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Influence of the superconducting ground plane on the performance of RSFQ cells

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1. Introduction

The current return paths of the dc bias line and associated magnetic field can unexpectedly shift the point of operation and lead to a reduction of bias margins. The specific position of the dc bias pads on the superconducting chip can lead to different operation margins of the digital circuit.

In order to take into account these intrinsic features associated to the geometry of the circuits we studied the JTL with different geometric configurations of the ground plane and bias pads. We found with the use of InductEx that the return current follow paths that are far from what intuition tells, which can lead to non optimised designs.

2. Algorithm

The inductance values and mutual coupling was calculated mathematically by defining three superconducting loops in the JTL and using Kirchhoff's voltage law to solve the set of linear equations.

The first loop connects both junctions through to ground, and the other two connect the bias port with each junction through to ground.

$$\begin{bmatrix} I_1 & -I_1 & 0 \\ I_2 - I_1 & 0 & I_1 \\ 0 & I_1 - I_2 & -I_1 \end{bmatrix} \begin{bmatrix} M_{12} \\ M_{13} \\ L_{gvb} \end{bmatrix} = \begin{bmatrix} L_1 I_3 - L_2 I_2 \\ L_2 I_2 - \frac{1}{j\omega} \\ -L_3 I_3 + \frac{1}{j\omega} \end{bmatrix}$$

Here M12 and M13 are defined as the mutual inductance between L2, L3 and the bias inductance, see Fig. 2.

3. Ground plane configuration

- The bias pads are distributed around the periphery of the ground plane.
- The coupling factor is the largest when the current direction from the bias port to the ground contact is parallel with the current flow in the inductor.
- Since the JTL is a very stable circuit, we increased the bias current exponentially to observe the effect the return current has on the circuit margins, see Fig. 5.
- The return current in the ground plane follows the path directly under the circuit back to the bias port and then spreads to the ground contact.
- The current in the ground plane tends to spread out to the sides of the plane, as shown in Fig. 3.

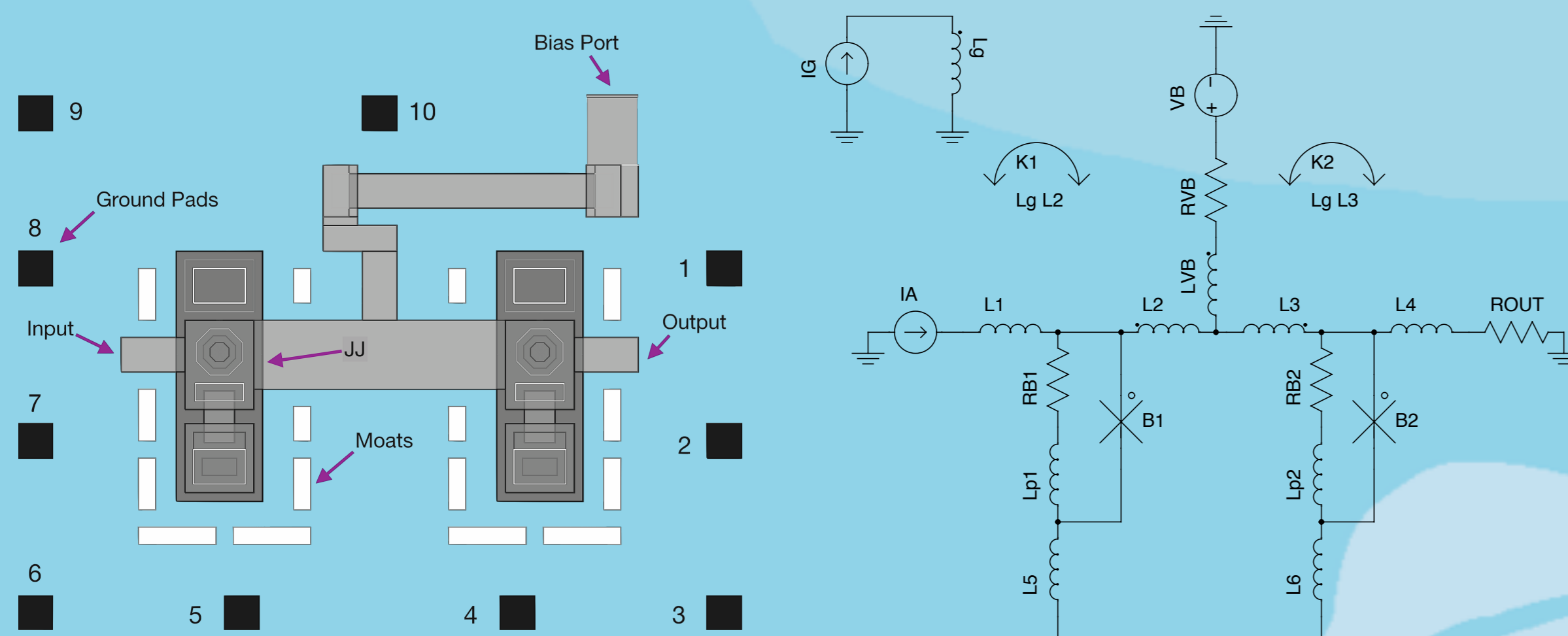


Fig 1, Basic IPHT JTL layout with ground contacts added around the periphery of the ground plane, numbered 1-10.

Fig 2, JTL schematic with the current induced by the external magnetic field IG. The coupling between Lg - L2 and Lg - L3 is given by K1 and K2, respectively.

Acknowledgements

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3. External magnetic field

- The magnetic fields was calculated using our in-house tool, Magix.
- The magnetic field magnitude was plotted from the top view, to analyse the effect that the external magnetic field has on the circuit's magnetic field.
- Since the JTL is a very stable circuit, we increased the bias current exponentially to observe the effect the return current has on the circuit margins.
- The external magnetic field can be represented in JSIM by a current through an inductor that has a mutual coupling with a the circuit inductance loops, shown in Fig. 2.
- The coupling factors of L2 and L3 with the bias line or external magnetic field is equal but with opposite signs, because they are identical in size and form part of the same loop.

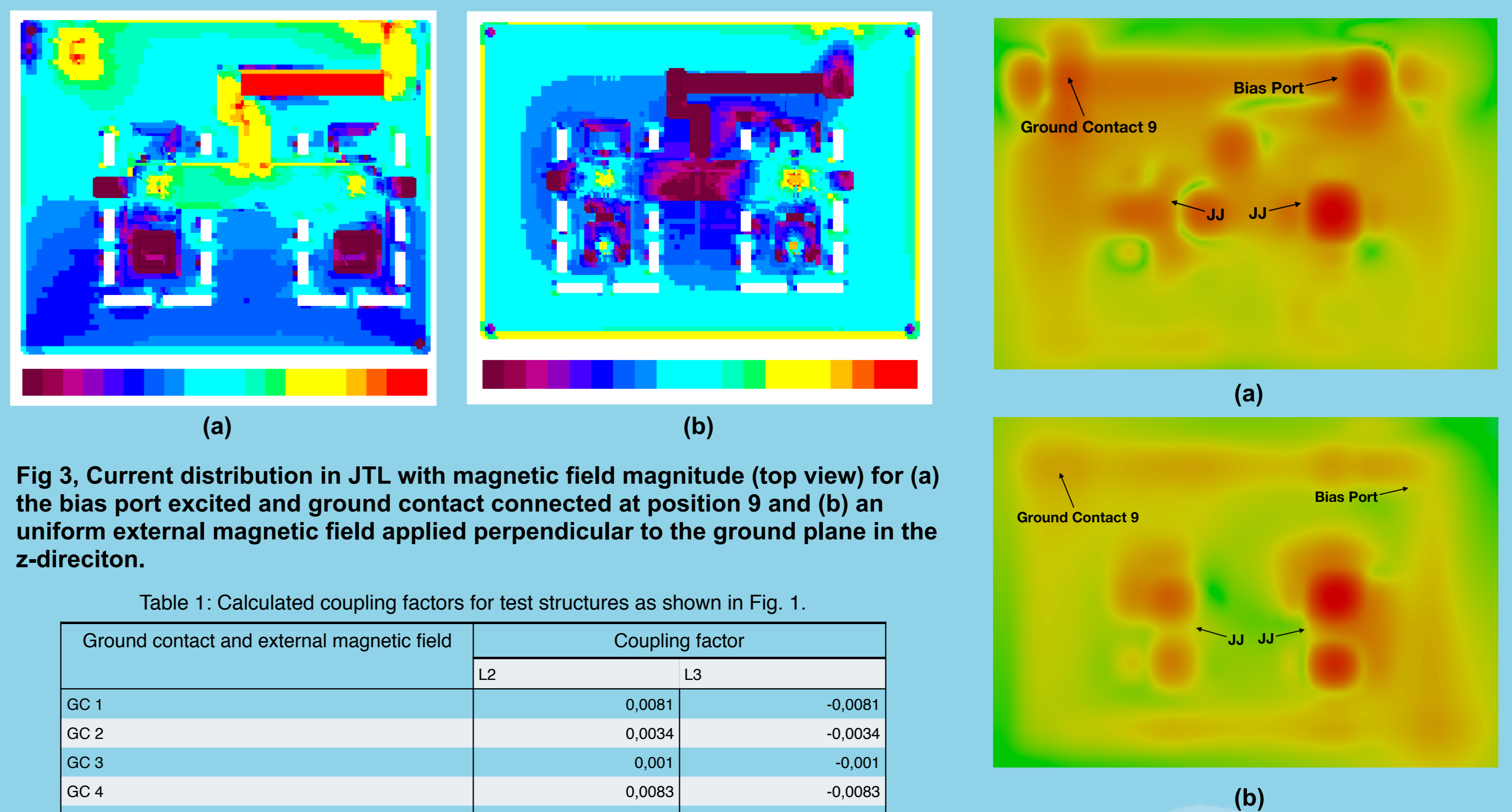


Fig 3, Current distribution in JTL with magnetic field magnitude (top view) for the bias port excited and ground contact connected at position 9 and (b) an uniform external magnetic field applied perpendicular to the ground plane in the z-direction.

Table 1: Calculated coupling factors for test structures as shown in Fig. 1.

Ground contact and external magnetic field	Coupling factor	
	L2	L3
GC 1	0,0081	-0,0081
GC 2	0,0034	-0,0034
GC 3	0,001	-0,001
GC 4	0,0083	-0,0083
GC 5	0,0287	-0,0287
GC 6	0,0326	-0,0326
GC 7	0,04	-0,04
GC 8	0,04	-0,04
GC 9	0,044	-0,044
GC 10	0,0214	-0,0214
Ext Mag in the z-direction	0,148	-0,148

Fig 4, Magnetic field magnitude (top view) for (a) the bias port excited and ground contact connected at position 9 and (b) an uniform external magnetic field applied perpendicular to the ground plane in the z-direction.

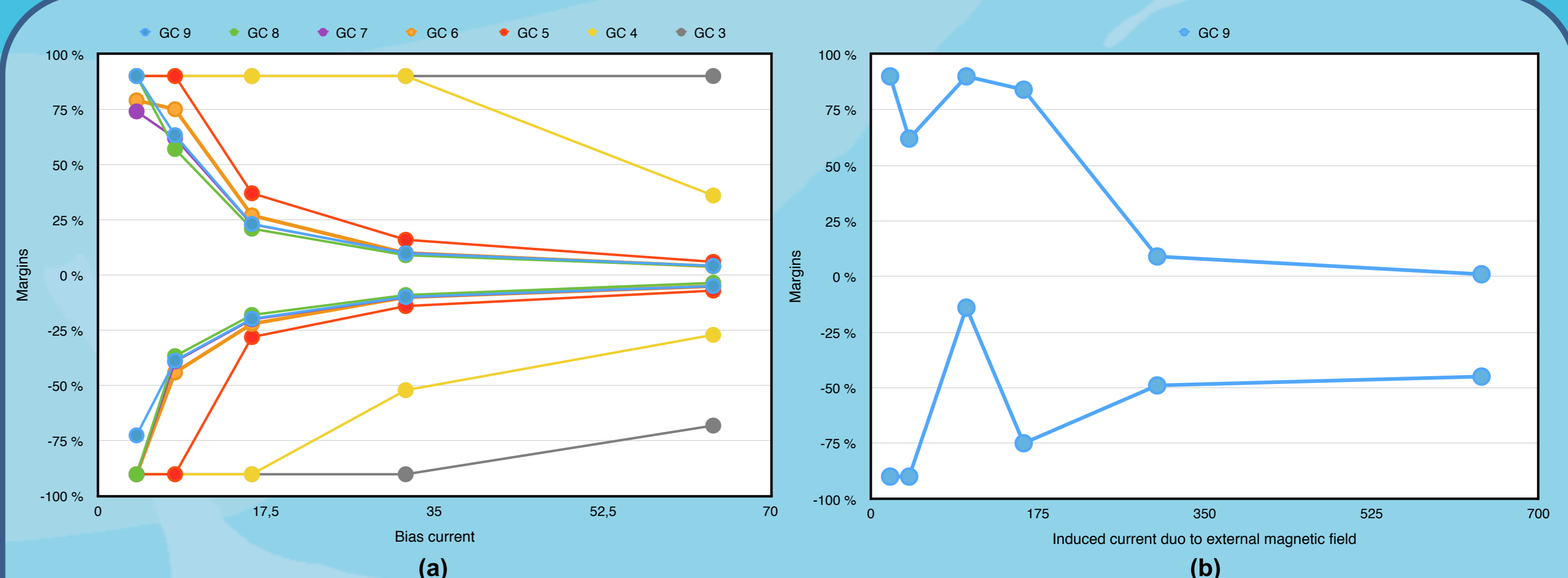


Fig 5, Circuit margin analyses for inductor L2 as the bias current changes (L3 has similar results), where (a) the margins change as the ground contact are placed at different locations around the ground plane, and (b) the margin analyses of L2 with the external magnetic field applied.

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