Scoping study of dissipative divertor scenarios for SPARC

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What is SPARC?

- DT-burning tokamak designed to demonstrate net fusion energy production
  - $Q > 2$
  - 50 MW fusion power
  - $R_{maj} = 1.8$ m
  - $B_{tor} = 12$ T

- Based on newly developed high temperature superconductor technology

- Under design by Commonwealth Fusion Systems (CFS), MIT, and collaborators
Comparison of high-field tokamak designs

**ADX**
- $R_{\text{maj}} = 0.73$ m
- $R_{\text{min}} = 0.2$ m
- $B = 6.5$ T
- Mission: Divertor testing

**SPARC**
- $R_{\text{maj}} = 1.78$ m
- $R_{\text{min}} = 0.55$ m
- $B = 12.5$ T
- Mission: $Q > 2$

**ARC**
- $R_{\text{maj}} = 3.3$ m
- $R_{\text{min}} = 1.1$ m
- $B = 9.2$ T
- Mission: Fusion reactor
Projected parameters for SPARC edge plasma and divertor

- \( P_{\text{sol}} \sim 20 \text{ MW} \)
- Narrow SOL
  - \( \lambda_q = 0.16 \text{ mm} \ [1] \)
  - \( \lambda_q = 0.34 \text{ mm} \ [2] \)
  - \( \lambda_q = 0.34 \text{ mm} \ [3] \)
- Relatively long pulse but not steady-state operation, \( \tau \sim 10 \text{ s} \)
- Divertor design ongoing, exploring
  - Single-null and double-null
  - Tightly baffled long vertical leg
  - Radially extended divertor leg
  - Seeded impurity radiation
  - Strike points sweeping

Matching projected parameters of SPARC for setting up UEDGE:
- Geometry, input power based on the design
- Midplane plasma profiles, based on empirical scaling

- Modeling lower half of up-down symmetric domain
- Standard collisional plasma model
- Fluid neutrals model
- Initially no drifts included
- Boundary conditions at core interface set to match input power and midplane plasma density at separatrix
- Ad-hoc anomalous transport coefficients set to match projected profiles and in-out power asymmetry
Anomalous transport profiles for UEDGE SPARC model used as knobs for matching design projections

For matching plasma profiles and in-out power asymmetry, using:

- Radial profile of $D$ (could use $V$ instead as transport model)
- Transport barrier in $\chi$
- Levels of $D$ and $\chi$ on HFS
Why use $D_{\text{eff}}$ increasing radially in SOL?

- Overwhelming evidence for enhanced radial transport in far SOL upstream
- Interchange drive responsible for enhanced plasma transport in far SOL
- Based on experiments and modeling, this mechanism apparently exists in the divertor as well

**MAST**

**NSTX**

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1Harrison et al., *Journal of Nuclear Materials* 463, 757–760 (2015)
2Scotti et al., *Nucl. Fusion* 58, 126028 (2018)
Comparing four UEDGE cases for SPARC V1C

<table>
<thead>
<tr>
<th>Case UE1a</th>
<th>Case UE1a_0.1C</th>
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<tbody>
<tr>
<td>• Low transport everywhere on HFS</td>
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<tr>
<td>• No impurity radiation</td>
<td>• Impurity radiation for 0.1% C</td>
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<tr>
<td>• Peak power flux on divertor plates</td>
<td>• Peak power flux on divertor plates</td>
</tr>
<tr>
<td>➢ outer = 1.34038D+02</td>
<td>➢ outer = 1.35118D+02 MW/m²</td>
</tr>
<tr>
<td>➢ inner = 1.42862D+02</td>
<td>➢ inner = 1.10163D+02 MW/m²</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Case UE1b</th>
<th>Case UE1b_0.1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low transport everywhere on HFS except inner leg region</td>
<td>• Low transport everywhere on HFS except inner leg region</td>
</tr>
<tr>
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<td>• Impurity radiation for 0.1% C</td>
</tr>
<tr>
<td>• Peak power flux on divertor plates</td>
<td>• Peak power flux on divertor plates</td>
</tr>
<tr>
<td>➢ outer = 1.31711D+02</td>
<td>➢ outer = 1.31700D+02</td>
</tr>
<tr>
<td>➢ inner = 9.41024D+01</td>
<td>➢ inner = 8.23039D+01</td>
</tr>
</tbody>
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All use 10 MW of input power into the lower-half domain
UEDGE radial transport coefficients for cases UE1a and UE1a_0.1C
UEDGE radial transport coefficients for cases UE1b and UE1b_0.1C
UEDGE finds steady-state plasma profiles, consistent with SPARC design projections

- $n_{\text{sepx}} = 10^{20} \text{ m}^{-3}$
- $P_{\text{out}} : P_{\text{in}} = 4:1$
- $\lambda_q = 0.16 \text{ mm}$

For otherwise identically same parameters, overall similar plasma profiles with or without altering transport in inner leg or adding 0.1%C radiation
Plasma profiles upstream are weakly sensitive to altering inner leg transport or adding impurity radiation.
Plasma profiles upstream are weakly sensitive to altering inner leg transport or adding impurity radiation.

**UE1a**

- **Inner midplane**: $T_e$ and $T_i$ profiles.
- **Outer midplane**: $T_e$ and $T_i$ profiles.

**UE1a_0.1C**

- **Inner midplane**: $T_e$ and $T_i$ profiles.
- **Outer midplane**: $T_e$ and $T_i$ profiles.

**UE1b**

- **Inner midplane**: $T_e$ and $T_i$ profiles.
- **Outer midplane**: $T_e$ and $T_i$ profiles.

**UE1b_0.1C**

- **Inner midplane**: $T_e$ and $T_i$ profiles.
- **Outer midplane**: $T_e$ and $T_i$ profiles.
Plasma profiles on target plates are more sensitive to altering inner leg transport and adding impurity radiation.

**UE1a**

**UE1a_0.1C**

**UE1b**

**UE1b_0.1C**
Plasma profiles on target plates are more sensitive to altering inner leg transport and adding impurity radiation.

**UE1a**

**Inner plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**Outer plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**UE1a_0.1C**

**Inner plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**Outer plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**UE1b**

**Inner plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**Outer plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**UE1b_0.1C**

**Inner plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

**Outer plate**

\[ T_e \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]

\[ T_i \text{ vs. } R_{\text{omp}} - R_{\text{sep}} \]
UEDGE impurity radiation for cases UE1a_0.1C (left) and UE1b_0.1C (right)

1.3 MW impurity radiation loss

1.4 MW impurity radiation loss

- Peak heat flux on the plate ~100 MW/m²
- Radiation localized near the plates?
Summary

• SPARC divertor will have challenging peak heat flux due to high exhaust power and narrow SOL width
• UEDGE has been set up for SPARC to guide solutions for divertor design
• Initial UEDGE solutions have been obtained for SPARC, consistent with known empirical scalings and projections
• Sensitivity to unknown transport in divertor leg region is probed
• Impurity radiation with fixed-fraction 0.1% C results in radiation loss of ~15% of $P_{SOL}$
• A larger impurity fraction is needed to reduce significantly the peak heat flux (core plasma can tolerate up to 5% C impurity)
• Search for radiating impurity species and fraction ongoing with UEDGE to help find partially or fully detached divertor solutions for SPARC