Phase Geometry Series — Part I
Resonant Field Symmetry in Superconductors: A Standing-Wave Picture of Meissner Screening and Josephson Barriers

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Abstract

We propose a phase–geometric view of superconductivity that we call *resonant field symmetry.* Instead of treating the Meissner effect, surface screening currents and Josephson weak links as separate ingredients, we model a superconductor as a phase–coherent medium in which electric and magnetic field components form standing structures. In this picture, Meissner screening is understood not as the disappearance of magnetic field inside the sample, but as a rearrangement of a standing wave and surface currents such that the *macroscopic* magnetic flux through the superconductor vanishes, while field energy remains localized within a thin surface layer of thickness λ_L.

Within this language a Josephson barrier or a thick SNS bridge is naturally described as a *phase rotator*: a local region in which the phase flow is turned by a finite angle, and part of the energy can be stored in a localized magnetic configuration around the weak link. The barrier thickness then controls the balance between purely tunneling transport and local magnetic "tension" in this region.

The formalism is meant as a compact effective language on top of the standard Ginzburg–Landau, London–Maxwell and Josephson theory, not as an alternative microscopic model. In the companion paper *Resonant Field Framework and Classical Basis* (Phase Geometry Series — Part I-B) the same objects are introduced in a more technical way, and the phase–flux sensitivity of a weak link is described by a normalized coefficient $\alpha(d,\omega) = (\Phi_0/2\pi)\,\partial\varphi_J/\partial\Phi_{\text{ext}}$, computed within the classical GL/Usadel, London–Maxwell and RCSJ framework for a concrete geometry: a thick SNS weak link driven by a local microcoil. Here we focus instead on an intuitive standing-wave picture of Meissner screening, Josephson barriers and thick weak links as phase rotators with localized resonant field cells.

Standard. All ingredients remain within conventional Ginzburg–Landau theory, London–Maxwell electrodynamics and Josephson phenomenology; no microscopic BCS assumptions are modified, and all observable consequences are consistent with standard superconductivity.
New in this note. A phenomenological standing–wave picture of Meissner screening, the notion of phase rotators and localized resonant field cells, and a qualitative map between barrier thickness, phase–flux sensitivity $\alpha(d,\omega)$ and possible microcoil-based phase-control experiments.

Contents

1 Introduction

The conventional description of superconductors is usually built as a set of separate blocks: London equations for screening currents, Josephson phenomenology for weak links, models of tunneling barriers, and SQUID circuit theory. In this standard approach, Meissner screening, supercurrents and Josephson phase dynamics appear as different effects that must be manually "glued together" when one considers a specific device or geometry.

In this work we propose a phenomenological, more geometric reinterpretation, which we call *resonant field symmetry.* Instead of treating the magnetic field, currents and barriers separately, we view a superconductor as a phase–coherent medium in which the electromagnetic field can form a standing structure. Meissner "expulsion" is then understood not as the absence of field, but as a rearrangement of the standing wave and screening currents such that the *net* flux through the sample is zero.

On this level it is more convenient to speak not about "magnetic field inside" and "current at the surface", but about a phase field $\phi(\mathbf{r})$ that encodes the standing structure. A weak link (a Josephson tunnel junction, an SNS bridge, a nanobridge) is then naturally described as a *phase rotator*: a local region in which the phase flow is turned by a finite angle $\Delta\phi$, and part of the energy can be stored in a localized magnetic configuration around the weak link. The thickness of the barrier controls the balance between purely tunneling transport and local magnetic "tension" in this region.

This language is practically useful because it compresses a complicated configuration of fields and currents into a small number of geometric objects: a phase field $\phi(\mathbf{r})$, rotators (places where the phase is turned), and localized resonant regions — *Resonant Field Cells* — where the field and phase form a standing pattern. For device design this is often enough: one can mentally assemble a "phase circuit" from rotators and standing segments and immediately see where the system stores energy and where it efficiently transmits phase.

At the same time, the present language is not meant to replace microscopic BCS theory or the standard Ginzburg–Landau framework. It is intended as a compact *upper layer* above the familiar theory. In the companion paper *Resonant Field Framework and Classical Basis* (Phase Geometry Series — Part I-B) the same objects are introduced more formally: a phase rotator is identified with a weak link whose normalized phase–flux response

$$\alpha(d,\omega) = \frac{\Phi_0}{2\pi}\,\frac{\partial\varphi_J}{\partial\Phi_{\rm ext}}\Big|_{\omega}$$

is expressed in terms of GL/Usadel, London–Maxwell and RCSJ parameters. There we show, for a particular geometry of a thick SNS weak link with a local microcoil, how one can estimate $\alpha(d,\omega)$ and identify a strong–rotator regime with $|\alpha| \sim 0.3$–0.6.

The present text should therefore be read as a *manifest* and an intuitive introduction to a phase–geometric view of superconductivity. We deliberately use simplified schematics and qualitative reasoning: the goal is to understand how Meissner screening, a Josephson barrier and a thick bridge look if one thinks in terms of standing phase structures and local rotators. Readers who need detailed calculations of $\alpha(d, \omega)$, critical currents or Shapiro step heights can use the companion Part I-B as a "working dictionary", where the resonant field picture is tied to the standard classical theory.

In what follows we proceed as follows. In Sec. 2 we discuss wave geometry and standing symmetry in a simple superconducting cylinder and reinterpret Meissner screening in terms of a standing B-field mode and surface currents. In Sec. 3 we discuss the Josephson barrier as a phase rotator. In Sec. 4 we consider thick weak links and the qualitative emergence of a localized resonant field cell around a bridge. In Sec. 5 we sketch the expected qualitative dependence of the phase–flux coefficient $\alpha(d)$ on barrier thickness and the transition to a strong–rotator regime. In Sec. 6 we outline possible phase-control experiments with local microcoils. Finally, in Sec. 7 we discuss how Manifest I, its Part I-B companion and subsequent Parts II and III of the Phase Geometry Series fit together into a broader phase–geometric framework that also covers phase clocks and weak gravitational fields.

2 Standing-wave symmetry and Meissner screening

We begin with a simple textbook geometry: a long superconducting cylinder in an external magnetic field. In the conventional picture, the London equations imply that the field is expelled from the bulk, decaying on the length scale of the London penetration depth λ_L, while surface supercurrents j_s flow in a thin layer near the boundary. The Meissner effect is then often phrased as "the superconductor expels magnetic field".

In the resonant field picture, we instead think of the cylinder as hosting a standing structure of the electromagnetic field. In the Meissner state the macroscopic flux through the cross-section vanishes, but the field energy is concentrated in a thin surface layer of thickness λ_L, where the magnetic field B and the surface current j_s form a resonant pattern.

Schematically, as shown in Fig. 1, we represent this as two counter-propagating B-waves along the cylinder axis, forming a standing mode, and a surface current j_s flowing along the boundary within a layer of thickness λ_L. The emphasis is not on the exact solution of Maxwell's equations for this geometry, but on the interpretation: the Meissner state is viewed as a standing-wave symmetry between internal field energy and surface current, arranged in such a way that the net flux through the sample vanishes.

From this point of view, a superconducting body is a *phase resonator*. The Meissner effect reflects the ability of the system to adjust its standing phase and field structure to minimize the macroscopic magnetic energy while keeping phase coherence and field energy stored in a thin surface layer.

3 Josephson barriers as phase rotators

In the standard Josephson picture, a weak link between two superconducting banks supports a current–phase relation

$$I_s = I_c \sin \varphi_J, \tag{1}$$

where φ_J is the phase difference between the order parameters on the two sides of the barrier. The barrier thickness and type (SIS, SNS, nanobridge) determine the critical current I_c and the detailed form of the current–phase relation.

In the resonant field language we instead focus on how the phase field $\phi(\mathbf{r})$ is *turned* by the barrier. A Josephson weak link is pictured as a *phase rotator*: a localized region where the phase

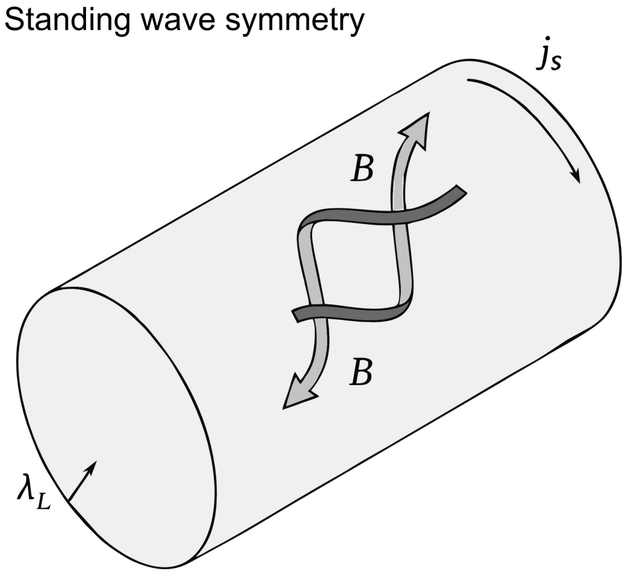

Figure 1: Standing-wave symmetry in a superconducting cylinder. Two counter-propagating components of the magnetic field B form a standing mode inside the sample, while the macroscopic flux is cancelled by a surface supercurrent j_s flowing in a layer of thickness λ_L. The picture is schematic: it is meant to emphasize the standing-wave interpretation rather than provide an exact field profile.

flow changes by a finite angle $\Delta\phi$, and where the standing field structure is allowed to distort and store energy.

Qualitatively, a very thin tunnel barrier corresponds to a sharp phase jump concentrated in a narrow region, with negligible internal field structure: the rotator is "stiff". As the barrier becomes thicker (for instance, in an SNS bridge with thickness $d \sim \xi$), the phase drop is distributed over a larger region and a localized pattern of currents and fields can develop around the weak link. In this regime the weak link behaves as a more "flexible" rotator that can store field energy in a localized resonant field cell.

4 Thick weak links and localized Resonant Field Cells

A key qualitative prediction of the resonant field picture is that thick weak links (for example, SNS bridges with normal-layer thickness d of order the coherence length ξ) can host localized field structures that are much more responsive to external excitation than thin tunnel junctions.

To make this concrete we consider a thin superconducting strip with a central thick weak link and a local microcoil placed above the weak-link region, as in Fig. 2. A DC bias current I_{DC} flows along the strip, while an AC current I_{AC} in the microcoil produces a time-dependent magnetic field $B_{\mathrm{AC}}(t)$ localized near the weak link.

In the resonant field language the weak link plus its surrounding field structure are treated as a compact object: a phase rotator surrounded by a Resonant Field Cell. The cell can support a quasi-standing mode of current and field, which couples the external drive from the coil to the phase across the weak link. The strength of this coupling is characterized by a dimensionless phase–flux coefficient α, defined at the effective level by

$$\delta\varphi_{\mathrm{mag}}(t) = \alpha\,\frac{2\pi}{\Phi_0}\,\Phi_{\mathrm{AC}}(t), \tag{2}$$

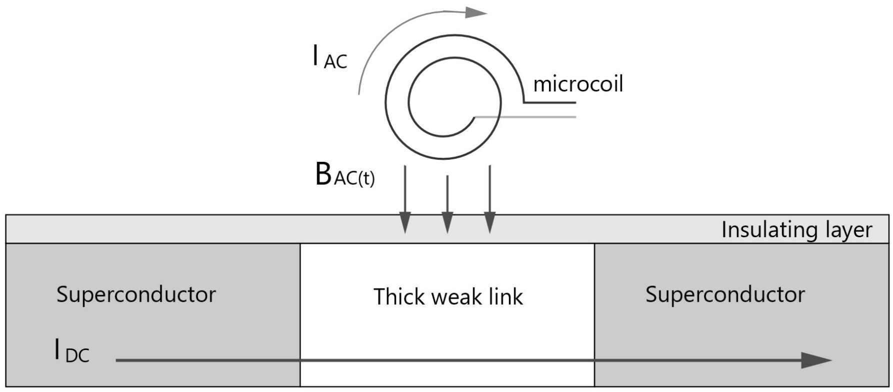

Figure 2: Schematic geometry: a superconducting strip with a central thick weak link and a local microcoil above it. A DC current I_{DC} flows along the strip, while an AC current I_{AC} in the coil generates a local magnetic field $B_{\mathrm{AC}}(t)$ above the weak-link region. The weak link acts as a phase rotator embedded in a localized Resonant Field Cell.

where $\Phi_{\mathrm{AC}}(t)$ is the effective flux seen by the weak link, and $\delta\varphi_{\mathrm{mag}}(t)$ is the magnetic contribution to the Josephson phase.

Thin junctions typically have extremely small $|\alpha|$, so that a local coil produces negligible phase modulation. Thick weak links with a well developed Resonant Field Cell, on the other hand, can in principle reach $|\alpha| \sim 0.1$–1 under resonant excitation, making them strong phase rotators controllable by local microcoils.

5 Qualitative dependence $\alpha(d)$ and the strong–rotator regime

From the resonant field viewpoint the dependence of $|\alpha|$ on the thickness d of the weak link is expected to be non-monotonic:

- For very thin barriers ($d \ll \xi$), the phase drop is sharp and the internal field structure is negligible; the weak link behaves as a very weak rotator with $|\alpha(d)| \ll 10^{-2}$.
- For $d \sim \xi$ (thick SNS bridges), the phase drop is spread over a wider region, a localized standing pattern of currents and fields can form, and the coupling to a local microcoil can increase dramatically. In this regime a well defined Resonant Field Cell appears around the weak link, and $|\alpha(d)|$ can reach values of order 0.1–1 under resonant drive.
- For very large $d \gg \xi$, the superconducting coupling across the weak link is degraded, the cell becomes diffuse and lossy, and $|\alpha(d)|$ is expected to decrease again.

Qualitatively, one can introduce a target range for a *strong rotator* regime,

$$|\alpha_{\mathrm{target}}| \sim 0.3\text{–}0.6, \qquad d \sim \xi, \tag{3}$$

corresponding to a two– to three–order-of-magnitude enhancement of local phase sensitivity compared to the tunnel limit. The detailed shape of $\alpha(d)$ and its frequency dependence $\alpha(d, \omega)$ must eventually be obtained from microscopic calculations or from experiment. In the companion Part I-B the same picture is developed within the classical GL/Usadel + RCSJ framework, and a simple oscillator estimate $\alpha_{\mathrm{res}} \approx \alpha_{\mathrm{static}} Q$ is derived for resonant enhancement of the phase response.

6 Possible phase-control experiments with local microcoils

The resonant field picture suggests a simple and direct experimental test: take a thick SNS weak link (with $d \sim \xi$) embedded in a superconducting strip, place a microcoil above it, and measure coil-driven phase modulation via Shapiro steps or other phase-sensitive signatures.

In the standard Josephson framework, Shapiro steps on the I–V characteristic arise when the phase is driven by an AC voltage at frequency ω, leading to phase locking and quantized voltage plateaus. In the present context, the coil acts as a *magnetic* drive: an AC current $I_{\mathrm{AC}}(t)$ generates an AC flux $\Phi_{\mathrm{AC}}(t)$, which modulates the phase via the phase–flux coupling characterized by α. In a weak rotator ($|\alpha| \ll 10^{-2}$), coil-only drive produces negligible Shapiro steps; in a strong rotator ($|\alpha| \sim 0.3$–0.6), the same drive produces clearly visible steps, even without a direct RF voltage on the junction.

An experiment of this type would provide a direct measurement of $\alpha(d)$ for different weak-link thicknesses, and would test the qualitative prediction that thick SNS bridges can act as strong phase rotators. A more detailed design and analysis of such an experiment is the subject of the companion device-oriented work *Magnetic Phase Control of a Thick SNS Weak Link*, which builds on both the present Manifest I and the classical framework of Part I-B.

7 Outlook and relation to the Phase Geometry Series

In this Manifest I we have introduced the idea of *resonant field symmetry* as an intuitive, standing-wave picture of superconducting screening and weak links. Superconductors are treated as phase resonators, Josephson barriers as phase rotators, and thick weak links as centers of localized Resonant Field Cells that can strongly couple local magnetic excitation to the Josephson phase.

The present work is deliberately phenomenological and device-oriented. The companion paper *Resonant Field Framework and Classical Basis* (Phase Geometry Series — Part I-B) develops the same ideas in a more technical form for a concrete system: a thick SNS weak link driven by a local microcoil. There the phase–flux coefficient $\alpha(d, \omega)$ is defined as a calculable response function within the GL/Usadel, London–Maxwell and RCSJ framework, and the strong–rotator regime $|\alpha| \sim 0.3$–0.6 is identified as a realistic target for resonant SNS structures.

In *Phase Geometry Series — Part II* we take a different step: the macroscopic phase is embedded into a five-dimensional phase-fibre geometry of Kaluza–Klein type, and used as a time-keeping variable for *phase clocks* in weak gravitational fields. There we derive a phase-rate law $d\varphi/dt = \omega_0\sqrt{-g_{00}}$ and apply it to the gravitational redshift of Josephson frequencies and rotation-induced phase shifts in SQUIDs. In *Phase Geometry Series — Part III* we further develop a phase-field version of Newtonian gravity, where gradients of a phase field act as an effective mass density sourcing the usual Poisson equation, and phase clocks probe the resulting potential.

Together, Manifest I, its Part I-B companion and Parts II–III of the Phase Geometry Series provide three complementary layers: a phenomenological standing-wave picture of superconducting structures, a classical GL/London/RCSJ dictionary for phase rotators and resonant cells, and a phase-geometric framework that connects macroscopic coherence to weak gravitational and inertial effects.

- an *intuitive* standing-wave and rotator picture of superconducting coherence (Manifest I);
- a *calculational* framework that ties this picture to the standard GL/Usadel + London–Maxwell + RCSJ theory and to measurable quantities such as $\alpha(d, \omega)$ (Part I-B);
- a more *geometric* viewpoint in which phase and electromagnetic structure are embedded into an extended spacetime-like geometry used for phase clocks and weak gravity (Parts II and III).

The goal is not to replace the existing theories, but to provide a coherent phase–geometric language that makes it easier to think about, design and generalize superconducting devices and phase-based clocks. The resonant field symmetry introduced here is the first step in that direction.

Acknowledgements

References

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