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Passive deconfinement of runaway electrons using an in-vessel helical coil

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ABSTRACT

- Numerical modeling of a helical coil designed to passively generate non-axisymmetric fields during a plasma disruption shows efficient deconfinement of runaway electrons (RE).
- Optimization of coil geometry is performed using TokSys[1] electromagnetic analysis of inductive coupling during current quench (CQ), and SURFMN[2] vacuum island overlap width (VIOW) generated in experimental equilibria.
- Relativistic drift orbit tracing using the linear MHD code MARS-F[3,4] predicts up to 70% of RE orbits lost after 200μs.

BACKGROUND

- REs are an existential problem for high-current tokamaks, have kinetic energy in the tens of MeV range, and can seriously damage hardware.
- Previous studies[5] have demonstrated the feasibility of RE deconfinement via the application of 3D fields.
- A proposed in-vessel helical coil would inductively couple to the disruption current quench and generate a large 3D field to limit RE formation. Ideal tokamak models have defined thresholds for coil current and field[6]:

$$\frac{I_{coil}}{I_P} \gtrsim 2\%, \qquad \frac{\delta B}{B_0} \gtrsim 10^{-2}$$

- This study investigates the parametric optimization of an in-vessel helical coil as a passive safety measure against RE beam formation.
  1. What is the optimal coil geometry to maximize RE orbit loss?
  2. How would an RE coil design installed and validated on DIII-D scale to reactor-relevant devices?

OPTIMIZATION WORKFLOW

COIL PARAMETRIZATION

The helical coil geometry is defined by three parameters (Fig. 1):

1. Pitch angle of centerpost helix (Z_{CP} = height of n=1 helix)
2. Discrete number of vertical helix segments (n_{seg})
3. Absence/presence of poloidal outboard loop

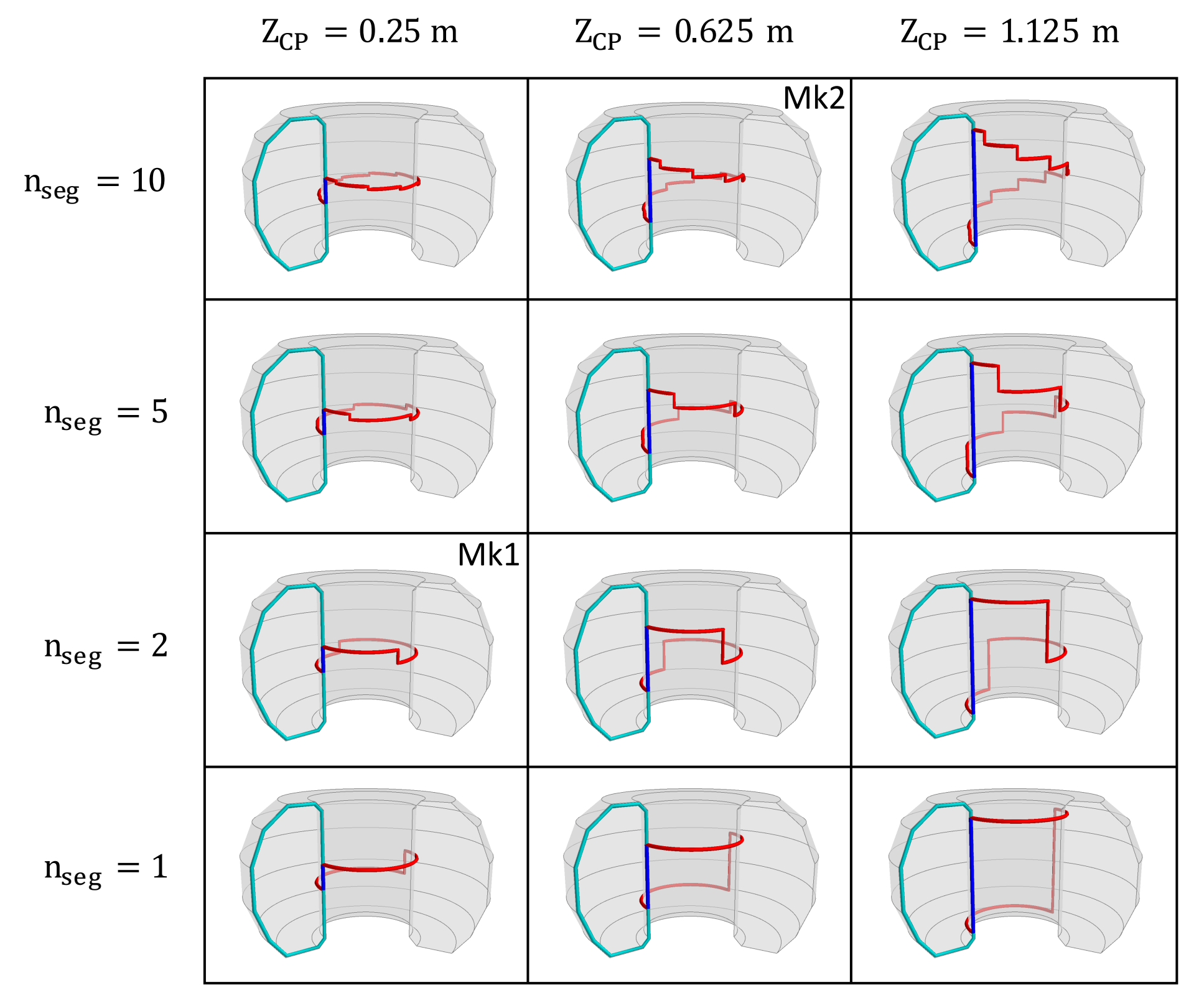

Fig 1. Coil geometry parametrization (red: helix, blue: return loop)

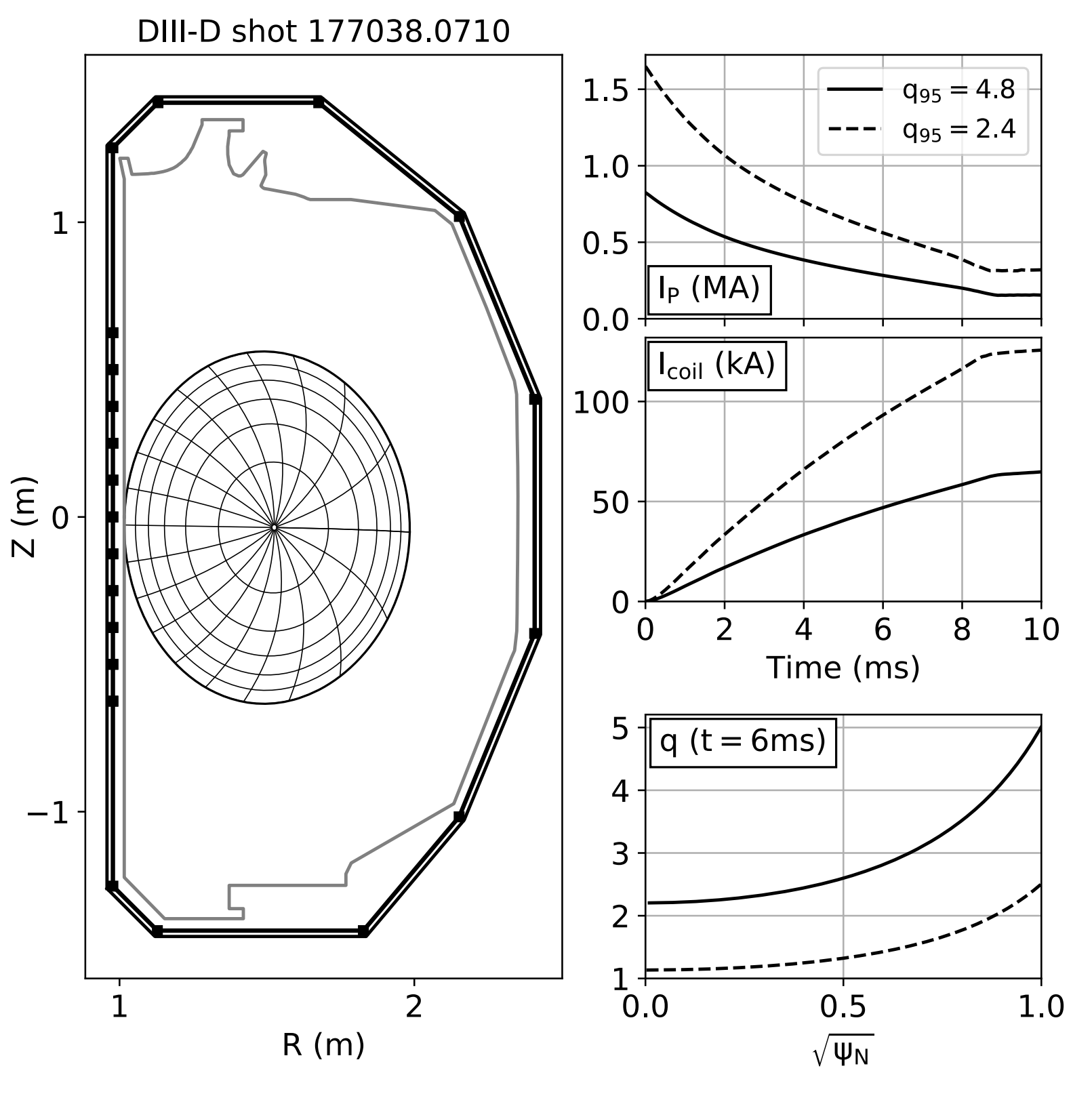

Fig 2. DIII-D equilibria and current evolution example

VACUUM FIELD OPTIMIZATION

An RE mitigation coil must maximize the inductive coupling with the plasma current as well as the magnetic coupling to the plasma equilibrium. TokSys and SURFMN are used to calculate two vacuum field metrics over a range of coil geometries:

1. Non-resonant mode amplitude on magnetic axis $\delta B_{pol}(n)$
2. Resonant vacuum island overlap width (VIOW: from plasma edge inward)

Two mid-CQ equilibria from RE-producing experiments on DIII-D are used as test cases (Fig. 2), with high-I_P (q_{95}=2.4) and low-I_P (q_{95}=4.8).

RELATIVISTIC DRIFT ORBIT TRACING

Based on the vacuum field results, several coil geometries are selected for analysis in MARS-F. The full plasma response is calculated, and the orbits of an initial distribution of relativistic test particles are traced. The loss fraction of RE orbits is compared between coil geometries and equilibria.

ACKNOWLEDGEMENTS / REFERENCES

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-FC02-04ER54698, as well as by internal General Atomics funds.

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RESULTS

- Inductive coupling modeling shows that the inducted coil current can be as large as 12% of the pre-disruption plasma current (Fig. 3).
  - Adding an outboard poloidal loop decreases this by up to a factor of 2.
  - Induced current is highest for shallow helical angle (low Z_{CP}), which minimizes the average distance between the coil and the plasma.
- Vacuum field modeling shows that δB can be a large as 1% of equilibrium toroidal field, and that an optimized coil will generate VIOW of up to 0.7 Ψ_N.
  - VIOW increases discontinuously with coil current as n=1 and n=2 vacuum islands grow large enough to overlap each other (Fig. 4).
  - The VIOW-optimized parameter space is broad, allowing a single coil shape to efficiently couple to resonant plasma modes in both test equilibria (Fig. 5).

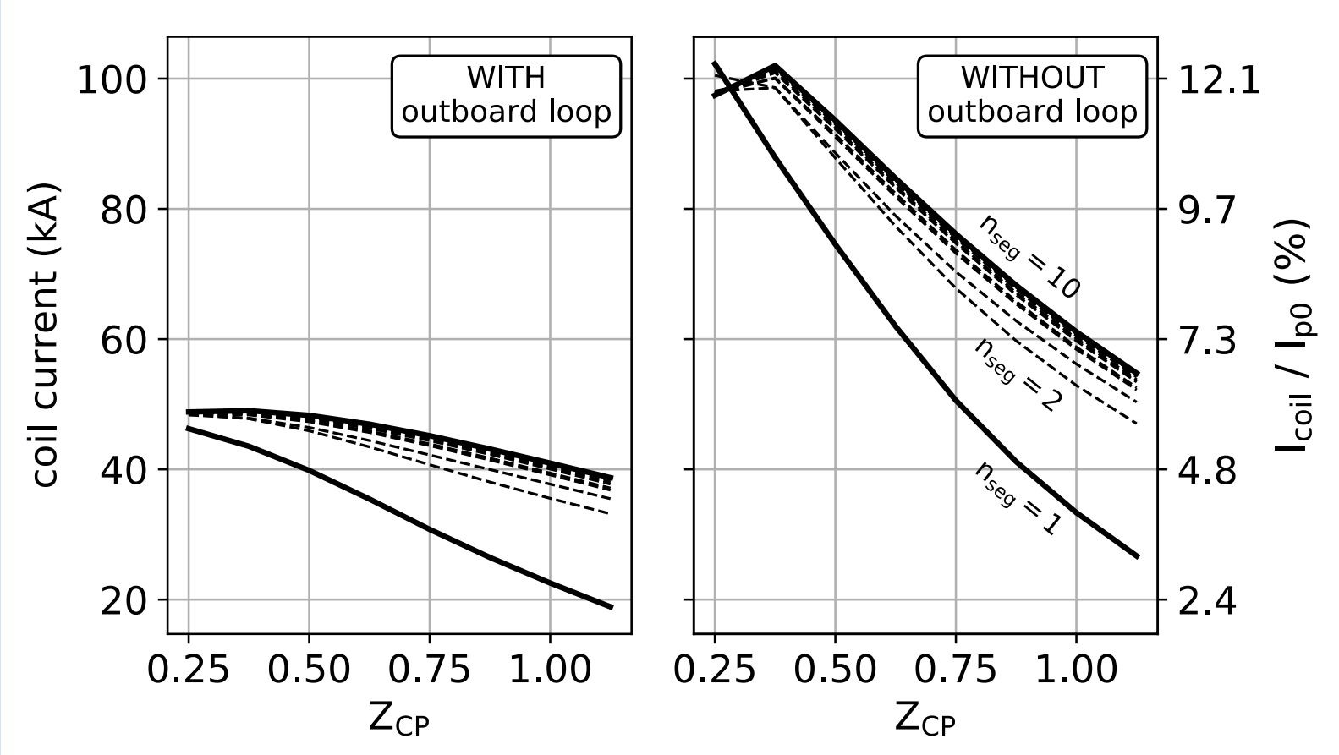

Fig 3. Induced current scan, t = 6ms

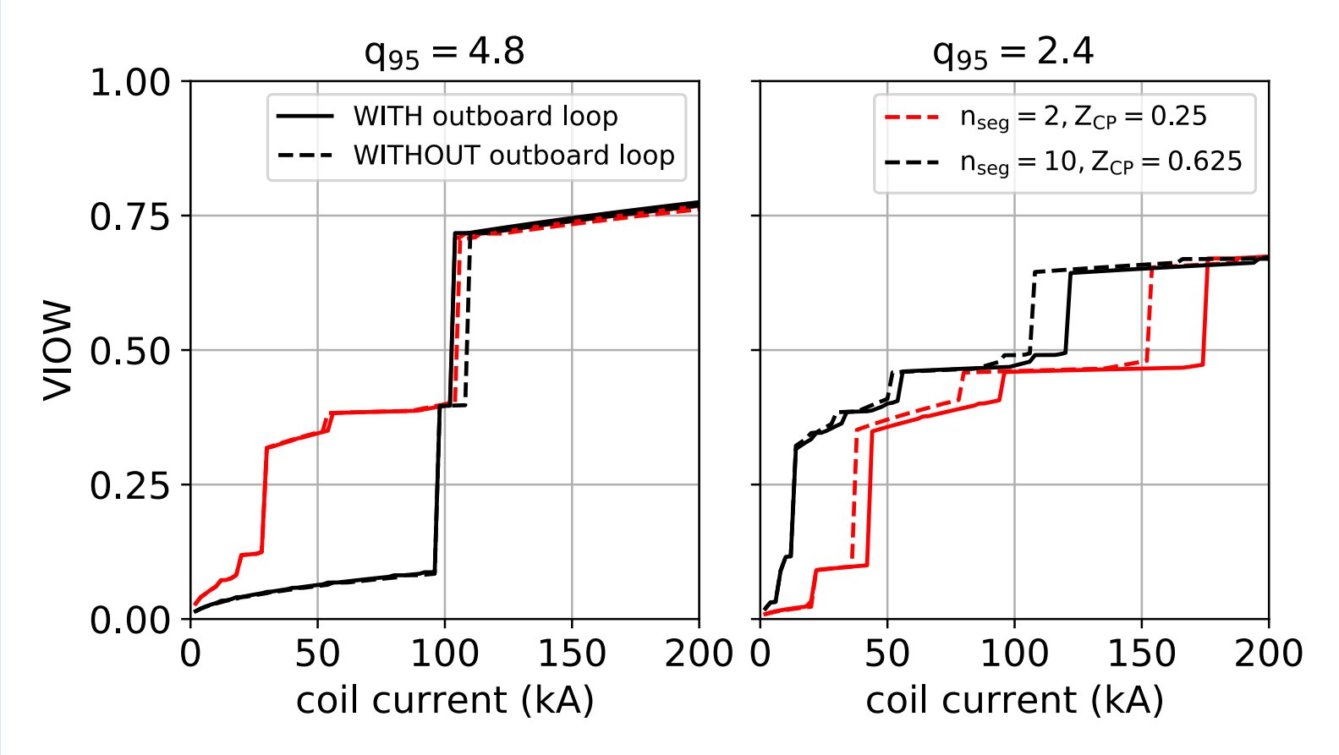

Fig 4. VIOW vs. coil current for Mk1 & Mk2 coils

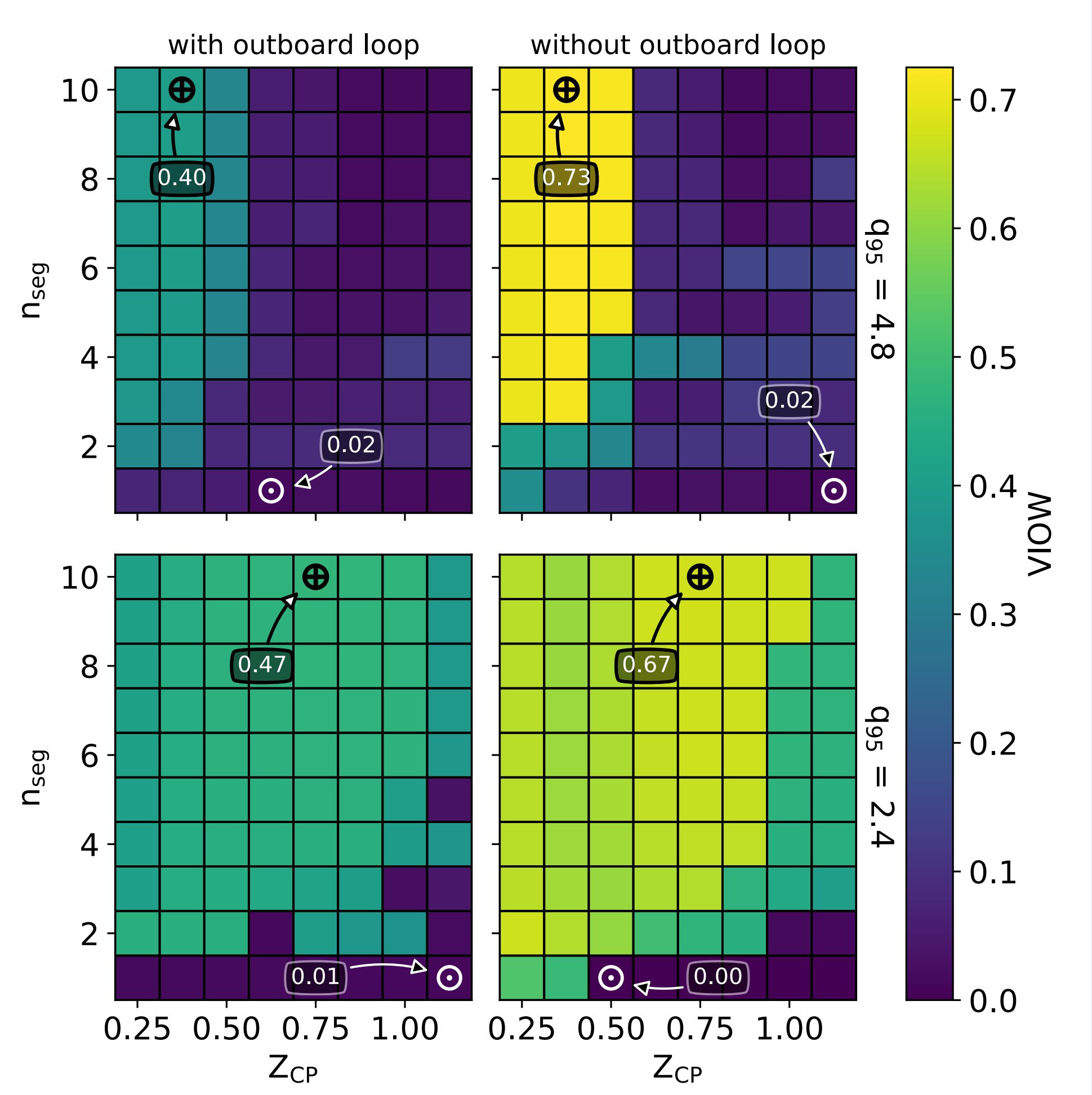

Fig 5. Induced VIOW over coil geometry scan, for both test equilibria

- Drift orbit tracing shows that up to 70% of RE orbits are lost within 200μs, with increased loss fraction observed at higher coil current and plasma current.
  - Two coil shapes were chosen for MARS-F modeling: Mk1 and Mk2 (see Fig. 1)
  - Mk2 (n_{seg}=10, Z_{CP}=0.625m) outperforms Mk1 (n_{seg}=2, Z_{CP}=0.25m) in all cases, although for low-I_P there is a delay in the orbit loss fraction (Fig. 6).
- Further analysis of outboard RE orbits reveals evidence of RE trapping between q=3/1 and q=4/1 island chains in low-I_P equilibrium (Fig. 7).
  - Larger islands formed by 100kA Mk2 coil decreases outboard-born RE orbit loss fraction via resonant trapping; explains 2-step evolution of orbit loss.
  - This phenomenon is not observed at high-I_P, which has fewer n=1 surfaces.

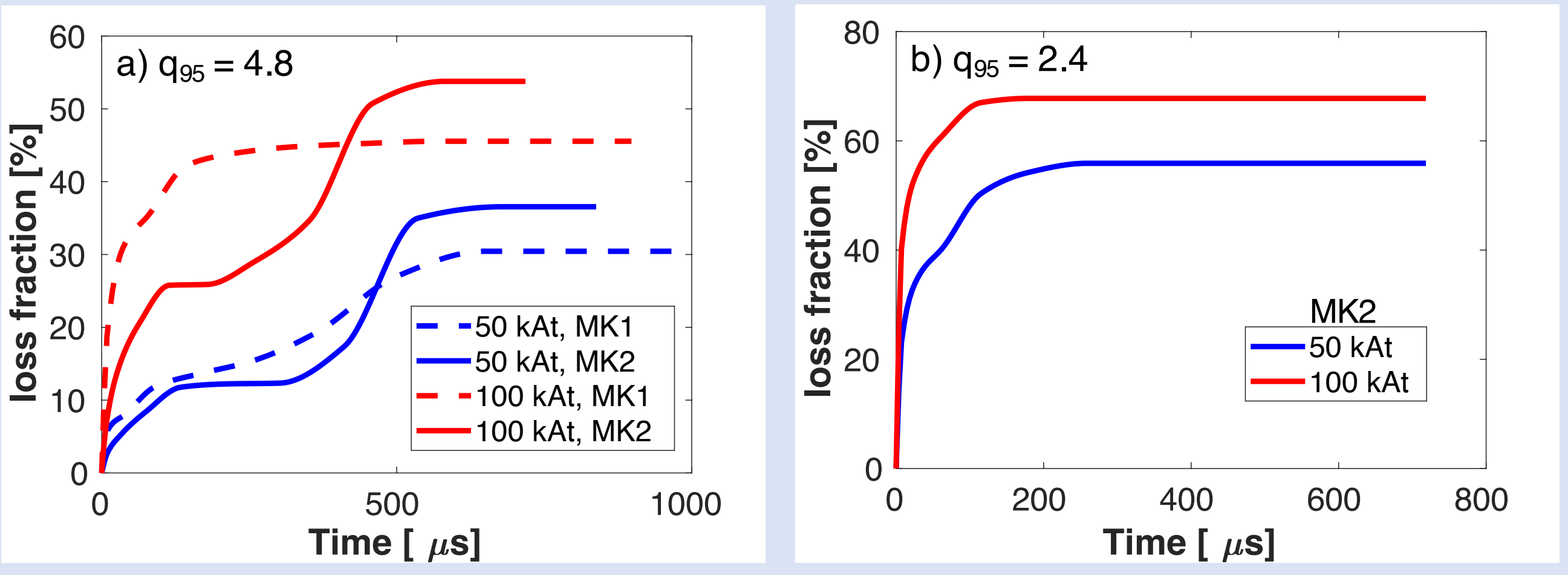

Fig 6. RE orbit loss fraction for a) low-I_P, b) high-I_P cases

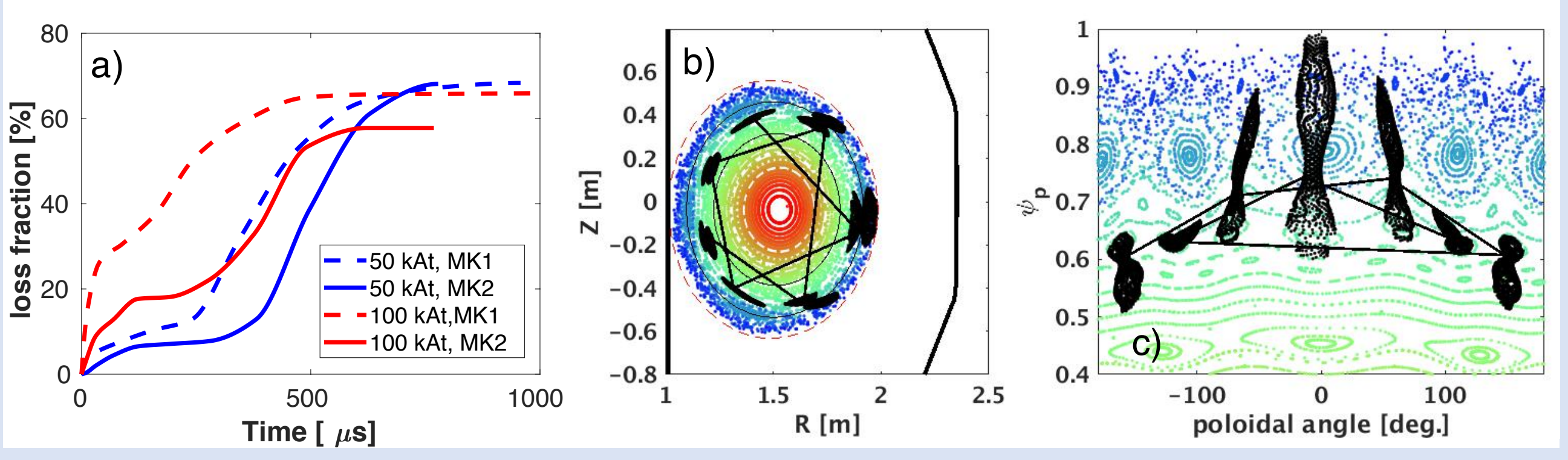

Fig 7. RE orbit-trapping in low-I_P case: a) outboard-born RE loss evolution, b,c) RE orbit for 100kA Mk2 for 0 < t < 283μs.

Param	Scale factor	ITER-like
I_P	M_I	7.5
B_T	M_B	2.0
R_0	M_R	3.75
N	M_N	1
q_{95}	$M_R M_B / M_I$	1
τ_{CQ}	M_R^2	14
I_{coil}/I_P	M_i/M_I	1
$\delta B/B_T$	$M_N M_b / M_B$	1
$F_{J\times B}$	M_I^2/M_R	15
$\sigma_{J\times B}$	$M_N M_I^2 / M_R^3$	1.07
P_{Joule}	$M_N^2 M_I^2 M_R$	210
ΔT_{coil}	$M_N^2 M_I^2$	56

Table 1. Stress and thermal scale factors

CONCLUSIONS

- Vacuum field optimization of RE mitigation coil geometry shows a broad minimum in parameter space, and drift orbit tracing of two specific coil shapes shows efficient RE loss for multiple plasma equilibria.
- I_{coil}/I_P and $\delta B/B_T$ are scale-independent (at constant aspect ratio and q_{95}), so an experimentally validated DIII-D coil design will be equally efficient on larger, higher-current reactor-relevant tokamaks.
  - Structural and thermal stresses are not scale-independent, but are still manageable on an ITER-size device (Table 1). Notably, while ΔT_{coil} increases by a factor of 56 from DIII-D to ITER scales, $\Delta T_{ITER} \sim 100°C$.
- Future work will focus on non-linear MHD simulations (M3D-C1, NIMROD) to model the time-evolution of RE generation and loss.