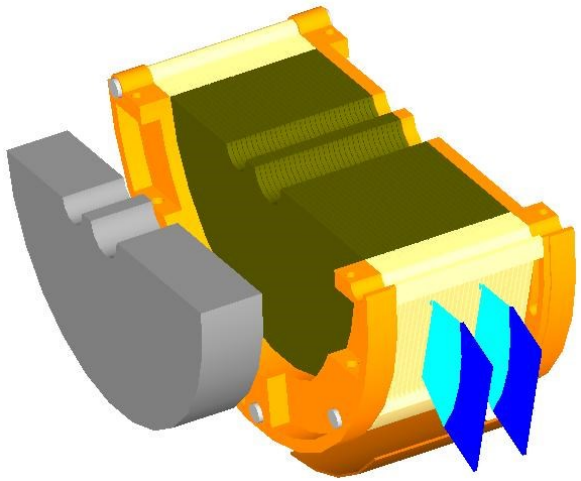
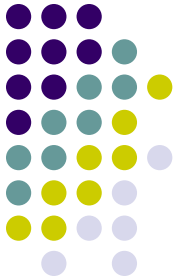
Sapphire sensors for BeamCal

Sergej Schuwalow, DESY Hamburg

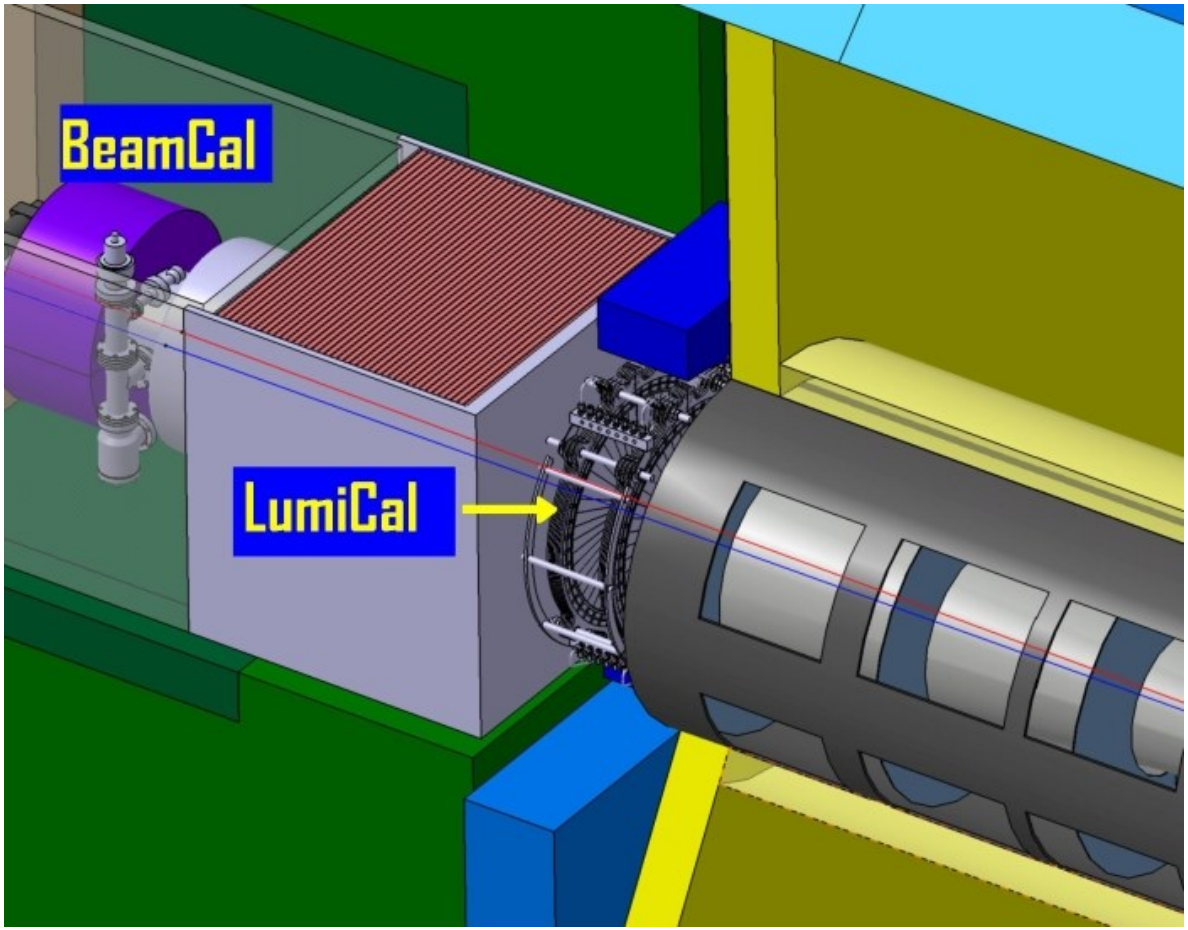


Contents



- BeamCal sensor requirements
- Sapphire (Al_2O_3) properties (+diamond, GaAs, Si)
- Synthesis of sapphire
- Radiation hardness
- Application at FLASH, signal shape
- Charge collection efficiency
- Detection of MIPs with sapphire sensors
- BeamCal sensor configurations
- First simulation results
- Conclusions and outlook

BeamCal sensor requirements



BeamCal should be compact, small Moliere radius needed:
-sampling calorimeter with solid state sensors, tungsten as absorber.

Severe load at small radii due to beamstrahlung:
- radiation hard sensors (up to 1 MGy annual dose)

Bunch-by-bunch operation:
- fast response of sensors

Test beam studies, physical calibration:
- sensitivity to MIPs

Sensor material properties

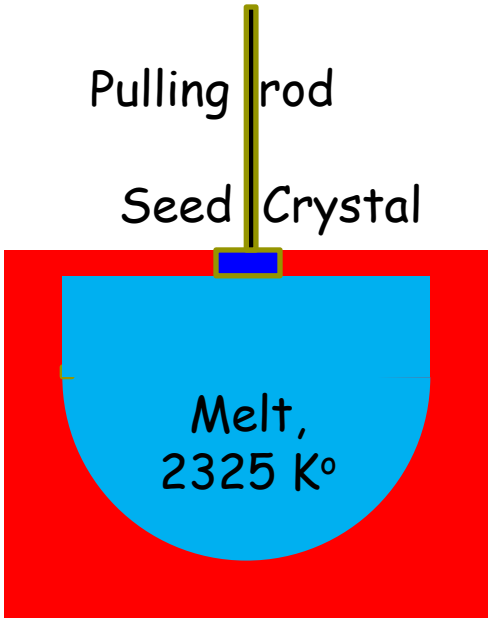
	Sapphire	Diamond	GaAs	Si
Density, g/cm^3	3.98	3.52	5.32	2.33
Dielectric constant	9.3 – 11.5	5.7	10.9	11.7
Breakdown field, V/cm	~10^6 *	10^7	$4 \cdot 10^5$	$3 \cdot 10^5$
Resistivity, Ω·cm	>10^{14}	>10^{11}	10^7	10^5
Band gap, eV	9.9	5.45	1.42	1.12
El. mobility, cm^2/(V·s)	>600 **	1800	~8500	1360
Hole mobility, cm^2/(V·s)	-	1200	-	460
MIP eh pairs created, eh/μm	22	36	150	73

* Typical operation field ~1-2·10^4 V cm^{-1}

** at 20ºC, ~30000 at 40ºK

Synthesis of sapphire (Al_2O_3)

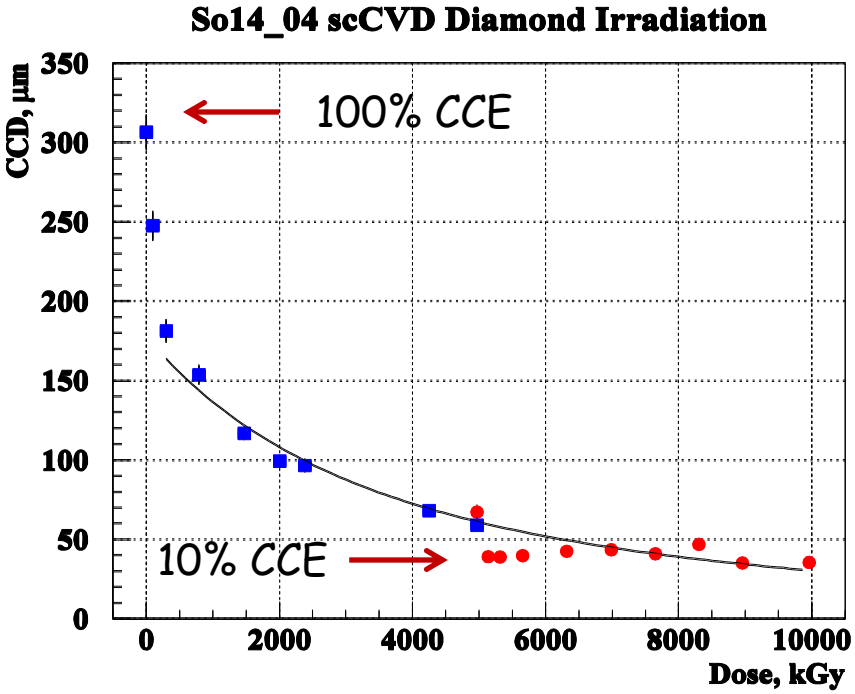
- Single crystals are grown by Czochralski process
- Growing speed ~100 mm/hour
- Up to 440 mm diameter crystals
- Crystal weight up to ~500 Kg
- World annual production >250 tons
- Used in chemistry, electronics, semiconductor industry, lasers, etc.



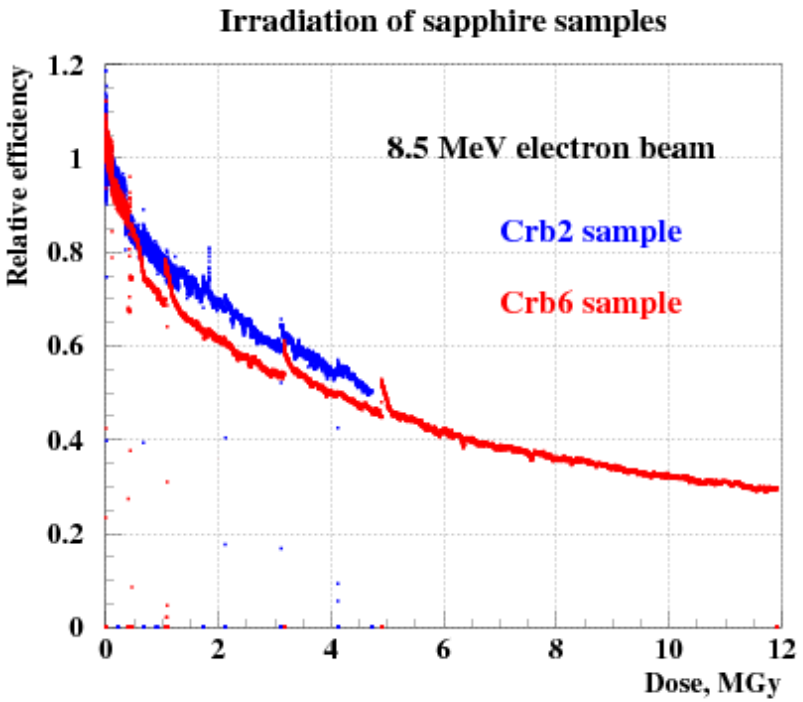
Impurity	Na	Si	Fe	Ca	Mg	Ni	Ti	Mn	Cu	Zr	Y
ppm	8	2	5	5	1	<3	<1	3	<3	2	2

Irradiation of sapphire and diamond sensors at ~10 MeV electron beam

Single crystal CVD diamond



Single crystal sapphire

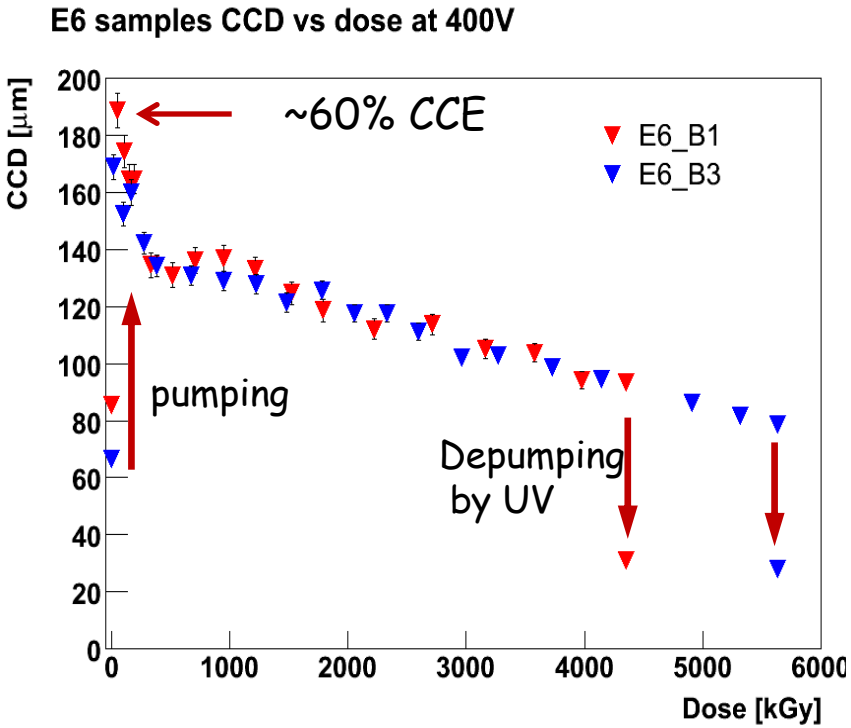


Leakage current after irradiation is still at few pA level

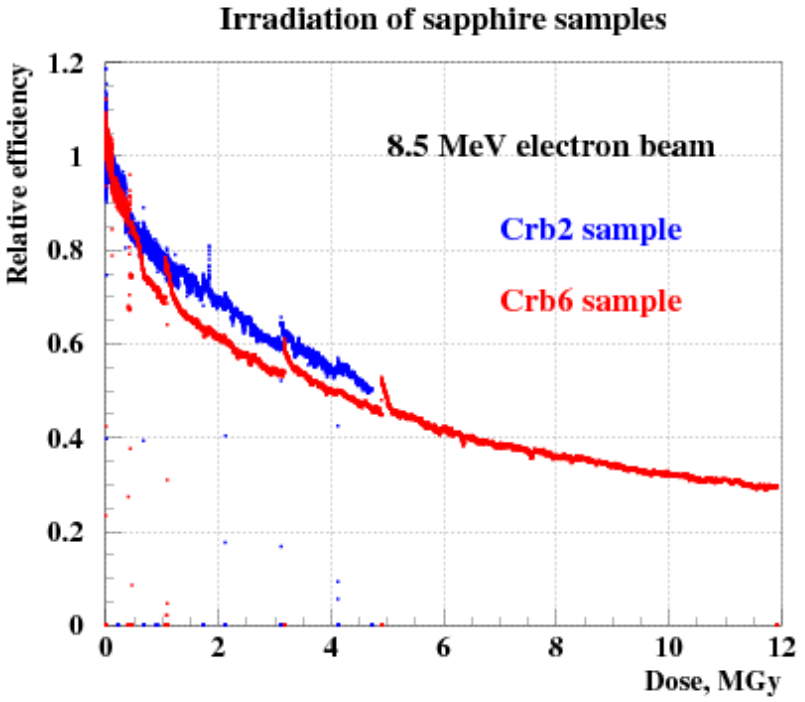
10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL,Summers)

Irradiation of sapphire and diamond sensors at ~10 MeV electron beam

Polycrystalline CVD diamond



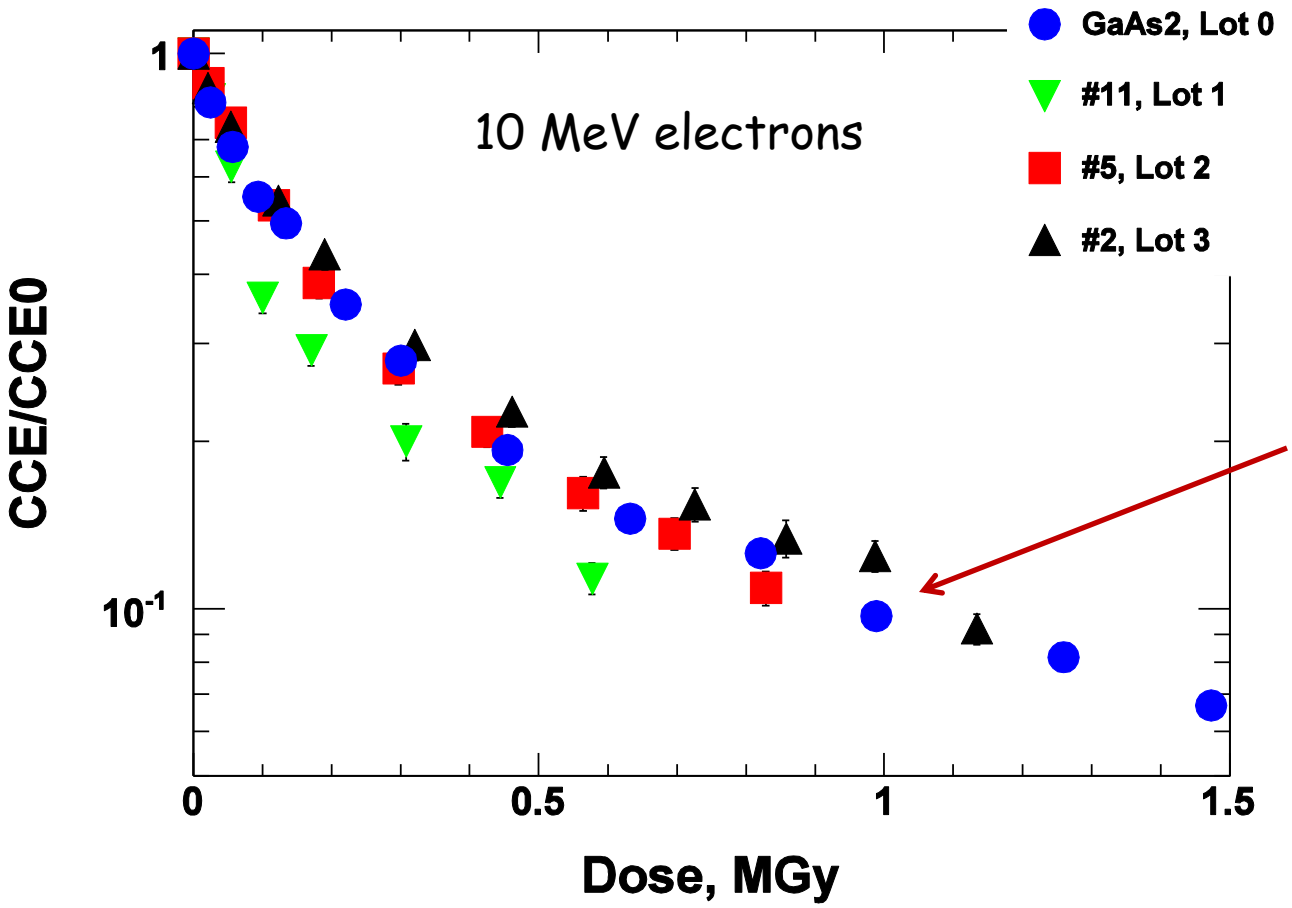
Single crystal sapphire



Leakage current after irradiation is still at few pA level

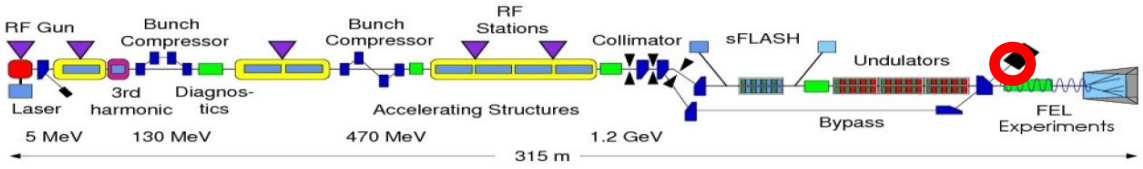
10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL,Summers)

Irradiation of GaAs sensors



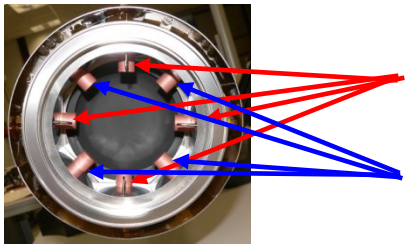
Few μA leakage current after 1 MGy dose (extra noise!)

Beam Halo Monitor at FLASH



4 artificial sapphire sensors

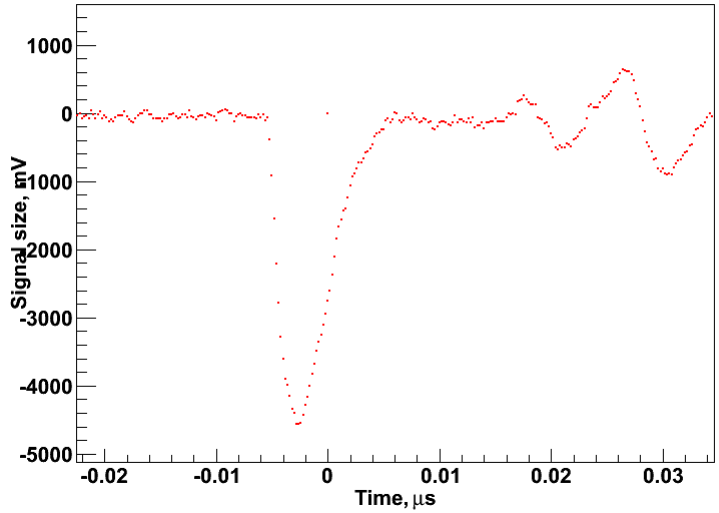
4pCVD diamond sensors



Sapphire sensors

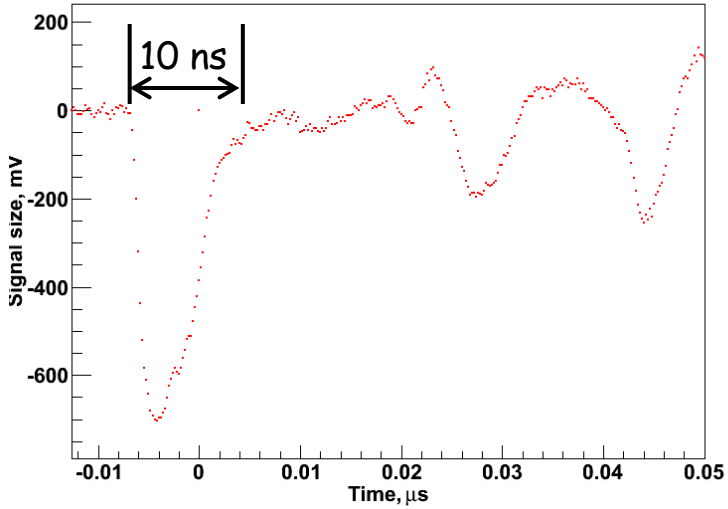
Diamond sensors

DL signal 50 Ohm



Analog signal from diamond sensor

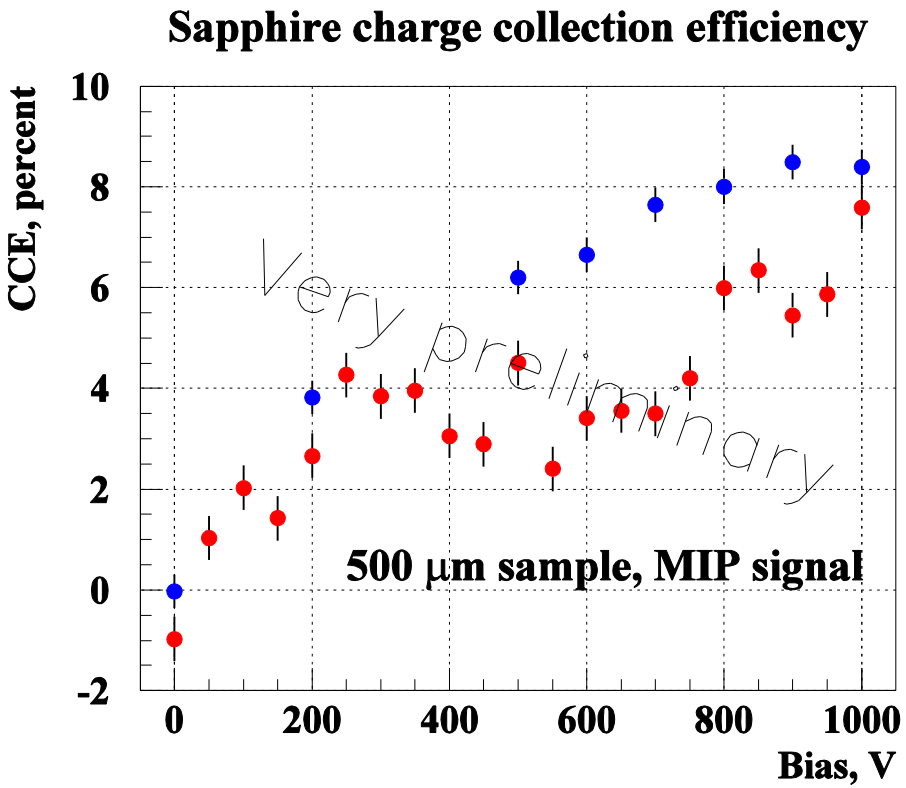
U signal 50 Ohm, 500pC, 20 dB



Analog signal from sapphire sensor

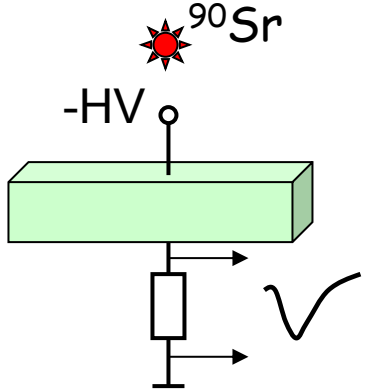
Sapphire charge collection efficiency

Measured at ^{90}Sr setup

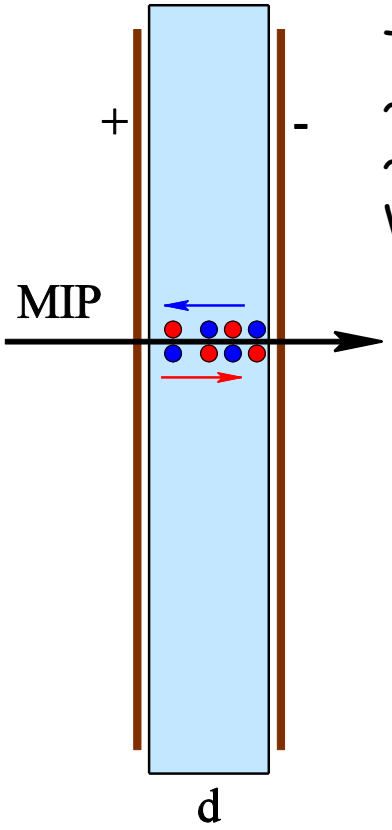


SC Sapphire
10x10x0.5 mm^3
Metallization
Al+Ti+Au

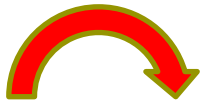
Signal ~ 600 e$^-$

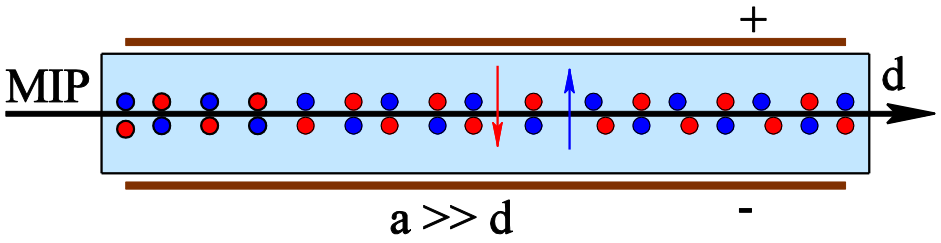


Detection of MIPs



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



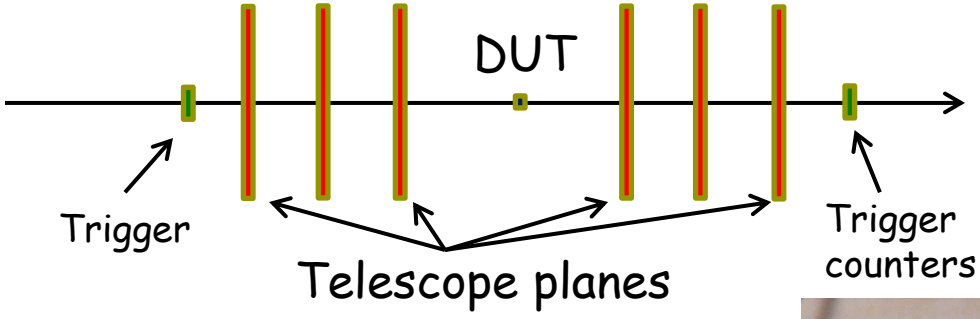


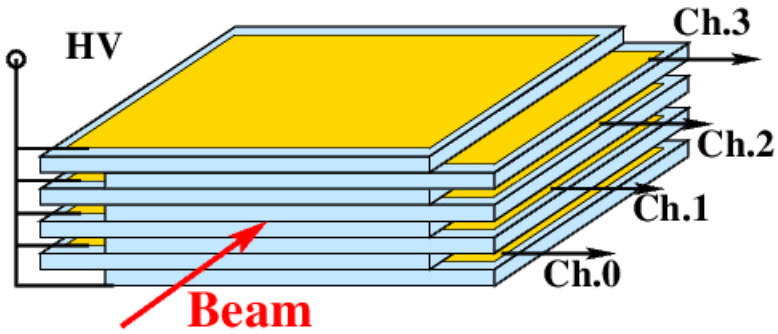
a=10 mm => 220K e-h pairs produced
~5% CCE -> ~11000 e signal, similar to
100% efficient scCVD diamond detectors.

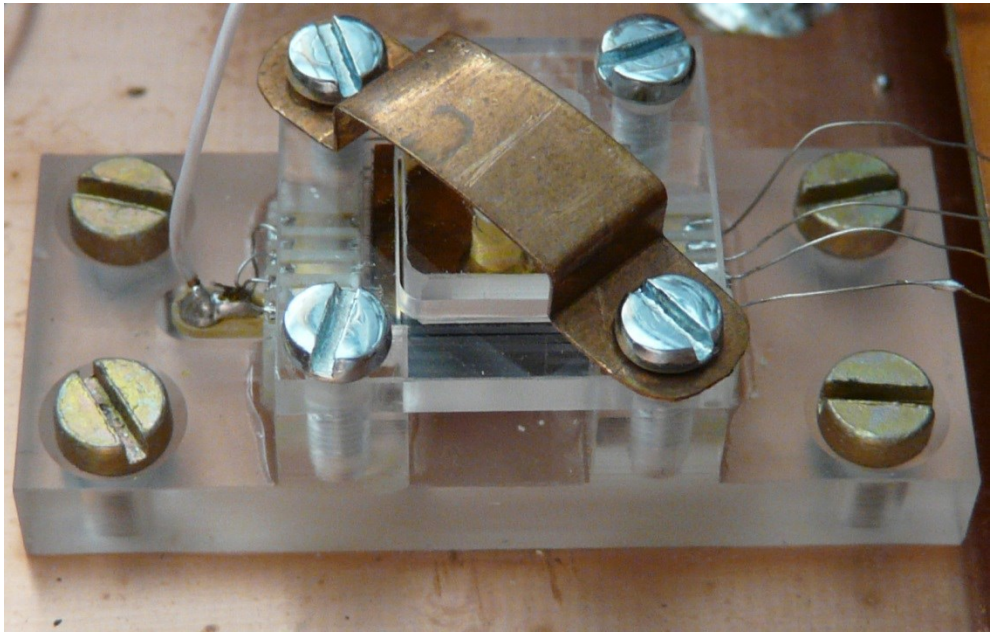
Test beam 2014, DESY

Stack of 8 sapphire plates

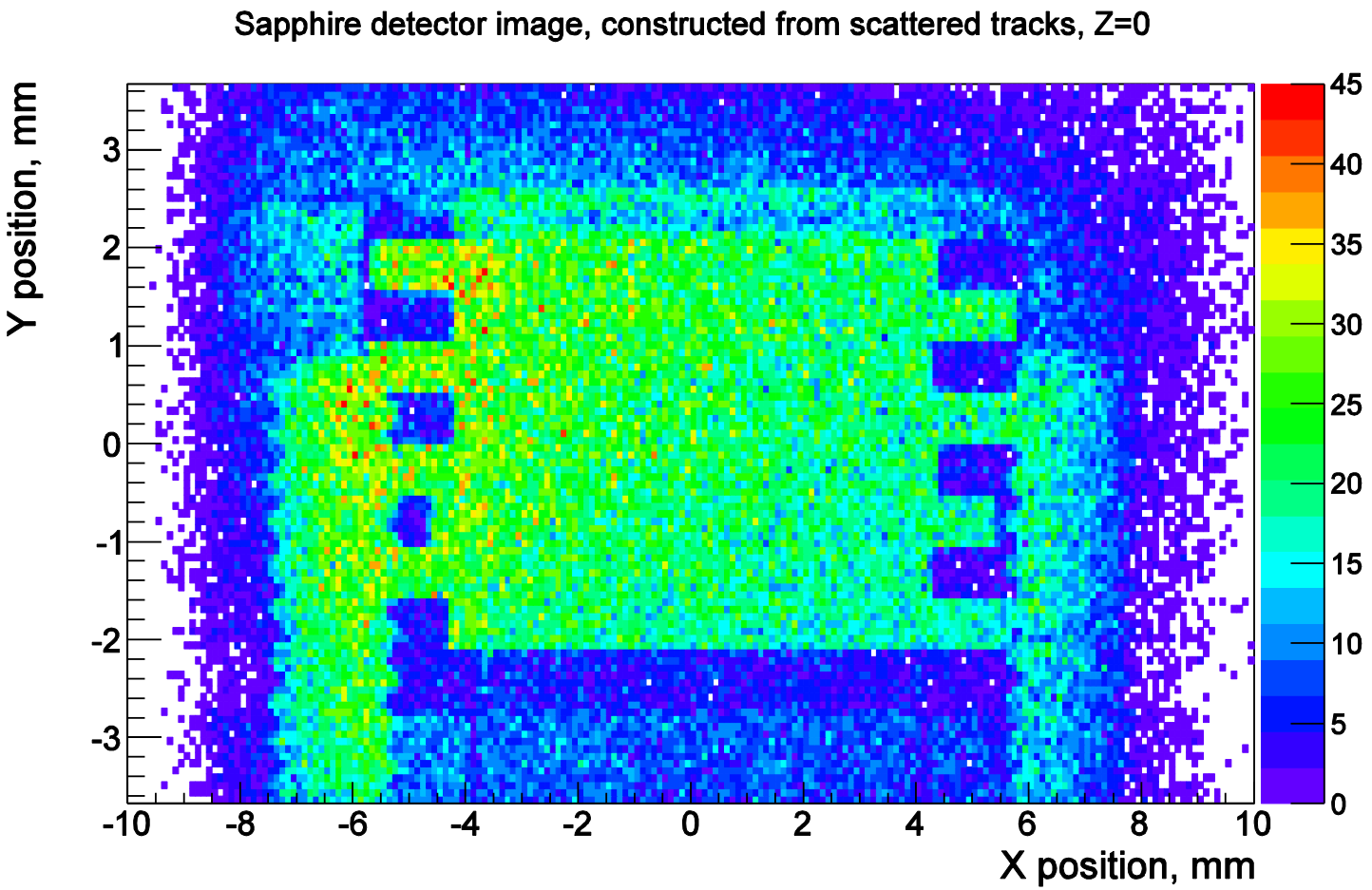
- 5 GeV electrons + EUDET pixel telescope





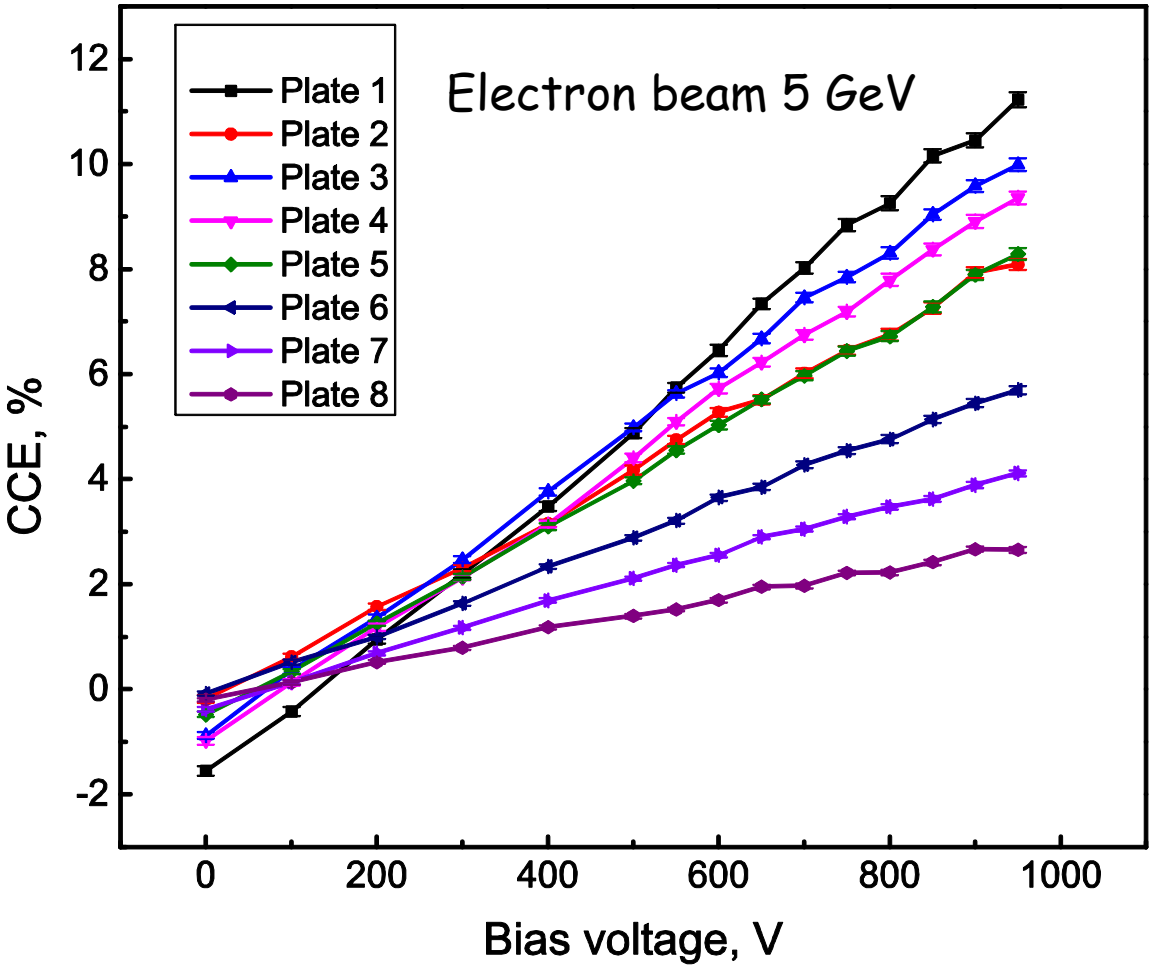


Stack image, scattered tracks



Resolution ~10 μm

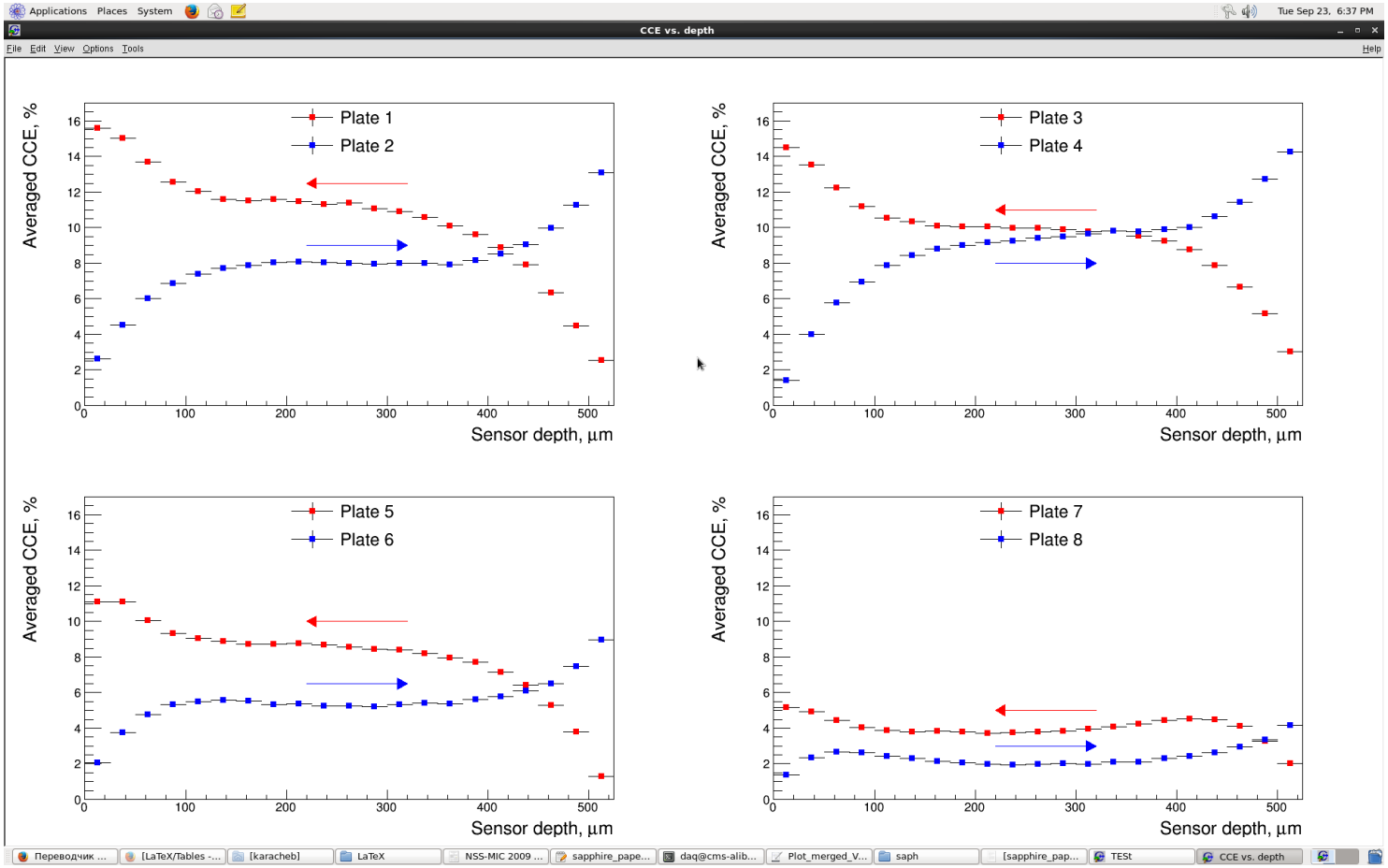
Sapphire charge collection efficiency



CCE linearly depends on the field strength

CCE for good plates ~5% at 1 V/μm

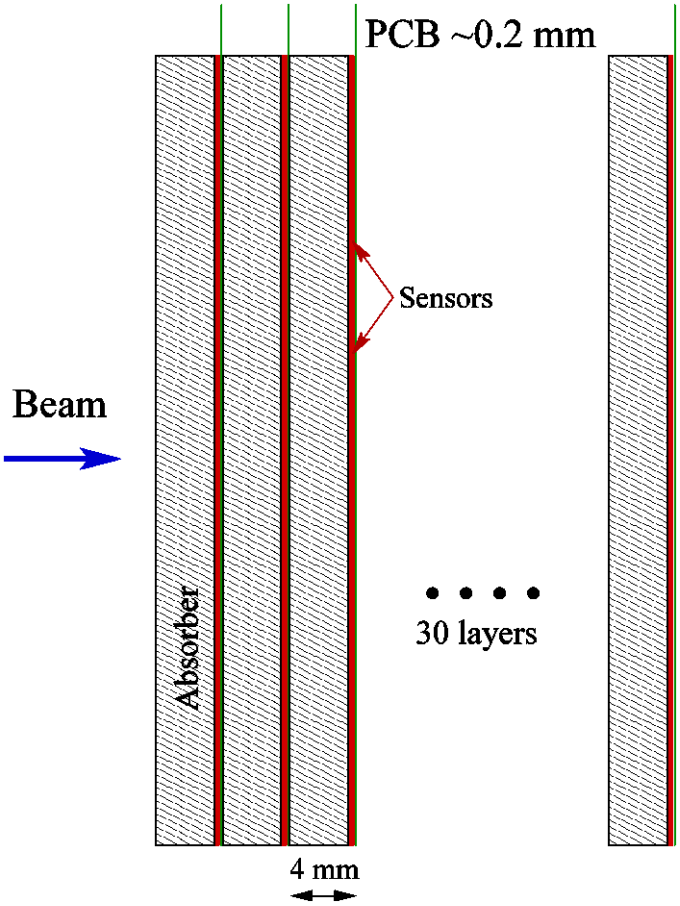
CCE as a function of sensor depth

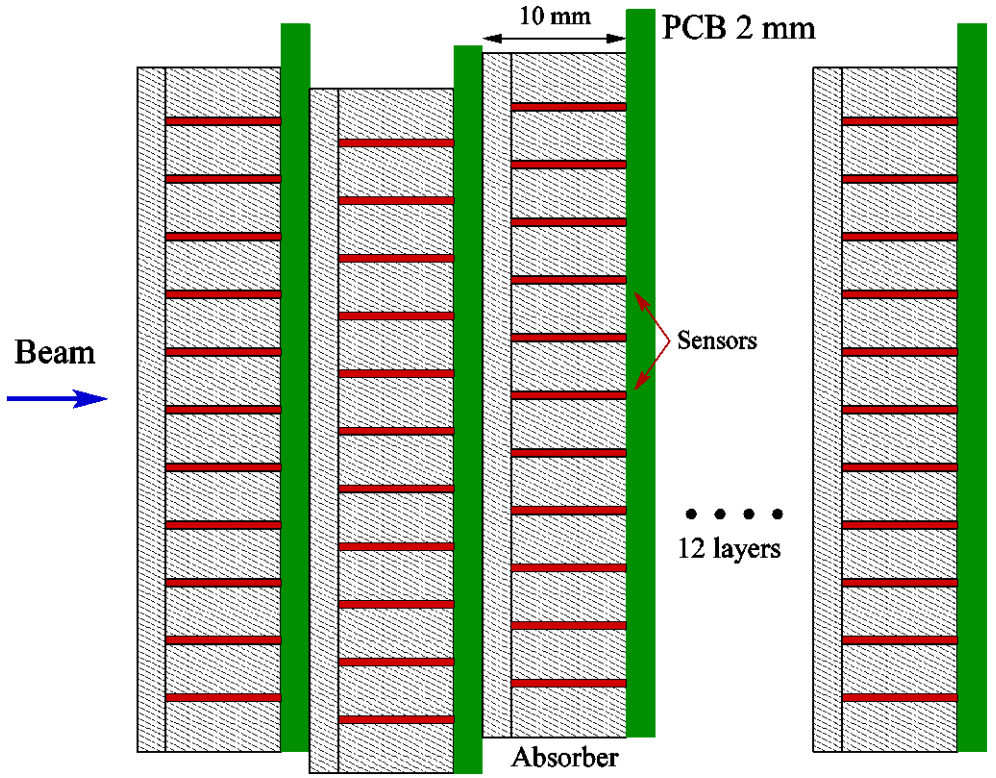


Electron beam 5 GeV

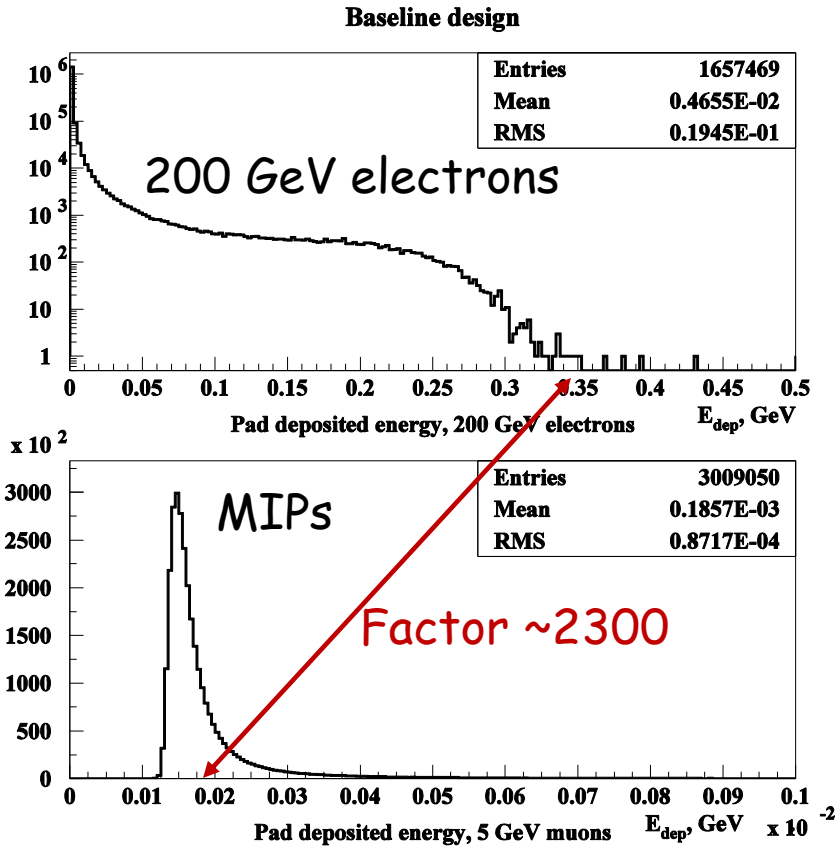
Charge collection by electrons only
Indication to the presence of polarization field

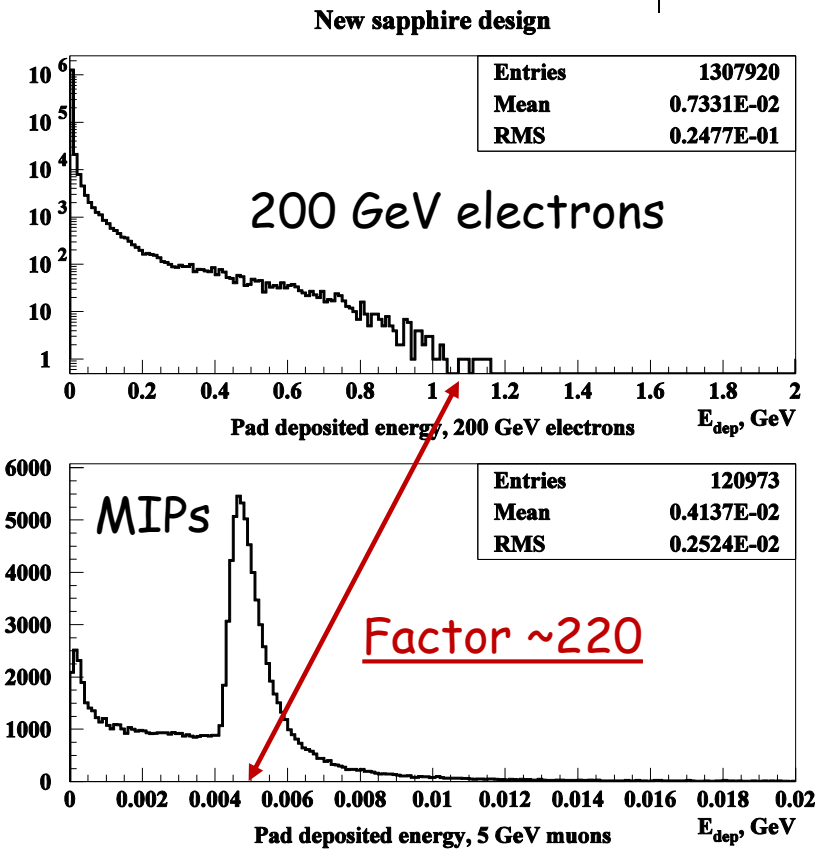
Modification of BeamCal design for sapphire sensors application





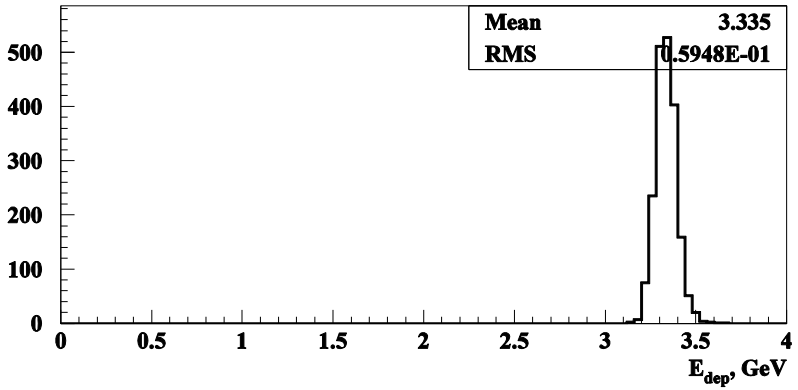
Dynamic range needed for Readout



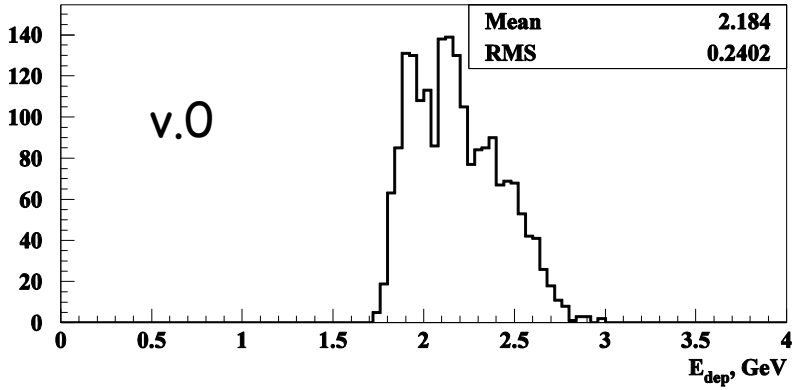


BeamCal energy resolution

200 GeV electrons, GEANT3 Monte Carlo



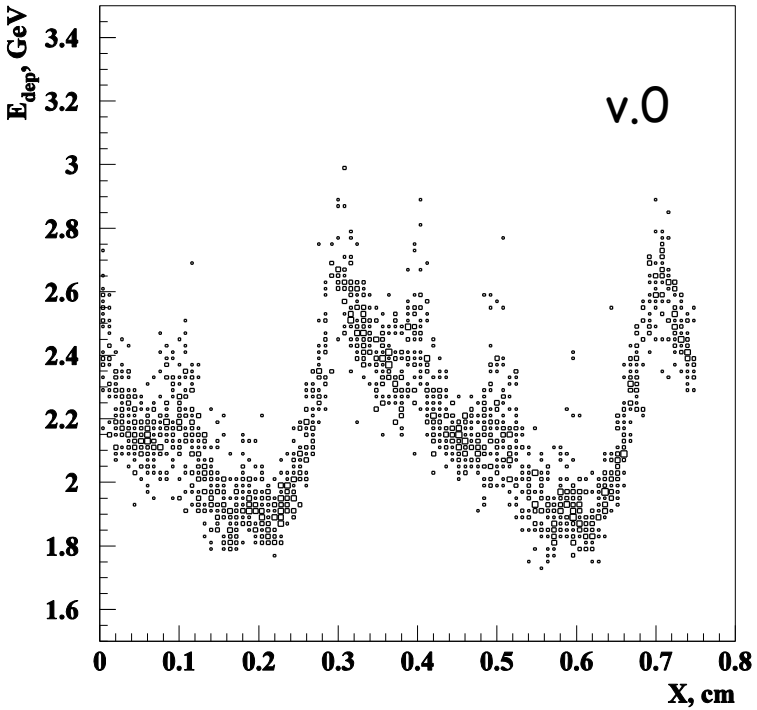
Baseline design.
δE/E = 1.6%

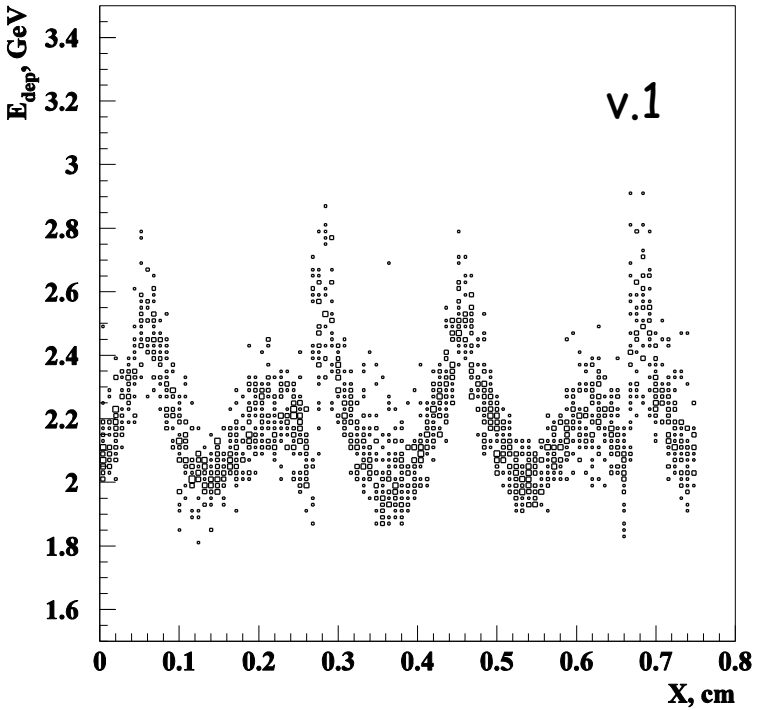


New design.
δE/E ~ 11%
Nonuniform response!

New design. Response (X) nonuniformity.

Along the strips response is uniform.
Response nonuniformity in the direction, perpendicular to the strips, depends on relative layer positioning. Further optimization is needed.

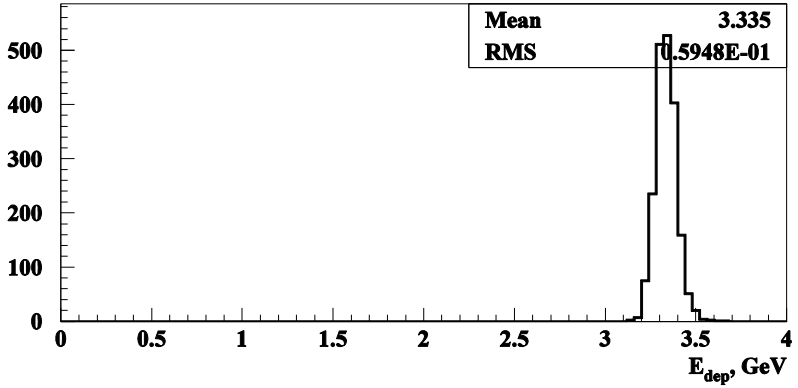


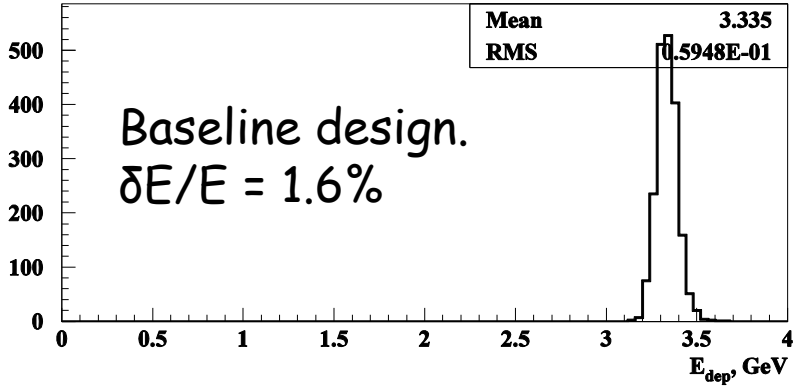


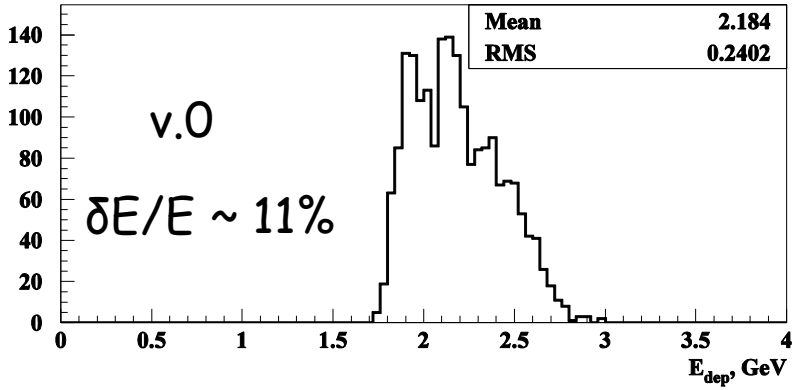
200 GeV electron showers

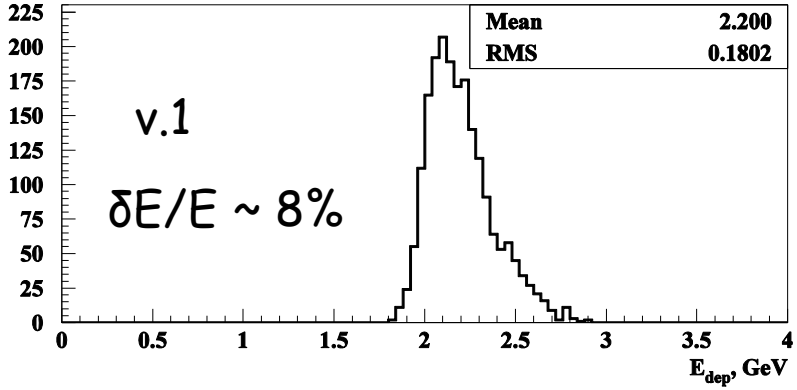
BeamCal energy resolution-1

200 GeV electrons, GEANT3 Monte Carlo



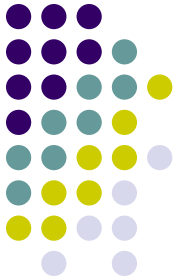






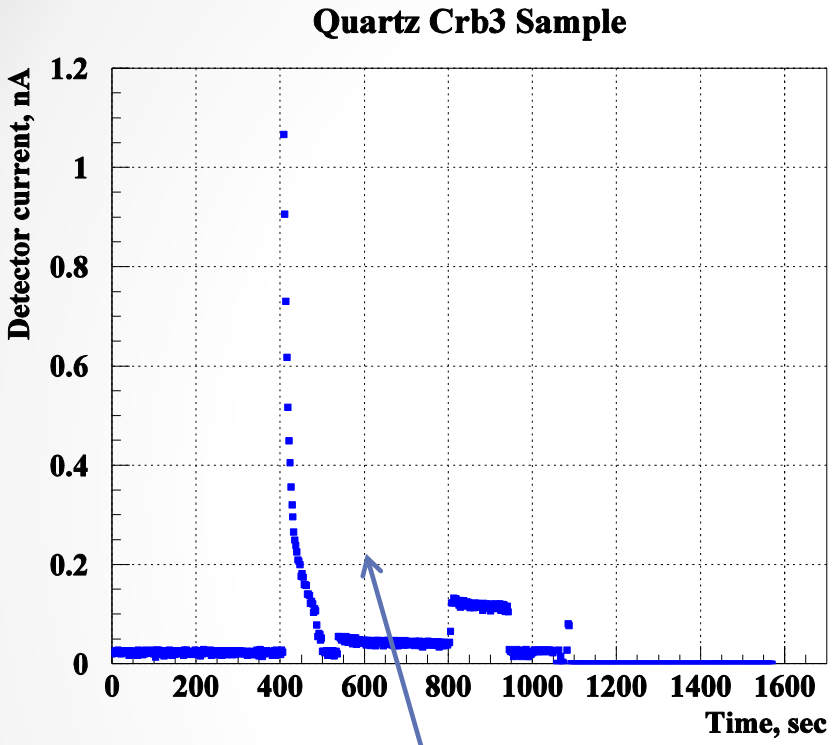
Conclusions and outlook

- Sapphire (single crystal Al_2O_3) is a very promising wide-bandgap material for HEP applications
- Produced in large quantities for industrial purposes, large size wafers are available (~25 cm, up to 40 cm diameter is possible), not expensive
- Perfect electrical properties, excellent radiation hardness, but presently low charge collection efficiency (~ 5%, probably due to high level of impurities)
- For many applications, where radiation hardness is an issue (large particle fluxes), sapphire could be used as it is, i.e. leakage current sensors, detection of particle bunches, calorimetry etc
- Sapphire detector designed for MIP detection was tested at the beam. Results will be published soon.
- Design of the ILC BeamCal, based on sapphire sensors, is presented.
- First Monte Carlo simulations show promising results.
- Further plans: optimization, prototyping, test beam measurements …



Backup slides

Test of sapphire and quartz sensors at the 10 MeV electron beam

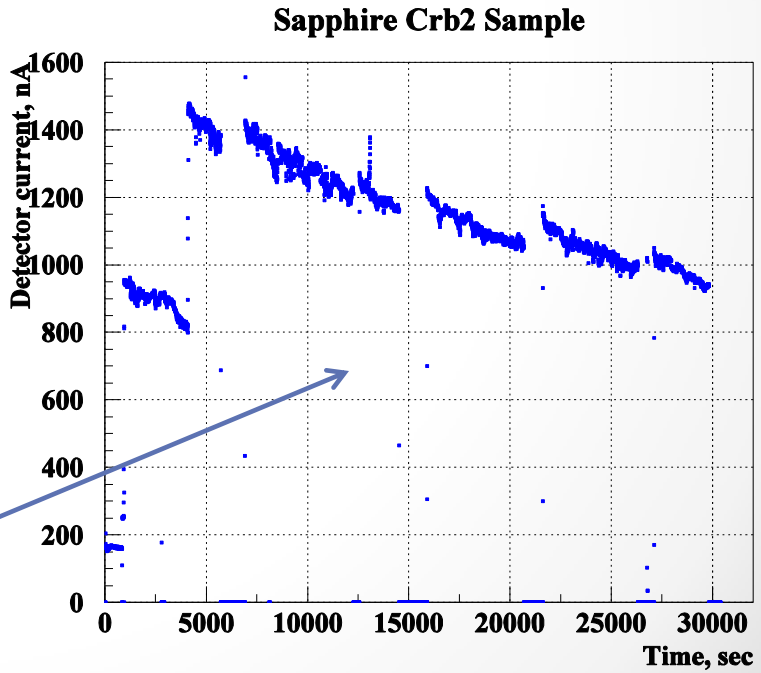


Test samples 10 x 10 x 0.5 mm^3

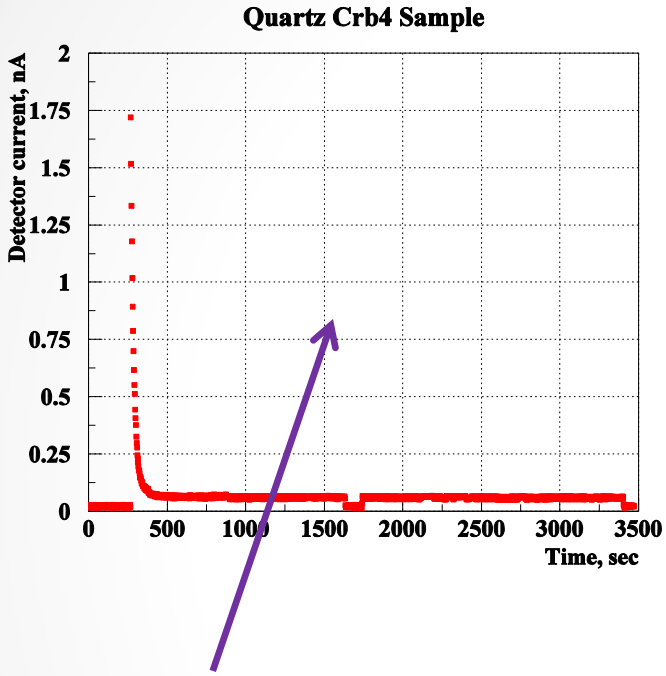
Beam current ~ 5 nA

Strong polarization, seems like electric field is fully compensated. No charge collection.

Normal charge collection

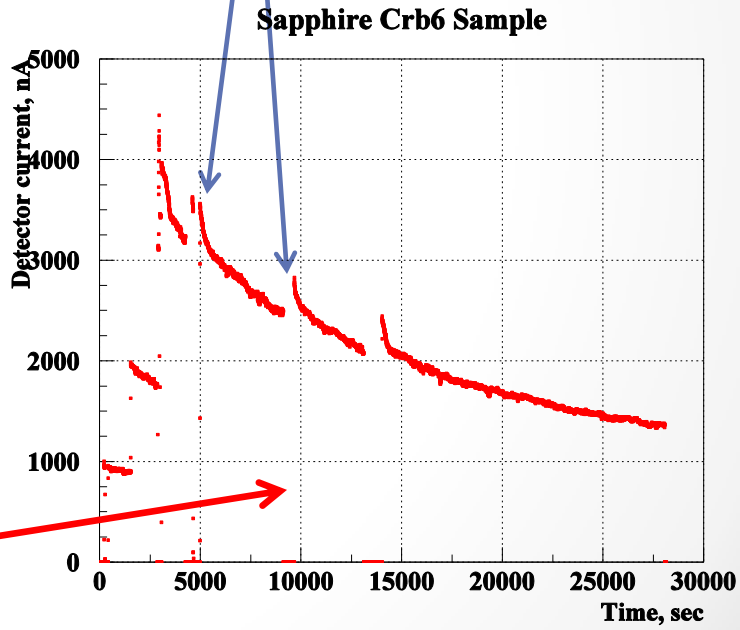


Test of sapphire and quartz sensors at the 10 MeV electron beam



Silicon oxide

Other two samples. Some recovery effect for sapphire during beam interruptions.



Aluminum oxide