Higher Temperature Superconductors from the Perspective of Applications

Things we all know but need to think about

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Outline:

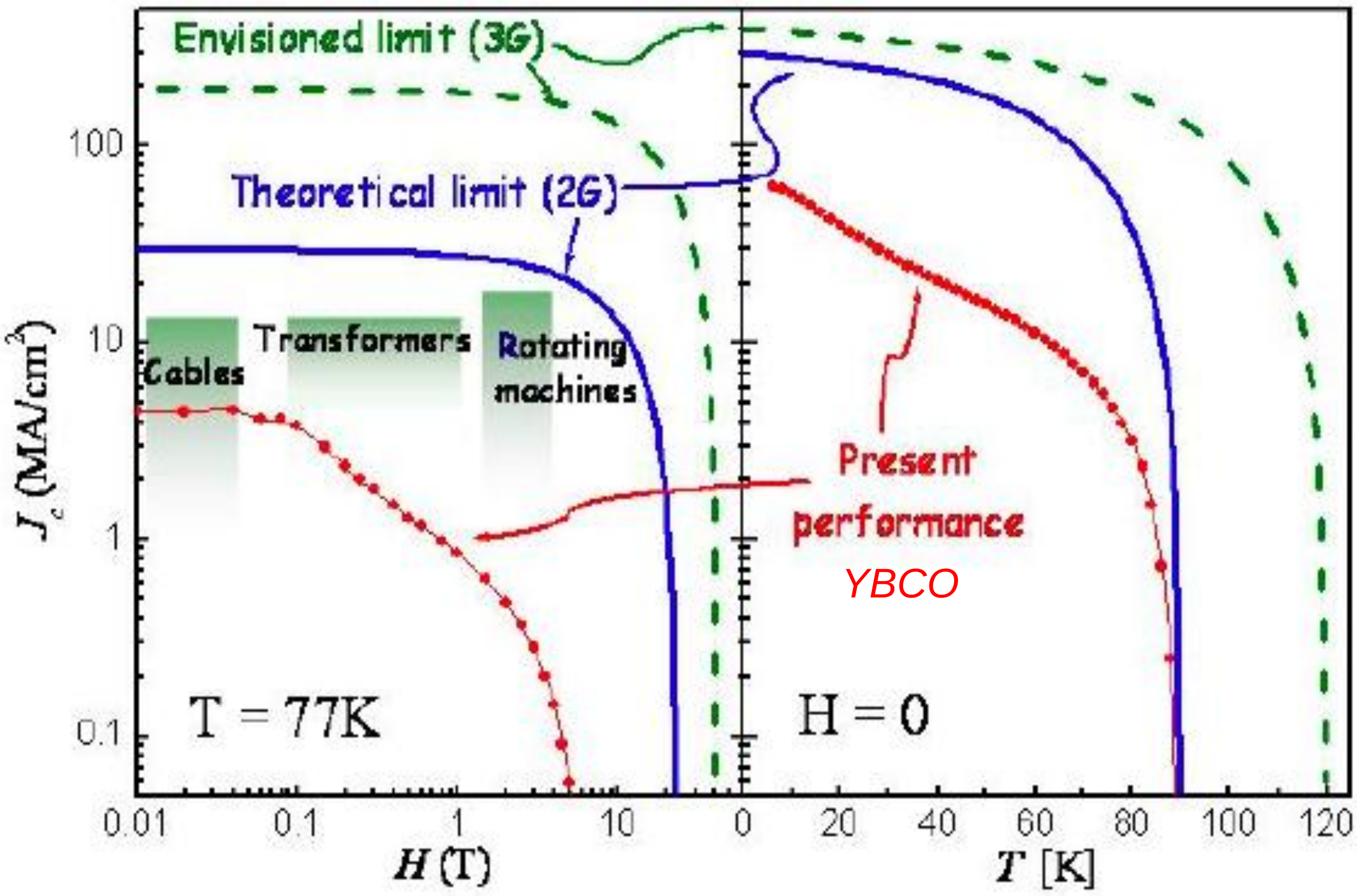
- *Limitations of present HTS*
- *Sources of these limitations*
- *Key material characteristics any new HTS will require in order to be useful*

Practical Rationale for Seeking Higher T_c Superconductors

- *To meet all the desired applications of superconductivity at 77K or higher may require a new superconducting material*

- *The classes of newly discovered superconductors is burgeoning*
  - *Some with high transition temperatures.*
  - *We have no real understanding of the limits of existence of superconductivity.*

Limitations of YBCO for Electrical Applications



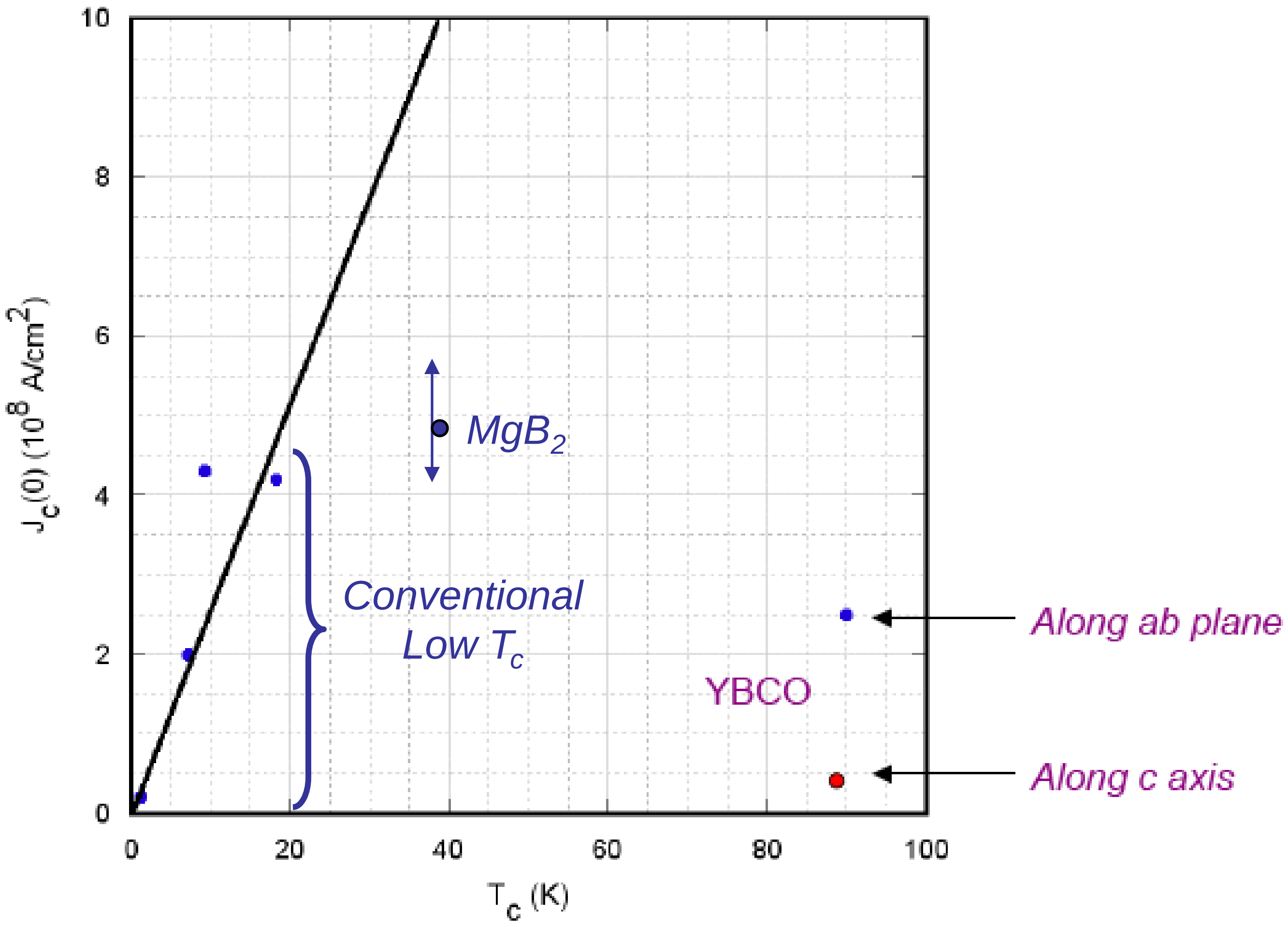
From DoE report

Classes of Superconductors Based on T_{co}

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

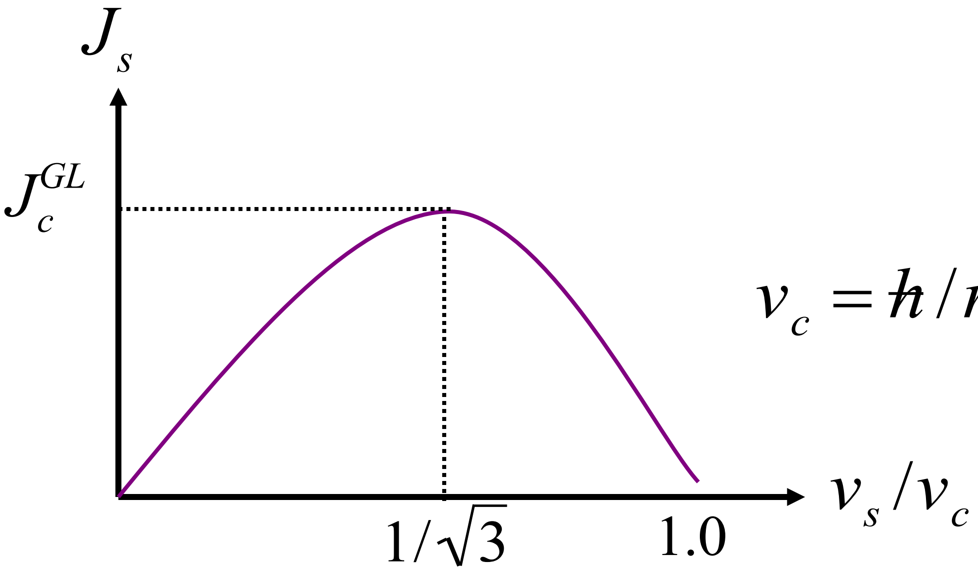
From DoE Report

□Depairing Critical Current Density vs T_{co}



GL Depairing Critical Current Density

(Kinetic energy density limit)



$$J_s = n_s^* e^* v_s$$

$$v_c = \hbar / m^* \xi$$

$$J_c^{GL} = (2/3\sqrt{3}) n_s^* e^{*2} \hbar / m^* \xi = (2/3\sqrt{3})(c^2/4\pi)\frac{1}{\lambda^2 \xi}$$

$$\lambda^2 = m^* c^2 / 4\pi n_s^* e^{*2}$$

Theoretical Dependence on T_{co}

*Relations from BCS**

$$\xi = hv_F / kT_{c0} \propto \frac{v_F}{T_{c0}}$$

$$\frac{c^2}{8\lambda^2} = \underbrace{\frac{\pi}{2}\,\frac{n_s^* e^{*2}}{m^*}}_{\textit{weight of } \delta(0) \textit{ in } \sigma_{s1}(\omega)} \approx \int_0^\Delta \sigma_{n1}(\omega)\,d\omega \le \int_0^\infty \sigma_{n1}(\omega)\,d\omega = \underbrace{\frac{\pi}{2}\,\frac{ne^2}{m}}_{\substack{\textit{normal state property} \\ \textit{- independent of } T_{co}}}$$

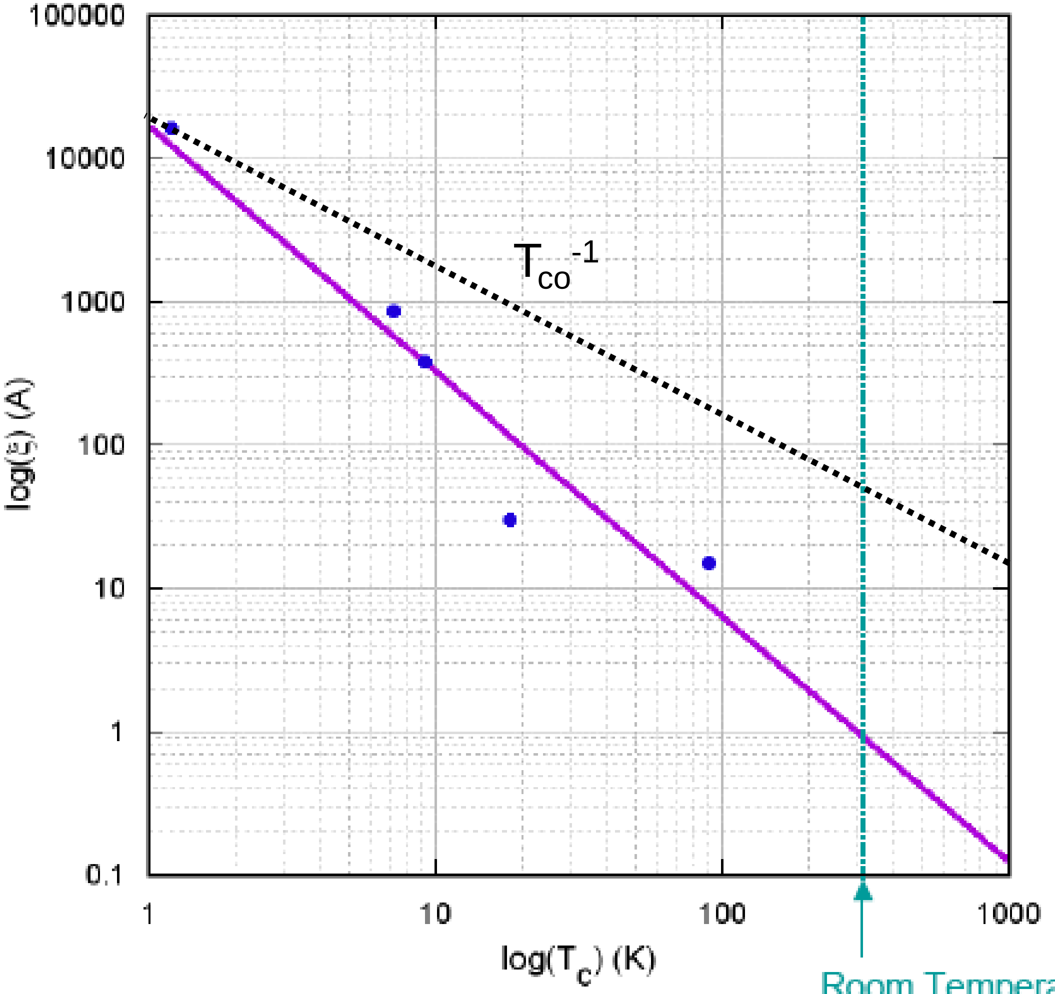
$$\Longrightarrow \begin{cases} J_c^{GL} \propto \dfrac{nT_{c0}}{v_F} \\[2ex] \dfrac{H_c^2}{8\pi} = \dfrac{1}{8\pi}\left[\dfrac{\Phi_o}{2\sqrt{2}\pi\lambda\xi}\right]^2 \propto \dfrac{nT_{co}^2}{v_F^2} \end{cases}$$

* *Note we use clean limit because dirty limit is worse -- $n_s^* < n/2$*

Superfluid Density vs T_{co}

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Size of Cooper Pair ξ *vs* T_{co}



Inter-electron separation

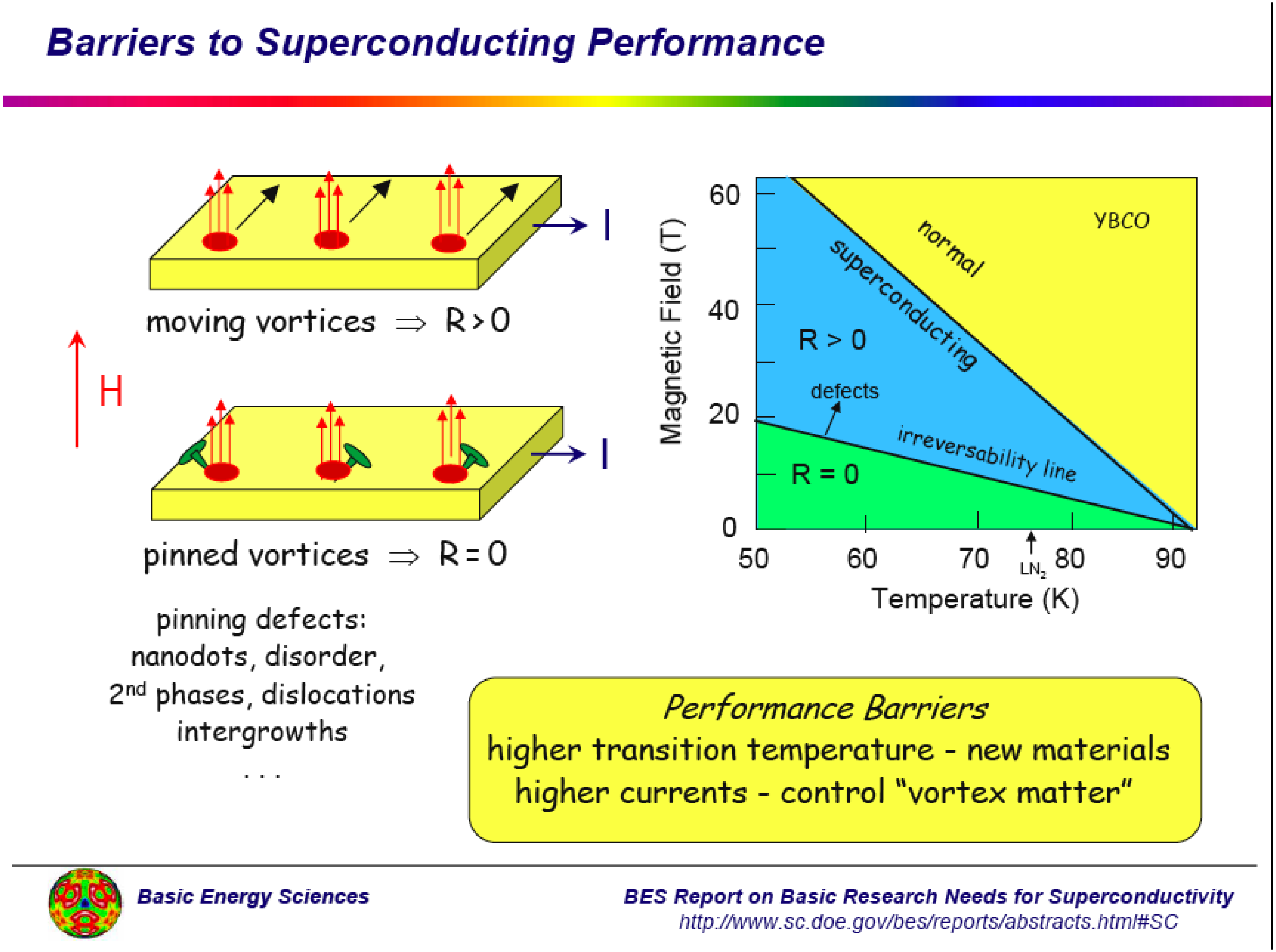
10^{21} el/cm^3

10^{22}

10^{23}

Room Temperature Superconductor

Vortex Pinning, Vortex Phases and Vortex Motion



Barriers to Superconducting Performance

pinning defects:
nanodots, disorder,
2nd phases, dislocations
intergrowths
. . .

Performance Barriers
higher transition temperature - new materials
higher currents - control "vortex matter"

Basic Energy Sciences

BES Report on Basic Research Needs for Superconductivity
http://www.sc.doe.gov/bes/reports/abstracts.html#SC

Thermal Fluctuations in Vortex Phases

Ginzburg Number*:

- *Relative measure of the thermal energy and the condensation energy in a coherence volume*
- *The smaller, the better*

$$Gi = \frac{1}{2}\left[\frac{kT_{co}}{H_c{}^2 \varepsilon \xi^3}\right]^2 \qquad \varepsilon^2 = inverse\ GL\ mass\ ratio\ \gamma^{-2} = m/M \le 1$$

$$\propto \left[\frac{T_{co}{}^2}{\varepsilon n v_F}\right]^2$$

$$\mathrm{Gi}(YBCO) \approx 0.01$$

$$\mathrm{Gi}(BSCCO) \approx 1.0$$

**From Blatter et al., RMP*

Notional Third-Generation (3G) Conductor Relataive to YBCO (v_F constant)

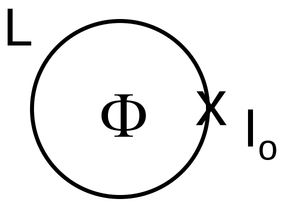
Cumulative Affect →

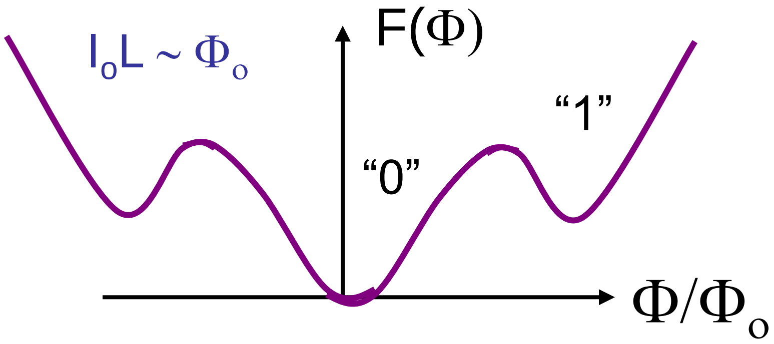
T_{co}	Performance Parameters	Affect of T_{co} alone	ε−>1 (1/5->1)	n X 2	n X 10
90 K	Jc/ Jc(YBCO)	1	1	2	10
	Gi/Gi(YBCO)	1	1/25	1/100	1/2500
180 K	Jc/ Jc(YBCO)	2	2	4	20
	Gi/Gi(YBCO)	16	16/25	16/100	16/2500
270 K	Jc/Jc(YBCO)	3	3	6	30
	Gi/Gi(YBCO)	81	81/25	81/100	81/2500

$$J_c^{GL} \propto \frac{nT_{c0}}{v_F}$$

$$Gi \propto \left[\frac{T_{co}^{2}}{\varepsilon n v_F}\right]^2$$

Limitations for Josephson Junction Memory Circuits





- *Basic design constraints:*

$$I_o L \approx \Phi_o$$

(Desired double well; can trade off I_o and L)

$$E_J \approx \Phi_o^2 / L > \eta k_B T,\ \ \eta >> 1 \Rightarrow L < \Phi_o^2 / \eta k_B T$$

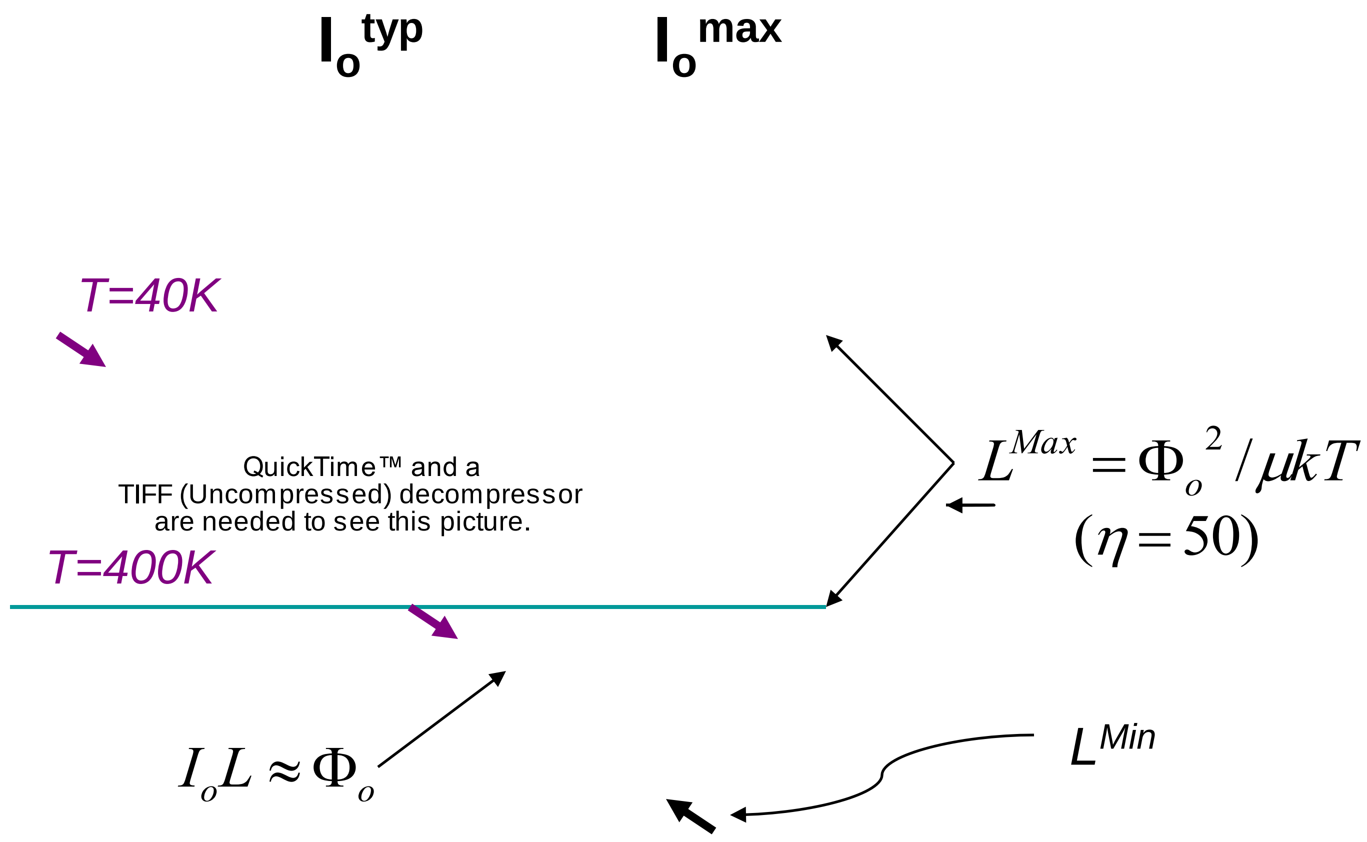
(Stable against thermal disruption)

$$I_o < I_o^{\max} = J_o \lambda_J^2 = c\Phi_o / 8\pi(2\lambda + d) \Rightarrow L > \Phi_o / I_o^{\max}$$

(No self-shielding in junction)

L constrained from above and below

Tightning of Design Window



I_o^{typ} I_o^{max}

T=40K

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T=400K

$$L^{Max} = \Phi_o^{\,2} / \mu k T$$

$$(\eta = 50)$$

$$I_o L \approx \Phi_o$$

L^{Min}

Josephson Junction Memory Circuit - 2

⇨ $$\Phi_o / I_o^{\max} < L < \Phi_o^{\;2} / \eta k_B T$$

$$I_o^{\max} = c\Phi_o / 8\pi(2\lambda + d) \approx 1\, ma$$

$$I_o^{\max} \propto \sqrt{n}$$

⇨ Design window closes at a temperature

$$T_{\max} = \frac{I_o^{\max}\Phi_o}{\eta k} \approx 3000K \;\; for \;\; \eta = 50$$

but

$$T_{\max} = 300K \;\; for\ the\ more\ typical \;\; I_o = 0.1ma$$

Guidelines for Practical Higher T_c Superconductors

- *High Tc (immediate target is operation at 77K, 3G conductor)*
- *Low anisotropy*
- *High electron density*
- *Take care with large unit cell volumes*
- *Take care with Josephson-coupled nano/meso-units*

Correlative questions:

- *Does highT_c require low n and/or dimensionality < 3?*
- *What is practical superconductivity like in the local pairing (Bose-□Einstein?) limit?*
- *How good can a bad superconductor be?*
- *How good is good enough?*