PhaseGeometry Resonance Programme: Operational Phase Framework for Superconducting and Quantum Devices

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Abstract

The PhaseGeometry Resonance programme provides an operational phase-based language for superconducting and quantum devices. Instead of treating each device (Josephson junctions, SNS weak links, SQUIDs, tunnelling diodes, mesoscopic interferometers) with a separate collection of models, the Resonance framework describes them as phase rotators, phase meters and resonant field cells characterised by a small set of effective parameters. This note summarises the rôle of the Resonance layer within the broader PhaseGeometry architecture and explains five concrete advantages of this language: (i) unification and compression of device descriptions, (ii) a clear figure of merit based on the phase–flux coupling coefficient $\alpha(d,\omega)$, (iii) a clean interface to the Z_2 and Phase-Fibre (5D) branches, (iv) direct experimental testability via thick SNS phase-rotator devices, and (v) a conceptual shift from "SQUID-only" phase control to strongly localised phase rotators.

1 Resonance within the PhaseGeometry architecture

The PhaseGeometry programme consists of three main branches:

- the *Resonance* series, which introduces an operational phase-based description of superconducting and quantum devices in standard $3+1$-dimensional physics (Maxwell, London, Josephson, proximity effect);
- the *Phase-Fibre* (5D) series, in which phase is promoted to a genuine geometric coordinate ϕ on a compact fibre, leading to a five-dimensional description of gravity, electromagnetism and phase clocks;
- the Z_2 series, where a binary phase medium provides a unified dark sector and quantum-foundational substrate.

In this architecture the Resonance layer plays a specific rôle:

- it is formulated entirely in standard condensed-matter and electromagnetism language (no explicit Z_2 or 5D assumptions);
- it provides a compact operational dictionary for devices: superconductors are phase media, weak links are phase rotators, local standing-wave configurations of fields and currents are resonant field cells, and the phase–flux coupling is encoded in a single coefficient $\alpha(d,\omega)$;

- it is explicitly designed to be embeddable into both the Z_2 and Phase-Fibre (5D) branches: once devices are written in this common phase language, they can be reinterpreted as effective manifestations of either a binary phase medium or a 5D phase fibre.

The aim of this note is to clarify *why* such an intermediate Resonance layer is useful and what concrete advantages it offers over a collection of device-specific models.

2 Advantage I: Unification and compression of device descriptions

In conventional device physics each superconducting or mesoscopic element typically comes with its own model:

- Ginzburg–Landau and London theory for bulk superconductors;
- Usadel or Eilenberger equations for diffusive weak links;
- RCSJ-type models for Josephson junction dynamics;
- device-specific treatments for SQUIDs, resonators, hybrid structures, and so on.

While each model is well established, the conceptual landscape quickly becomes fragmented. It is not obvious, for example, how to place a thick SNS weak link, a Dayem bridge, an Esaki diode and an Aharonov–Bohm ring into a single schematic framework without diving into their microscopic details.

The Resonance framework instead operates with a deliberately small set of phase-based objects:

- a *phase field* $\phi(\mathbf{r}, t)$ representing the superconducting order parameter phase or an effective phase of a transport mode;
- a *phase rotator*: a local region where the phase changes by some amount $\Delta\phi$ in response to an applied drive (voltage, current, magnetic flux, RF field);
- a *resonant field cell*: a local standing-wave configuration of currents and fields associated with the phase rotator;
- a *phase–flux coupling coefficient* $\alpha(d, \omega)$, which quantifies the efficiency with which external fields or flux modulate the phase across the rotator.

In this language:

- a standard Josephson junction is a simple phase rotator with moderately weak coupling α;
- a thick SNS weak link with an on-chip microcoil is a potentially *strong* phase rotator with $|\alpha| \sim 0.3$–0.6;
- a SQUID loop with two junctions is a phase interferometer (phase meter) built from two rotators in a global flux quantisation condition;
- more exotic devices (Esaki diodes, resonant-tunnelling diodes, Aharonov–Bohm rings, quantum point contacts) can be added to the "phase-device zoo" as normal-state phase rotators or phase meters.

The key point is that many devices can be described *schematically* with the same few building blocks, and the microscopic diversity is compressed into the calibration of $\alpha(d, \omega)$ and related effective parameters.

3 Advantage II: A clear figure of merit via $\alpha(d, \omega)$

In standard superconducting device discussions one often hears that a given weak link is "small", "moderately sensitive" or "strongly coupled" without a universal quantitative comparator. The Resonance framework introduces a clean figure of merit:

$$\alpha(d, \omega) \; = \; \frac{\Phi_0}{2\pi} \frac{\partial \phi_J}{\partial \Phi_{\text{ext}}} \bigg|_{d,\omega}, \tag{1}$$

where ϕ_J is the phase difference across the weak link, Φ_{ext} is an external magnetic flux (or more generally a local field integrated over a suitable area), Φ_0 is the flux quantum, d is a characteristic thickness or length of the active region, and ω labels the drive frequency.

This dimensionless coefficient encapsulates how efficiently an external field or flux drives the phase across the device:

- $|\alpha| \ll 10^{-2}$ corresponds to a *weak* phase rotator: the phase is only slightly modulated, and the device acts more like a passive element;
- $|\alpha| \sim 10^{-1}$–1 corresponds to a *strong* phase rotator: local fields can produce large phase excursions and strong modulation of the supercurrent.

In the thick SNS with microcoil proposal developed in the Resonance series, one finds that realistic geometries can achieve $|\alpha| \sim 0.3$–0.6, comparable in phase efficiency to a well-designed SQUID loop but in a compact, local geometry. The same $\alpha(d, \omega)$ becomes a unifying figure of merit across different devices, allowing direct comparison of how "phase-active" they are, independent of microscopic details.

4 Advantage III: Interface to Z_2 and Phase-Fibre (5D) branches

The Z_2 and Phase-Fibre (5D) branches of PhaseGeometry are interpretational and structural extensions:

- the Z_2 programme treats the world as a binary phase medium with cosmological and quantum-foundational consequences;
- the Phase-Fibre programme promotes phase to a fifth coordinate ϕ on a compact fibre, giving a Kaluza–Klein-like unified picture of gravity, electromagnetism and phase clocks.

Both branches need a way to connect to *real laboratory devices*. The Resonance framework provides this bridge:

- it packages devices into phase rotators, phase meters and resonant cells with well-defined phase fields and couplings $\alpha(d, \omega)$;
- once this is done, the same devices can be reinterpreted as probes of a binary Z_2 phase medium or as trajectories in a 5D phase fibre;
- derivations of Josephson-like relations, gravitational redshift of phase clocks, and Sagnac-type phase shifts become statements about how the Z_2 medium or 5D geometry affects the phase rate and phase coupling in the operational layer.

In this sense the Resonance series is the *shared device layer* for both deeper branches: it keeps the device physics grounded in standard SC/EM theory while making it immediately compatible with the higher-level PhaseGeometry structures.

5 Advantage IV: Direct experimental testability

A crucial strength of the Resonance framework is that it is not only a conceptual language but also a basis for *concrete experimental proposals*. In particular, the thick SNS phase-rotator scheme with a local microcoil provides:

- a fully standard setup in terms of materials and fabrication: a superconducting strip, a $\sim 500\,\mathrm{nm}$ long diffusive SNS weak link, and a micron-scale on-chip spiral coil;
- a clear experimental protocol: drive the coil at microwave frequencies and compare the resulting Shapiro-step pattern (phase modulation induced by the coil) to that produced by a conventional RF drive applied to the junction;
- a direct extraction of $\alpha(d, \omega)$ from the relative height of magnetically driven and RF-driven Shapiro steps.

If the measured $\alpha(d, \omega)$ reaches the predicted $|\alpha| \sim 0.3$–0.6 regime, this would confirm that strongly localised phase rotators are experimentally feasible. If not, the same framework provides a clear target for refining designs or revising assumptions.

This experimental anchoring makes the Resonance layer *falsifiable* and practically relevant: it is not merely an abstract rephrasing, but a way to design and test new classes of phase-sensitive devices.

6 Advantage V: Conceptual shift beyond SQUID-only phase control

In the traditional picture, strong magnetic control of superconducting phase is typically associated with macroscopic loops:

- SQUIDs, where the phase difference is tied to the total flux through the loop;
- extended superconducting rings in Sagnac-type configurations.

The Resonance framework reframes this intuition. By focusing on local phase rotators and resonant field cells, it highlights that:

- strong phase control does not require a large loop; it can be achieved in a compact, locally driven region (e.g. a thick SNS with microcoil), provided the geometry and frequency place the system in a high-Q, large-α regime;
- loops and rings (SQUIDs, superconducting interferometers) then appear as *global constraints* on networks of local rotators, rather than the only way to access phase;
- the line between "interferometric" devices (SQUIDs, AB rings) and "local" devices (weak links, rotators) becomes more fluid: both are built from the same phase elements, arranged differently.

This conceptual shift is modest but important. It opens the door to:

- designing new families of compact, strongly phase-sensitive devices that do not rely on large loops;
- thinking of circuits and lattices of phase rotators as programmable phase media, which is particularly relevant for both the Z_2 and Phase-Fibre branches;
- using the same language to compare and combine devices from superconducting, normal-state and mesoscopic domains within the phase-device zoo.

7 Outlook

The current Resonance framework already:

- unifies superconducting weak links, SQUIDs and related devices as phase rotators and phase meters;
- provides a clear figure of merit $\alpha(d, \omega)$ for phase coupling strength;
- supports concrete experimental proposals, particularly thick SNS phase-rotator devices;
- interfaces cleanly with both the Z_2 and Phase-Fibre (5D) branches of PhaseGeometry.

Future work can extend this operational layer in several directions:

- incorporating normal-state devices (Esaki, RTD, Gunn, IMPATT) and mesoscopic interferometers (Aharonov–Bohm rings, QPCs, SETs) into a fully developed phase-device zoo, calibrated via normal-state analogues of $\alpha(d, \omega)$;
- constructing networks of phase rotators and meters as programmable phase media, providing a circuit-level laboratory analogue of Z_2 and 5D phase structures;
- integrating more detailed microscopic calculations (Usadel, NEGF, microscopic Josephson theory) into the calibration of $\alpha(d, \omega)$ and related effective parameters, reinforcing the link between the Resonance layer and standard condensed-matter theory.

In summary, the Resonance programme is not a replacement for existing microscopic models, but a compact operational layer that makes the phase nature of devices explicit, quantifiable and transferable across domains. It is this layer that allows PhaseGeometry to speak simultaneously to experimental device physics and to its own deeper Z_2 and Phase-Fibre structures.