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Fusion Magnet Quench Risk Increase with Irradiation Damage

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HENRY ROYCE INSTITUTE

NNUF National Nuclear User Facility

EPSRC Engineering and Physical Sciences Research Council

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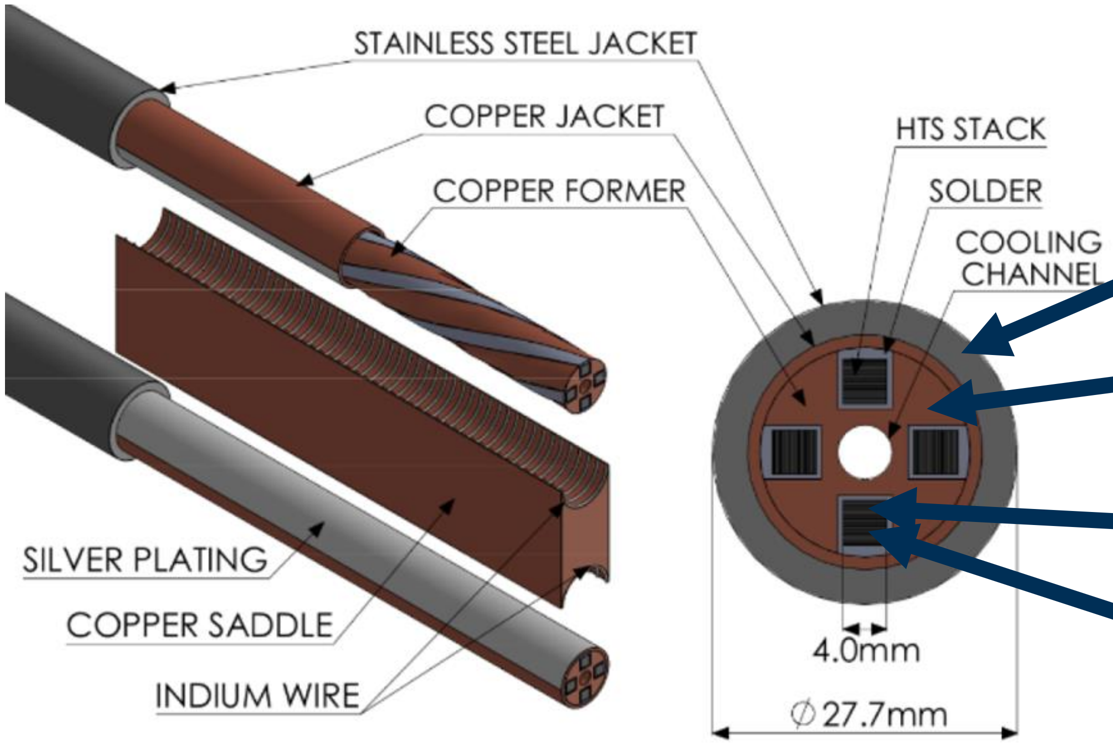
MRF is part of the National Nuclear Users Facility (NNUF) and the Sir Henry Royce Institute for Advanced Materials

Superconducting Magnets Materials



Structural (SS316)

Stabilizer (Copper)

Insulator (Kapton®)

Superconductor (ReBCO)

Erica Salazar, "Quench dynamics and fiber optic quench detection of VIPER high temperature superconductor cable". MIT, 2021

Superconducting Magnet Materials

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Structural (SS316)

Support magnet to ensure low strain in superconductor

Stabilizer (Copper)

Provide a medium of cooling (Coolant channel to superconductor)

Carries current during a quench

Insulator (Kapton®)

Prevents short circuits and ensures safe voltage isolation

Superconductor (ReBCO)

Zero resistance pathway for current during reactor operation

Magnet

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What is a quench?

Superconducting fusion magnets can store ~20 GJ of electromagnetic energy (4780 kg of TNT)

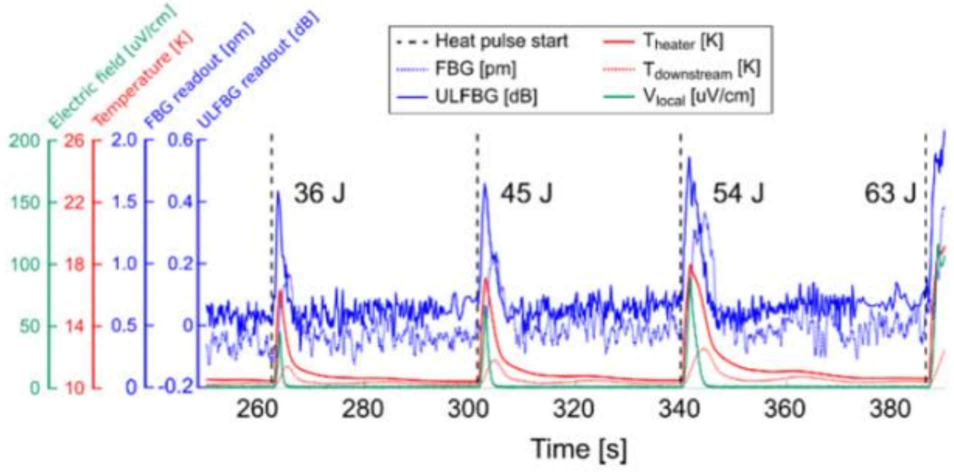

Fig. 7: VIPER cable signal output while carrying 41 kA and subject to an increasing thermal energy disturbance [5]. 36 J, 46 J, 54 J trials did not result in a quench whereas the 63 J trial did.

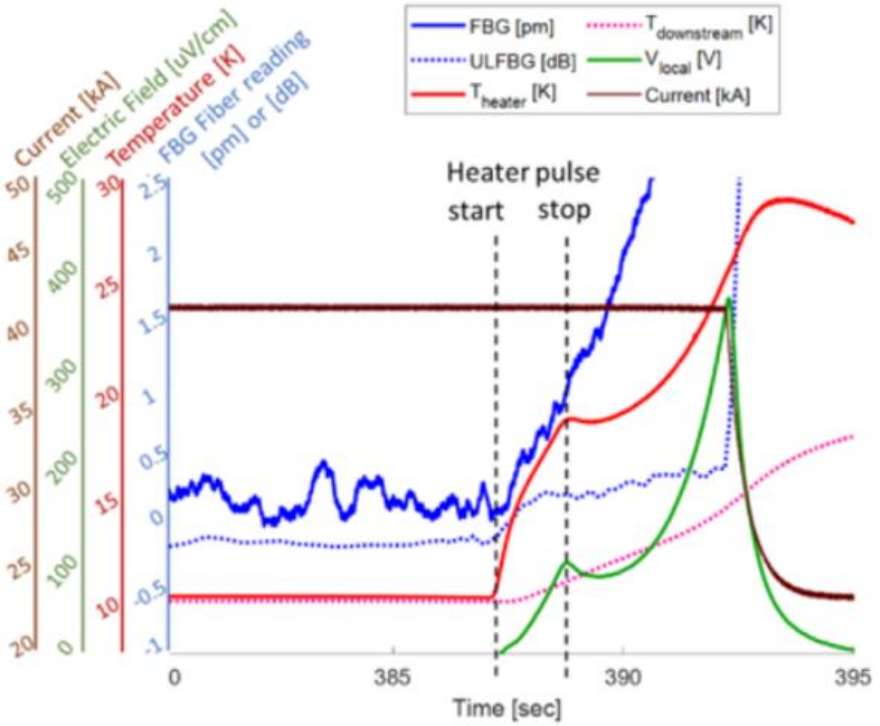

Fig. 8: 63 J thermal disturbance initiating a quench [5]. Close-up of the fourth trial in Figure 7. See the rapidly increasing temperature signal given by the red line.

Erica Salazar, “Quench dynamics and fiber optic quench detection of VIPER high temperature superconductor cable”. MIT, 2021

Temperature Margin

Quenches initiate at the critical temperature

$$T_{\text{margin}}(t) = T_{\text{critical}}(t) - T_{\text{operation}}$$

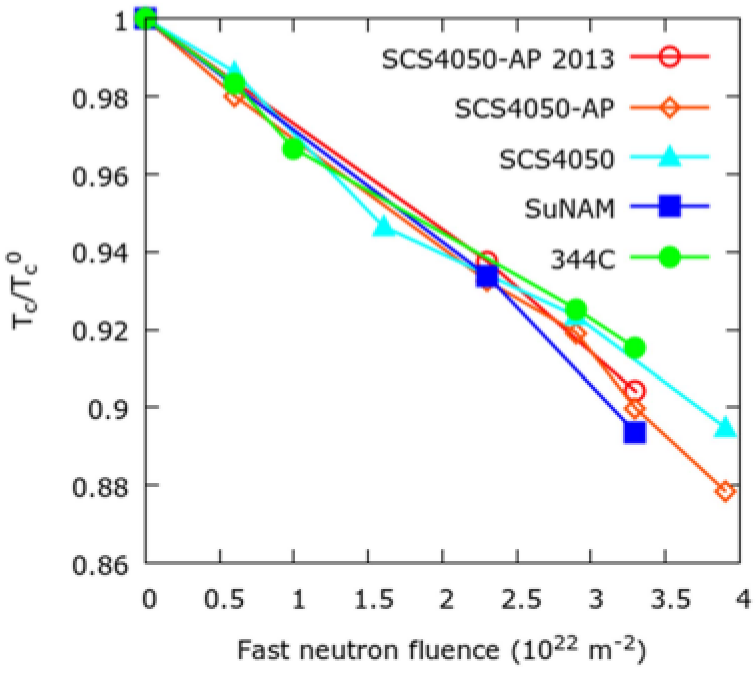

Figure 4. Data from figure 3 as a function of the normalized critical temperature.

Fischer, David X., et al. "The effect of fast neutron irradiation on the superconducting properties of REBCO coated conductors with and without artificial pinning centers." *Superconductor Science and Technology* 31.4 (2018): 044006.

Temperature Margin

Quenches initiate at the critical temperature

$$T_{\text{margin}}(t) = T_{\text{critical}}(t) - T_{\text{operation}} - T_{\text{wigner}}(t)$$

What is Wigner energy?

Wigner Energy

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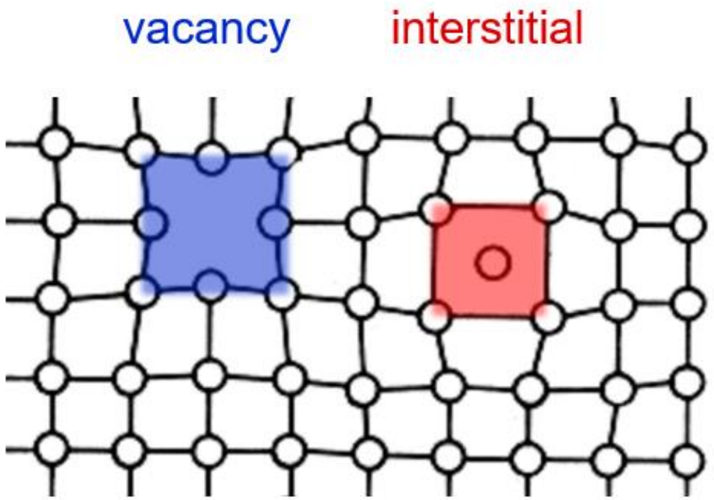
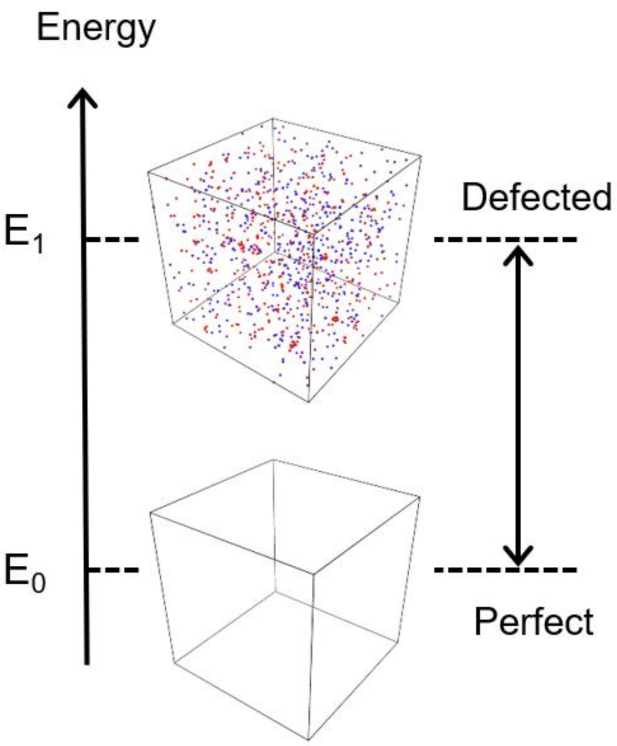


Cu	Formation Energy [eV]	Migration Energy [eV]
Vacancy	1.27	0.8
Interstitial	2.2	0.12
Sum	3.5	



Hirst, Charlie – Wigner Energy Presentation

$$E = kT$$

$$20\,K \propto 0.00172347\,eV$$

$$40\,K \propto 0.00344693\,eV$$

$$\Delta E = 0.00172346\,eV/\text{atom}$$

$$E_{CuFP} = 3.5\,eV$$

$$\frac{E_{CuFP}}{\Delta E} \approx 2031\,\text{atoms}$$

Was, Gary S. *Fundamentals of radiation materials science: metals and alloys*. springer, 2016.
Hirst, Charlie – Wigner Energy Presentation

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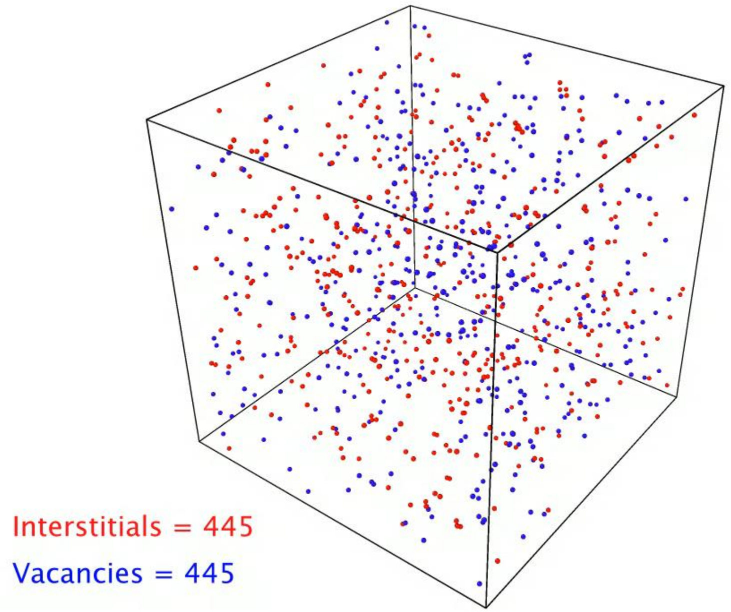
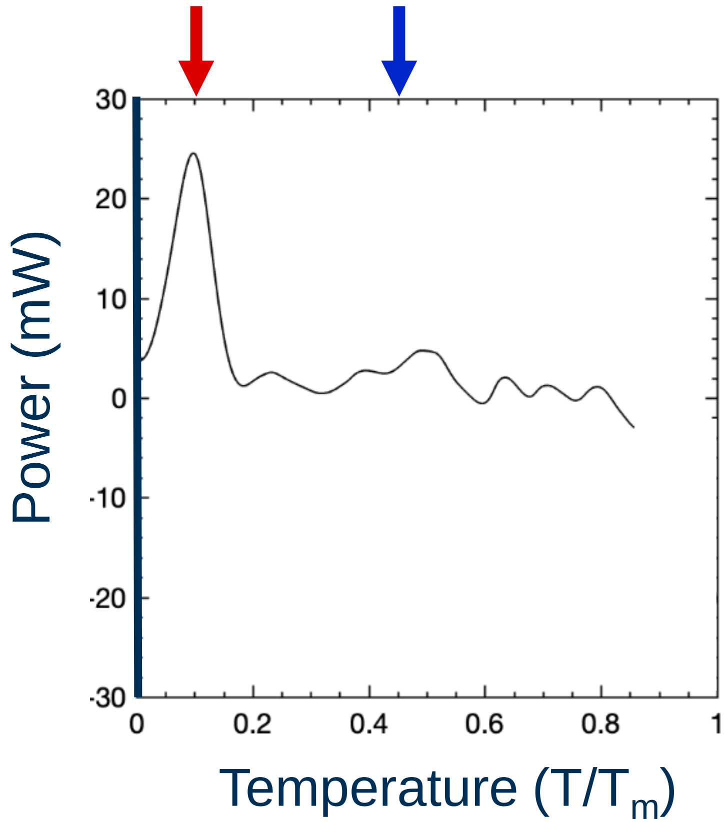
Wigner Energy





T_m = melting point

Hirst et al. Thermochim. Acta. (in prep)

Simulation produced by Hirst, Charlie – Wigner Energy Presentation

Consequences of Defects

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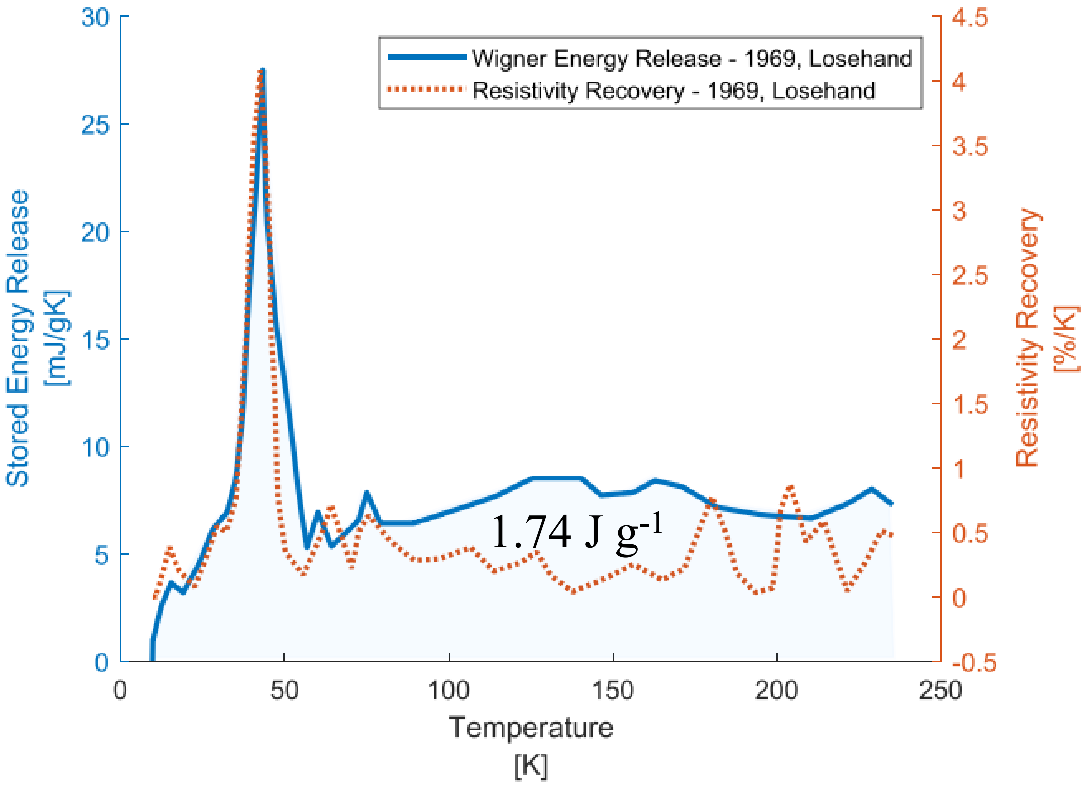

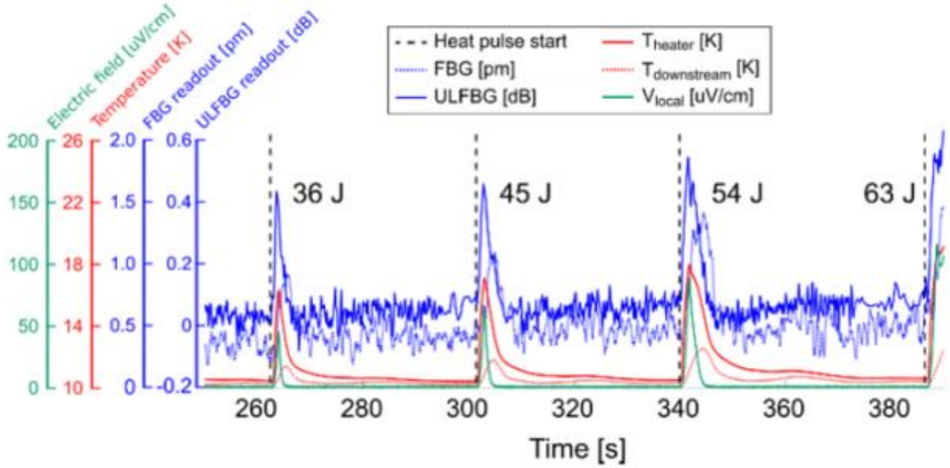

63.0 J input to heat Cu from **10K → 18K**

- Implies **~3000 g** of Cu, using **0.021 J/g**

Losehand et al. (fluence: **0.45 × 10^{18} n/cm²**)

- Wigner energy: **0.023 J/g**
- Total release: **68.3 J**

Richard et al. (fluence: **3.5 × 10^{18} n/cm²**)

- Wigner energy release: **33.0 J**

R. Losehand, F. Rau, and H. Wenzl, "Stored energy and electrical resistivity of Frenkel defects in copper," *Radiation Effects*, vol. 2, no. 2, pp. 69–74, 1969, doi: 10.1080/00337576908235586.

Erica Salazar, “Quench dynamics and fiber optic quench detection of VIPER high temperature superconductor cable”. MIT, 2021

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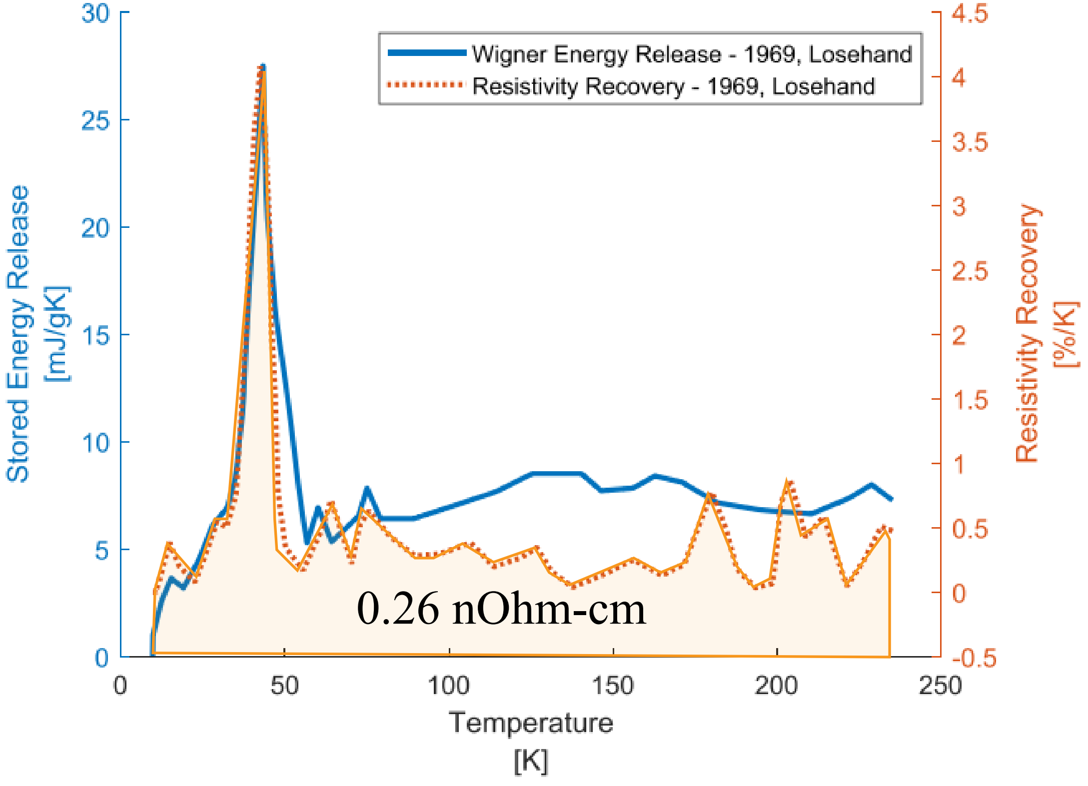
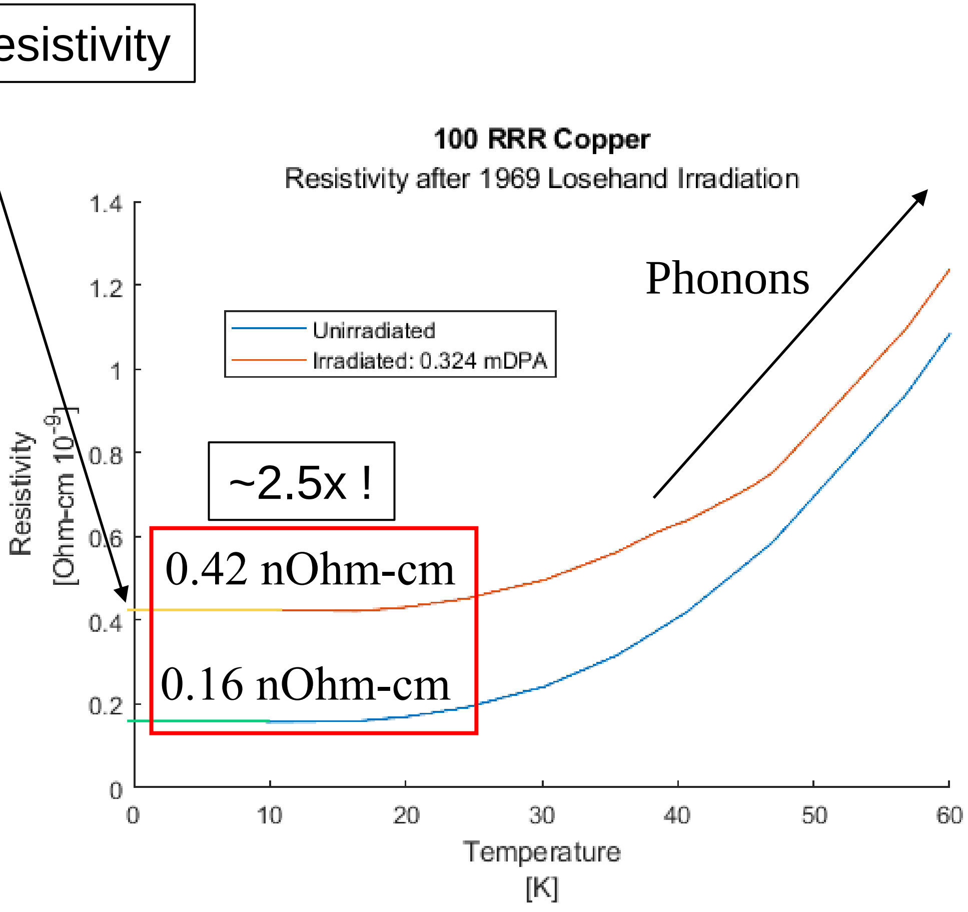
Consequences of Defects





R. Losehand, F. Rau, and H. Wenzl, "Stored energy and electrical resistivity of Frenkel defects in copper," *Radiation Effects*, vol. 2, no. 2, pp. 69–74, 1969, doi: 10.1080/00337576908235586.

N. J. Simon, E. S. Drexler, and R. P. Reed, *Properties of Copper and Copper Alloys a Cryogenic Temperatures*, NIST Monograph 177, Natl. Inst. Stand. Technol., 1992. [Online]. Available: https://doi.org/10.6028/NIST.Mono.177

Temperature Margin

$$W_{T_{\text{operation}}}^{T_{\text{critical}}} = C_{T_{\text{operation}}}^{T_{\text{critical}}}$$

$$\int_{T_{\text{operation}}}^{T_{\text{critical}}(t)} w(T,t)\,dT$$

$$\int_{T_{\text{operation}}+T_{\text{margin}}(t)}^{T_{\text{critical}}(t)} c_p(T)\,dT$$

$$W_{T_{\text{operation}}}^{T_{\text{critical}}} = \cancel{C_{T_{\text{operation}}}^{T_{\text{disturbance}}}} + C_{T_{\text{disturbance}}}^{T_{\text{critical}}}$$

$$\boxed{\int_{T_{\text{operation}}}^{T_{\text{critical}}(t)} c_p(T) - w(T,t)\,dT = \int_{T_{\text{operation}}}^{T_{\text{operation}}+T_{\text{margin}}(t)} c_p(T)\,dT}$$

General expression for Temperature margin!

Temperature Margin (special case 1)

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$$\int_{T_{\text{operation}}}^{T_{\text{critical}}(t)} c_p(T) - w(T,t)\, dT = \int_{T_{\text{operation}}}^{T_{\text{operation}}+T_{\text{margin}}(t)} c_p(T)\, dT$$

Special case: t=0, above simplies to

$$T_{\text{margin}}(t=0) = T_{\text{critical}}(t=0) - T_{\text{operation}}$$

Aligning with current definition of Temperature margin

$$T_{\text{margin}}(t) = T_{\text{critical}}(t) - T_{\text{operation}}$$

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Temperature Margin (special case 2)

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$$\int_{T_{\text{operation}}}^{T_{\text{critical}}(t)} c_p(T) - w(T,t)\, dT = \int_{T_{\text{operation}}}^{T_{\text{operation}}+T_{\text{margin}}(t)} c_p(T)\, dT$$

Special case: T_critical is constant

$$T_{\text{margin}} = \left(1 - \frac{W(t)_{T_{\text{operation}}}^{T_{\text{critical}}}}{C_{T_{\text{margin}}}^{T_{\text{critical}}}}\right)(T_{\text{critical}} - T_{\text{operation}})$$

Echoes………

$$T_{\text{margin}}(t) = T_{\text{critical}}(t) - T_{\text{operation}}$$

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Temperature Margin (special case 3)

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$$\int_{T_{\text{operation}}}^{T_{\text{critical}}(t)} c_p(T) - w(T,t)\, dT = \int_{T_{\text{operation}}}^{T_{\text{operation}}+T_{\text{margin}}(t)} c_p(T)\, dT$$

Special case: Cp(T)=w(T,t_critical)

$$\int_{T_{\text{operation}}}^{T_{\text{critical}}(t_{critical})} c_p(T) - w(T,t_{critical})\, dT = 0$$

Implying that

$$T_{\text{margin}}(t_{critical}) = 0$$

Meaning: at the critical span (t=t_critical) a quench may occur spontaneously

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The Well's number

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With the case,

$$T_{\text{margin}}(t_{critical}) = 0$$

and the definition,

$$t_{Critical} = \frac{\Phi_{Critical}}{\phi_{FPY}}$$

$$We = log\left(\frac{\Phi_{Critical}}{\Phi_{Continuous}}\right)$$

The Well's number can be used to interpret, across magnet designs, the likelihood of quench initiation after a specified operating duration. Below zero, a quench is potentially spontaneous.

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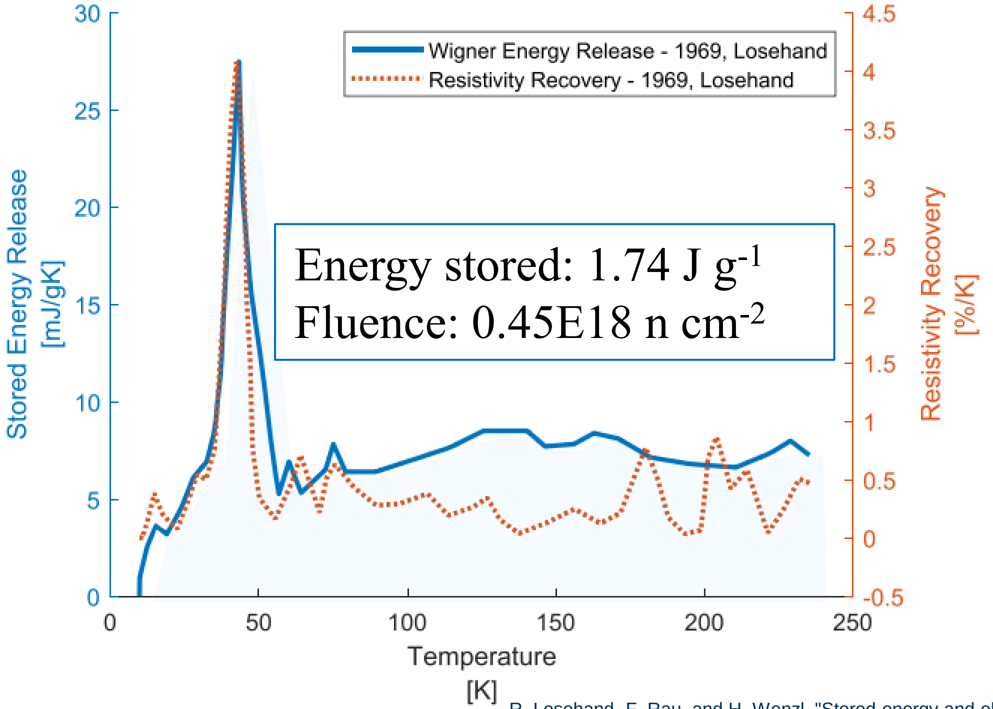
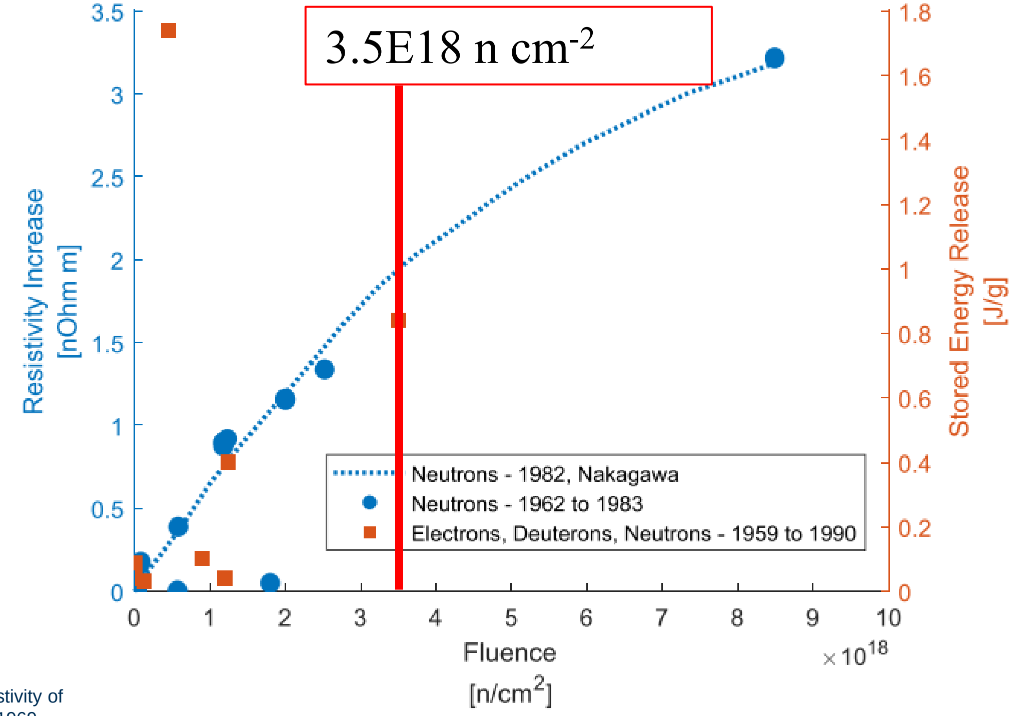
Engineering relevance

TABLE III: Wigner energy release of Cu due to cryogenic irradiation from different spectra.

Temperature K	Particle	Fluence $10^{18}/cm^2$	E. Released J/g	E. Released per particle $[J/g]/[10^{18}/cm^2]$	Study Reference
17	X-10 Neutron	1.2	0.04	0.033	1959 Blewitt [7]
5	1.2MeV Electron	0.9	0.1	0.11	1959 Meechan [27]
15	11 MeV Deuteron	0.0029	0.04	13.79	1960 Granato [28]
15	11 MeV Deuteron	0.0083	0.09	10.84	1960 Granato [28]
5	FRM I (Munich Research Reactor) Neutron	0.45 (Section II)	1.74	3.87	1969 Losehand [9]
5	HFIR Neutron	0.13	0.03	0.23	1990 Richard [29]
5	HFIR Neutron	1.24	0.4	0.32	1990 Richard [29]
5	HFIR Neutron	3.5	0.84	0.24	1990 Richard [29]





R. Losehand, F. Rau, and H. Wenzl, "Stored energy and electrical resistivity of Frenkel defects in copper," *Radiation Effects*, vol. 2, no. 2, pp. 69–74, 1969, doi: 10.1080/00337576908235586.

Engineering relevance (ignoring HTS degradation)

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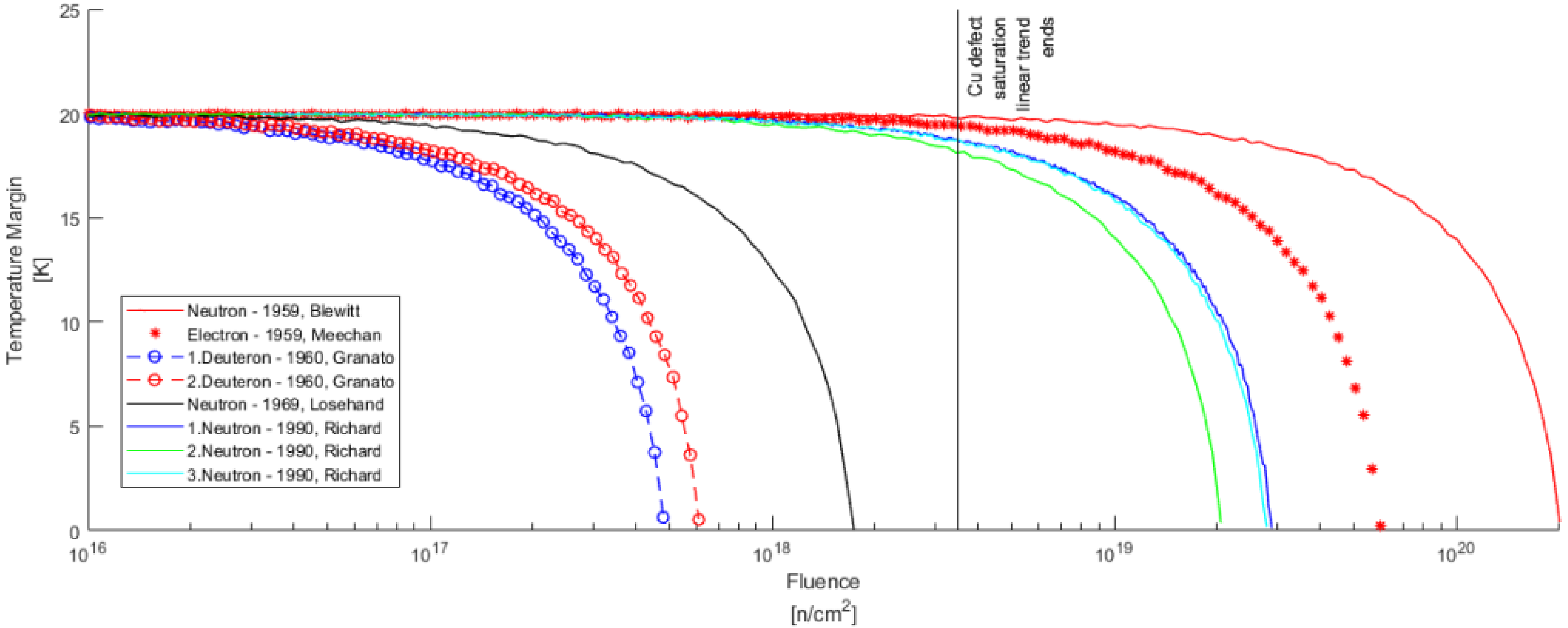

Fig. 9: Temperature margin reduction with fluence resulting from Wigner energy release in the magnet's stabilizer material. These predictions are produced using an equation derived from first principles, equation (7). This equation is a special case of equation (6) where the critical temperature is treated as constant. The difference between each line is due to the difference in how the stored energy release was predicted for each case. Linear extrapolations between zero fluence and the reported fluence from experiments referenced in Table III were used to predict stored energy release for each case. The linear extrapolation was assumed to be valid up to 3.5×10^{18} n/cm^2 given the linear trend of Cu resistivity change with fluence observed in Figure 5.

Engineering relevance (accounting for HTS degradation)

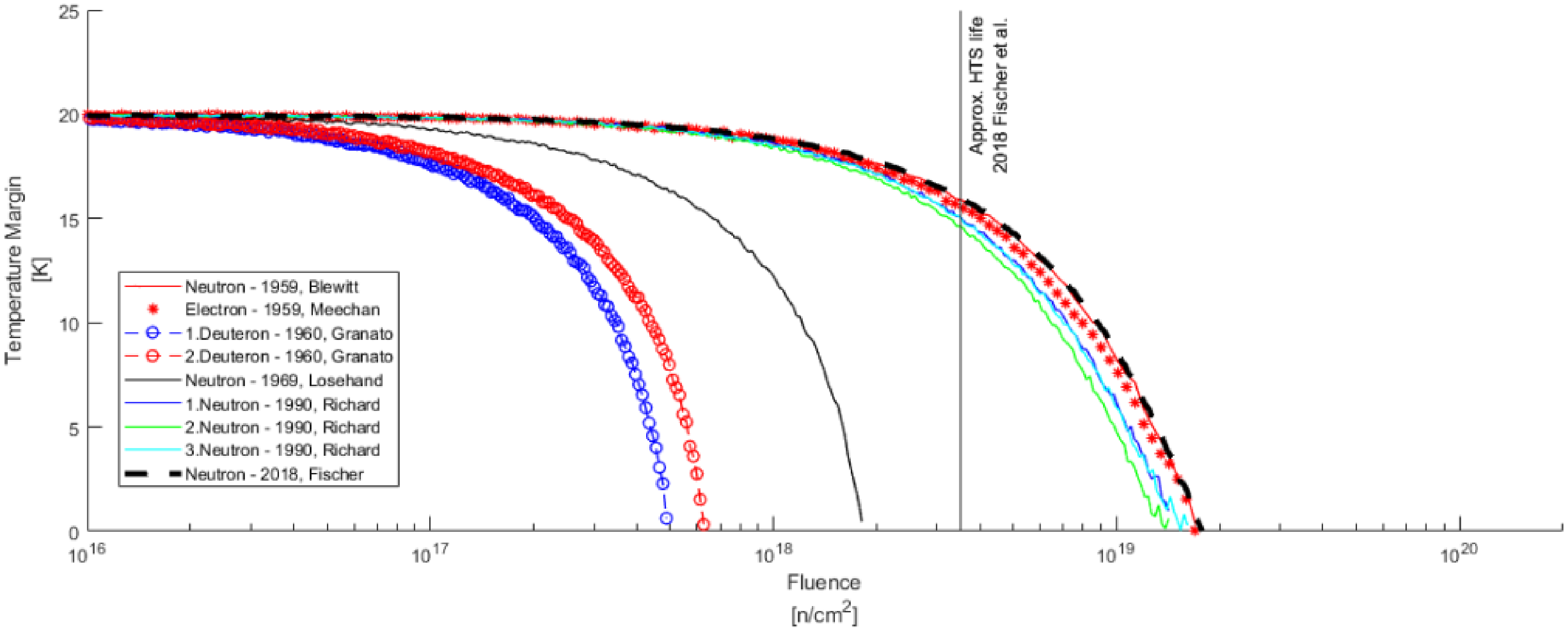

Fig. 10: Temperature margin reduction with fluence resulting from Wigner energy release and HTS degradation. These predictions are produced using an equation derived from first principles, equation (6). This is the same calculation presented in Figure 9 but with the consideration of a reducing upper limit on the integrals with fluence, $T_{critical}(t)$, in equation (6) to account for HTS degradation. Fluence is assumed to be linearly proportional to time for steady-state operation and the $T_{critical}(t)$ term is assumed to reduce with fluence as described by Fischer et al. [3]. Values are only reported up to 3.5×10^{18} n/cm^2, so these predictions should only be considered valid up to 3.5×10^{18} n/cm^2. Comparison of Figure 9 and Figure 10 describes that energy storage in the magnet's stabilizer material is an important consideration in the continuous operation of the machine, and may even play a rate-determining factor role for continuous operating regimes.

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Thank you!!