Physics 108 Presentation

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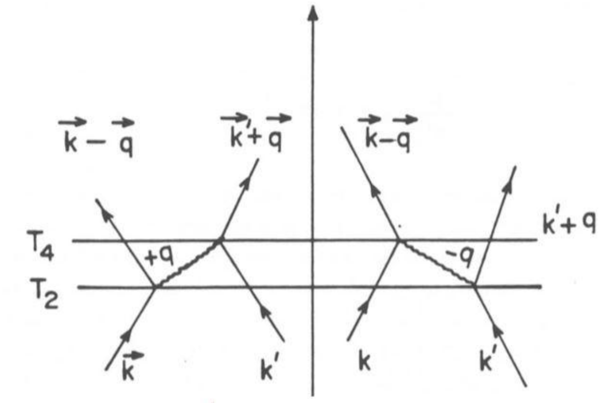
Presentation Outline

- Introduction to Superconductivity and SLUGs
- What can you measure?
  - Original goal and final measurements
- Overview of Experimental Procedure
- Experimental Design
  - Solder blog jig
  - Probe, SLUG/BNC mount
  - Wire cutting jig
  - Electronics and data acquisition
- Results
- Discussion
- Outlook

Introduction to Superconductivity



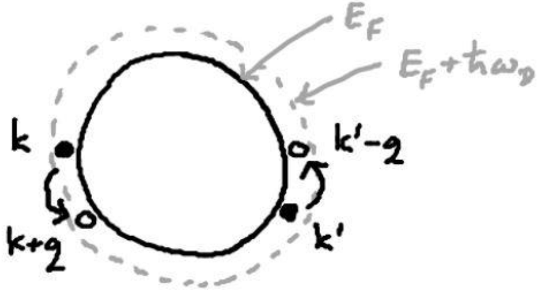
$$\Delta E = \frac{g_q^2}{(E_k + E_{k'}) - (E_{k-q} + E_k + \hbar\omega_q)} + \frac{g_q^2}{(E_k + E_{k'}) - (E_{k+q} + E_k + \hbar\omega_{-q})}$$

apply conservation of energy

$$\implies V_{eff} = \frac{2\hbar\omega_q g_q^2}{(E_k - E_{k-q})^2 - \hbar^2\omega_q^2}$$

notice this is negative if $|E_k - E_{k-q}| < \hbar\omega_q$

Thus, there is an **attractive** interaction if the change in electron energy is small relative to phonon energy.



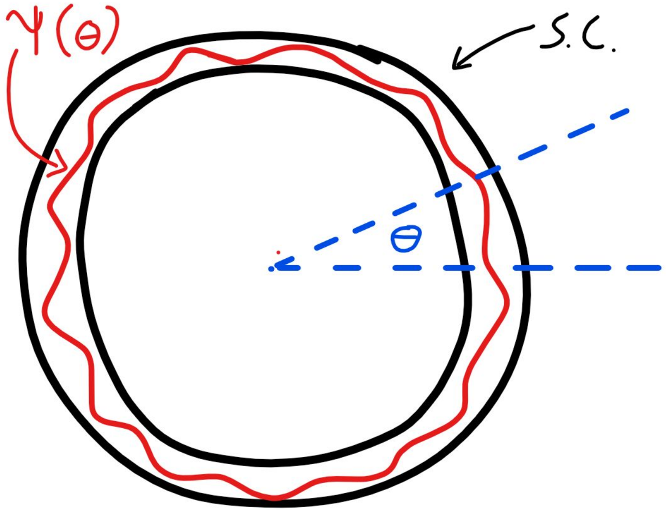
T increases, thermally populate of states -> fewer states to participate in pairing.

The BCS wavefunction is in a singlet state. Thus, since an applied field will try to align spins, B will be expelled.

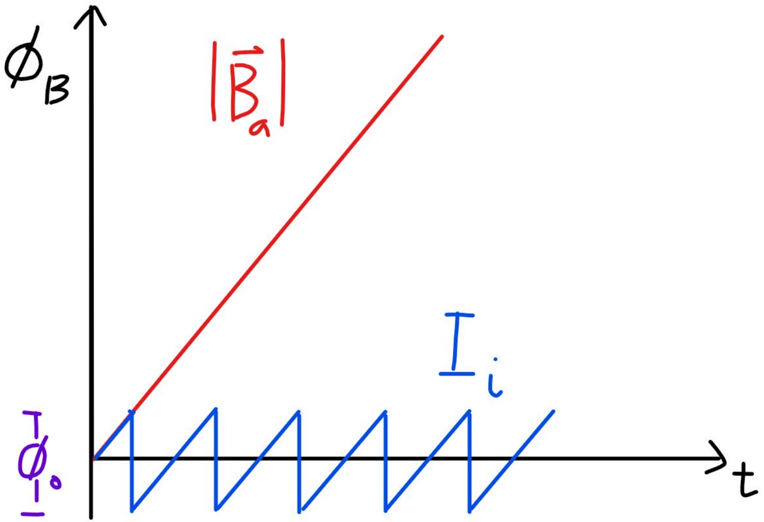
With an applied current, fermi surface will shift, allowing fewer states to participate in pairing.

Introduction to Superconductivity

The BCS wave function is macroscopic, which imposes macroscopic continuity requirements on the state. This leads to fluxoid quantization.



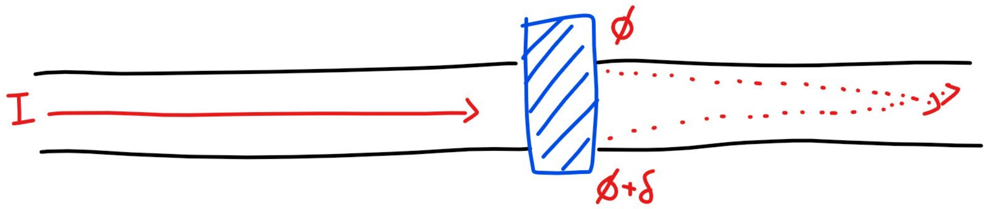
As B is applied to a SC ring, fluxoid quantization will induce a current in the ring with periodicity given by the inductance between the ring and the source of B.

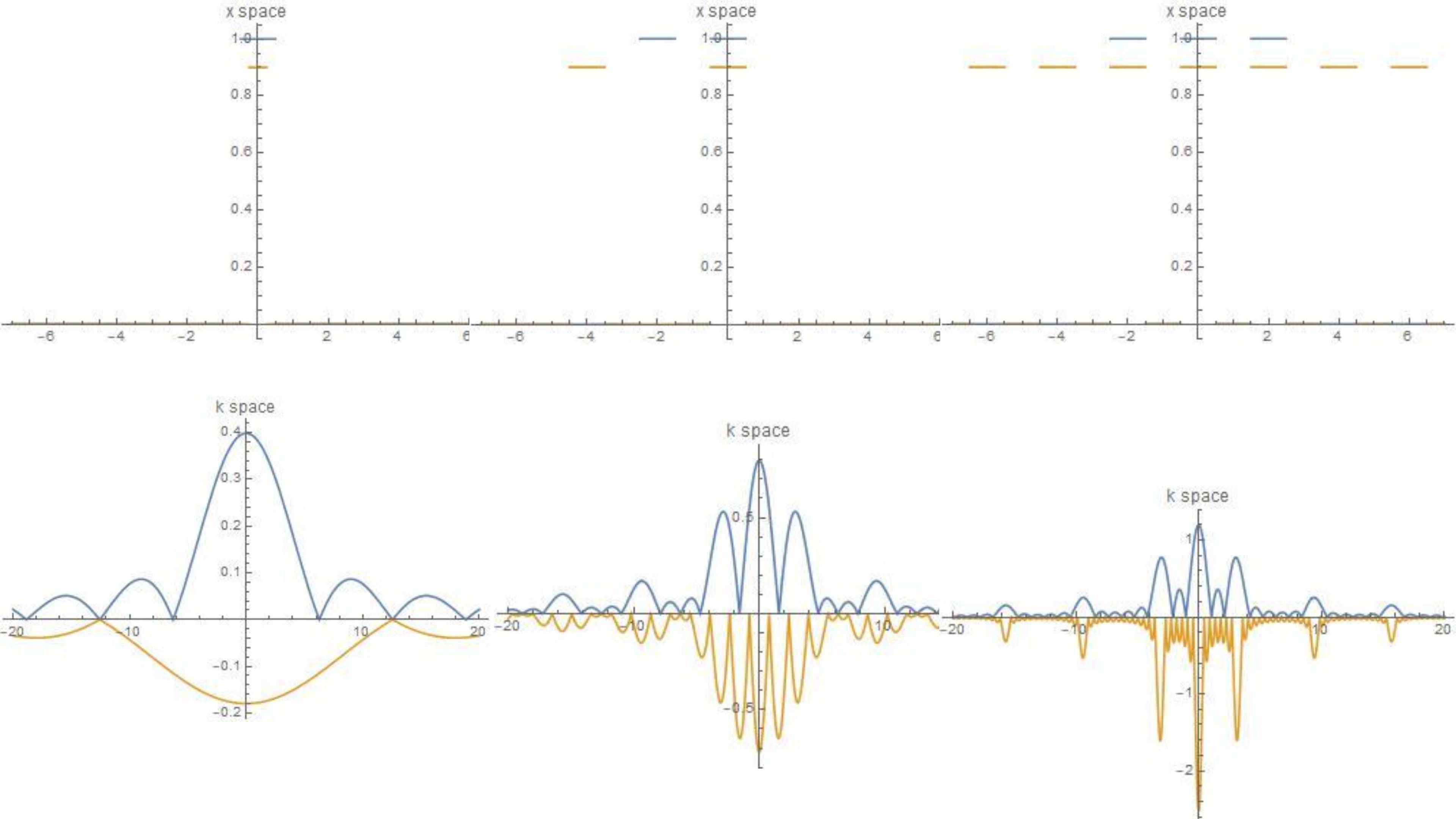


Weak Link - Josephson Junction

If you insert a weak link between two superconductors, cooper pairs may tunnel across the junction, preserving superconducting behavior. At a specific current (Ic), the junction will enter a resistive phase. Under an applied field, it is possible to modulate this Ic.

Due to coherence of the macroscopic wave function, it is possible for a weak link to exhibit interferometric properties. Analogously, multiple weak links in parallel will exhibit interference, in almost exact analogy to coherent laser light going through an aperture pattern.




x space
x space
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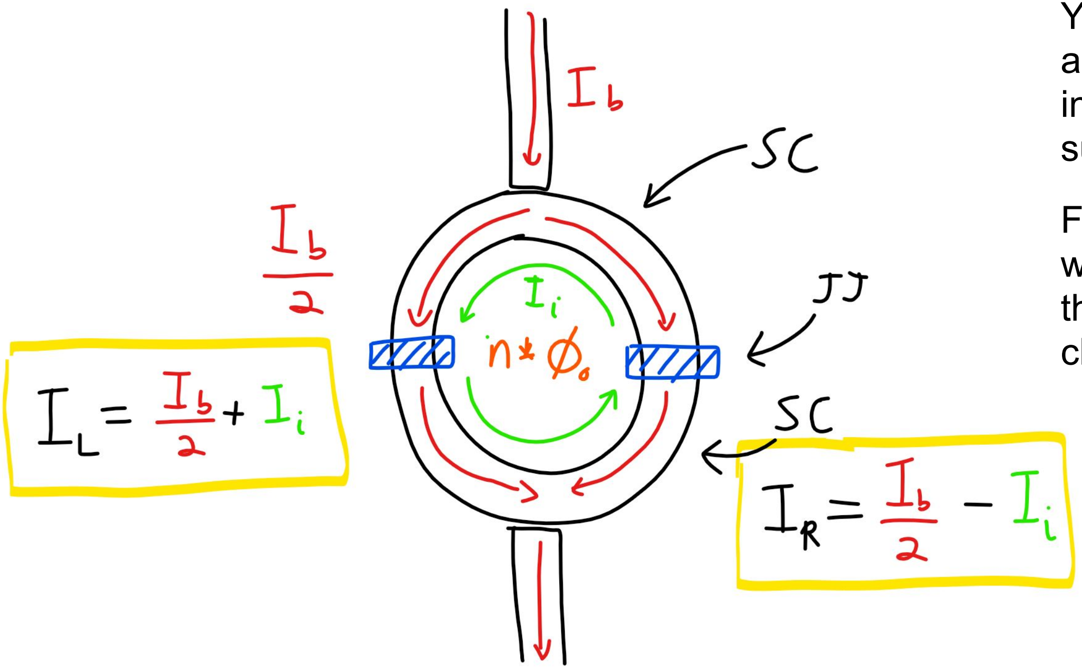
k space

Constructing a SQUID

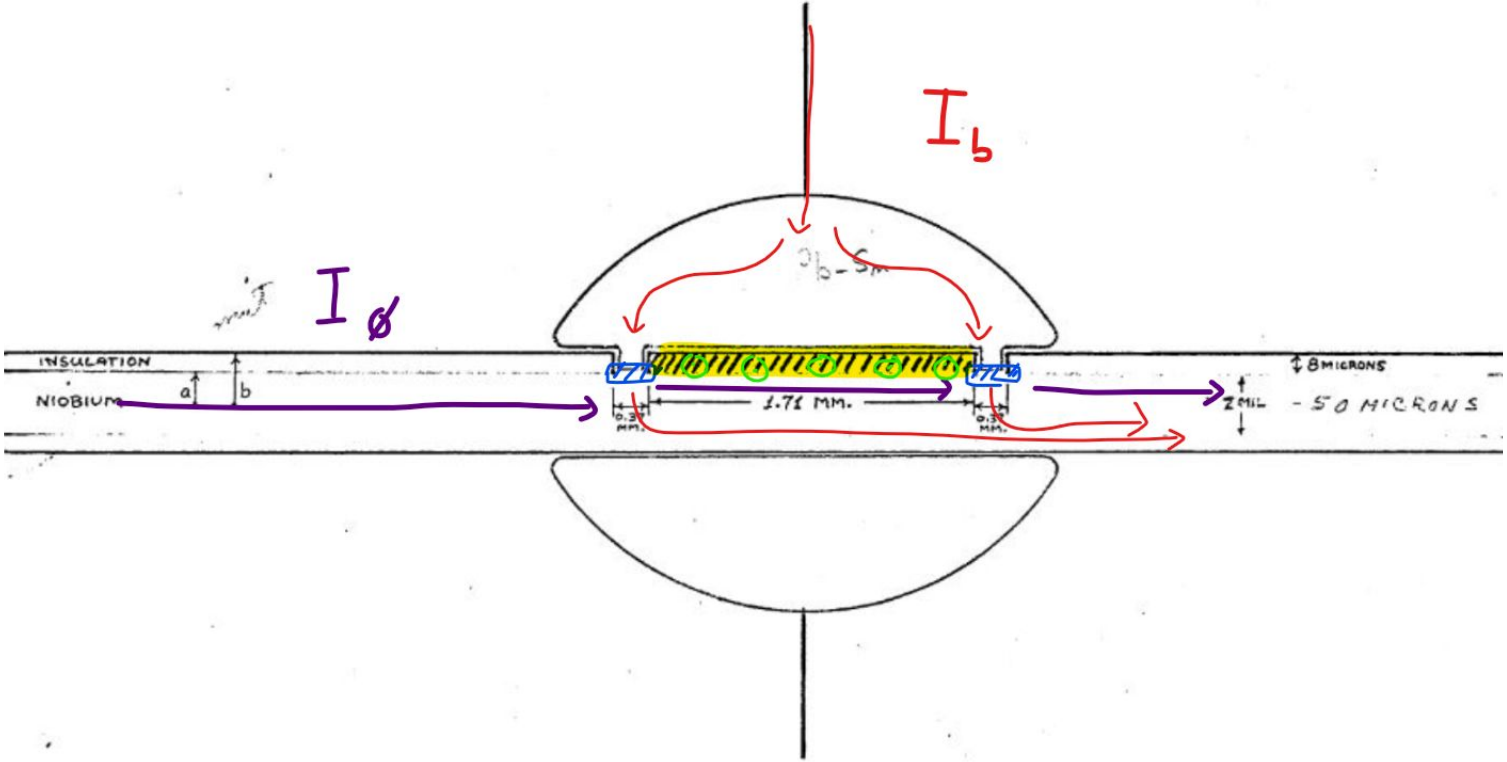
In general, you need two pieces of superconductors arranged in a certain topology with Josephson junctions interrupting the superconductor.



You can also imagine interference arising from the bias current and induced current adding or subtracting from one another.

For large enough bias current, you will pass through Ic as you change the flux penetrating the loop, which changes the induced current.

From SQUID to SLUG



Notice some of the bias current will also flux bias the junction due the asymmetry of grounding the Nb wire.

What can you measure?

Purely geometric considerations

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Calculate mutual inductance between flux bias wire and SLUG

↓

Change I bias to measure periodicity of critical current

↓

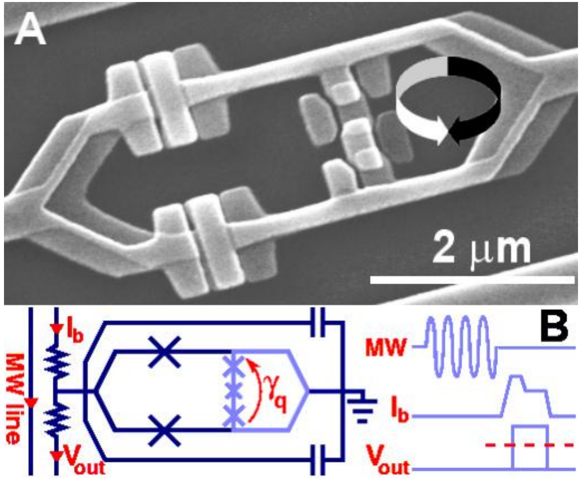
Extract value of flux quantum

$$\Phi_0 = \frac{h}{2e}$$

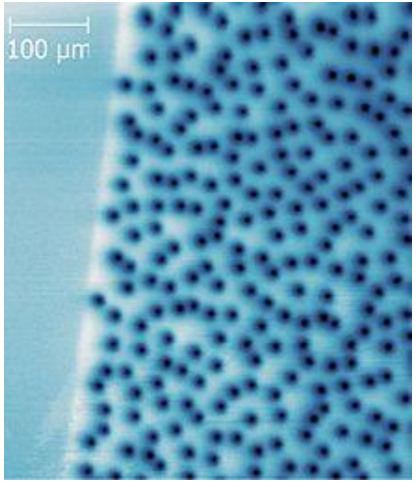
With window size and window spacing, should see a difference in the diffraction pattern.

~Outside the scope of our project~

Flux/Phase Qubits



Magnetic Imaging



Original Measurement Plan

Using the method above, we can **measure the flux quantum** with a two-windowed SLUG.

It would be interesting to see how the modulation patterns depends on the **size and spacing of junctions.**

Adding **several junctions** also changes the modulation pattern.

Critical current should show some **temperature dependence** - requires thermometry.

Optimize wiring and probe design to **reduce noise**.

Optimize geometry of SLUG connections and windows to make a **symmetric SLUG**.

Measurement Results

~ Using the method above, we can **measure the flux quantum** with a (two-windowed?) SLUG ~

Critical current should show some **temperature dependence** - ~~requires thermometry~~.

~~It would be interesting to see how the modulation patterns depends on the **size and spacing of junctions.**~~

~~Optimize wiring and probe design to **reduce noise**~~.

~~Adding **several junctions** also changes the modulation pattern.~~

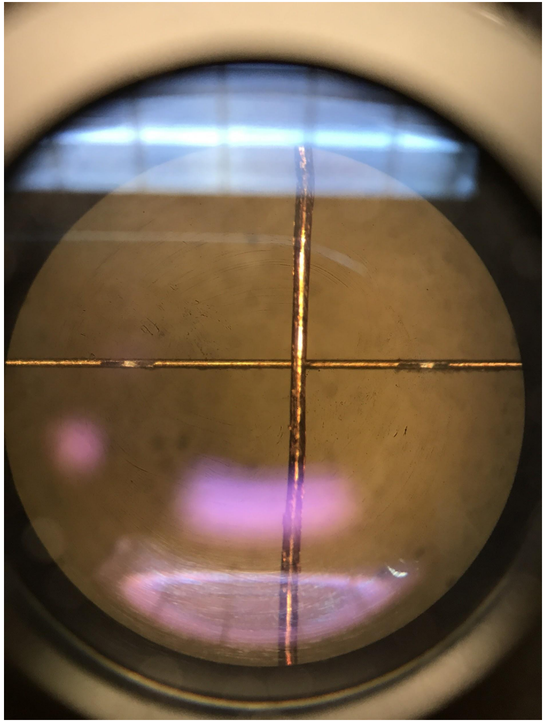
~~Optimize geometry of SLUG connections and windows to make a **symmetric SLUG**~~.

Best laid plans...

Overview of Experimental Design

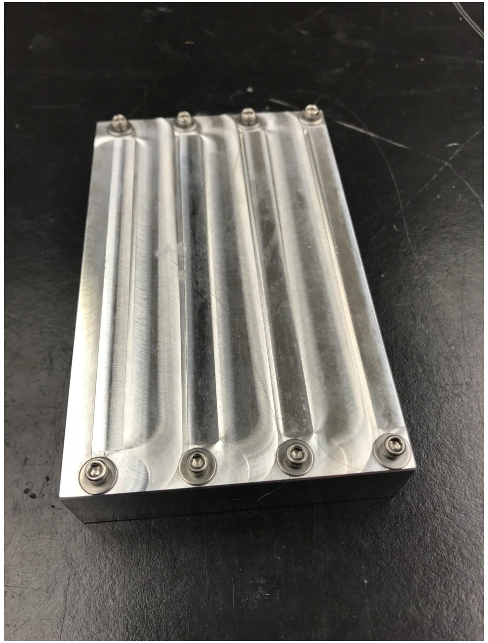
1. Nb, Cu crossover, encapsulated within solder blob

    - Nb ends stripped with Strip_X for electrical connection
    - Cu stripped carefully with razor blade



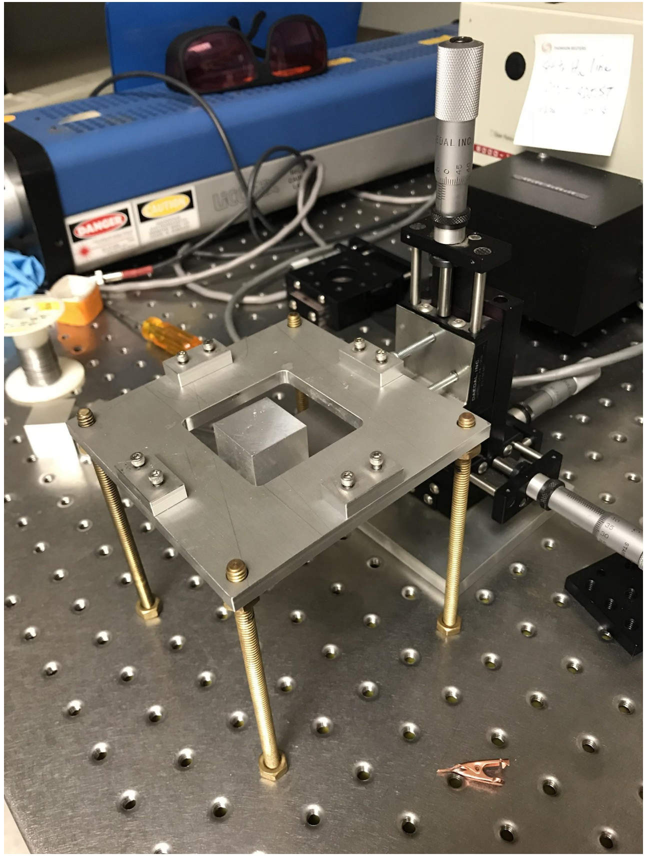
Design: Wire Cutting Jig

- Nb precision machine cut (big thanks to KarlHeinz!)
- Wires fastened across the jig with GE Varnish
- Snug against a step to expose all the insulation layer
- 2 Windows: ~14 mil wide with ~70 mil spacing
- Step height: ~1.5 mil, all insulation + some wire



Design: Solder Blob Jig

- Wires fastened into square jig
- Window crossover exposed in center
- Al cube on platform raises to the junction
- Solder blob carefully placed atop connection



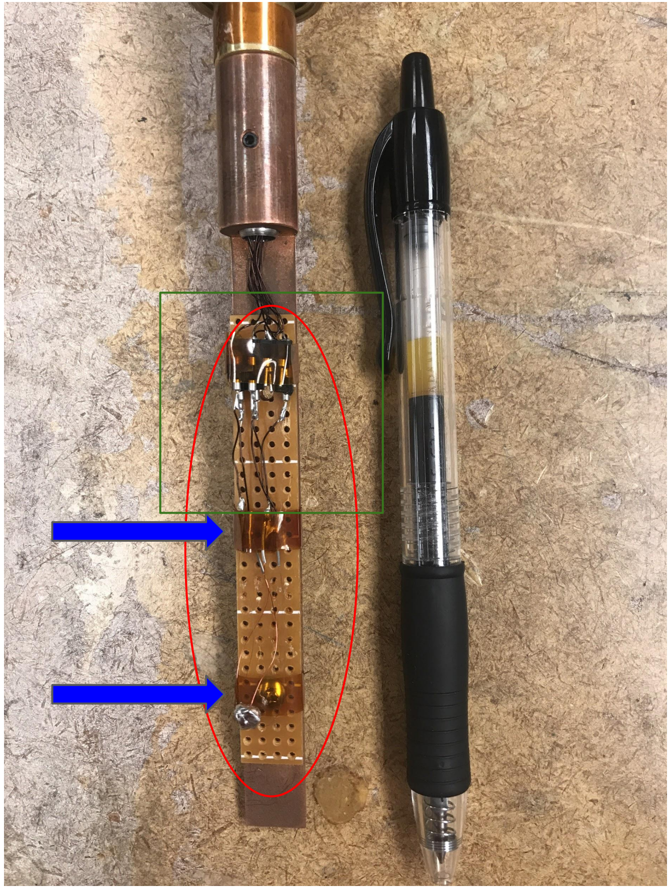
Overview of Experimental Design

2. Making the Probe for Liquid Helium Cooling

- Piece to hold the squid in dunking process
- Electrical connection to RT with braided Manganin wires from base to top.
- External electronics connections

Design: SLUG Holder

- SLUG placed atop PCB
- Insulating tape added for security
- Manganin connections from wire ends to SIP pins that feed through entire probe.



Design: SLUG Holder (Cont.)

- To ensure secure connections between stripped ends of Nb, Cu, used crimping method

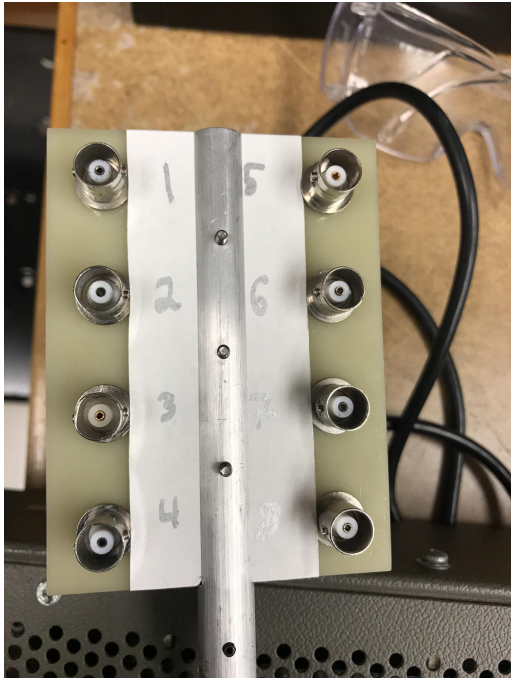
Iteration 1:

- Copper plates glued down to hold wire connections in place with GE Varnish

Iteration 2:

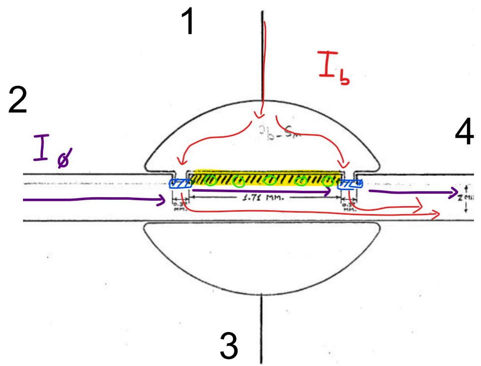
- Cu/Nb wire ends placed in end of a hollow Ni cylinder
- Cylinder then flattened to secure the connection, soldered to Manganin
- Insulating tape used to isolate connections electrically.

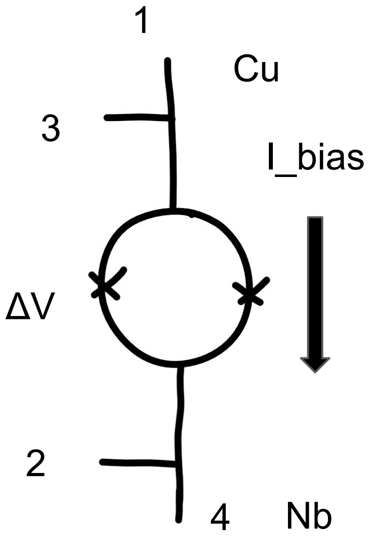
Design: BNC Mount



- Manganin soldered to BNC connectors
- Clearly labeled connections from each wire to a specific numbered BNC port

Design: IV Measurement

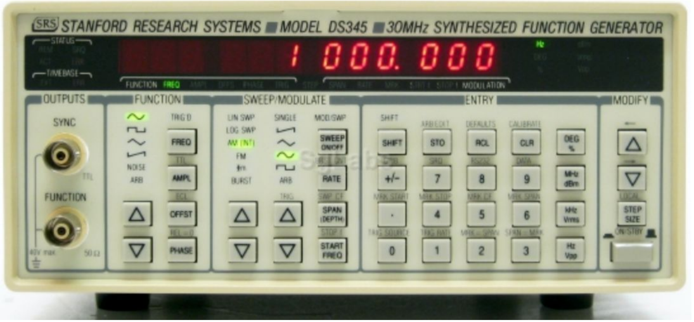




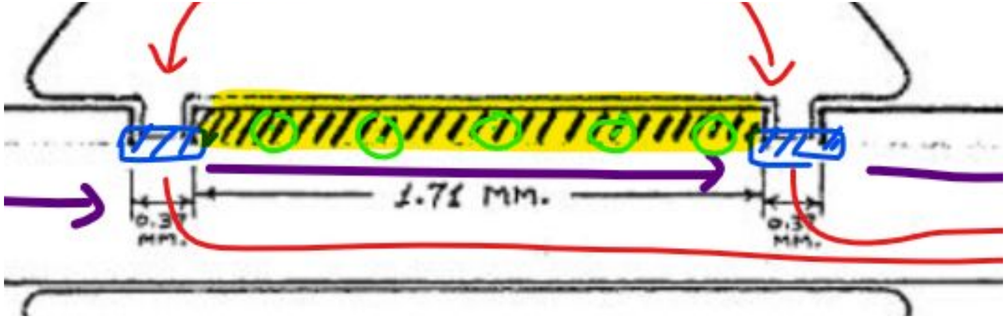
- SRS Function Generator along with a series resistor of known resistance to generate the current bias.

- Current through junction generates a voltage drop across the junction which we read out using a 4 terminal setup.

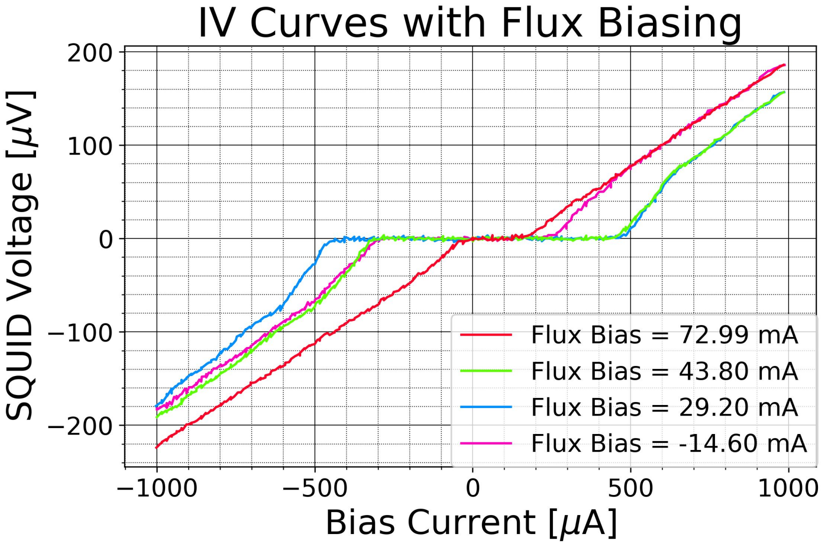
- The small voltage signal is amplified by a pre-amp G~10^4, low passed to exclude 60 Hz noise.



Design: Flux Biasing



- Current through Nb produces a modulation in critical current



Design: Data Acquisition

Oscilloscope Traces

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Excel Sheets

↓

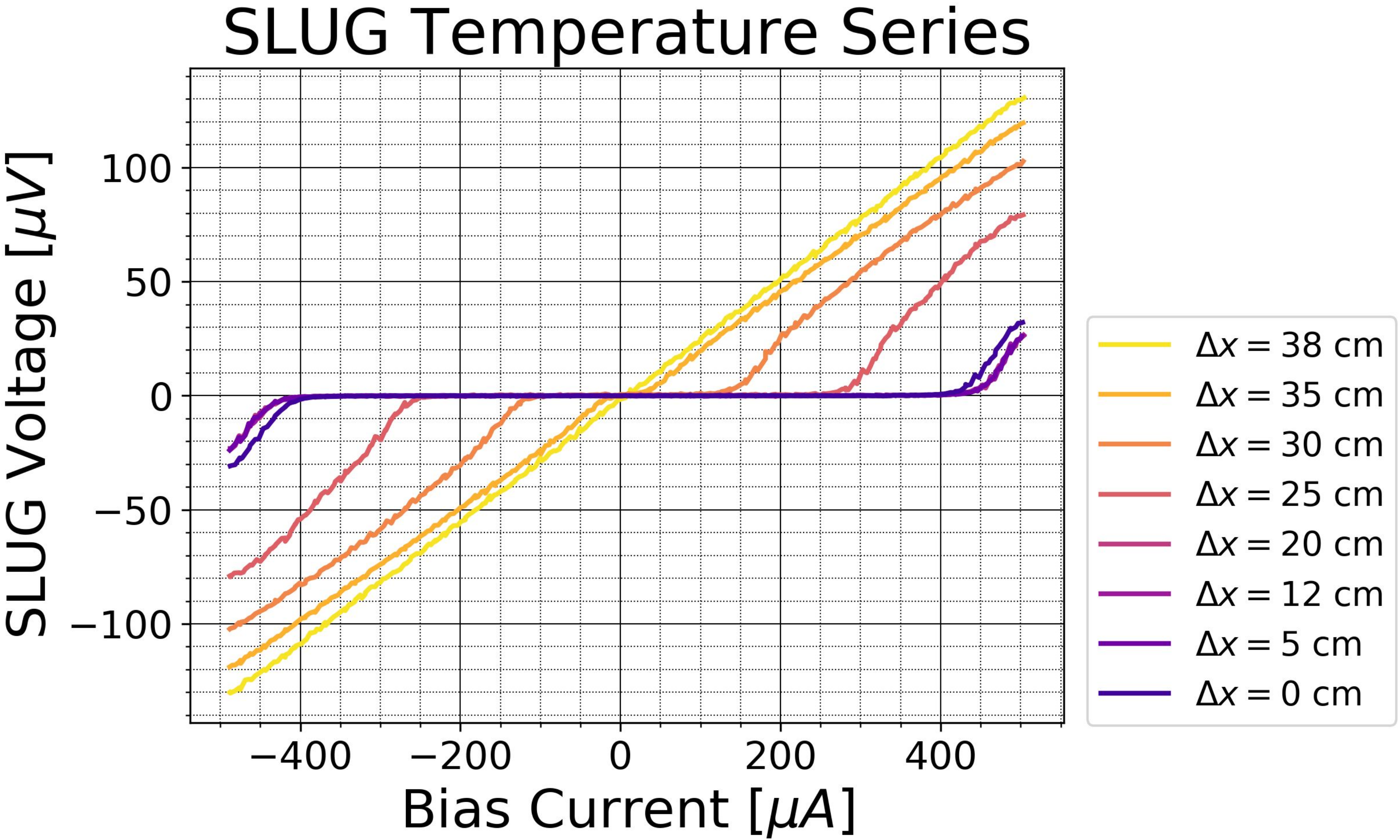
Python

↓

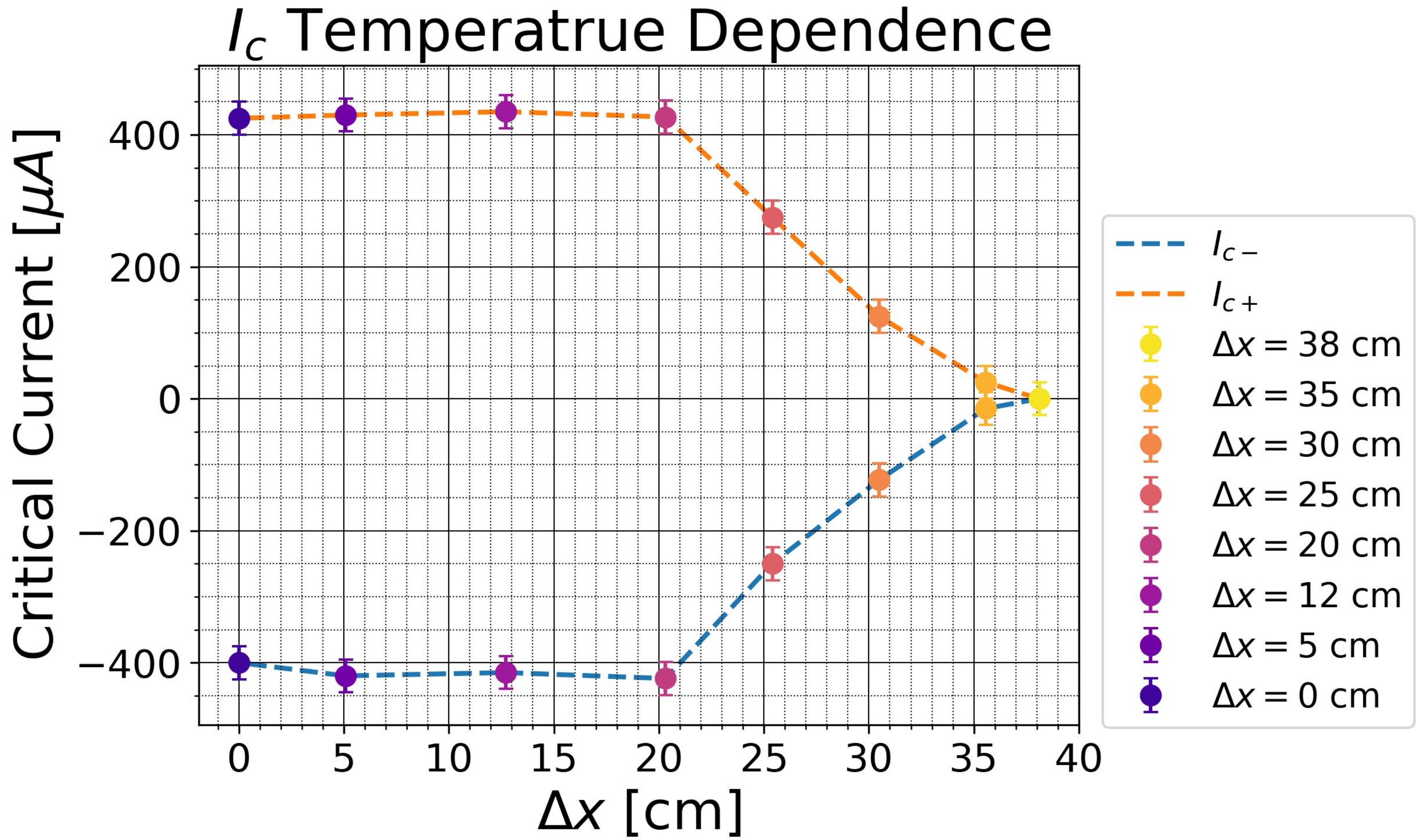
DataSheet Class

Results Overview

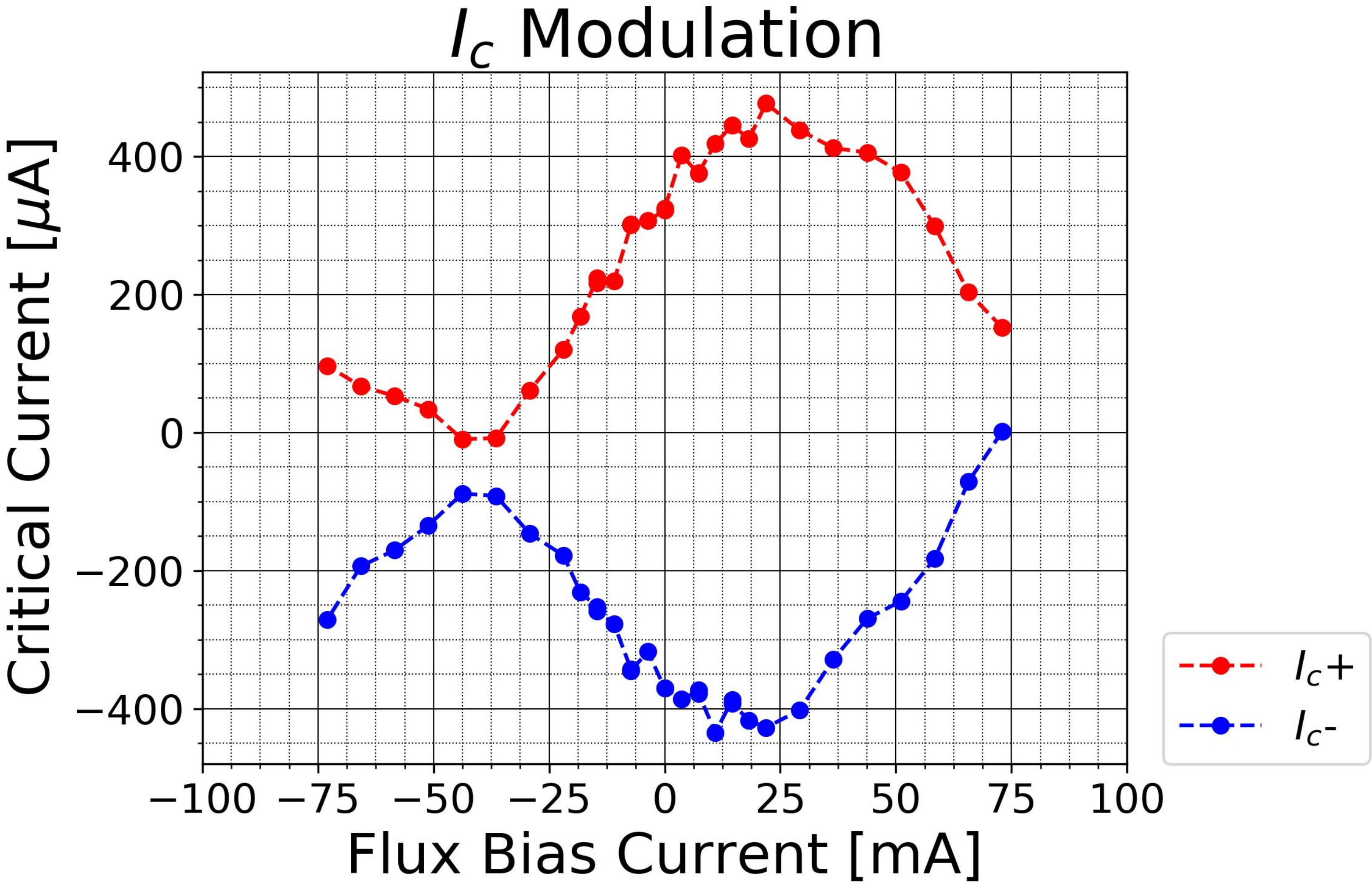
1. Temperature Series Results
2. Flux Bias Results
   a. Review of flux bias analysis fitting procedure
3. Magnetic flux quantum calculation



SLUG Temperature Series
SLUG Voltage [μV]
Bias Current [μA]
100
50
0
−50
−100
−400
−200
0
200
400
$\Delta x = 38$ cm
$\Delta x = 35$ cm
$\Delta x = 30$ cm
$\Delta x = 25$ cm
$\Delta x = 20$ cm
$\Delta x = 12$ cm
$\Delta x = 5$ cm
$\Delta x = 0$ cm



I_c Temperatrue Dependence
Critical Current [μA]
400
200
0
−200
−400
0
5
10
15
20
25
30
35
40
Δx [cm]
I_{c-}
I_{c+}
$\Delta x = 38$ cm
$\Delta x = 35$ cm
$\Delta x = 30$ cm
$\Delta x = 25$ cm
$\Delta x = 20$ cm
$\Delta x = 12$ cm
$\Delta x = 5$ cm
$\Delta x = 0$ cm

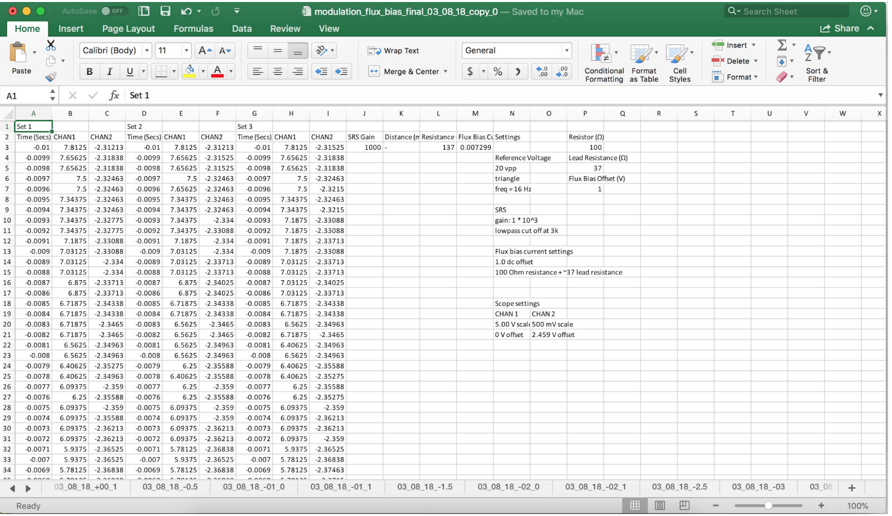


I_c Modulation
Critical Current [μA]
Flux Bias Current [mA]
400
200
0
−200
−400
−100
−75
−50
−25
0
25
50
75
100
I_c+
I_c-

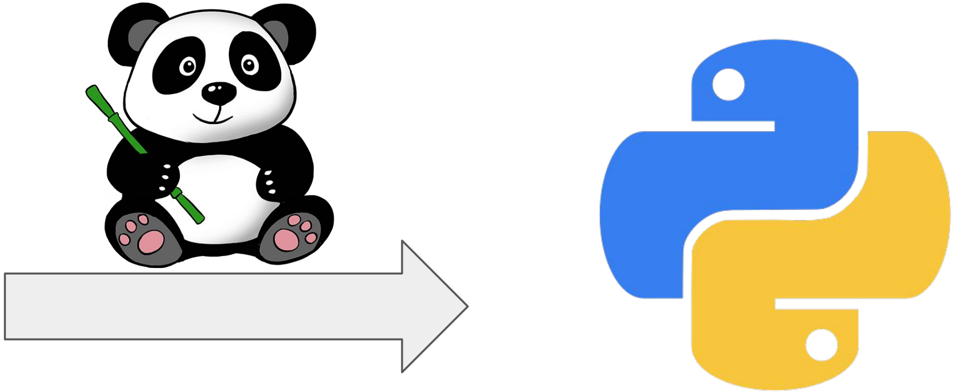
Results: Flux Bias Modulation

Analysis Procedure

0. Data reading and reduction
    a. Read data from Excel files to Python using Pandas package
        i. DataSheet custom Python object



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Set 1			Set 2			Set 3									
2	Time (Secs)	CHAN1	CHAN2	Time (Secs)	CHAN1	CHAN2	Time (Secs)	CHAN1	CHAN2	SRS Gain	Distance (m	Resistance	Flux Bias Cu	Settings		Resistor (Ω)
3	-0.01	7.8125	-2.31213	-0.01	7.8125	-2.31213	-0.01	7.8125	-2.31525	1000	-	137	0.007299			100
4	-0.0099	7.65625	-2.31838	-0.0099	7.65625	-2.31525	-0.0099	7.65625	-2.31838					Reference Voltage		Lead Resistance (Ω)
5	-0.0098	7.65625	-2.31838	-0.0098	7.65625	-2.31525	-0.0098	7.65625	-2.31838					20 vpp		37
6	-0.0097	7.5	-2.32463	-0.0097	7.5	-2.32463	-0.0097	7.5	-2.32463					triangle		Flux Bias Offset (V)
7	-0.0096	7.5	-2.32463	-0.0096	7.65625	-2.32463	-0.0096	7.5	-2.3215					freq = 16 Hz		1
8	-0.0095	7.34375	-2.32463	-0.0095	7.34375	-2.32463	-0.0095	7.34375	-2.32463							
9	-0.0094	7.34375	-2.32463	-0.0094	7.34375	-2.32463	-0.0094	7.34375	-2.3215					SRS		
10	-0.0093	7.34375	-2.32775	-0.0093	7.34375	-2.334	-0.0093	7.1875	-2.33088					gain: 1 * 10^3		
11	-0.0092	7.34375	-2.32775	-0.0092	7.34375	-2.33088	-0.0092	7.1875	-2.33088					lowpass cut off at 3k		
12	-0.0091	7.1875	-2.33088	-0.0091	7.1875	-2.334	-0.0091	7.1875	-2.33713							
13	-0.009	7.03125	-2.33088	-0.009	7.03125	-2.334	-0.009	7.1875	-2.33088					Flux bias current settings		
14	-0.0089	7.03125	-2.334	-0.0089	7.03125	-2.33713	-0.0089	7.03125	-2.33713					1.0 dc offset		
15	-0.0088	7.03125	-2.334	-0.0088	7.03125	-2.33713	-0.0088	7.03125	-2.33713					100 Ohm resistance + ~37 lead resistance		
16	-0.0087	6.875	-2.33713	-0.0087	6.875	-2.34025	-0.0087	7.03125	-2.34025							
17	-0.0086	6.875	-2.33713	-0.0086	6.875	-2.34025	-0.0086	7.03125	-2.33713							
18	-0.0085	6.71875	-2.34338	-0.0085	6.71875	-2.34338	-0.0085	6.71875	-2.34338					Scope settings		
19	-0.0084	6.71875	-2.34338	-0.0084	6.71875	-2.34338	-0.0084	6.71875	-2.34338					CHAN 1	CHAN 2	
20	-0.0083	6.71875	-2.3465	-0.0083	6.5625	-2.3465	-0.0083	6.5625	-2.34963					5.00 V scal	500 mV scale	
21	-0.0082	6.71875	-2.3465	-0.0082	6.5625	-2.3465	-0.0082	6.71875	-2.3465					0 V offset	2.459 V offset	
22	-0.0081	6.5625	-2.34963	-0.0081	6.5625	-2.34963	-0.0081	6.40625	-2.34963							
23	-0.008	6.5625	-2.34963	-0.008	6.5625	-2.34963	-0.008	6.5625	-2.34963							
24	-0.0079	6.40625	-2.35275	-0.0079	6.25	-2.35588	-0.0079	6.40625	-2.35588							
25	-0.0078	6.40625	-2.34963	-0.0078	6.40625	-2.35588	-0.0078	6.40625	-2.35275							
26	-0.0077	6.09375	-2.359	-0.0077	6.25	-2.359	-0.0077	6.25	-2.35588							
27	-0.0076	6.25	-2.35588	-0.0076	6.25	-2.35588	-0.0076	6.25	-2.35275							
28	-0.0075	6.09375	-2.359	-0.0075	6.09375	-2.359	-0.0075	6.09375	-2.359							
29	-0.0074	6.09375	-2.35588	-0.0074	6.09375	-2.359	-0.0074	6.09375	-2.36213							
30	-0.0073	6.09375	-2.36213	-0.0073	6.09375	-2.36213	-0.0073	6.09375	-2.36213							
31	-0.0072	6.09375	-2.36213	-0.0072	6.09375	-2.36213	-0.0072	6.09375	-2.359							
32	-0.0071	5.9375	-2.36525	-0.0071	5.78125	-2.36838	-0.0071	5.9375	-2.36525							
33	-0.007	5.9375	-2.36525	-0.007	5.9375	-2.36525	-0.007	5.78125	-2.36838							
34	-0.0069	5.78125	-2.36838	-0.0069	5.78125	-2.36838	-0.0069	5.78125	-2.37463							



Results: Flux Bias Modulation

Analysis Procedure

0. Data reading and reduction
    a. Read data from Excel files to Python using Pandas package
        i. DataSheet custom Python object
    b. Downsample data (reduce from 3,000 → 300 points to kill off noise)
    c. Mean subtract

data_reduction.py

```python
import pandas as pd
import numpy as np

# Read the two relevant files up front and load them into the global scope
xlsx_temp_series = pd.ExcelFile('temp_series_final_03_07_18_copy_0.xlsx')
xlsx_modulation  = pd.ExcelFile('modulation_flux_bias_final_03_08_18_copy_0.xlsx')

df_label_names = {'set 1 chan 1':'Unnamed: 1', 'set 1 chan 2':'Unnamed: 2', 'set 2 chan 1':'Unnamed: 4', 'set 2 chan 2':'Unnamed: 5',
'set 3 chan 1':'Unnamed: 7', 'set 3 chan 2':'Unnamed: 8', 'srs gain':'Unnamed: 9', 'distance':'Unnamed: 10',
'resistance':'Unnamed: 11', 'flux bias current':'Unnamed: 12'}

# DataSheet object for our data from the scope traces of one data collection run (i.e. one sheet of data on the Excel files).
class DataSheet:
    def __init__(self, xlsx, filename_str='', sheet_num = 0):
        '''
        Create a data object given its Excel Pandas object and sheet number. (And also a string that says which filename it comes from)
        '''

        self.description = 'From "{}", sheet number {}'.format(filename_str, sheet_num)

        sheet_data = pd.read_excel(xlsx, sheet_num)

        # Get the three data sets
        set_1 = []
        set_2 = []
        set_3 = []

        for i in range(1, 1001): # Data is in rows 1 to 1000 (inclusive)

            tuple_1 = (sheet_data.loc[i, df_label_names['set 1 chan 1']], sheet_data.loc[i, df_label_names['set 1 chan 2']])
            set_1.append(tuple_1)

            tuple_2 = (sheet_data.loc[i, df_label_names['set 2 chan 1']], sheet_data.loc[i, df_label_names['set 2 chan 2']])
            set_2.append(tuple_2)

            tuple_3 = (sheet_data.loc[i, df_label_names['set 3 chan 1']], sheet_data.loc[i, df_label_names['set 3 chan 2']])
            set_3.append(tuple_3)

        self.set_1 = set_1
        self.set_2 = set_2
        self.set_3 = set_3

        self.combined_set = []
```

Line 49, Column 41 Tab Size: 4 Python

jupyter data_reduction_testing Last Checkpoint: an hour ago (autosaved)

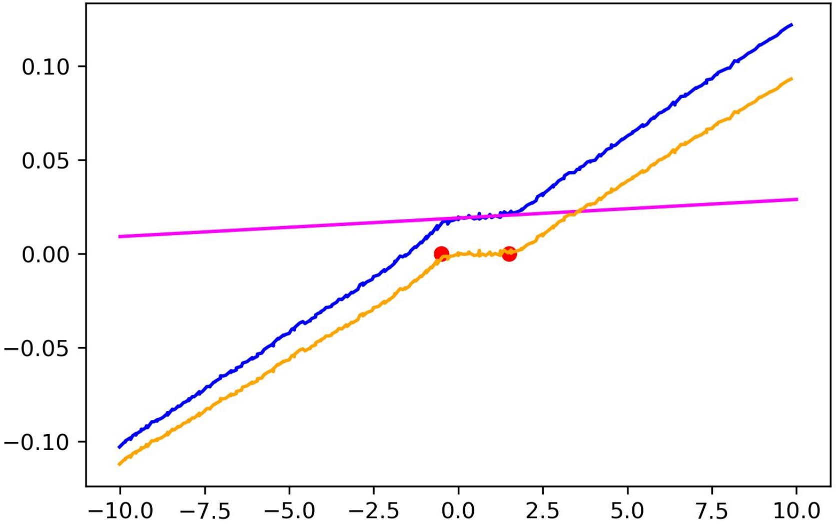
File Edit View Insert Cell Kernel Help | Python 3

```python
In [3]: from data_reduction import DataSheet, xlsx_temp_series, xlsx_modulation, df_label_names
        import numpy as np
        from scipy.optimize import curve_fit
        import matplotlib.pyplot as plt
        %matplotlib inline
        from IPython.core.debugger import Tracer

In [4]: # Define constants
        NUM_SHEETS_MOD = 32
        NUM_SHEETS_TEMP = 8

In [5]: # Create a list of DataSheet objects for the flux bias current/modulation Excel sheet
        mod_DataSheets = []
        for j in range(NUM_SHEETS_MOD):
            mod_DataSheets.append(DataSheet(xlsx_modulation, 'modulation', sheet_num = j))

        temp_DataSheets = []
        for j in range(NUM_SHEETS_TEMP):
            temp_DataSheets.append(DataSheet(xlsx_temp_series, 'temperature series', sheet_num = j))

In [6]: # Mean subtract
        for sheet in mod_DataSheets:
            sheet.mean_subtract()

        for sheet in temp_DataSheets:
            sheet.mean_subtract()

In [7]: # Combine the three sets for each sheet
        for sheet in mod_DataSheets:
```

Results: Flux Bias Modulation

Analysis procedure:

1. Detrend linear component in raw modulation data
    a. ~~Fitting procedure to identify critical current locations~~
        i. Identify critical current locations by hand
    b. Fit line to superconducting region
    c. Subtract out linear trend

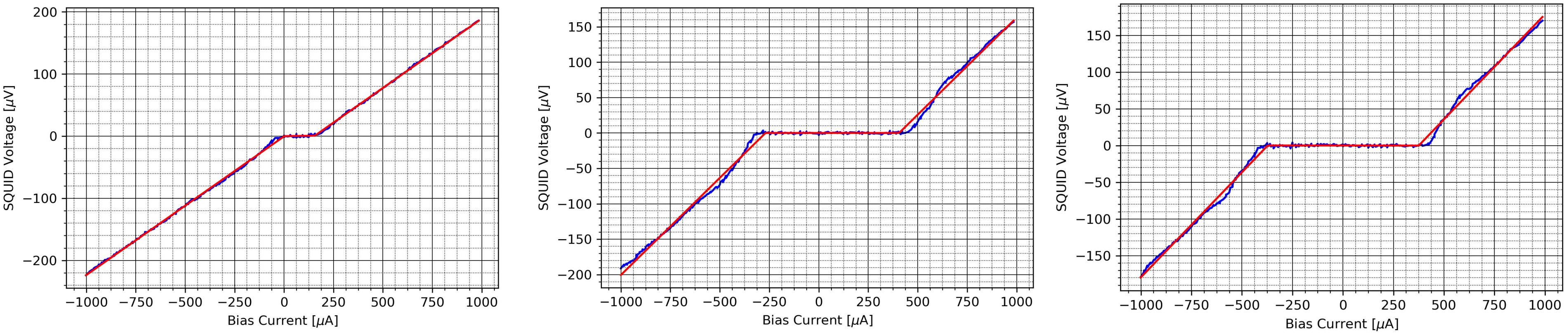


Results: Flux Bias Modulation

2. Fit super_model() to resulting IV curves
   a. Fit for the slope of the resistive regions (m_n), superconducting region (m_s), and the two critical current “kinks” (I_c_left and _right).

In [14]:
```
def heaviside(x1):
    return 0.5*(np.sign(x1) + 1)
```

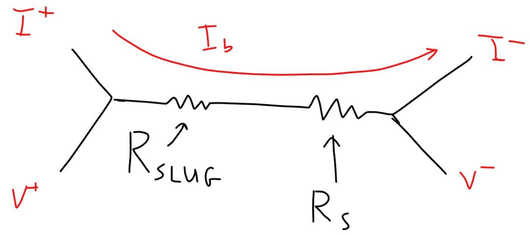
In [15]:
```
def super_model(x, m_n, m_s, I_c_left, I_c_right):
    return m_n*(x-I_c_left)*(1 - heaviside(x - I_c_left))+m_n*(x-I_c_right)*heaviside(x - I_c_right) +
m_s*x*(heaviside(x - I_c_left) - heaviside(x - I_c_right))
```



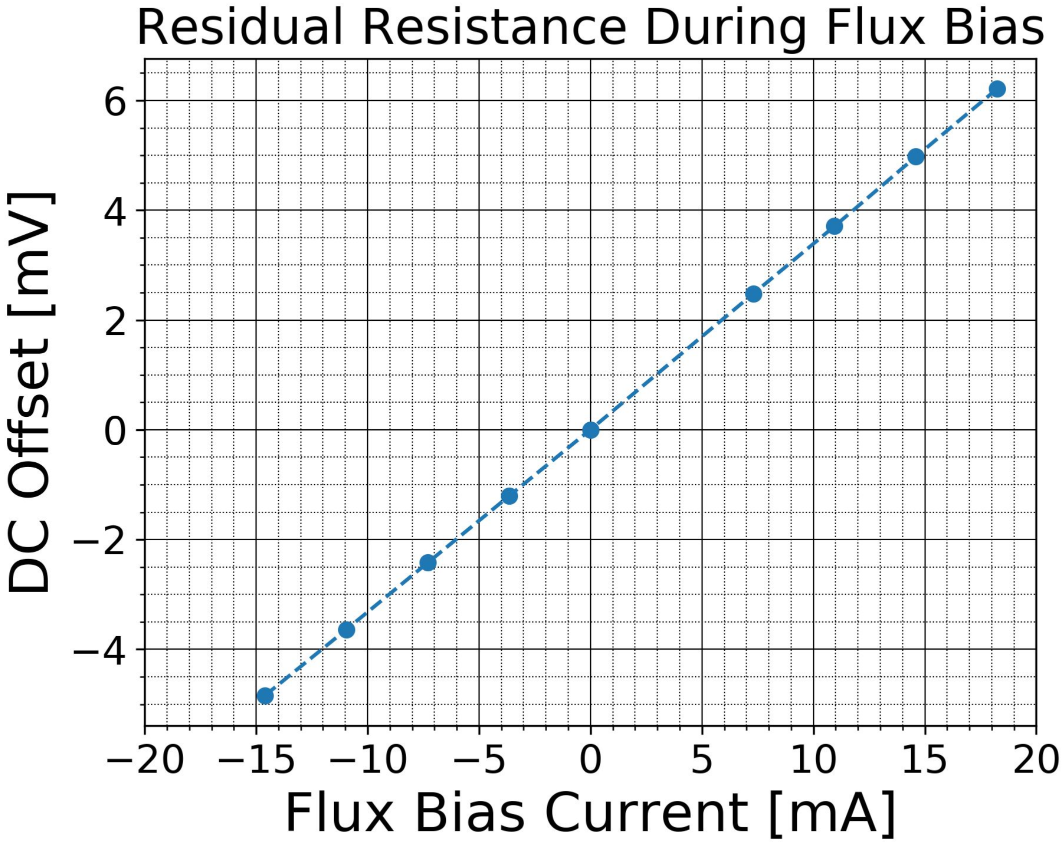
Results: Flux Bias

Residual resistive DC offset

- Running current and voltage through same Nb wire to SLUG.
- When DC coupled, see additional resistance from residual resistive element.



$R \cong 3\ \Omega$



Nb Oxide Thickness

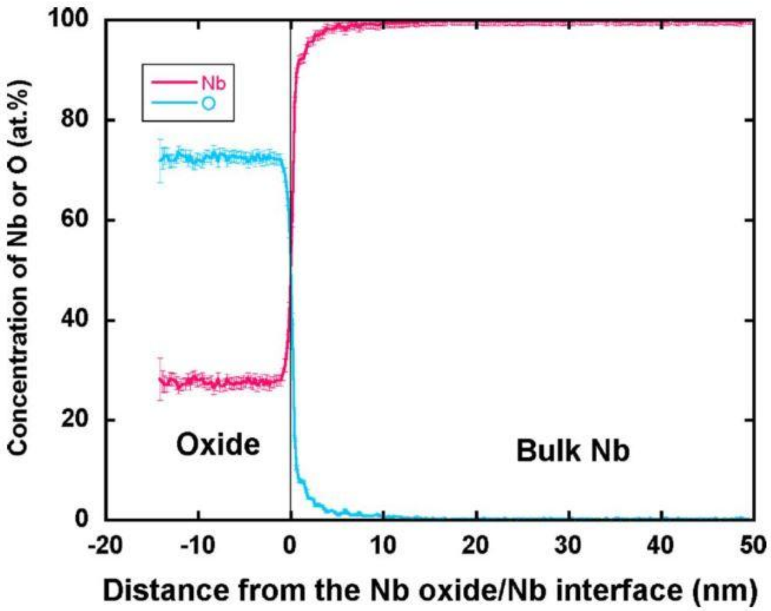


FIG. 4. (Color online) Proxigram showing quantitative Nb and O concentration profiles corresponding to the atomic reconstruction displayed in Fig. 3. The profiles yield a thickness of the surface niobium oxide of 15 nm, with a constant surface Nb oxide composition corresponding to Nb_2O_5.

So, we're going to go with 15 nm.

Results: Flux Modulation

$$I_c = I_0|\text{sinc}(\pi\phi_j/\Phi_o)|$$

Thus, for the central interference feature, the zeros are separated by 2 flux quanta.

Quantity	Value	Error
\Delta I	140 mA	10 mA
d_wire	1.5 mil	0.3 mil
L_w	14.5 mil	2 mil
d_ox	15 nm	3 nm

$$\Delta\phi/\Phi_0 = \frac{\mu_0 \Delta I}{2\pi r_{\text{wire}} 2\Phi_0} L_{\text{w}} d_{ox}$$

= 2.0(9)

Conderations of Systematics:

- Proximity of SC to the oxide layer is going to focus flux, causing more flux to go through the junction than the left calculation. This would push our value higher.
- Incomplete covering/wetting of the window will reduce L and push our value lower.
- It is a bit difficult to intuit how large each of these effects are with only one SLUG measurement.

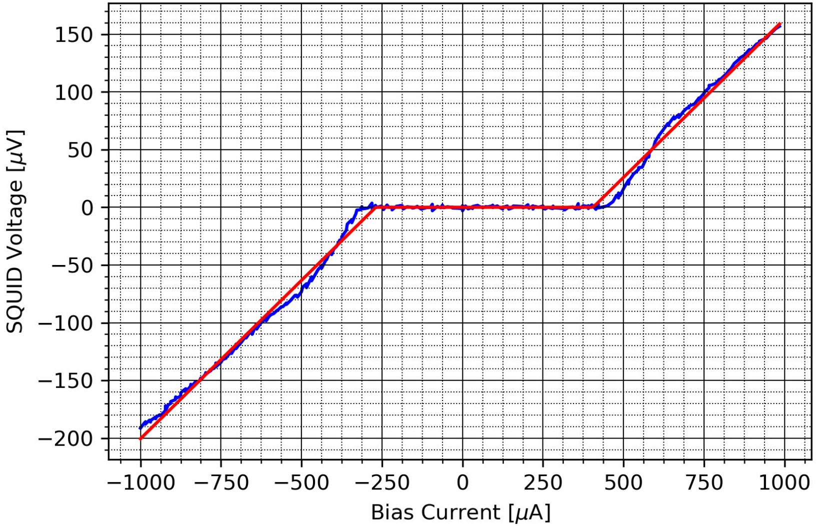
Discussion - Experimental

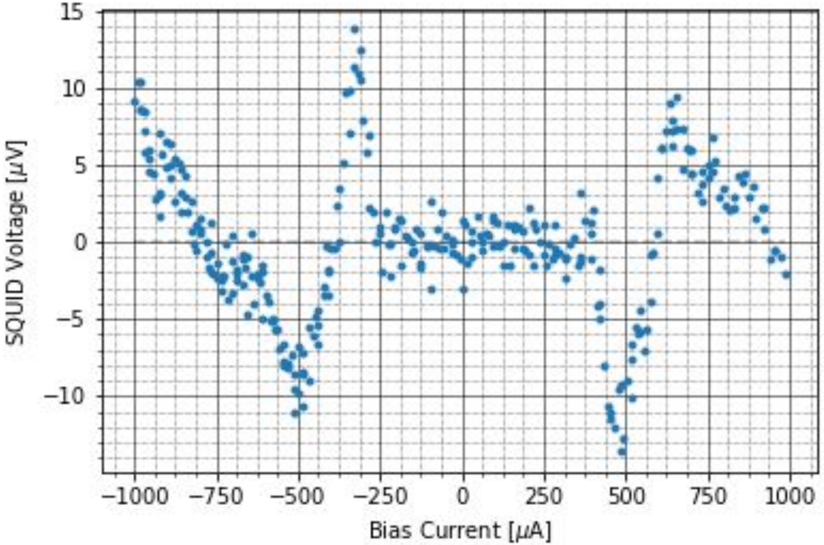
- we found unresolved grounding problems which lead to offsets and possible redirection of currents
- strong pickup at 60 Hz and also above ~kHz - look into lower noise electronics or batteries as current sources
- crimping and solder blob placement may introduce systematics

- at low modulation frequencies, signal to noise was high
    - with earlier SLUGs of lower normal resistance, this was an issue.

Discussion - Analysis

- Fits of super_model() to IV curves for flux bias modulation are reasonable, have easily-attributed systematics (see residuals).
- Variance in critical current fit is O(1 uA)
  - Could probably reduce systematics in critical current fit by choosing locations by hand (again)





Outlook

Future probe design considerations

1. Better separation in Manganin threads to avoid potential shorting
2. More focus into Manganin to BNC port stability
3. Introduction of thermometry to probe
4. Improvements to crimping method
5. Grounding considerations, way to clearly and reliably ground the entire probe
6. Stabilize the SLUG on the PCB with all electrical connections separated

Outlook

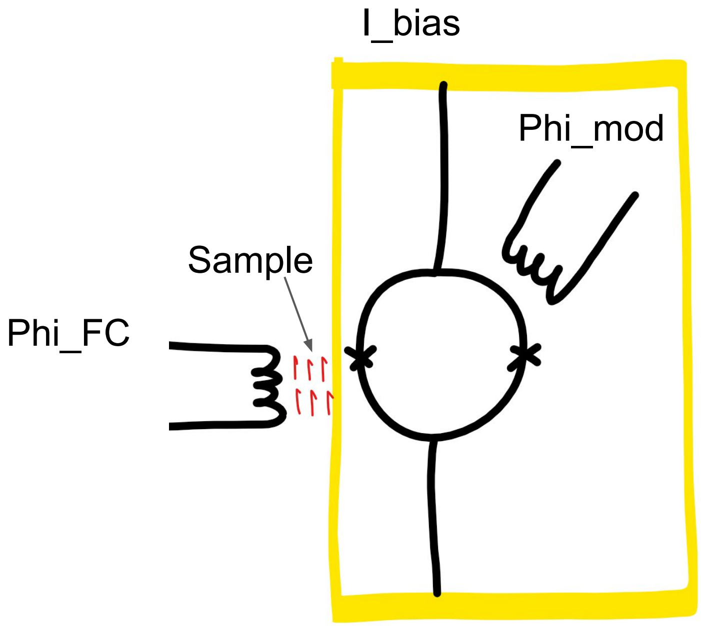
Future SLUG design considerations

- Vary window spacing
- Add additional windows to increase interference
- Methods to ensure contact between solder blob and Cu/Nb junction
- Crimping alternatives to remove residual resistive elements

Outlook

Magnetometry:

- The transition from SLUG to magnetometer is, in principle, simple to implement
- For low magnitudes of applied field, we can operate the SLUG in “open-loop” mode (no feedback)
- How would you implement feedback? We need at least one more component.



We only have what is in yellow.

The topology of surrounding the Nb wire with the solder blob makes it difficult to add another inductively coupled connection, let alone somewhere to measure a sample.

Outlook

Quantum Computing:

- Inspecting the equations governing josephson junctions, there is an interesting non-linearity.

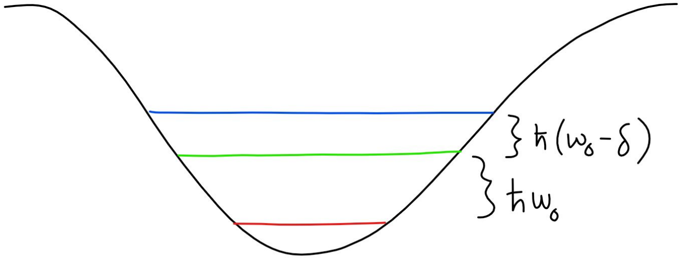
Josephson Equations:

$$I = I_0 \sin\phi(t) \qquad \hbar\frac{d\phi}{dt} = 2eV$$

$$\dot{I} = \frac{2eVI_0}{\hbar}\cos\phi \qquad V = -L\dot{I}$$

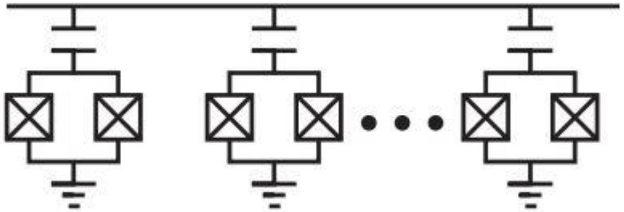
$$L_J = \frac{\hbar}{2eI_o\cos\phi}$$

Non-linear dependence on phase across junction results in an anharmonic oscillator hamiltonian.



Effectively a 2-level system

By coupling these systems together, you can construct a hamiltonian with which you can perform quantum computations.



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Questions?