Detector developments and investigation of radiation damage in semiconductor detectors in the Institute of Nuclear Research of HAS (ATOMKI), Debrecen

Gabor Kalinka

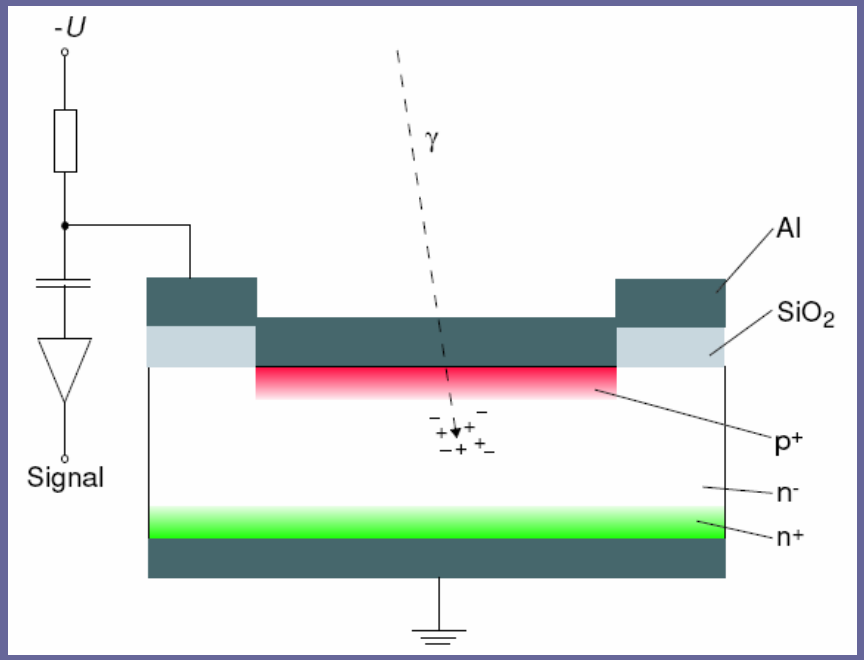
Semiconductor detector development between 1971-90 concentrated around Si(Li) X-ray detectors and complete X-ray spectrometers. Nowadays - in collaboration with Japanese partners - Si pin and SDD detectors, and HgI_2 planar detectors, all for X-ray detection, are under construction.

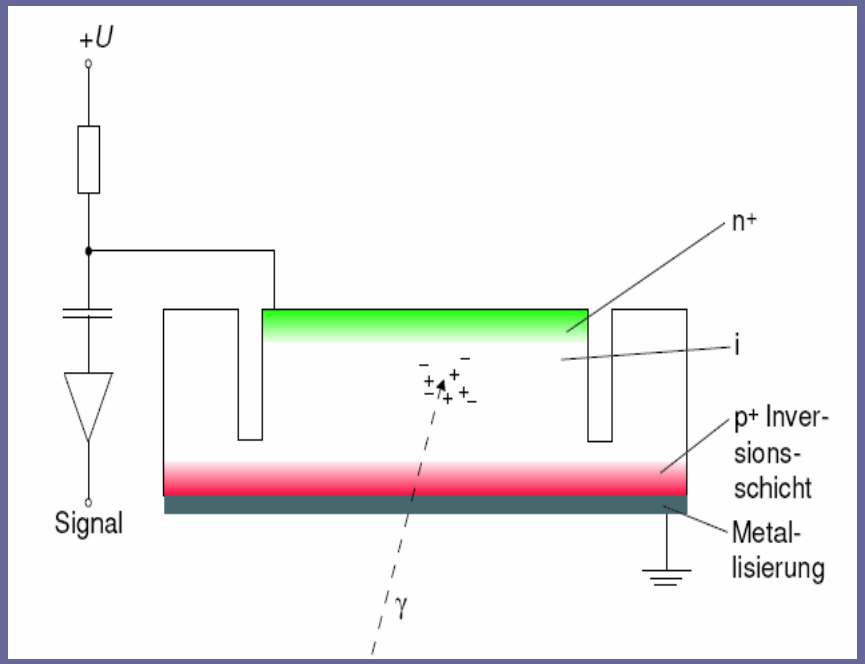
Scintillation charged particle detector systems using CsI(Tl) crystals coupled to Si pin photodiodes has been developed for nuclear physics (European, Japanese and South-African collaborations), while systems using LSO/LYSO crystals combined with Position Sensitive Photoelectron Multipliers are being developed for gamma-ray detection in Positron Emission Tomography (PET).

Detector radiation damage studies started very recently in ATOMKI with the increased use of Si pin photodiodes in conjunction with particle accelerators.

Semiconductor detector development

ionizing radiation: e-h pair creation in reverse biased diode structures,
charge collection, integration, signal shaping (noise filtering), amplitude measurement





P-N detector

Thin sensitive volume:

- low X/gamma efficiency
- large capacitance → noise

P-I-N detector, e.g. Si(Li)

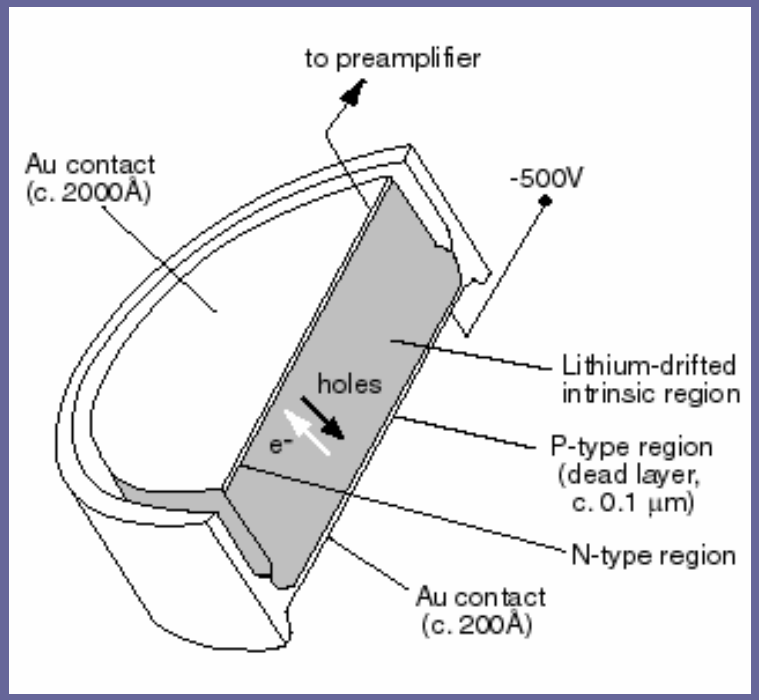
Thick sensitive volume:

- higher efficiency
- lower capacitance
- better energy resolution

X-ray spectrometer developed at ATOMKI between 1971-1980 : Si(Li) detector, liquid nitrogen cooling, pulsed drain feedback preamplifier, time variant (1980) and digital (1989) signal processing

150 eV FWHM , ~80 units sold between 1978-1992 to COMECON countries

High vacuum dewar Si(Li) detectors (1988) in cooperation with Tesla, Brno (Czechoslovakia)

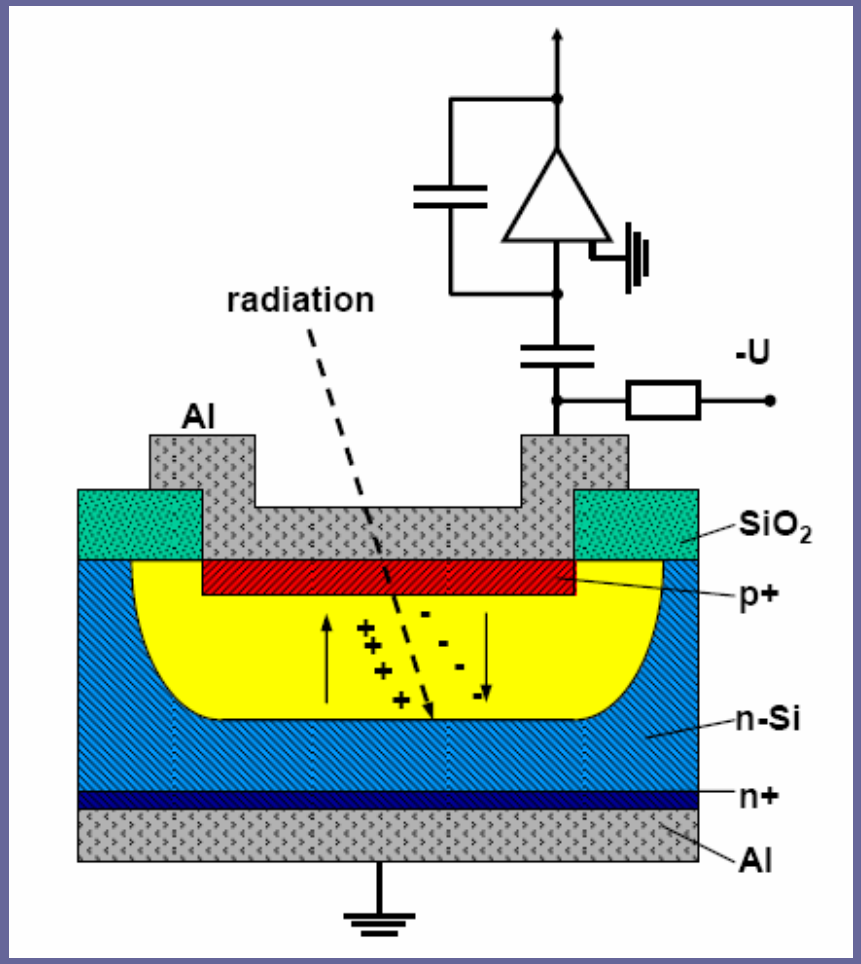


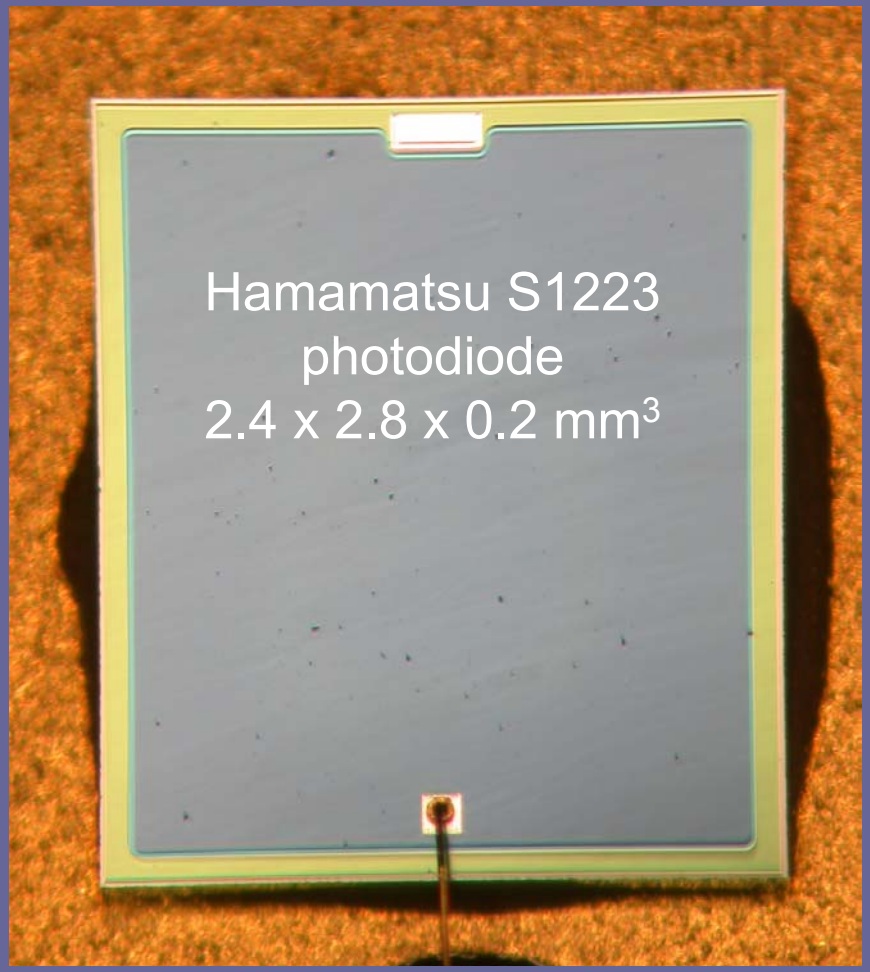
1986: XRF laboratory, Havanna

1990: Detector laboratory, Osaka

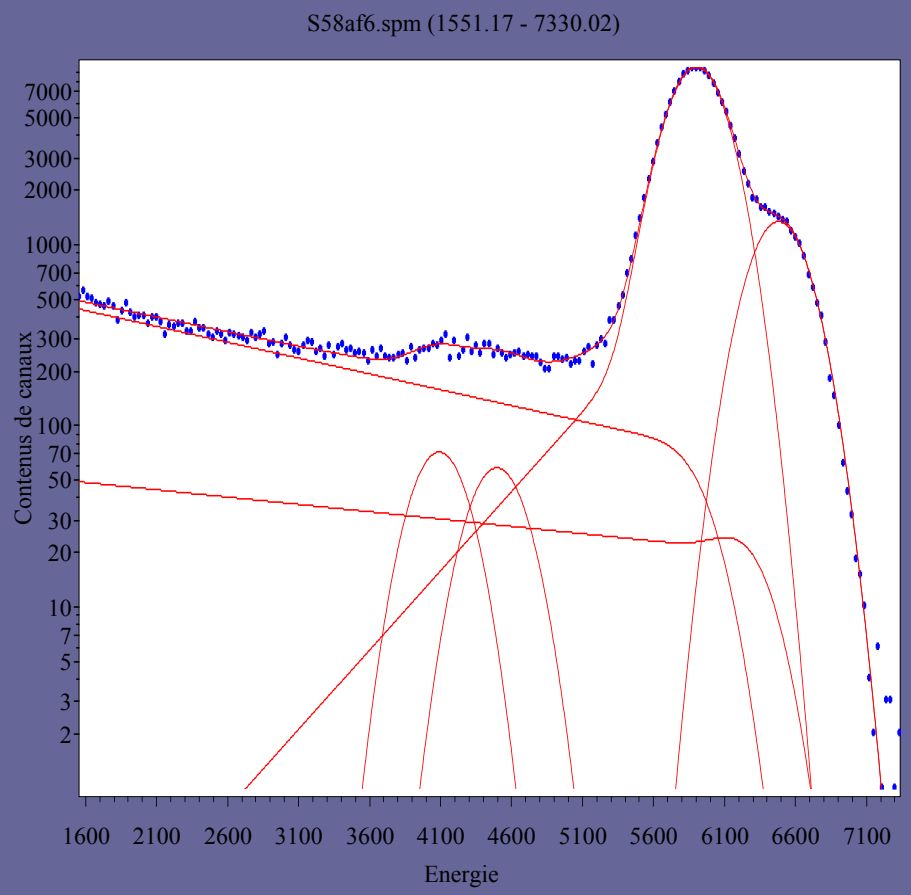
1991: end of Si(Li) era, ATOMKI
"detector clinics"

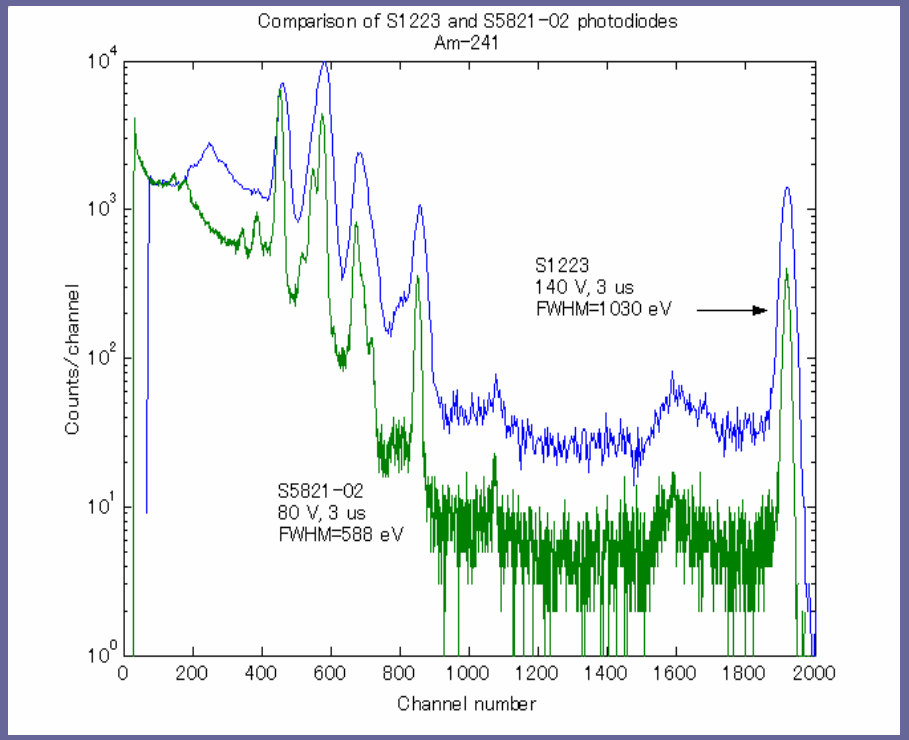
Microelectronics: advanced p-n or p-i-n detector (photodiode)
3-4 orders of magnitude (!) lower current → moderate cooling
~ 100-800 µm thickness, X-ray energy 1-20 keV
Good Si(Li) detectors have still been the standard!





Room temperature X-ray detection with Si-pin photodiodes





FWHM=440 eV @ 5.9 keV

FWHM=580 eV @ 60 keV

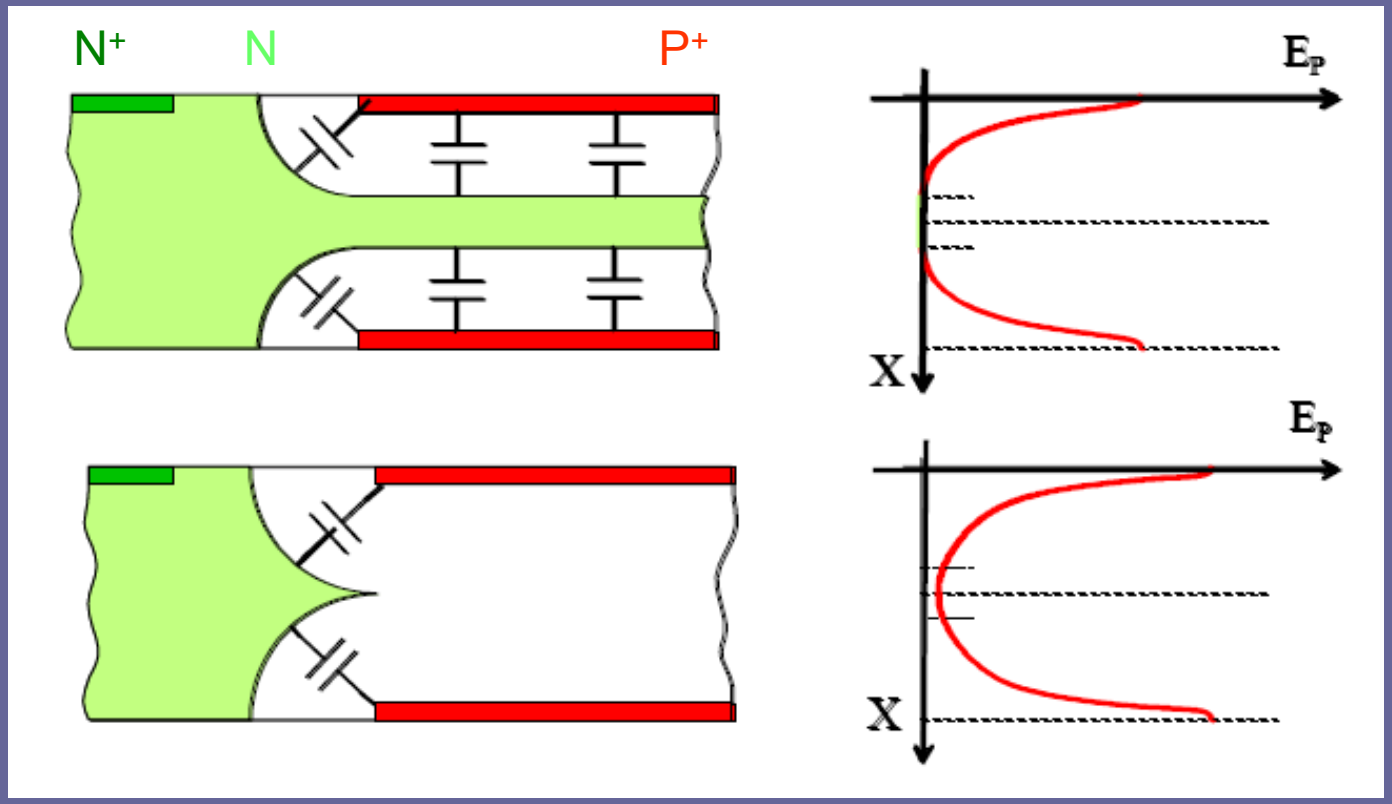
Fe-55

Am-241

Semiconductor Drift Detector (SDD)

1984, Gatti, Rehak

very small anode, very small capacitance, excellent resolution

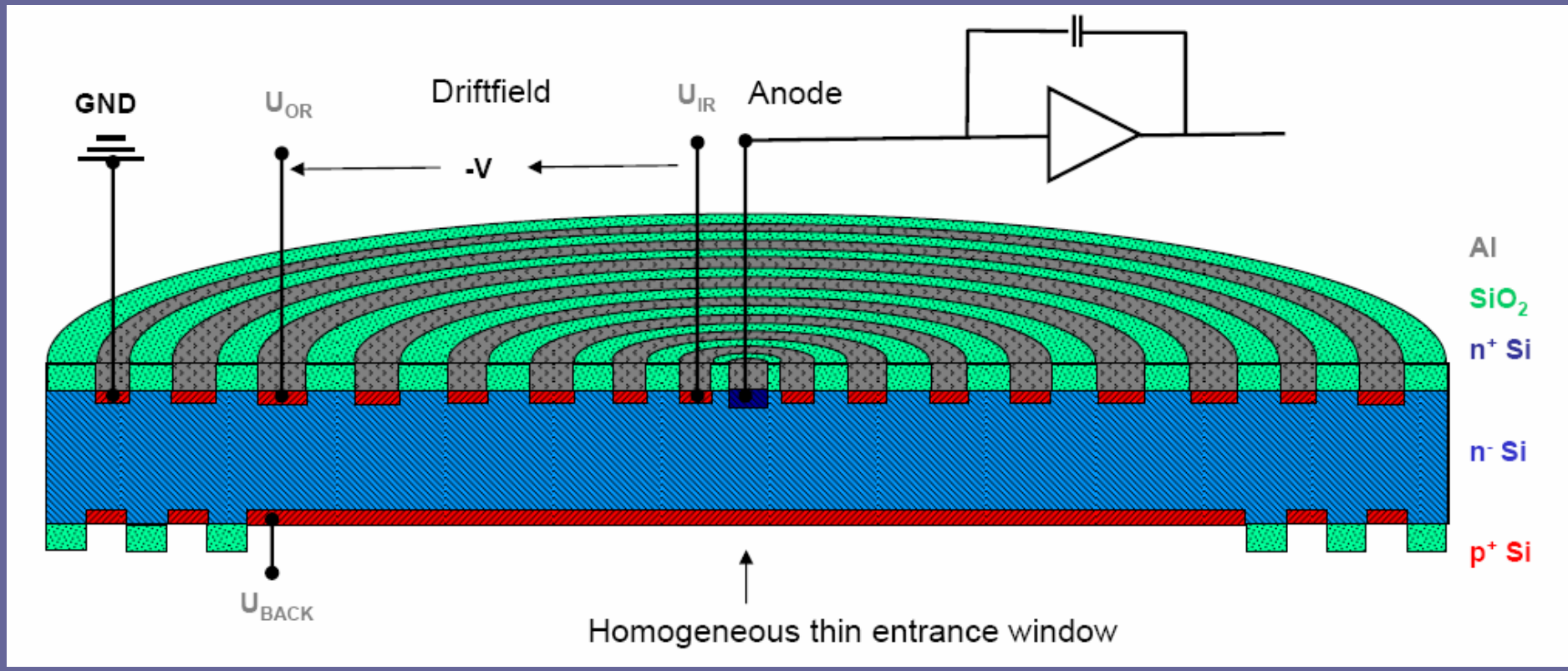


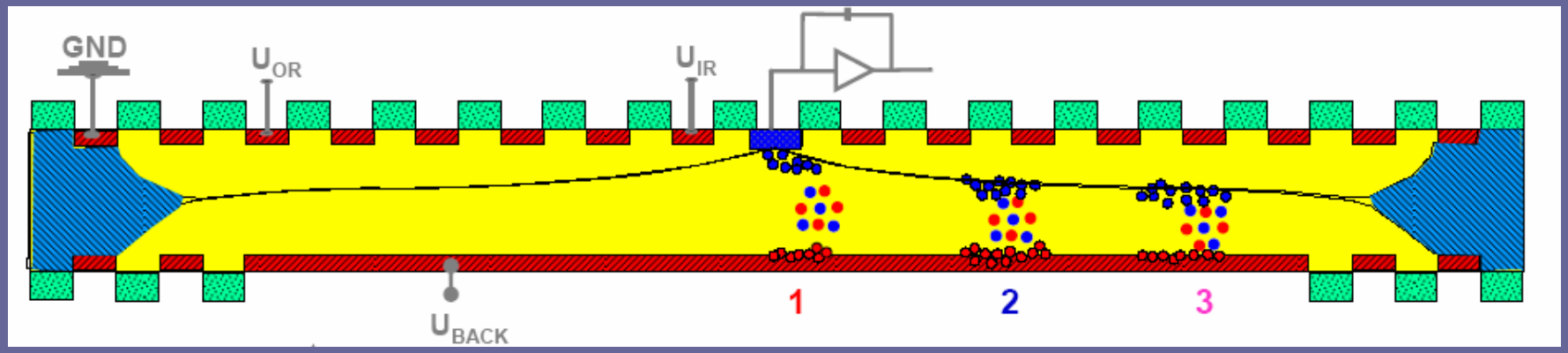
Partial depletion

Full depletion

Principle of the sideward depletion

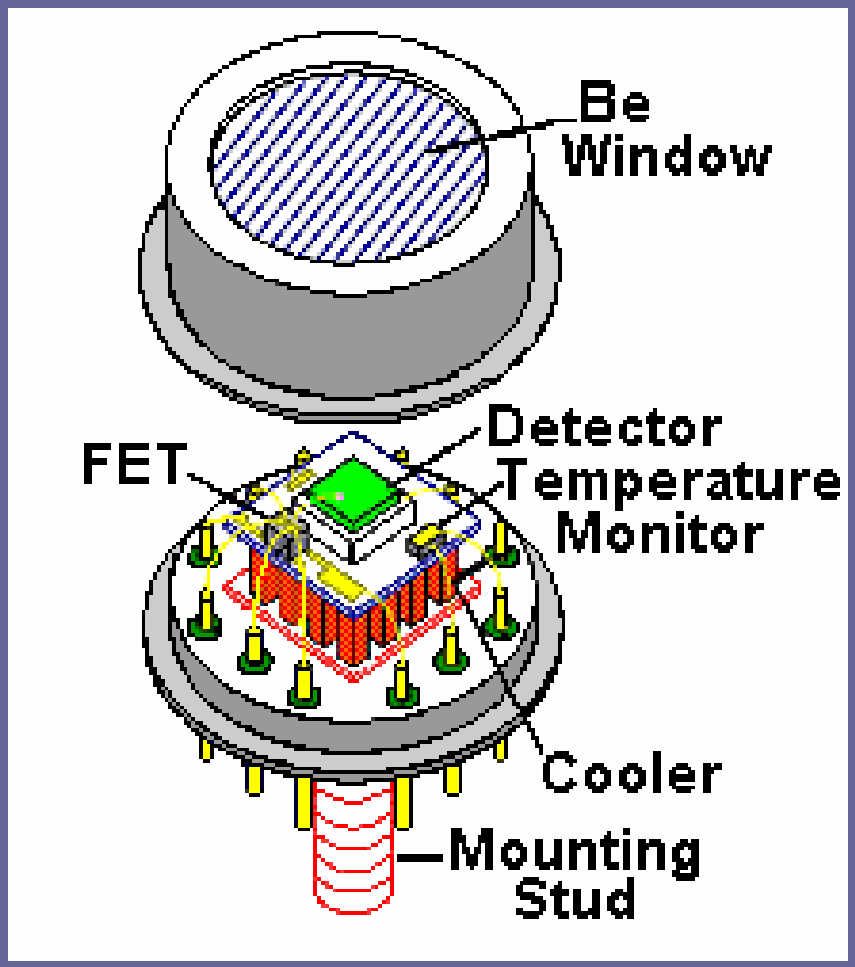
Realization of a circular drift detector

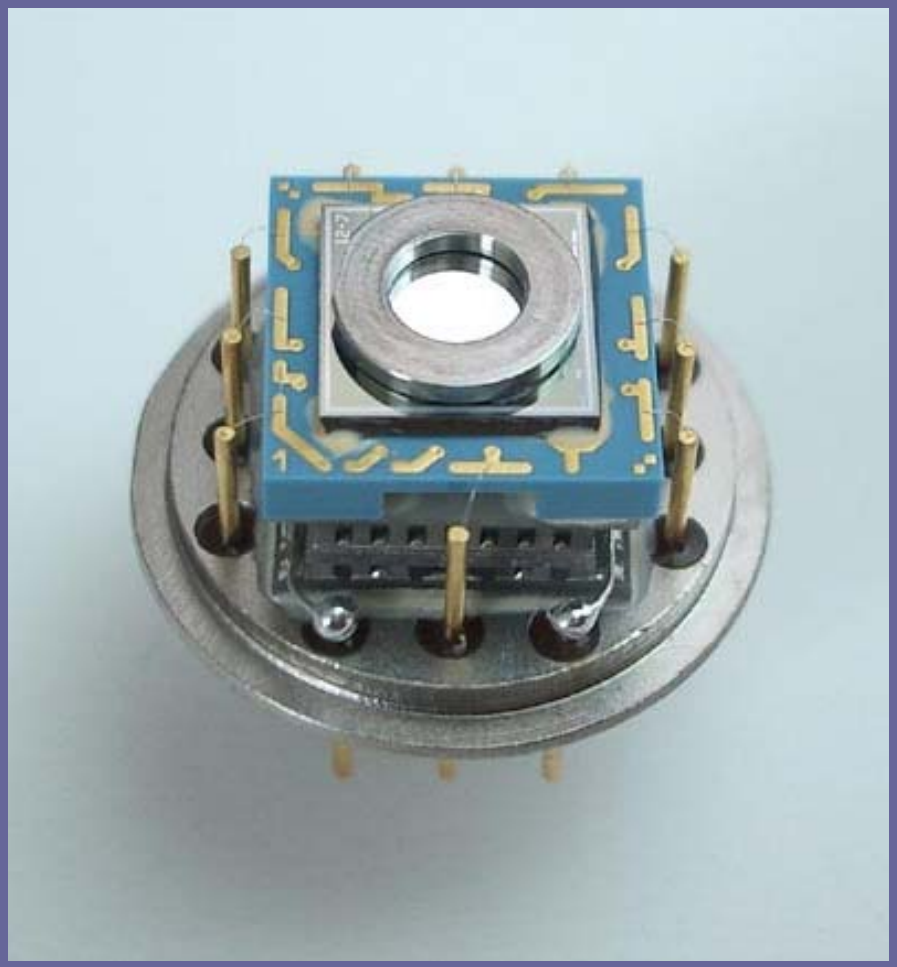




AMPTEK (USA) pin detector
-30 °C, 150 eV, 3000 USD

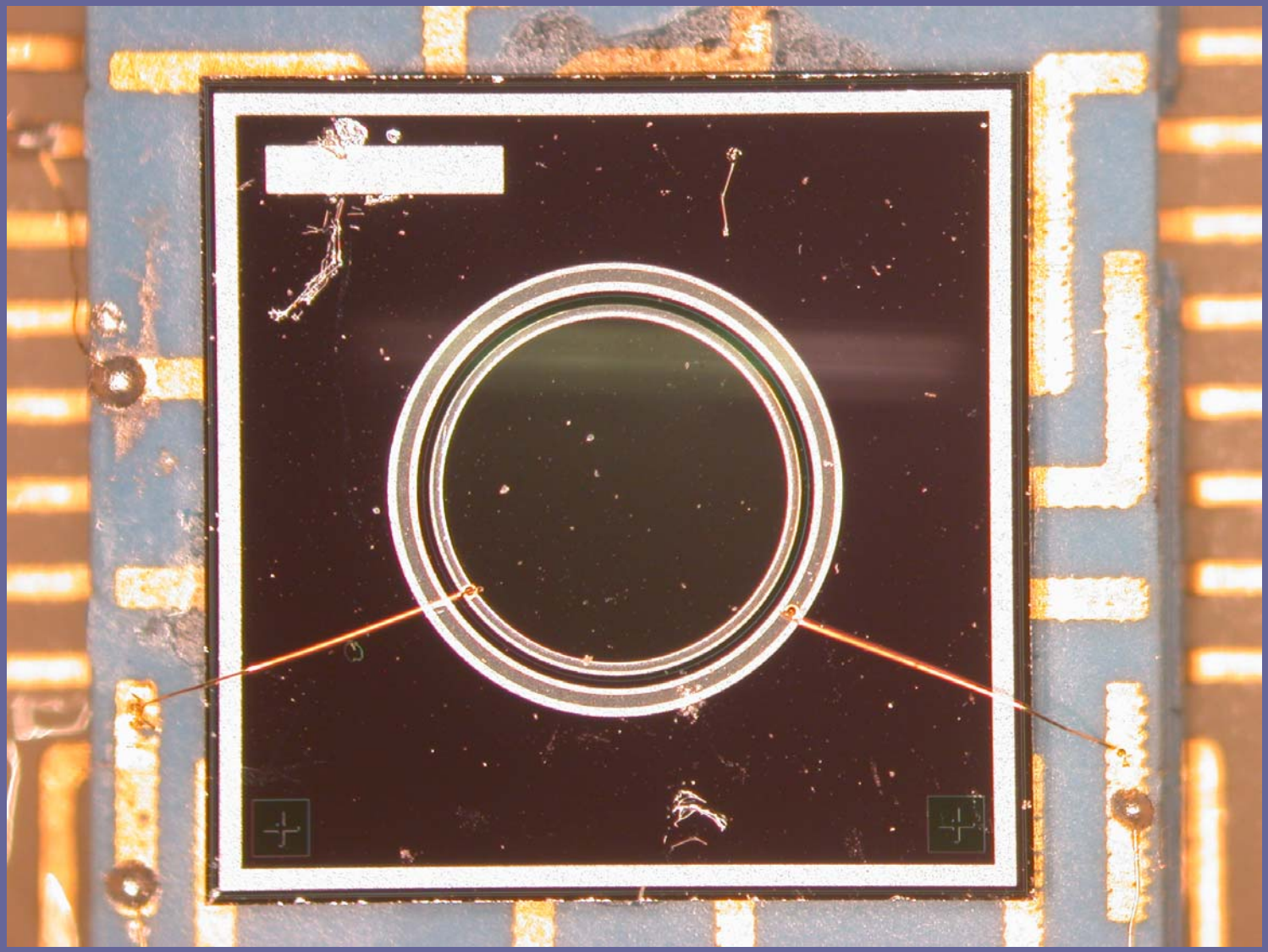
KETEK (Germany.) drift-detector
-30 °C, 125 eV, 10000 EU





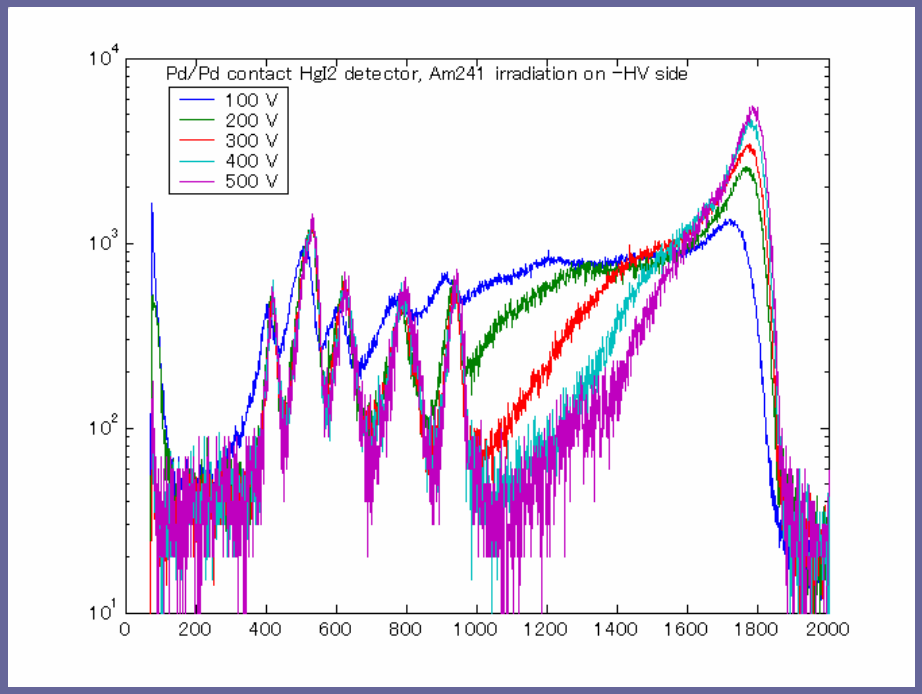
Aim: construction of similar pin/SDD detector units
International collaboration with Osaka Electro-Communication University and a Japanese Semiconductor Company

Prototype Si pin/SDD detector (radiation entrance side)

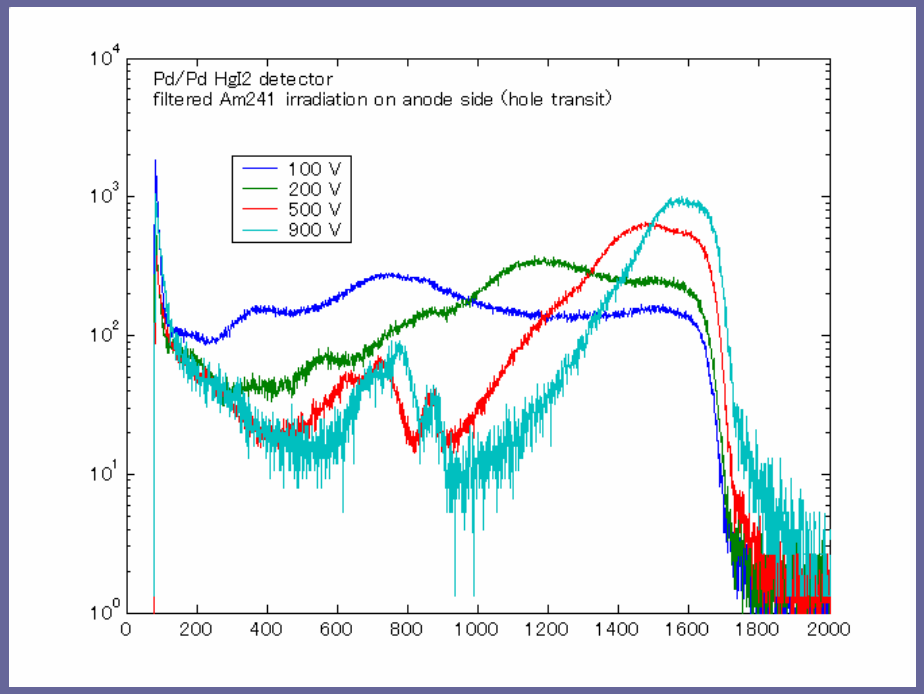


HgI_2 detector development

single crystal from Constellation Technology, Florida
50 mm^2 area, 1 mm thickness



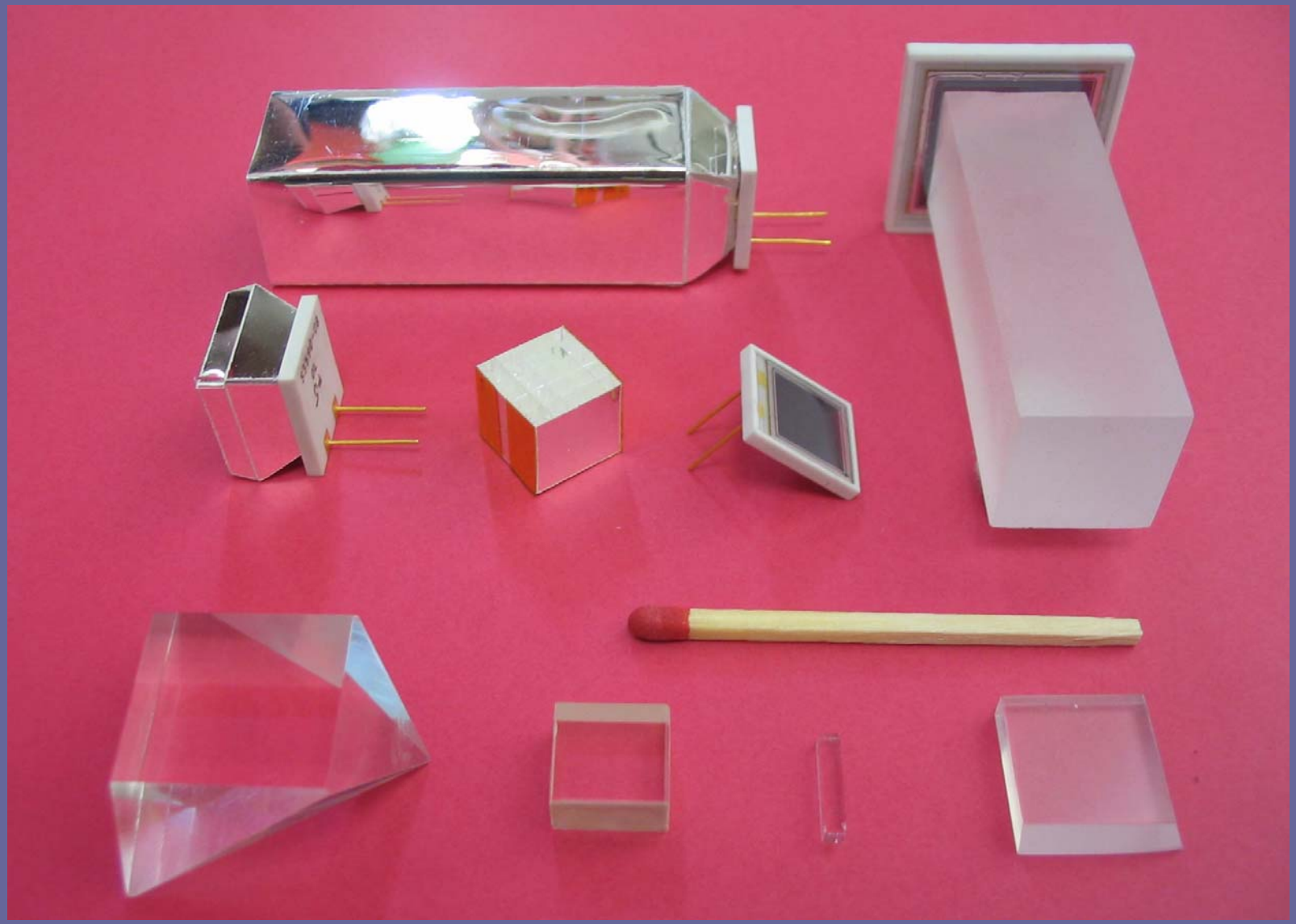
- HV side irradiation
Electron traversal



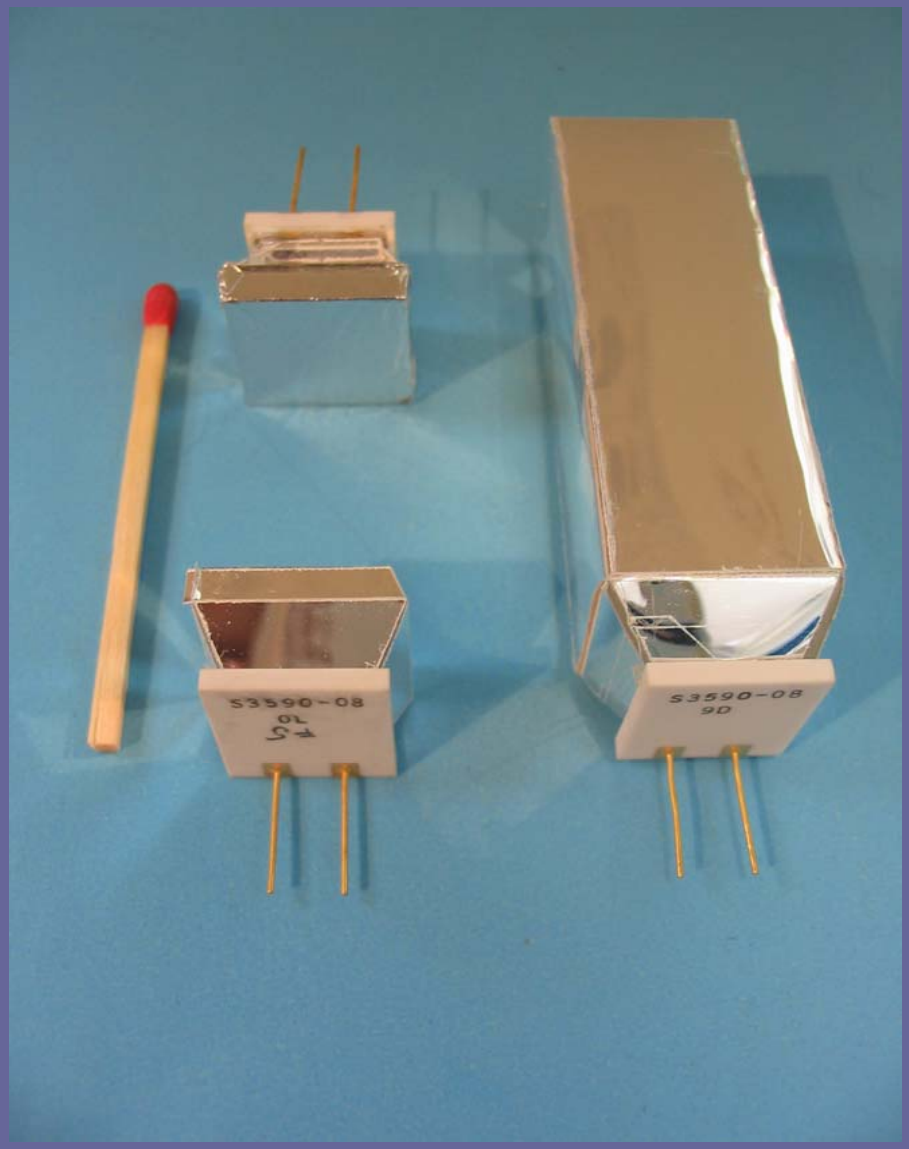
+ HV side irradiation
Hole traversal

Scintillation detector developments (1991-)

- CsI(Tl) scintillator (550 nm) + Si pin photodiodes
- LSO scintillator (420 nm) + PMT



Scintillation charged particle detector systems developed by ATOMKI using multilayer polymer mirror reflector wrapping based on Giant Birefringent Optics

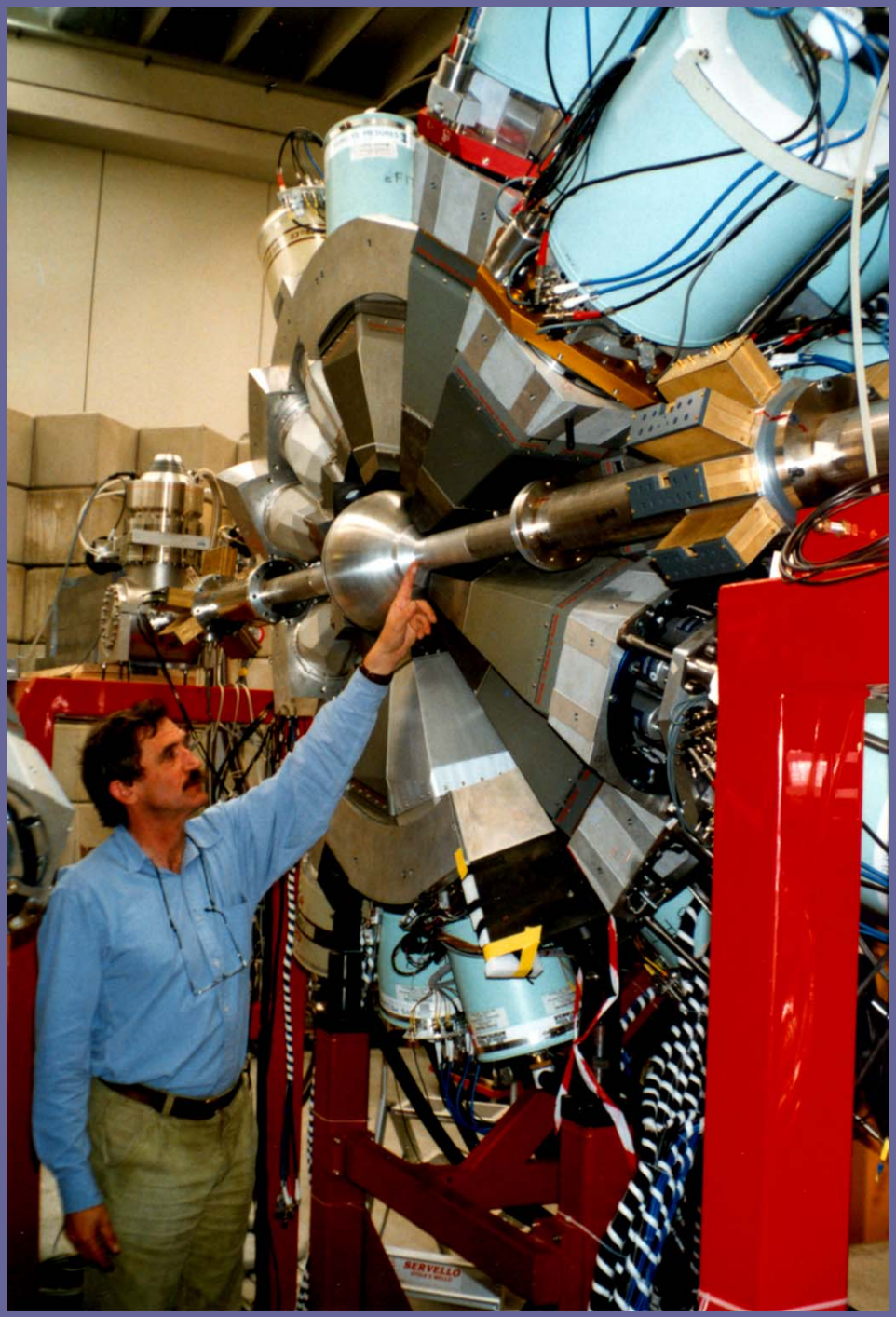


100 element CsI(Tl) + Si pin photodiode detector system (DIAMANT + ChessBoard) for

- EUROBALL, (France, Italy)
- EXOGAM (Ganil, France)
- AFRODITE (iThemba, South Africa)
- Collaboration with CENBG, Bordeaux; MSI, Stockholm; INFN, Napoli
- scintillator : 14 x 14 x 3 mm^3
- photodiode : 10 x 10 mm^2
- for ~ 30 MeV/ amu particles
- Dedicated preamplifiers and highly integrated dedicated electronics in VXI-standard
- Excellent energy- and particle-resolution
- (~ 2 times better than that of counterpart Microball at Gammasphere)

300 element CsI(Tl) + Si pin photodiode detector system (GRACIA) for RIBF at RIKEN (Japan)

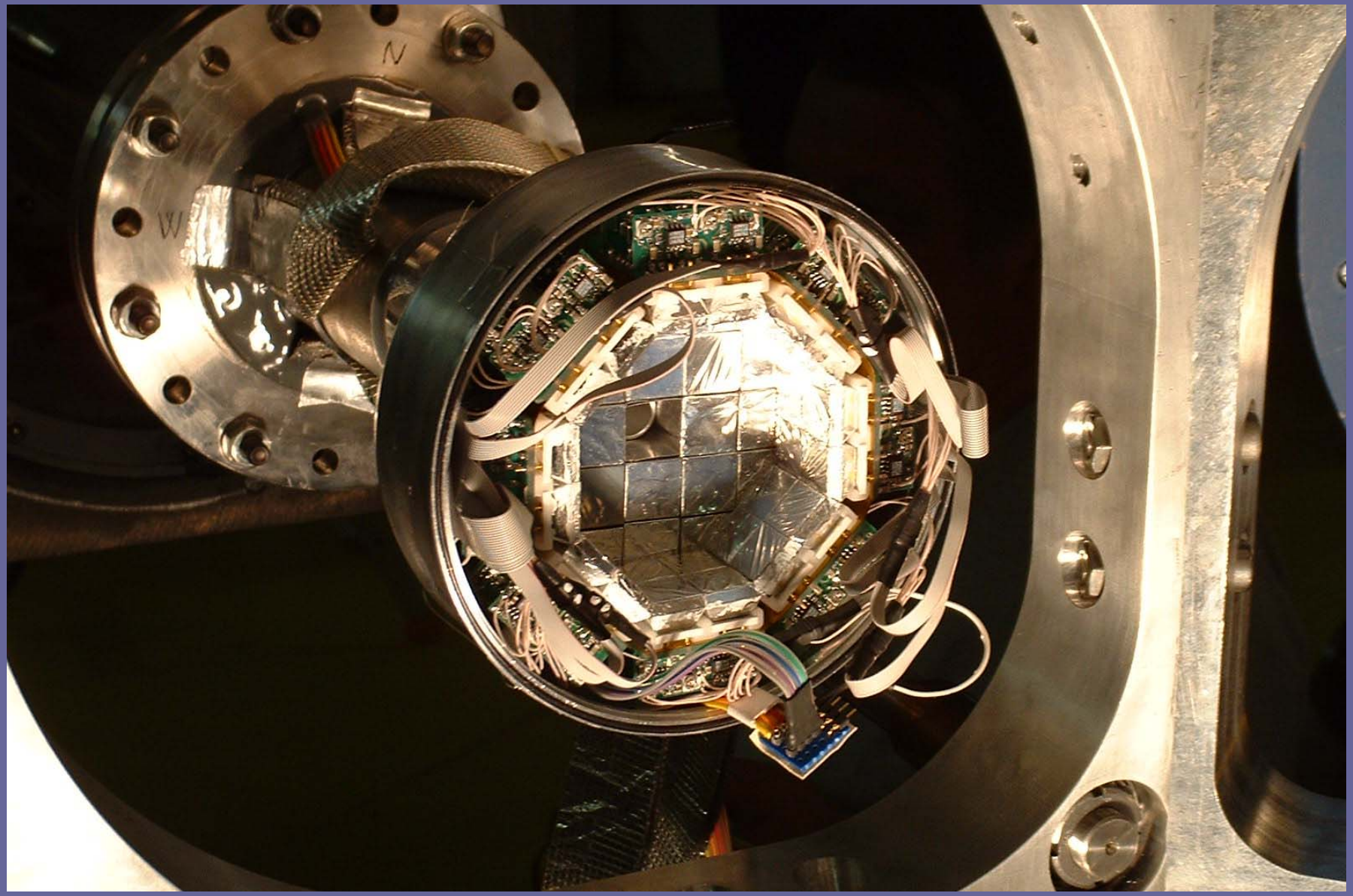
- Collaboration with Riken and Rikkyo University
- scintillator : 16 x 16 x 55 mm^3
- photodiode : 10 x 10 mm^2
- for ~ 130 MeV/ amu particles
- Dedicated preamplifiers, (yet) standard signal processing electronics
- Performance is only a little bit inferior to the DIAMANT system (det. size 24x larger !)



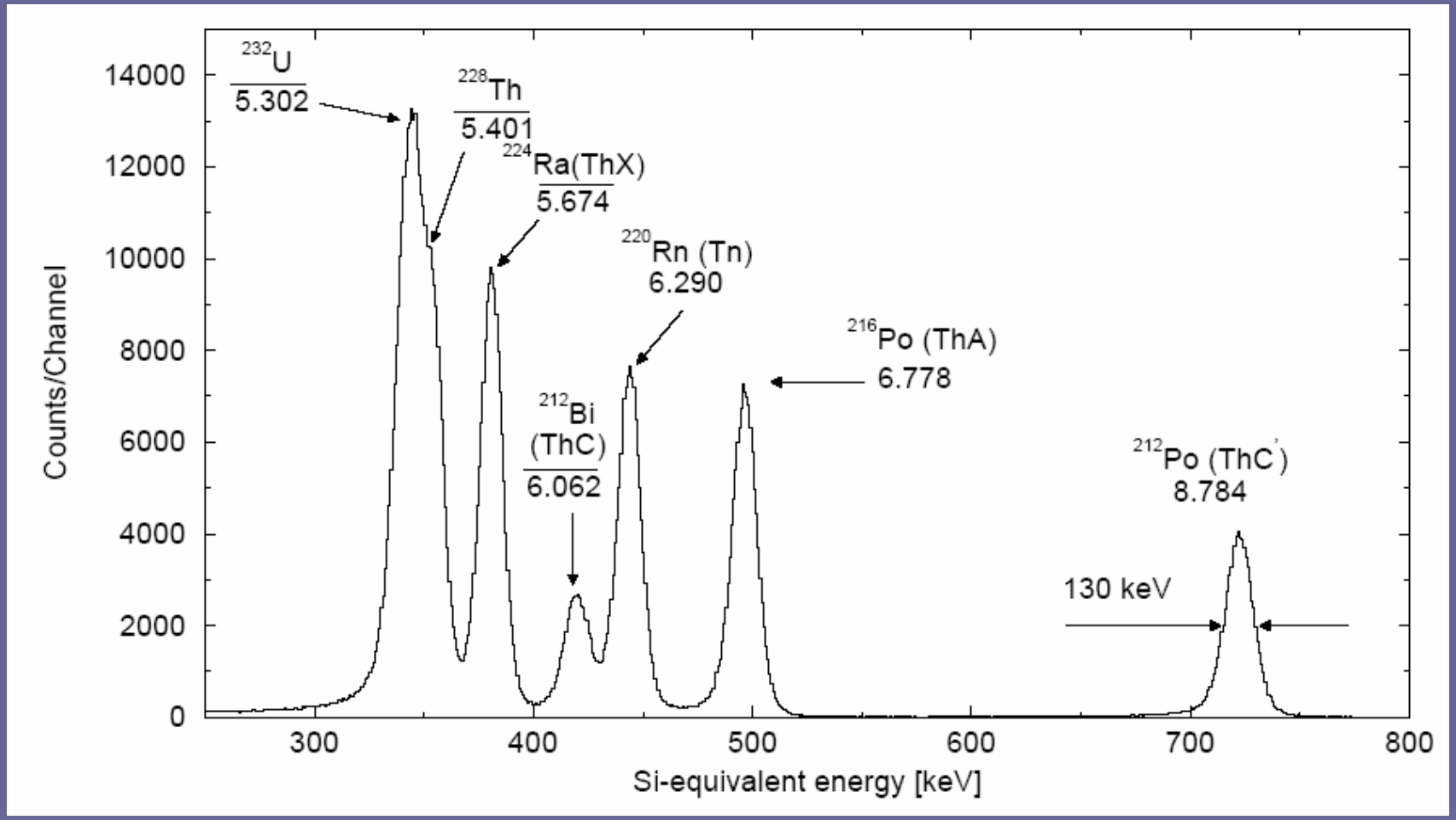
The DIAMANT charged particle detector system built into the target chamber of the EUROBALL gamma-detector system (Strasbourg, 2004)

The electronic units for processing scintillation detector signals synchronously with Germanium detector signals has also been developed in ATOMKI (not shown in the photo).

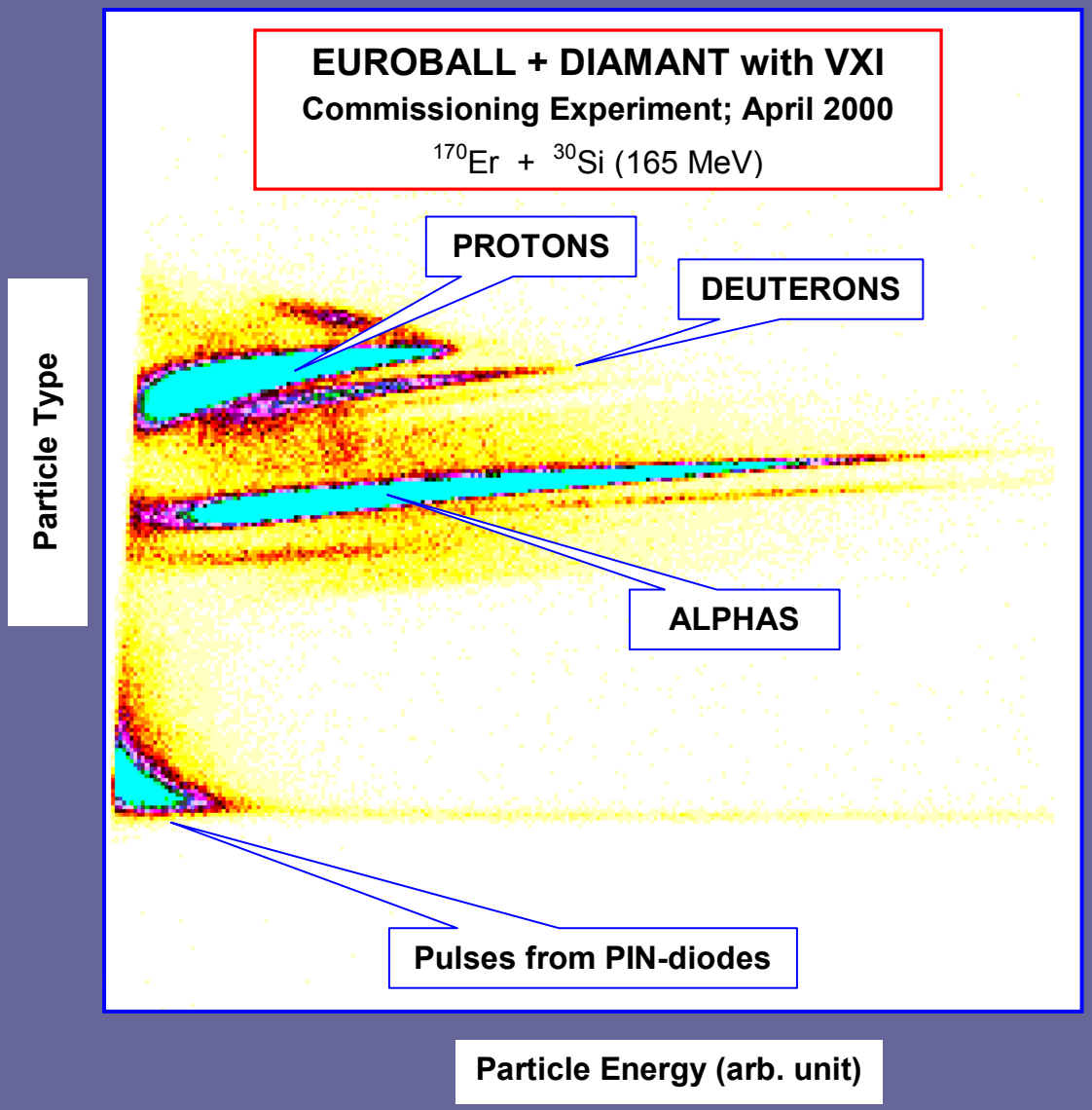
The forward hemisphere of DIAMANT detector system together with mounted preamplifiers inside the target chamber



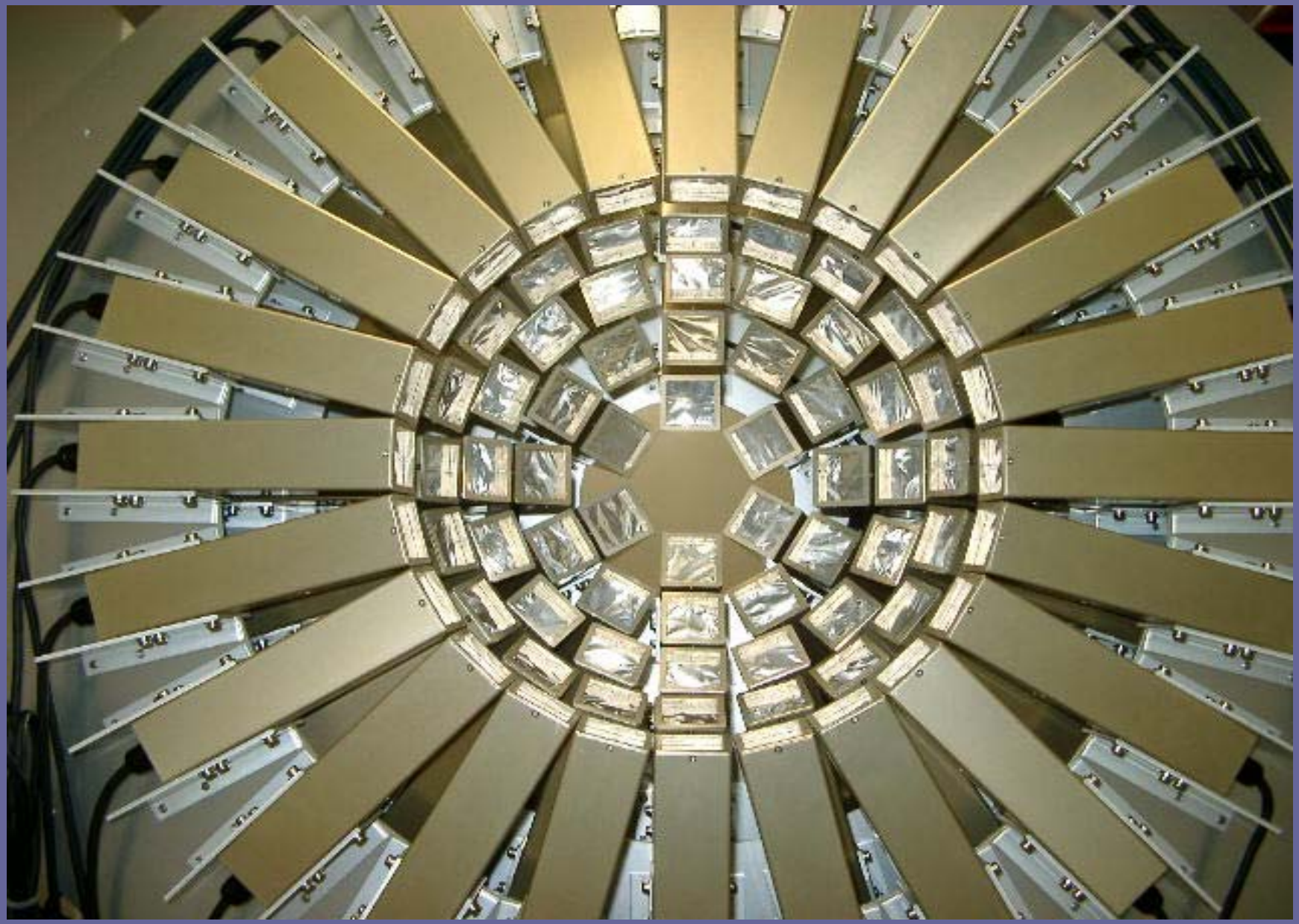
Energy resolving capability of DIAMANTscintillation detectors (low energy alpha spectrum of U-232)



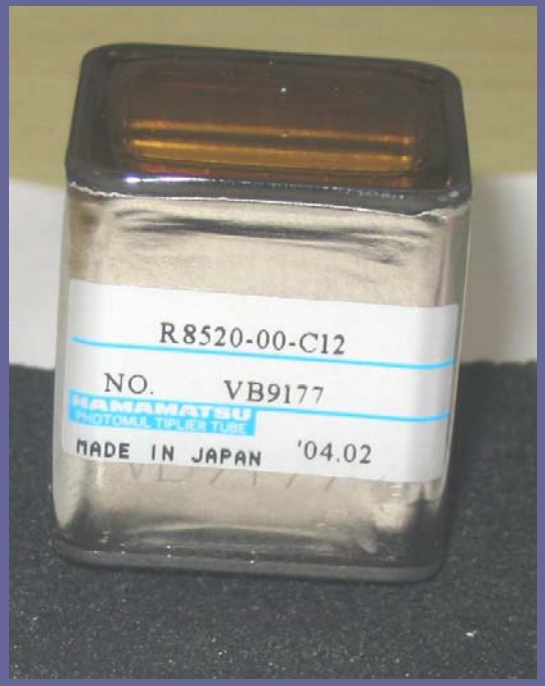
Particle resolving capability of DIAMANT scintillation detectors (low energy region < 50 MeV)



Part of the 300 element (detectors packed in quad units) CsI(Tl)+Si pin photodiode charged particle detector system GRACIA at RIKEN RARF



Detector blocks for small animal PET systems

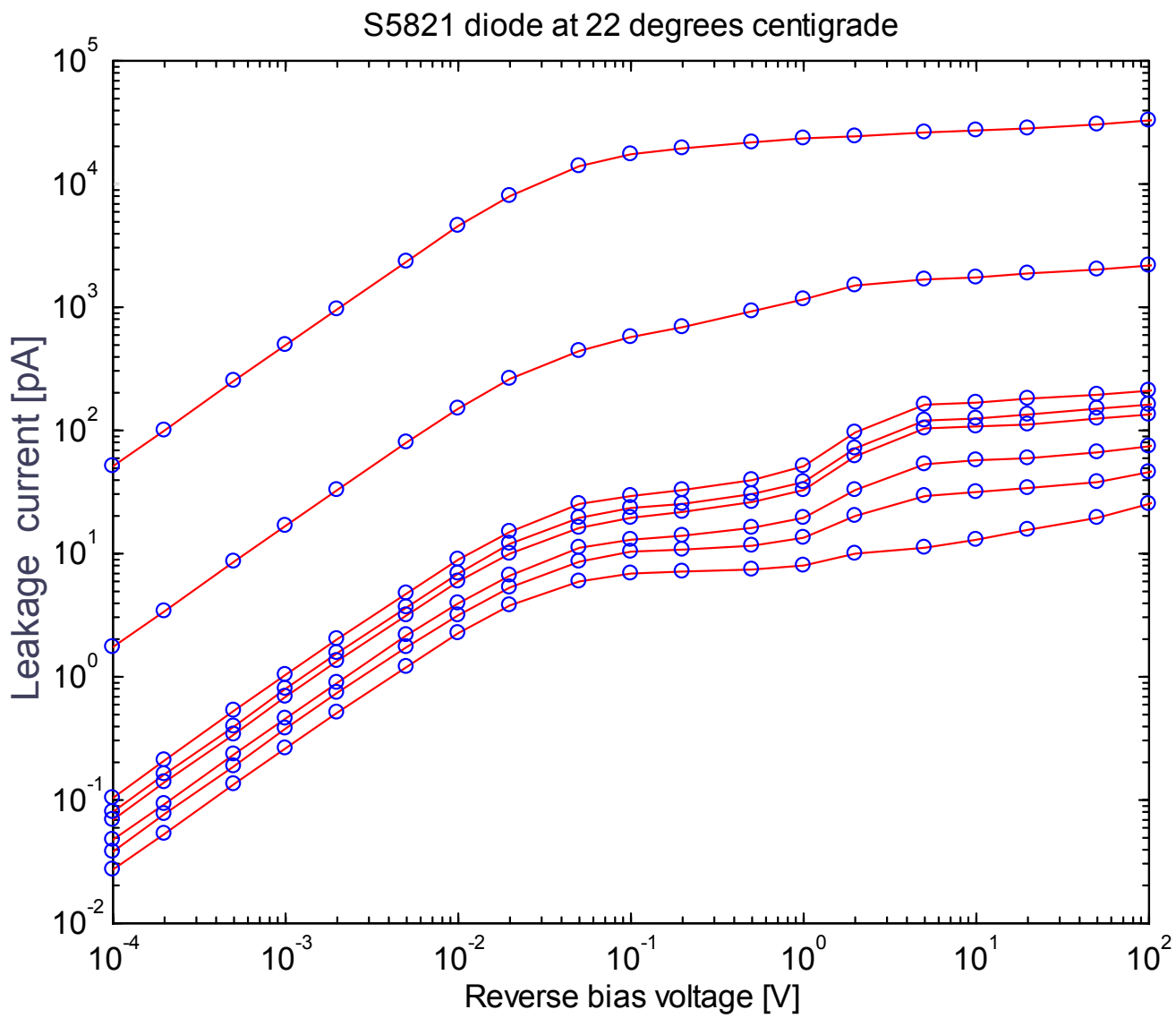


- **Crystal type: LSO scintillator**
- **Crystal size: 2x2x10 mm^3**
- **8x8 crystal matrix unit**
- **Lumirror light reflector**
- **Position Sensitive PhotoMultiplier Tube**
- **Recently: 33x33 matrix unit of 1.4x1.4x12.5 mm^3 LYSO crystals 16x16 anode PSPMT**

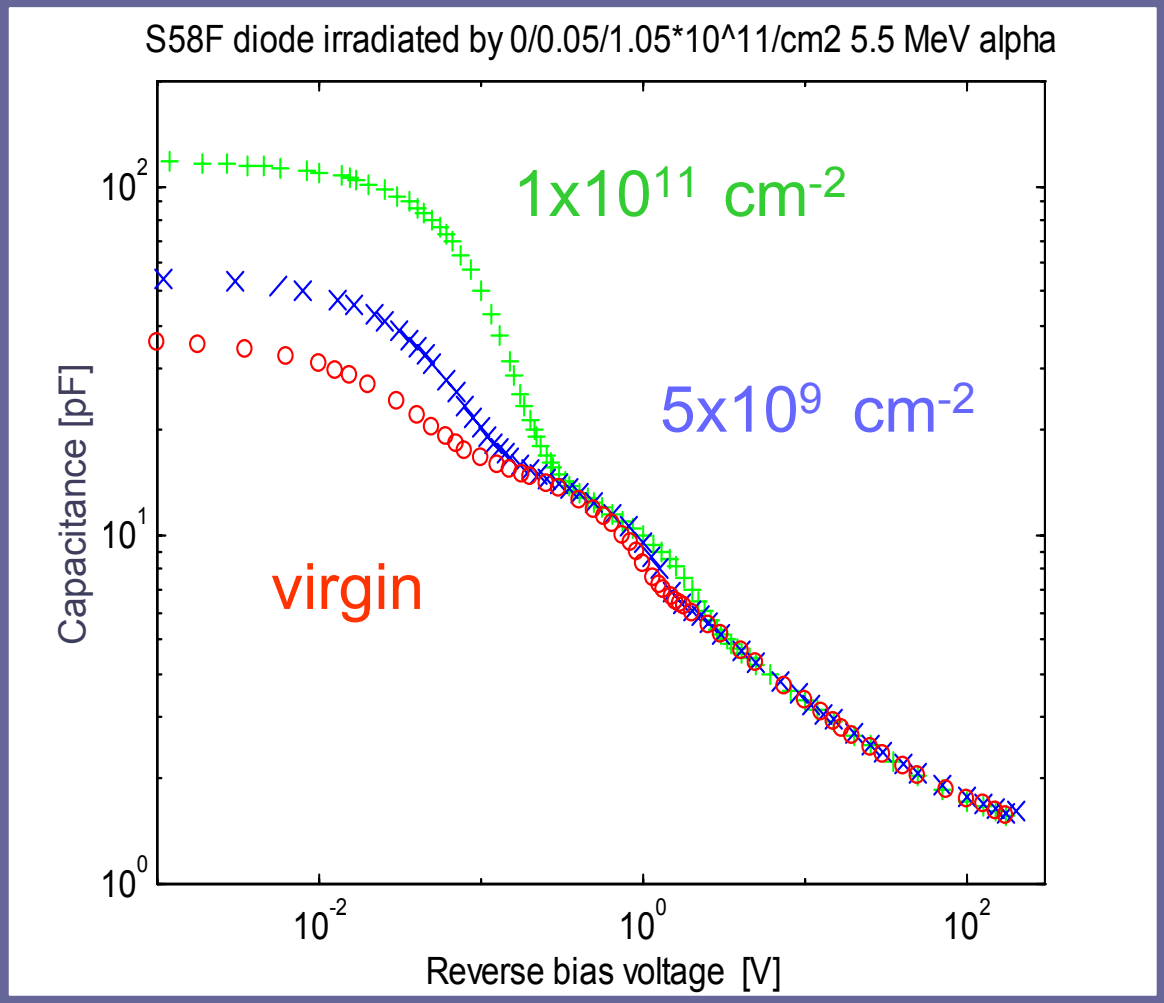
Radiation damage research

Detector radiation damage studies started very recently in ATOMKI with the increased use of Si pin photodiodes in conjunction with particle accelerators. Preliminary results has been obtained with 5.5 MeV alpha particle irradiation from Am-241 isotope, with 6.5 MeV oxygen, 2.15 MeV lithium, 0.43 MeV hydrogen ions (both with 5 um range in Si), and 2 MeV protons (50 um range). Photodiodes irradiated uniformly were characterized by I-V and C-V techniques and charge collection measurements with 5.5 MeV alpha particles. Diodes irradiated with a patterned way were evaluated with Ion Beam Induced Charge (IBIC) method, using μm focussed beam of the same particle at the same energy as during irradiation either online or offline.

Summary of I-V plots versus 5.5 MeV alpha fluence up to 1×10^{11} cm^{-2} (generation centers)



C-V plots versus fluence of 5.5 MeV alpha (ionized impurity centers)

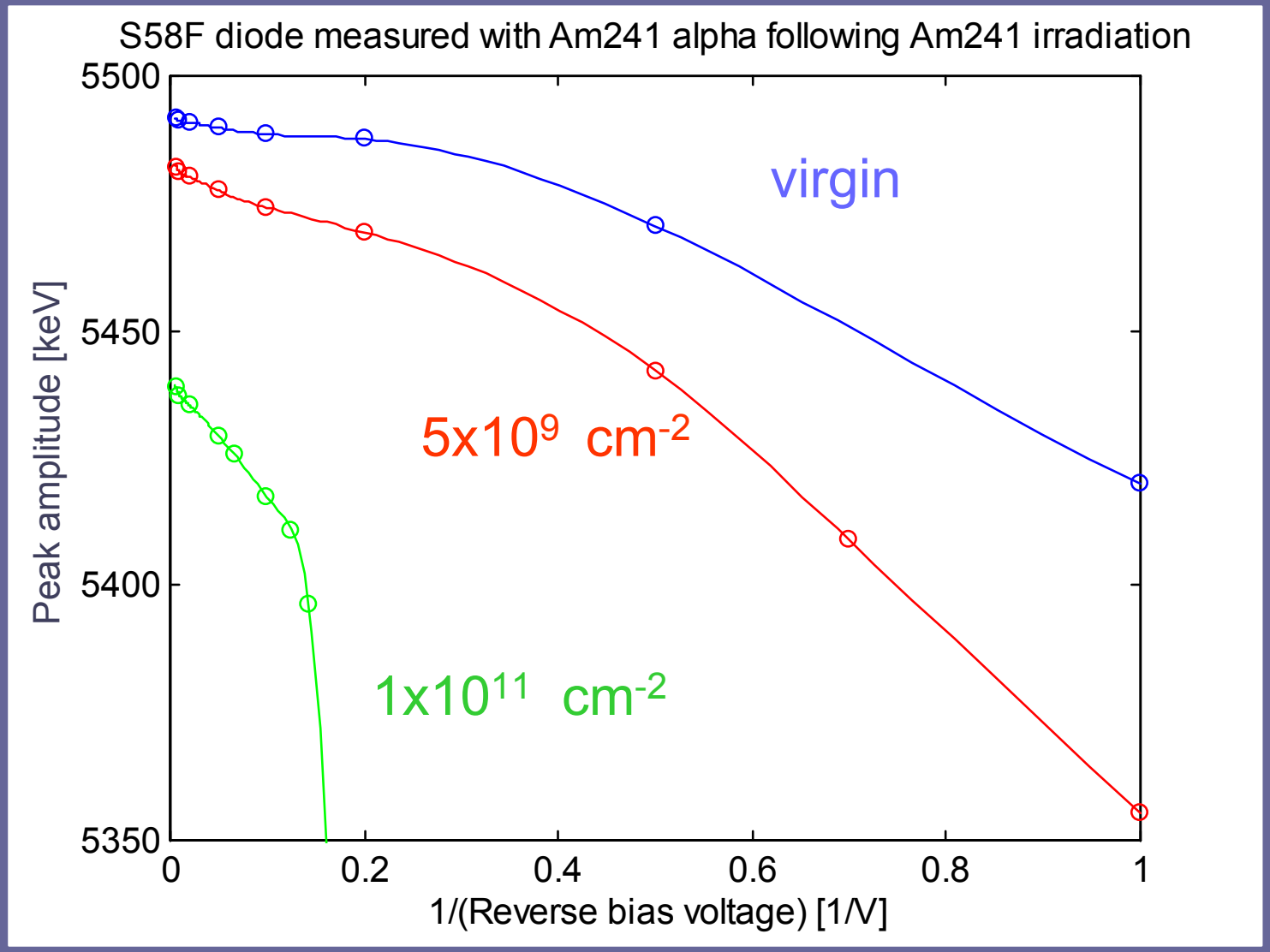


$$C = \varepsilon_S \frac{A}{W}$$

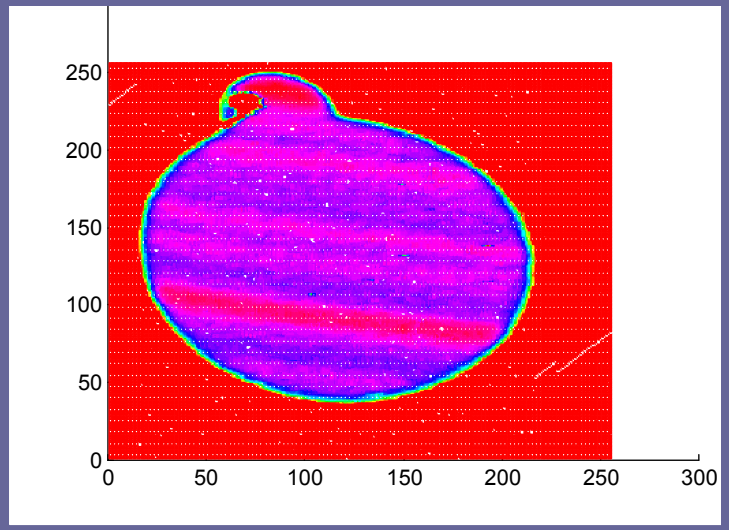
if N_d= *const.*

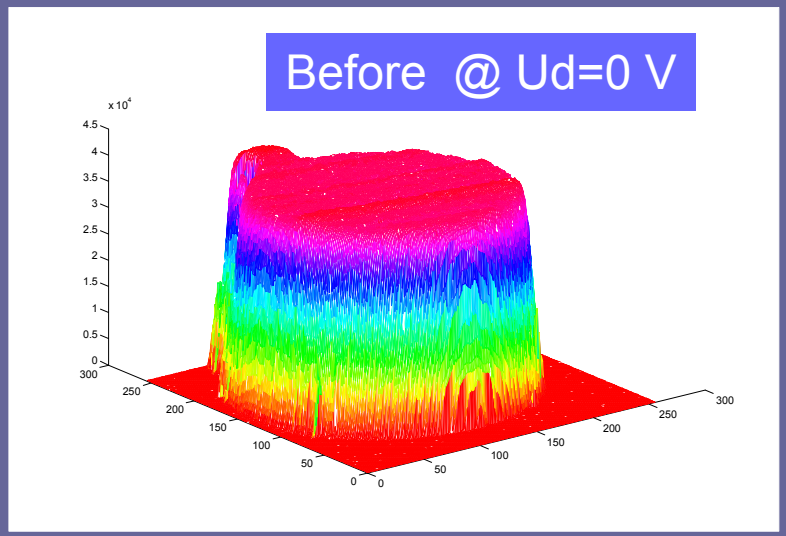
$$W = \sqrt{\frac{2\varepsilon_S}{q} \frac{(U_R + U_{bi})}{N_D}}$$

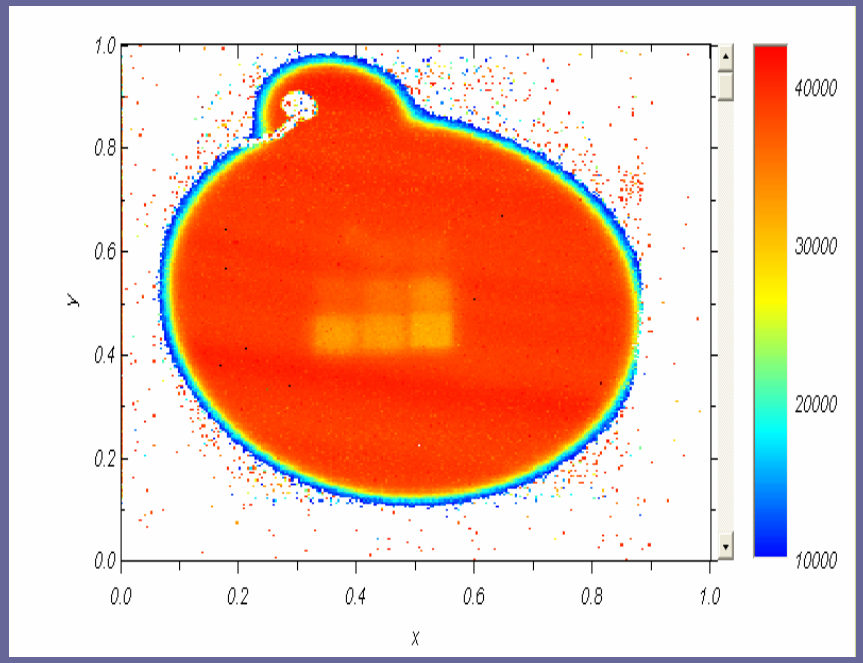
CCE measurement with 5.5 MeV alpha particles after different fluences of 5.5 MeV alpha particles (trapping and/or recombination centers)

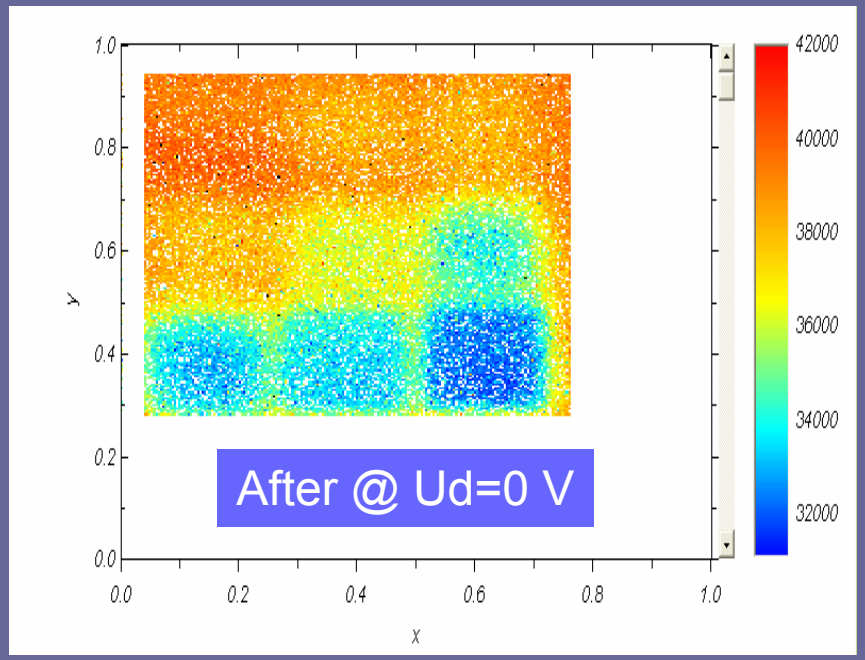


2 MeV H^+ irradiation (50 μm range) of 3x3 squares of 100x100 μm^2 area in logarithmically evenly spaced fluence steps from 0 to $5x10^{11}$ cm^{-2}



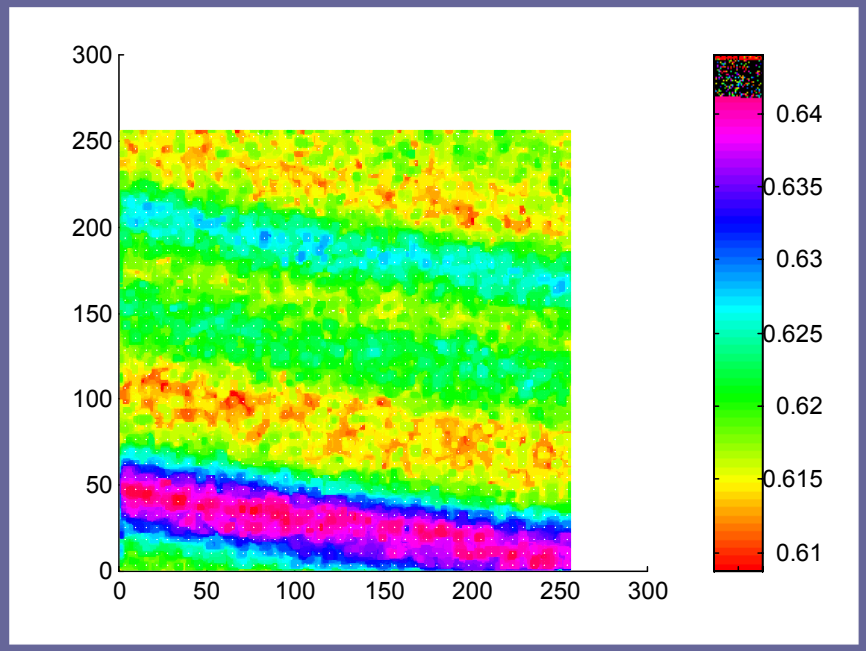


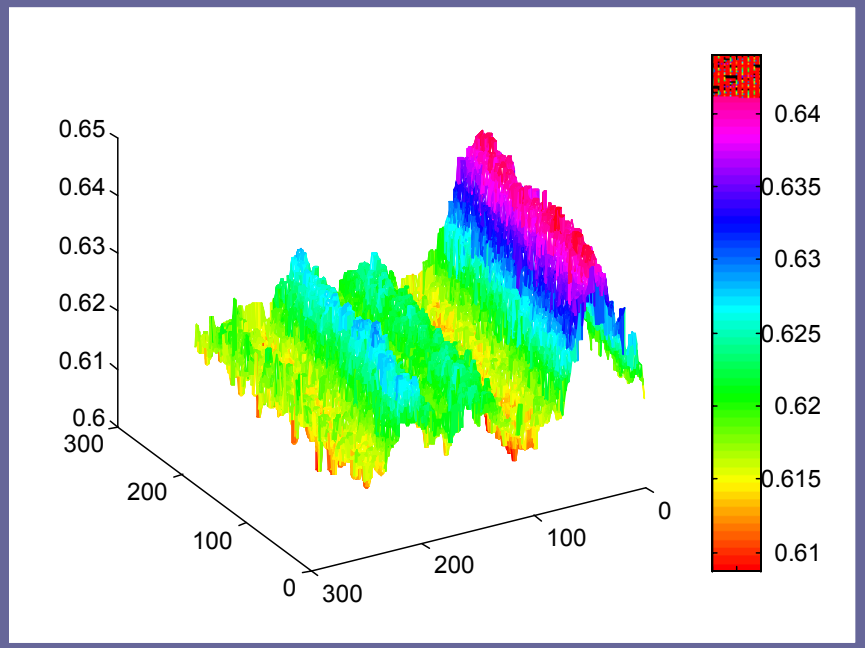




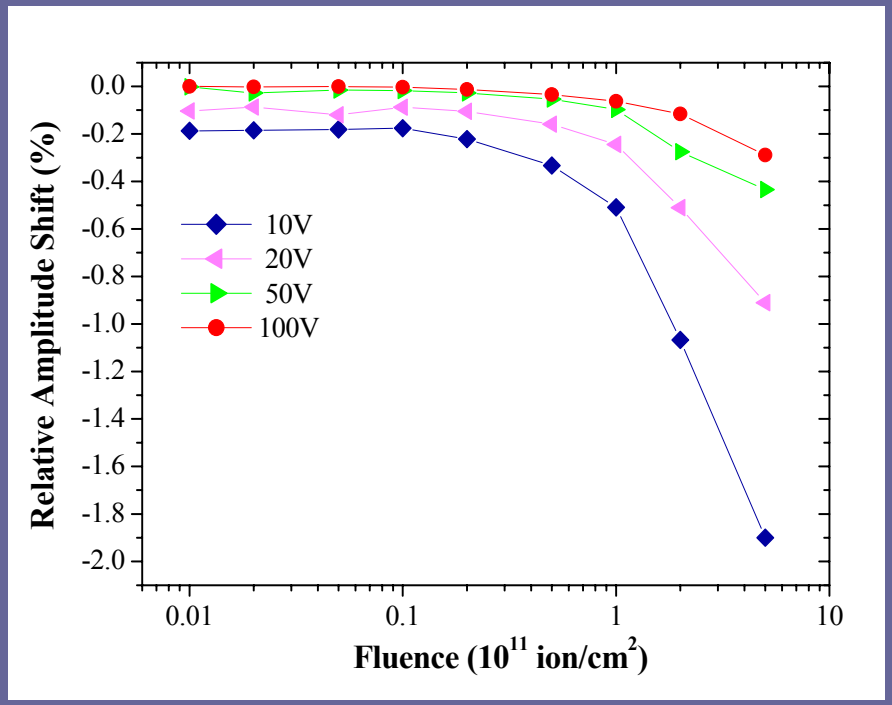
2 MeV H^+ IBIC scan of the irradiation site prior to irradiation at U_d=0 V

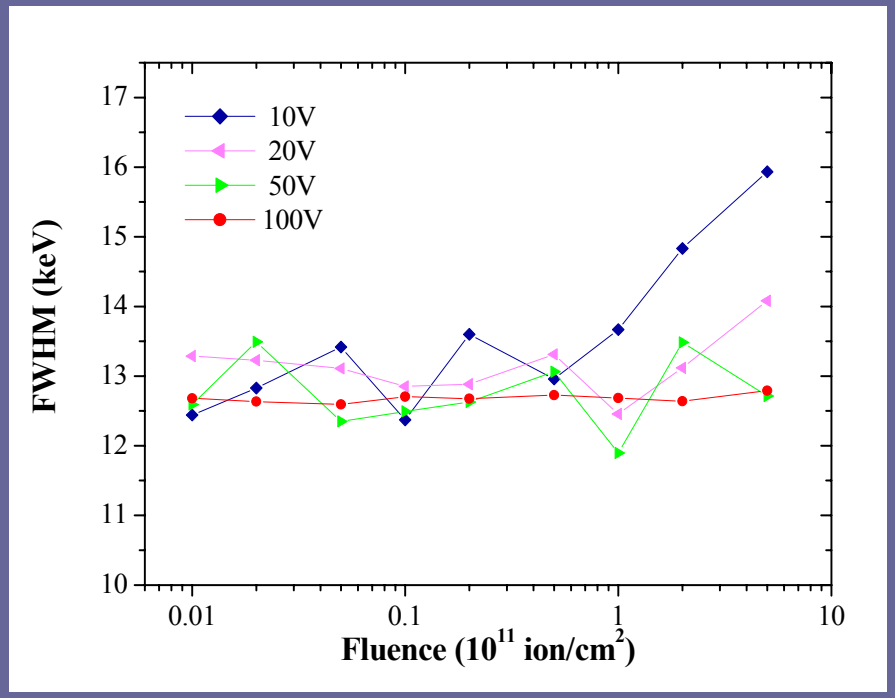
Detector material nonuniformity (growth striations)





Results relevant for detector applications: degradation for the $U_d \geq 10$ V case





$$\delta(CCE)_{rad} = (2.2 \pm 0.5) \times 10^{-15} [cm^2] \Phi [cm^{-2}] + (-3.3 \pm 0.5) \times 10^{-13} [cm^2 V] \frac{\Phi [cm^{-2}]}{U [V]}$$

$$\Delta_{rad} [keV] = (4.0 \pm 1.5) \times 10^{-5} \frac{\sqrt{\Phi [cm^{-2}]}}{U [V]}$$

$$\Delta = \sqrt{\Delta_0^2 + \Delta_{rad}^2}$$