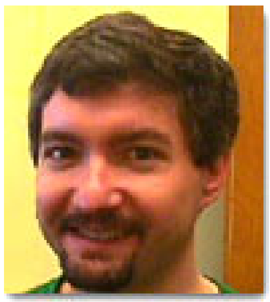
Tuning a short coherence length Josephson junction through a metal-insulator transition



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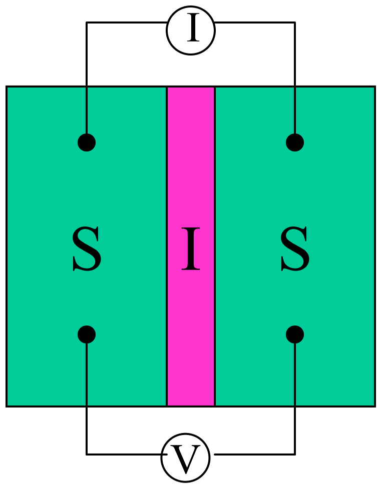
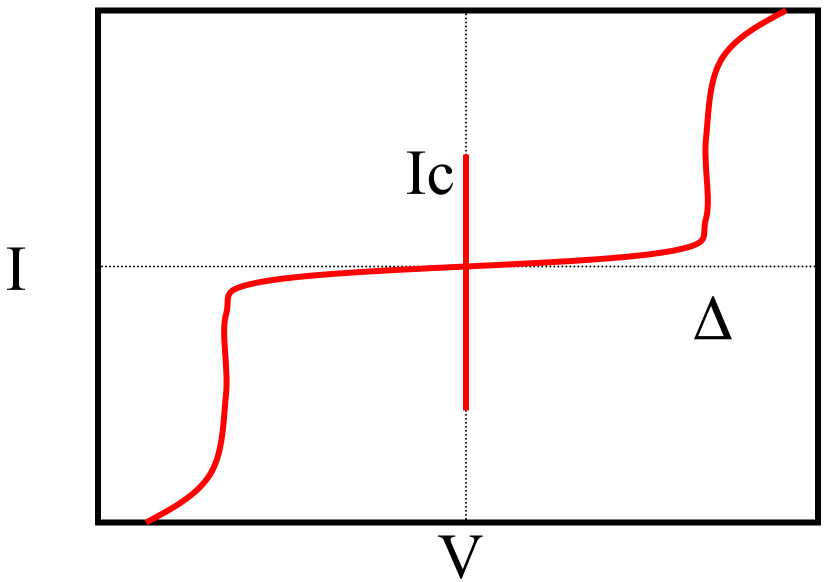
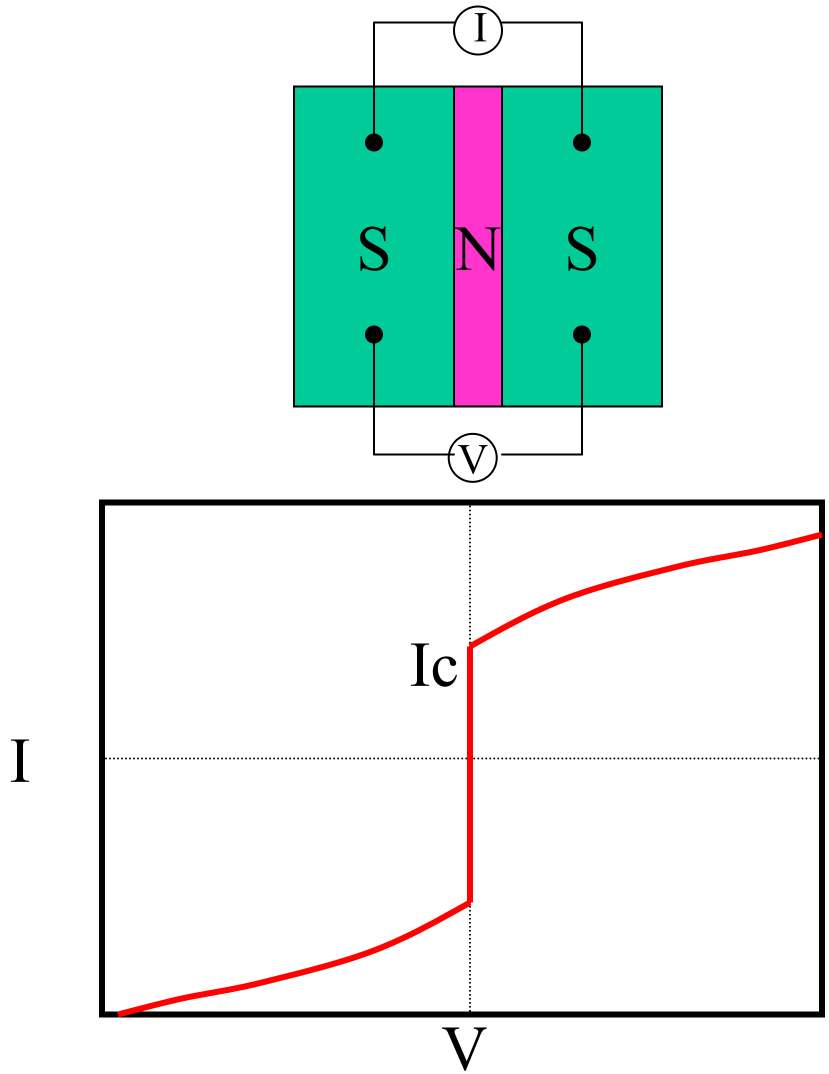
Josephson Tunnel Junctions





- 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).

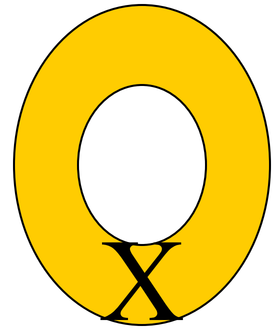
Josephson Proximity-Effect Junctions



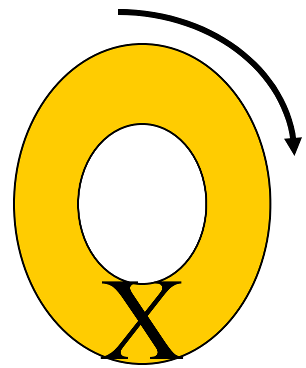
- A Superconductor-Normal metal-Superconductor sandwich where the weak link between superconductors occurs through the **proximity effect**.
- Andreev reflection at the N-S boundaries leads to **sub-gap bound states** that carry the pair current.
- Single-valuedness of the IV characteristic allows for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

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. (Much faster than latching technologies.)
- 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.
- High Tc junctions, with IcRn products larger than 20 mV can **possibly** produce speeds in excess of **1 THz**!
- The goal for fast electronics is to **optimize the IcRn product** of a junction, while maintaining **nonhysteretic** IV curves.



Binary 0, no flux

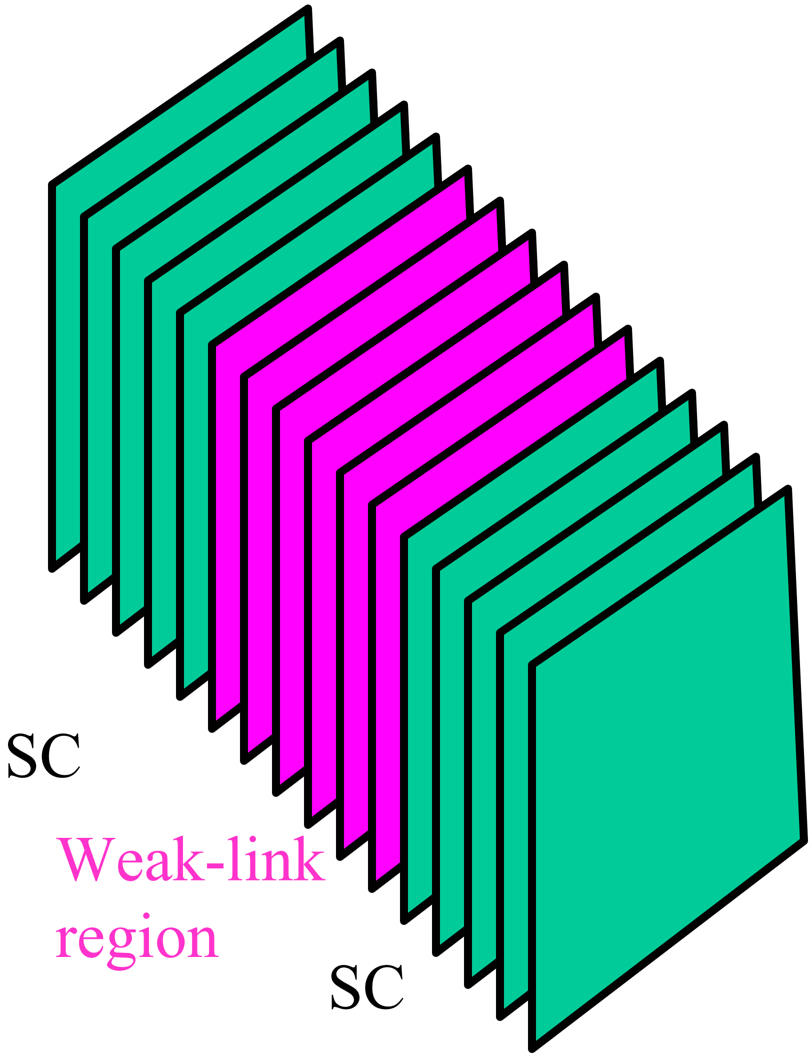


Binary 1, one flux quantum

Navy Interest

- High precision, high speed, **analog-digital converters** for the **A**dvanced **M**ultifunction **R**adio **F**requency **S**ystem **concept** for use in radar, electronic warfare, and communications.
- Long-term specs include 12 bit ADC with 1GHz of bandwidth. **Processing speed is more important than resolution.**
- Short-term goal is a 20 bit ADC with 20MHz of bandwidth.
- **Superconducting digital electronics may provide the solution**.
- The theoretical calculation and modeling is a **scalable massively parallel solution to a scientific problem**.
- Work would have an impact on the HTMT JJ-based petaflop computer which could be competitive with IBM's blue-gene project. (***But the JJ computer may no longer be funded***.)

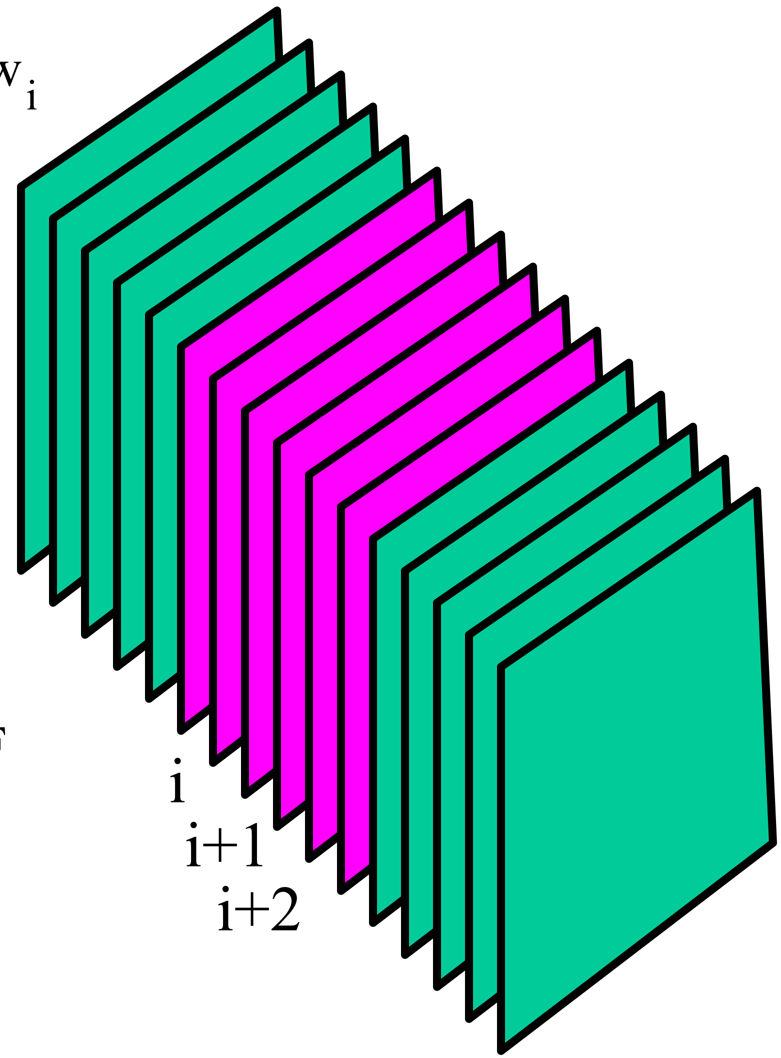
Optimization of the speed of a JJ



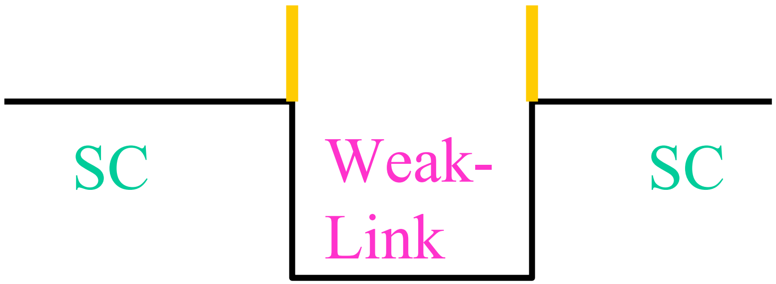
- Insulating barriers found in tunnel junctions have a **high resistance** and a **low Josephson** current.
- Metal barriers found in proximity-effect junctions have a **low resistance** and a **high Josephson** current.
- Is the speed **optimized** (i.e. the product IcRn maximized) when the barrier lies **near the metal-insulator transition**? What type of material produces the best Josephson junction weak-link region?
- Here we examine what happens as the barrier is **tuned through** a metal-insulator transition.

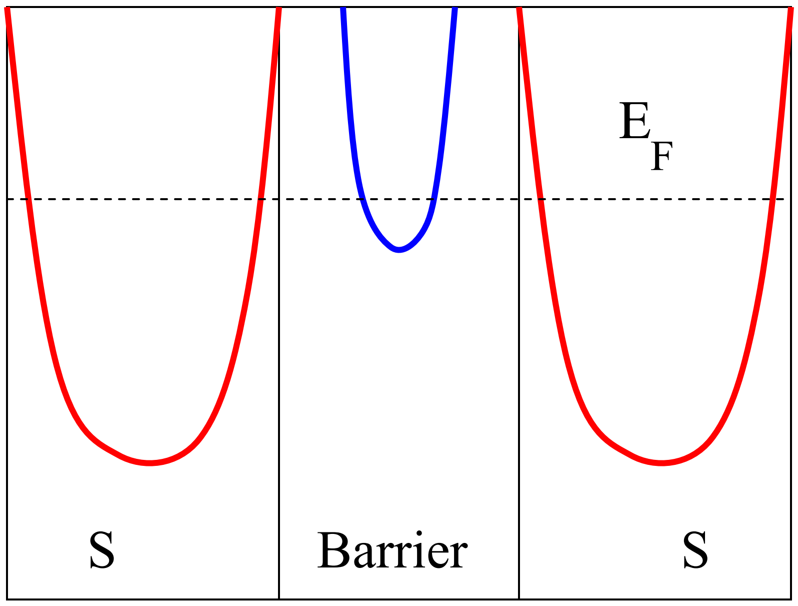
Many-Body Formalism

- **Inhomogeneous system**, with planes stacked along the z-direction.
- $H = -\sum t_{ij}\, c^{*}_{i\sigma} c_{j\sigma} + \sum U_i n_{i\uparrow} n_{i\downarrow} + \sum U^{FK}_i (n_{i\uparrow} + n_{i\downarrow})\, w_i$
- Hopping, site energy, Coulomb interaction, and the impurity interaction can **vary** from one plane to another.
- 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 Bogulubov-deGennes equations for a short-coherence length, s-wave superconductor.



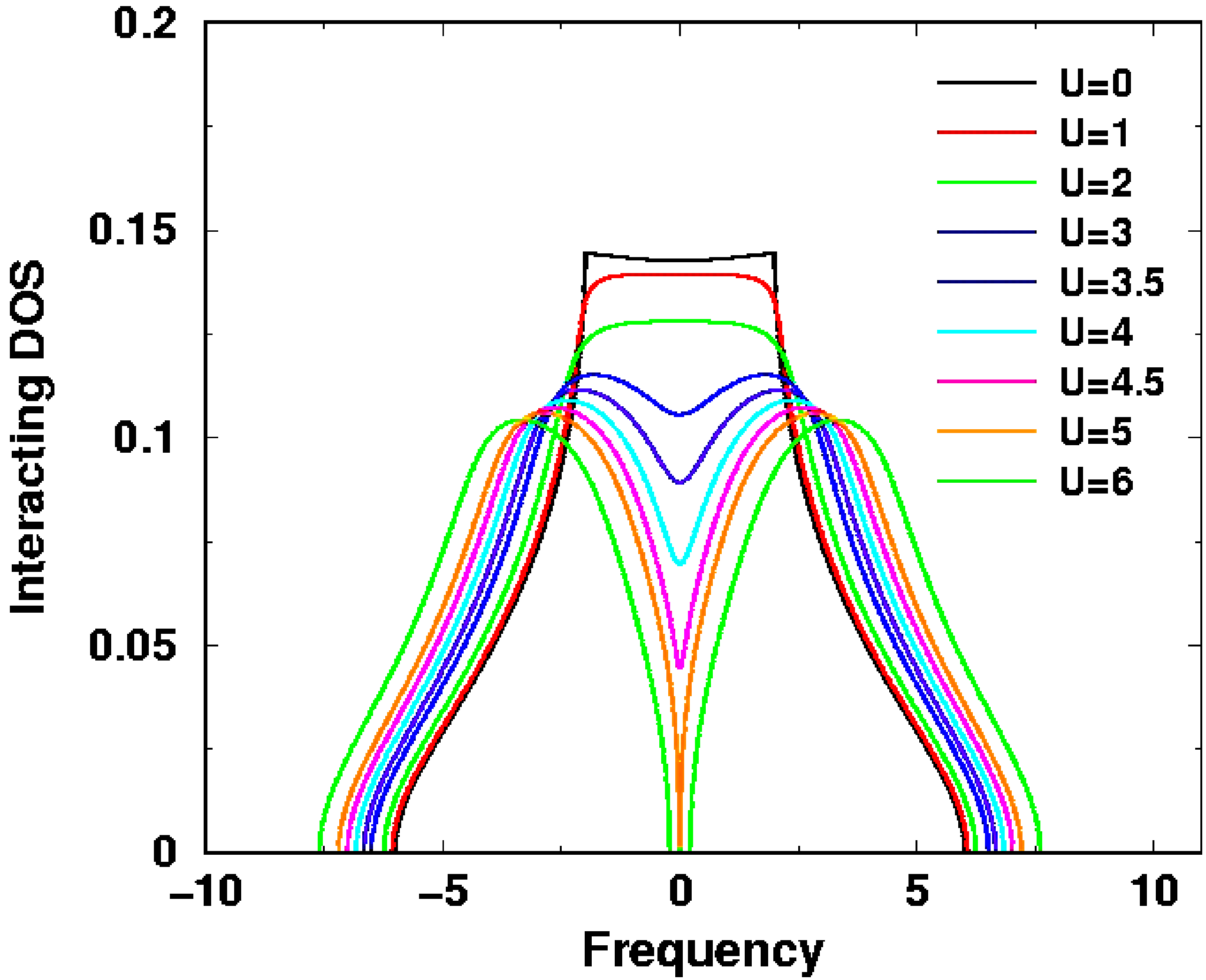
Conventional Models





- BTK model, interface scattering, no self-consistency, no electron-electron interactions in the barrier, no bandstructure effects. Simple exercise of **matching boundary conditions** for plane waves.
- Generalizations to include **bandstructure** effects (Fermi wavevector mismatch, varying effective mass) are easy to include.
- **Self-consistency** and especially **correlations** have been much more difficult.
- **All of these effects are automatically included in our approach!**

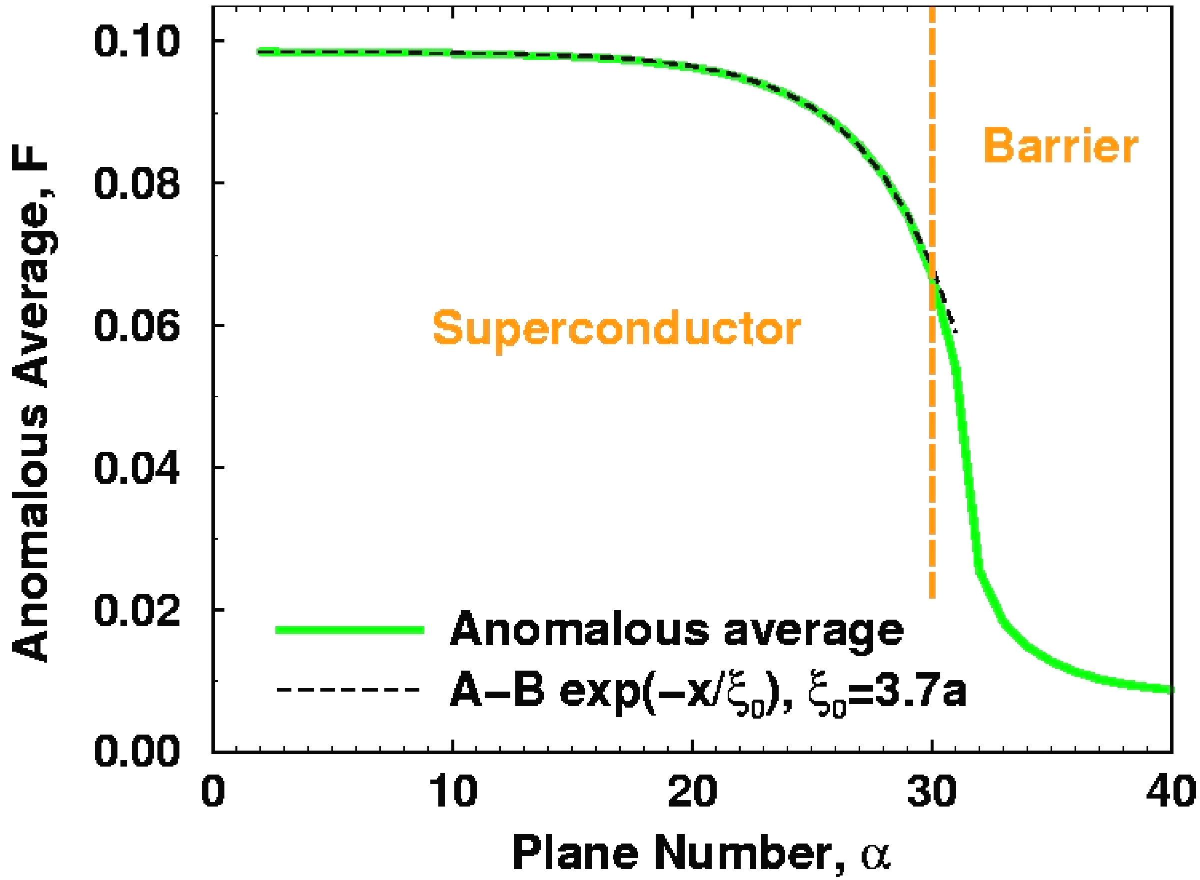
Metal-insulator transition



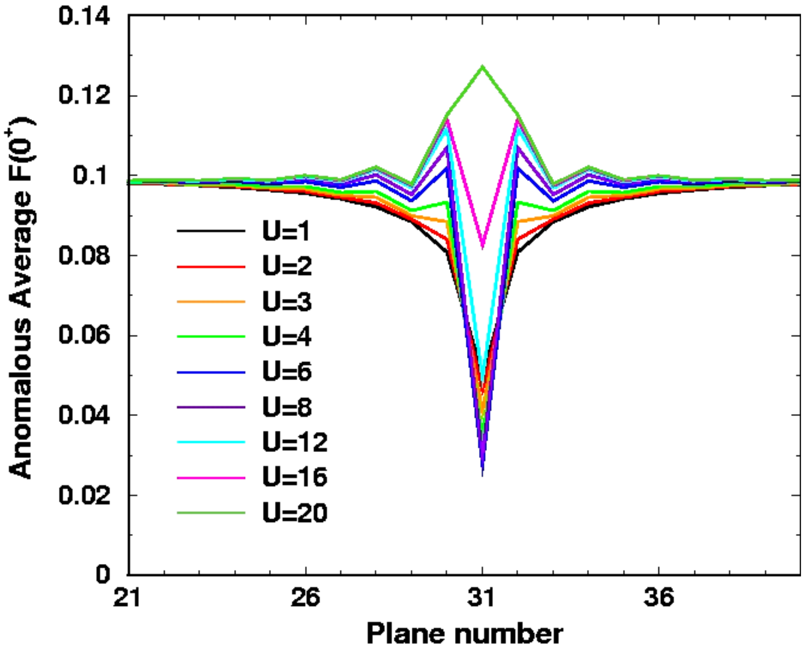
The Falicov-Kimball model has a **metal-insulator transition** that occurs as the correlation energy U is increased. The interacting DOS shows that a **pseudogap** phase first develops followed by the opening of a **true gap** above U=4.9 (in the bulk). Note: the FK model is **not a Fermi liquid** in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

Bulk superconducting properties

- T_c=0.11t, Δ=0.198t, $2\Delta/k_B T_c$=3.6--- **behaves like a BCS superconductor**
- Bulk coherence length ξ_0=3.7a= $v_F/\pi\Delta$ ---**short coherence length superconductor**

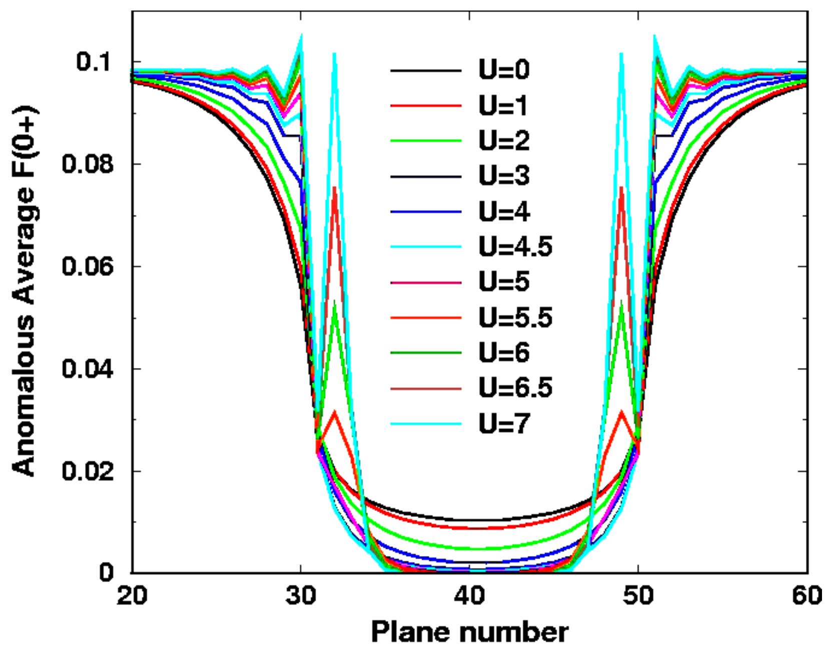


Proximity effect

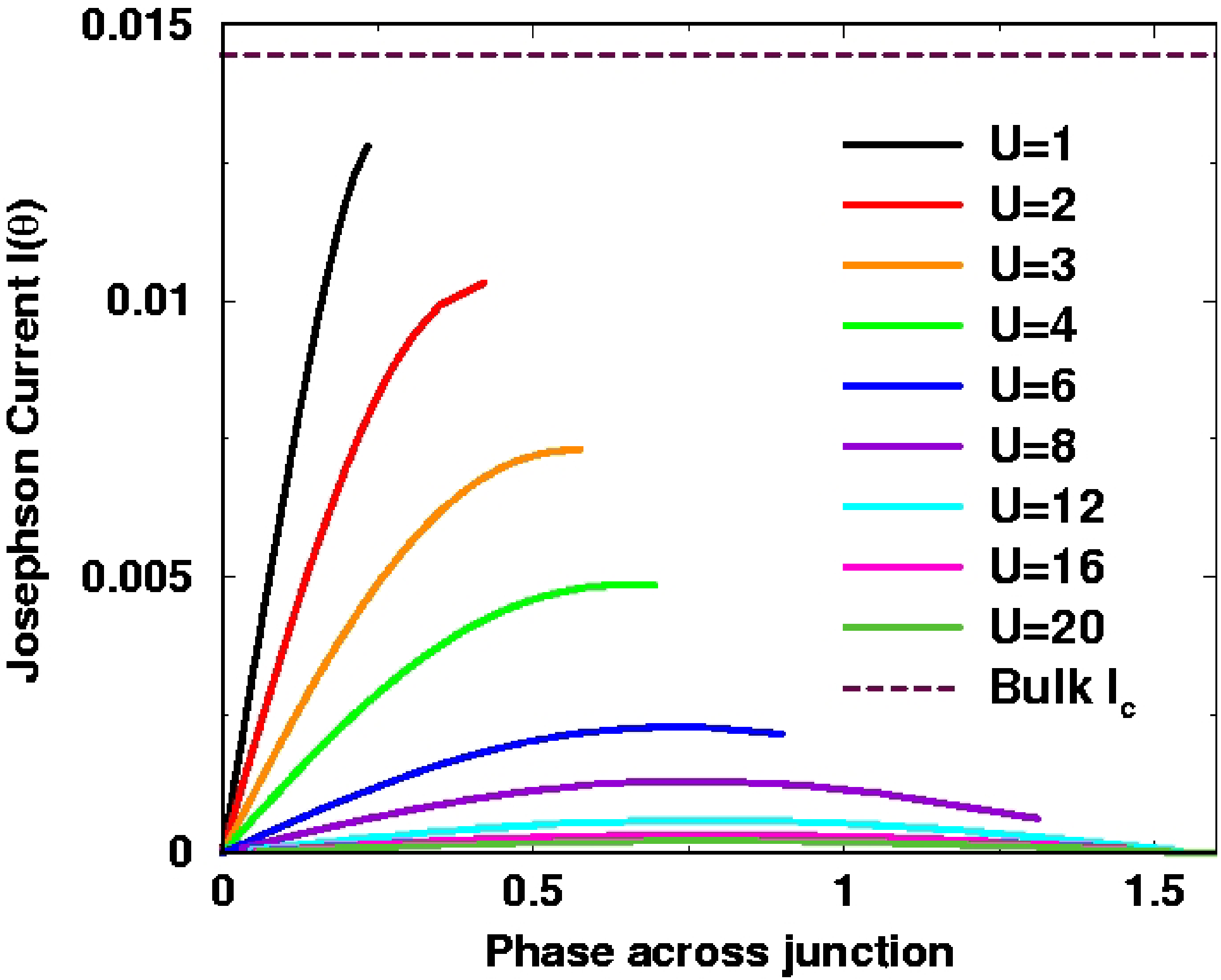


Thin barrier (N_b=1). Note how oscillations develop as U becomes larger than 3 and how the anomalous average **increases** for U> 12 and is **enhanced** for U > 18!

- **Thick barrier (N_b=20).** Note how the anomalous average is reduced as the barrier makes the transition to an insulator. The anomalous average decreases rapidly within the pseudogap phase as the insulator is approached. The **sharp oscillations** within the insulator **decay** on the order of the bulk coherence length.



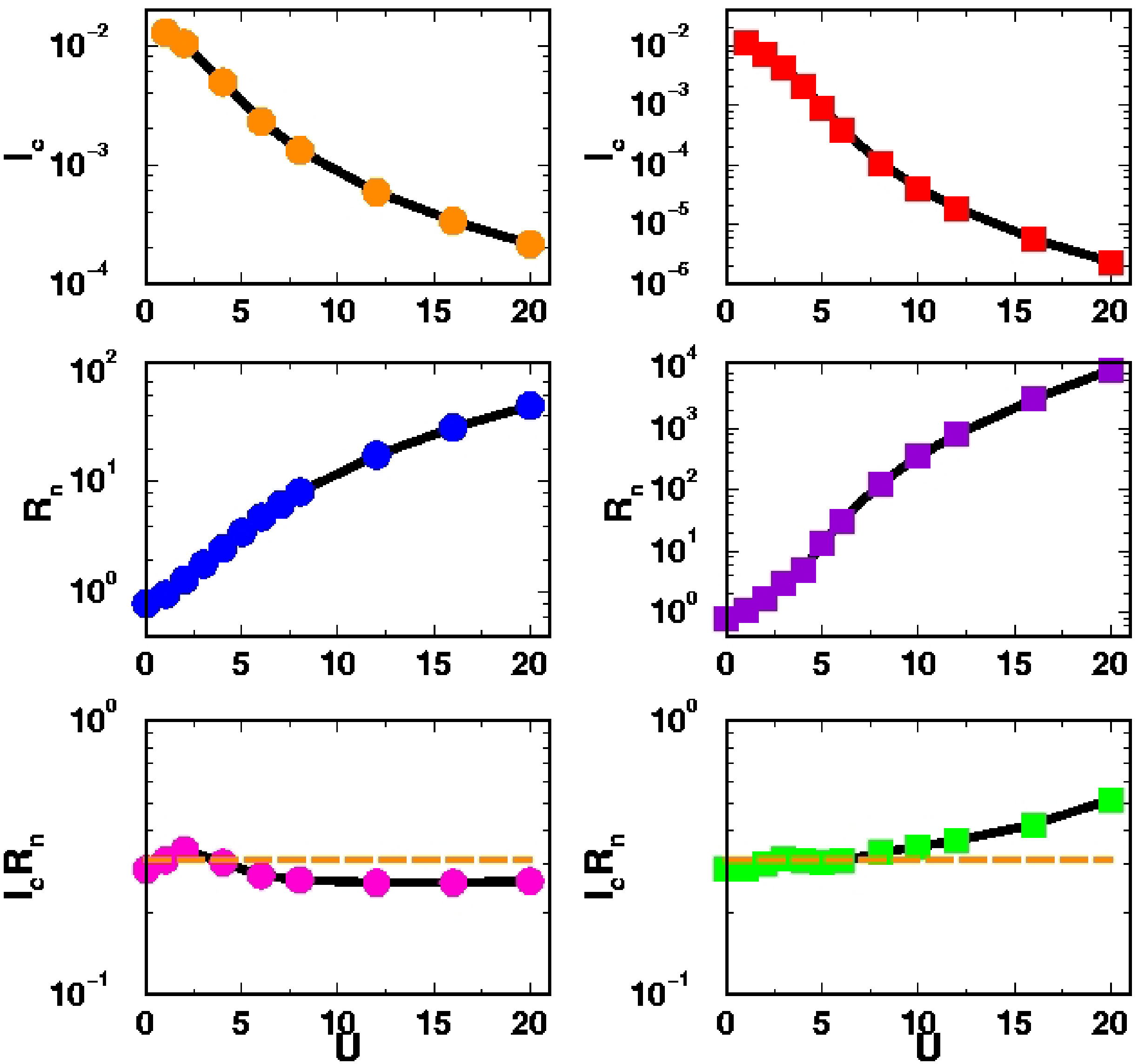
Current-phase relation (thin barrier)



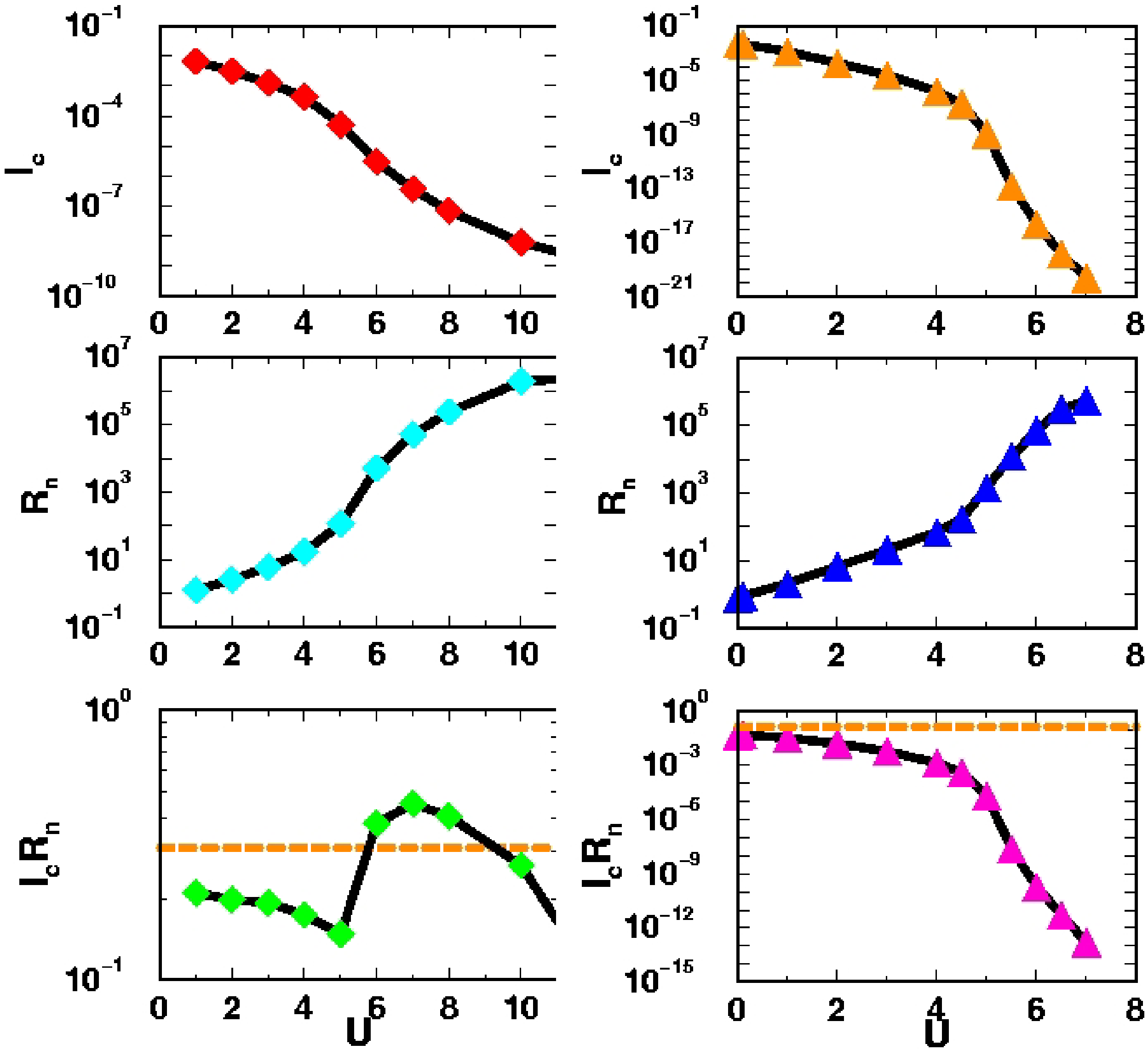
- When Ic approaches the bulk critical current, **little total phase** can be put across the junction.
- As the barrier becomes more insulating, the current phase relation **approaches sinusoidal behavior**.

Critical current and resistance (thin)

- The semilogarithmic plots show the expected **decrease** in Ic and **increase** in Rn. The IcRn product becomes **constant** for a thin barrier, showing the Ambegaokar-Baratoff behavior (renormalized by 10%).
- The biplane barrier does not show AB behavior, but rather continues to **increase** it's characteristic voltage as the correlations increase. However, the IV characteristic must become **hysteretic** in the insulating phase.

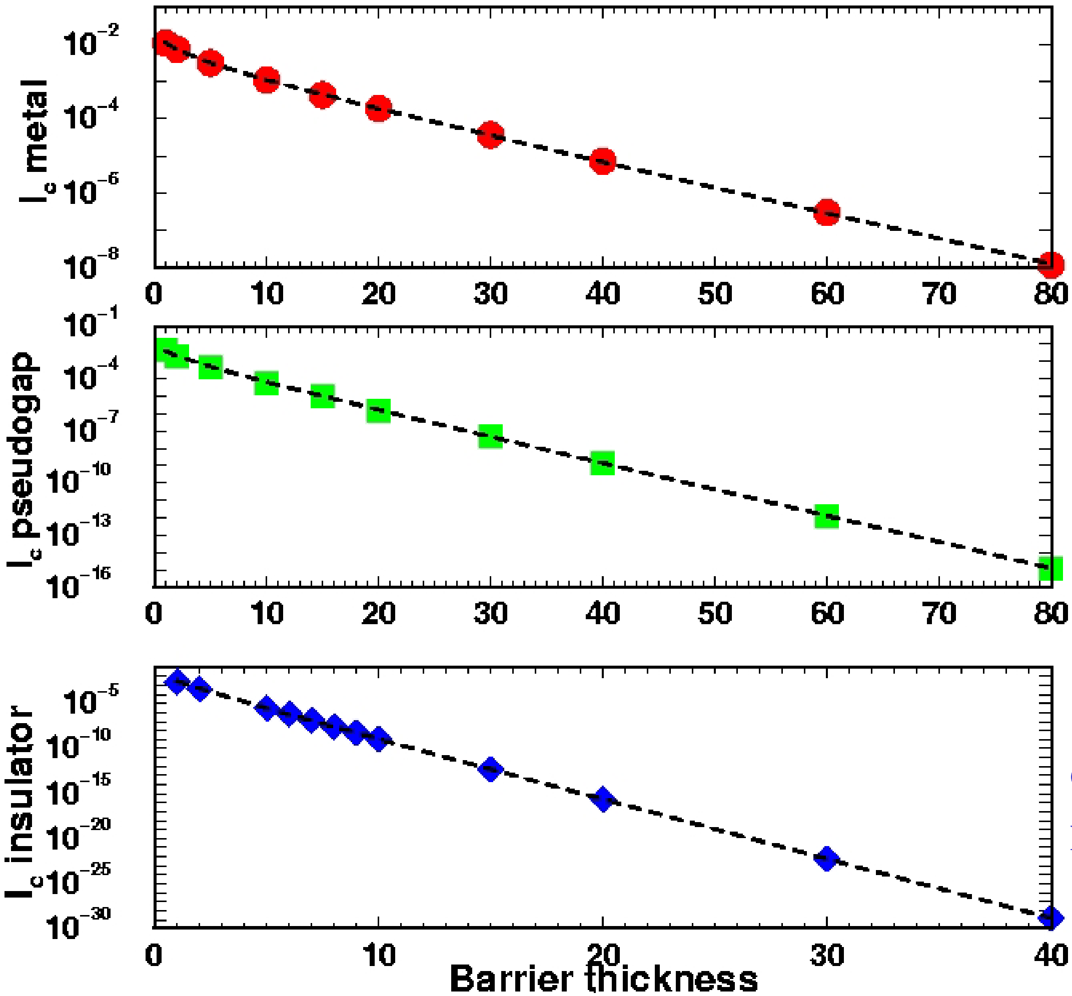


Critical current and resistance (thick)



- For N_b=5, the characteristic voltage first decreases, then shows a **sharp increase and peak** just on the insulating side of the metal-insulator transition.
- The thick junction (N_b=20), has a **sharp reduction** of the characteristic voltage because of the **strong temperature dependence** of the resistance in the insulating phase.

Critical current versus barrier thickness



ξ_0=6.75
x=-0.4

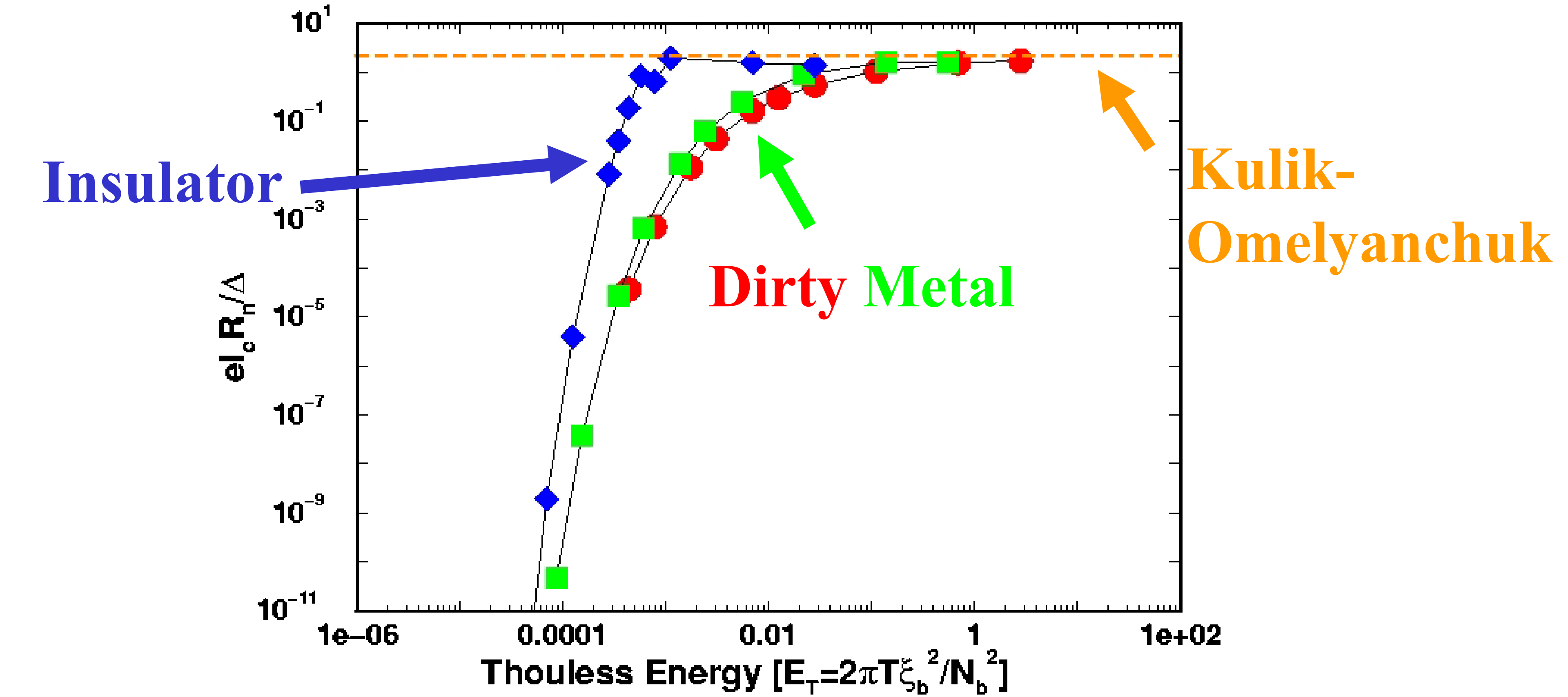
ξ_0=2.96
x=-0.45

ξ_0=0.67
x=-0.5

- Fit of the critical current versus barrier thickness for three cases: (i) **weakly correlated metal**; (ii) **strongly correlated metal** (pseudogap); and (iii) **correlated insulator**.

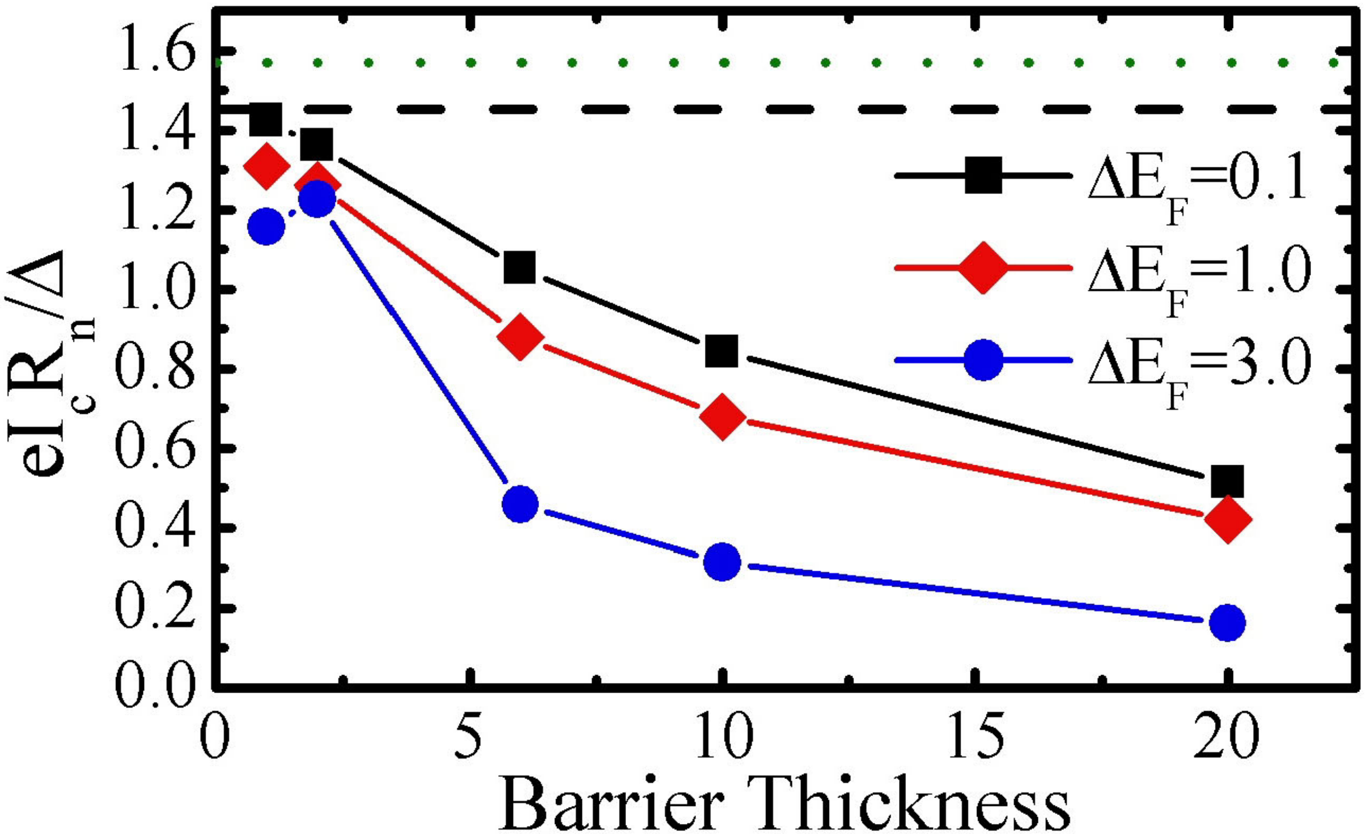
$$I_c = AN_b^x \exp[-N_b / \xi_0]$$

Characteristic voltage versus Thouless energy



- 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".**

Characteristic voltage (Screened-dipole layer barrier)



Screened dipole layer barrier "teaser"--- characteristic voltage decreases sharply in clean "dipole"-based SINIS junctions.

- The characteristic voltage is always less than the "planar" contact limit of the bulk critical current times the Sharvin resistance. Note how the voltage **decreases dramatically with thickness**.

Outstanding Technical Issues

- Incorporate **charge redistribution physics**, **correlations**, plus long-range **spatial ordering**, to describe behavior of grain boundaries in high-Tc. (Collaborations being developed with Mannhart's group in Augsburg.)
- Generalize from **s-wave** to **d-wave** to examine high-Tc systems better.
- Add **spin-dependent physics** to model hybrid superconductor-ferromagnetic structures and to understand spin-scattering effects.
- Generalize the formalism to calculate **nonequilibrium** effects needed to determine IV characteristics and to calculate subgap structure.
- Applications possible to other devices (**spintronics** and **hybrids**).

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.
- Discovered that **temperature effects** and **“intrinsic pinhole” effects** can both be **quite strong** when the system sits close to the quantum critical point of the metal-insulator transition, which can help understand some **difficulties with maintaining low spreads** in high-Tc devices.