Study of the flux vs critical current relationship in asymmetric superconducting rings

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Introduction

The quantization of the magnetic flux through a superconducting ring dictates that it contains a persistent supercurrent, which switches direction when the magnetic flux normal to the ring Φ is a half-integer multiple of Φ_0, where Φ_0=2h/e is the flux quanta. This characteristic of the persistent supercurrent manifests in critical current and resistance (Little–Parks) oscillations as a function of Φ. In practice, a bias current is sent through the two branches forming the ring and one observes the value at which the ring switches into normal state. The current has thus two components, one that goes across the ring and one that circulates inside the ring (persistent current) and their sum makes that the two branches will see different currents passing through them. Usually, the two branches are symmetric, fact that ensures a certain symmetry of the problem with resulting symmetry in the modulation of the switching current (I_{sw}) vs external flux. Without entering in details, we state here that the modulation curve has important technological applications in the construction of SQUID-based magnetometers; basically its slope determines the flux sensitivity. It is therefore of interest to analyze if there are ways to optimize the I_{sw} vs flux relationship by changing the geometry of the ring. We are analyzing the influence of width and/or length asymmetry between the two branches of the ring and our theoretical analysis predicts an interesting dependence of the switching current vs flux. The modulation curve is no longer symmetric and has a sudden transition between different mathematical solutions.

Experimental

In a recent experiment [1] it was shown that in an asymmetrically connected superconducting ring, the critical current may exhibit anomalous periodic behavior with external magnetic flux, including discontinuous jumps. However, significant inconsistencies exist between experimental and simulation results. We performed an analytical analysis of length and width asymmetry of the two parts of a ring. We will fabricate devices to study these fundamental aspects of transport in persistent currents and the measurements will be performed at NHMFL.

Results and Discussion

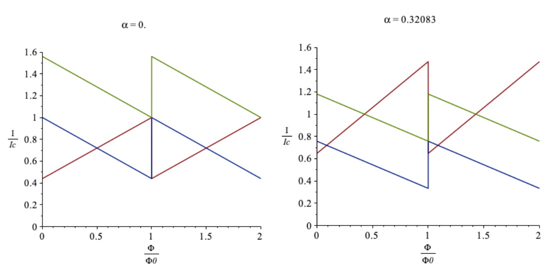

Fig. 1. Switch at $\Phi_0/2$ for the I_{sw} vs flux: with no asymmetry (left), the sequence is blue-red while for large length asymmetry (right), a jump blue-green is expected at $\Phi_0/2$.

The analytical analysis of a ring with asymmetric connections (length asymmetry) and/or unequal cross-sections is based on the well-known relation for flux quantization, which makes use of Cooper pairs velocities in the two branches. At switch, one velocity reaches the critical values, which provides the condition necessary to evaluate the switching current. In Fig. 1, the symmetric case is shown on the left, with a symmetric I_{sw} vs Φ curve (blue-red). For a large enough length asymmetry, the switching current at $\Phi_0/2$ will jump from the blue branch onto the green branch (corresponding to an additional Φ_0 in the loop) instead of the red one. Such discontinuous behavior has never been observed experimentally and can have significant impact in the way superconducting electronics can be used and designed.

Conclusions

We study the multi-valued and discontinuous nature of I_{sw} vs flux in asymmetric rings. Our simulations indicate that the persistent current might not switch direction at the most energetically favorable locations, and the geometric asymmetry could be used to control the switching. Experimentally, asymmetric superconducting rings have been fabricated by electron-beam lithography, and the critical current will be measured and compared with the simulations. The results may find implications in novel superconducting electronics relying on flux quantization such as superconducting qubits and nano SQUIDs.

Acknowledgements

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References

[1] Butrlakov, A.A. *et al*, JETP Lett. **99**, 169 (2014).