DIAMOND-BASED PARTICLE DETECTION

Studies of Charge Collection

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CVD DIAMONDS

Is it the next great advancement in detector technology?

CHEMICAL VAPOR DEPOSITION

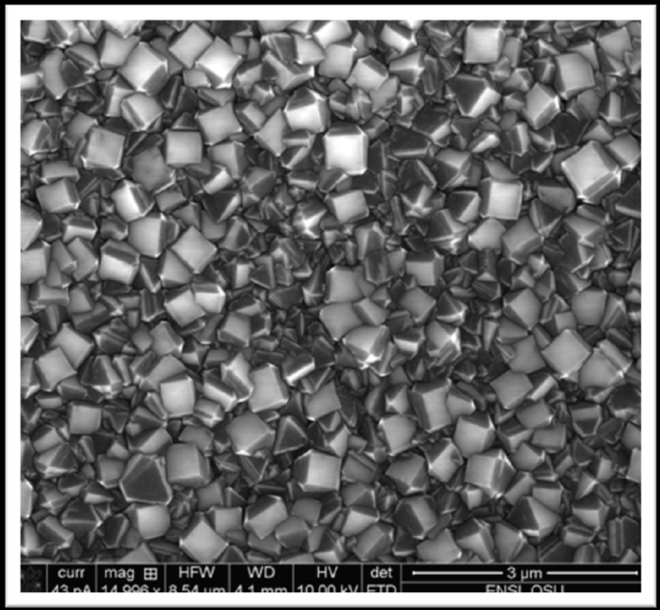
- Artificial process by which a gas containing carbon is decomposed and the carbon atoms are deposited on the surface.
- Graphite is the thermodynamically stable crystalline phase of carbon, so it must be suppressed to allow for diamond formation.
- The graphite sp^2 bonds are usually broken by "non-carbon etchants" such as atomic hydrogen by mixing large amounts of hydrogen with the process gas and activating it either thermally or by plasma.
- These diamonds have many applications.
- One of which is for detecting charged particles.

(Fraunhofer Institute IAF)

GENERAL PROPERTIES

- Strength of material → rigidity of it's lattice & relative small mass of carbon atom
- High melting point → 4363 K
- Highest thermal conductivity of any known material
- Electrical properties → Bandgap of 5.45 eV
  - High resistivity → $10^{13} - 10^{16}$ Ωcm
  - Insulator and Semiconductor
- High refractive index (n=2.419)

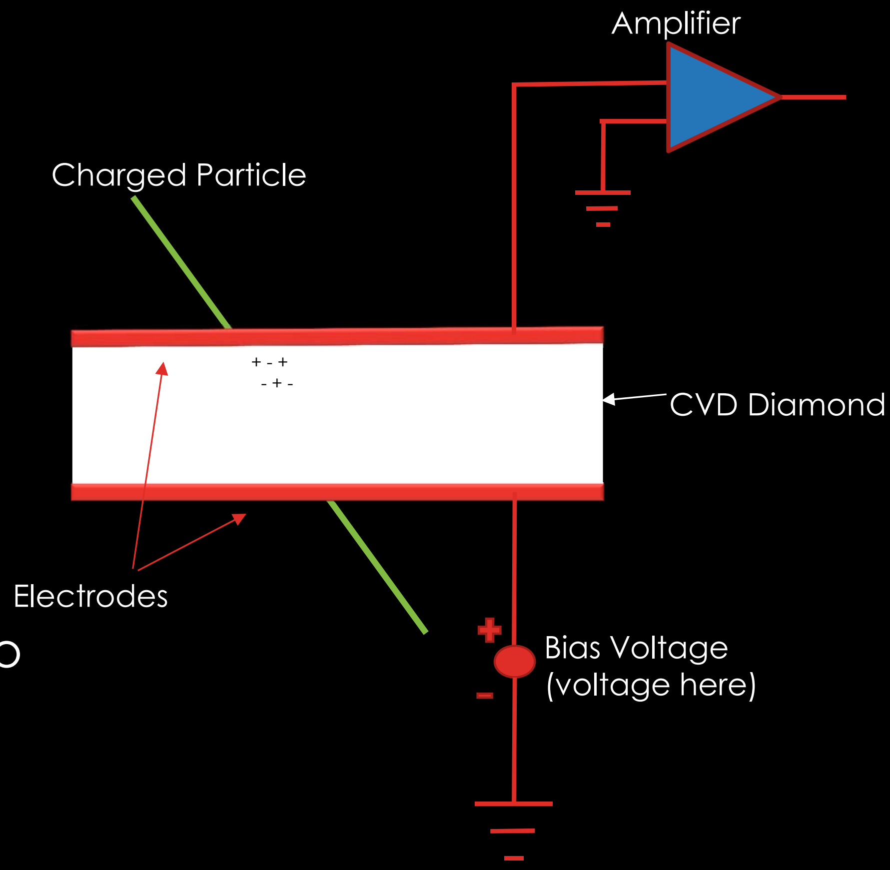
(R J Tapper 2000)



Microscopic CVD Diamonds grown on a substrate at 100 µm

DETECTING INDIVIDUAL PARTICLES

- Determining Quality: we are concerned with the generation of mobile charge within the material
- Also, it's consequent movement in response to an applied electric field (R J Tapper 2000)
- Deposition of energy by charged particles through the material is of most importance
- In our setup, the charges get trapped at the surface, and a certain amount of charge is generated, which is compared to a total amount of charge that should be collected.

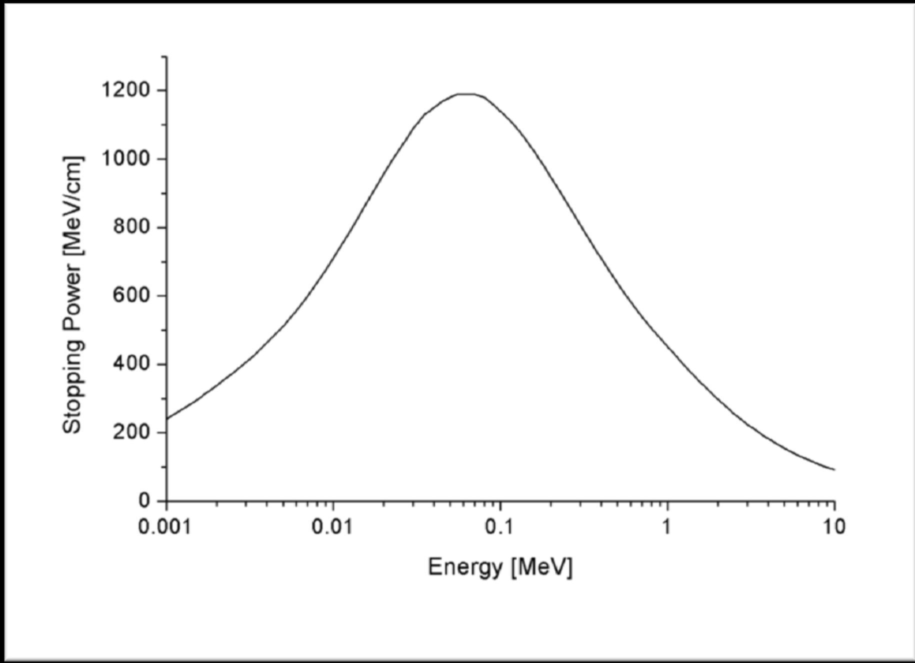


BASIC DETECTION MECHANISM

- General approach by Ramo's Theorem (Ramo 1939)
- $i_A = \frac{dQ_A}{dt} = -\frac{q}{\varphi_A}\frac{d\varphi_A}{dt} = -\frac{q}{\varphi_A}E_A \cdot v$
- Where charge q moves with inst. velocity v in the vicinity of a number of conductors with fixed potentials by external voltages. A is a conductor held at potential φ_A, deliver current i_A to voltage source as q moves, **creating a signal**.
- This signal can then be measured by our setup.

STOPPING POWER

- In passing through matter, fast charged particles ionize the atoms or molecules which they encounter.
- The fast particles gradually lose energy in many small steps.
- Stopping power is defined as the retarding force acting on the particle during the interaction with materials.
- Picture → The stopping power of aluminum for protons, plotted versus proton energy.



CHARGE COLLECTION EFFICIENCY

- $cce \approx \frac{Q_m}{Q_0}$ (Defined as the ratio of measured charge over the total charge generated)
- With CVD diamonds and charge-sensitive measurements, the charge collection efficiency is the main signature of whether the diamond is a good detector or not.
- With additional radiation damage, the charge collection efficiency is lowered.
- Also, the more Bias voltage put through the diamond detector, the more charges are displaced and therefore more charge is collected, raising the efficiency.

CHARGE COLLECTION DISTANCE

- CCD: The distance to collect all charge deposited
- To maximize the amount of charge collection and obtain the best possible signal → We want a large charge collection distance (CCD) on the atomic scale.
- Diamonds perform so well for this because they have been shown to have a large charge collection distance on the atomic scale (**tens to hundreds of μm**) → Compared to silicon.
- However, charge collection distance is not what our primary focus is with this setup.

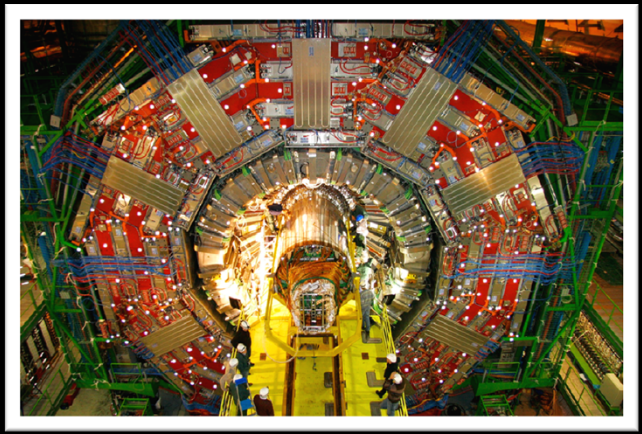
(R J Tapper)

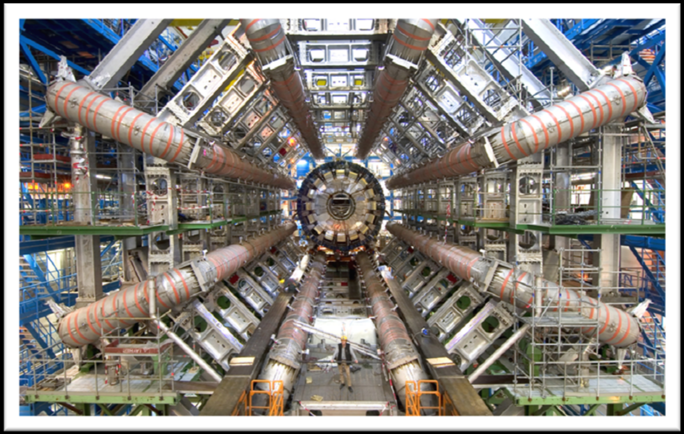
THE LHC

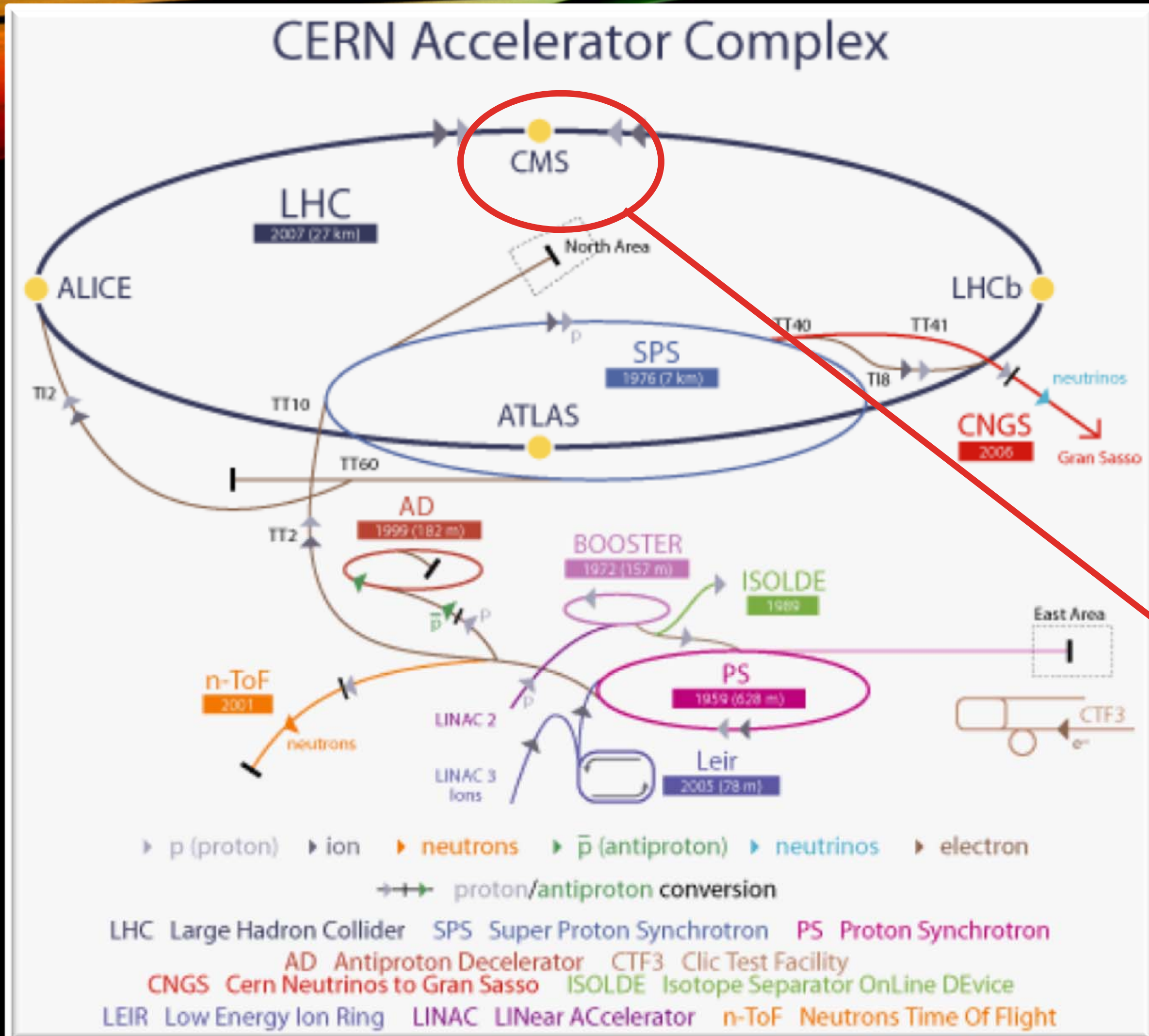
A look into CMS and ATLAS

THE LARGE HADRON COLLIDER (LHC)

- Largest accelerator in the world.
- Capable of probing energies in excess of 7 TeV, in 2015 this will double when upgrades are finished.
- CMS (Bottom Left) and ATLAS (Right) are the two major detection locations.
- Primary goal is to observe new, rare particles.

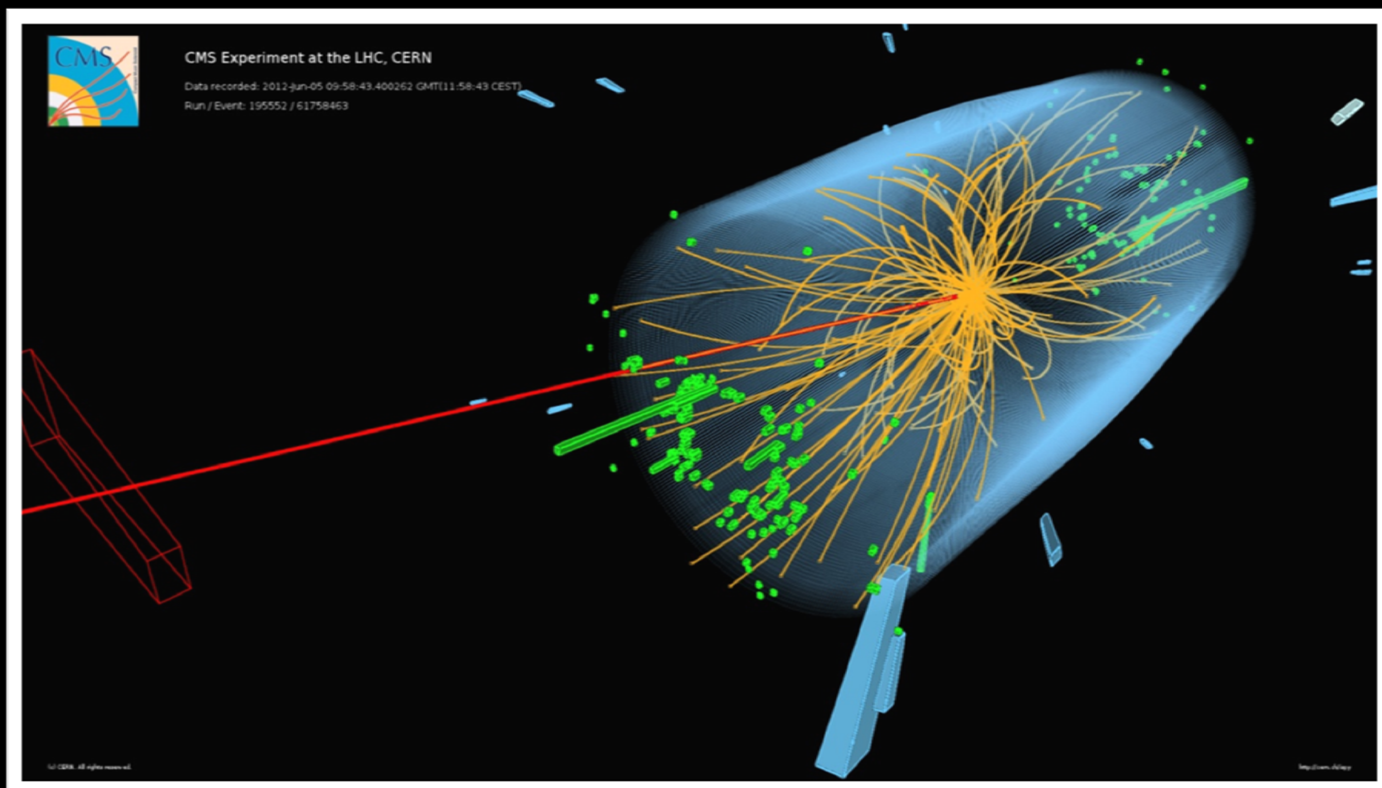


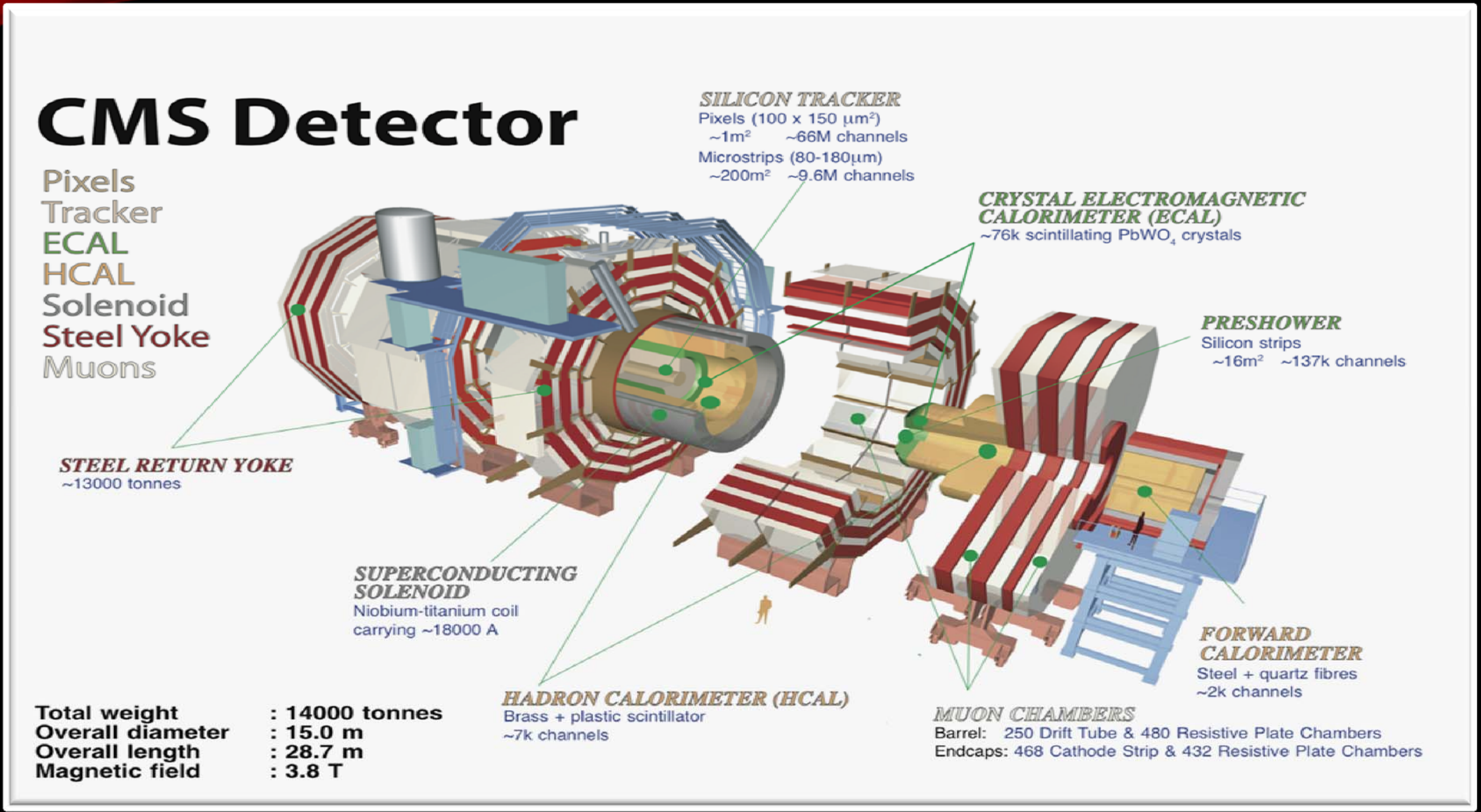




I work with CMS Data

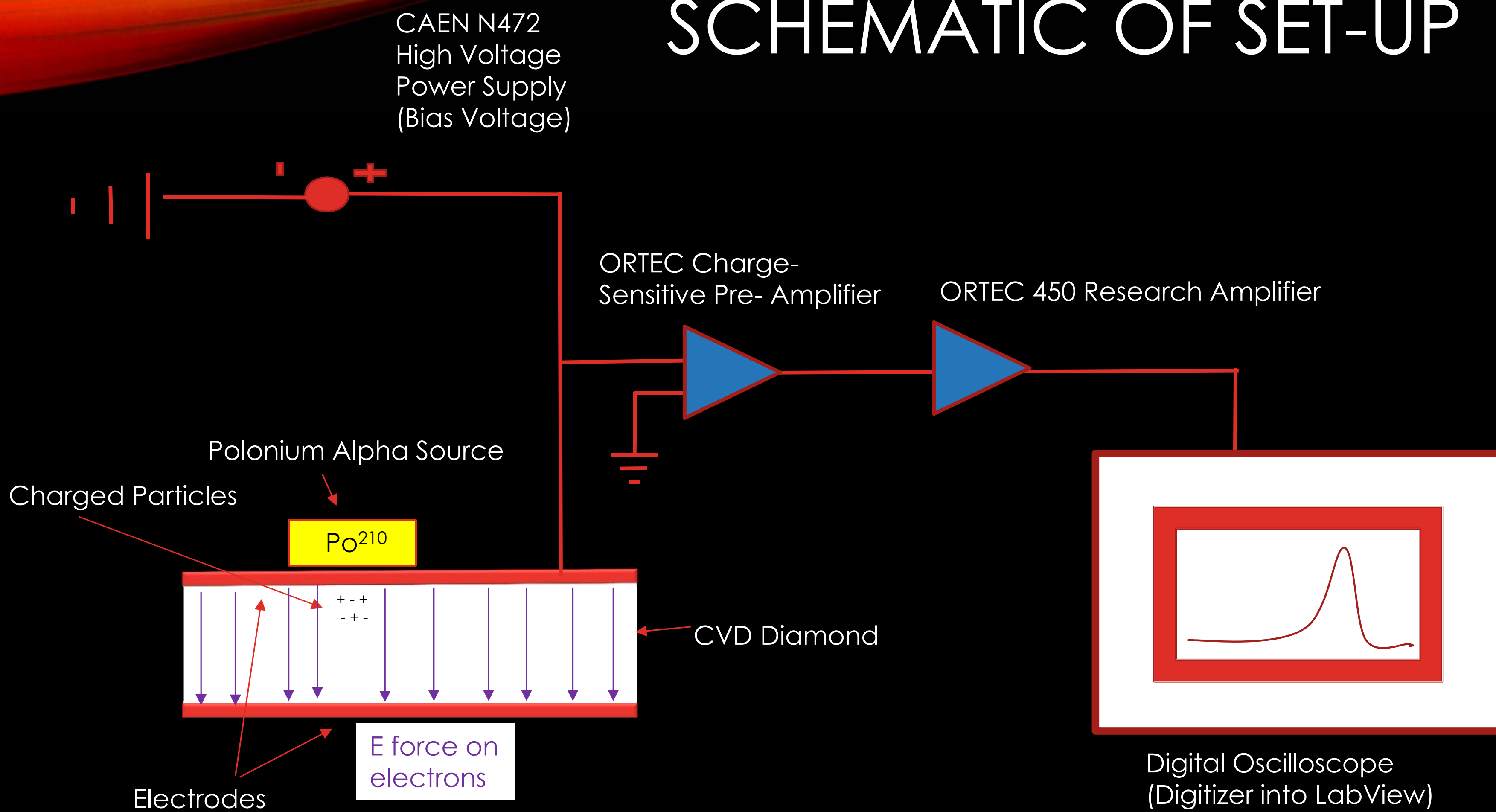
EVENT DISPLAY




CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

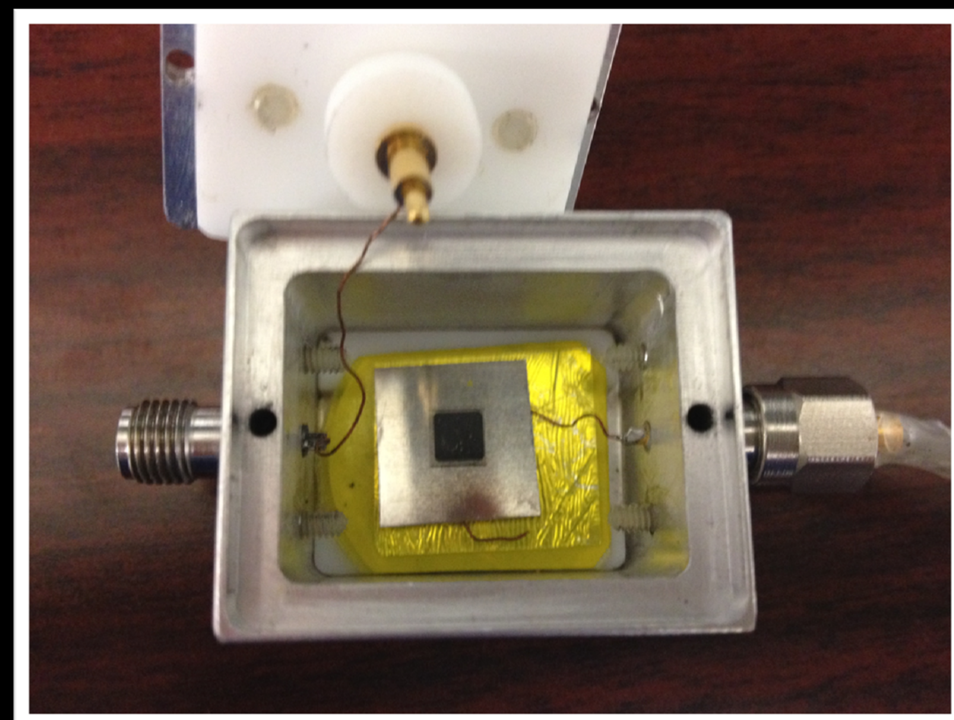
MEASURING RADIATION HARDNESS

SCHEMATIC OF SET-UP



PICTURES OF SET-UP

Detector (Outer View)



Detector (inside view) with Diamond and Strontium exposed

MORE PICTURES

NI-5154 Digitizer

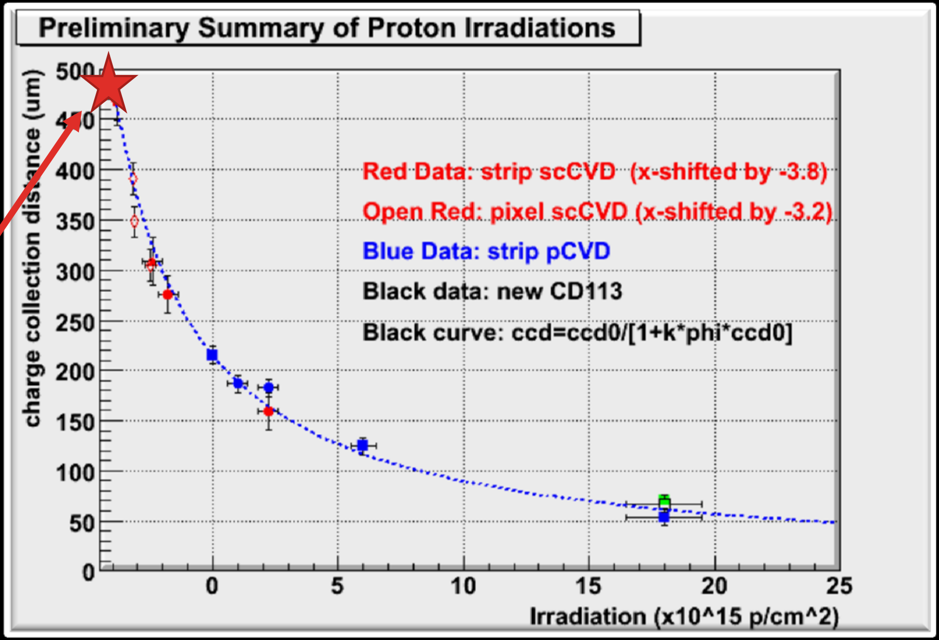
Light-tight housing

Pre-Amp, Power Source, and Shaping Amp

RADIATION DAMAGE

- NOTE: This is for PROTON irradiation.
- Affects the charge collection distance, lowering it.
- This weakens the signal received by a displaced charge in the diamond.
- Highly studied by the RD-42 Collaboration based out of CERN

S131



RD42 Collaboration, Cristinziani, Markus Nucl.Instrum.Meth. A623 (2010) 174-176 arXiv:0910.0347

EXPERIMENTS RUN

- Using two diamonds, S130 and S131, and a Polonium 210 alpha source, I used the test set-up from the previous slide to perform the following tests:
  - S130 and S131:
  - Standard Exposure:
    - Measure charge collection before exposure to alpha particles, then measure again after exposed for roughly 24 hours.
  - Light-Tight and Voltage:
    - Measure charge collection with the detector in a "light-tight" box and by leaving the bias voltage across diamond at a constant 500V during exposure periods.
  - Standard Exposure occurred in December 2013 and March 2014

CVD DIAMOND S130

- No irradiation
- Thickness: 536 microns
- Dimensions: 4.6 X 4.6 mm
- Bandgap of 5.4 eV

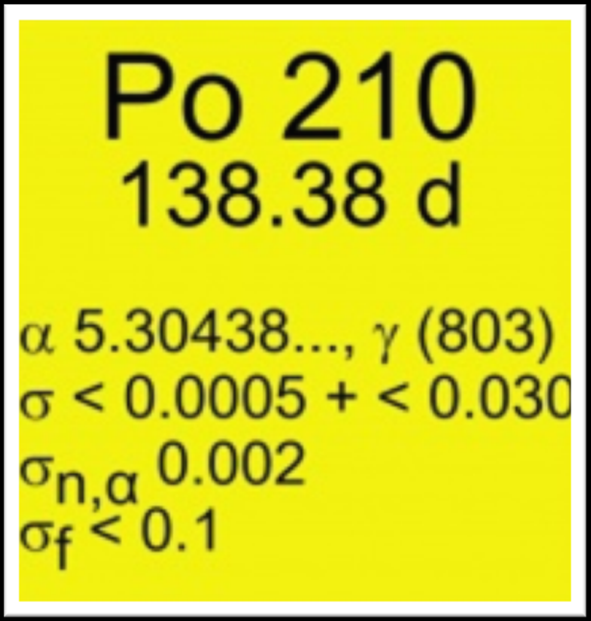
CVD DIAMOND S131

- Irradiation of 0.5×10^{14} neutrons/cm^2
- Thickness: ≈500 microns
- Dimensions: Roughly the same size as S130:
  - ≈ 4.6 X 4.6 mm
- Bandgap of 5.4 eV

ALPHA SOURCE

- Source is Polonium-210
- Decays into Lead-206 by alpha decay
- Emits alpha particles in the process
- We use this alpha source to generate electron-hole pairs in the diamond, to measure the ***electron drift*** within the diamond.

$$^{210}_{84}\mathrm{PO} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{206}_{82}\mathrm{Pb}.$$



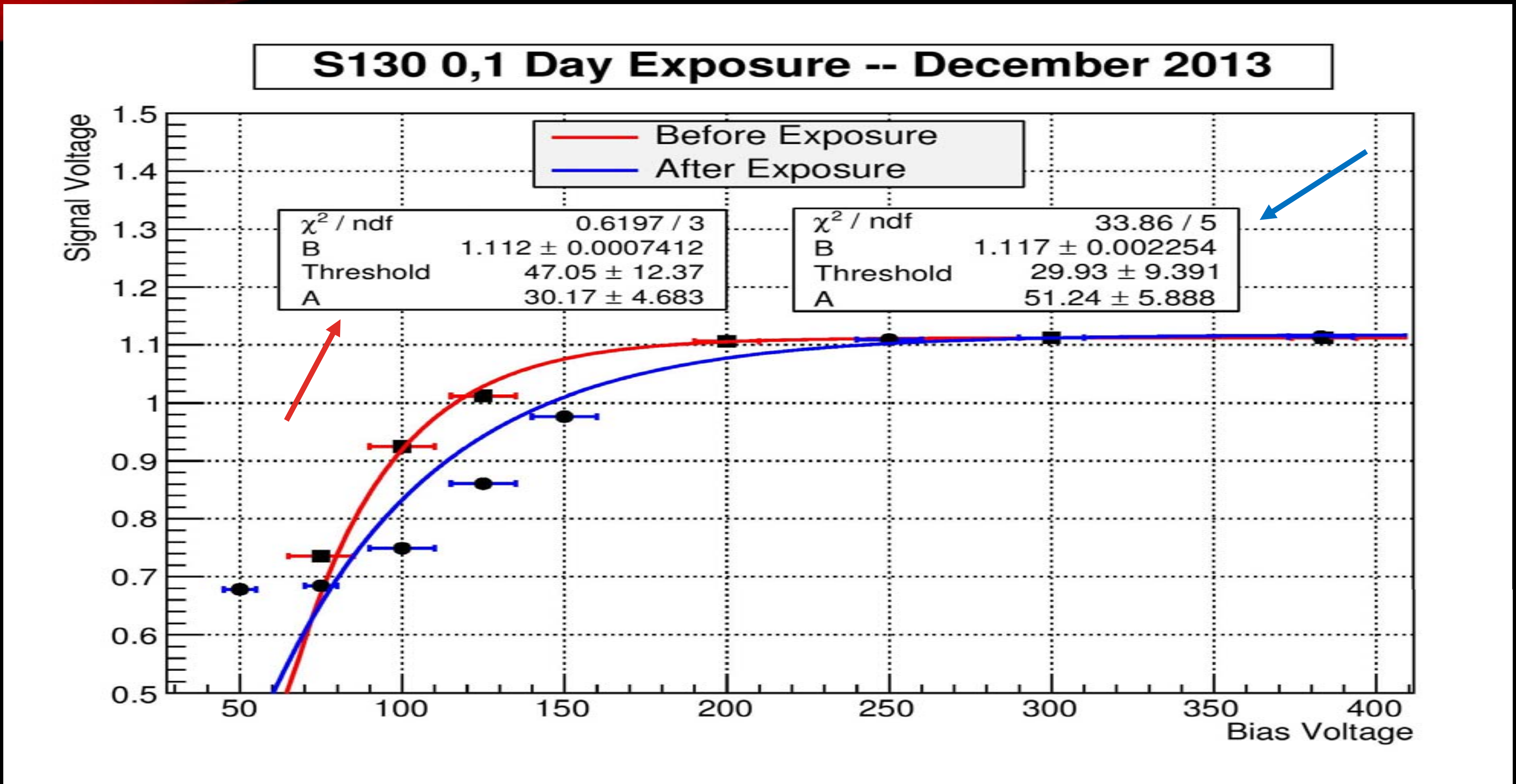
CALCULATING % CHARGE COLLECTION

- Take into account:
  - Source: Polonium-210
  - 5.30438 MeV alpha particles generated by Polonium^{210} source
  - 1 electron-hole pair generated per 13 eV
- To get the % charge collection: must divide amount of charge collected at certain bias voltage by total amount of charge that *should* be collected overall.
- **However, this is difficult without knowing the specific qualities of the electronics and the setup; therefore, I will normalize the max collection to the saturation value given by the baseline of each test.**
- $E - H\ pairs = \frac{1^{e^-}}{13\ eV} * 5.30438\ MeV = 408{,}030\ (e - h\frac{pairs}{particle})$
- → Total charge that should be collected.

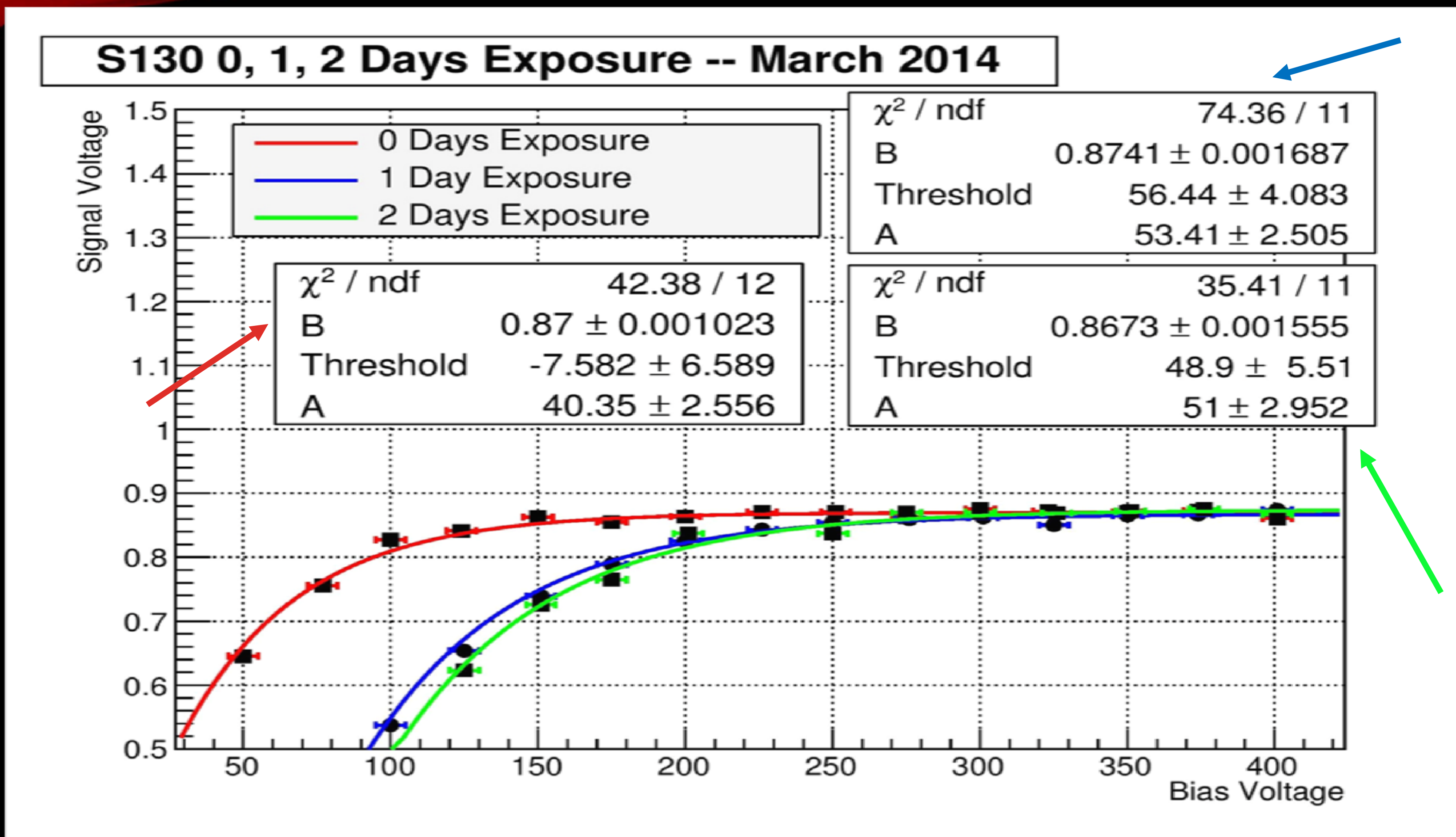
FITTING METHODS

- Double Gaussian Fit:
  - Employed for each data set containing a bin of charges collected and amplitude of each.
- Fermi Function:
  - Employed for fitting the graphs of bias versus signal voltage.
  - Modeled by:
  - $y = \left(1 - e^{-\frac{x-x_0}{A}}\right)B$
    - $where\ A\ and\ B\ are\ parameters, and\ x_0\ is\ the\ threshhold.$
- S131 Long Term Fit:
  - $y = B + e^{Ax/\tau}$
    - $where\ A\ and\ B\ are\ parameters\ and\ \tau\ is\ the\ capacitive\ time\ constant\ RC.$
- All fits done in ROOT data analysis framework.

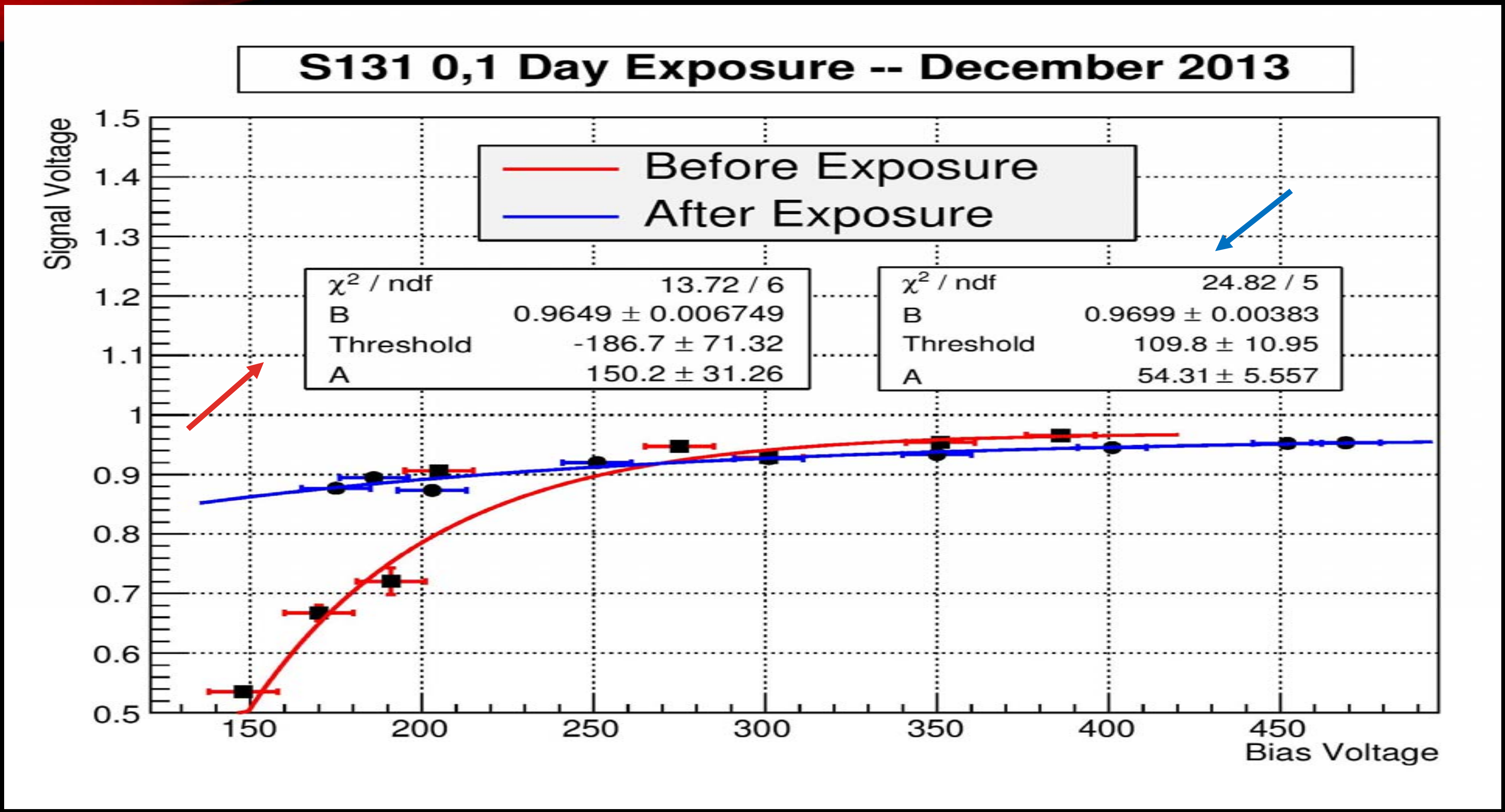
S130 STANDARD EXPOSURE



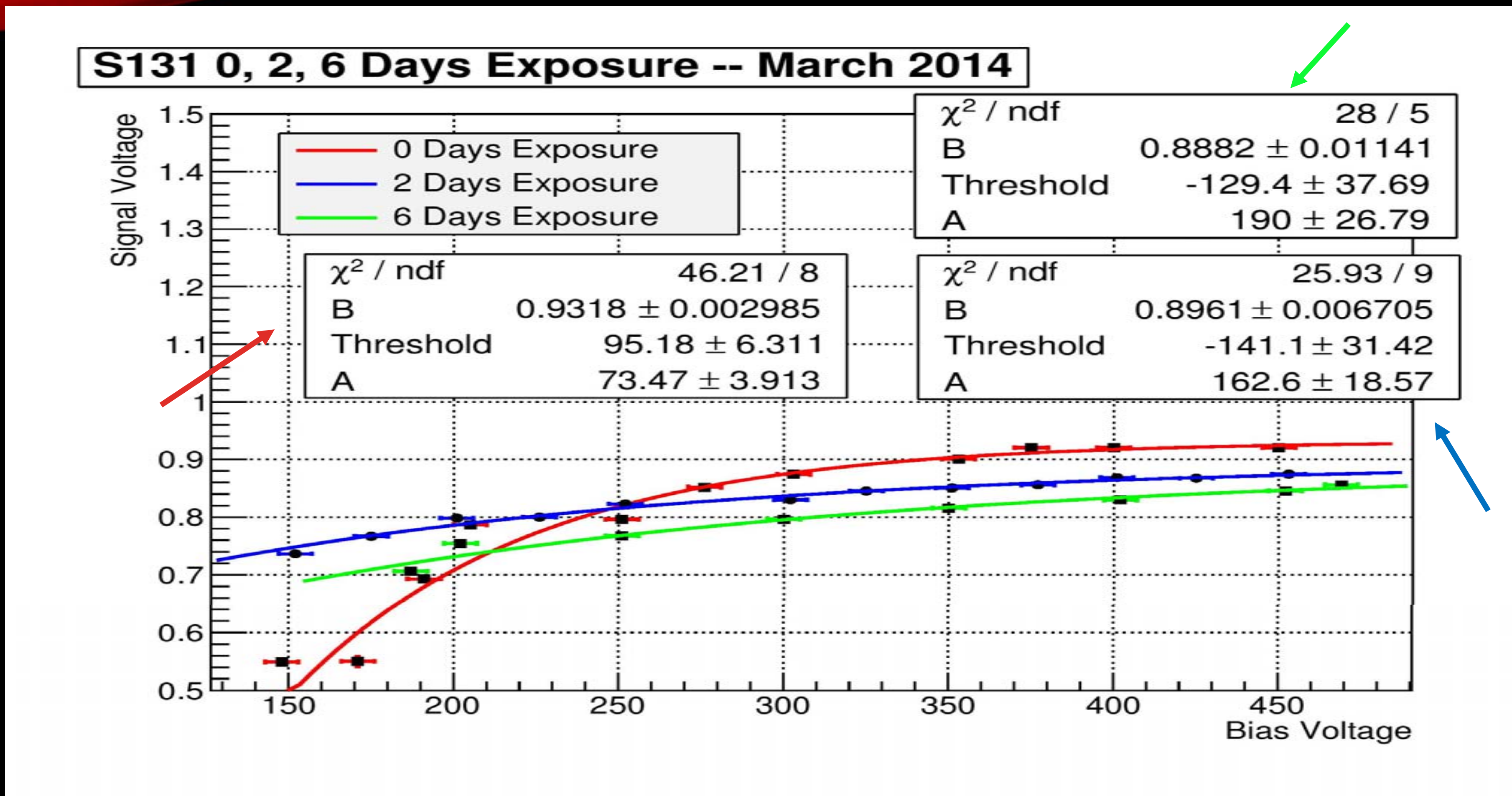
S130 LIGHT TIGHT/VOLTAGE TEST



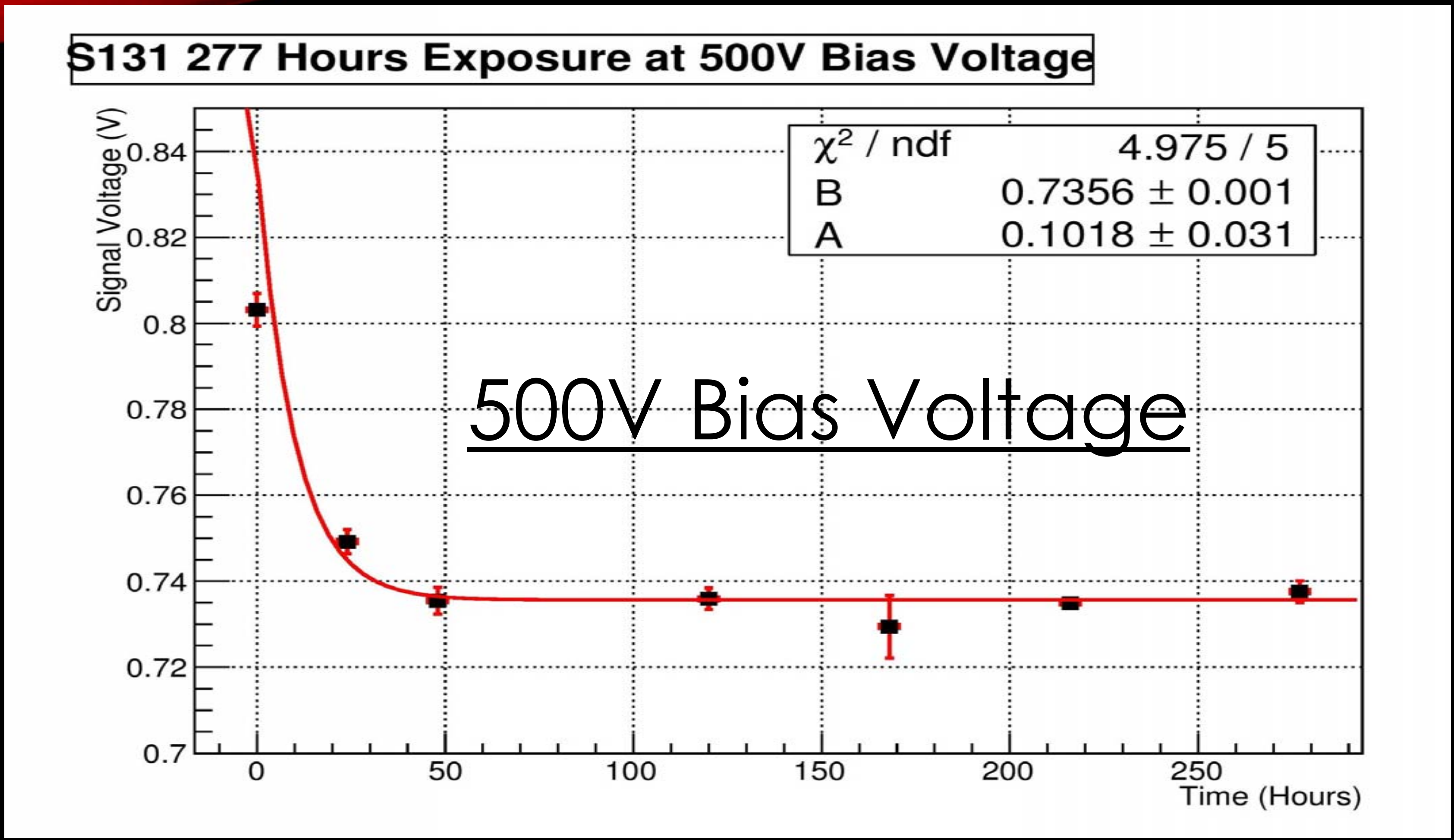
S131 STANDARD EXPOSURE



S131 STANDARD EXPOSURE TEST 2



S131 SIGNAL DECAY VERSUS TIME



RESULTS – S130

S130	% Charge Collection	Threshold/Trigger-Level
Standard Exposure – December 2013		
After 0 Days	≈100%	0.1 V
After ≈1 Day	≈100%	0.1 V
Light-Tight/Voltage – March 2014		
After 0 Days	100%	0.1 V
After ≈1 Day	99.5%	0.1 V
After ≈2 Days	99.2%	0.2 V

RESULTS – S131

S131	% Charge Collection	Threshold/Trigger-Level
Standard Exposure Test 1 – December 2013		
After 0 Days	100%	0.1 V
After ≈1.1 days	99.5%	0.2 V
Standard Exposure Test 2 – March 2014		
After 0 Days	100%	0.2
After ≈1.7 Days	96.2%	0.2
After ≈5.9 Days	95.3%	0.4
Light-Tight/Voltage – March 2014		
After 0 Days	100%	0.25
After ≈1 Day	93.6%	0.25
After ≈2 Days	91.9%	0.3
After ≈5 Days (500 V)	91.3%	0.1
After ≈6 Days (500 V)	91.1%	0.1
After ≈8 Days (500 V)	91.3%	0.1
After ≈11 Days (500 V)	91.9%	0.1

CONCLUSION

- Overall, it is clear that as a diamond is more heavily irradiated, the charge collection efficiency is lowered.
- Furthermore, over time that the diamond is left under constant voltage and exposure to radiation, the efficiency is also lowered.
- Some unknowns:
  - We believe there may be a reverse field created immediately after the voltage is taken off the diamond where the electrons and holes are pulled in the opposite direction.
  - What about 3D diamond detectors?
- It is clear that diamonds will not be used as the next upgrade of the detectors in the LHC, but they still have many other uses.

FUTURE OUTLOOK

- 2014
  - May 2014: Continue trials of diamonds on our test stand
    - Continued testing of S131
    - Testing of more damaged diamonds and other detector materials (e.g. silicon)
  - Early June 2014: Travel to FNAL (FermiLab) to perform tests on high energy particle beam with current set-up (Predicted).
  - Late June 2014: Analyze Data from FNAL and tests at UT-K.
  - July 2014: Organize data and written report to present later in month
  - Fall Semester 2014: continue work with HEPG
- 2015
  - Spring Semester 2015: continue work with HEPG
  - Summer 2015: REU at CERN?

BIBLIOGRAPHY

- R J Tapper "Diamond Detectors in Particle Physics" H H Wills Physics Laboratory, UK. 2000.6.1
- H. Kagan and W. Trischuk "Radiation Sensors for High Energy Physics Experiments" 2009
- RD42 Collaboration, Cristinziani, Markus Nucl.Instrum.Meth. A623 (2010) 174-176 arXiv:0910.0347