

# Final Report for UCLA - ADR

## Development of Single Crystal Chemical Vapor Deposition Diamonds for Detector Applications

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### Summary

Diamond was studied as a possible radiation hard technology for use in future high radiation environments. With the commissioning of the LHC expected in 2010, and the LHC upgrades expected in 2015, all LHC experiments are planning for detector upgrades which require radiation hard technologies. Chemical Vapor Deposition (CVD) diamond has now been used extensively in beam conditions monitors as the innermost detectors in the highest radiation areas of BaBar, Belle and CDF and is installed and operational in all LHC experiments. As a result, this material is now being discussed as an alternative sensor material for tracking very close to the interaction region of the super-LHC where the most extreme radiation conditions will exist.

Our work addressed the further development of the new material, single-crystal Chemical Vapor Deposition diamond, towards reliable industrial production of large pieces and new geometries needed for detector applications. Our accomplishments include:

- Developed a new U.S. company to produce electronic grade diamond,
- Worked with companies and acquired 1cm × 1cm diamond pieces,
- Performed radiation hardness tests using various proton energies: 70 MeV (Cyric, Japan), 800 MeV (Los Alamos), and 24 GeV (CERN).

# Final Report

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## 1 Introduction

Detectors and radiation monitors of future experiments will be situated in radiation environments several orders of magnitude harsher than those of any current detector [1]. At present detectors for tracking close to the interaction region are based on the mature silicon technology which functions very well in relatively low radiation environments. However, new radiation hard technologies must be developed to fill the gap between the present radiation hardness of silicon and what is required in the future. Diamond is one such technology.

In Table 1, we summarize the properties of diamond and, for comparison, those of silicon that are of interest when considering the material for use as a detector. The most distinctive feature of diamond is its large band gap, 5.5 eV. This large band gap along with the associated large cohesive energy are responsible for much of the radiation hardness of diamond. The large band gap also makes diamond an excellent electrical insulator. As a result, a large electric field can be applied without producing significant leakage current. Thus, there is no need for a reverse biased *pn*-junction and the diamond detector functions much like a “solid-state” ionization chamber. Diamond has two additional properties that compare favorably to silicon. Its smaller dielectric constant yields, for a given geometry, a lower detector capacitance and thereby, lower noise performance of the associated front-end electronics. In addition, even though diamond is an electrical insulator, it is an excellent thermal conductor with a thermal conductivity exceeding that of copper by a factor of five at room temperature. This is important since a common problem with large detector systems is the management of the thermal load generated by the large number of electronic channels used in the detector readout. The handling of this thermal load would be simplified if the detectors were constructed from diamond since the diamond would act as a heat spreader.

Although diamond appears ideal in many respects it does have a limitation: the large band gap which produces many of its outstanding properties also means that its signal size is at most half that of silicon for a given detector thickness in radiation lengths. This is somewhat

compensated by lower front-end electronic noise due to diamond’s nearly non-existent leakage current and diamond’s lower capacitive load.

Property	Diamond	Si
Band Gap [eV]	5.5	1.12
Breakdown field [V/cm]	$10^7$	$3 \times 10^5$
Resistivity [ $\Omega$ -cm]	$> 10^{11}$	$2.3 \times 10^5$
Intrinsic Carrier Density [ $\text{cm}^{-3}$ ]	$< 10^3$	$1.5 \times 10^{10}$
Electron Mobility [ $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ]	1800	1350
Hole Mobility [ $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ]	1200	480
Saturation Velocity [km/s]	220	82
Mass Density [ $\text{g cm}^{-3}$ ]	3.5	2.33
Atomic Charge	6	14
Dielectric Constant	5.7	11.9
Thermal Expansion Coefficient [ $\text{K}^{-1}$ ]	$0.8 \times 10^{-6}$	$2.6 \times 10^{-6}$
Thermal Conductivity [ $\text{W m}^{-1} \text{K}^{-1}$ ]	1000-2000	150
Cohesive Energy [eV/atom]	7.37	4.63
Energy to create e-h pair [eV]	13	3.6
Radiation Length [cm]	12.0	9.4
Spec. Ionization Loss [MeV/cm]	6.07	3.21
Ave. Signal Created/100 $\mu\text{m}$ [e]	3600	8900
Ave. Signal Created/0.1% $X_0$ [e]	4500	8400

Table 1: *The physical properties of diamond and silicon at 293K [2].*

## 1.1 CVD Diamond

The discovery of the growth of diamond using the Chemical Vapor Deposition (CVD) process allowed the consideration of large scale use of diamond detectors. In this process, a hydrocarbon gas, such as methane, is mixed with a large concentration of molecular hydrogen gas. The gas mixture is then excited by an energy source. The resulting reactive gas mixture is brought into contact with a substrate where carbon based radicals are reduced and the carbon atoms link together with single bonds ( $sp^3$  hybridized orbitals) forming a diamond lattice. Raman spectroscopy and X-ray diffraction unambiguously show that the CVD films are diamond where the detailed structure (polycrystalline or single-crystal) depends on the substrate employed during growth. For the last ten years the RD42 Collaboration at CERN has worked to develop detectors based on polycrystalline CVD (pCVD) diamond [3]. They have succeeded in constructing detectors with feature sizes from  $\mu\text{m}$  to cm. They have measured the radiation hardness up to fluences greater than  $10^{15}$  hadrons per  $\text{cm}^2$  and have found it to be sufficient to allow diamond detectors to operate for several years at the highest design luminosity of the LHC. Moreover, RD42 found that diamond detectors show no evidence of any damage from electrons and photons up to 1000 MRad. Our work builds on this work.

## 1.2 Principles of Diamond Detectors

In Fig. 1, we show the basic principle of using diamond as a particle detector. A voltage is applied across a layer of diamond a few hundred microns thick. When a charged particle

traverses the diamond, atoms in crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3,600 electron-hole pairs are created per 100  $\mu\text{m}$  of diamond traversed by a minimum ionizing particle. These charges drift across the diamond in response to the applied electric field producing a signal that can be measured. Since there may be traps in pCVD material we use the term “collection distance” to denote the average distance the electron-hole pair drift apart.

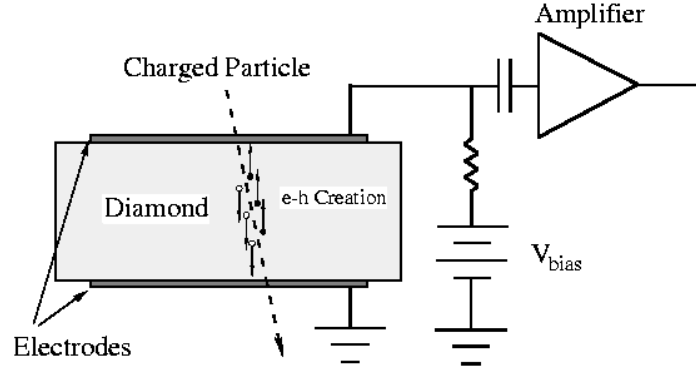


Figure 1: A schematic view of a diamond detector.

## 2 Single-Crystal CVD Diamond

Eight years ago the first single-crystal diamonds grown by a chemical vapor deposition process [5] became available. The samples were synthesized with a microwave plasma-assisted CVD reactor using a specially prepared  $\langle 100 \rangle$  oriented single-crystal synthetic diamond substrate. These diamonds were typically 0.1-0.2  $\text{cm}^2$  in area and 400  $\mu\text{m}$  thick. Our group together with RD42 developed and tested this material. To date, members of our group have obtained the following results:

- The pulse height distribution for scCVD diamond is very narrow,
- Up to a diamond thickness of 770  $\mu\text{m}$  full charge collection is observed,
- The largest area high quality diamond produced was just over 1  $\text{cm}^2$ ,
- Strip and pixel detectors show charge collection and charge sharing as expected,
- Up to high fluences, scCVD and pCVD have the same damage constant.

These results are discussed below.

In Fig. 2 (a) we show the pulse height spectrum observed from a 450  $\mu\text{m}$  thick single-crystal CVD diamond. We observe a collection distance consistent with full charge collection; most probable charge of 13,400 $e$ ; FWHM of 4000 $e$ ; and more than 10,000 $e$  separation between the pedestal and the beginning of the charge distribution. The FWHM/MP for these single-crystal

CVD diamonds is approximately 0.3, about one third that of polycrystalline CVD diamond and about two thirds that of correspondingly thick silicon. In Fig. 2 (b) we show the most probable charge for scCVD diamond versus thickness of the material. A clear linear relationship is evident out to thicknesses of  $770 \mu\text{m}$ .

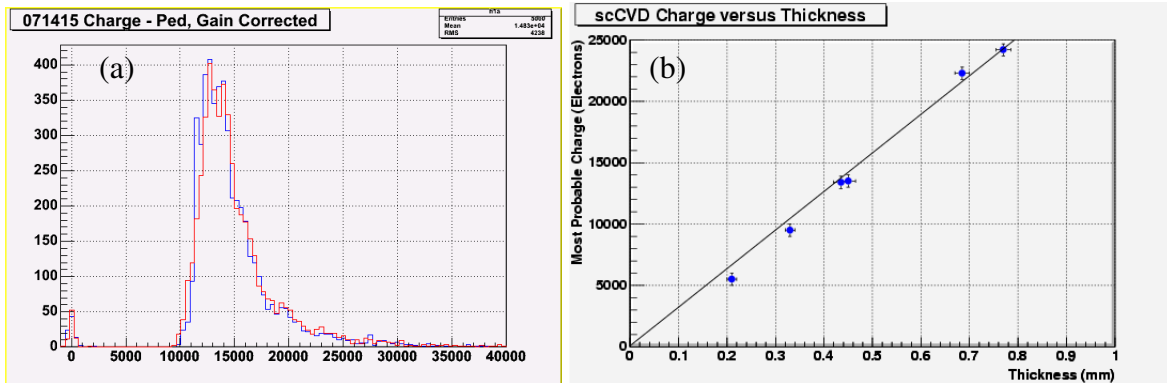


Figure 2: (a) The pulse height distribution from a  $450 \mu\text{m}$  thick scCVD diamond. The red and blue curves are the data for positive and negative bias applied to the diamond. (b) The most probable pulse height versus thickness for scCVD diamonds.

In Fig. 3 we show a photograph of the most recent scCVD diamonds which are approximately  $1\text{cm}^2$  in size. These diamonds were characterized and made into strip and pixel detectors [6].

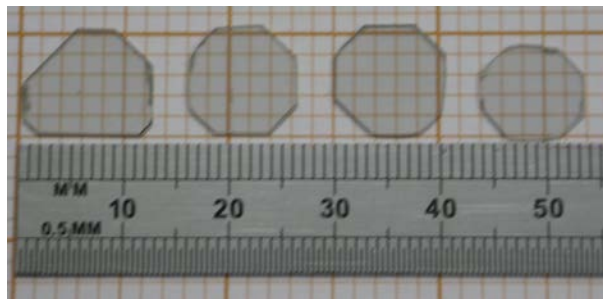


Figure 3: Picture of the latest scCVD diamonds which our group tested.

### 3 New Manufacturers of CVD Diamond

Most of the diamonds we have tested have been manufactured by Element 6 the main manufacturer of electronic grade CVD diamond of detector quality. During the last year we have made significant progress in helping a U.S. manufacturer enter this market. Having a second manufacturer should increase competition and reduce pricing.

The new manufacturer we have worked with is II-VI Inc. in Saxonburg PA. They are a large company who are considered a worldwide leader in crystal growth technology. They have

developed their own growth recipes with feed back from us and have delivered four 18mm  $\times$  21mm parts of excellent quality. Fig 4 shows the parts we have received.

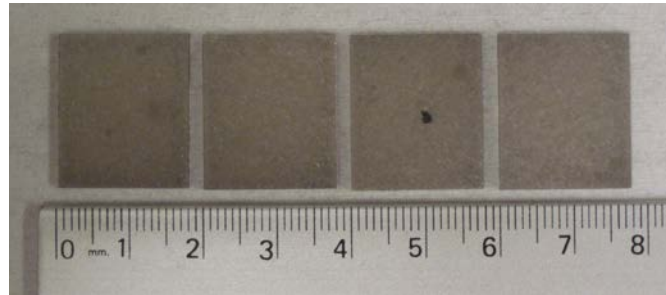


Figure 4: *Photograph of the four 18mm  $\times$  21mm diamond samples produced by II-VI.*

In Fig. 5 we show the collection distance measured with a Sr90 source for three of the diamonds shown above. One can observe the new material is extremely uniform and of excellent quality. II-VI plans to use these results to improve the quality of their diamond manufacturing. We expect the availability of state-of-the-art material from them shortly.

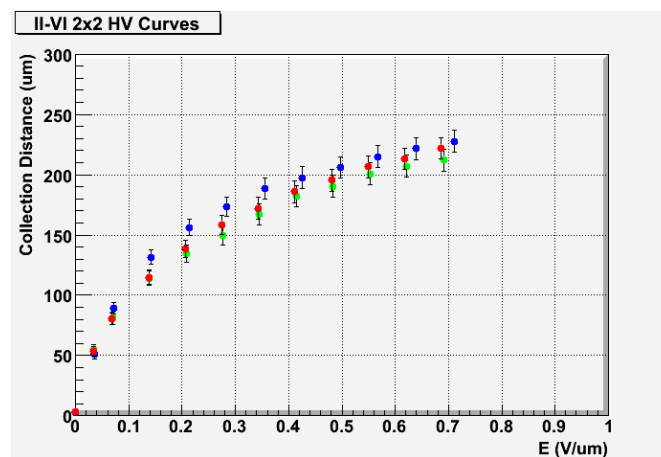


Figure 5: *The collection distance of the II-VI diamonds measured with a Sr90 source..*

## 4 Radiation Hardness Studies with CVD Diamond

In order to obtain the most reliable irradiation results, together with RD42, our irradiation program consists of testing each sample prepared as a strip detector in a CERN test beam before and after irradiation of the samples. During the last year we have performed three irradiations of diamond samples and correspondingly three test beams at beam energies of 70MeV (Cyric facility in Japan), 800 MeV (LANL in the US), 24 GeV (CERN). Fig. 6 shows a photograph of four scCVD samples prepared as strip detectors and read-out with VA-2 electronics for characterization in the test-beam at CERN. All pCVD and scCVD samples we tested were prepared in this manner.

Fig. 7 shows the results of the pulse height spectrum for a recent pCVD diamond after  $1.4 \times 10^{15}$  p/cm<sup>2</sup>. A clear Landau distribution is observed in the data with the mean observed charge of 7300e and a most probable charge of 6000e. To set the scale, for use at the LHC as a pixel detector with ATLAS FE-I3 electronics it is estimated that a minimum charge of 2200e (1400e threshold plus 800e overdrive) corresponds to an efficiency of > 99%. Fig. 8 shows the results of the pulse height spectrum for a recent scCVD diamond before and after  $1.5 \times 10^{15}$  p/cm<sup>2</sup>. Clear Landau distributions are observed in the data with the mean ADC counts of 1393 before irradiation and 837 after irradiation. This data has been added to the previous irradiation data to summarize the proton irradiation results. In order to estimate the radiation effects on the collection distance we have compared the collection distances for pCVD and scCVD samples before and after irradiation. The scCVD diamond is expected to be representative of the next generation high quality polycrystalline material. By comparing the effective damage constants for the two different materials we can definitively find the relation between the two. In Fig. 9 we overlay the collection distance measurements of pCVD and scCVD samples before and after irradiation so that 0 on the x-axis corresponds to the un-irradiated collection distance of our pCVD material. In addition the scCVD fluences are shifted by  $-3.8 \times 10^{15}$  p/cm<sup>2</sup>. In effect the scCVD material starts with a signal advantage that corresponds to a fluence of about  $4 \times 10^{15}$  p/cm<sup>2</sup>. Another way of thinking of this is that our un-irradiated pCVD material has that same number of trapping centers as the scCVD material after a dose of  $4 \times 10^{15}$  p/cm<sup>2</sup>.

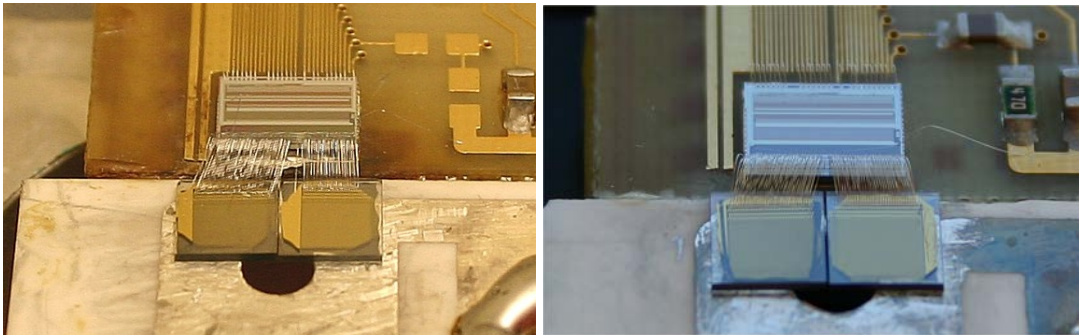


Figure 6: *Photographs of the four 0.5cm × 0.5cm scCVD samples characterized in the 120 GeV pion beam at CERN in Fall 2007 and Fall 2008.*

Fig. 9 shows that all of the irradiations fall along a single damage curve given by the equation  $1/ccd = 1/ccd0 + k\phi$  where  $ccd0$  is the initial collection distance and  $k$ , the damage constant is independent of the initial collection distance. This result now includes scCVD samples that have initial collection distances in excess of 400 microns. We do not expect the higher quality pCVD material to be any different. The data indicate a single damage constant  $k$  for both materials indicating that the next generation of material should follow a similar curve.

These studies were extended by performing irradiations at the Cyrlic Facility in Sendai, Japan (70 MeV protons) and at Los Alamos National Laboratory (800 MeV protons). In each case we went to a fluence of  $1 \times 10^{16}$  p/cm<sup>2</sup>. The goal of these studies is to map out the NIEL curve for diamond. Beam tests of the 70 MeV irradiation were performed in the Fall 2009 while beam tests of the 800 MeV irradiation will occur in June 2010. Fig. 10 shows the preliminary results. The black data is the 70 MeV beam test data and the blue data is the 800 MeV source

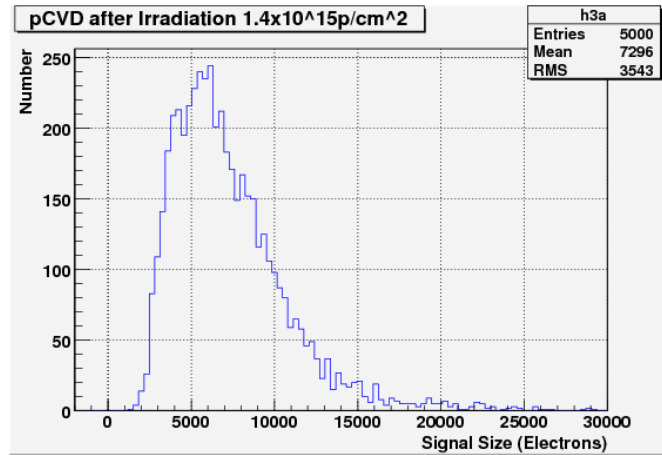


Figure 7: The pulse height spectrum from an irradiated pCVD strip detector after  $1.4 \times 10^{15} p/cm^2$ . A clear Landau distribution of pulse heights is observed.

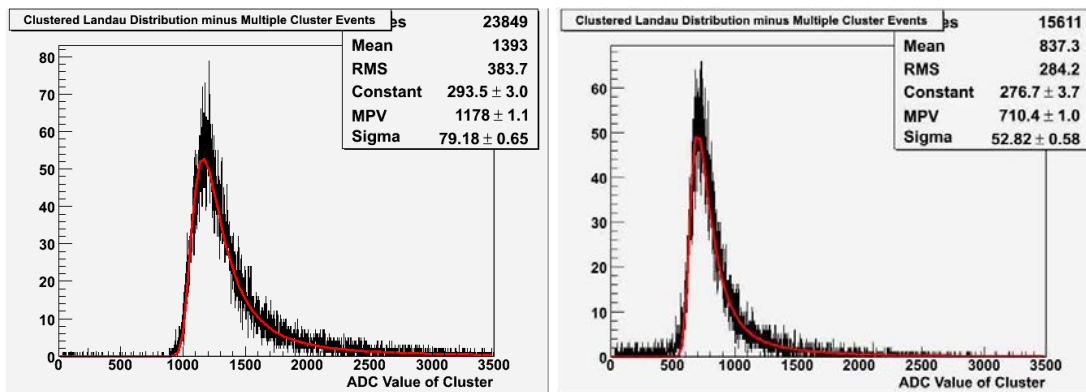


Figure 8: The pulse height spectrum from an irradiated scCVD strip detector before and after  $1.5 \times 10^{15} p/cm^2$ . Clear Landau distributions are observed.

results. This plot clearly indicates 800 MeV protons damage diamond with approximately one half the damage constant of 70 MeV protons.



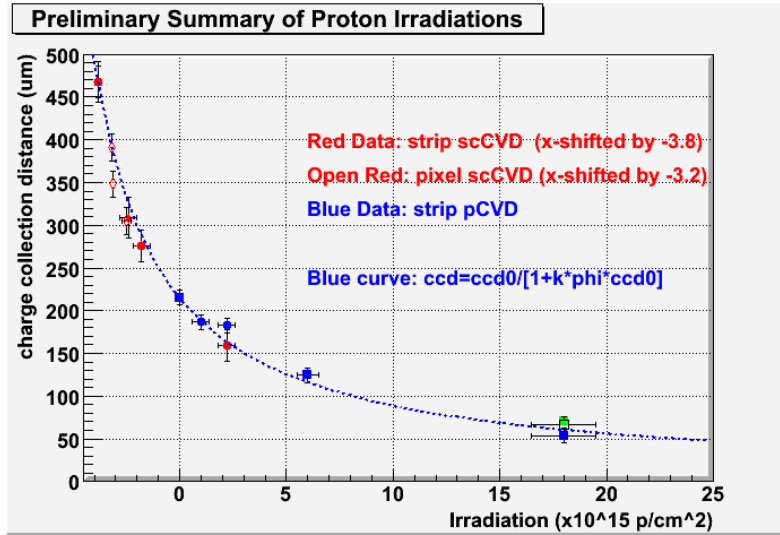


Figure 9: Summary of proton irradiation results for pCVD (blue points) and scCVD (red points) material at an electric field of  $1 \text{ V}/\mu\text{m}$  and  $2 \text{ V}/\mu\text{m}$  (solid green square point) to a fluence of  $1.8 \times 10^{16} \text{ p/cm}^2$ . The black curve is a standard damage curve  $1/ccd = 1/ccd_0 + k\phi$ . The scCVD data has been shifted to the left by a fluence of  $3.8 \times 10^{15} \text{ p/cm}^2$  where its un-irradiated collection distance falls on the curve. With this shift the pCVD and scCVD data fall on a single curve indicating the damage due to irradiation is common to both.

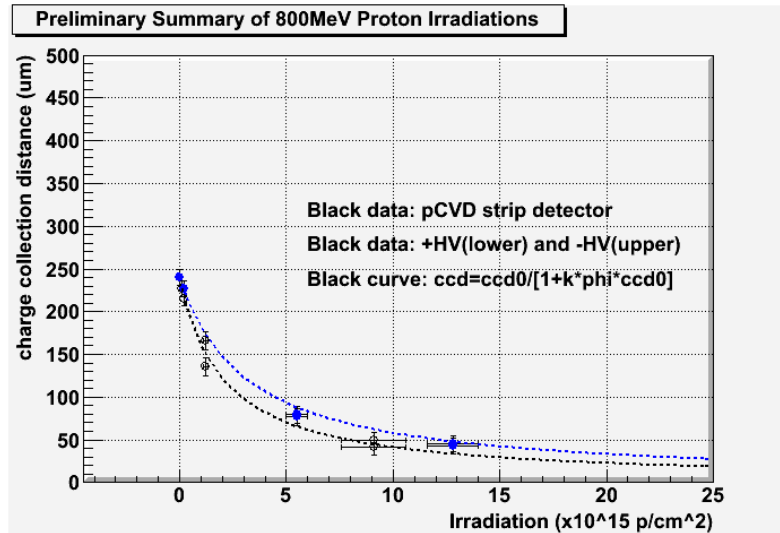


Figure 10: Preliminary proton irradiation results (charge collection distance) comparing the 800 MeV LANL irradiation (blue points) with the 70 MeV CYRIC irradiation (black points). The data clearly indicates 70 MeV protons are more damaging than 800 MeV protons.

## References

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