Self-consistent modeling of SINIS and SNSNS Josephson junctions

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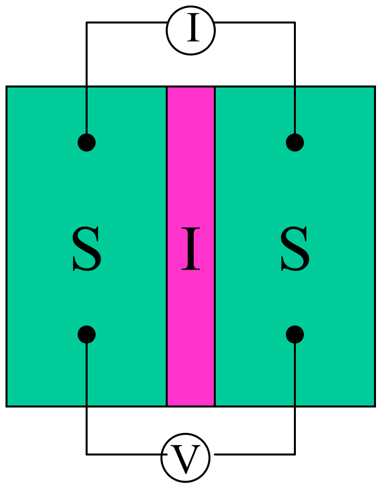
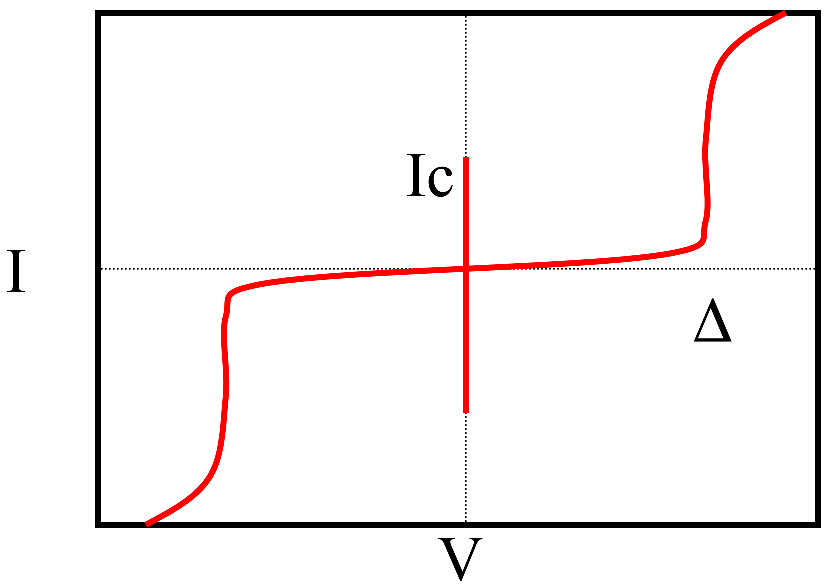
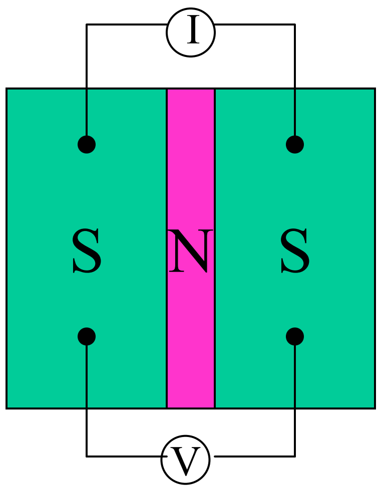
Josephson Tunnel Junctions

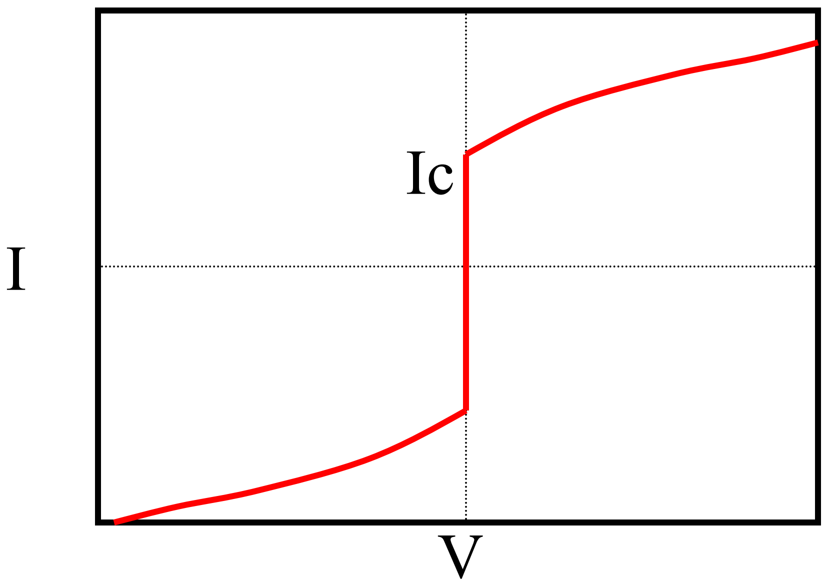




- A Superconductor-Insulator-Superconductor sandwich can tunnel coherent Cooper pairs (Josephson current) or can tunnel broken pairs (quasiparticles) through the barrier.
- If the phases of the superconducting wavefunctions differ, then there is a DC Josephson current $I=I_c \sin \theta$.
- The I-V characteristic 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").

Josephson Proximity-Effect Junctions

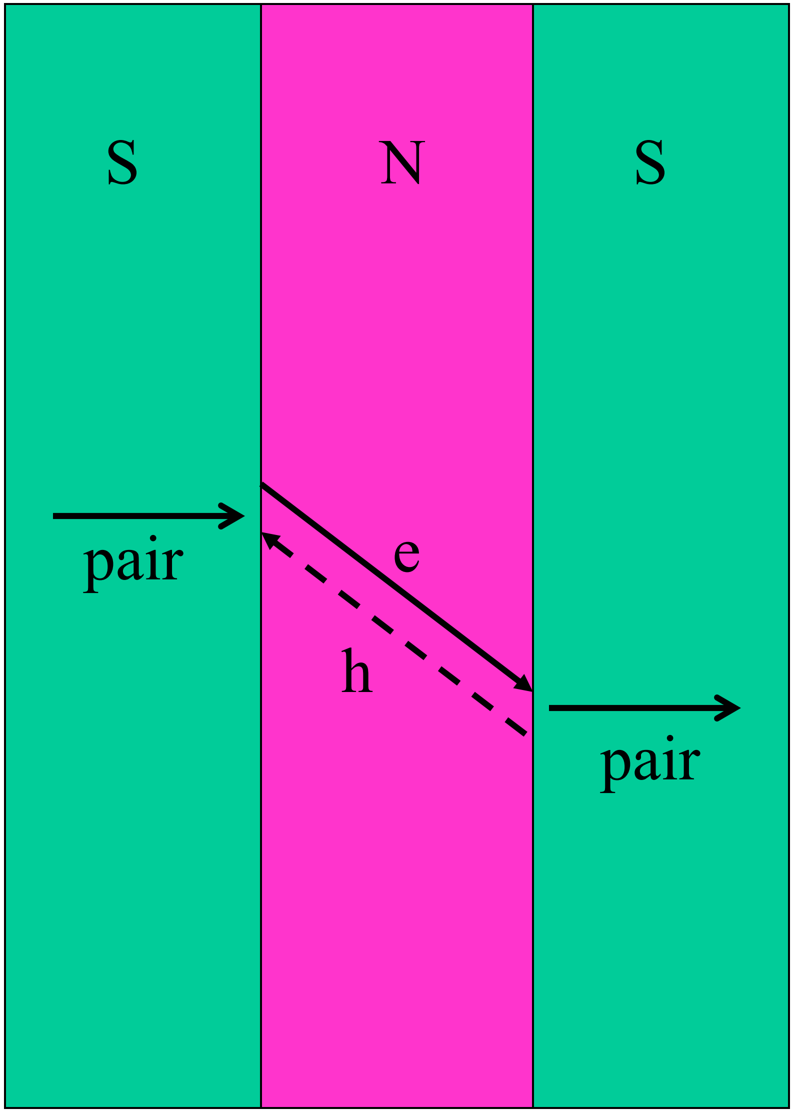




- A Superconductor-Normal metal-Superconductor sandwich where the weak link between superconductors occurs through the proximity effect.
- Andreev reflection at the N-S boundaries leads to sub-gap bound states that carry the pair current.
- Single-valuedness of the IV characteristic allows for non-latching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

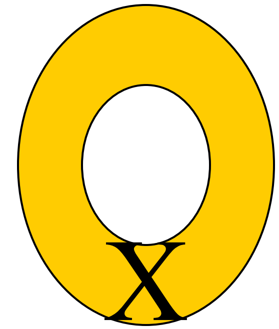
Andreev Bound States

- 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.

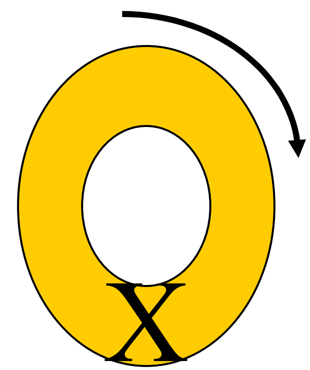


Digital Electronics and RSFQ logic

- 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.

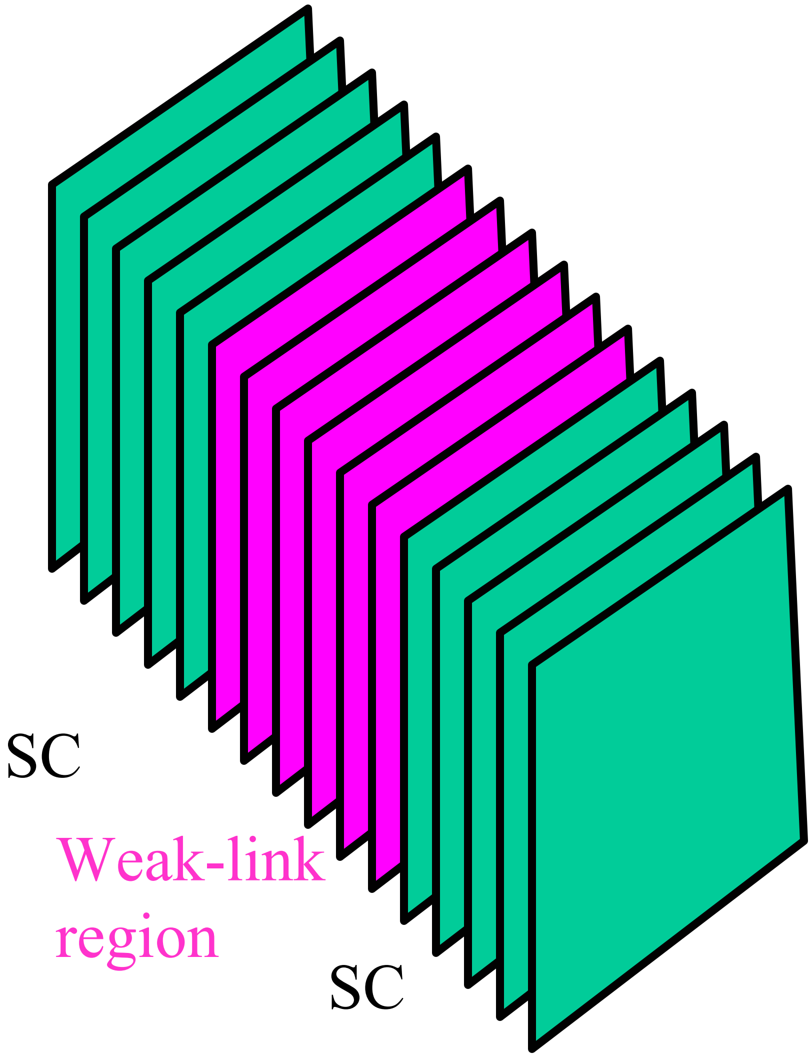


Binary 0, no flux



Binary 1, one flux quantum

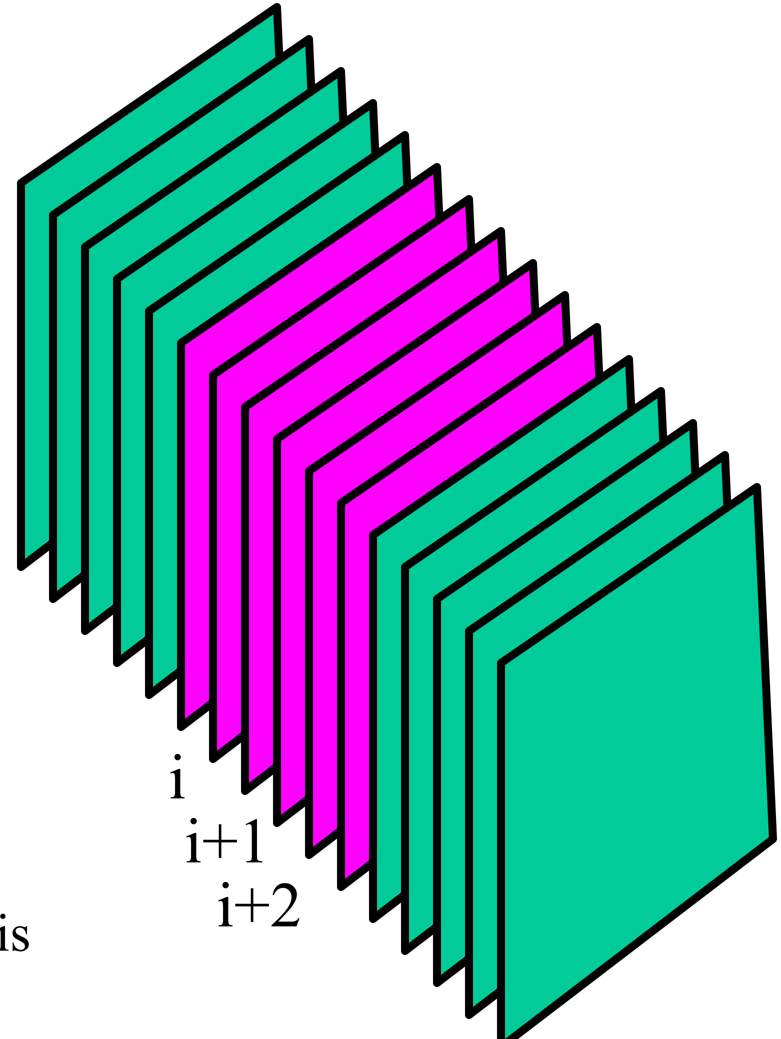
Optimization of the speed of a JJ



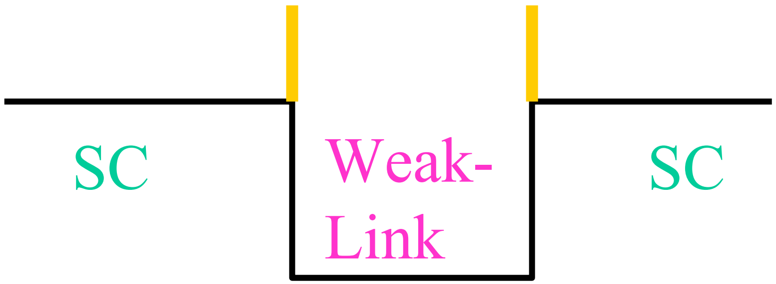
- Insulating barriers found in tunnel junctions have a high resistance and a low Josephson current.
- Metal barriers found in proximity-effect junctions have a low resistance and a high Josephson current.
- Is the speed optimized (i.e. the product IcRn maximized) when the barrier lies near the metal-insulator transition? What type of material produces the best Josephson junction weak-link region?
- We have adopted an efficient massively parallel materials-specific formalism to model and optimize the characteristics of a JJ.

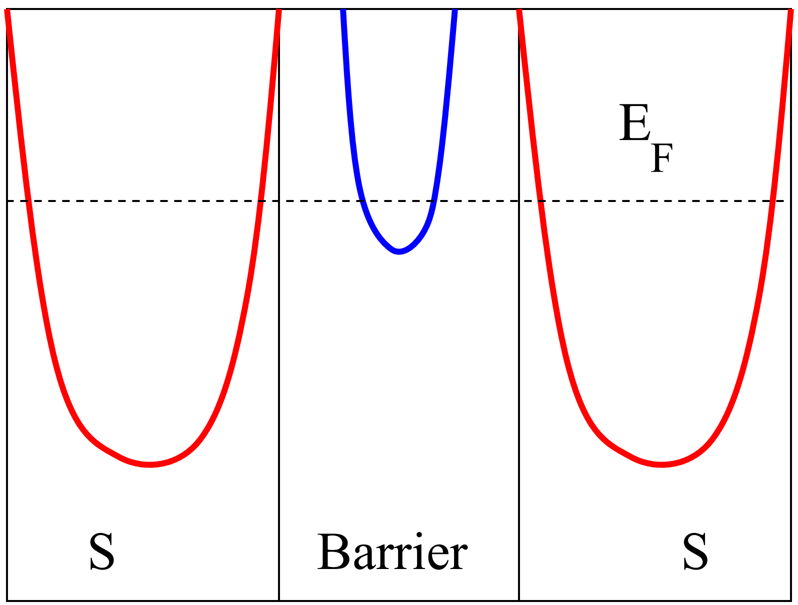
Many-Body Formalism

- Inhomogeneous system, with planes stacked along the z-direction.
- $H = -\Sigma\, t_{ij} c^*_{i\sigma} c_{j\sigma} + \Sigma\, U_i n_{i\uparrow} n_{i\downarrow}$
- Hopping, site energy, and the Coulomb interaction, can vary from one plane to another. Charge redistribution is allowed due to work-function mismatch.
- Local dynamical correlations are explicitly included for each plane via DMFT. The self-consistency relation is now modified to include effects that couple the effective medium between the planes.
- We illustrate the solution of the super-conductor in the H-F approximation, which is identical to a *self-consistent solution* of the Bogulubov-deGennes equations (our method is 1000 times faster than conventional ones).



Conventional Models

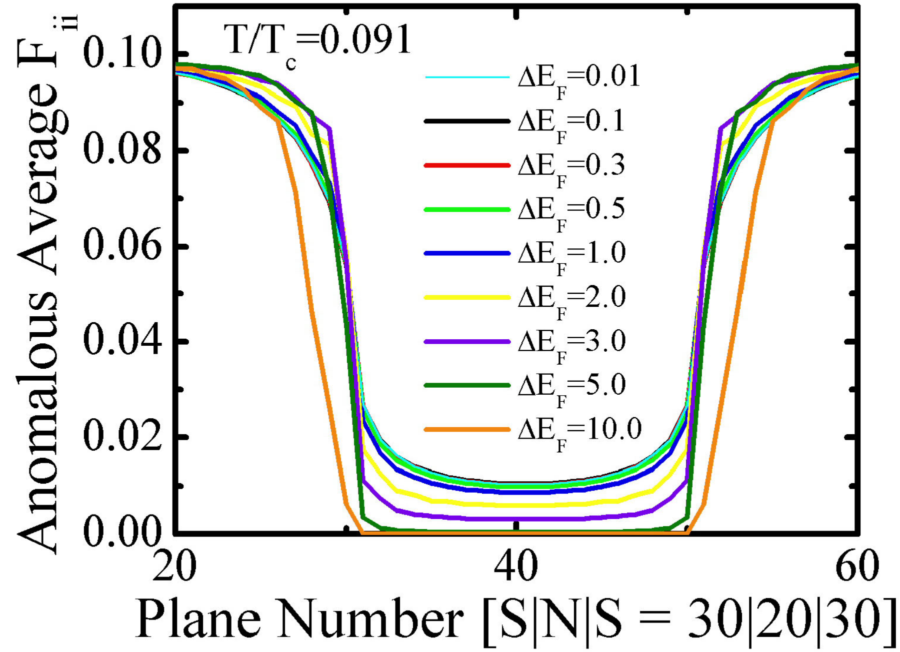


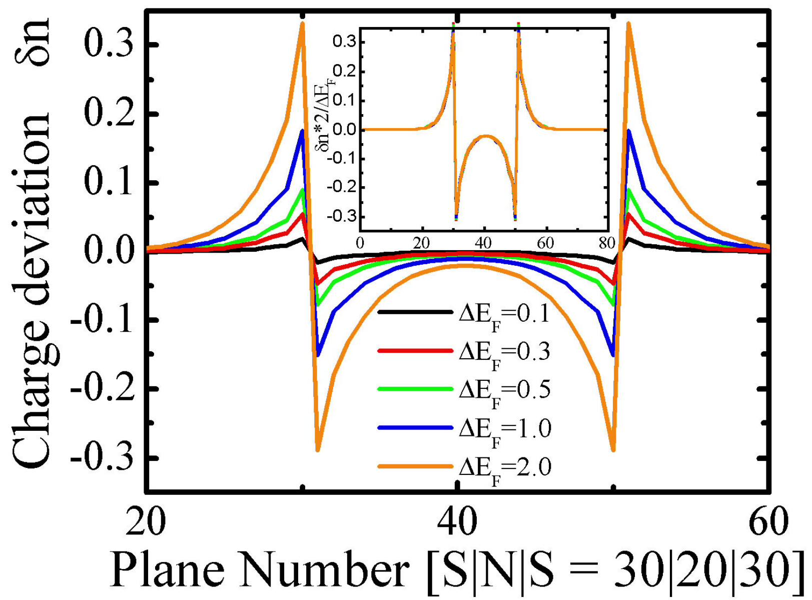


- BTK model, interface scattering, no self-consistency, no electron-electron interactions in the barrier, no bandstructure effects. Simple exercise of matching boundary conditions for plane waves.
- Generalizations to include bandstructure effects (Fermi wavevector mismatch, varying effective mass) are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

Proximity Effect and Schottky Barriers

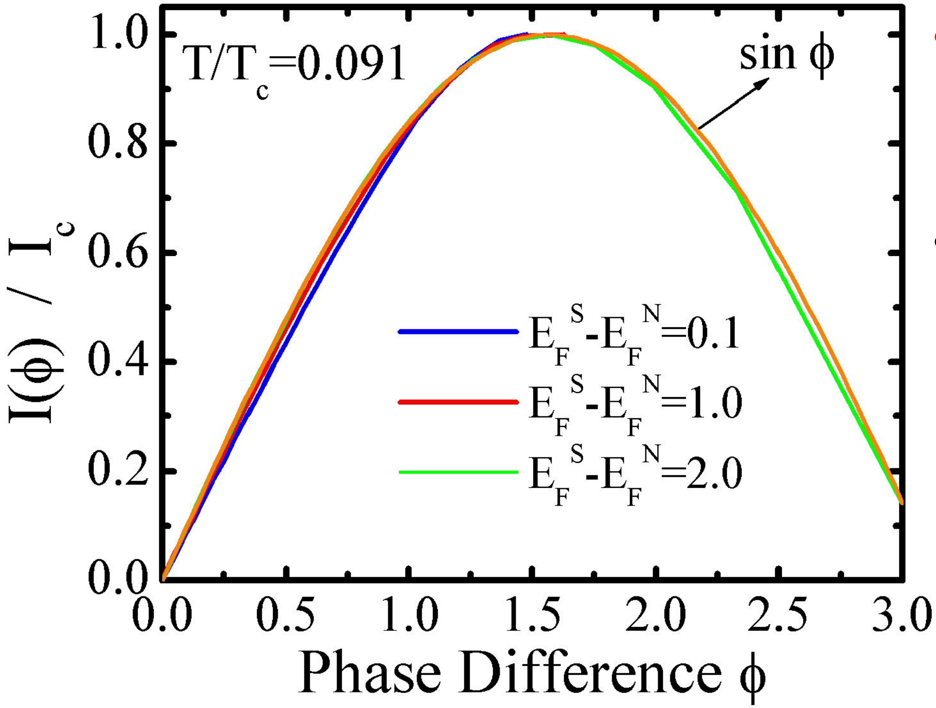
- Bulk superconductor has U= - 2 and half filling, which yields Tc=0.11, Δ = 0.198, and a coherence length of 10 lattice spacings. Barrier width is 20 lattice spacings.
- Note how the anomalous average does not depend too strongly on the Schottky barrier until it becomes large.



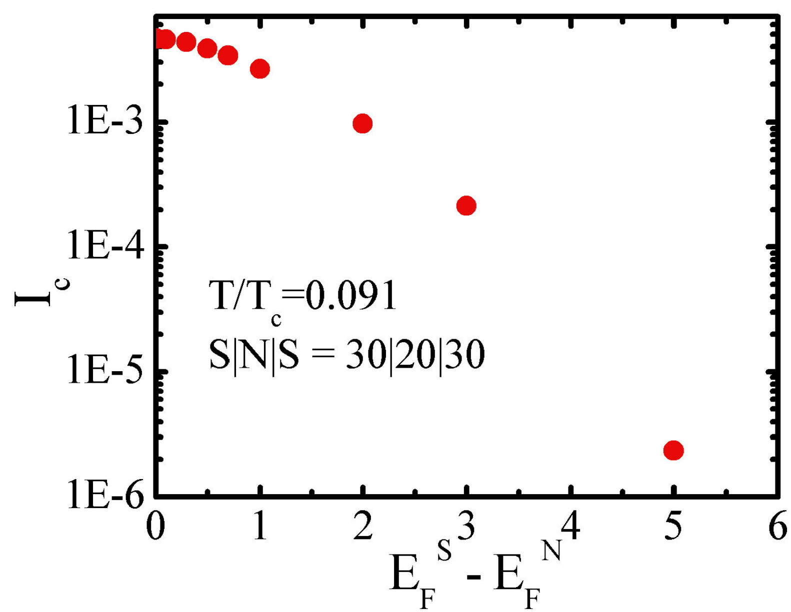


- The Schottky barrier scales with the work-function mismatch, but the anomalous average does not. As the Schottky barrier increases, the anomalous average sharpens.

Current-phase relation and Ic

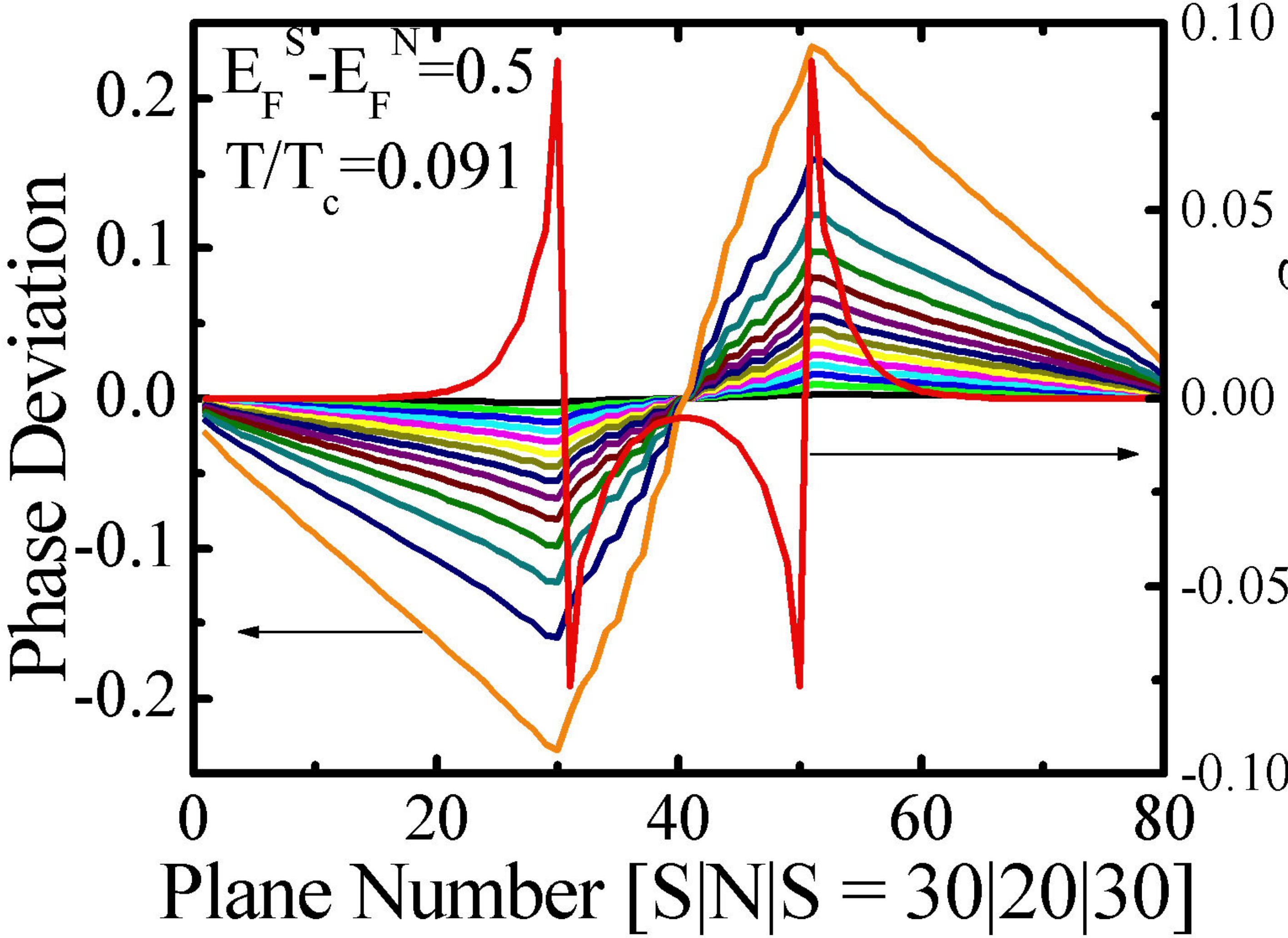


- Current-phase relation for SINIS junctions as a function of the work-function mismatch.
- Note how the curves have essentially a sinusoidal dependence for the SINIS systems with only a small dependence on the barrier height.



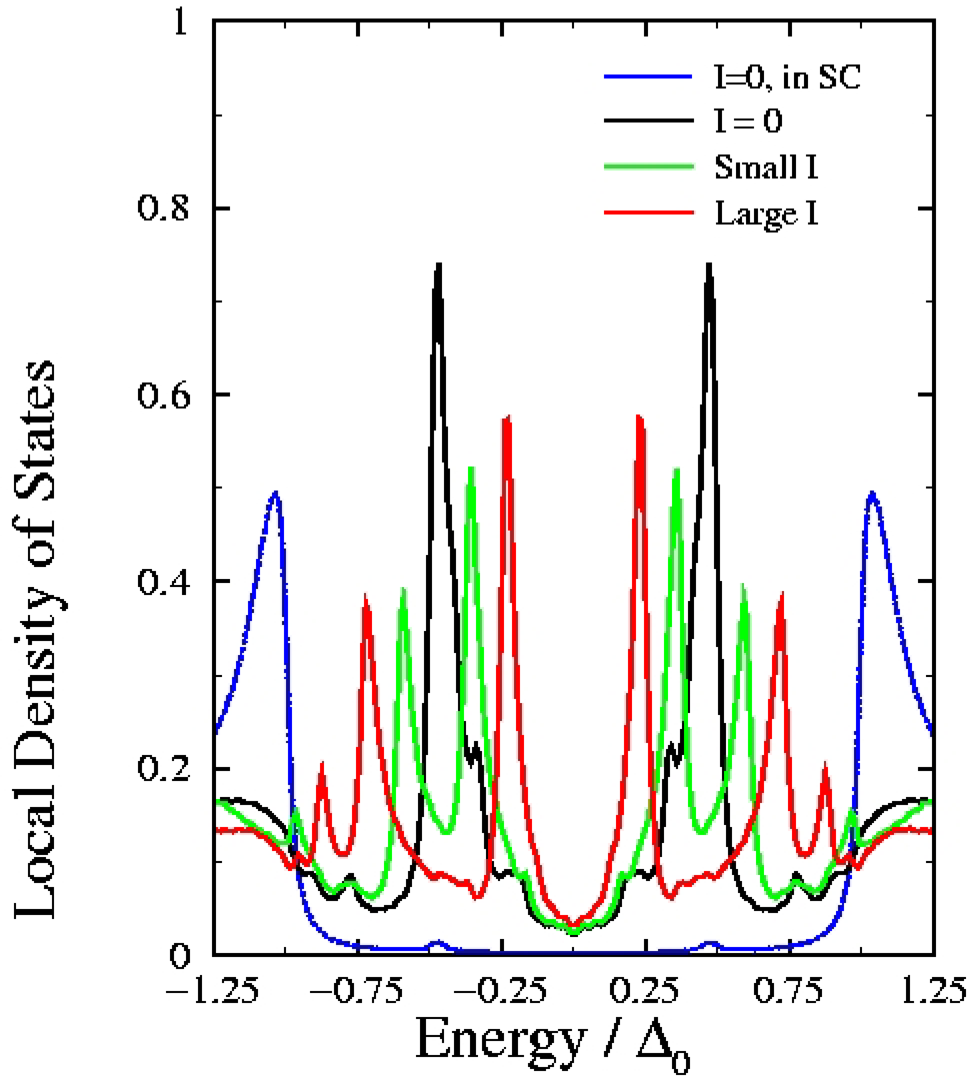
- Plot of the logarithm of the critical current Ic initially shows that it is not too strongly affected by the Schottky barrier, but then rapidly decreases as the barrier becomes large.

Phase deviation per plane (med. mismatch)

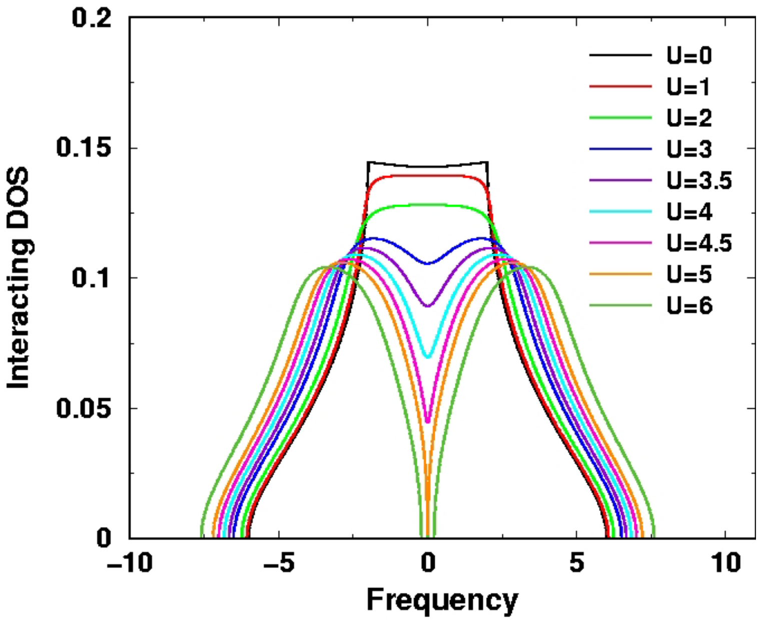


Many-Body Density of States

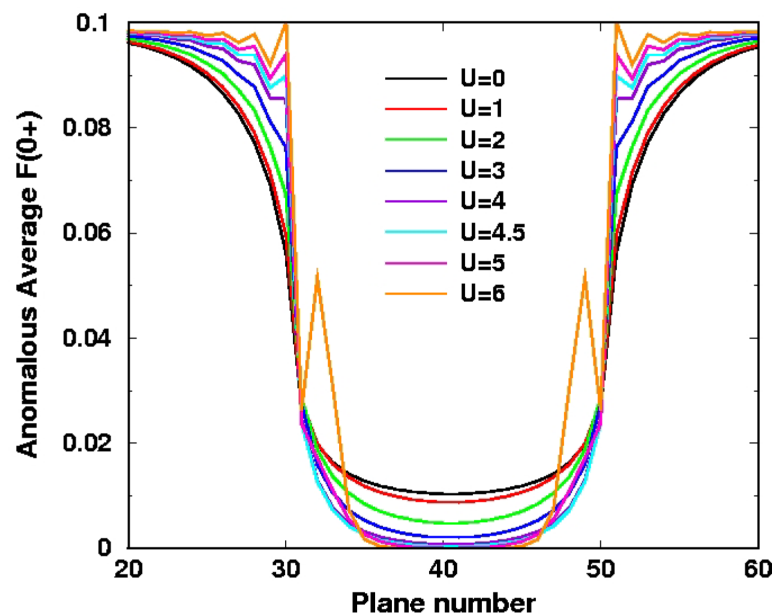
- The density of states is plotted at the center of the barrier with no current, small current, and large current. As the current increases, the splitting of the Andreev bound states into the left- and right-moving states becomes clear.
- For comparison, the density of states is shown just inside the superconductor, where the effects of the Andreev bound states can be seen arising from the self-consistency.



Correlated Barriers

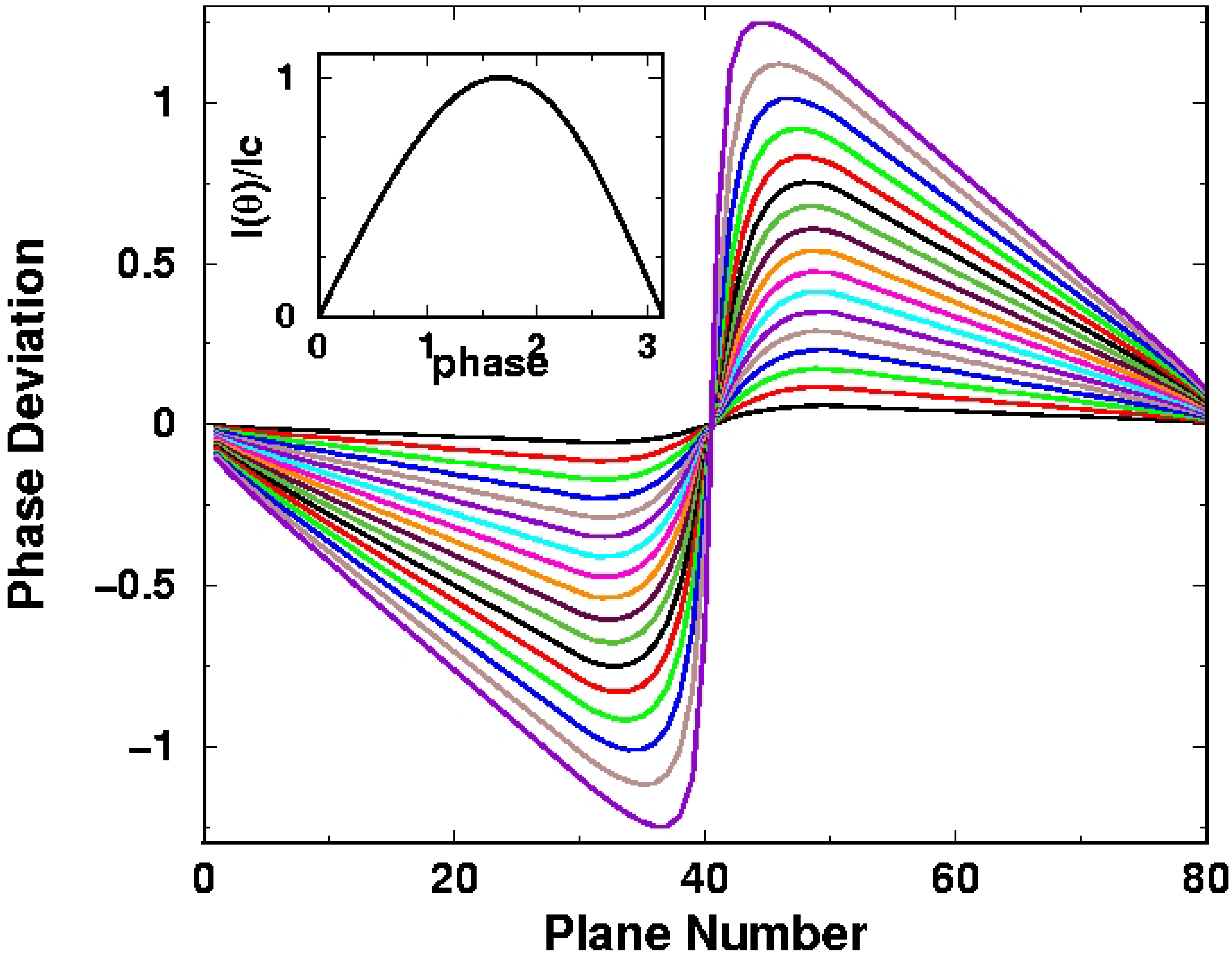


The Falicov-Kimball model has a metal-insulator transition that occurs as the correlation energy U is increased. The interacting DOS shows that a pseudogap phase first develops followed by the opening of a true gap above U=4.9.



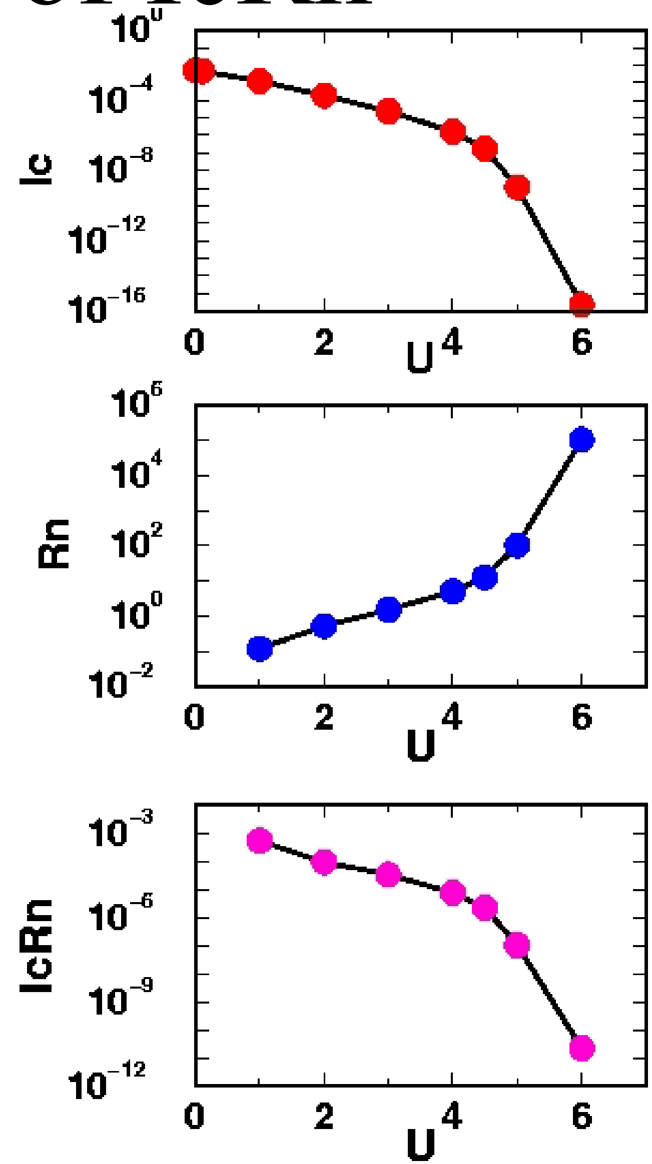
- Note how the anomalous average is reduced as the barrier makes the transition to an insulator. The anomalous average decreases rapidly within the pseudogap phase as the insulator is approached. The sharp oscillations within the insulator phase are not well understood.

Phase deviation per plane (pseudogap)



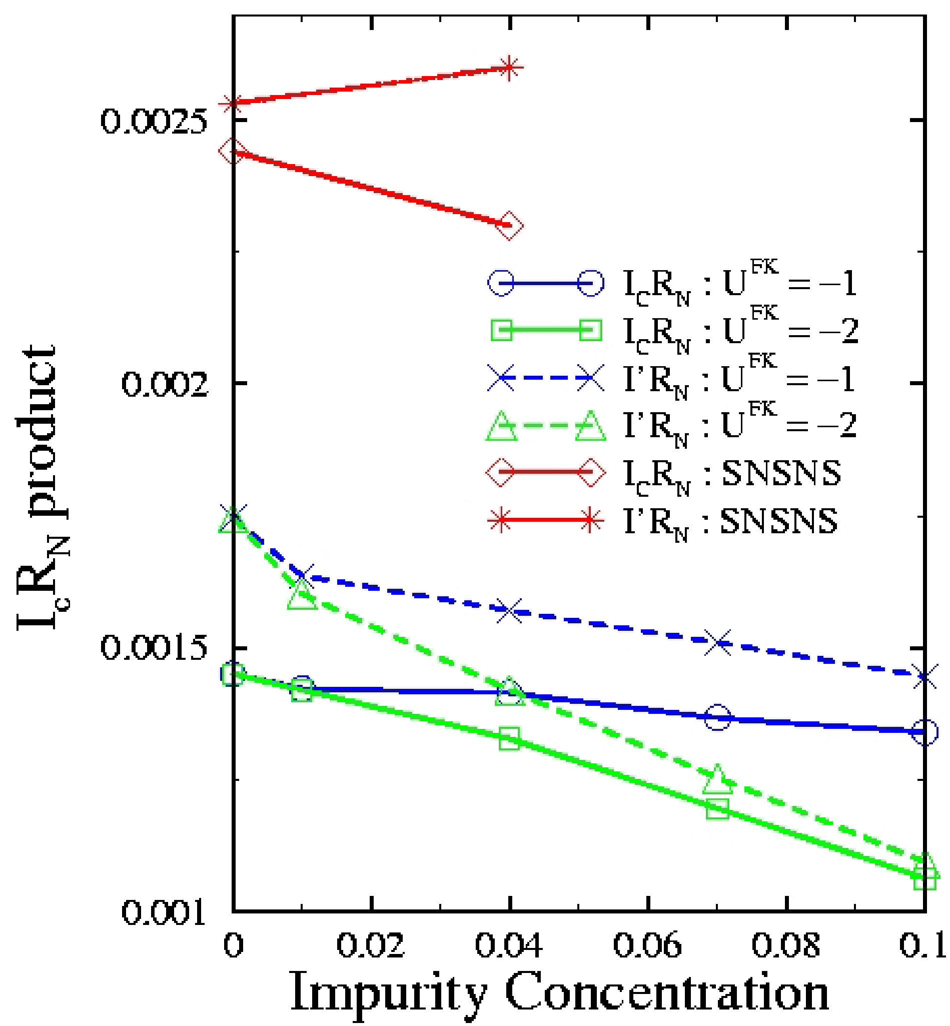
Optimization of IcRn

- For the correlated barriers we can calculate the critical current at zero voltage and the normal state resistance via the Kubo formula. Here our preliminary results are calculating Rn for the bulk barrier, which likely only underestimates Rn in the weakly correlated regime.
- The logarithmic plots show the expected decrease in Ic and increase in Rn, but the product of the two, in general, decreases.
- Hence the Falicov-Kimball model does not show an optimization of IcRn near the MI transition!



Optimization of SNSNS speed

- Ic is determined by the maximal phase gradient that can be carried across the weakest link of the barrier.
- Boosting the SC pairing on the central planes of the barrier can therefore enhance Ic.
- The additional scattering of the new interfaces can compensate for the reduced resistance and produce a net enhancement to IcRn.
- Here we find a large enhancement of IcRn for systems that have no Schottky barrier, but have additional SC planes added in the center of the junction.



Conclusions

- Presented a new formalism that provides an efficient means to self-consistently determine the properties of Josephson junctions from a microscopic model. This allows for the smooth potential associated with charge redistribution to be self-consistently included in the description of a SINIS junction and the many-body effects of correlations to also be included.
- Showed that generically the central plane is the most important plane for determining the critical current as there is a maximal phase gradient that can be put across it. This motivates SNSNS junctions as having higher Ic's and possibly also higher Rn's.
- Scaling phenomenon appears to hold for a number of parameters in the system, but the Ic and Rn values depend crucially on the self-consistency. The stronger the insulating barrier, the more the system generically approaches those described by analytical techniques.
- Proximity to a metal-insulator transition does not always guarantee a maximalization of IcRn. A clearer understanding of the MI transitions that do lead to enhancements of IcRn is needed.