Sapphire sensors for particles detection

Sergej Schuwalow, DESY Hamburg

Contents

- 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
- Testbeam results
- Charge transport in sapphire
- Possible applications: tracker, TOF, calorimetry
- Conclusions and outlook

Sensor material properties

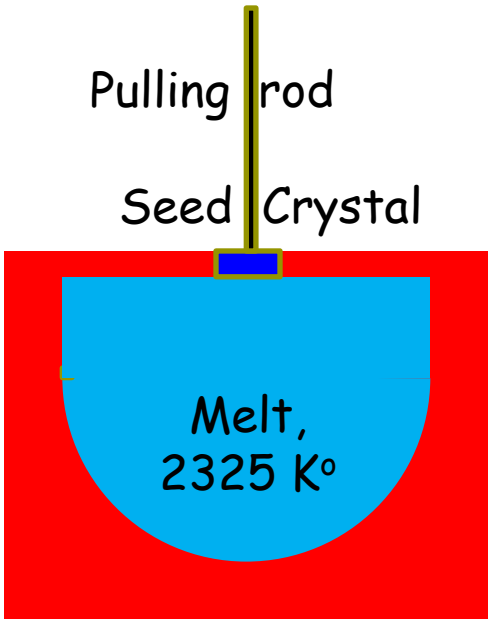
	Sapphire	Diamond	GaAs	Si
Density, g/cm^3	3.98	3.52	5.32	2.33
Dielectric constant	9.3 – 11.5	5.7	10.9	11.7
Breakdown field, V/cm	~10^6 *	10^7	$4 \cdot 10^5$	$3 \cdot 10^5$
Resistivity, Ω·cm	>10^{14}	>10^{11}	10^7	10^5
Band gap, eV	9.9	5.45	1.42	1.12
El. mobility, cm^2/(V·s)	>600 **	1800	~8500	1360
Hole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

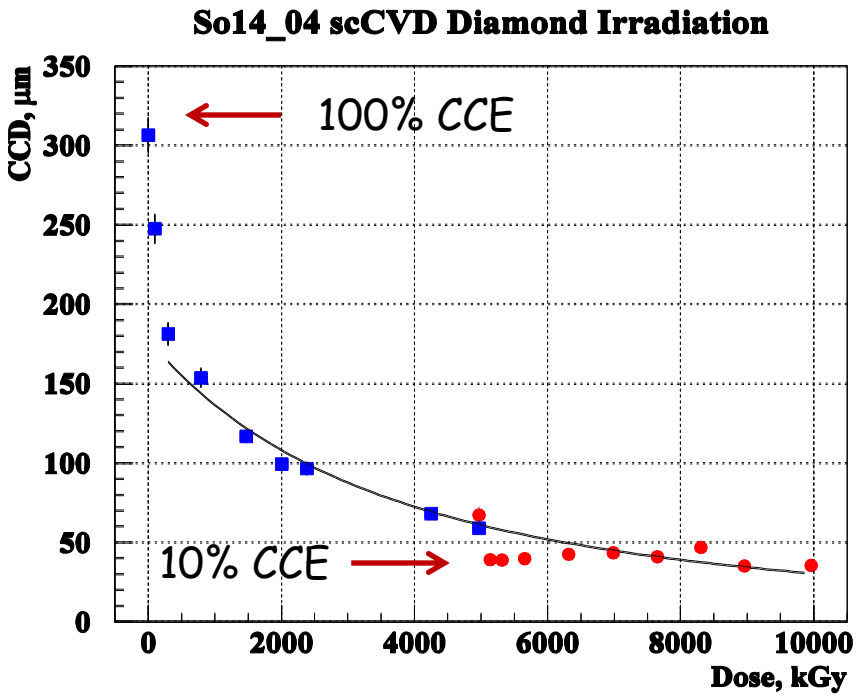
- Single crystals are grown by Czochralski process
- Growing speed ~100 mm/hour
- Up to 440 mm diameter crystals
- Crystal weight up to ~500 Kg
- World annual production >250 tons
- Used in chemistry, electronics, semiconductor industry, lasers, etc.



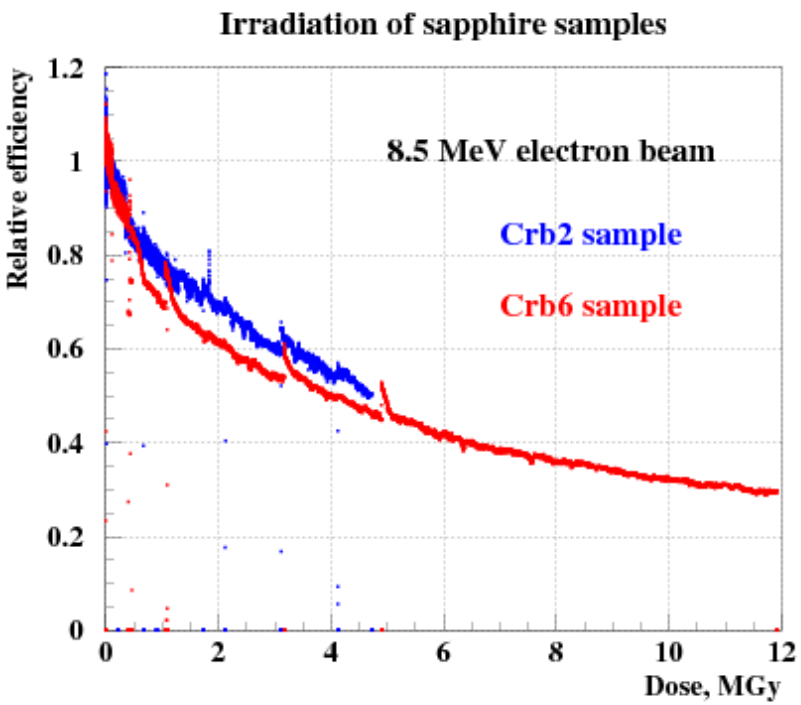
Impurity	Na	Si	Fe	Ca	Mg	Ni	Ti	Mn	Cu	Zr	Y
ppm	8	2	5	5	1	<3	<1	3	<3	2	2

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

Single crystal CVD diamond



Single crystal sapphire

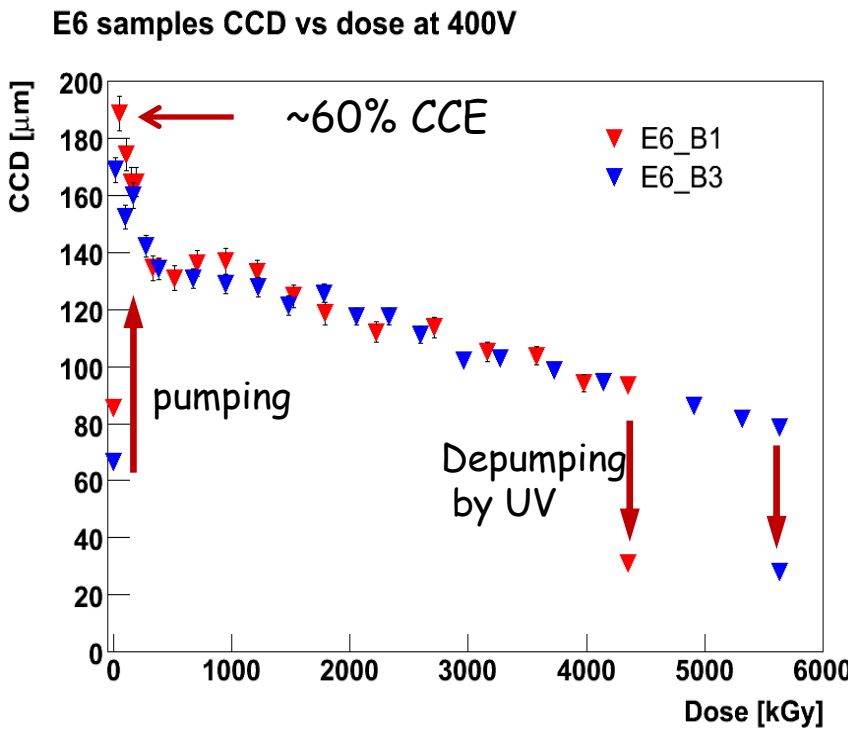


Leakage current after irradiation is still at few pA level

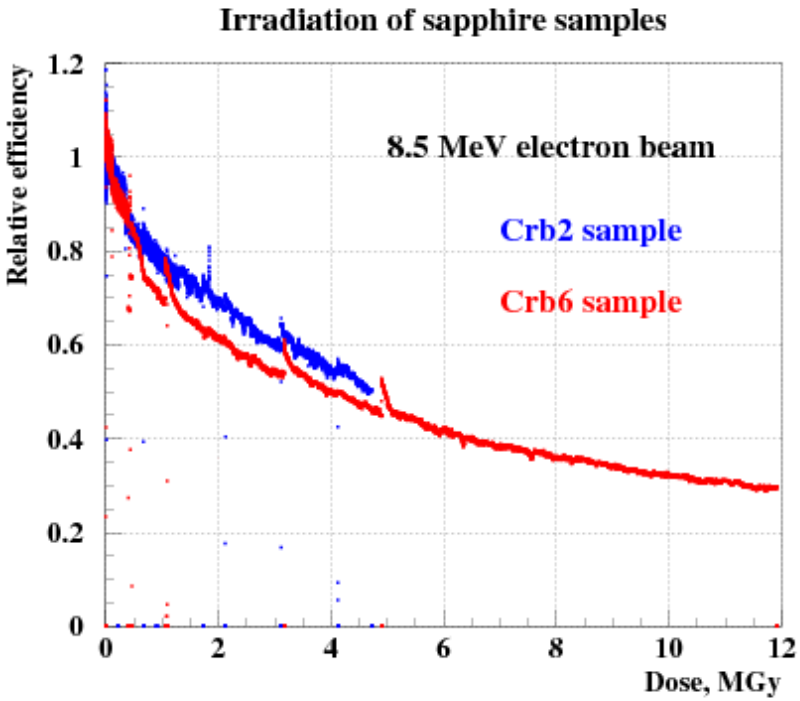
10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL,Summers)

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

Polycrystalline CVD diamond



Single crystal sapphire



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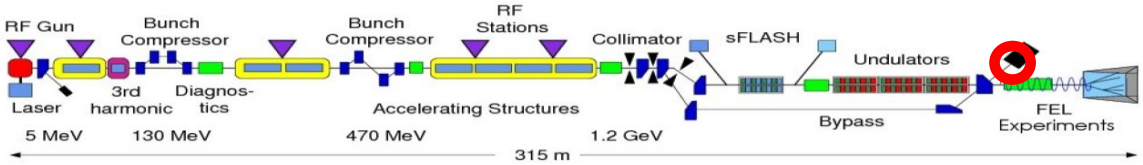
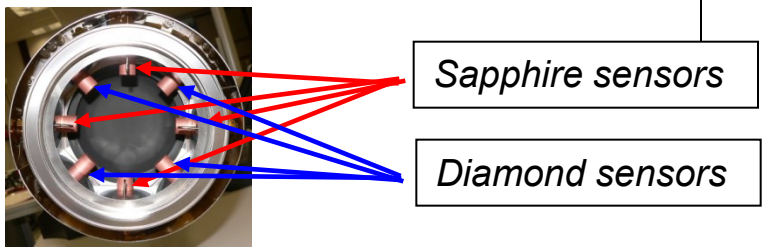
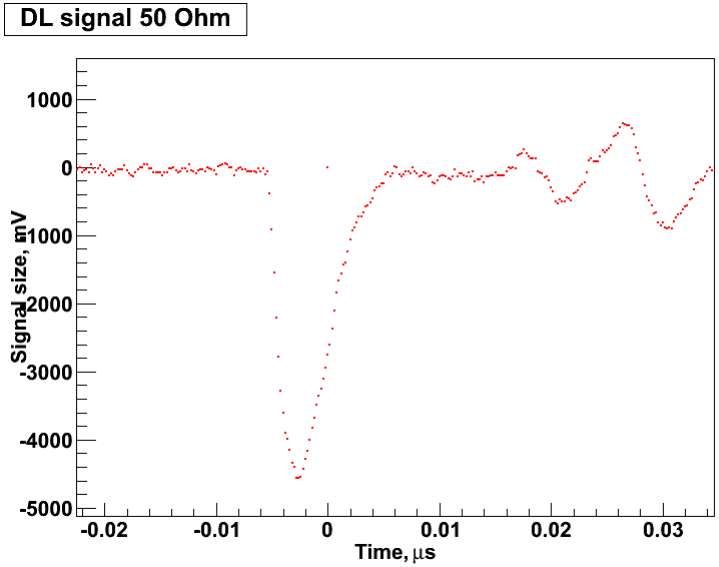
Beam Halo Monitor at FLASH



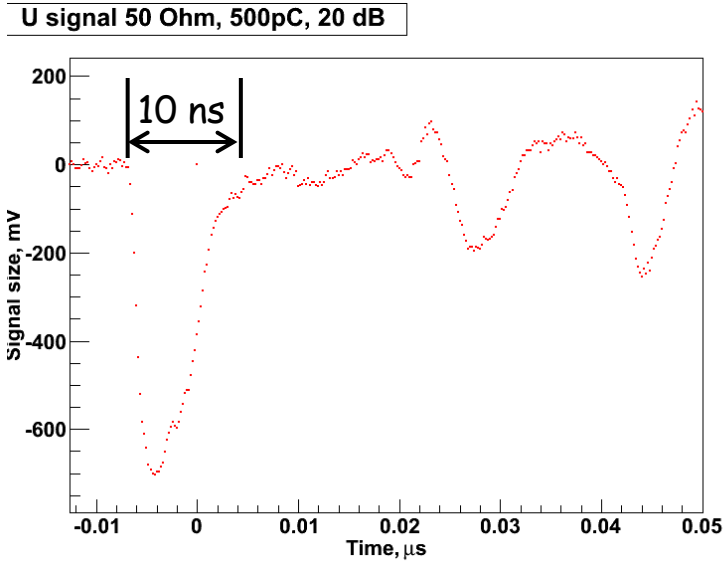
4 artificial sapphire sensors

+ 4pCVD diamond sensors





Analog signal from diamond sensor

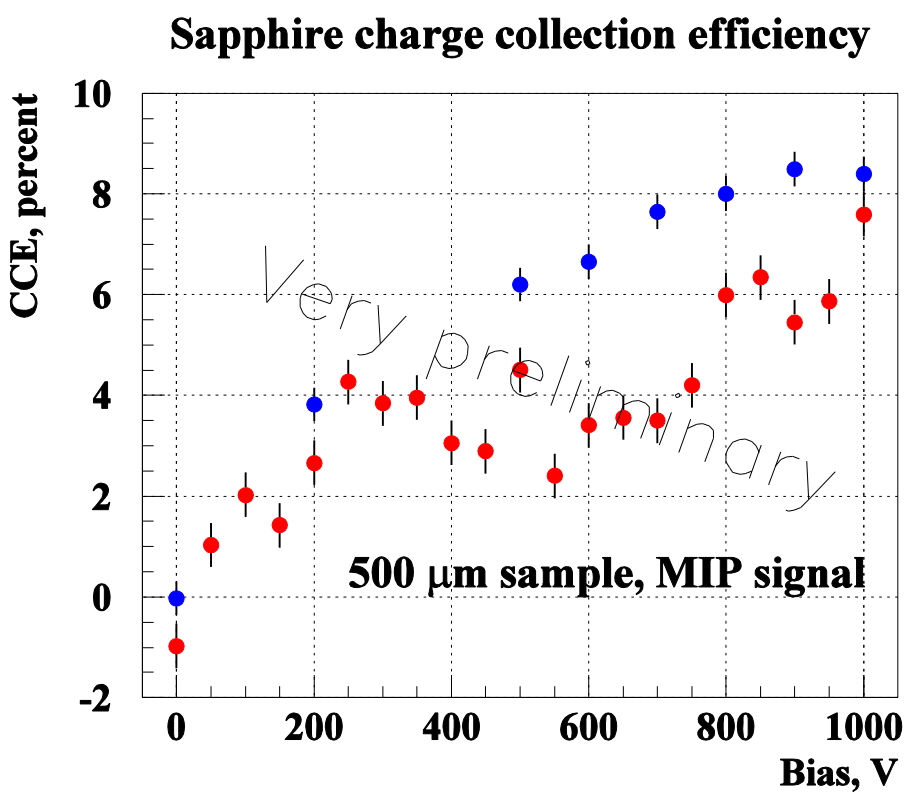


Analog signal from sapphire sensor

For more detailes, see talk by Alexandr Ignatenko at this workshop

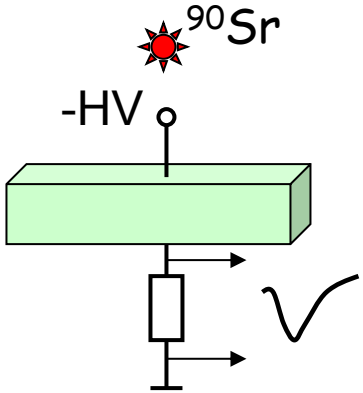
Sapphire charge collection efficiency

Measured at ^{90}Sr setup

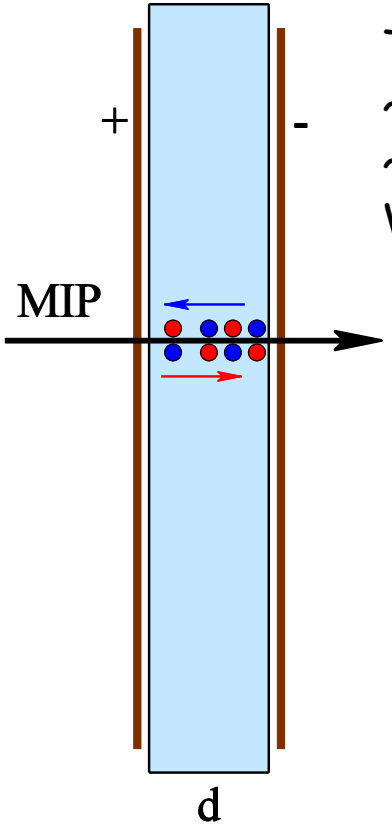


SC Sapphire
10x10x0.5 mm^3
Metallization
Al+Ti+Au

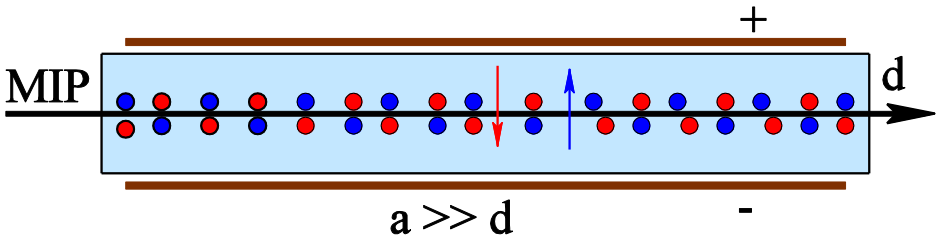
Signal ~ 600 e$^-$



Detection of MIPs



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

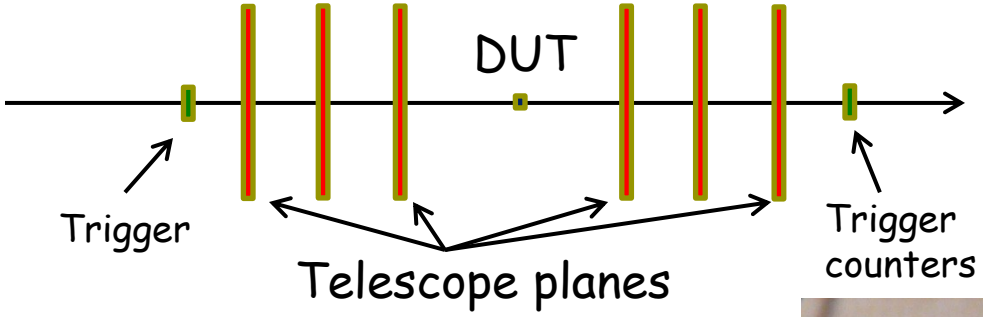


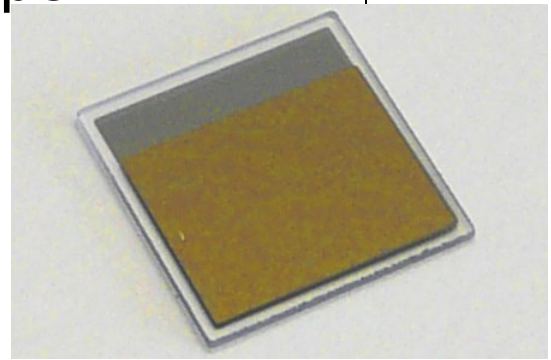
a=10 mm => 220K e-h pairs produced
~5% CCE -> ~11000 e signal, similar to 100% efficient scCVD diamond detectors.

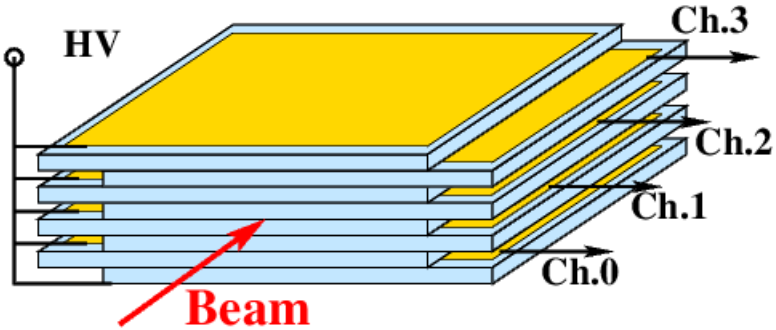
Test beam 2014, DESY

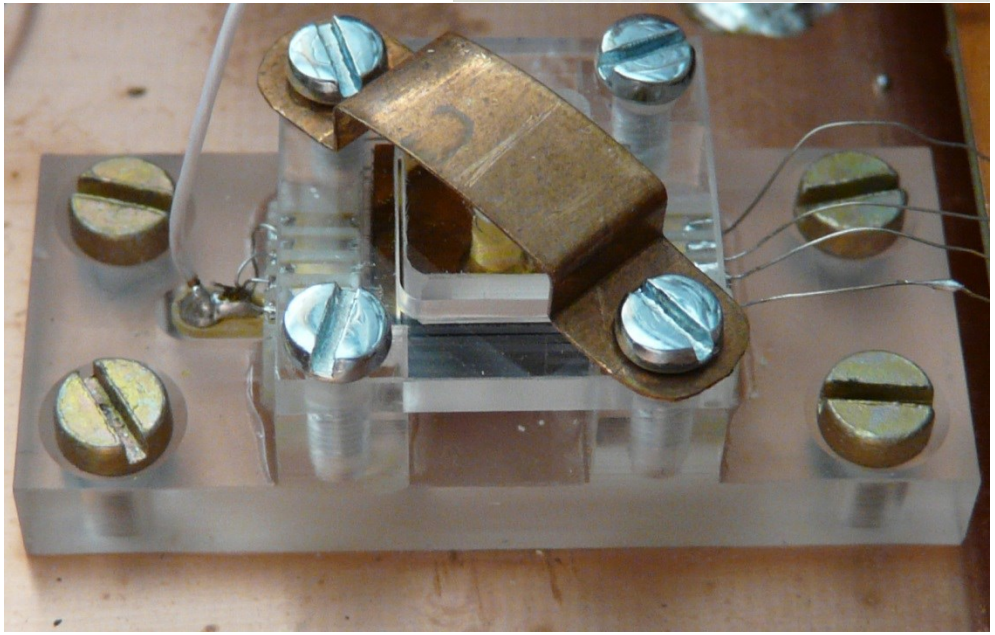
Stack of 8 sapphire plates

- 5 GeV electrons + EUDET pixel telescope

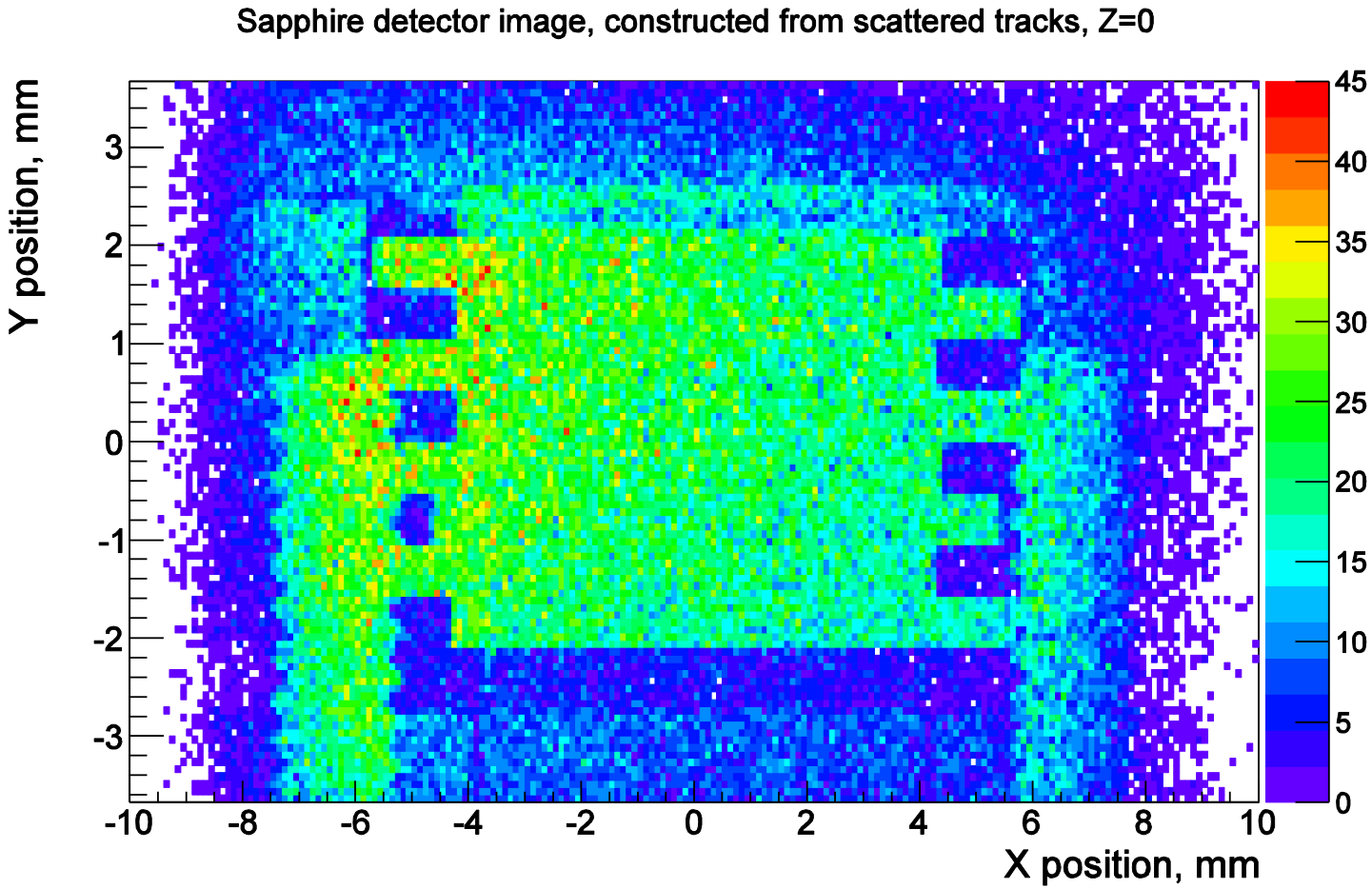






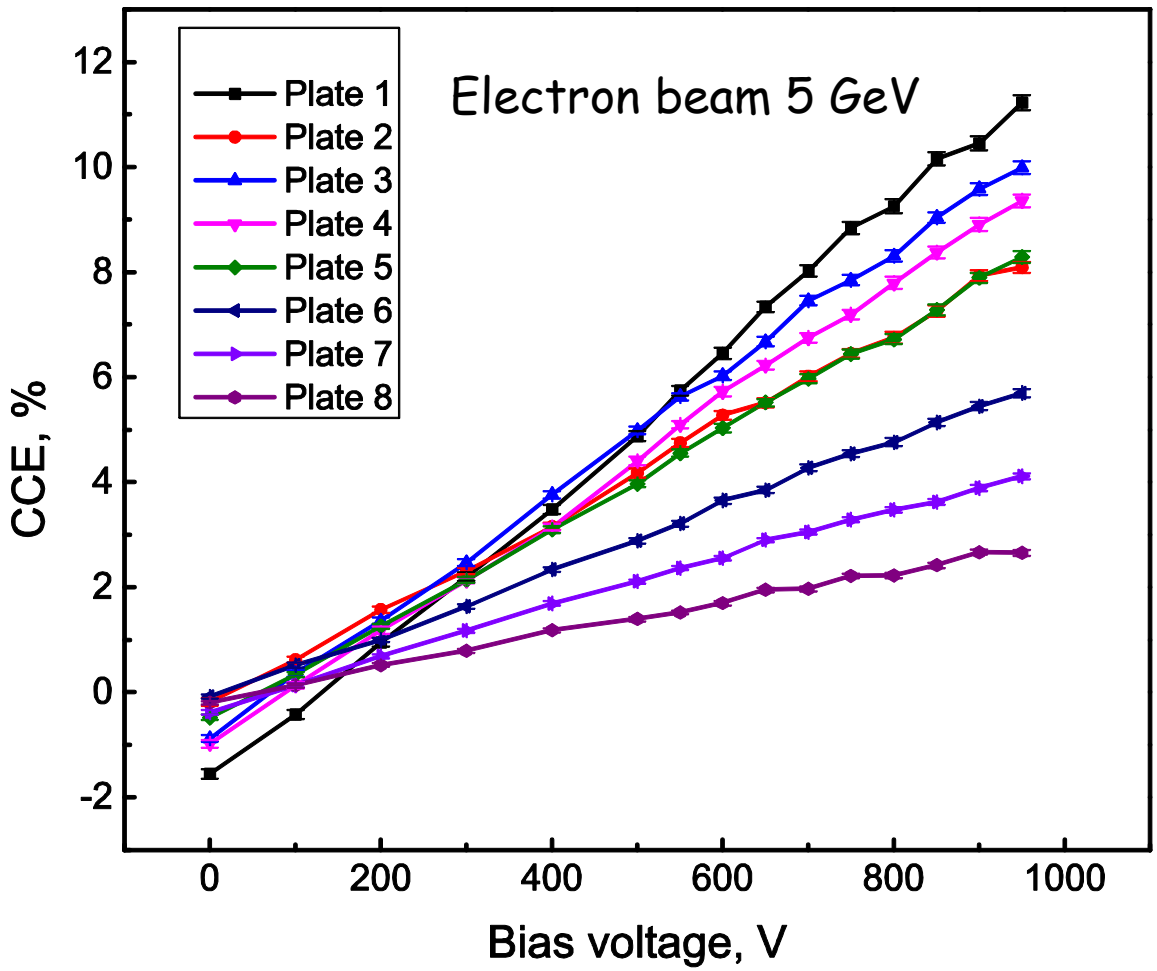


Stack image, scattered tracks



Resolution ~10 μm

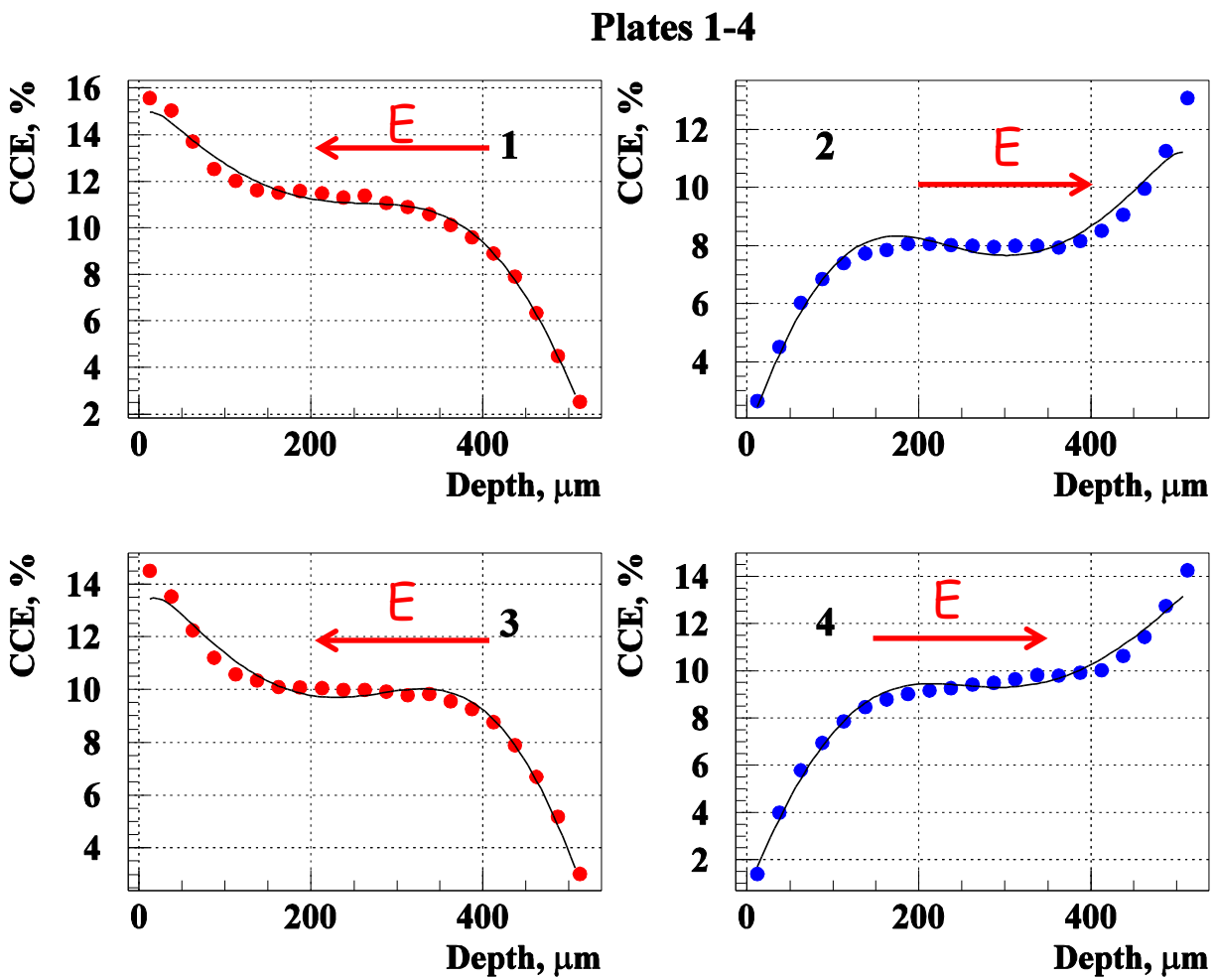
Sapphire charge collection efficiency



CCE linearly depends on the field strength

CCE for good plates ~5% at 1 V/μm

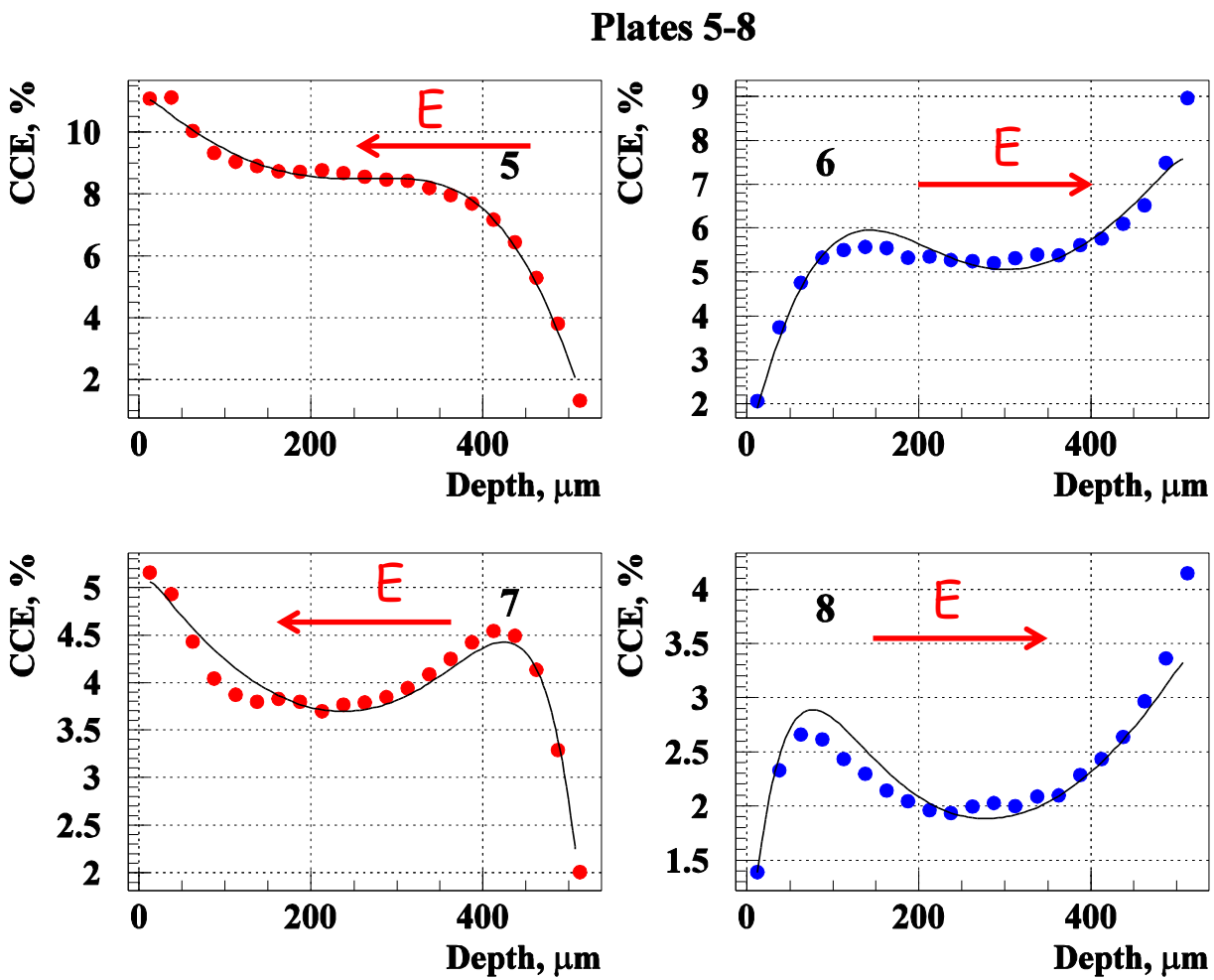
CCE as a function of sensor depth



Electron beam 5 GeV

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

CCE as a function of sensor depth



Electron beam 5 GeV

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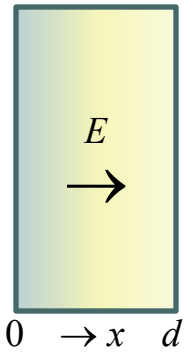
Charge transport in sapphire



Space charge creation due to the trapped carriers

Space charge is a linear function of depth: $\rho = p(2x - d)$

Parabolic electric field $E(x) = A\left(x - \frac{d}{2}\right)^2 + B$

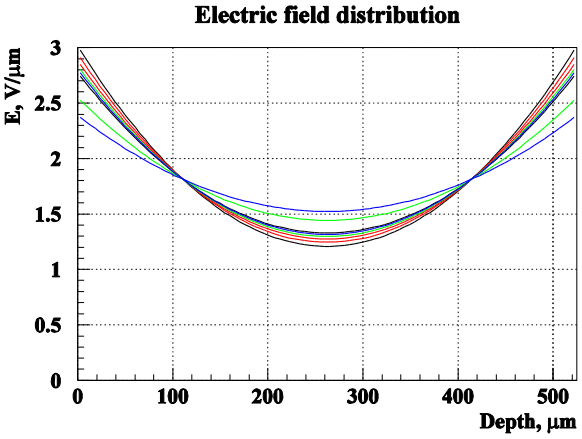
$$\int_0^d E\,dx = \frac{Ad^3}{12} + Bd = V$$ boundary condition

$x_0 \to d$ charge drift

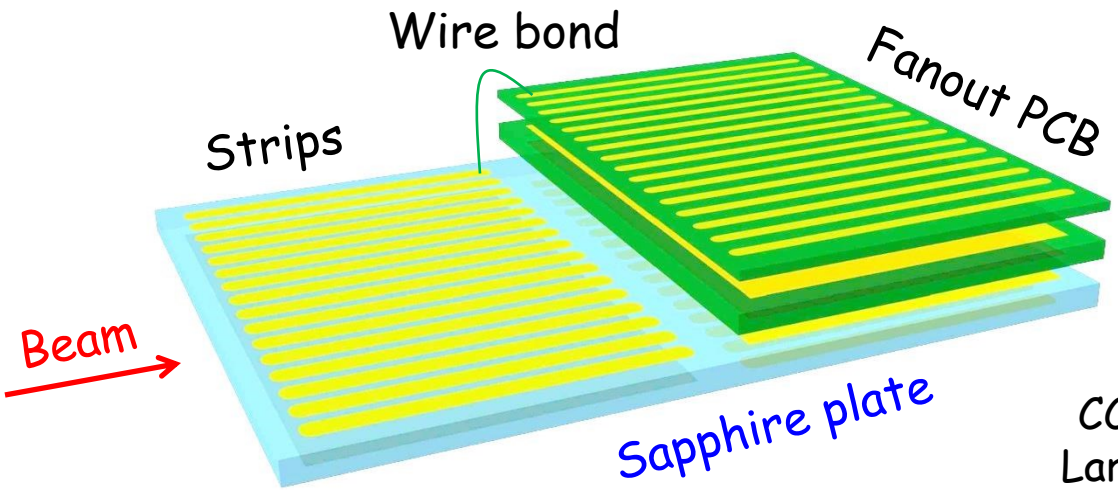
Collected charge for one carrier type:

$$Q = \frac{N_0}{d} e^{\frac{\arctan\left(\left(x_0 - \frac{d}{2}\right)\sqrt{\frac{A}{B}}\right)}{\mu\tau\sqrt{AB}}} \int_{x_0}^{d} e^{-\frac{\arctan\left(\left(x - \frac{d}{2}\right)\sqrt{\frac{A}{B}}\right)}{\mu\tau\sqrt{AB}}} dx$$

Plate number	$B,\ V/\mu m$	$\mu\tau(e),\ \mu m^2/V$	$Norm,\ \%$	$\mu\tau(h),\ \mu m^2/V$	χ^2
1	1.328±0.011	79.4±1.0	52.4±0.4	4.7±0.2	18
2	1.207±0.011	62.0±1.0	47.0±0.5	5.7±0.2	59
3	1.274±0.009	66.7±0.9	53.2±0.5	6.1±0.2	35
4	1.243±0.010	76.6±1.0	48.6±0.5	2.3±0.2	35
5	1.441±0.010	61.0±1.0	48.6±0.8	2.4±0.3	16
6	1.297±0.011	40.5±0.9	44.2±0.9	4.2±0.3	67
7	1.521±0.006	18.7±0.3	60.4±1.4	2.3±0.2	17
8	1.314±0.009	14.2±0.5	46.3±1.9	1.9±0.3	46



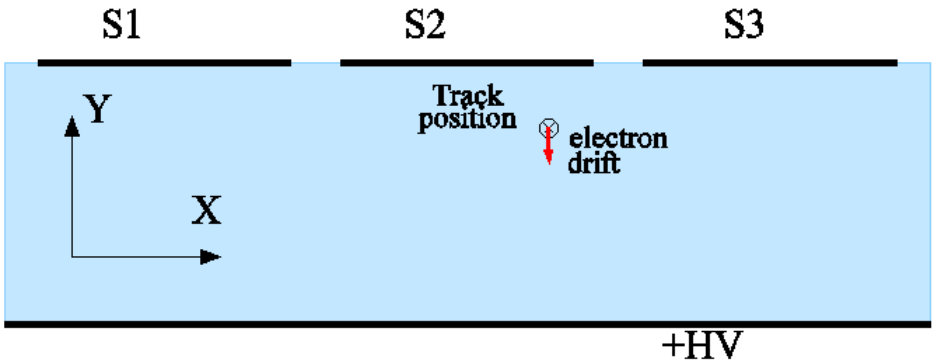
Sapphire possible application: tracker/TOF



Sensor thickness ~ 500μm
Strip pitch ~ 400μm
Expected resolution ~ 10μm

Tracker

CCD << d at room temperature
Large signals at adjacent strips
High sensitivity to the track XY position

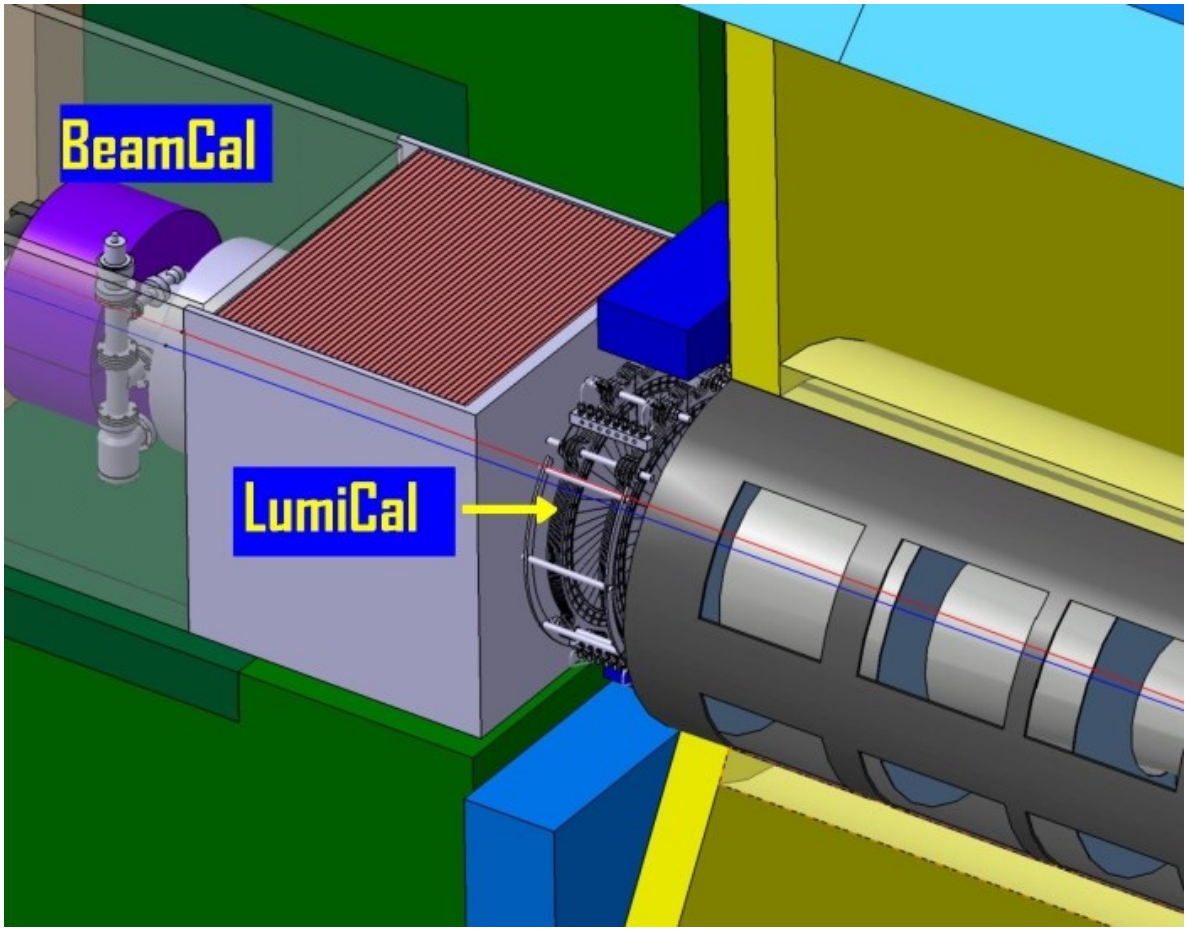


TOF

Mobility of carriers gets much larger at low (cryogenic?) temperatures

Very fast signals, higher CCE expected, although spatial resolution gets worse, being comparable with strip pitch.

BeamCal sensor requirements

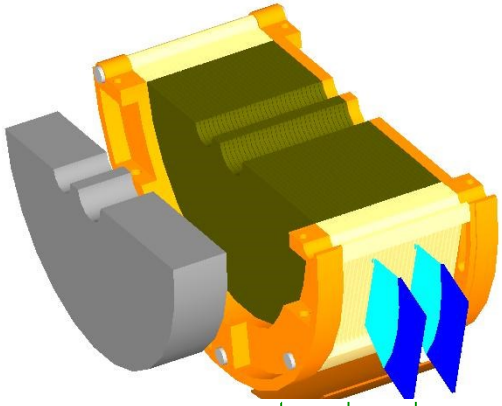


BeamCal should be compact, small Moliere radius needed:
- -sampling calorimeter with solid state sensors, tungsten as absorber.

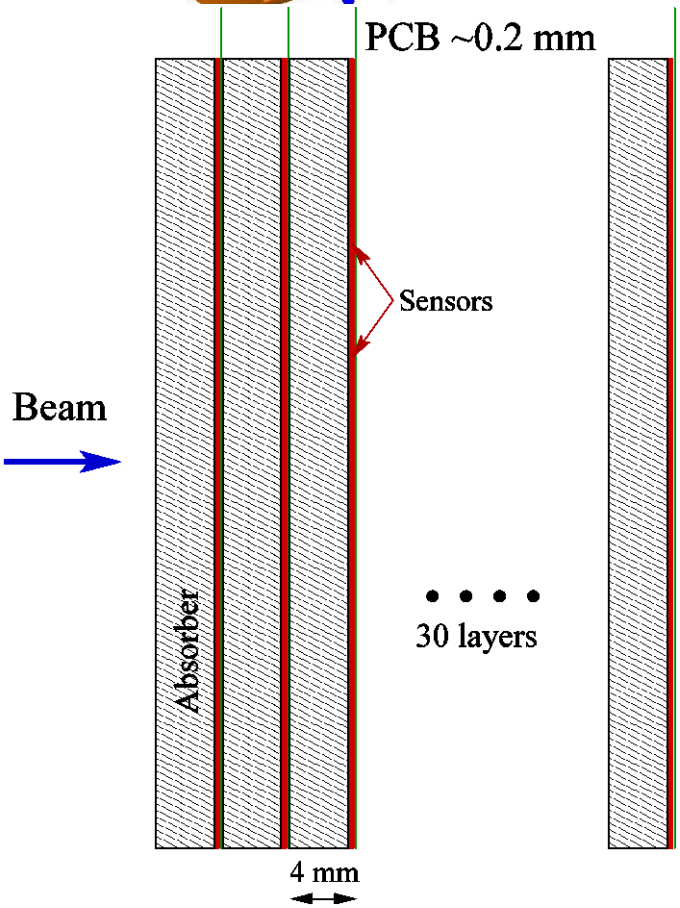
Severe load at small radii due to beamstrahlung:
- - radiation hard sensors (up to 1 MGy annual dose)

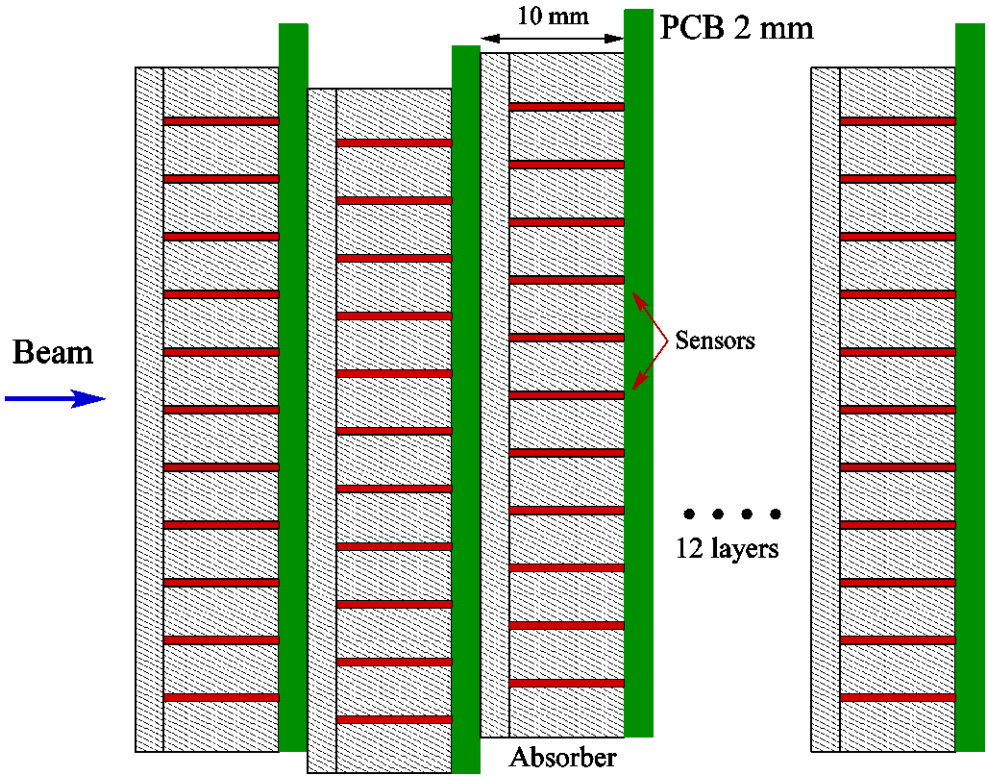
Bunch-by-bunch operation:
- - fast response of sensors

Test beam studies, physical calibration:
- - sensitivity to MIPs

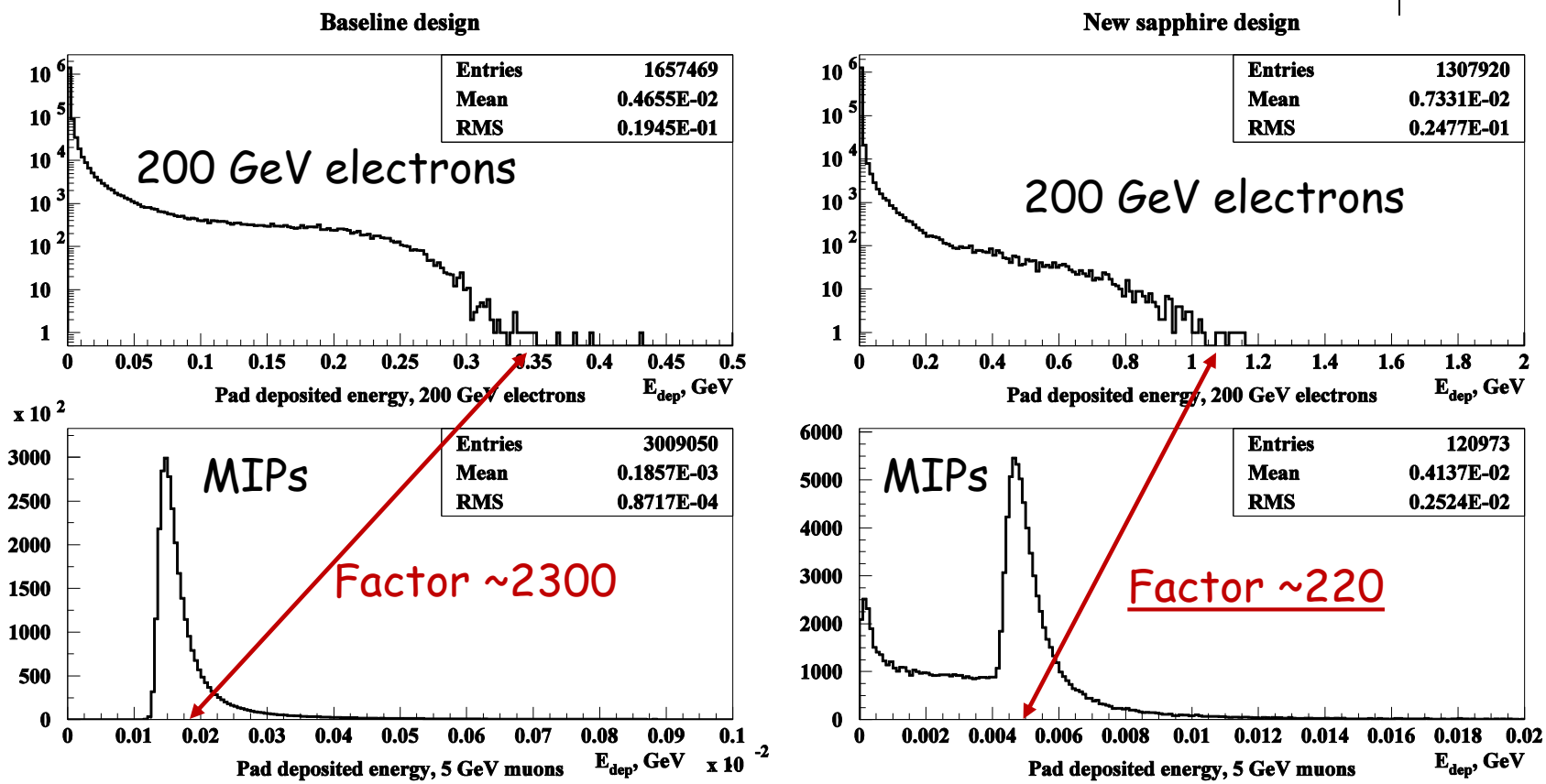


Modification of BeamCal design for sapphire sensors application



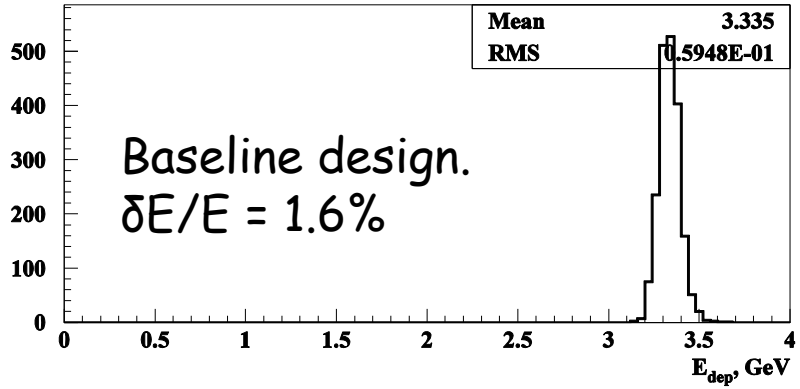


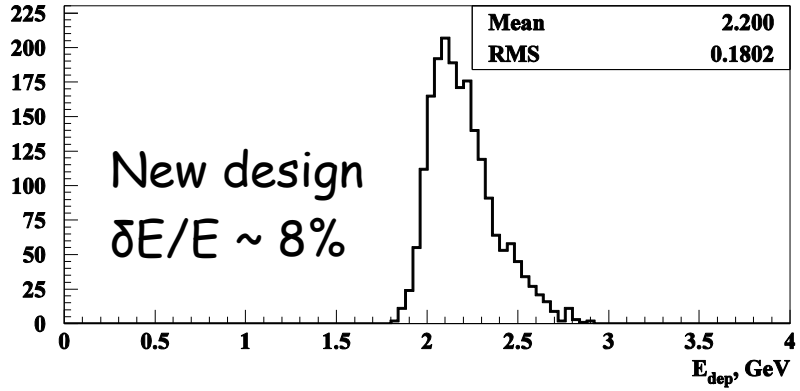
Dynamic range needed for BeamCal Readout (high energy electrons/MIPs)

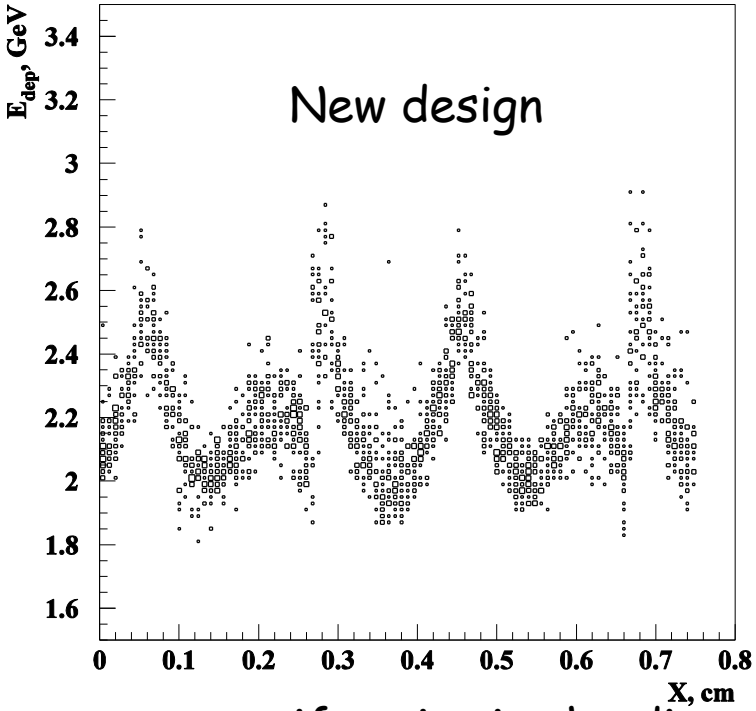


BeamCal energy resolution

200 GeV electrons, GEANT3 Monte Carlo







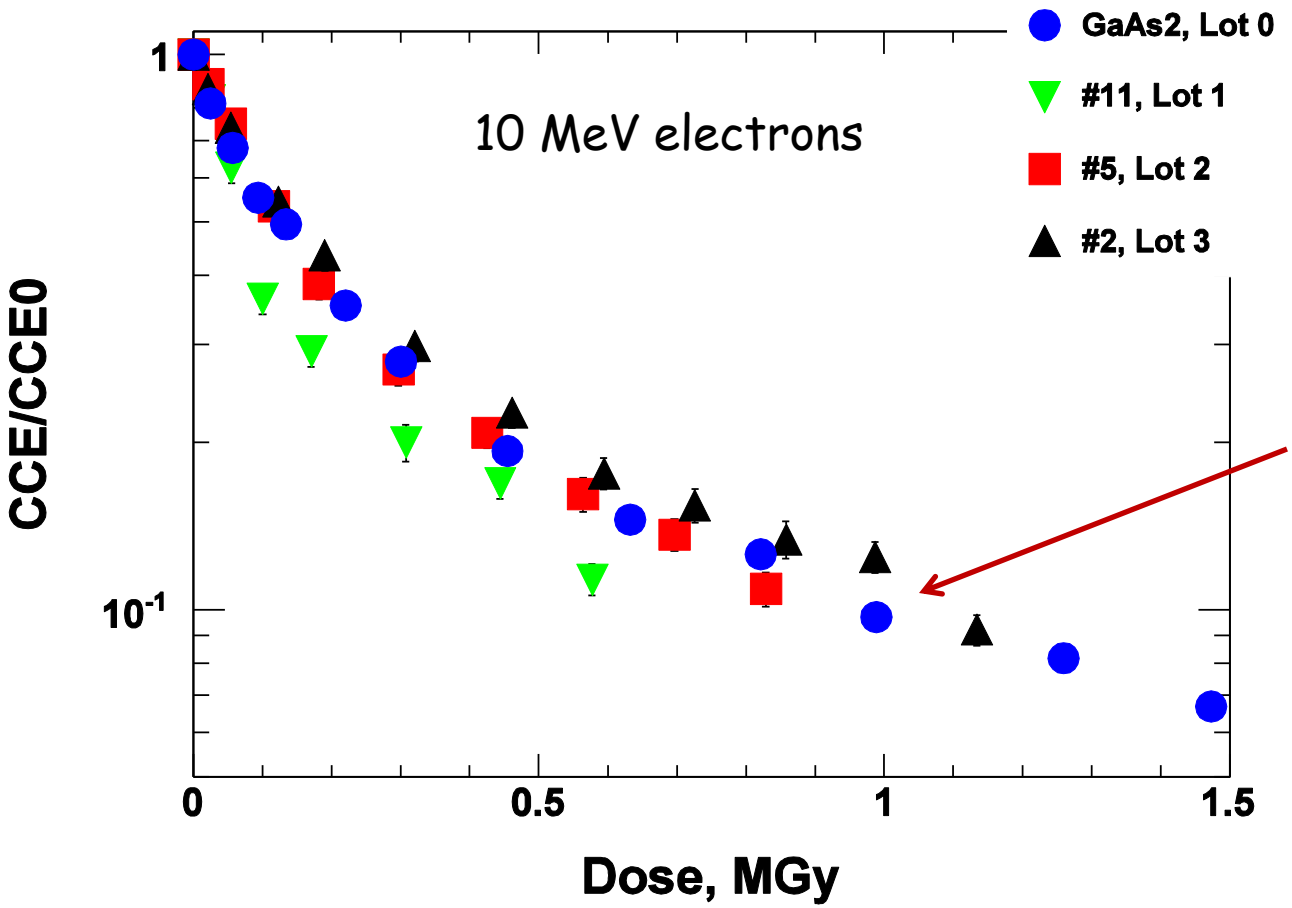
Response nonuniformity in the direction, perpendicular to the strips, depends on relative layer positioning. Further optimization is needed.

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 are in agreement with expectations, will be published soon.
- Preliminary 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 …

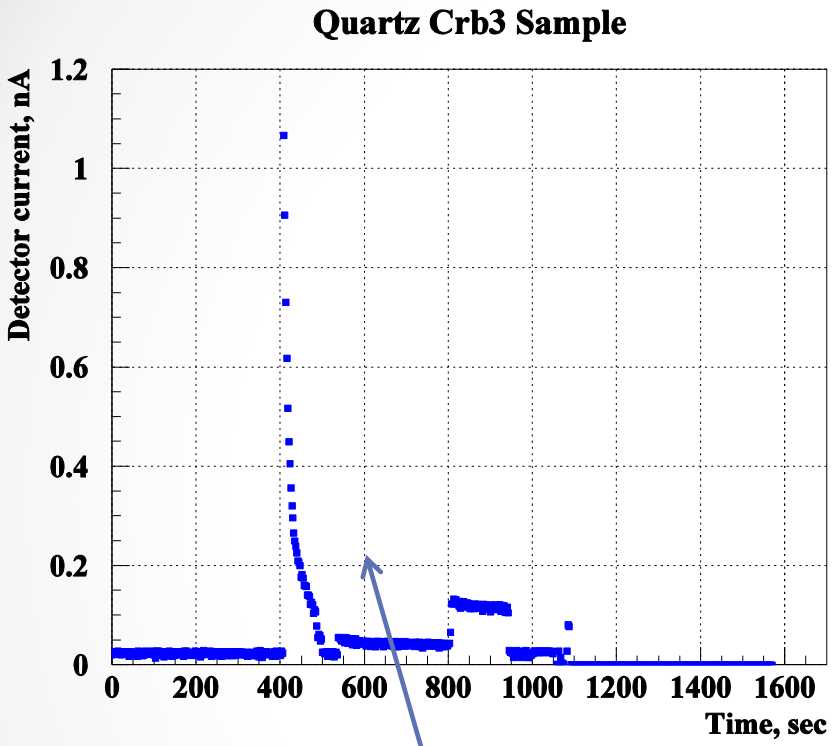
Backup slides

Irradiation of GaAs sensors



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

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

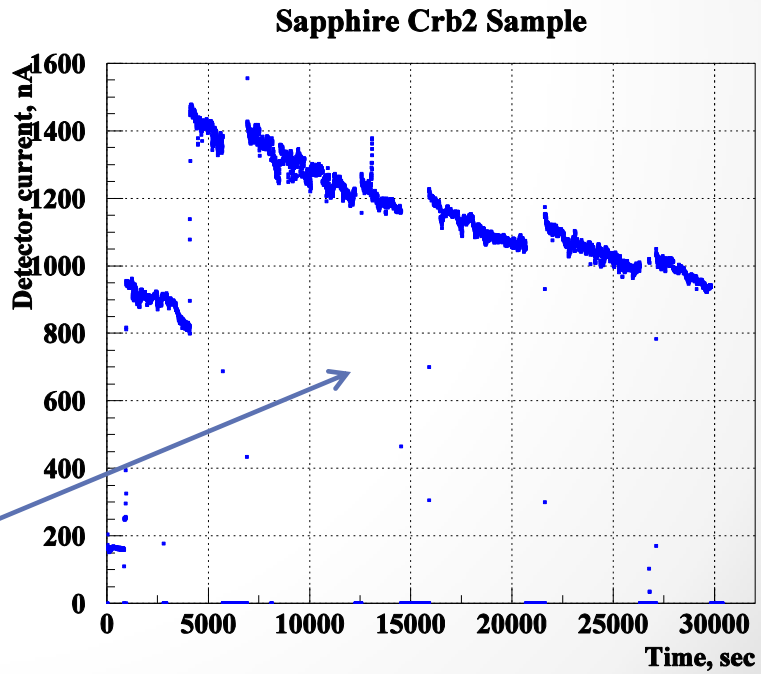


Test samples 10 x 10 x 0.5 mm^3

Beam current ~ 5 nA

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

Normal charge collection



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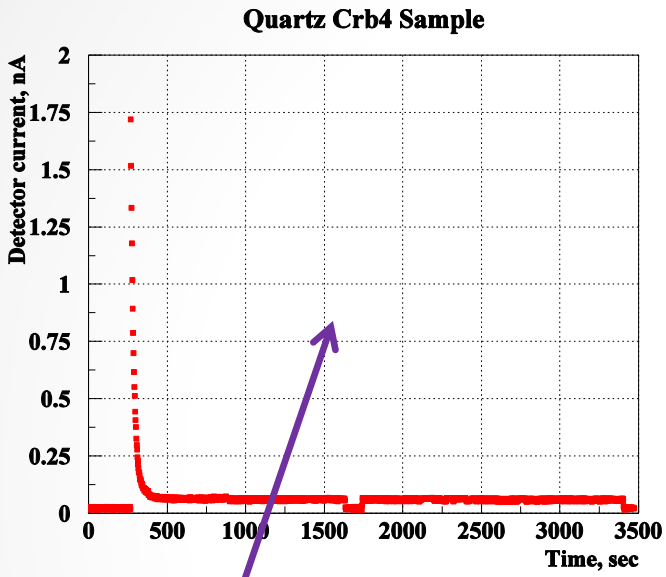
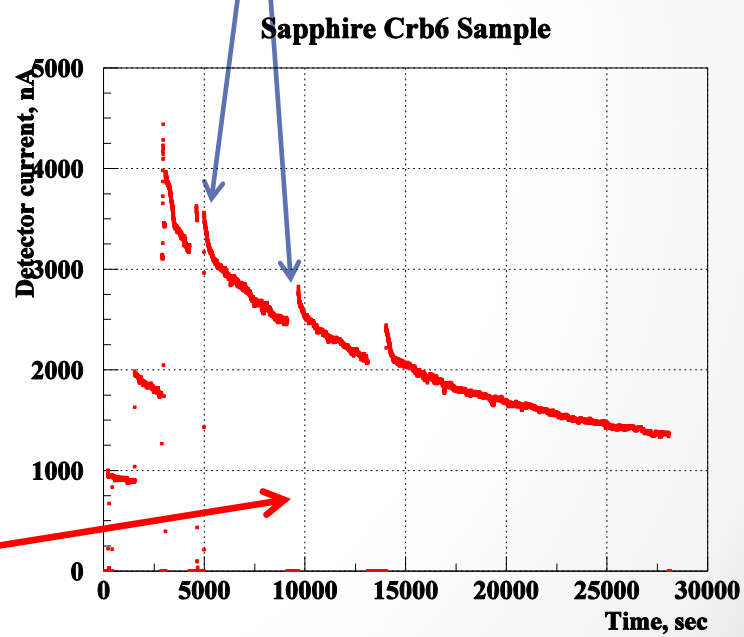


Silicon oxide

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



Aluminum oxide