Advanced Detectors for Nuclear, High Energy and Astroparticle Physics
Bose Institute Kolkata

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Comparison of Silicon, Germanium and Diamond sensors for Using it in HEP Detector Applications

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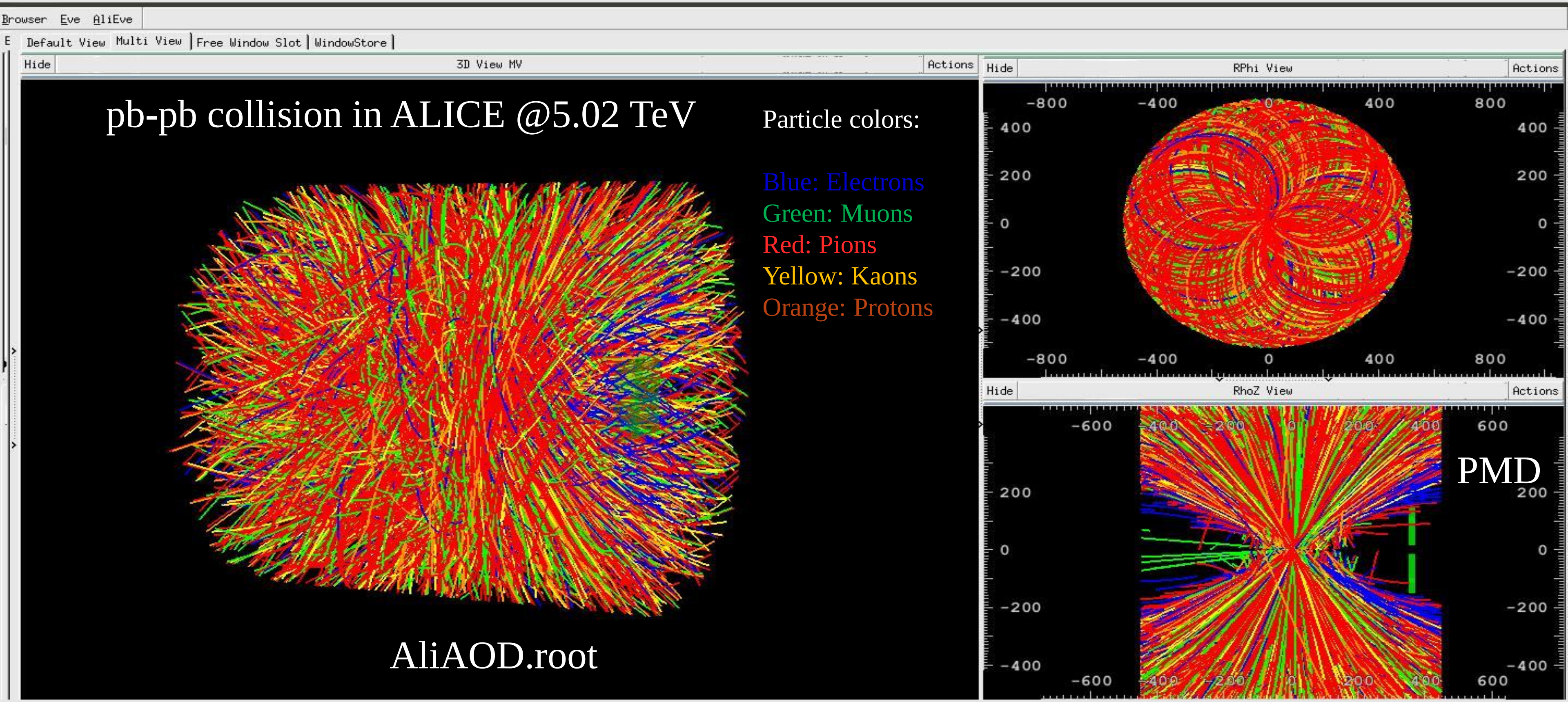
Outline

- Important properties of HEP detectors
- Simulation for Charge created by MIP
- Comparison of Radiation damage
- Particle Identification capabilities
- MPCVD System designing
- Growth of diamond film and Characterization
- Summary and Future Plan

Important properties of HEP detectors



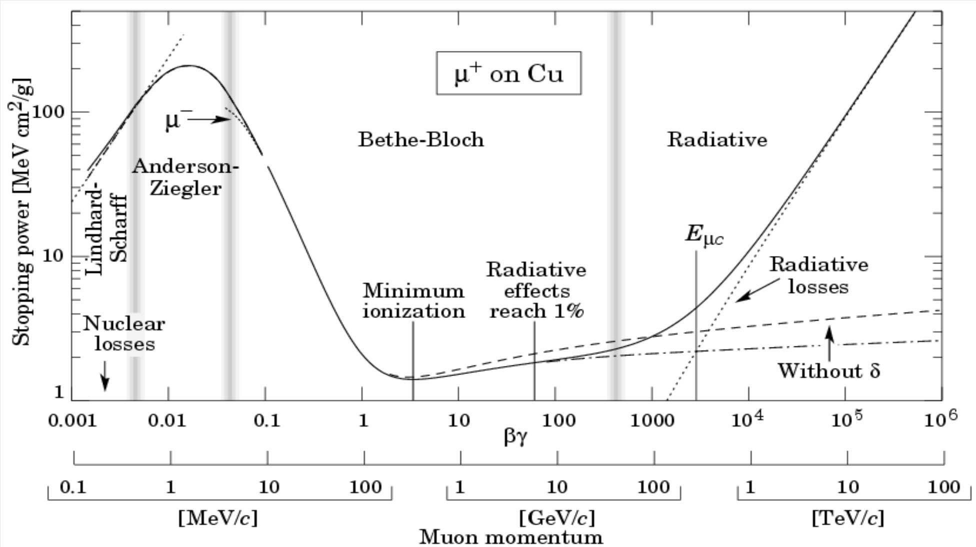
- High precision tracking=> Semiconductor detectors
- Typical choice of semiconductors are Si, Ge and Diamond
- Material should have following properties:

1. High signal to noise ratio for good position resolution
2. Low material budget for less multiple scattering
3. Fast pulse timing for less pile up
4. Low radiation damage
5. Particle Identification capabilities

In this talk we will compare Si, Ge and Diamond and will try to figure out the suitable material for High energy and high luminosity experiments

Simulation for Charge created by MIP

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

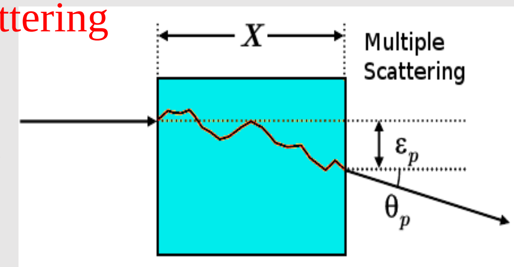


Diamond has low multiple scattering

$$\rho_{Si} = 2.33\ g/cm^3$$

$$\boldsymbol{\rho_{Di} = 3.51\ g/cm^3}$$

$$\rho_{Ge} = 5.3\ g/cm^3$$



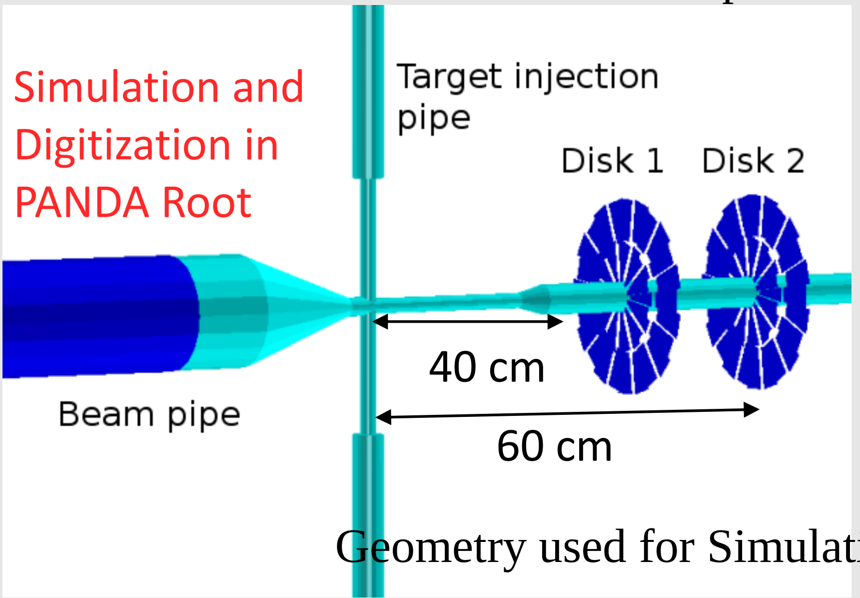
Diamond ($X_0 = 12.14\ cm$) has low material budget than Si ($X_0 = 9.37\ cm$) and Ge ($X_0 = 2.3\ cm$) for same thickness i.e. diamond will have less θ_p and ϵ_p

$$\theta_p = 13.6 \frac{MeVz}{\beta cp} \sqrt{\frac{X}{X_0}} [1 + 0.038 \ln \frac{X}{X_0}]$$

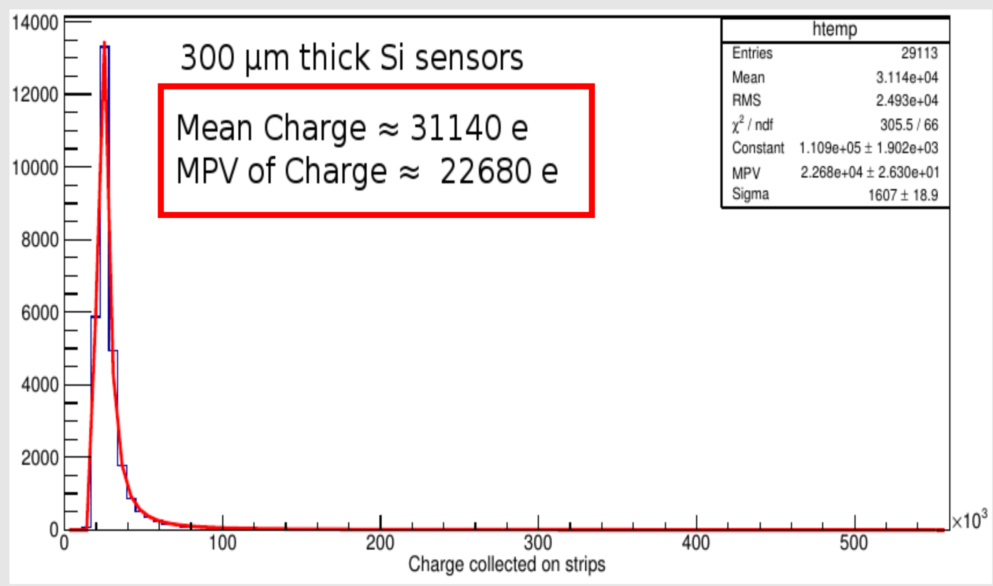
Ref: "Particle Detectors", C. Grupen and B. A. Shwartz

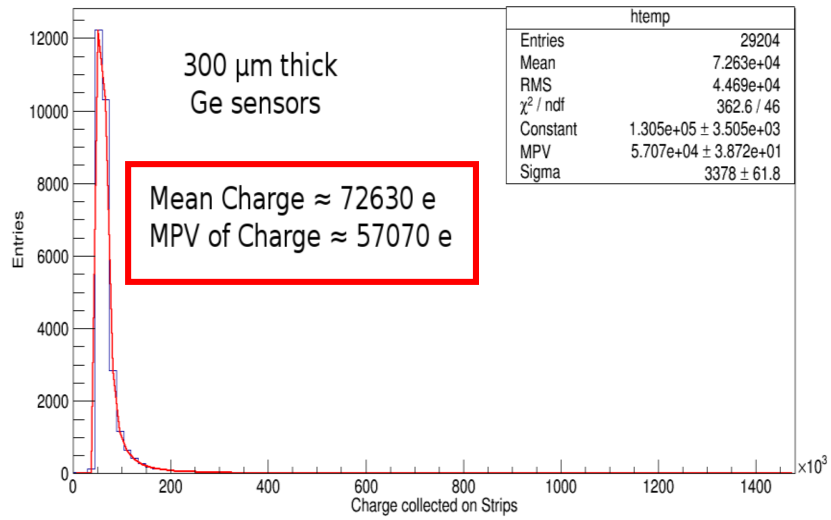
$$\epsilon_p \approx \frac{1}{\sqrt{3}} \theta_p X$$

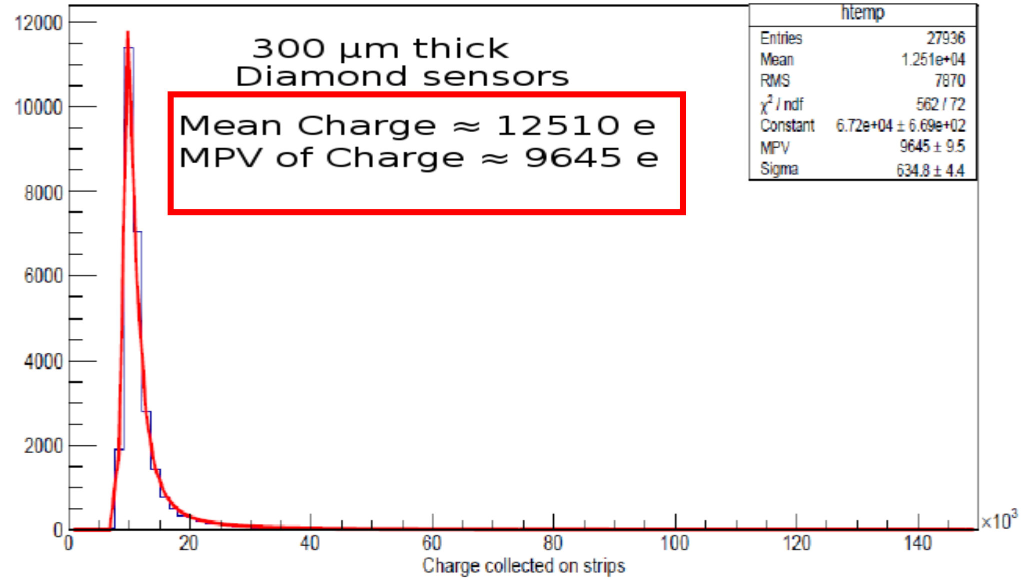
Double sided strip sensors



Geometry used for Simulation

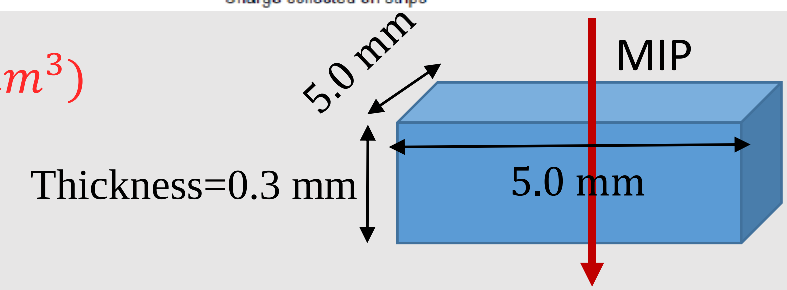






Signal to Noise ratio for Sensors ($5.0 \times 5.0 \times 0.3\ mm^3$)

$\sigma = q(n_e\mu_e + n_h\mu_h)$ for Intrinsic material $n_e = n_h = n_i$



Material	MPV Signal	$\rho\ (\Omega\ m)$	$\mu_e\ \left(\frac{cm^2}{Vs}\right)$	$\mu_h\ \left(\frac{cm^2}{Vs}\right)$	Noise (e)
Silicon	22680	640	1450	505	3.8×10^8
Germanium	57070	0.46	3900	1800	1.5×10^{11}
Diamond	9645	10^{13}	1800	1600	0.013

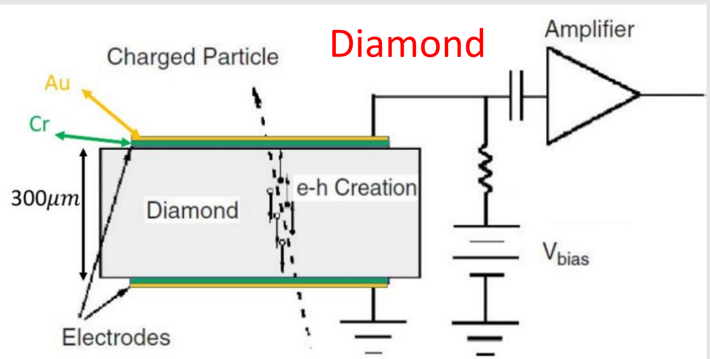
- Signal to Noise ratio for intrinsic Si, Ge are very small so we can not use them intrinsic material but diamond can be used as intrinsic material

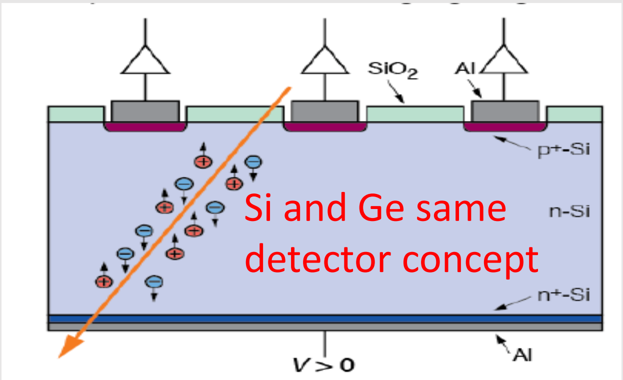
- The intrinsic noise can be reduced by increasing some how resistivity=> p-n junction in reverse bias condition

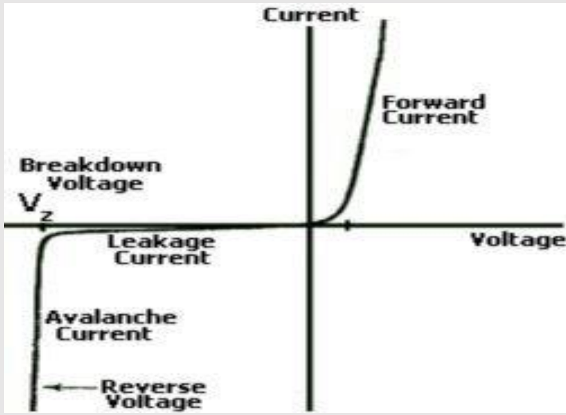
Just rough numbers

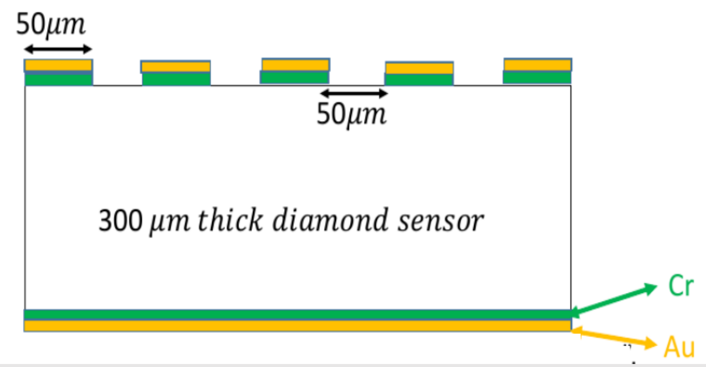
Silicon sensor reverse biased: $5.0 \times 5.0 \times 0.3\ mm^3$

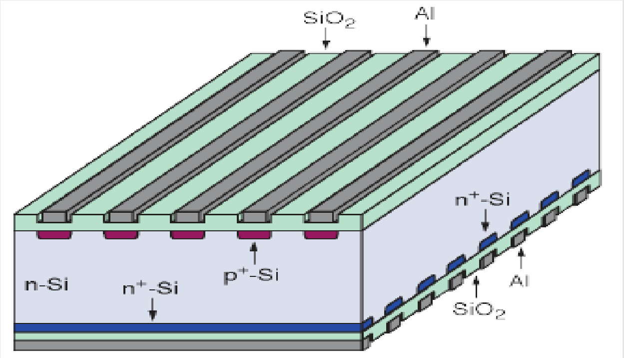
Material	Voltage	Current	$\rho\ (\Omega\ m)$	Noise (e)	Signal/Noise
Silicon	300 V	$1\ \mu A$	2.5×10^{7}	9591	2.365
Silicon	300 V	$1\ nA$	2.5×10^{10}	10	2268



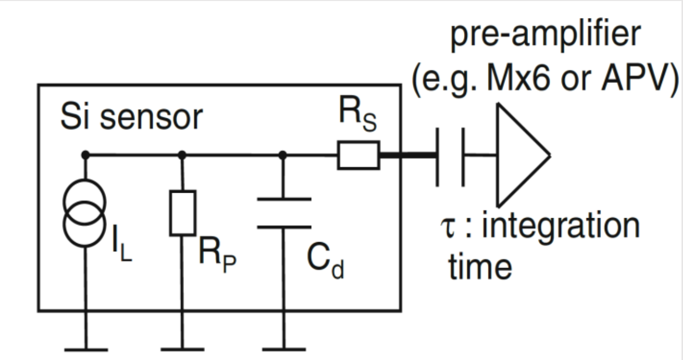








Signal to Noise Ratio: Expressed in terms of **ENC (Equivalent Noise Charge)**



$$ENC(e) = \sqrt{ENC_{I_L}^2 + ENC_C^2 + ENC_{R_p}^2 + ENC_{R_s}^2}$$

1. Shot Noise due to I_L: $ENC_{I_L} \approx 107\sqrt{I_L(nA)t_p(\mu s)}$

2. Parallel thermal noise: $ENC_{R_p} \approx 44.5\sqrt{\dfrac{T(K)t_p(\mu s)}{R_p(M\Omega)}}$

3. Series thermal noise from metal strip resistance: $ENC_{R_s} \approx 0.025\ C_d\ (pF)\sqrt{\dfrac{T(K)R_s(\Omega)}{t_p\ (\mu s)}}$

4. Preamplifier noise: $ENC_C = a + b\ C_d(\mathrm{pF})$, a and b preamplifier design parameters

❖ For making the small noise design follow the below specification:

➢ Small load capacitance C_d=C_{strip}

(~ depends on strip dimension) to minimize ENC_{R_s} and ENC_C

➢ low leakage current I_L to minimize $\mathrm{ENC}_{\mathrm{I_L}}$

➢ high parallel resistance R_{bias} to minimize $\mathrm{ENC}_{\mathrm{R_p}}$

➢ small series resistance R_{strip} to minimize ENC_{R_s}

Ref: Evolution of Silicon sensor technology in Particle Physics: pages: 27-28
Frank Hartmann

❖ ENC Silicon: (DELPHI microvertex)

$t_p = 1.8\,\mu s, I_L = 0.3\,nA, R_p = 36\,M\Omega, R_s = 25\,\Omega,$
$C_d = 9\,pF\,(Strip), a = 340, b = 20, T = 20^0C$

$\boldsymbol{ENC_{I_L} = 78\,e}$
$ENC_{R_P} = 170\,e$
$ENC_{RS} = 14\,e$
$\boldsymbol{ENC_C = 520\,e}$ **(Preamplifier)**

Total $\boldsymbol{ENC = 553\,e}$

- For 300 μm thickness $\Rightarrow \frac{Signal}{ENC} = \frac{22680}{553} = 41$

❖ Binary Readout:

- Limited position resolution $\propto \frac{Pitch}{\sqrt{12}}$ or $\frac{Pitch}{2\sqrt{12}}$

❖ Analogue Readout:

- Nonlinear Eta Algorithm- For small track angles where diffusion is large
- Simple linear Analogue Head Tail algorithm- For large angle tracks
- Charge Centre of gravity method- For middle range of angles

Ref: "Spatial resolution of silicon microstrip detectors", R. Turchetta, Nuclear Instruments and Methods in Physics

❖ ENC Diamond: (Estimation)

$t_p = 5.0\,\text{ns}, I_L = 1\,pA, R_p = 36\,M\Omega, R_s = 25\,\Omega,$
$C_d = 2\,pF, T = 20^0C$

Low Noise Viking Amplifier: $ENC_C = 135 + 13\,C_d$

$\boldsymbol{ENC_{I_L} = 0.24\,e}$
$ENC_{R_P} = 9\,e$
$ENC_{RS} = 61\,e$
$\boldsymbol{ENC_C = 161\,e}$

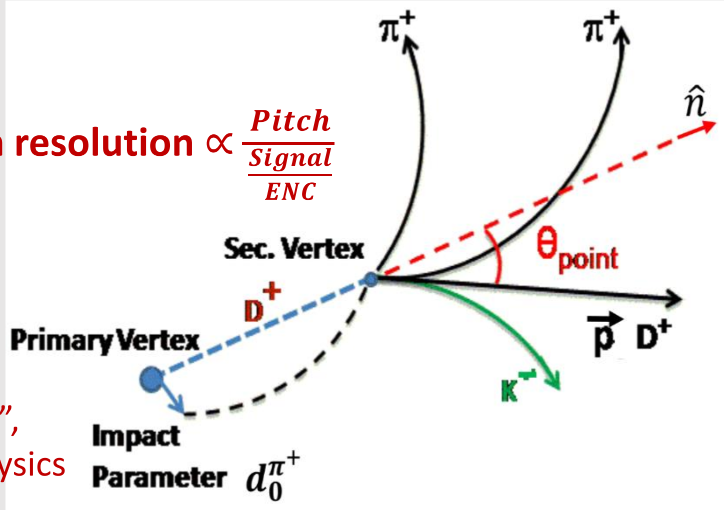
Ref: First measurements with a diamond microstrip detector, NIM, Research A 354 (1995) 318-327

Total $\boldsymbol{ENC = 172\,e}$

For 300 μm thickness $\Rightarrow \frac{Signal}{ENC} = \frac{9645}{172} = 56$

- Impact Parameter IP: for short lives particles, If life time τ is $10^{-13} - 10^{-11}\,sec$ => Impact parameter 30-3000 $\mu m\ (c\tau)$

Best Position resolution $\propto \frac{Pitch}{\frac{Signal}{ENC}}$

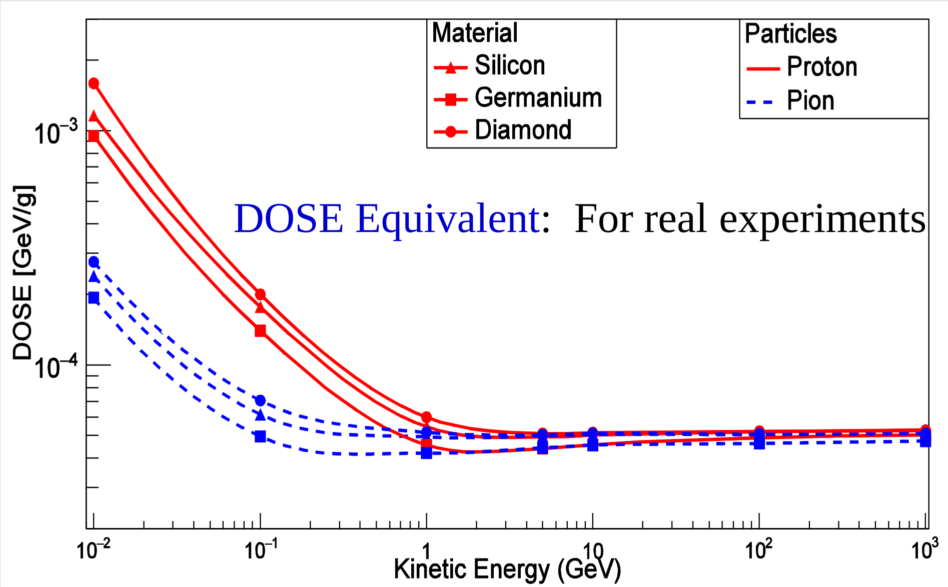


Comparison of Radiation damage

Fluka Simulation

- Surface damage: Ionizing energy loss due to electron stopping=> Not present in diamond sensors as no oxide layer
- Bulk damage: Non-Ionizing energy loss due to Nuclear stopping

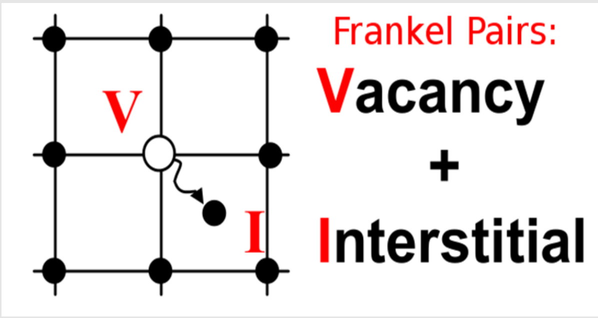
Both types of damage reduces Signal to Noise ratio ≤ 10 is critical value



$$E_{min} = \frac{1}{2}\left[E_{rec} + \sqrt{E_{rec}^2 + 4\, m_p^2 + 2\, E_{rec}\, M_{atom} + \frac{2\, E_{rec}\, m_p^2}{M_{atom}}}\right] - m_p$$

Table 1. E_{min} of incident particles in eV

Particles	Silicon	Germanium	Diamond
Electron	255915	457390	199668
Muon	1560	3212	1176
Pion	1184	2434	896
Kaon	344	695	269
Proton	187	371	153
Neutron	187	370	153



$$S = S_{electronic} + S_{nuclear}$$

$E_{th} = 25\ eV$ (Si)

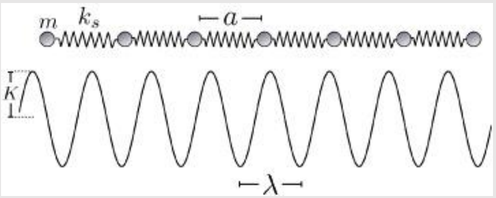
$E_{th} = 20\ eV$ (Ge)

$E_{th} = 43.6\ eV$ (Di)

Diamond has low radition damage than others

$$D(E) = \sum_k \sigma_k(E) \int dE_R\, f_k(E, E_R)\, P(E_R)$$

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



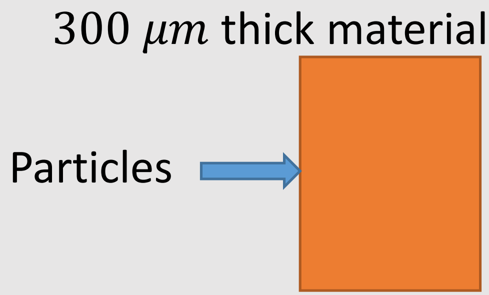
$$k_s \sim m_{atom} \omega_D^2$$

$$\hbar\omega = k\theta_D$$

$$\theta_D(Carbon) = 2230\ K \Rightarrow k_s \sim 1614\ N/m$$

$$\theta_D(Si) = 645\ K \Rightarrow k_s \sim 315\ N/m$$

$$\theta_D(Ge) = 374\ K \Rightarrow k_s \sim 275\ N/m$$

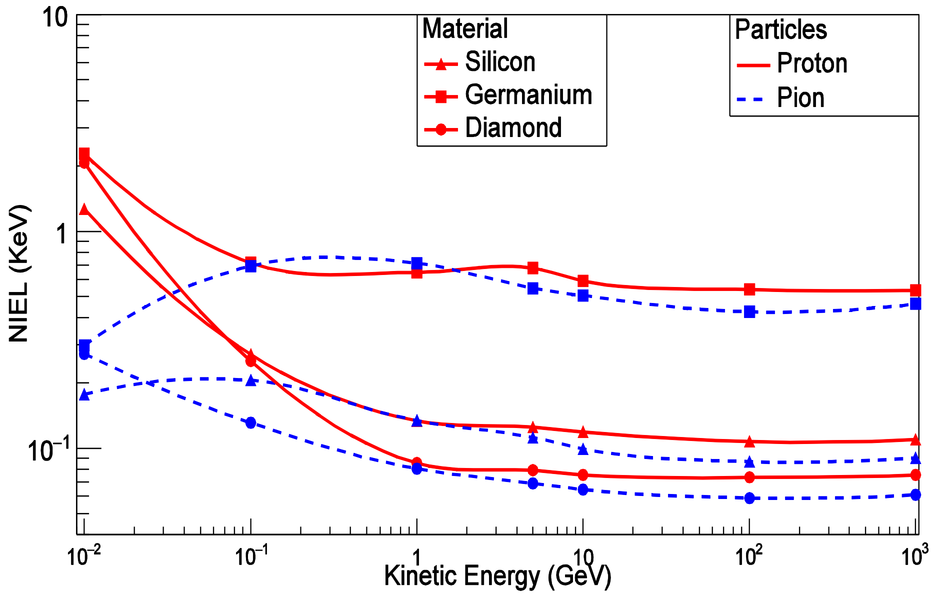


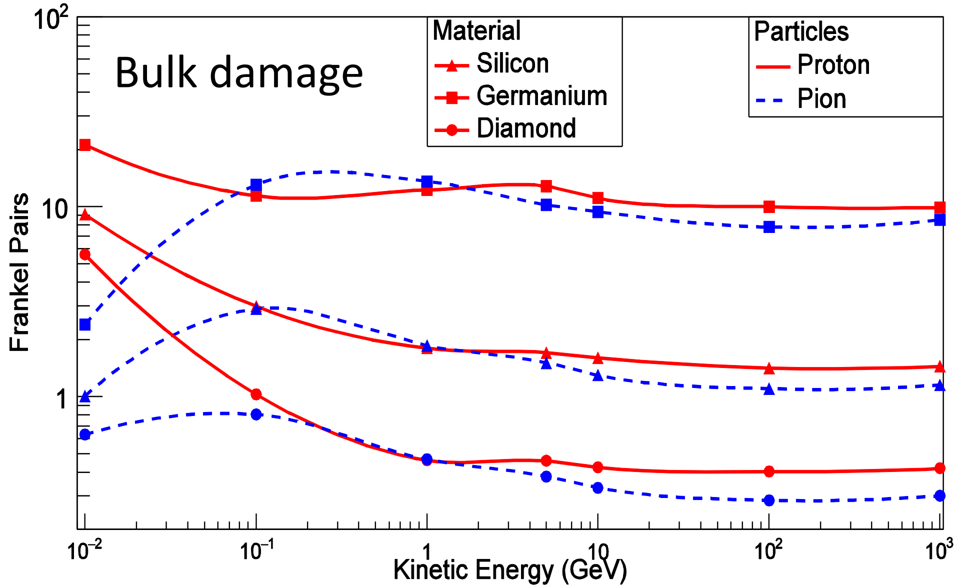
Thanks to Michael Moll (RD50), CERN and Moritz Guthoff, CMS (CERN)

SEU: Single Event Upset (Random in time) may cause loss of data but temporary most of the time

In diamond, there will be no surface damage , bulk damage will be smallest and also less number of Single Event Upset (simple concept of detector as compared to Si, CMOS, LGAD)

Si1MeVNeutronEquivalent: For real experiments





Particle Identification capabilities

➢ Particle Identification: Determination of mass and charge of the Particle

Diamond can be used as dEdX detector

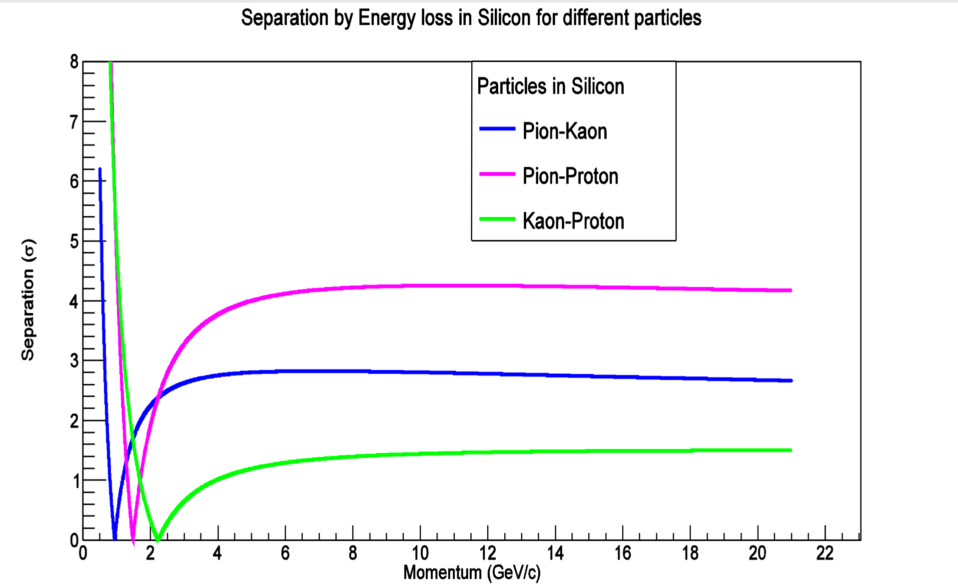
1. dEdX vs Momentum method => Band merging due to Landau distribution and MIP

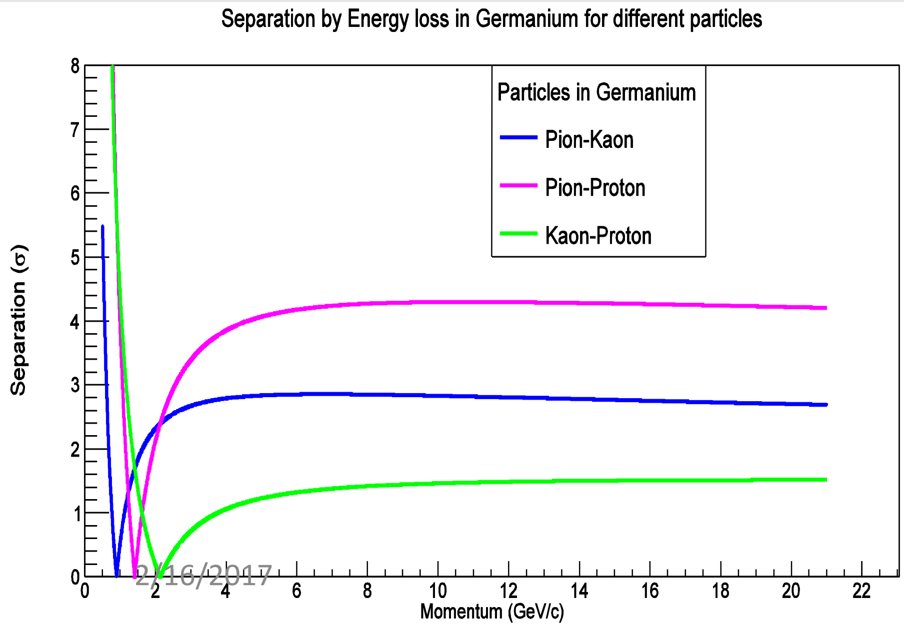
2. Time of Flight=> Measurement of time of flight and β vs momentum plot, band merging due to time resolution of detectors

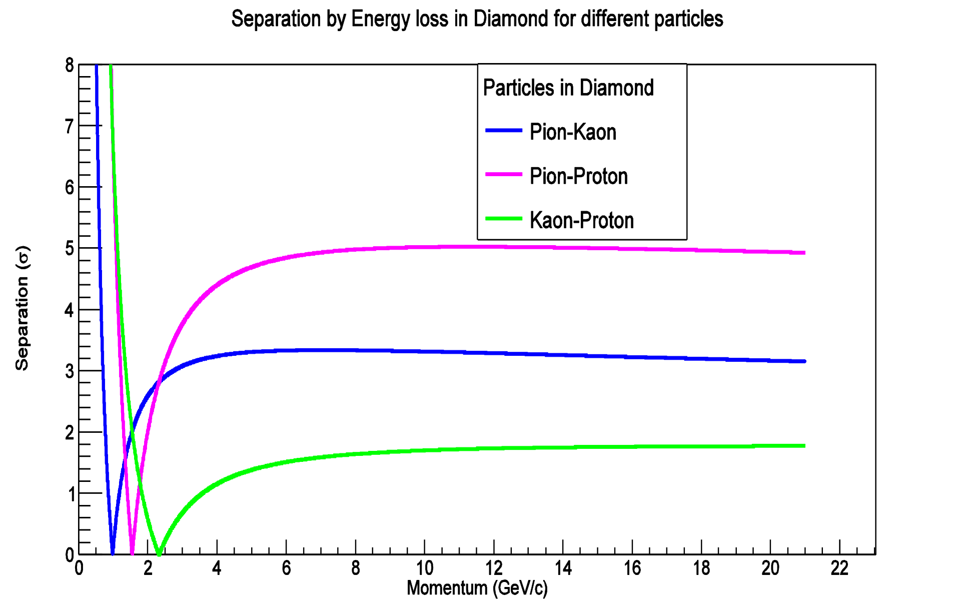
dEdX considered up order of β^2

$$Separation\ (Sigma) = \frac{\left(\frac{dE}{dx}\right)_A - \left(\frac{dE}{dx}\right)_B}{\sigma\left(\frac{dE}{dX}\right)}$$

$$Separation\ (Sigma) = \frac{Tof_A - Tof_B}{\sigma_t}$$







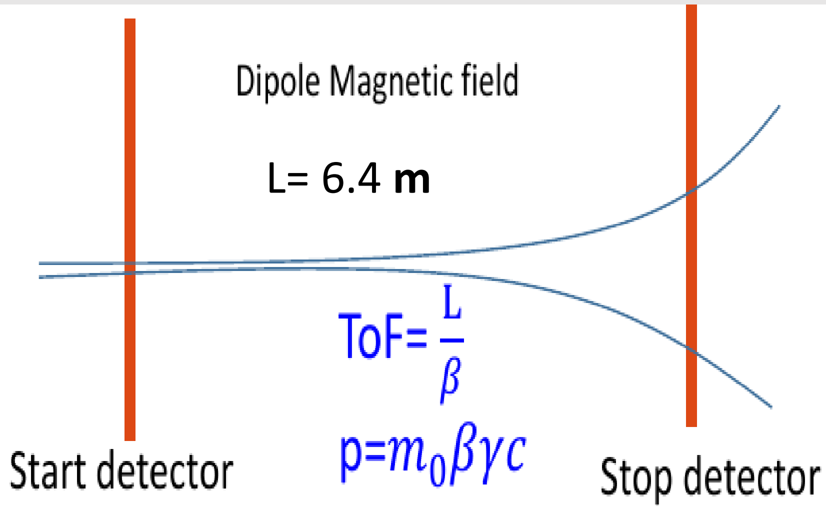
Diamond can also be used as ToF detector

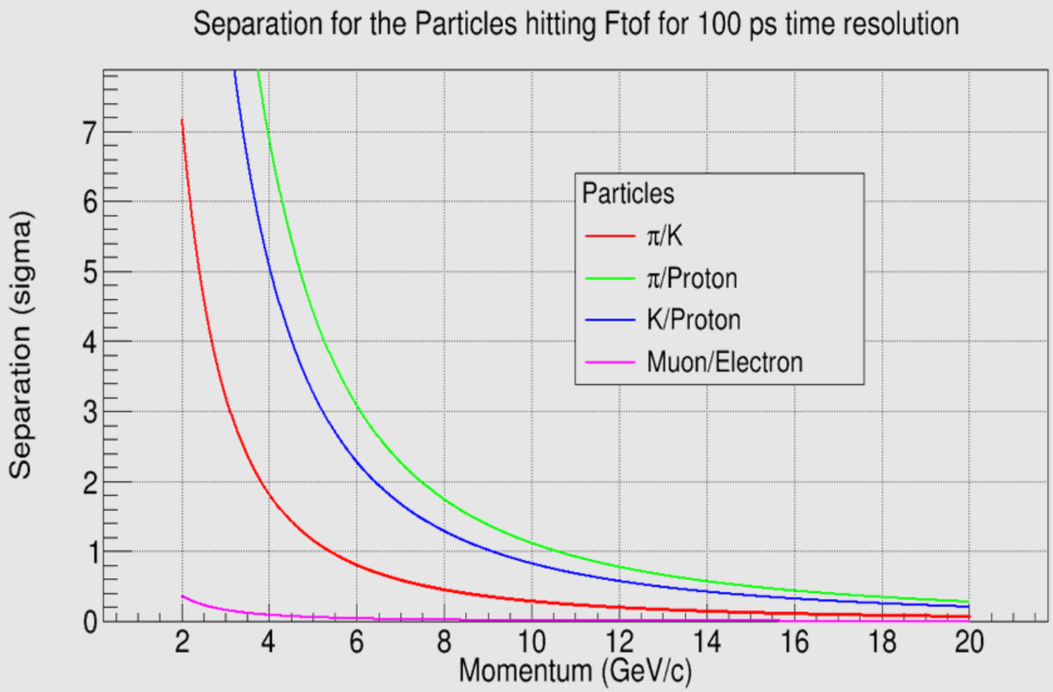
$$t = t_2 - t_1$$

$$\sigma_t = \sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2}$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

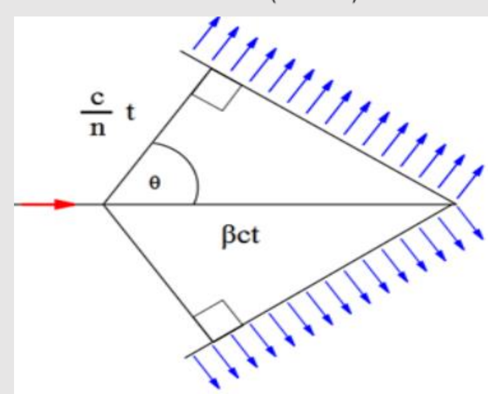
$$\sigma_t \leq 100\ ps\ (diamond)$$





3. Cherenkov PID:

$$Cos\theta_p = \frac{1}{\beta n}$$



Refractive Index n= 2.417 ??????

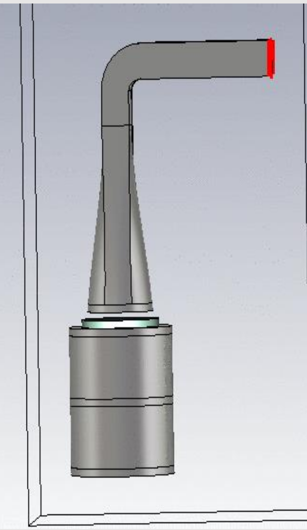
Computer Simulation Technology

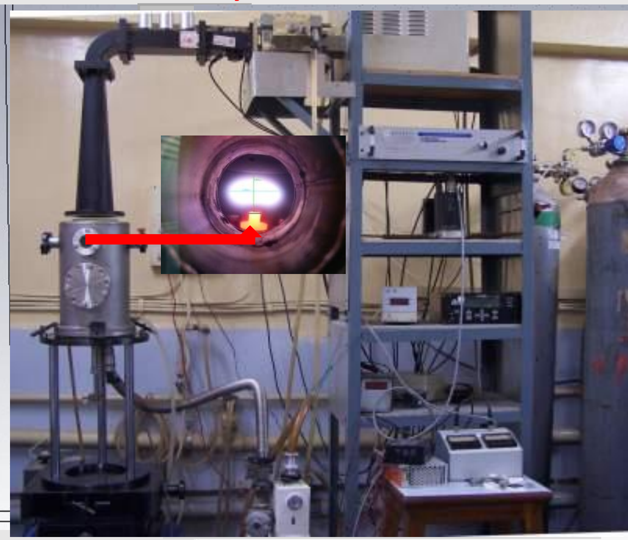
Used also in accelerator designing

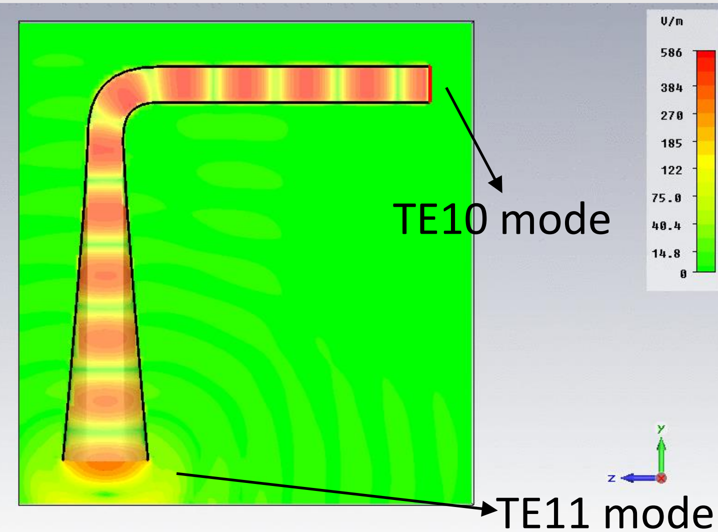
MPCVD System designing

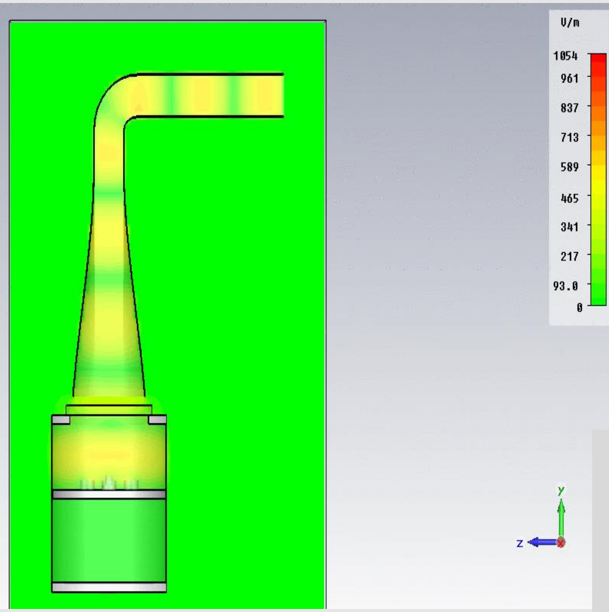
MPCVD : Microwave Plasma Chemical Vapour Deposition System & Resonant Cavity

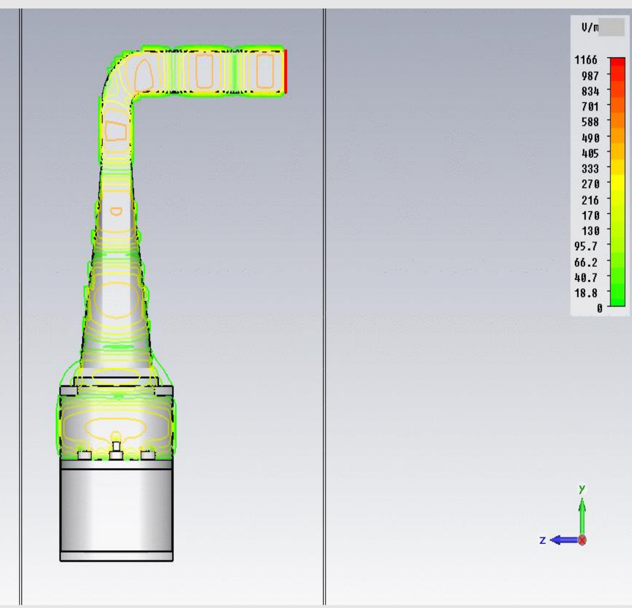
Real System in Lab





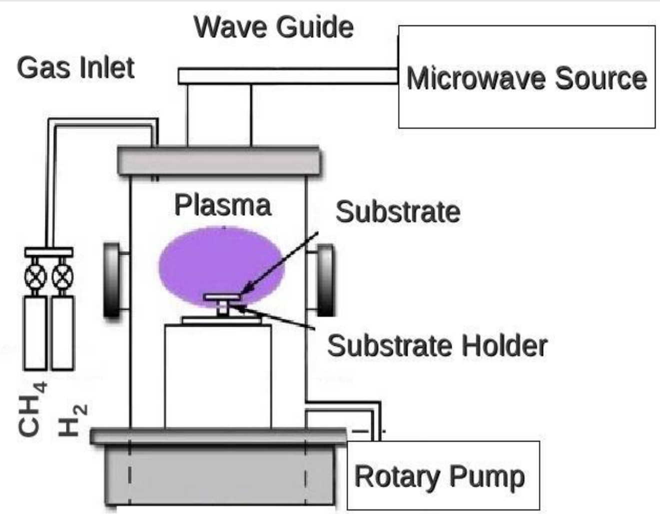






Growth of diamond film and Characterization

Thanks to Aman Bajaj, Sushant Raniwala, Krishna Chaitanya and Nilormi (summer student)

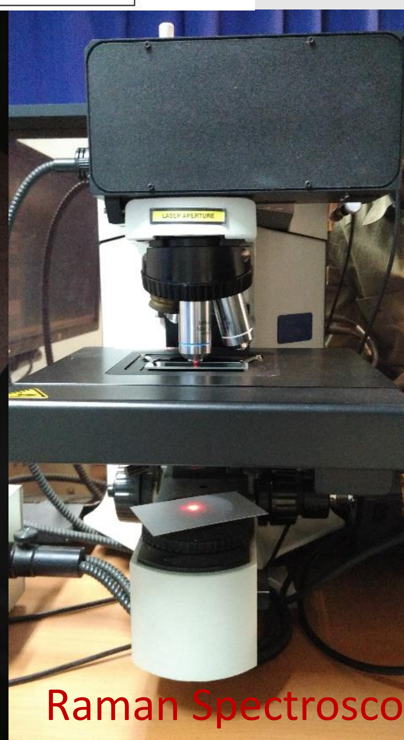


- Growth Parameters of Diamond film:
  - HPHT diamond (100) substrate
  - Hydrogen=250 sccm and Methane=2.0 sccm
  - Pressure 90-91 torr (atmospheric pressure=760 torr)
  - Temperature =916-938 ℃
  - Power Input = 0.7 kW
  - Power reflected = 0 kW
  - Deposition time=198.5 hrs
  - Thickness of film ≈ 1 mm (grown)

1 mm thick diamond

Diamond looking yellow due to Nitrogen content

Diamond Picture



Raman Spectroscopy

Range of G Band ~ 1500-1600 cm^{-1}

Range of D Band ~ 1300-1400 cm^{-1}

2D Band ~ 2650-2700 cm^{-1}

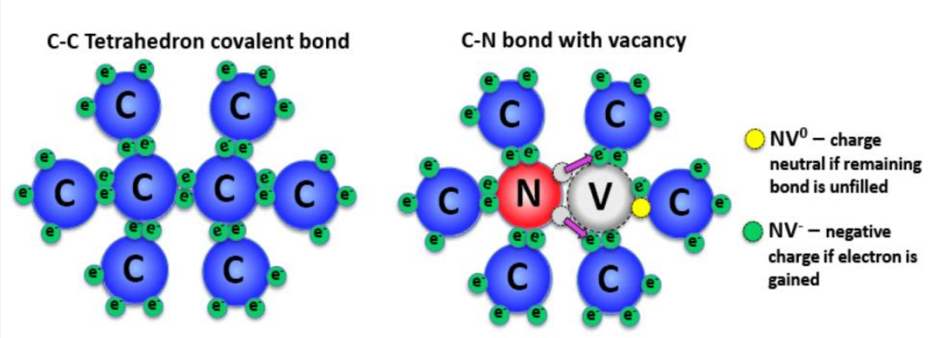
Electronic grade diamond has N in Parts per billion level (ppb)

Characterization techniques

- ➢C-DLTS: Capacitance Deep Level Transient Spectroscopy
- ➢XPS (X-ray photoelectron spectroscopy): For elemental composition
- ➢I-DLTS: Current Deep Level Transient Spectroscopy

Ref. Diamond nitrogen vacancy impurity ppt, April 2013, physics 6530, Stefan Thonnard

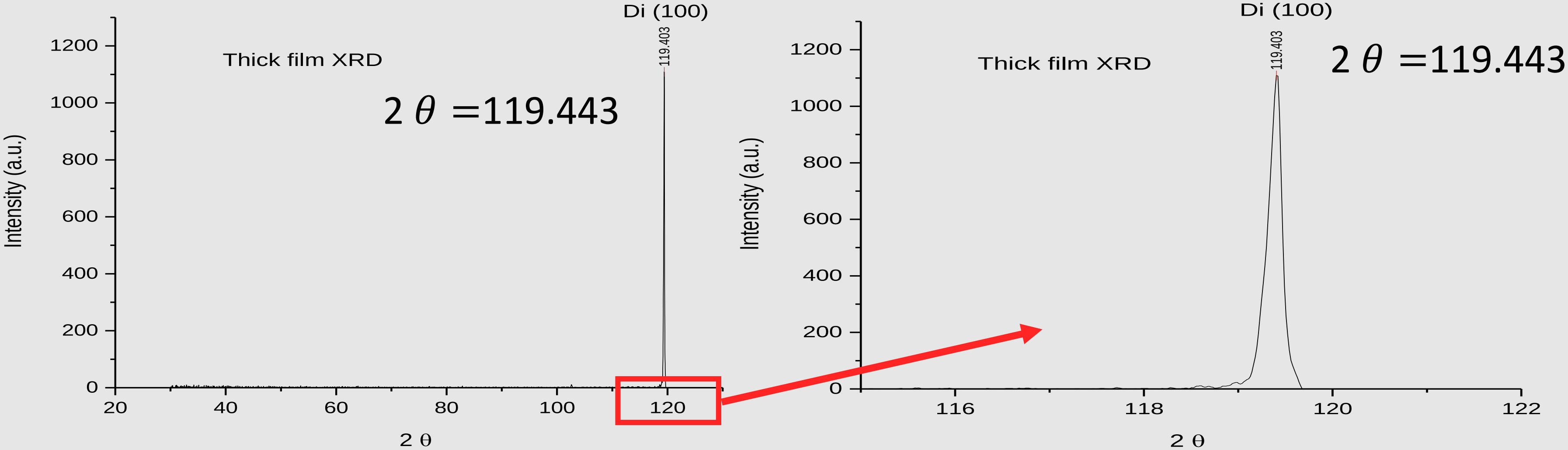
- ➢TSC: Thermally Stimulated Currents
- ➢RL: Recombination Life-time Measurements
- ➢PC: Photo Conductivity Measurements
- ➢PL –Photoluminescence



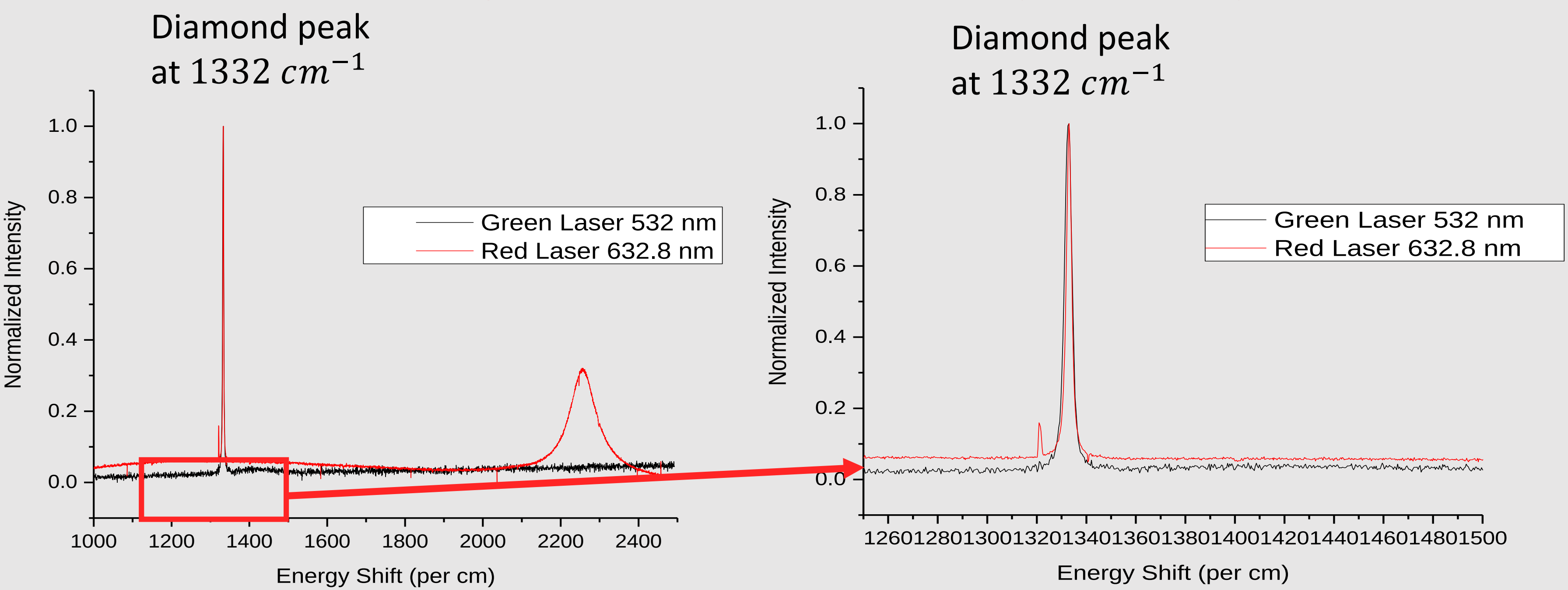
N-V Center reduces CCE

- ➢Raman Spectroscopy
- ➢IV-CV Characteristics: For leakage current and capacitive noise determination
- ➢Atomic Force Microscopy (AFM)
- ➢Transient current technique (TCT): For electron and hole mobility determination
- ➢HRXRD: High Resolution X-ray Diffraction

Diamond film shows the good XRD and Raman spectrum



High Resolution XRD @ Department of Physics IIT Bombay



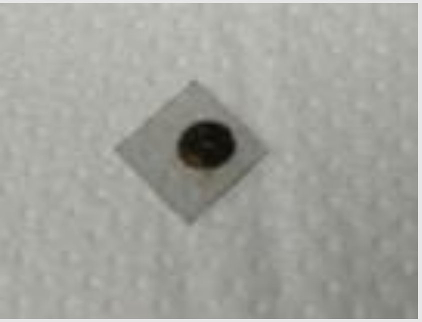
Raman Spectroscopy @ CRNTS, IIT Bombay

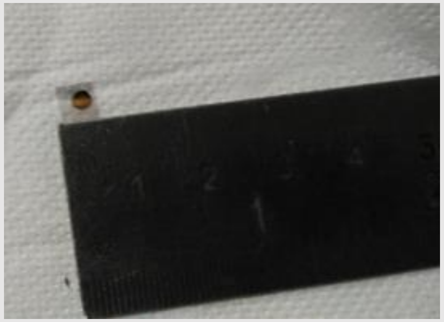
I-V looking promising

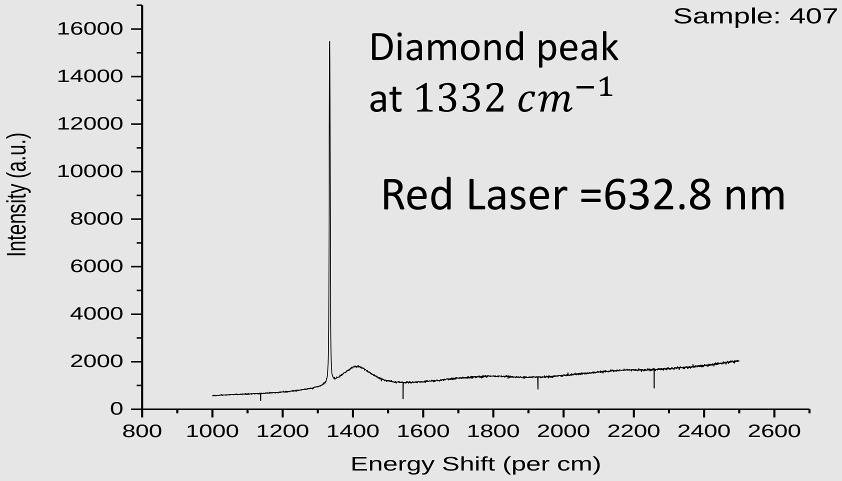
- Ohmic Contact: Thermal Evaporation (Both side)
- Cr/Au: 20 nm/100 nm
- Slow Annealing of the sample up to 605 K

Contact made @ CEN, IIT Bombay

Sample 407 : $5.0 \times 5.0 \times 0.4\ mm^3$

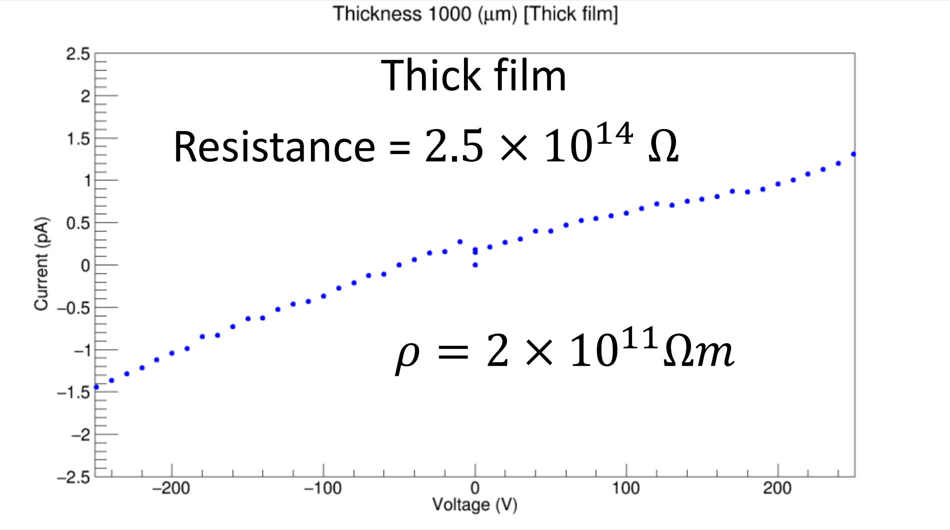






Diamond peak at 1332 cm^{-1}

Red Laser =632.8 nm



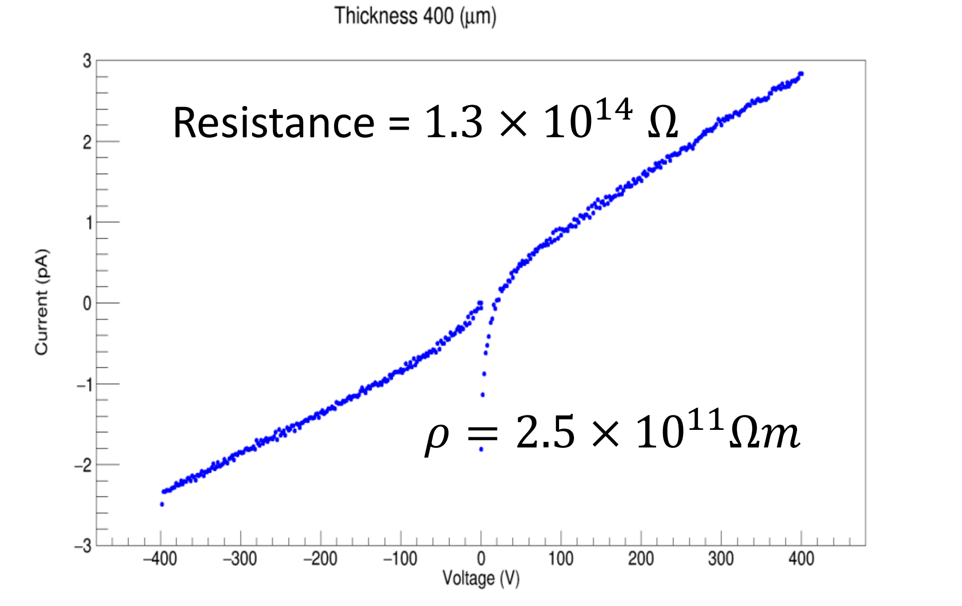
Thick film

Resistance = $2.5 \times 10^{14}\ \Omega$

$\rho = 2 \times 10^{11} \Omega m$

I-V done at BARC, Thanks to Amit and Dr. Anita Topkar (Electronics division BARC)

Sample 407

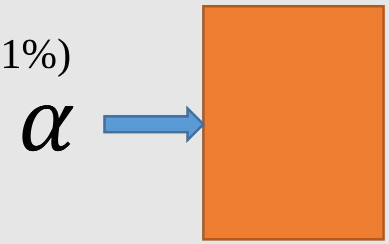


Resistance = $1.3 \times 10^{14}\ \Omega$

$\rho = 2.5 \times 10^{11} \Omega m$

Transient Current Technique (TCT) measurement for diamond

300 μm thick material



Am^{241}- α source of energy, 5486 KeV (85%), 5443 KeV (13%) and 5388 KeV (1%)

❖ **Silicon**

- IEL $\approx$ 5485.9 KeV
- NIEL $\approx$ KeV
- Signal=5485900/3.6

= 1523861 e-h pairs

❖ **Germanium**

- IEL $\approx$ 5485.8 KeV
- NIEL $\approx$ KeV
- Signal=5485800/2.96

= 18,53311 e-h pairs

❖ **Diamond**

- IEL $\approx$ 5485.9 KeV
- NIEL $\approx$ KeV
- Signal=5485900/13.6

=403375 e-h pairs

$$\boldsymbol{\epsilon = 2.73\, E_g + 0.55\, eV}$$

Ref: Electron-Hole-Pair Creation Energies in Semiconductors , PRL, Volume 35, Number 32

Range of α in Material: Fluka simulation (Ionizing Energy Loss (IEL))

Curve highly useful in cancer treatment (Medical Applications)

- Experimental measurement:
- $3.5\times 3.5 \times 0.4\ mm^3$ diamond (IIA technologies)
- α will stop with in 15 μm of diamond

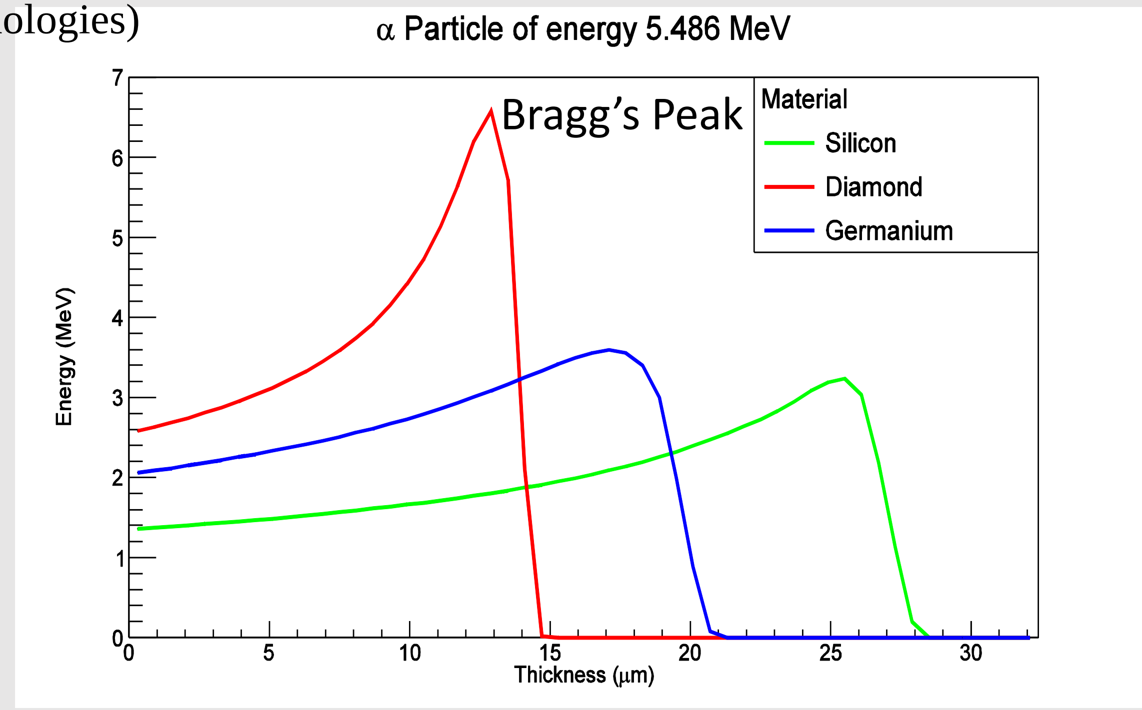
Gain of cividec amplifier= +40 dB =>

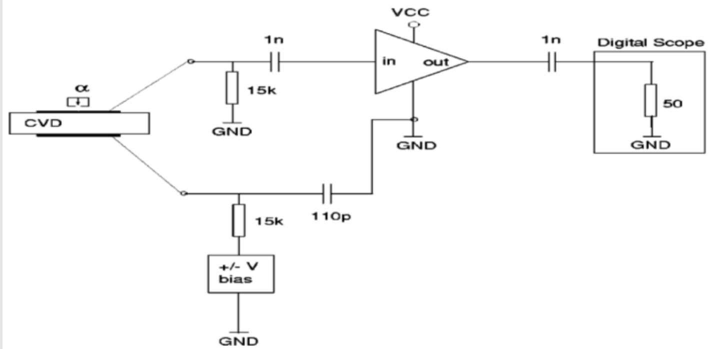
$$\frac{v_{out}}{v_{in}} = 100$$

$$v_{out} = 100\ v_{in} = 100\ \times 50\ \Omega \times I_{in}$$

$$I_{in}(mA) = \frac{v_{out}\ (mV)}{5000}$$

$$Q_{collected} = \int I_{in}\ dt$$

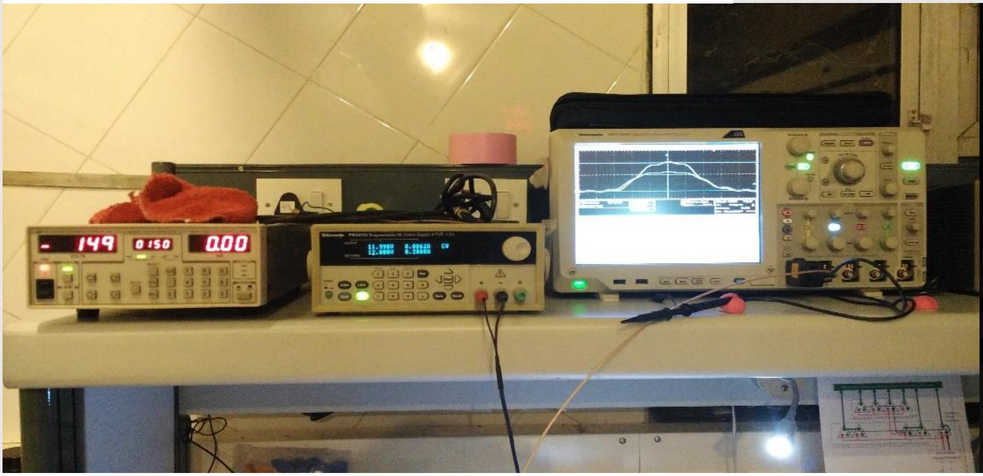


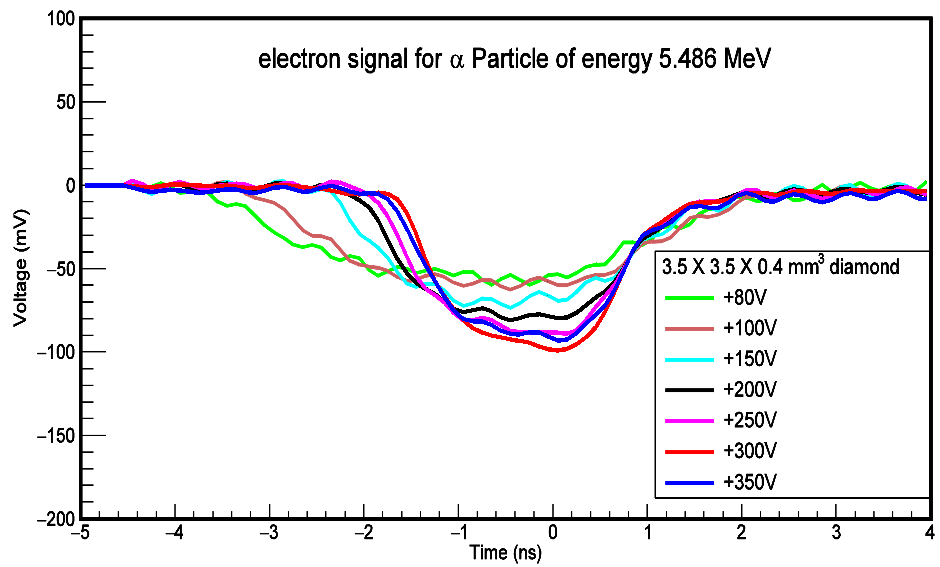


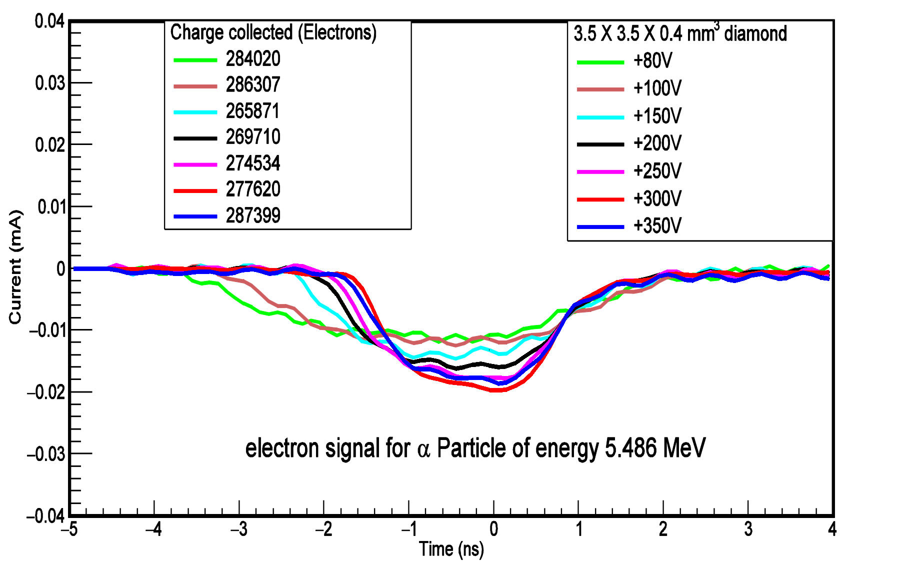
Timing of diamond pulse of the order of ns

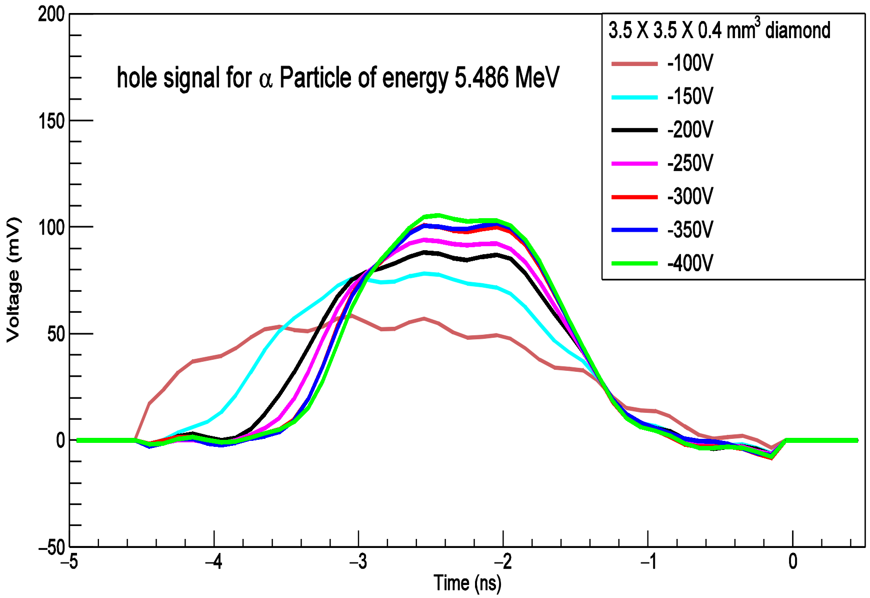
$$CCE = \frac{Q_{collected}}{Q_{created}} \times 100 = \frac{Q_{collected}}{403375} \times 100$$

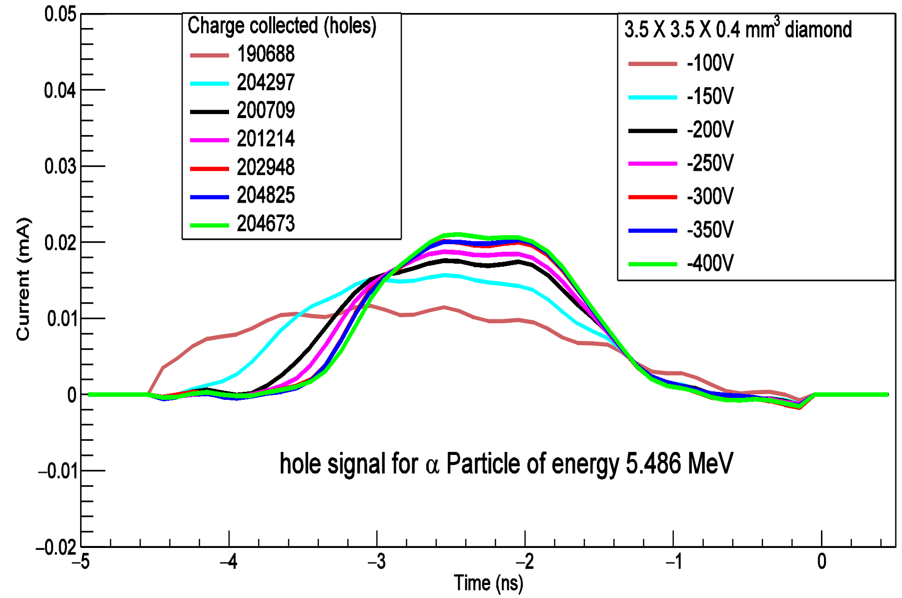
Cividec Amplifier CERN, used for testing

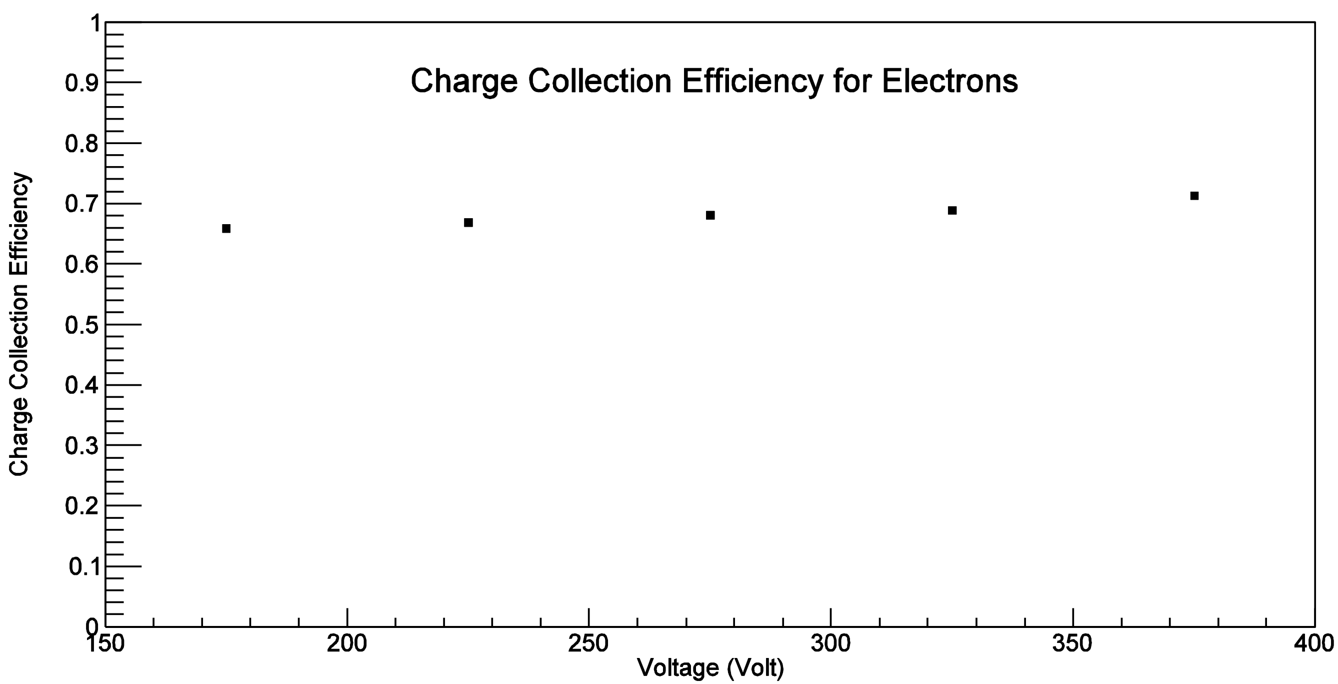







hole signal for α Particle of energy 5.486 MeV
3.5 X 3.5 X 0.4 mm^3 diamond
-100V
-150V
-200V
-250V
-300V
-350V
-400V
Voltage (mV)
Time (ns)


Charge collected (holes)
190688
204297
200709
201214
202948
204825
204673
3.5 X 3.5 X 0.4 mm^3 diamond
-100V
-150V
-200V
-250V
-300V
-350V
-400V
hole signal for α Particle of energy 5.486 MeV
Current (mA)
Time (ns)


Charge Collection Efficiency for Electrons
Charge Collection Efficiency
Voltage (Volt)

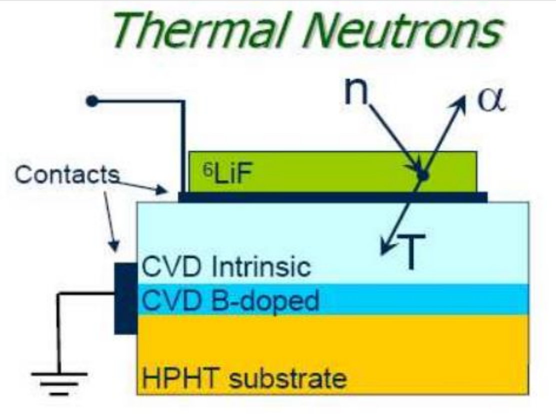
Summary and Future Plan

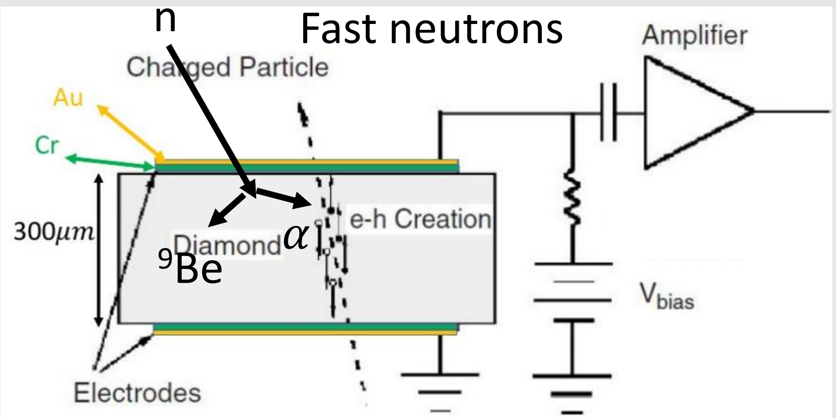
- Diamond has good signal to noise ratio, fast timing, low material budget, low radiation damage and good particle identification capabilities, so it will be a good choice for HEP experiments
- Diamond has large e-h pair creation energy so less disturbance in charge center of gravity
- Diamond can also be used for the detection of slow and fast neutrons
- We have grown diamond film up to 1 mm thickness it has nitrogen, I will do cutting and polishing and will test again
- We have also tested good quality diamond from IIA technologies
- The only problem with diamond we don't have large area high quality diamond
- Still working on growing high quality diamond in Lab

FLUKA Simulation used Ref : "FLUKA: a multi-particle transport code"
A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft,
CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

Thank You !!!

Diamond as Neutron detectors





n interacts with ^6Li in 6LiF layer (95%)

n directly interact with carbon ^{12}C

$$n +^6 Li \rightarrow Tritium + \alpha + 4.8\ MeV$$

$$n +^{12} C \rightarrow \alpha +^9 Be - 5.7MeV$$

Tritium (2.73 MeV) and α $(2.06\ MeV)$ emitted at 180^0C, only α or Tritium is detected

14.1 MeV n, with α and ^9Be having a total energy of 8.4 MeV

Ref: CVD Diamond Neutron Detectors, Arnaldo Galbiati

Diamond Pulse time Estimation $(d = 400\ \mu m\ thick)$ at E field = $1V/\mu m$:

$$t_e = \frac{d}{v} = \frac{d^2}{\mu_e \mathrm{V}} = \frac{16 \times 10^{-8}}{0.18 \times 400} = 2.2\mathrm{ns}$$

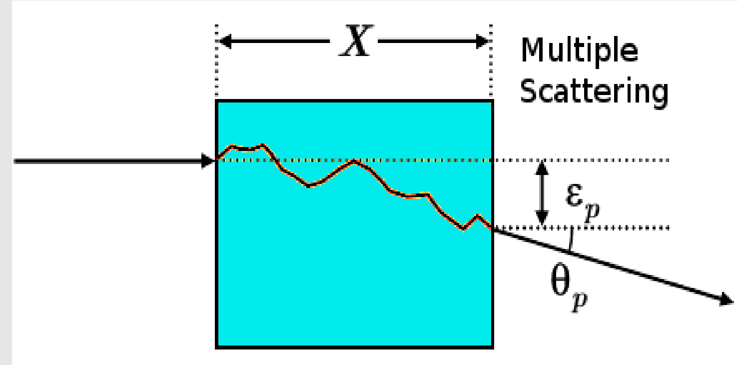
$$t_h = \frac{d}{v} = \frac{d^2}{\mu_e \mathrm{V}} = \frac{16 \times 10^{-8}}{0.16 \times 400} = 2.5\ \mathrm{ns}$$

Experimental $t_e \approx 3.2\ ns\ and\ t_h \approx 3.2\ ns$

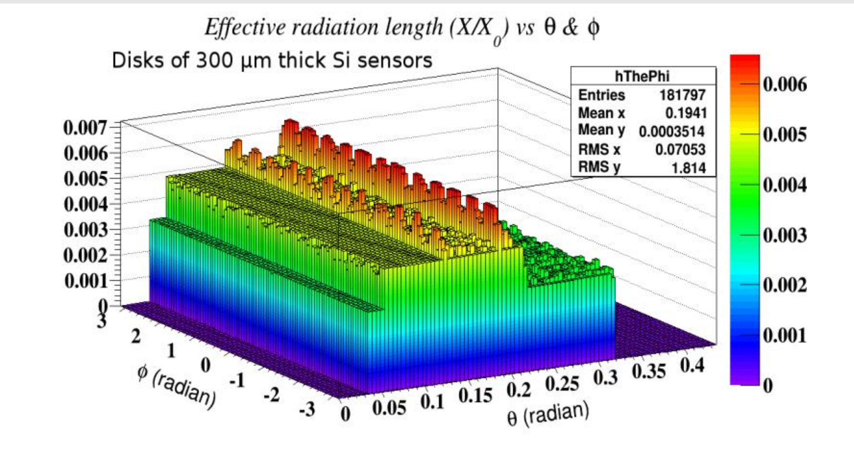
Comparison of Material budget [For geometry in Slide 4]

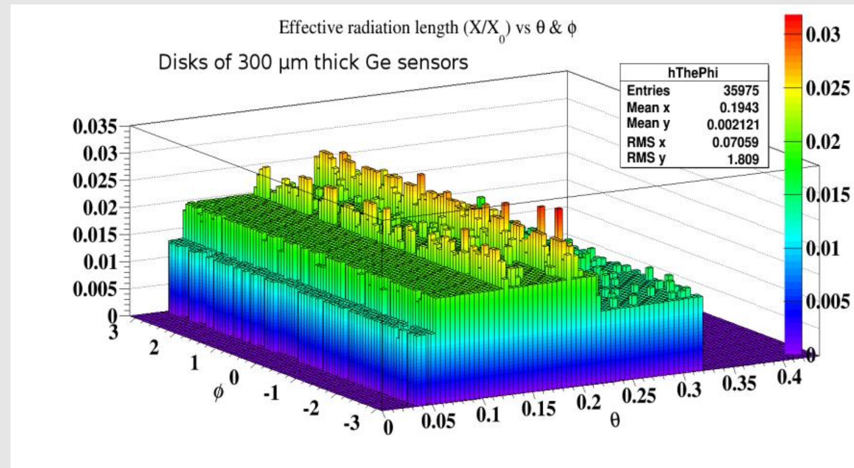
$$X_0 = 716.4 \frac{A\,[\frac{g}{mol}]}{Z(Z+1)\ln\left(\frac{287}{\sqrt{Z}}\right)}\ g/cm^2$$

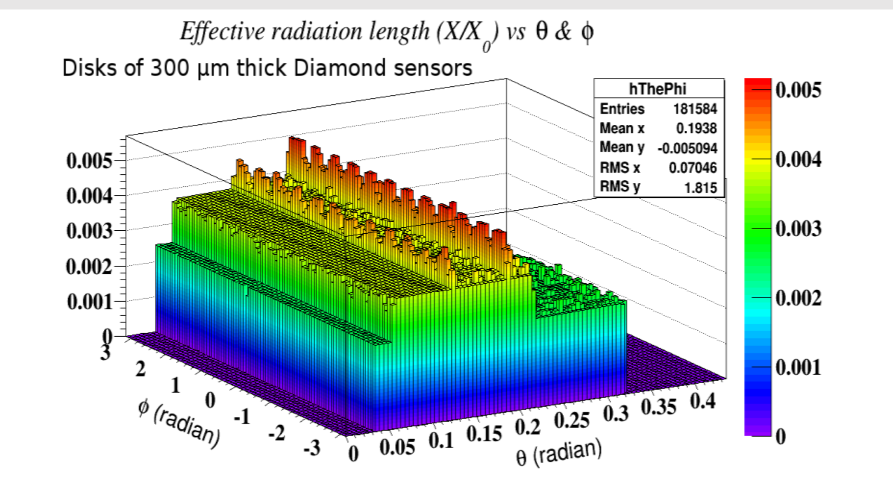
$$\frac{X}{X_0} = \frac{X_1}{X_{01}} + \frac{X_2}{X_{02}} \ldots \frac{X_n}{X_{0n}}$$

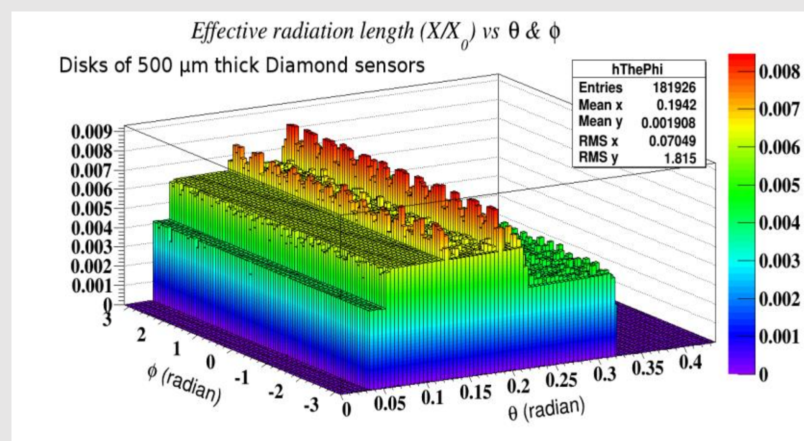


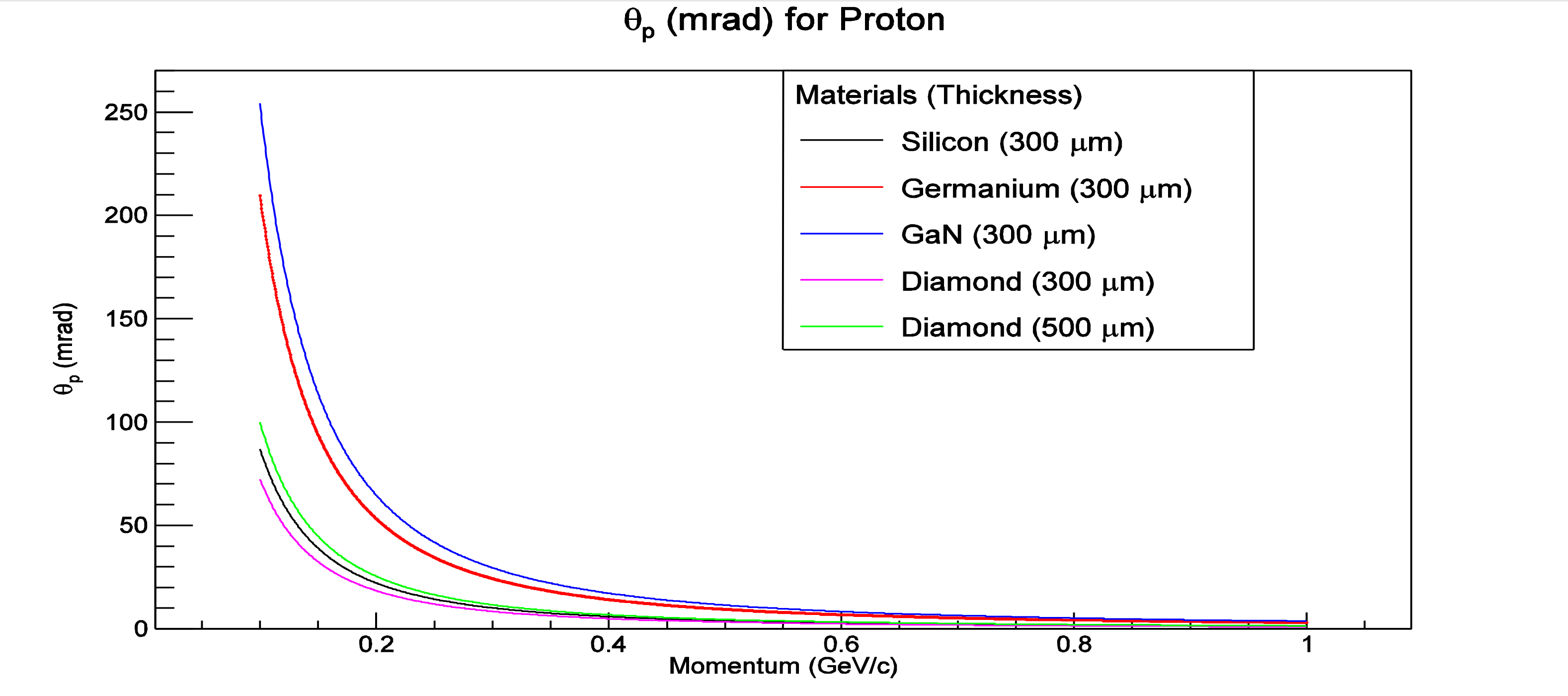
1000000 Geantino particle with multiplicity 5 of 0.1- 0.5 GeV/c



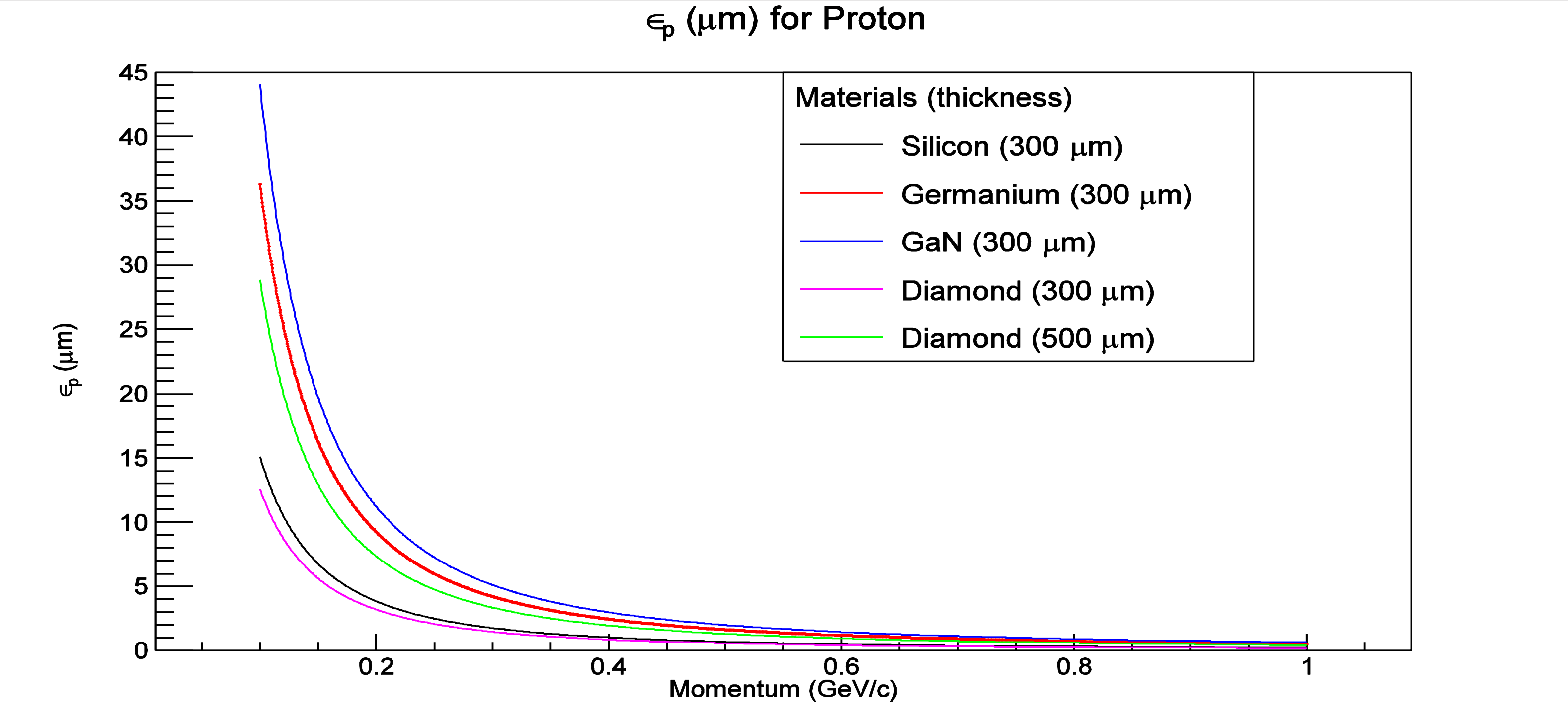






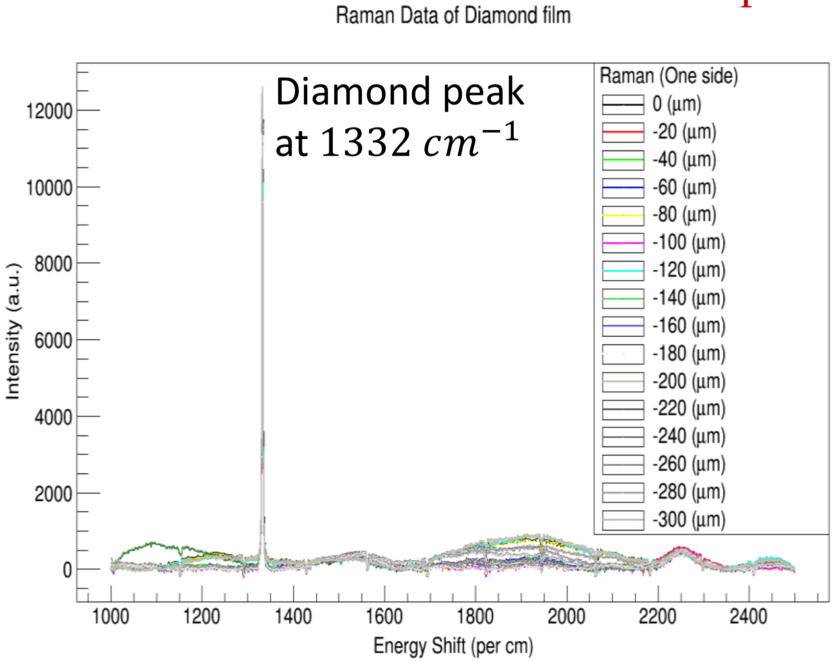


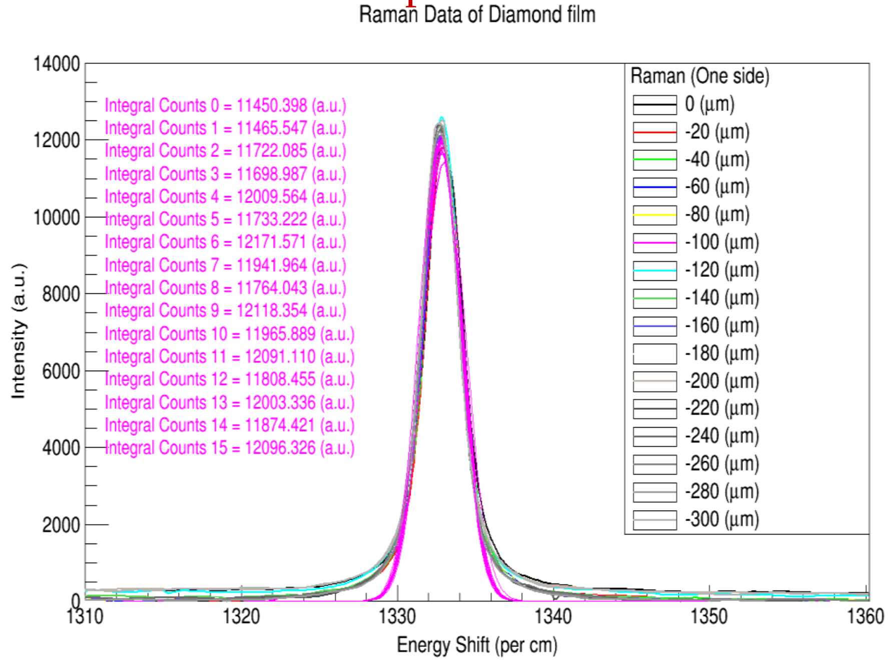
θ_p (mrad) for Proton
Materials (Thickness)
Silicon (300 μm)
Germanium (300 μm)
GaN (300 μm)
Diamond (300 μm)
Diamond (500 μm)
θ_p (mrad)
Momentum (GeV/c)
0
50
100
150
200
250
0.2
0.4
0.6
0.8
1

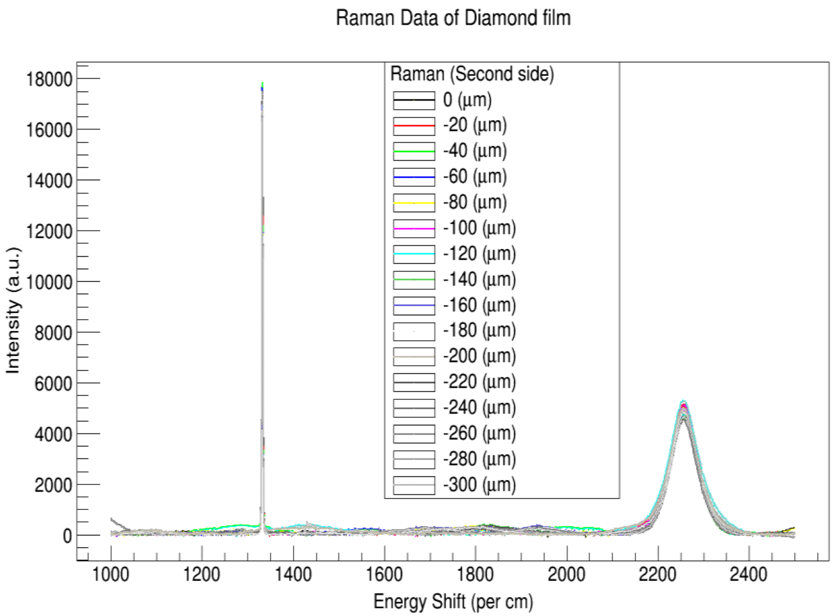


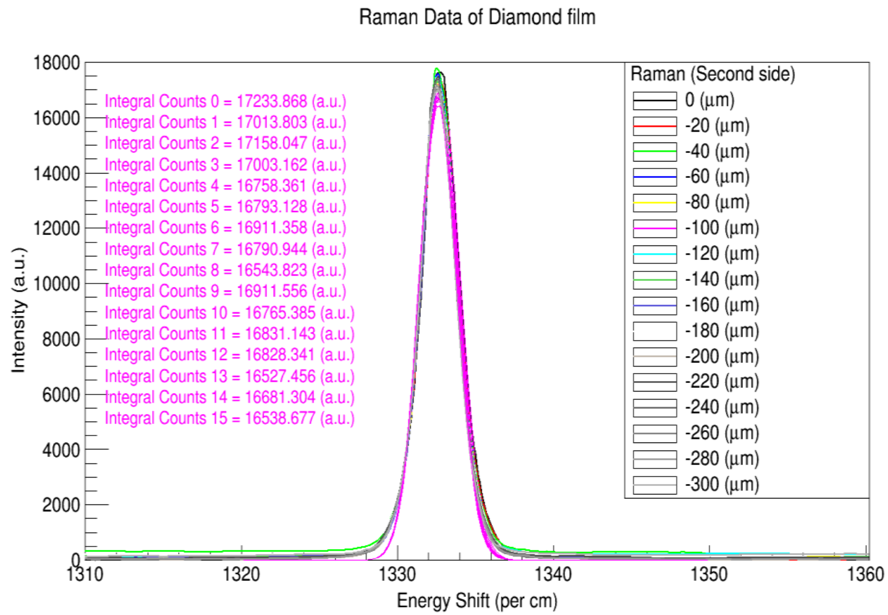
ϵ_p (μm) for Proton
Materials (thickness)
Silicon (300 μm)
Germanium (300 μm)
GaN (300 μm)
Diamond (300 μm)
Diamond (500 μm)
ϵ_p (μm)
Momentum (GeV/c)
0
5
10
15
20
25
30
35
40
45
0.2
0.4
0.6
0.8
1

Raman Spectra taken as a function of depth



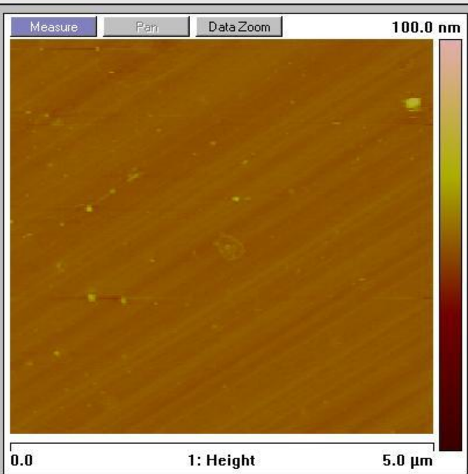






Atomic force Microscopy (AFM) [Polishing of 407 is compared to thick film]

407 film



Execute

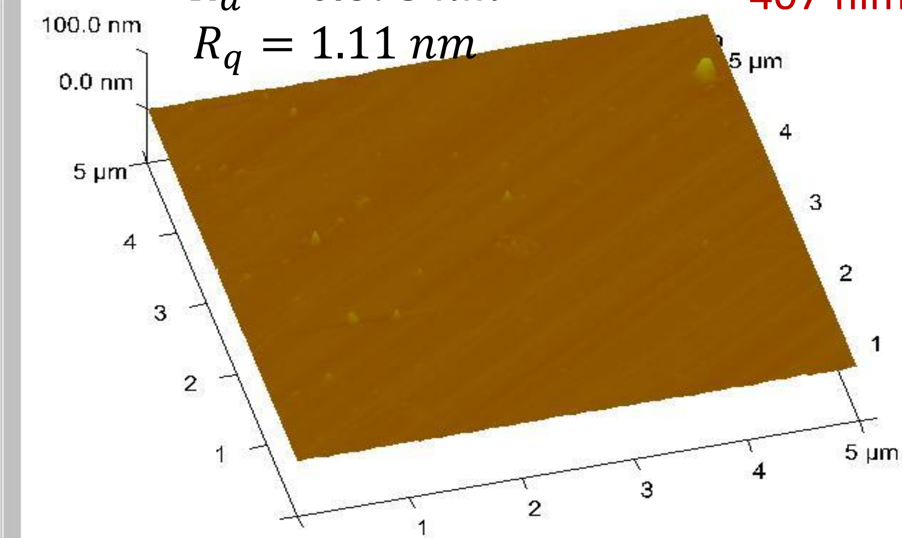
Inputs	
Peak	Off
Zero Crossing	Off

Name	Value	Report	Limits
Results			
Image Raw mean	376 nm	Yes	No
Image Mean	-0.00303 nm	Yes	No
Image Z Range	33.6 nm	Yes	No
Image Surface area	25.0 µm²	Yes	No
Image Projected surface area	25.0 µm²	Yes	No
Image Surface area difference	0.121 %	Yes	No
Image Rq	1.11 nm	Yes	No
Image Ra	0.675 nm	Yes	No
Image Rmax	33.5 nm	Yes	No
Raw mean	0.00 nm	Yes	No
Mean	0.00 nm	Yes	No
Z Range	0.00 nm	Yes	No
Surface area	0.00 µm²	Yes	No
Projected surface area	0.00 µm²	Yes	No
Surface area difference	0.00 %	Yes	No
Rq	0.00 nm	Yes	No
Ra	0.00 nm	Yes	No
Rmax	0.00 nm	Yes	No
Skewness	0.00 nm	Yes	No
Kurtosis	0.00 nm	Yes	No
Rz	0.00 nm	Yes	No
Rz Count	0.00	Yes	No
Max peak ht (Rp)	0.00 nm	Yes	No
Av max ht (Rpm)	0.00 nm	Yes	No
Max depth (Rv)	0.00 nm	Yes	No
Av max depth (Rvm)	0.00 nm	Yes	No
Line density	0.00 /µm	Yes	No
Box x dimension	0.00 µm	Yes	No
Box y dimension	0.00 µm	Yes	No

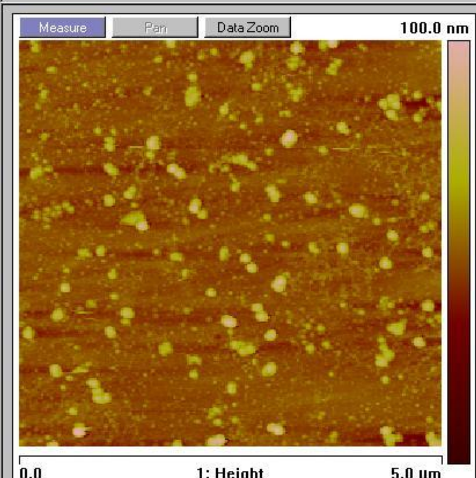
$R_a = 0.675\ nm$

$R_q = 1.11\ nm$

407 film



Thick film



Execute

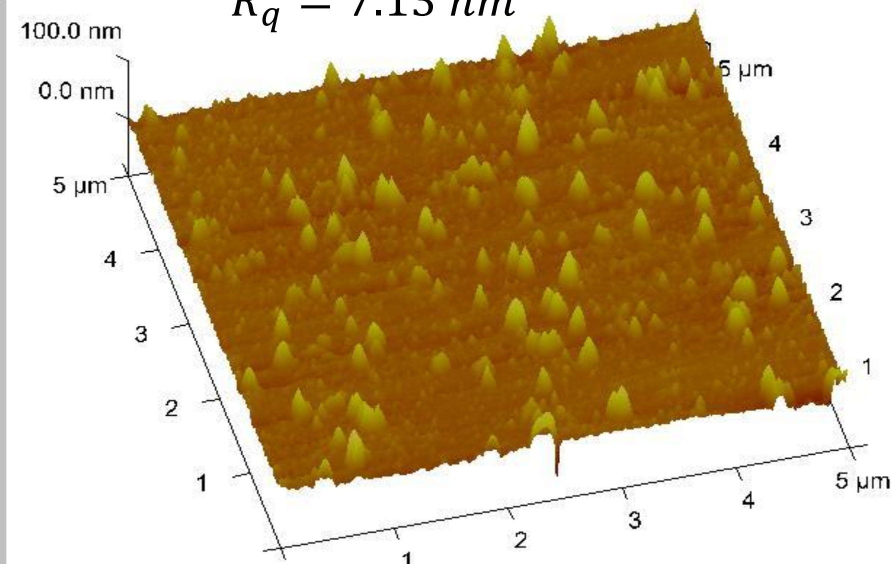
Inputs	
Peak	Off
Zero Crossing	Off

Name	Value	Report	Limits
Results			
Image Raw mean	165 nm	Yes	No
Image Mean	0.000005 nm	Yes	No
Image Z Range	147 nm	Yes	No
Image Surface area	25.9 µm²	Yes	No
Image Projected surface area	25.0 µm²	Yes	No
Image Surface area difference	3.62 %	Yes	No
Image Rq	7.13 nm	Yes	No
Image Ra	4.47 nm	Yes	No
Image Rmax	147 nm	Yes	No
Raw mean	0.00 nm	Yes	No
Mean	0.00 nm	Yes	No
Z Range	0.00 nm	Yes	No
Surface area	0.00 µm²	Yes	No
Projected surface area	0.00 µm²	Yes	No
Surface area difference	0.00 %	Yes	No
Rq	0.00 nm	Yes	No
Ra	0.00 nm	Yes	No
Rmax	0.00 nm	Yes	No
Skewness	0.00 nm	Yes	No
Kurtosis	0.00 nm	Yes	No
Rz	0.00 nm	Yes	No
Rz Count	0.00	Yes	No
Max peak ht (Rp)	0.00 nm	Yes	No
Av max ht (Rpm)	0.00 nm	Yes	No
Max depth (Rv)	0.00 nm	Yes	No
Av max depth (Rvm)	0.00 nm	Yes	No
Line density	0.00 /µm	Yes	No
Box x dimension	0.00 µm	Yes	No
Box y dimension	0.00 µm	Yes	No

$R_a = 4.47\ nm$

$R_q = 7.13\ nm$

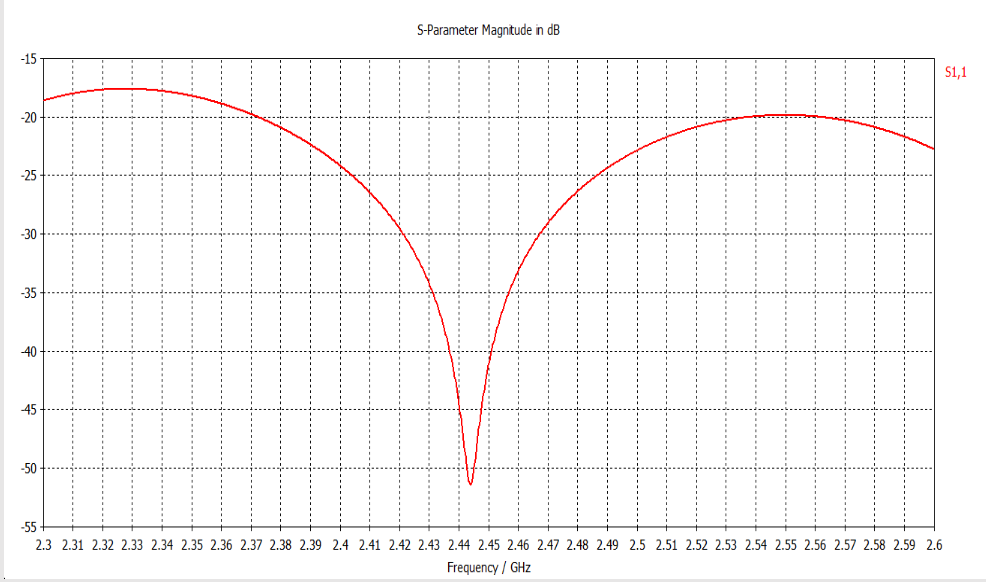
Thick film



AFM @ Department of Physics IIT Bombay

TE10 to TE11 mode converter simulation

Single Port S_{11} – reflection coefficient,
For two Ports S_{11}, S_{12}, S_{21} *and* S_{22}



Frequency= 2.45 ± 0.020 GHz

Decibel-milliwatts (dBm)= Decibel watt (dBW) +30

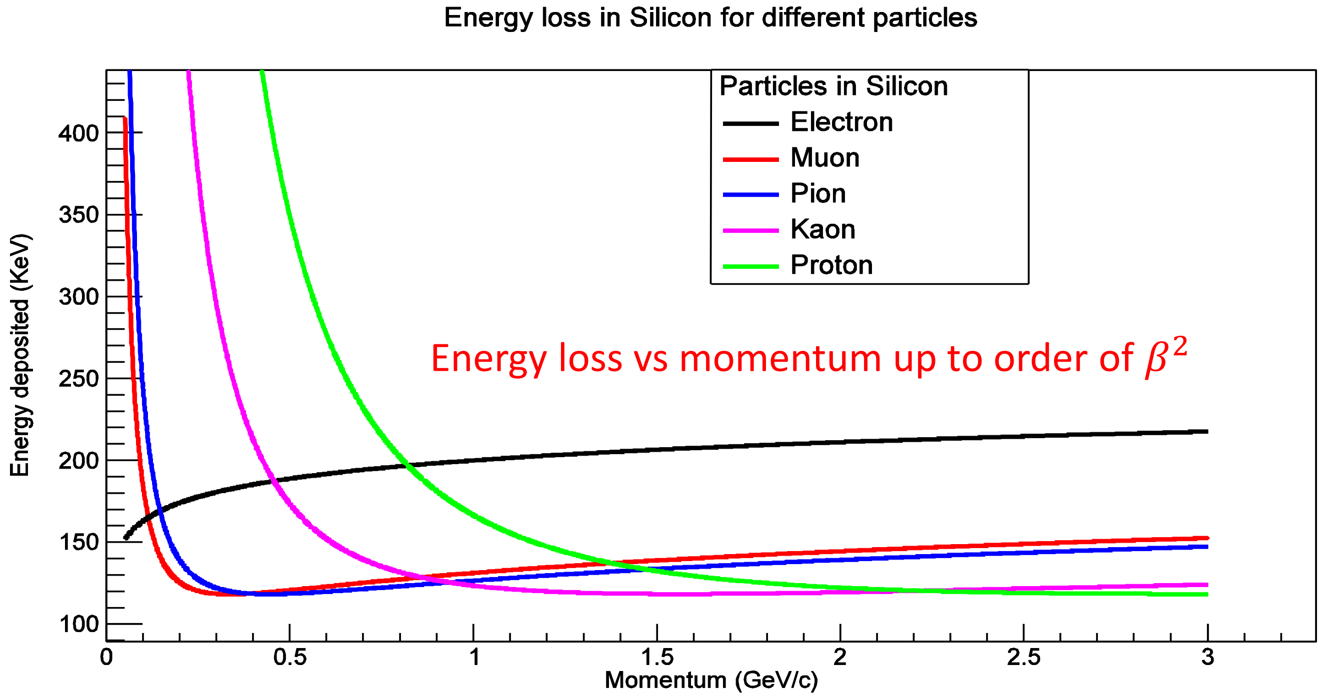
S parameter ≈ -50 dBW = -20 dBm=10 μW

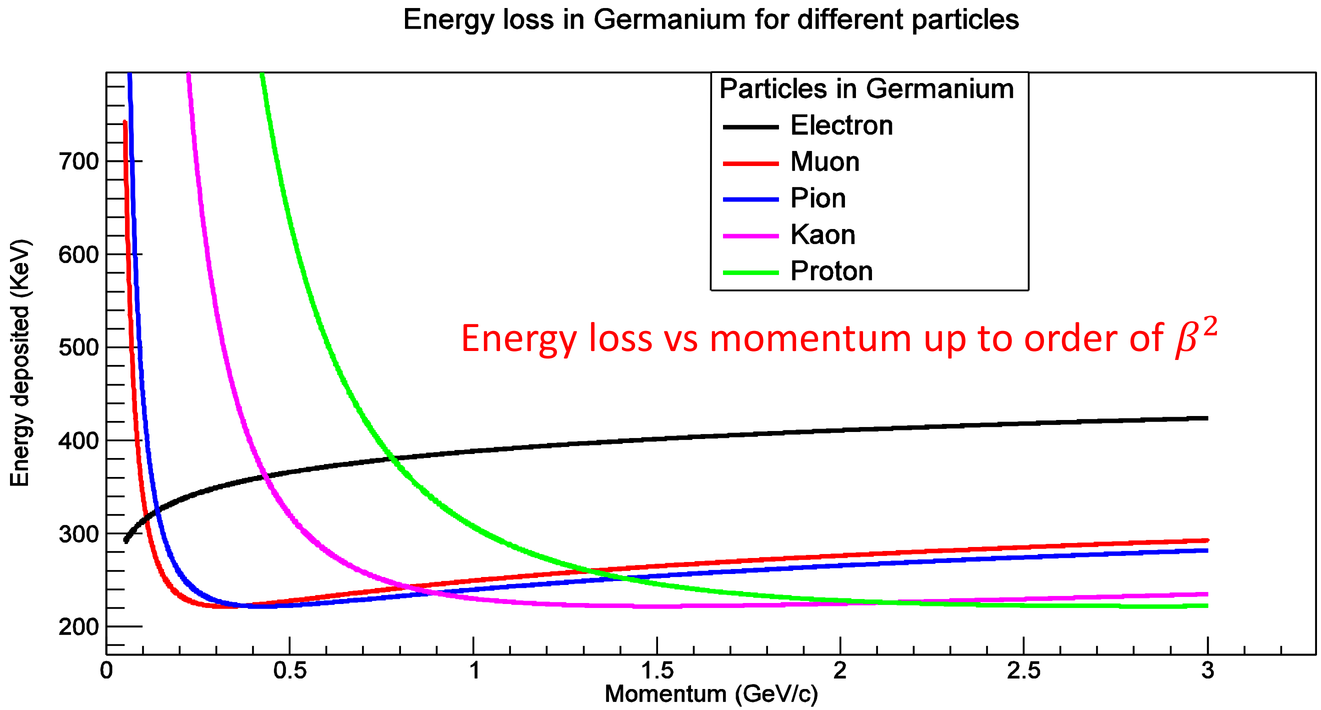
MPCVD : Advantages

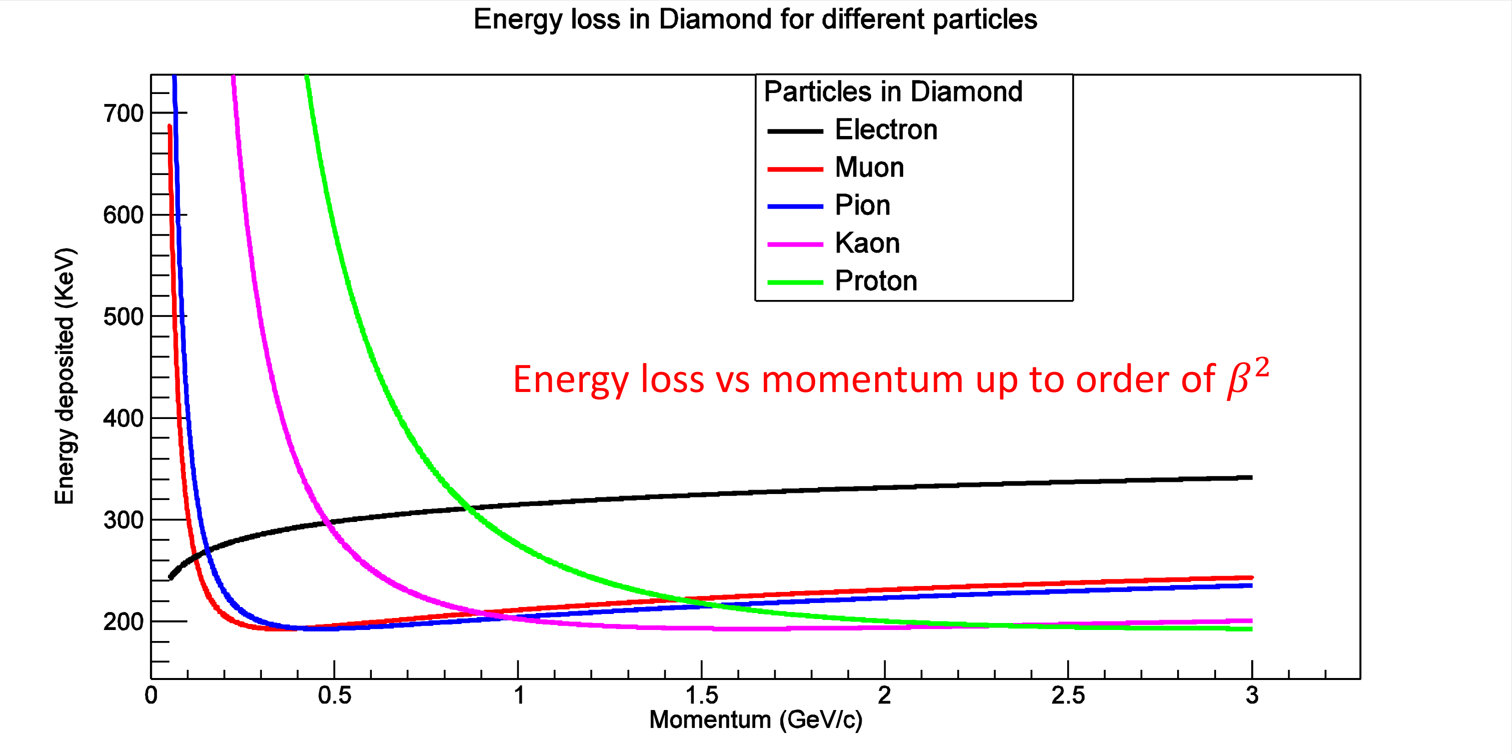
- Electrode less process=> No Plasma sheath

formation take place

- Plasma density is high
- Stability of Plasma up to many days
- Ability to scale up the process over large substrates
- Quality of film grown is high

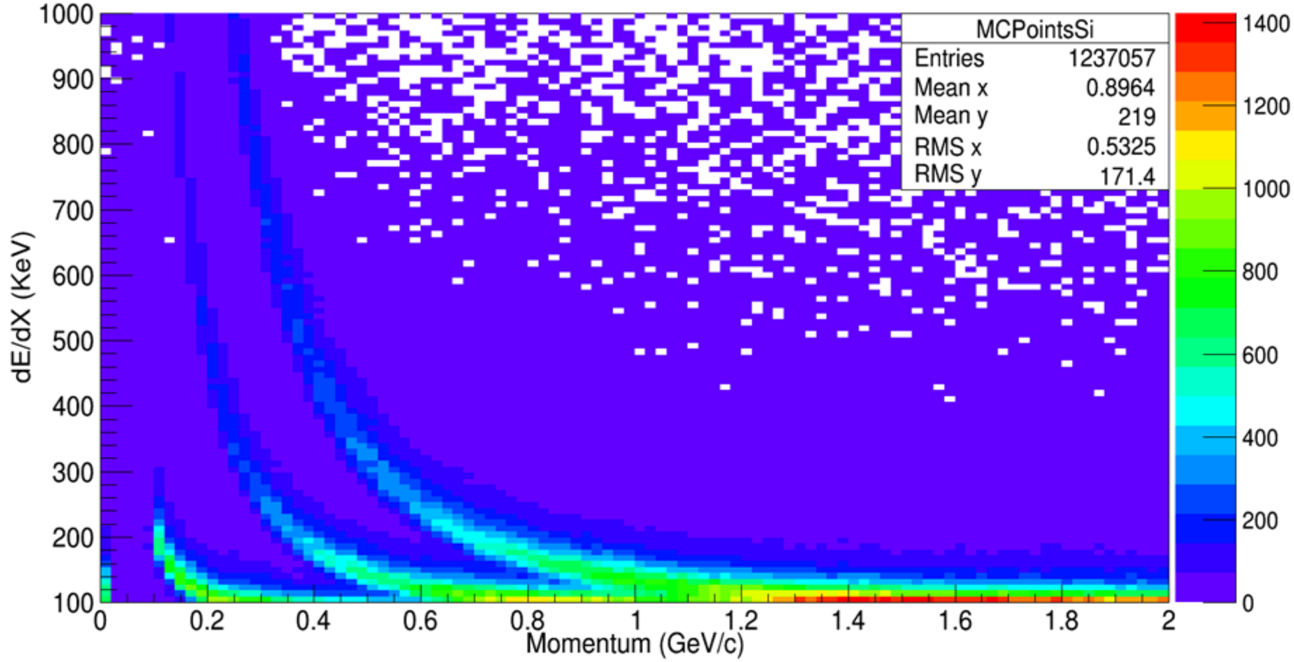

Energy loss in Silicon for different particles
Particles in Silicon
Electron
Muon
Pion
Kaon
Proton
Energy loss vs momentum up to order of β^2
Energy deposited (KeV)
100
150
200
250
300
350
400
0
0.5
1
1.5
2
2.5
3
Momentum (GeV/c)


Energy loss in Germanium for different particles
Particles in Germanium
Electron
Muon
Pion
Kaon
Proton
Energy loss vs momentum up to order of β^2
Energy deposited (KeV)
200
300
400
500
600
700
0
0.5
1
1.5
2
2.5
3
Momentum (GeV/c)

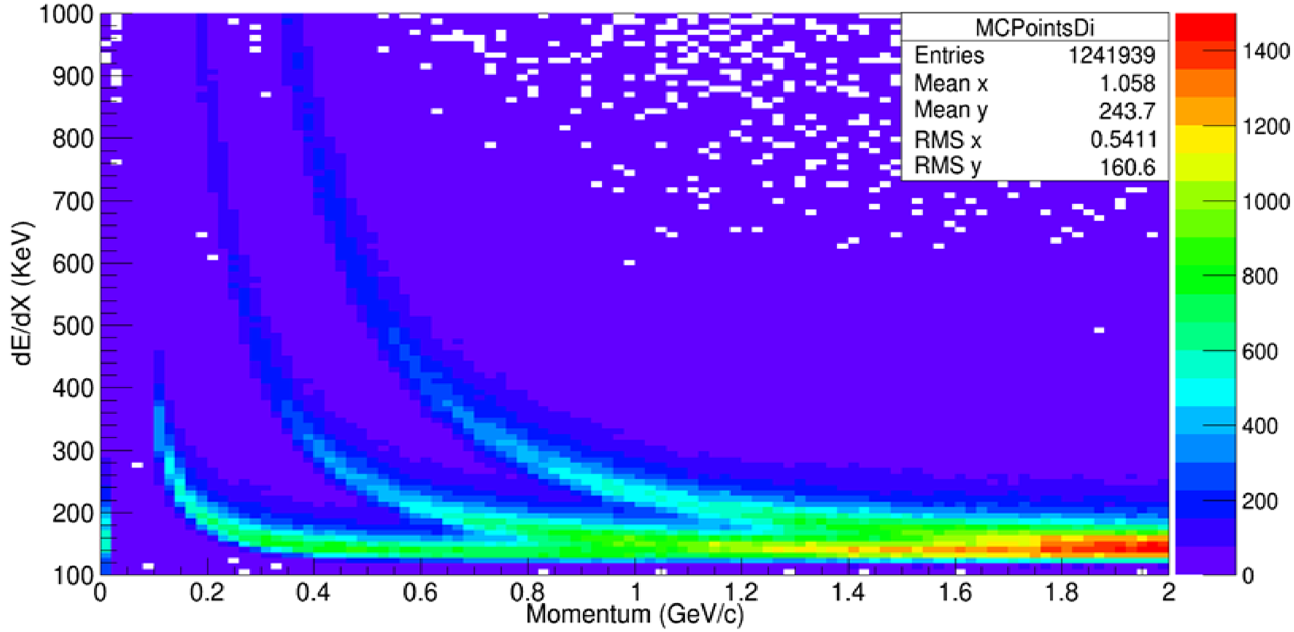

Energy loss in Diamond for different particles
Particles in Diamond
Electron
Muon
Pion
Kaon
Proton
Energy loss vs momentum up to order of β^2
Energy deposited (KeV)
700
600
500
400
300
200
0
0.5
1
1.5
2
2.5
3
Momentum (GeV/c)

dEdX band separation is good in diamond

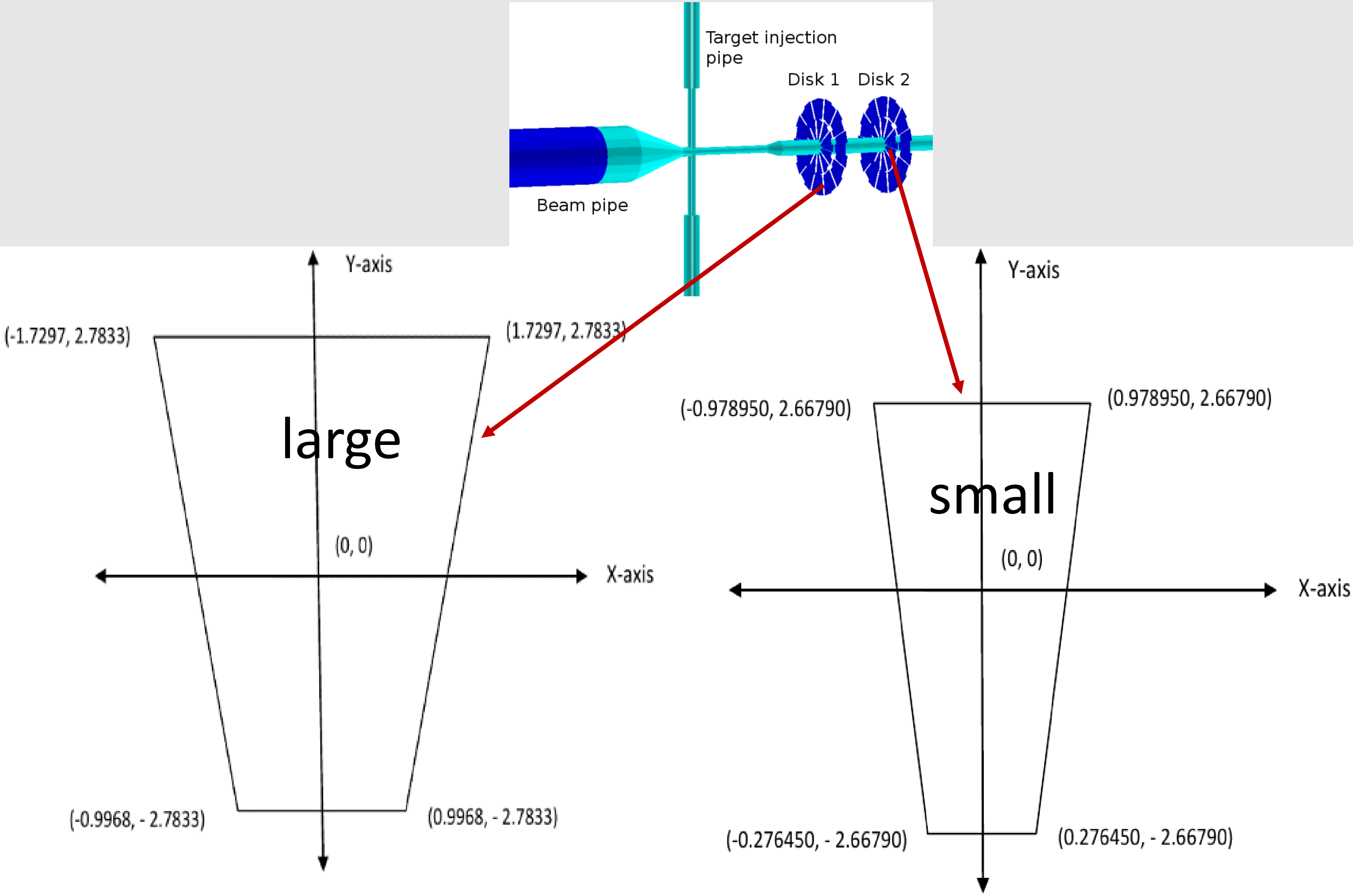
Silicon



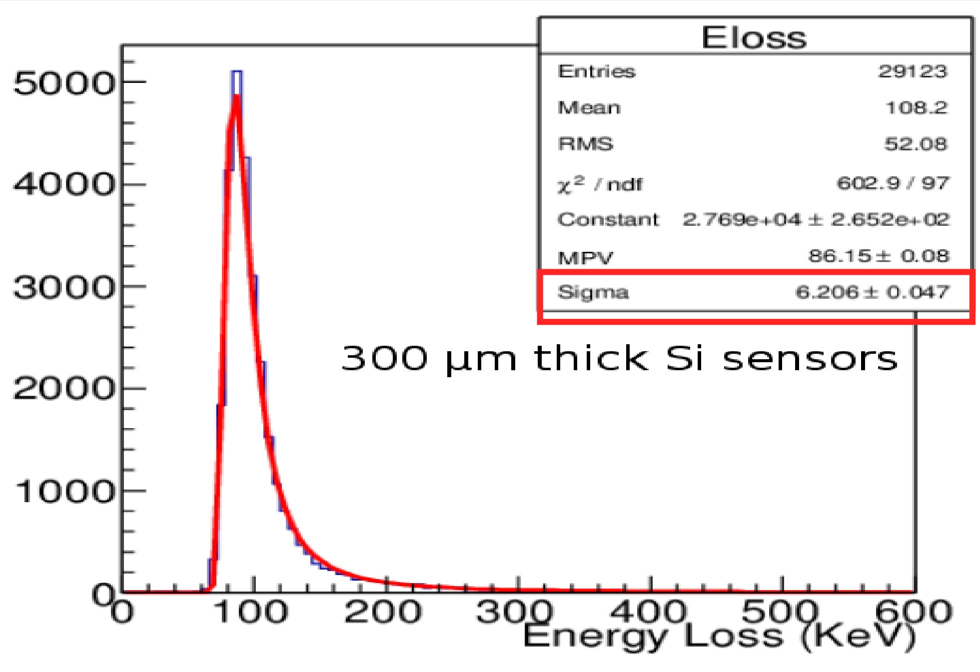
Diamond

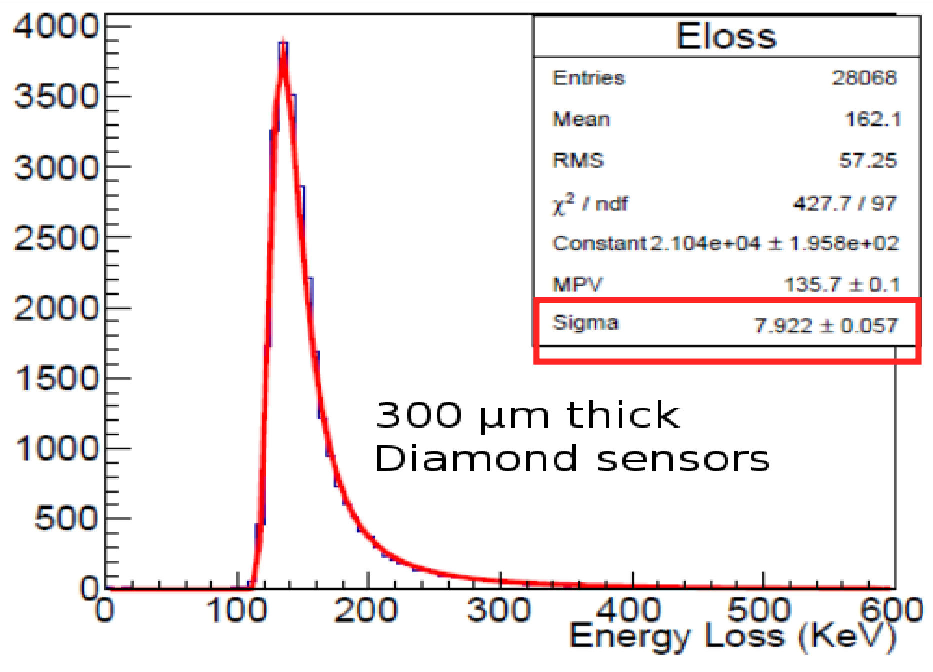


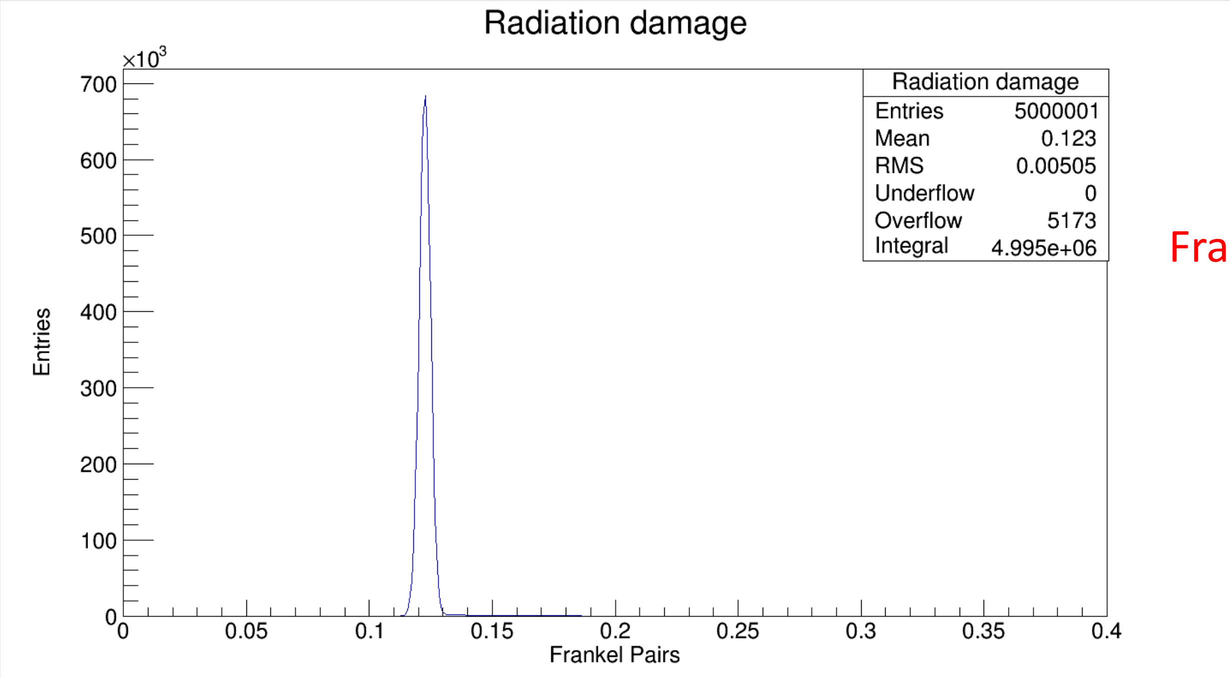
Large and Small Trapezoid used for Simulation in PANDAROOT

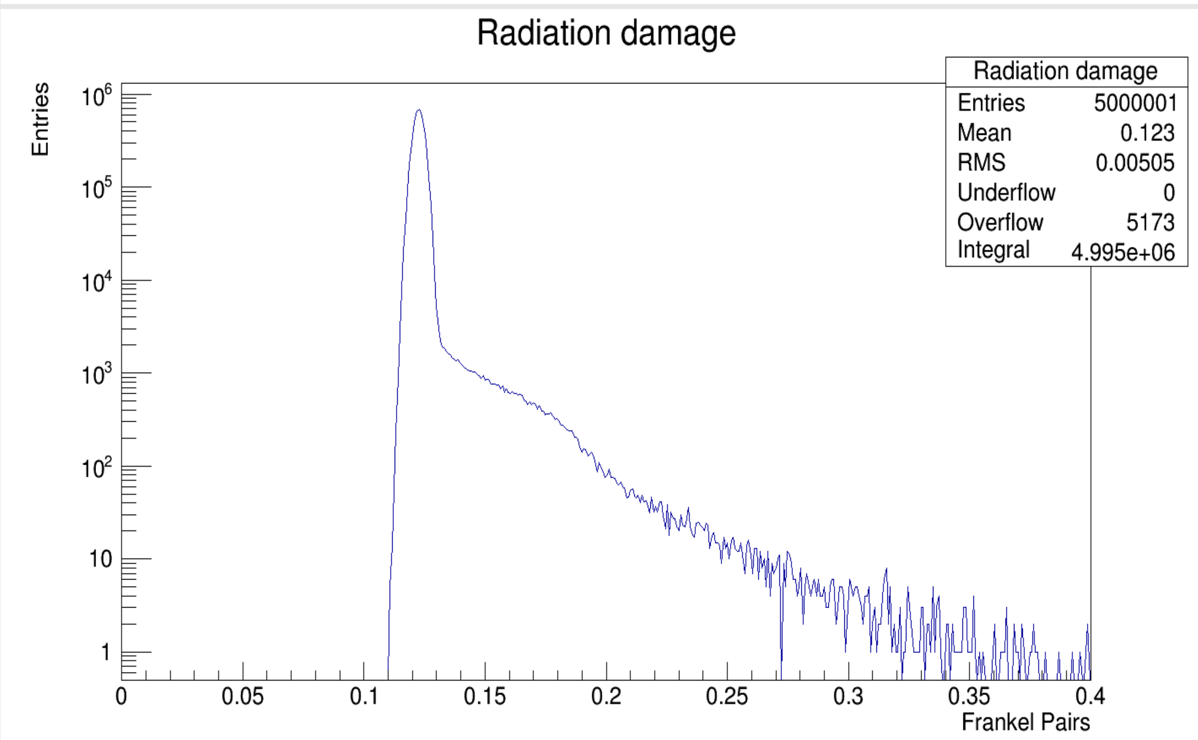


Energy deposited in 300 μm thick sensors (Geant3) PANDA Root









Frankel Pairs distribution for 1 GeV proton in 300 $\mu m\ thick$ Si

Frankel Pairs distribution for 1 GeV proton in 300 μm $thick$ Si