Week 2: 13/10/2021 – Wednesday

1. Outline of meeting and tasks

Prior to the meeting on the 12th, I had the opportunity to visit the camera in North Building on the lower ground floor. Tom Brien explained the briefly basics of the detector and how the 2 stage-active cooling of camera allowed the temperature to remain in the ranges of mK.

The meeting with my supervisor was to discuss the aims and objectives of the project and to complete the "Aims and Objectives and safety overview" sheet for submission. The discussed aims and title are shown in the following section. The risk assessment and safety section of the sheet was also discussed.

After this, seeing as there was time, my supervisor proceeded with explaining the topic of superconductivity and how it relates to the detector. The topics covered and further reading material is given in the final section of this week's diary.

My supervisor also provided the literature to read for a better understanding of the topic. The literature given was: "Lumped Element Kinetic Inductance Detectors" by Dr. Simon Doyle, and the recommended section to read was Chapter 3.1 to 3.4, page 13-25. Further outline of the materials elaborated in the final section of this diary.

2. Aims and Objectives Sheet

The title of the project is ***Characterizing Arrays of Kinetic Inductance Detectors.*** The Kinetic Inductance Detectors (KIDs) as mentioned will be used in an SFAB Security Imaging System. The discussed aims of the experiment are:

To fully characterise the SFAB Security imaging system in terms of detector sensitivity and yield. This will involve.

1) Learning and understanding the microwave properties of superconductors

2) Learning and understanding how a Lumped Element Kinetic Inductance Detector works

3) Be able to form a simple simulation of a LEKID detector

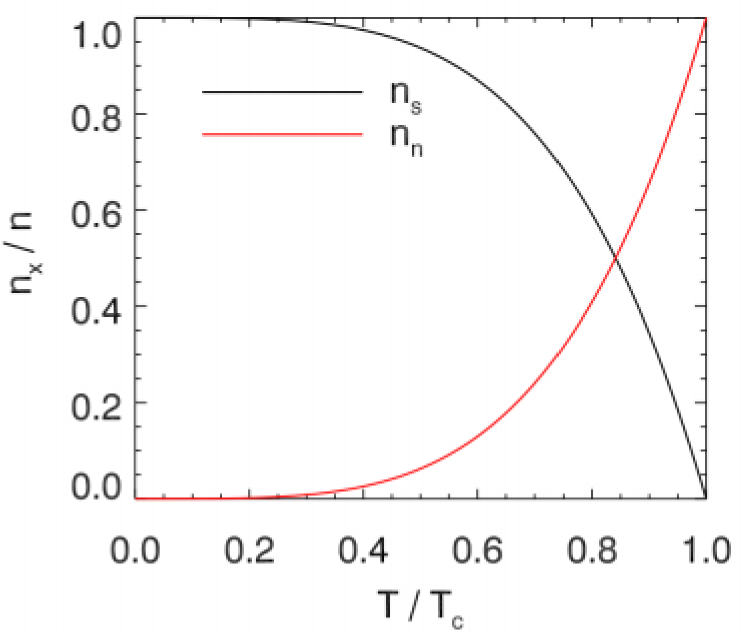
4) Understand how to analyse data from a LEKID array and to make sensitivity measurements from this data

5) Be able to compare the data of each detector in the array to the expected photon noise limit.

3. Notes and Materials Covered

Based on the literature provided in the pages outlined above, from the theory of superconductivity the phenomenon of kinetic inductance arises from it and as such is an important concept as a prerequisite to the fundamentals of the detector. A simple notes and explanation of superconductivity and kinetic inductance is given below:

In some elemental metals such as Niobium, Aluminium and Tin, the DC resistance falls to zero below a certain temperature known as the critical temperature, and as such these materials are known as superconductors. In normal metals, electrons scattering off the ions in the lattice cause a loss in kinetic energy and this leads to non-zero resistance. However, in superconductors below the critical temperature T_c, a fraction of the electron population start to "pair-up" into Cooper-pairs and these pairs are immune to scattering and as such have 0 resistance. The ratio, $\frac{n_s}{n_n}$ of the population of superconducting Cooper pairs n_s to unpaired electrons n_n is inversely proportional to the temperature T below the critical temperature. As T decreases, the number of cooper pairs increases. A plot of this relationship is shown:



Source: Simon Doyle Understanding Superconductivity and KIDs Slides

When an electrical current is applied on a superconducting material, the current simply passes through the population of superconducting electrons and thus arises zero resistance. When the temperature increases, the kinetic energy of the electrons break Cooper pairs and the population of n_n increases.

Another important concept about superconductivity is the Meissner Effect. Essentially, a superconducting material will completely expel any magnetic flux density from within the bulk by creating surface currents to cancel any flux that penetrates it. The relationship of the field into the material is characterized by the 2 London equations:

$$\frac{dJ}{dt} = \frac{n_s e^2}{\omega m}$$

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

λ_L is the London Penetration depth. It is the value at which the field decays to $^1/_e$ of its value at the surface within the distance $\sqrt{m/\mu_0 n_s e^2}$. The result of the London equations are essential in characterizing the inductance of the material.

The next portion touches on the two fluid model of the behaviour of the electrons in the material. As mentioned previously, below T_c, the populations of the electrons split into 2 different populations n_s and n_n which coexist within the lattice. n_n is affected by the usually scattering and exhibits loss. n_s on the other hand, does not undergo scattering and thus no loss. The Cooper pairs are bound together with an energy gap of 2Δ (1 from each electron). The model takes into account that the current in the superconductor has 2 paths to travel through, n_s and n_n. The ratio of n_s/n (n being the total conducting electrons) is given by:

$$\frac{n_s}{n} = 1 - (\frac{T}{T_c})^4$$

$$n_n = n - n_s$$

The above gives the temperature dependence of the population of the superconducting electrons, and will be essential in future calculations for the conductivity of the material. The conductivity of n_s can be denoted by σ_s and conductivity of n_n is denoted by σ_n. Taken directly from the notes: "At low frequencies, the σ_s is far greater than σ_n, thus displaying zero resistance. At higher frequencies however, especially in the microwave region, σ_n can play a considerable part in the conductivity. This is due to the kinetic inductance of the superconducting electrons. The inertia of these electrons produces a reactance giving us a large impedance at high frequencies. This effect is likened to an inductance as the energy drawn from the field E is stored in the kinetic energy of thse non-scattering electrons." As the temperature or frequency increases, more of the current will be shunted through the non-superconducting resistive path. From this, derives the temperature dependence of the London Penetration Depth, LPD:

$$\lambda_L = \lambda_L(0)\ [1 - \left(\frac{T}{T_c}\right)^4]^{-0,5}$$

Where $\lambda_L(0)$ is the LPD at 0 Kelvin.

By summing up the kinetic energies of all the superconducting electrons, we can use this to determine the kinetic inductance of the material given by the following expression:

$$L_k = \frac{\mu_0 \lambda^2}{Wt}$$

Where W is the width of the sheet and t is the thickness. It is also further simplified by calculating the L_k of a square of the material and thus the W term vanishes. We are also often working in the limits of t << λ and t >> λ, thus we need to perform surface integrals for current over the entire cross-sectional area to take into account variations in current density. L_k and L_m, the magnetic inductance is given by:

$$L_k = \frac{\mu_0 \lambda^2}{4}[\coth\left(\frac{t}{2\lambda}\right) + \left(\frac{t}{2\lambda}\right) cosech^2\left(\frac{t}{2\lambda}\right)$$

$$L_m = \frac{\mu_0 \lambda^2}{4}[\coth\left(\frac{t}{2\lambda}\right) - \left(\frac{t}{2\lambda}\right) cosech^2\left(\frac{t}{2\lambda}\right)$$

The total internal inductance is thus given by:

$$L_{int} = L_m + L_k = \frac{\mu_0 \lambda}{2}\coth\left(\frac{t}{2\lambda}\right)$$