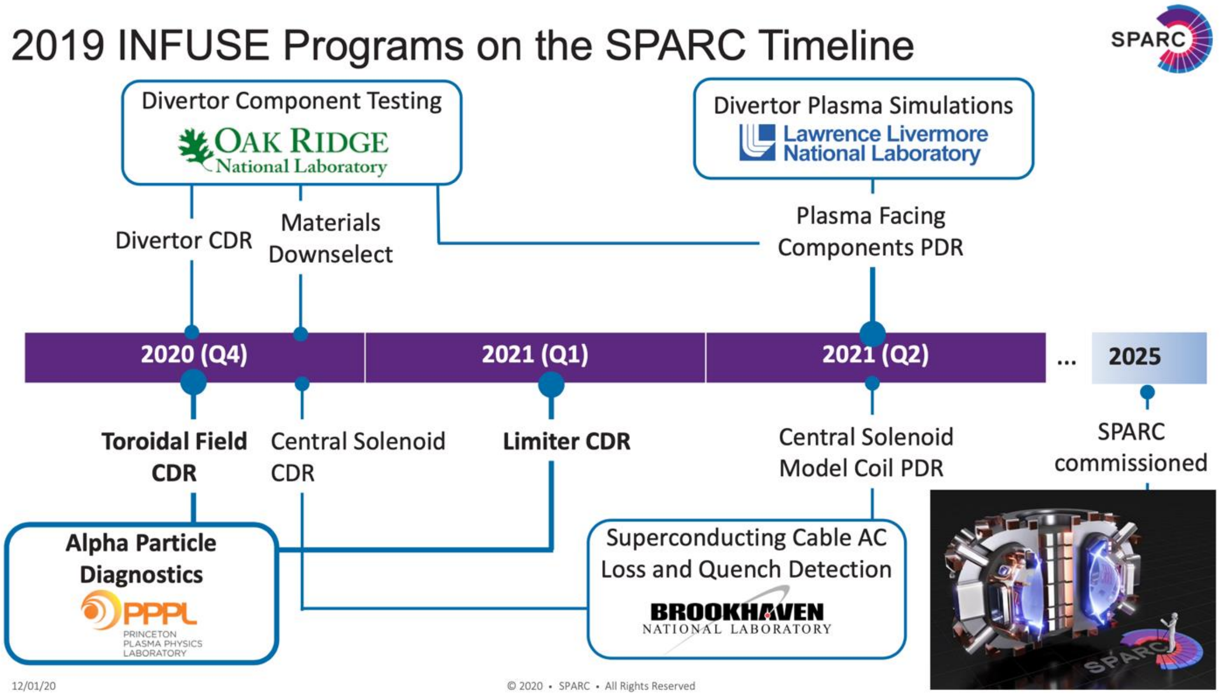
2 Impact

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 results of this project will allow CFS to define the maximum TF ripple that is acceptable from surface power-handling considerations, it will inform decisions regarding the shape and position of limiters and the shape of the first wall components, and it will inform decisions regarding possible operational regime limitations, e.g. a minimum density to limit the energy of an RF-driven tail. This research will also provide valuable data on fabrication tolerances for e.g. TF coil size and alignment. The maximum allowable TF ripple affects decisions regarding the number and size of the TF coils, which has a direct bearing on the total system cost.

The figure below shows the intersections of CFS' INFUSE programs with the SPARC timeline: this project (bottom left) provided data for SPARC's TF Conceptual Design Review (CDR) and Limiter CDR.



2019 INFUSE Programs on the SPARC Timeline

12/01/20

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2.2 Fusion Energy Impact

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

Localized heat loads on the plasma facing components in tokamaks can be dangerous for the wall integrity. After the bench marking exercise, the SPIRAL code can now be used to study localized heat loads on the plasma facing components in the design phase and modify the design to mitigate these heat loads.

Other simulation tools, such as the guiding-center ORBIT code, are also available to study alphas particle loss mechanisms. The code's guiding-center formalism does not provide such accurate representation of the localized heat loads as full-orbit codes such as SPIRAL and ASCOT, but it can be used for less computationally expensive scans of parameters such as TF ripple amplitude and/or amplitude of internal perturbations such as sawteeth. These tools, including TRANSP/NUBEAM enhanced by the EP *kick model*, are now available to CFS personnel for further studies.

2.3 Intellectual Property, Publications and Conferences

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

This work resulted in a journal publication (which has been cited 4 times as of writing) and a presentation at a conference.

Journal publication:

"Fast ion physics in SPARC," S.D. Scott, G.J. Kramer, E.A. Tolman, A. Snicker, J. Varje, K. Sarkimaki, J.C. Wright, and P. Rodriguez-Fernandez, J. Plasma Phys. 86 (2020) 865860508.

Conference presentation:

"Ripple-induced fast-ion loss in SPARC due to misaligned TF Coils," S.D. Scott, G.J. Kramer, E.A. Tolman, A. Snicker, J. Varje, K. Sarkimaki, J.C. Wright, and P. Rodriguez-Fernandez, 62nd Annual Meeting of the APS Division of Plasma Physics, Virtual, JO08.00010 (2020).

3 References

Goldston1981: R. Goldston et al, Phys. Rev. Lett. 47 (9) p. 647 (1981).
Kurki-Suonio2009: T. Kurki-Suonio et al, Nucl. Fusion 49 (9) 095001 (2009).
Stringer1972: T. Stringer, Nucl. Fusion 12 (6) p 689 (1972).