

## AN INSIGHT INTO RADIATION TOLERANCE OF DIAMOND DETECTORS

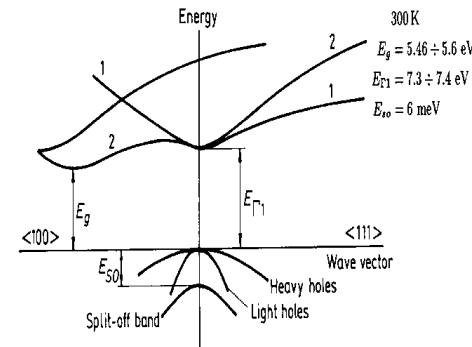
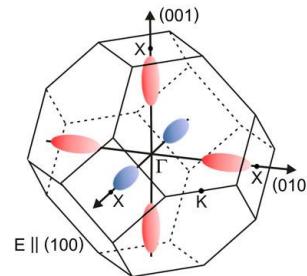
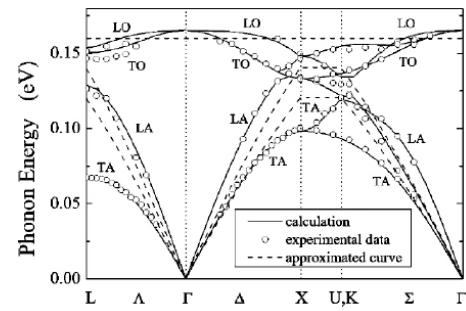
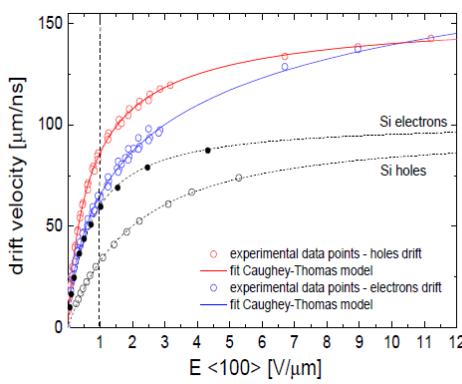
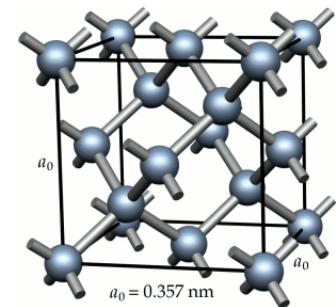
Journée Thématique du réseau R&D semi-conducteurs 16/06/2016 | Pomorski Michal  
Diamond Sensors Laboratory

- Diamond Physical Properties
- Diamond Detectors - State of the Art
  - Diamond Material
  - Diamond Detectors
- Radiation Hardness
  - NIEL - Non Ionizing Energy Loss
  - Radiation Damage in Diamond
  - Influence on Detector Parameters
  - Recovery after Radiation Damage - Annealing, High Field Operation
- Summary and Outlook

# DIAMOND PHYSICAL PROPERTIES

'a wish list'

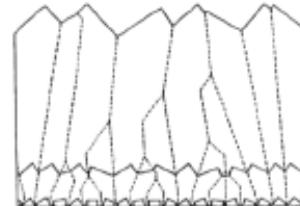
property	diamond	silicon	4H-SiC	detector operation
band gap [eV]	5.48	1.12	3.26	+ high T operation
dielectric strength [V/cm]	$10^7^*$	$3 \times 10^5$	$5 \times 10^6$	+ high field operation
intrinsic resistivity [ $\Omega/cm$ ]	$>> 10^{11}$	$2.3 \times 10^5$	$> 10^5$	+ low leakage current
electron mobility [ $cm^2/Vs$ ]	1900 – 4500*	1350	1000	+ fast signal
hole mobility [ $cm^2/Vs$ ]	1800 – 3500*	480	115	+ fast signal
electron lifetime [s]	$10^{-10} - 10^{-6}*^*$	$> 10^{-3}$	$5 \times 10^{-7}$	+ full charge collection
hole lifetime [s]	$10^{-10} - 10^{-6}*^*$	$10^{-3}$	$7 \times 10^{-7}$	+ full charge collection
saturation velocity [ $cm/s$ ]	$1.2 - 2.7 \times 10^7^*$	$1 \times 10^7$	$3.3 \times 10^6$	+ fast signal
density [ $g/cm^3$ ]	3.52	2.33	3.21	
average atomic number	6	14	10	+ therapy - tissue equiv.
dielectric constant	5.72	11.9	9.7	+ low capacitance
displacement energy [eV]	43	13 – 20	20 – 35	+ radiation hardness
thermal conductivity [ $Wm^{-1}K^{-1}$ ]	2000	150	120	+ heat dissipation
energy to create e-h [eV]	11.6 – 16*	3.62	7.8	- lower signal
radiation length, $X_0$ [cm]	12.2	9.36	8.7	+ low background
Energy loss for MIPs [MeV/cm]	4.69	3.21	4.32	
Aver. Signal Created / 100 $\mu m$	3602	8892	5100	+ lower signal
e-h pairs/ $X_0$ ( $10^6 cm^{-1}$ )	5.7	10	4.5	



# DIAMOND MATERIAL

- **pcCVD**

- Large area: Si wafer size (8 cm diam. Diamond Materials)
- Thickness: nm to mm
- Price: few k€/cm<sup>2</sup>



**Diamond Materials**  
Advanced Diamond Technology

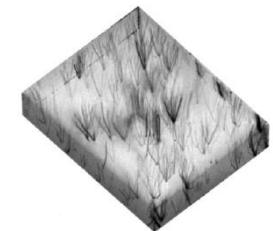


- **scCVD**

- Area: HPHT size ~5 x 5 mm (up to 2" R&D mosaic)
- Thickness: few microns to mm
- Price: ~ 2k€/sample (5x5 mm)

**II-VI** ADVANCED MATERIALS

**IIa** TECHNOLOGIES



**elementsix™**

- **DOI - diamond on iridium**

- Area: Si size (2 x 2 cm samples already synthetized)
- Thickness: hundred of microns
- Price: start-up created

- **Natural scCVD**

- Rare, not reproducible in any aspects
- Price: Not commercial

- **HPHT IIa - electronic grade (?)**

- Area: up to cm (?)
- thickness: few microns to cm
- Price: few hundreds €/5x5 mm



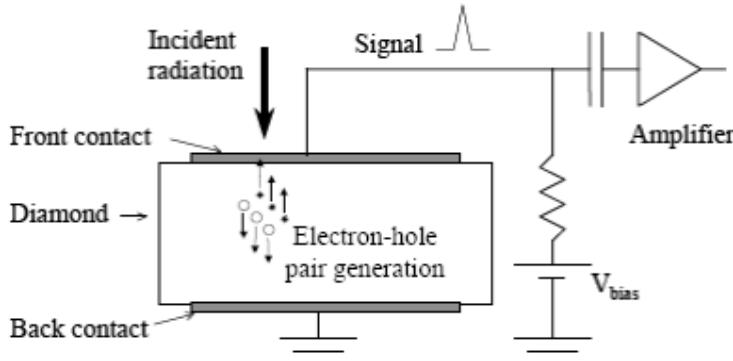
**UNIA** Universität Augsburg University



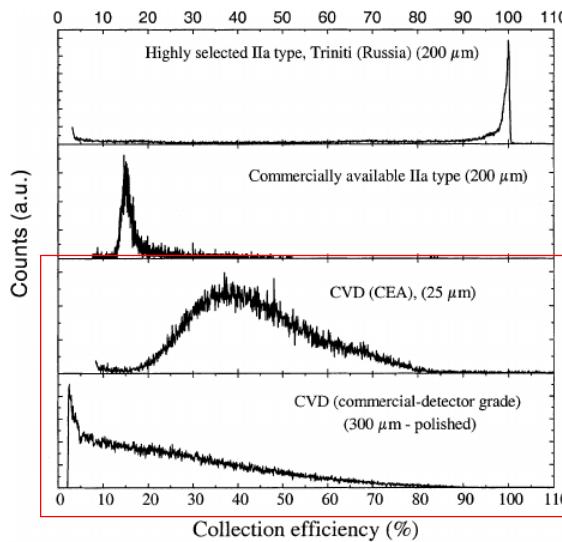
**NEW DIAMOND**  
TECHNOLOGY

# DIAMOND DETECTORS BASICS

solid state ionization chamber



pcCVD in 2001



$$\epsilon \nabla^2 \Psi = -\rho$$

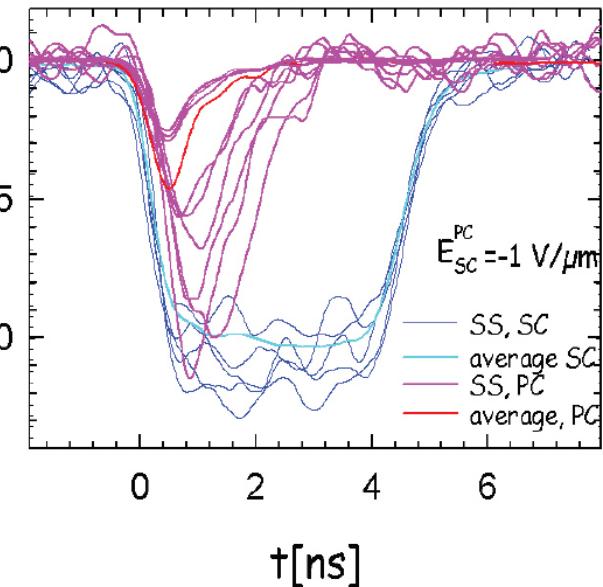
$$q \frac{\partial p}{\partial t} = -\nabla J_p - qR$$

$$q \frac{\partial n}{\partial t} = -\nabla J_n - qR$$

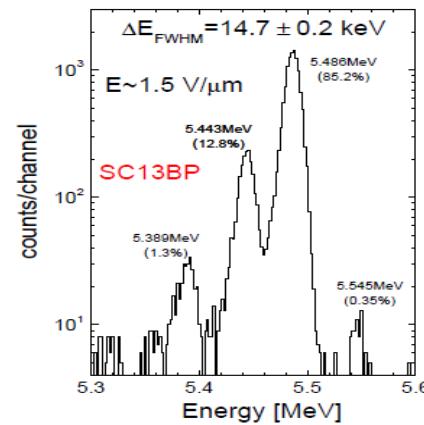


drift-diffusion

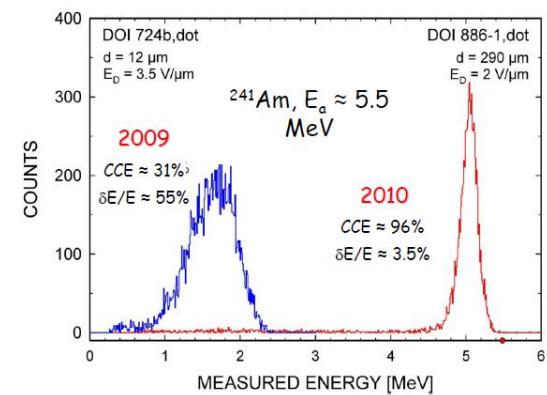
Pulse Height [V]



scCVD in 2004

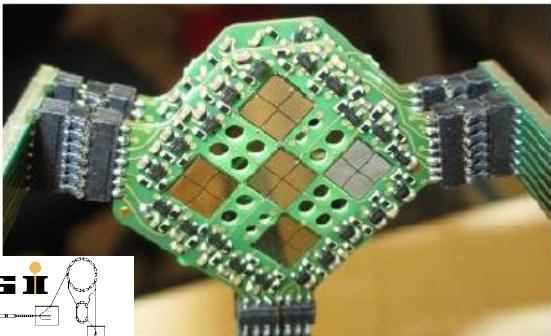


DOI in 2010



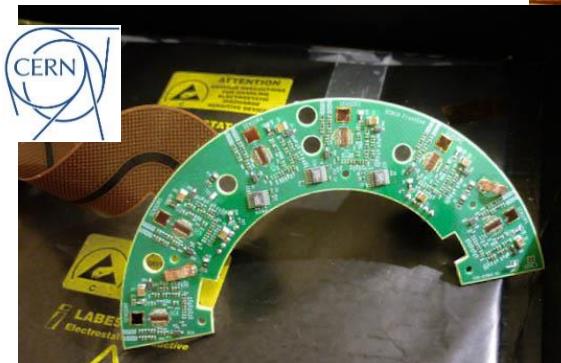
# DIAMOND DETECTORS IN USE

Start detectors scCVD



W. Koenig, J. Pietraszko, HADES Collaboration

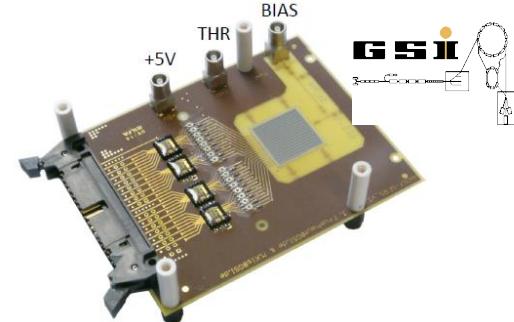
CMS beam condition monitors pcCVD



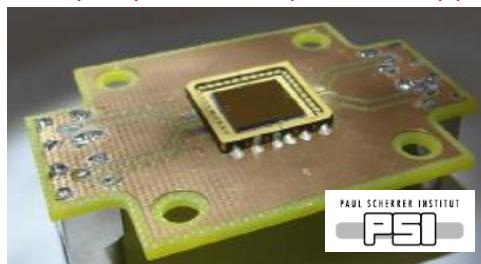
scCVD PSD for X-ray beam monitoring



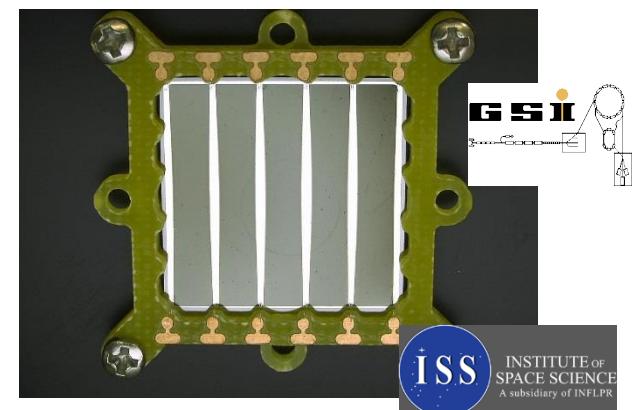
2x2 cm pcCVD strip ToF heavy ions



mosaic scCVD fast n detector

High temp  $\alpha$ -particles spectroscopy of SHE

2x2 cm pcCVD PSD particle beam monitoring



CMS PLT pixel system scCVD



# DIAMOND DETECTORS COMMERCIAL SOLUTIONS

## Some Commercial Solutions for Diamond Detectors:



**CIVIDEC**  
Instruments

**CIVIDEC products**

CIVIDEC Instrumentation specializes in the fabrication of radiation monitors for diagnostics based on CVD-diamond detectors and, in particular, on low-noise speed preamplifiers that fully exploit the intrinsic properties of the sCVD and diamond detectors.

Download our full product catalogue below, or browse through our product range online by selecting from the main menu categories or items.

**MICRON SEMICONDUCTOR Ltd**

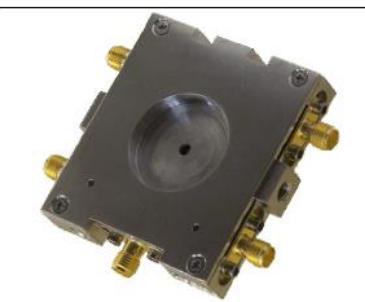
+44 1903 755252  
[direct@micronsemiconductor.co.uk](mailto:direct@micronsemiconductor.co.uk)

- **Crystal type:** both single and polycrystalline substrates are available. They possess different properties and are used for different purposes ;
- **Crystal size:** various sizes are available, the most common ones being 4.5 x 4.5 mm for single crystals and 5 x 5 mm for polycrystalline substrates ;
- **Crystal thickness:** the typical thicknesses we work with are 500 µm and 100 µm ;
- **Device contact:** a single area or a patterned metal contact pad can be deposited on the substrate surfaces. Different geometries can be incorporated on the front and back surfaces. The nature of the contact pad itself depends essentially on the particles to detect and the operating temperature ;
- **Device packaging:** custom-designed ceramic substrates, high frequency



**SYDOR**  
INSTRUMENTS, LLC

**Sydor Diamond**



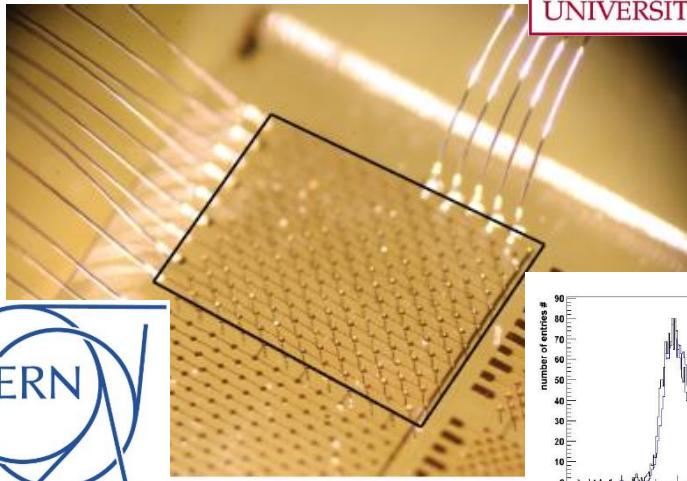
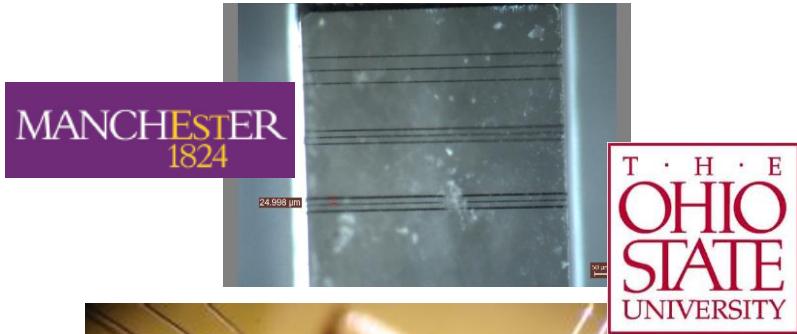


**PTW**

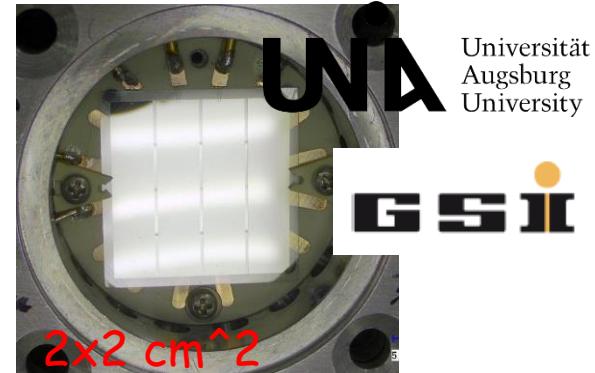
True Innovation  
First synthetic diamond for dosimetry

# NEW DEVELOPMENTS

## 3D diamond detectors (laser 3D printing)

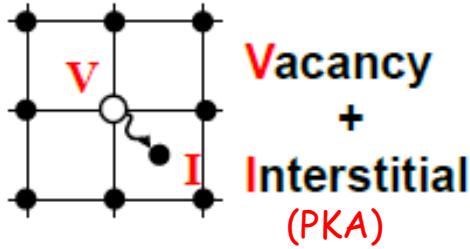


## Diamond on Irridium DOI



courtesy Mladen Kis, GSI, Darmstadt

# NIEL – NON IONIZING ENERGY LOSS

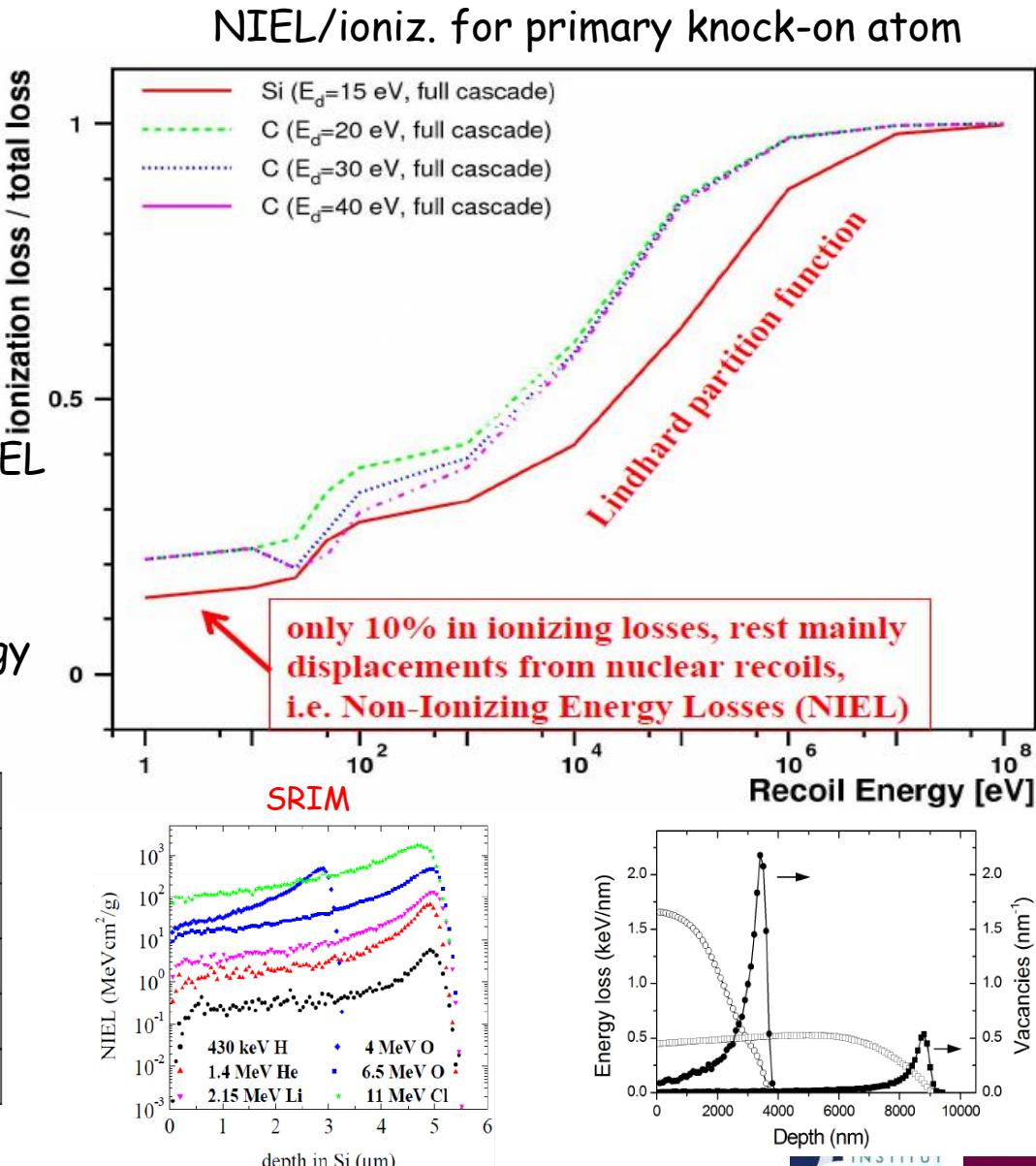


- crystal lattice damage through NIEL
- PKA → damage cascades
- most damage caused by low energy particles

Hardness factor

particle	Energy	Relative $k_\lambda$
P	24 GeV	1
	800 MeV	1.7
	70 MeV	2.7
	25 MeV	4.2
$\pi^+$	300 MeV/c	2.9

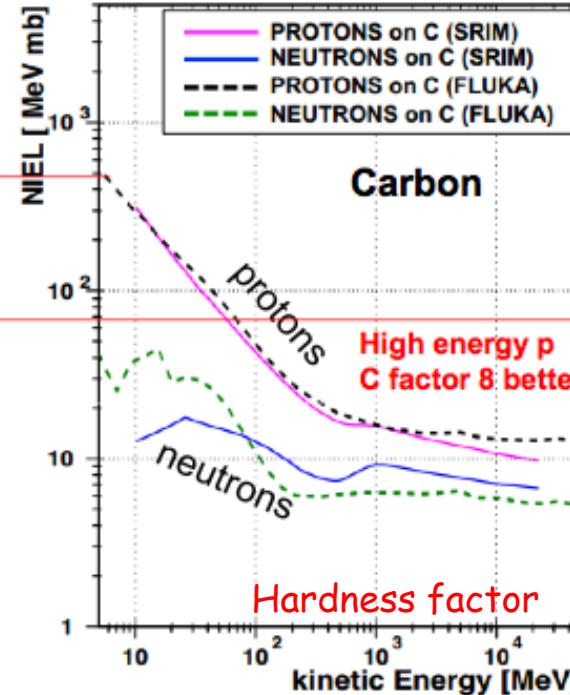
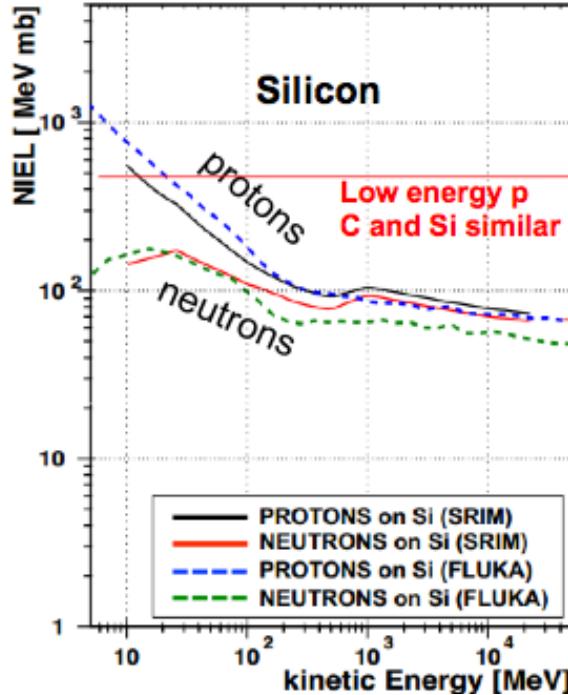
RD42



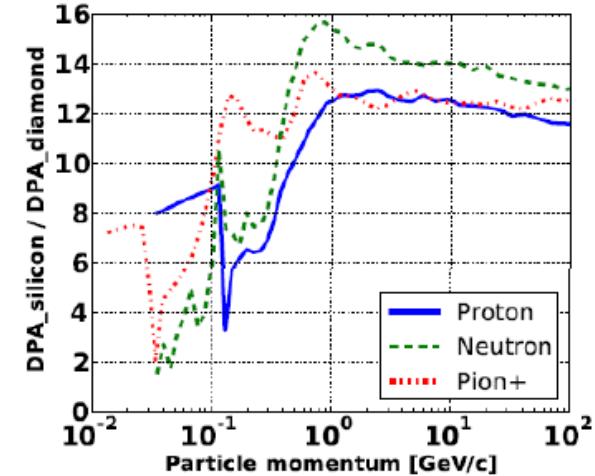
# NIEL – NON IONIZING ENERGY LOSS

Lower NIEL and higher atom displacement energy - more radiation hard ?

## NIEL (Non-Ionizing Energy Losses) in Si and C



$$CPD(E_k) = \frac{\rho}{2E_d} (NIEL)$$



RDA2

particle	Energy	Relative $k_\lambda$
P	24 GeV	1
	800 MeV	1.7
	70 MeV	2.7
	25 MeV	4.2
$\pi^+$	300 MeV/c	2.9

Simulation of beam induced lattice defect  
Xiv:1308.5419

# RADIATION DAMAGE IN DIAMOND

A recent study (simulation) of primary defects production in diamond

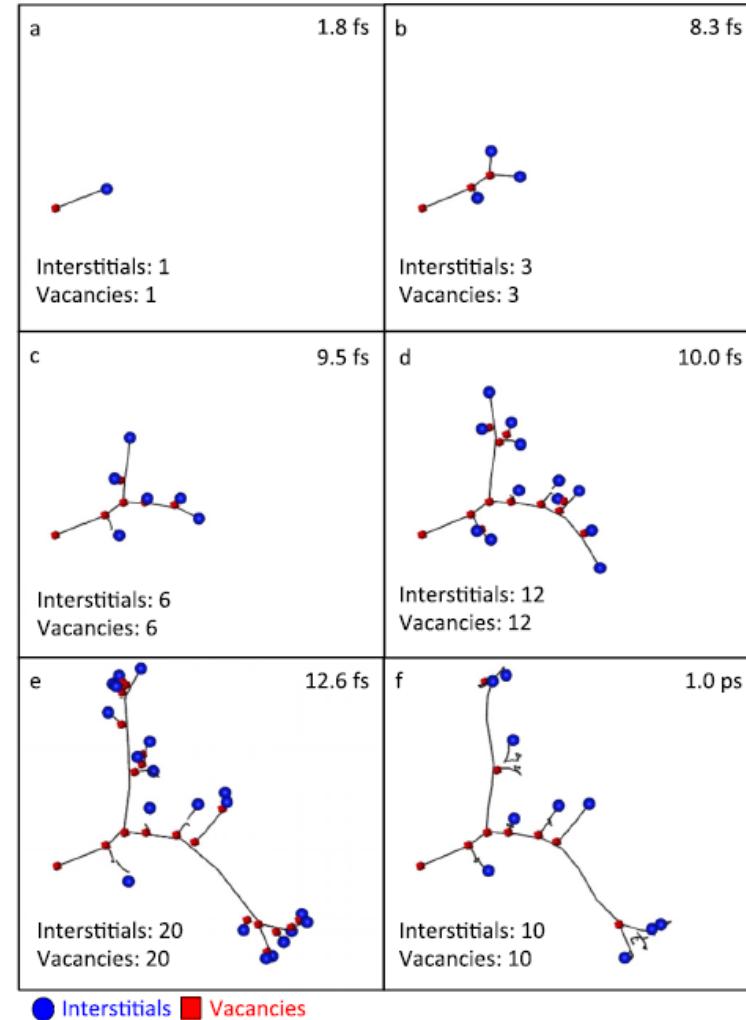
JOURNAL OF APPLIED PHYSICS 117, 245901 (2015)

The predominant insight to emerge from this study is that radiation cascades in diamond are distinctive as compared to many other materials, in the sense that the properties of the radiation damage process fall at the far end of the spectrum.

Similar to graphite, cascades in diamond generate isolated point defects and a branched trajectory structure created by distinct heavy collisions. Statistical averaging over a uniformly

displacement energy (Fig. 10). All of these differences combine to the high radiation hardness of diamond and contribute to the widespread interest in exploiting diamond as a detector, dosimeter, and other radiation-hard situations.

Damage cascades in diamond (2keV)



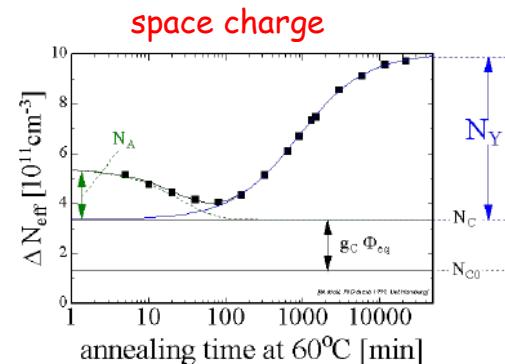
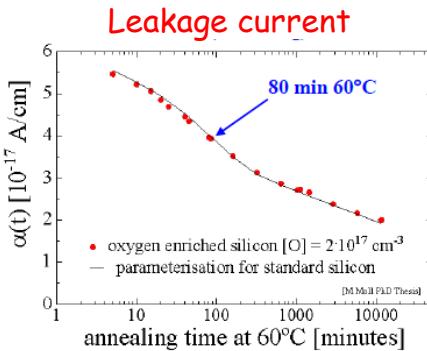
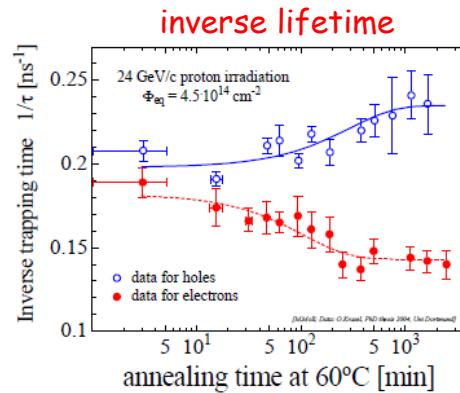
50% of self-annealing

# RADIATION DAMAGE IN DIAMOND

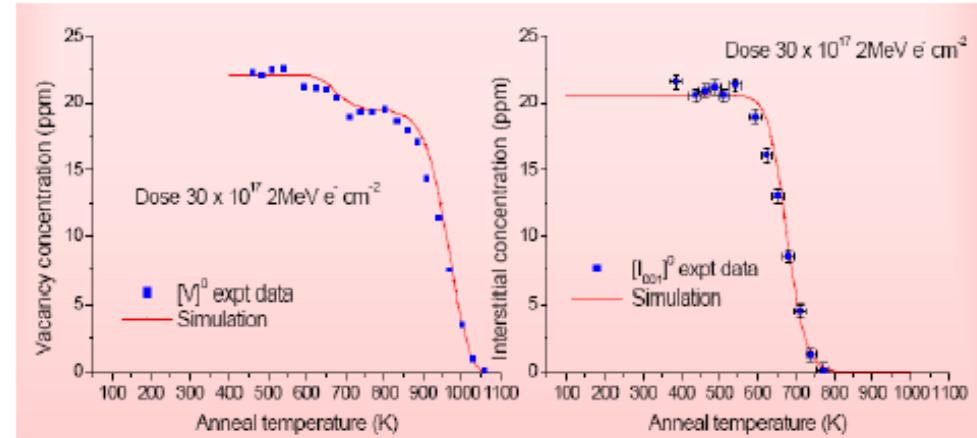
## Secondary defects formation in diamond ?

At RT primary defects in Si migrate:

- Formation of secondary defects
- change in time of detector parameters  
..Si needs cooling



A. Mainwood et al.

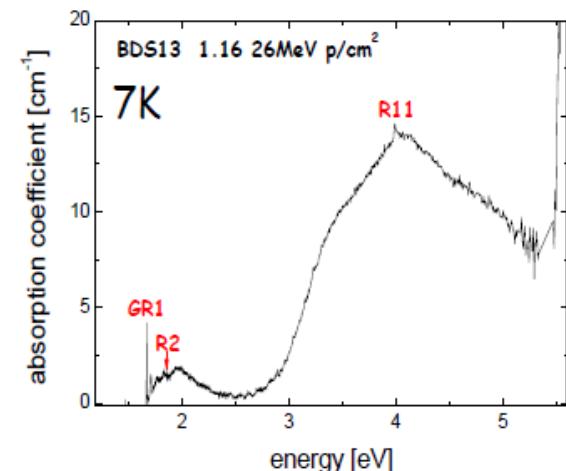
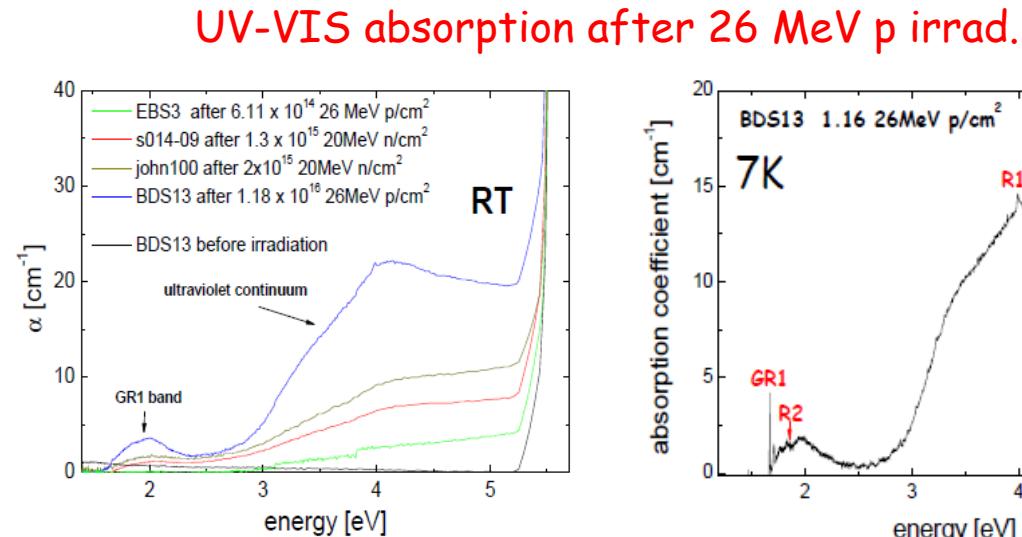
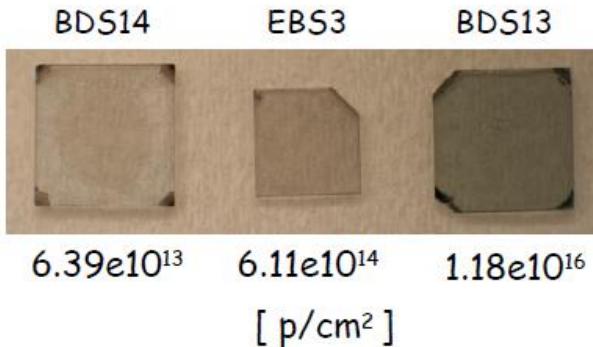


At RT V0 and I0 are immobile in diamond

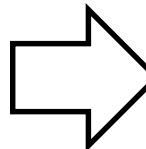
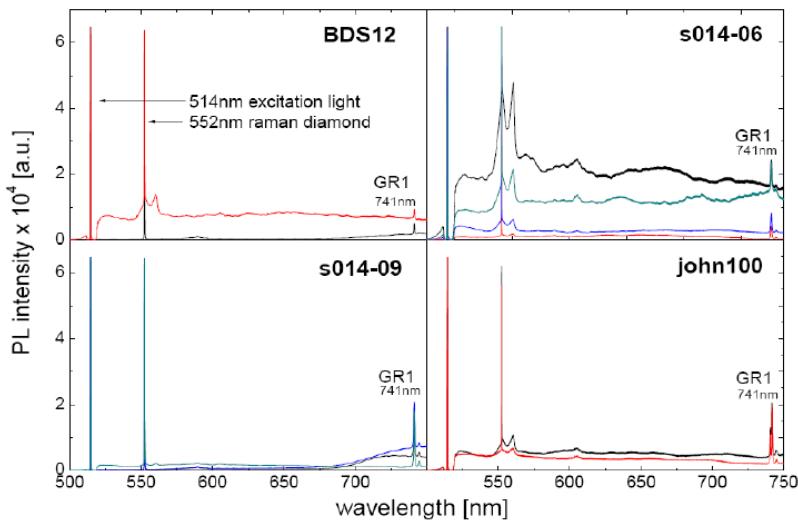
- defects engineering  
and NIEL violation in Si

- diamond should be more static  
after irradiation

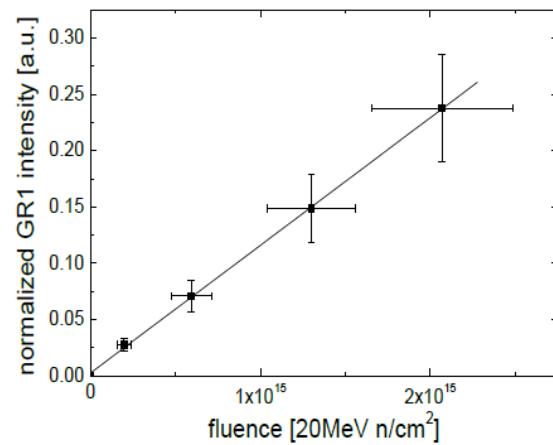
# RADIATION DAMAGE IN DIAMOND



Photoluminescence after fast n irrad.

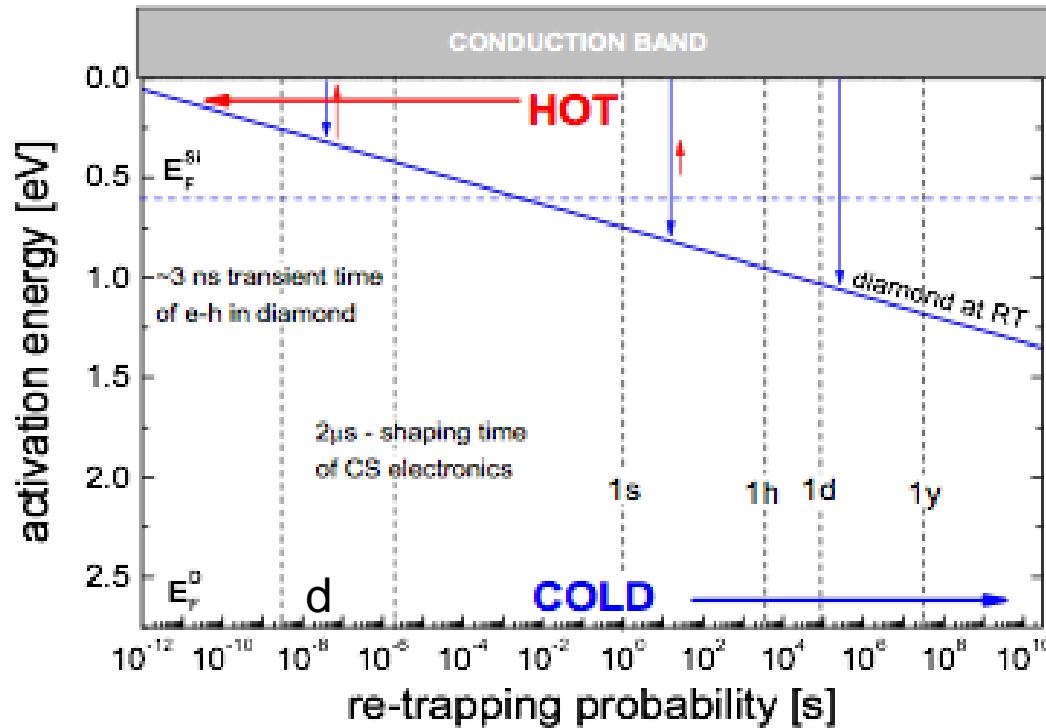


GR1 - monovacancy related center  
R2, R11 - interstitial related centres



# RADIATION DAMAGE IN DIAMOND

Radiation induced defects affect charge carriers transport in semiconductors



**Si is hot at RT**

- trapping $\leftrightarrow$ de-trapping
- Charged defects (Neff, Vdep)
- high leakage current (limiting factor)

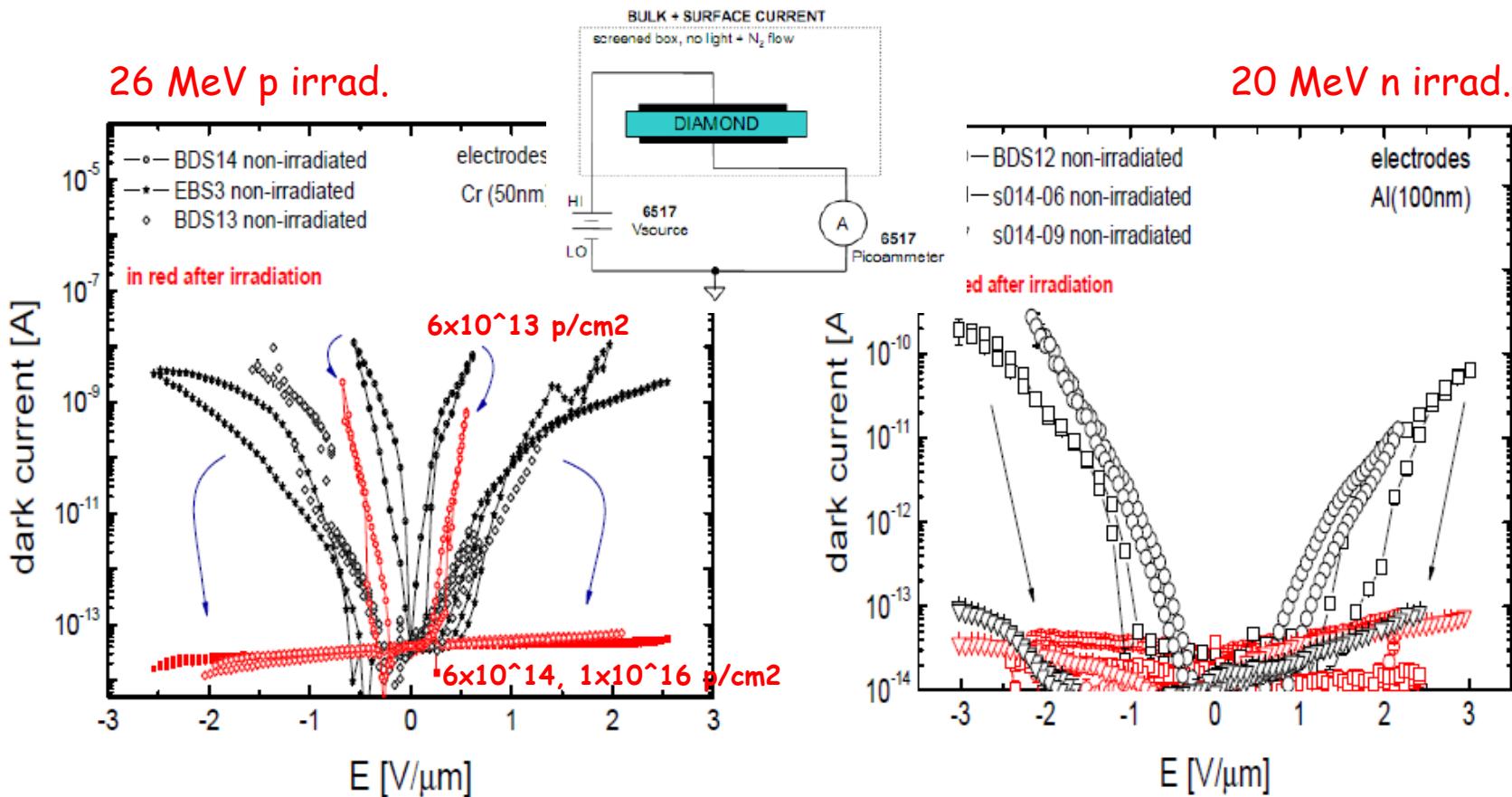
**Diamond is COLD at RT.....**

- trapping (low CCE)  $\rightarrow$  space charge
- Leads to: polarization and priming
- no leakage current at high fluxes..

**Short summary:**

- lower defects production (NIEL) rate for diamond compared to Si
- mainly point defects creation ( $V_0 + I$ )
- no secondary (complex) defects production after irrad. at RT
- charge trapping but no leakage currents

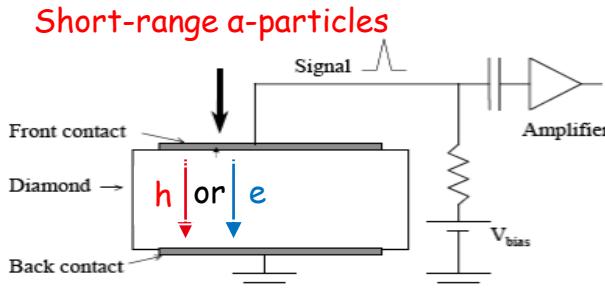
## INFLUENCE ON DETECTOR PARAMETERS – I-V



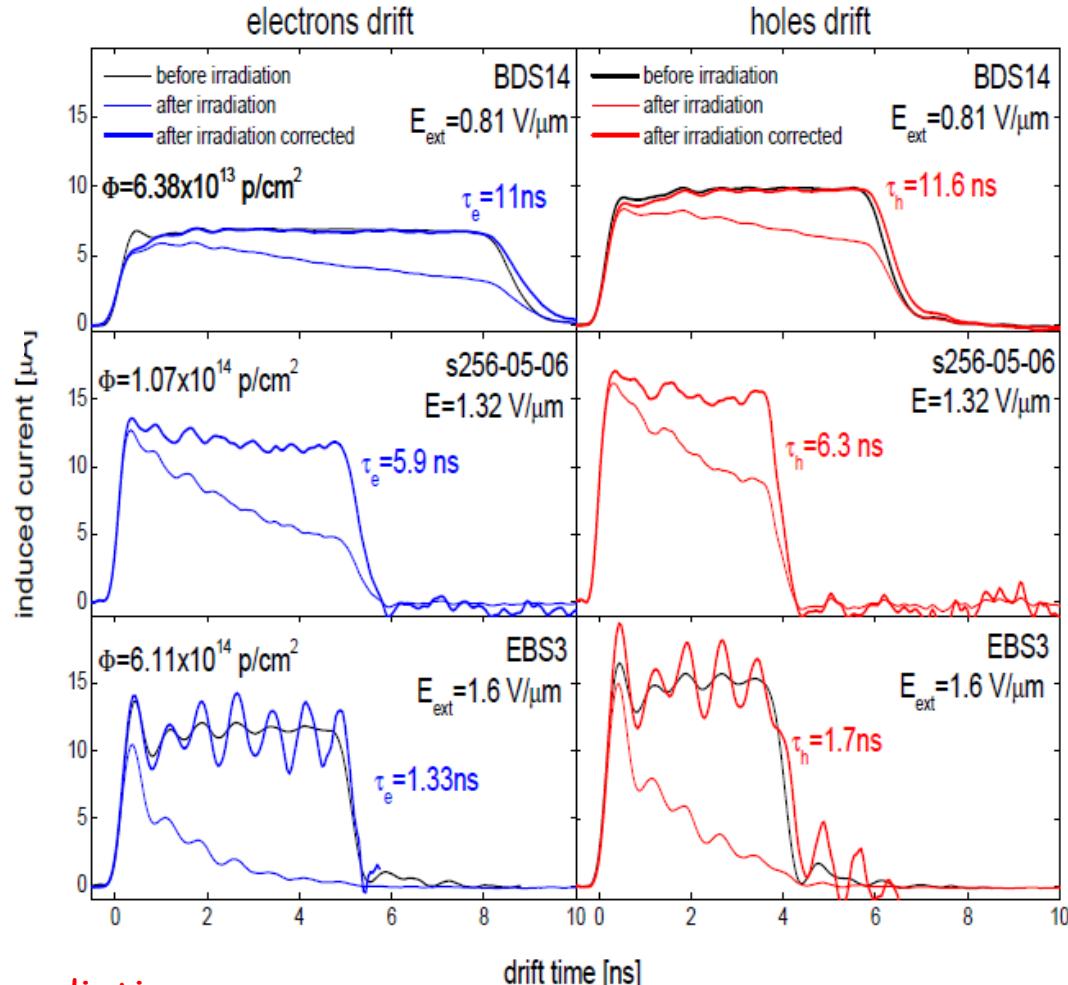
No increase in leakage current for diamond detectors after irradiation  
Actually dark current is getting better with fluence → passivation of already existing defects

# INFLUENCE ON DETECTOR PARAMETERS - CCE

Example: TCT measurements after 26 MeV proton irradiations



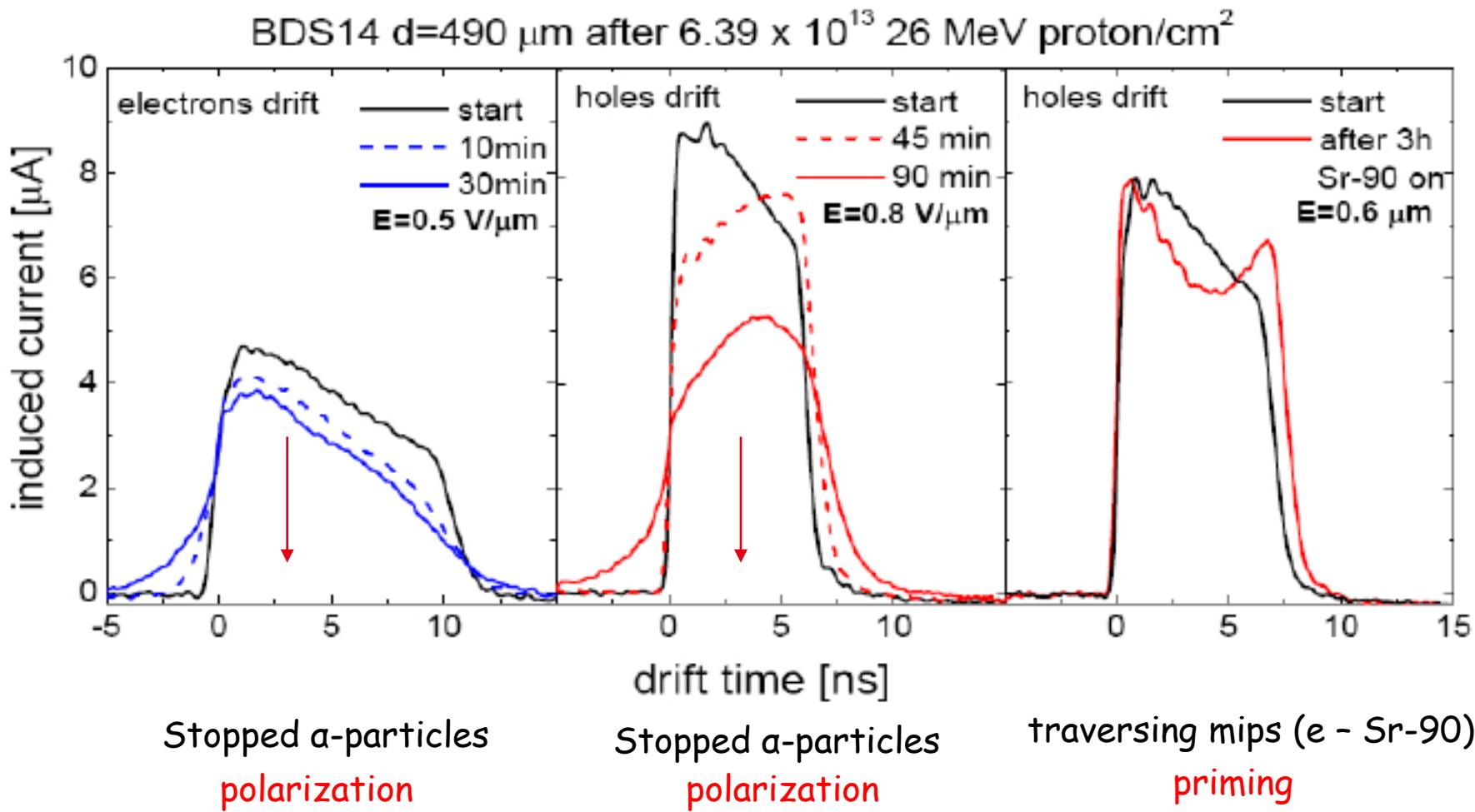
- defects homogenously distributed
- no space charge  
created defects are neutral
- drift velocity not affected
- cross-sections for trapping  $e$  and  $h$   
very similar



Similar behaviour for fast 20 MeV n irradiation

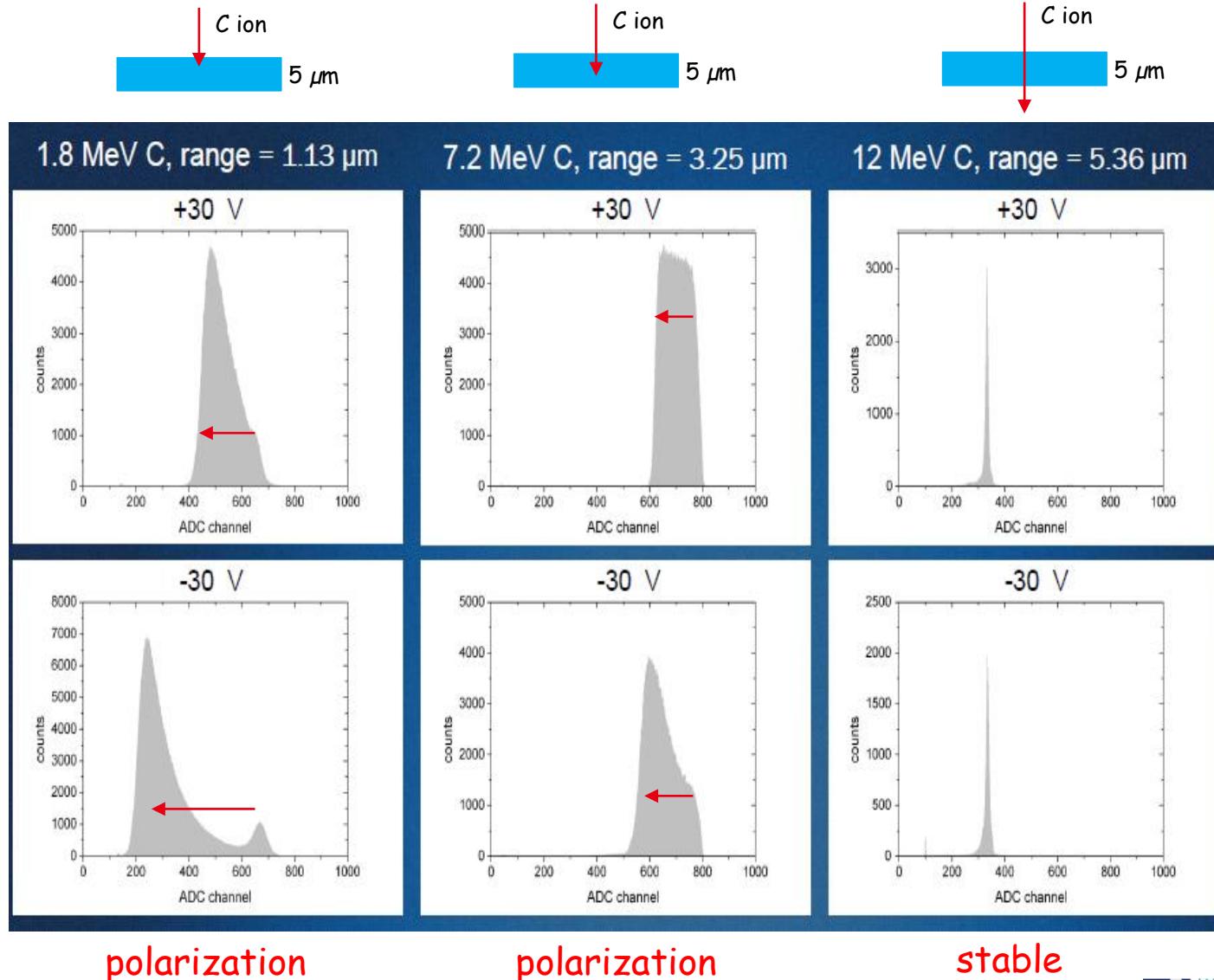
## INFLUENCE ON DETECTOR PARAMETERS - CCE

Progressive filling of deep-traps, changes internal E → build-up of space charge



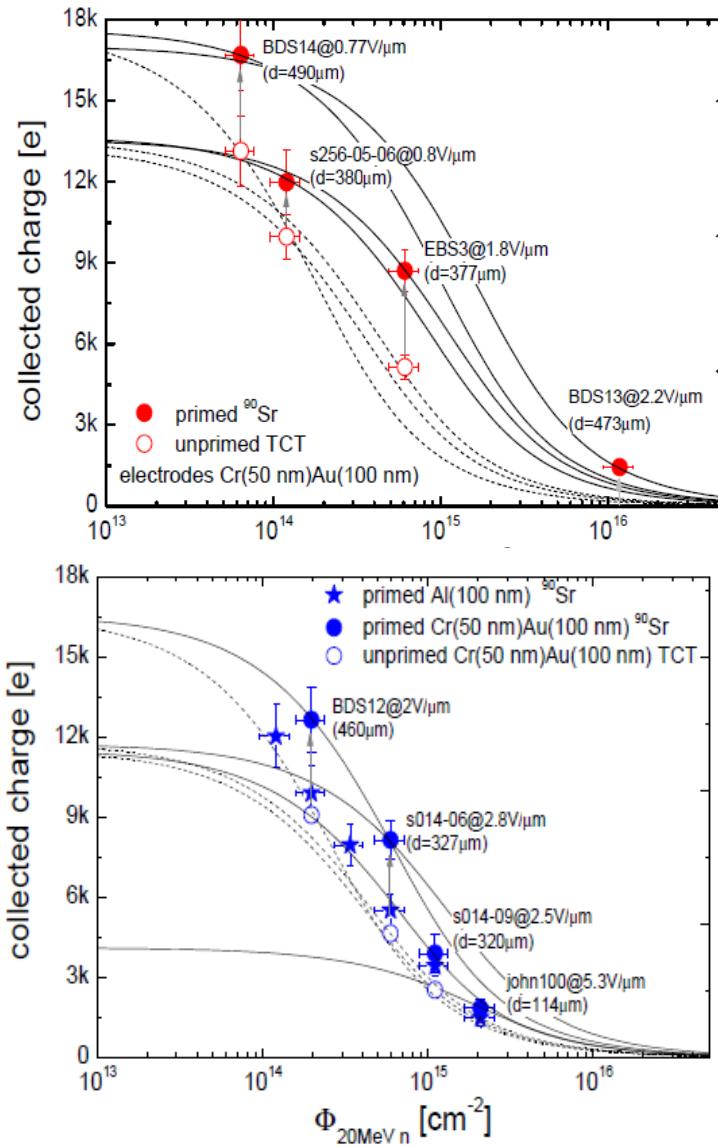
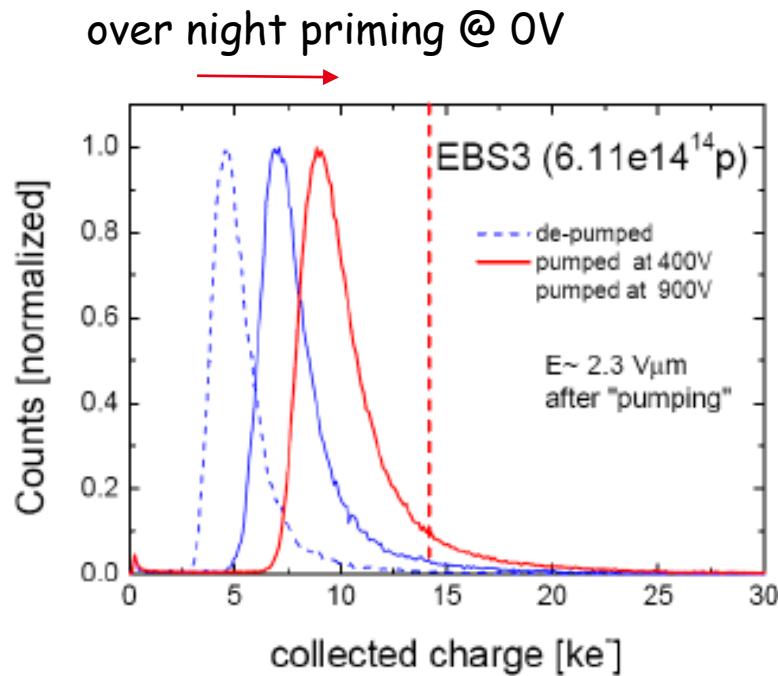
# INFLUENCE ON DETECTOR PARAMETERS-POLARIZATION

6 microns scCVD membrane detector low energy C beam (damage and probe)



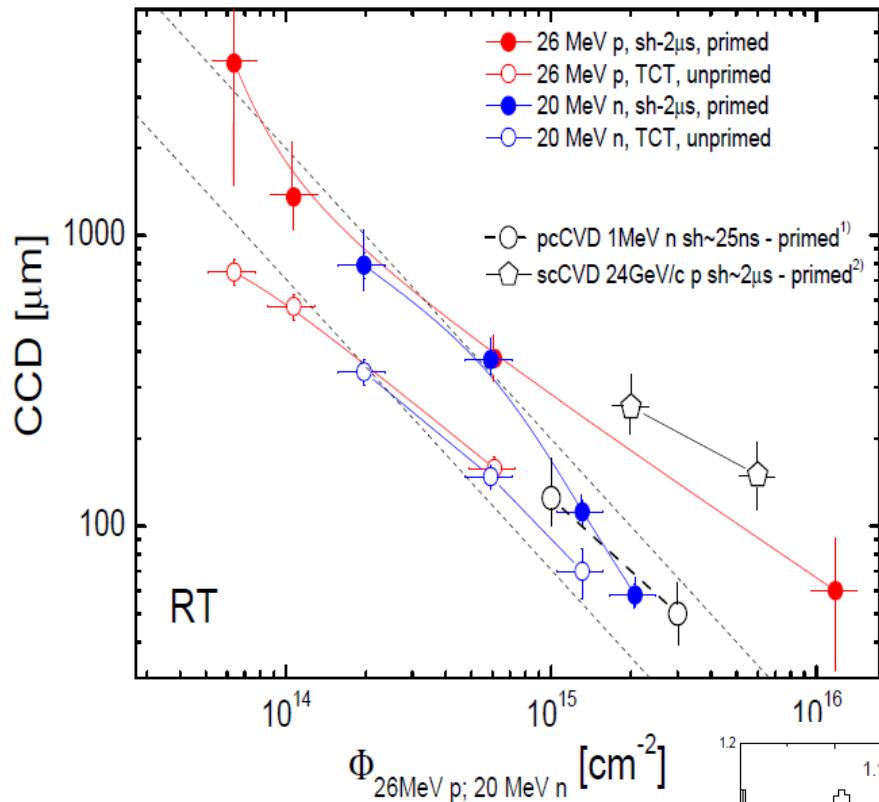
# INFLUENCE ON DETECTOR PARAMETERS - PRIMING

'Thick' 300 microns scCVD,  
a mip pumping and a probe (Sr-90 e)

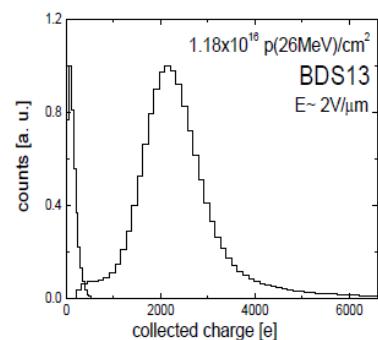


# INFLUENCE ON DETECTOR PARAMETERS- CCD

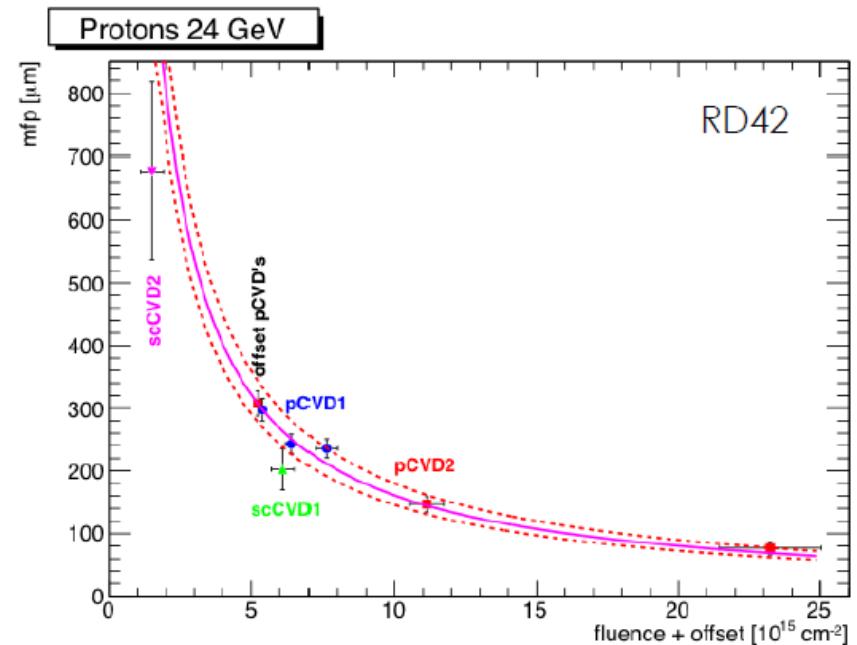
$$CCD = (\mu_n \tau_n + \mu_p \tau_p) E \sim \frac{Q_{\text{measured}}}{Q_{\text{deposited}}} * \text{thickness} = \frac{Q_{\text{measured}} [e]}{36 [e / \mu\text{m}]}$$



no leakage current =  
no change in the noise

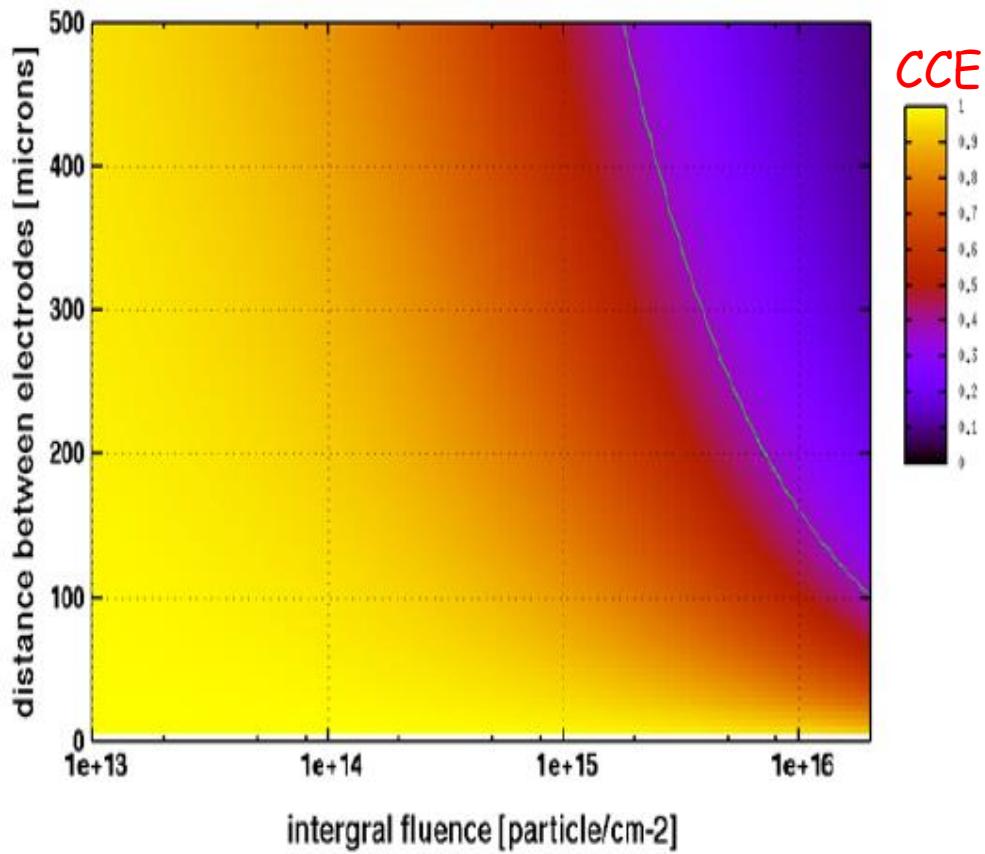


a mip spectrum after  $1.18 \times 10^{16}$  26 MeV p/cm<sup>2</sup>  
irradiation with a scCVD detector



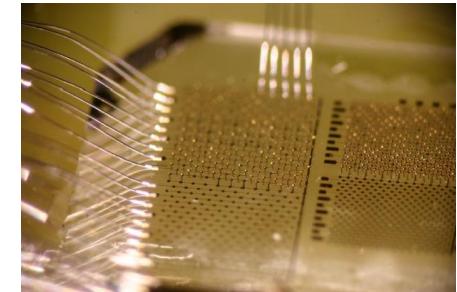
# INFLUENCE ON DETECTOR PARAMETERS

Expected CCE vs. electrode distance and integral fluence  
(for 26 MeV p irradiation)

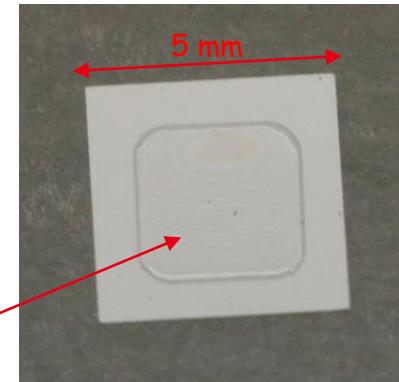


Superior radiation hardness  
through device engineering:

→ 3D Diamond Detectors

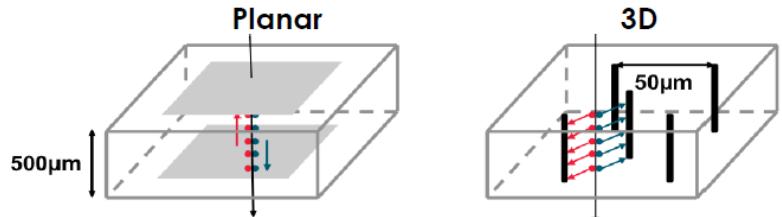


→ Membrane Detectors



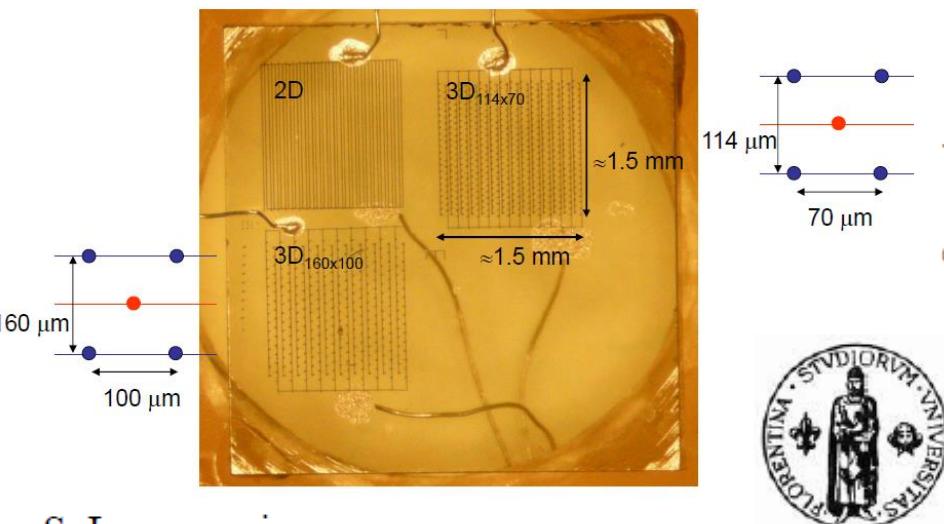
# 3D DIAMOND DETECTORS

## 3D geometry



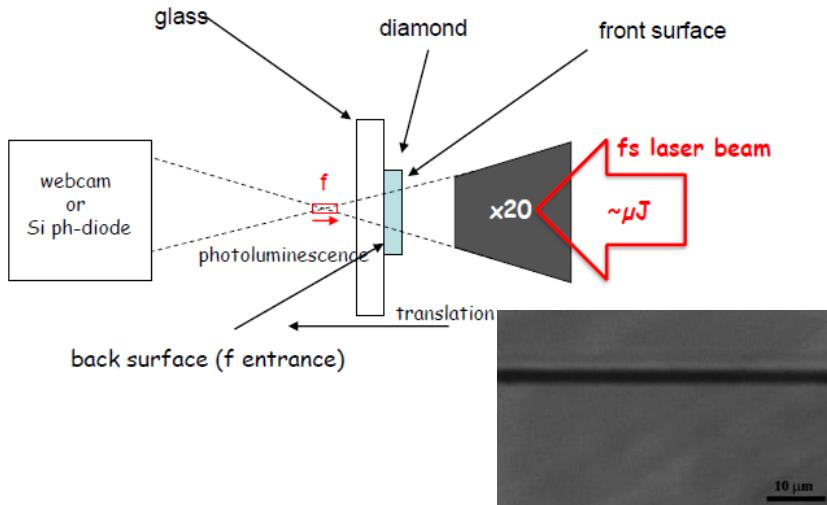
Large volume reduced drift distance: mips, fast n

## 3D laser printing of diamond detectors

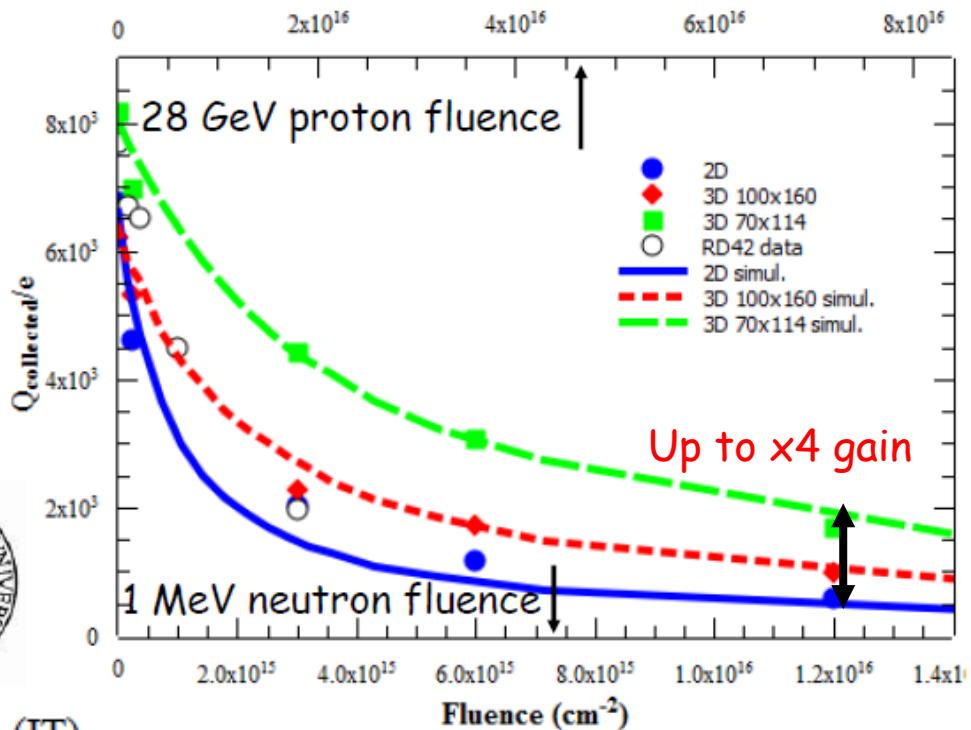


S. Lagomarsino

INFN, Department of Physics University of Florence (IT)

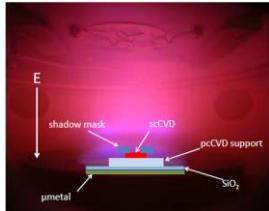


## First (neutron) RadHard data from 3D diamond



# MEMBRANE DETECTORS

Ar/O plasma etching

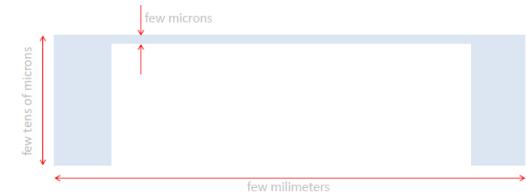
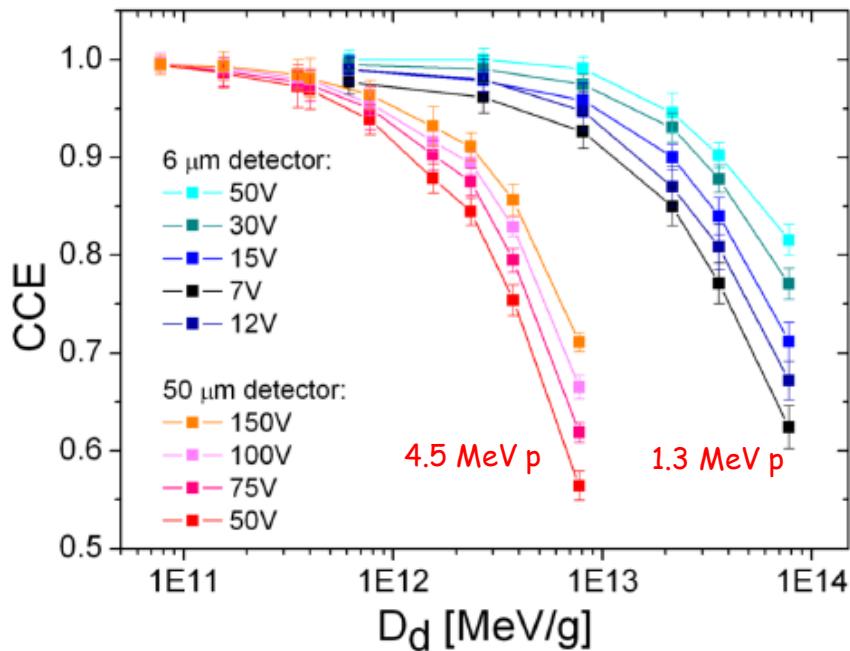


Free standing scCVD down to 3 microns  
(limited by a size of diamond slab)

Developed for low E x-ray beam monitoring  
and external microbeams.

also good for  $\Delta E$  telescopes, thermal n, HI

**50  $\mu\text{m}$  vs. 6  $\mu\text{m}$  scCVD**

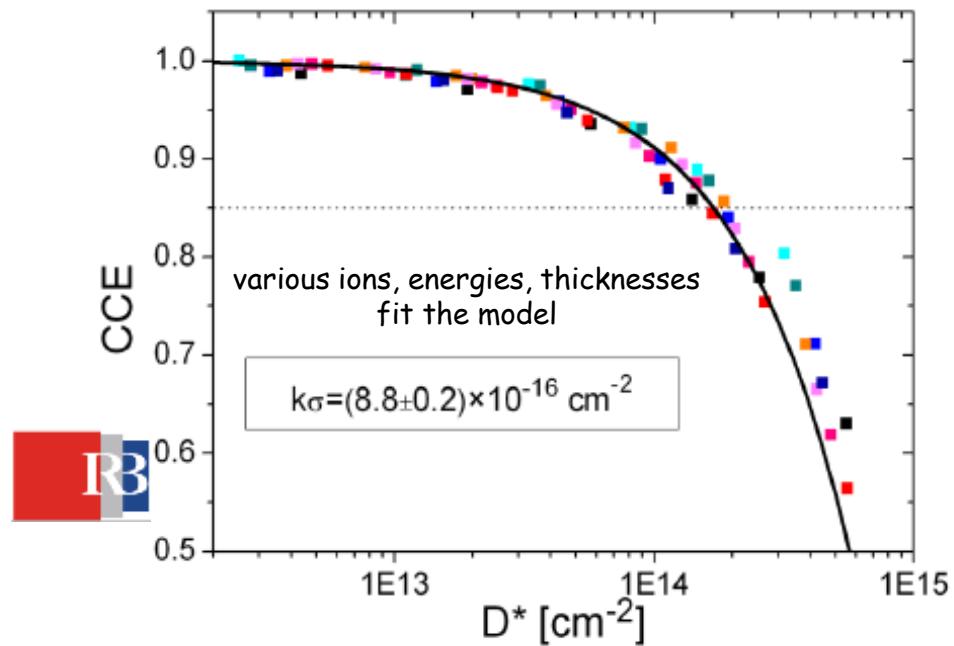


Analytical solution

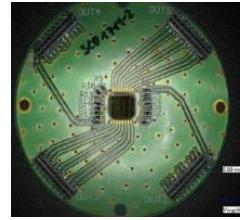
$$\text{CCE}(\Phi) = 1 - \Phi \cdot \frac{\overline{\text{vac}} \cdot d}{6} \cdot \left( \frac{v_{\text{th},e}}{v_e} + \frac{v_{\text{th},h}}{v_h} \right) k\sigma$$

D\* - effective fluence

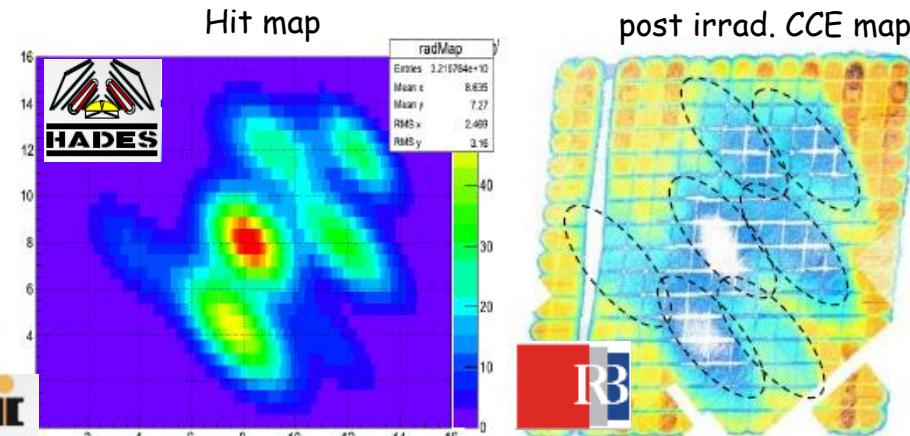
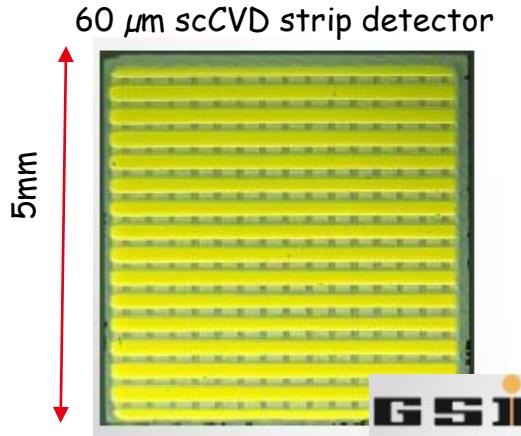
Traversing (both probe and damage)  
same trapping for e-h, moderate damage



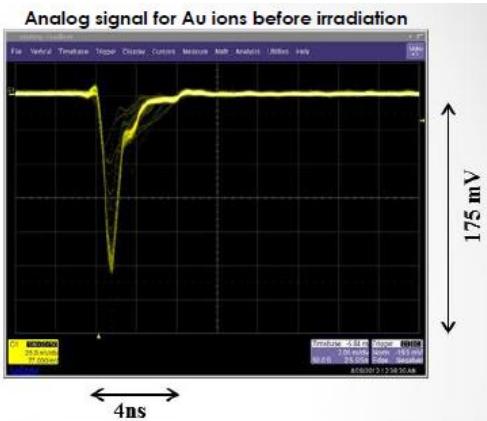
# HEAVY IONS DAMAGE -1.23 AGeV Au BEAM



HADES (GSI) diamond start detector (T0, beam profile, counting  $10^7/\text{s ch}$ )



'Continuous'  
damage  
model  
coming  
this year



## Preliminary observations:

**Very stable detector behavior after irradiation ( $\sim 10^{12}$  Au ions / mm $^2$ ):**

- Leakage current below 10 nA
  - Time resolution below 60 ps

#### Possible long term solution:

- original signal amplitude: 150 mV
  - radiation damage: reduction by a factor of 6 ?
  - additional amplification x 10

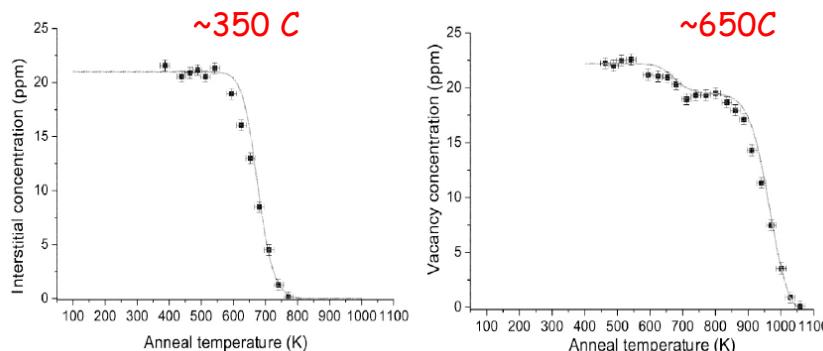
→ very long running period

J. Pietraszko, 4th ADAMAS Workshop, GSI, 2. – 4.

**Radiation hardness definition depends on application**

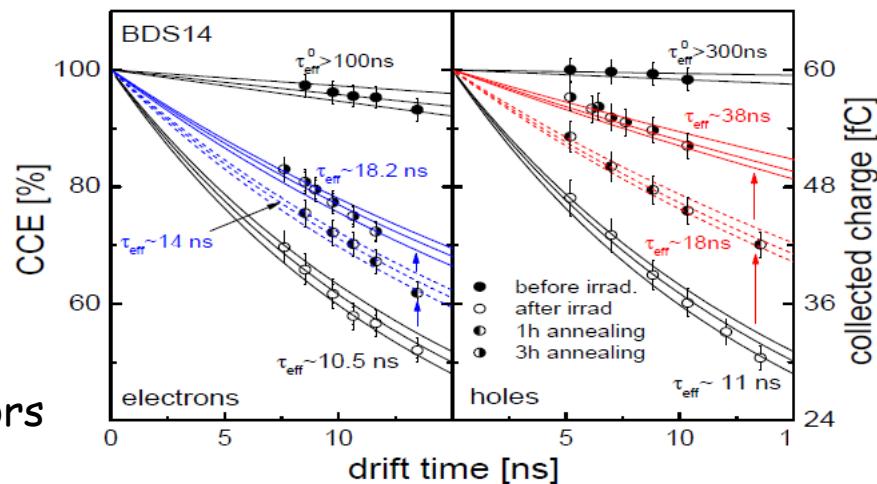
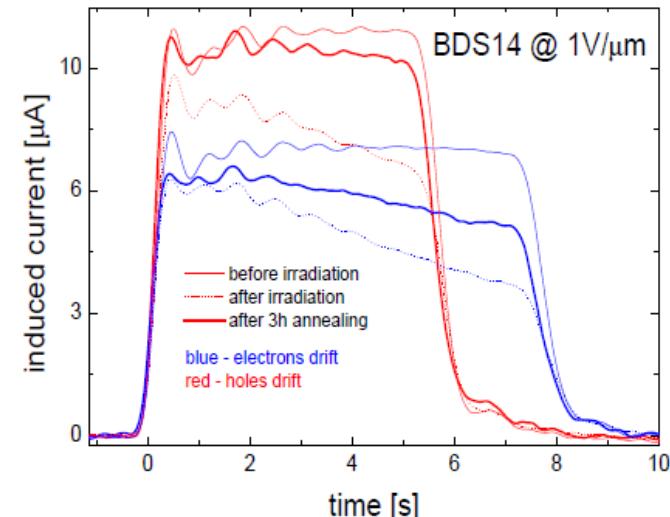
# CCE RECOVERY – HIGH TEMP. ANNEALING

Annealing of I + VO in diamond (optical absorption)



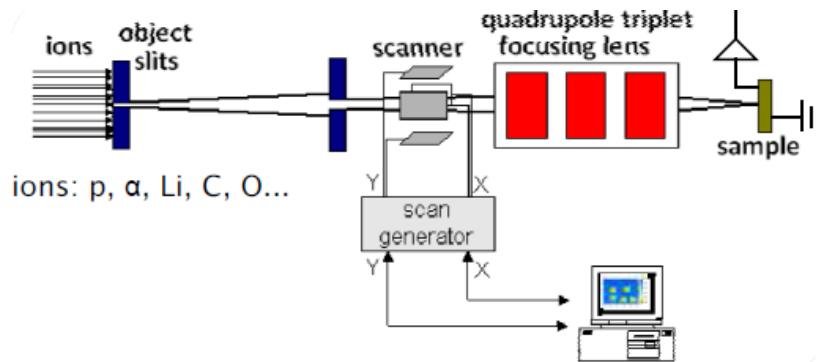
- samples annealing @ 1000 C
- almost complete recovery for holes
- less recovery for e (secondary defects?)
- ok for bare diamond - difficult for detectors

Annealing of electronic defects in diamond (TCT)

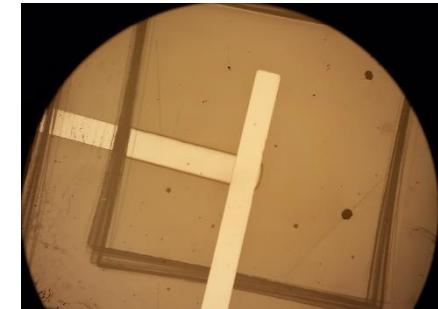


# CCE RECOVERY – HIGH FIELD OPERATION

RBI Zagreb, microbeam facility, 18MeV O ions



Sample: 4x4 mm 3.5 micron thick  
scCVD membrane e6 (<1ppm N e6)



Unpublished data was here, interested ? Please contact the author at:

[michal.pomorski@cea.fr](mailto:michal.pomorski@cea.fr)

# CCE RECOVERY – HIGH FIELD OPERATION

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[michal.pomorski@cea.fr](mailto:michal.pomorski@cea.fr)

## SUMMARY AND OUTLOOK

Diamond detectors are not forever ...

They degrade as other semiconductor materials do:

Creation of **immobile** primary defects (mainly VO+I) leads to:

charge trapping → reduced CCE  
trapped charge → polarization( $CCE \downarrow$ ) and priming( $CCE \uparrow$ )  
there is no leakage current after radiation damage

We can recover damaged diamond detectors by:

Thermal annealing (unpractical  $T > 600C$ )  
High Electric field operation (very promising)

## SUMMARY AND OUTLOOK

Some hints if you are going to operate radiation damaged diamond detectors:

- use thin detectors if you can (or 3D)
- forget about  $1 \text{ V}/\mu\text{m}$  operation field - as high as possible, if no leakage current
  - alternating detector bias fights polarization effect

I do not know if diamond detectors are radiation hard

it depends what is your criteria of RH

!!! THANKS FOR YOUR ATTENTION !!!

Commissariat à l'énergie atomique et aux énergies alternatives  
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