# Improvement of Silicon-Based Neutron Spectrometry

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Research supported by Italian INFN
in collaboration with STMicroelectronics

# Outline

- Motivation
- The low-energy limit of the neutron spectrometer
- The coincidence detector for the $\gamma$-field discrimination
- Electron vs. proton identification and discrimination
- Results
- Conclusions

# Motivation

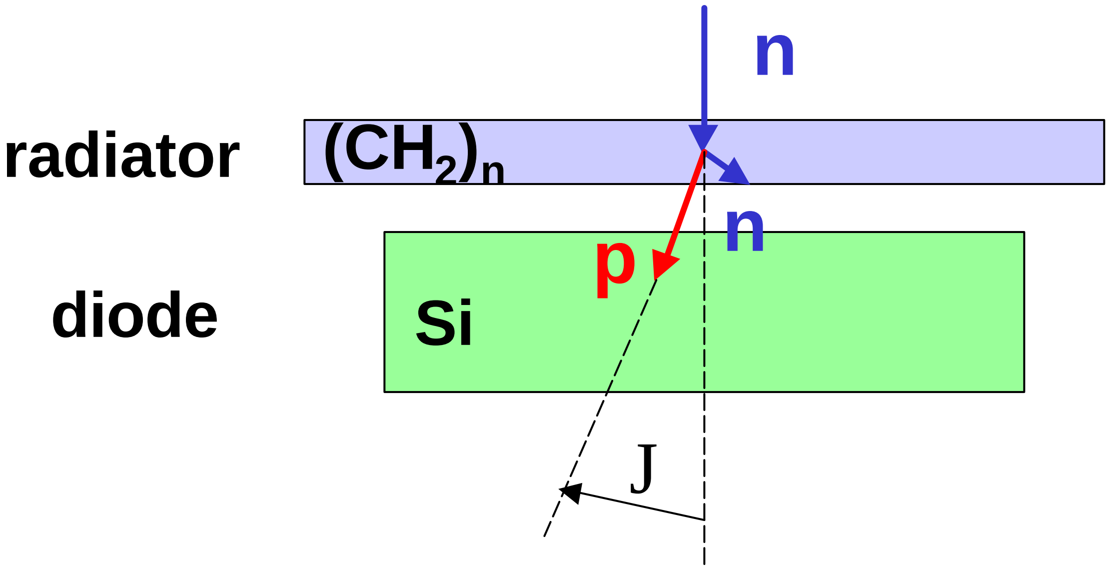
Development of a neutron spectrometer
for the characterization of neutron fields
in the range 100 keV - 10 MeV

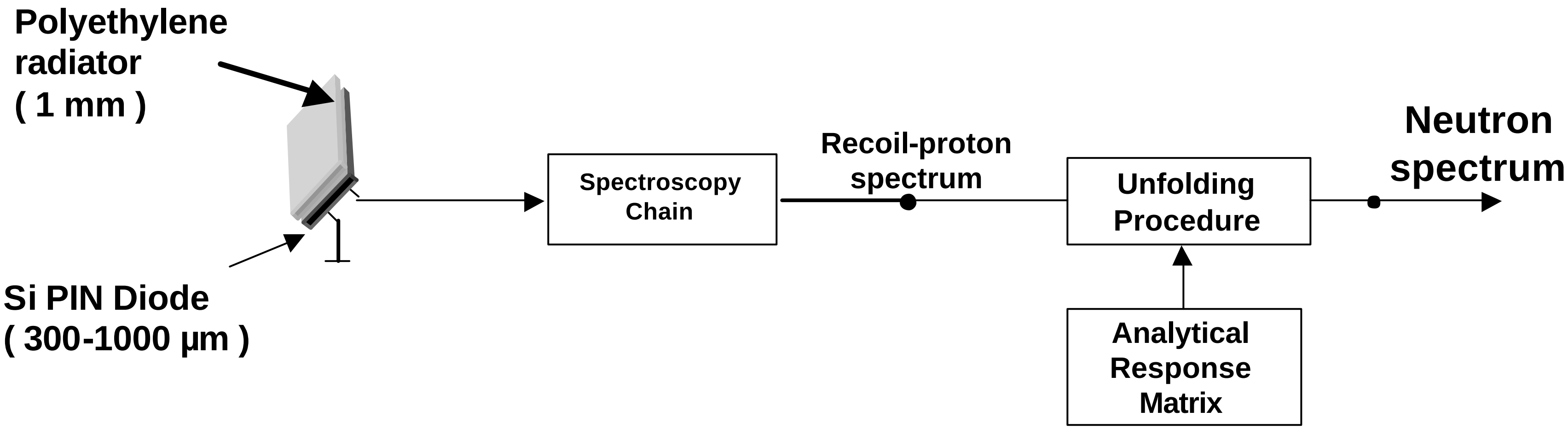
with fluence rate $10^4$–$10^6$ $cm^{-2}$ $s^{-1}$
(e.g. generated by low-energy ion accelerators)

based on silicon diodes
good spatial and energy resolution

- Biological cultures irradiations
- Electronic circuit radiation damage studies
- Shielding calculation for radiation protection

# Recoil-proton neutron spectrometer



# Distribution of the recoil proton energy $p(E_p)$

The collision between n and p in the center of mass reference system is isotrope and elastic in the MeV energy range

In the laboratory system $\theta$ is the angle between the incoming n and the recoil p:

$Vp = Vin \cos\theta$ , $Ep = Ein \cos^2\theta$ and differentiating $dEp = -\ Ein\ 2 \cos\theta \sin\theta\, d\theta$.

Integrating the differential cross section (Lab) in the solid angle between $\theta$ and $\theta+d\theta$

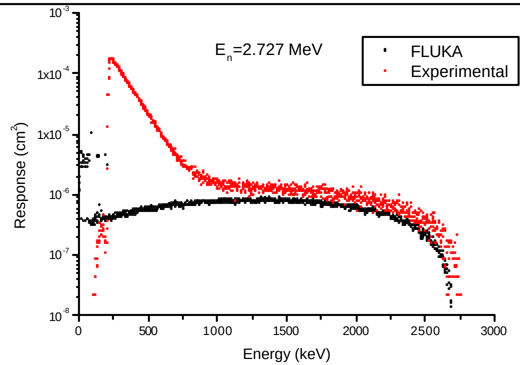
$p(\theta)\, d\theta = 2 \cos\theta \sin\theta\, d\theta$ maximum for $\theta = \pi/4$

$p(Ep)\, dEp = p(\theta)\, d\theta$

Substituting there is a cancellation and

$p(E_p) = 1/E_n$ with $0 < Ep < En$ CONSTANT

From 2003 Seminar




# Distribution of the deposited energy by recoil protons in silicon $p(E_d)$

Model equations:

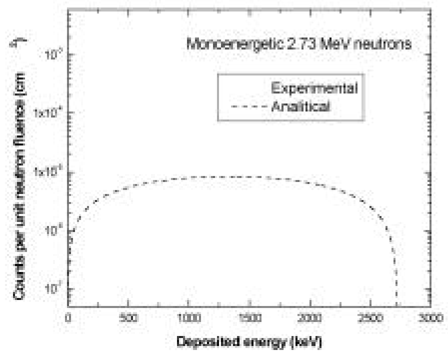
$p(E_p) = 1/E_n$ in the interval $(0 – E_n)$

$R_p = R_0 \cdot E_p^{ß}$ range-energy power law

$R_{total} = R_{radiator} + R_{detector}$ (no dead layer)

$E_d = [(E_n \cdot \cos^2\theta)^{\beta} - h/(R_0 \cdot \cos\theta)]^{1/\beta}$

$p(E_d) = 2/3 \cdot ß \cdot (E_d/E_n)^{ß-1}/E_n \cdot [1 – (E_d/E_n)^{3/2}]$



# Recoil-proton neutron spectrometer efficiency

Efficiency [$cm^2$] = count rate [count $s^{-1}$] / fluence rate [neutrons $s^{-1}$ $cm^{-2}$]

$\sigma$ = 3.675 barn @ 1.3 MeV (~ $E^{-1/2}$ )

$\Sigma_{polyethylene} = \sigma \, n_H$ = 0.3 $cm^{-1}$

t = $R_{p\ p}$ = 35 $\mu$m @ 1.3 MeV (~ $E^{\beta}$ ) thickness of int vol

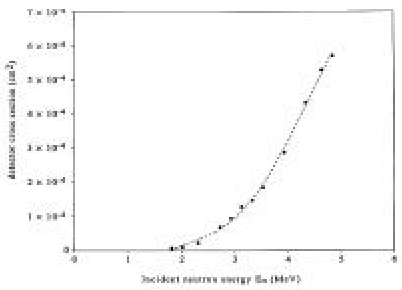
$N_{r\text{-}p} / N_n \sim \Sigma \, t \sim 10^{-3}$ @ 1.3 MeV r-p ejected

Rec-prot auto-absorption ~ 1/3

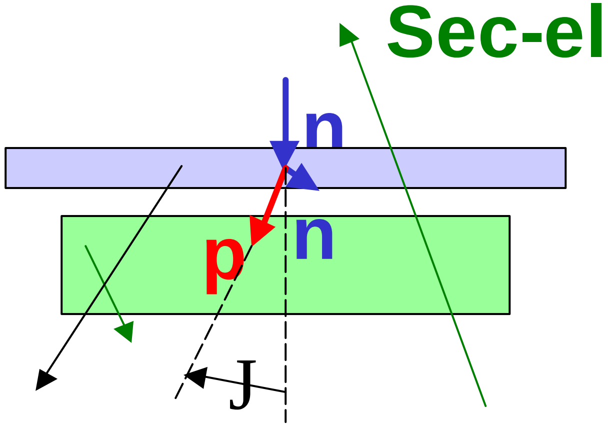
Efficiency [$cm^2$] / Area [$cm^2$] ~ 1/3 ($N_{r\text{-}p}$ / $N_n$ ) ~ 3 $10^{-4}$ (~ $E^{1.78 - 0.5}$ )

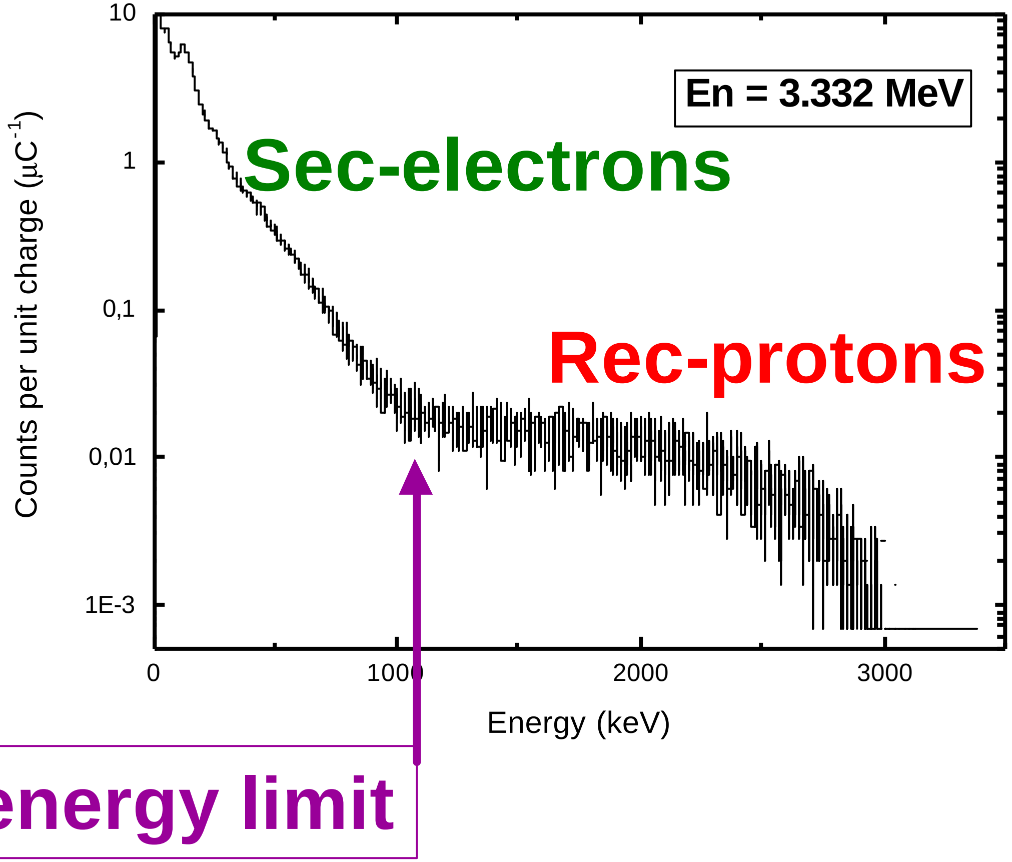
A = 1 $mm^2$, $\nu$ = 1 cps fr = 3 $10^{5}$ $s^{-1}$ $cm^{-2}$

A = 10 $mm^2$, $\nu$ = 1 cps fr = 3 $10^{4}$ $s^{-1}$ $cm^{-2}$



# Low-energy limit of the response function

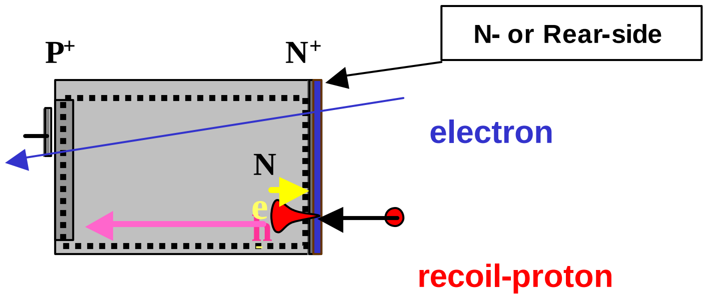


# Pulse Shape Discrimination with silicon p-i-n diode

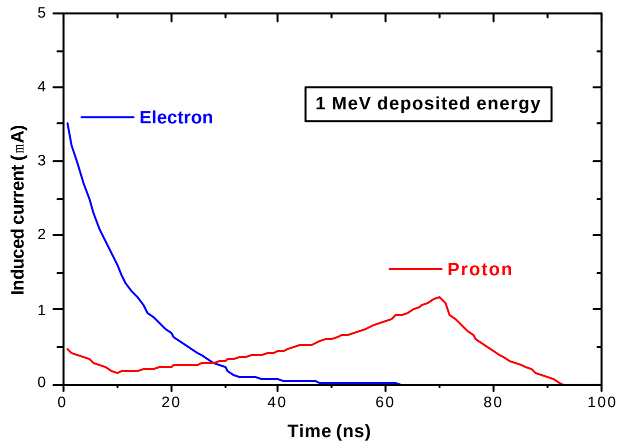
A. Fazzi et al. 2003 IEEE NSS

**“Rear-side injection”**

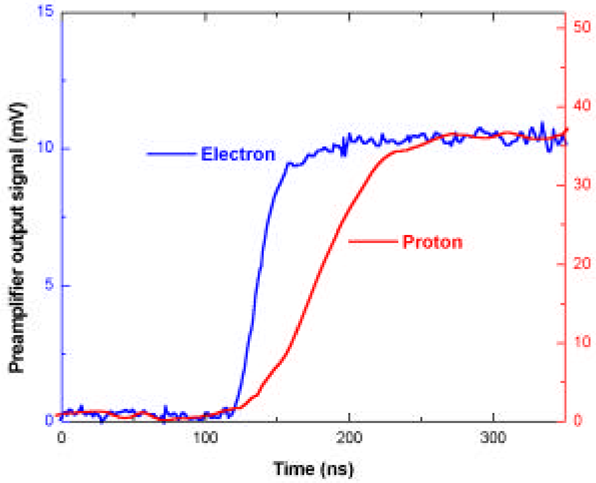



FZ High Res Silicon
300 μm thick
3 $mm^2$ area

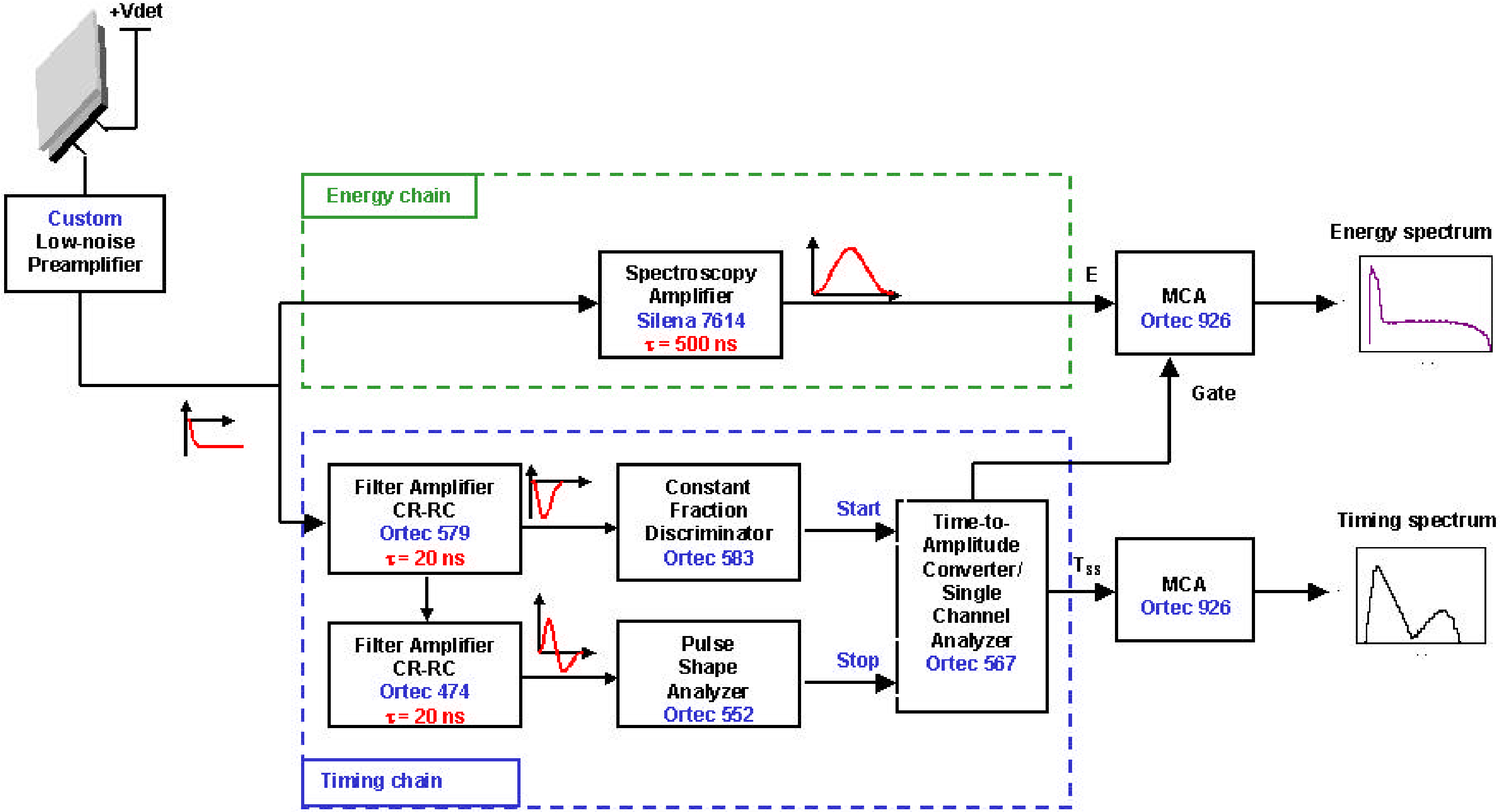
simulation



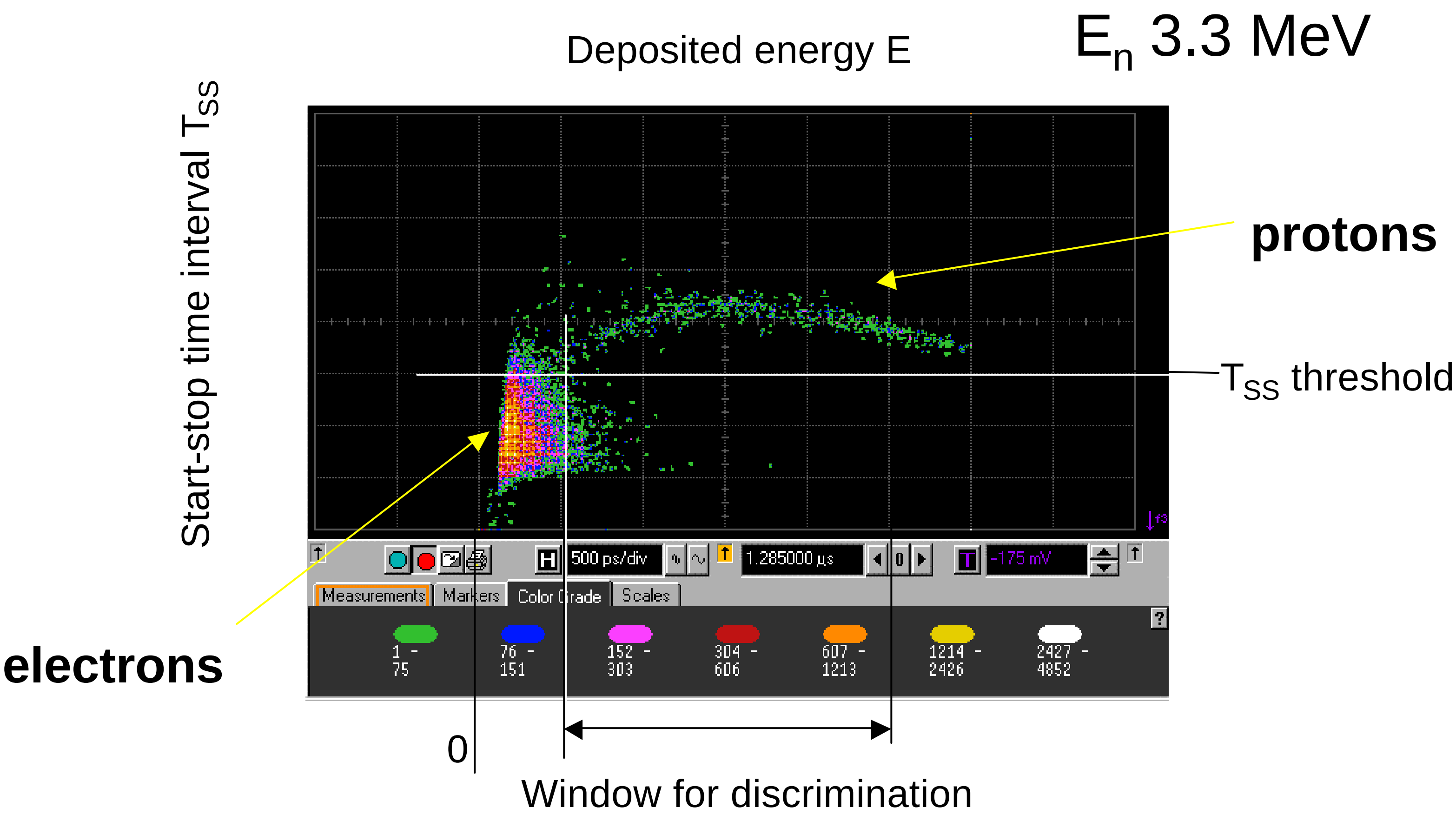

experimental



# Electronics for pulse shape analysis

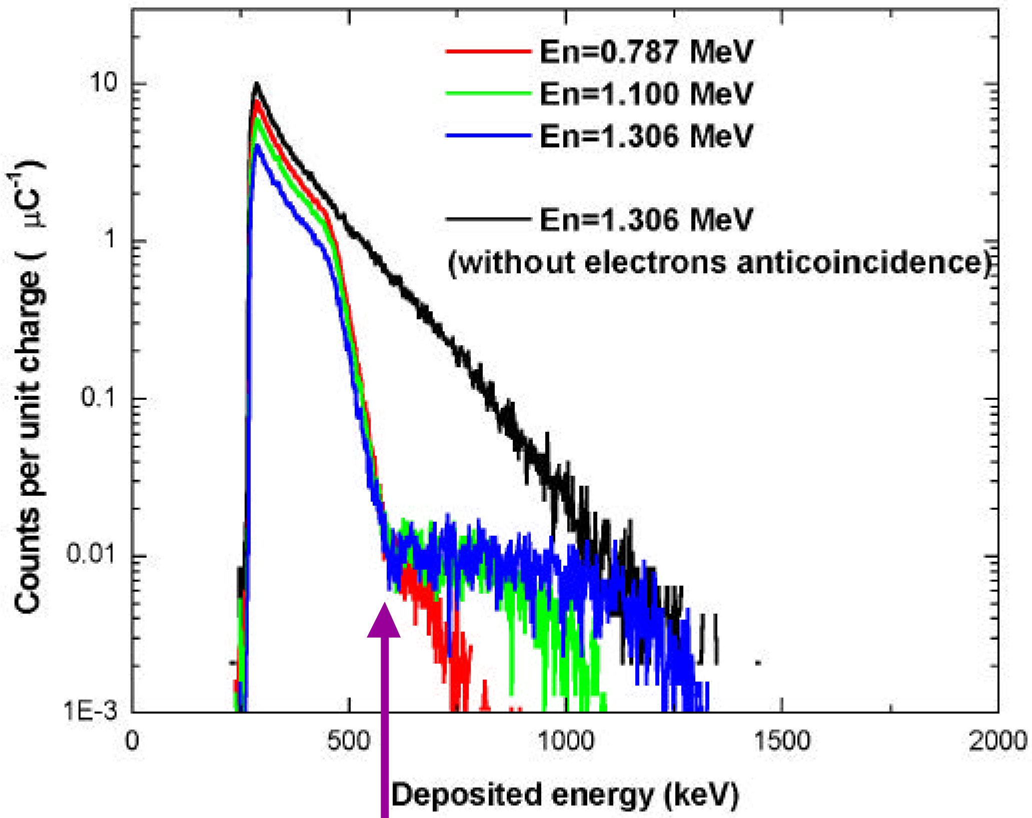


# Energy-time scatter plot for monoenergetic neutrons



# Pulse shape discrimination of secondary-electrons

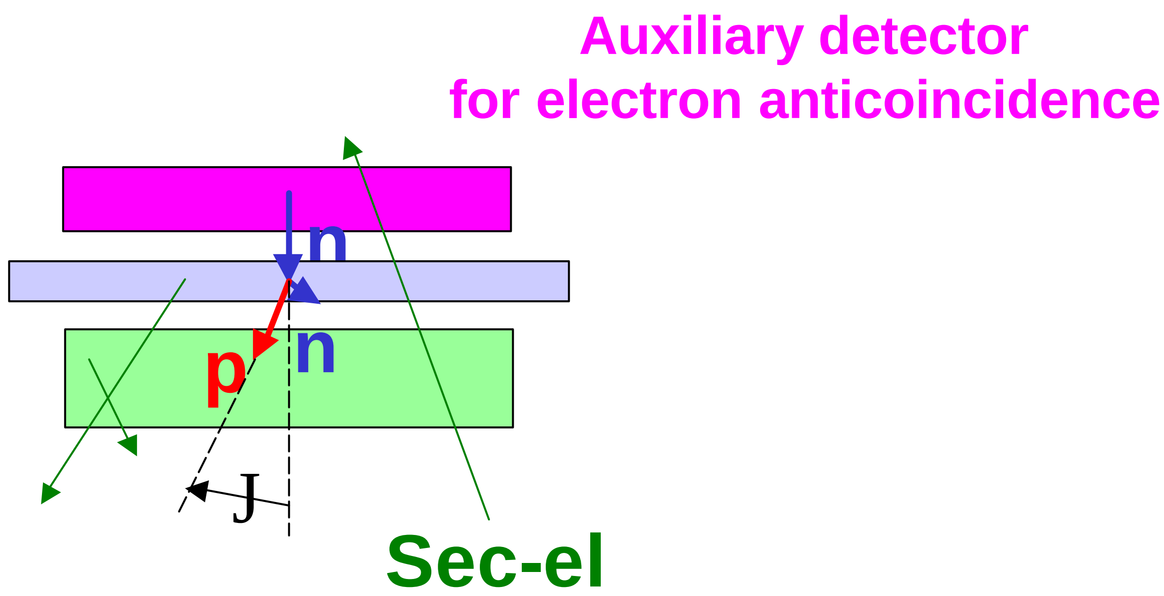
## Response functions for "low-energy" neutrons



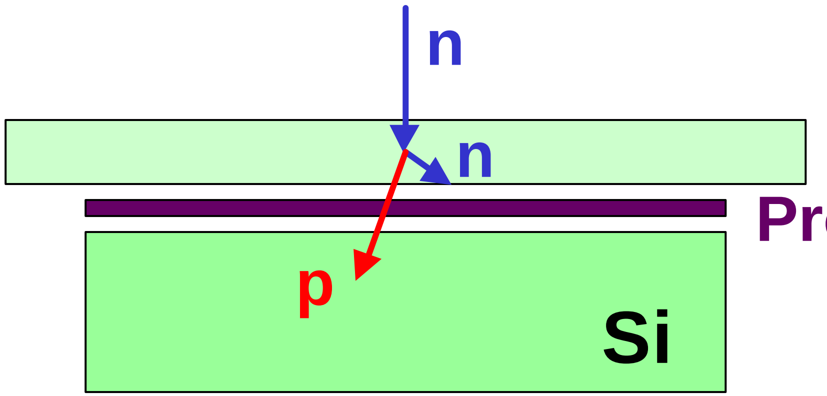

**Low-energy limit ~ 600 keV**

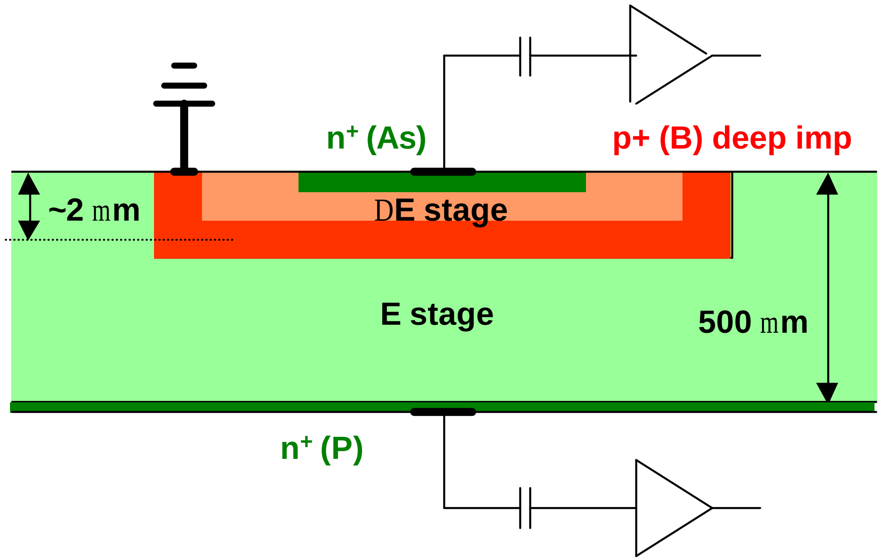
**A. Fazzi et al., 2003 IEEE NSS**

# Bo Yu suggestion after 2003 seminar



# Thin monolithic coincidence detector

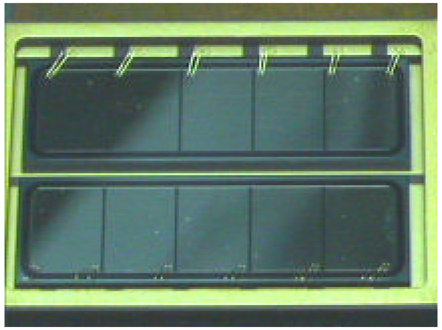


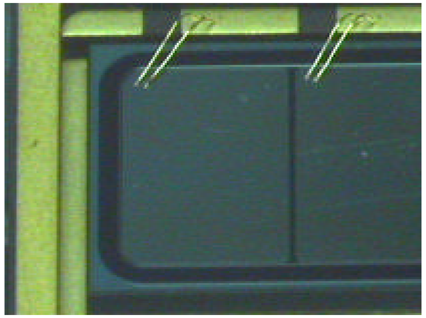




ΔE-E schematic cross section

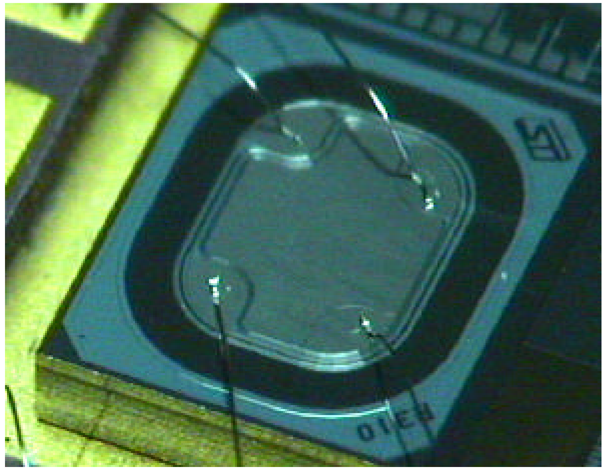
G. Cardella et al., NIM A 378 (1996)

# The DE-E monolithic silicon telescope



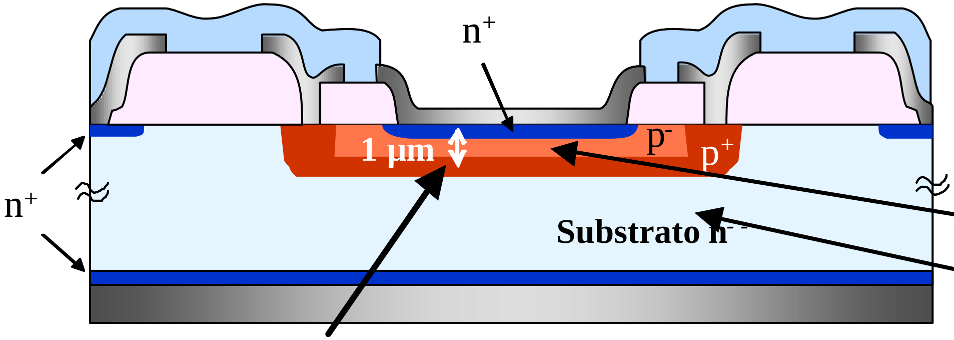


10 mm$^2$



Detailed cross section of DE-E (STM)

Active area: ~ 1 mm$^2$



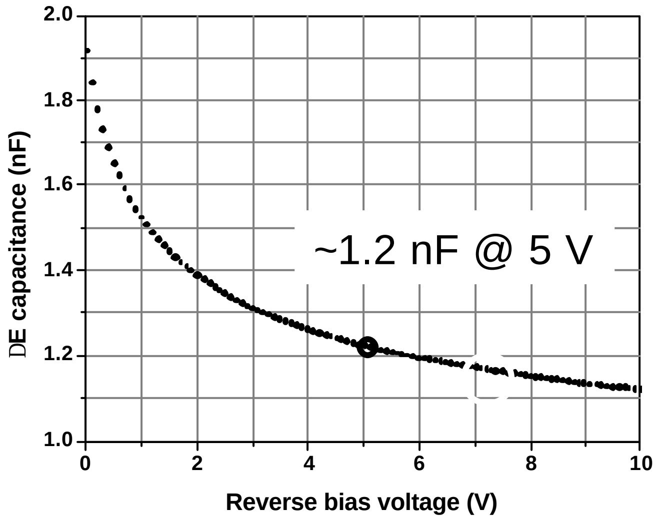

DE thickness: ~ 2 mm

E thickness: ~ 500 mm

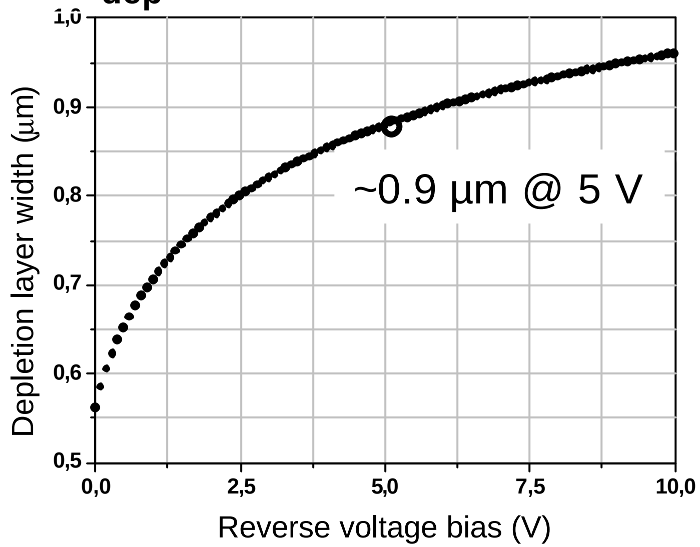
The p$^+$ cathode acts as a “watershed” for the charge collection

# DE-E electrical characterization (10 mm$^2$)

## C - V curve



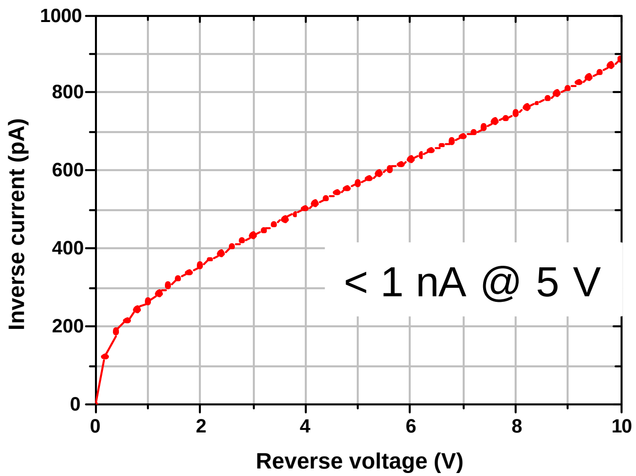

## $X_{dep}$ – V characteristic

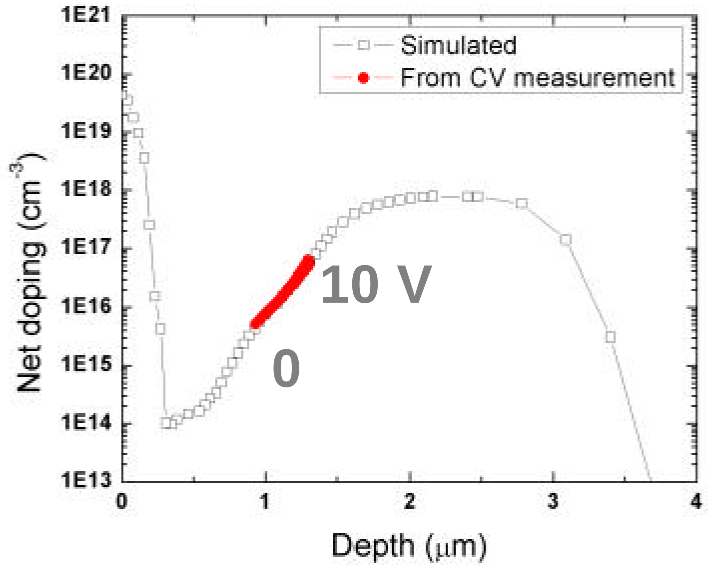



$C^0$ = 0.12 nF·mm$^{-2}$

$J_L$ = 0.1 nA·mm$^{-2}$

## Reverse I - V curve

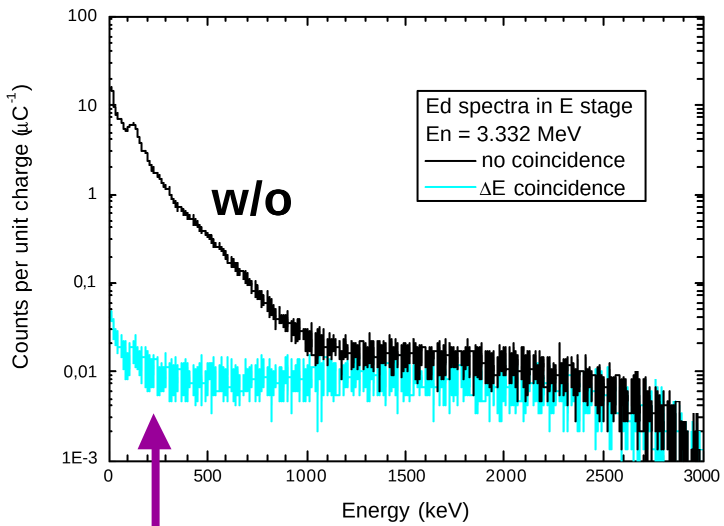



**DE**
**A = 1 mm$^2$**
**C = 165 pF**
**$I_L$ = 135 pA**
**E**
**C = 6pF**
**$I_L$ = 500 pA**

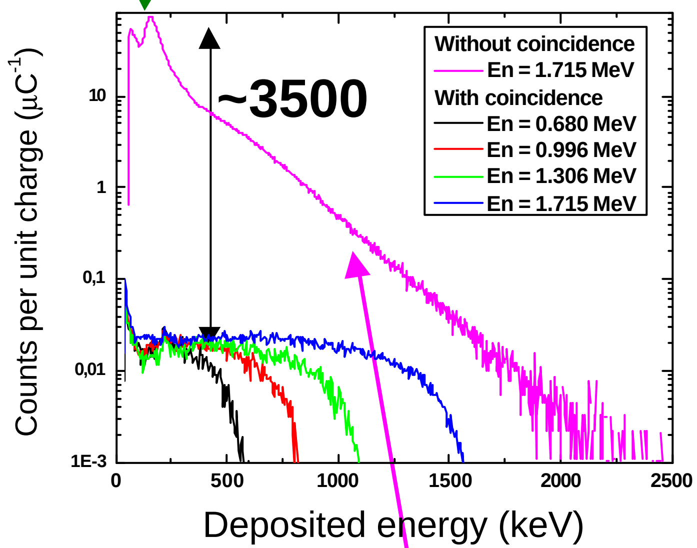
# DE-coincidence response functions

## Strong g-field rejection




**Low-energy limit ?**

Peak at ~200 keV




**w/o DE coincidence**

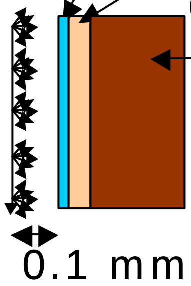
**Complete sec-electron discrimination ?**

# MC simulation of the secondary electrons

Dead layer (Ti) 0.24 mm

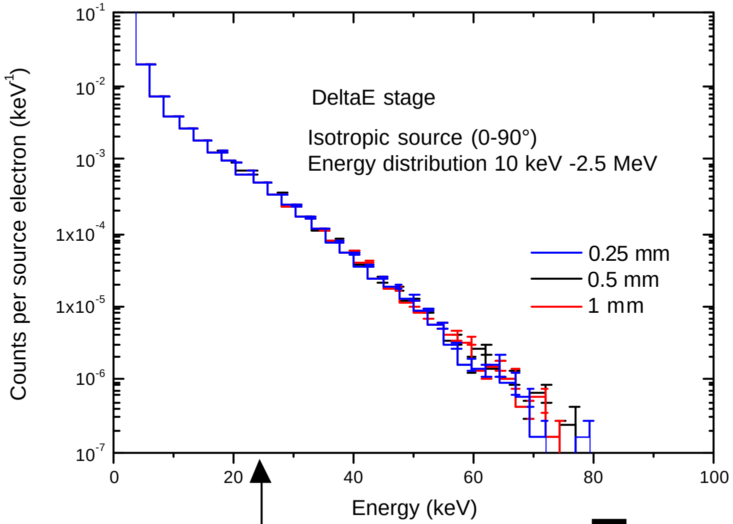
DE detector (1.9 mm)

E detector (500 mm)



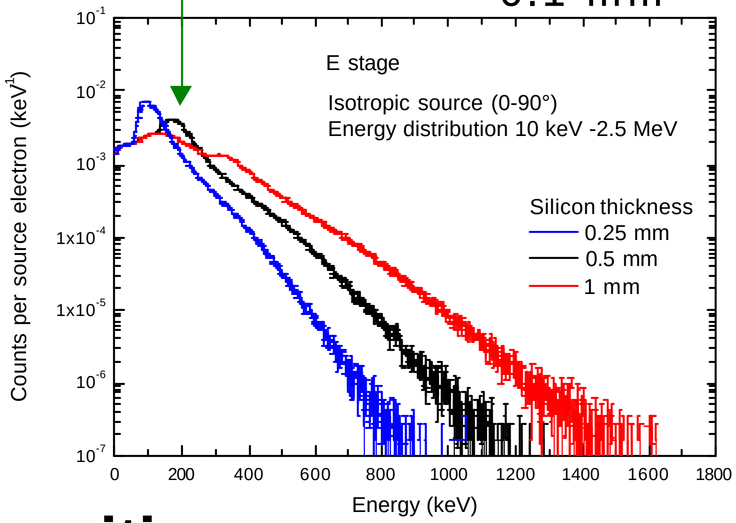

**Homogeneous source of electrons**
**constant distribution 10 keV - 2.5 MeV**

## DE stage




Electronic noise threshold

Peak at ~200 keV



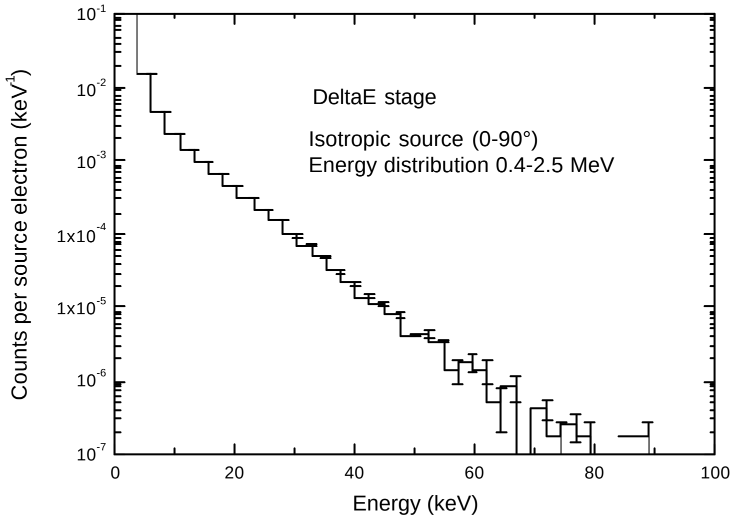

## Energy deposition

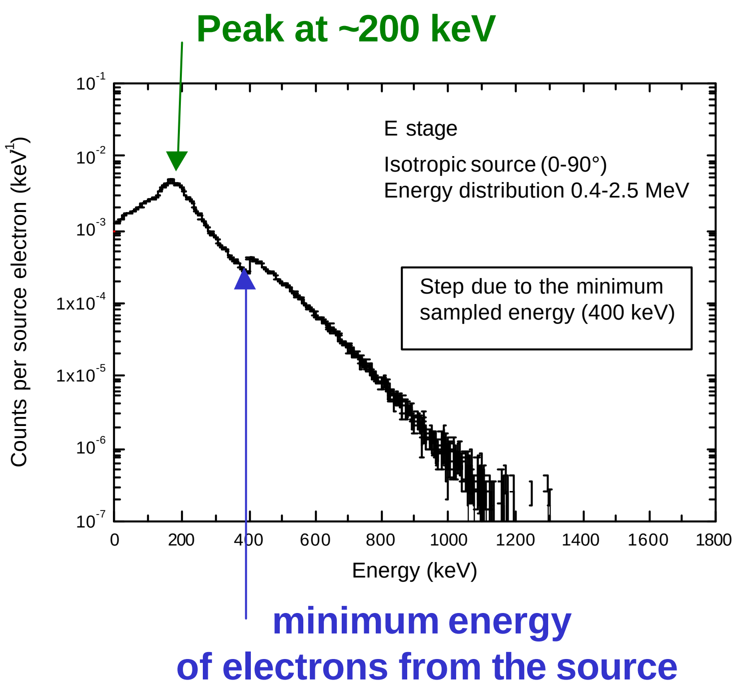
## E stage

**Also sec-el are triggered in DE-coincidence !**

# MC simulation of the secondary electrons 2

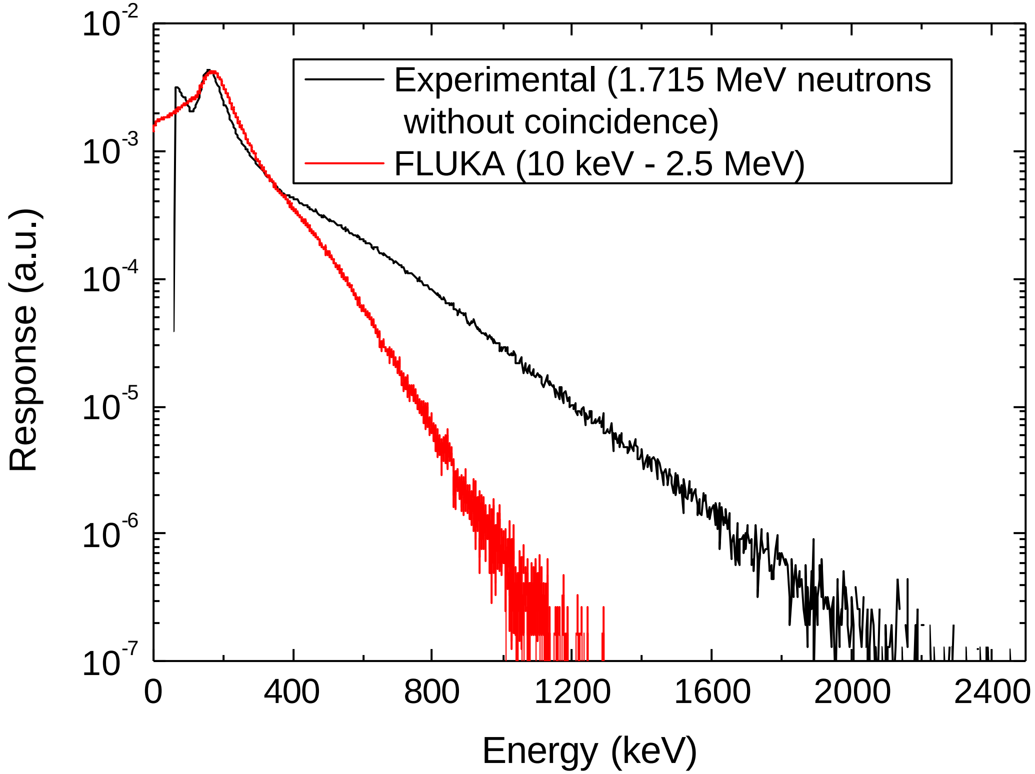
## Homogeneous source of electrons
## constant distribution 400 keV - 2.5 MeV



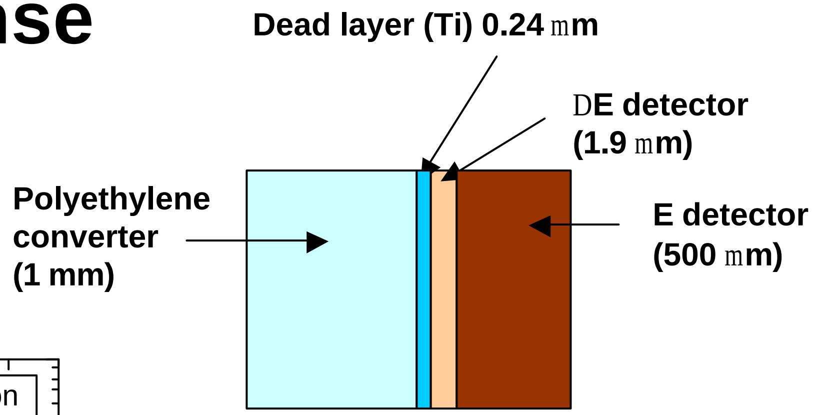



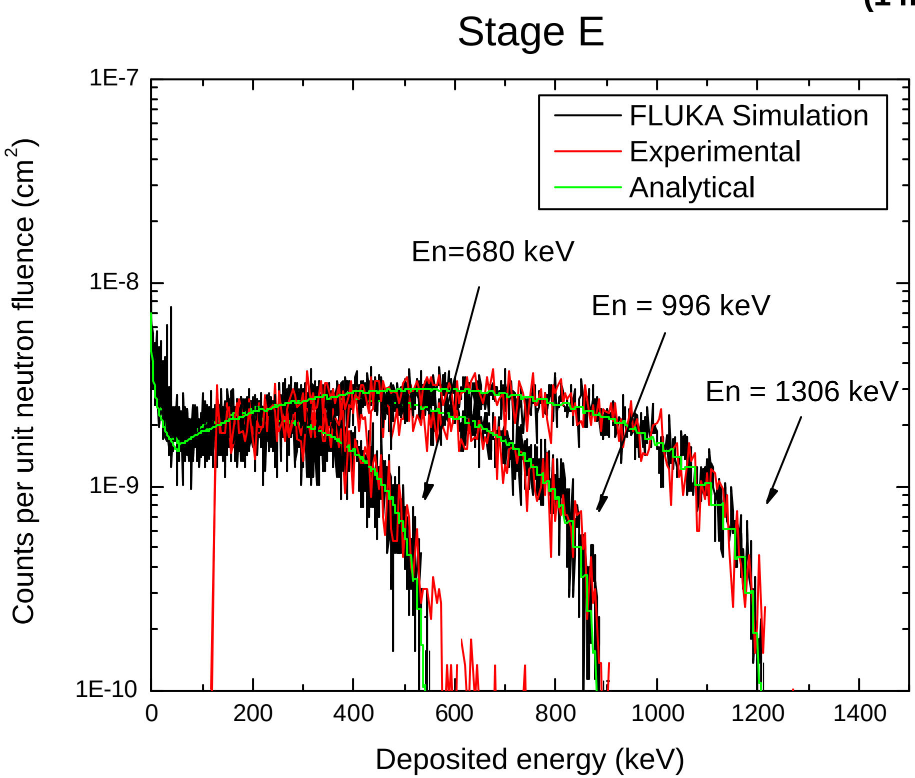
# Response to electrons:
## experimental vs. simulated

**Pile-up rate: @ 8 s$^{-1}$**



# E response



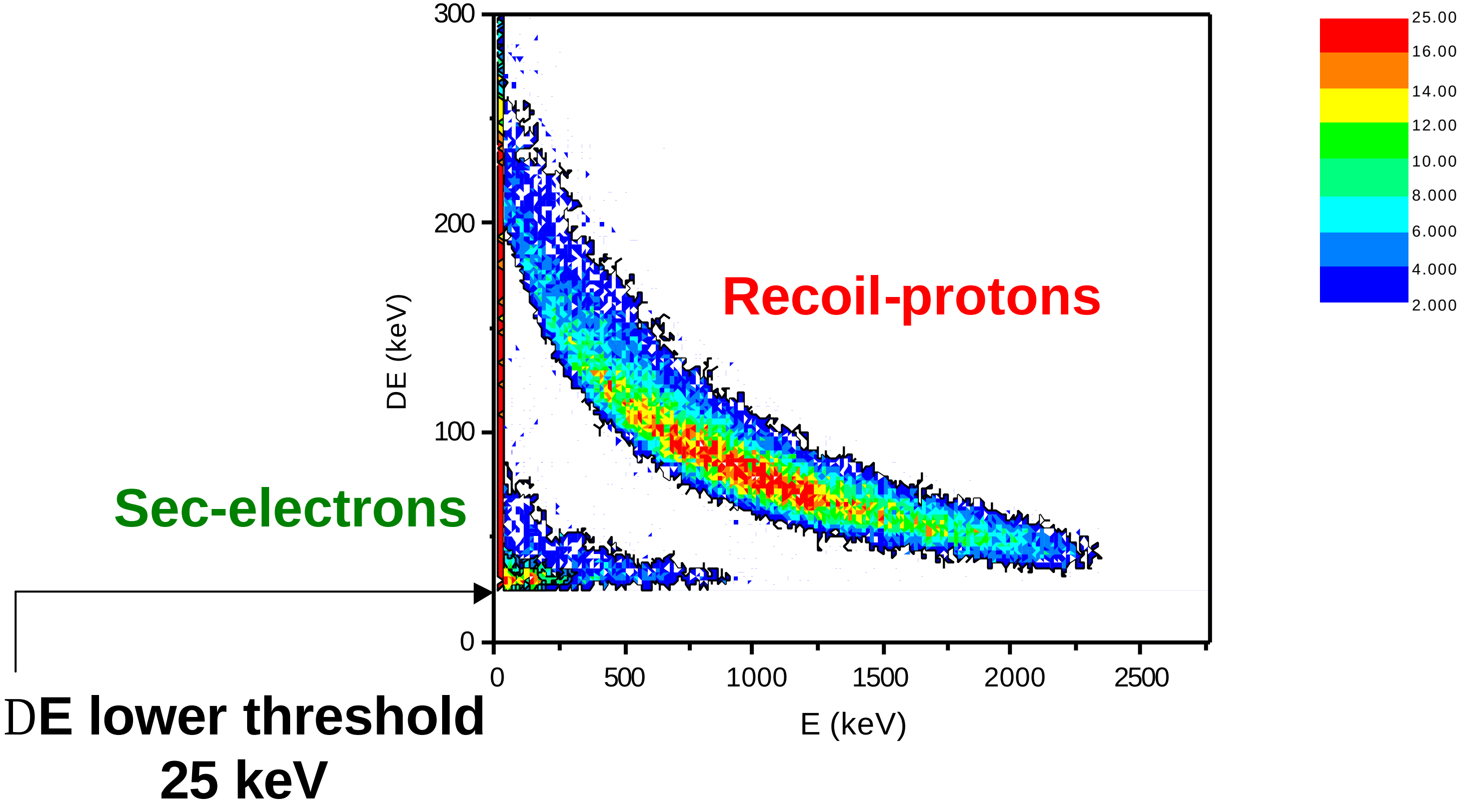




The E stage is in coincidence with the ΔE stage

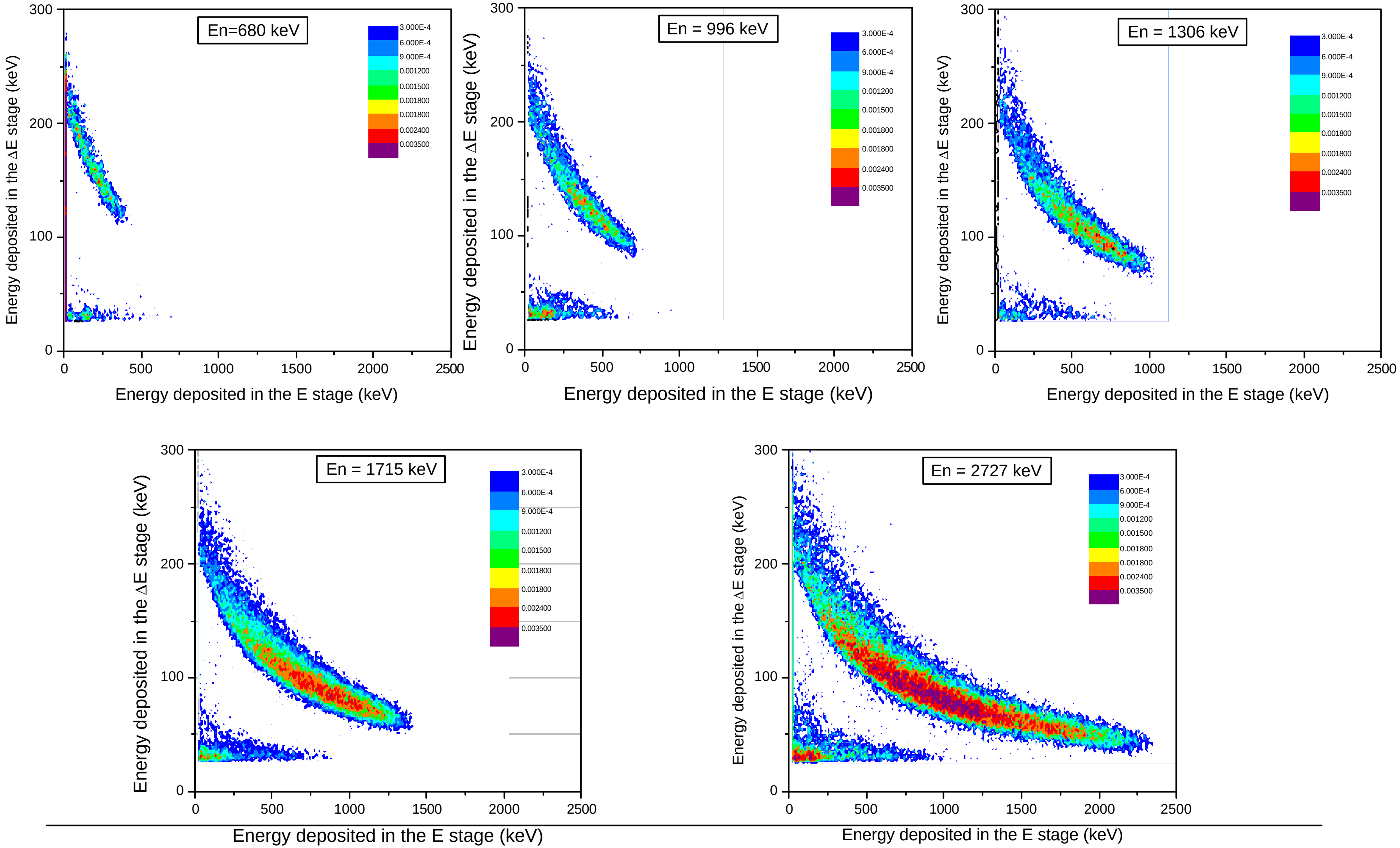
# DE-E scatter plot of recoil protons in strong g-field

**Irradiations at Van de Graaff CN accelerator of INFN Legnaro Labs.**

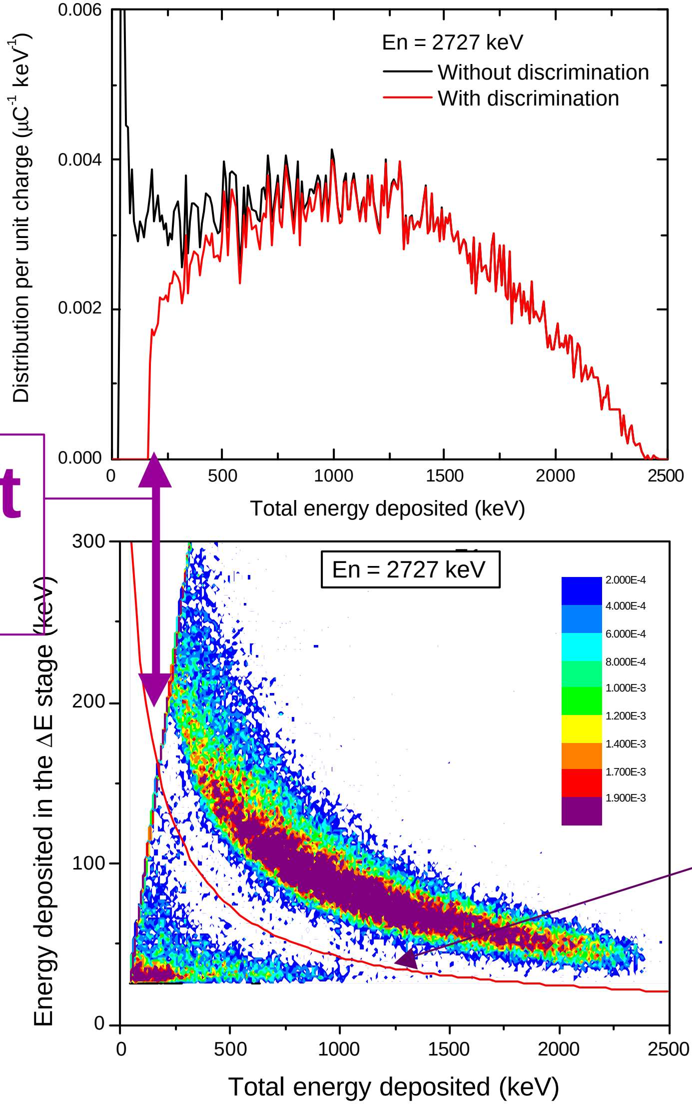
**Monoenergetic neutrons at 2727 keV**



# DE-E scatter plots of the response function



# Total energy spectrum with electron discrimination

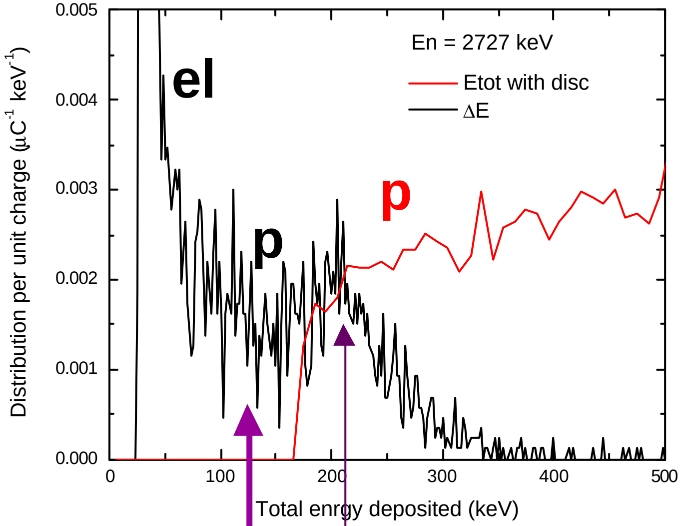


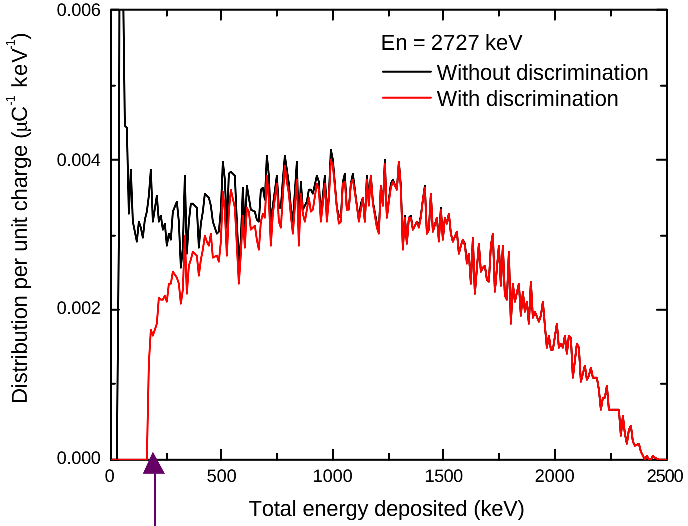

**Low energy limit ~160 keV**

**Discrimination line ~ $4\ 10^4 / E_{tot}$**

$E_{tot} = E + \Delta E$

# Stopper analysis




connection
~210 keV

**Low-energy limit ~130 keV**

**cutting line**

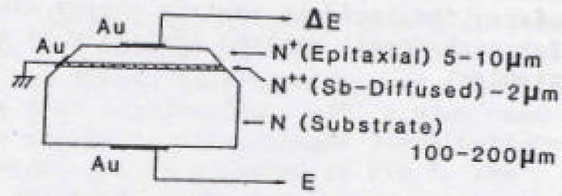



Fig.1-(a) Cross sectional view of the epitaxial integrated dE-E detector.

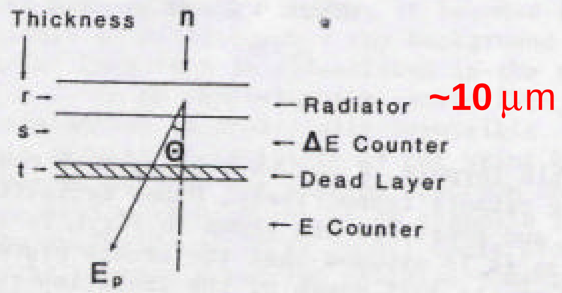
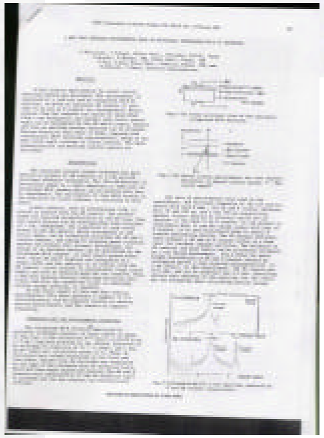



Fig.1-(b) Recoil proton spectrometer for fast neutron detection. $E_p$ :Recoil proton energy. θ : The recoil angle.

F. Shiraishi, Y. Takami, H. Husimi, C. Kim, Y. Kim, K. Kikuchi, T. Sakai, “A new fast neutron spectrometer made of epitaxial integrated DE-E Si detector”, IEEE Trans. Nucl. Sci. Vol.NS-32, No 1, Feb 1985, pp. 471-475

C. Kim, H. Kim, K. Kikuchi, K. Husimi, S. Ohkawa, Y. Fuochi, “Epitaxial integrated E – dE silicon detector with a buried low-resistive diffused layer”, IEEE Trans. Nucl. Sci. Vol.NS-27, No 1, Feb 1980, pp. 258-265



$$E_n = E_p/\cos^2\theta$$

$$= ( E + \Delta E\cdot(r/2s+1+t/s))\cdot\Delta E^2/(s\cdot(dE/dx))^2 \quad - (1)$$

$dE/dx$ : in dE counter

$r << R_p = 10\ \mu m$ @ 600 keV

**Efficiency** [$10^{-6}$ $cm^2$]
for thick and thin converter
(1 $mm^2$, 1 Al dead layer, 700 μm Si)

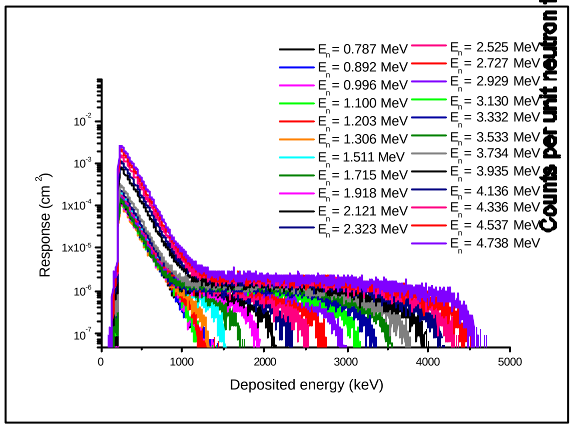
| | Thickness | En 5 MeV | En 10 MeV |
|---|---|---|---|
| Thick | >Rp | 14 | 28 |
| Thin | 10 μm | 1.1 | 0.67 |
| Ratio | | 13 | 42 |

**Thin** converter: small energy range
Low precision @ low energy

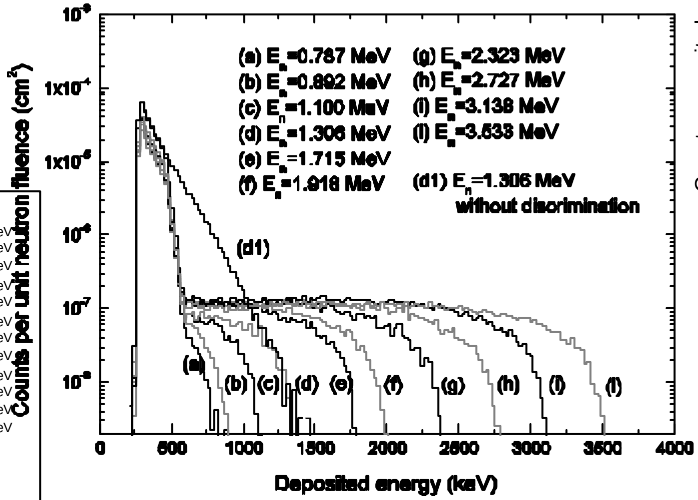
Low efficiency @ high energy

# Spectra for monoenergetic neutrons

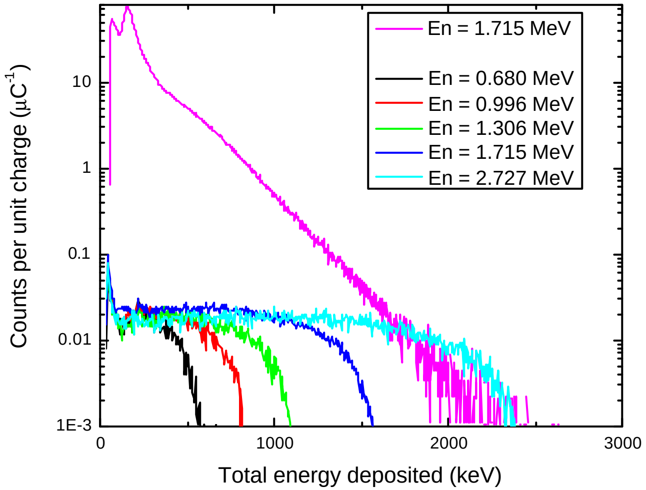
Spectra for monoenergetic neutrons (0.8–4.7 MeV )




Spectra with PSD ( 0.8 - 3.5 MeV )




Spectra with ΔE/E discrimination ( 0.68 – 2.73  MeV )



# Conclusions

- **The low-energy limit of a recoil-proton neutron spectrometer has been substantially improved**
- **Effective rejection of secondary electrons (in the strong $\gamma$-field) has been obtained operating in coincidence with a second thin diode**
- **Further discrimination is based on electron identification on the $\Delta$E-E scatter plot**
- **Monolithic $\Delta$E-E structure allows to reach much lower discrimination threshold ( < 150 keV) with respect to PSD technique (~ 600 keV)**