Qweak Technical Note:

Irradiation and Field Test of the TRIUMF Preamplifier for the Qweak Experiment

D. Mack
TJNAF
12/27/05

Abstract

A prototype of TRIUMF's low noise preamplifier, built for the Qweak experiment, was dosed to 18 kRad in JLab's ^{137}Cs irradiation facility. No increase in noise was seen during irradiation, nor was there any significant deterioration in performance noted following the irradiation. The specification for radiation hardness for this component was only 1 kRad of gamma dose, so this test exceeded the specification by more than an order of magnitude. This was also something of a field test of the prototype, and no actual problems were identified. A potential problem related to shavings from the self-tapping screws is easily resolved. With some minor changes in the choice of gains, TRIUMF plans to start production on the first lot that will be used in the main detector.

1 Introduction

The 2200 hour long running time for the Qweak experiment demands that we operate as close to counting statistics as possible. We can achieve this only if all other sources of noise, besides track counting statistics, are negligible. One source of concern is radiation damage in the I-to-V preamplifiers which must necessarily be located close to the detectors. Rumors of excess noise in the E158 experiment from "electronics" suggests that instantaneous ionization and RF pickup may also be concerns, at least at pulsed machines. The TRIUMF preamplifiers have been tested to have a noise level which is not only well below the noise level of our track counting statistics, but also significantly below the shot noise expected in a battery test.[1] We want to make sure they'll stay that way during beam operations. The two important questions addressed in this note are:

- Does the noise level increase significantly in the expected field of ionizing radiation?

- Will the noise level be permanently increased after soaking in the expected field?

As we'll see below, these questions were answered by a combination of on-site irradiation and measurement effort, combined with much more sensitive off-site noise measurements at TRIUMF. Along the way, general operational experience (ie, field testing) with the preamplifiers was obtained.

A cartoon of the detector and electronics chain, with the radiation hardness specifications, appears in Figure 1. The best-justified number is the expected dose to the fused silica radiator of about 100 kRads. This is well known because it is a thin radiator whose dose is determined by the nearly 1 GHz of electrons passing through it. All other electronics are outside the beam envelope, but at varying distances from it. For example, we have assigned a radiation hardness specification for the nearby phototube/base combination of 10 kRad (10% of the radiator dose), and for the more distant preamplifier of 1 kRad (1% of the radiator dose).

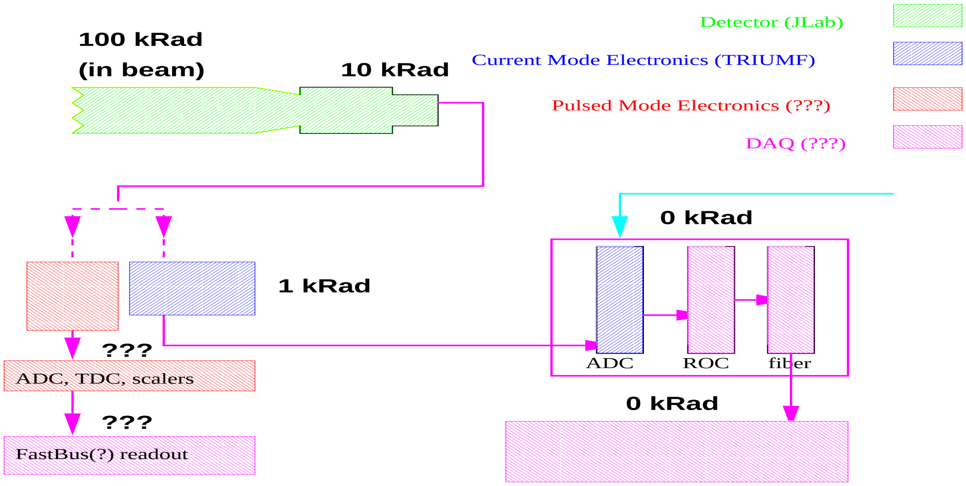


Figure 1: Radiation hardness specifications for different parts of the Qweak detector and electronics chain.

The latter figure is arguably optimistic, corresponding to only 0.5 mR/hour for a 2200 hour experiment.[1] The Qweak shield house wall will be penetrated by 8

---

[1] During the G0 forward angle measurement, with standard badge dosimeters I found about 25 mR/hour near the magnet controls rack which was located behind a wall of Iron shielding blocks.

large windows so is clearly not hermetic. Fortunately, with low-capacitance cable, the preamplifer can be located almost anywhere inside the detector hut and can sit in a well-shielded box.

2 Experimental Setup

2.1 Irradiator

The TRIUMF preamplifer is based on an OPA2604 front end with an OPA2227 cable-driving output stage. It also contains a DC-DC converter, and a few protection diodes. Other than these potentially sensitive components, the remaining resistors and capacitors should be extremely rad-hard.

The irradiation was done in an Eberline ^{137}Cs irradiator, with a current activity of about 94.4 Curies.[2][2] Any particle physics booklet gives the information in Table 1.[3] The resulting dose is primarily from gammas, but with a significant electron component. Figure 2 is a figure of the irradiator. For the particular shelf I used, the maximum nominal dose rate (with the shutter completely pulled out) was 86 Rads/hour. The irradiator is interlocked so that the source shutter cannot be opened unless the door is closed and secured with a key. A 1 kRad dose can be acquired in half a day, or a 10 kRad dose in 5 days. The compartment in which the sample is placed has convenient cable penetrations so equipment can be irradiated while energized. Basically, the setup is nearly ideal for the irradiation and real-time monitoring of small, powered electronics up to total doses of about 10 kRad.

Table 1: $^{137}_{55}Cs$ *source emitted energies. The half-life is 30.2 years.*

$\boldsymbol{\beta^-}$	γ
0.514 MeV (94%)	0.662 MeV (85%)
1.176 MeV (6%)	

In order to make the test as realistic as possible, the preamplifier was powered

---

This area had no roof, however, so the dose was presumably dominated by neutrons and air glow. Clearly, during a high luminosity experiment, any spot in the forward half of the hall which is not hermetically shielded can acquire at least 10's of kRad over 2200 hours.

[2] For reference, the original activity was 170.1 Curies on June 5, 1980.

during irradition with a Topward 6306D regulated DC supply set to +5 Volts. Because a potential failure mode is for the DC-DC converter in the preamplifier to fail to a short, and I didn't want to supervise the irradiation full time while smelling for smoke, the current was limited to slightly above the standard operating current of 0.19 A. Note that each 2-channel box will therefore draw about 1 Watt, so a rack of 10 such boxes can be well-shielded from radiation without having to provide a large airflow for cooling.

A current source was made from a 9 Volt battery and a 2.5 MOhm resister. This provided a -3.6 μA input to channel 1 of the preamplifier through 2 feet of RG58 (50 Ohm) cable. The specific channel selected for study had a nominal transimpedance of -1 MOhm, so it would convert -1 μA of input current to +1 V at the output. The output offset happened to be set to nominally +1 V, so the total output voltage was about +4.7 V and was a reasonable imitation of the future data signal. In Figure 2 the battery is barely visible hanging down the left side of the irradiator, a foot or so above the base. The battery was later moved inside the irradiator box when it was realized that the unshielded leads were picking up relatively large amounts of noise from the room.

Dosimetry was placed above and below the preamplifier (Figure 3) in case the field changed with distance from the source. Each plastic capsule also contained two rods as a consistency check.

The spectrum analyzer was an HP (now Agilent) 3588A. With a +4.7 V input bias and DC coupling, the spectrum analyzer showed signs of severely distorting the noise spectrum, so AC coupling was used as the lesser evil. This may have produced some attenuation at lower frequencies.

3 Dosimetry Results

The dosimetry report is given in Figure 4. Recall that the TOP and BOTTOM dosimeters bracketed the preamplifier. As a consistency check, two rods were contained in each of the TOP and BOTTOM capsules. Within a capsule, the two results are consistent within a few percent suggesting a small random error. However, the average readings of the TOP and BOTTOM dosimeters were quite different, ranging from about 14 kRad to 21 kRad. This suggests that a significant fraction of the beam consists of low energy electrons which are stopped by one or both walls of the preamplifier Aluminum casing. However, there may be a small contribution from beam divergence as well. Averaging the results, and assigning a generous uncertainty corresponding to half the full range of values, the estimated dose was 17.9 ± 3.5 kRad, or 0.2 Joules/gram.

The above relative error of ± 20% is adequate for this task. The total dose was more than an order of magnitude greater than our specification of 1 kRad. However, if we use this irradiator again, it would be a good idea to put the dosimetry *inside* the electronics casing. The shielding of low-energy electrons is a systematic issue that probably won't go away with a different irradiator. For example, there are many intense ^{60}Co facilities in the world, but with a 100% branch to a 0.316 MeV β ray, plus additional electron production via Compton scattering, a significant fraction of the dose in a γ irradiation is always going to come from low energy β rays which are sensitive to shielding details.

What about damage from neutrons? A Rad is a Rad, but for biological damage the weighting factors for neutrons are 5-20 times higher depending on the neutron energy (peaking around 1 MeV).[3] This is because neutron scattering produces heavily ionizing recoils which are more likely to produce non-repairable DNA scission. Note that this higher weight for neutrons also reflects the higher production of dislocations, which is relevant to semiconductor damage. Gamma rays near 1 MeV mostly lose energy through Compton scattering from electrons with a relatively small probability of producing dislocations.[4] I deliberately extended the total dose to almost 20 times our specification of 1 kRad to simulate the greater damage that might be expected (assuming biological weight factors) for up to about 1 kRad of neutrons. However, there are suggestions that for a worst case field of 1 MeV neutrons, displacement damage could be 100 times worse compared to gammas.[5]

4 Irradiation Results

Observations are summarized in Table 2. I saw a small increase in noise level when the current source was attached. While some of this may have been due to shot noise, I realized only at the end of the run that there was significant baseline distortion caused by large 60 Hz pickup on the battery leads. When the battery source was moved inside the irradiator, most of the 60 Hz pickup went away and the baseline shifted. This final baseline can be seen in Figure 5.

Table 2: *Brief summary of JLab measurements during the irradiation.*

$V_{baseline}$ (μV rms)	**Conditions**	**Comments**
0.38 ± 0.01	no signal input (Vout = 1.V)	
0.43 ± 0.01	with battery input (Vout = 4.72V)	shift probably due to distortion, not shot noise battery leads unshielded
0.45 ± 0.01	irradiation on or off (Vout = 4.72 ± 0.01V)	many days, many measurements
2.0 ± 0.1	moved battery inside	60 Hz dropped. baseline shifted see figure for final spectrum

With the final, minimally distorted baseline of roughly 2 μV, I calculated the noise in a 50 KHz bandwidth as follows:

$$2\mu V/bin \times 2bins/Hz \times \sqrt{50,000Hz} = 894\mu V$$

which is significantly greater than the approximately 300 μV that Des Ramsay calculates for a battery source.[3] I interpret this to mean that the spectrum analyzer noise floor is significantly larger than the preamplifier noise level. In the future, to make useful measurements we'll need at least a x10 amplifier before the input to the spectrum analzyer, and a x100 amplifier would be needed to be able to completely ignore the noise from the spectrum analyzer's front end and make accurate measurements which can be compared to PSpice. (The TRIUMF guys use a x200 amplifier.)

There was no observable change in the noise level, shutter in versus shutter out, at the dose rate of approximately 86 Rads/hour. Despite the high noise floor of the spectrum analyzer, since the dose rate was about 190 times the specified dose rate during the experiment, we can conclude that ionization noise during the experiment will be completely negligible.

There was also no change in the DC output voltage. In principle, the DC offset

---

[3] Note that the 0-400 Hz range was spanned by 800 bins, and I assume the spectrum analyzer has applied the proper anti-aliasing filter for this frequency range.

and transimpedance are set by resistors which are almost infinitely rad-hard, but in principle there could have been radiation damage to the cable-driver output section.

After irradiation, the preamplifier was sent to Bill Roberts at TRIUMF for precision noise measurements. Bill confirmed that the noise levels were consistent with his original measurements (170 μV rms for the 1 MOhm setting on channel 1) and that no damage was evident.[6]

The current draw dropped from about 0.19 A to 0.17 A over the course of the irradiation. This seemed to be systematic effect rather than simply flicker in the last displayed digit. I don't know what it means.

5 Summary of Preamplifier Field Testing

5.1 end-user warm and fuzzies

From the end-user's point of view, the TRIUMF preamplifier modules are robust, well-shielded from RF, have very low power consumption, aren't picky about the input voltage, and introduce such little noise that only an expert with special equipment can even measure it (ie, not me). At 0.2 Amps per module, we can run 8+1 preamplifier boxes (16 channels + 2 background detectors) with a 1.8 Amp, 5 V DC supply.

Most of our gain changes should be done by adjusting the high voltage. When we run out of dynamic range in the HV, and a factor of 2 change in gain is needed, this can be done by opening the box with a screwdriver and changing a dip switch. This is cumbersome, but it's the price we pay for excellent RF isolation.

The only potential quality control issue identified was that, when the boxes are assembled, the self-tapping screws create Aluminum dust and shavings which can be as large as several mm. This has the potential to produce intermittent shorts since the legs on the chips are separated by only a few mm. This means that the boxes will have to be assembled, disassembled, have the shavings blown off the board, have the screw threads brushed to remove the turnings which are hiding there, then gently reassembled.

5.2 potential as-installed failure modes

If a problem occurs, we need to be able to find it and fix it. We also want to be sure that irreplaceable equipment won't be damaged, and that no serious safety problem presents itself. Without trying to be comprehensive, I'll consider a few potential failure modes:

- Assuming a shared +5 V power supply, if one of the preamplifier modules were to fail to a short in its DC-DC converter, there would immediately be an obvious loss of signal in *all* the detectors (voltage too low). With the total current limited to 2.0 Amps, the local power dissipation would be less than 10 Watts so it wouldn't be a fire hazard. We could quickly locate the problem by first verifying that the power supply itself is working, then sequentially unplugging each of the preamps from the power supply in turn to see which one was causing it to current limit. We would then replace the down module with another (with dip switches set to the same gain) and start running again.
- If one of the DC-DC converters were to go bad and put noise on the shared +5 V line, the working DC-DC converters on the other preamplifiers should reject most of this noise. Hence, only the two channels which share the flakey preamp module should be affected. So again, we would replace, set, and run.
- Most other failure modes would take down only one of the two channels (e.g., dead input or output stage.) Replace, set, and run.
- In the event of a lightning strike conducted to the shared +5 V line, or to the PMT HV supply, we could lose our entire stock of preamplifiers. Recovery would be costly in time and money, so we just can't allow this to happen. Both low and high voltage DC power supplies need to be on excellent surge suppressors.
- In some voltage dividers, an unterminated anode could float up to cathode potential if the HV is left on. When the anode is later connected to the preamplifier input, the discharge could damage the front end. In all our bases, the PMT anodes will be tied to ground through a large resistor, so this should not be a failure mode for us.
- Electrostatic Discharge (ESD): The problem with low-noise preamplifiers is that they don't necessarily stop working when damaged; sometimes they just

get noisier. Only regular testing, such as monitoring the width of beam-off pedestals, can tell. The front end of the TRIUMF design has a diode network which provides some degree of protection for low energy transients. Additional bench testing during the coming dry, winter months will tell us if we have to ban cats in wool sweaters from connecting or disconnecting the preamplifier inputs. More seriously, if we find a problem with ESD, we'll have to address it with administrative procedures because the hardware protection is already in place.

In summary, most of these potential failure modes are either easily fixed or can be engineered away, and don't present significant safety hazards. We want to keep in mind ESD sensitivity and implement regular monitoring of pedestal widths.

6 Summary

The TRIUMF preamplifiers suffered no permanent damage from 18 kRad of (mostly) γ rays. No visible increase in noise was produced by the high instantaneous levels of ionization. Even with our less sensitive techniques for measuring noise at JLab, if ionization noise were significant we would have seen it since the dose rate was 200 times that expected during the experiment. To duplicate the TRIUMF noise tests at JLab we'll need to use a x10 or x100 amplifier. It should have a bandwidth greater than 50 KHz to match the TRIUMF flash ADC currently under design.

The ^{137}Cs irradiation facility at JLab is very nice for gamma irradiating small powered electronics where one would like to monitor the output signals. However, the presence of low energy electrons in the beam demands some care with dosimetry. In the future, we'll try to put the dosimeters inside the casings of the electronics. We would like to use the irradiator again later for our PMT/base assembly for the main detector.

The applicability of this gamma irradiation measurement to neutron fields requires both the neutron spectrum and knowledge of the energy-dependent weighting factors reflecting dislocation probability. To keep a simple irradiation from turning into a career, we should conservatively allow gamma irradiations to run 100 times longer than our specification. We should eventually try to simulate neutron fields and put some neutron dosimetry in the detector shield house.

To safely and reliably operate a bank of these preamplifiers inside the shielding hut, we'll need a small shielding box which includes the DC power supply and allows for a small amount of air cooling. The +5V DC supply will be current-limited and will in turn be powered by line AC through an isolation transformer/surge protection system.

Getting interpretable measurements of extremely small noise levels was a lot more difficult than expected. Measuring zero is evidently hard work. Not only is the noise of the spectrum analyzer front end worse than the TRIUMF preamplifiers, but it is easy to distort the results whether the coupling is DC or AC. Even a simple battery source is trickier than I expected, since exposed leads pick up plenty of 60 Hz and harmonics from AC power lines, as well as 20-30 KHz from the fluorescent lights. Our battery sources will have to be located in Pomona boxes, or equivalent, to provide RF shielding.

The TRIUMF preamplifiers look great and Des Ramsay tells me they can start production soon.

Acknowledgements

Thanks to Bill Roberts for the low noise measurements at TRIUMF, to Des Ramsay for pretty much holding my hand by email throughout, to Roger Carlini for helping me find a manual on the Web for our old spectrum analyzer, to Bill Vulcan for advice on the current source, to Steve Wood for converting HP spectrum analyzer files from binary to ascii, to various RadCon angels who literally opened locked doors for me, and especially to Dave Hamlette of the RadCon group for the dosimetry and generally putting up with me for so long on the test range. (I hope I haven't worn out my welcome.)

References

[1] See any of Des Ramsay's recent talks, such as his PowerPoint presentation on "Current Mode Electronics for the Qweak Experiment" at the October 14-15, 2005, collaboration meeting in Vancouver, Canada.

[2] Dave Hamlette, private communication.

[3] Particle Physics Booklet, July 2002, by the particle data group.

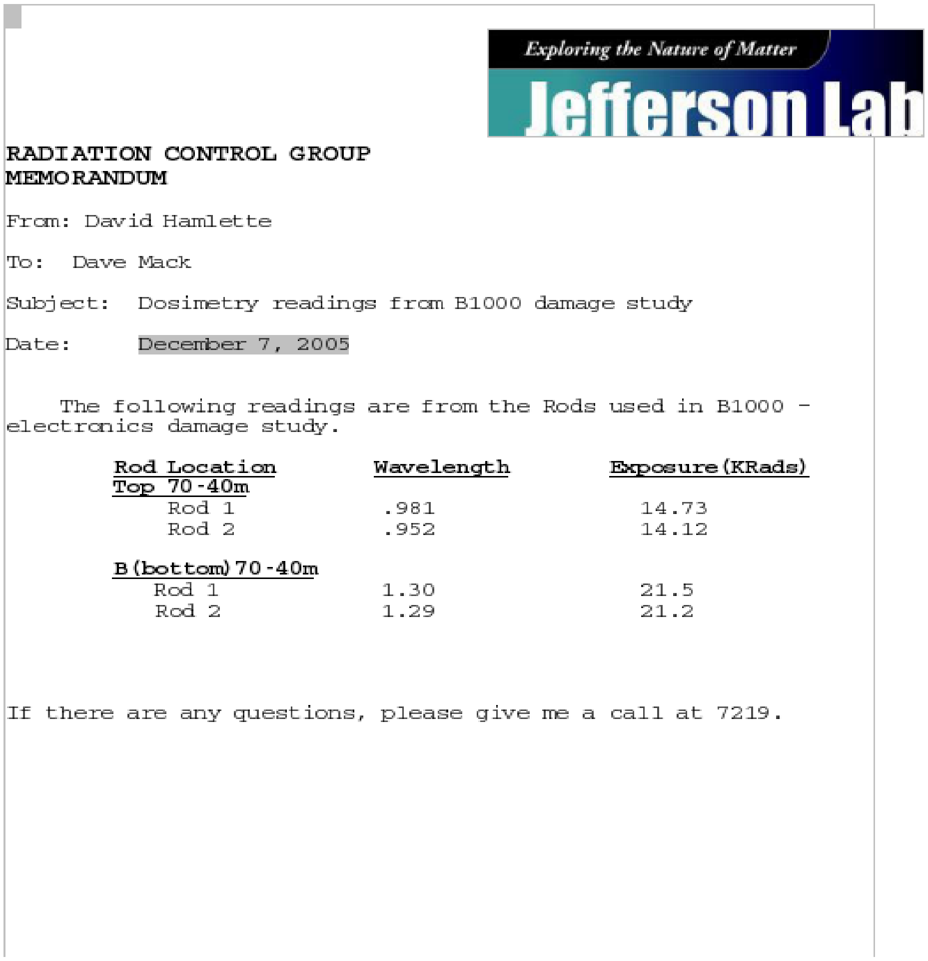
[4] "Passage of Particle Through Matter", Review of Particle Physics, Phys. Lett. B **592** (2004), pp 1-1110.

[5] M. Keil, CERN, NA60 Note 2003-2, August 21, 2003; referenced Figure 1.

[6] Bill Roberts, private communication.

Figure 2: ^{137}Cs irradiation facility location in the RadCon test range. The top opens like a refrigerator in which samples can be placed on shelves for irradiation. The ^{137}Cs source is located in the bottom section. On top of the irradiator is our regulated DC power supply, and sitting in front of it is our spectrum analyzer.

Figure 3: The box in which samples are irradiated. When the door is closed and the shutter is opened, γ's are emitted from the hole in the bottom. Dosimeters are visible above and below the preamplifier.



Exploring the Nature of Matter

Jefferson Lab

RADIATION CONTROL GROUP
MEMORANDUM

From: David Hamlette

To: Dave Mack

Subject: Dosimetry readings from B1000 damage study

Date: December 7, 2005

The following readings are from the Rods used in B1000 - electronics damage study.

Rod Location	Wavelength	Exposure (KRads)
Top 70-40m		
Rod 1	.981	14.73
Rod 2	.952	14.12
B (bottom) 70-40m		
Rod 1	1.30	21.5
Rod 2	1.29	21.2

If there are any questions, please give me a call at 7219.

Figure 4: Dosimetry report from David Hamlette.

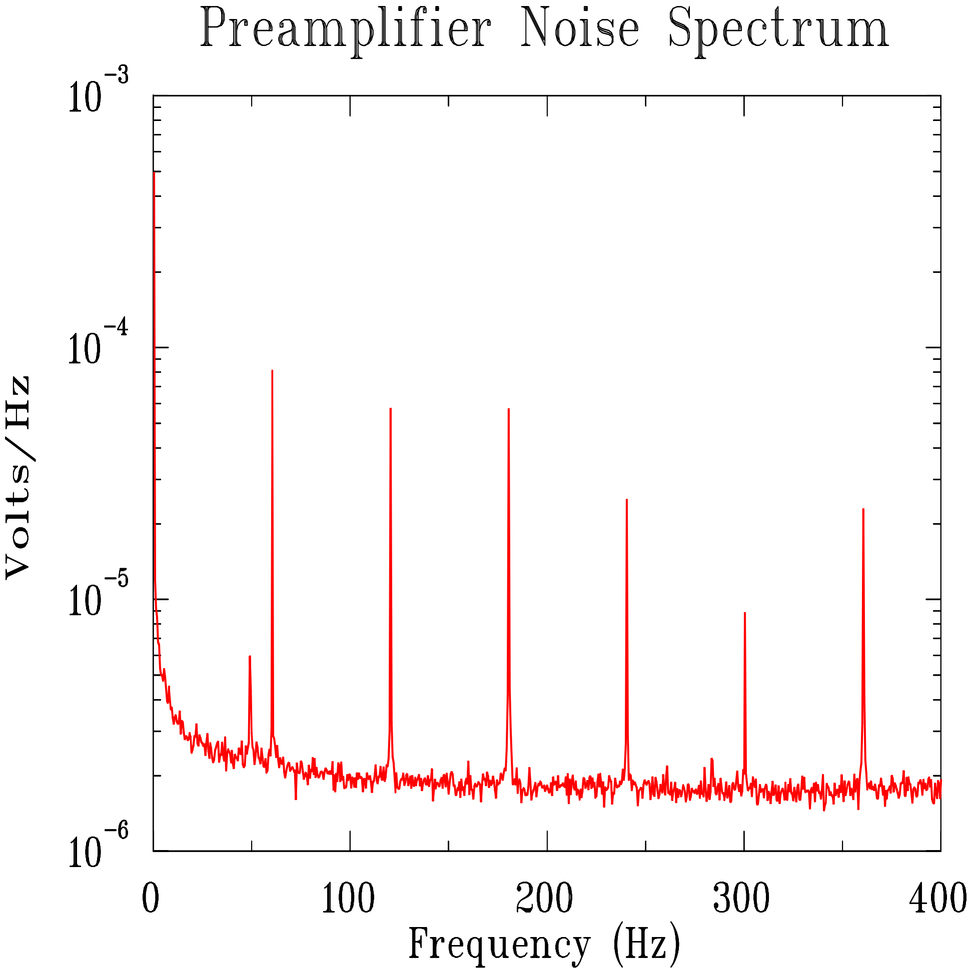


Figure 5: Noise spectrum from the biased preamplifier after moving the battery source inside the irradiator. If our reversal rate is around 270 Hz, then the noise near 135 Hz will be most relevant.