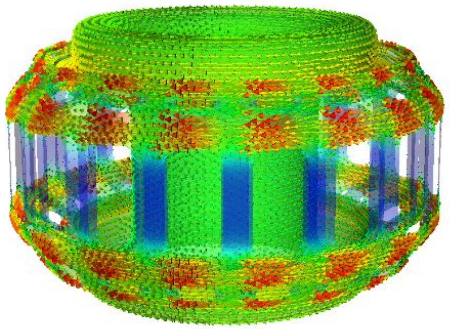
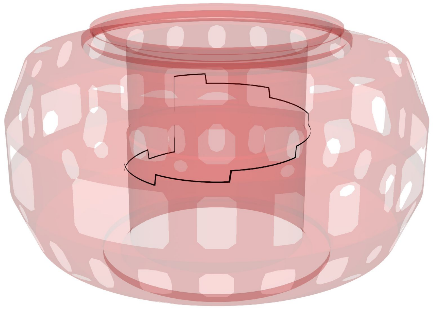
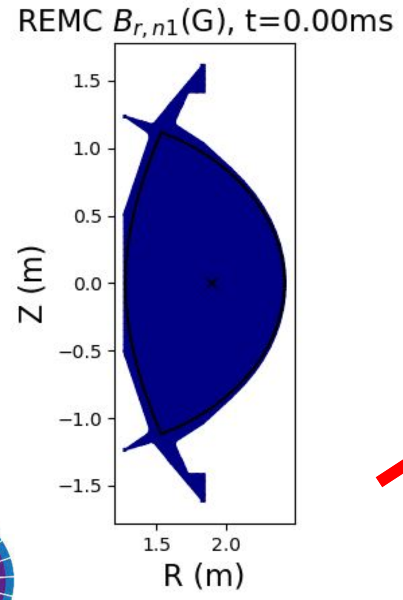
Design of Passive and Structural Conductors for Tokamaks Using Thin-Wall Eddy Current Modeling







C. Hansen[1], **A.F. Battey**[1], **A. Braun**[1], D. Garnier[2], D. Weisberg[3], C. Paz-Soldan[1], R. Sweeney[4], R.A. Tinguely[2], A.J. Creely[4]

1- *Columbia University*
2- *MIT*
3- *General Atomics*
4- *Commonwealth Fusion Systems*

3D eddy currents can be an important consideration for tokamak design and engineering

- **Large eddy currents are induced in tokamak conducting structures during both start-up and plasma disruptions**

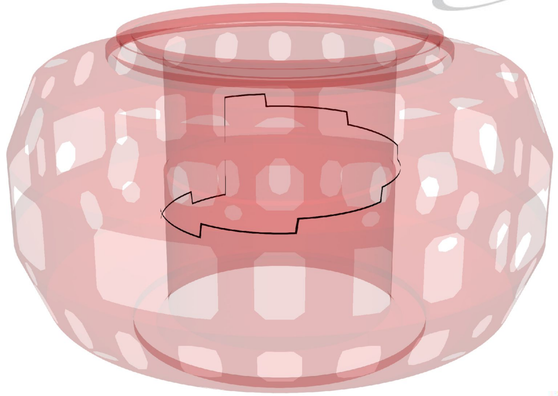
- **These eddy currents can produce large non-axisymmetric fields which can:**
  - Affect <u>magnetic field null</u> for start-up
  - Induce <u>large forces</u> on conducting components
  - Drive dangerous <u>MHD instabilities</u>

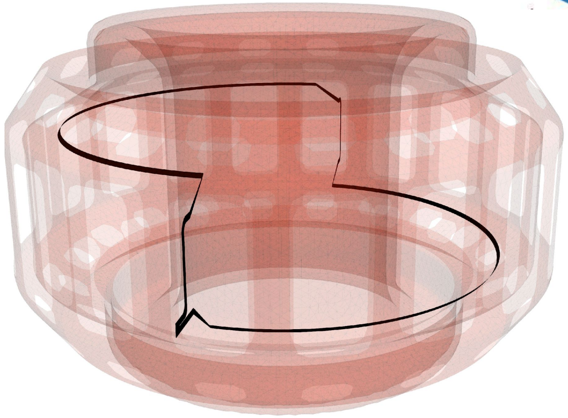
- **Conducting paths can also be explicitly designed to generate desirable 3D fields, such as the proposed Runaway Electron Mitigation Coils (REMCs)**

- **The ability to model these conductors and their interactions <u>with high fidelity early in the design process</u> is important capability for tokamak engineering**

Runaway Electron Mitigation Coils (REMC) couple to loop voltage produced by disruption current quench

- **Runaway electrons (RE) are generated during a disruption current quench (CQ)**
  - RE avalanche drives exponential growth ($\sim I_P$)
- **Passive non-axisymmetric coil designed to inductively couple to changing plasma current**
  - Current driven by large toroidal electric field created during CQ
- **<u>If properly designed</u> the coil will produce large 3D field during CQ**
  - Will destroy confining flux surfaces and drive large deconfining MHD
  - Both DIII-D and SPARC REMC are designed to create n=1 radial field
  - Modeling and experiment have demonstrated the efficacy of 3D field in deconfining REs





*** Talks by Izzo and Sweeney**

Boozer, *PPCF* **53** 084002 (2011)
Mlynar, *PPCF* **61** 014010 (2019)
Paz-Soldan, *PPCF* **61** 054001 (2019)
Tinguely, *Nucl. Fusion* **61** 124003 (2021)
Weisberg, *Nucl. Fusion* **61** 106033 (2021)
Izzo, *Nucl. Fusion* **62** 096029 (2022)

Outline

- Motivation
- The ThinCurr 3D thin-wall E-M code
- Runaway Electron Mitigation Coil modeling for DIII-D and SPARC
  - Coil to vessel separation (DIII-D only)
  - Coil resistance
  - Current quench duration
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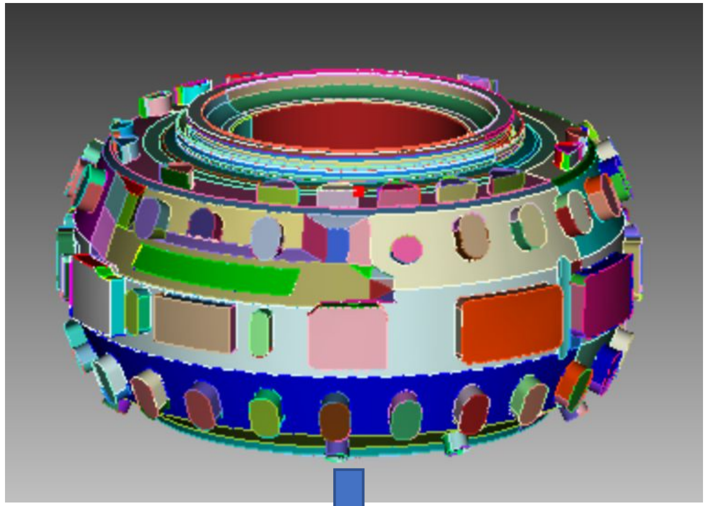
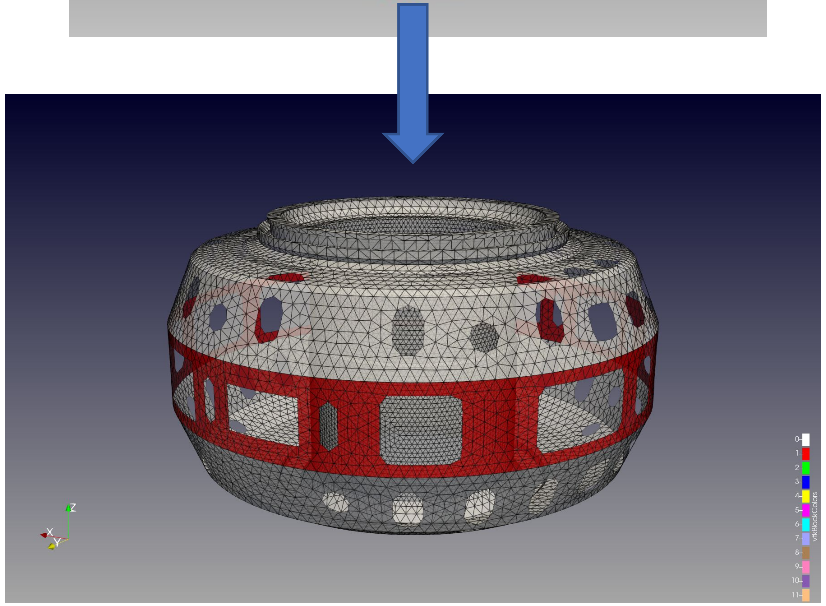
- Conclusions and future work

ThinCurr is a new 3D thin-wall eddy current modeling tool based on the PSI-Tet 3D MHD code

- **Workflow begins with <u>CAD model</u> of tokamak conducting structures (VV, etc.)**
  - Geometry is reduced to sheet representation (thin-wall limit)
- **These models are then defeatured to optimize computation**
  - Important details such as <u>port holes</u>, <u>stability plates</u>, etc. are retained
- **The surfaces are then meshed to the desired resolution**
  - Different components can have higher/lower resolution
- **Different materials and thickness can all be captured in a single model**
  - DIII-D model has 4 resistivities
  - SPARC model has 6+ resistivities





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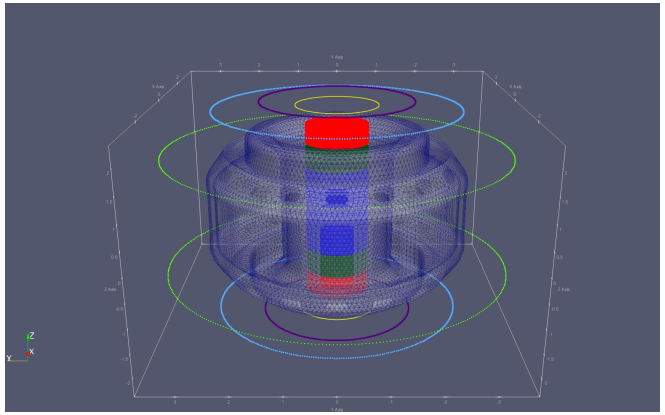
ThinCurr models 3D conducting structures as a series of coupled circuit equations discretized with a finite elements

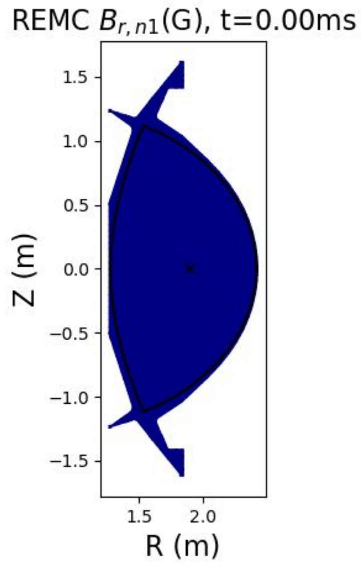


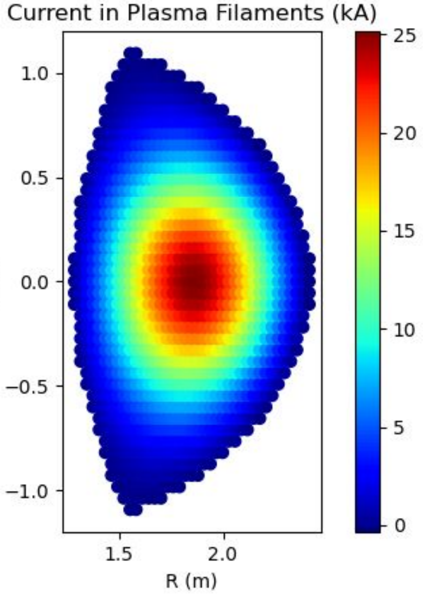
- **Physics governed by inductance/resistance**

$$L_{i,j}\frac{\partial I_i}{\partial t} + R_{i,j}I_i = V_j(t)$$

- **Additional currents/voltages can be included**
  - Filament coils ($I(t)$ or $V(t)$)
  - Plasma “modes” (eg. DCON)
- **Magnetic fields available anywhere in space**
  - Sensor signals with eddy currents
  - Lorentz forces on structures
  - Discontinuities in $\boldsymbol{B}\times\hat{\boldsymbol{n}}$ at surfaces

SPARC





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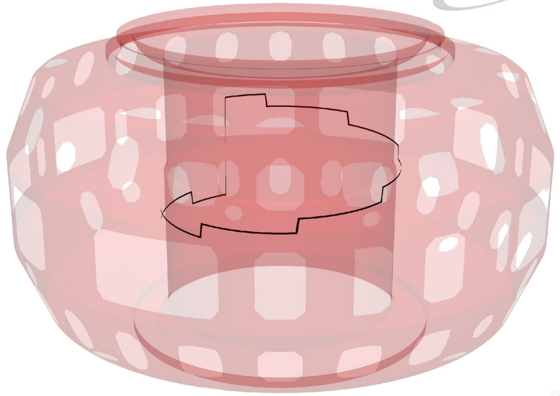
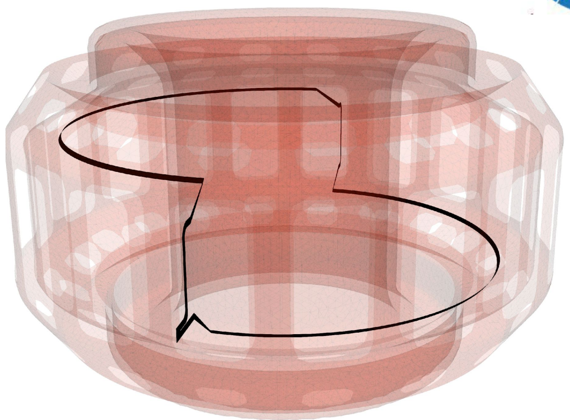
Multiple studies were completed to assess effectiveness and inform the design of DIII-D and SPARC REMCs

- **REMC designs modeled using the ThinCurr code**
- **Simulated with fully 3D REMC models**
  - Coil modeled as thin sheet with variable resistor
  - Toroidally flowing current measured using “jumper”
- **Effect of standoff, variable resistor value, CQ time, and vertical plasma position**
- **<u>Publication on results</u>: A. Battey, et al. *under review***





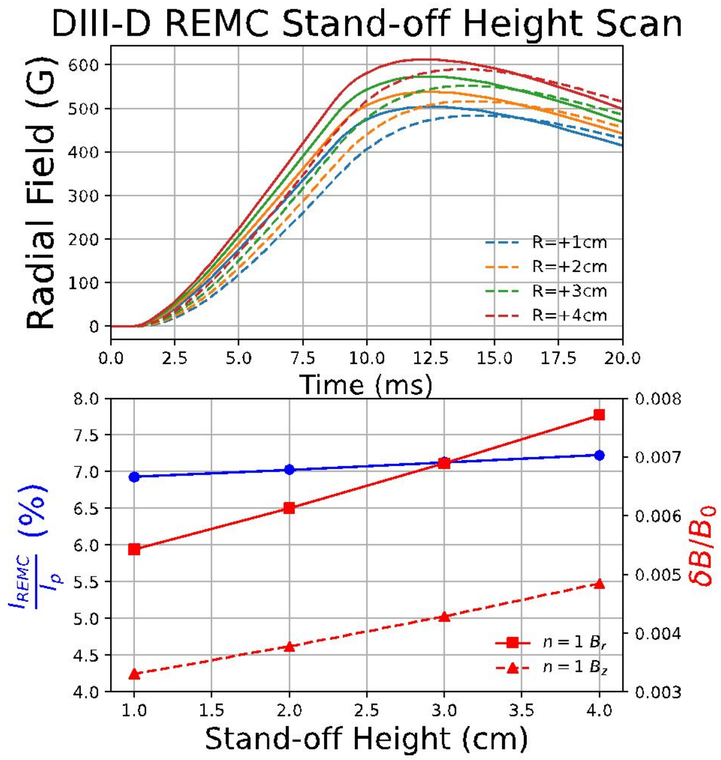
DIII-D's coil location makes it sensitive to position relative to the center stack structure

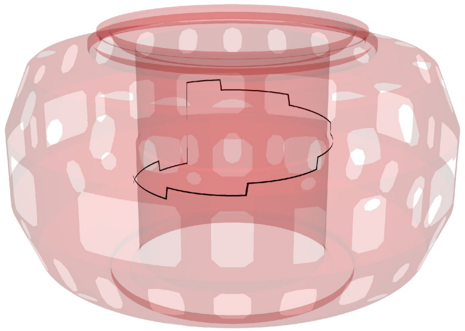
- **Eddy currents induced in the center stack <u>significantly slow the time-response</u>**
  - Primarily due to image currents that cancel the coil field

- **Maximum change in induced current: 4.1%**

- **Maximum change in applied radial field: <u>29.6%</u>**

- **Maximum change in applied vertical field: <u>31.7%</u>**

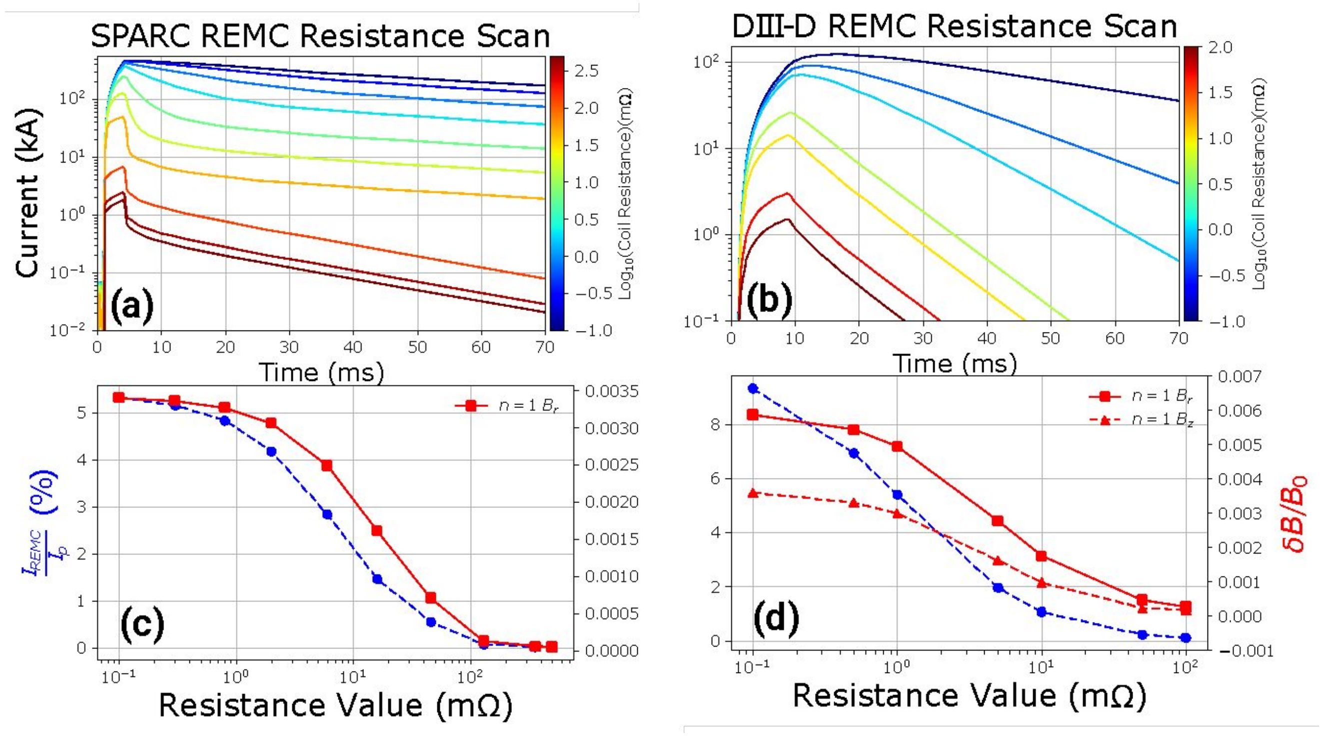




$\tau_{CQ} \approx 9\, ms$

External resistors can be added to limit total impulse, but can also reduce REMC-produced field during CQ

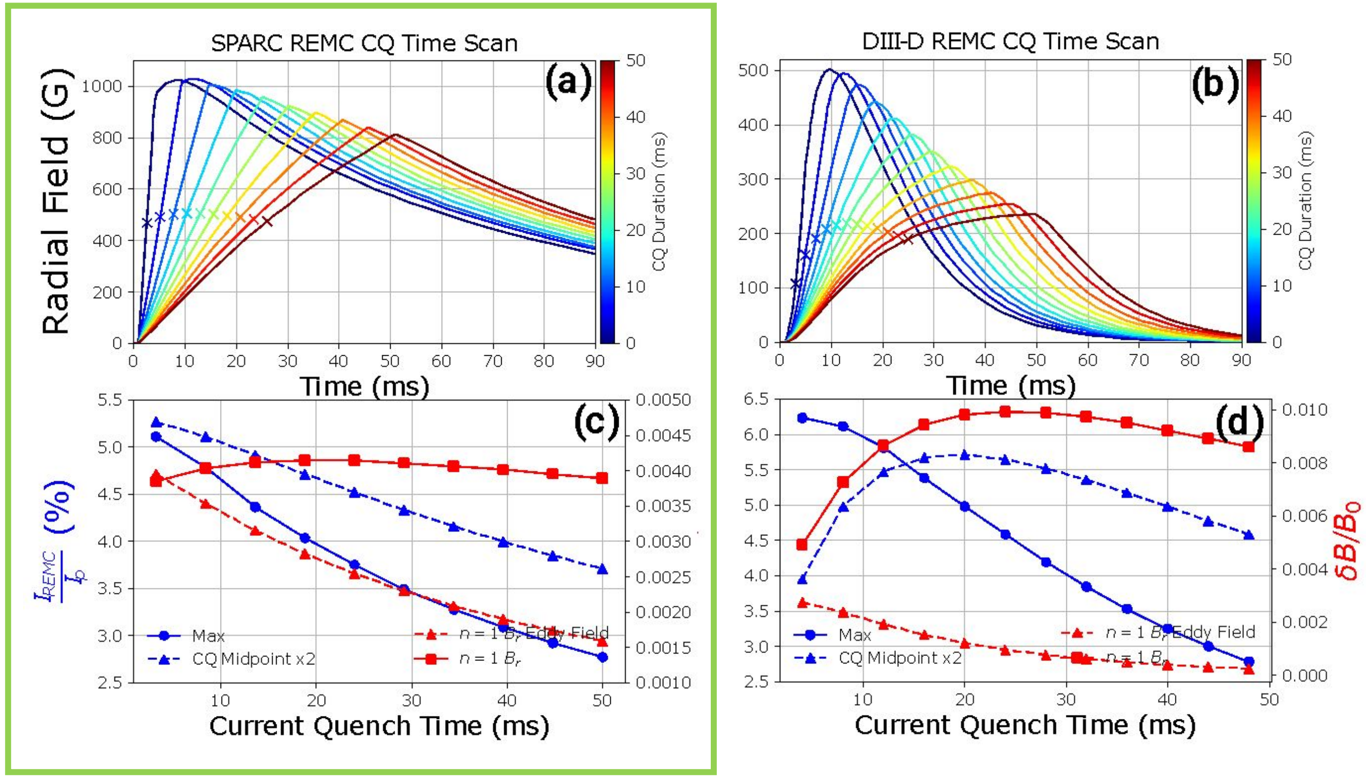
$\tau_{CQ} \approx 4\,ms$



$\tau_{CQ} \approx 9\,ms$

- **Primarily impacts current mid to late in CQ (inductively limited early in time)**
- **On SPARC longer characteristic vessel times maintain currents for longer**

REMC-produced field stays fairly constant across expected current quench durations in SPARC and DIII-D



- **For SPARC, the applied field depends only weakly on CQ length**
  - Current induced in the coil varies by 43%
  - Eddy currents limit the applied field more for fast quenches, leading to a nearly constant value (5%)

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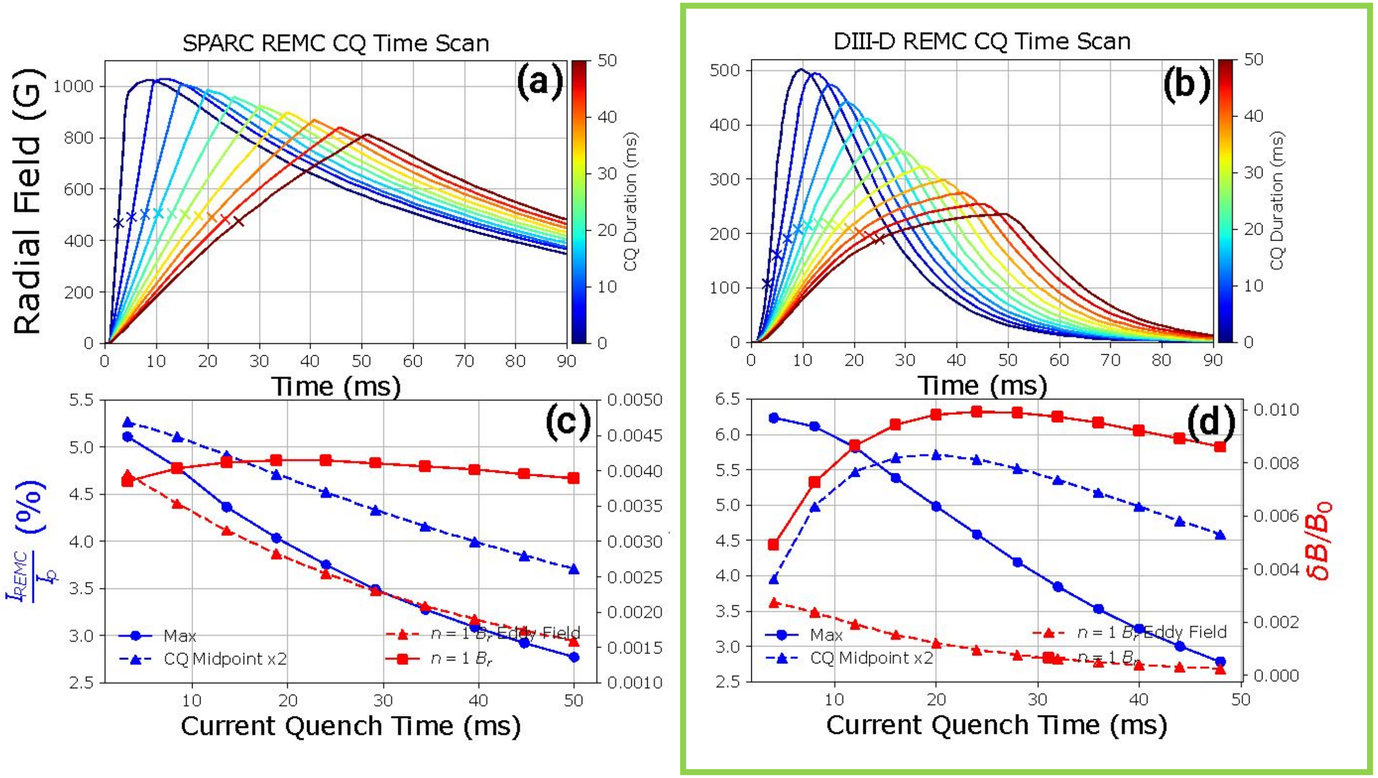
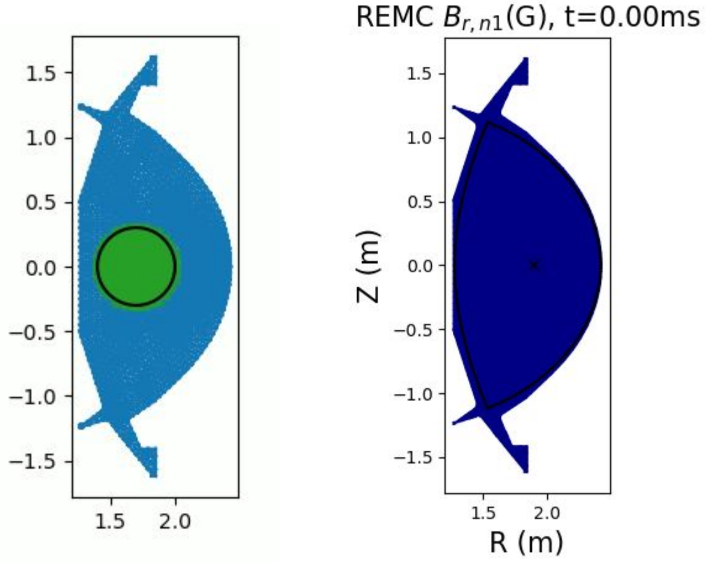


- **DIII-D REMC field is lower for the fastest CQ times, before plateauing**
  - Peak in applied field occurs at intermediate (larger than common experimental) CQ times
  - Caused by strong reduction in effective plasma-REMC coupling on fast time scales (due to VV)

For VDEs the coupling to the REMC and the magnitude of the REMC-produced field on the plasma changes in time

- **Important for REMCs to be <u>robust to vertically unstable plasmas</u>**
  - Performance evaluated for vertically shifted plasma
- **Circular cross section plasma shifted vertically**
  - CQ always modeled with a stationary position



The SPARC and DIII-D designs exhibit different changes in REMC effectiveness during VDEs

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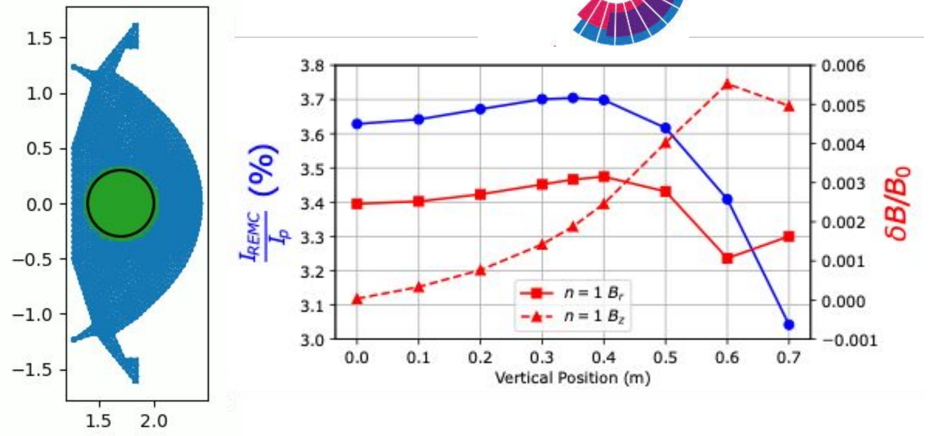
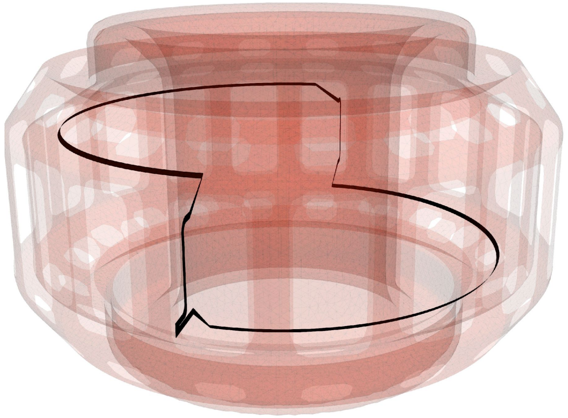
  - Due to position of coil on upper low-field side
  - More than compensates for decreasing radial field

SPARC





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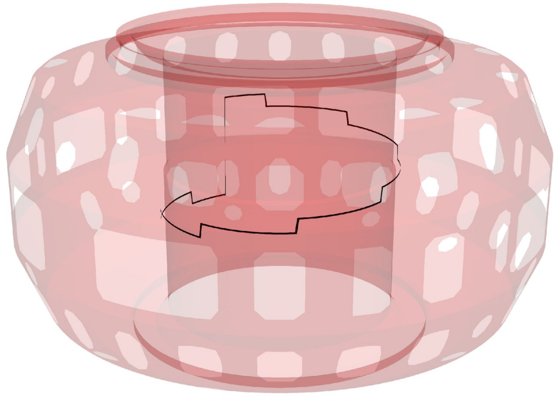
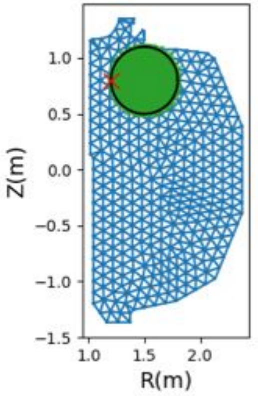
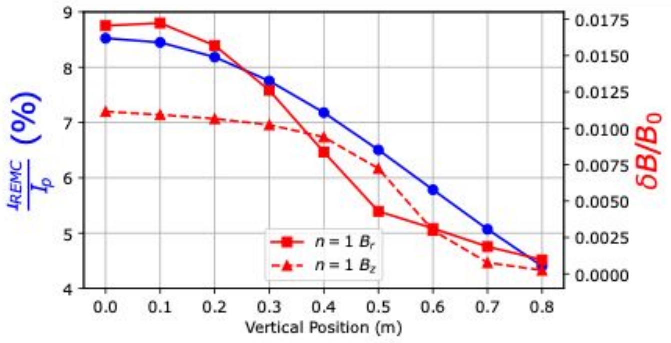
  - Plasma moves uniformly away from coil







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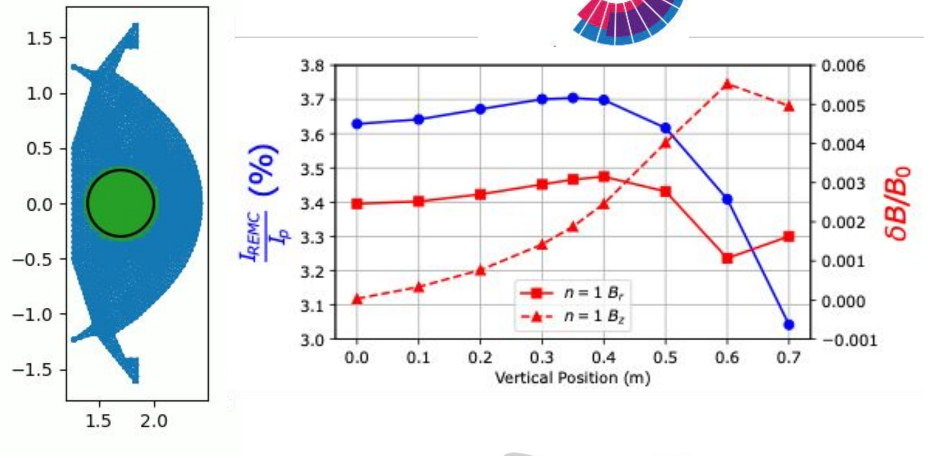

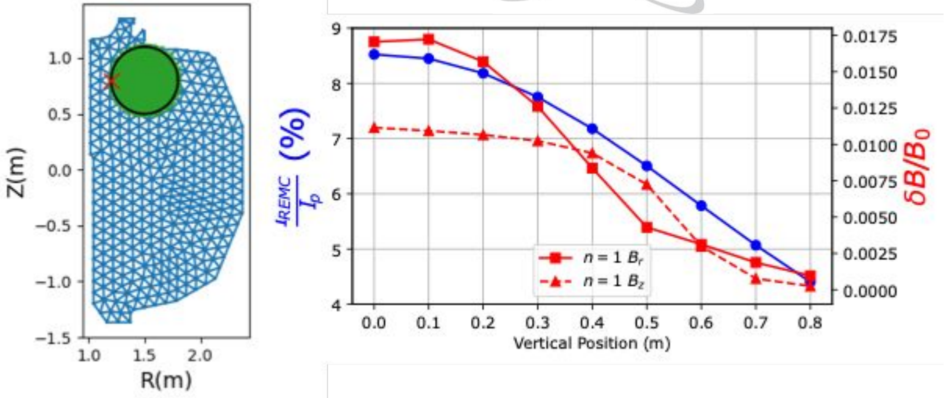

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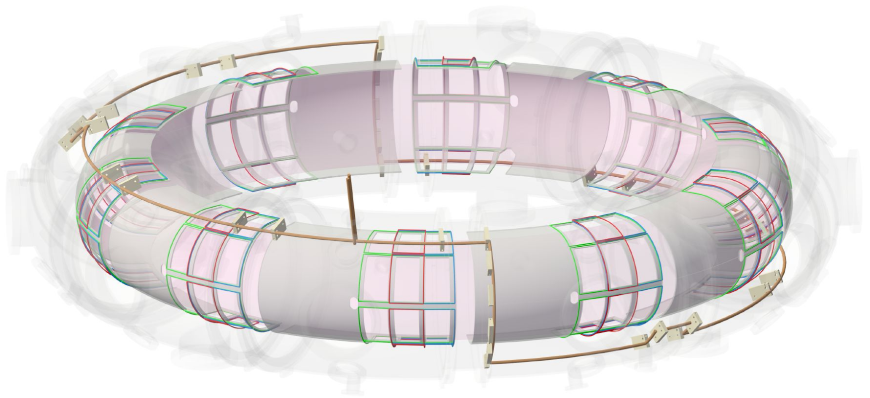
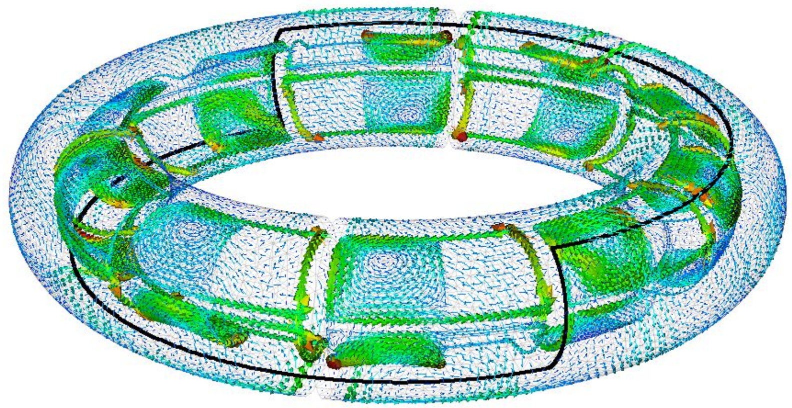
An REMC-like coil has been proposed for HBT-EP to validate E-M and plasma response models

- **An REMC-like coil was designed for HBT-EP to validate ThinCurr and related models**
  - Focused on validating plasma-coil coupling
  - Install and test within 2 years
- **Coil can be passively driven (disruptions) or actively driven by external supplies**
  - Study plasma response
  - Interact with startup-generated runaways
- **Leverages unique features of HBT-EP**
  - Control coil array for baseline comparison





*** Poster by Braun**

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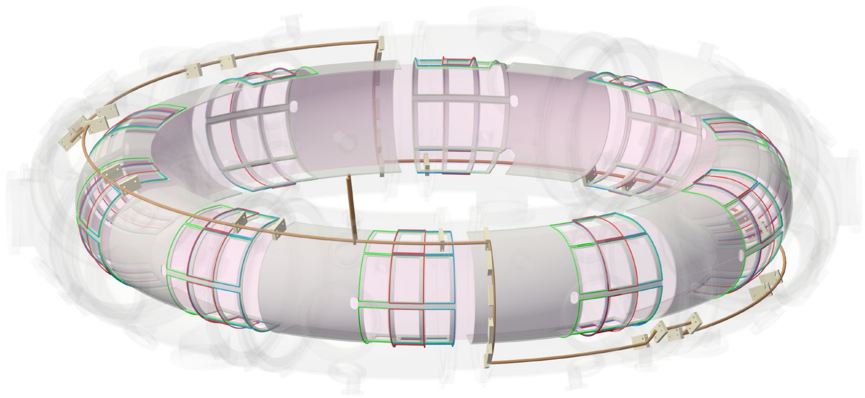

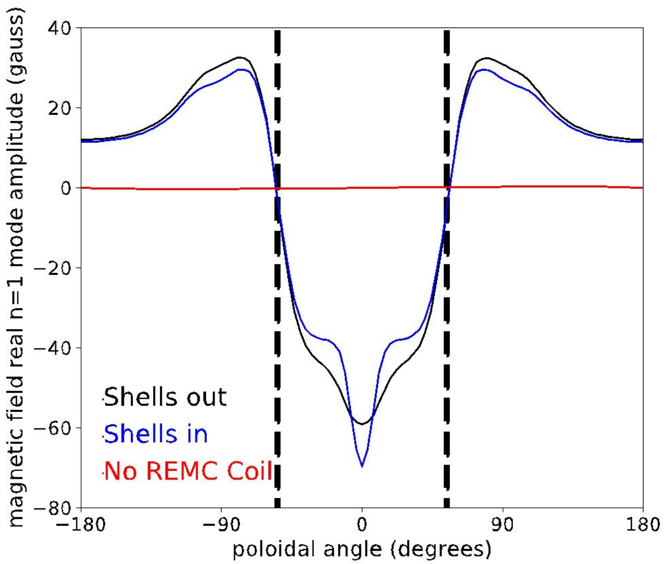

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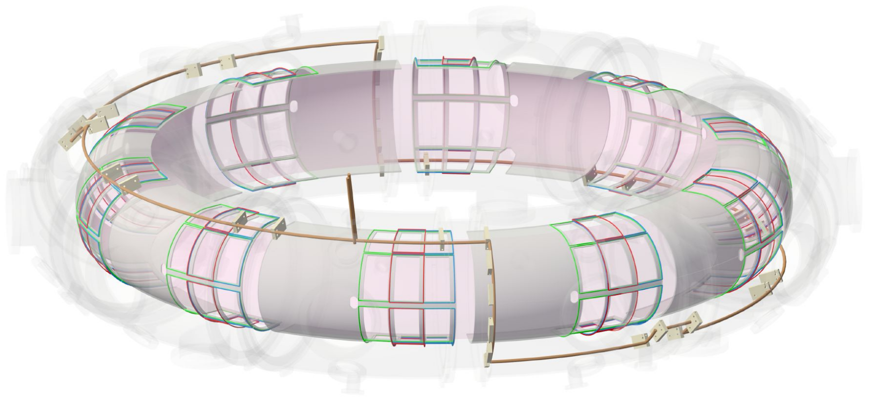

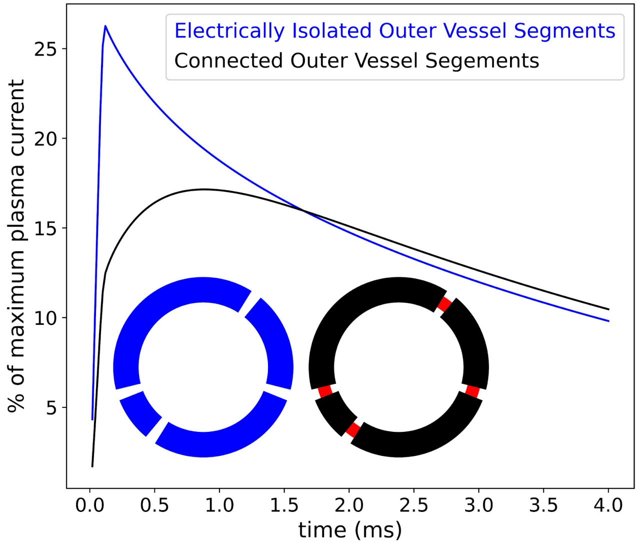

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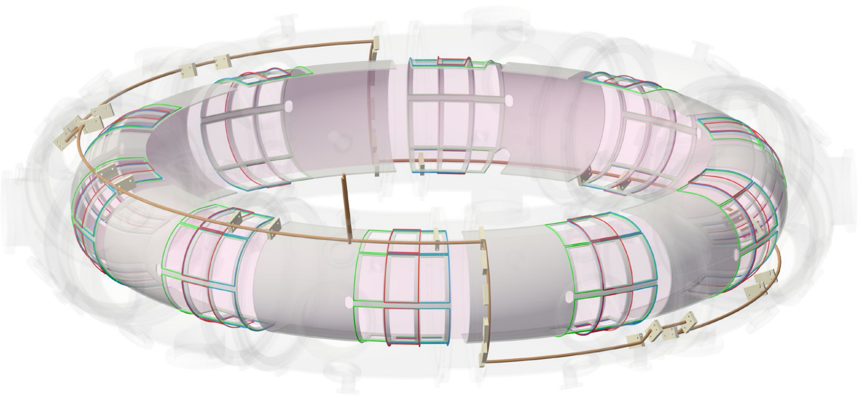

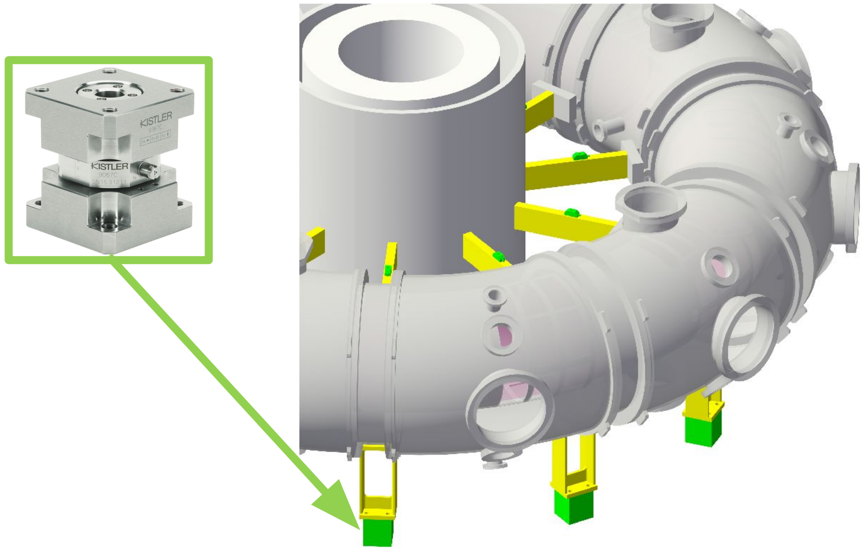

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Conclusions

- The newly developed ThinCurr 3D E-M modeling code has been used to predict the behavior of REMC coils proposed for DIII-D, SPARC, and HBT-EP
  - Code is open-source and available for other applications as well (reach out to me)
- Standoff height was found to be particularly import for DIII-D REMC design
- Both DIII-D and SPARC coils exhibit only modest performance dependence on current quench duration
- For VDEs, the strength of the applied field appears more consistent for the SPARC design than the DIII-D design
- A coil has been designed and proposed for HBT-EP to enable the validation of E-M and some plasma response models for REMCs