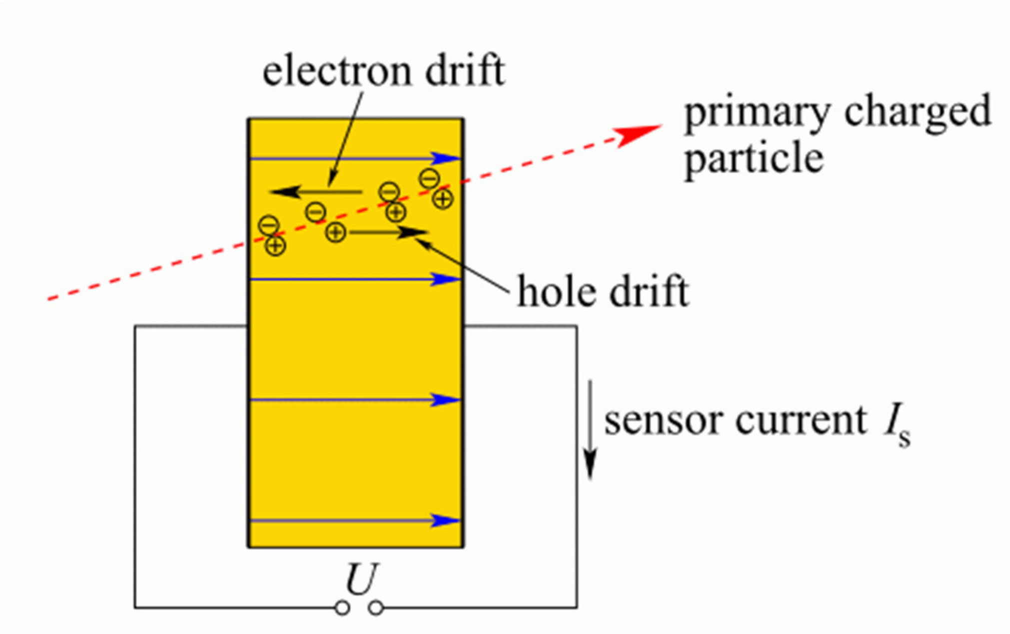
Radiation hard sensor materials for forward calorimeter

K. Afanaciev on behalf of FCAL collaboration

CLIC Workshop
CERN 2015

Solid state detectors with direct electrical signal readout
(not scintillators, gas or liquid detectors)

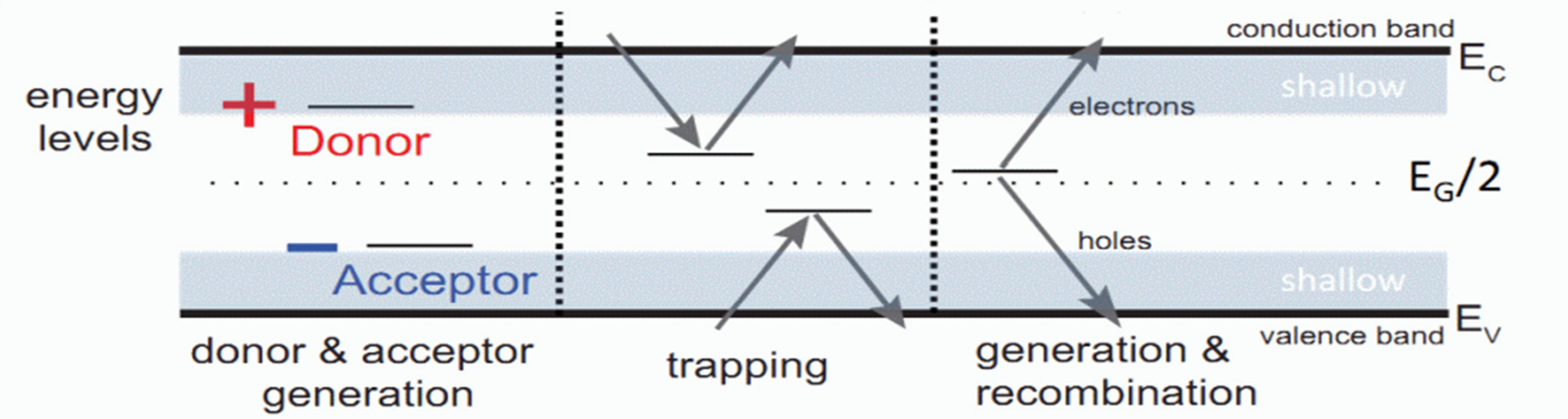
Silicon, GaAs, Diamond and Sapphire



Detector functions
As a solid state
Ionisation chamber

Charge carriers are
Generated by a particle
And then drift in a E field
 Signal is readout by an
amplifier

Particle knocks atoms out of the crystal lattice – introduces defects
These defects could act in different ways



I. Change of N_{eff}, V_{dep}
⇒ type inversion ,
⇒ decrease of signal

II. Increase of charge carrier trapping
⇒ loss of charge

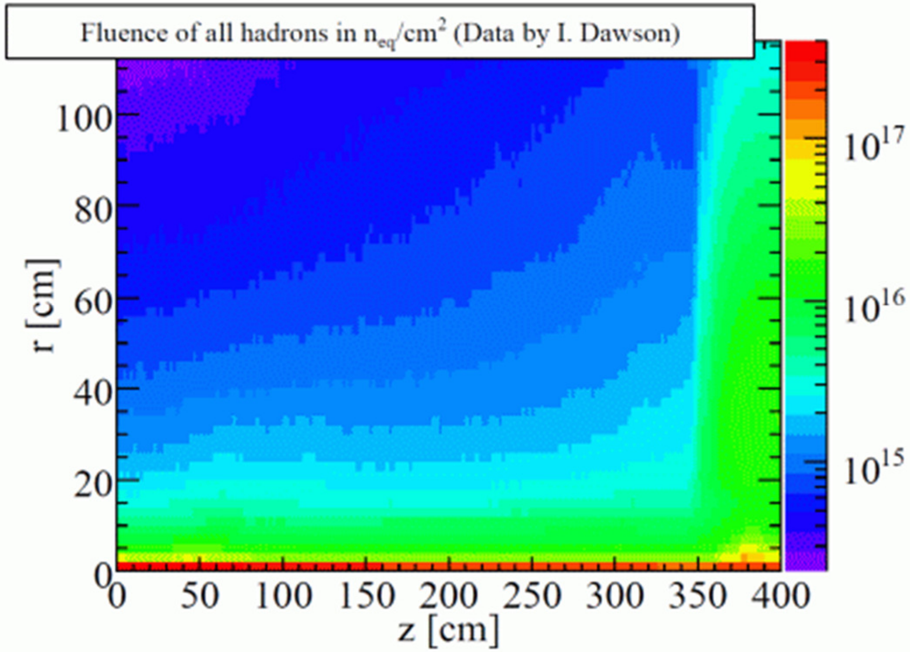
III. Increase of leakage current
⇒ increase of noise
Cooling during operation!

Not so important
For undoped materials

Not so important
For wideband materials

+ surface effects (charge trapping in SiO_2) affects electronics

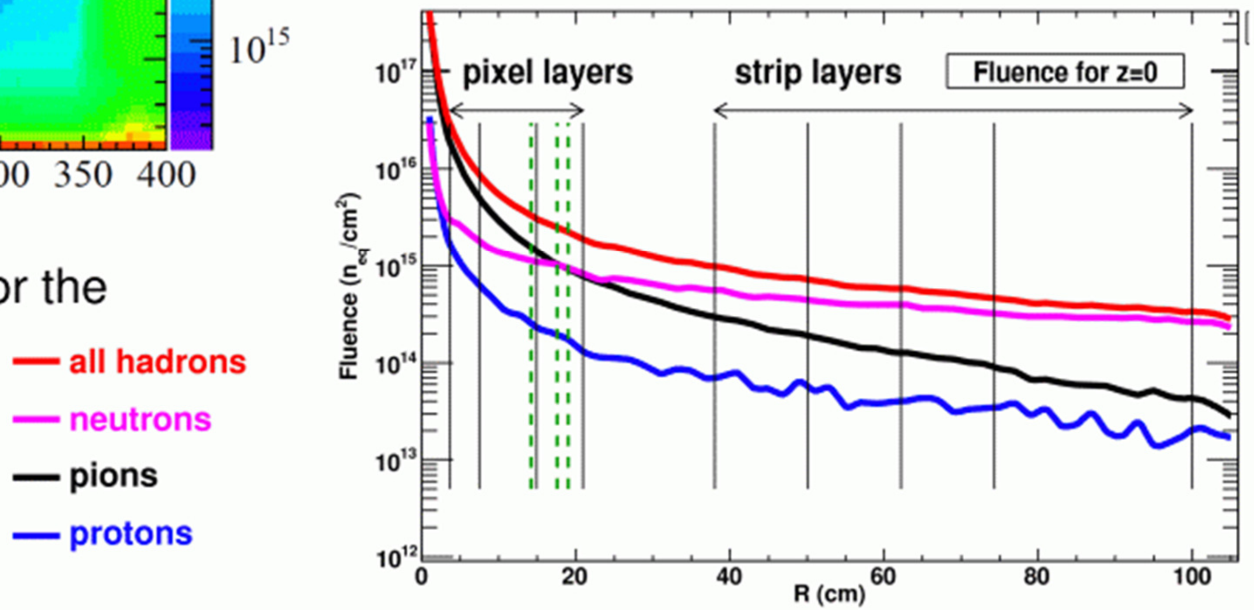
Planned upgrade of the LHC in ~ 2022:



- 3000 fb^{-1} expected integrated luminosity
- high radiation exposure to the tracking detector:

  $2*10^{16}$ neq/cm^2 for inner pixel layers
  up to $1*10^{15}$ neq/cm^2 in the strip region

Expected particle fluences for the ATLAS Inner tracker:



Similar for CMS

Silicon. Motivation and who is doing it

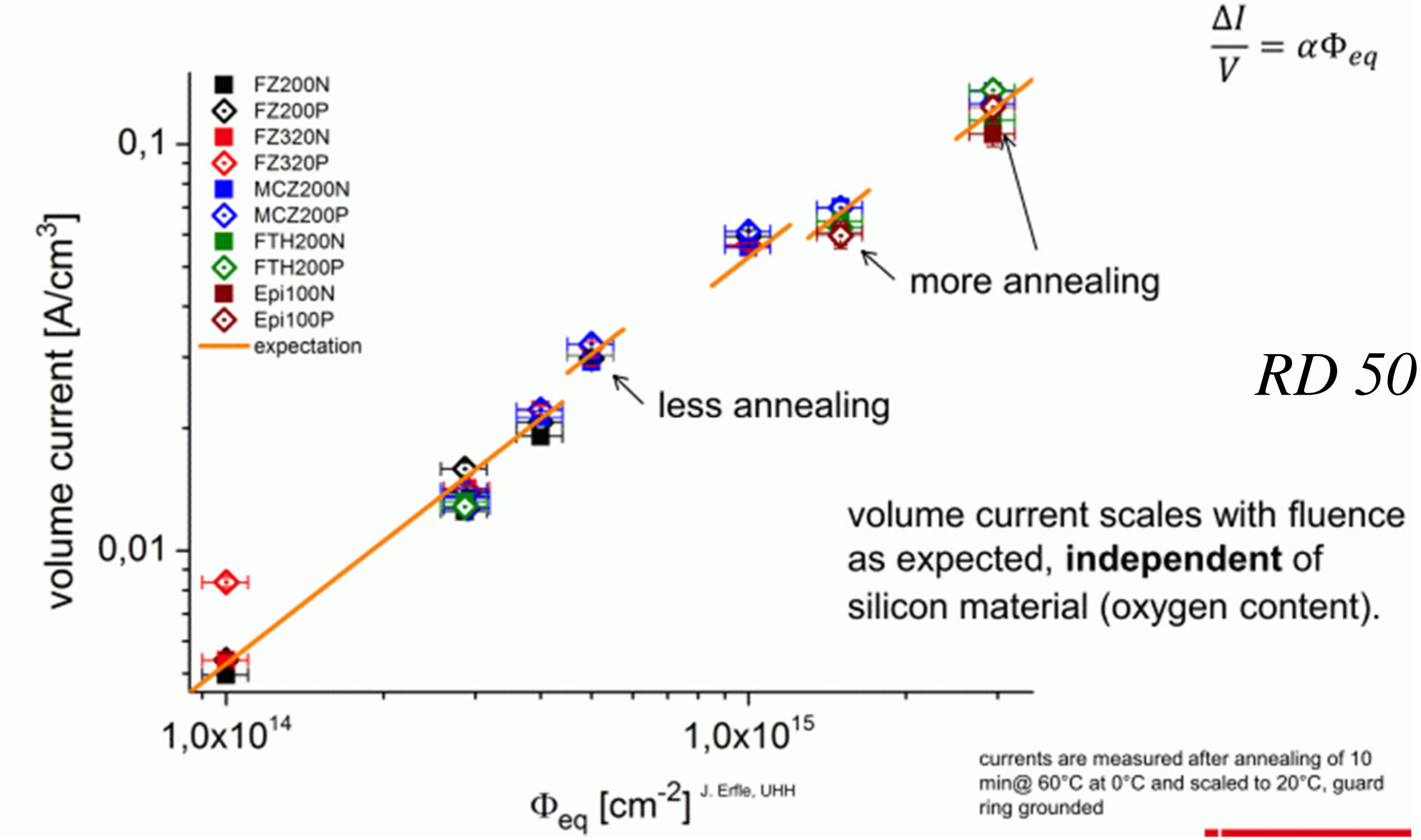
RD 50 collaboration (www.cern.ch/rd50/) since 2003
> 250 members working on radiation hard silicon detectors
Goal => Silicon detectors able to withstand fluence upto
10^{16} 1 MeV neutron equivalent per cm^{-2}
+ A working group WODEAN (Workshop on Defect Analysis in Silicon Detectors)

RD 50 mostly study strip and pixel detectors
Hadronic irradiation

Recently finished a comprehensive campaign of sensor
Irradiation and study

Dark current rises linearly with the fluence

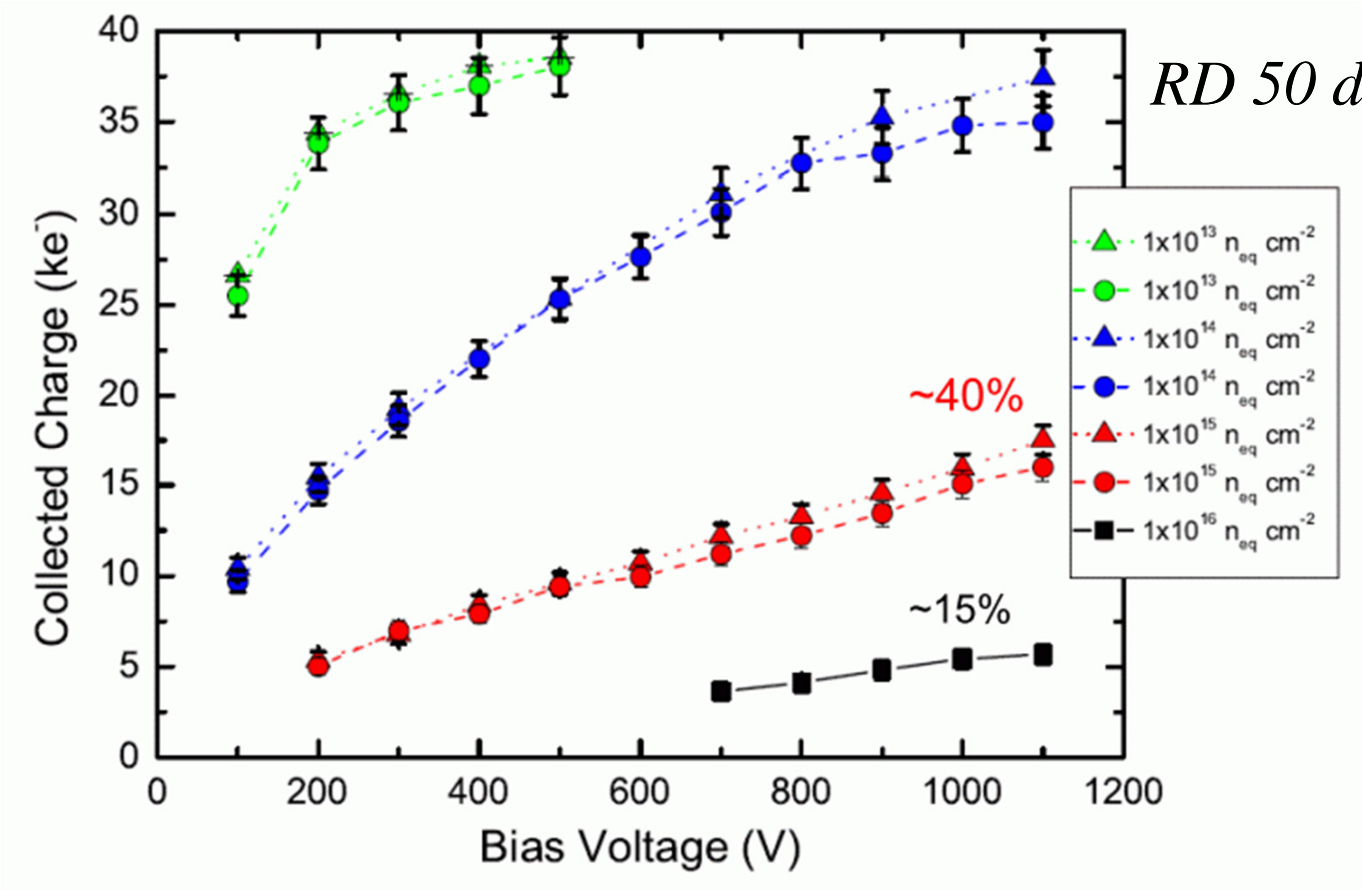
$$\frac{\Delta I}{V} = \alpha \Phi_{eq}$$



RD 50 data

This means for 10x10x0.3 mm detector Idark ~ 1 mA @ room temp.
=> Needs cooling to at least -20C and up to -50C (still uA currents)

Silicon. Results overview. CCE

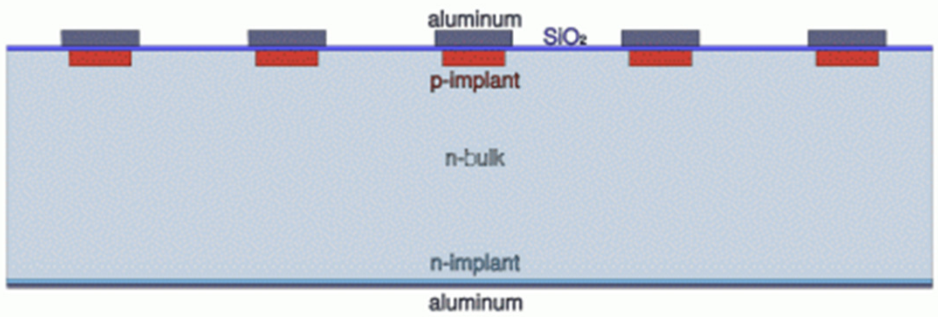


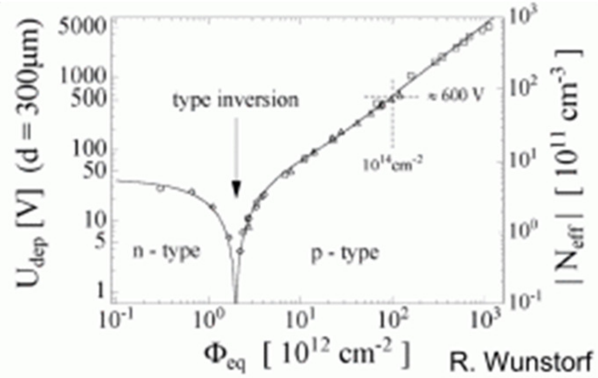
RD 50 data

Signal is visible after 10^{16} n/cm^{-2}, but V_{fd} goes into kilovolt range
Needs at least 1kV bias (no full depletion) and cooling

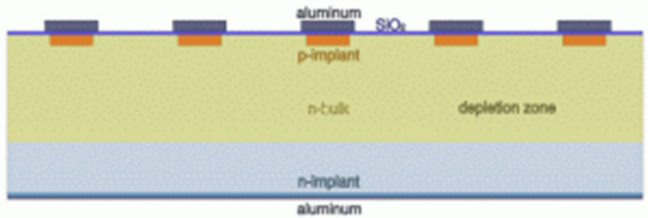
Silicon. Results overview. Type inversion

Basic layout of a strip sensor





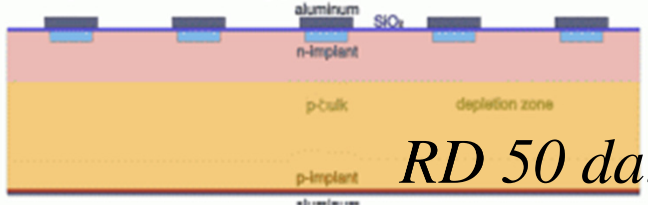
Depletion of a standard sensor



Basically two different types:

- N doped bulk:
  - Hole readout
  - Easier to produce
  - Tends to undergo type inversion
- P doped bulk:
  - Electron readout
  - Harder to produce

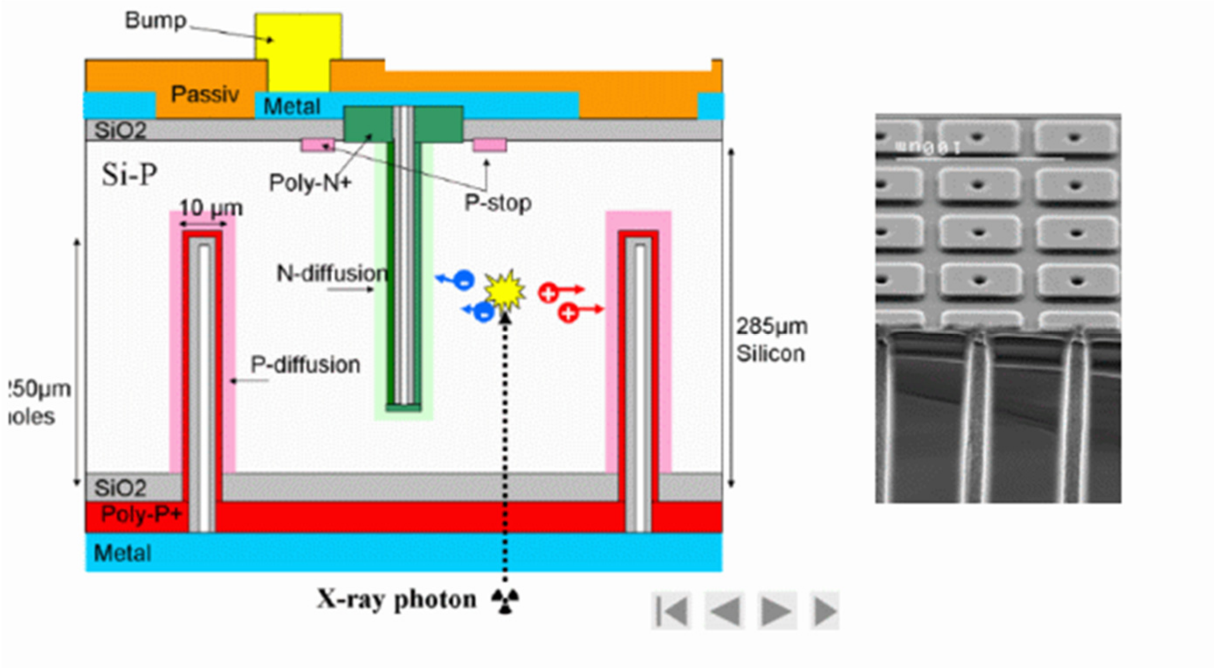
Depletion of a type inverted sensor



RD 50 data

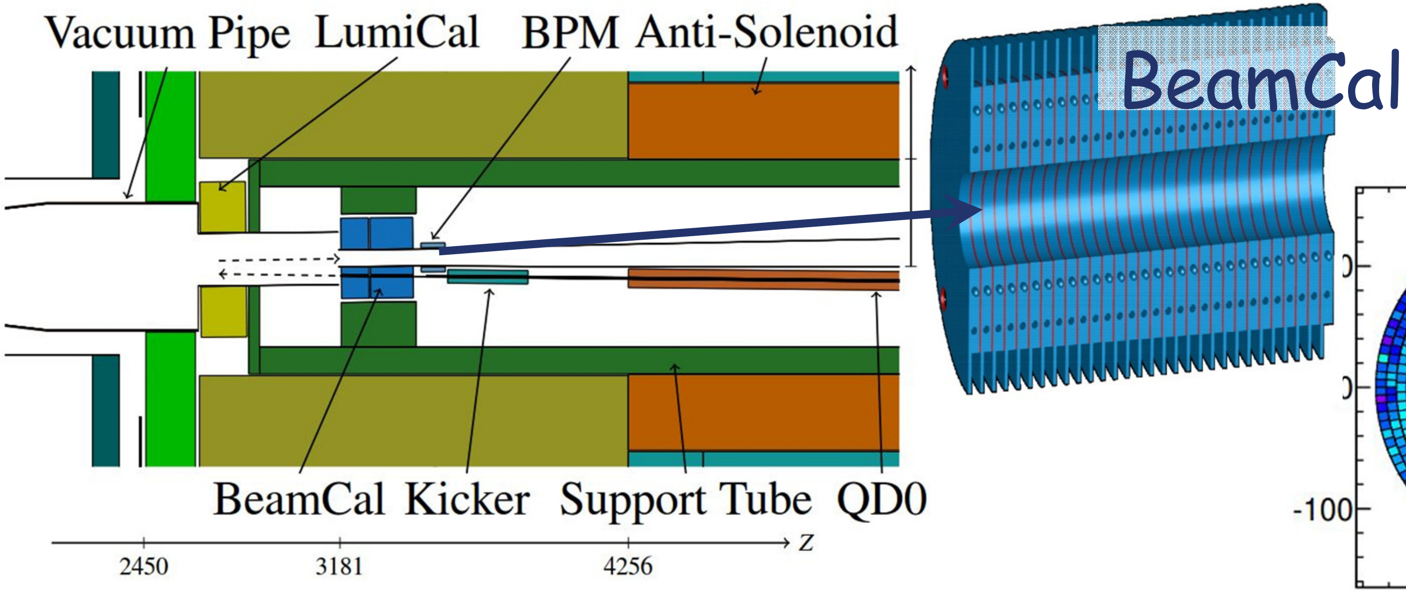
P-type Si does not have type inversion upto 10^{16} fluences

Silicon. Results overview. 3D Silicon

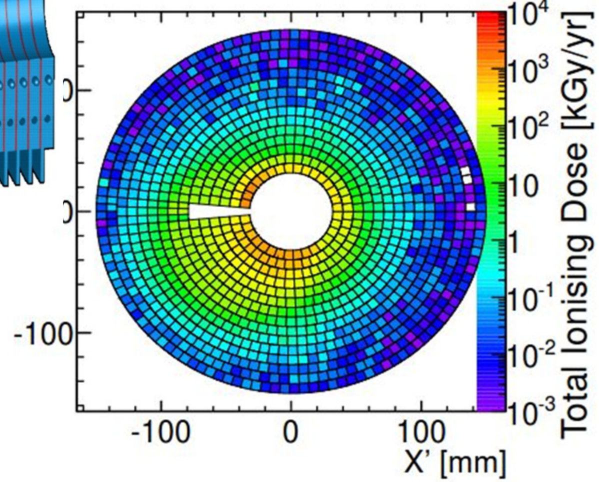


This approach allows to decouple V_{fd} from detector thickness
Operational upto 10^{16} fluences, lower bias voltages
Very suitable for pixel detectors
Sophisticated technology, more expensive

Motivation. Very Forward Region



From A. Sailer



EM calorimeter with sandwich structure:

30 layers of 1 X_0, 3.5mm W and 0.3mm sensor, Moliére radius $R_M \approx$ 1cm

Angular coverage from 10 mrad to 43 mrad ,

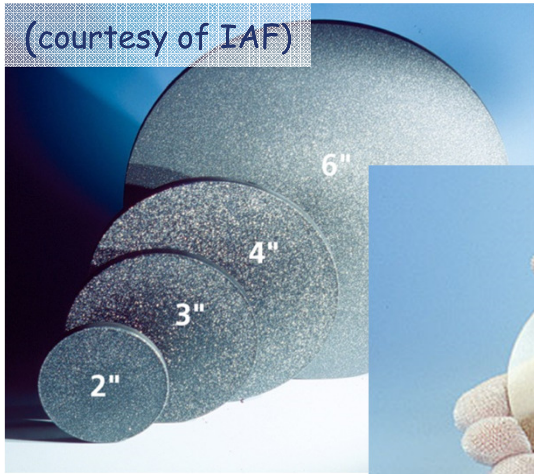
Max expected dose about 1 MGy per year of operation (3TeV CLIC, ~0.5 ILC). Background from beamstrahlung-generated pairs. Mostly EM, energy ~ 10 MeV. Need for a radiation hard material, cooling is difficult.

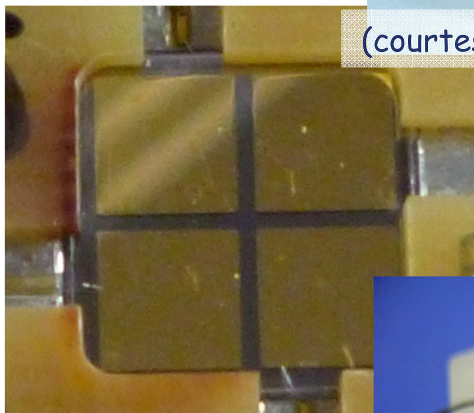
Gallium arsenide (GaAs),
Polycrystalline CVD (chemical vapour deposition) Diamond (pCVD)
Single crystall CVD Diamond (sCVD)
Sapphire

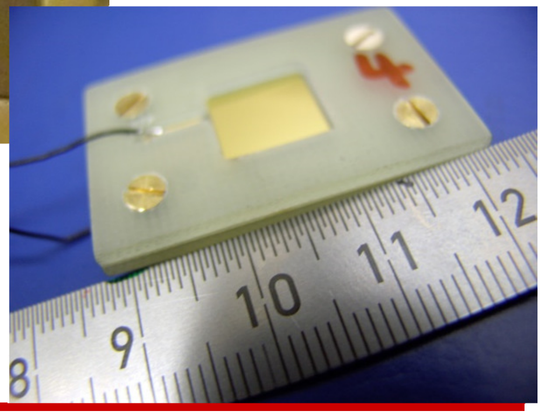
		GaAs	Si	Diamond	Sapphire
	Density	5.32 g/cm^3	2.33	3.51	3.98
•	Pair creation E	4.3 eV/pair	3.6	13	24.6
•	Band gap	1.42 eV	1.14	5.47	9.9
•	Electron mobility	8500 cm^2/Vs	1350	2200	>600
	Hole mobility	400 cm^2/Vs	450	1600	-
•	Dielectric const.	12.85	11.9	5.7	9.3-11.5
•	Radiation length	2.3 cm	9.4	18.8	
	Ave. E_{dep}/100 µm (by 10 MeV e^-)	69.7 keV	53.3	34.3	
	MPV pairs/100 µm	15000	7200	3600	2200
	Structure	p-n or insul.	p-n	insul.	insul.

pCVD Diamond

- pCVD diamond:
  - radiation hard
  - Good properties : high mobility, low $\varepsilon_R = 5.7$, thermal conductivity
  - availability on wafer scale
- Samples investigated:
  - Element Six (ex-DeBeers)
  - 1 x 1 cm^2
  - 200-500 μm thick
    (typical thickness 300μm)
  - Ti(/Pt)/Au metallization



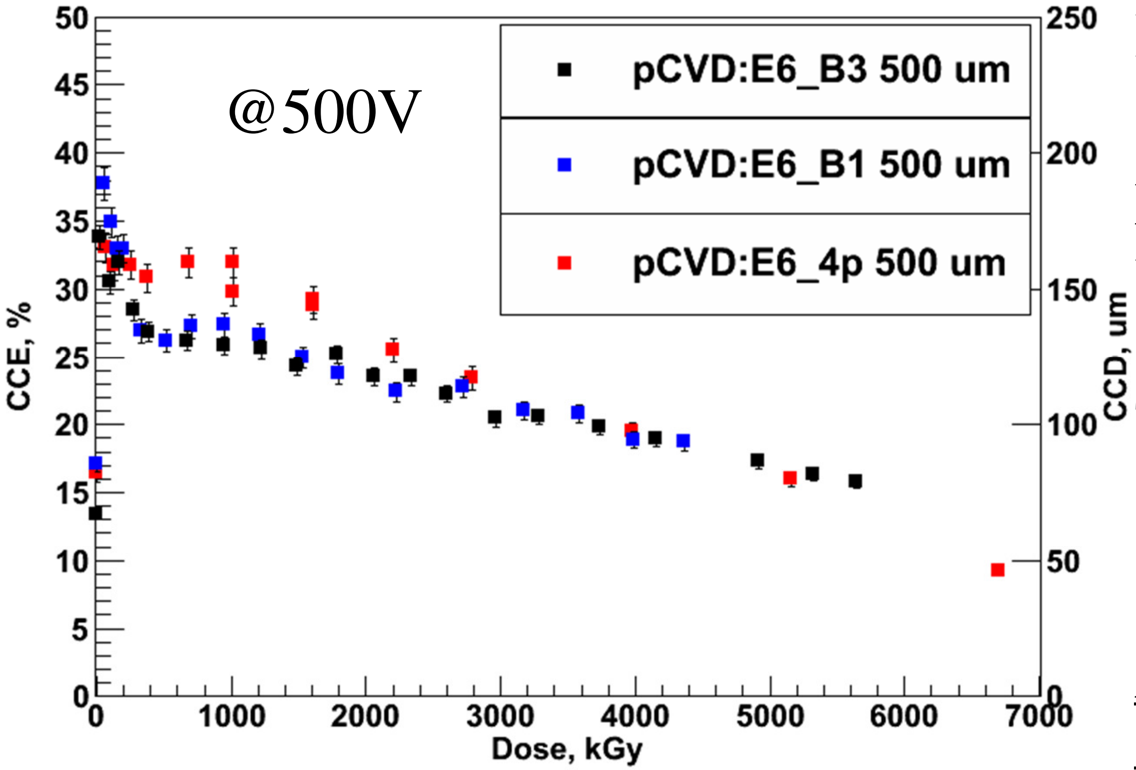




The only problem is that there is only one detector-grade material manufacturer
Price is still too high for large-scale application

pCVD Diamond. CCE

A number of samples were irradiated (10 MeV electrons)



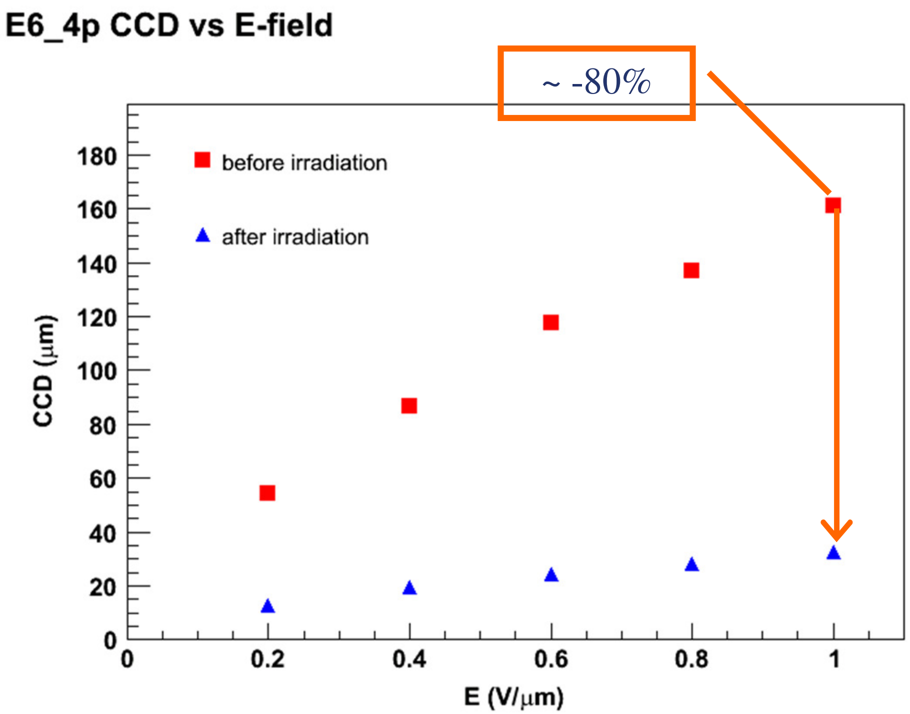
Typical behaviour:
Increase in CCD at low dose =>
pumping - i.e. filling of the traps

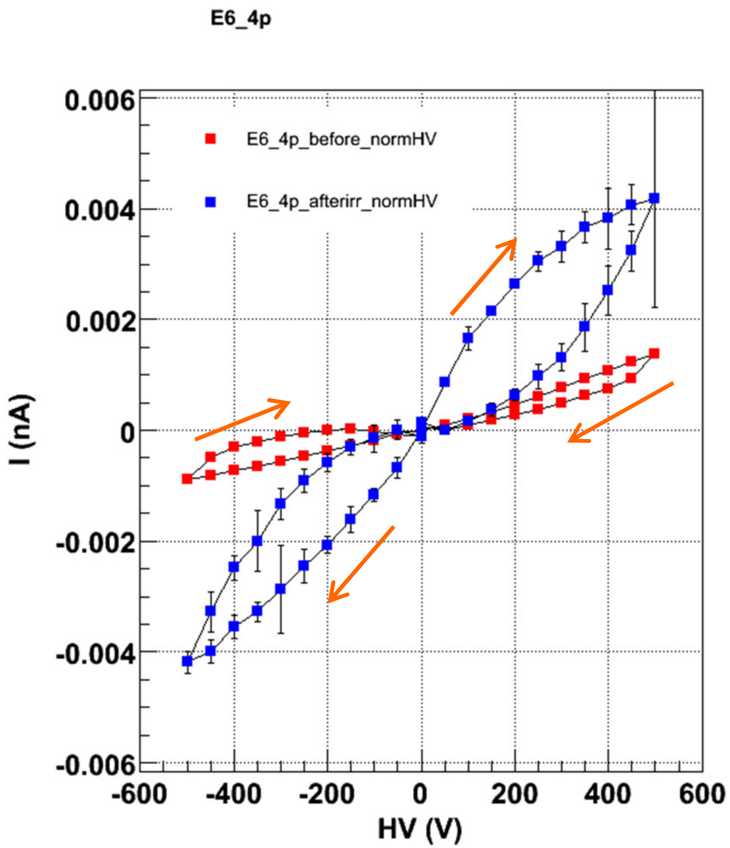
Then gradual decrease of efficiency with dose

<u>After absorbing 7MGy: CVD diamonds still operational</u>.

10 MGy for diamond roughly correspond to 10^{16} n/cm^{-2} for Si

E6_4 sample from Element 6, 500 μm





Signal decreased by ~ 80 % after absorbed dose of about 7 MGy

Slight increase in dark current, but still in pA range

sCVD Diamond detector

Single crystal CVD (chemical vapour deposition) diamond

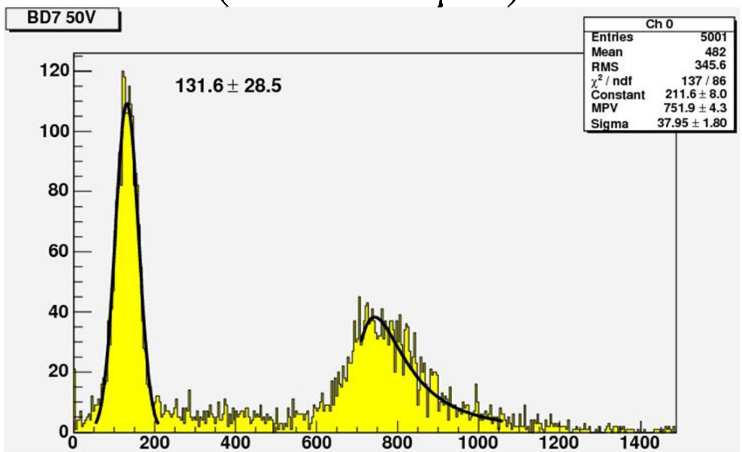
CVD growth on top of diamond substrate

+ Low defect content, very good detector properties
- Small area (up to 5x5 mm), very high price

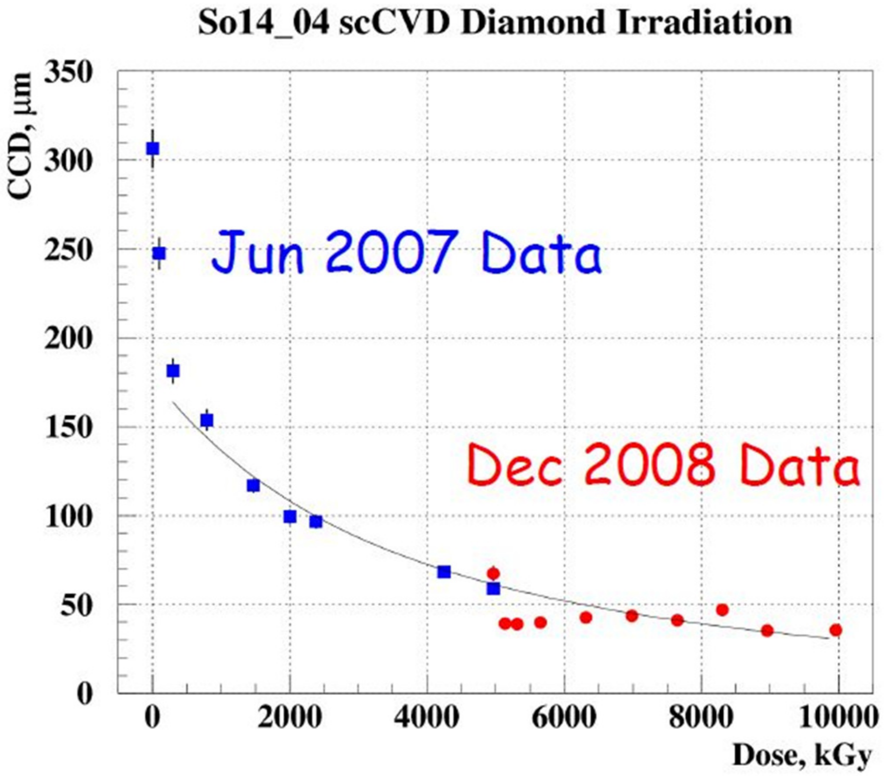
Sample produced by Element Six

5x5 mm, 320µm thickness

initial charge collection efficiency about 100% (CCD 320µm)

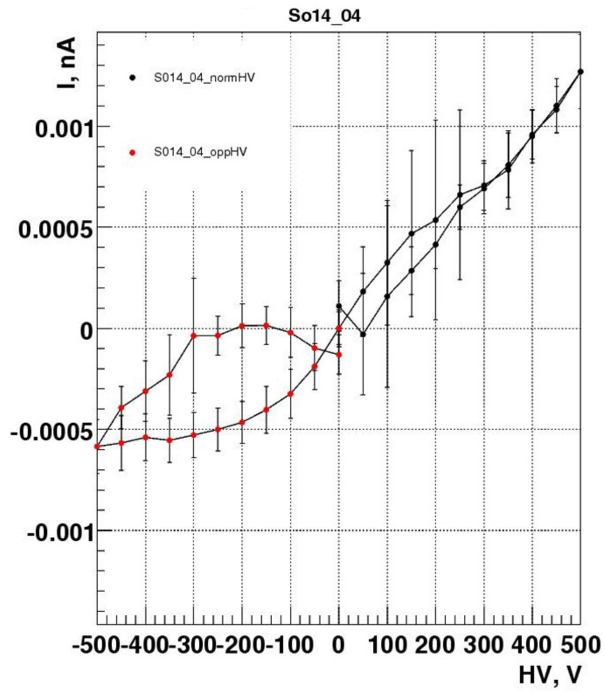


sCVD Diamond. Irradiation results



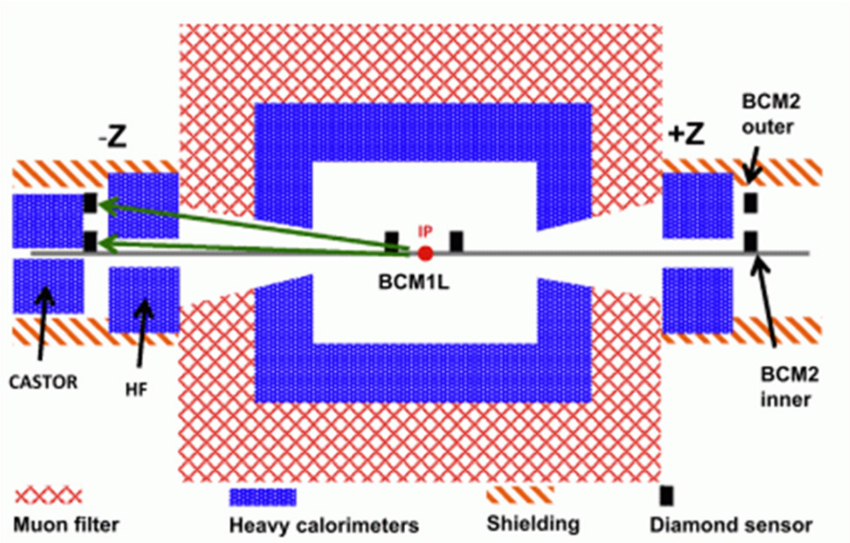
<u>Irradiation to 10 MGy</u>
<u>CCE dropped to 10%</u>
<u>of the initial value</u>

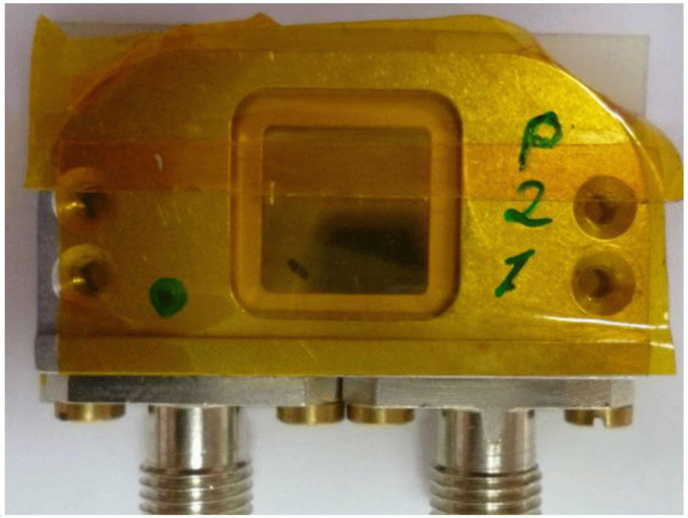
No visible annealing in 18 month

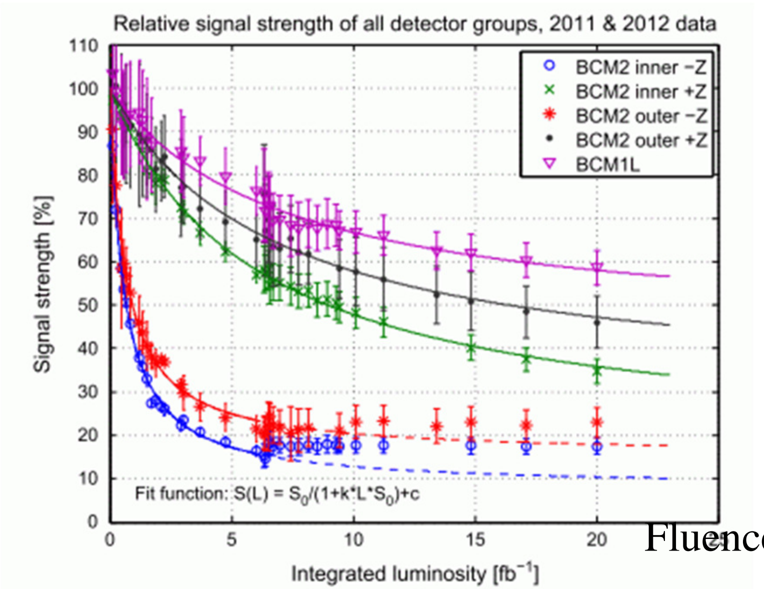


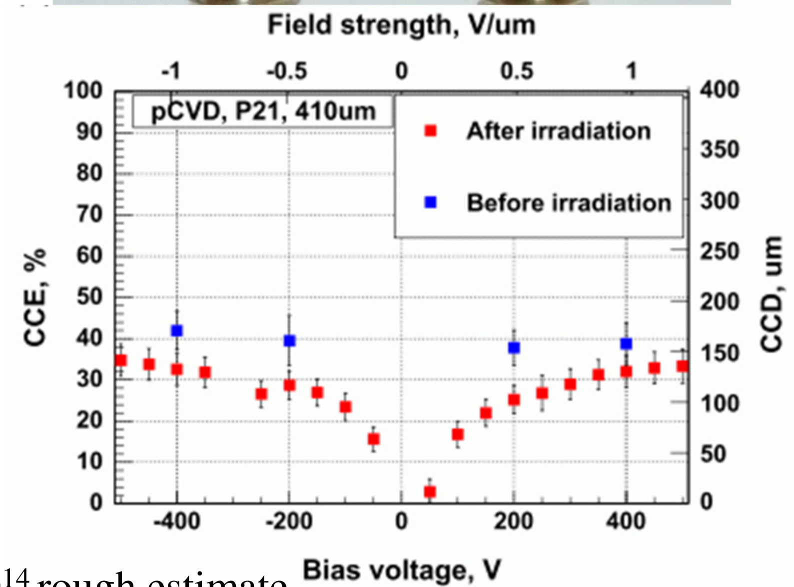
No significant increase in the dark current after the irradiation (still in pA range)

Diamond detector application. CMS beam monitoring





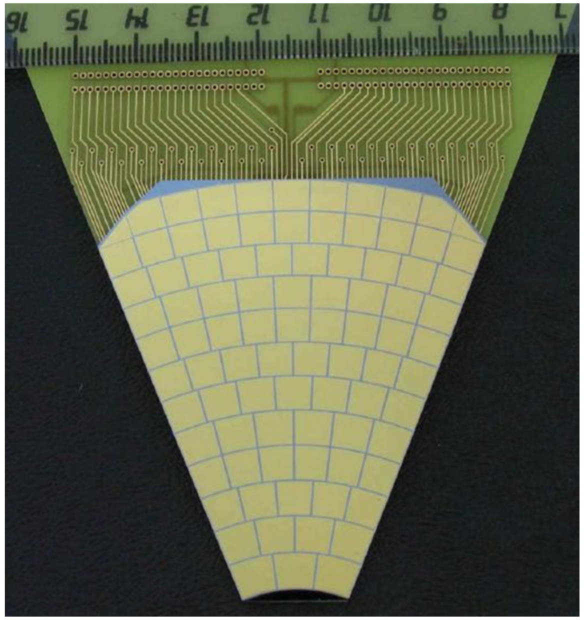




Fluence ~ 3x10[14] rough estimate

GaAs Detector

Supplied by FCAL group at JINR
Produced in Tomsk



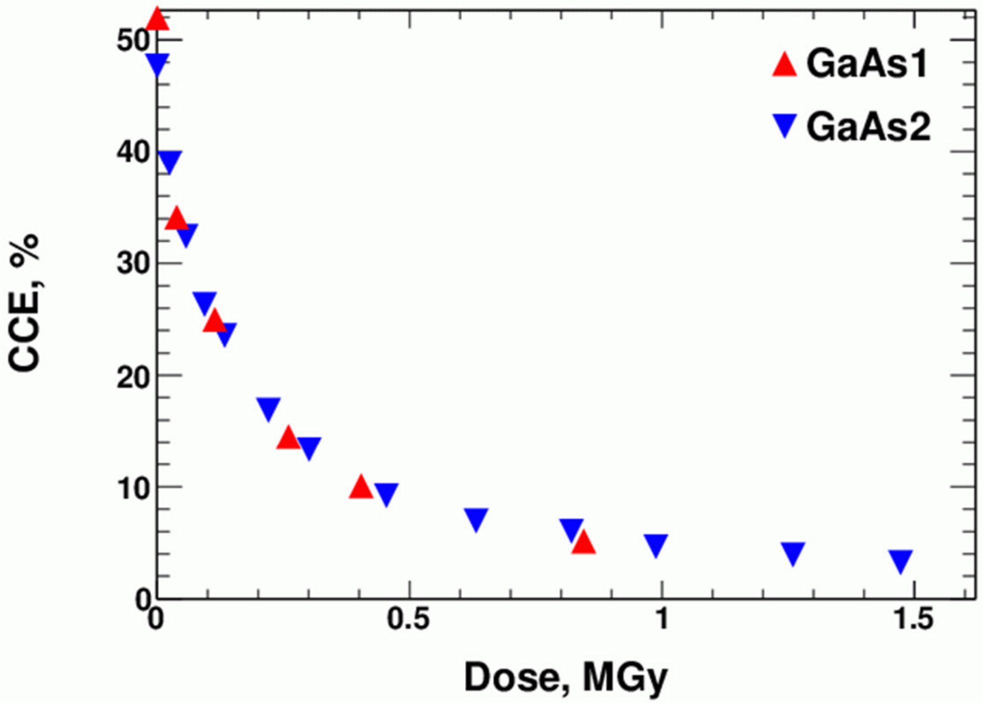
Sample is semi-insulating GaAs doped by Sn (shallow donor) and compensated by Cr (deep acceptor). This is done to compensate electron trapping centers EL2+ and provide *i*-type conductivity. Charge transport by electrons only. CCE ~ 50% by default.

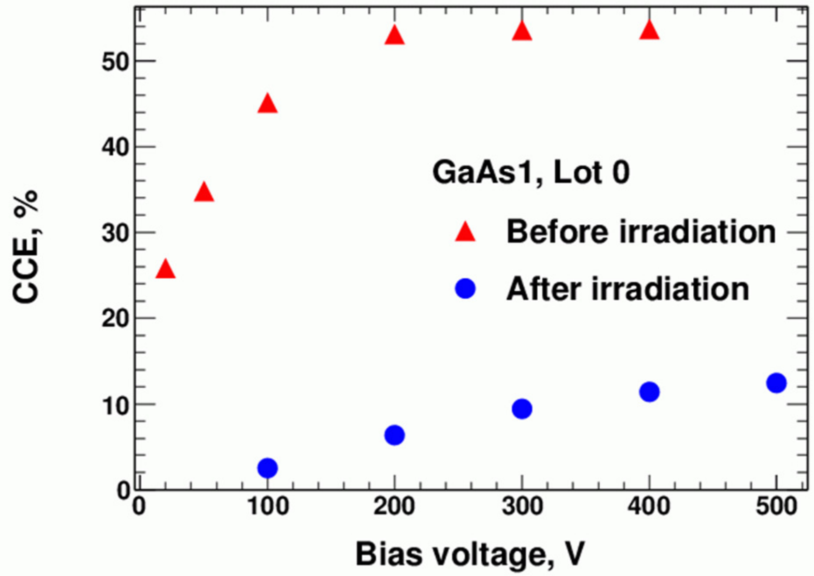
Sample works as a solid state ionisation chamber
Structure provided by metallisation (similar to diamond)

500 μm thick detector is divided into 87 5x5 mm pads and mounted on a 0.5mm PCB with fanout

Metallisation is V (30 nm) + Au (1 μm)

GaAs. Irradiation results. CCE

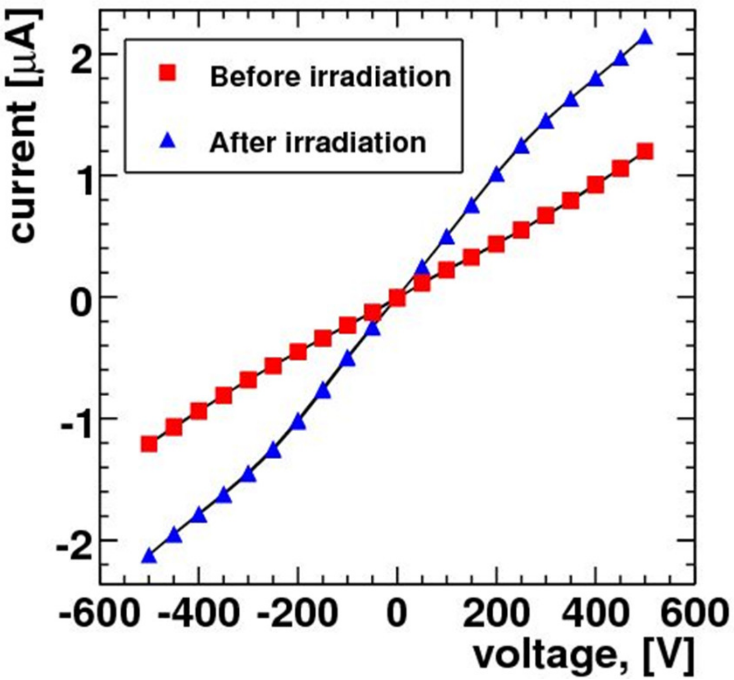




Results: CCE dropped to about 5% from ~50% after 1.5 MGy

this corresponds to signal size of about 2000 e$^-$

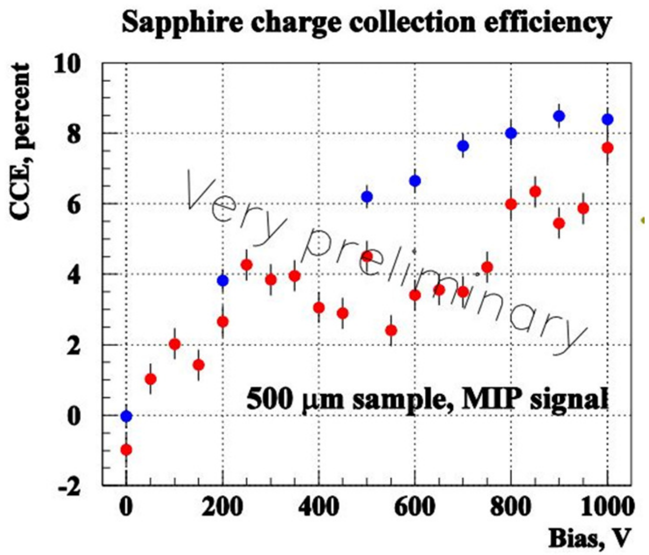
No saturation, signal could be increased with bias voltage



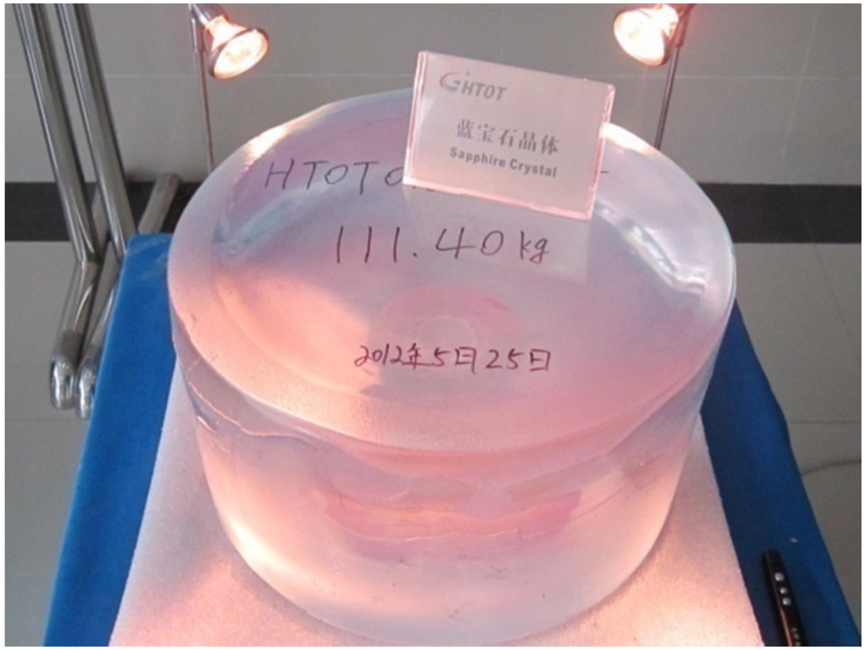
Dark current increased ≈ 2 times (from 0.4 to 1 μA @ 200V)

Signal is still visible for an absorbed dose of about 1.5 MGy

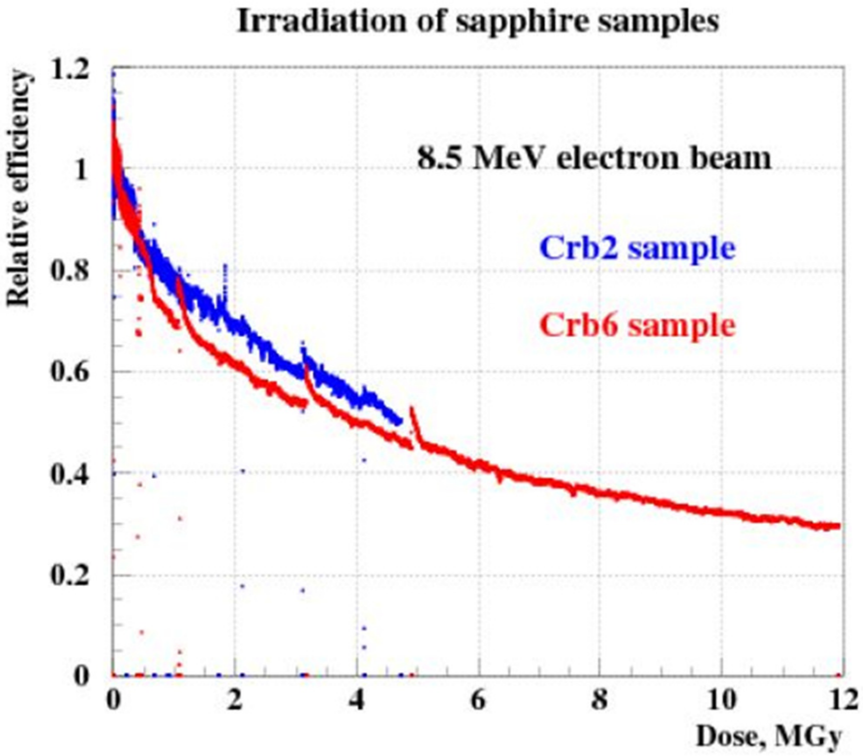
Single crystal Al_2O_3 grown by Czochralski process
Large scale production: crystals up to 500 kg
Positive: Cheap, large area, wide bandgap
Negative: small response to MIPs (~2200 eh pairs per 100 um)
Low charge collection efficiency (~5%) => signal from MIP in
Typical 500 um detector ~500 e



Courtesy S. Schuwalow



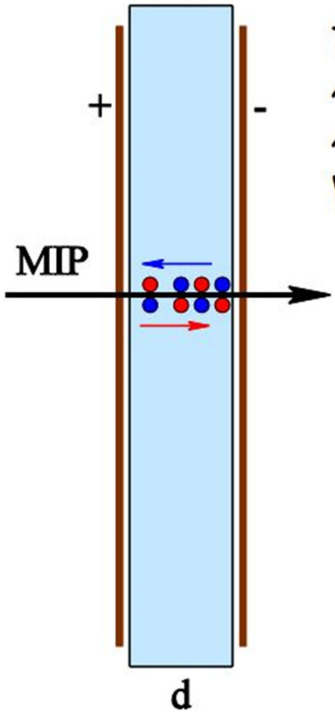
Sapphire



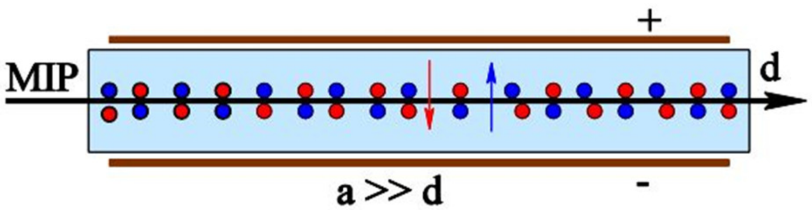
Response measured in current mode.
Good radiation hardness
Dark current ~pA before and after irradiation

Possible application

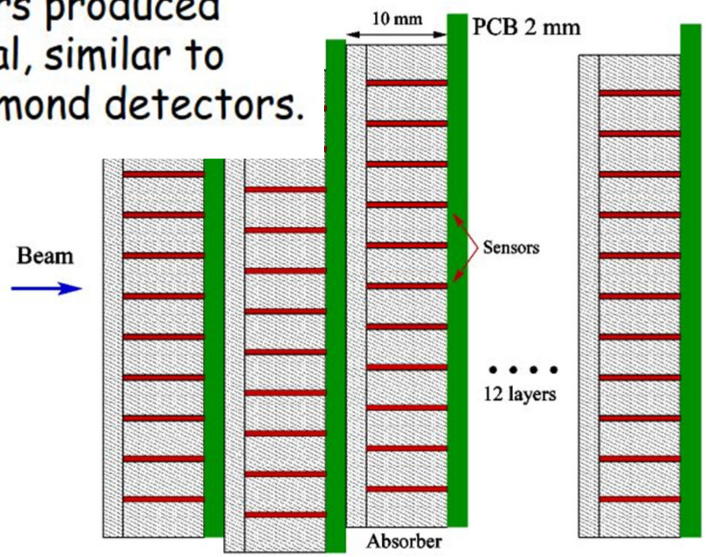
from S. Schuwalow



Typical thickness ~0.5 mm
~11K e-h pairs created
~5% CCE -> 550 e signal
Very hard to detect



a=10 mm => 220K e-h pairs produced
~5% CCE -> ~11000 e signal, similar to
100% efficient scCVD diamond detectors.



THANK YOU