Vertical Tests of ILC Cavities and Detection of X-Rays from Field Emission

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The International Linear Collider (ILC) is a proposed accelerator for studying electron-positron collisions at Terascale energies, at which synchrotron radiation makes circular e^+e^- machines infeasible. Cornell is involved in many aspects of the research and development for the ILC, among which is testing samples of 9-Cell Niobium superconducting RF cavities that will be the building blocks of the accelerator in the ILC. During the test, there is the possibility of field emission. Since field emission dissipates the power that is being stored in the cavity, it will set a limit on accelerator performance. In order to improve the performance of these cavities, it is important to recognize the source of these field emissions. To that end, an X-ray detector was built using PIN diodes and tested both in room temperature and after being cooled down by liquid nitrogen for future ILC 9-cell cavity tests. Future work will test these detectors in the liquid helium surrounding a cavity under test.

Introduction

The goal for the ILC is to accelerate electrons to 500 GeV. The current design for the ILC accelerators includes Niobium Superconducting RF cavities, cooled to 2 Kelvin, which must maintain a 35 MV/m on axis E-field. The length of the ILC, from one end to the other, is approximately 31 km, meaning it will be made of 18,000 9-cell SRF cavities. At Cornell, once or twice a month, a 9-cell SRF cavity is cooled down (inside a pit) to 2 degrees Kelvin (using liquid nitrogen and liquid helium) and its average accelerating E-field and its Q_0 factor is measured. 2K is well below the critical temperature for superconducting Niobium, 9.3K. This temperature allows a high RF magnetic field to be supported without losing the superconducting state. Operating at 2K, which is below the lambda point of helium, also takes advantage of superfluid helium's efficient cooling of localized heat sources on the cavity. The Q_0 factor is the measure of how slowly the power stored in the cavity is dissipated in the walls of the cavity $Q_0 \equiv \frac{\omega_0 U}{P_c}$ or in the other words over how many oscillation periods the transmitted power will decay from the resonance frequency. As $Q_0 \equiv \frac{\omega_0}{\Delta\omega}$, Q_0 is also a (reciprocal) measure of the resonance width. The measured E-field, also referred to as E_{acc}, is the maximum energy gain possible during the transit per electron divided by the length of the cavity: $E_{acc} \equiv \frac{V_c}{d}$. If the Q_0value maintains a reasonable value up to $E_{acc} = 35$ MV/m, the cavity is suitable for the ILC. In practice, the test is often stopped before that point due to quench (when the Niobium loses its superconducting state) or loss of power (when Q_0 drops so much that the necessary power exceeds the amplifier capability).

Today's understanding of the behavior of SRF cavities know two main factors that limit the E_{acc} . One is the peak surface magnetic field of the cavity which can not be above the critical RF magnetic field because the cavity will not be able to resist high magnetic field applied to it, causing it to quench. The other factor is the peak surface electric field that can cause field emission at high field region [Padamsee 98]. Having field emission means that there are free electrons in side the cavity that will use the power intended to accelerate the beam, and cause the Q_0 value to go down. These electrons can also hit the wall of the cavity and heat up the wall of the cavity. Thus, it is essential to keep track of the field emission.

There are two ways of monitoring the field emission. One is temperature mapping: since collision of the electrons to the wall increases the temperature of a region of the wall, it is possible to estimate the region of field emission by monitoring the temperature of the wall of the cavity. However, it is possible that a temperature peak be observed in a region without field emission. On the other hand detecting X-ray radiation definitely indicates that field emission exists. The current detector that is being used during the tests at Cornell is left outside the pit; there is a significant path length between the detector and possible source of field emission. Since finding the cell or the location of the X-ray emission's source can help the improvement of the cavities, detectors that can be left inside the pit during the test are desired.

Silicon PIN diodes were used to build such detectors. When X-ray photons hit the active region of the diode, they deposit a charge on the diode due to Compton scattering and photo electric effect. Due to the characteristics of silicon such as the relationship of its band gap energy with temperature, the theory suggests that the Silicon PIN diodes would work even at low temperatures. A prototype detector, based on a design borrowed from KEK, was made and tested.

Methodology

Initially, the detector was assembled on a breadboard using a Si PIN photodiode (S 1223 series), as shown in Fig. 1. The diode is forward biased and connected to an op-amp integrator. The signal from the integrator goes through an amplifier with a gain of 10 and finally through a low pass filter. The board was then installed in a project box and the diode was taken off the board and put out of the box, as shown in Fig. 2. Voltage of -12 V and +12 V was applied to power the circuit. The output signal was read by an Tektronix TDS 2000 series oscilloscope. Two programs, one for fast and convenient reading of the traces off the monitor of the oscilloscope, and one for reading the trigger rate of several runs and averaging their results, were written in Python which allowed a computer to communicate with the scope through a GPIB-USB connection. A Cs-137 radioactive source with activity of about 23μCi was used. All experiments were done while the light in the room was off to avoid noise in the signals.

Initially the detector was placed directly in front of the source. The trigger rate of the oscilloscope was recorded for different distances between the source and the detector. In another setup the source was placed 2 mm away from the detector for 45 minutes and the signals that were received by the oscilloscope were saved. Then the source was placed exactly in front of the detector–so that only the glass (made of borosilicate) was between the source and the detector–and the trigger rate was measured. Finally, the detector was cooled down by liquid Nitrogen (re: source and diode dunked in dewar) and the signal recorded.

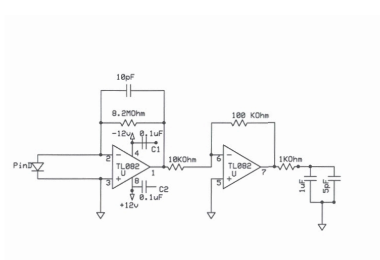

Figure 1: X-ray Detector Schematic Designed at KEK

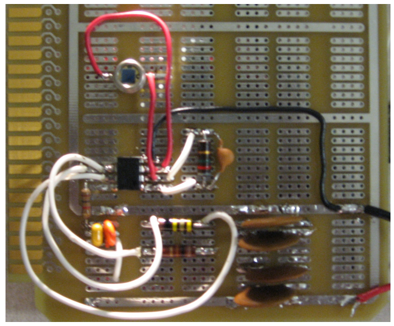

Figure 2: The Prototype Detector

Theory

The radioactive Cs-137 source has a half life of 30.2 years. It has β decay and emits electrons of 0.514 MeV with a 94 percent probability and subsequently photons of 0.662 MeV with emission probability of 85 percent [Montanet 94]. Considering the 0.662 MeV photons' effect in the diode, the energy required to create an electron-hole pair in the silicon is about 3 times the band gap energy of the silicon. This indicates that if all the energy of the photon is deposited on the silicon, 0.063pC charge will be received by the detector and after passing thought the 10 pF capacitor and x10 amplifier, the final output of the circuit for a photon of maximum energy, 100 percent absorbed by the diode, should be 63 mV.

Charge deposited on the diode=
$\frac{21.6\times10^{-16}(C)662000(eV)}{3\times1.12(eV)} = 0.063pC \times \frac{1}{10pF} = 6.3mV \times 10 = 63mV$

The number of photons that pass through the detector can be obtain from this relationship: $N = \frac{2\times S(s^{-1})}{4r^2\pi}\frac{photon}{cm^2 s}$. If r (the distance between the detector and the source) is 2 cm and S is the activity of the source in $s^{-1} \Rightarrow 23\mu Ci \times 37000 = 851000 s^{-1}$ then the number of photons that pass through the detector's area in cm^2per s is 33900. Since the active area of the detector is 13 mm^2 we expect 4400 photons/s to pass through the diode. This number can be used for calculating the efficiency when we measure the trigger rate of the circuit. One other relationship that can be used is that as the source moves away from the detector simple geometry dictates that the number of photons that make it to the detector decrease proportionally to the inverse square of the distance between the detector and the source. $N \propto \frac{1}{r^2}$

Some effects of low temperature on the diode's silicon was also considered. For example, the change in silicon bandgap due to temperature T has been studied by many and there is an experiment based approximation for it where α is 473 $meV K^{-1}$ and β is 636 K, as read from the fitting curve. Band gap energy for silicon at 0 K is 1.17 eV. So the band gap energy can be calculated knowing the temperature and using the following formula from [Van Zeghbroeck 2004]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}$$

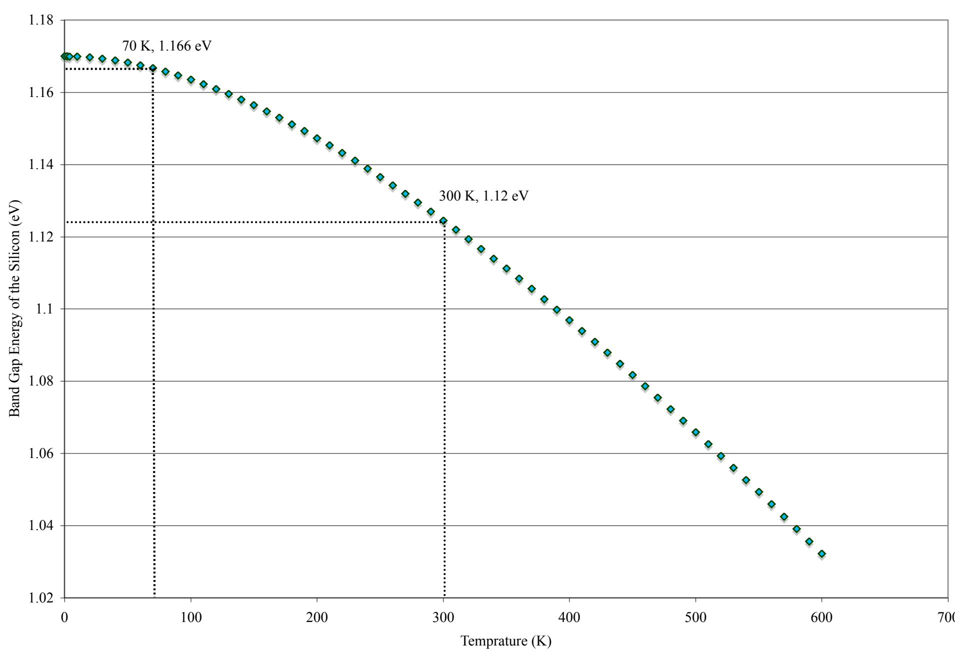

Figure 3: The relationship of the Silicon bandgap energy and Temprature

Results

The detector, both at room temperature and at after cooled by liquid nitrogen did detect X-rays, however its efficiency was approximately 0.1 percent. Given more time, we would have calculated (e.g. using a table of cross sections) or simulated (e.g. using EGS, GEANT, etc.) the probability of a given 662 keV photon's depositing a given fraction of its energy in the PIN diode. (A quick check of tables of average energy losses indicates that it is plausible for a beam of 662 keV photons to lose about 1% of its energy in a couple of hundred microns of silicon. A follow-up study should consider how the energy loss would be distributed photon-by-photon.) When the distance between source and detector was varied, the number of photons that passed through the detector per second were proportional to the inverse of square of the distance between the source and the detector, which proves that the signals received by the detector were from the radiation of the source rather than noise. This data is shown in Figure 4. Figure 5 is a histogram of the signals received by the detector over a 45 minute period with a constant distance between the source and the detector. Note that all signals received by the detector, except for one, have energies below 63 mV. The average of the signals received was 37.01 mV. When the source was very close to the detector the trigger rate was about 3 Hz. When we calculated an anticipated 4400 photons/s in the diode, and only see 3, this led to our conclusion that the detector was only 0.1 % efficient. Figures 6 and 7 show example traces that were read from the oscilloscope first at room temperature and second, while cooled down with liquid nitrogen. The amplitude of both signals is the same, but the cooled down signal is much noisier. We believe that this noise was an artifact of our test and not a fundamental problem. In order to test the detector during the ILC test an PCB board was designed and made at the very end of this project. (Fig 9.)

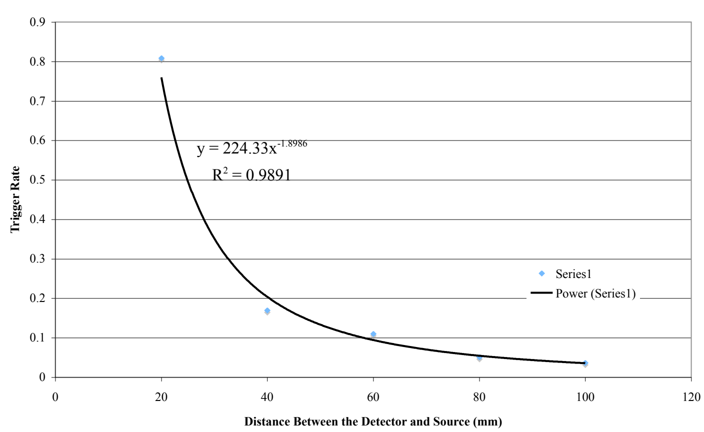

Figure 4: Number of Photons passed through the Detector vs. Inverse square of Distance

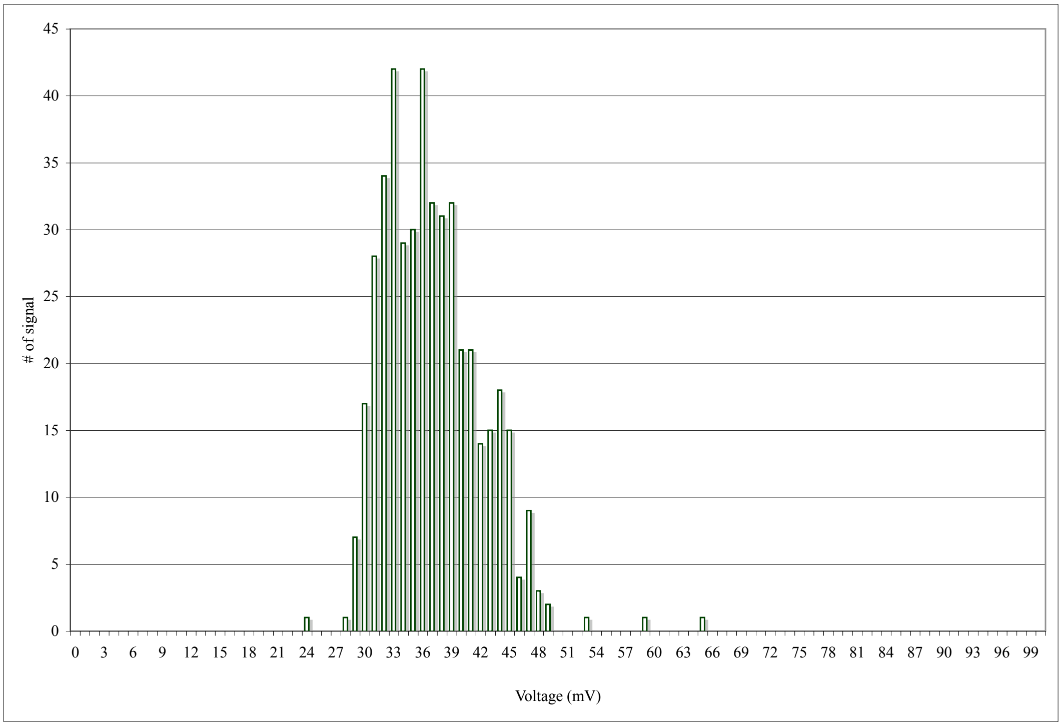

Figure 5: Histogram of the Signals received by the Detector in 45 min

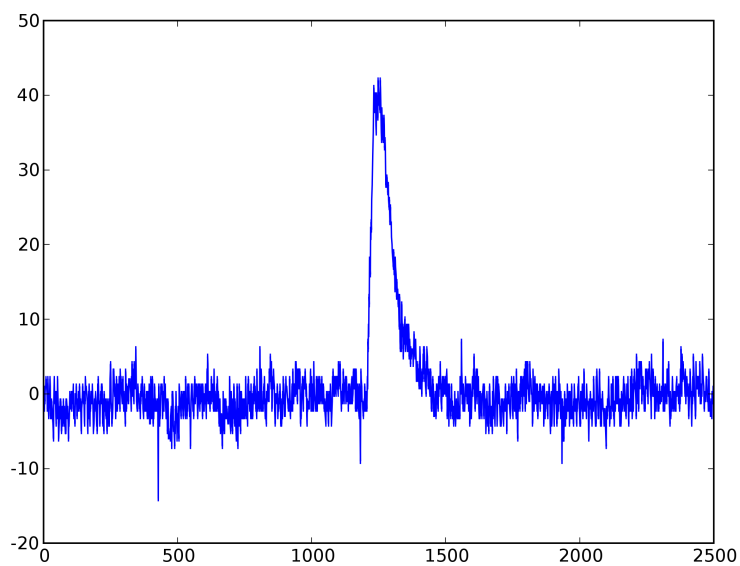

Figure 6: Trace of the Signal from Oscilloscope at Room Temprature (Voltage (mV) vs. Time (μs))

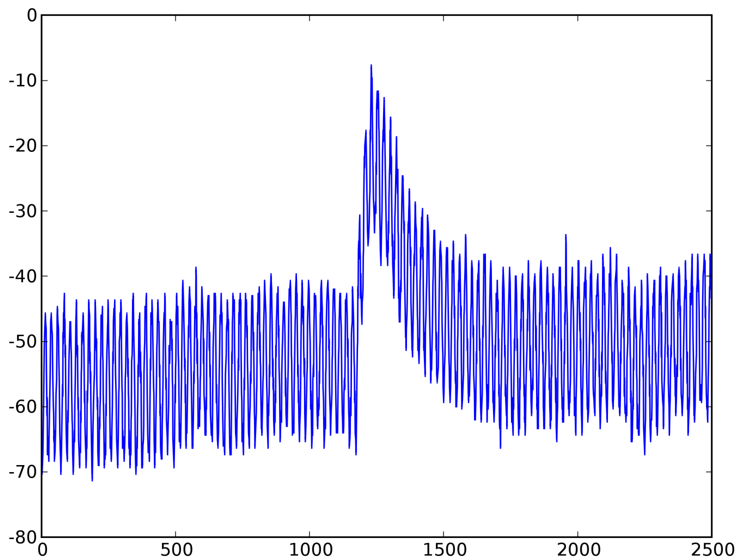

Figure 7: Trace of the Signal from Oscilloscope after cooled down by liquid Nitrogen (Voltage (mV) vs. Time (μs))

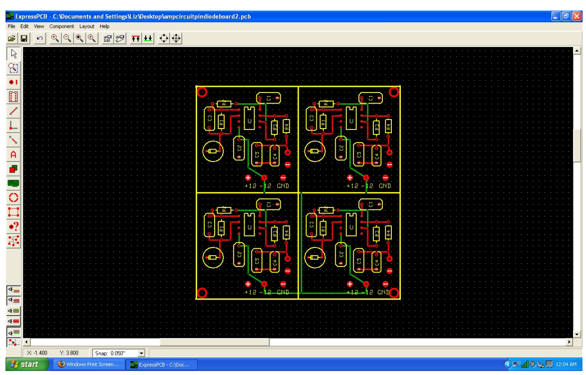

Figure 8: PCB Circuit Design

Conclusion

The results from the experiments with the PIN diode X-ray detector are promising. The detector was operational at approximately 70 K, though the efficiency rate was very low, approximately 0.1 percent. The radiation from the field emission is much greater than the Cs137 source. The maximum exposure rate of the X-rays observed during the last test was $2.4 \times 10^3 \ mR/hr$, while Cs-137 with 23 μCi had an exposure rate of $1.38 \times 10^{-1} \ mR/hr$, which is 4 orders of magnitude less than what is expected during the test, so we anticipate that if there is field emission during the test, a detector in the correct location could see it. On the other hand, it is also to important to know how long the diodes can stand the high rate of radiation during the cavity test before they are destroyed. The factors studied in this experiment are a few important aspects of X-ray detection at low temperatures. However, many quirks of the detector and the best way to install it can probably best be investigated during an ILC Cavity Test.

Acknowledgment

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References

[Montanet 94] L. Montanet et al., *Particle Physics Booklet* URL: http://pdg.lbl.gov/, (1994).

[Padamsee 98] H. Padamsee et al., *RF Superconductivity for Accelerators,* John Wiley and Sons, New York, (1998).

[Van Zeghbroeck 2004] B. Van Zeghbroeck *., Principle of Semiconductor Devices,* URL: http//ece-www.colorado.edu/bart/book/, (2004).