Recent Results on Diamond Radiation Tolerance

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Representing the RD42 Collaboration
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- Overview of diamond and radiation damage issues
- Investigation of the application of the FLUKA DPA model to diamond in the radiation regime relevant to the LHC
- Measurement of the response of diamond resistivity to proton fluence and temperature
- Summary, conclusions

Chemical vapor deposition (CVD) diamond holds promise as a radiation-tolerant substrate for detecting particles close to an interaction point at the LHC.

Important features of diamond:

- Band gap 5.5 eV (compare silicon's 1.1 eV)
- Minimum lattice displacement energy 43 eV (compare Si 25 eV)

Positive consequences of these:

- Negligible leakage current - low readout noise
- Guard rings eliminated or simplified - lower capacitance
- Diamond dielectric constant is 5.7 (compare Si 11.9) - reduced cap
- Negligible free carriers at room temperature – relaxed cooling need
- Fast signal collection
- 50% longer radiation length than Si – less material per length

Related challenge:

- Average energy needed to liberate an e-h pair is 13.1 eV (compare silicon's 3.6 eV) - smaller signal before irradiation

- Inner tracking detectors in the LHC upgrade era must withstand fluences > 1×10^{16} 1-MeV n_{eq}/cm^2.
- Damage is caused by a mixture of species, but below about 24 cm radius from the IR, the damage arises primarily from charged pions.
- The pion spectrum peaks at about 2 GeV with FWHM from 300 MeV to 6 GeV.

- It is important to model the damage mechanism to predict detector lifetime and operational conditions.
- The CERN PS beam (24 GeV protons) and Los Alamos LANSCE beam (800 MeV protons) bracket this energy and thus provide especially important benchmarks.

The CERN RD42 Collaboration is studying the ability of FLUKA DPA to describe damage in diamond for a range of beam types and energies. FLUKA* is a MC package that provides a general tool for calculations of particle transport and interactions in matter.

An important addition to FLUKA is DPA, which was overviewed in the talk “DPA for FLUKA” by Vasilis Vlachoudis at the Nov 2008 FLUKA Users Meeting.

FLUKA-DPA predicts** that diamond damage will vary by 20% across the range 800 MeV to 24 GeV.

*www.fluka.org

** S. Mueller, CERN-THESIS-2011-085.

- DPA, displacements per atom, is a measure of the amount of damage caused by all particles in a hadronic cascade.
- 1 DPA means: each atom in the material has been displaced from its site within the lattice an average of 1 time.

$$DPA = \frac{1}{\rho} \sum_i N_i N_F^i$$

ρ = density in atoms/cm^3
N_i = number of particles per interaction channel i
N_f^i = number of Frenkel pairs (compound defect with adjacent interstitial and vacancy)

- For N_f^i, number of Frenkel pairs,

$$N_f^{\ i} = \mathrm{K}\frac{\xi(T)T}{2E_{th}}$$

K = 0.8, the displacement efficiency. The difference from 1.0 reflects the forward scattering.
T = the kinetic energy of the primary knock-on atom.
$\xi(T)$ is the Lindhard partition function* that gives the fraction of stopping power that goes to non-ionizing energy loss (NIEL)**, from LSS-theory.
E_{th} is the damage threshold energy for the crystal (i.e. minimum energy needed to produce a defect), averaged over all crystallographic directions.

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*J. Lindhard et al., Kgl. Danske Videnskab. Mat. Fys. Medd. Vol 33 no. 10
** G. Lindstroem, NIM 512 (2003) 30-43.

RD42 has undertaken a study of damage factors in single-crystal (sc) and polycrystalline (poly) diamond exposed to 5 beam conditions.

Figure of merit: Mean Free Path $\lambda_{e/h}$ of the charge carriers (electrons, holes):

$$\boxed{\lambda_{e/h} = v_e\tau_e + v_h\tau_h}$$

v = velocity; τ = lifetime.

Damage in diamond typically follows a curve of the form*

$$\boxed{\frac{1}{\lambda_{e/h}} = \frac{1}{\lambda_0} + k\Phi}$$

Φ = fluence

λ_0 = the mean free path before irradiation, reflects traps present before irradiation, material purity.

k = damage coefficient.

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*S. Zhao, “Characterization of the electrical properties of polycrystalline diamond films,” Ohio State Univ. Ph.D. thesis, 1994.

Goal: to extract damage constant k for each beam condition and compare it to the FLUKA DPA prediction. In this study, it was assumed that $v_e\tau_e = v_h\tau_h$. This influences the result by a few percent.

$\lambda_{e/h}$ is obtained by inverting

$$\boxed{\frac{Q_{collected}}{Q_{ionized}} = \frac{\lambda_{e/h}}{d} \cdot \left[1 - \frac{\lambda_{e/h}}{d}\left(1 - e^{-\frac{d}{\lambda_{e/h}}}\right)\right]}$$

d is sensor thickness.

$Q_{collected}$ is measured in the CERN SPS pion test beam.

The most probable value of $Q_{ionized}$ is calculated as

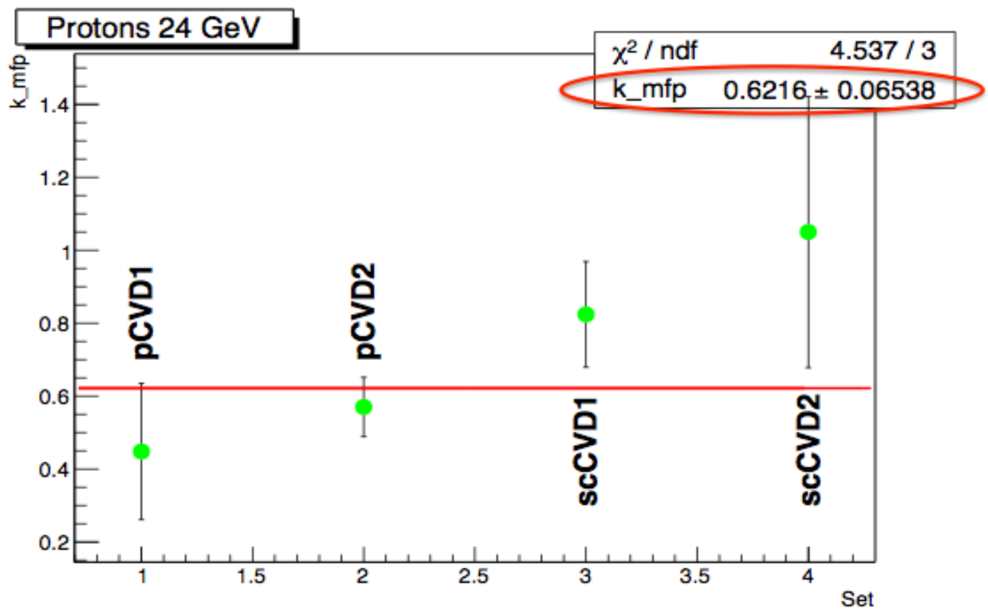
$$\boxed{Q_{MPV} = \xi\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + 0.2 - \beta^2 - \delta\right]}$$

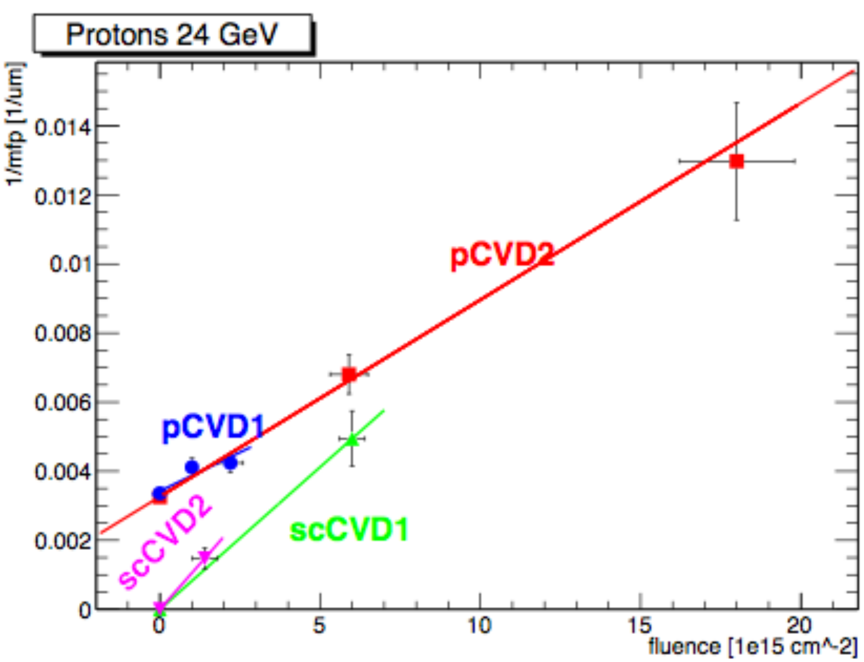
where $\xi = \dfrac{KZx}{2A\beta^2}$ for a detector of thickness x,

δ = 1.84 parameterizes the density effect on the energy loss
I = 81 eV is the average ionization energy, and
$K = 4\pi N_A r_e^2 m_e c^2$.

The inverse of mean free path, 1/λ, is graphed versus fluence and fitted to a straight line for each of several diamonds from the same series. The slope gives damage constant k. The fluence offset measures the intrinsic trap density.

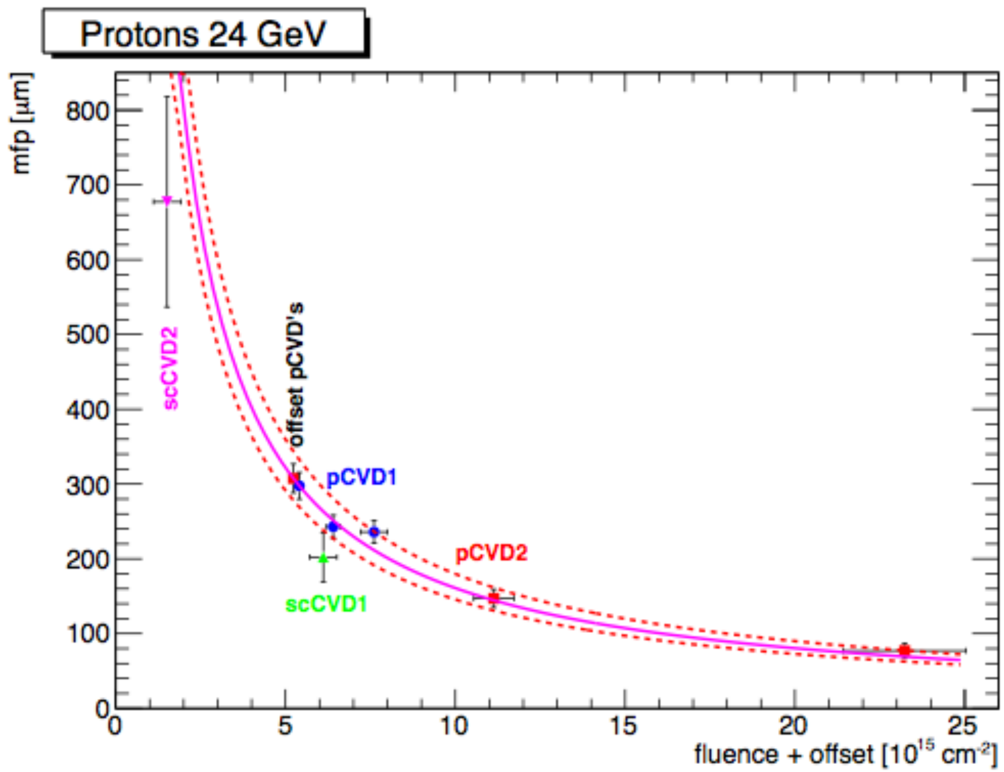
Example results of the extracted k values are here:





Unirradiated single crystal diamond is assigned infinite k.

First result of the program to compare data to FLUKA DPA predictions, for diamond:

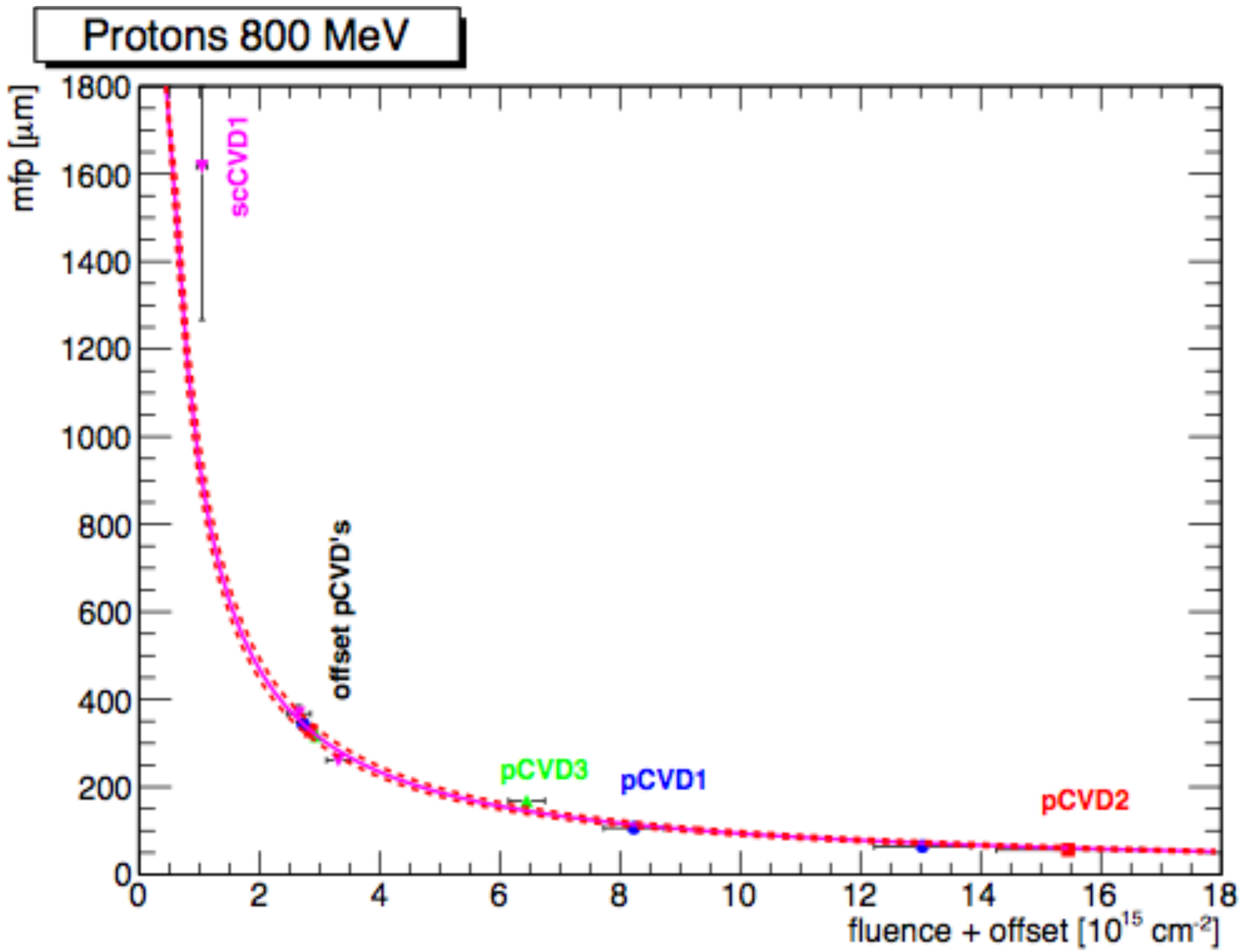


Polycrystalline and single crystal diamond exposed to **24 GeV protons** at the CERN PS. Points are adjusted by the intrinsic trap density (i.e. effective fluence) offset.

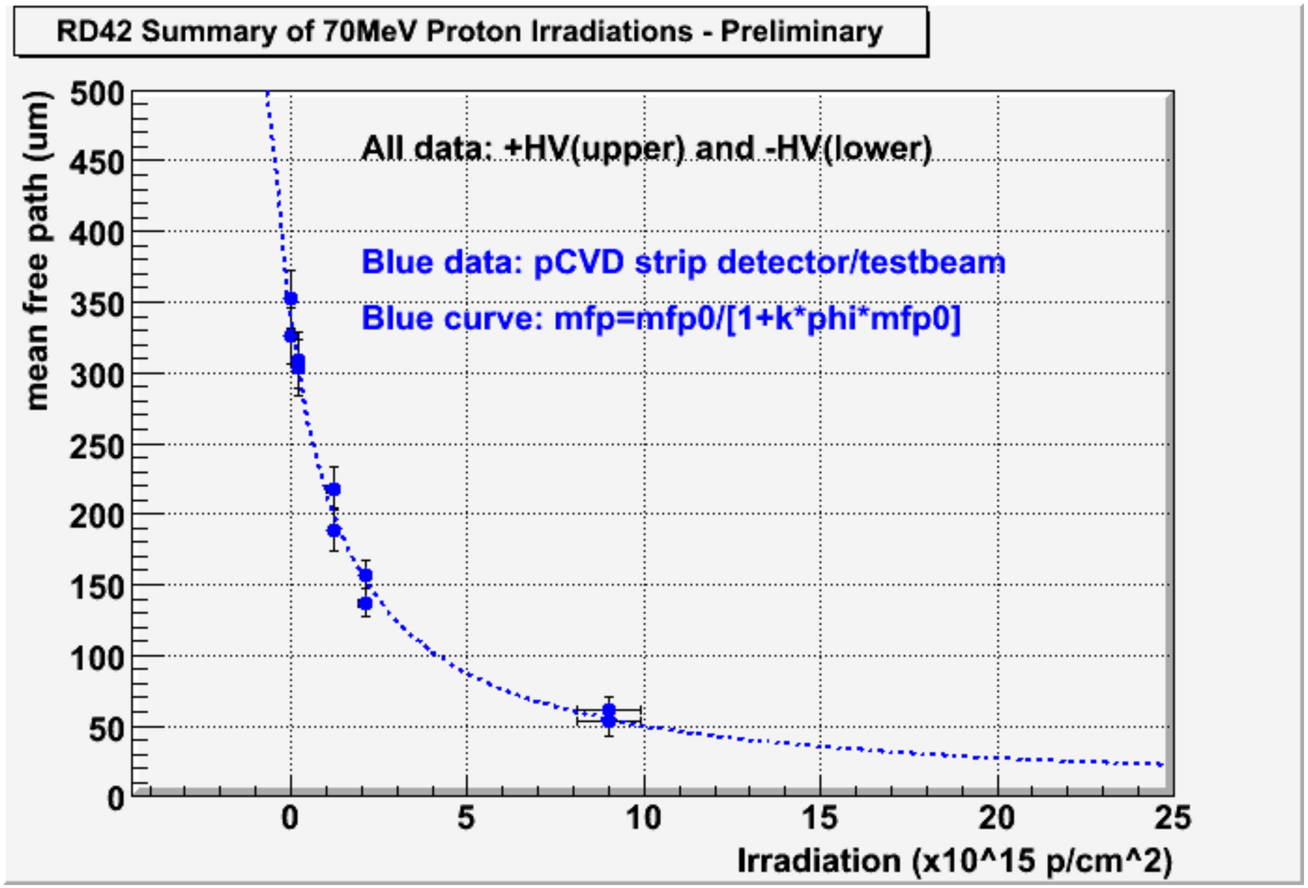
Damage constant k = $(0.62 \pm 0.7) \times 10^{-18}$ $\mu m^{-1} cm^{-2}$ for both poly and sc, indicating a common damage mechanism.

This serves as the normalization for the other beam conditions.

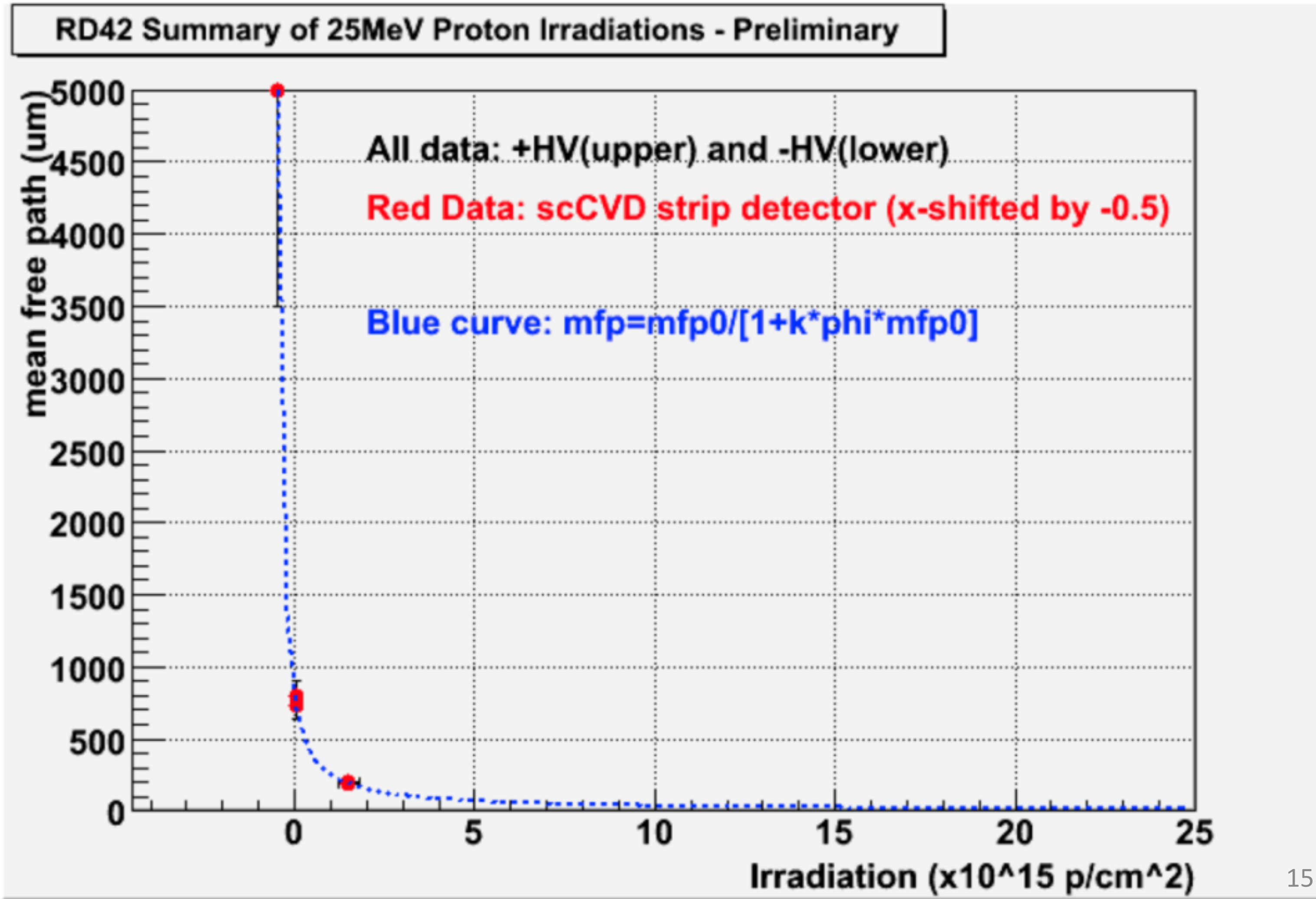
Polycrystalline diamond exposed to **800 MeV protons** in Los Alamos.
Extract damage constant $k = (1.07 \pm 0.05) \times 10^{-18}\ \mu m^{-1} cm^{-2}$.
This is 1.7x more damaging than the 24 GeV protons.
FLUKA DPA predicts factor 1.3.



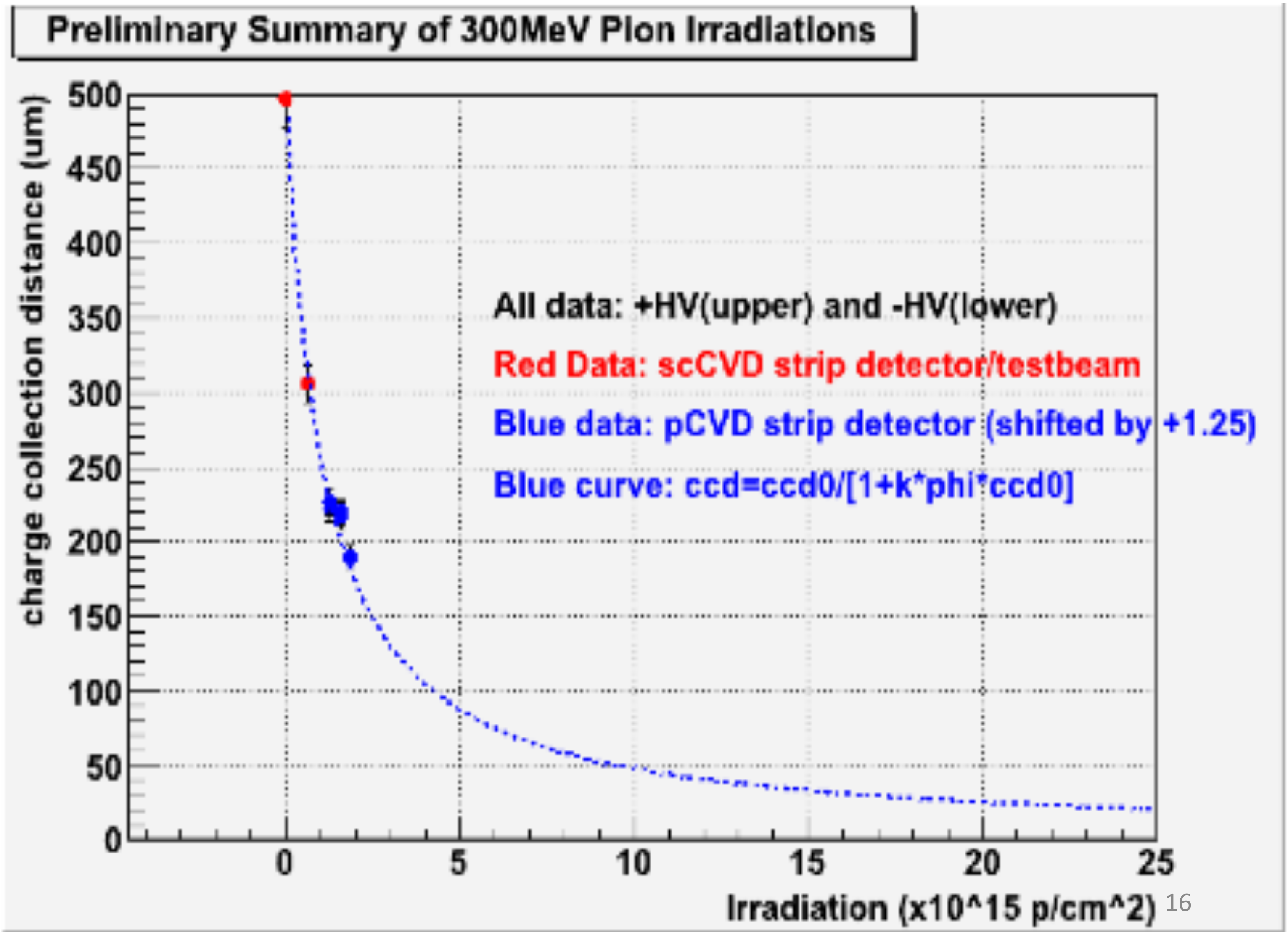
Polycrystalline diamond exposed to **70 MeV protons** at Cyric, Sendai.
k =1.7 x 10^{-18} $\mu m^{-1} cm^{-2}$ (uncertainty still being estimated): 2.6x more damaging than 24 GeV p.
Measurement confirmed as k = (1.8 ± 0.3) 10^{-18} $\mu m^{-1} cm^{2}$ in **62 MeV proton** beam at INFN LNS (Catania).
FLUKA DPA predicts 6x.



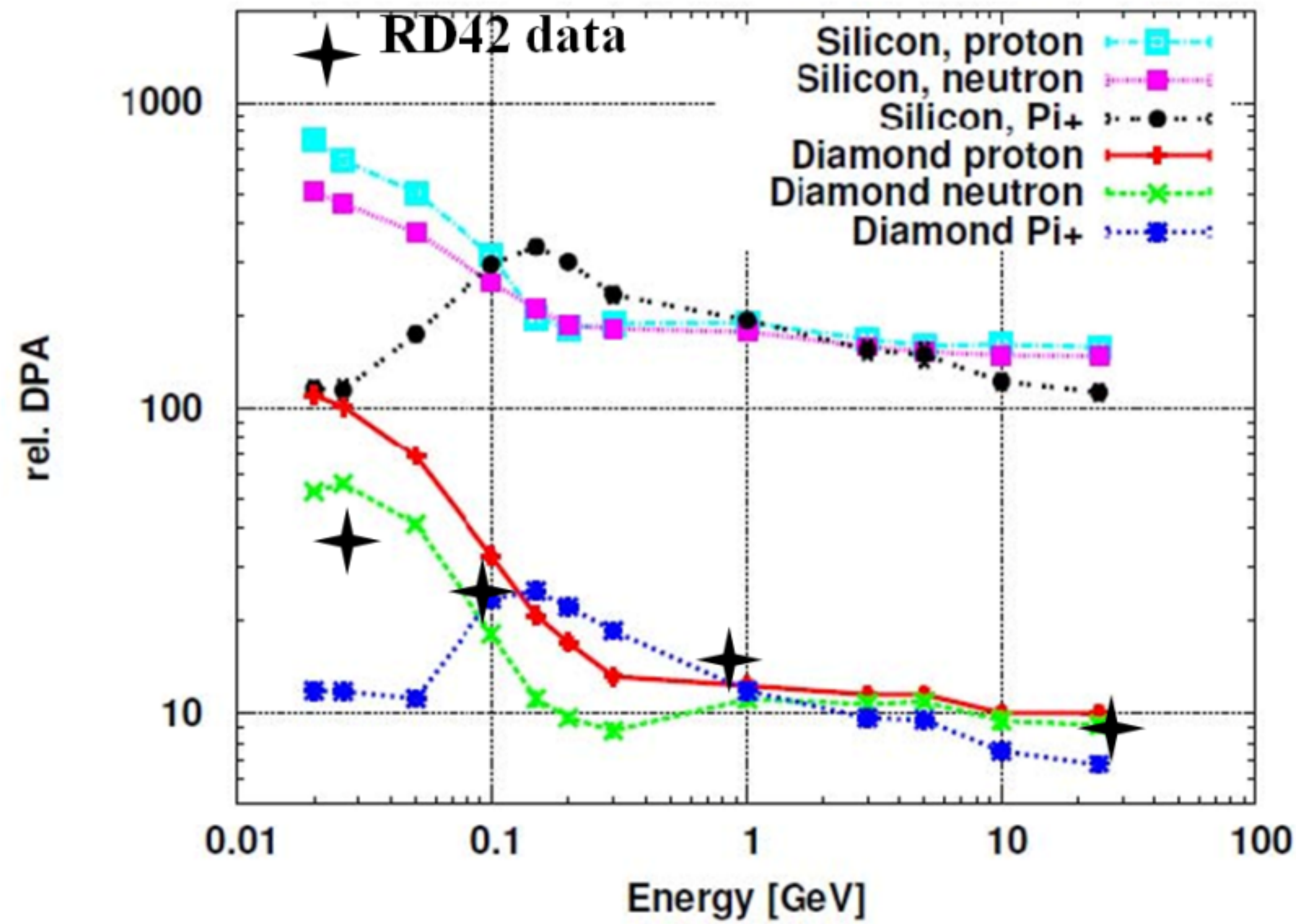
Single crystal diamond exposed to **25 MeV protons** at Karlsruhe.
$k = 2.6 \times 10^{-18}\ \mu m^{-1} cm^{-2}$ (uncertainty still in preparation): 4x more damaging than 24 GeV p.
FLUKA DPA predicts 8x.



Poly and single crystal diamonds exposed to **300 MeV pions** at PSI
$k = 1.8 \times 10^{-18}\ \mu m^{-1} cm^{-2}$: 2.9x more damaging than 24 GeV p
FLUKA DPA predicts x2.2



Summary of measured diamond relative DPA proton data (proportional to damage constant k) and FLUKA predictions versus energy:



Conclude: reasonable agreement in range 0.07 – 24 GeV. Work is still in progress.

*A study of the dependence of diamond resistivity on fluence and temperature**

Changes in the resistivity of a diamond substrate propagate to the leakage current. Leakage current is used to infer many properties of a sensor including active volume and charge collection distance.

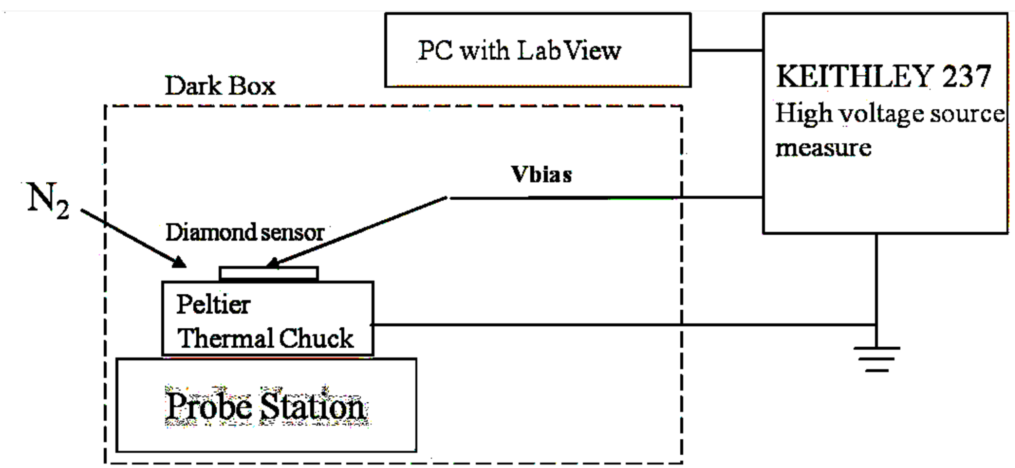
The resistivity of 2 polycrystalline diamonds was measured before and after exposure to 800 MeV protons at five fluences in the range zero to $1.6 \times 10^{16}/\mathrm{cm}^2$.

Resistivity $\boldsymbol{\rho}$ is computed from $\boxed{\boldsymbol{\rho = AR/d},}$

d = sensor thickness, nominally 440 μm, measured to 2% precision
A = sensor area, measured optically to 0.2% precision
R = inverse slope of a linear fit to a graph of $I_{leakage}$ versus V_{bias}

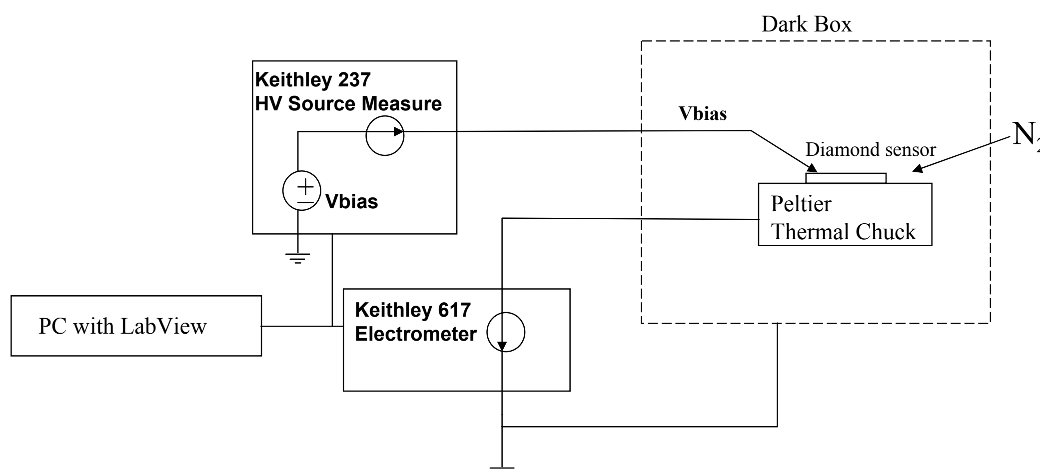
* R.Wang et al., doi: 10.1016/j.nima.2013.10.007

2 measurement setups, to assess systematics:

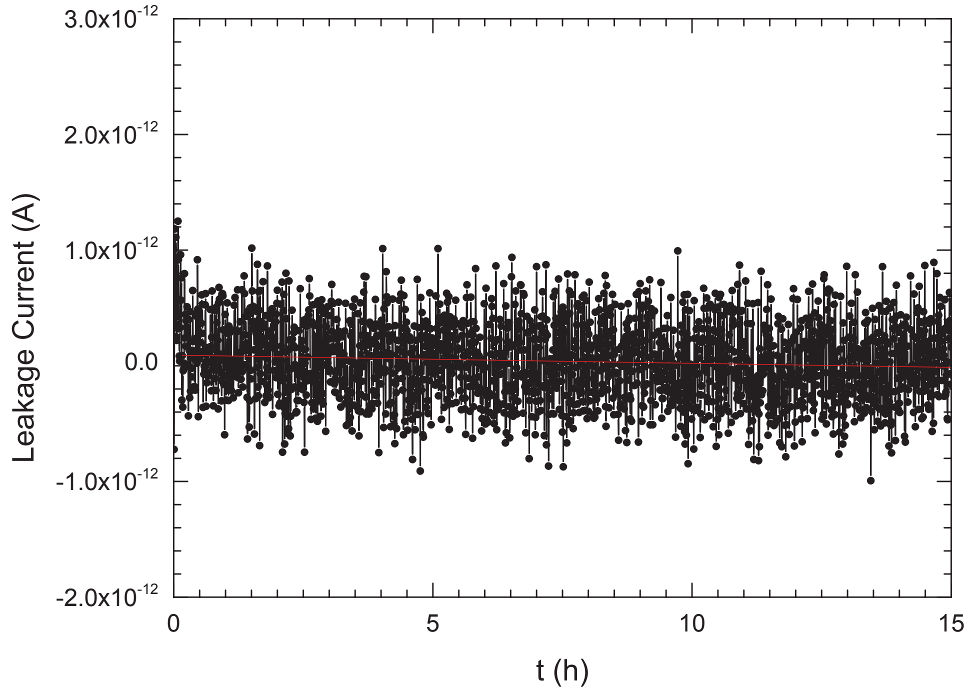


←Setup 1: ground on detector back side, HV on front, bulk $I_{leakage}$ acquired by Keithley 237 source measure unit. *Advantage: simplicity. A single instrument measures sourced current.*

Setup 2: ground on detector back side, HV on front, bulk $I_{leakage}$ acquired by Keithley 617 electrometer. *Advantage: measurement is made on the returned current so sourced current that did not cross the bulk is excluded.*→



The diamonds: From E6. *Stable operation:*

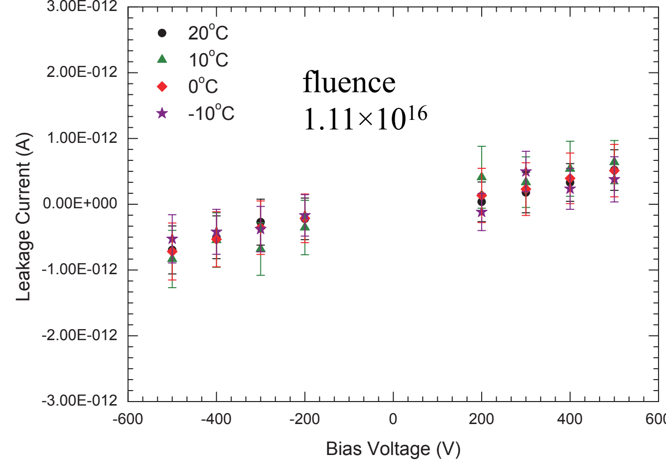


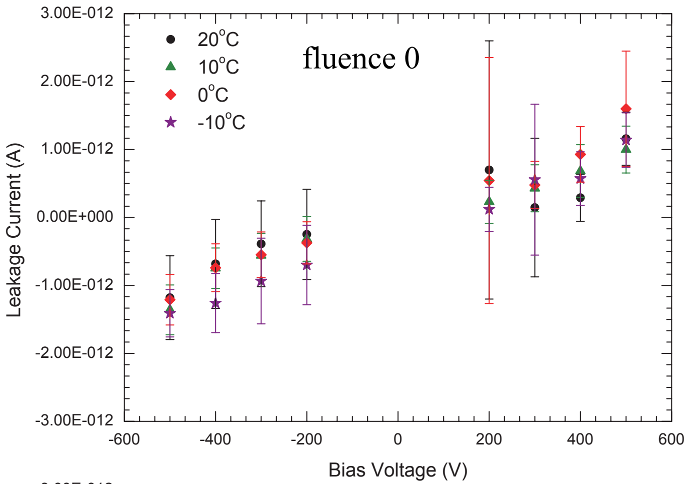
- Equilibration takes ~30 minutes
- Data are acquired beginning 1 hour after installation and continuing 4 hours.
- Example I-t data here for a sensor at 20°C after 1.63×10^{16} p/cm^2: the slope of the line fitted to the range 1-4 hours is $(-2.29 \pm 1.65) \times 10^{-16}$ A/hr.

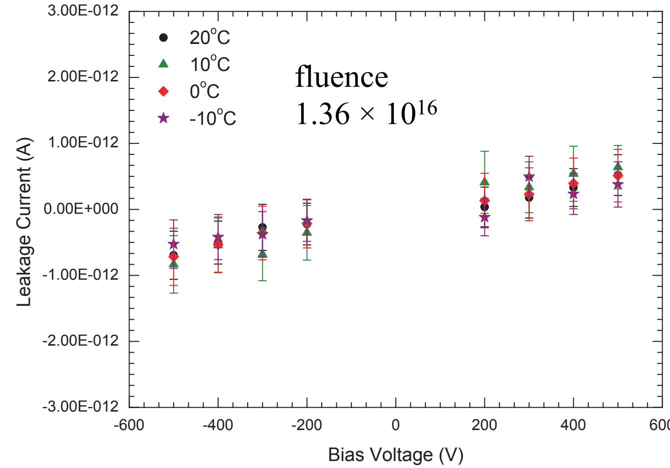
Method:

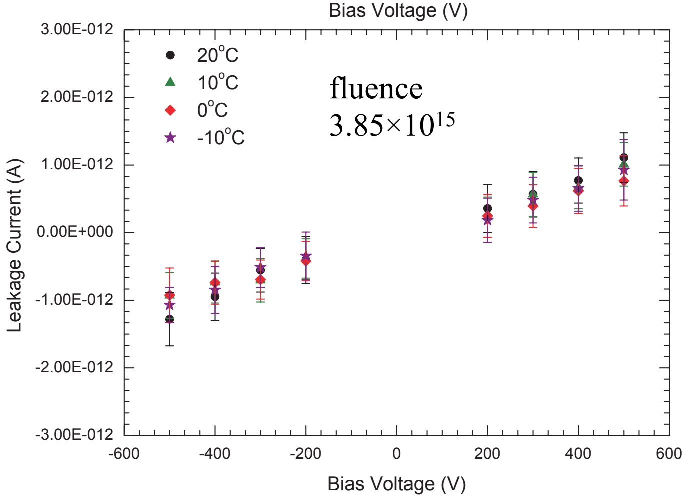
- Measurements are made at -10°C, 0°C, +10°C, and +20°C with thermal control through the chuck.
- Apply dry N_2 to prevent condensation. Relative humidity < 5% for all measurements below room temperature, < 35% for RT measurements.
- Ramp bias from -500 V to +500 V and confirm in both directions.
- Data taken with positive and negative bias are fitted separately for ranges 200-500V. Fits are consistent. Slope *R* is their average.

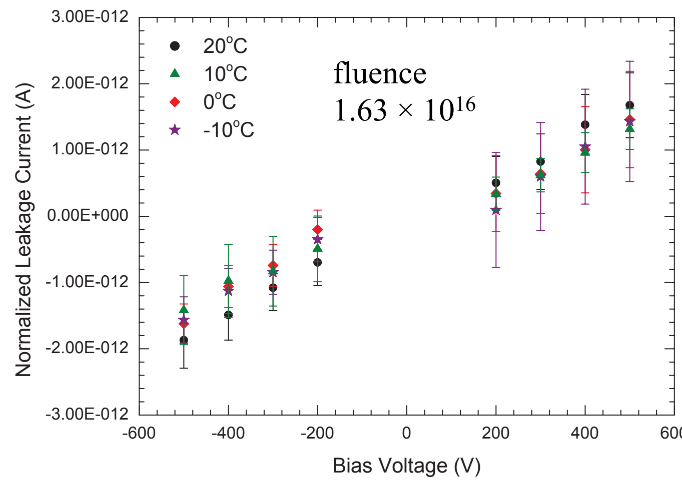
Example leakage currents measured, with 800 MeV proton fluences (cm^{-2}) inset:







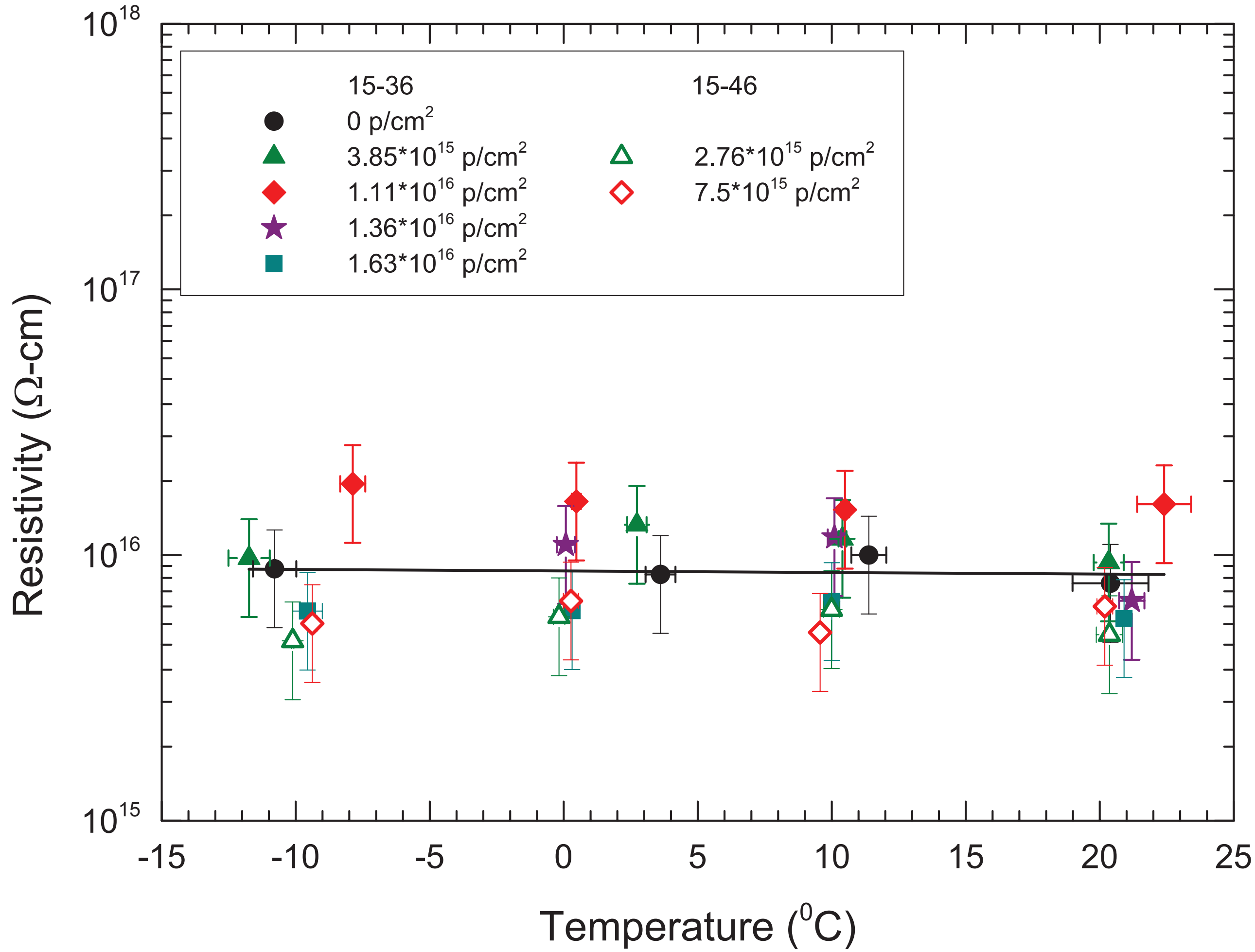




Measurement uncertainties:

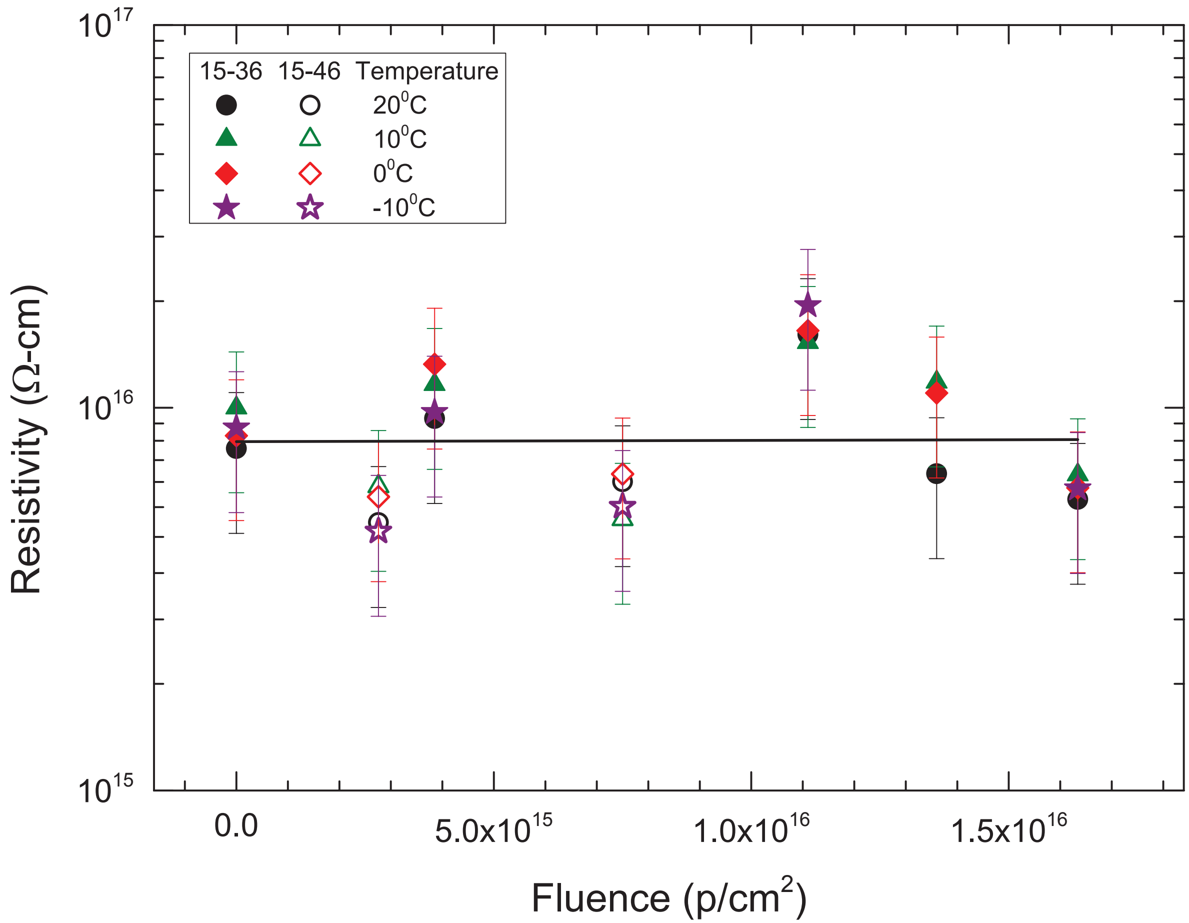
- Statistical error on current is [3 – 9] $\times 10^{-13}$ A, represents average of 3 – 5 measurements under identical conditions.
- Temperature uncertainty < 0.1°C per individual measurement.
- Manufacturer's accuracy specifications: ±(0.04% +240 mV) for Keithley 237 and ±(0.3% + 100 fA) for Keithley 617.
- Measured dimensions: 2% on thickness, 0.2% on length and width.
- 10% - 30% on fluences.
- 40% on setup configuration---due to different intrinsic accuracies of Keithley 617 (1.6%) versus Keithley 237 (0.3%).

Result #1: resistivity versus temperature, all fluences, both diamonds:



Free linear fit, intercept $(8.37 \pm 0.55) \times 10^{15}$ Ω-cm, slope $(-0.63 \pm 4.13) \times 10^{13}$ Ω-cm/°C, χ^2/dof = 0.62. ***Conclude: no significant dependence of diamond resistivity on temperature over the range ~ -10° to +20°C.***

Result #2: resistivity versus fluence, all temperatures, both diamonds:



Free linear fit, intercept $(8.01 \pm 0.81) \times 10^{15}$ Ω-cm, slope $(0.49 \pm 8.54) \times 10^{-2}$ Ω-cm/(p/cm^2), χ^2/dof = 0.62. ***Conclude: no significant dependence of resistivity on proton fluence over the range 0 to 1.6×10^{16} 800 MeV-p/cm^2 (0 to 1.13×10^{16} 1-MeV-n_{eq}/cm^2).***

Summary

- Damage constants for single crystal and polycrystalline diamond have been measured in 5 different beam conditions and compared to predictions from FLUKA DPA. The study is still ongoing but seems to indicate reasonable and increasing agreement between data and theory with energy. All measurements conform to the equation

$$\frac{1}{\lambda_{e/h}} = \frac{1}{\lambda_0} + k\Phi$$

  to better than 2 sigma, demonstrating a common radiation damage mechanism in CVD diamond.

- The resistivity of polycrystalline diamond has been found to be independent of temperature and fluence over the ranges [-10°C to +20°C] and [zero to 1.63×10^{16} 800-MeV-p/cm^2].