Lecture 13: Radiation detectors II

- Germanium detectors
  - Planar
  - Coaxial
  - Energy resolution
  - Efficiency

Interaction of gamma-rays with matter

- Gamma radiation is a very penetrating form of radiation that does not directly ionise the material through with it travels.
- The three main interaction processes responsible for gamma-rays interacting with matter are:
  - Photoelectric absorption
  - Compton Scattering
  - Pair Production
- Following such an interaction an electron with a finite amount of energy will be left in the semiconductor material.

Germanium : Advantages

- Germanium semiconductor detectors are the configuration of choice for gamma-ray spectroscopy:
  - Can be made hyperpure and therefore large crystals can be fully depleted.
  - High Z (32) compared to Silicon (14) (Cross-section for photoelectric absorption $\propto Z^4$).
  - Excellent energy resolution due to low (3eV) ionisation energy – much better than scintillator technology

Germanium detectors

- Germanium semiconductor detectors are the detector of choice for applications in gamma-ray spectroscopy.
- The major limitation is the maximum depletion depth or active volume that can be created ~3mm for normal semiconductor purity.
- Much thicker detectors are required for gamma-ray spectroscopy.

$$d \cong \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$$

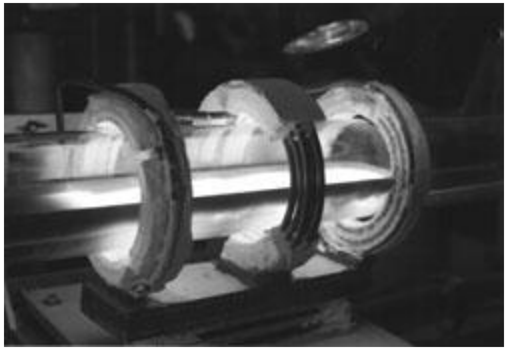
Germanium detectors

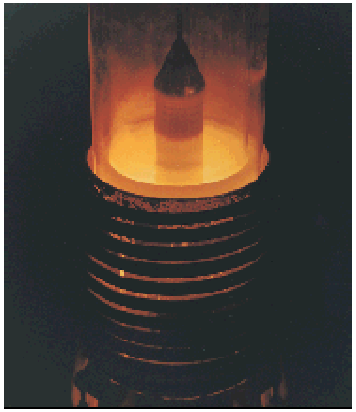
- To accomplish this goal there are two general approaches:
  - Further refine the semiconductor reducing the impurity concentration to ~10^{10}atoms/cm^3. Such an impurity concentration would give a 1cm depletion depth at 1000V reverse bias. Techniques have been developed to achieve this goal in Germanium, but not in Silicon. Detectors based on this technique are called High-Purity Germanium detectors (HPGe).
  - Create a compensated material where residual impurities are balanced by equal concentration of dopant atoms. Such lithium ion drifting is added to the semiconductor following crystal growth. Such detectors are called Ge(Li) detectors.
- HPGe detectors have superseded Ge(Li) detectors because HPGes offer much better operational convenience.

Exercise: Calculate d for a planar HPGe detector with a net impurity concentration of $N=10^{10}$ atoms/cm^3 and a reverse bias of 2000 V

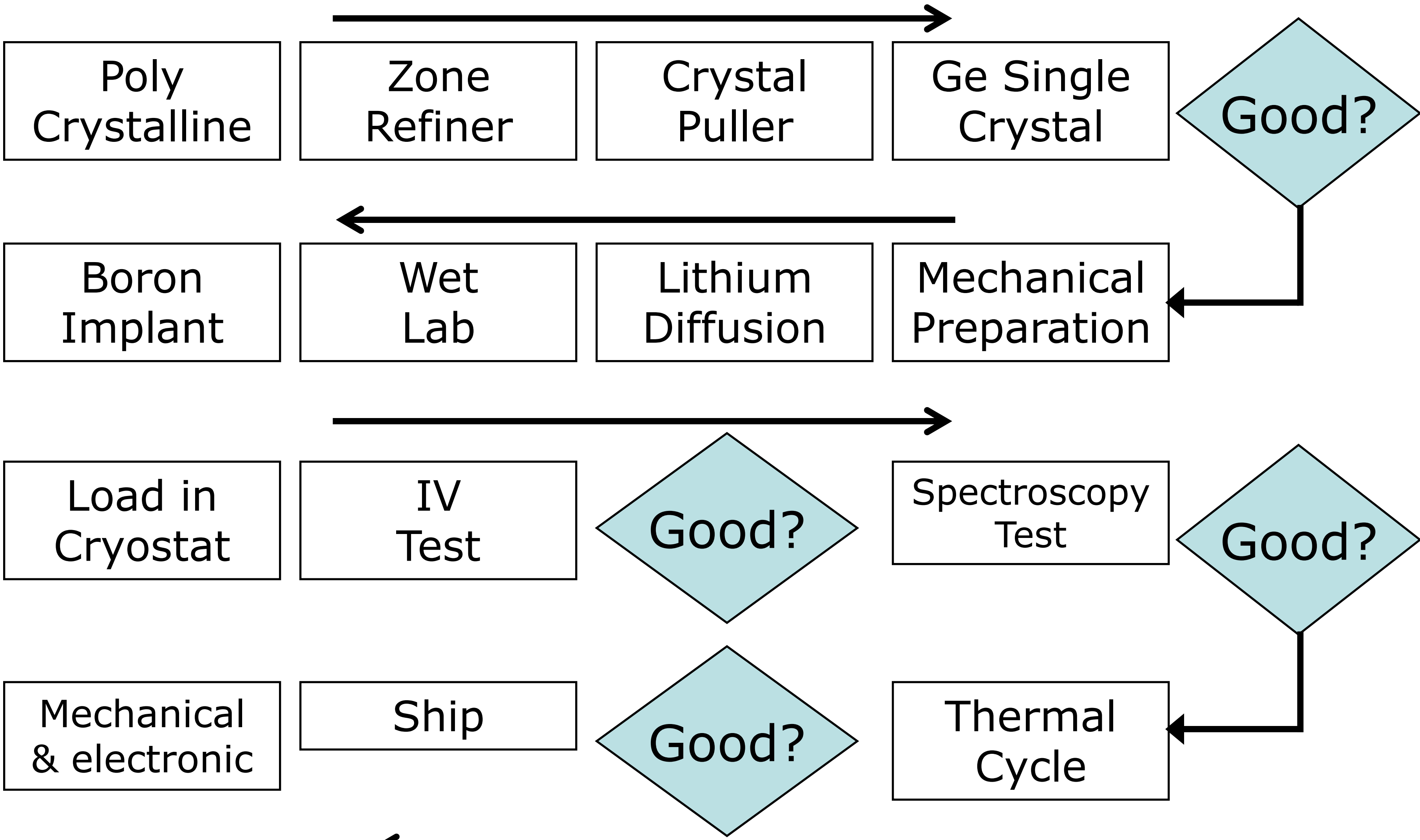
HPGe detector fabrication

- Starting material is bulk Ge for semiconductor industry, already of high purity
- Processed by **zone refining**: impurity levels are progressively reduced by locally heating and slowly passing a melted zone through the material many times
- Impurities are more soluble than Ge: they are transferred to the molted zone and swept away
- Large single crystals of Ge are slowly grown from this material of extremely high purity





HPGe detector manufacturing



Poly Crystalline

Zone Refiner

Crystal Puller

Ge Single Crystal

Good?

Mechanical Preparation

Lithium Diffusion

Wet Lab

Boron Implant

Load in Cryostat

IV Test

Good?

Spectroscopy Test

Good?

Thermal Cycle

Good?

Ship

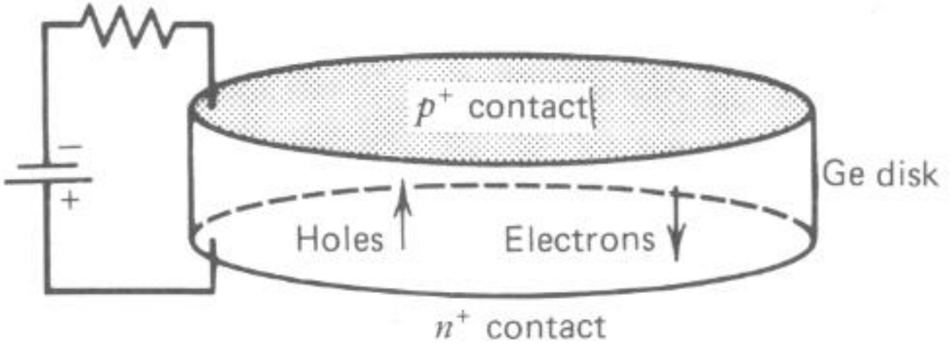
Mechanical & electronic

Courtesy Ortec, Oak Ridge, USA

HPGe detector configurations

- Planar detectors:
  - The n⁺ contact can be formed by lithium evaporation and diffusion or ion implantation.
  - The detector depletion region is formed by reverse biasing the n^+-p junction.
  - The other contact must be non-injecting for a majority carrier. It may consist of a p⁺ contact formed by ion implantation of acceptors (thin) or a metal-semiconductor surface barrier (Shottky barrier).

Fully depleted detector



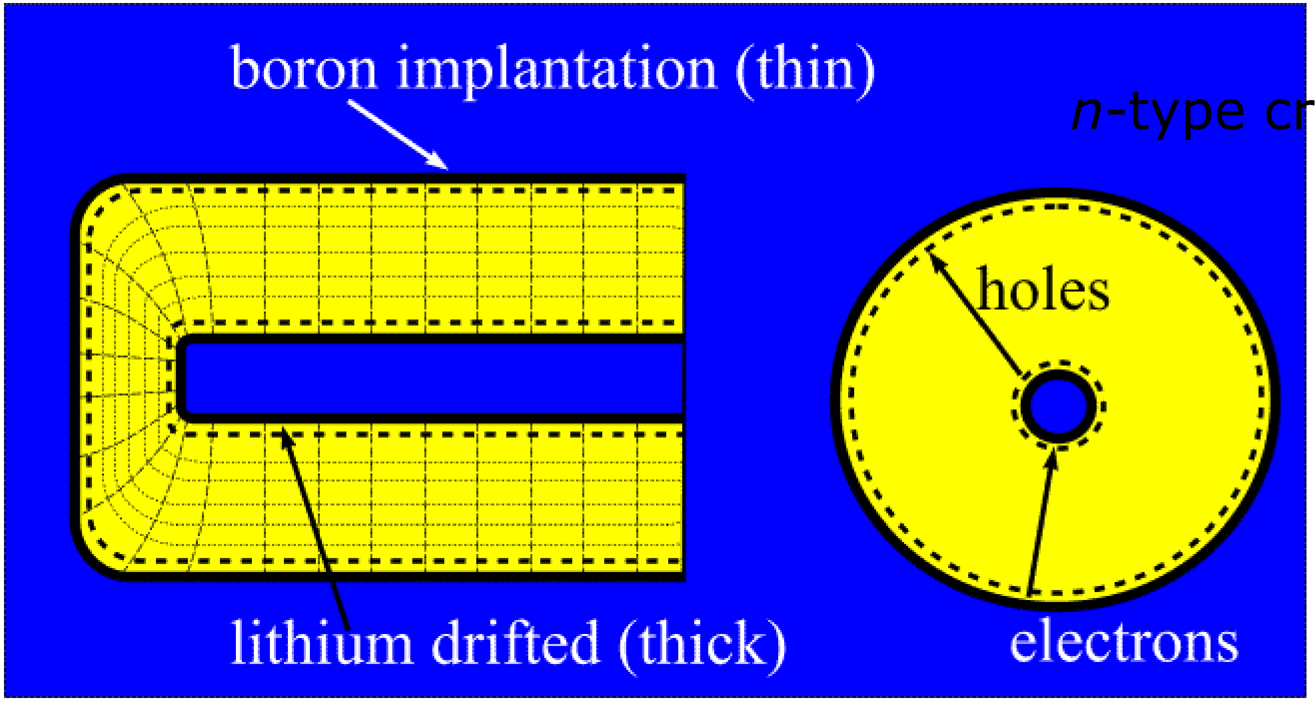
Operated at 77K

Planar Germanium detectors

- Are operated as fully depleted detectors.
  - Reverse bias requires that a positive voltage be applied to the n^+ contact with respect to the p^+ surface.
  - The depletion region begins at the n^+ contact and extends further into the detector as the voltage is raised.
  - Further increases in voltage increase the E-field everywhere by a uniform amount.
- The detector voltage is increased in order to saturate the drift velocity of the charge carriers minimising collection time and detrimental effects due to carrier recombination and trapping.
- Saturation velocity for electrons in germanium at 77K is reached with a minimum field of 10^5V/m

Closed-end coaxial Germanium

- In the closed end coaxial configuration the electric field lines are no longer radial, as they would be in the true coaxial case.
- The bulletized closed end geometry rounds the corners of the crystal which helps prevent localised weak E-fields.



Types of contacts on coaxial detectors

- Li diffusion is used to form the n+ contact
- Boron is ion implanted to produce the p+ contact.

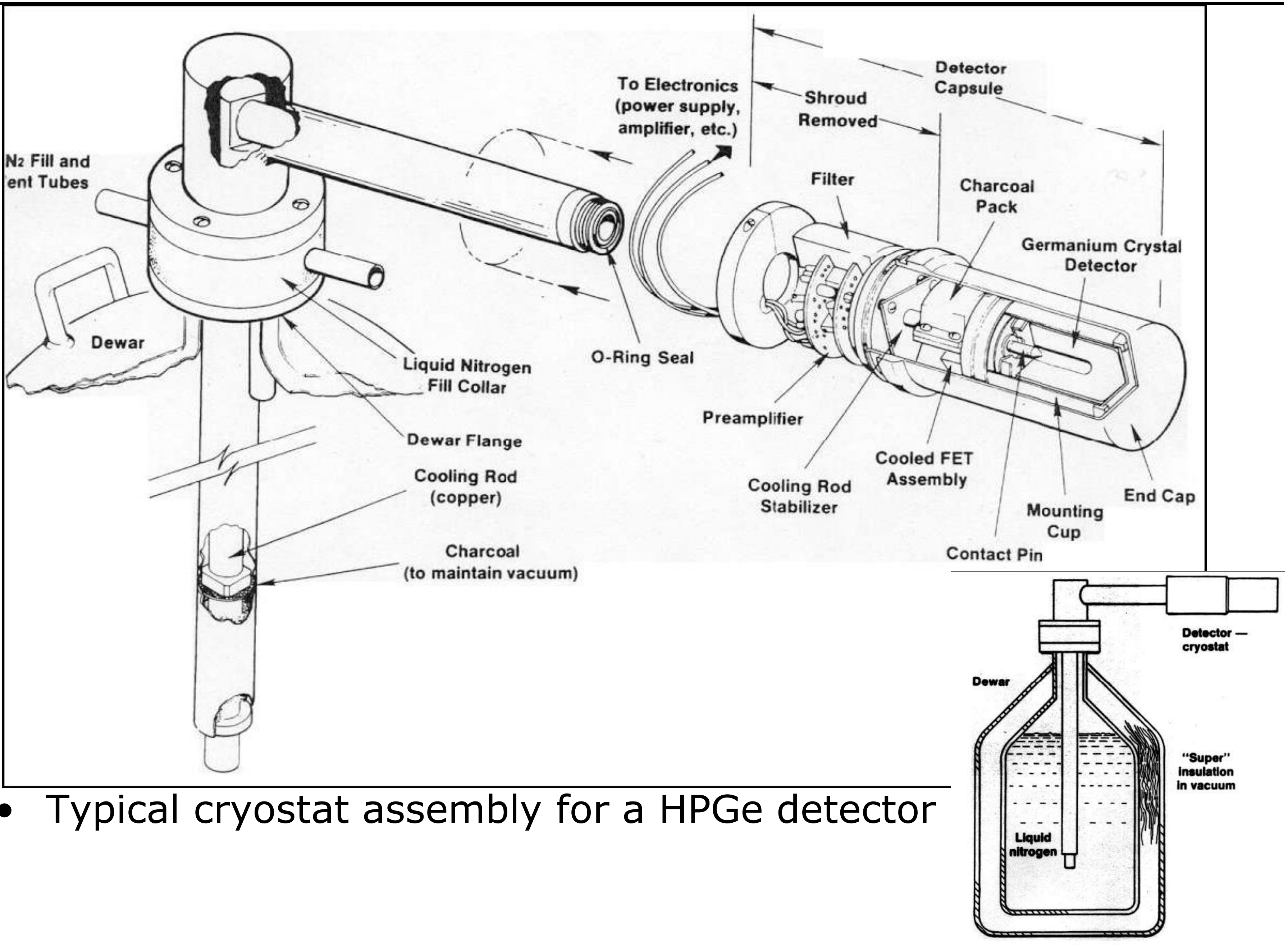
In Coaxial crystals:

	Outer Contact	Inner Contact
p-type	n(Li)	p(B)
n-type	p(B)	n(Li)

The n ~ 600 μm - 1 mm, p contact is very thin ~ 0.3 μm.

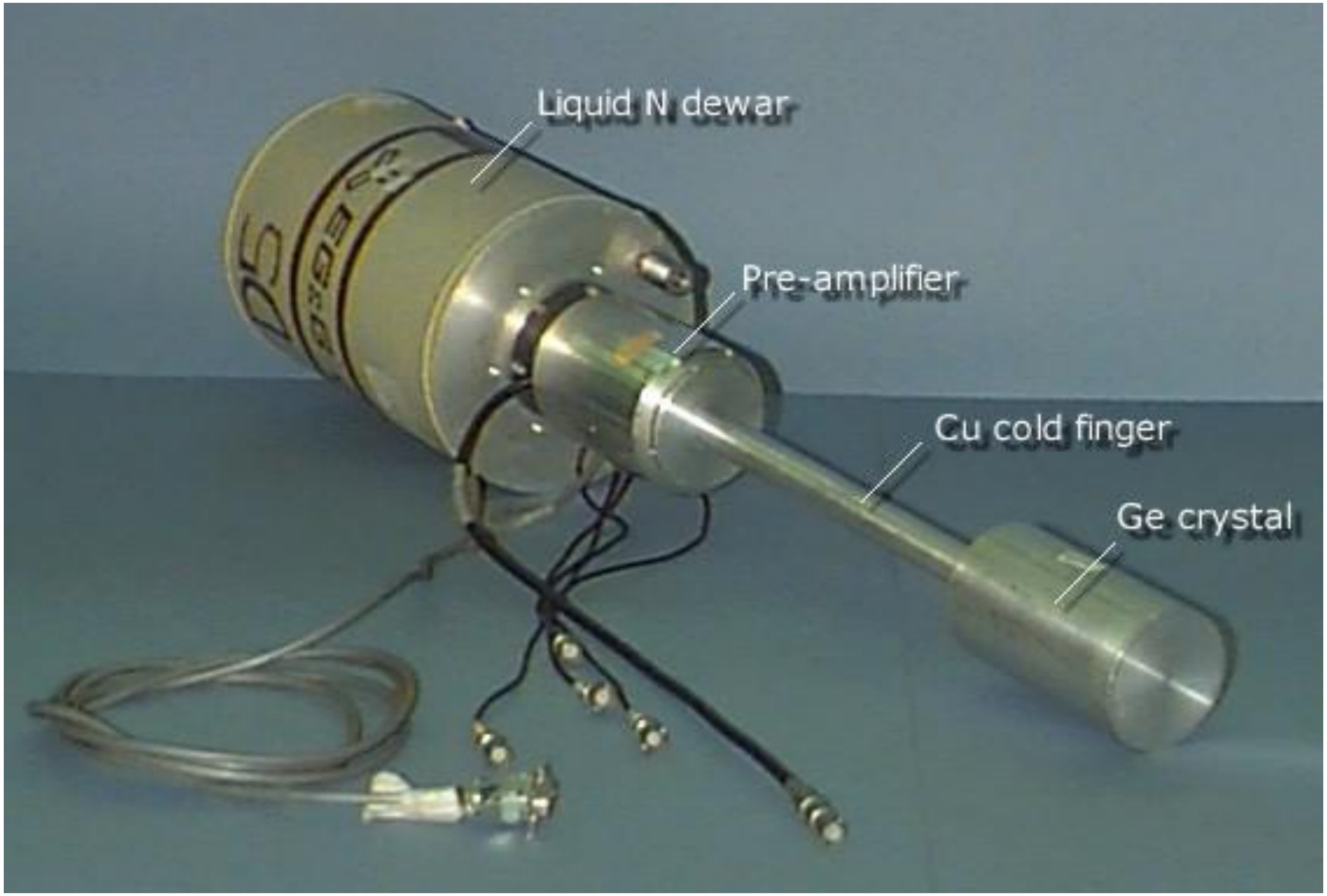
- Advantages of n-type material:
  1. usable to lower energy
  2. about 20 times more resilient to neutron damage.
- Disadvantages:
  1. Expensive
  2. coincidence summing between γs and low energy x-rays.

HPGe detectors



- Typical cryostat assembly for a HPGe detector

Coaxial Germanium detector



Coaxial Germanium detector

- In order to determine the drift velocity of the charge carriers within the detector volume Poisson's equation is solved.
- Poisson's equation in cylindrical coordinates becomes:

$$\frac{d^2\varphi}{dr^2} + \frac{1}{r}\frac{d\varphi}{dr} = -\frac{\rho}{\varepsilon}$$

- Treating the case of a true coaxial detector the voltage needed to fully deplete the detector can be written:

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

- Notice the depletion voltage decreases linearly with dopant level.

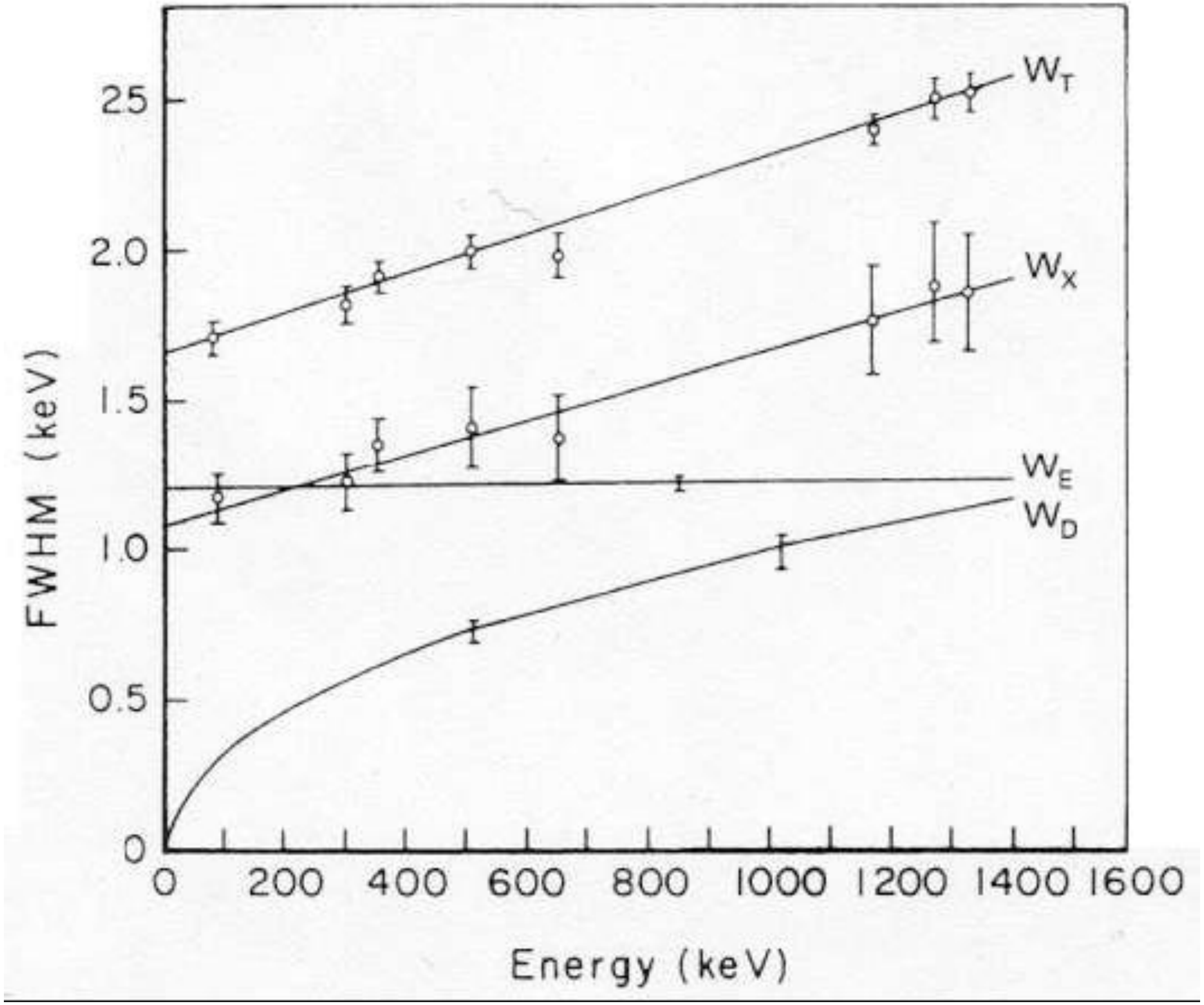
Germanium: Energy resolution

- The overall energy resolution is normally determined by a combination of three factors:

$$W_T^2 = W_D^2 + W_X^2 + W_E^2 + W_{Doppler}^2$$

- W_D is the inherent statistical fluctuation in the number of charge carriers created.
  - This is given by: $W_D^2 = (2.35)^2 F\varepsilon E$
  - Where F is the Fano factor, ε is the ionisation energy and E is the gamma-ray energy
- W_X is due to incomplete charge collection (important in large volume detectors).
- W_E is from the broadening effects of all electronic components following the detector.
- $W_{Doppler}$ is the Doppler component from a moving source

Germanium: Energy resolution

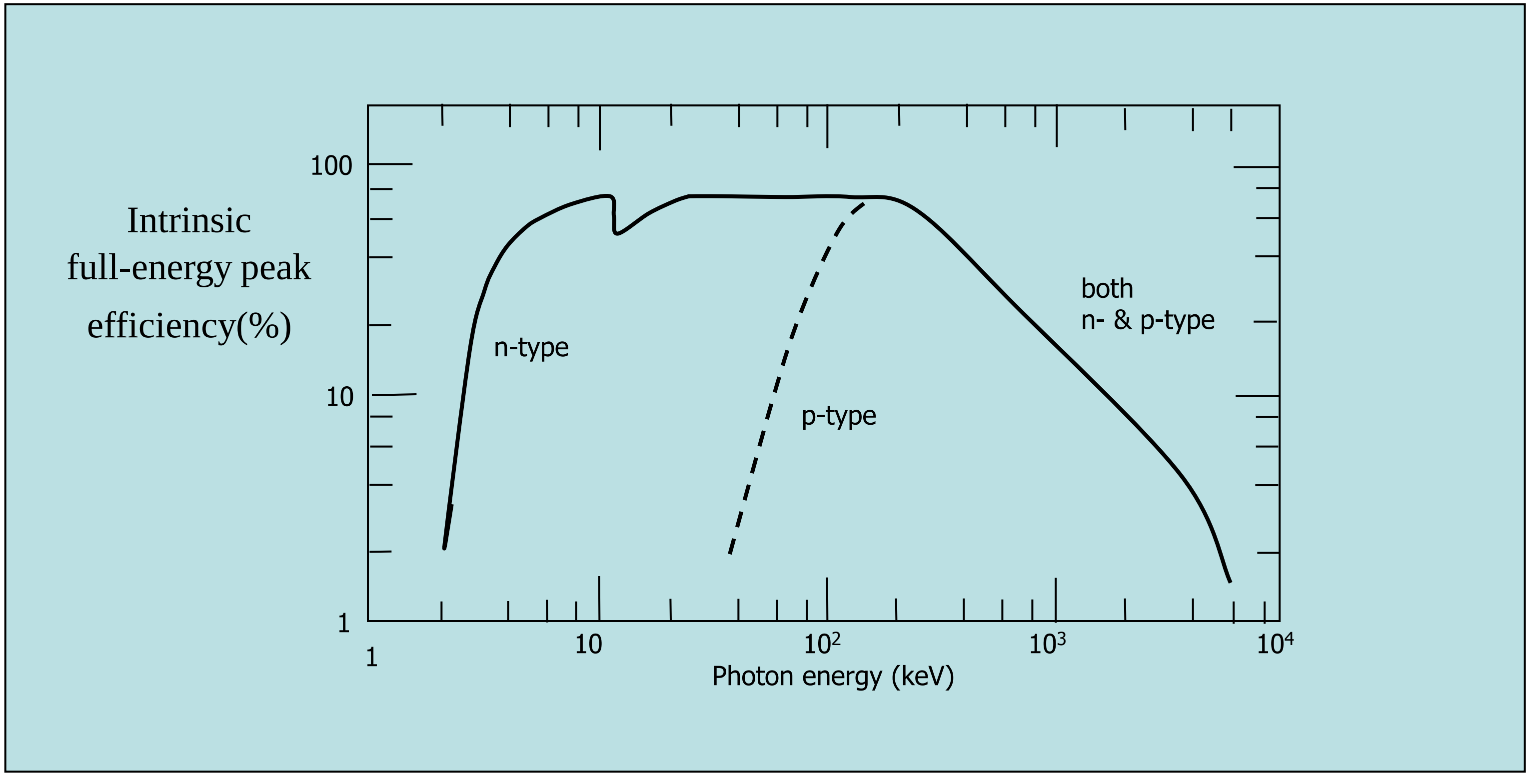


Typical values for a standard coaxial HPGe:

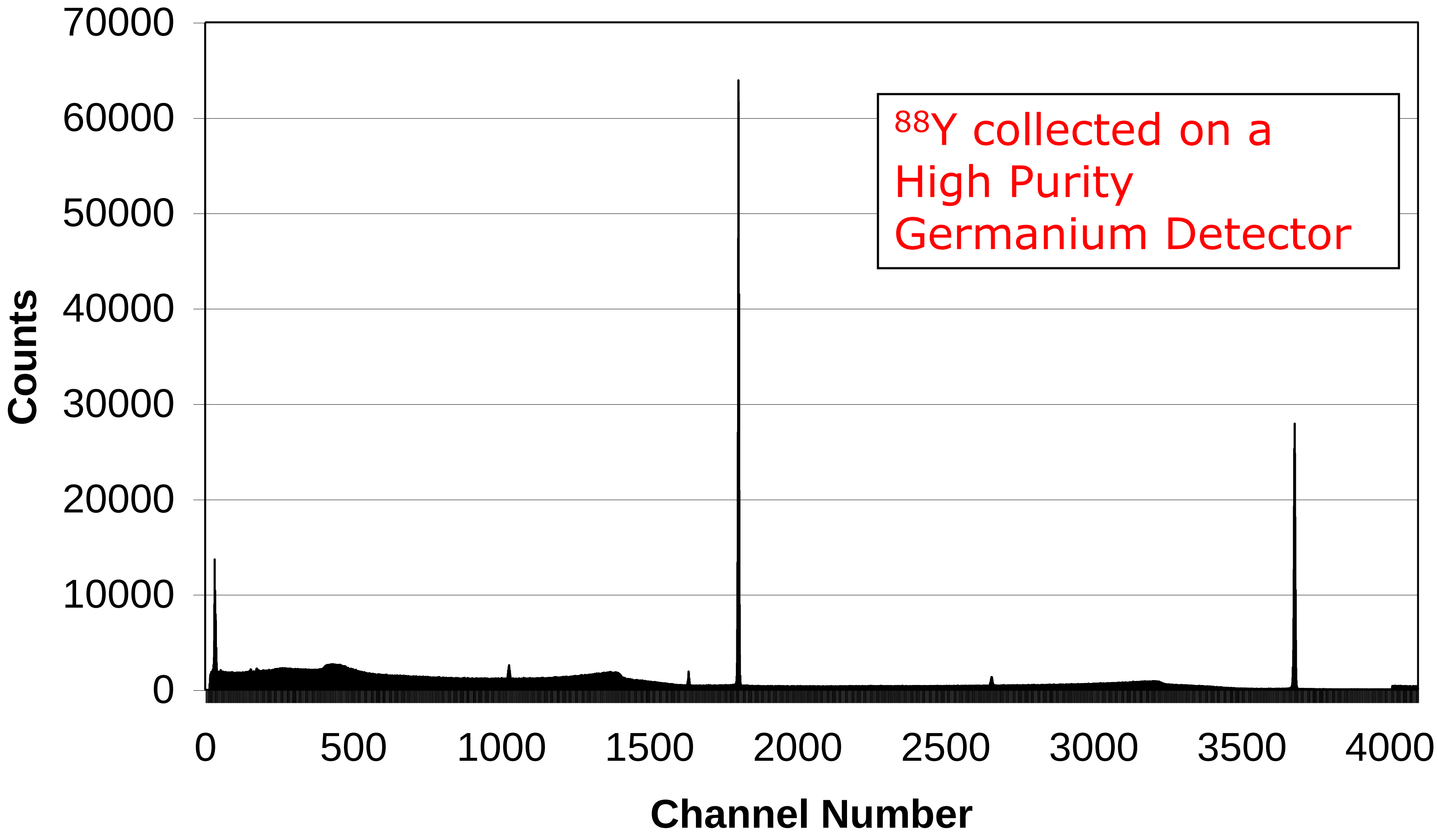
- WT = 1.0 keV at dE = 122 keV
- WT = 2.0 keV at dE = 1332 keV (WT/dE=0.15%)

Detector Efficiency

- Absolute full-energy efficiency = (counts in peak) / (number of emitted gamma rays)
- Intrinsic full-energy efficiency = (counts in peak) / (number of gamma rays incident on the detector)
- Relative full-energy efficiency = efficiency at 1332 keV (^{60}Co source) relative to a 3 x 3 in. cylindrical NaI(Tl) crystal with a source-detector distance of 25 cm



Germanium detector spectrum



^{88}Y collected on a High Purity Germanium Detector

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