Changes in disruption dynamics during the first operation of a Runaway Electron Mitigation Coil (REMC) on a tokamak

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Runaway electrons (REs) generated by the large loop voltage during disruptions in high current tokamaks pose a significant hazard for damaging first-wall components[1-3]. RE beams with large energies and currents have been observed to cause local melting[4] and cooling tube rupture[2] at impact sites. Mitigating the RE problem is a necessity to ensure that first-wall components can survive disruptive events in reactor-scale tokamaks.

While active means of mitigating REs is a possibility[5–8], a passive system that does not require disruption prediction and minimally relies on control systems would be optimal. One potential passive mitigation scheme is known as a Runaway Electron Mitigation Coil (REMC)[9,10]. Here, the loop voltage induced during disruptions can be used to drive a large current in a non-axisymmetric coil or other asymmetric conducting feature, thereby generating large asymmetric fields that couple to plasma modes. The intent is to excite multiple plasma modes to cause stochastization of magnetic fields over large regions, reducing energetic particle confinement and subsequent RE avalanching[11,12].

We report results from the first ever installation and utilization of the REMC concept. A dedicated n=1-like REMC (Figure 1) has been installed and operated in the HBT-EP tokamak[13,14] starting in late 2024. The geometry is similar to the n=1 REMC envisioned for the SPARC tokamak[15-17]. An ex-vessel switch allows the coil to be open-circuit during routine plasma operation, and closed during disruptions or other requested times. To date, the coil has been operated by closing the switch via pre-programming the desired time or by passively using the disruption's induced loop voltage as a trigger. Closure of the switch could also be completed in less than 30µs by a real-time control algorithm if desired.

Design considerations for the REMC system are presented, along with progress on modeling the system using the ThinCurr code[18], which is also being used to design and predict performance of REMCs on larger tokamaks including DIII-D[17,19], TCV, and SPARC[17]. ThinCurr simulations with an accurate model of HBT-EP's conducting structures show good agreement with experiments.

With the REMC activated during disruptions, we measure changes to asymmetric distributions of halo currents[20,21] entering and exiting the high-field side (HFS) of the vessel (Figure 2). Changes are associated with asymmetric plasma-wall contact on either side of the tokamak, or equivalently with a large-scale locked n=1 perturbation. This is measured via current-collecting limiter tiles and magnetic sensor arrays. Changes in halo currents near the end of the current quench are consistent with expectations from filament reconstructions of the last closed flux surface, as well as experiments in which in-vessel low-field side (LFS) 3D control coils are used to move the plasma up or down to observe changes in small-scale LFS scrape-off-layer (SOL) currents.

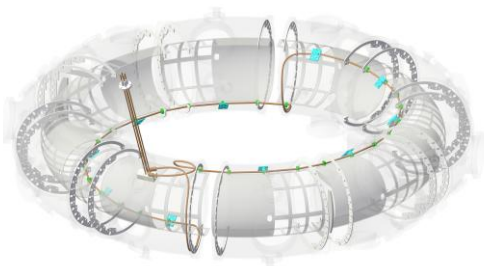

Figure 1: Rendering of the REMC installed in-vessel in HBT-EP.

For normal conditions, roughly 12% of the pre-disruption plasma current (I_{p0}) is driven in the

REMC by the midpoint of the current quench (Figure 3), a time which is significant for evaluating effects on confinement. Differences in efficiency of coupled current would be expected if a large fraction of the plasma current remains in REs without a substantial decrease in overall plasma current. Around 17% of I_{p0} is coupled into the REMC at the peak of the REMC current. Although the peak coil current happens at the end of the current quench, when the bulk of any prior energetic particle population would already be lost, the peak current is significant for evaluating forces on the coil or attached components.

Discharges with a significant slide-away electron[22] population are produced in order to study confinement of energetic electrons in HBT-EP. Hard x-ray (HXR) emission produced by impacts of these energetic electrons around the vessel is measured and compared for cases with/without the REMC activated. With the REMC active, the distribution of HXR emission around the tokamak changes relative to non-perturbed cases, implying changes in the loss of energetic electrons. While these electrons are not avalanche-generated in HBT-EP, they still offer insight into the behavior of energetic electrons in the presence of large scale magnetic perturbations.

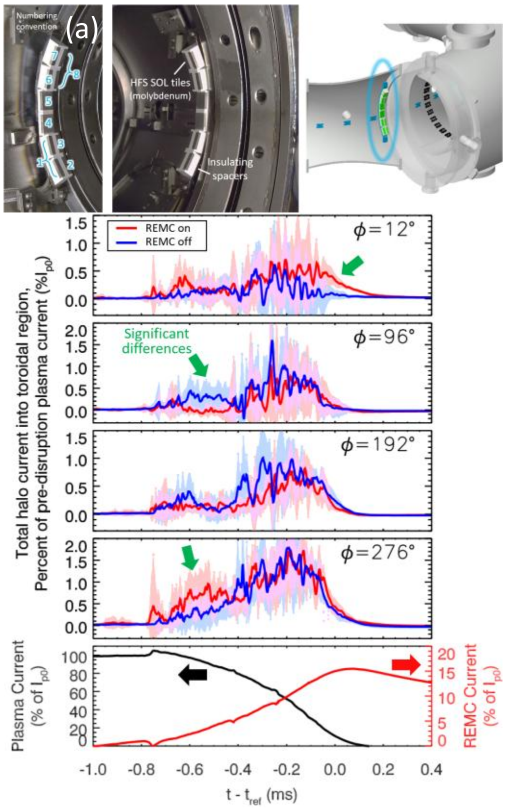

Figure 2: (a) *Detail of HFS halo current diagnostic tiles.* (b-e) *Asymmetric halo currents entering the vessel in four toroidal regions for 16 similar discharges.* (f) *Plasma current and REMC current for an example disruption in the set.*

Implications and considerations for applying the REMC concept in larger tokamaks will also be discussed. The REMC remains to be demonstrated for high current tokamaks.

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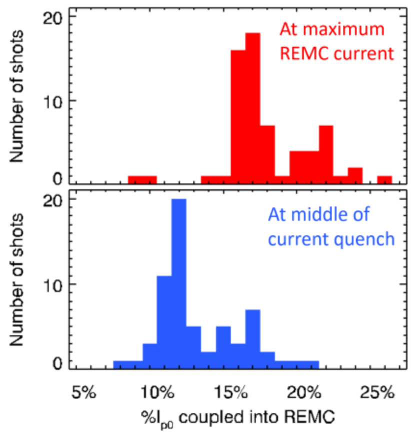

Figure 3: Histograms of pre-disruption plasma current coupled into the REMC at maximum REMC current (red), and midway through the current quench (blue).

[1] BREIZMAN, B.N. et al., *Nucl. Fusion* **59** 8 (2019) 083001.
[2] NYGREN, R. et al., *J. Nuclear Materials* **241–243** (1997) 522.
[3] LEHNEN, M. et al., *J. Nuclear Materials* **463** (2015) 39.
[4] MATTHEWS, G.F. et al., *Phys. Scr.* **T167** (2016) 014070.
[5] SHIRAKI, D. et al., *Nucl. Fusion* **58** 5 (2018) 056006.
[6] ZHANG, Y.P. et al., *Rev. Mod. Plasma Phys.* **7** 1 (2023) 12.
[7] BANERJEE, S. et al., *Nucl. Fusion* **61** 1 (2021) 016027.
[8] GUO, Z. et al., *Physics of Plasmas* **25** 3 (2018) 032504.
[9] BOOZER, A.H., *Plas. Phys. Contrl. Fus.* **53** 8 (2011) 084002.
[10] SMITH, H.M. et al., *Phys. Plasmas* **20** 7 (2013) 072505.
[11] JAYAKUMAR, R. et al., *Phys. Letters A* **172** 6 (1993) 447.
[12] ROSENBLUTH, M.N. et al., *Nucl. Fusion* **37** 10 (1997) 1355.
[13] MAURER, D.A et al, *Plas. Phys Cont. Fus.* **53** 7 (2011) 074016
[14] LEVESQUE, J.P. et al., *Nucl. Fusion* **57** 8 (2017) 086035.
[15] TINGUELY, R.A. et al., *Nucl. Fusion* **61** 12 (2021) 124003.
[16] IZZO, V.A. et al., *Nucl. Fusion* **62** 9 (2022) 096029.
[17] BATTEY, A.F. et al., *Nucl. Fusion* **64** 1 (2024) 016010.
[18] HANSEN, C. et al., arXiv:2412.14962 (2024).
[19] WEISBERG, D.B. et al., *Nucl. Fusion* **61** 10 (2021) 106033.
[20] STRAIT, E.J. et al., *Nucl. Fusion* **31** 3 (1991) 527.
[21] SAPERSTEIN, A.R. et al., *Physics of Plasmas* **30** 4 (2023) 042506.
[22] STAHL, A. et al., *J. Phys.: Conf. Ser.* **775** (2016) 012013.