SEMICONDUCTOR DETECTORS

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Outline

- ✓ General features of semiconductor detectors
- ✓ Silicon detectors
- ✓ High-Purity Germanium detectors
- ✓ Diamond detectors

INSIS

General features

In many radiation detection applications, the use of solid media is greatly advantageous:

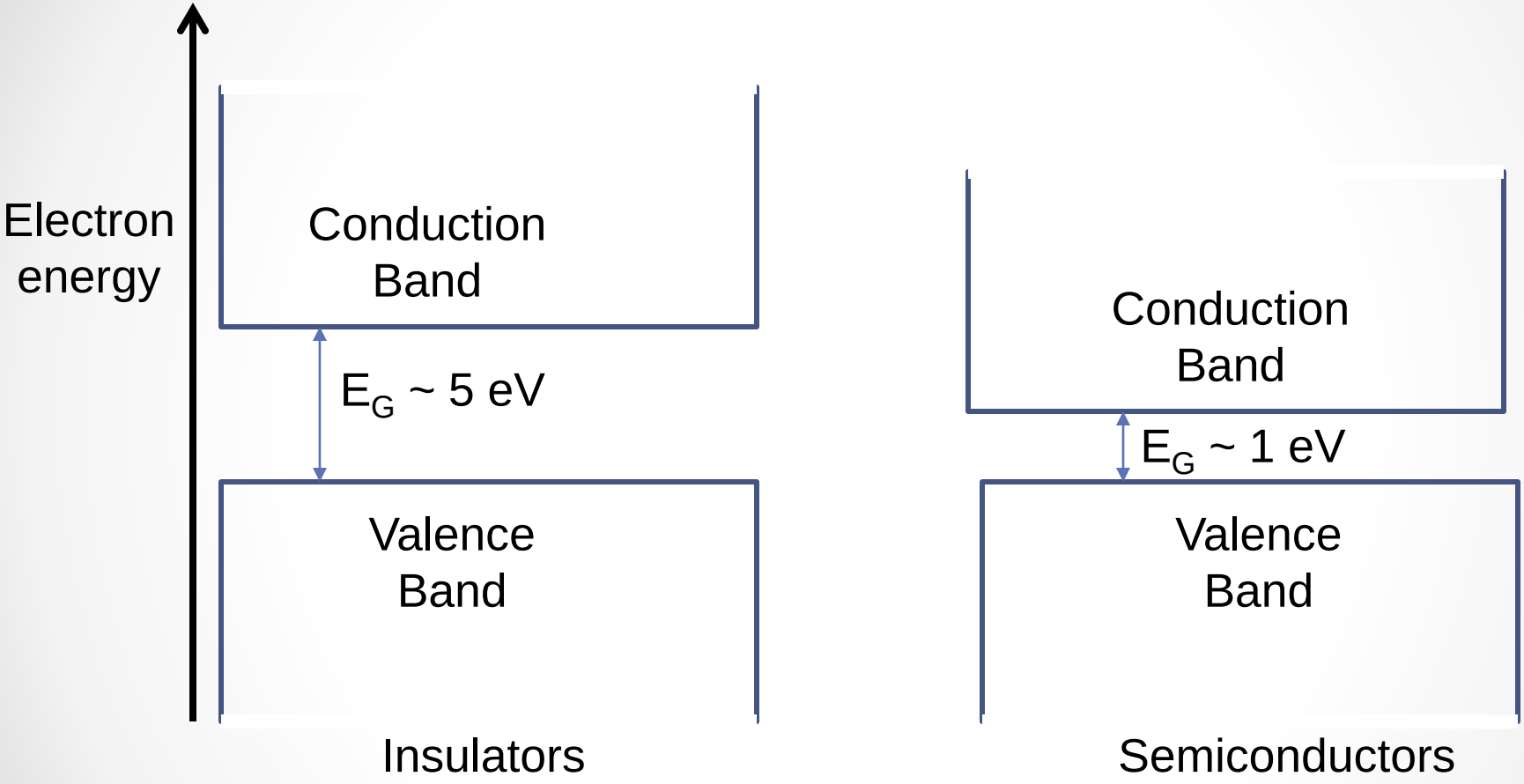
Small size (thickness) to reach same intrinsic efficiency of gaseous detectors (1000 times higher density)

More information carriers are produced with respect for example to scintillators (solid as well) so that statistical fluctuactions that determine the energy resolution are lower and the best energy resolution are achieved.

Typically work at low temperature (we will see why) and in general suffer by radiation damage, especially by neutrons

☹

BAND STRUCTURE



At any nonzero T thermal energy may promote with a certain probabability an electron from the valence to the conduction band leaving a hole in the forner. An electric field E make the e-h pair move in opposite directions, the motion of both particles being responsible of the observed conductivity of the material

$$p(T) = CT^{3/2}\exp\left(-\frac{E_G}{2kT}\right)$$

Probability of e-h thermal generation per unit time

T absolute temperature

E_G: Bandgap energy

k: Boltzmann constant

C: constant (material dependent)

After their formation e and h are subject to random thermal motion due to diffusion. After a time t particles generated at the same point have a spatial distribution of Gaussian form

$$\sigma = \sqrt{2Dt}$$

$$D = \mu\frac{kT}{e}$$

•Upon application of an electric field, e and h migrate with a net velocity given by:

$$v_h = \mu_h E$$

$$v_e = \mu_e E$$

That adds to the diffusion motion.

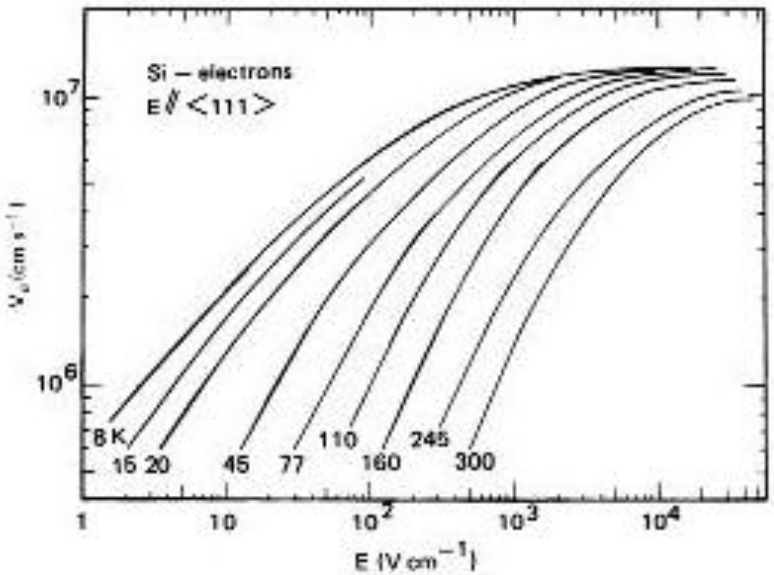
Due to diffusion there is a spread in space that has a gaussian form whose standard deviation is given by:

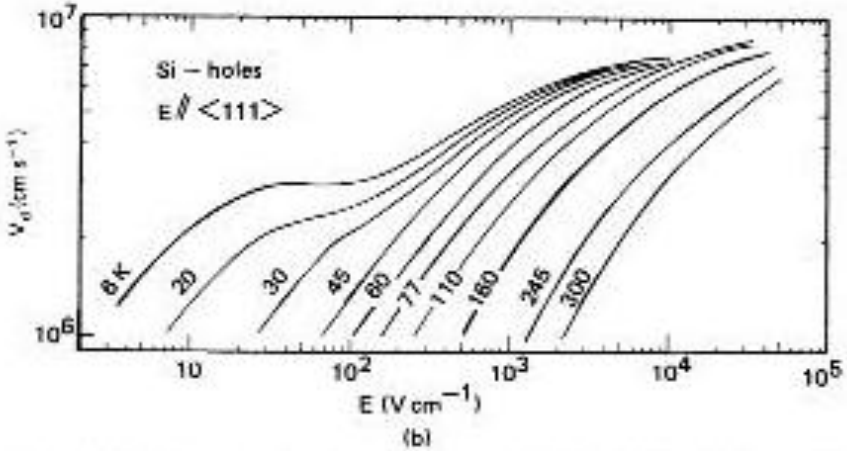
$$\sigma = \sqrt{\frac{2kTx}{eE}}$$

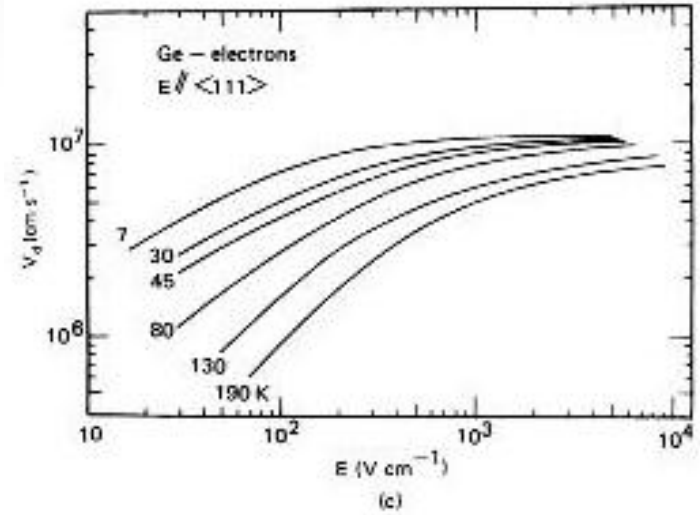
Table 11.1 Properties of Intrinsic Silicon and Germanium

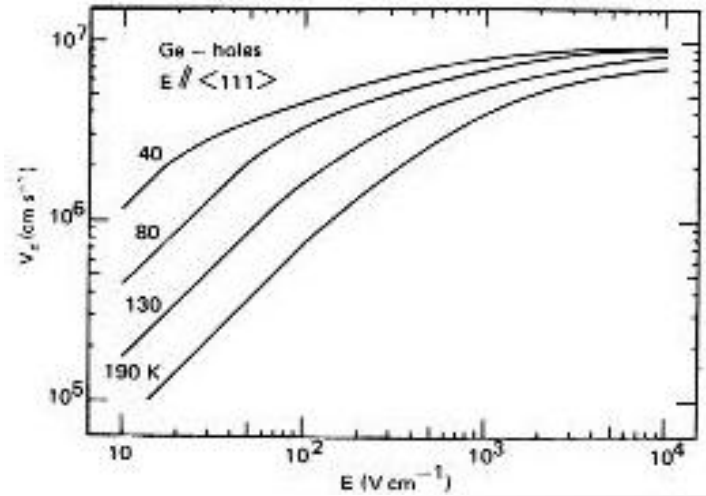
	Si	Ge
Atomic number	14	32
Atomic weight	28.09	72.60
Stable isotope mass numbers	28-29-30	70-72-73-74-76
Density (300 K); g/cm³	2.33	5.32
Atoms/cm³	4.96×10^{22}	4.41×10^{22}
Dielectric constant (relative to vacuum)	12	16
Forbidden energy gap (300 K); eV	1.115	0.665
Forbidden energy gap (0 K); eV	1.165	0.746
Intrinsic carrier density (300 K); cm⁻³	1.5×10^{10}	2.4×10^{13}
Intrinsic resistivity (300 K); Ω · cm	2.3×10^{5}	47
Electron mobility (300 K); cm²/V · s	1350	3900
Hole mobility (300 K); cm²/V · s	480	1900
Electron mobility (77 K); cm²/V · s	2.1×10^{4}	3.6×10^{4}
Hole mobility (77 K); cm²/V · s	1.1×10^{4}	4.2×10^{4}
Energy per electron–hole pair (300 K); eV	3.62	
Energy per electron–hole pair (77 K); eV	3.76	2.96
Fano factor (77 K)	0.143 (Ref. 7)	0.129 (Ref. 9)
	0.084 (Ref. 8)	0.08 (Ref. 10)
	0.085 to 0.137 (Ref. 12)	< 0.11 (Ref. 11)
		0.057 to 0.064 (Ref. 12)
	0.16 (Ref. 13)	0.058 (Ref. 14)

Source: G. Bertolini and A. Coche (eds.), *Semiconductor Detectors*, Elsevier-North Holland, Amsterdam, 1968, except where noted.









Drift velocity as a function of the electric field applied along the <111> crystallographic direction for different temperatures.

Intrinsic semiconductors

It is an ideal situation!

In a pure semiconductor, the electrons thermally excited in the conduction band and holes in left in the valence band are equal in number. This is called and INTRINSIC semiconductor.

$$n_i = p_i$$

where **n** and **p** are the concentration of e^- in the conduciton band and h in the valence band, respectively also known as intrinsic carriers densities. The higher the bandgap the lower **n_i, p_i (remember the table of before),**

While in metals only the flow of electrons contribute to conductivity, in intrinsic semicinductors both e and h contribute.

suppose to have a slab of intrinsic semiconductor of area A and thickness t, the current that flows across t when a voltage V is applied is:

$$I = \frac{AV}{\rho t} \quad \text{so that} \quad \rho = \frac{AV}{It}$$

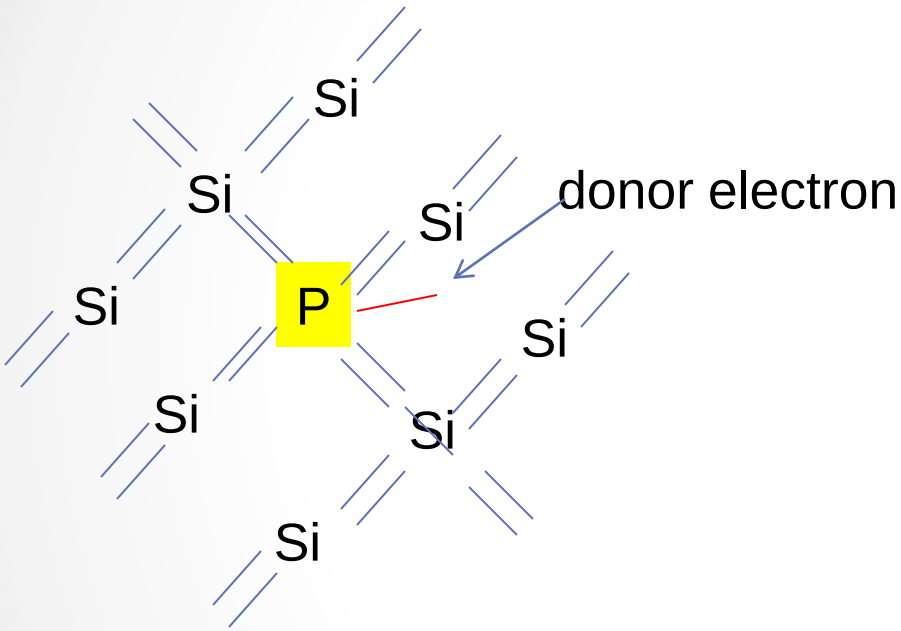
The current is made up of two separate components, namely $\mathbf{I_e}$ and $\mathbf{I_h}$ that add together.

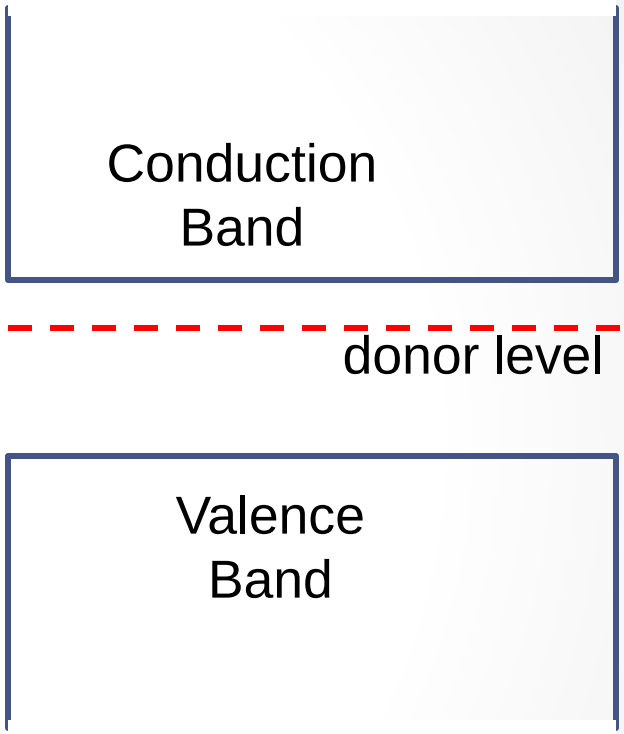
$$I = I_e + I_h = An_i e(v_e + v_h)$$

$$I = An_i eE(\mu_e + \mu_h) = An_i e\frac{V}{t}(\mu_e + \mu_h)$$

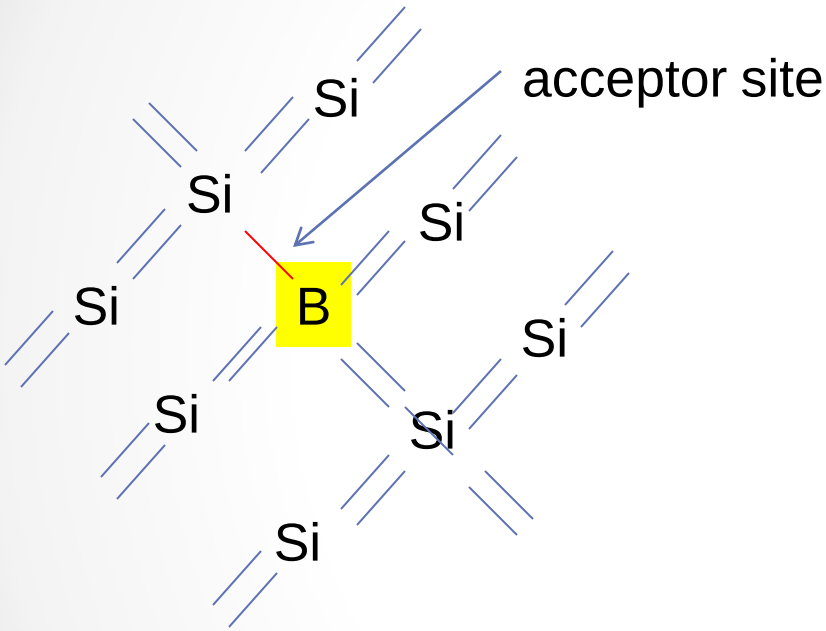
$$\rho = \frac{1}{en_i(\mu_e + \mu_h)} = 2.3 \cdot 10^5\,\Omega \cdot \text{cm} \quad \text{for silicon}$$

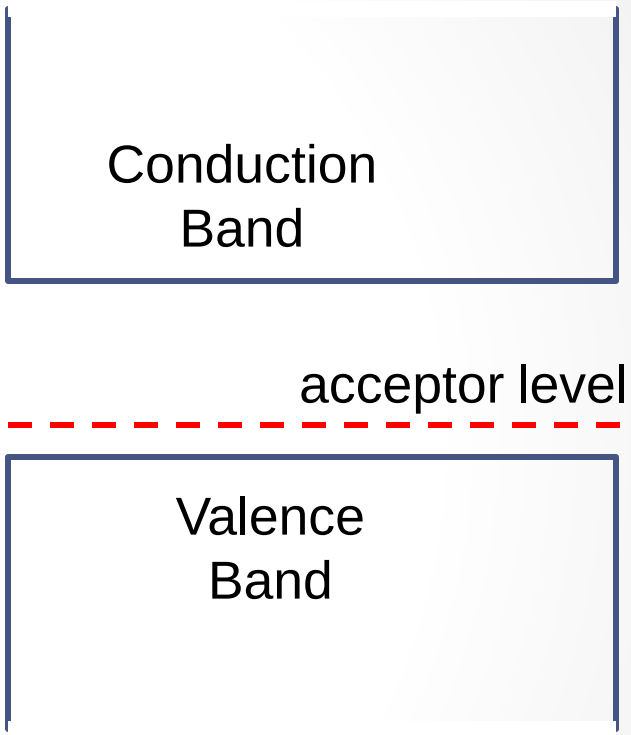
n-type semiconductors





p-type semiconductors

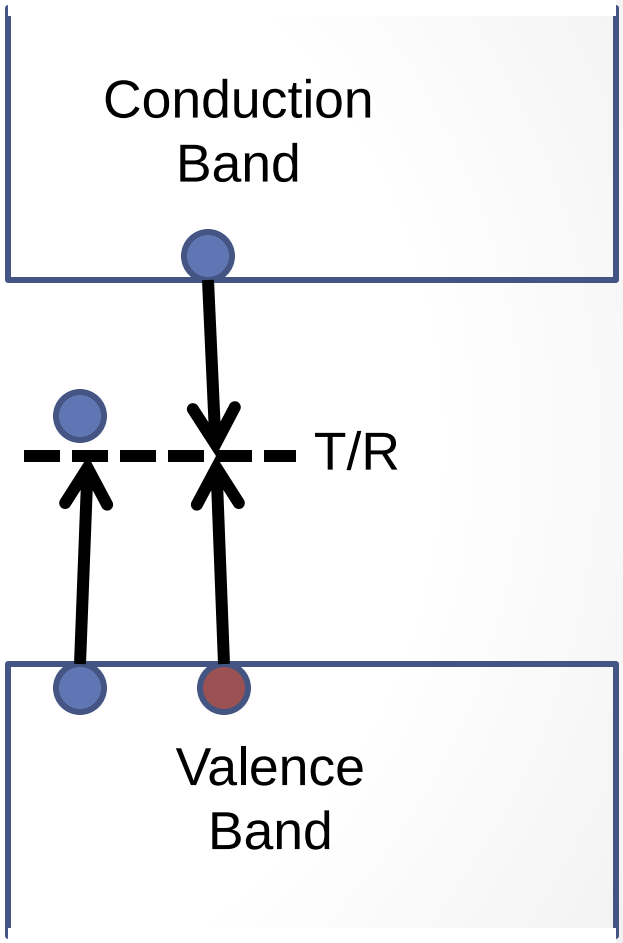




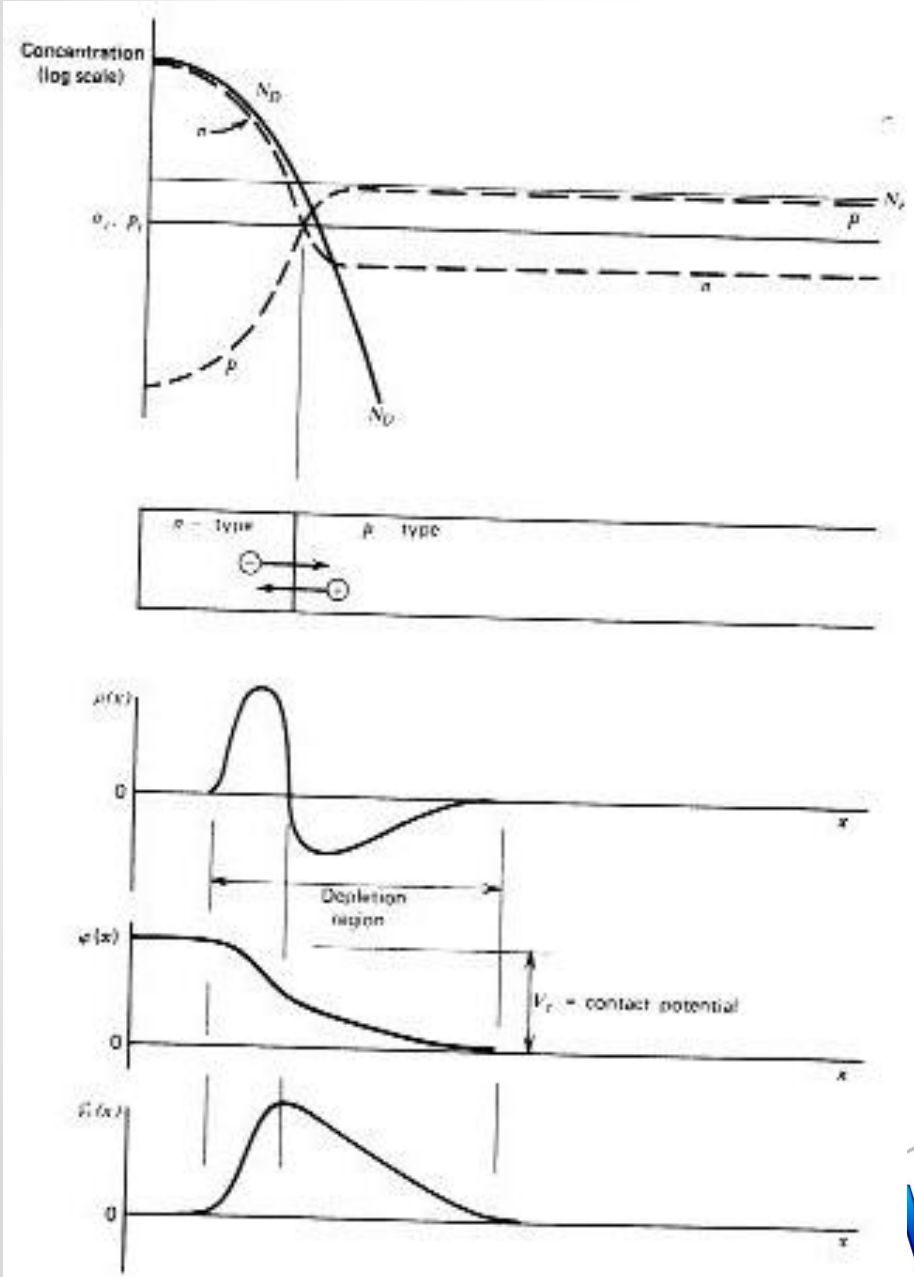
After formation, e and h migrate for diffusion or under the effect of an external applied electric field. In pure semiconductors e-h recombination may occur over time as large as 1 s (carrier lifetime).

Due to the presence of impurities and/or structural defects there are “deep impurity levels” inside the forbidden gap that act as trapping and recombination centers.

The relaxation times for these process reduce the carrier lifetime to about 10^{-5} s.



The semiconductor junction



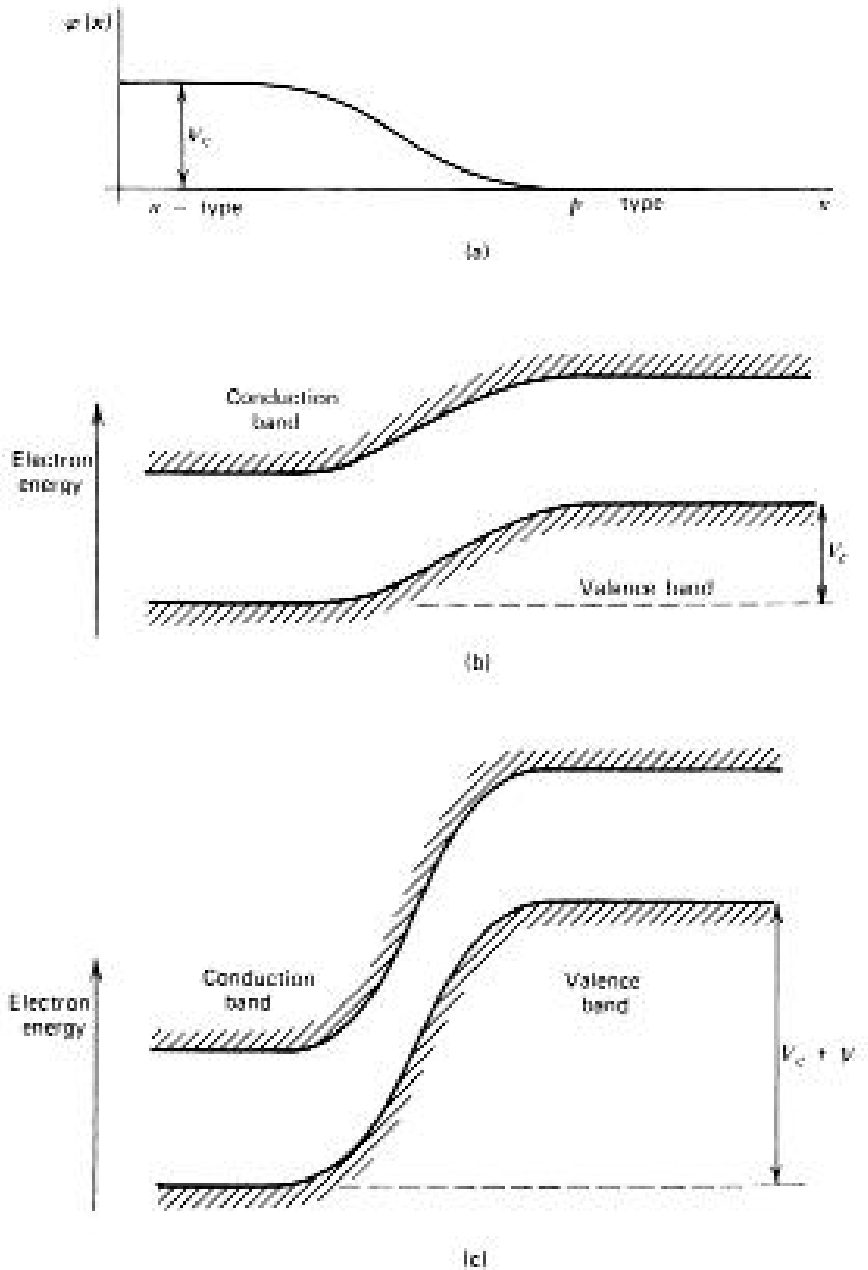
$$\Delta\varphi = -\frac{\rho}{e}$$ Poisson Equation

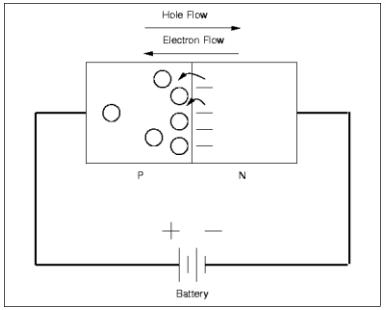
$$\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{e}$$ 1D Poisson Eq.

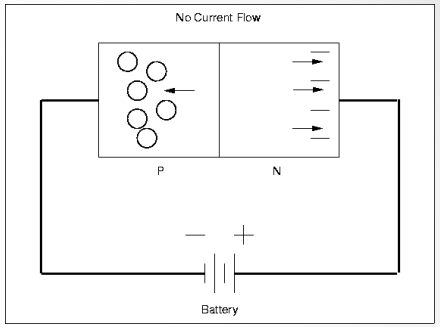
$$E = -\mathrm{grad}\,\varphi$$

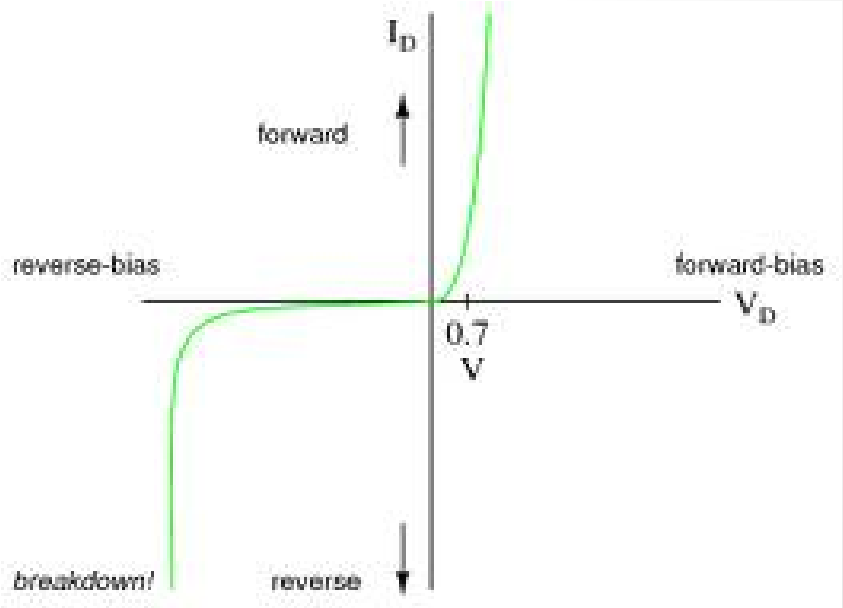
$$E(x) = -\frac{d\varphi}{dx}$$ In 1D

Reverse bias junction

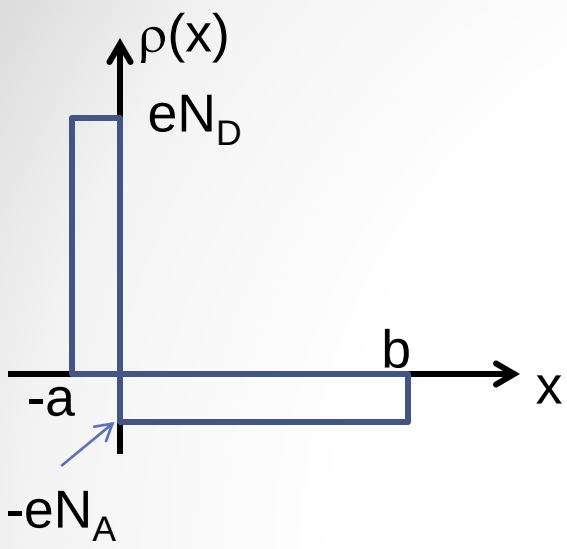








Properties



$$\rho(x)=\begin{cases} eN_D & (-a<x\le 0) \\ -eN_A & (0<x\le b) \end{cases}$$

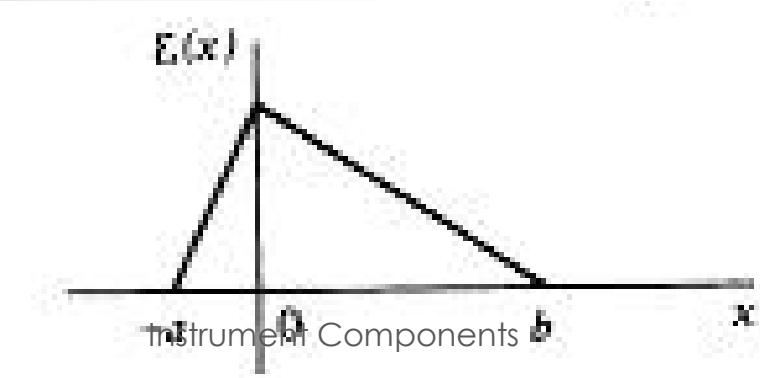
$$\frac{d^2\varphi}{dx^2}=\begin{cases} -\dfrac{eN_D}{\varepsilon} & (-a<x\le 0) \\ +\dfrac{eN_A}{\varepsilon} & (0<x\le b) \end{cases}$$

$$\frac{d\varphi}{dx}(-a)=\frac{d\varphi}{dx}(b)=0 \quad \text{boundary condition}$$

and thus

$$\frac{d\varphi}{dx}=\begin{cases} -\dfrac{eN_D}{\varepsilon}(x+a) & (-a<x\le 0) \\ +\dfrac{eN_A}{\varepsilon}(x-b) & (0<x\le b) \end{cases}$$

$$-\frac{d\varphi}{dx}=E(x)$$

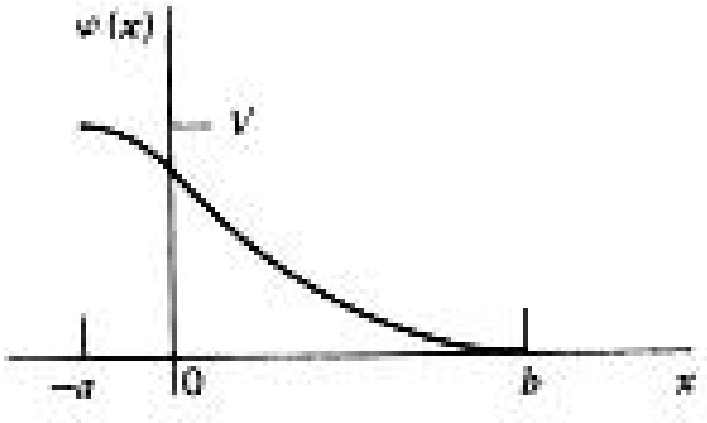


the boundary condition for $\varphi(x)$:

$\varphi(-a) = V$ and $\varphi(b) = 0$

this leads to:

$$\varphi(x) = \begin{cases} -\dfrac{eN_D}{\varepsilon}(x+a)^2 + V \quad (-a < x \le 0) \\ +\dfrac{eN_A}{\varepsilon}(x-b)^2 \quad (0 < x \le b) \end{cases}$$



at $x = 0$ we have to match the solutions:

$$V - \frac{eN_D a^2}{2\varepsilon} = \frac{eN_A b^2}{2\varepsilon} \quad \text{or} \quad N_A b^2 + N_D a^2 = \frac{2V\varepsilon}{e}$$

being $N_A b = N_D a$ thus $(a+b)b = \dfrac{2V\varepsilon}{eN_A}$

$N_D >> N_A \Rightarrow b >> a$

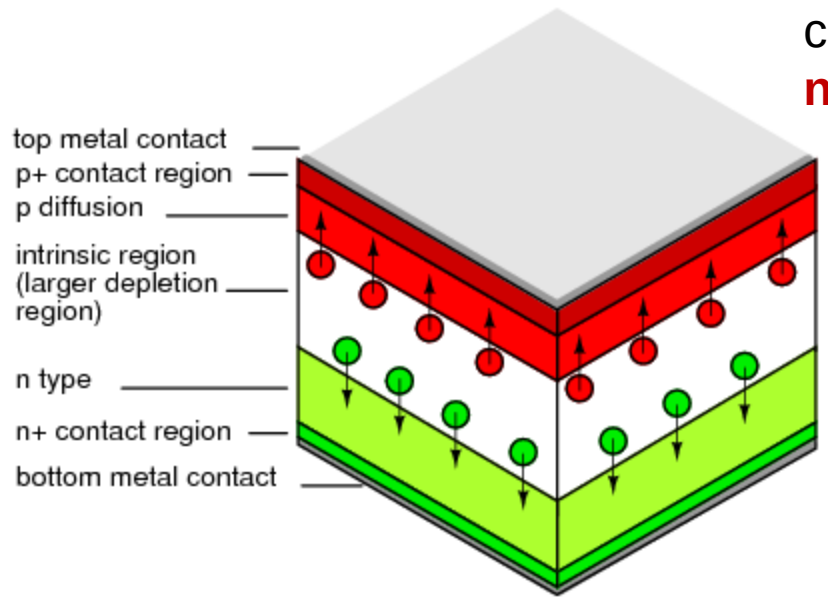
$$d = \sqrt{\frac{2\varepsilon V}{eN_A}} \qquad C = \frac{\varepsilon}{d} = \sqrt{\frac{eN_A\varepsilon}{2V}}$$

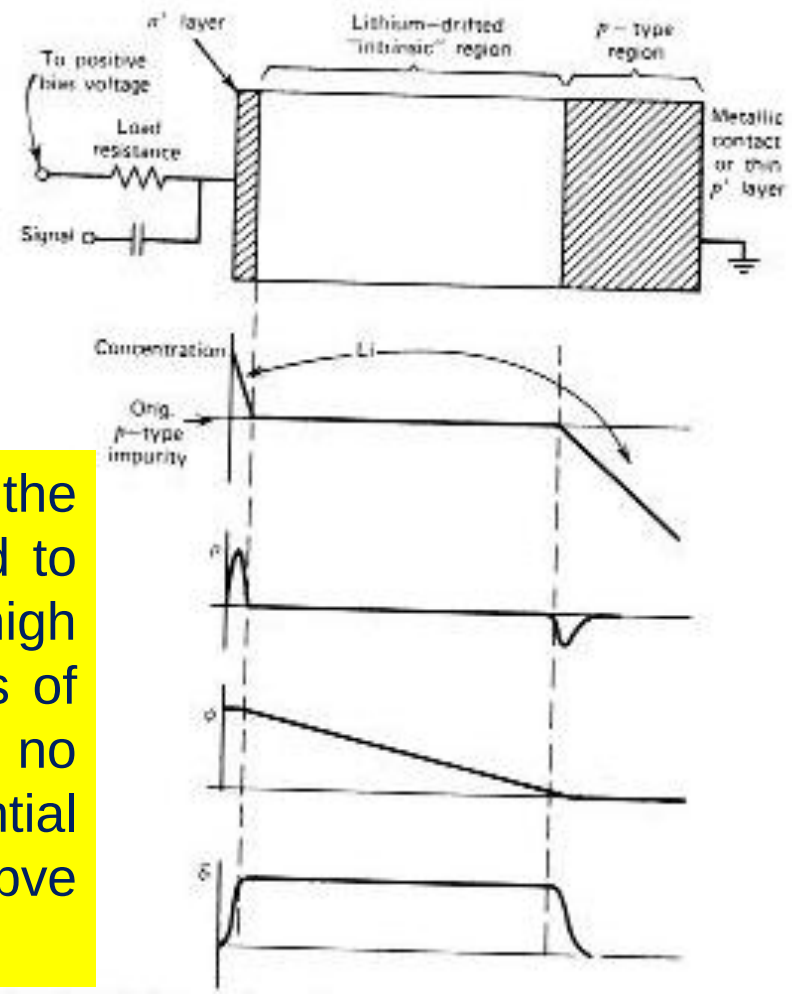
$$E_{max} = \frac{2V}{d} = \sqrt{\frac{2VN_A e}{\varepsilon}} \text{(@transition between n and p type)}$$

Silicon Detectors

p-i-n configuration

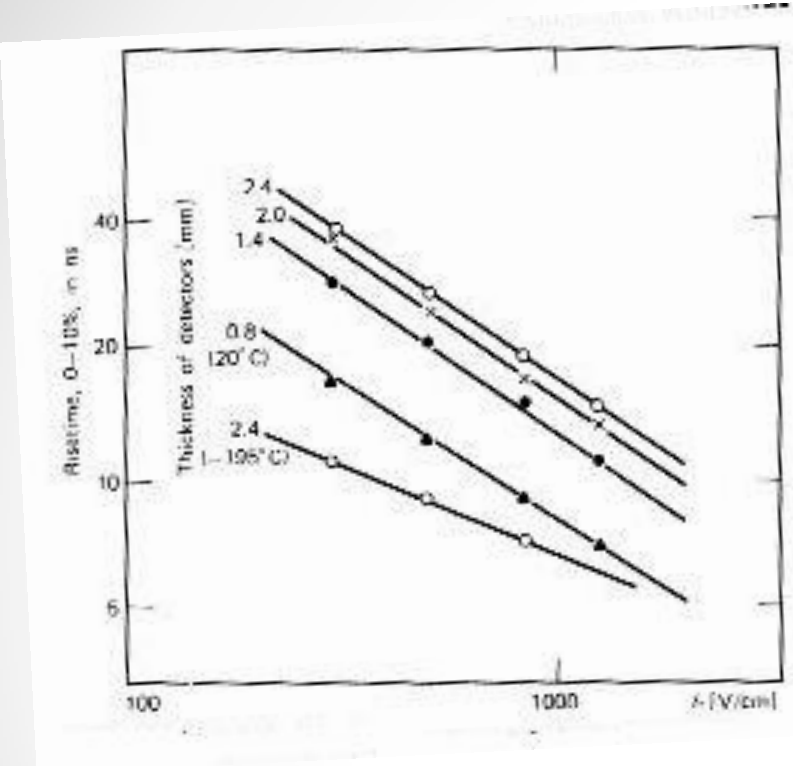
Using silicon of the highest purity achievable, the depletion layer is limited to 1-2 mm. ***Lithium drifting*** is commonly used to created a compensated region to make this **intrinsic** with **n=p** as seen before.



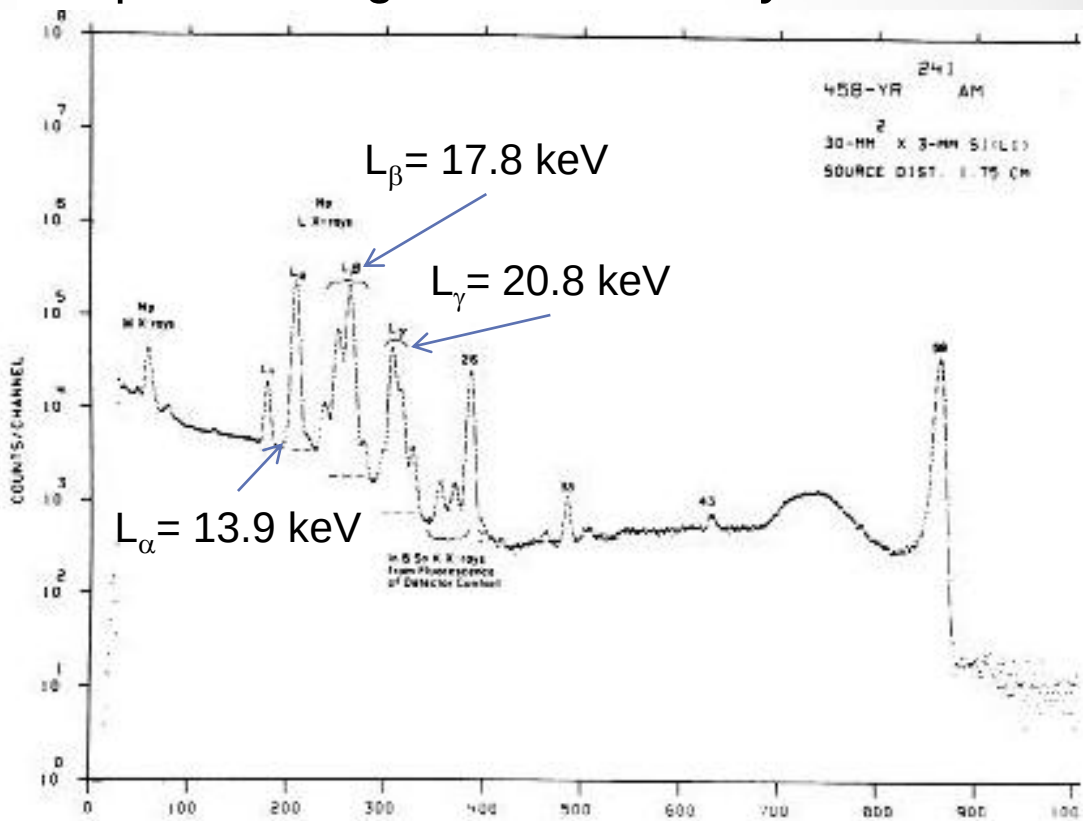


The lifetime of charge carriers generated in the intrinsic region is made longer as compared to collection time at both electrodes anyway high voltage is needed 10^3 V for intrinsic regions of several millimiters. As in the intrinsic region no net charge is present (r=0) the electric potential varies linearly in the planar configuration abpve and E is unform across this region

Timing and resolution



Observed rise times for Si(Li) detectors of different thickness as a function of the applied electric field for beta radiation. The time resolution achievable in this case is of a few ns. Poorer resolution expected for gamma and X rays



Photon spectrum from ^{241}Am with a 30 mm^2 x 3 mm Si(Li) detector

An interesting application

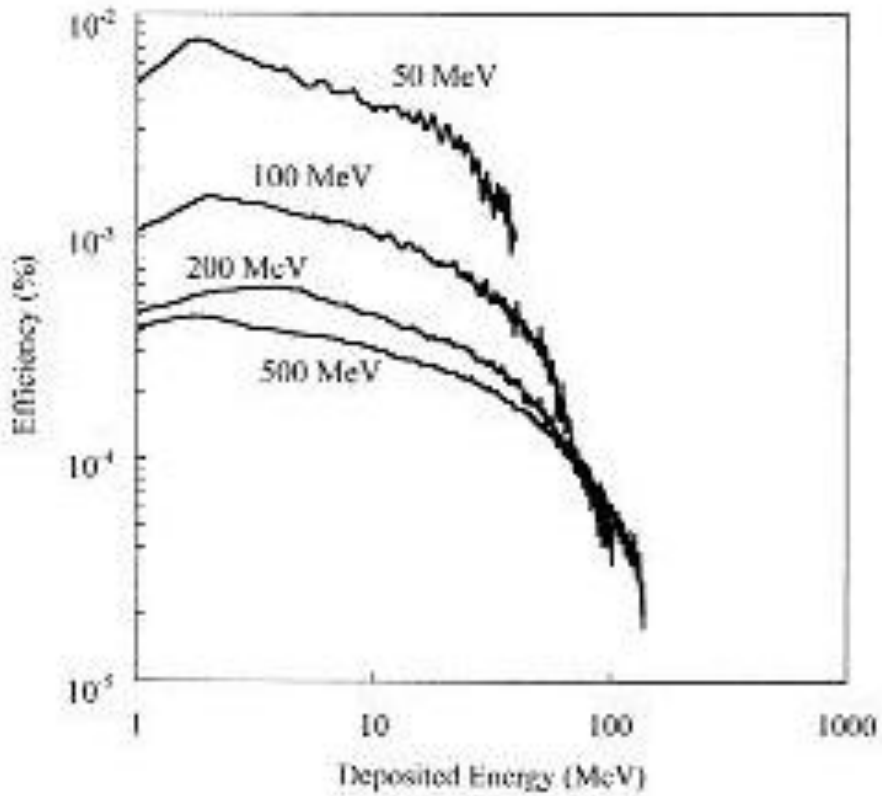


FIG. 2. Depositions from monoenergetic slices of the LANSCE neutron beam. Individual deposition curves correspond to single time-of-flight channels with narrow neutron energy width. These curves show that deposition spectra (and corresponding response functions) for different neutron energies are distinct, which indicates that the responses are suitable for use in the inversion process described in this work. Note that only a few curves are shown for clarity.

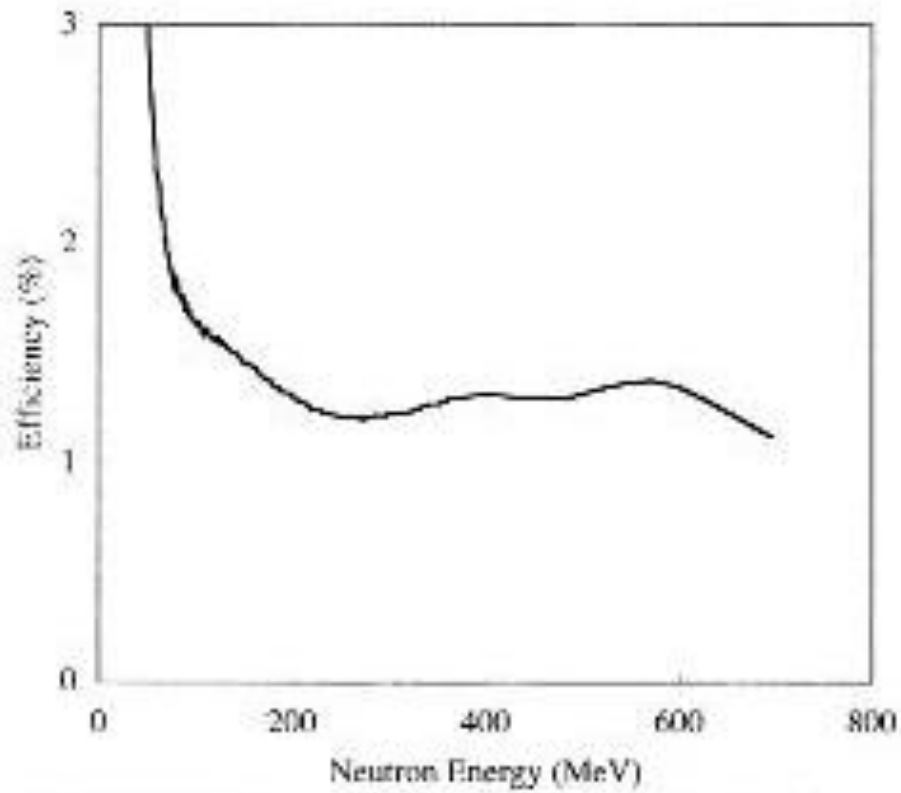
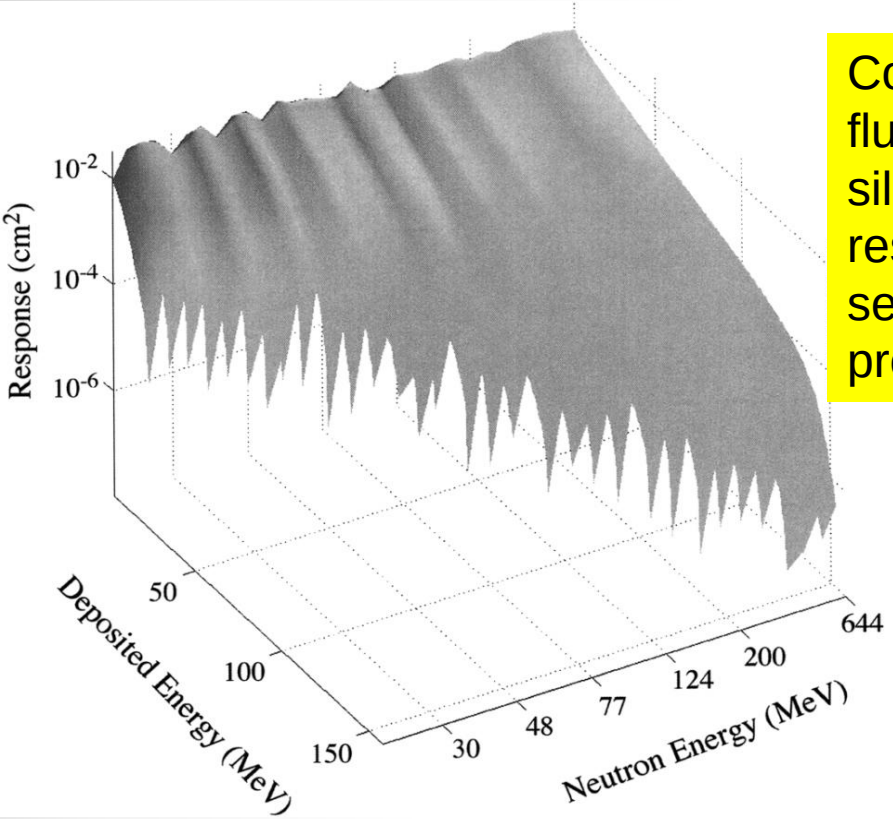
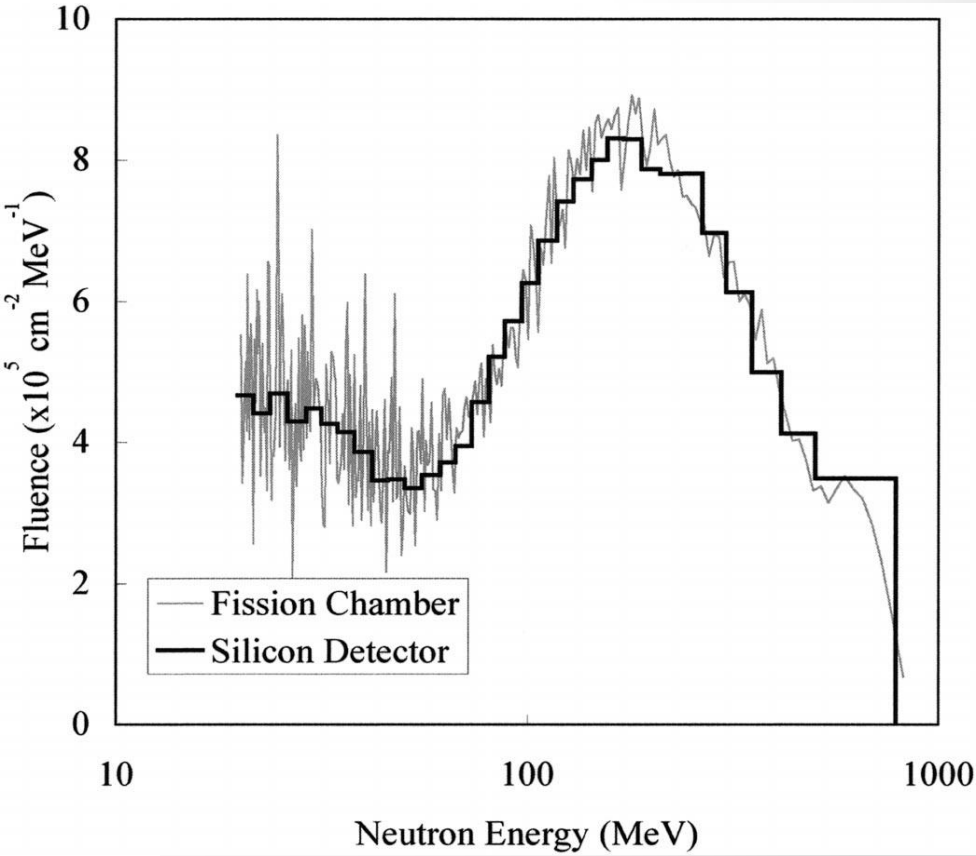


FIG. 3. Total efficiency in the silicon detector as a function of neutron energy. The increase in efficiency above 280 MeV represents the addition of charged pion generating reactions with a threshold of about 260 MeV.

Neutron applications



Comparison of measured differential neutron fluence from the fission foil chamber and the silicon detector for the experiment in which the response function was measured. These data serve as a consistency check of the inversion process and the measured response function.

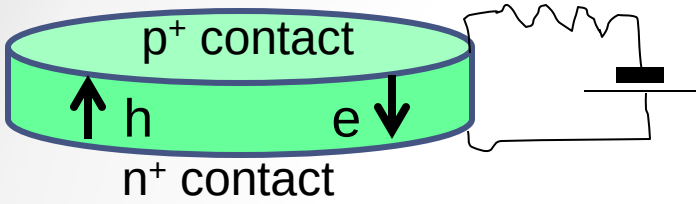


Surface plot of response matrix as a function of incident neutron energy and deposited energy. The response is the number of events which deposit more than a given energy per unit neutron fluence and is a macroscopic cross section for the silicon detector.

Germanium detectors

Detector configurations

PLANAR GEOMETRY



$$d = \sqrt{\frac{2V\varepsilon}{\rho}}$$ Depth of the depletion region

$$V_d = \frac{\rho L^2}{2\varepsilon}$$

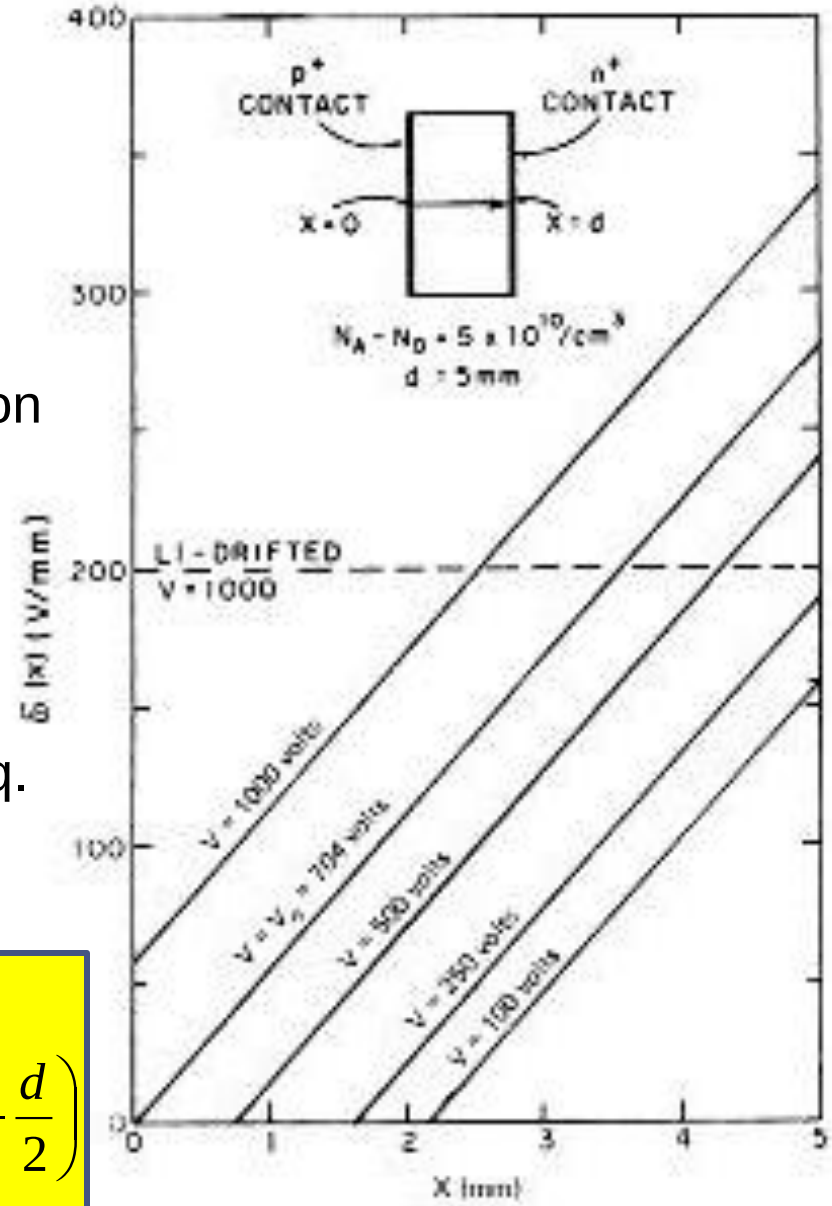
Minimum potential to have d=L (thickness of the slab)

$$\frac{d^2\varphi}{dx^2} = \frac{\rho}{\varepsilon}$$

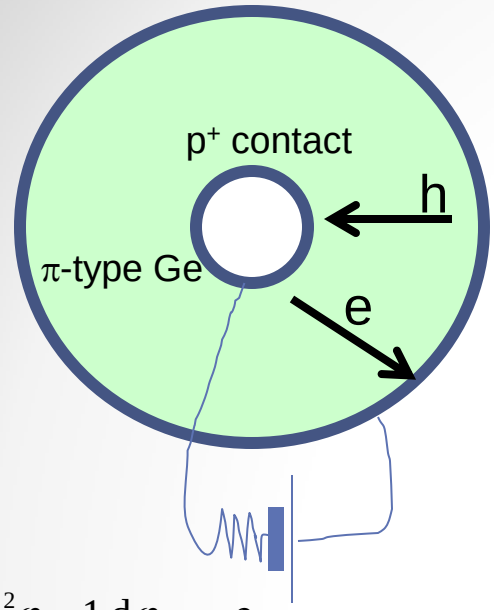
1D Poisson Eq.

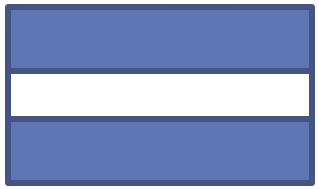
$$\varphi(d) - \varphi(0) = V \ (boundary\ condition)$$

$$-E(x) = \frac{V}{d} + \frac{\rho}{\varepsilon}\left(\frac{d}{2} - x\right) \ or \ |E(x)| = \frac{V}{d} + \frac{eN_A}{\varepsilon}\left(x - \frac{d}{2}\right)$$

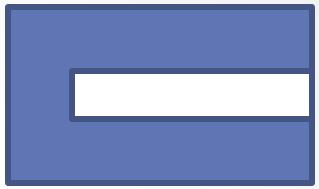


COAXIAL GEOMETRY





True coaxial



Closed ended coaxial

$$\frac{d^2\varphi}{dr^2}+\frac{1}{r}\frac{d\varphi}{dr}=-\frac{\rho}{\varepsilon} \qquad BC \quad \varphi(r_2)-\varphi(r_1)=V$$

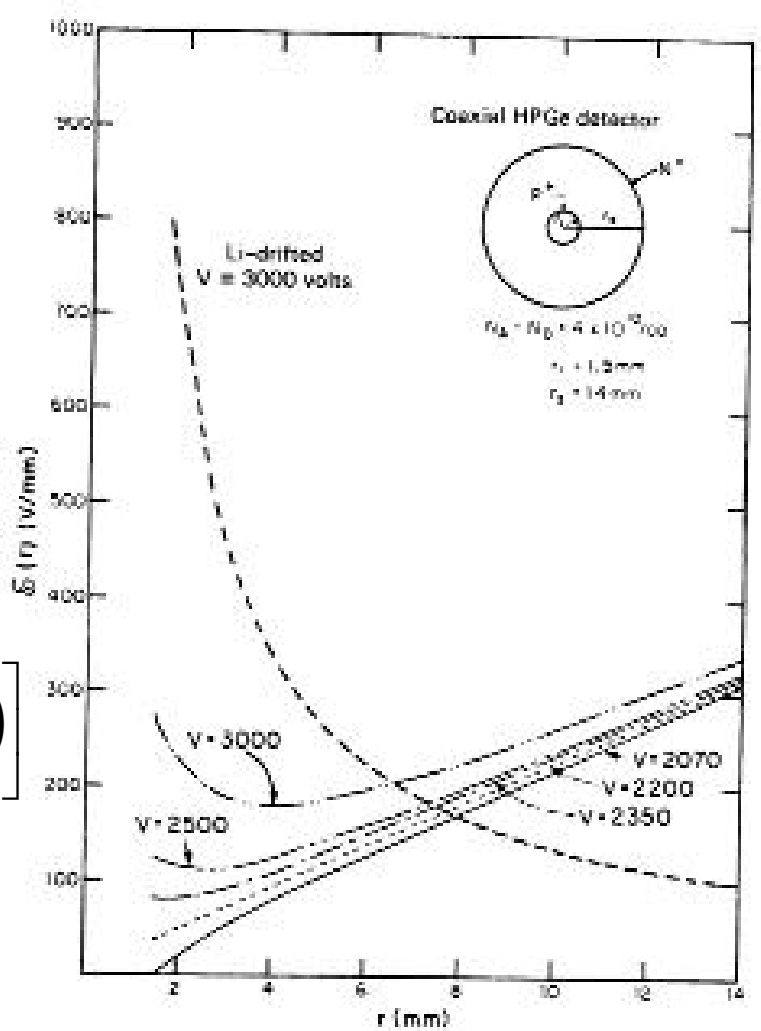
$$-E(r)=-\frac{\rho}{2\varepsilon}r+\frac{V+\frac{\rho\left(r_2^2-r_1^2\right)}{4\varepsilon}}{r\ln\left(r_2/r_1\right)} \quad or \quad |E(x)|=\frac{eN_A}{2\varepsilon}r+\frac{V+\frac{eN_A\left(r_2^2-r_1^2\right)}{4\varepsilon}}{r\ln\left(r_2/r_1\right)}$$

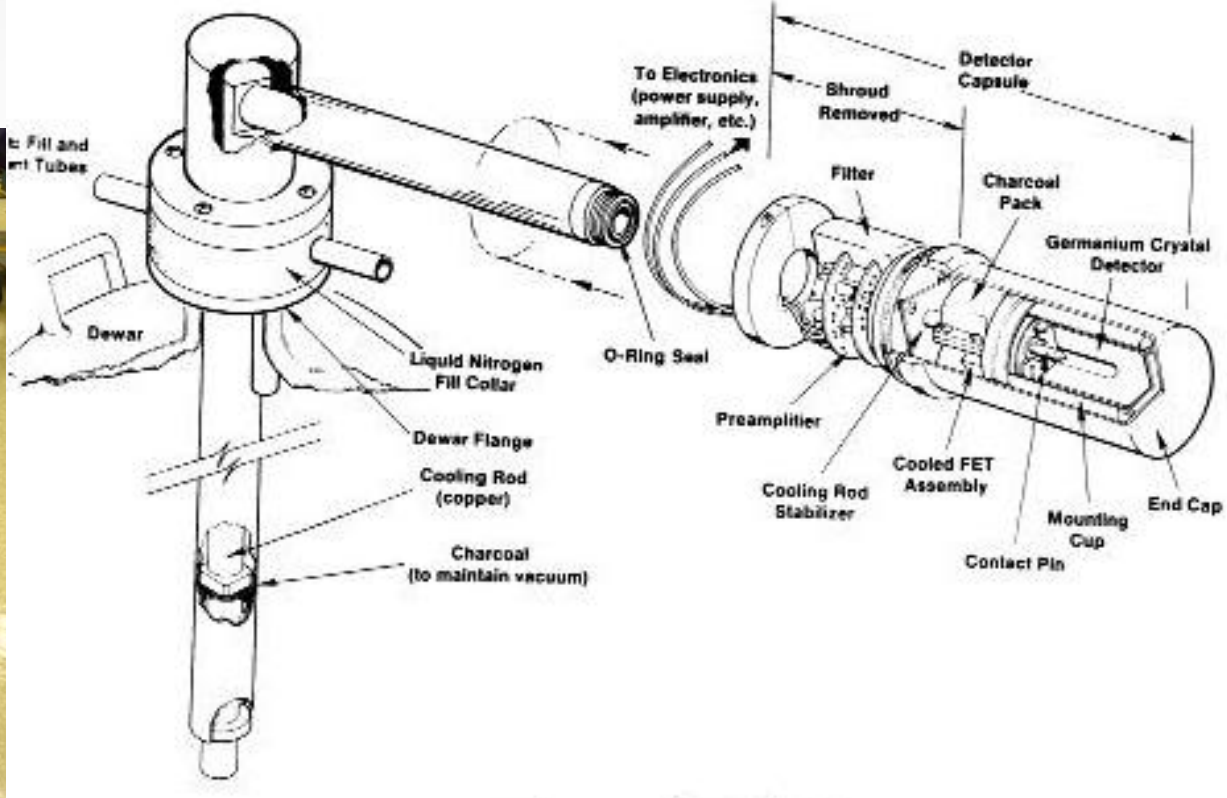
For $E(r_1)=0$ we find the voltage to fully deplete the detector

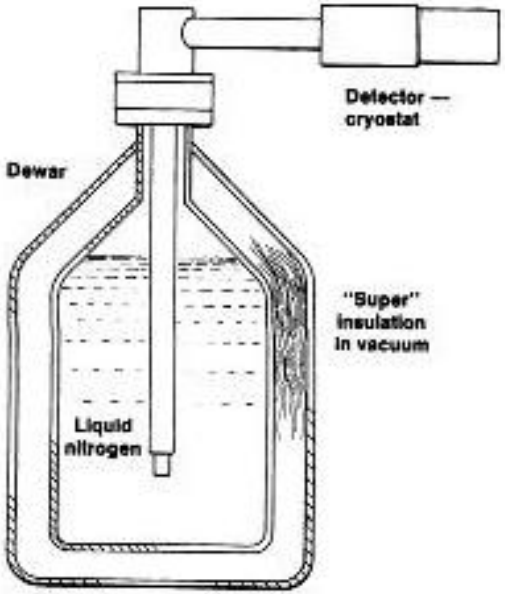
$$V_d=\frac{\rho}{2\varepsilon}\left[r_1^2\ln\left(\frac{r_2}{r_1}\right)-\frac{1}{2}\left(r_2^2-r_1^2\right)\right]$$

to minimise detector capacitance r_1 should be kept small

$$C=\frac{2\pi\pi}{\ln\left(\frac{r_2}{r_1}\right)}$$

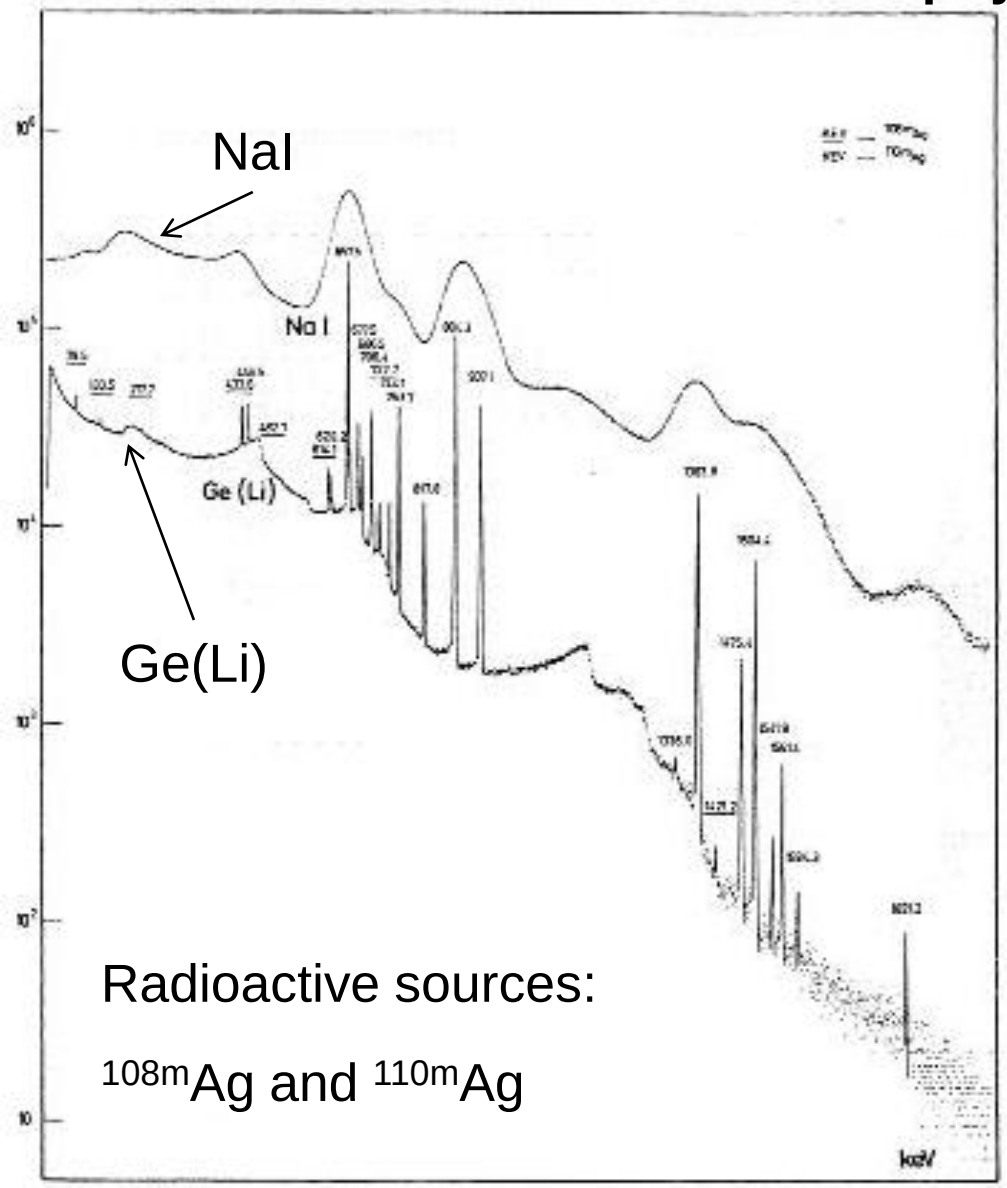






- Instrument Components

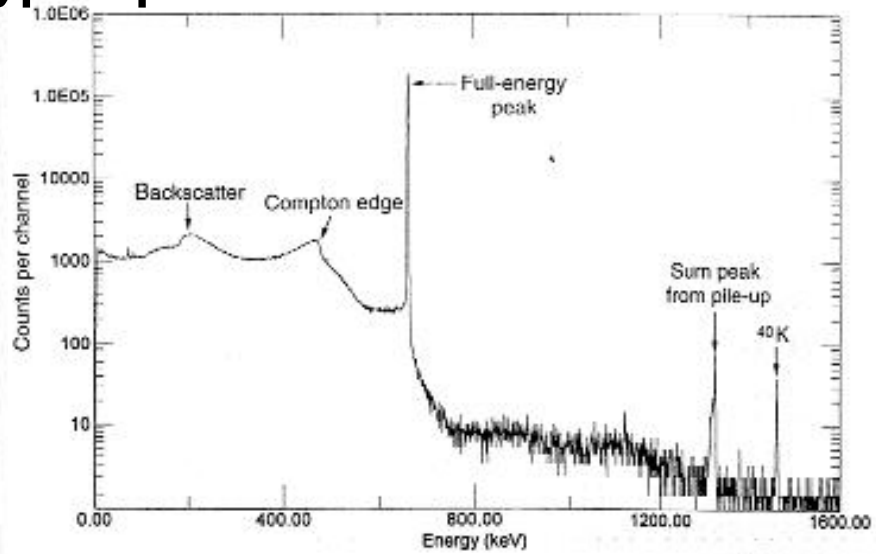
Typical gamma ray spectra with Ge detectors



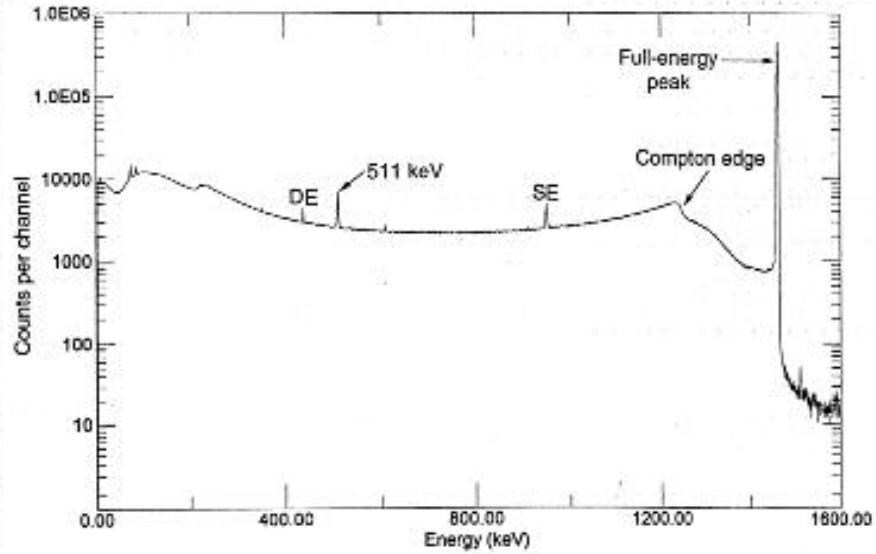
Radioactive sources:

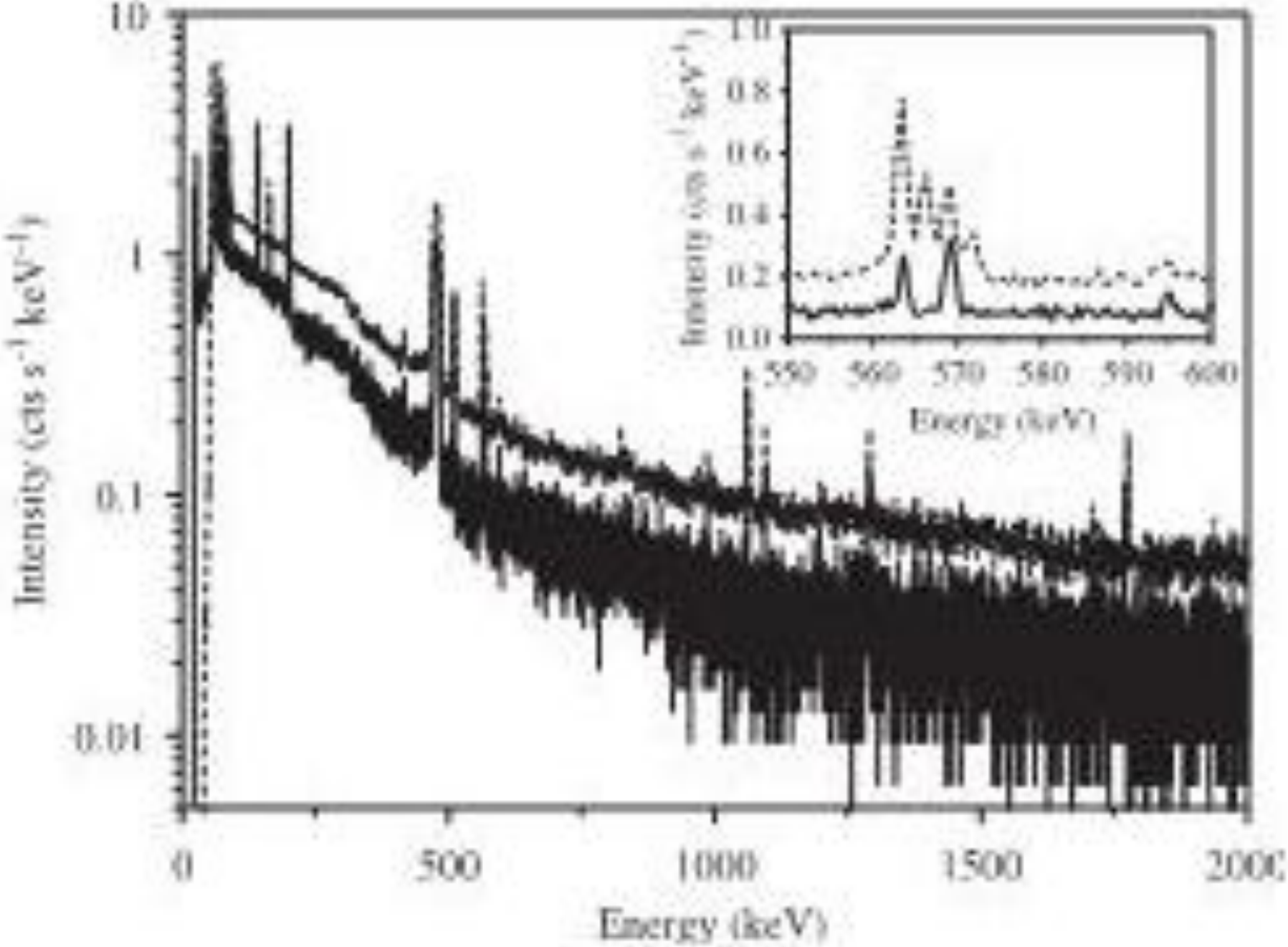
^{108m}Ag and ^{110m}Ag

p-type HpGe with 662 keV ^{137}Cs source

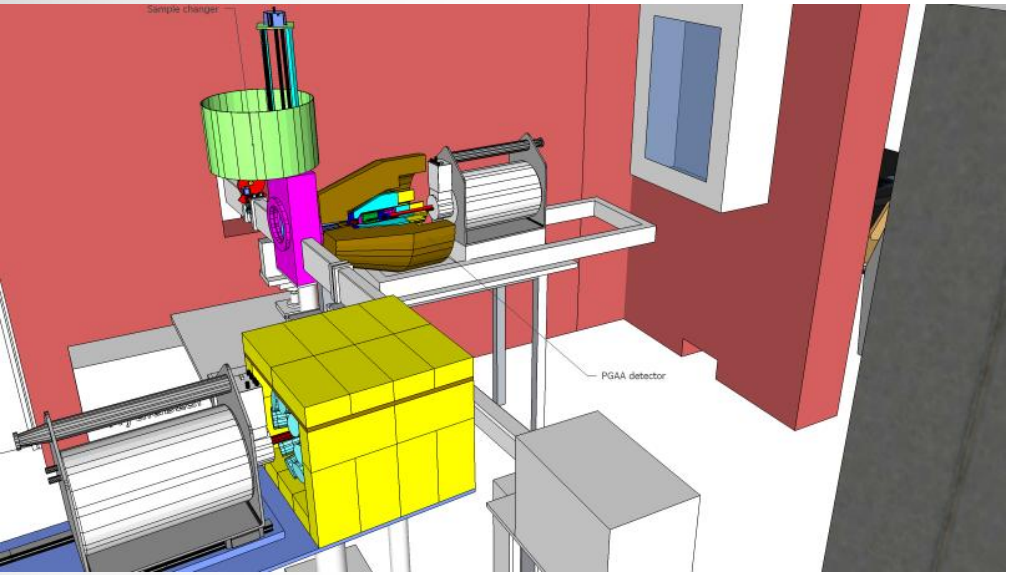


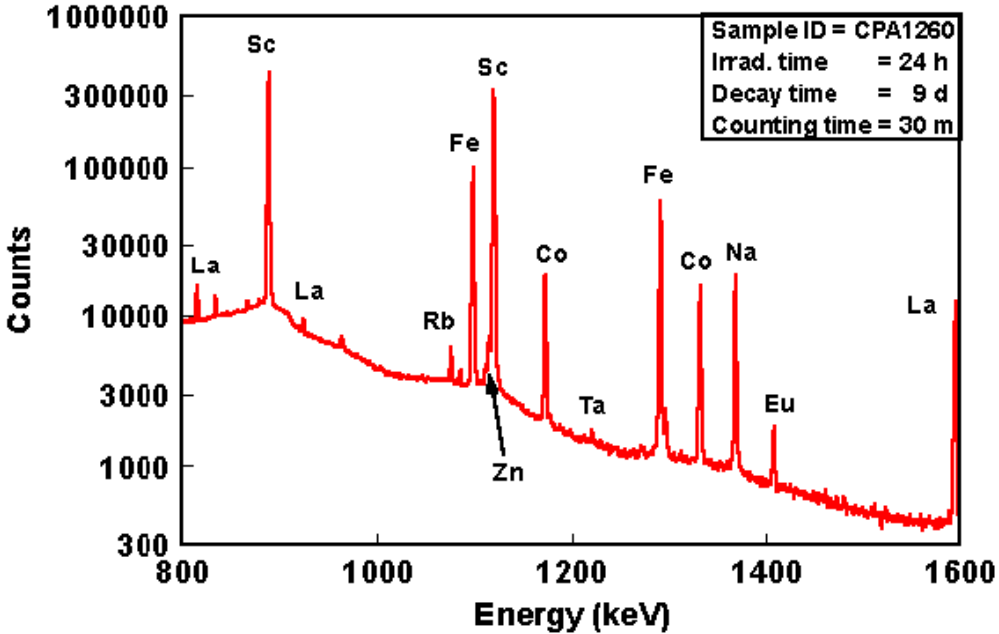
p-type HpGe with 1460 keV ^{40}K source

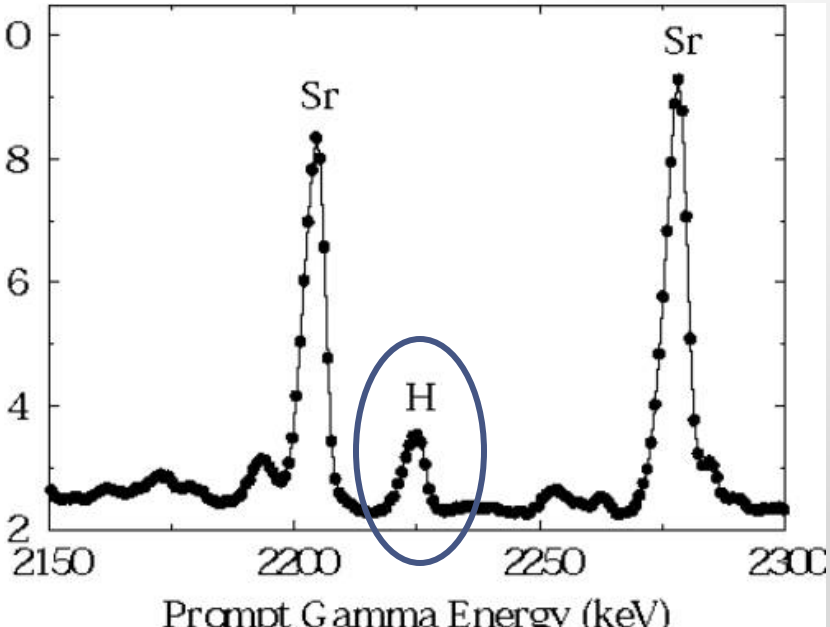



Intensity (cts s^{-1} keV^{-1})
10
1
0.1
0.01
0
500
1000
1500
2000
Energy (keV)
Intensity (cts s^{-1} keV^{-1})
1.0
0.8
0.6
0.4
0.2
0.0
550
560
570
580
590
600
Energy (keV)

Prompt gamma activtion analysis







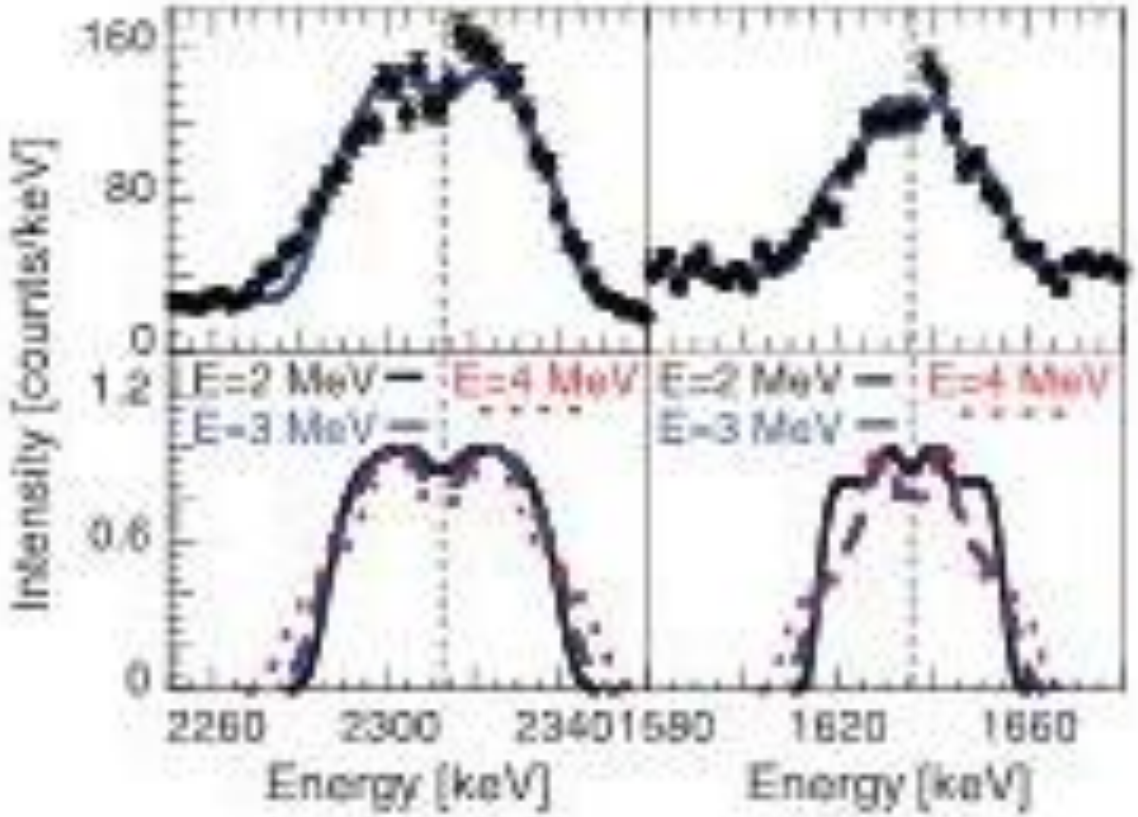
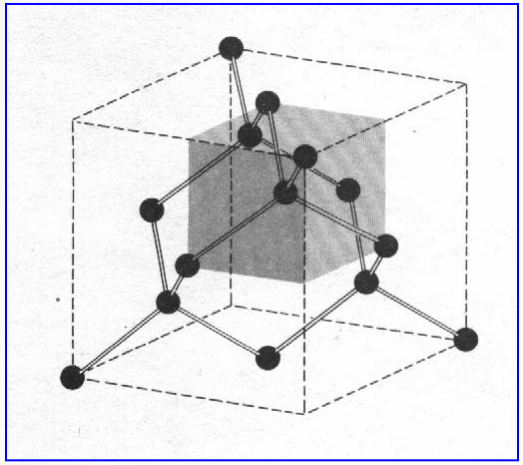
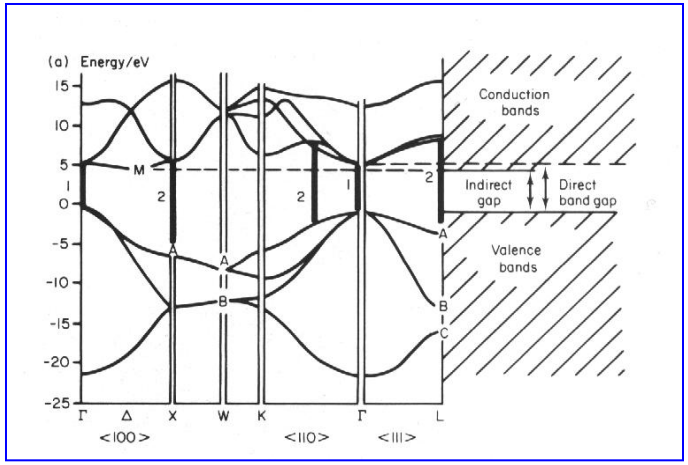


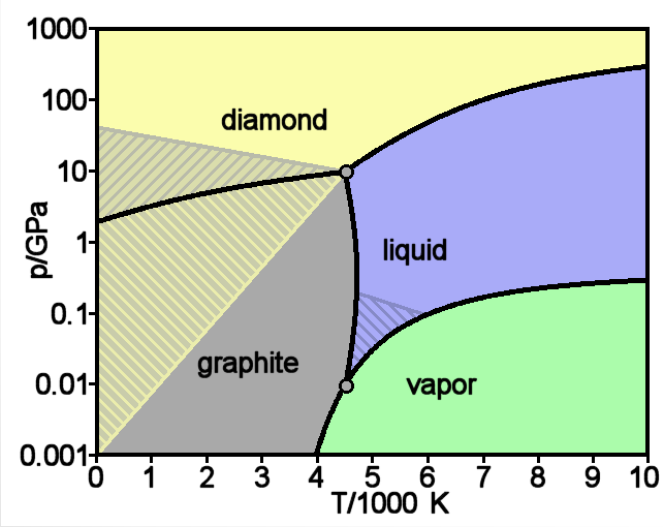
FIG. 1 (color). Top: experimental and fitted (solid line) peak shapes for the $E_{\gamma 1}$ (left) and $E_{\gamma 2}$ (right) γ-ray emission peaks. The unshifted $E_{\gamma 1} = 2313$ keV and $E_{\gamma 2} = 1635$ keV values are marked with vertical dashed lines. Bottom: Normalized simulated $E_{\gamma 1}$ (left) and $E_{\gamma 2}$ (right) peak shape for monoenergetic ^{3}He ions with Gaussian pitch angle distribution centered at $\theta_p = 90°$ and with FWHM $= 10°$.

Diamond detectors

Diamond properties







Lattice constant	**3.56 Å**
Nearest neighbours	**1.54 Å**
Band Gap	**5.5 eV**
$V_{breakdown}$	**10 V/µm**

Low intrinsic cariier density and thus room tempetature operation

Diamond properties

HARDNESS	9000 Kg/mm2	(the higest)
YOUNG'S MODULES	1012 N/m2	(the strongest)
FRICTION	0.05	(the lowest)
THERMAL CONDUCTIVITY	20 W/cm K	(5 times Cu)
ELECTRICAL RESISTIVITY	10^{16} Ωcm	
ELECTRICAL BREAKDOWN	10^{7} V/cm	(30 times GaAs)
ELECTRON, HOLE MOBILITY	>2000 cm2/V s	
OPTICAL ABSORPTION	transparent from IR to IV (5.4 eV)	
MELTING POINT	3350 °C	
RADIATION HARDNESS	very high	
CHEMICAL REACTIVITY	extremely low	

Diamond growth

Natural Diamond

- Syngle crystal
- Small in size
- Low availability - high cost
- No reproducibility

- Synthetic diamond

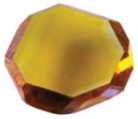
Chemical Vapor Deposition (CVD)

High Pressure – High Temperature (HPHT)

Diamond growth

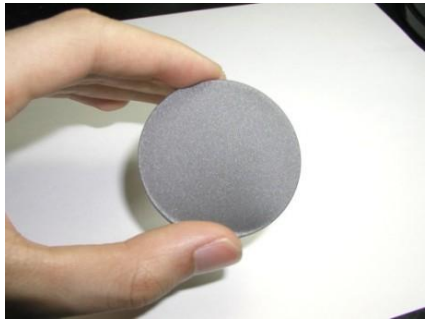
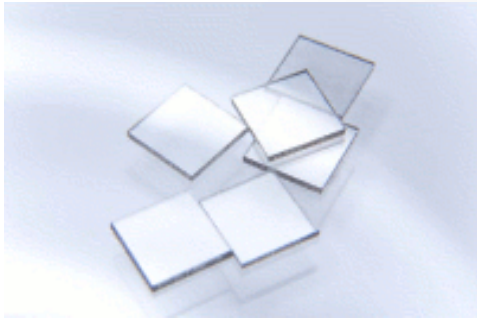
Synthetic HPHT diamond

- Single crystal
- Small in size
- Low cost
- Poor electronic quality



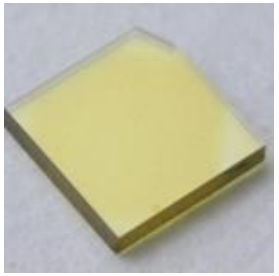
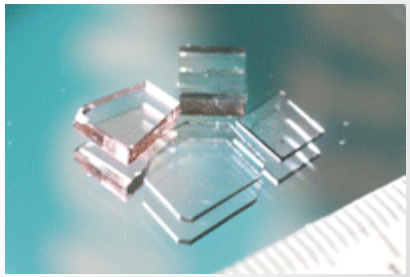
Polycrystalline CVD diamond

- Low cost and large area possible
- Polycrystalline (no energy resolution)
- Effect of “priming” or “pumping”
- Polarization and memory effects

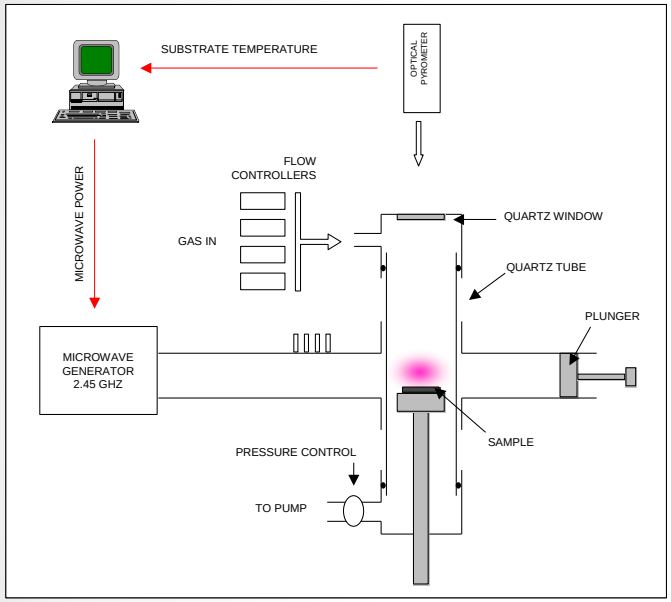
Synthetic CVD single crystal diamond

- Single crystal
- Small in size
- High electronic quality

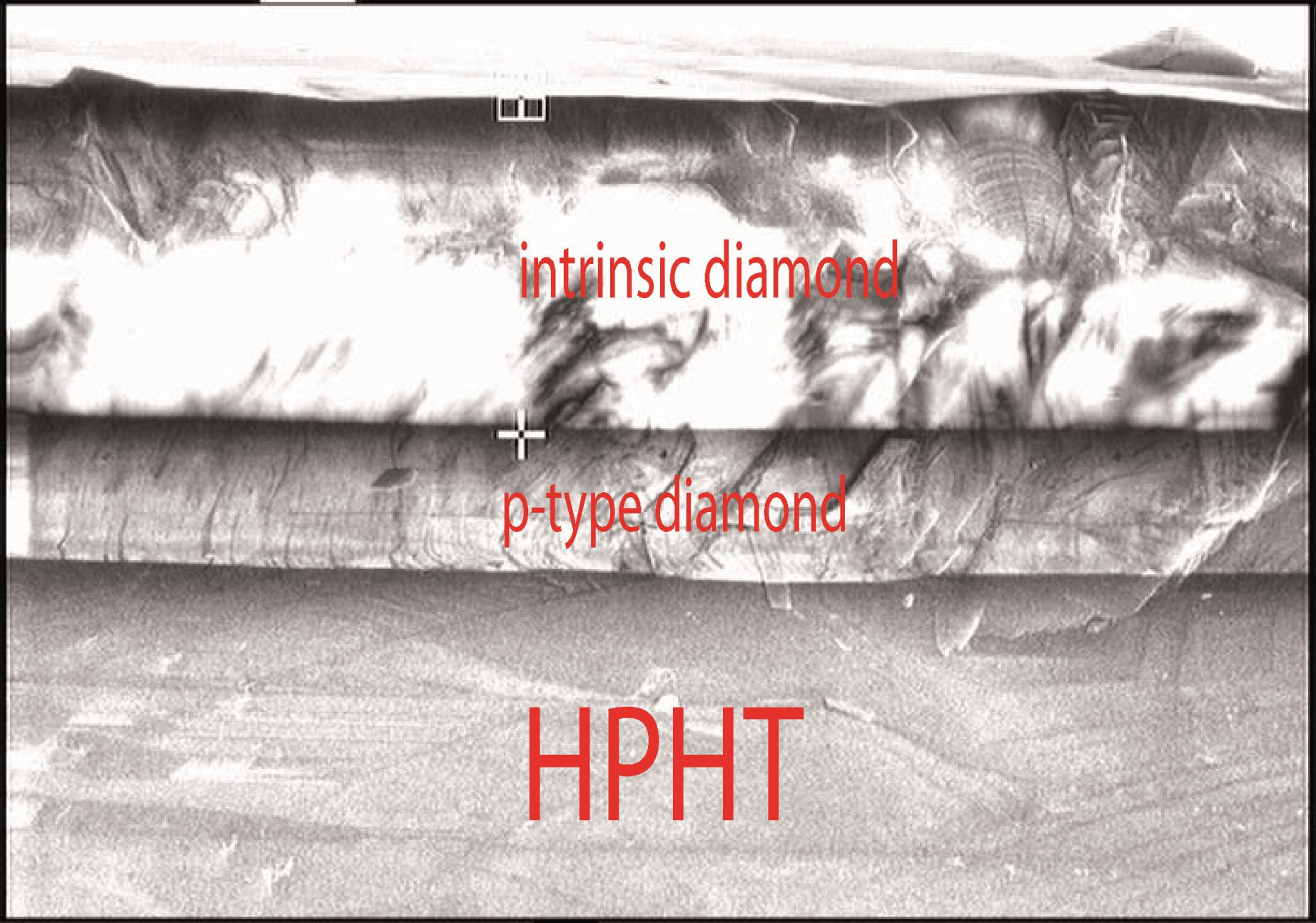
CVD diamond deposition

•Microwave Plasma CVD



•Typical growth parameters

Plasma composition	99% H_2- 1% CH_4,
Temperature	650 – 800 °C
Microwave power	600 - 1300 W
Pressure	100 - 150 mbar
•Gas flow rate	100 sccm


612X 30kV WD:65mm S:00000 P:00000
49.3um POINT-TO-POINT
intrinsic diamond
p-type diamond
HPHT

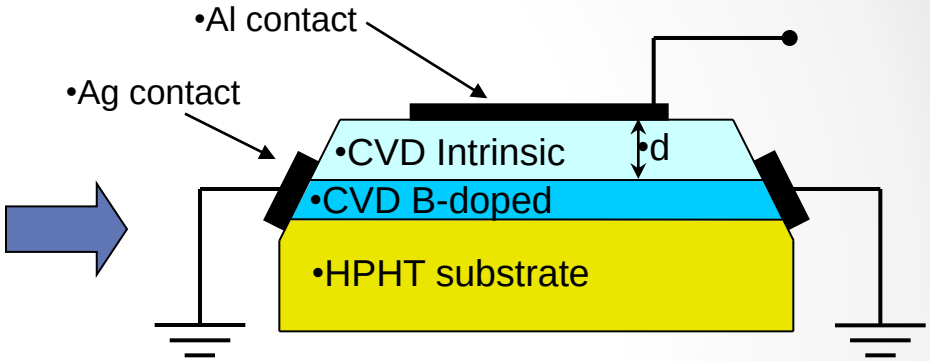
Particle detectors

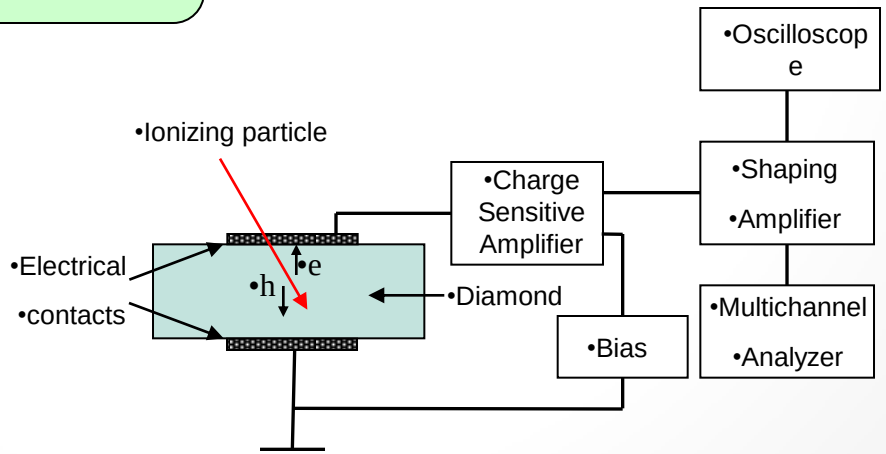
Performance, Stability and Reproducibility needed

-Diamond quality

-Electrical contacts

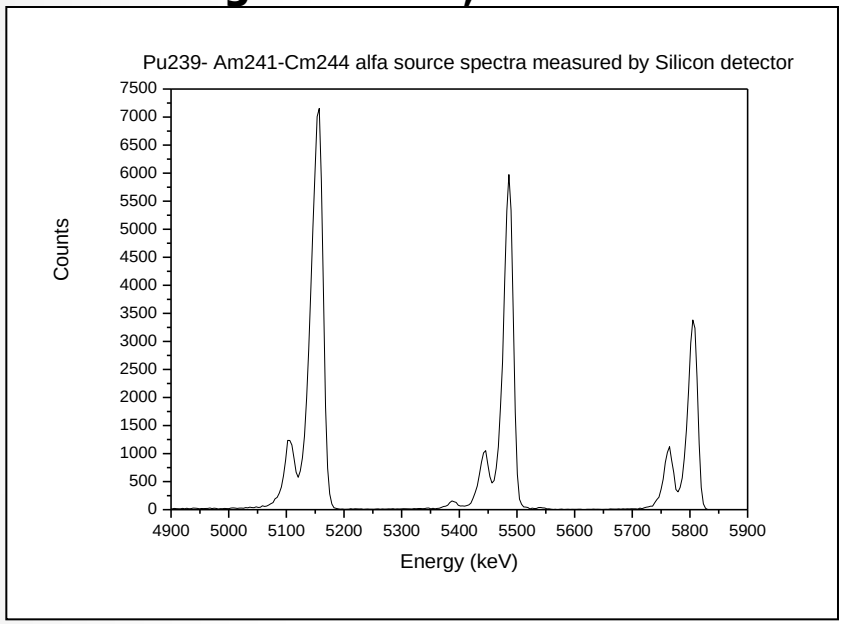
- Remove substrate contribution

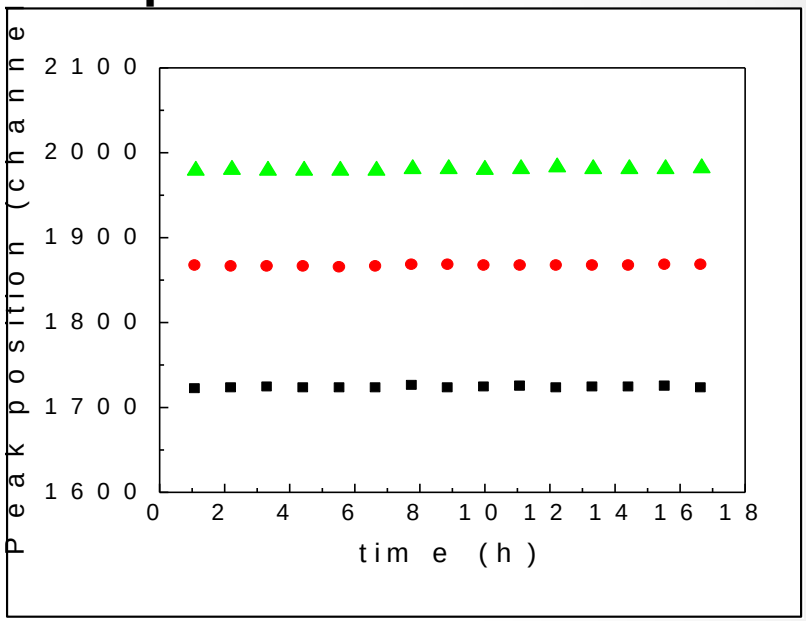




α particle test

- **Triple α source (^{239}Pu, ^{241}Am, ^{244}Cm)**
- **emitting 5.16 MeV, 5.48 MeV and 5.80 MeV α-particles**

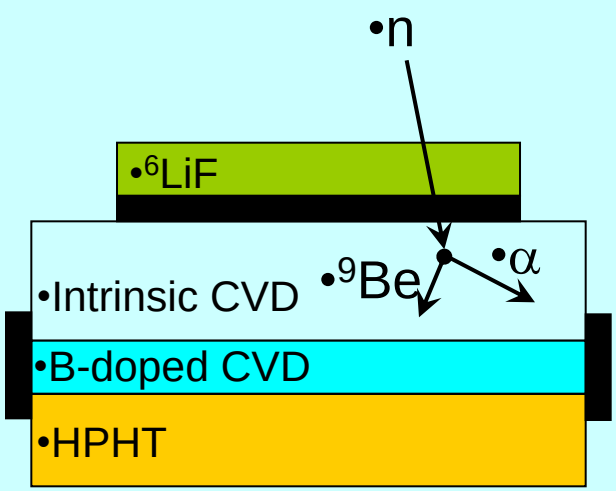




- ✓ **100 % charge collection efficiency**
- ✓ **100 % detection efficiency**
- ✓ **0.5-1.8 % energy resolution**
- ✓ **No pumping (priming) effects**
- ✓ **Long term stability**

Neutron detection

•Fast neutrons

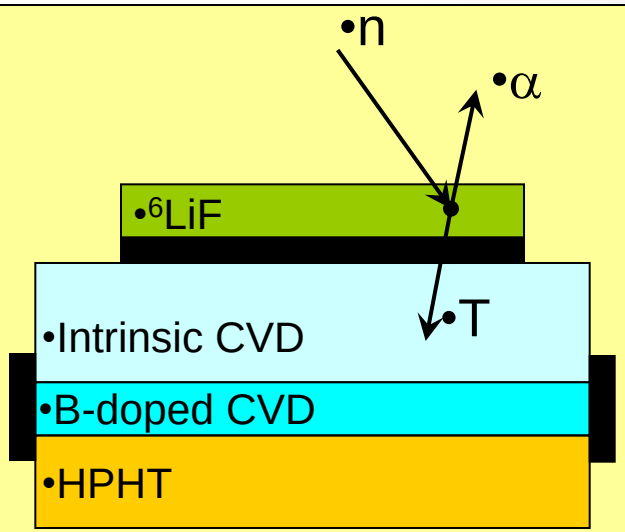


$^{12}C(n,\alpha)^9Be$ reaction

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

$$Q = -5.7 \text{ MeV}$$

•Thermal neutrons



•95% enriched ^{6}LiF layer deposited onto the Al contact area

Thermal neutron are detected through the products of the reaction:

$$n + {}^{6}Li \rightarrow T + \alpha$$

$$E_T = 2.73 \text{ MeV}$$

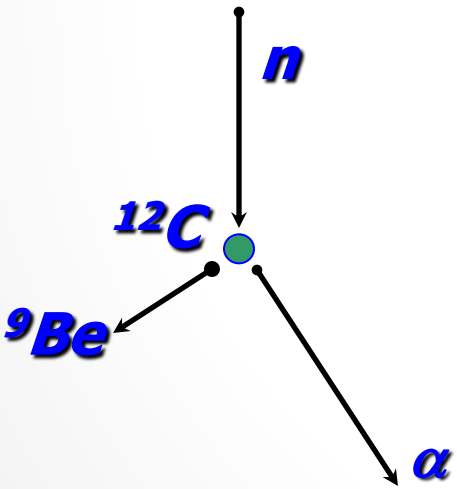
$$E_\alpha = 2.06 \text{ MeV}$$

INSIS

“Fast” Neutron detection

•Fast neutrons directly interact with C in the diamond sensing layer :

$^{12}C(n,\alpha)^{9}Be$ reaction



α and ^{9}Be are simultaneously detected whith a total energy:

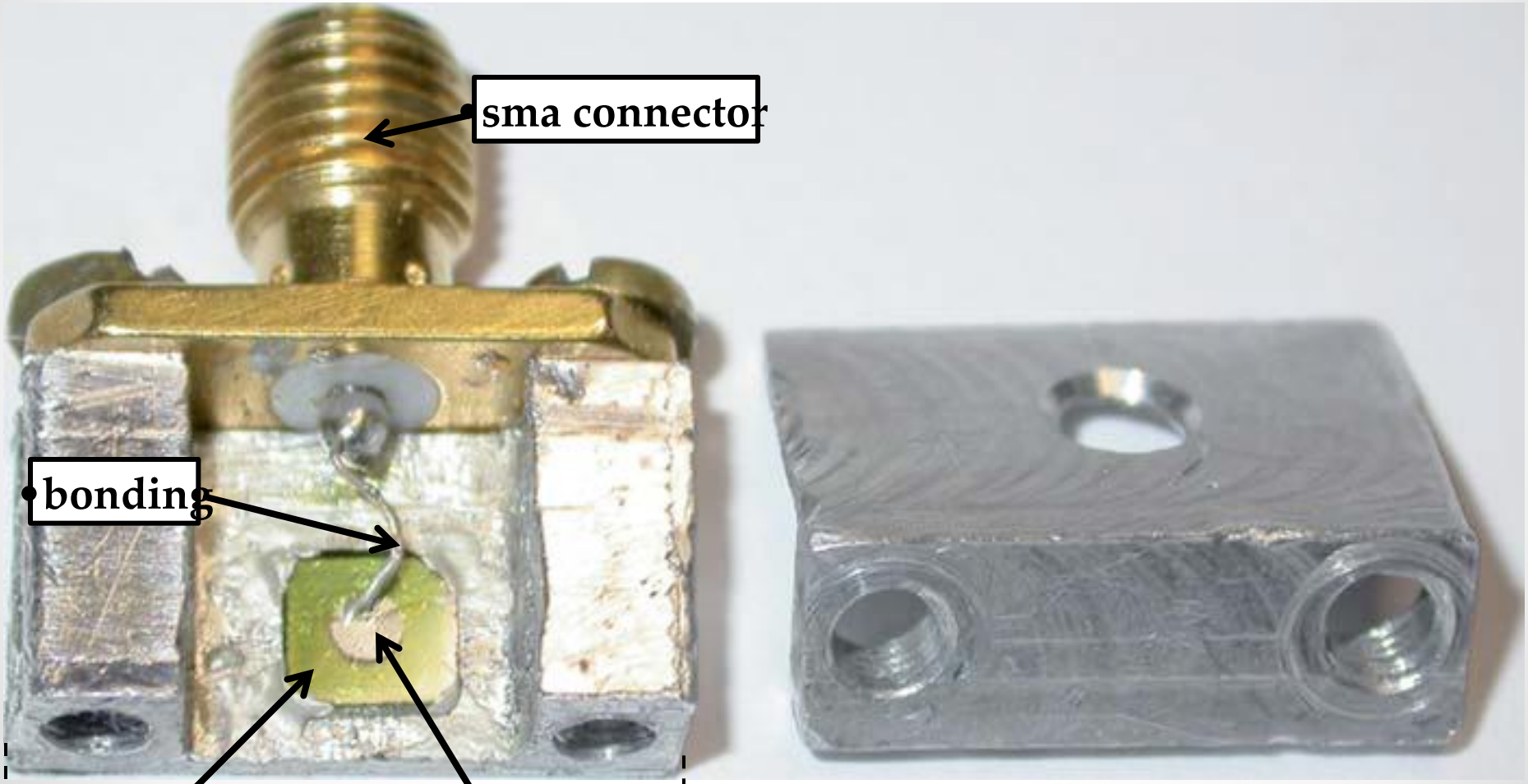
$E_{rel} = E_n - 5.7MeV$:

E_n =14.8 MeV ⇒ E_{rel} = 9.1 MeV

E_n=14.1 MeV ⇒ E_{rel} = 8.4 MeV

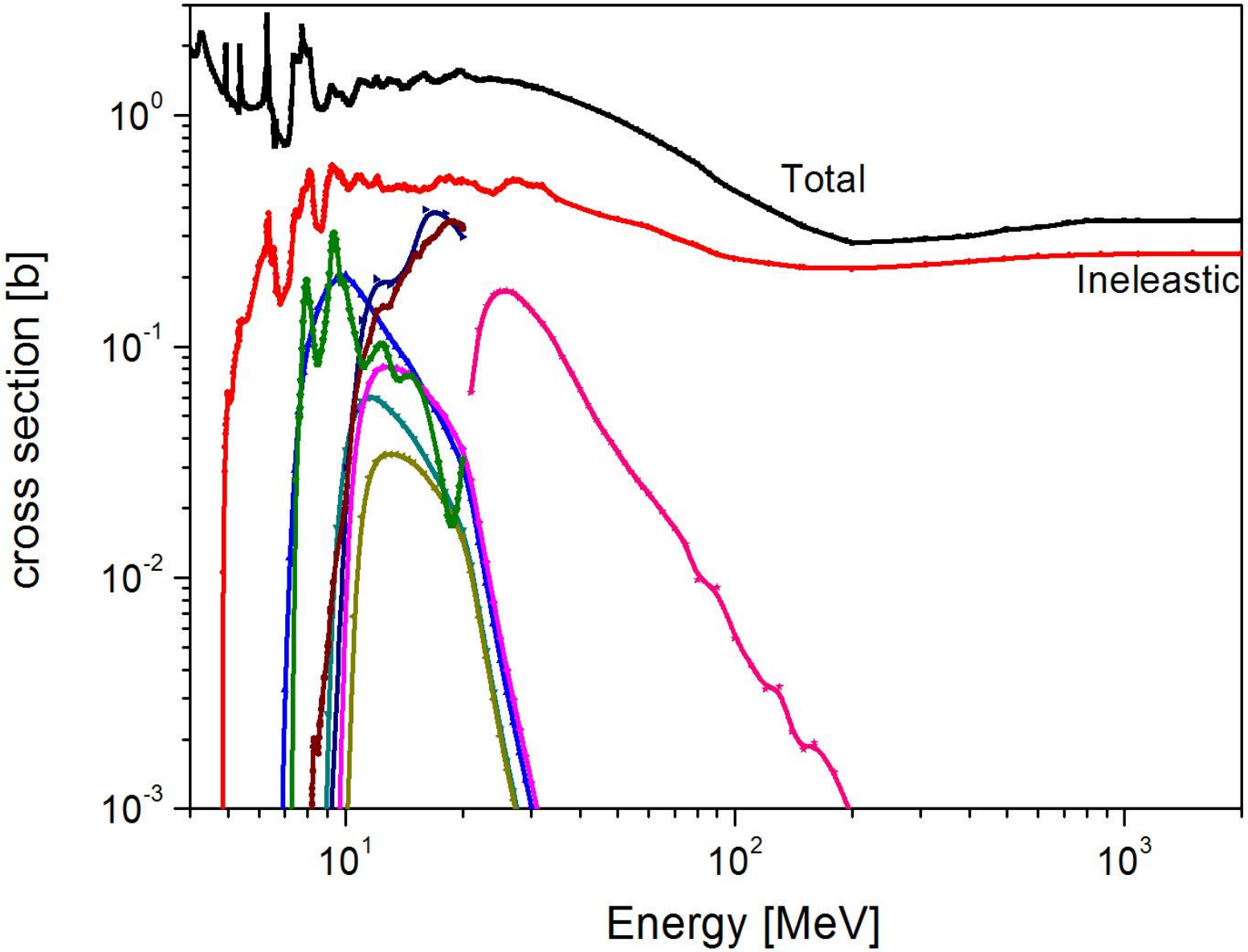
- Localized flux monitoring: Single Crystal Diamonds

SCD by Chemical Vapor Deposition



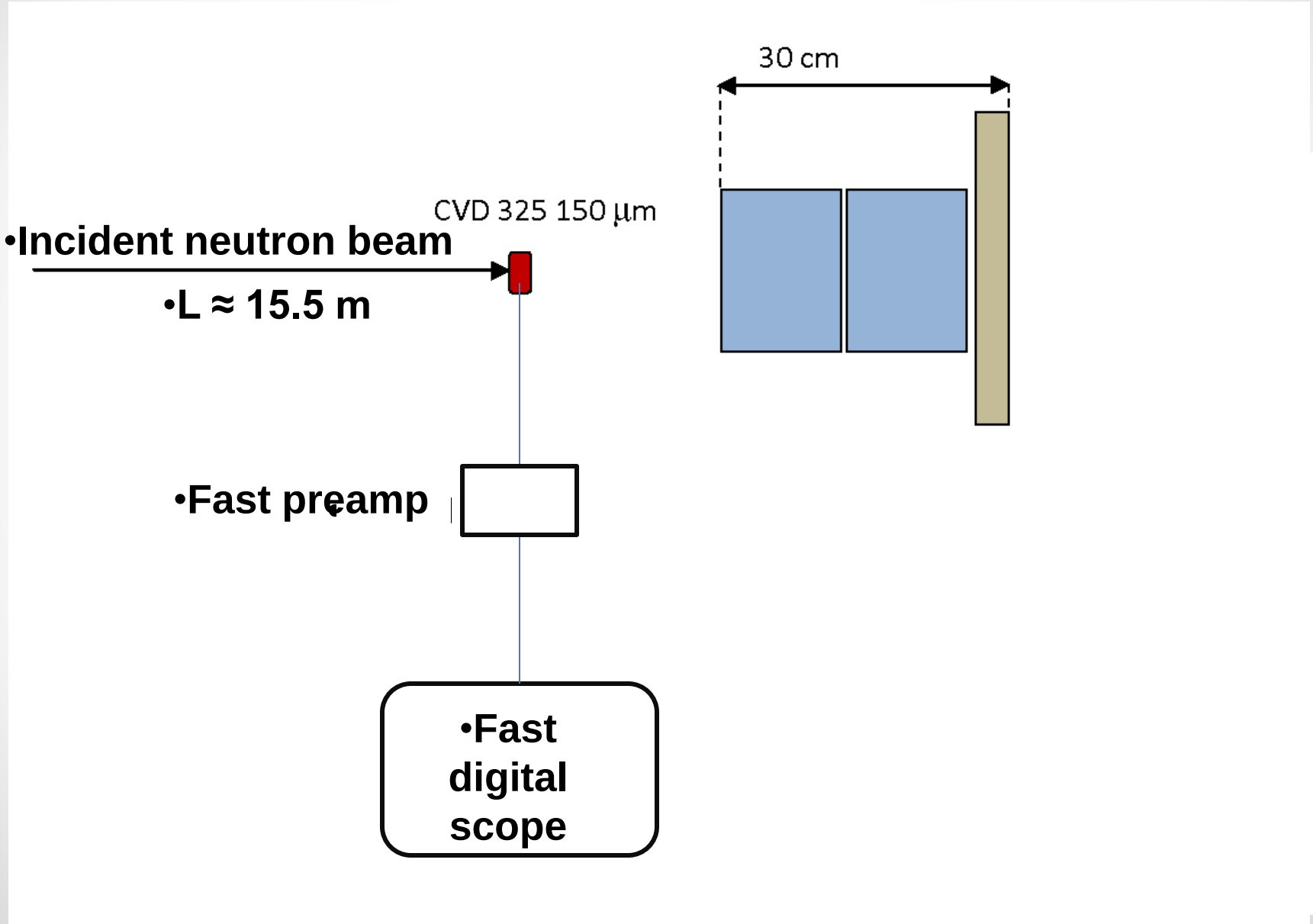
•~15 mm

•*n-^{12}C* neutron cross sections

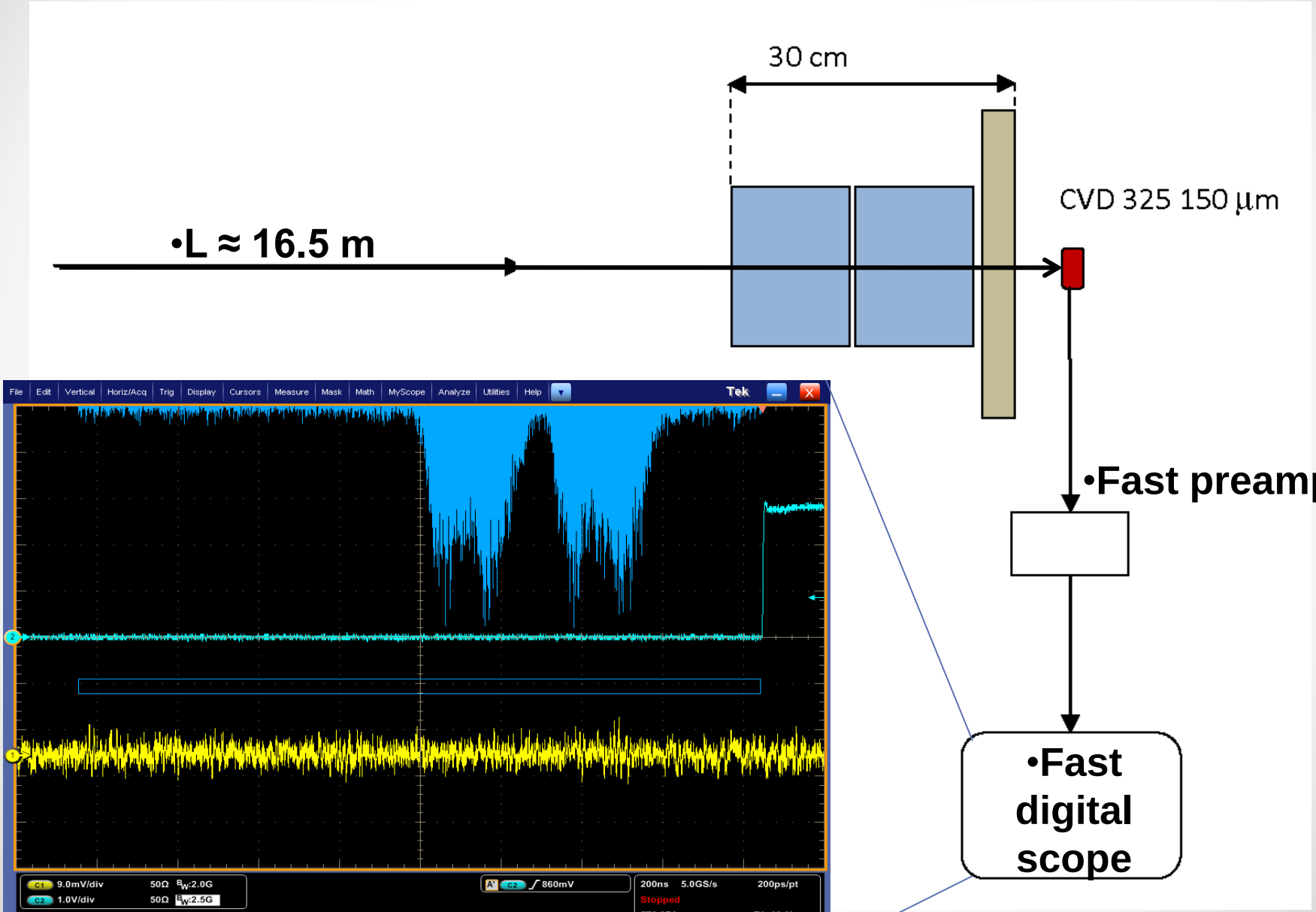


- **Test results: TOF spectra on ROTAX beam line at ISIS-TS1**

SET UP

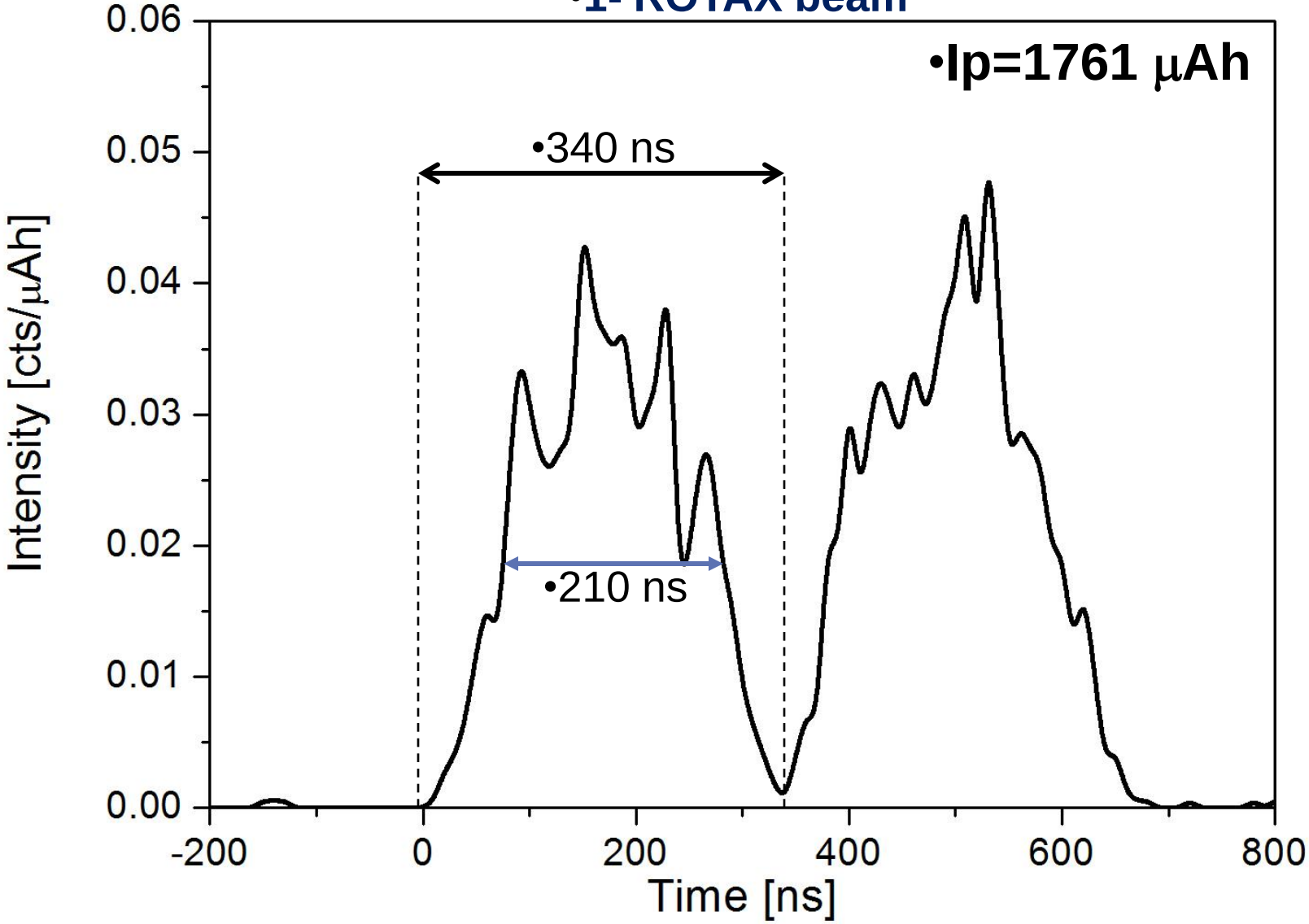

30 cm
CVD 325 150 µm
•Incident neutron beam
•L ≈ 15.5 m
•Fast preamp
•Fast digital scope

SET UP


30 cm
CVD 325 150 µm
•L ≈ 16.5 m
•Fast preamp
•Fast digital scope
File Edit Vertical Horiz/Acq Trig Display Cursors Measure Mask Math MyScope Analyze Utilities Help
Tek
C1 9.0mV/div 50Ω BW:2.0G
C2 1.0V/div 50Ω BW:2.5G
A C2 860mV
200ns 5.0GS/s 200ps/pt
Stopped
573 371 acqs RL:10.0k
Auto October 15, 2008 02:35:37

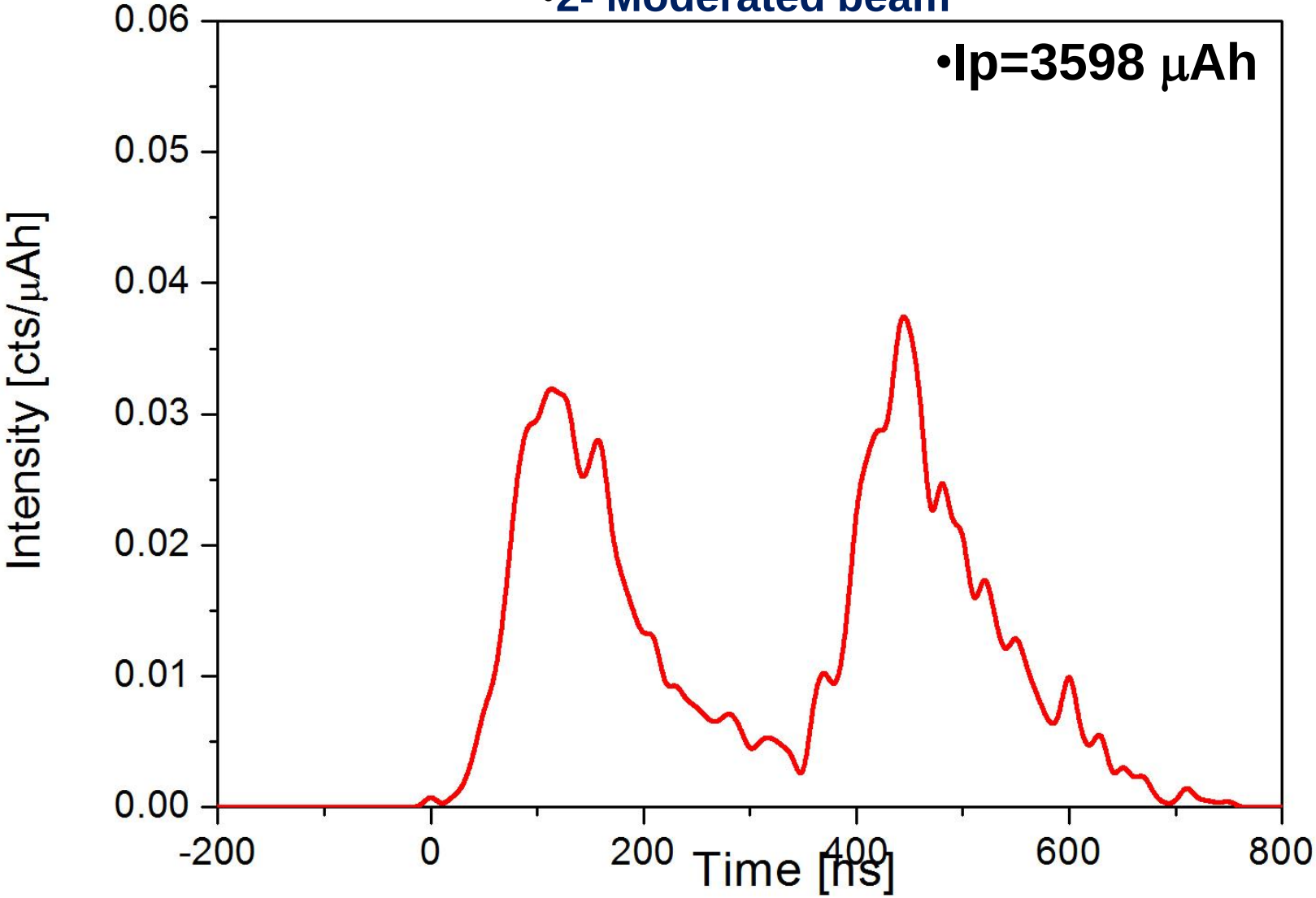
•TOF SPECTRUM FROM DIAMOND

•1- ROTAX beam

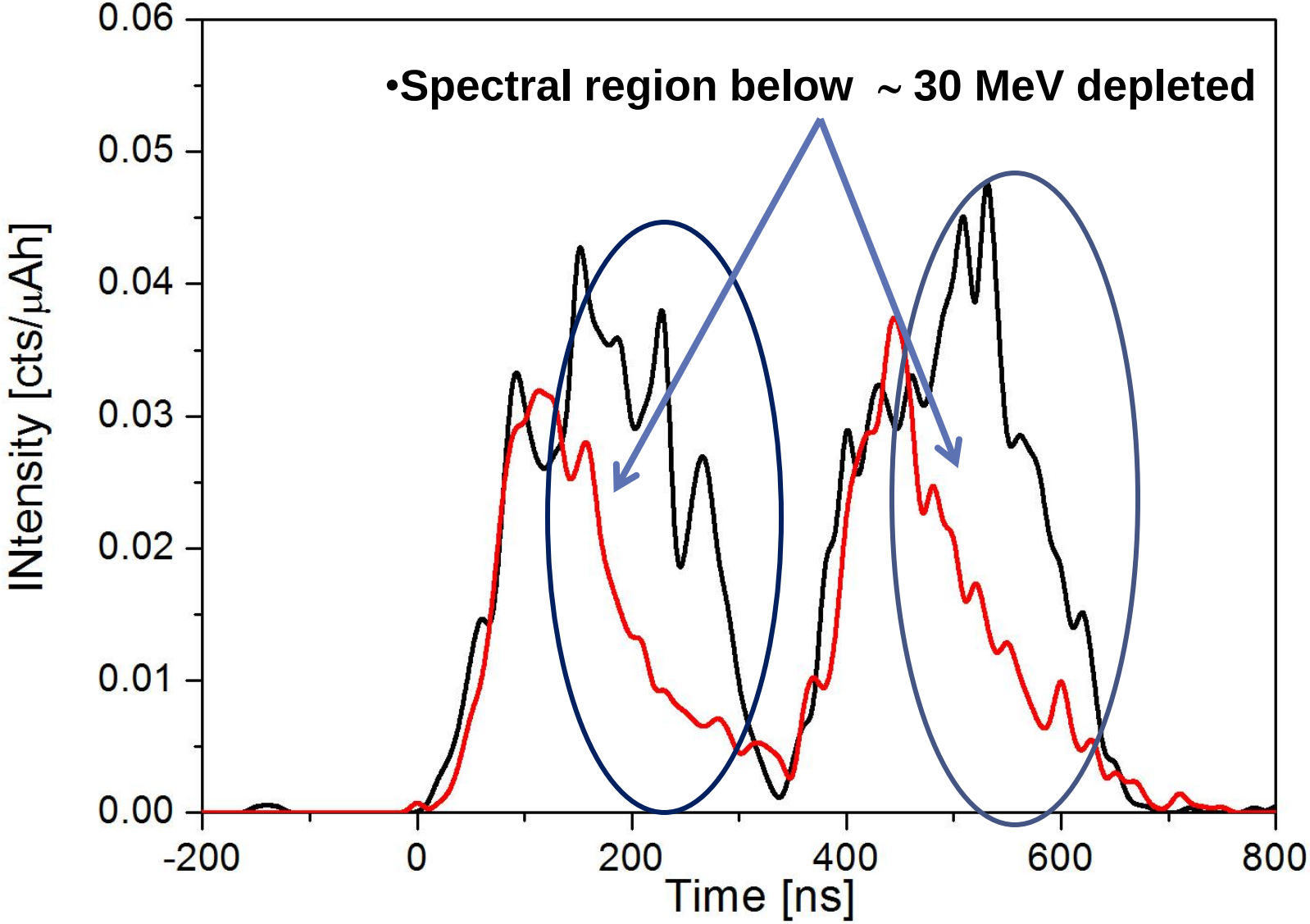


•TOF SPECTRUM FROM DIAMOND

•2- Moderated beam



•TOF SPECTRA FROM DIAMOND

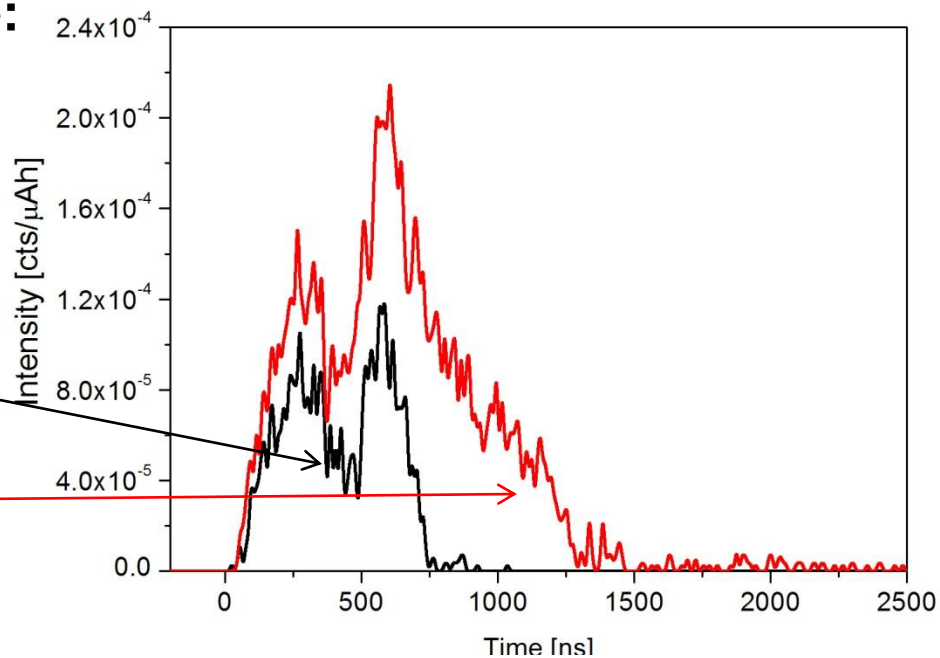


•**Modifying the diamond response:**

1- with a fissile material

Only diamond

Diamond + ^{nat}U sheet 30 μm



THANK YOU FOR YOUR ATTENTION