Superconductor-Correlated metal-Superconductor Josephson junctions for high-speed digital electronics

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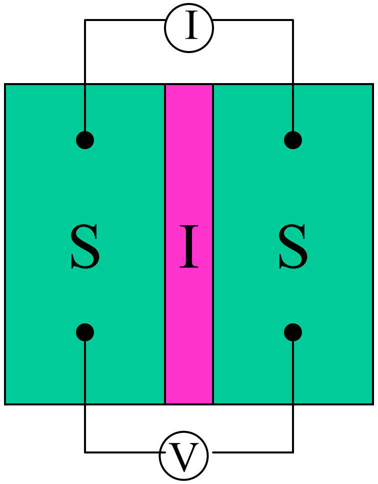
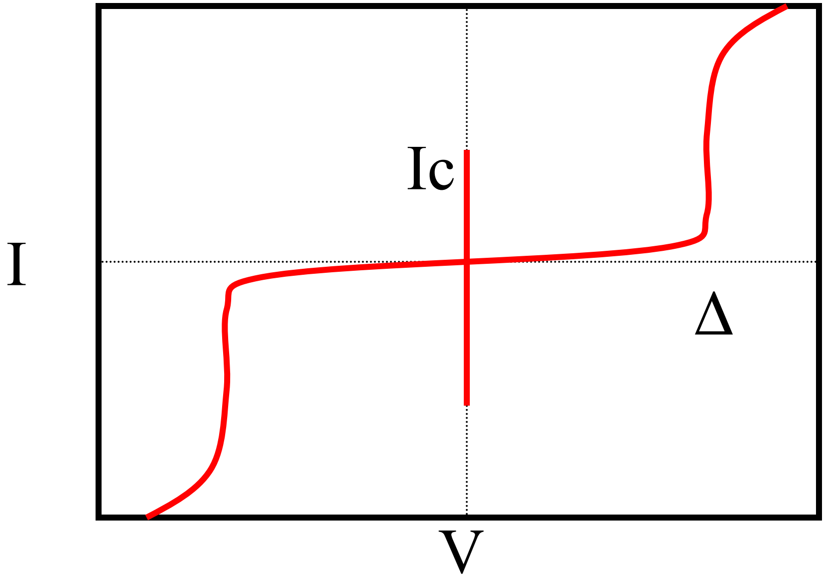
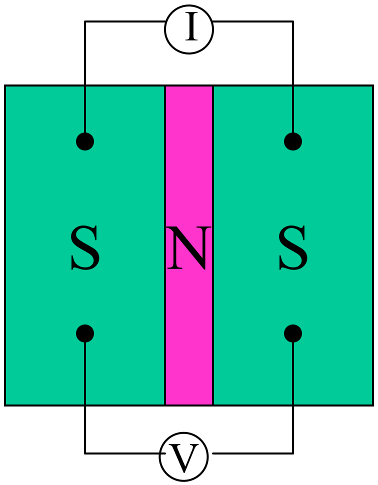
Josephson Tunnel Junctions

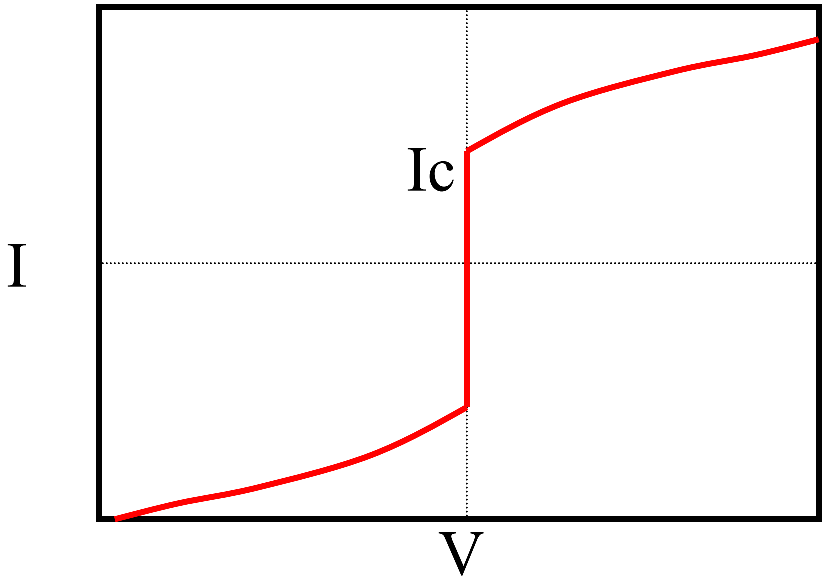




- A Superconductor-Insulator-Superconductor sandwich can tunnel **coherent Cooper pairs** (Josephson current) or can tunnel **broken pairs** (quasiparticles) through the barrier.
- If the phases of the superconducting wavefunctions differ, then there is a **DC Josephson current** $I = I_c \sin \theta$.
- The I-V characteristic is **highly nonlinear** at low voltages, leading to the possibility of important electronics applications (based on latching technologies which are slow and subject to “punch-through”, because of the hysteretic IV curves).

Josephson Proximity-Effect Junctions



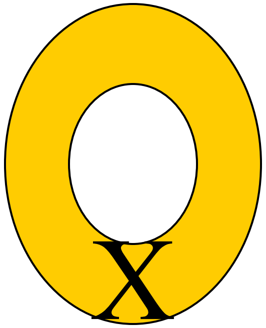


- A Superconductor-Normal metal-Superconductor sandwich where the weak link between superconductors occurs through the **proximity effect**.
- Andreev reflection at the N-S boundaries leads to **sub-gap bound states** that carry the pair current.
- Single-valuedness of the IV characteristic allows for non-latching technologies like **RSFQ logic**.
- Goal is to optimize the switching speed of these junctions by **maximizing IcRn**, while maintaining **nonhysteretic** behavior.

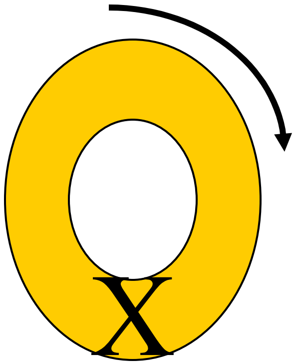
J. K. Freericks, Georgetown University, Josephson Junction talk, 2002

Digital Electronics and RSFQ logic

- **Rapid single-flux quantum logic** is used for high-speed applications. A loop of superconducting material has one JJ interrupting it. The absence or presence of a flux quantum in the loop is the binary 0 and 1 of the device.
- The flux is changed by generating a **voltage pulse** through the junction, whose time integral is equal to a flux quantum. Since the voltage scale is set by the product IcRn, which is on the order of a few mV in low-Tc superconductors, **operating speeds of up to 770 GHz** have been already demonstrated.
- New superconducting materials like **MgB_2** and novel barriers like **TaN_X** show a promise for even higher characteristic voltages, and hence faster operating speeds of circuits.

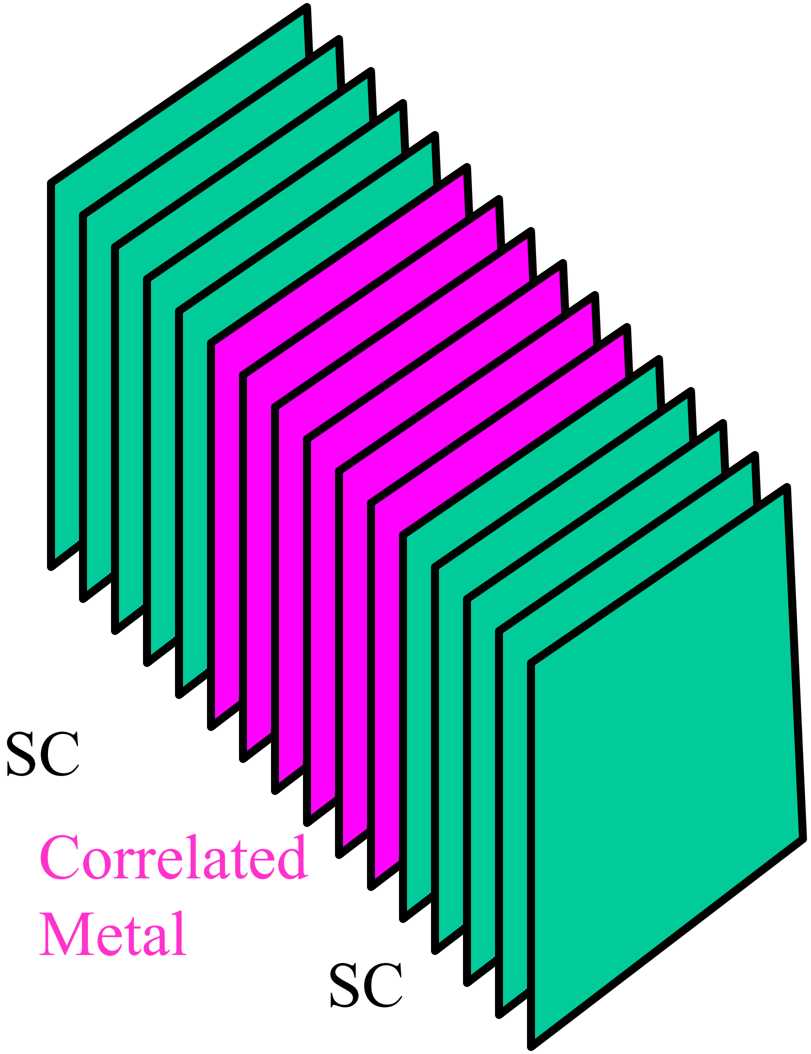


Binary 0, no flux



Binary 1, one flux quantum

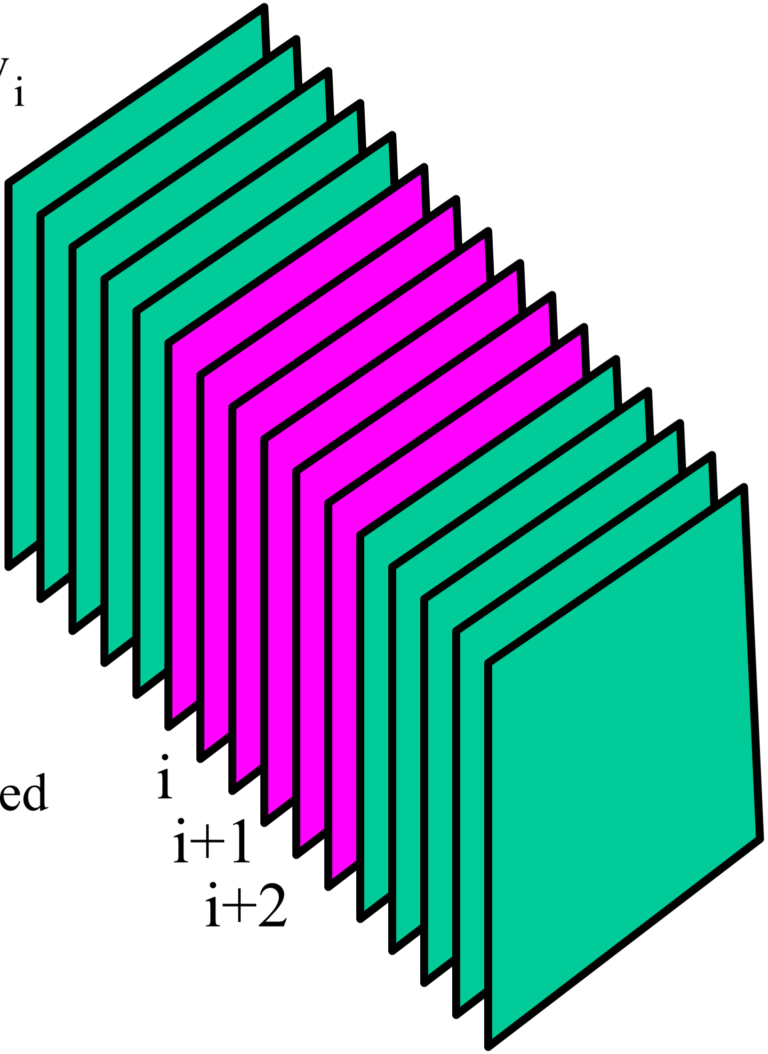
Optimization of the speed of a JJ



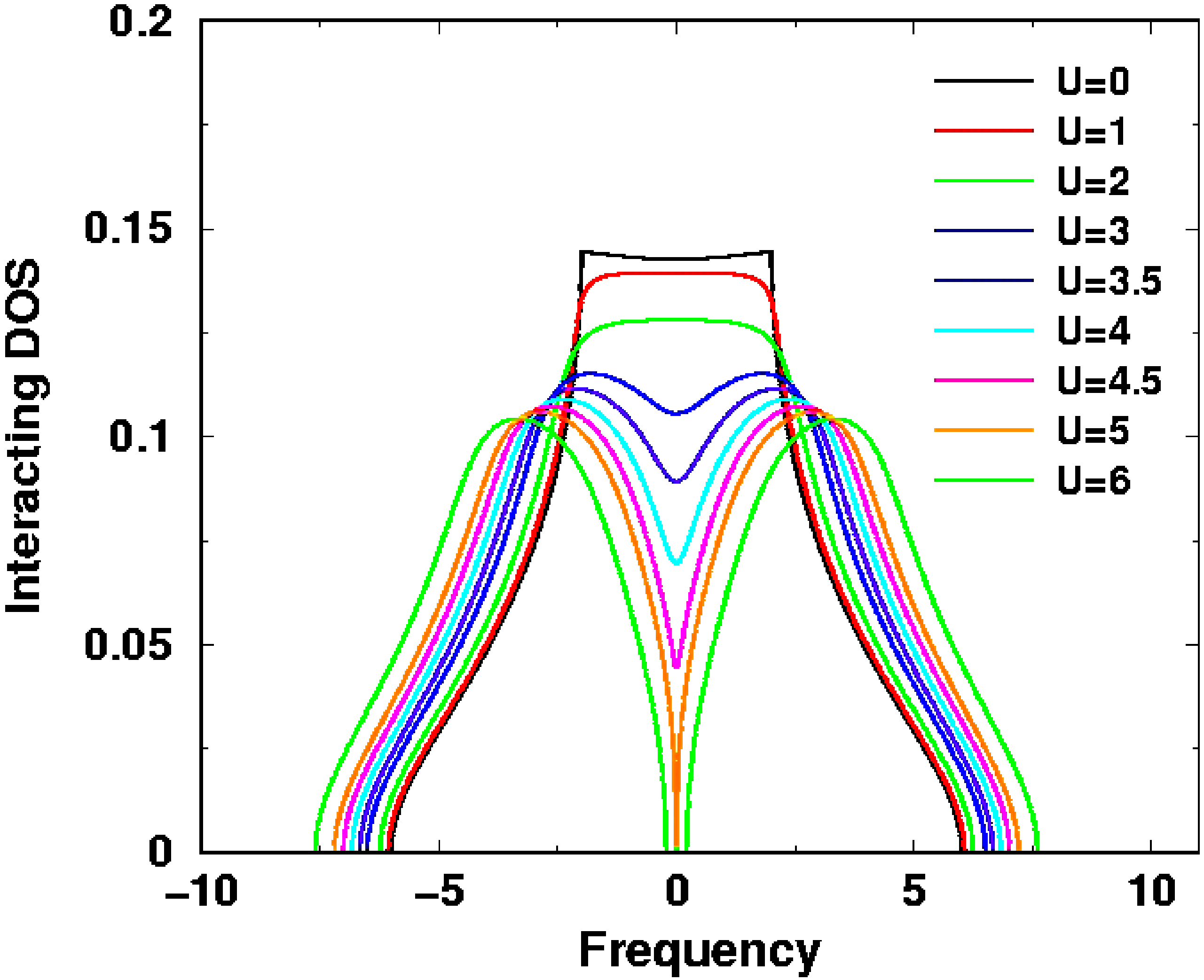
- Three elements are needed for high speed digital electronics based on JJs: (i) a **large figure-of-merit** IcRn; (ii) **good thermal stability** of the characteristic voltage within the operating temperature range; and (iii) **nonhysteretic** current-voltage characteristics.
- Can the next generation of JJ technology be built out of a new class of **SCmS junctions** where the correlated metal barrier has its thickness and metallicity tuned to lie **close to the metal-insulator transition**?

Many-Body Formalism

- **Inhomogeneous system**, with planes stacked along the z-direction.
- $H = -\Sigma\, t_{ij}\, c^{*}_{i\sigma} c_{j\sigma} + \Sigma\, U_i n_{i\uparrow} n_{i\downarrow} + \Sigma\, U_i^{FK} (n_{i\uparrow} + n_{i\downarrow})\, w_i$
- Local dynamical correlations are explicitly included for each plane via the **dynamical mean field theory**. The self-consistency relation is now modified to include effects that couple the effective medium between the planes.
- The superconductor is described by the H-F approximation, which is identical to a ***self-consistent solution*** of the Bogoliubov-deGennes equations for a short-coherence length, s-wave superconductor. The correlated metal is described by an exact form of the **coherent-potential approximation** which displays a metal-insulator transition.



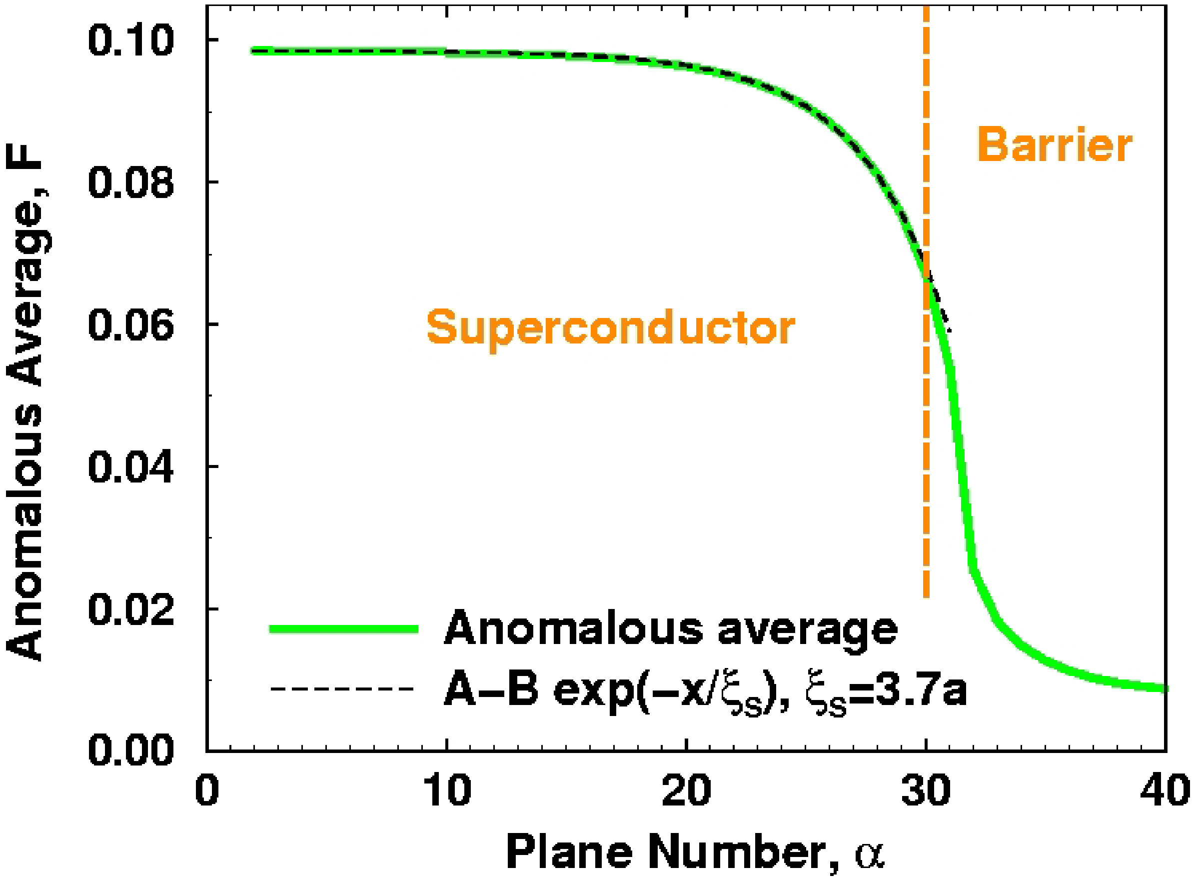
Metal-insulator transition



The Falicov-Kimball model has a **metal-insulator transition** that occurs as the correlation energy U is increased. The interacting DOS shows that a **pseudogap** phase first develops followed by the opening of a **true gap** above U=4.9 (in the bulk). Note: the FK model is **not a Fermi liquid** in its metallic state since the lifetime of excitations is always finite.

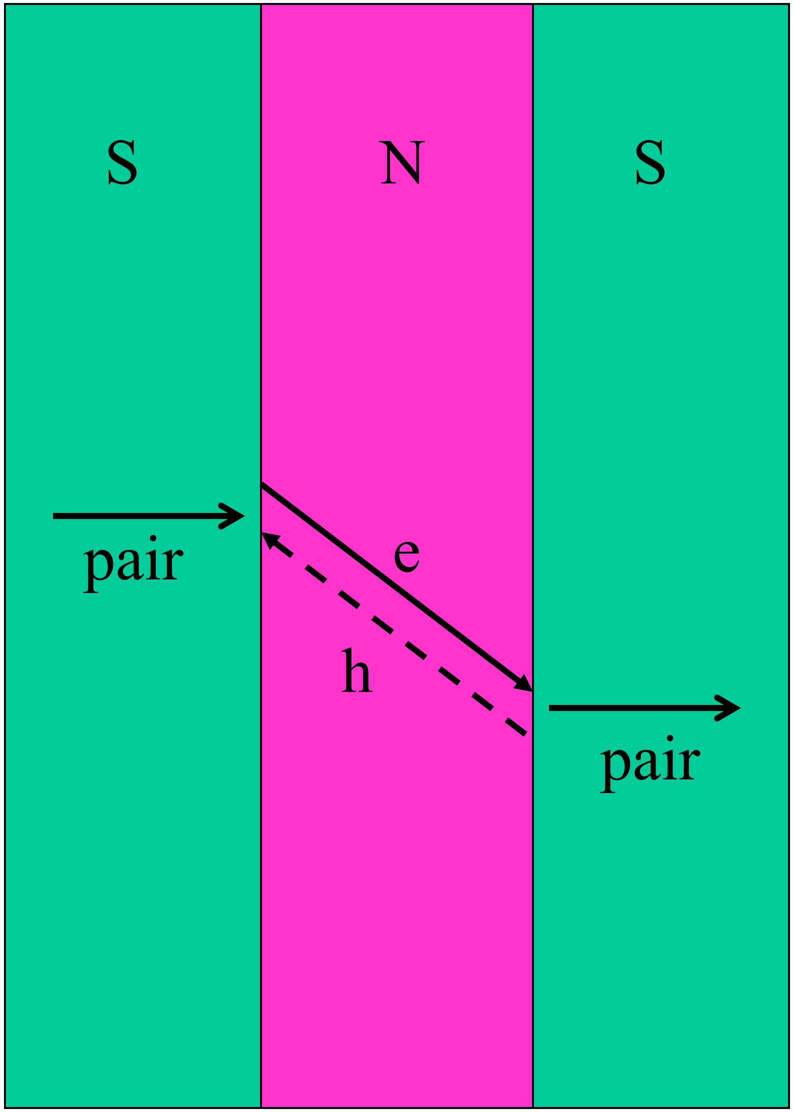
Bulk superconducting properties

- T_c=0.112t, Δ=0.198t, $2\Delta/k_BT_c$=3.56--- **behaves like a BCS superconductor**
- Bulk coherence length ξ_S=3.7a= $v_F{}^S/\pi\,\Delta$ ---**short coherence length superconductor**



Andreev Bound States

- At an N-S interface an incoming electron from the normal metal can be **reflected** into a superconducting pair and a hole (especially at low energies).
- Reflection off both N-S boundaries leads to a **bound state** in the weak-link region.
- Since Andreev reflection is strongest for voltages less than the superconducting gap, **most bound states are sub-gap states localized within the barrier**.
- It is the left and right-moving "pieces" of these bound states that **carry the Josephson current** when there is a phase difference across the junction.



Thouless energy

- The **Thouless energy** measures the quantum energy associated with the time that an electron spends inside the barrier region of width L.

$$E_{Th} = \hbar / t_{Dwell}$$

- A **unifying form** for the Thouless energy can be determined from the resistance of the barrier region and the electronic density of states:

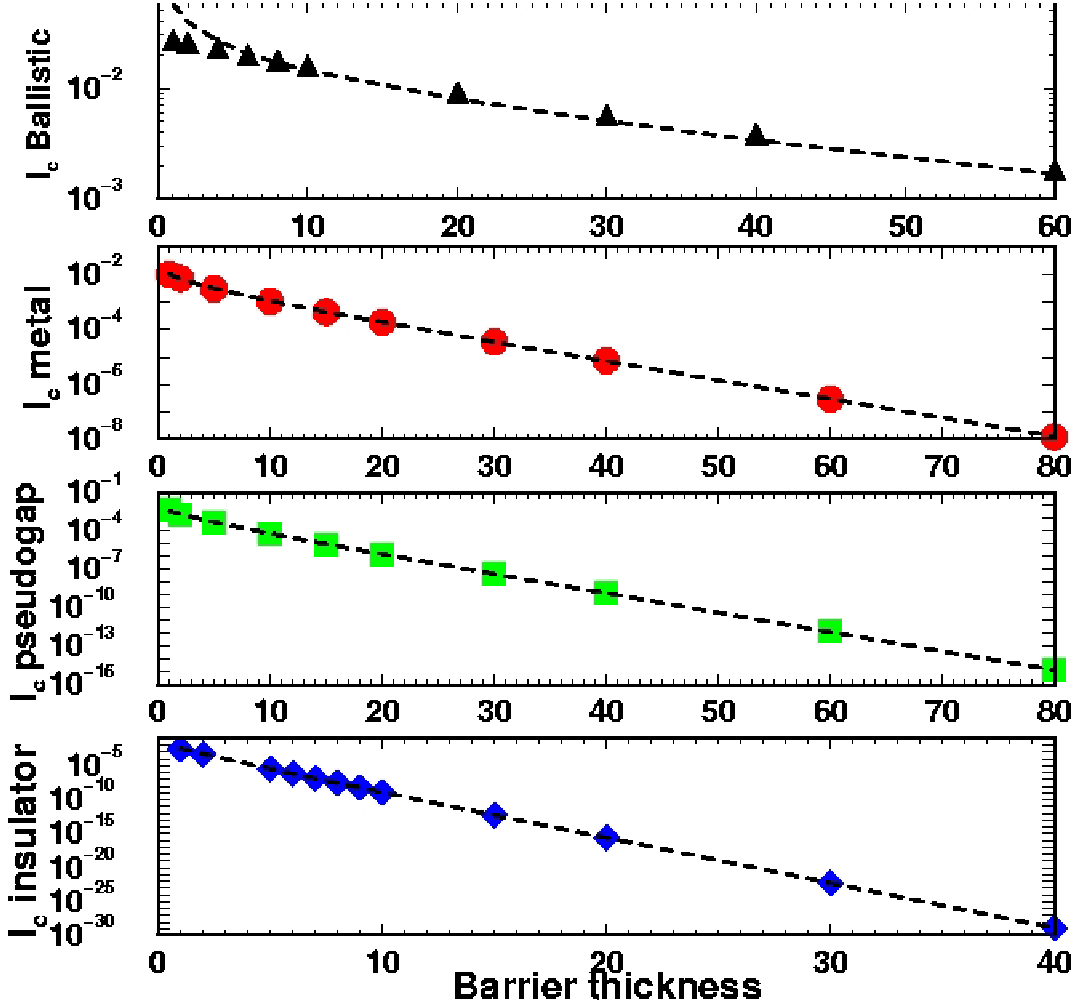
$$E_{Th} = \frac{\hbar}{2e^2 \int d\omega N(\omega) \frac{df(\omega)}{d\mu} R_N a^2 L}$$

- This form produces both the **ballistic** $E_{Th} = \hbar v_F^N / \pi L$ and the **diffusive** $E_{Th} = \hbar D / L^2$ forms of the Thouless energy.

Length scales

- The **Fermi wavelength** is determined by the inverse wavevector at the Fermi surface (here $\lambda_F \sim 2a$)
- The bulk **superconductor coherence length** is $\xi_S = \hbar v_F^S / \pi\Delta$ (here ~3.7a).
- The **Josephson junction coherence length** ξ_0 is found by determining the width L when the Thouless energy is equal to the superconducting gap ($E_{th} = \Delta$). This produces the well-known results of $\hbar v_F^N / \pi\Delta$ in the ballistic case and $\sqrt{\hbar D / \Delta}$ in the diffusive case (here $\xi_0 < 4a$).
- The **barrier coherence length** ξ_B is found by determining the width L when the Thouless energy is equal to the thermal energy ($E_{TH} = \pi k_B T$). This produces the well-known results of $\hbar v_F^N / \pi k_B T$ in the ballistic case and $\sqrt{\hbar D / 2\pi k_B T}$ in the diffusive case (here $\xi_B < 40$ a).

Critical current yields barrier coherence length (low T)



ξ_B=40
x=-0.4

ξ_B=6.75
x=-0.4

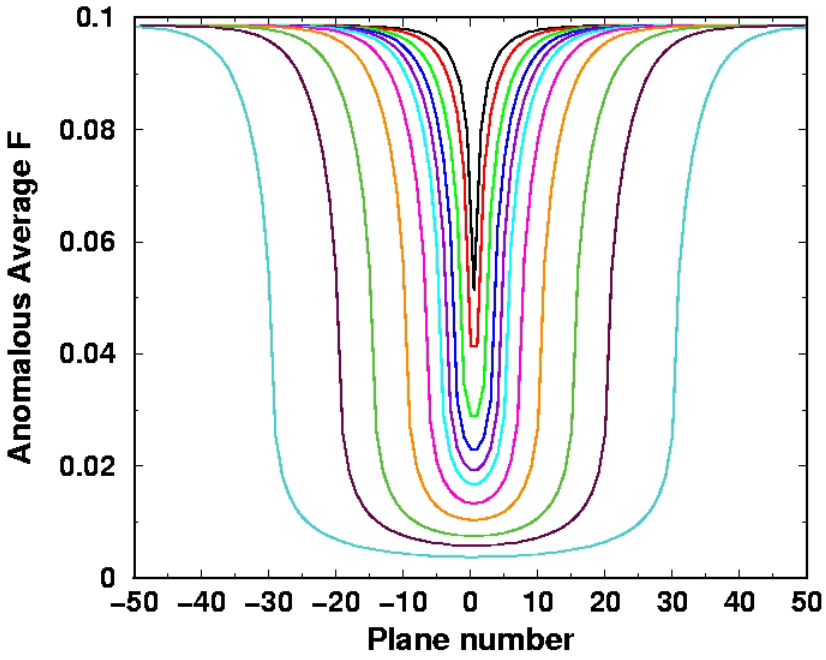
ξ_B=2.96
x=-0.45

ξ_B=0.67
x=-0.5

- Exponential fit of the critical current for: (i) **ballistic metal**; (ii) **weakly correlated metal**; (iii) **strongly correlated metal** (pseudogap); and (iv) **correlated insulator**.

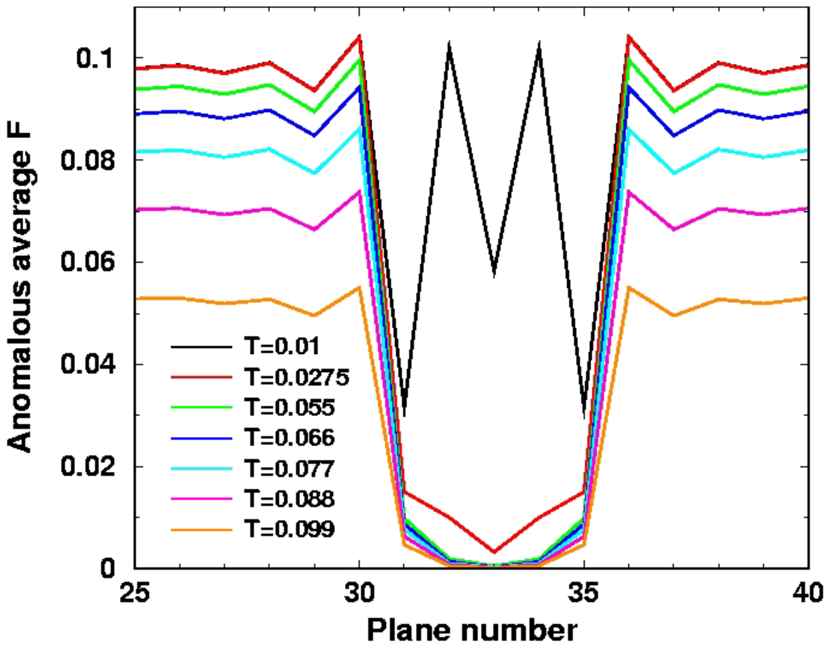
$$I_c = AL^x \exp[-L/\xi_B]$$

Lengths in the proximity effect



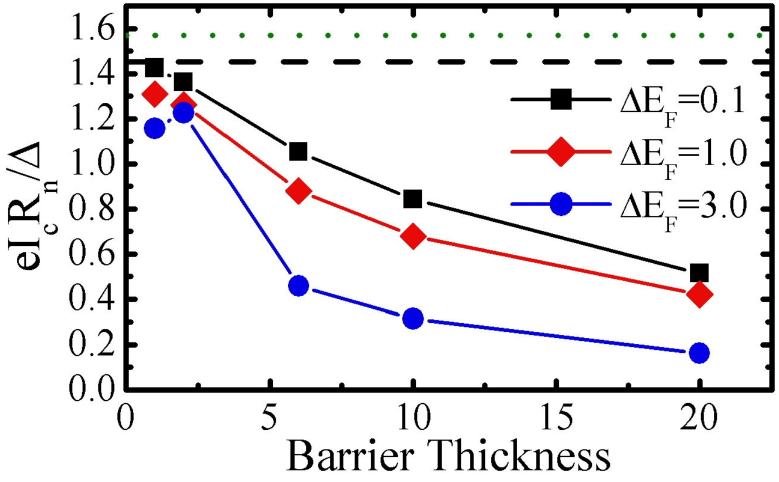
The **bulk coherence length** ξ_S determines the decay of F in the SC, the **JJ coherence length** ξ_0 determines the initial decay from the SN boundary, and the **barrier coherence length** ξ_B determines how F decays at the center of the barrier.

- At low T **oscillations develop in F** when the barrier becomes correlated. One can also see Fermi wavelength oscillations. The barrier oscillations rapidly disappear as T increases. The oscillations in the superconductor are only slightly reduced as Tc is approached.



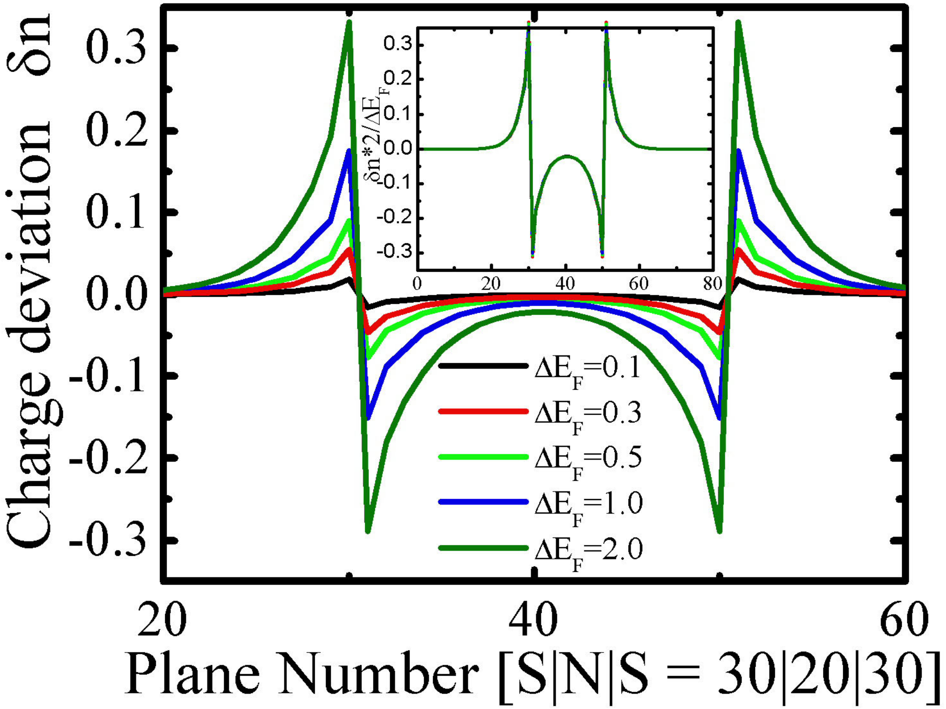
“Ballistic” SNS and SINIS junctions

- At low T, the JJ coherence length is **much smaller than** the barrier coherence length, hence one can enter a regime where $\xi_0 << L << \xi_B$. Here IcRn will be **independent of L** for a range of L, but because F has been reduced on the length scale of $\xi_{0,}$, **we expect IcRn to be diminished**.



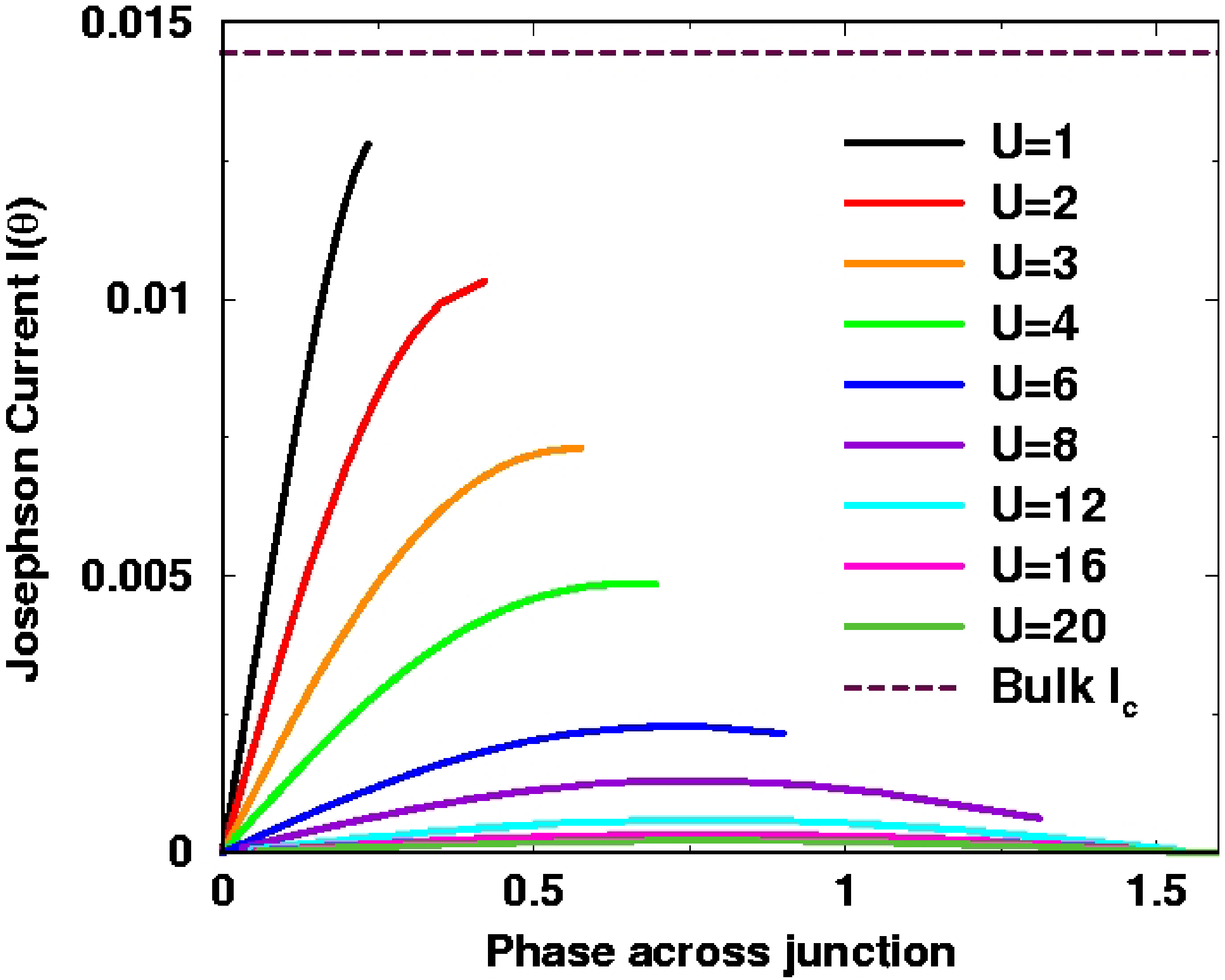
- **This phenomenon has been seen by Klapwijk’s group on NbInAsNb JJs!**

Scaling of Schottky barrier in SINIS



- Local charge for the 20-plane barrier as a function of the work-function mismatch. Rescaling the data against the maximum charge deviation produces a **data collapse**!
- The **shape** of the Schottky barrier is **independent of the size** of the mismatch near half filling. This is because the cubic DOS is relatively **flat** near half filling and does not hold in the general case.

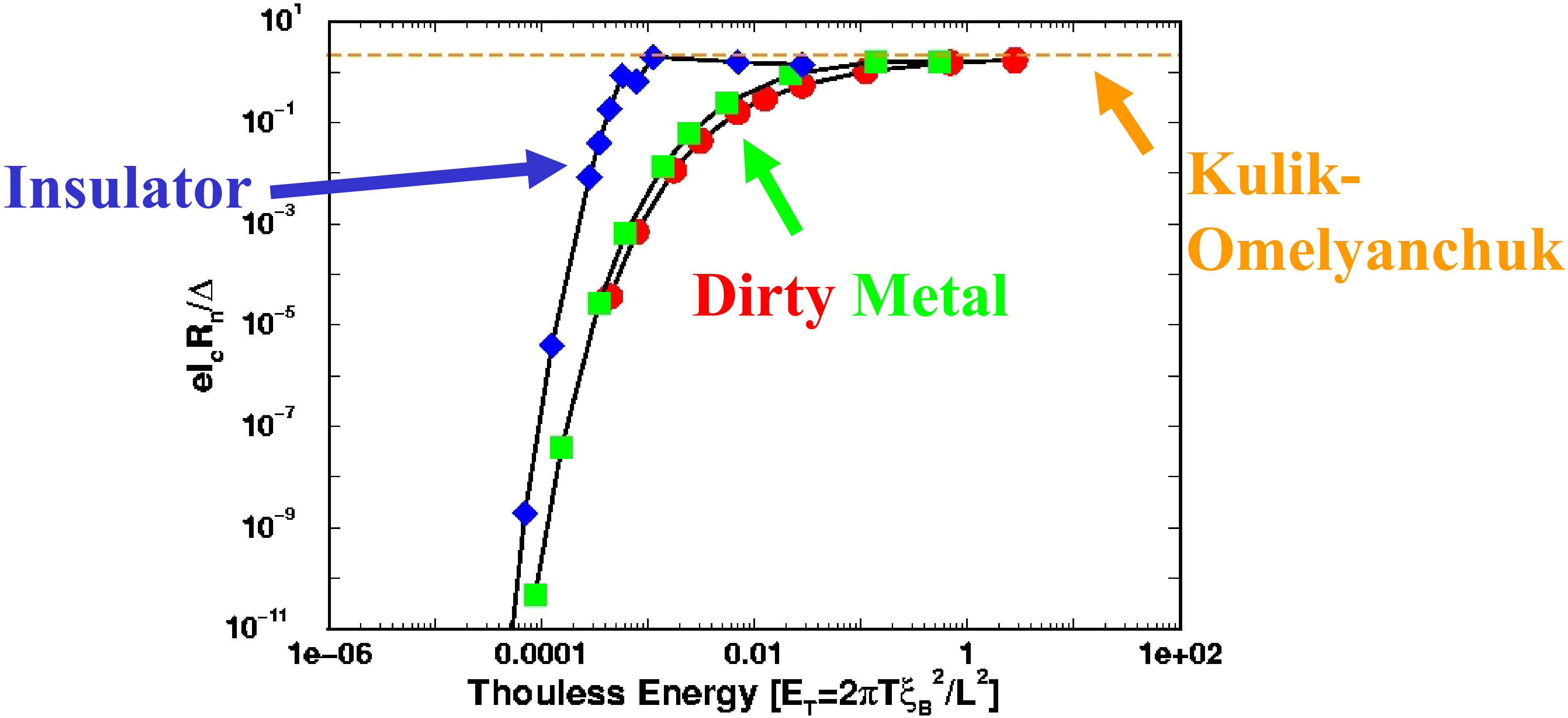
Current-phase relation (thin barrier)



- When Ic approaches the bulk critical current, **little total phase** can be put across the junction.
- As the barrier becomes more insulating, the current phase relation **approaches sinusoidal behavior**.

J. K. Freericks, Georgetown University, Josephson Junction talk, 2002

Characteristic voltage versus Thouless energy



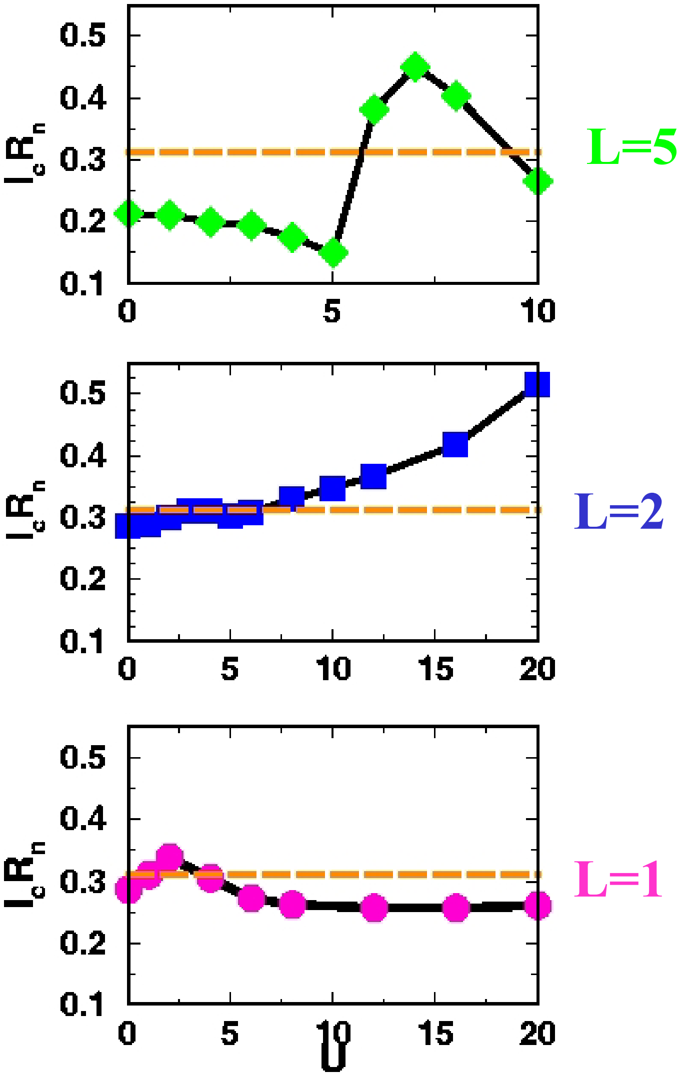
Insulator

Dirty Metal

Kulik-Omelyanchuk

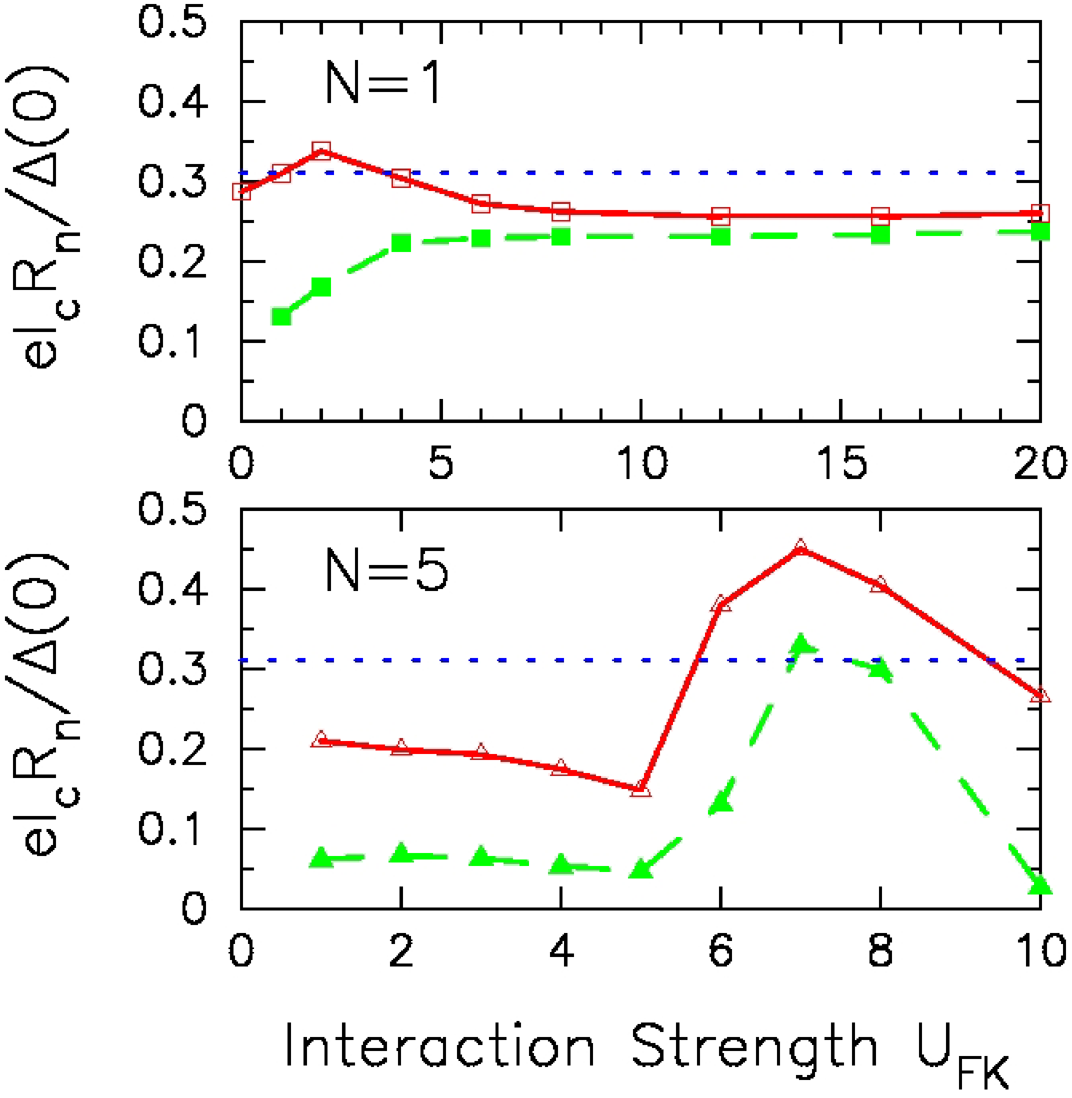
- Quasiclassical theory predicts a **universal form for dirty metals**, but we see different behavior for the correlated insulator which predicts a **greater sensitivity to “intrinsic pinholes”.**

Optimization of IcRn



- IcRn is **maximized just on the insulating side of the MIT** for moderately thick junctions!
- IcRn grows, seemingly **without bound** for a bilayer, but we expect hysteresis to enter as the barrier becomes more insulating.
- We reproduce the AB result of IcRn **independent of the properties of the insulator** for thin junctions, but our value for IcRn is **reduced** by about 15% due to the **inverse proximity effect**.

Thermal properties I



- The red curves are for T=Tc/11 and the green curves are T=Tc/2. As expected, the characteristic voltage **decreases as T increases**, but the more metallic barriers are **reduced much more** than the insulating barriers.
- The thicker barrier is reduced **almost uniformly** for a wide range of correlation strengths.
- The thin insulator has the most thermal stability.

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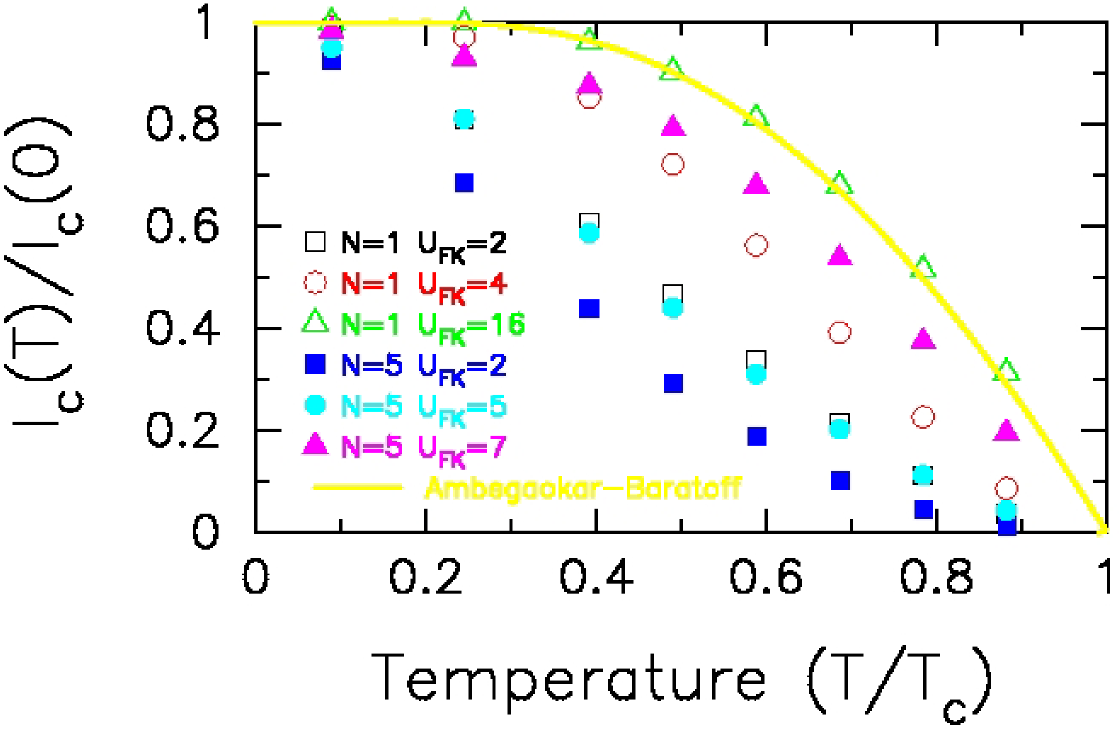
Thermal properties II

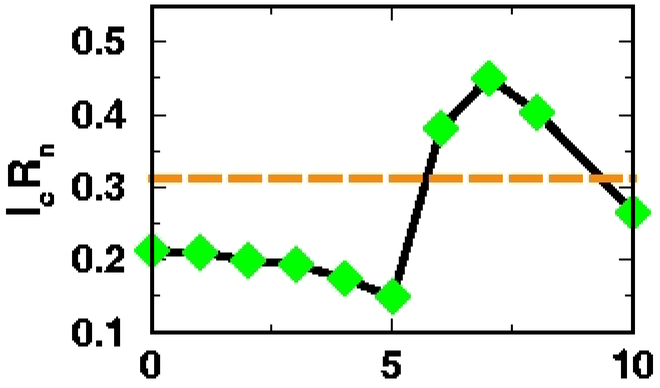


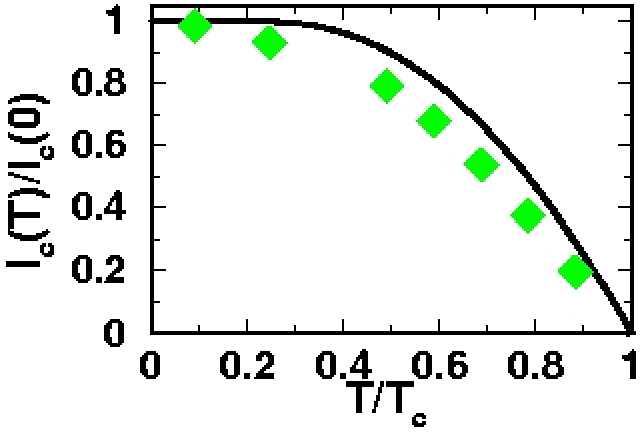
SNS junctions have **poor thermal stability** and will not function well in Josephson devices.

- Thin insulating junctions follow the AB prediction **exactly (solid yellow line)**!
- SCmS junctions suffer a faster initial drop for 0<T<0.3Tc, but then the slope becomes **similar to that of the AB form** for 0.3Tc<T<0.7Tc. Since the curve is only reduced by about 15-20% in this range, the 50% increase of IcRn at low T wins and **properties of this junction are superior to self-shunted SIS!**

Benefits of SCmS junctions

- When properly optimized for thickness and proximity to the MIT, **SCmS junctions have significantly enhanced IcRn products**.
- The thermal stability of SCmS junctions over the reasonable operating range of 0.3Tc-0.7Tc is **as good as the best case of an SIS junction**.
- **Overall SCmS junctions can have the best properties of any proposed junction type**.





Potential problems of SCmS junctions

- SCmS junctions may need **fine-tuning** to reach the “optimization zone”.
- Intrinisic pinholes may appear if the JJ coupling is **highly sensitive to the thickness of the junction** (producing dead zones or hot zones that can dominate the JJ effect).
- Fabrication **uniformity may be difficult** to achieve.

Future work in this area

- Generalize the formalism to calculate **nonequilibrium** effects needed to determine IV characteristics, to calculate subgap structure, and to determine when hysteresis enters.
- Develop a **many-body-theory** model for the MIT in bulk TaN.
- Incorporate **more realistic real materials modeling** for NbTiN-TaN-NbTiN SCmS junctions.
- Develop a **multiband and multigap** version of the computational engine to model MgB_2 including realistic sheets of the Fermi surface and of the intra and interband electron-phonon coupling.

Conclusions

- Examined properties of a Josephson junction **tuned through a metal-insulator transition**.
- Saw that optimization of the characteristic voltage requires a **careful understanding** of the **correlations**, **thickness**, and **operating temperature** of the device.
- Found an **optimization** on the insulating side of the metal-insulator transition for moderately thick barriers in the range $0.3T_c<T<0.7T_c$.
- Discovered that **temperature effects** are similar to the best case of an SIS junction in the expected operating range for a circuit.
- Conjecture that an **"intrinsic pinhole effect"** may make fabrication uniformity difficult for SCmS junctions.