Characterization of Turbulent Transport and Confinement in ARC with STEP and CGYRO

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1 Technical Overview

1. Problem Statement

In order to develop ARC [**Sorbom:2015**, **Creely:2021**] as cost-effectively as possible, reliable predictions of plasma transport and confinement in various possible configurations and operating scenarios are needed. Numerous studies of tokamak-based fusion power plants have found that the level of confinement obtained is a key determinant of overall performance and economic viability [**Menard:2011**, **Freidberg:2015**, **Sorbom:2015**, **Jian:2017**, **Federici:2019**, **Creely:2020, Buttery:2021**, **Holland:2023**]. A key measure of confinement is the energy confinement time $\tau_E = W_{plasma}/P_{heat}$, which when multiplied by the plasma pressure $p = nT$ gives the well-known "triple product" fusion metric $nT\tau_E$. Because τ_E is a dimensionful quantity, comparisons across different plasma regimes and devices are typically made using normalized confinement factors $H = \tau_E/\tau_{scaling}$. Here, $\tau_{scaling}$ is one of a variety of different empirical, semi-empirical, or theoretical scaling laws for τ_E [**IPB-TC:1999**]. The most commonly used tokamak scaling law is the empirical $\tau_{98(y,2)}$ scaling derived by the ITER Tokamak Physics Activity for ELMy H-mode tokamaks via a regression of data from a wide variety of different tokamaks around the world [**IPB-TC:1999**]. In this case, $H_{98(y,2)} = \tau_E/\tau_{98(y,2)}$ quantifies how much larger (better) or smaller (worse) the energy confinement observed in a plasma is relative to what is predicted by the multi-machine regression.

Scaling laws such as $\tau_{98(y,2)}$ can also be used to predict confinement in future devices, as they provide a way to translate specified engineering parameters (such as plasma size, field, and current) into a prediction of the plasma parameter τ_E, which when combined with the specified heating power yields a prediction of plasma pressure, and in turn used to determine fusion power and performance. However, extrapolation of any model outside its range of calibration and/or validation can introduce large uncertainties and errors into the predictions. Simple examples include extrapolating low Reynolds number laminar fluid behavior to turbulent large Reynolds number regimes, or the properties of a superconducting magnet across the critical temperature. More closely related to this proposal, the empirical τ_E scaling of low density Ohmic plasmas does not predict the transition to the saturated Ohmic confinement regime at higher densities (the so-called LOC-SOC transition [**Rice:2020**]). Thus, at least two potential "failure points" can be identified for extrapolating confinement scaling laws to future pilot plant conditions. First, the future conditions of interest may lie well outside the parameter regime where the empirical models were derived and/or calibrated. Therefore the relative weighting and importance of these parameters (and their various combinations) may change between regimes. Second, key physics and engineering parameters may be either missing or insufficiently treated in the empirical models. For instance, no current empirical model has been calibrated against data from a burning plasma, and so any new physical dynamics arising from plasma self-heating will not be captured by them. Moreover, the widely used $\tau_{98(y,2)}$ scaling was primarily derived from neutral beam-driven H-mode plasmas, but does not include any explicit dependence on the plasma triangularity or injected torque. However, since the derivation of the $\tau_{98(y,2)}$ scaling law, the fusion community has developed a clear understanding of how both of these parameters can be used to improve plasma performance, via pedestal optimization [**Snyder:2007**] and shear suppression of turbulent transport [**Burrell:2020**]. Thus, using a scaling law based on strongly rotating plasmas to predict confinement in a future system where rotation will likely be much lower (due to the larger moment of inertia and/or lack of externally injected torque) may significantly overestimate the confinement. On the other hand, by optimizing the plasma shape via changes in triangularity, confinement could be increased relative to the $\tau_{98(y,2)}$ scaling. Other potential "hidden variables" such as the plasma wall material may also impact confinement significantly, as documented in the recent formulation of the ITPA20-IL scaling [**Verdoolaege:2021**]. Determining whether one of these effects dominate, if they end up balancing out, or if some other physics (such as self-heating or impurity confinement) become dominant at parameters requires going beyond global scaling laws and using more detailed predictive transport models.

The current state of the art in practical predictive transport modeling is based upon the use of quasilinear turbulent models such as TGLF [**Staebler:2007**] or QualiKiz [**Bourdelle:2007**], which predict local particle, energy, and momentum fluxes as a function of local gradients and other plasma parameters. Transport solvers such as TGYRO [**Candy:2009**] then combine these models (along with corresponding predictions for neoclassical transport contributions [**Hinton:1976**]) with specified source terms and magnetic equilibria to self-consistently predict core flux-surface averaged density, temperature, and rotation profiles. Additional models that predict transport or other profile constraints near the separatrix (both inside and out) can be used to provide boundary conditions for the core transport solver. By combining these kinetic profile predictions with self-consistent evolution of the magnetic flux surfaces, integrated modeling tools such as TRANSP [**Breslau:2018**], IPS-FASTRAN [**Park:2018**], or the OMFIT STEP workflow [**Meneghini:2021**] can be used to make significantly more detailed predictions of plasma confinement and performance than empirical scaling laws allow. Examples of predicted profiles for a compact inductive tokamak power plant made using the STEP workflow, and for the SPARC tokamak [**Creely:2020**] made using TRANSP, are shown in Fig. **1**.

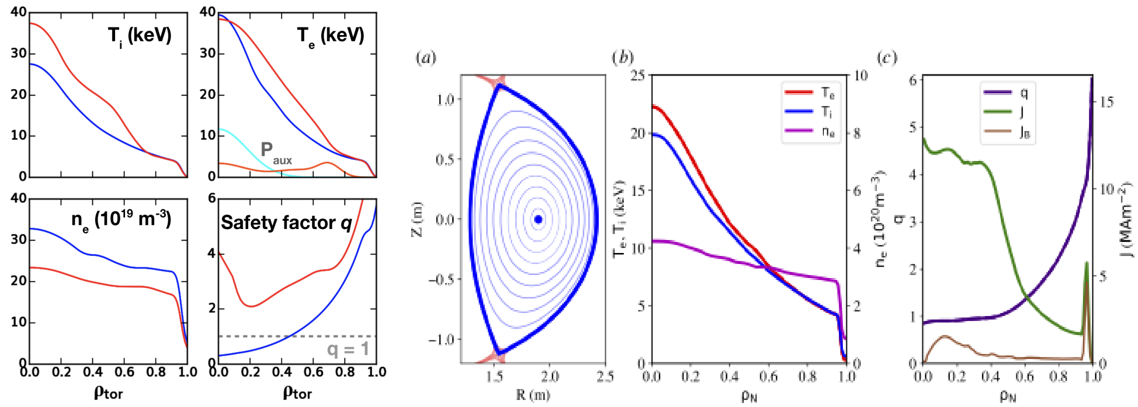


Figure 1. Comparisons of various profiles and equilbiria from 1.5D transport solutions for (left) compact inductive power plant made using STEP [**Holland:2023**] and (right) the SPARC tokamak made using TRANSP[**Rodriguez-Fernandez:2020**].

A key feature of quasilinear transport models like TGLF is that they are formulated in terms of local dimensionless plasma parameters, rather than dimensionful engineering quantities. A second key feature is that they are not calibrated using experimental data. Instead, they rely either purely on analytic models of the turbulent intensity, or semi-analytic models calibrated to databases of nonlinear turbulence simulation results. The combination of these features means that in principle they can be used to accurately predict confinement in future devices and regimes, so long as the underlying models and assumptions remain valid in those future plasmas. Therefore, in order to have the highest possible confidence in predictions of performance for a future device such as ARC, it is essential to use detailed predictive plasma dynamics models that have been verified and validated[1] in parameters and conditions as close to those expected in ARC as possible.

Verification of these models is a particularly vital first step because previous benchmarkings of, for example, different TGLF saturation rules and CGYRO for burning plasma conditions have identified potentially significant differences in turbulence characteristics such as the stiffness and ratios of various flux channels (e.g. the ratio of ion to electron energy flux Q_i/Q_e, or electron particle to energy flux Γ_e/Q_e) [**Rodriguez-Fernandez:2020**, **Howard:2021**, **Holland:2023**]. Examples are shown in Fig. **2**. As an example of potential impact on overall design and performance, previous ITER integrated modeling studies [**Fable:2019**] found that the amount of predicted density peaking (and thus fusion gain) can be significantly impacted by the inclusion of magnetic fluctuations. Any such differences need to be clearly identified and their possible impacts on ARC performance predictions quantified as early in the design process as possible.

[1] For readers not familiar with this terminology, verification essentially refers to determining correctness and mathematical accuracy of a particular solution ("Am I solving the model correctly?"), while validation refers to assessing the ability of a model to predict the physical phenomena of interest ("Am I using the right model?").

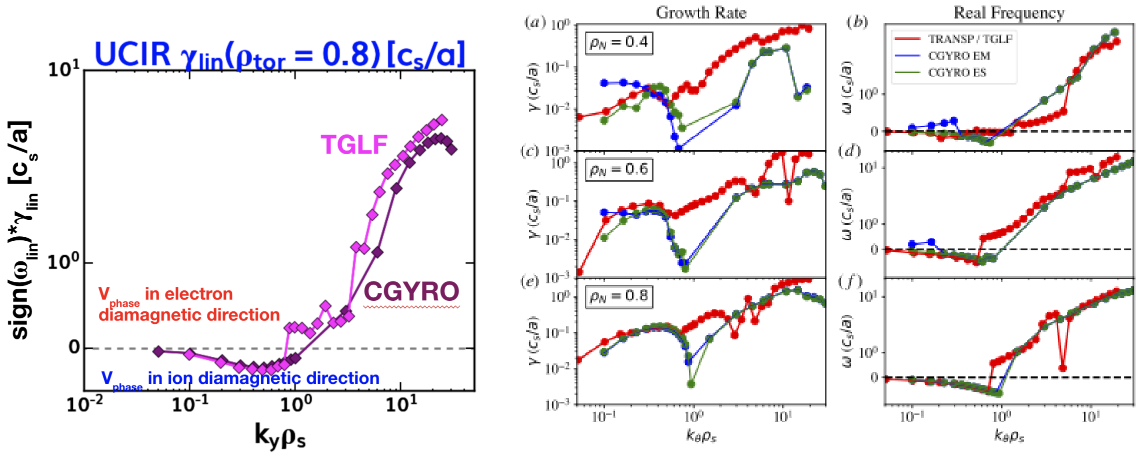


Figure 2. Comparisons of TGLF and CGYRO predicted growth rates for (left) a compact inductive power plant [**Holland:2023**] and (right) the SPARC tokamak [**Rodriguez-Fernandez:2020**].

2. Work Scope

To address the need for trusted predictive transport models verified at ARC-relevant parameters, a three-step research plan was jointly developed by UCSD researcher Dr. Christopher Holland and CFS team members. Dr. Holland brought extensive expertise in integrated modeling through the OMFIT STEP workflow to the collaboration, as well as in turbulent transport theory and simulation using TGLF and CGYRO. CFS provided an in-kind contribution via the involvement of Dr. Alex Creely, Head of Tokamak Operations at CFS; and through support of Pablo Rodriguez-Fernandez and Nathan Howard, both at the MIT Plasma Science and Fusion Center. In addition to providing details and parameters of the desired ARC operating point (the "V1C" configuration), Drs. Creely, Rodriguez-Fernandez and Howard also provided integrated modeling support, primarily through application of the PORTALS workflow developed by Dr. Rodriguez-Fernandez.

The proposed research plan entailed three sequential steps summarized below, along with explanations of changes in the actual work undertaken relative to this plan.

1. **Translate new 0D inductive ARC design points into 1.5D transport solutions**
    a. Use the STEP workflow to translate several 0D inductive design points identified by CFS into self-consistent 1.5D transport solutions.
        i. Use CHEASE for fixed-boundary equilibria calculations, NEO for neoclassical transport, TGLF for turbulent transport, TGYRO as core transport solver, and EPED for determining pedestal/near-edge boundary condition.
        ii. After discussion amongst PIs and advancements in ARC design relative to the submission of the proposal, it was decided to focus on translating and assessing the ARC V1C 0D operating point in this work.
    b. Assess self-consistency of key global measures such as fusion power produced and proximity to L-H power threshold.
    c. Determine sensitivity of 1.5D solutions to changes in parameters such as density, current, impurity mix, etc.

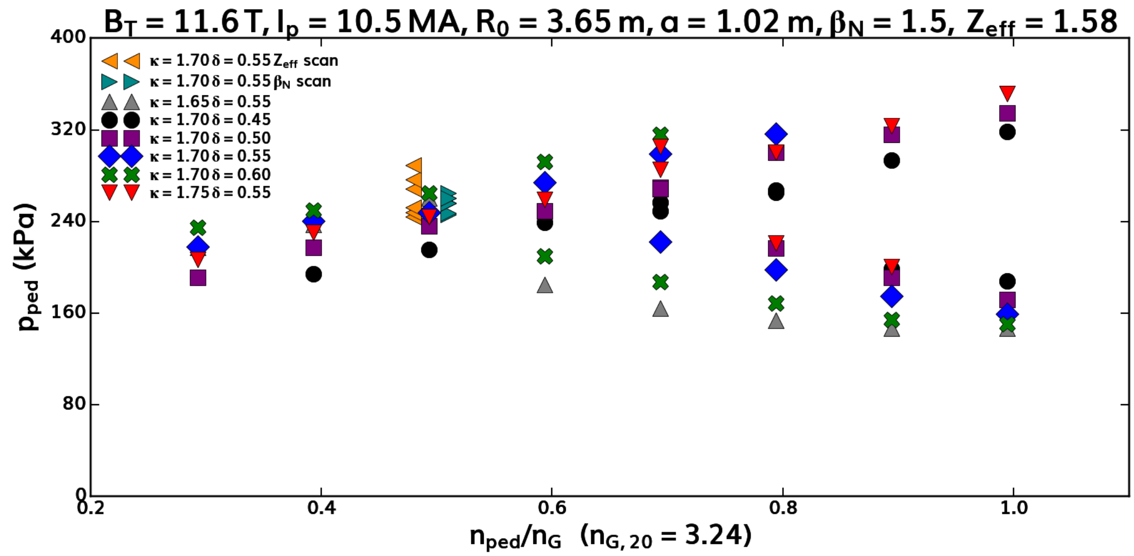
d. Benchmark STEP predictions against equivalent ones made with TRANSP.
    i. This element was not undertaken due to previous results showing relatively good agreement for SPARC between TRANSP and TGYRO-based workflows, as well as challenges setting up ARC geometry and actuators in TRANSP.

2. **Characterize turbulent transport across confined plasma using TGLF and CGYRO**
    a. Compare predictions made by TGLF SAT0, SAT1, and SAT2 saturation rules of turbulent growth rates and fluxes at different radii in a CFS-chosen transport solution obtained in step 1, focusing on scalings with parameters such as driving gradients and collisionality.
    b. Compare linear and nonlinear CGYRO predictions to the TGLF results to assess fidelity of TGLF as efficient proxy for CGYRO at the parameters of interest.

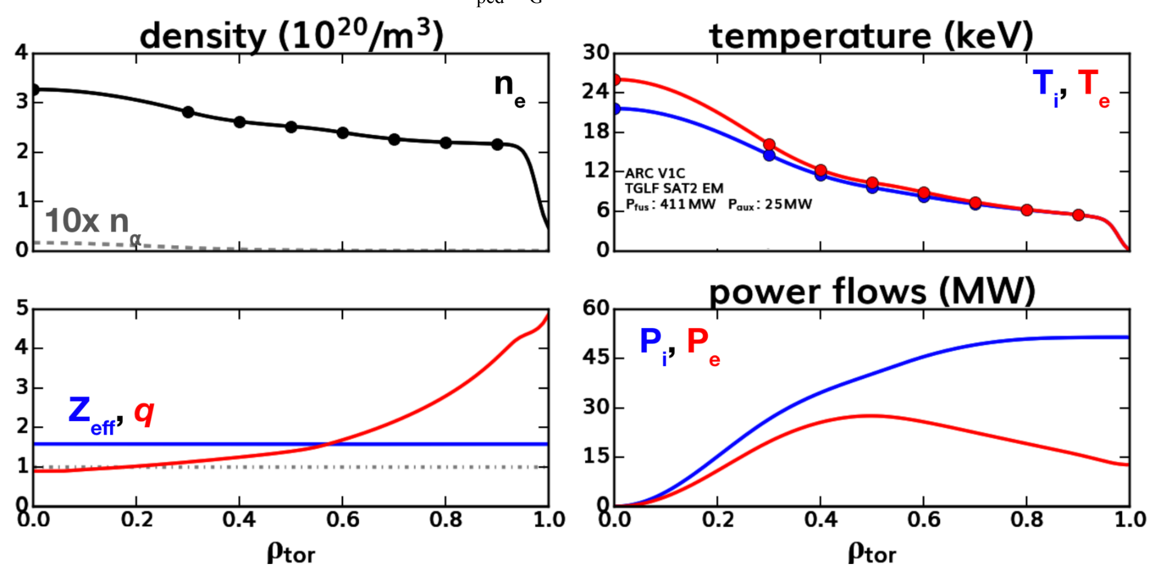
3. **Compare expected ARC and SPARC turbulence properties**
    a. Using results obtained in step 2, compare expected transport characteristics of SPARC and ARC via measures such as predicted critical gradients, transport stiffness, and dependencies on parameters such as on β, ν_*, and safety factor q, as well as flux ratios such as Q_i/Q_e and Γ_e/Q_e.
        i. Given results for SPARC which found relatively good agreement for energy flux predictions between TGLF SAT2 and CGYRO (which substantiated by the ARC results from step 2, above), it was decided to instead utilize computing time available from an ALCC award to carry out direct gyrokinetic predictions of ARC profiles using the PORTALS workflow as a means of addressing this gap.
    b. If time and resources permit, pursue predictions for transport and peaking of various low, mid, and high-Z radiative impurities.
        i. Within the time and resources available, it was not feasible to undertake this work.
    c. Identify any significant differences between scenarios that should be used to inform SPARC operation and research plans.
        i. The fundamental conclusion of this study is that the ARC V1C (and low-beta inductive tokamak burning plasmas in general) should have quite similar transport characteristics as both SPARC and ITER. In this respect, SPARC should provide a good proxy for conditions expected in ARC (assuming broadly similar operating scenario).

3. Results

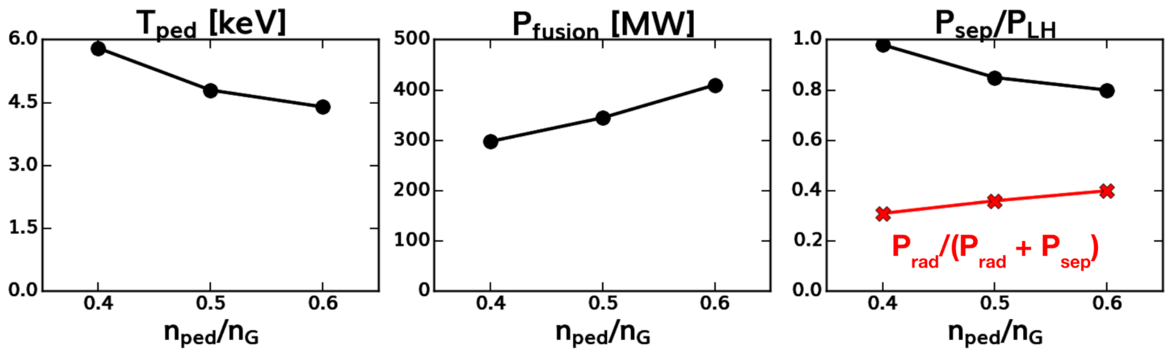
1. **Extensive EPED analysis identified operation at $n_{ped}/n_G \leq 0.6$ as being robust to operating in a peeling-limited high pedestal pressure regime for triangularity ≤ 0.5**
The nominal V1C operating point has $n_{ped}/n_G = 0.5$.



2. **Typical V1C transport solutions made using TGYRO and TGLF are qualitatively quite similar to SPARC PRD and ITER baseline: modest n_e peaking, $T_e > T_i$, $Q_i > Q_e$**
Results for a the V1C scenario with $n_{ped}/n_G = 0.6$.



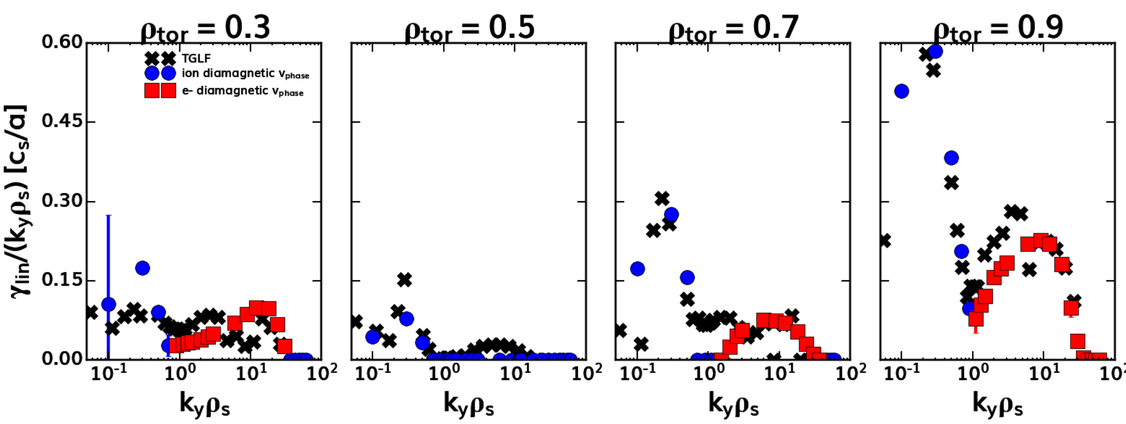
3. **From this initial operating point, no operating density was found that was consistent with the desired 500 MW of fusion power and sustaining $P_{sep} > P_{LH}$**
Although increasing density from n_{ped}/n_G =0.4 to 0.6 yields an increase in fusion power from 300 MW to 400 MW, it also lowers P_{sep}/P_{LH} from ~1 to 0.8 due to increased radiation losses and P_{LH} increasing with density. However, this drop is still well within the uncertainties of the scaling.



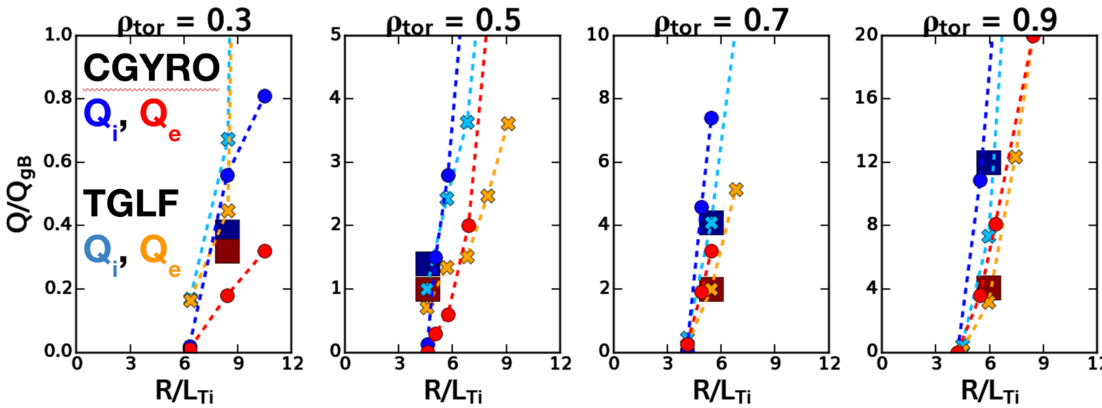
$$P_{LH} = 0.8 * (0.048\, n_{20}^{0.72}\, B_T^{0.8}\, A^{0.94})\ [1]$$

[1] Y. Martin *et al*, J. Phys. Conf. Series **123** 012933 (2008)

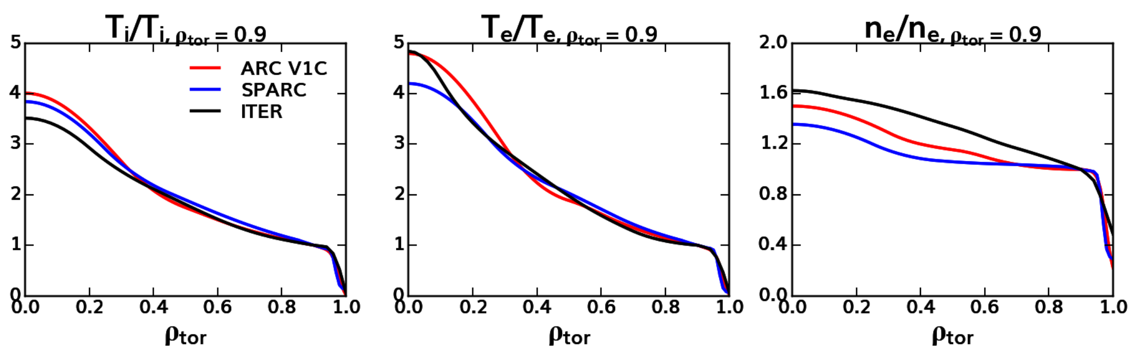
4. **TGLF SAT2 growth rates were found to be in reasonably good agreement with CGYRO predictions**



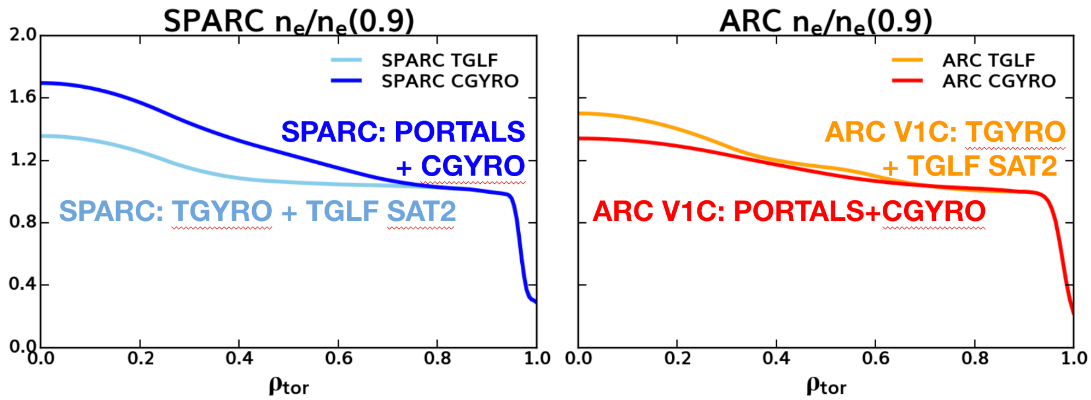
5. **TGLF SAT2 energy flux predictions track CGYRO flux predictions quite well over the region of interest**
   Likely due in large part to plasma being dominated by electrostatic ITG turbulence. Squares correspond to the power balance fluxes for V1C 1.5D solution at $n_{ped}/n_G = 0.6$.



6. **SPARC PRD, ITER baseline, and ARC V1C all predicted to have very similar profiles and transport mechanisms**
   All are low beta inductive burning plasmas with sufficient coupling that thermal transport is predominantly through ion channels, mediated by ITG turbulence. Some of the difference in ITER density peaking arises from the fact that it has core fueling via neutral beam injection heating.



7. **Surprise result- unlike SPARC work, PORTALS-CGYRO workflow does __not__ predict stronger density peaking for ARC then TGYRO-TGLF does**
   ARC modeling uses the same assumptions regarding impurities etc. as SPARC, differences in density peaking not explained by modest differences in assumed safety factor profiles. The source of this difference remains under investigation.



2 Impact

4. Use of Project Results

The research carried out through this project directly supports the CFS vision of systematic risk retirement to bring a simplified, compact, and economically competitive tokamak power plant to market in a timely fashion. Specific key contributions are summarized below.

1. The ARC 1.5D STEP transport solution predictions provide more rigorous and self-consistent assessments of plasma confinement than the initial 0D POPCON calculations. The solutions provide insight into the reliability of future POPCON calculations for the ARC-relevant parameter regimes, as well as into possible benefits, disadvantages, and trade-offs of various ARC design points, configurations, and scenarios under consideration.
2. The characterization of expected transport in ARC and its comparison to SPARC provide confidence for a smooth extrapolation in the underlying transport physics between the devices, helping to inform the SPARC research plans that will ensure this extrapolation. This data directly supports using SPARC as efficiently as possible to retire risks for ARC.
3. The cross-code benchmarking and verification (e.g. CGYRO vs. TGLF, STEP vs. TRANSP) provides valuable information on resolution requirements, parameter choices, and optimal model settings to most accurately and efficiently predict turbulent transport in ARC (and SPARC). This knowledge will also directly inform future modeling activities which will further refine and optimize possible compact tokamak power plant designs including, but not limited to, ARC.

5. Fusion Energy Impact

Beyond the specific benefits to CFS described below, the research enabled by this proposal provides significant value to the broader fusion energy community. To enable dissemination of this knowledge, UCSD PI C. Holland is currently writing a manuscript for submission to *Physics of Plasmas* documenting the non-proprietary scientific findings in peer-review journals, and identifying paths to make all non-proprietary data available for broader use after publication. Some specific examples of value provided to the general fusion community are listed below.

1. The project has provided some of the most detailed characterization of expected turbulent transport characteristics in fusion power plant-relevant conditions to date. To our knowledge, such a characterization of turbulent transport for specific ITER scenarios, or any other proposed fusion power plant design, has not been undertaken and publicly reported.

2. The project provided an essential benchmarking of widely used community tools and workflows (such as STEP vs. POPCON, various TGLF saturation rules and settings) in power plant-relevant conditions (i.e. even beyond ITER burning plasmas).

3. The extensive data generated by proposed parametric scans and sensitivity studies will be available for use in future predictive model improvements, such as training and developing new machine learning/neural net reduced models at power plant-relevant conditions, or improving saturation rules for quasilinear transport models. Such models will enable significant acceleration of future design work, and can help identify important regions of parameter space requiring further study.

6. Intellectual Property, Publications and Conferences

No proprietary IP was generated via this work. Results from this project were presented to the community through invited talks at the 2023 Transport Task Force workshop and APS-DPP meetings, as well as contributing to a variety of other conference posters and contributed talk presentations (including at the 2023 IAEA Fusion Energy Conference). A manuscript detailing the results is currently being prepared for submission to *Physics of Plasmas.*

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