Physics 108 Presentation

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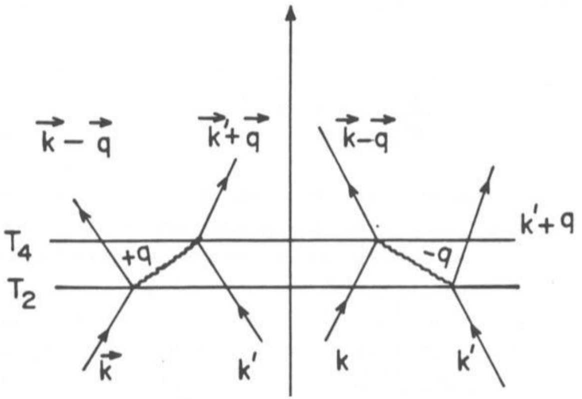
Presentation Outline

- 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



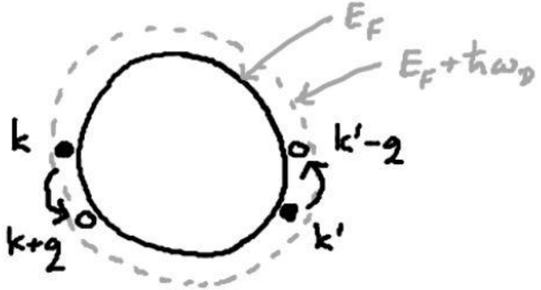
$$\Delta E = \frac{g_q^2}{(E_k + E_{k'}) - (E_{k-q} + E_k + \hbar\omega_q)} + \frac{g_q^2}{(E_k + E_{k'}) - (E_{k+q} + E_k + \hbar\omega_{-q})}$$

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.



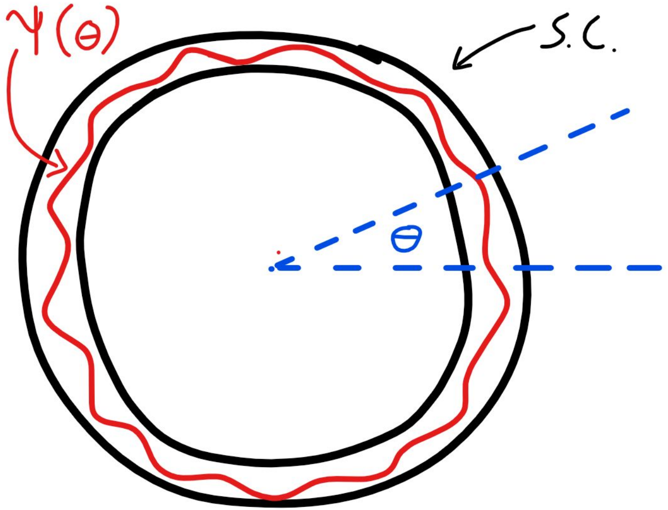
T increases, thermally populate of states -> fewer states to participate in pairing.

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

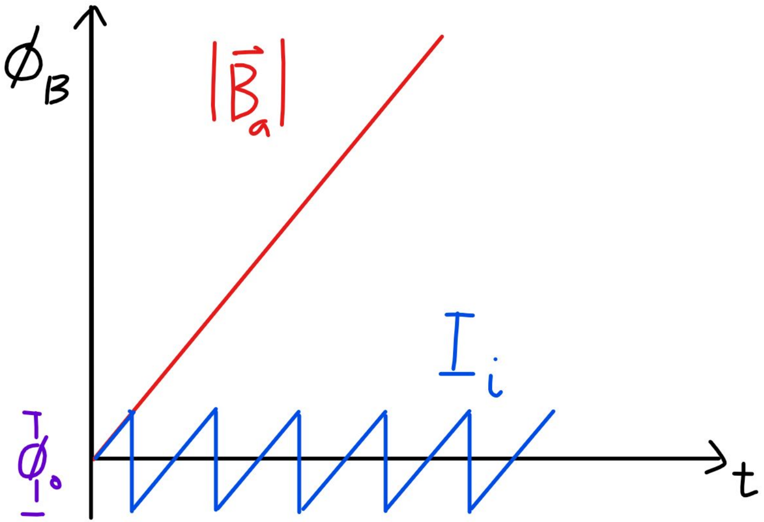
With an applied current, fermi surface will shift, allowing fewer states to participate in pairing.

Introduction to Superconductivity

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



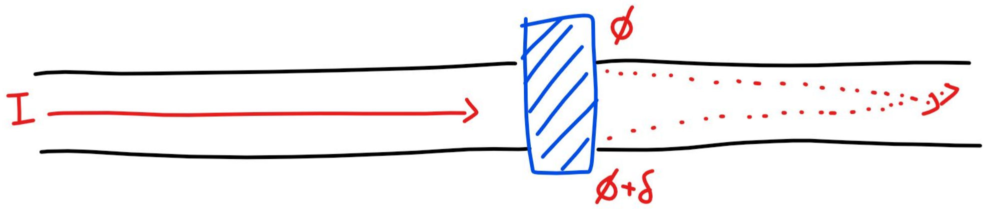
As B is applied to a SC ring, fluxoid quantization will induce a current in the ring with periodicity given by the inductance between the ring and the source of B.

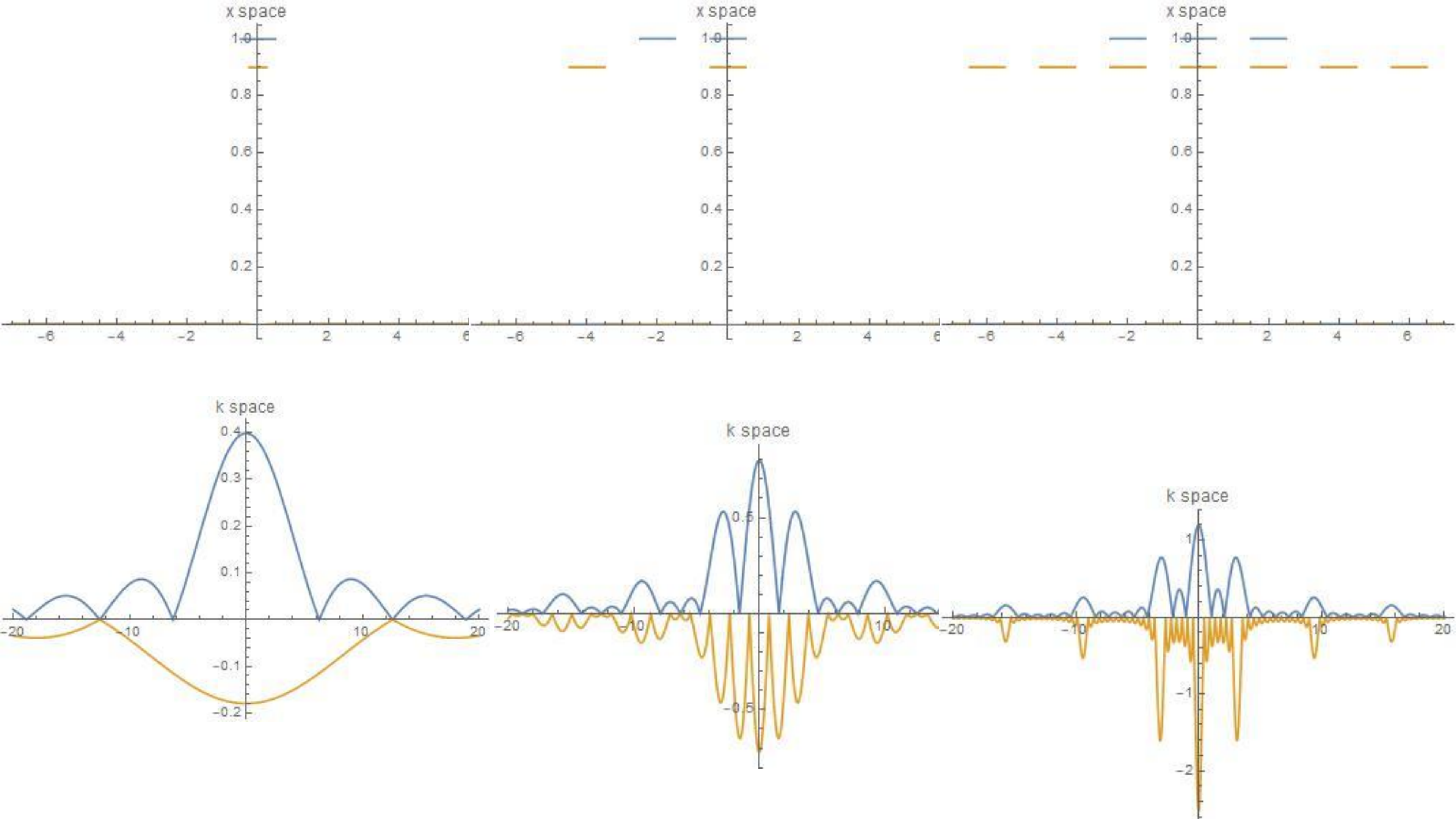


Weak Link - Josephson Junction

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
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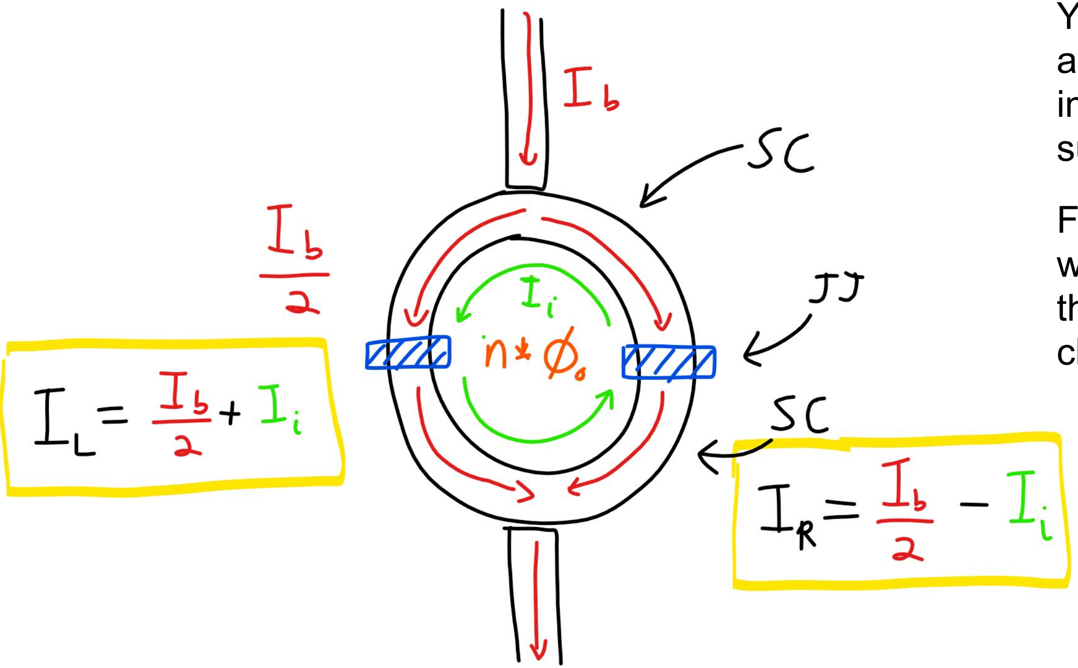
k space

Constructing a SQUID

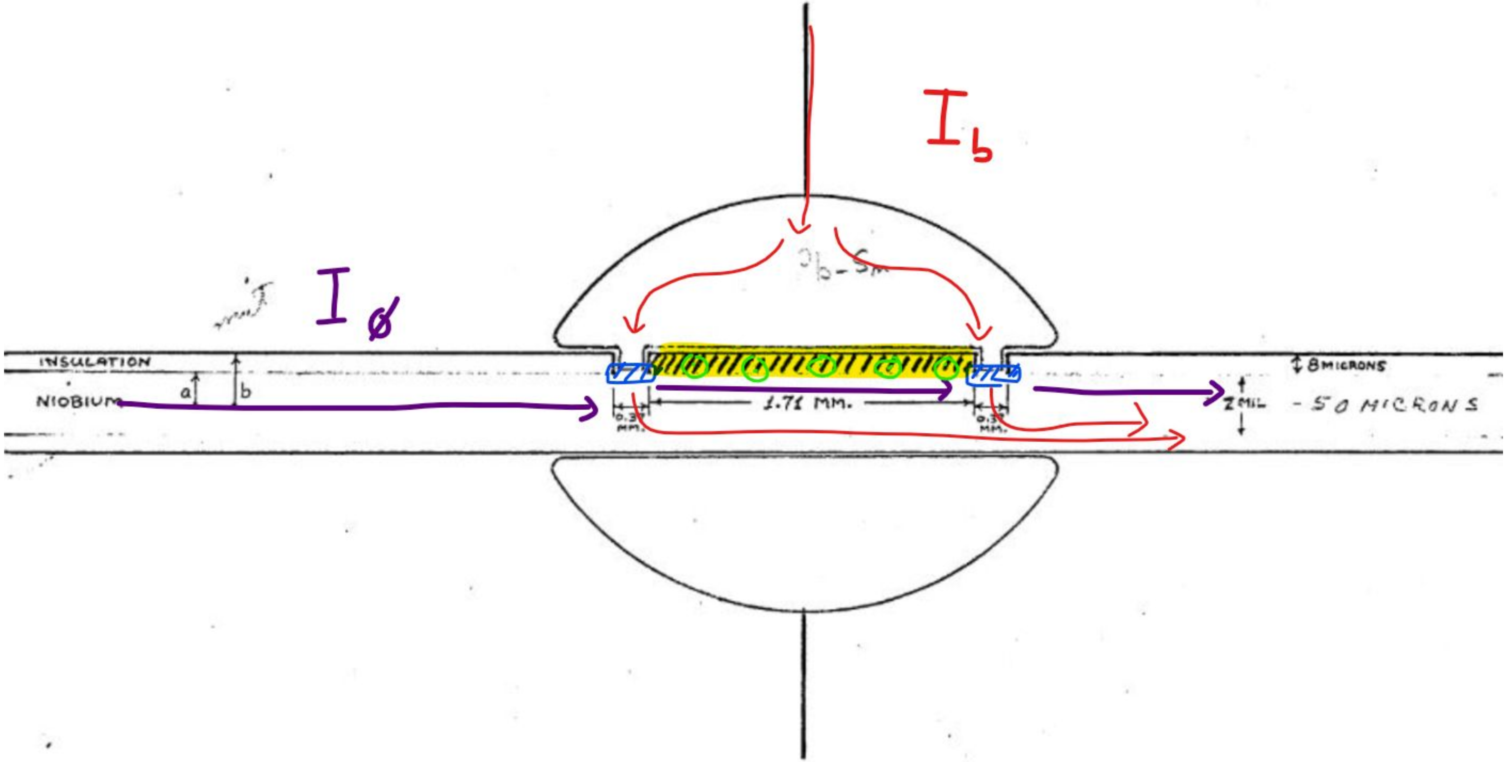
In general, you need two pieces of superconductors arranged in a certain topology with Josephson junctions interrupting the superconductor.



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

Calculate mutual inductance between flux bias wire and SLUG

Change I bias to measure periodicity of critical current

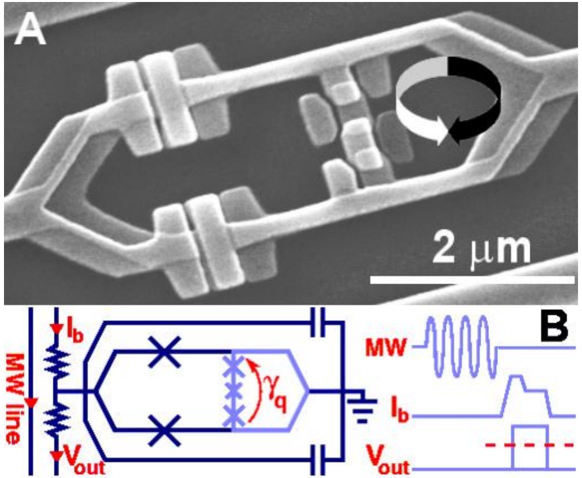
Extract value of flux quantum

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

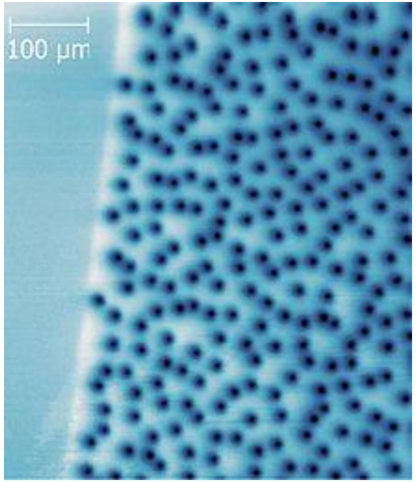
With window size and window spacing, should see a difference in the diffraction pattern.

~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.~~

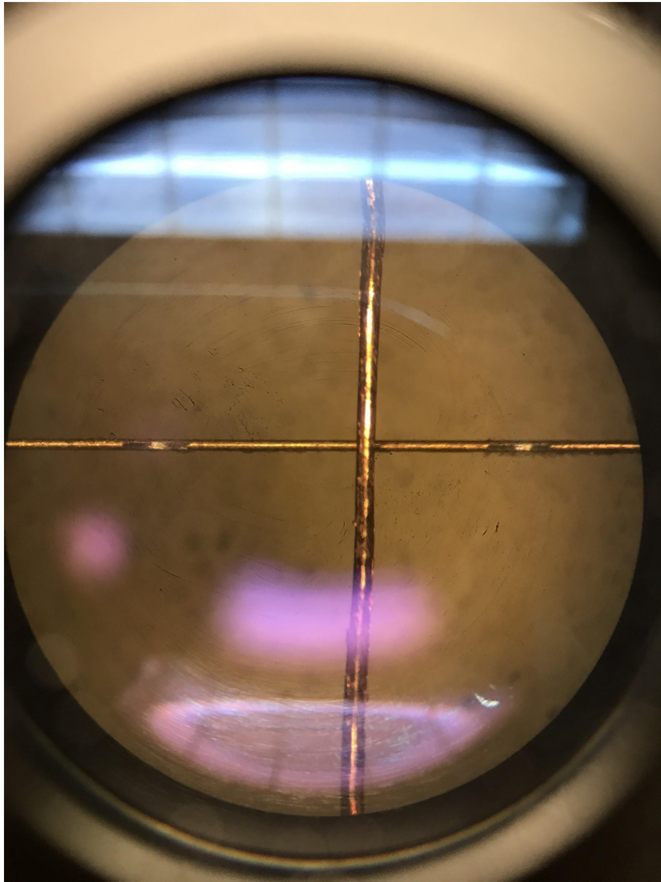
~~Optimize geometry of SLUG connections and windows to make a **symmetric SLUG**~~.

Best laid plans...

Overview of Experimental Design

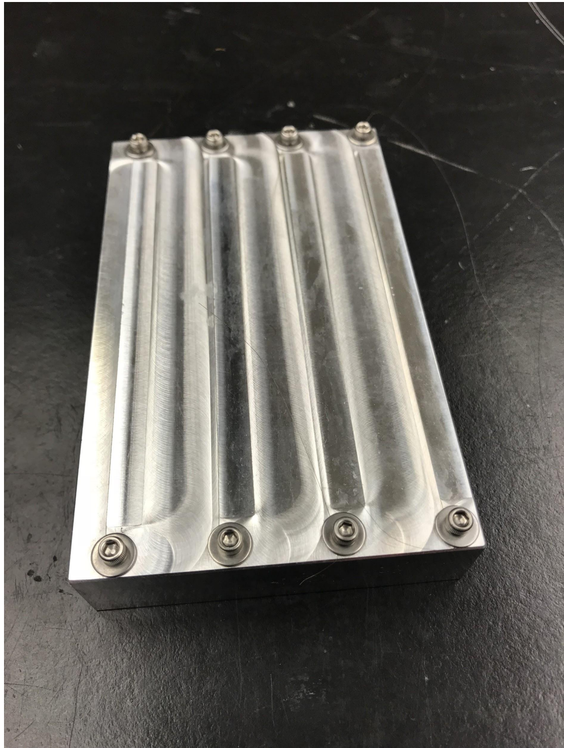
Nb, Cu crossover, encapsulated within solder blob

- optical microscopy of the crossed niobium (horizontal) and copper (vertical) wires before a solder blob was applied
- machined windows (method of machining discussed on the next slide) on the Nb wire are visible to the left and right of the crossed Cu wire.



Design: Wire Cutting Jig

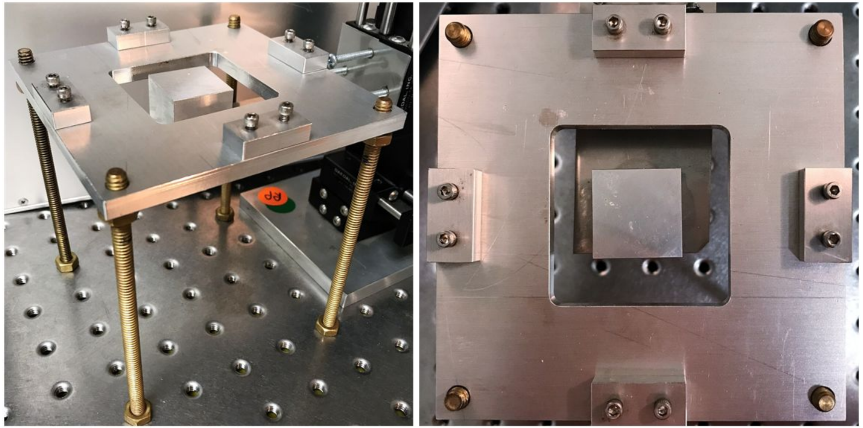
- Wires are pulled taught against a step in the block, fastened under the washers with screws, and secured with GE-7031 varnish
- a precision drill is aligned with the top of the step and passed over the wire to remove the insulation to expose windows of bare Nb wire.
- 2 Windows: ~14 mil wide with ~70 mil spacing
- Step height: ~1.5 mil, all insulation + some wire

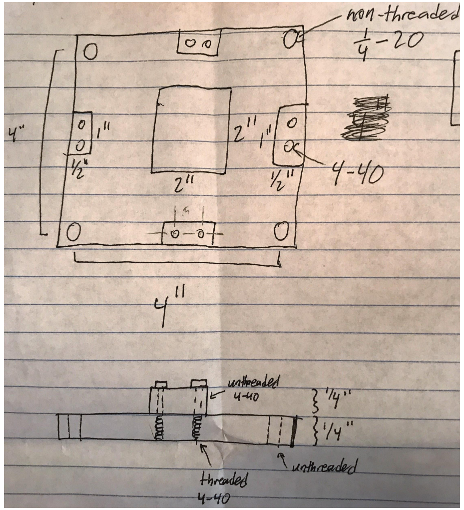


Design: Solder Blob Jig

- Wires fastened across jig held taught by four clamping pieces along the edge of the square
- Wires are crossed in the center window as shown a few slides ago
- Al cube raises from underneath to provide a place for the solder blob to rest
- Solder blob is placed over the crossed wires, rests on the Al cube, and cools.

Side Perspective Top Perspective





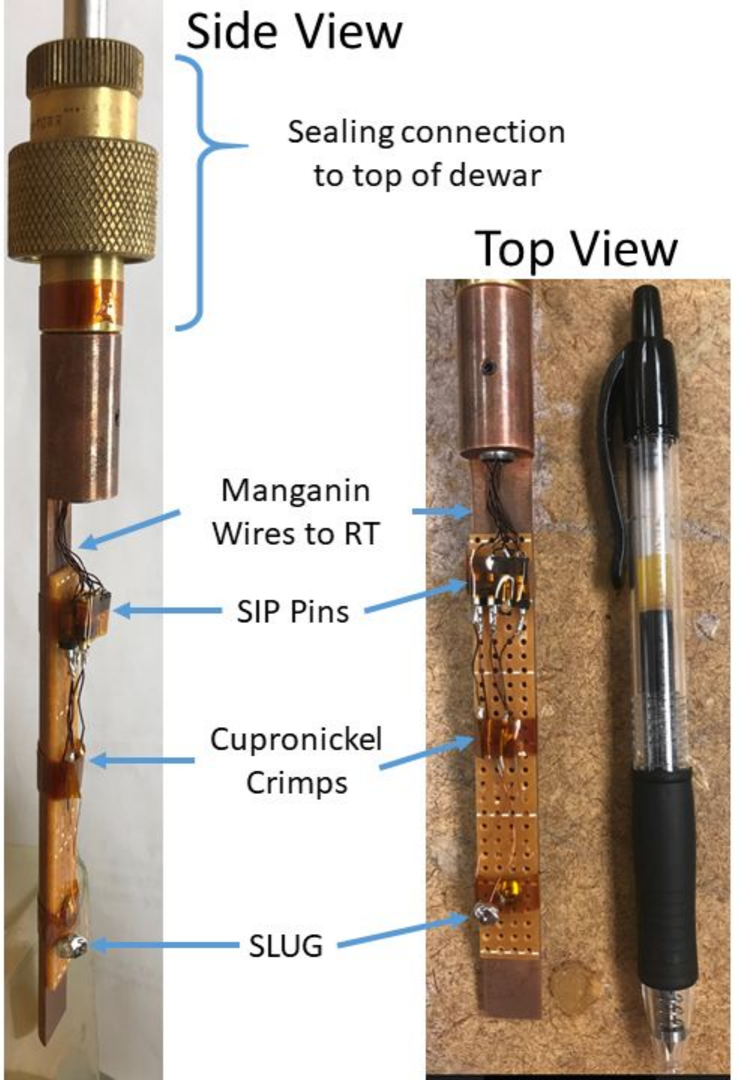
Overview of Experimental Design

Making the Probe for Liquid Helium Cooling

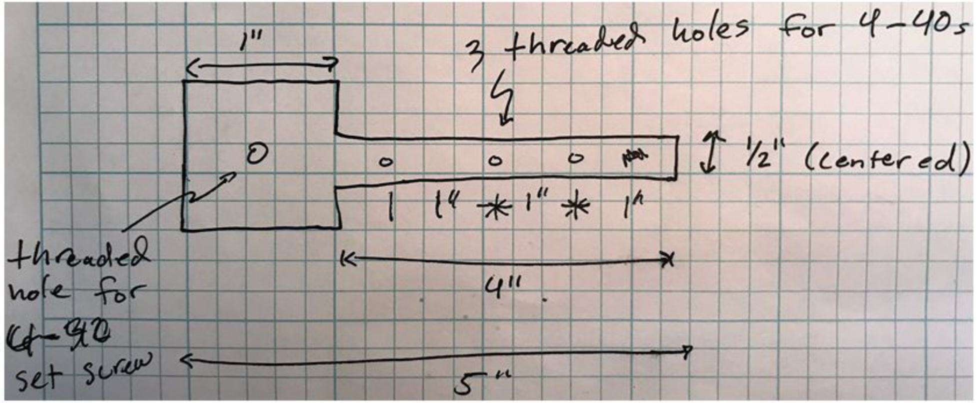
- SLUG holder (bottom)
- stainless steel dunking rod with Manganin wires threaded through its center (middle)
- room temperature BNC connection board (top)
- approximately one meter in length.

Design: SLUG Holder

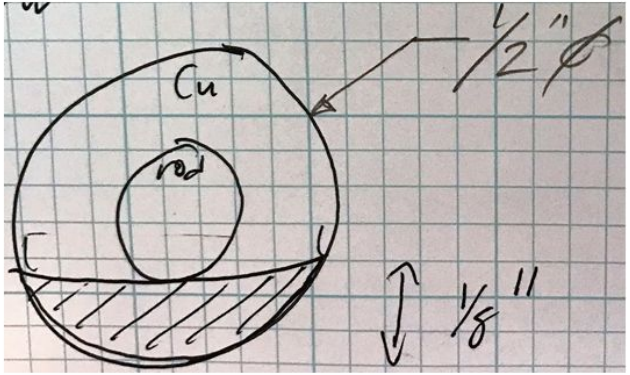
- connection between top of dewar and stainless steel rod for lowering probe into L-He
- #30 Manganin wires providing electrical connection from RT to L-He electronics
- SIP pins for easy connection and removal of SLUG components
- cupronickel crimps providing connection between #35 copper/ 2 mil niobium wires and #30 Manganin wires
- the SLUG itself.
- The top connection providing the air tight seal was causing grounding problems, so we added Kapton tape to the bottom connection for electrical insulation.
- This sealing mechanism was useful to allow the components to warm up before exposing them to atmosphere - resulting in no water vapor condensation.



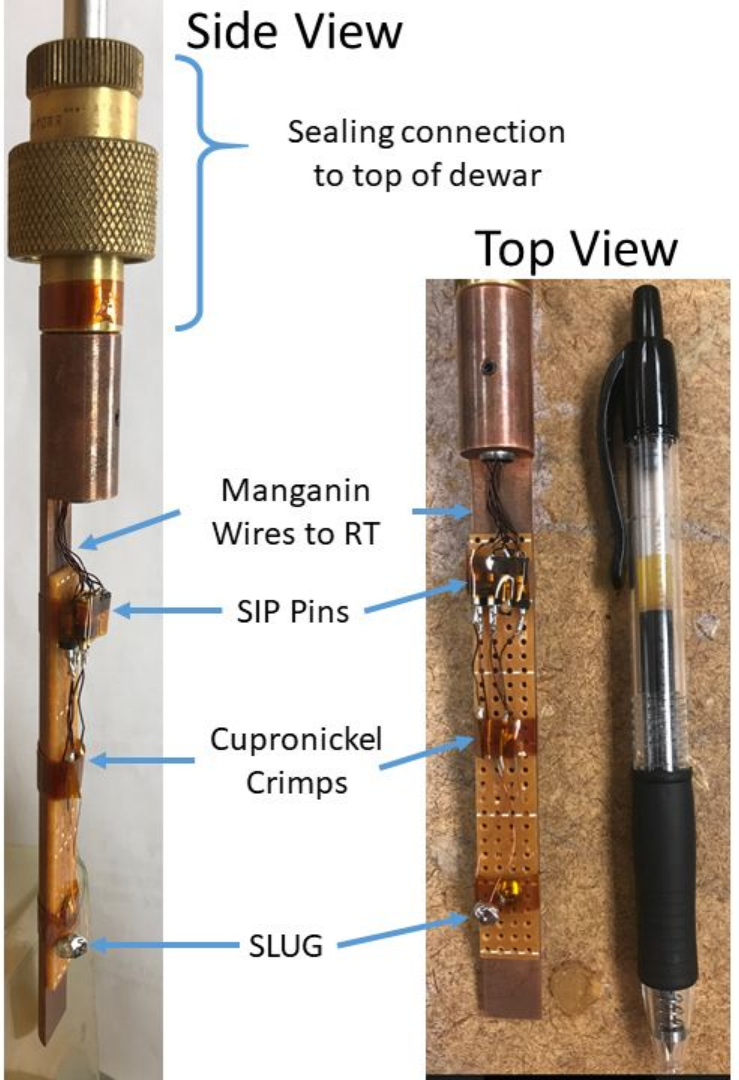
Design: SLUG Holder



Top Perspective



Barrel Perspective



Design: SLUG Holder (Cont.)

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

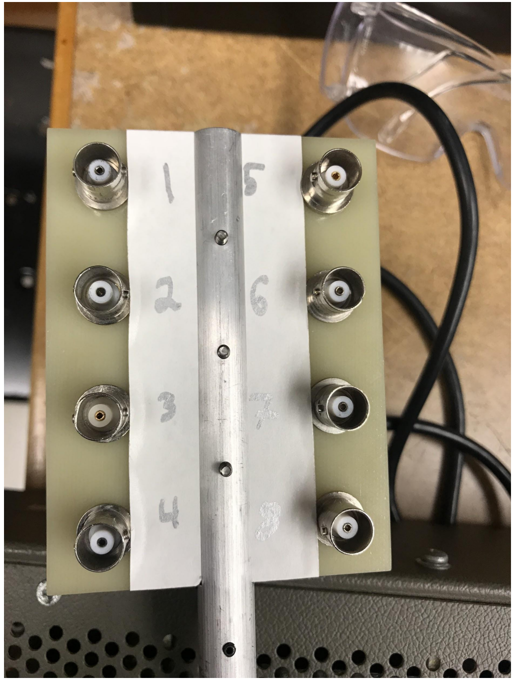
Iteration 1:

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

Iteration 2:

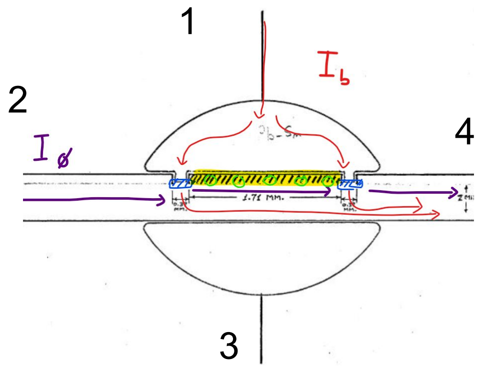
- Cu/Nb wire ends placed in end of a hollow Ni cylinder
- Cylinder then flattened to secure the connection, soldered to Manganin
- Insulating tape used to isolate connections electrically.

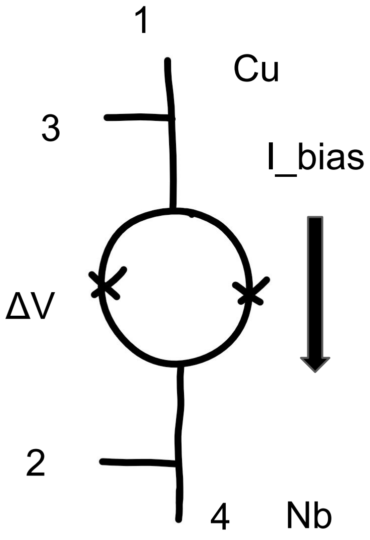
Design: BNC Mount



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

Design: IV Measurement

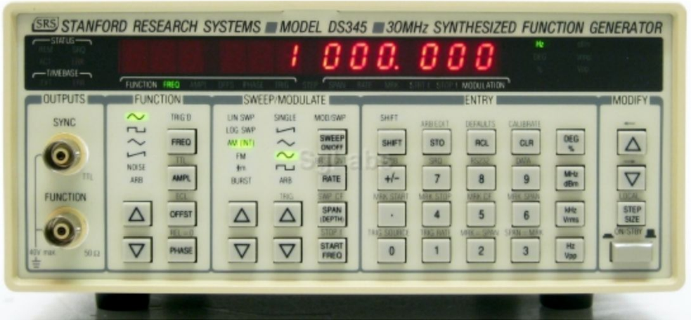




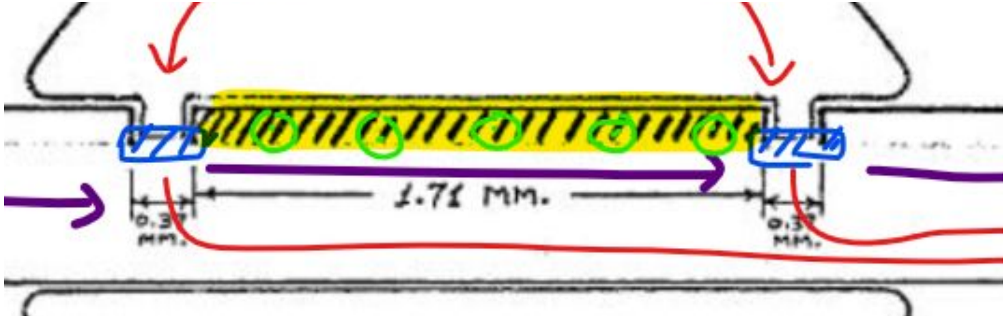
- SRS Function Generator along with a series resistor of known resistance to generate the current bias.

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

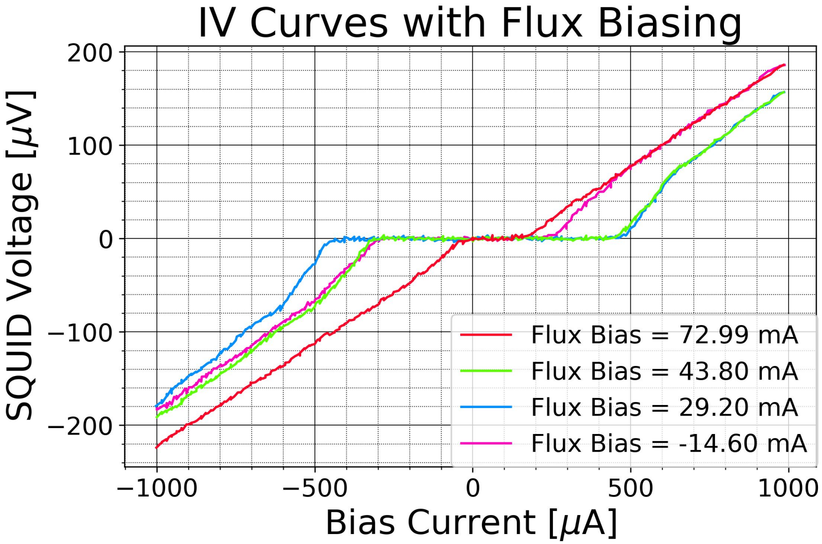
- The small voltage signal is amplified by a pre-amp G~10^4, low passed to exclude 60 Hz noise.



Design: Flux Biasing



- Current through Nb produces a modulation in critical current



Design: Data Acquisition

Oscilloscope Traces

⬇

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

Temperature Series Data

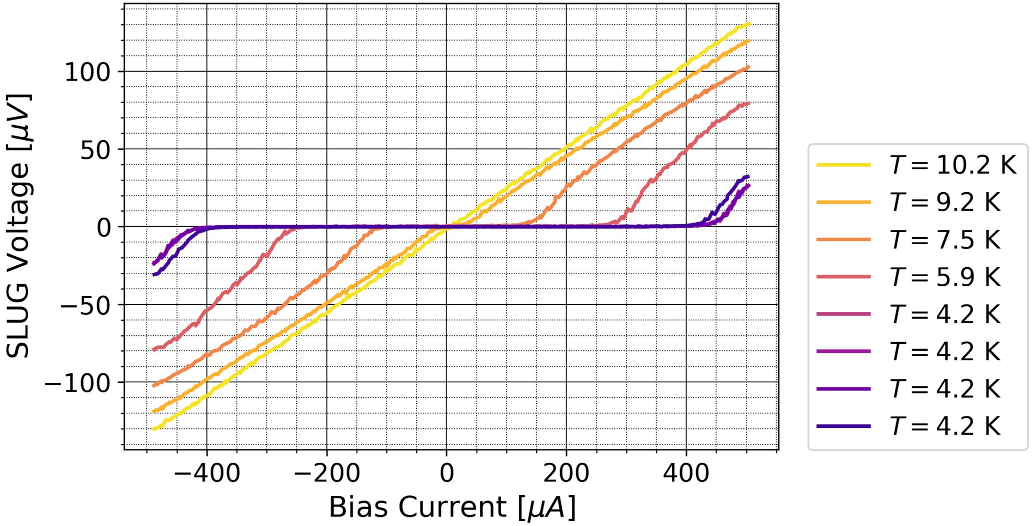
<ins>Top:</ins> Temperature series IV characteristics

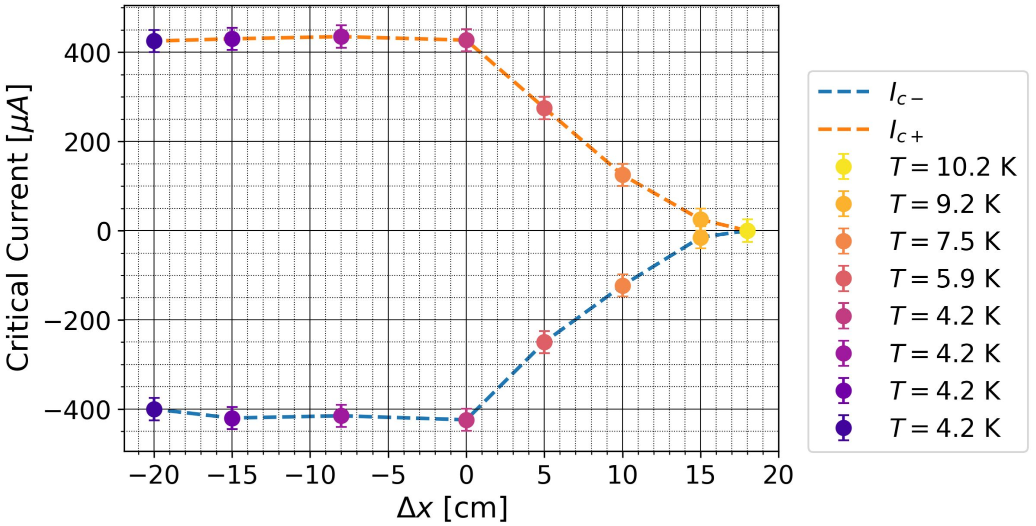
<ins>Bottom:</ins> Critical current as a function of probe position, relative to liquid helium surface

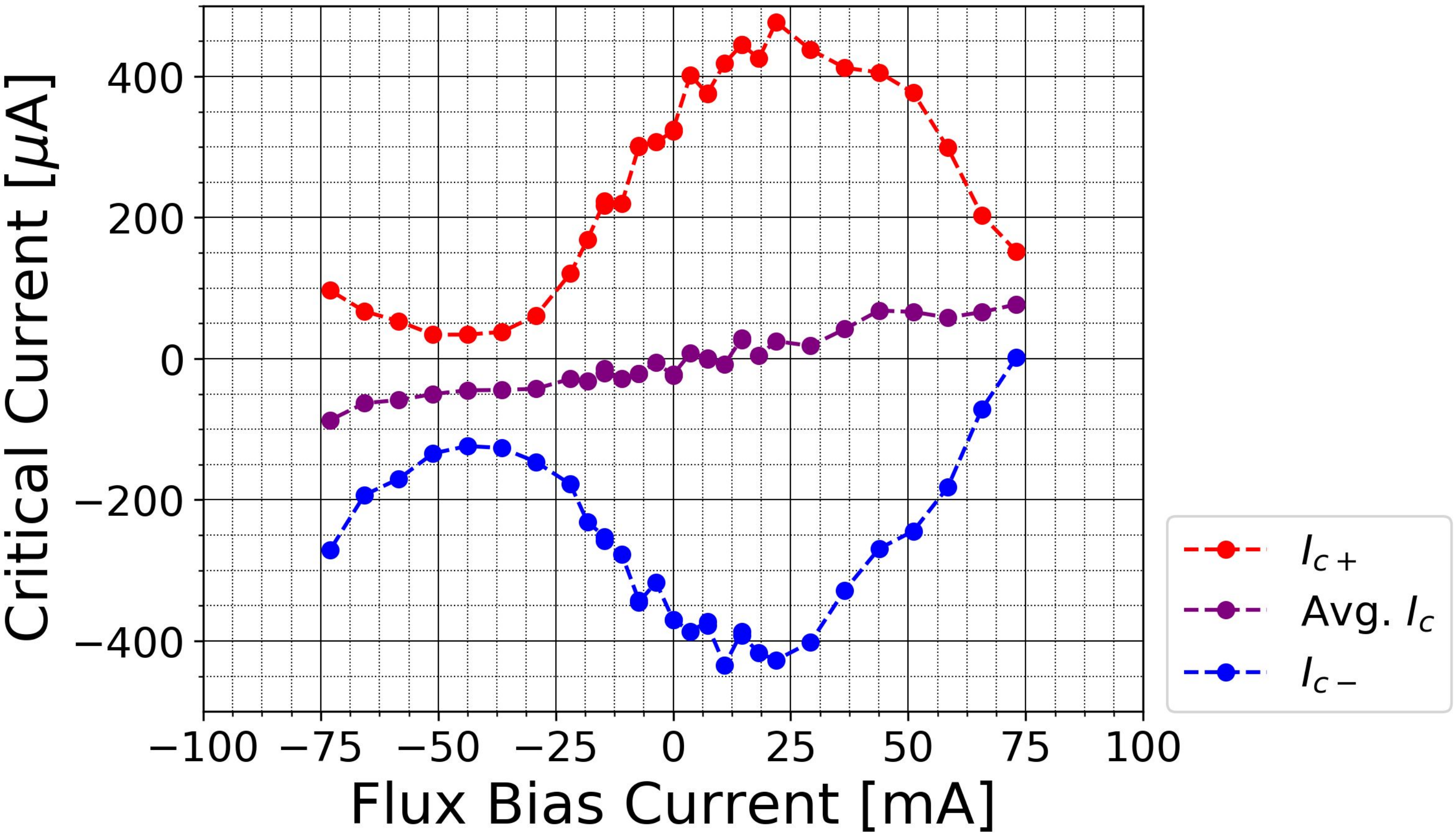
Temperatures are *estimates*:

- Assume linear temperature gradient
- Nb transition at 9.2 K
- Temperature of LHe = 4.2 K

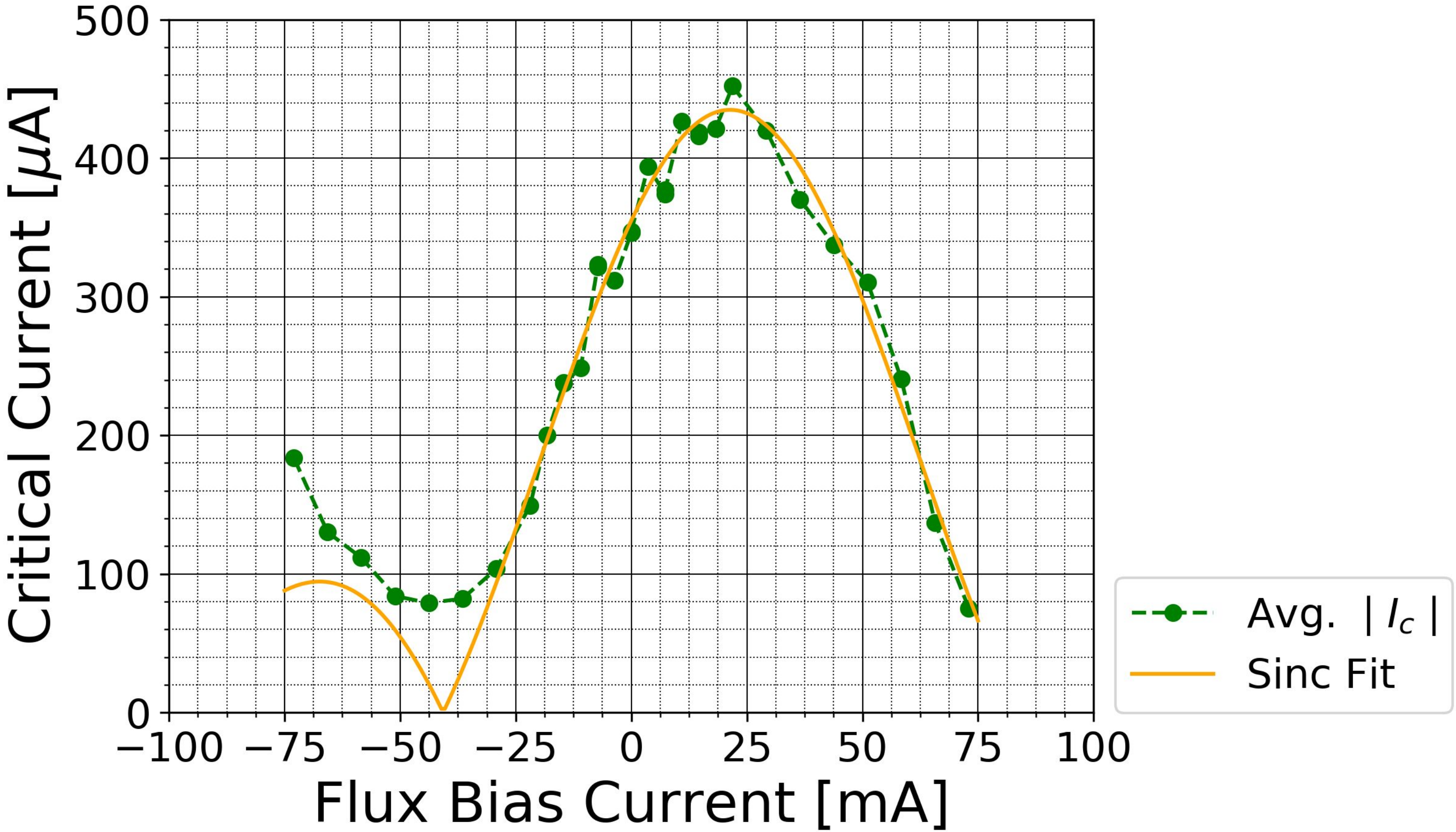
Assume that we reach transition temperature when critical current is non-zero. Assume LHe surface at Δx = 0 cm at which point T → constant 4.2 K







The purple trend is consistent with our observation of stray grounds in the probe. As the flux bias increases, some current goes to backward-biased the junctions, causing both critical currents to be pushed towards larger values to cancel the backward biasing.

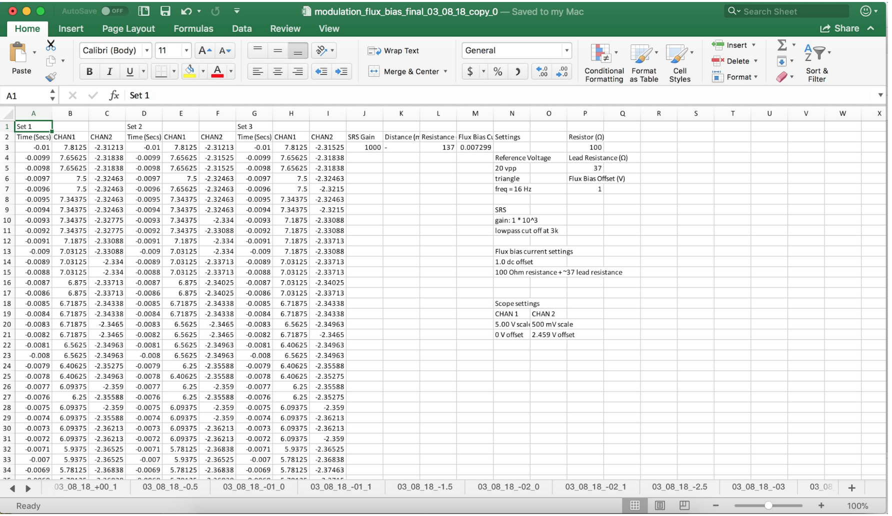


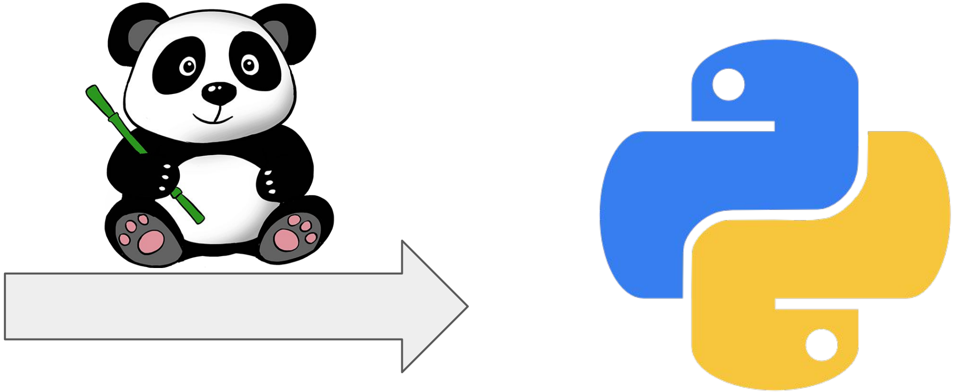
Spacing of first two zeros from fit: 124(3) mA

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





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

In [3]:
```python
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]:
```python
# Define constants
NUM_SHEETS_MOD = 32
NUM_SHEETS_TEMP = 8
```

In [5]:
```python
# 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))
```

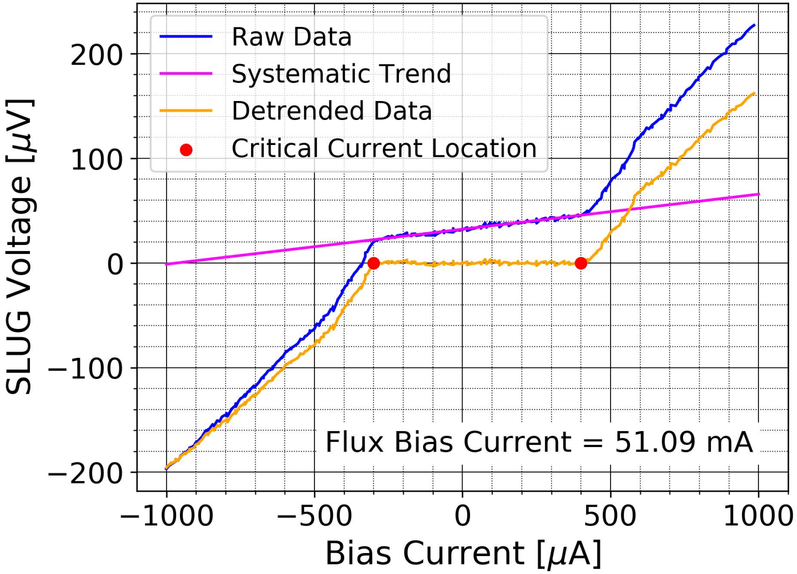
In [6]:
```python
# Mean subtract
for sheet in mod_DataSheets:
    sheet.mean_subtract()

for sheet in temp_DataSheets:
    sheet.mean_subtract()
```

In [7]:
```python
# 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

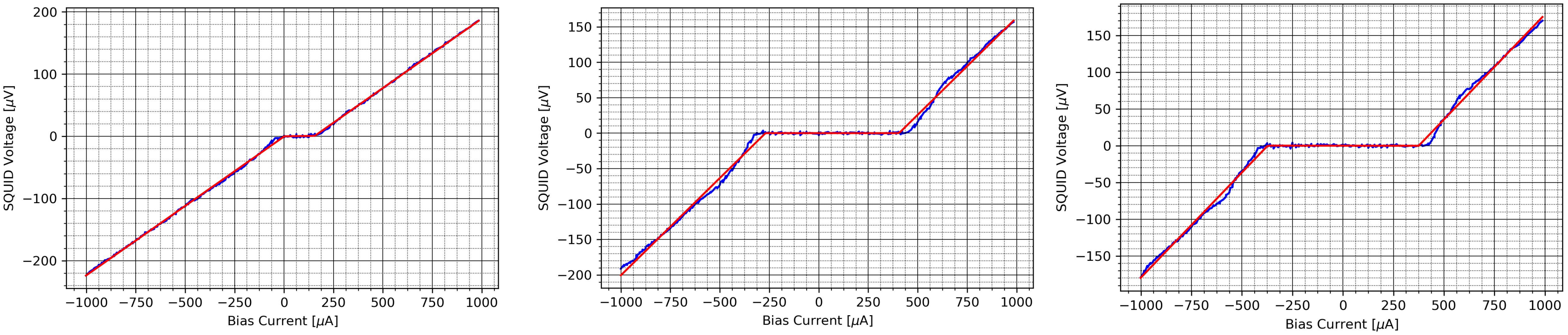


Results: Flux Bias Modulation

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)
```

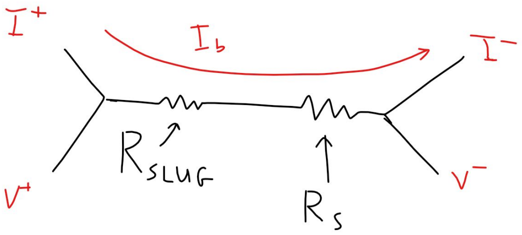
```
In [15]: def super_model(x, m_n, m_s, I_c_left, I_c_right):
             return m_n*(x-I_c_left)*(1 - heaviside(x - I_c_left))+m_n*(x-I_c_right)*heaviside(x - I_c_right) +
         m_s*x*(heaviside(x - I_c_left) - heaviside(x - I_c_right))
```



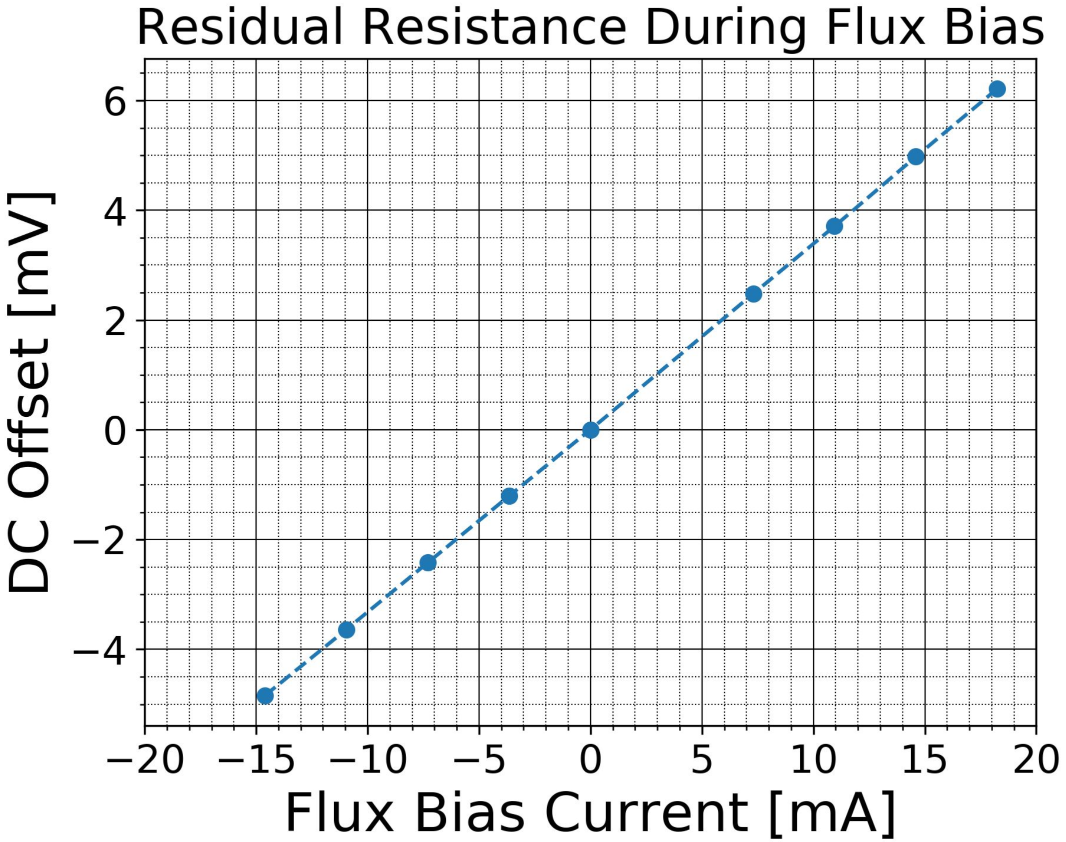
Results: Flux Bias

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

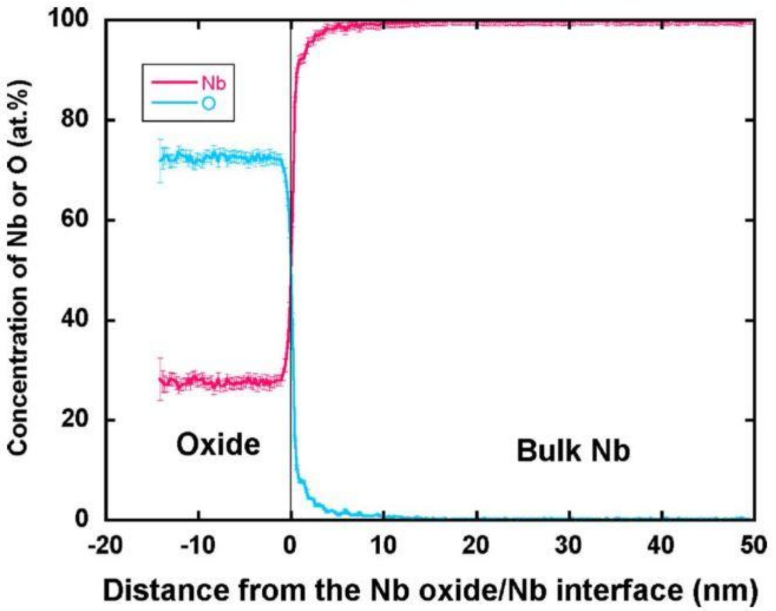


FIG. 4. (Color online) Proxigram showing quantitative Nb and O concentration profiles corresponding to the atomic reconstruction displayed in Fig. 3. The profiles yield a thickness of the surface niobium oxide of 15 nm, with a constant surface Nb oxide composition corresponding to Nb_2O_5.

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	124 mA	3 mA
d_wire	1.5 mil	0.3 mil
L_w	14 mil	2 mil
d_ox	15 nm	3 nm

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

= 1.7(5)

Conderations of Systematics:

- Proximity of SC to the oxide layer is not going to focus flux due to symmetry of the surrounding superconductor. A breaking of symmetry is needed for any flux to be focused.
- Incomplete covering/wetting of the window will reduce L and push our value lower.

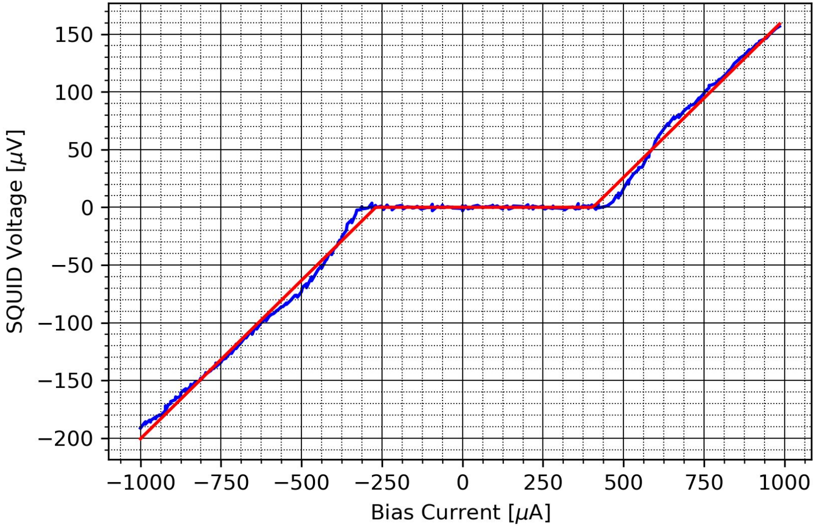
Discussion - Experimental

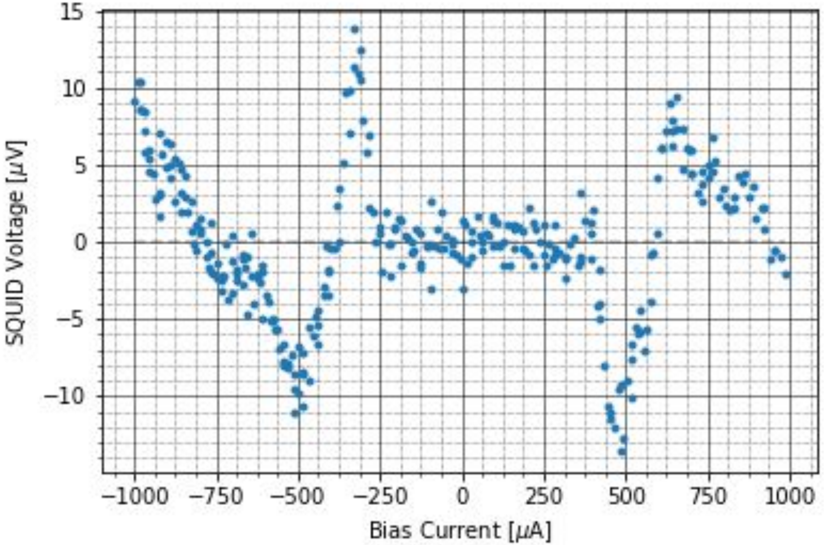
- we found unresolved grounding problems which lead to offsets and possible redirection of currents
- strong pickup at 60 Hz and also above ~kHz - look into lower noise electronics or batteries as current sources
- crimping and solder blob placement may introduce systematics

- 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

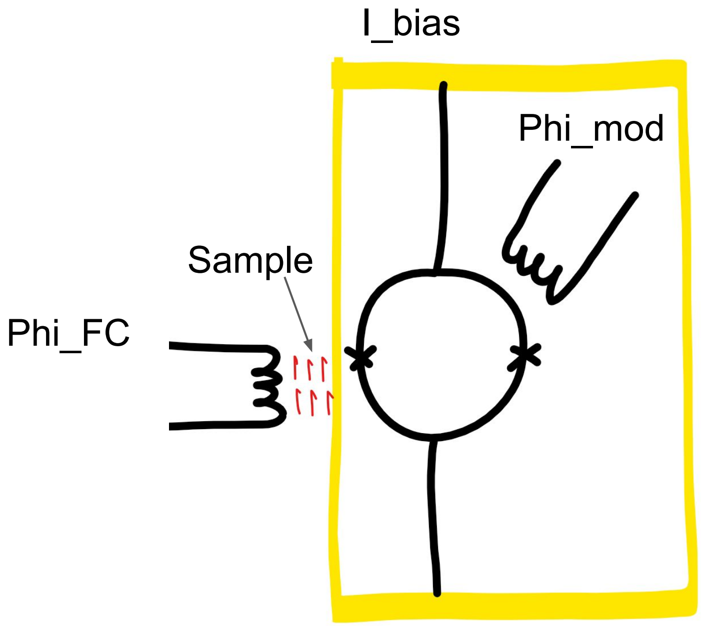
Future SLUG design considerations

- 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.

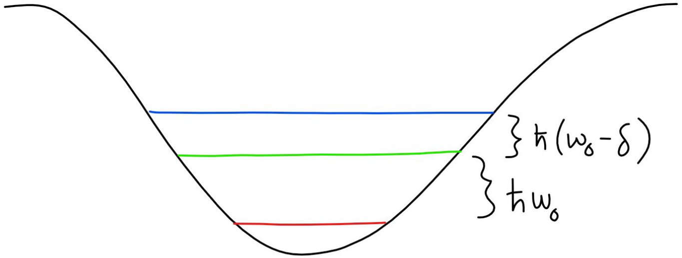
Josephson Equations:

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

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

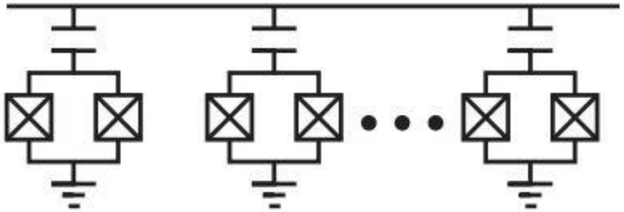
$$L_J = \frac{\hbar}{2eI_o\cos\phi}$$

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?