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Engineering Quench Resilience *via* Topological Transitions: a Proposal

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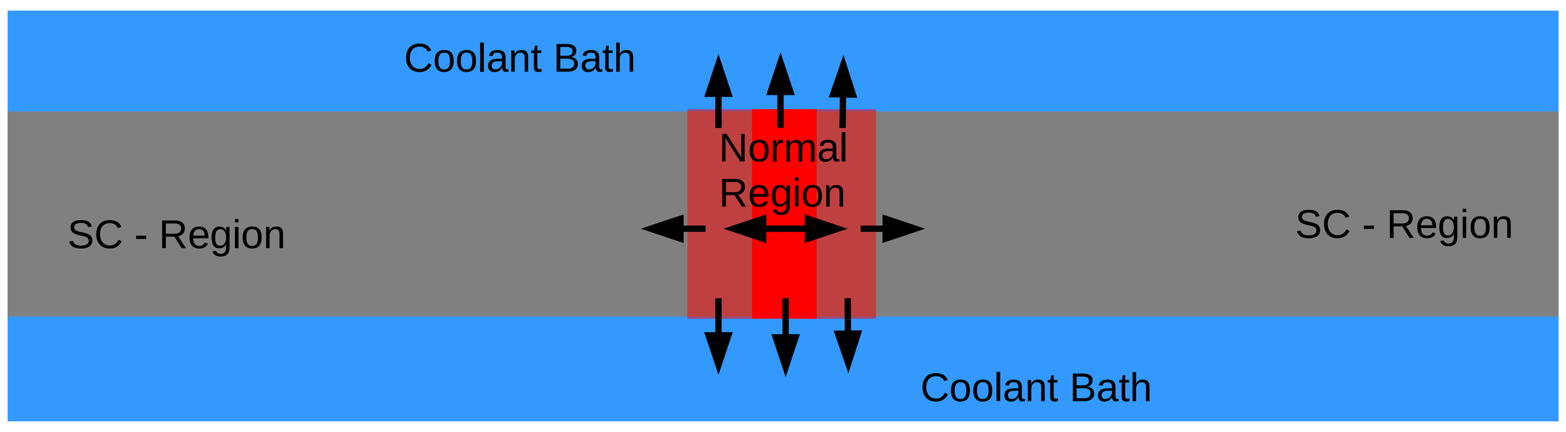
Basic Idea

A superconductor carrying a large current **quenches** when part of it enters the normal state, generating heat and a runaway instability that destroys the superconducting state. Quenches place severe limitations on the performance of superconducting cables in high-current applications. It is desirable to design materials which are intrinsically resilient to quenches.



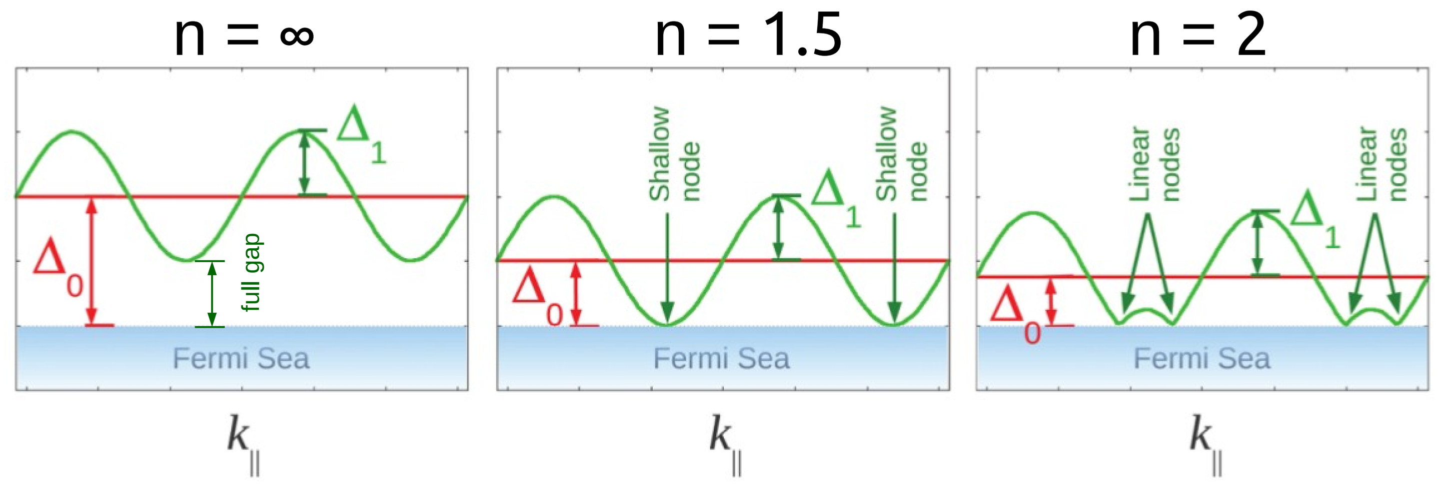
The **specific heat** of the superconductor sets the time scale for quench propagation. If the specific heat increases fast enough as a function of temperature, *T*, the runaway instability can be prevented.

This makes **nodal superconductors**, with their gapless quasiparticle excitations, attractive as their specific heat has a power-law dependence on temperature,

$$C \sim T^n \qquad (1)$$

The **exponent** n=3 when there is a point node on the Fermi surface and n=2 when there are nodal lines.

Anomalously-low exponents can be obtained at **topological transitions** where nodal lines cross (n=1.8), form (n=1.5) or even form and cross simultaneously (n=1.4). This is due to the non-linear quasi-particle dispersions at the transition points [1,2]:



The **fundamental question** we wish to address is:

Can we engineer intrinsic quench resilience in a material by chemically tuning it to a topological transition state?

Candidate **materials** include:

- the **noncentrosymmetric** series $\mathbf{Li_2Pd_xPt_{3-x}B}$ where topological transitions are expected as the extent of singlet-triplet mixing changes with doping *x* [1];
- the **pnictide** series $\mathbf{Ba(Fe_{1-x}}\boldsymbol{T}_{\mathbf{x}}\mathbf{)_2As_2}$ **(*T*=Co, Ni, Pd)** where as a function of *x* we can have linear nodes or a full gap with an intermediate "nascent node" state [2,3,4].

Model and method

We use a simple heat-diffusion equation [5] with uniform heat bath but generalised to include a temperature-dependent specific heat:

$$C_c\left(T(x,t),T_c\right)\frac{\partial T(x,t)}{\partial t} = \frac{\partial^2 T(x,t)}{\partial x^2} - \left(T(x,t)-T_h(x,t)\right) + \Theta\left(T(x,t)-T_c(x,t)\right)$$

$$\frac{\partial T_h(x,t)}{\partial t} = \beta\left(T(x,t)-T_h(x,t)\right)$$

Superconductor specific heat → $C_c(T(x,t),T_c)$; Superconductor heating rate → $\partial T(x,t)/\partial t$; Bath heating rate → $\partial T_h(x,t)/\partial t$.

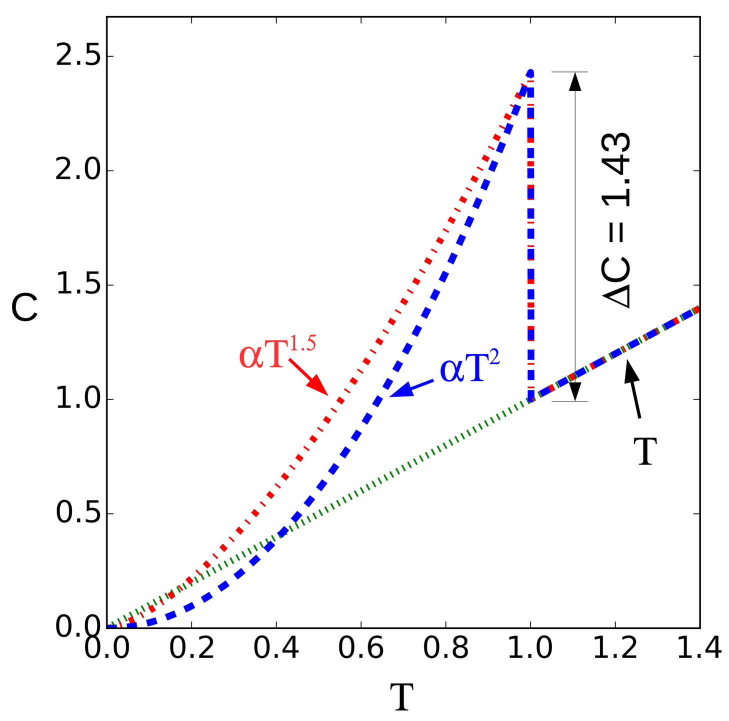
Heat diffusion within the superconductor ← $\partial^2 T(x,t)/\partial x^2$; Heat exchange with the bath ← $-(T(x,t)-T_h(x,t))$; Joule heating ← $+\Theta(T(x,t)-T_c(x,t))$; Heat exchange with the superconductor ← $\beta(T(x,t)-T_h(x,t))$.

scan QR code for animations

For the specific heat we assume a fixed BCS jump at Tc followed by power-law with varying exponent n:

$$C_c(T(x,t),T_c) = \alpha T(x,t)^n \Theta\left(T_c - T(x,t)\right) + T(x,t)\Theta\left(T(x,t)-T_c\right)$$

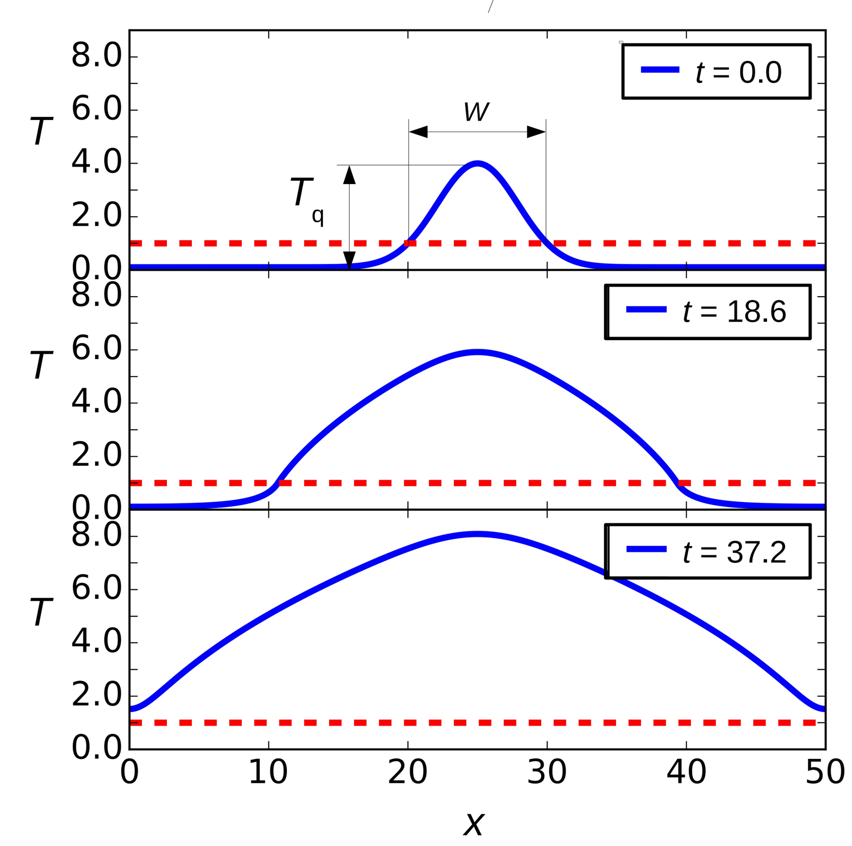
Power law for $T < T_c$ (first term); Fermi-liquid for $T > T_c$ (second term).



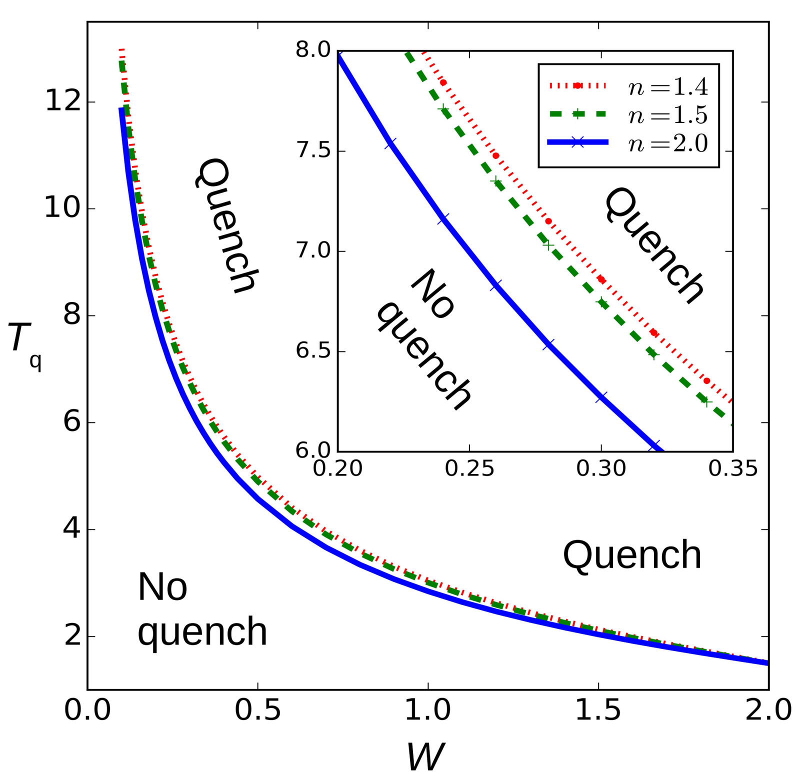
The model was solved numerically using a `Forward Time-Centred Space' scheme [6] and zero gradient boundary conditions.

The initial condition was a wire in thermal equilibrium with a coolant bath, except for a **Gaussian heat pulse** of width *W* and height T_q.

The pulse either broadened indefinitely (quench) or collapsed (no quench).



Results and conclusions



Our study confirms our proposal is **viable in principle**:

Lower specific heat exponents do lead to a broader range of heat pulse widths and heights where no quench occurs.

However, in our simple model the effect is relatively small.

Detailed studies taking into account specific material parameters [e.g. for $Li_2Pd_xPt_{3-x}B$ or $Ba(Fe_{1-x}T_x)_2As_2$ (*T*=Co, Ni, Pd)] and/or **experimental tests** will be needed to ascertain whether our proposal is viable in practice.

References

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[6] W. H. Press, "Numerical recipes 3rd edition: The art of scientific computing" (CUP, 2007).