



Radiation hard sensor materials for forward calorimeter

K. Afanaciev on behalf of FCAL collaboration

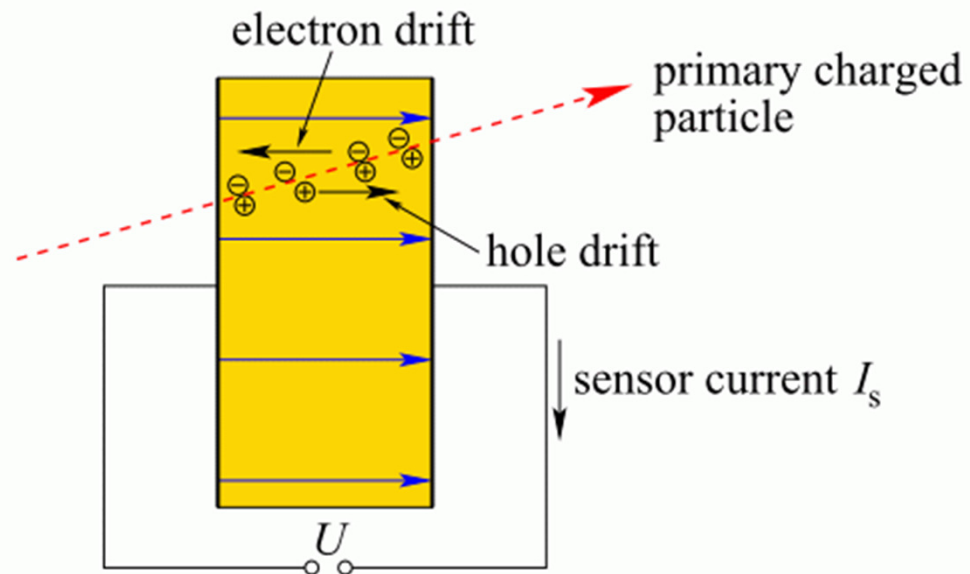
FCAL Workshop
Tel-Aviv 2016



Scope and purpose of the talk

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

Silicon, GaAs, Diamond and Sapphire



Detector functions

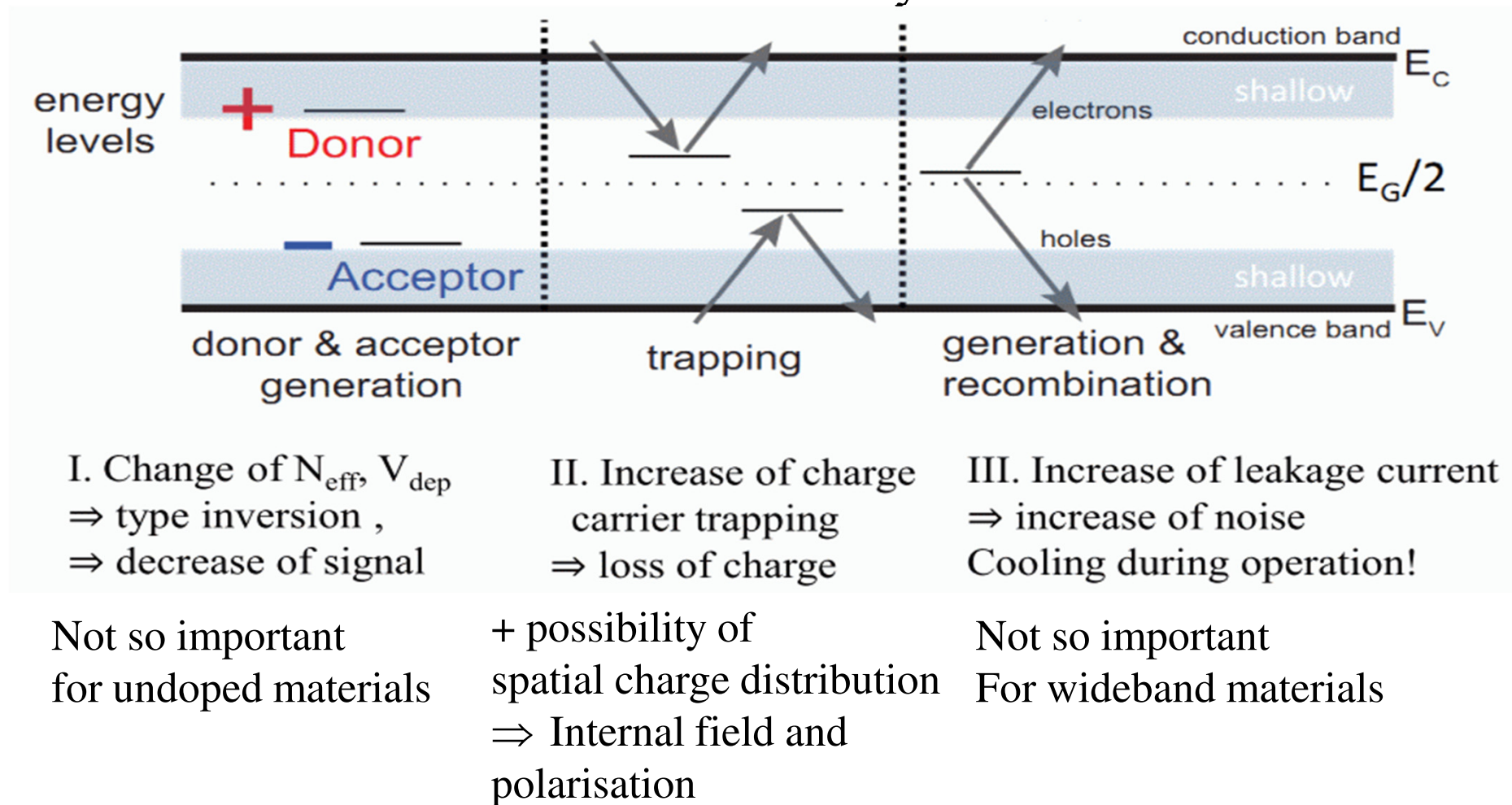
As a solid state
Ionisation chamber

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



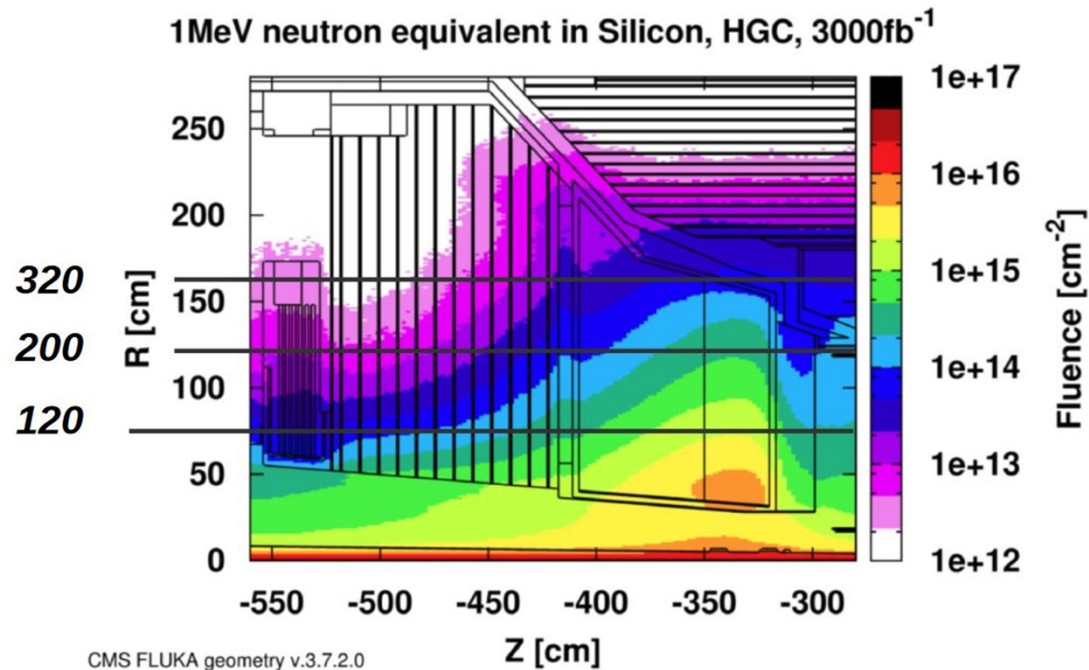
Radiation damage

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





Silicon. Motivation and who is doing it



Expected radiation load
For silicon detectors
HL-LHC 3ab⁻¹
Neutron Fluence
 1.5×10^{-16}
Dose ~ 5 MGy

Rough estimate

FCC 3ab⁻¹: Neutron Fluence 3×10^{-16} , Dose ~ 10 MGy

FCC 30ab⁻¹: Neutron Fluence 3×10^{-17} , Dose ~ 100 MGy



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)

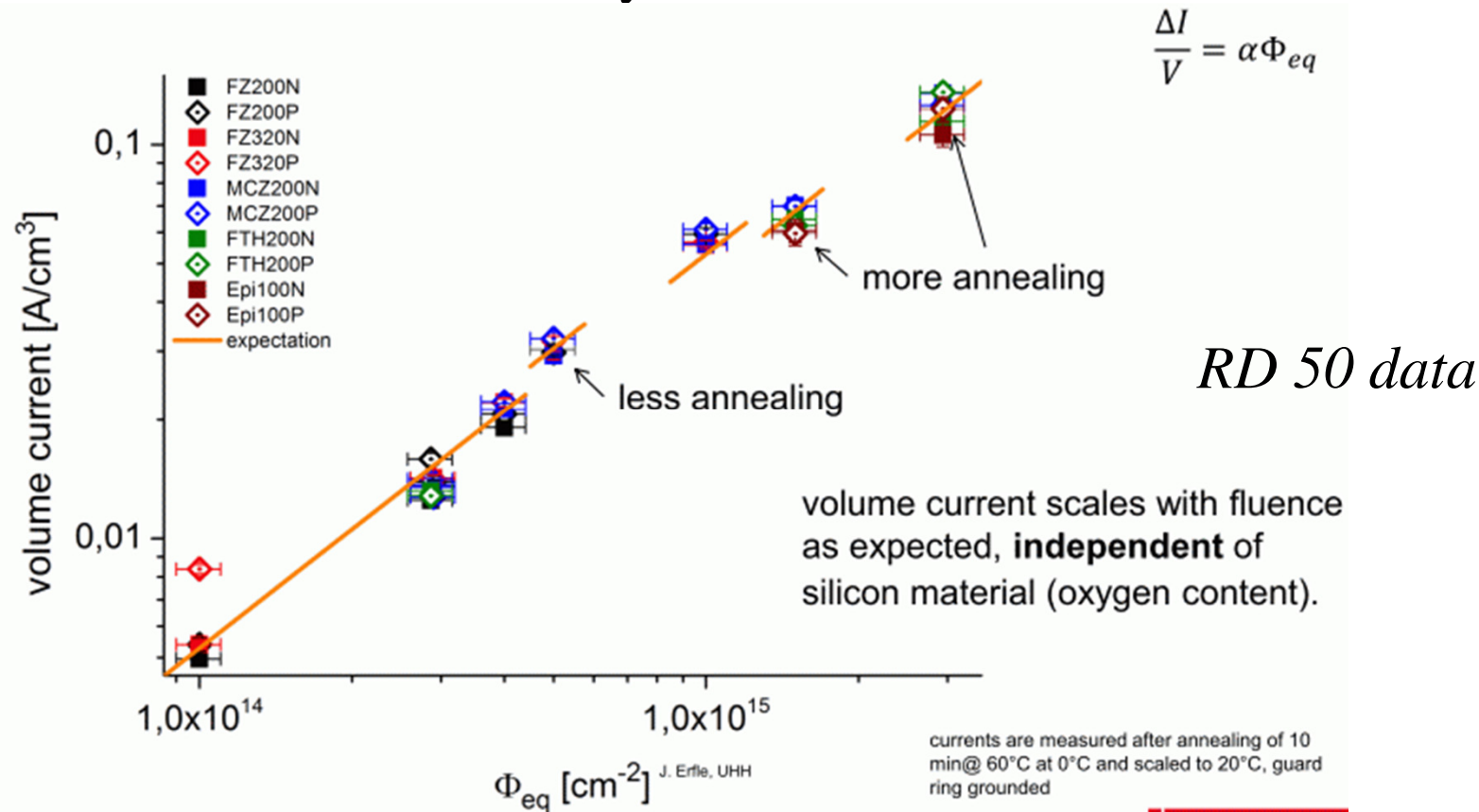
RD 50 mostly study strip and pixel detectors

Hadronic irradiation



Silicon. Results overview. Dark current

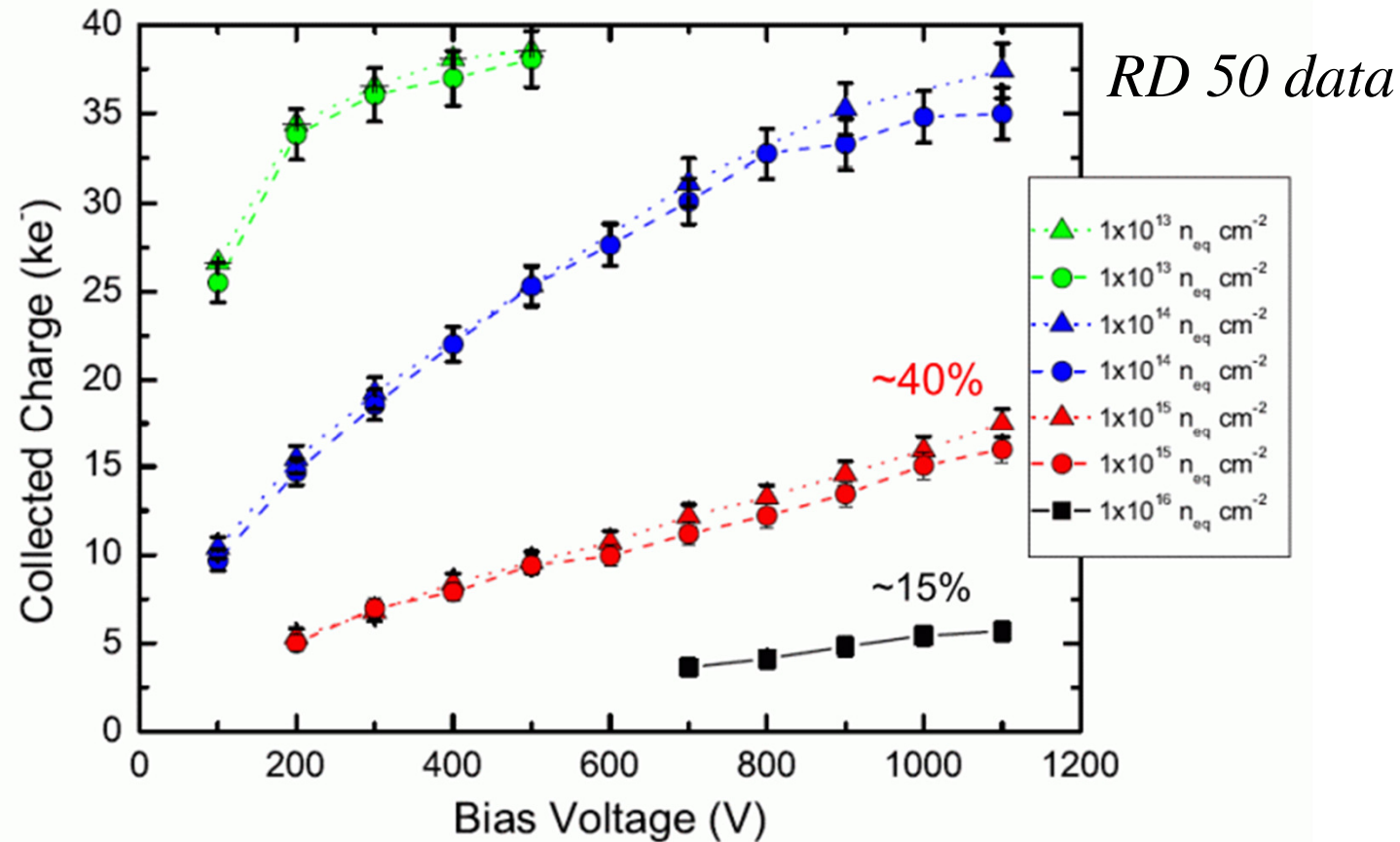
Dark current rises linearly with the fluence



This means for 10x10x0.3 mm detector $I_{dark} \sim 1 \text{ mA}$ @ room temp.
 => Needs cooling to at least -20°C and up to -50°C (still uA currents)



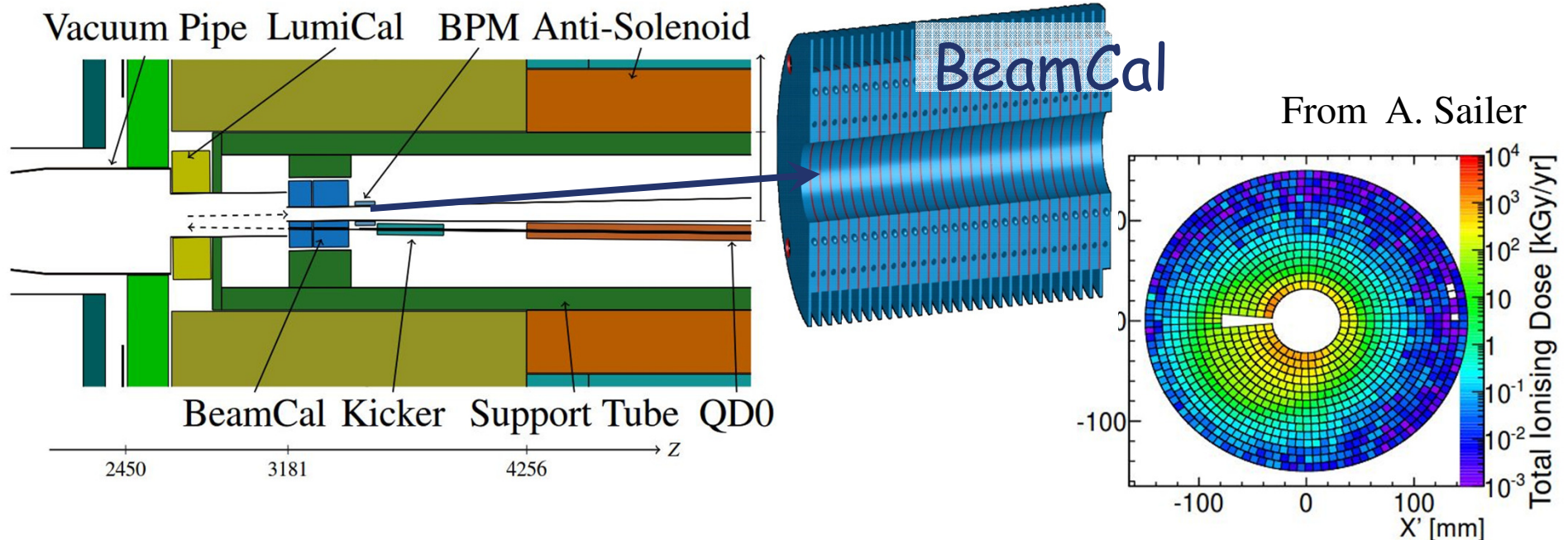
Silicon. Results overview. CCE



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



Motivation. Very Forward Region



EM calorimeter with sandwich structure:

30 layers of $1 X_0$, 3.5mm W and 0.3mm sensor, Molière radius $R_M \approx 1\text{cm}$

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.



Investigated materials

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 $\epsilon_R = 5.7$, thermal conductivity
 - availability on wafer scale
- Samples investigated:
 - Element Six (ex-DeBeers)
 - $1 \times 1 \text{ cm}^2$
 - 200-500 μm thick (typical thickness 300 μm)
 - 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

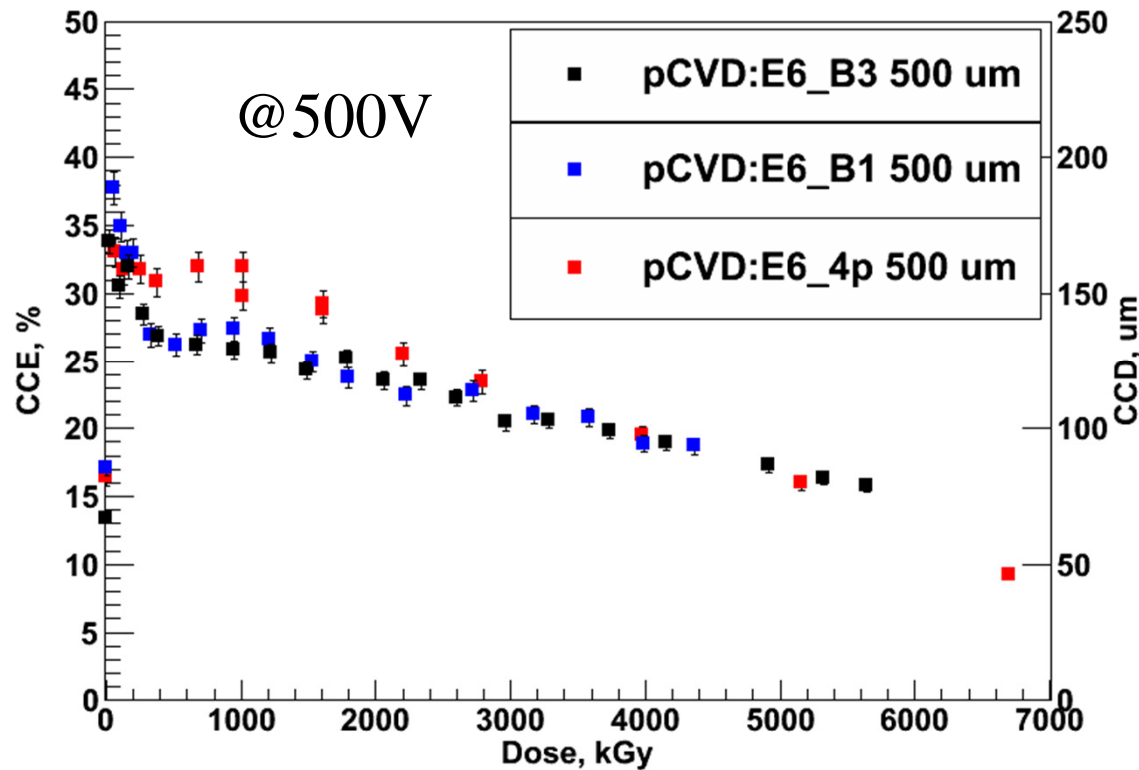
A number of samples were irradiated (10 MeV electrons)

Typical behaviour:

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

Then gradual decrease
of efficiency with dose

After absorbing 7MGy:
CVD diamonds still
operational.



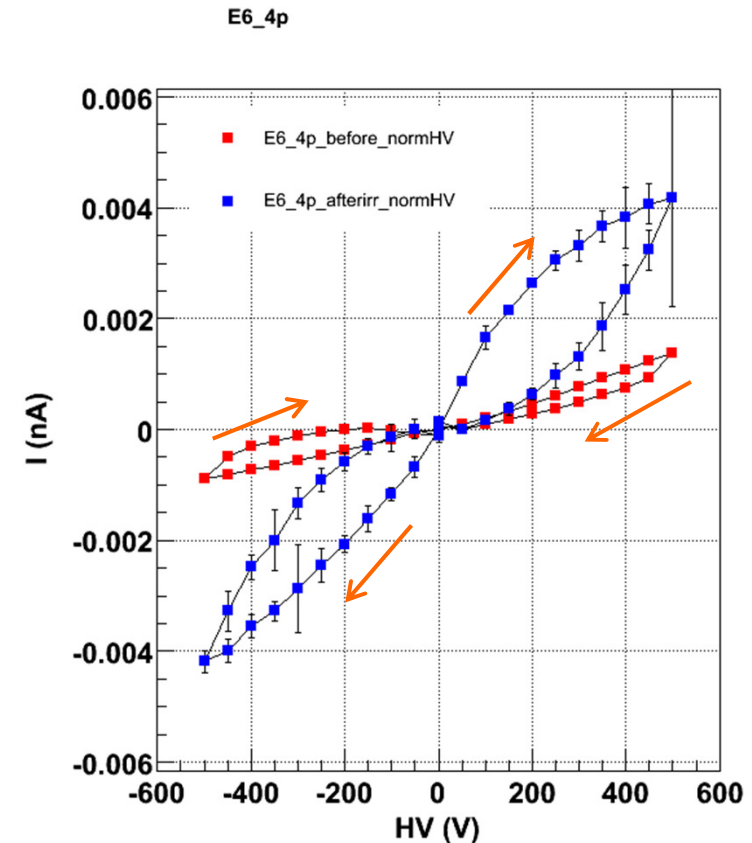
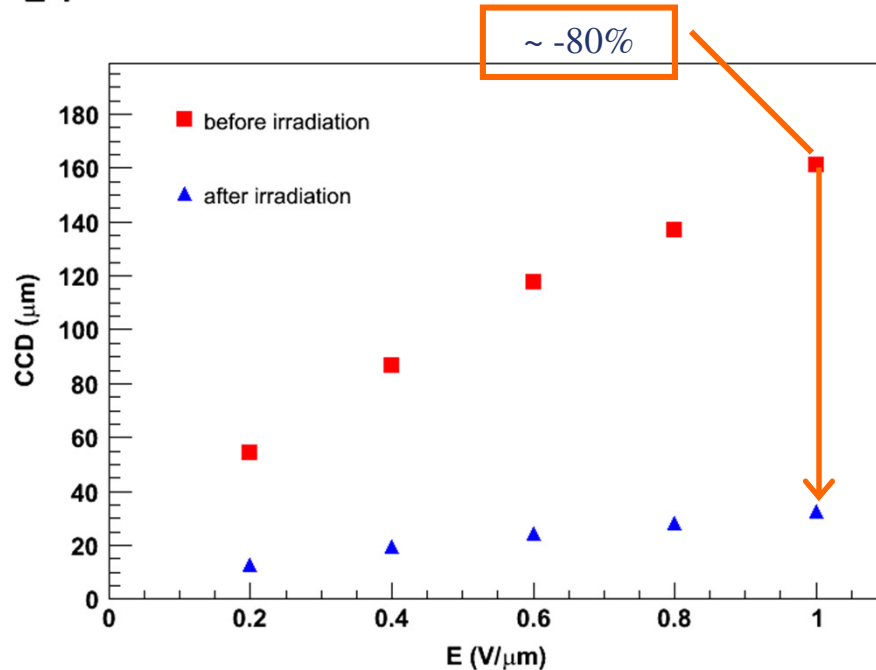
10 MGy for diamond roughly correspond to 10^{16} n/cm² for Si



pCVD Diamond. Dark current

E6_4 sample from Element 6, 500 μm

E6_4p CCD vs E-field



Signal decreased by $\sim 80\%$ after absorbed dose of about 7 MGy

Slight increase in dark current, but still in pA range



sCVD Diamond detector

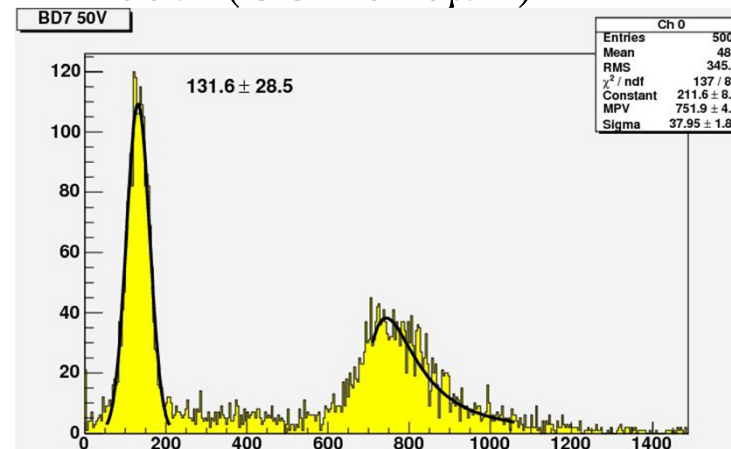
Single crystal CVD (chemical vapour deposition) diamond
CVD growth on top of diamond substrate

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

Sample produced by Element Six

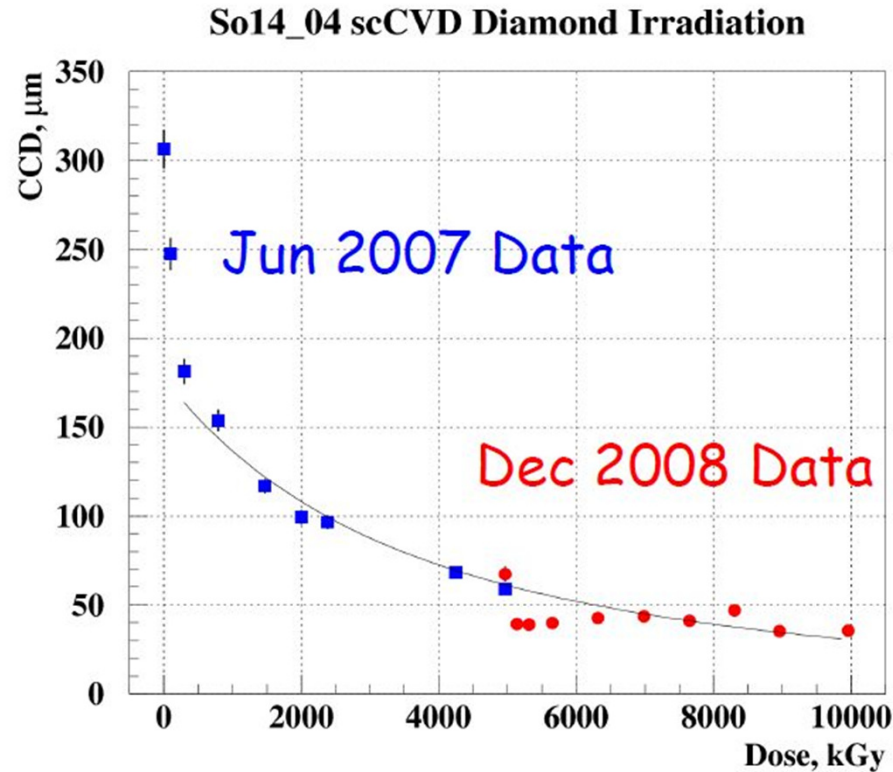
5x5 mm, 320 μ m thickness

initial charge collection efficiency about 100% (CCD 320 μ m)





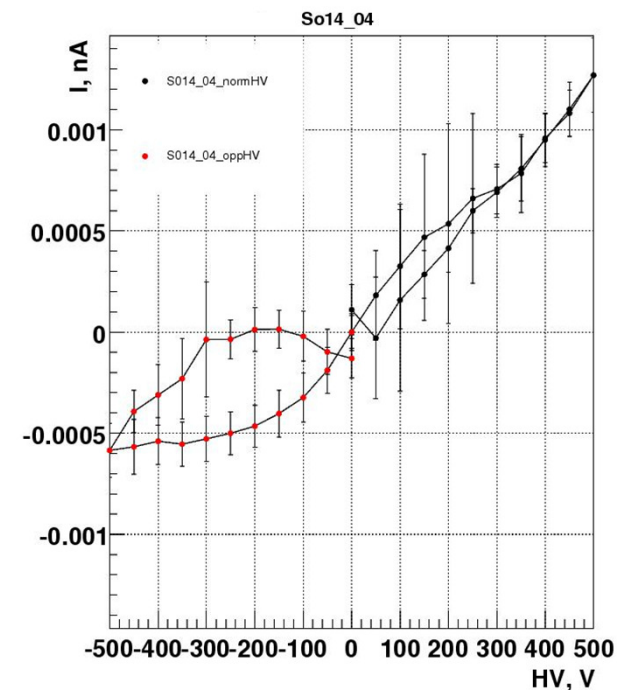
sCVD Diamond. Irradiation results



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

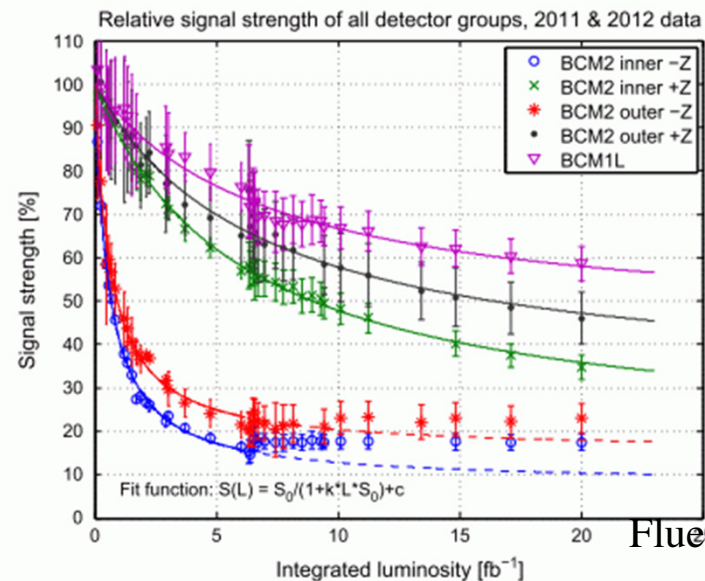
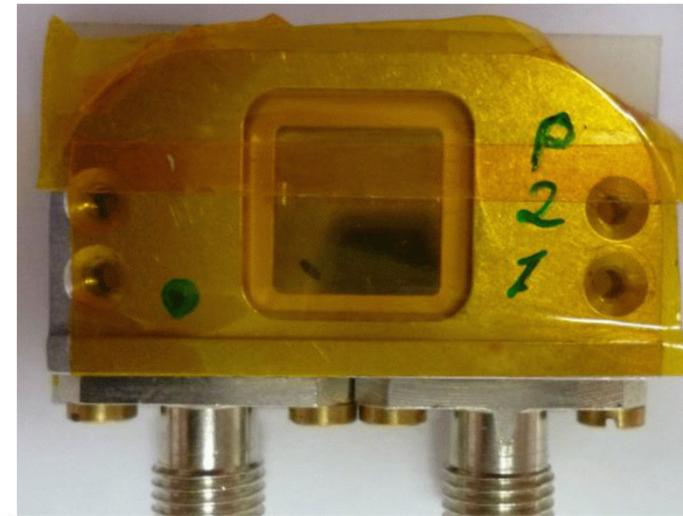
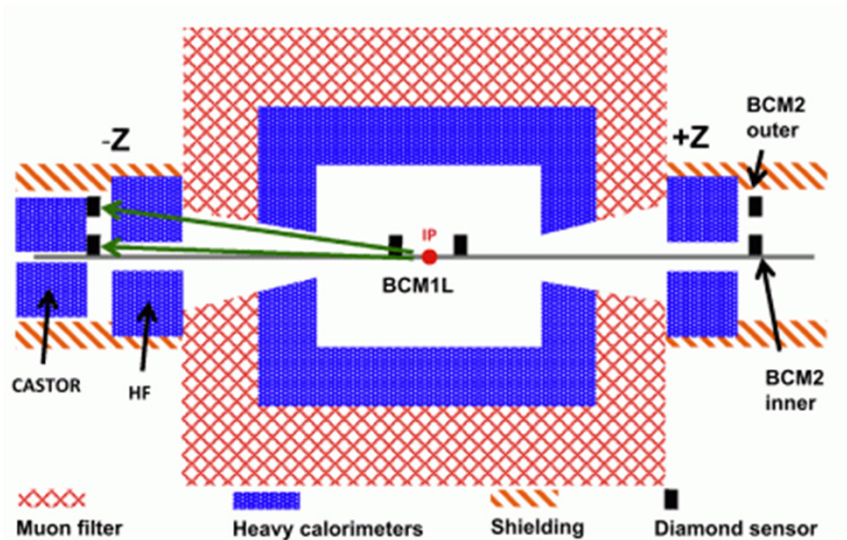
Irradiation to 10 MGy
CCE dropped to 10%
of the initial value

No visible annealing
in 18 month

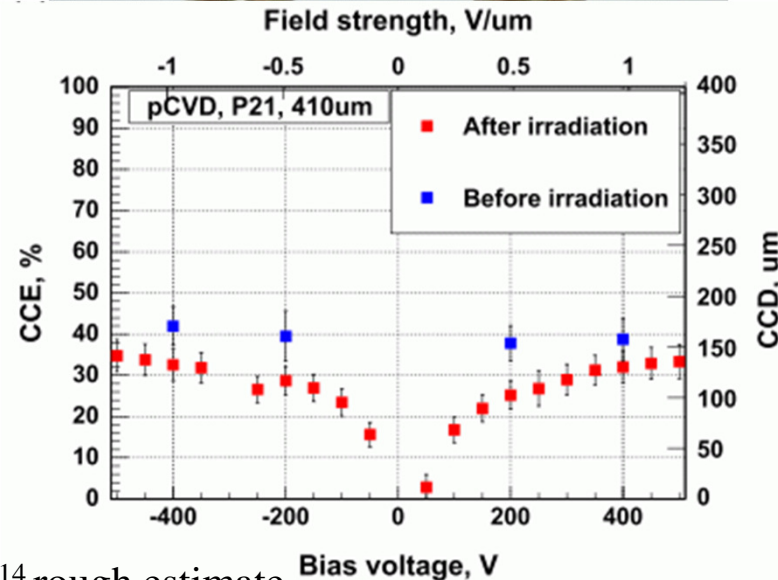




Diamond detector application. CMS beam monitoring



Fluence $\sim 3 \times 10^{14}$ rough estimate



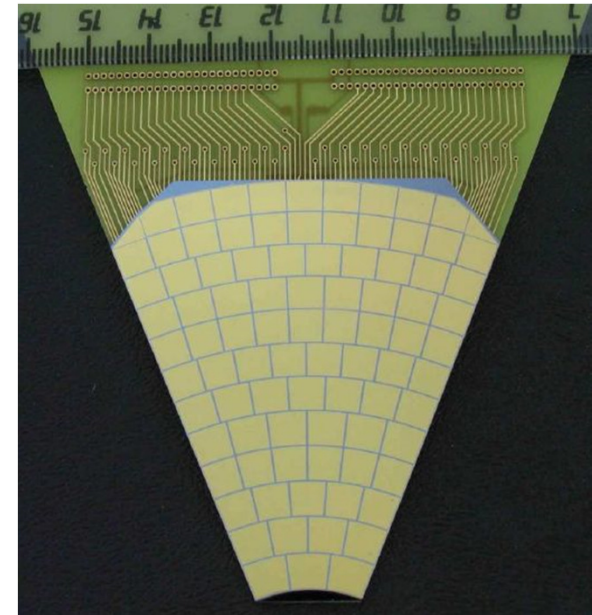


GaAs Detector

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.



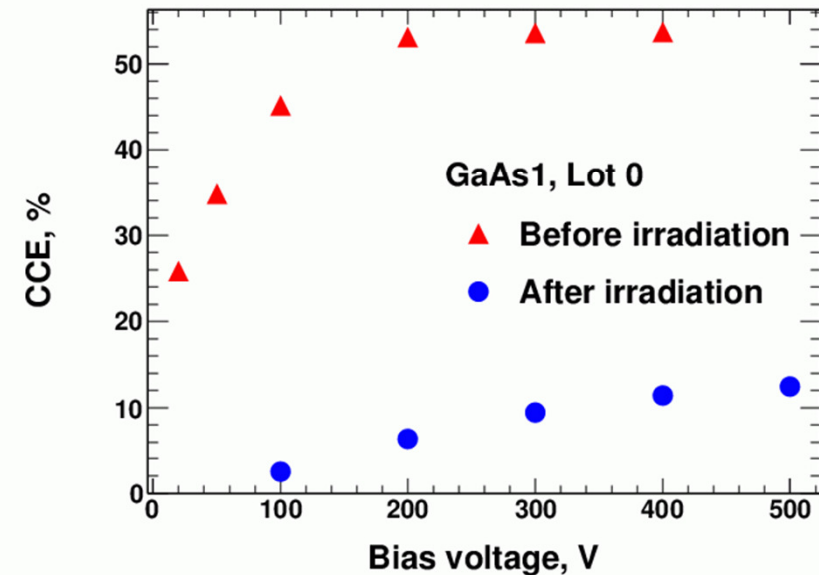
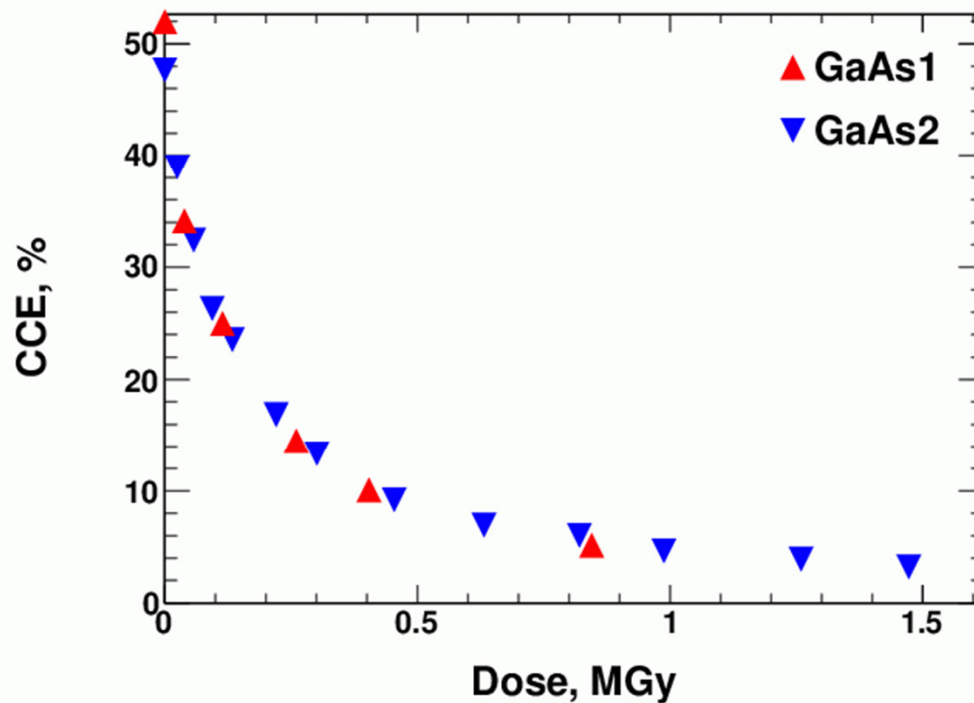
Sample works as a solid state ionisation chamber
Structure provided by metallisation (similar to diamond)

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)



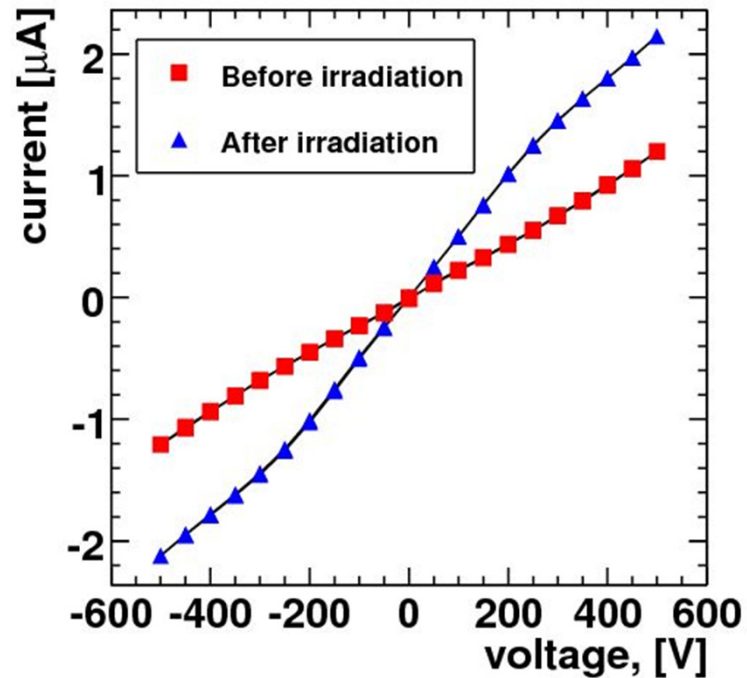
GaAs. Irradiation results. CCE



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



GaAs. Irradiation results. Dark current



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



Sapphire

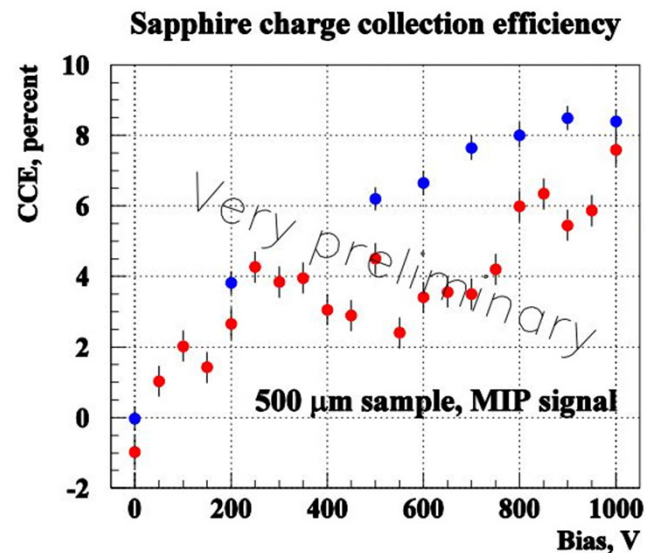
Single crystal Al_2O_3 grown by Czochralski process

Large scale production: crystals up to 500 kg

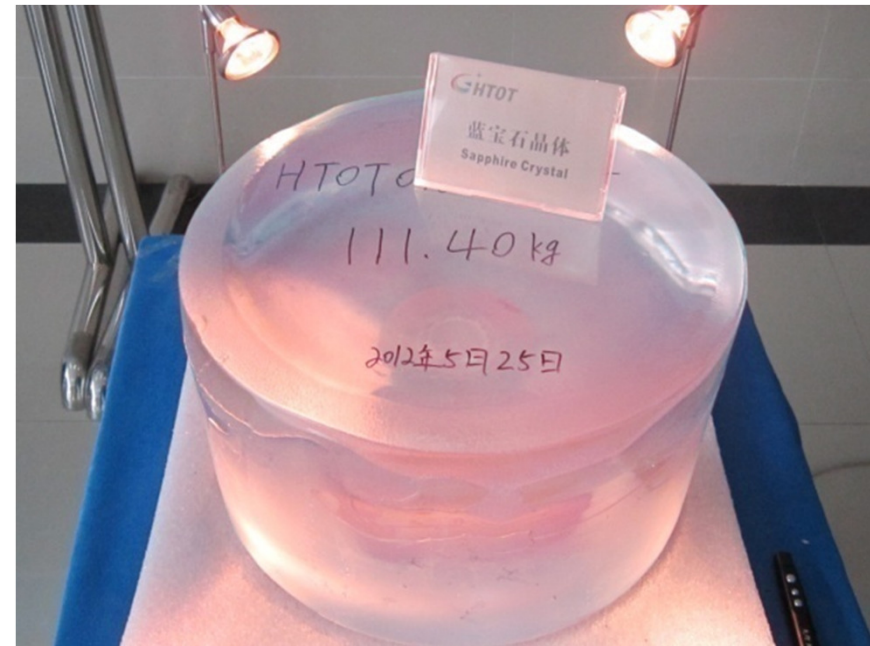
Positive: Cheap, large area, wide bandgap

Negative: small response to MIPs (~ 2200 eh pairs per 100 μm)

Low charge collection efficiency ($\sim 5\%$) \Rightarrow signal from MIP in typical 500 μm detector ~ 500 e

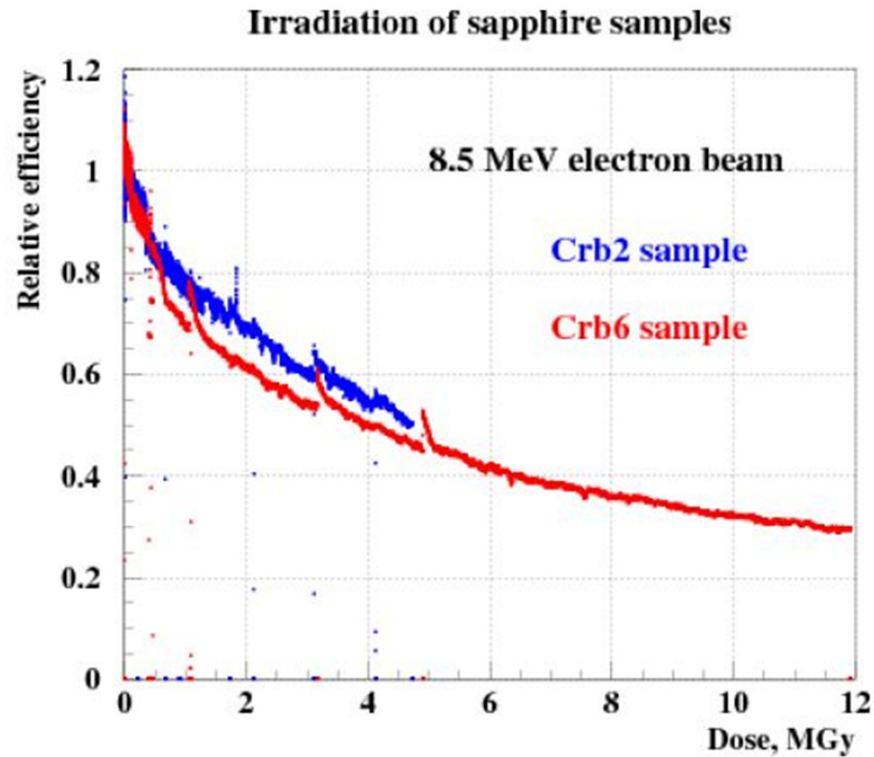


Courtesy S. Schuwalow





Sapphire

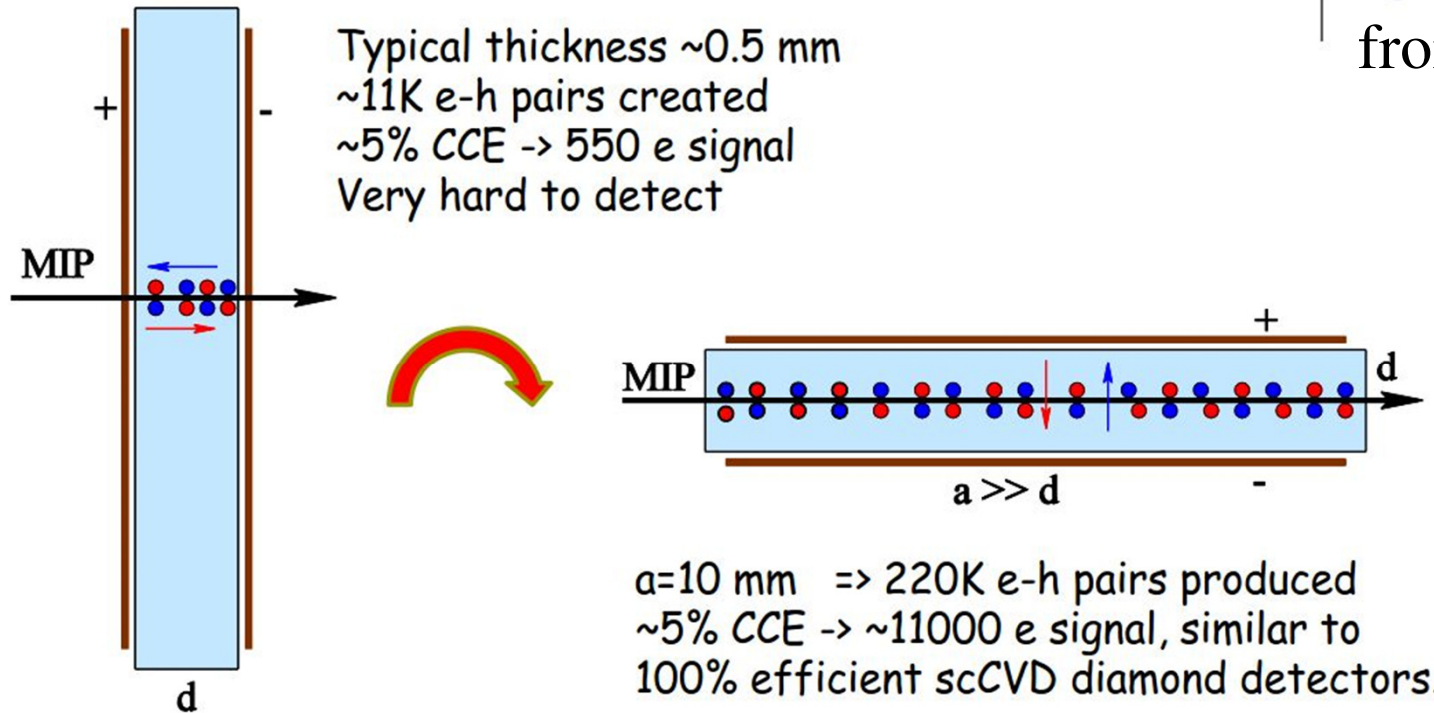


Response measured in current mode.
Good radiation hardness
Dark current ~pA before and after irradiation

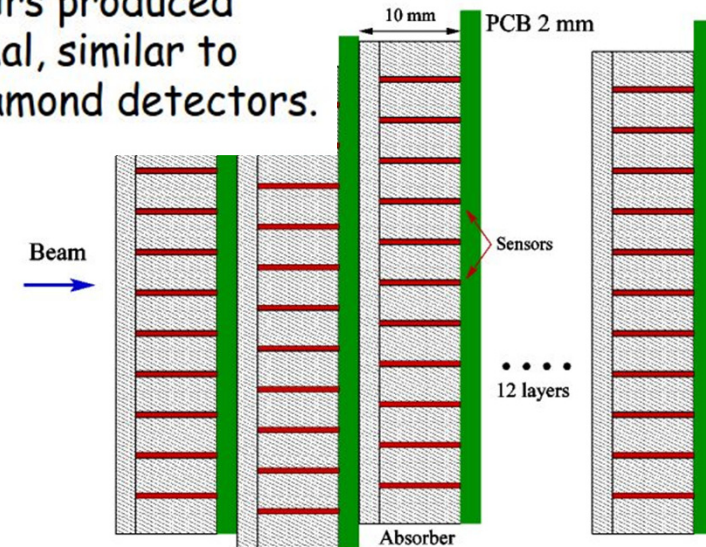


Possible application

from S. Schuwalow



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





THANK YOU