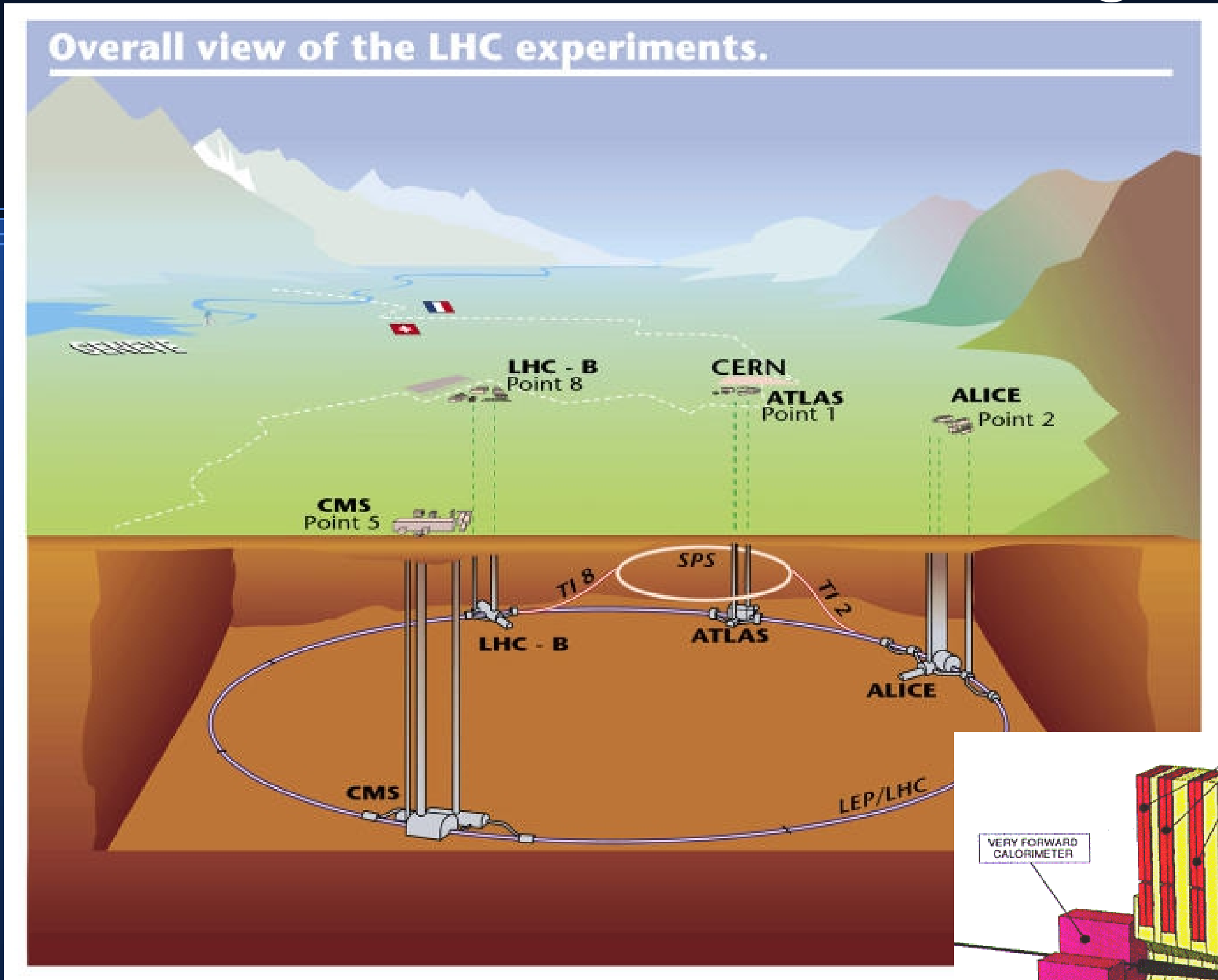
Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Brandenburg
University of Technology
Cottbus - Senftenberg

Characterisation of non-irradiated and irradiated diamond sensors before and after application at LHC

Martin Stegler

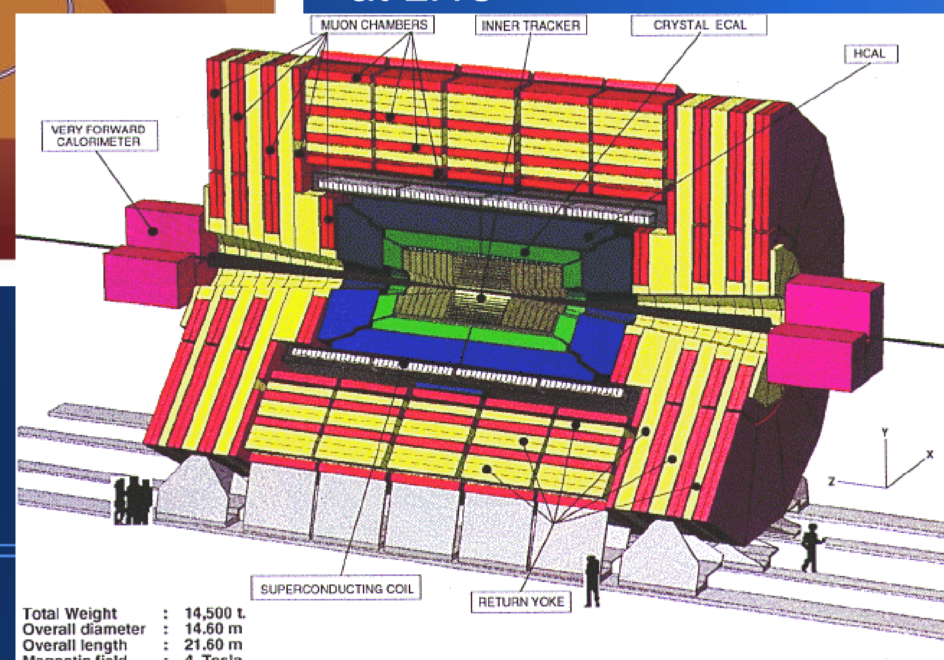
Diamond Sensors in High Energy Physics



Large Hadron Collider LHC at European organisation for Nuclear Research CERN

- Protons or heavy ions are accelerated in opposite direction
- At four locations the beams intersect to allow collision
- Very high particle flux and energies at LHC

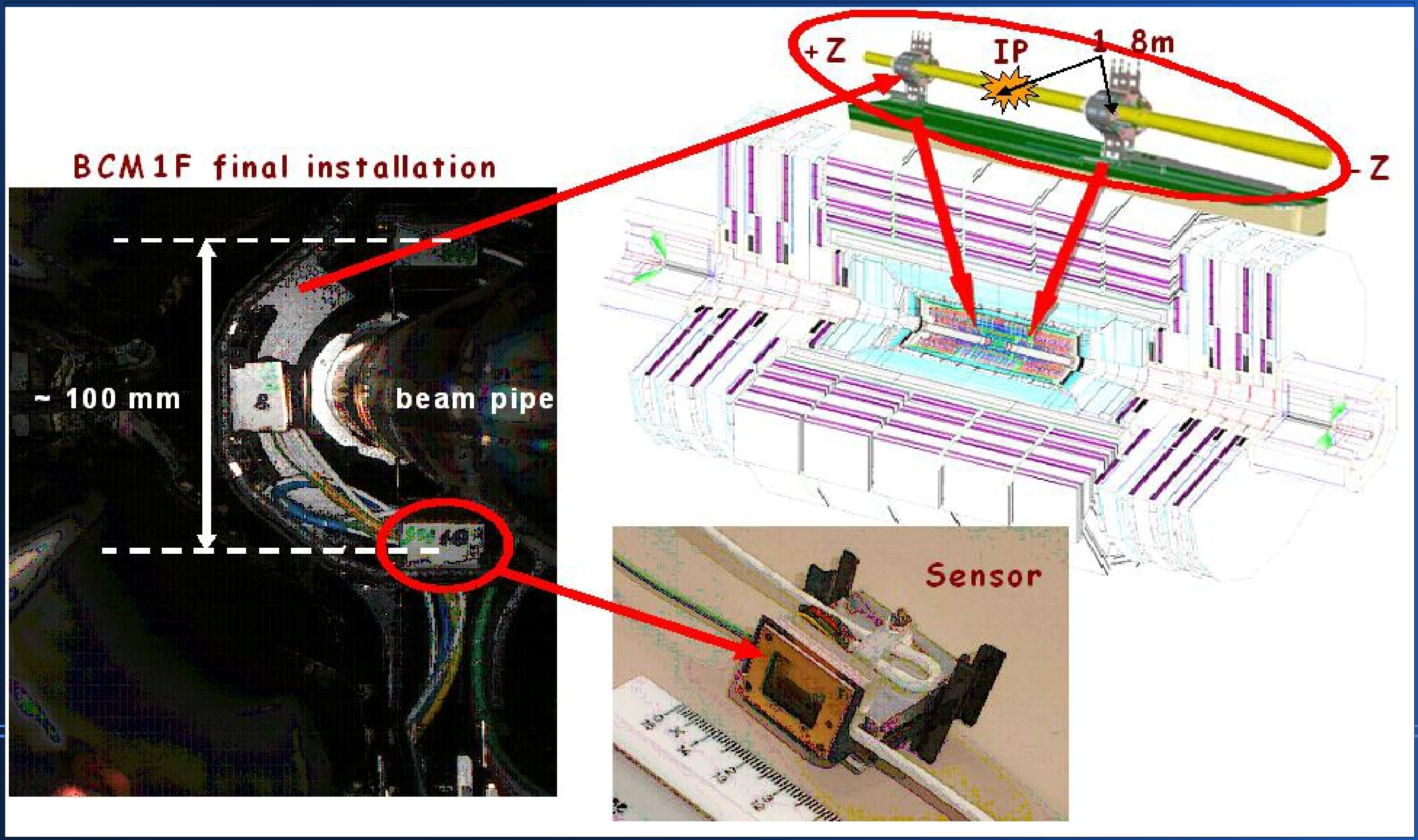
Compact Muon Solenoid CMS



Diamond Sensors in High Energy Physics

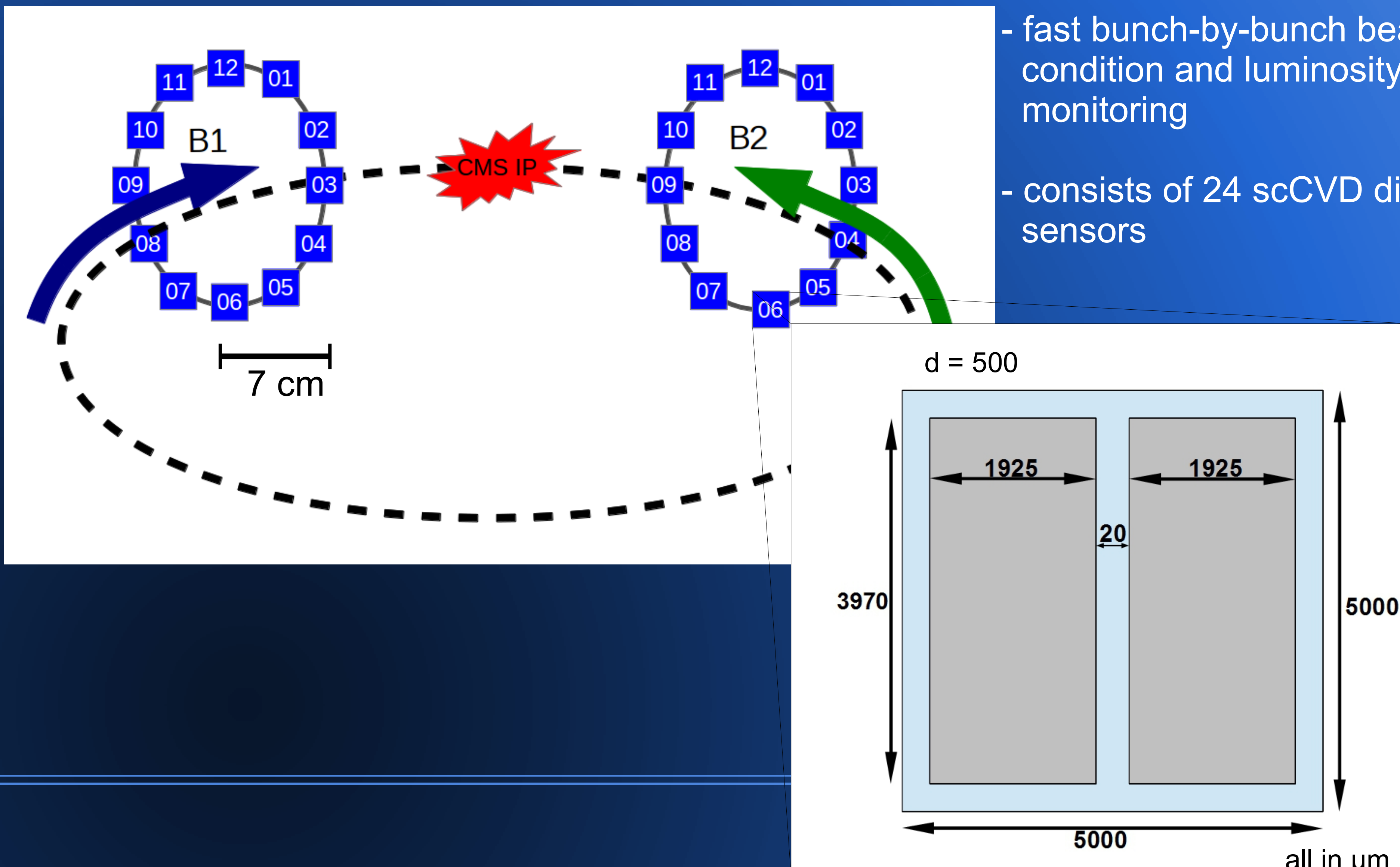
CMS installed several independent subdetectors for Beam and Radiation Instrumentation and Luminosity measurements (BRIL):

- safety: less beam losses → less damage to the experiments sub detectors
- performance: more luminosity and less background → better data



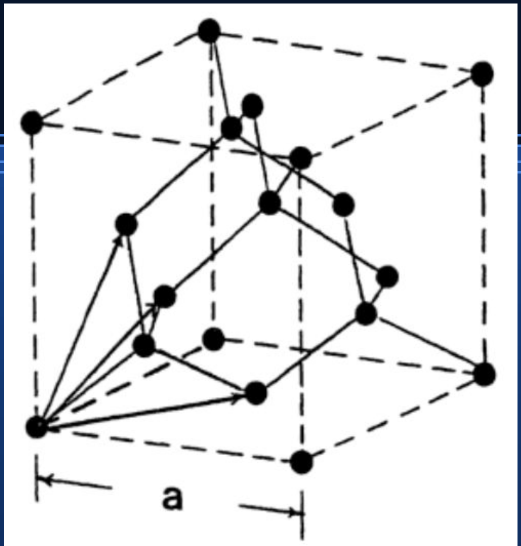
- **Fast Beam Condition Monitor BCM1F**

BCM1F



- fast bunch-by-bunch beam condition and luminosity monitoring
- consists of 24 scCVD diamond sensors

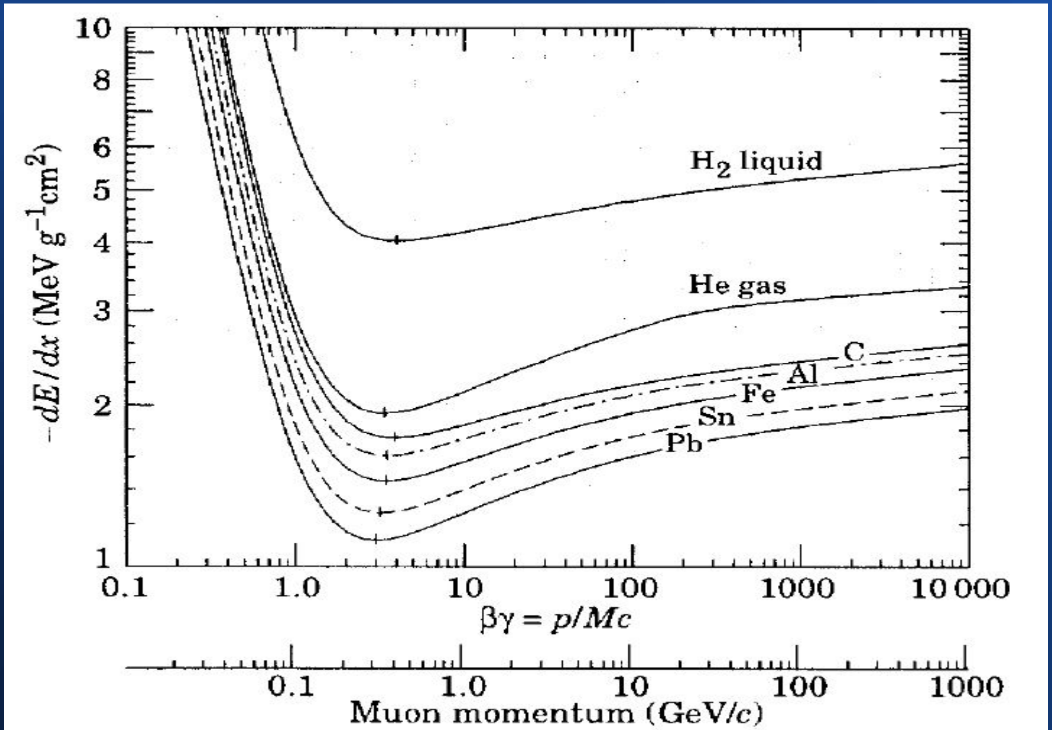
scCVD Diamond

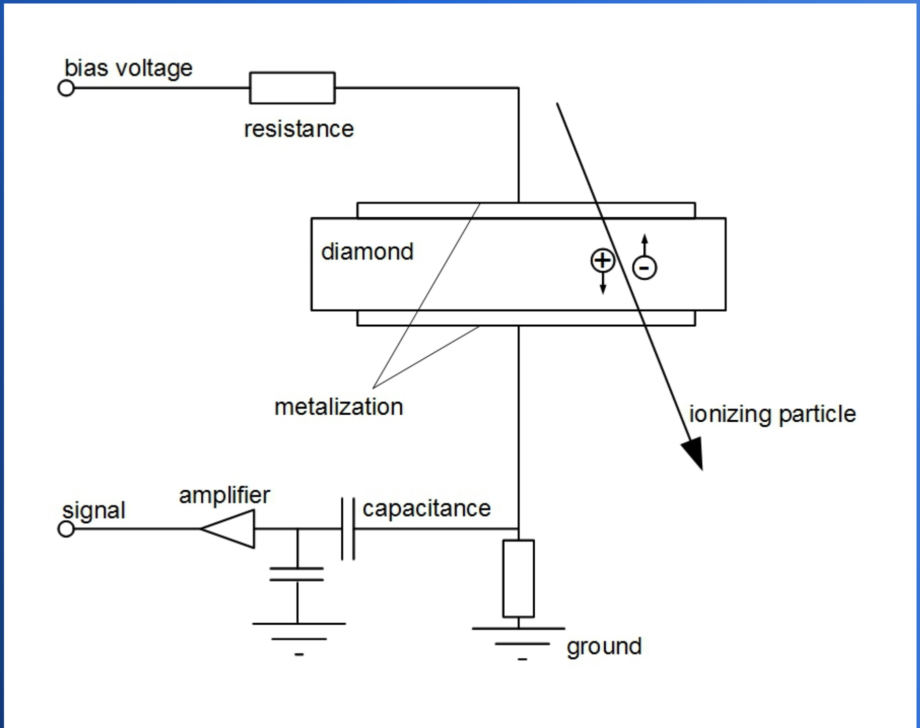


- low leakage current and radiation hard
  → used as solid state ionization chamber for particle detection in high radiation enviroment

Property	Diamond	Silicon	Units	Results for diamond
Band gap	5.5	1.12	eV	insulator
Specific resistance	$> 10^{11}$	$6.4 \cdot 10^2$	Ωcm	low leakage current
Breakdown field	20	0.3	MV/cm	high bias voltage possible
Electron mobility	4500	1450	cm^2/Vs	fast signal
Hole mobility	3800	480	cm^2/Vs	
Displacement energy	43	< 20	eV per atom	radiation hard
Thermal conductivity	2000	150	$Wm^{-1}K^{-1}$	heat spreader
Energy to create e-h pair	13	3.61	eV	low signal
Aver. signal created	3602	8892	e_0 per 100 µm	

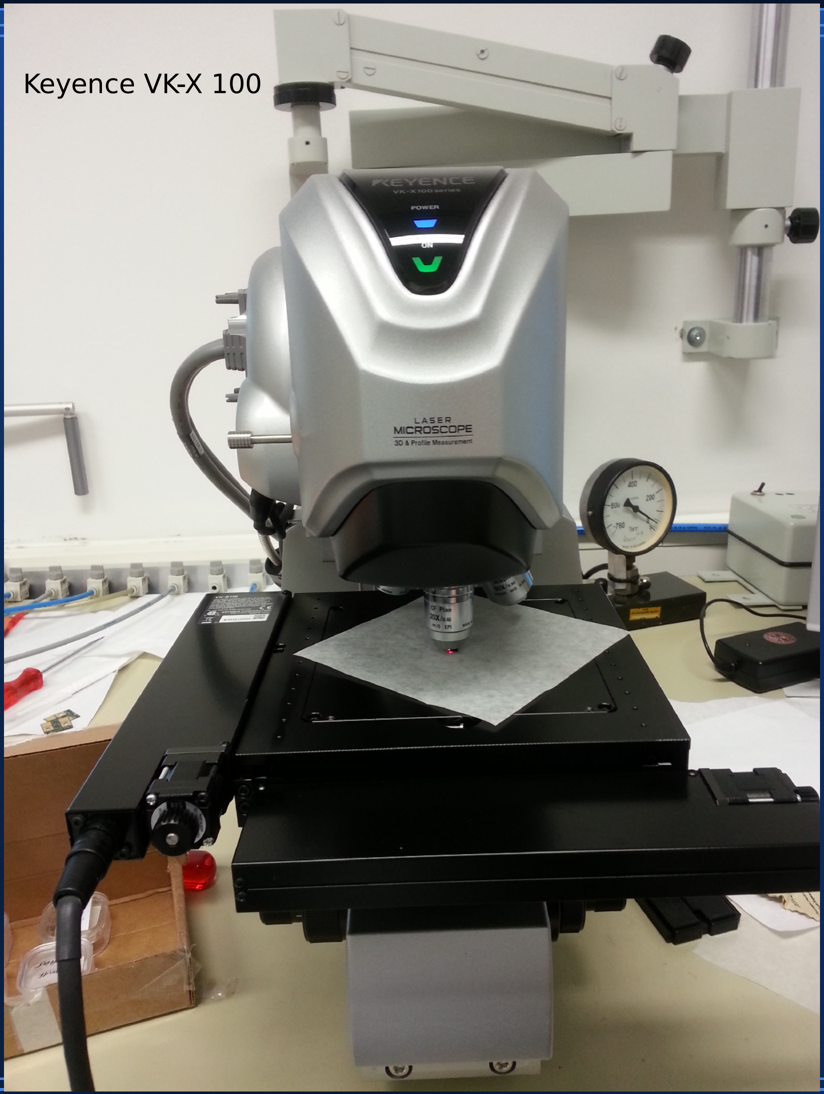
working principle of a diamond detector

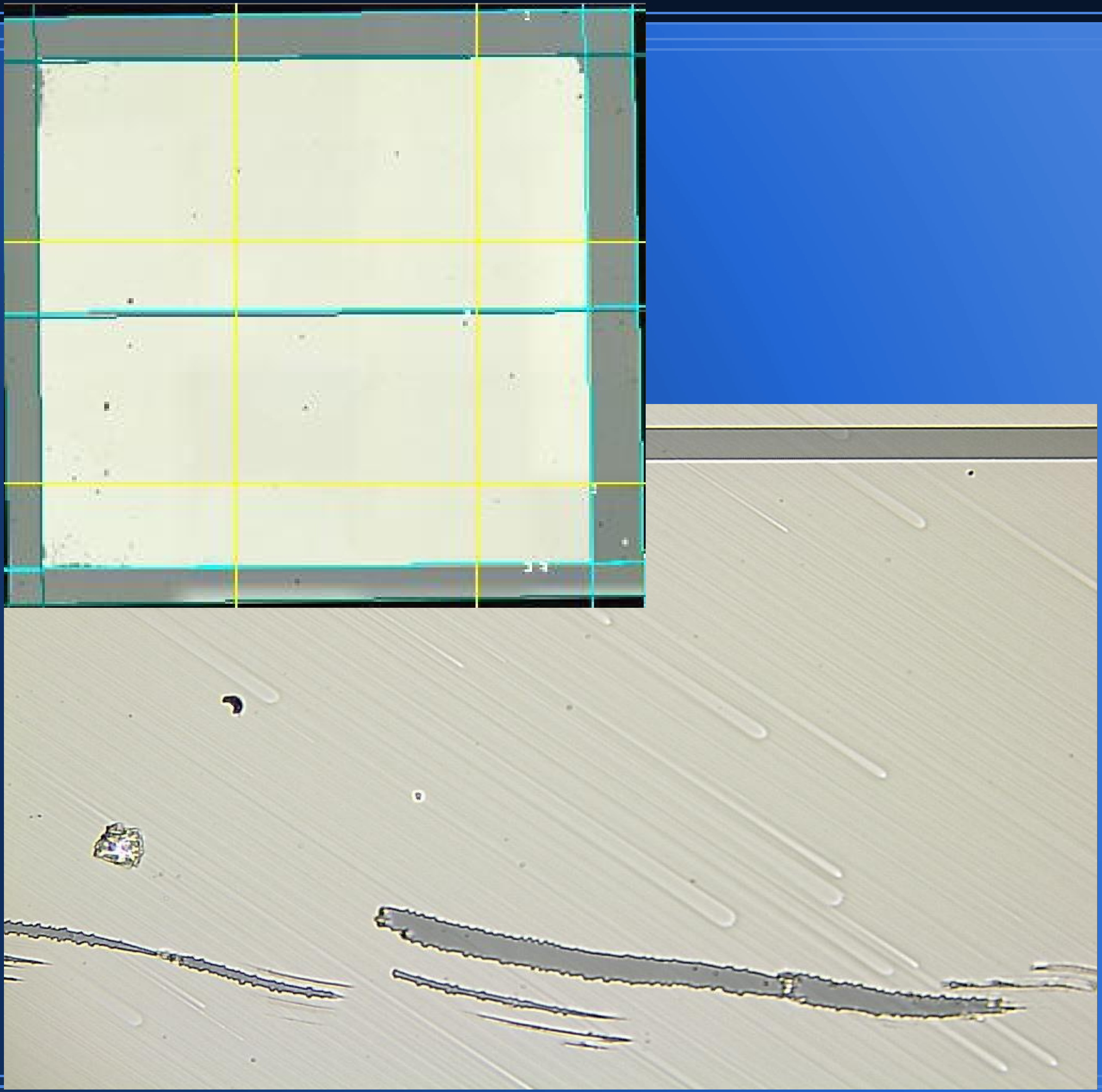




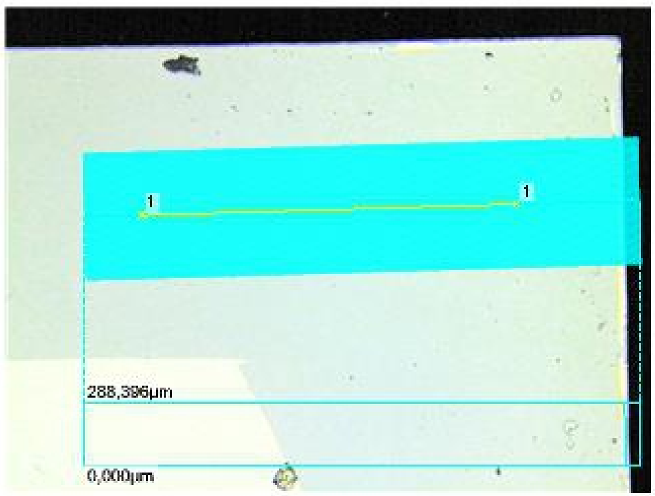
$$-\left(\frac{dE}{dX}\right) = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta\left(\beta\gamma\right)}{2}\right]$$

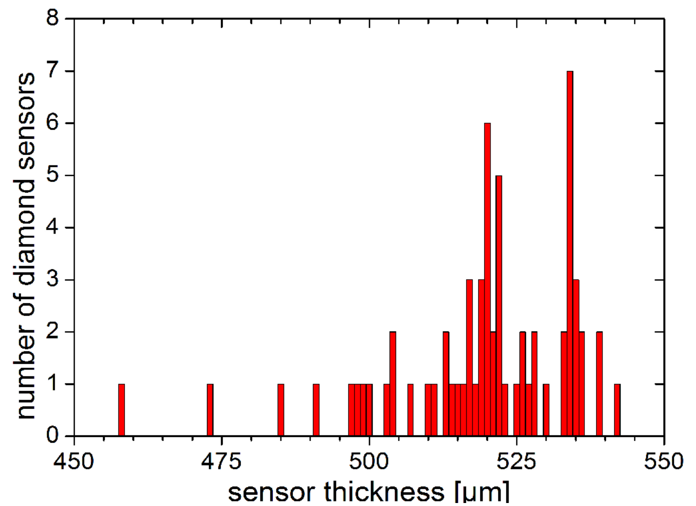
optical characterisation

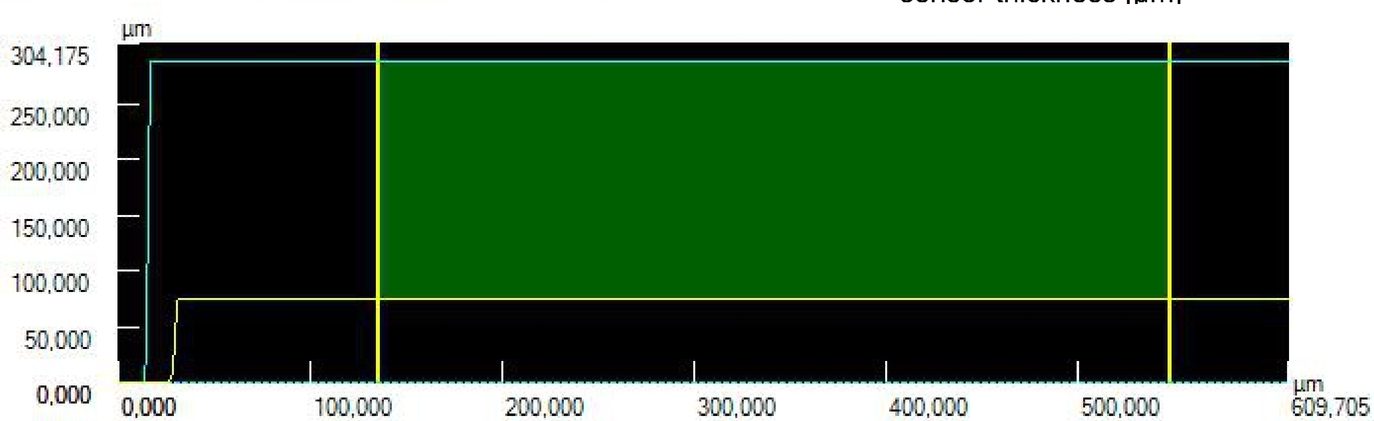




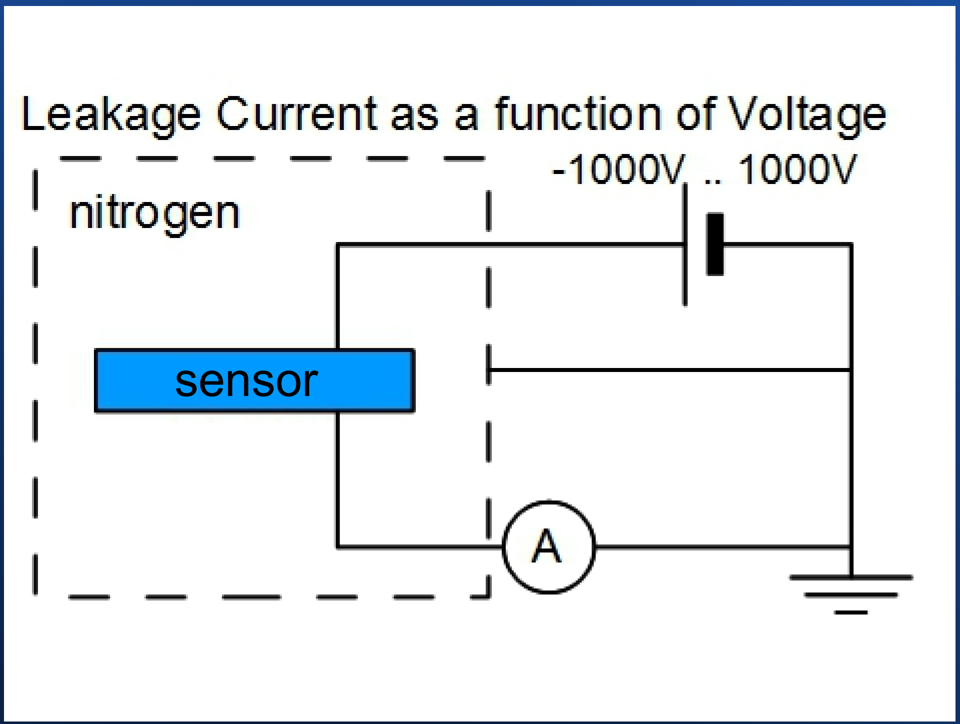
optical characterisation

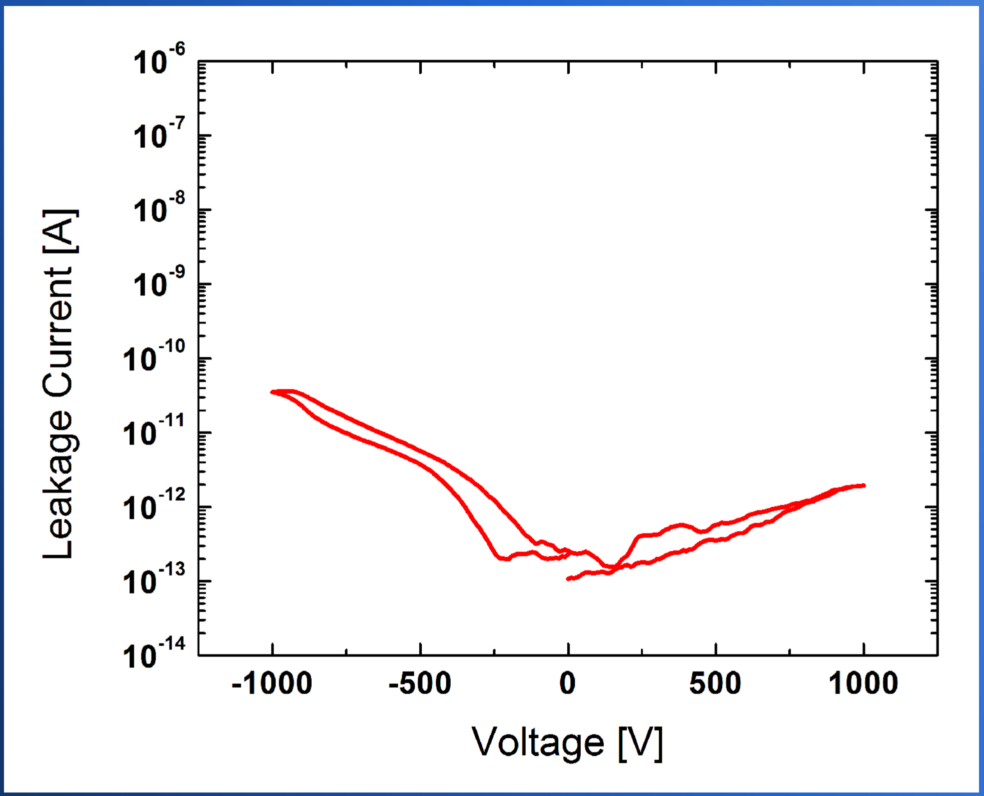






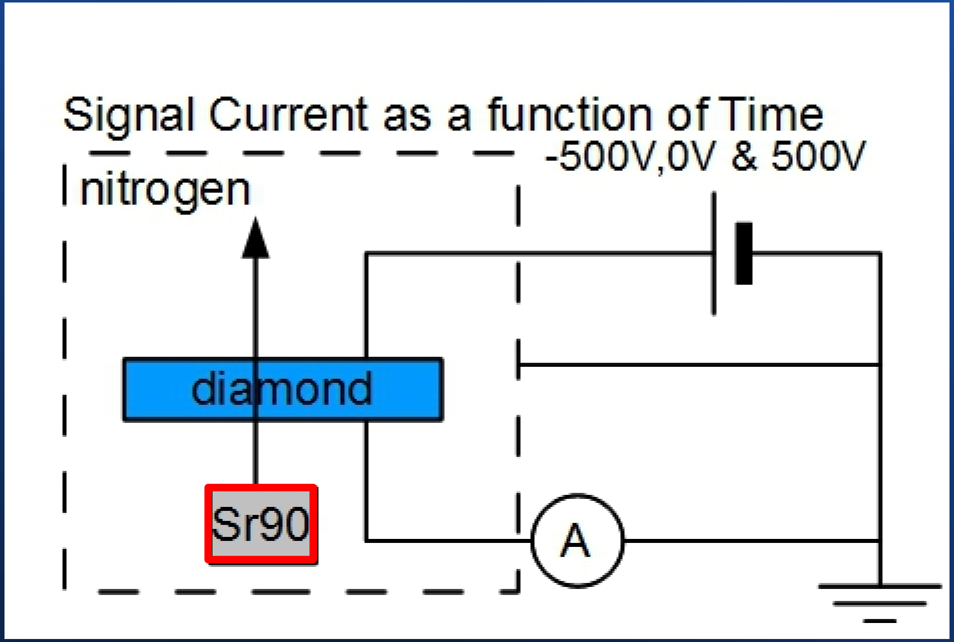
electrical measurements

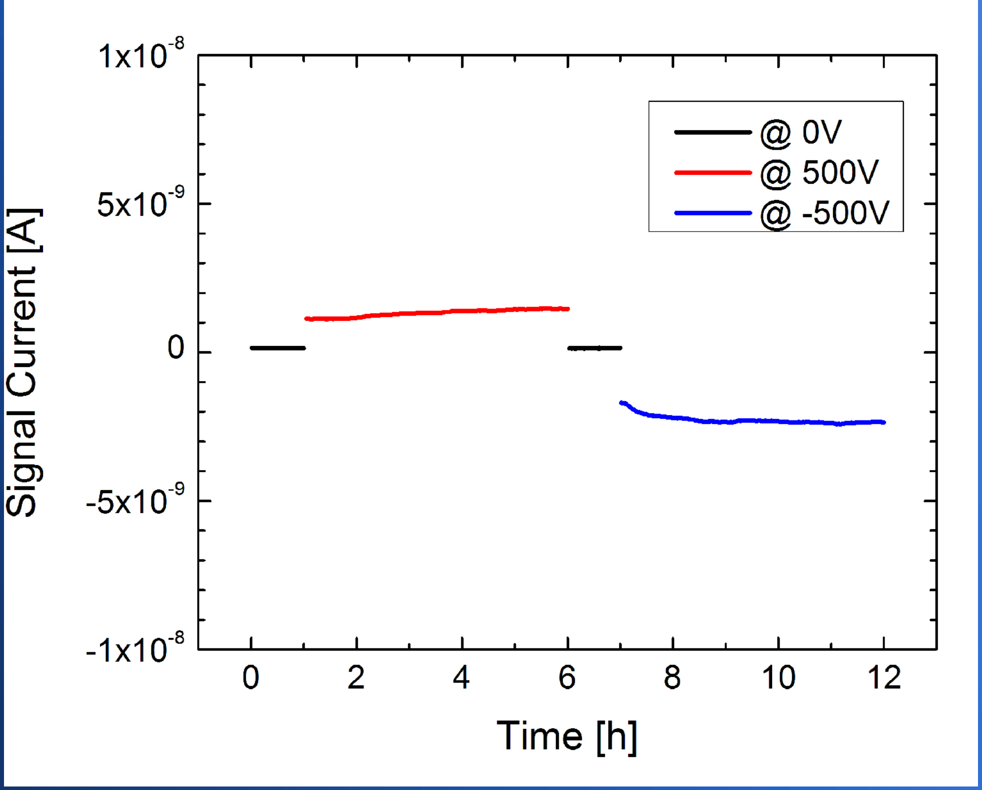




Done to observe the leakage current of the diamond sensor.
- lower leakage current
  better signal to noise ratio

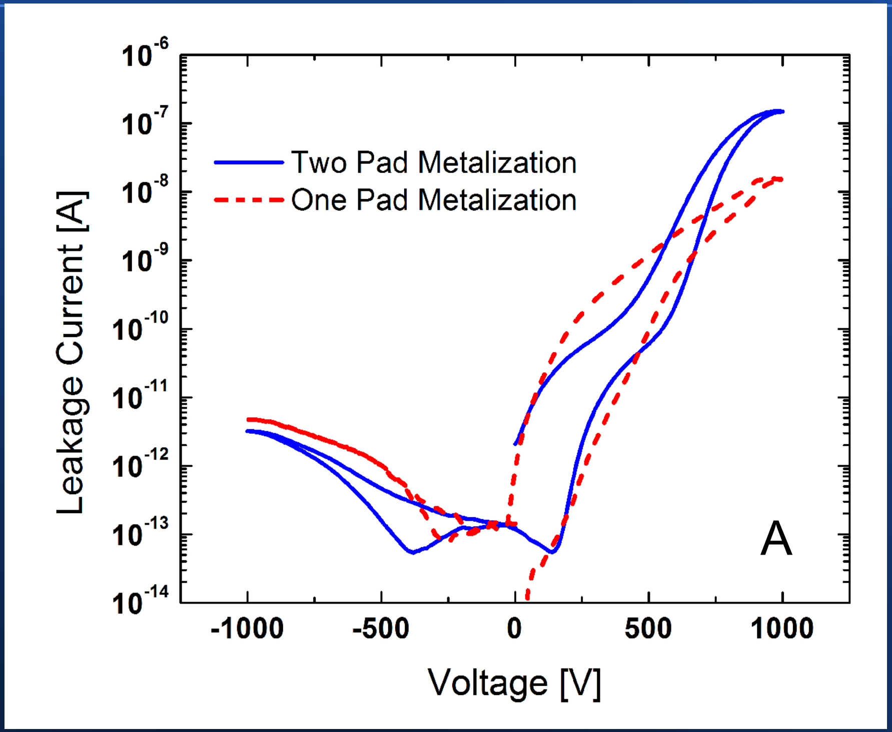
electrical measurements

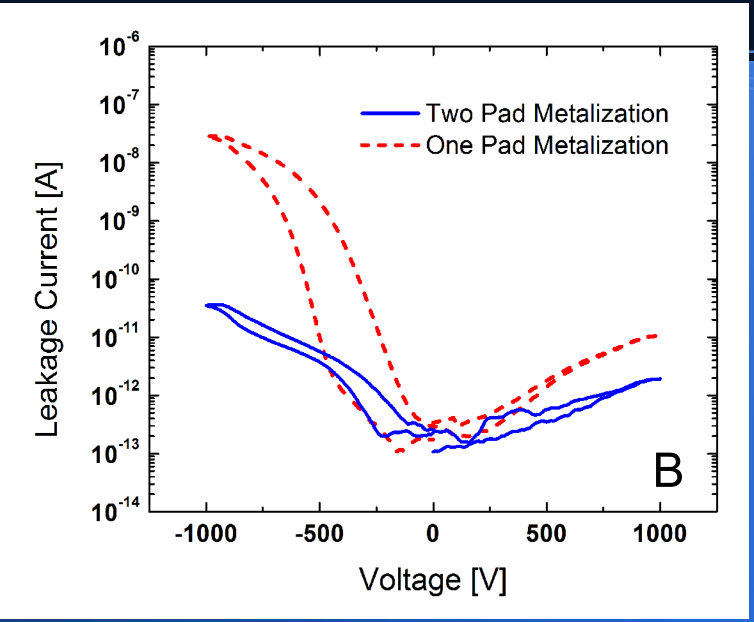


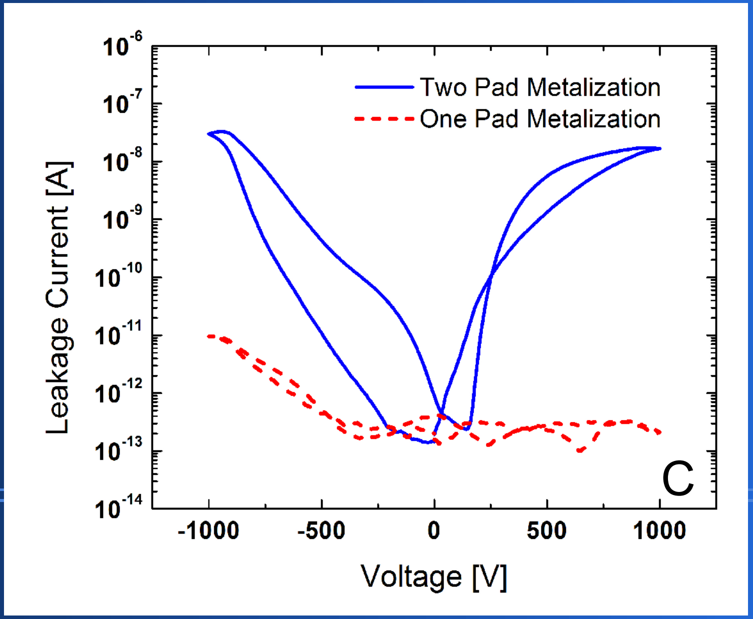


Oberserve the stability of the signal current of a diamond sensor under continously particle flux.

metallizations

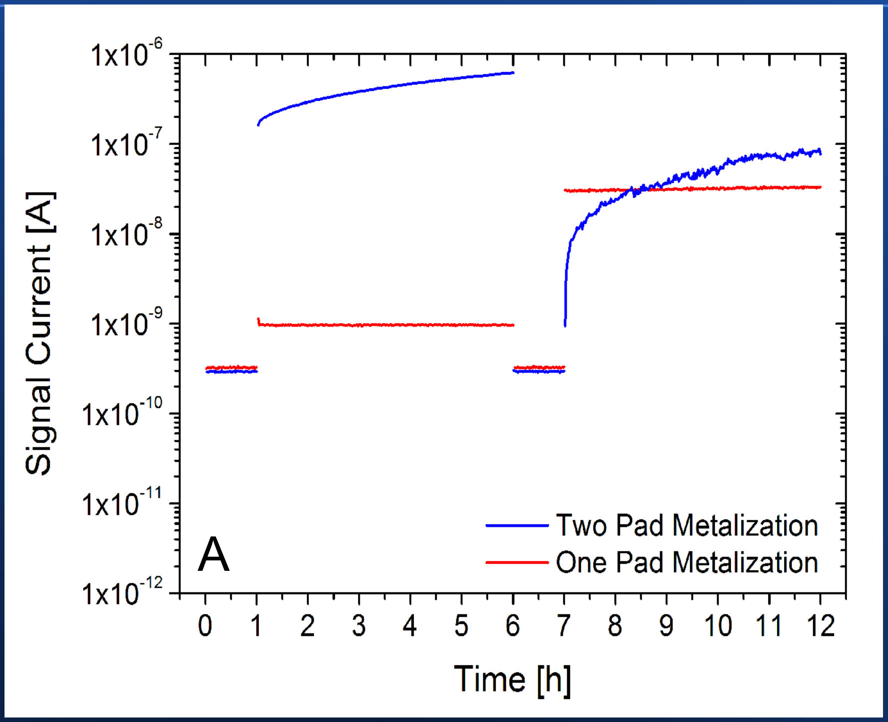


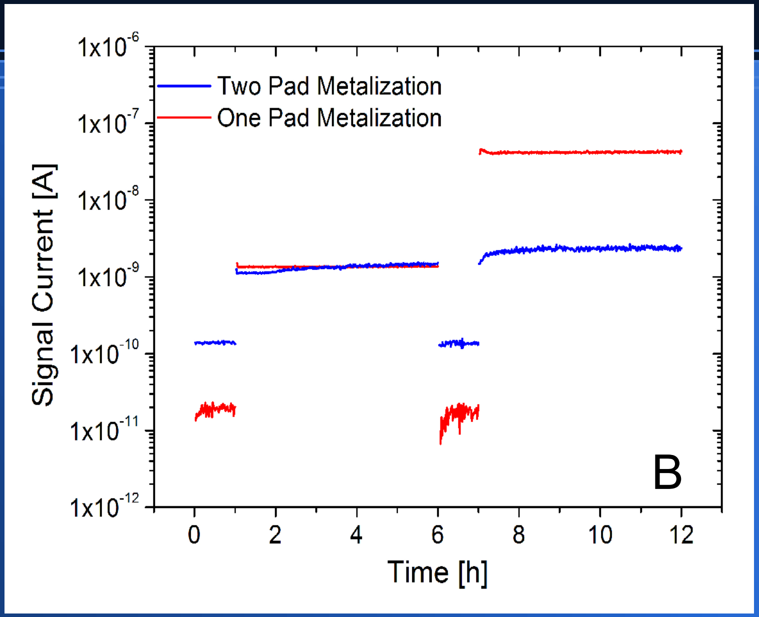


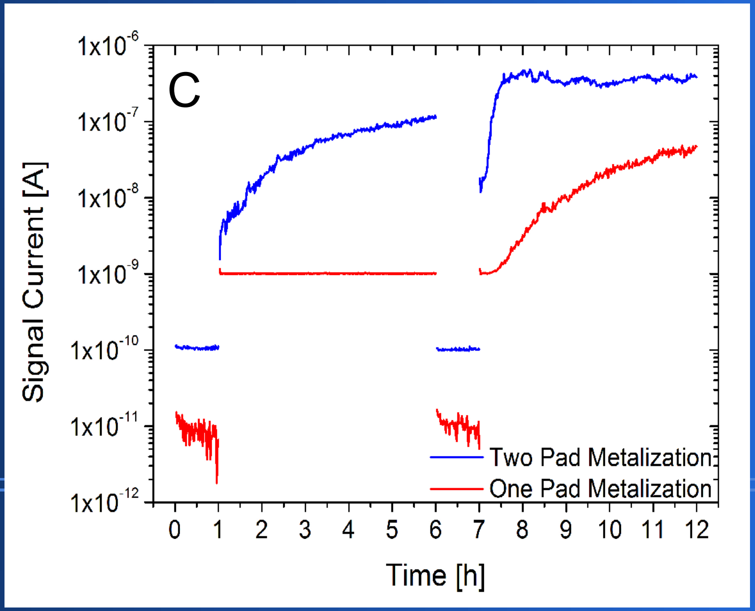


- first measured with one pad metallization then remeasured after remetallization with two pads

metallizations

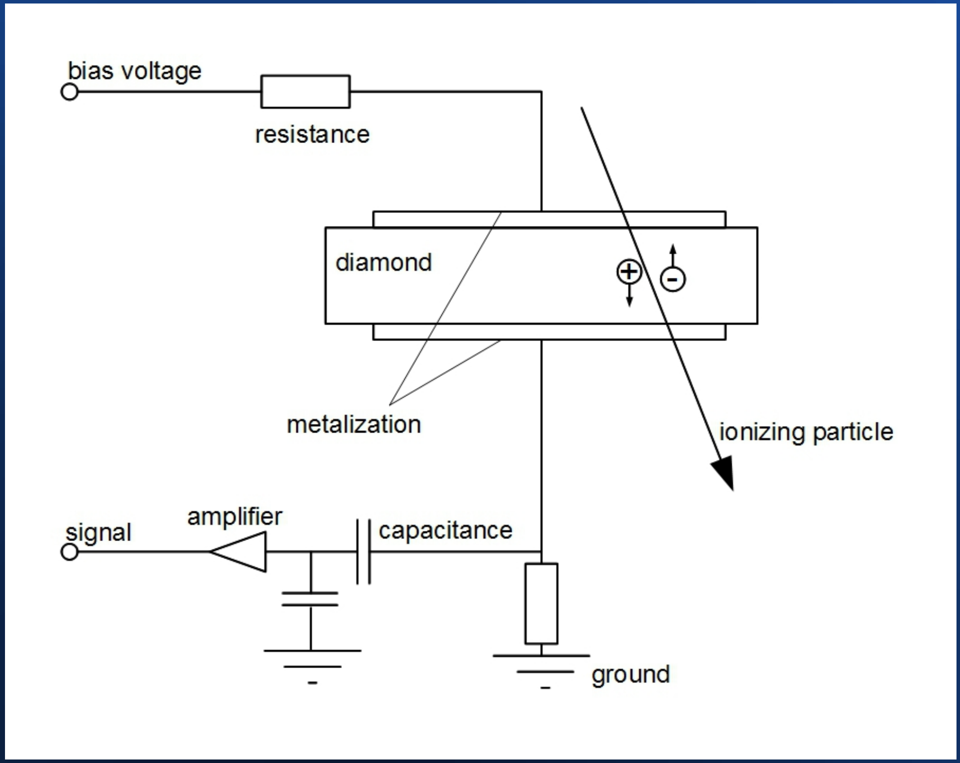






- first measured with one pad metallization then remeasured after remetallization with two pads

Charge Collelction Efficiency CCE



- working principle like a solid state ionisation chamber
- triggered on minimum ionizing particles from ^{90}Sr

→ quantity of generated e-h pairs is known

$$CCE = Q_m / Q_c$$

Q_m the measured charges and
Q_c the created charges

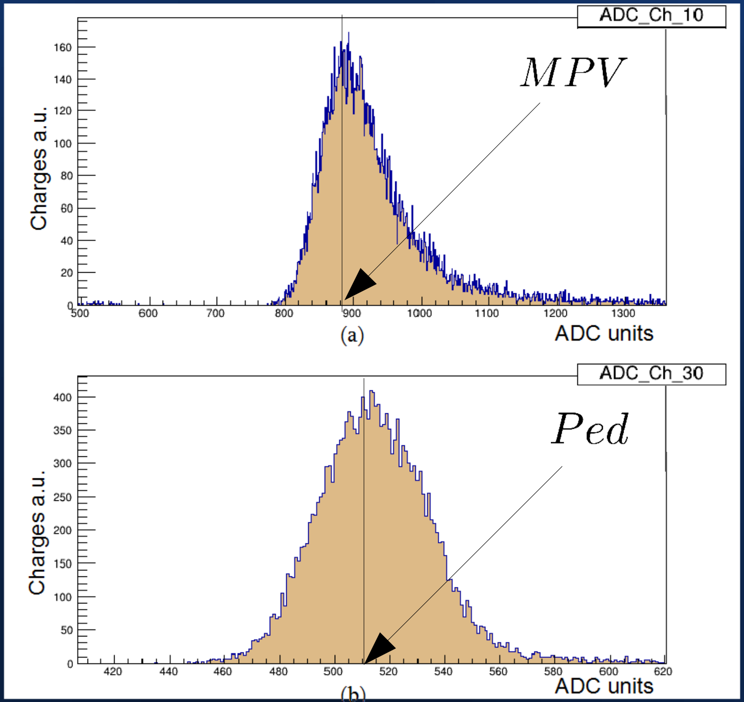
$$Q_c = \rho_{MIP} \cdot d \cdot sr_{corr}$$

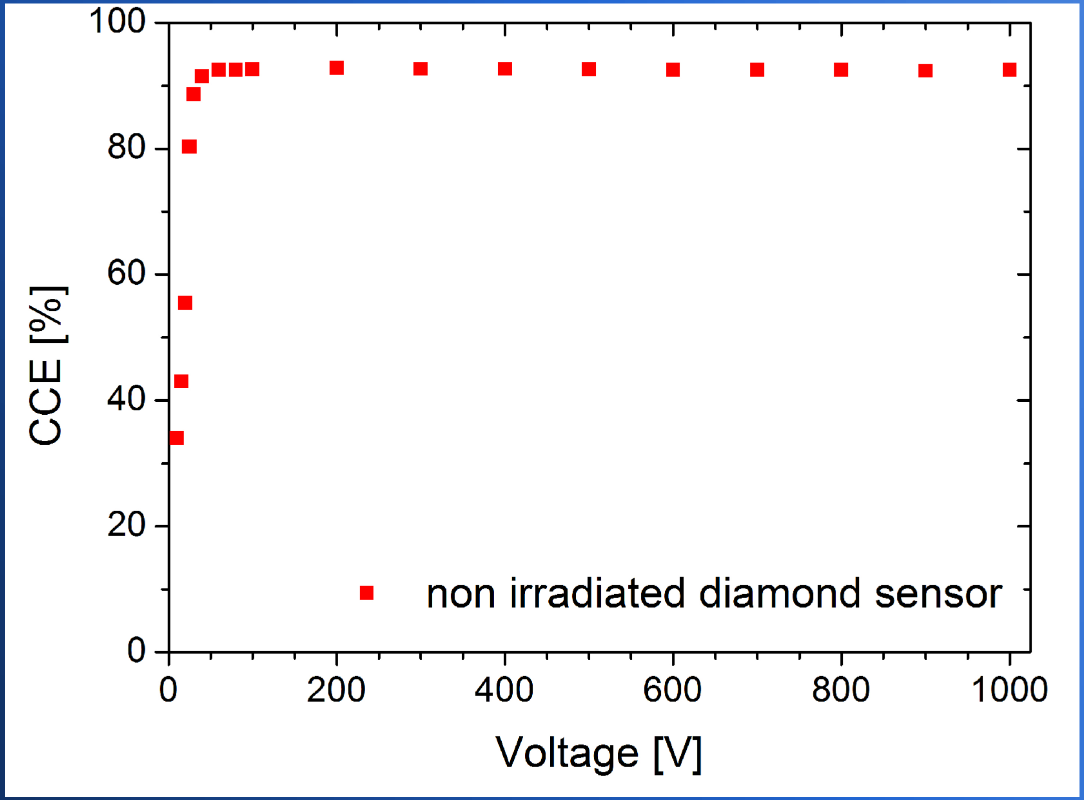
d the sensor thickness,
ρ_{MIP} the number of generated e-h pairs per length unit and
sr_{corr} a correction factor for ^{90}Sr

Charge Collelction Efficiency CCE

$$Q_m = (MPV - Ped) \cdot Calib$$

- mean value of pedastal Ped is the leakage current of measurement setup
- most propable value of landau distributed signal MPV





$$CCE = \frac{(MPV - Ped) \cdot Calib}{\rho_{MIP} \cdot d \cdot sr_{corr}}$$

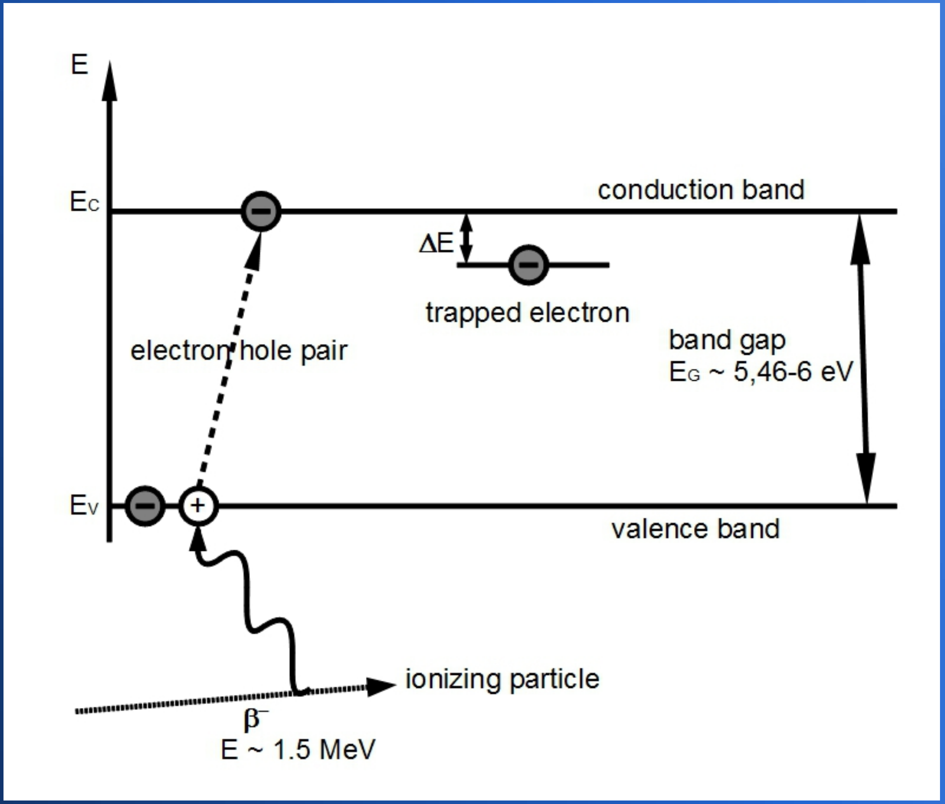
radiation damage

- radiation damage consists of lattice defects like vacancies and dislocations
  - creates intermediate band gap states

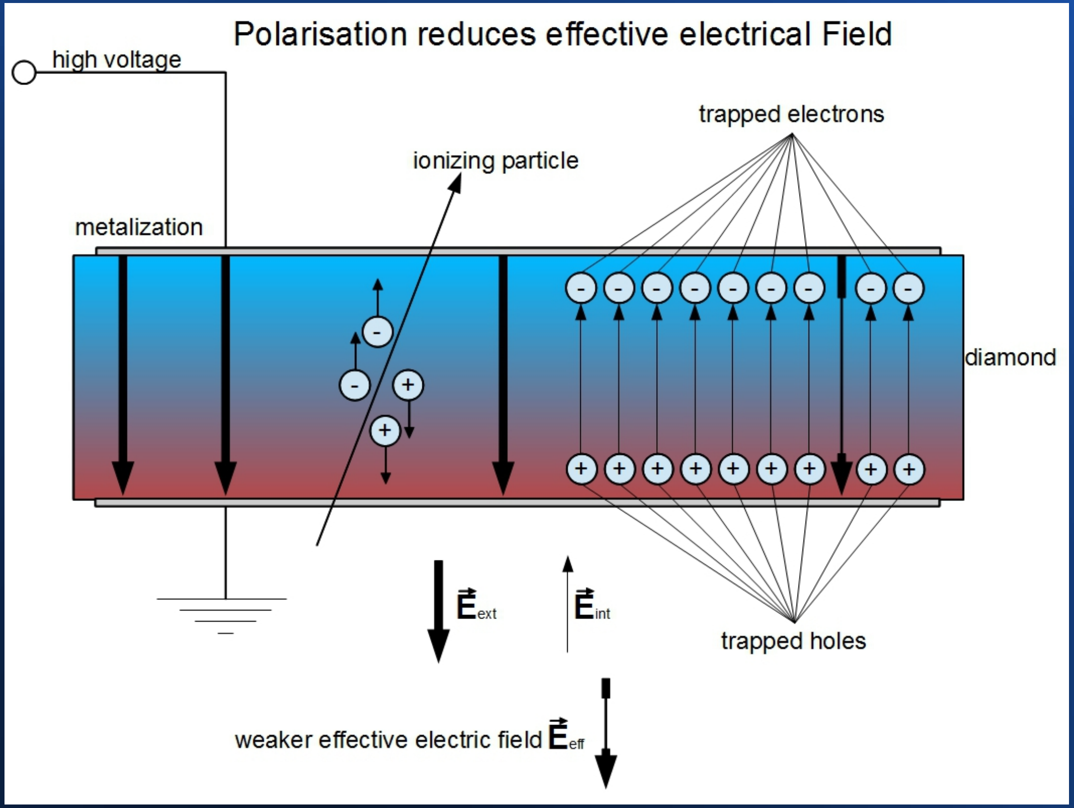
Trapping

- free charges can be trapped by intermediate band gap states
- trapped charges are released by intrinsic effects or by recombination

→ equilibrium between filled and free traps



radiation damage



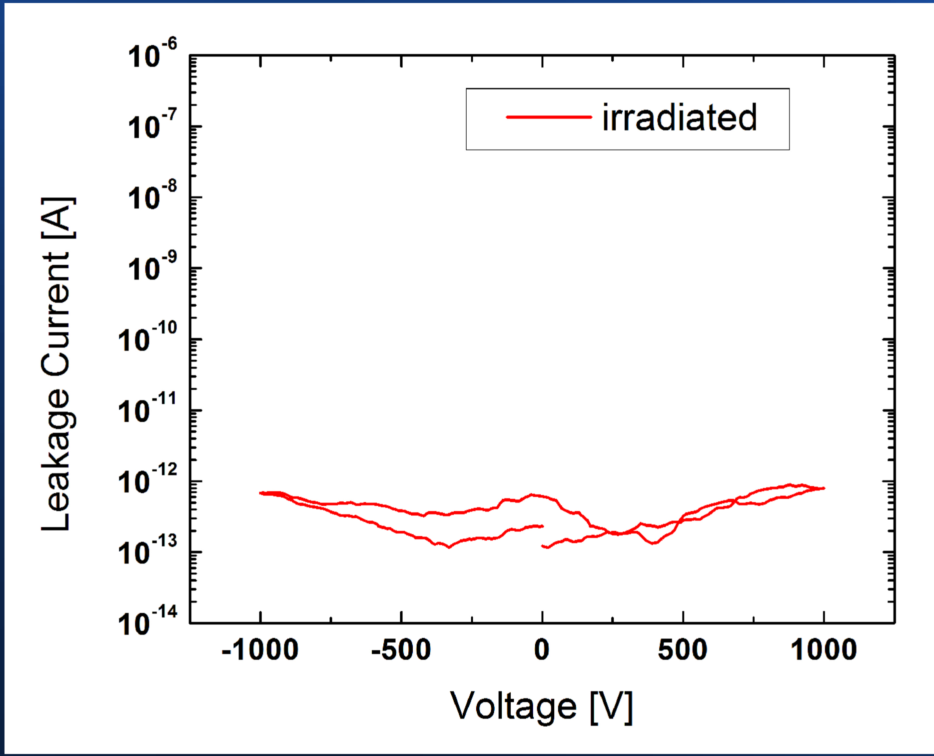
Polarization

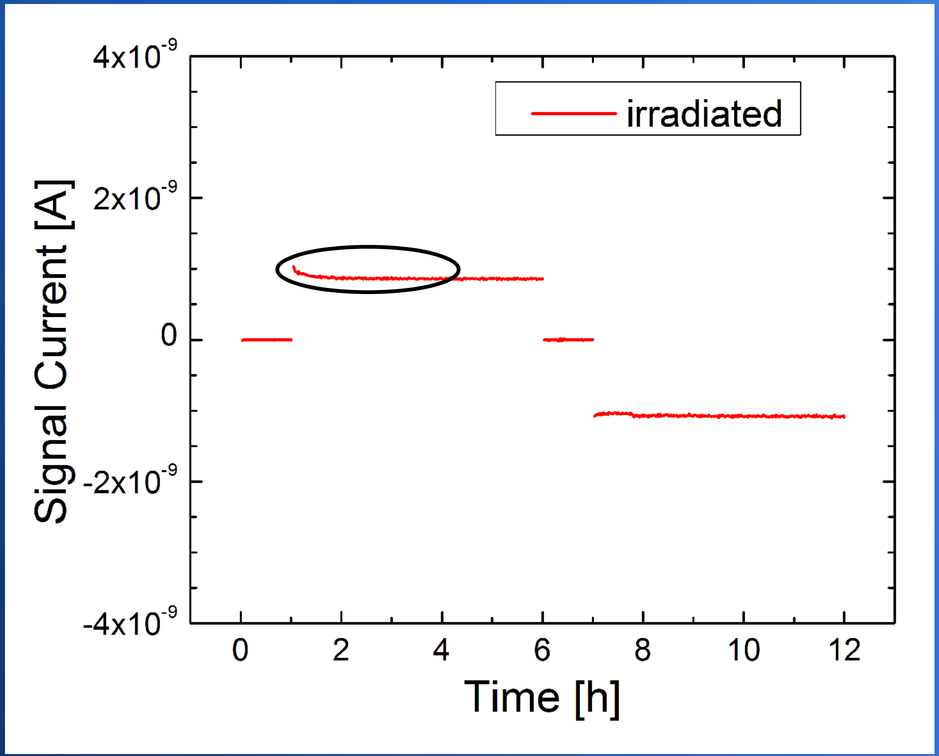
- generated electron-hole pairs are seperated by an external electrical field
- unevenly distributed free charges were trapped

→ unevenly distributed fixed charges[1]
→ internal electrical field

[1] (Sergej Schuwalow 15.12.2009, GSI talk, “Large bandgap solid-state sensors – some new developments“)

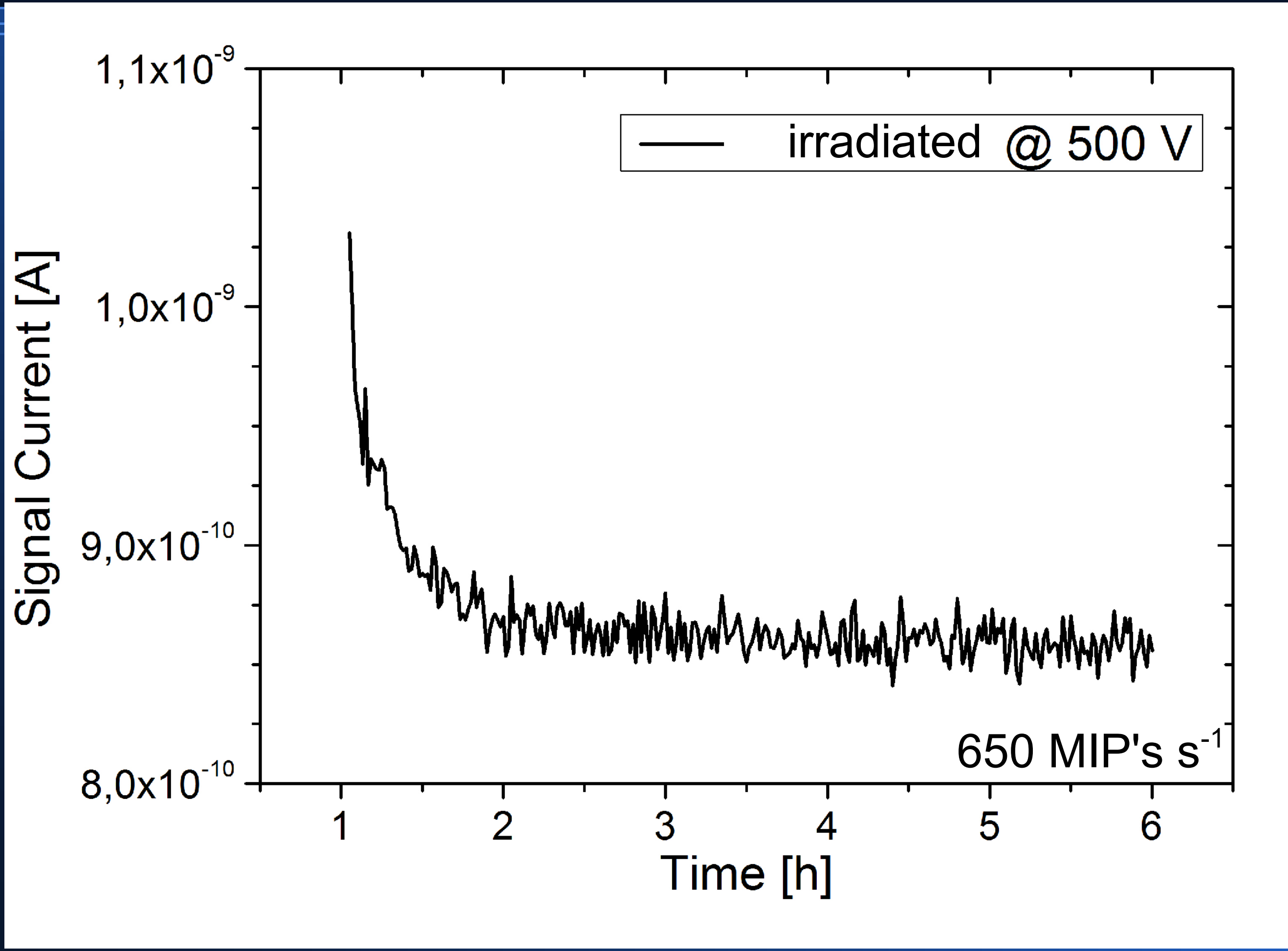
electrical measurements after irradiation





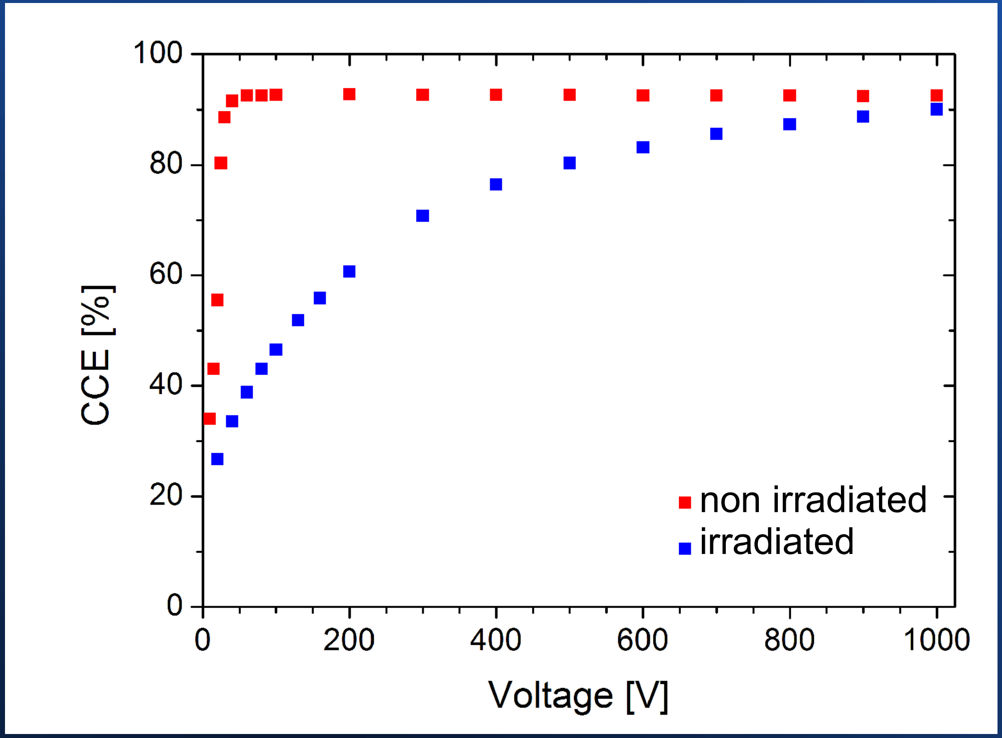
Irradiated diamond sensors from BCM1F installed from 2008 to 2014 show still <u>low leakage currents</u> and <u>stable signal currents</u>.

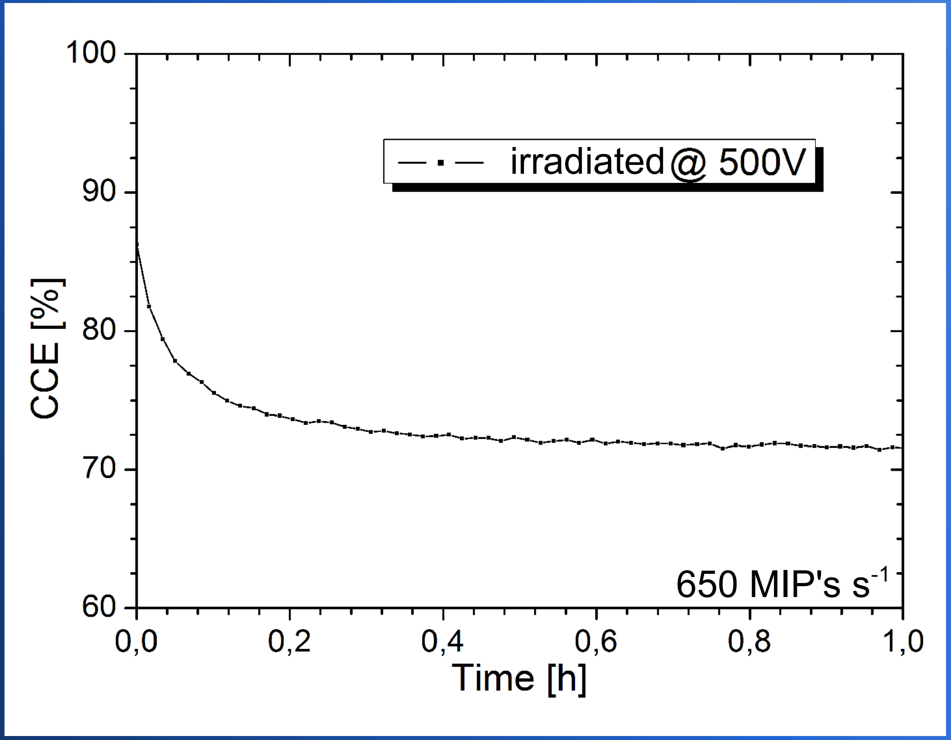
signal current after irradiation



After ramping from 0V to 500V polarization builds up about over several hours.

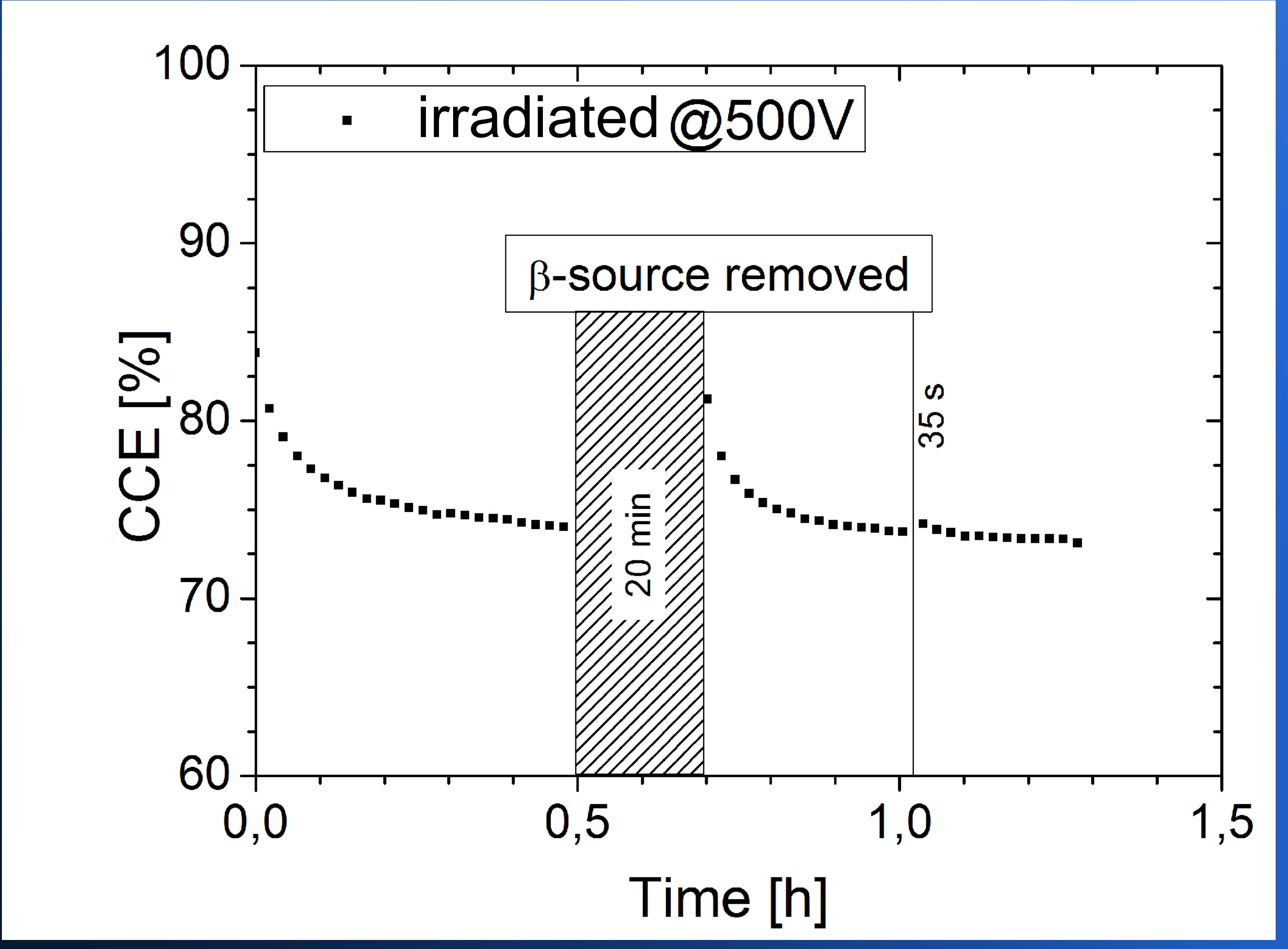
CCE after irradiation





CCE is decreased by trapping and polarization after irradiation.

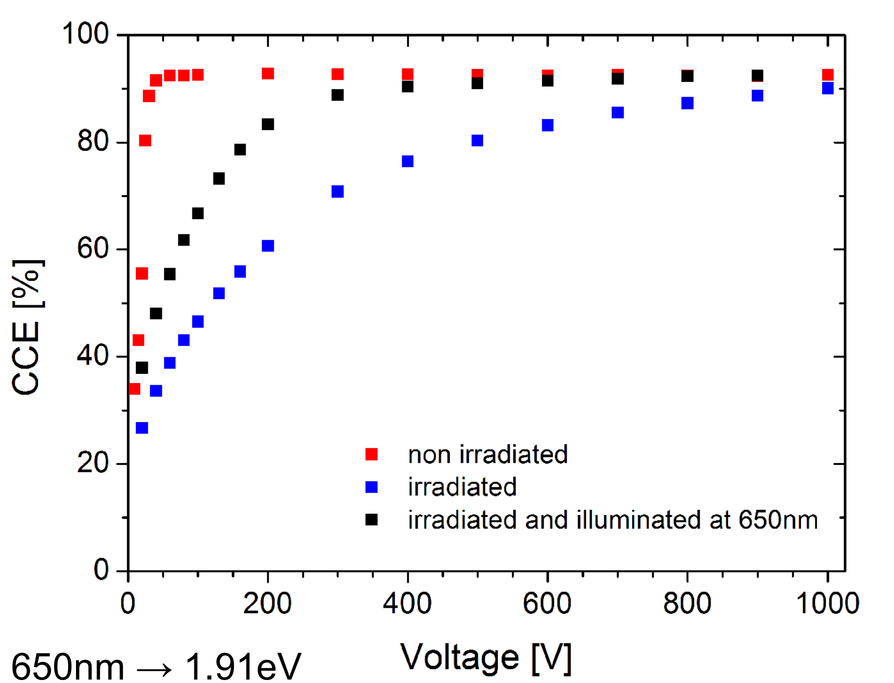
CCE after irradiation



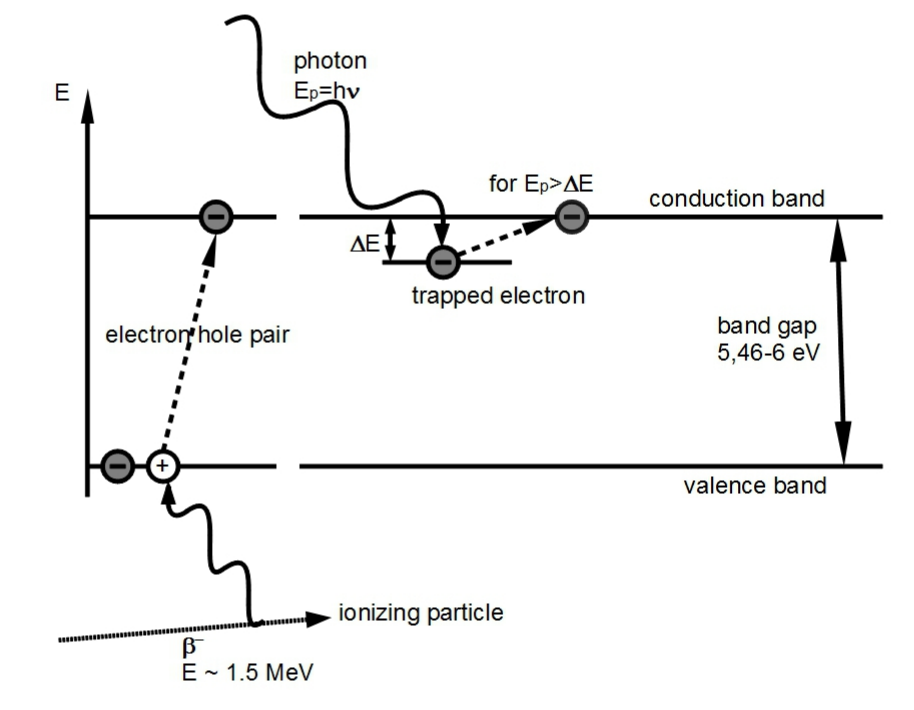
further investigation on radiation damage

- assumption intermediate band gaps states near the conduction band
- a photon lifts a trapped charge to conduction band if:

$$E_p > \Delta E$$
$$E_p = h \cdot \frac{c}{\lambda}$$
$$\Delta E = E_c - E_t$$

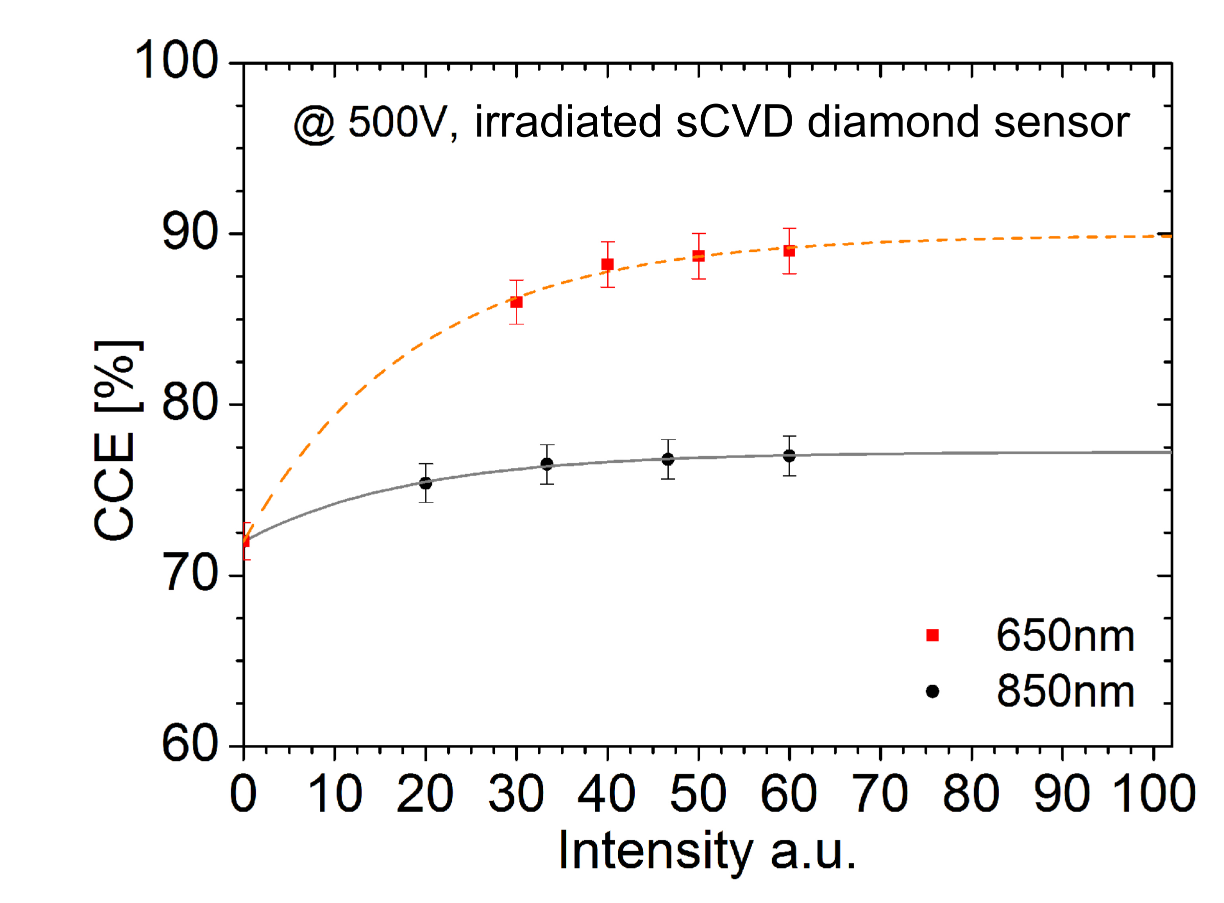


650nm → 1.91eV



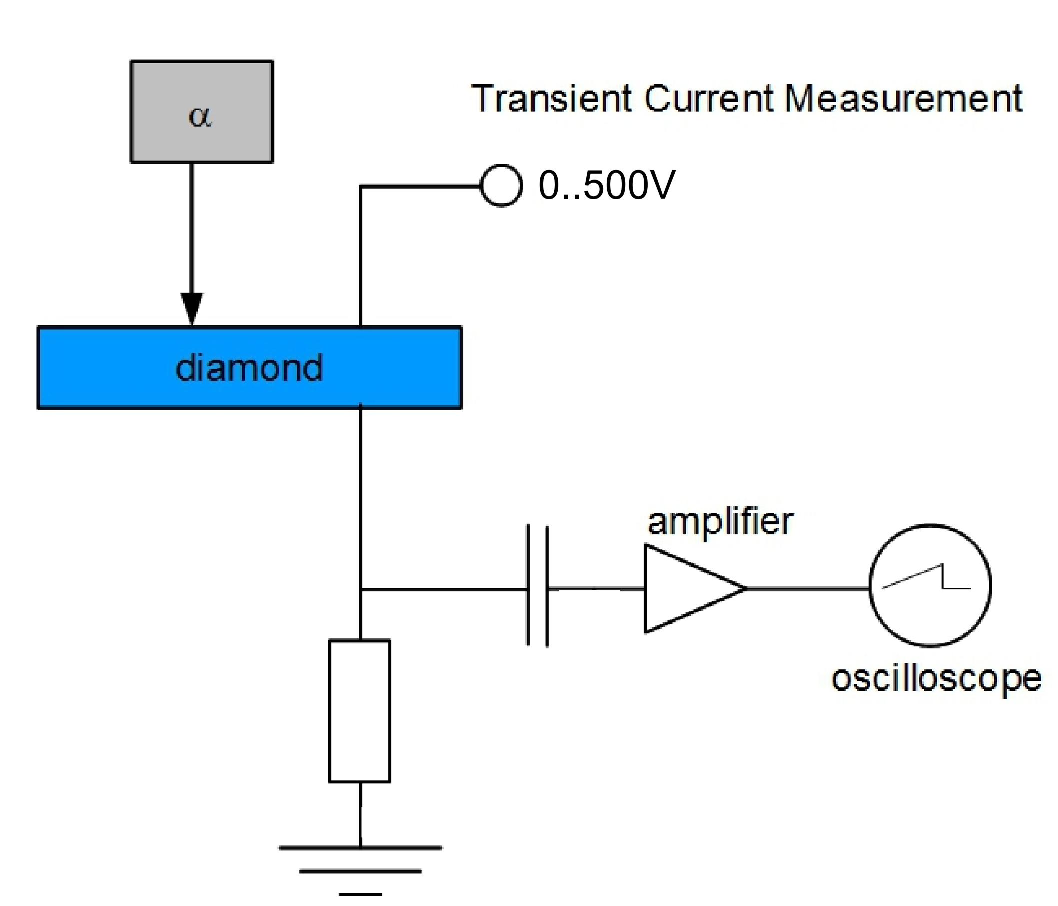
- equilibrium between filled and free traps shifted to more free trapps
→ polarization decreased

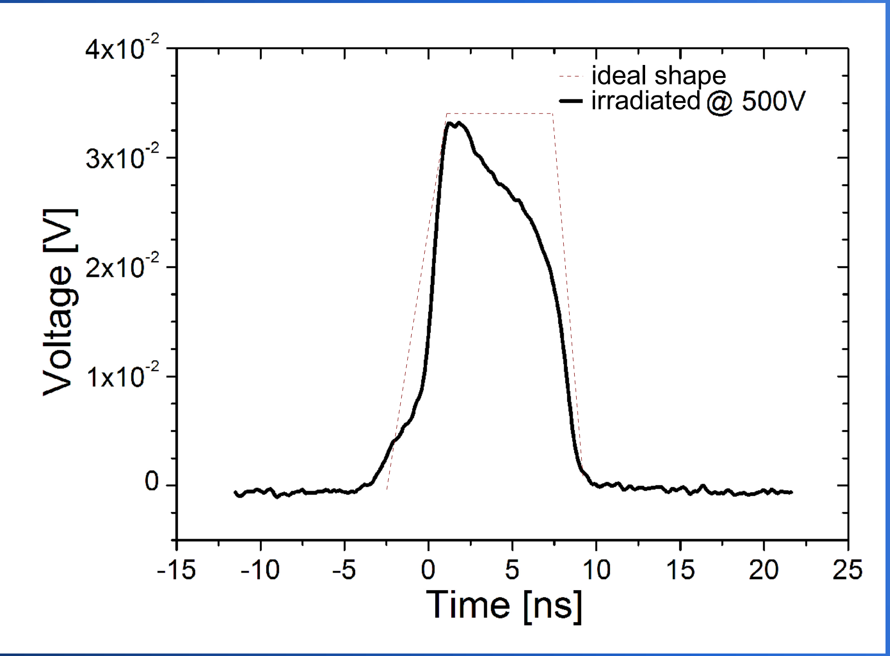
CCE dependence on intensity and energy of Light



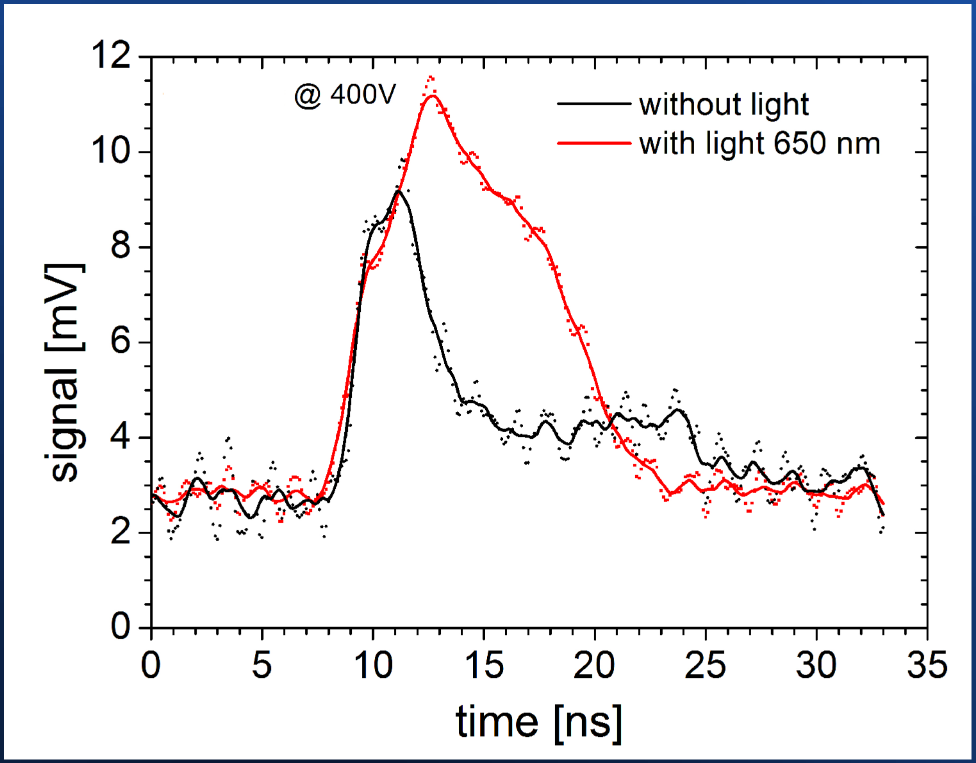
zero intensity – no light
higher intensities – more trapped charges released, less polarization effects
lower wavelength – higher photon energy, more trapped charges released

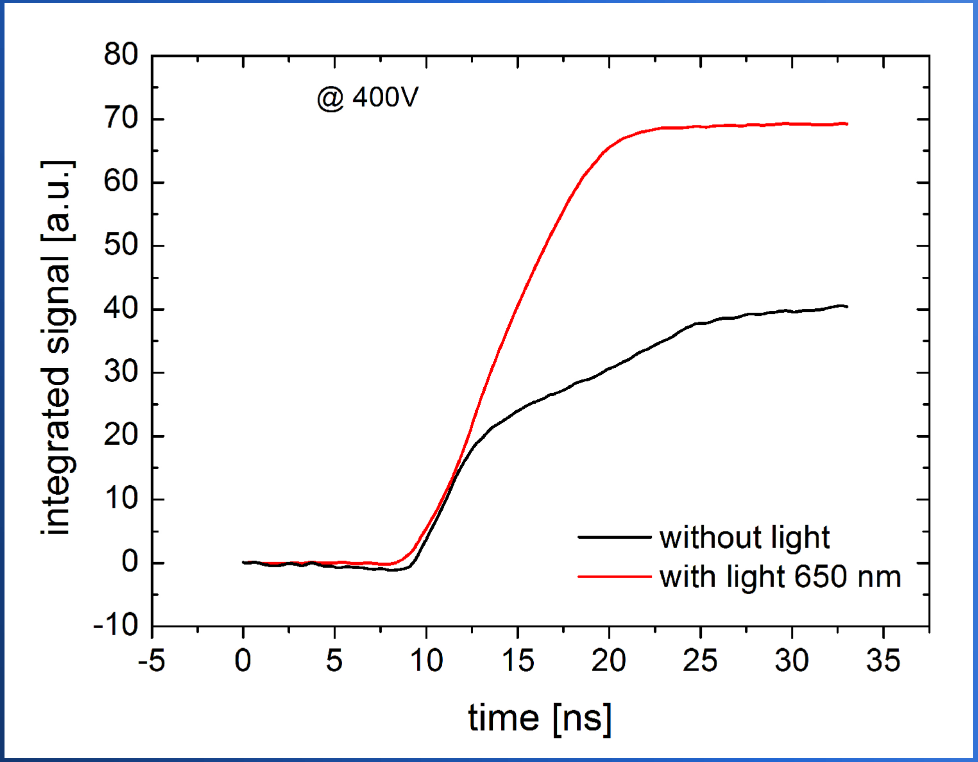
Transient Current Measurement





Transient Current Measurement





Conclusion

- 64 non-irradiated diamond sensors where characterized optically and electrically for the upgrade of BCM1F
  - 36 sensors fulfil the criteria to be used at BCM1F
- studies on different metallizations were done
  - process of metallization can cause problems

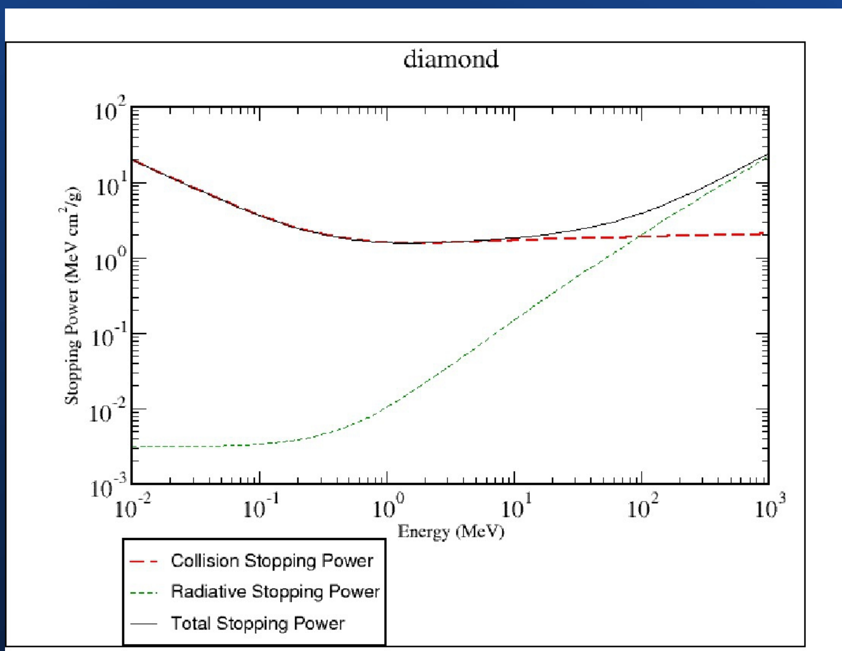
- comparrison of irradiated and non-irradiated diamond sensors
  - signal current and CCE is reduced after irradiation

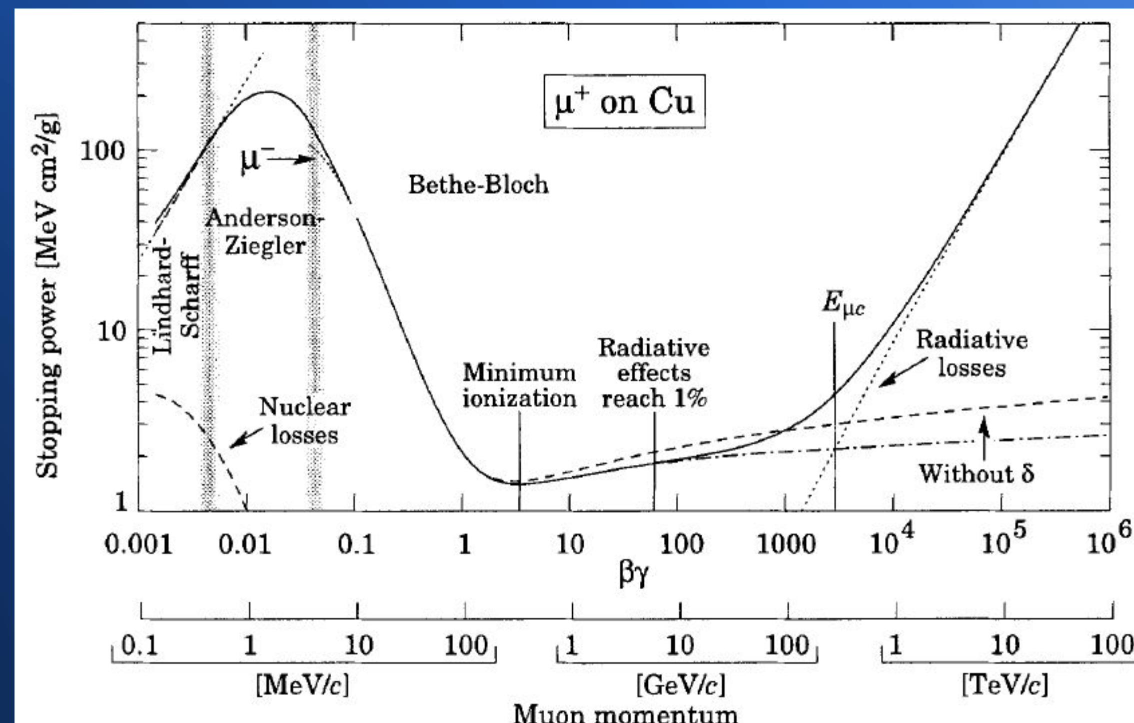
- method using light to mitigate irradiation based effects
  - CCE increase depends on wavelength and intensity of light
  - TCT signal become larger under illumination

Conclusion

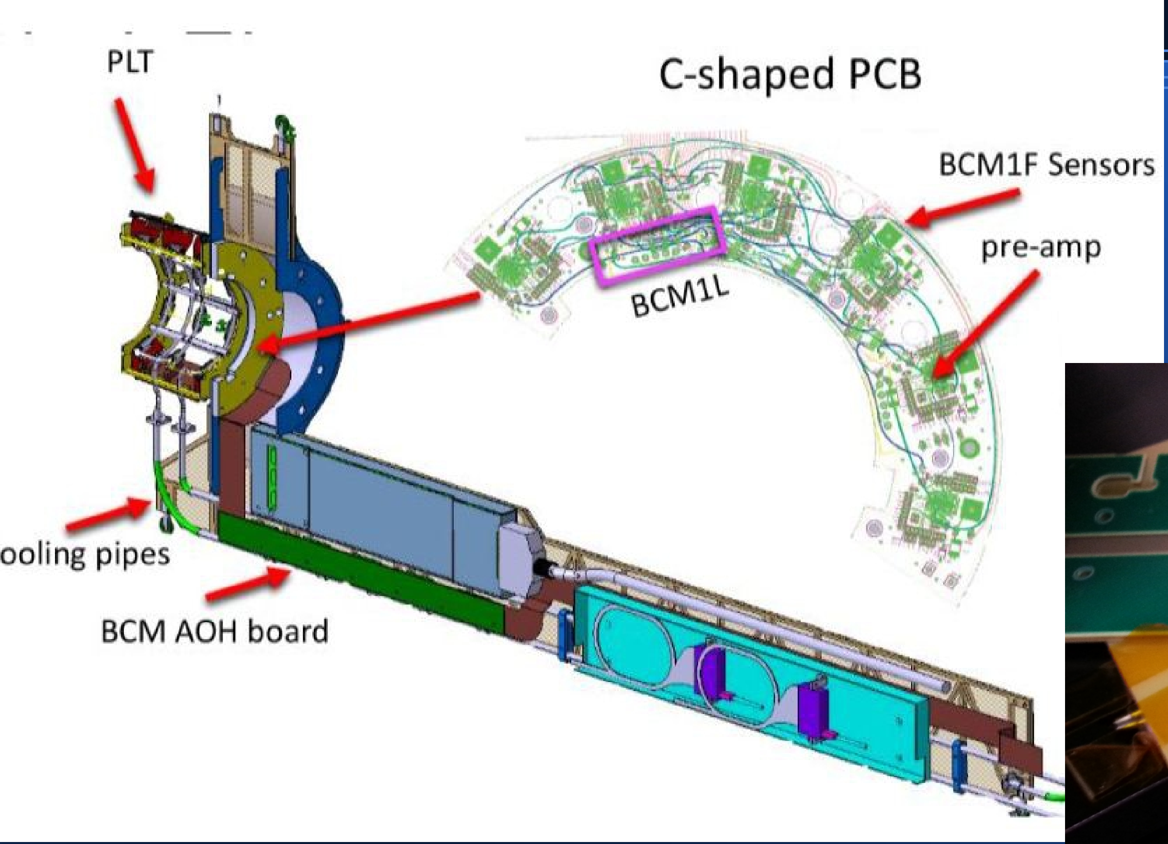
C-Shape

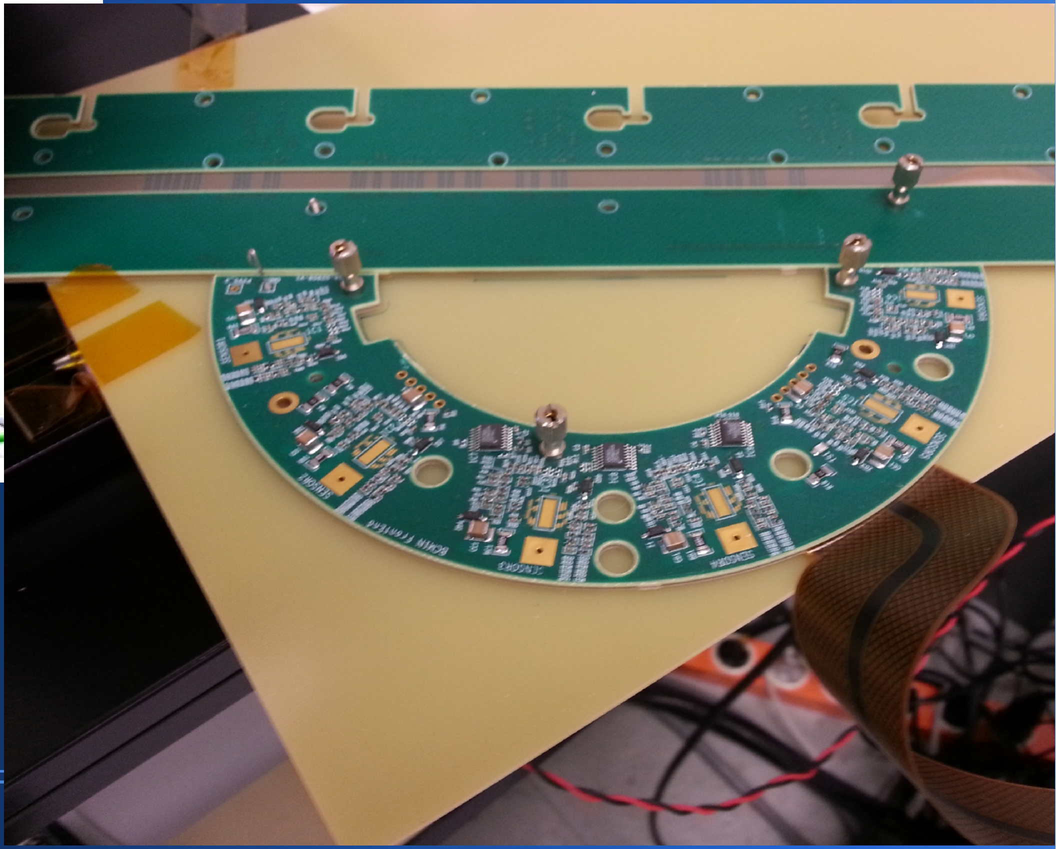
Bethe Bloch - scCVD diamond



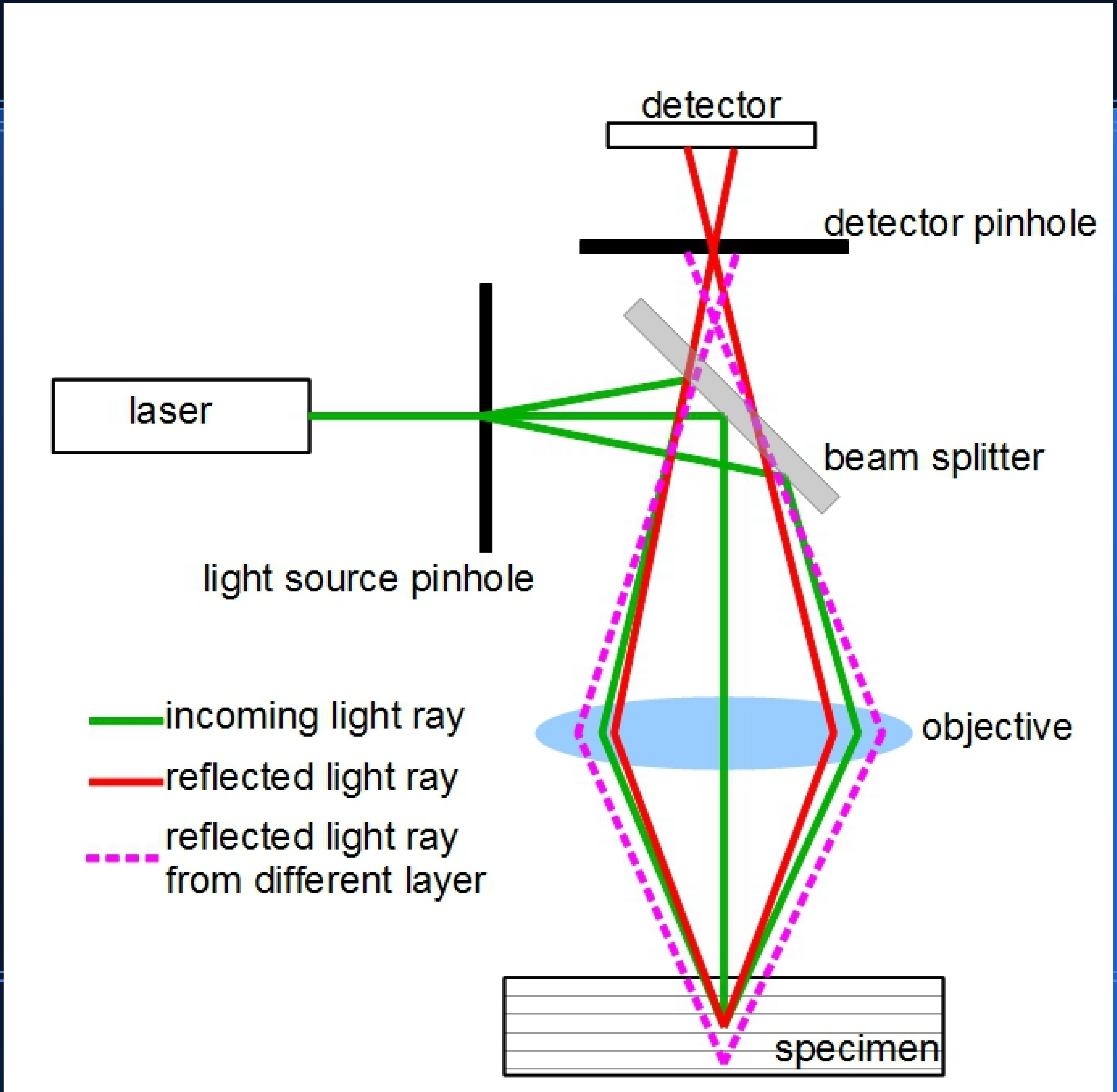


C-Shape

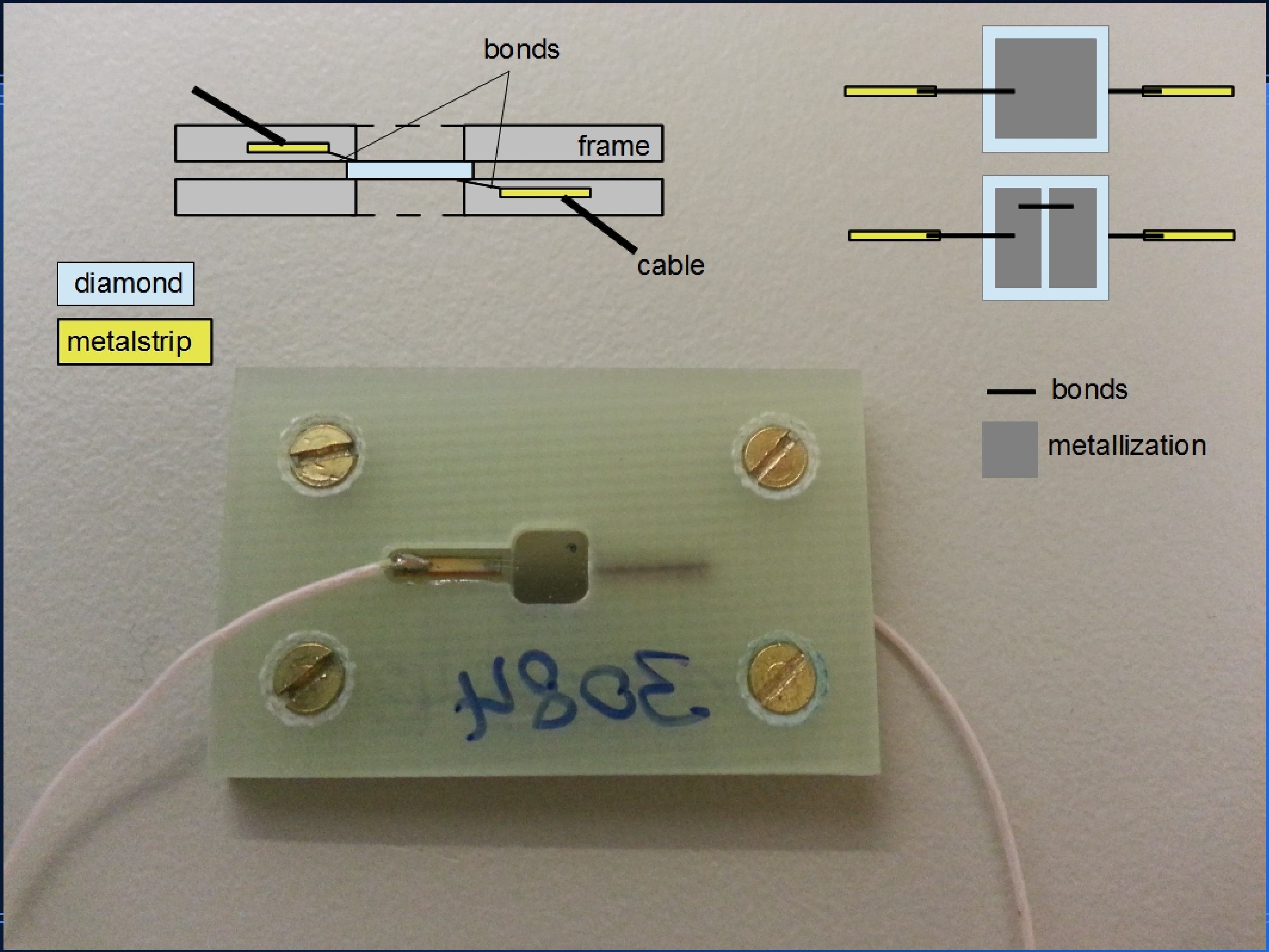

PLT
C-shaped PCB
BCM1F Sensors
pre-amp
BCM1L
ooling pipes
BCM AOH board



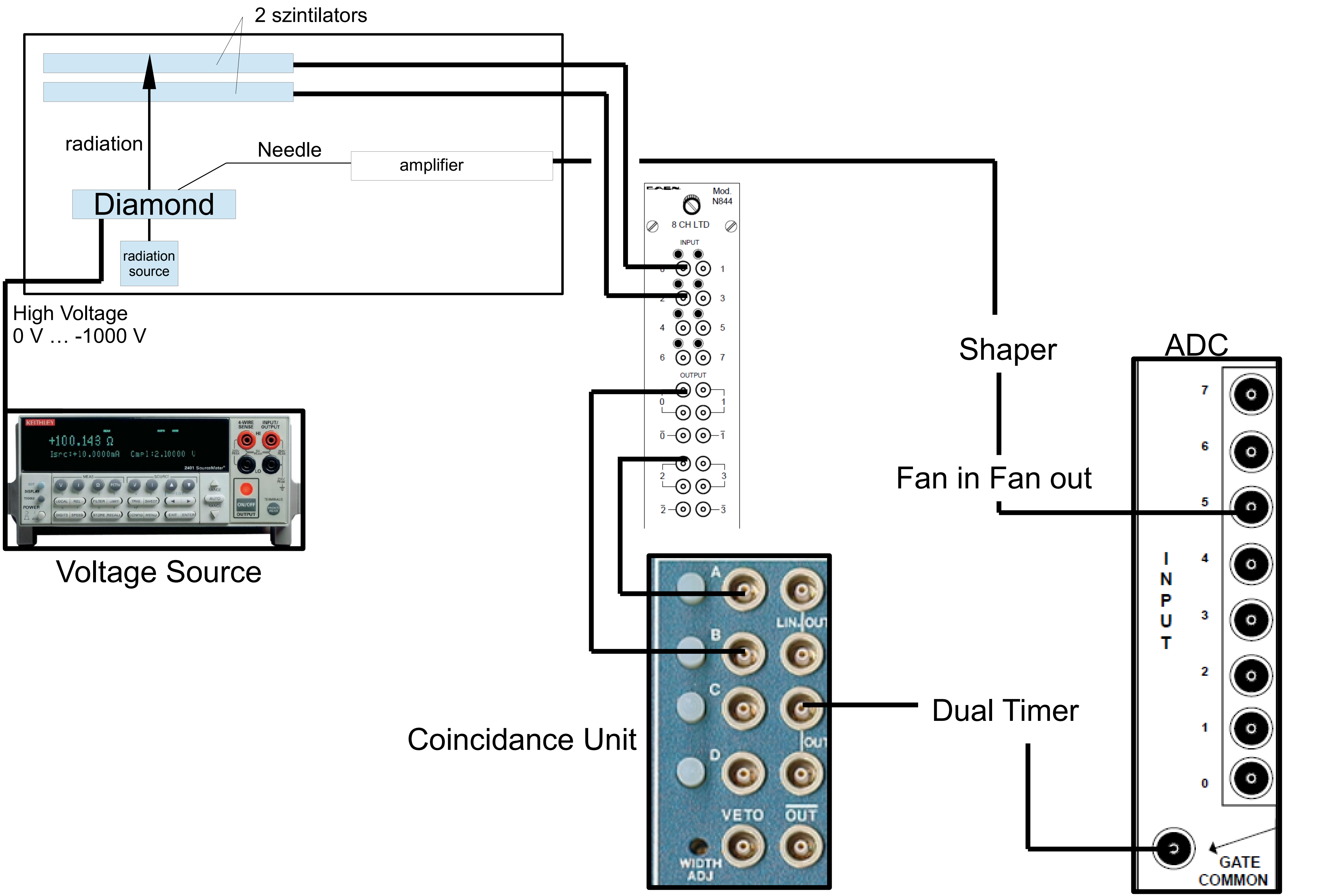
Confocal Microscope



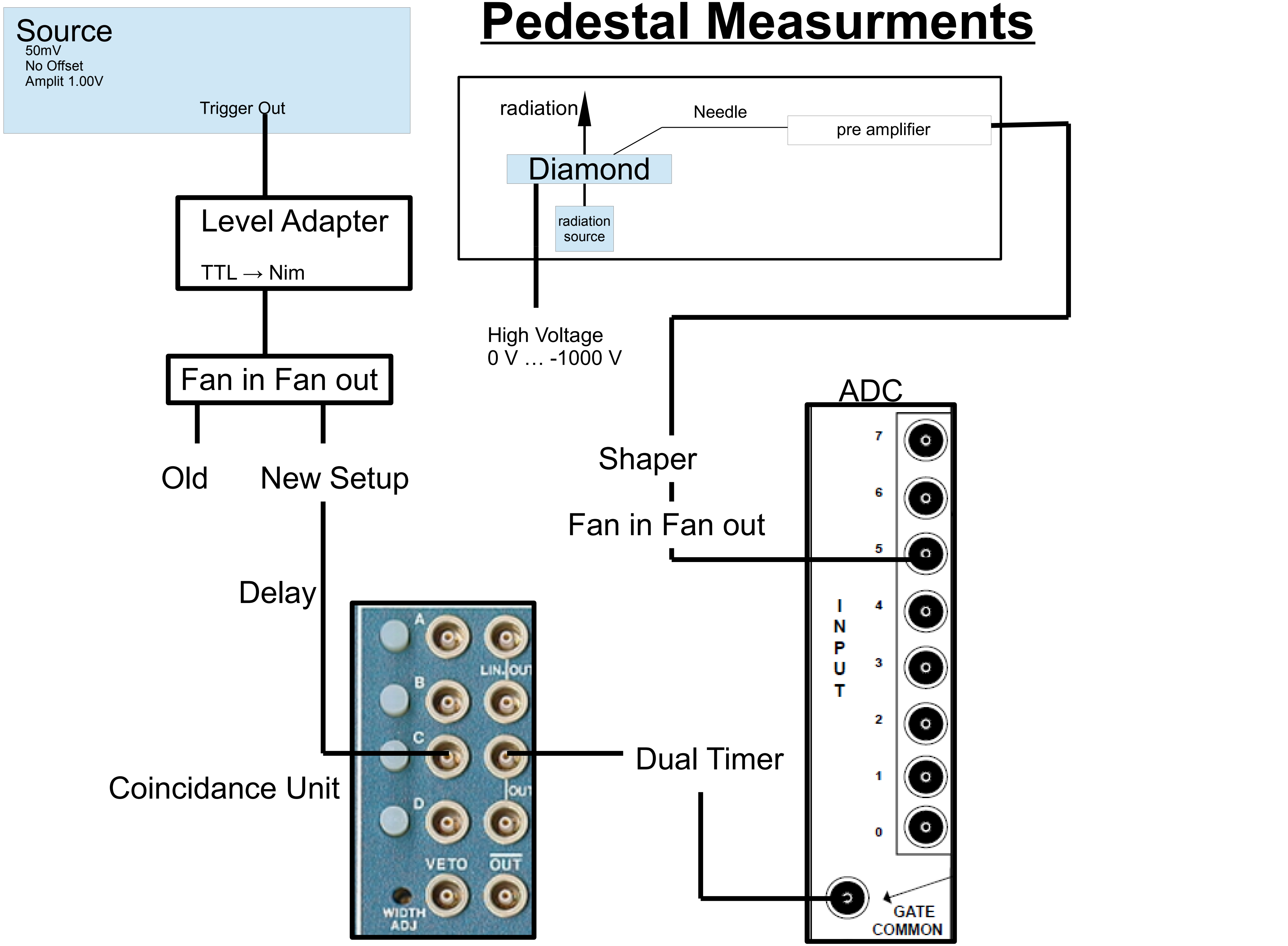
Diamond Sensor in Frame



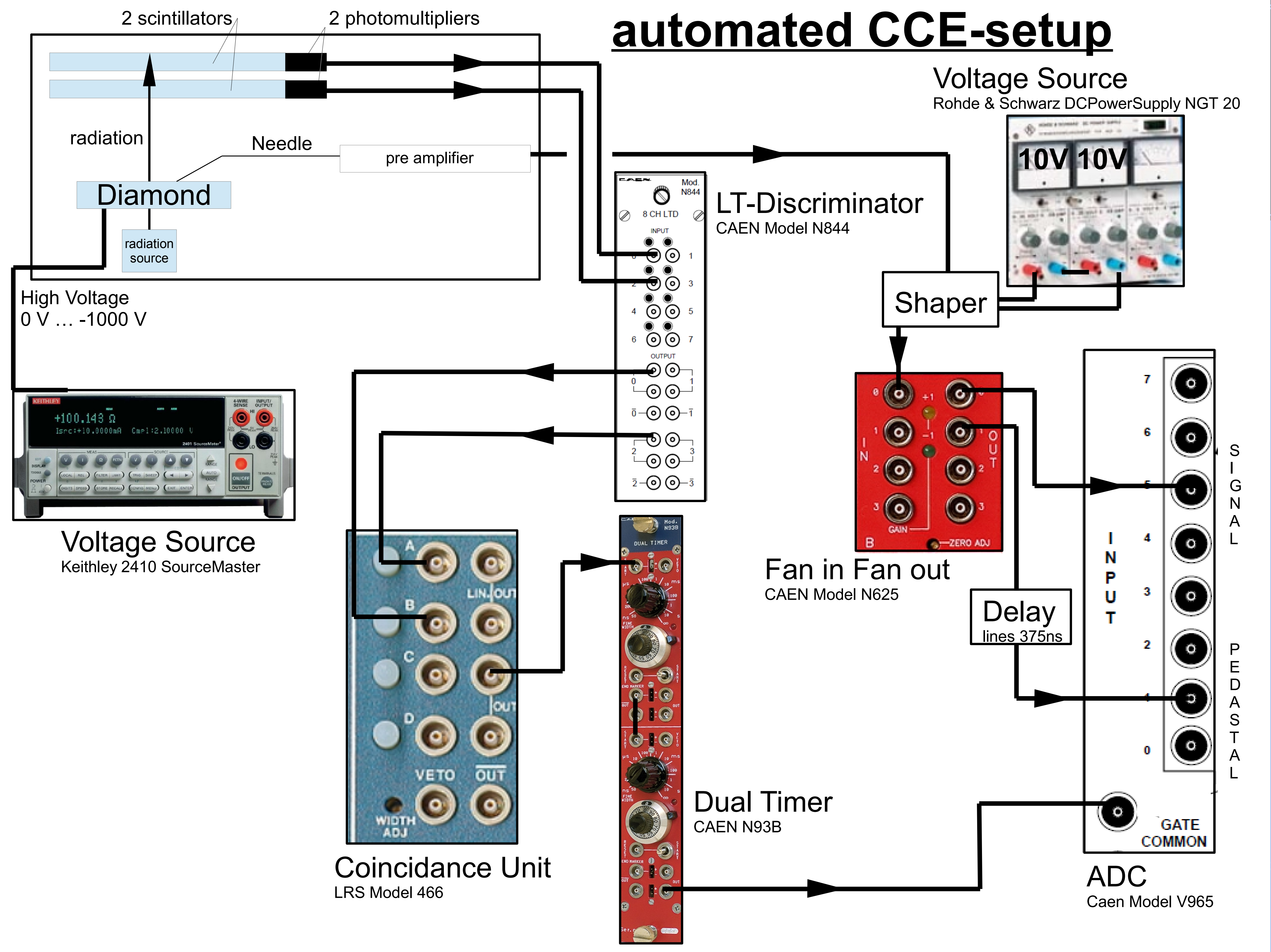
Signal Measurments



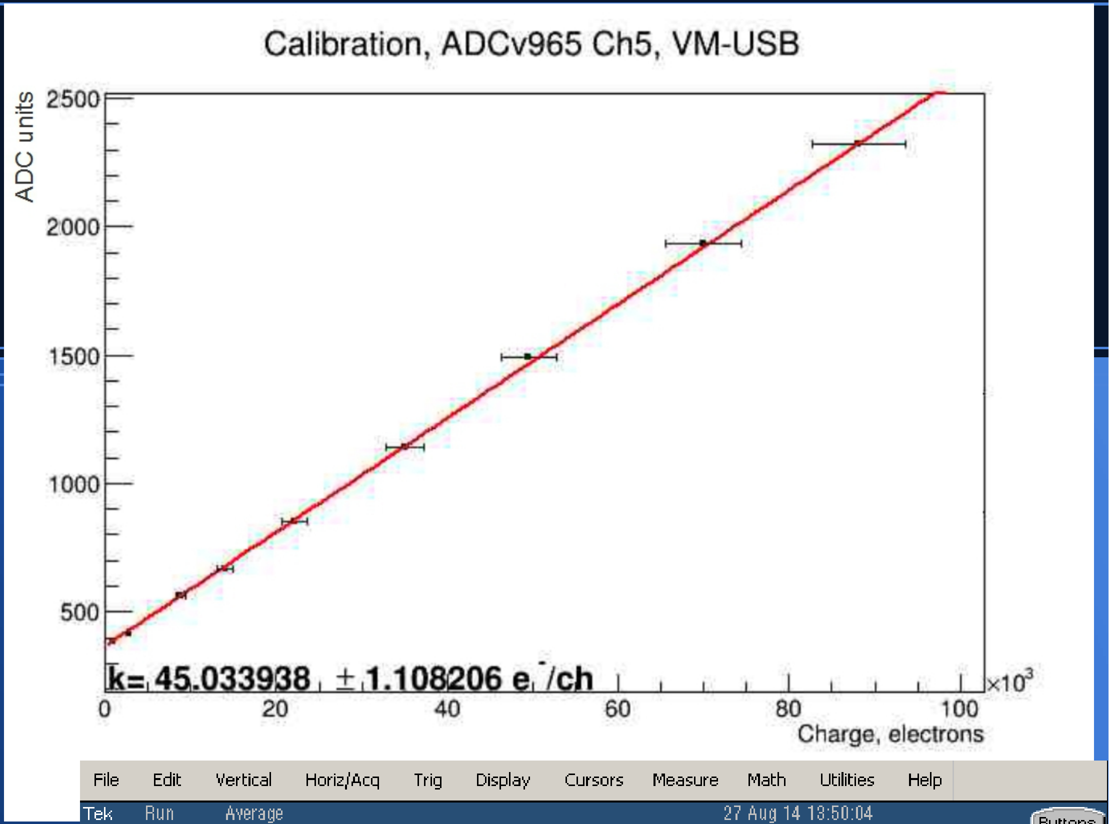
Pedestal Measurments

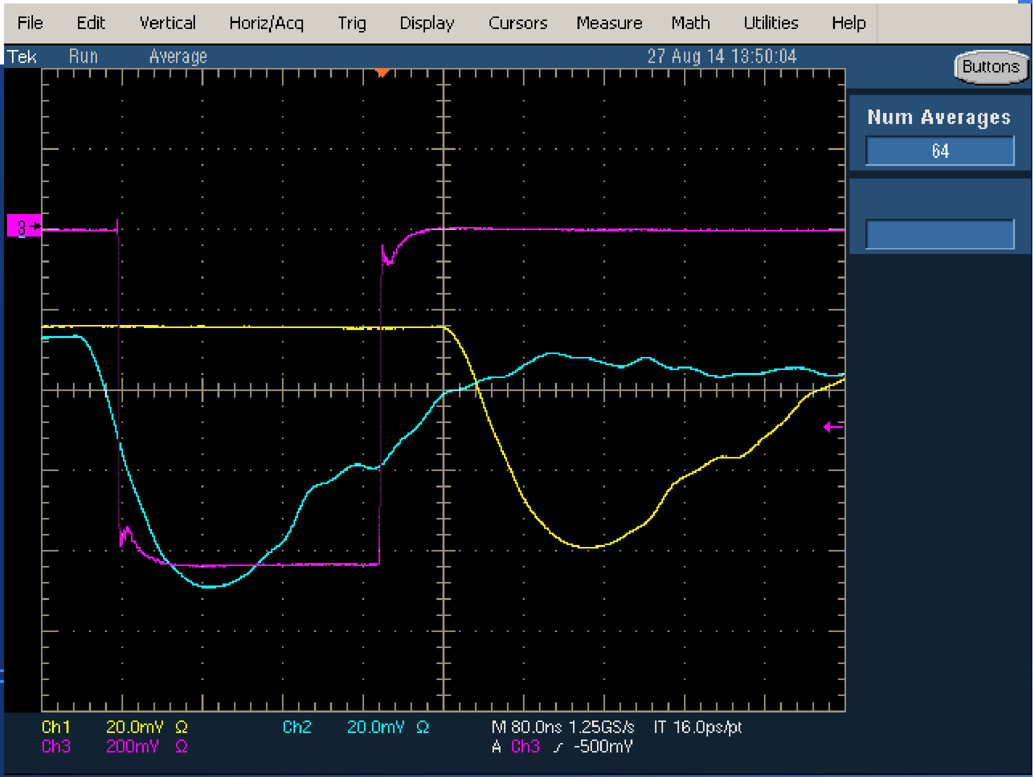


automated CCE-setup

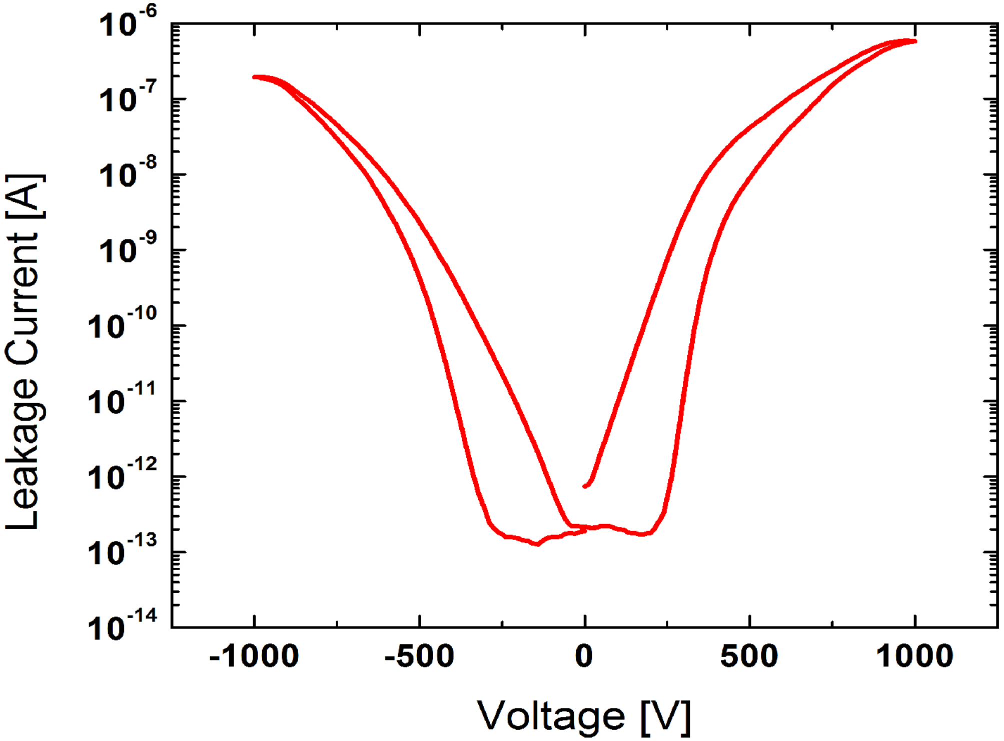


Calibration, Signal & Pedestal

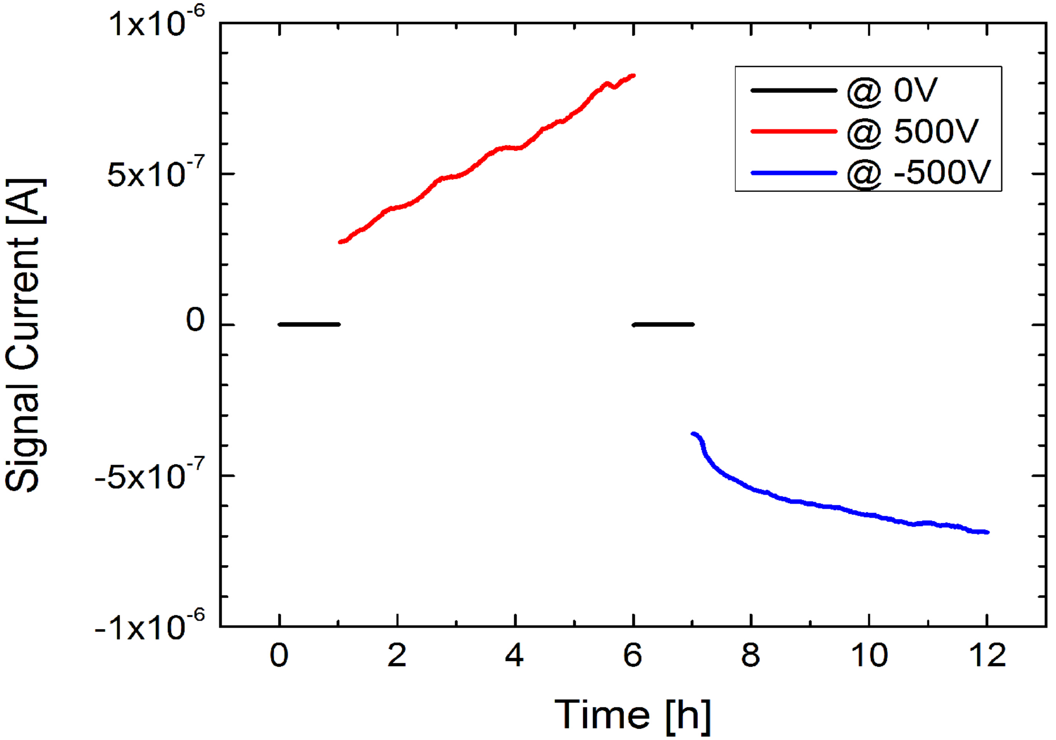




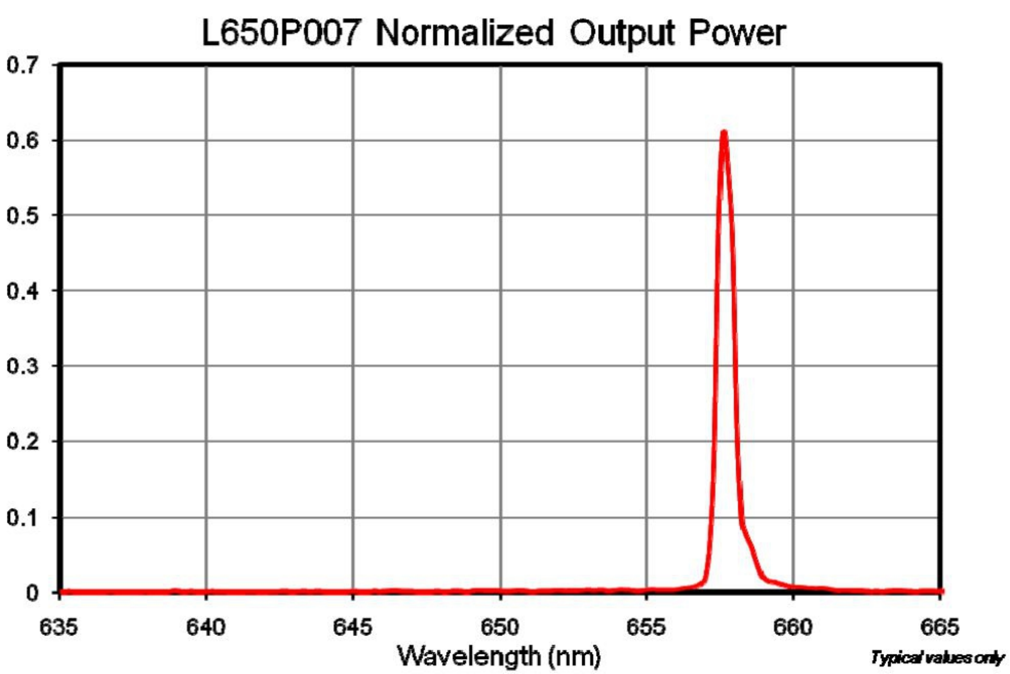
Backup II

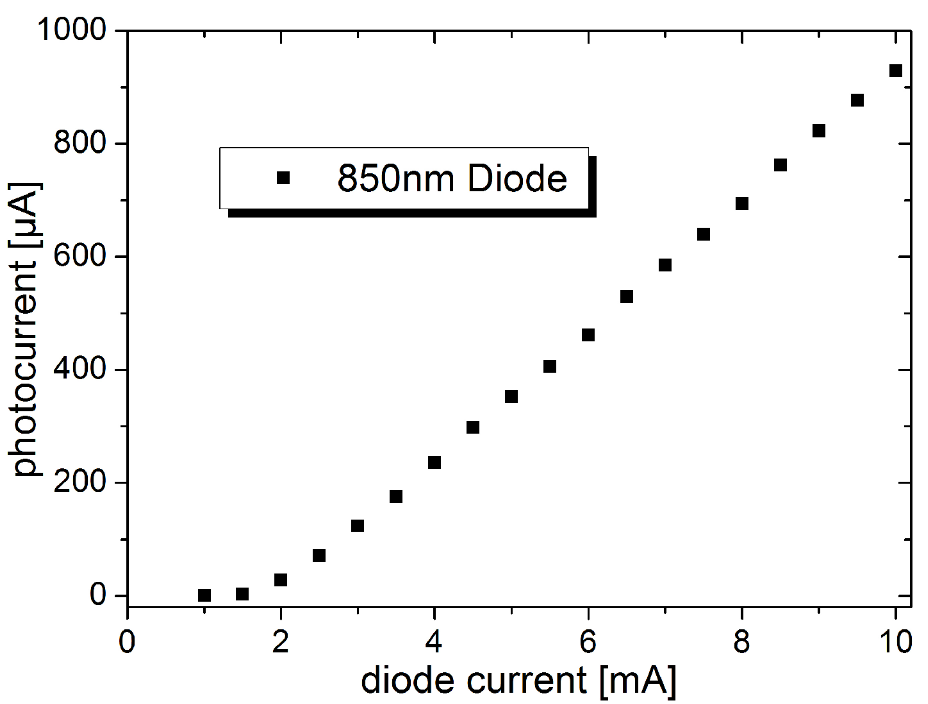


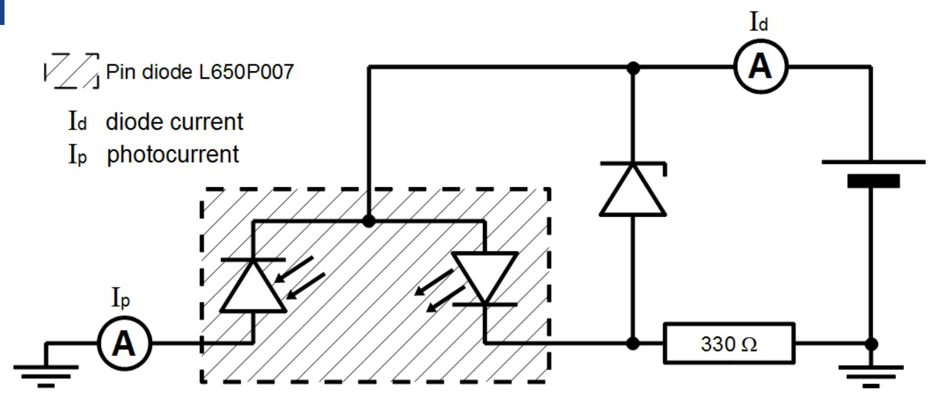
Leakage Current [A]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
-1000
-500
0
500
1000
Voltage [V]



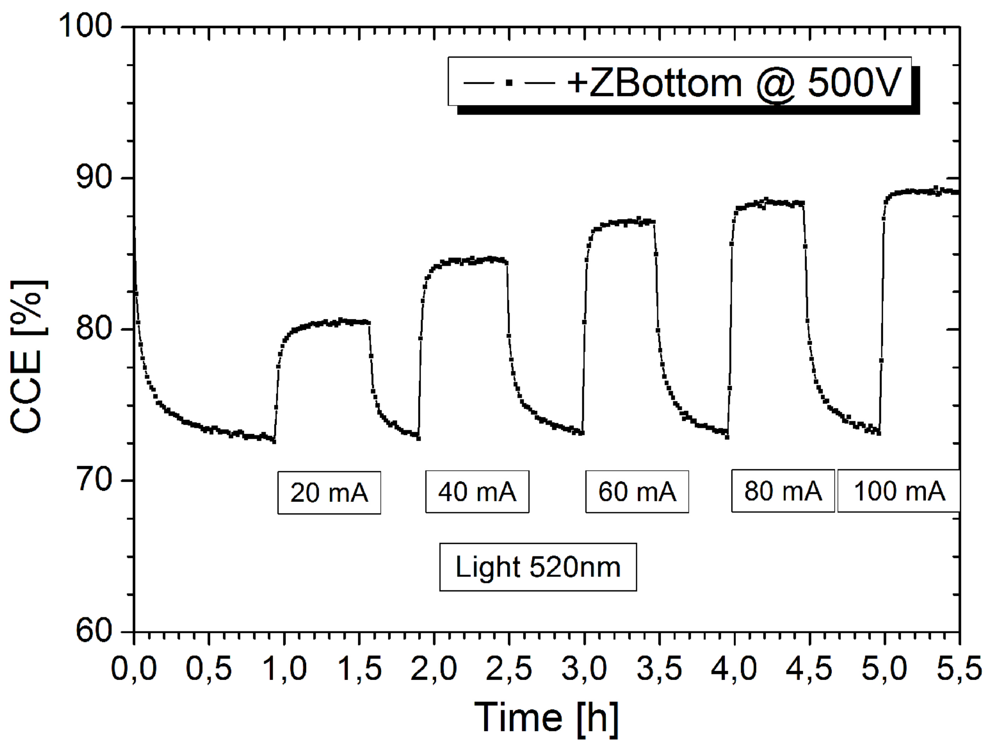
Signal Current [A]
$1x10^{-6}$
$5x10^{-7}$
0
$-5x10^{-7}$
$-1x10^{-6}$
0
2
4
6
8
10
12
Time [h]
@ 0V
@ 500V
@ -500V


L650P007 Normalized Output Power
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
635
640
645
650
655
660
665
Wavelength (nm)
Typical values only

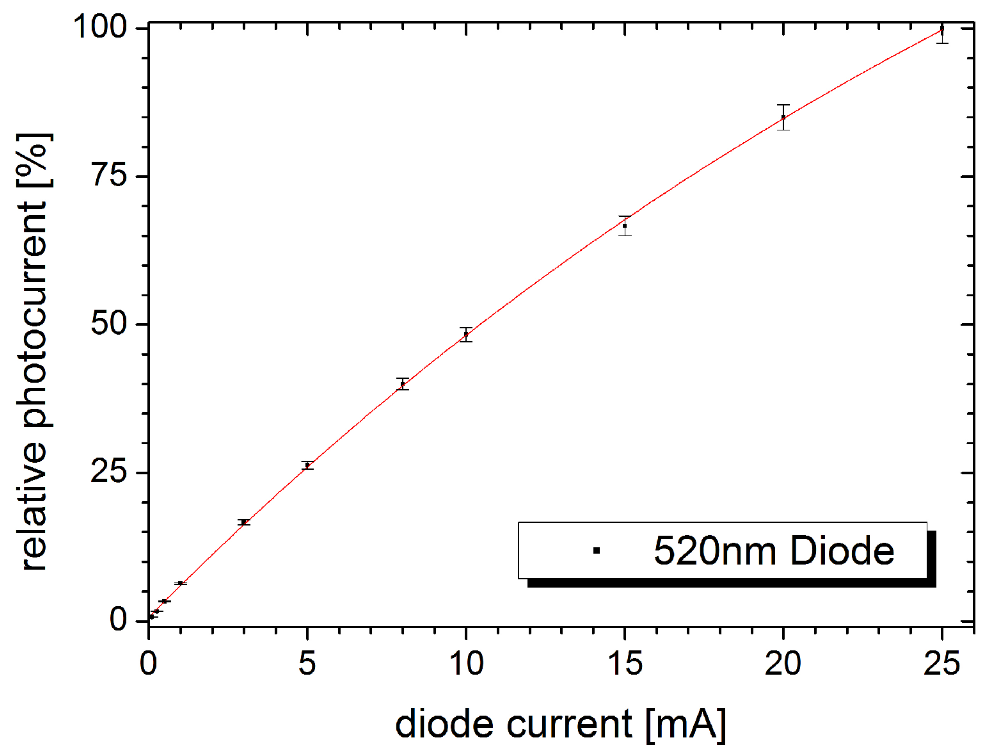

1000
800
600
400
200
0
0
2
4
6
8
10
850nm Diode
photocurrent [μA]
diode current [mA]


Pin diode L650P007
Id diode current
Ip photocurrent
Id
A
Ip
A
330 Ω

Backup I

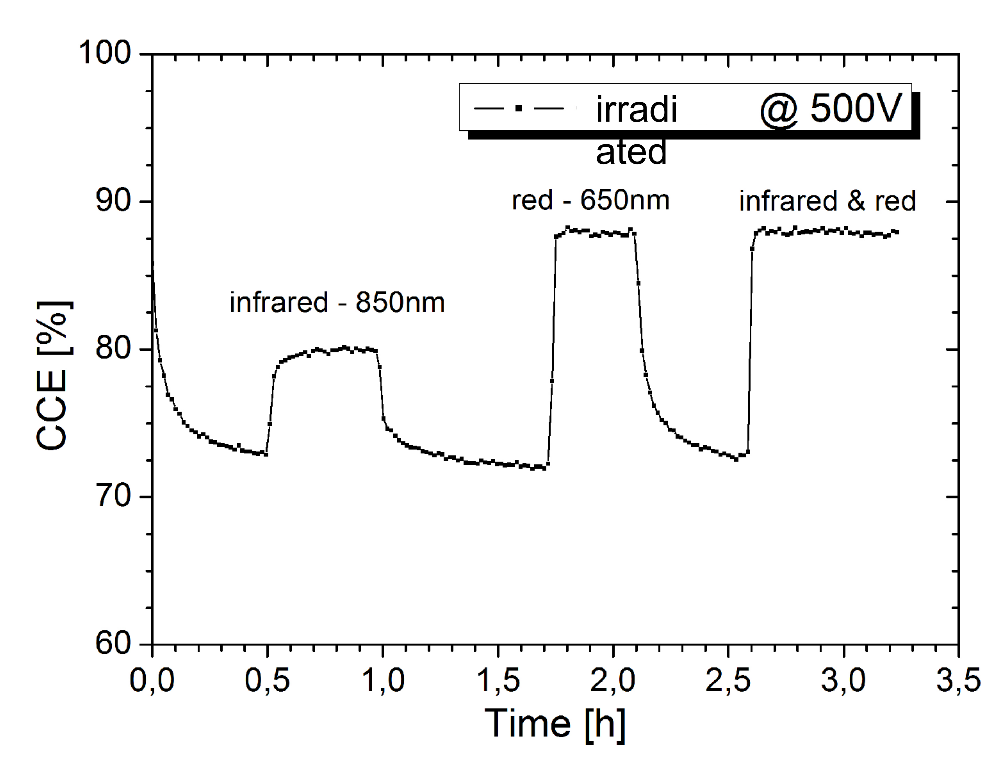


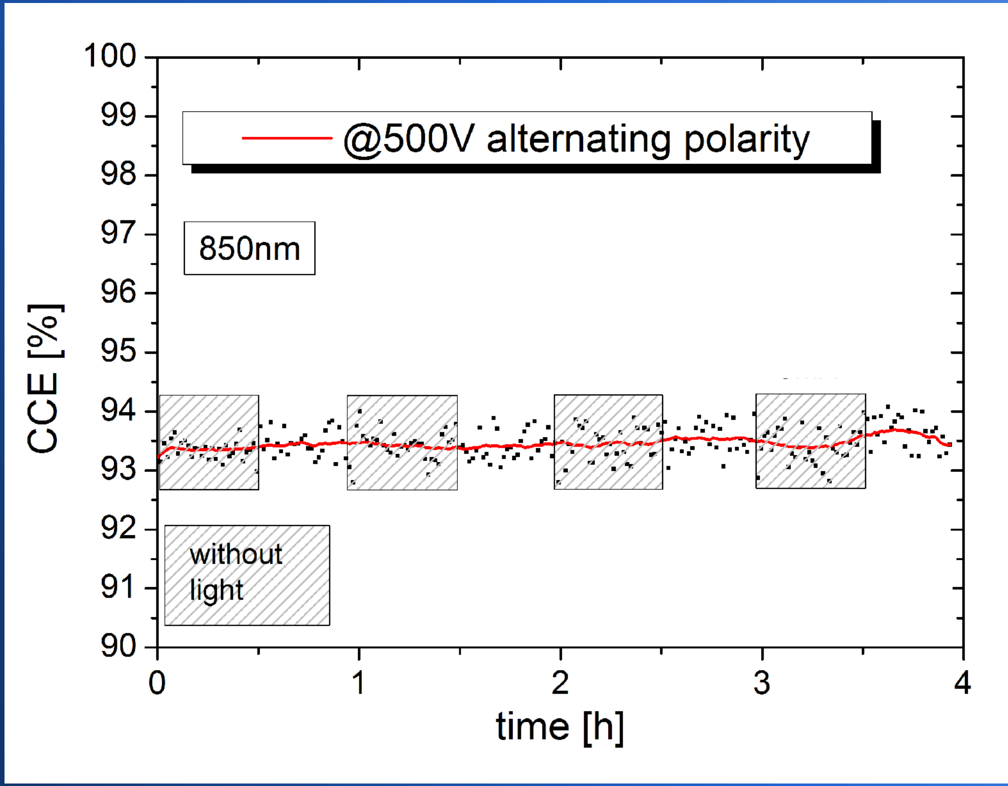
100
90
80
70
60
CCE [%]
+ZBottom @ 500V
20 mA
40 mA
60 mA
80 mA
100 mA
Light 520nm
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5,0
5,5
Time [h]



100
75
50
25
0
relative photocurrent [%]
520nm Diode
0
5
10
15
20
25
diode current [mA]

CCE for two lightsources and with alternating polarity





64 diamond sensors	16 CrAu	2 OP
		10 TP
		4 both
	46 WTi	42 TP
		4 both
	2 both	2 TP