Concluding
NoRHDia, CARAT & ADAMAS

Novel Radiation Hard CVD Diamond Detectors
NoRHDia
Hadron Physics

CARAT
Advanced Diamond Detectors

ADAMAS
Advanced Diamond Assemblies

JRAs of the Integrated Infrastructure Initiatives (I3) for Hadron Physics

Elèni Berdermann, GSI Darmstadt

Outline

I. Introduction - the ‚Diamond JRAs‘ of the I3HPs

Characteristics of CVDD Materials and Sensors Investigated

- NoRHDia (FP6) - Novel Radiation Hard CVD-Diamond Detectors
- CARAT (FP7) - Advanced Diamond Detectors
- ADAMAS (FP7) - Advanced Diamond Assemblies

II. Comparison and Classification of CVDD sensors

- Homoepitaxial single crystal (SC CVDD)
- Heteroepitaxial single-crystal Diamond-on-Iridium (DOI)
- PolyCrystalline Diamond (PC CVDD)

III. Outlook

The I3HP-Diamond Collaborations

Countries, 11 European and 1 African

CONTRACTORS (receiving support)	OTHER INVOLVED INSTITUTIONS (without support)
NoRHDia: GSI, LUC, CEA List, IFIN-HH CARAT: GSI, UA, IFIN-HH, UGlasgow ADAMAS: GSI, UA	8 (start) to 15 (end) academic institutions + two SMEs Austria, Belgium, Bulgaria, Croatia, France, Germany, Italy, Romania, Russia, South Africa, Spain, and UK. ‚Experts' from Japan and USA

Diamond detector USERS ➡ HADES, FOPI, FRS, AND AP, BIO COLLABORATIONS

Novel Radiation Hard
CVD Diamond Detectors for Hadron Physics

Diamond Detectors for Spectroscopy and Timing

NoRHDia

NoRHDia Activities

SC CVDD (E6), Limburg/Saclay

TASKS

- Establishment of standard preparation and characterization procedures – contacts, materials, and detectors
- Optimization of HPHT growth substrates, growth processes, sensor size, and thickness
- Study of bulk and surface defects
- Radiation hardness tests up to $10^{16}/cm^2$ p, n, and e
- Development of dedicated diamond detector FE electronics

Diamond detector FE electronics

Dedicated BB and CS amplifiers

BB: *P. Moritz, GSI; M. Ciobanu, ISS Bucharest*

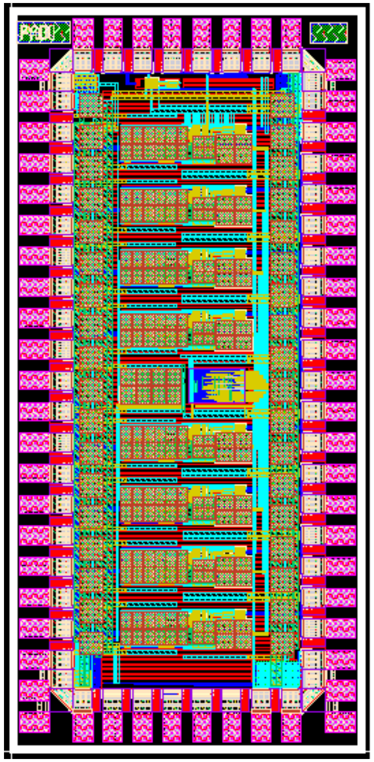
CSA: *A. Caragheorgheopol, IFIN Bucharest; U. Bonnes,TUD; A. Pullia et al. INFN-Mi*

Single-channel amplifiers

- DBA, FEE-1 (GSI) for ps-timing
- CSA (IFIN), CSTA2 (TUD) for ion spectroscopy

BB - ASIC designs, e.g. PADI 8

- 8 channel fast PreAmplifier-Discriminators;
- 180 nm CMOS technology;
- diff. amplifier input and discriminator output;
- variable input impedance ≈ 40 – 400 Ω



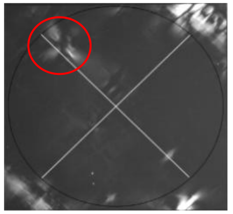
NoRHDia

SCD bulk and surface defects, contacts

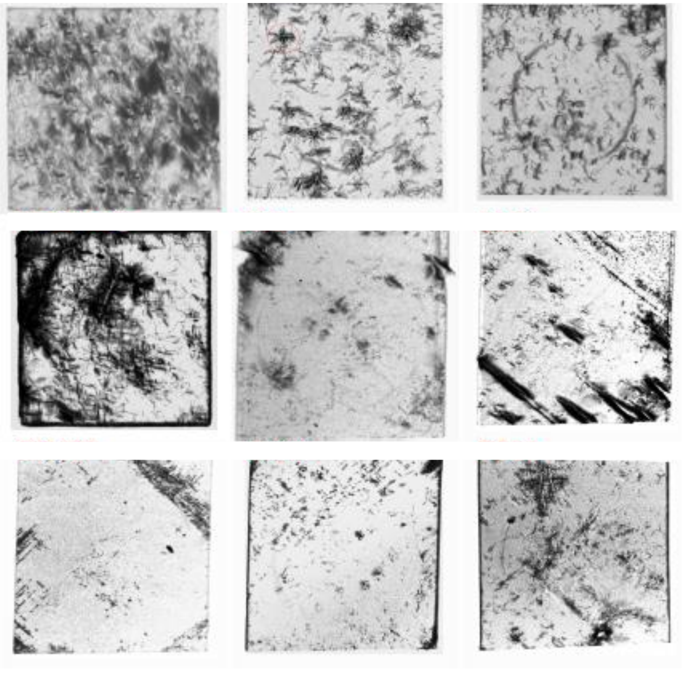
S. H. Connel, R. Lovrinčić, J. Morse, S. Noebel, Michal Pomorski

- Structural defects also in SC CVDD 'isolated threading dislocations', structural defects, and stress.

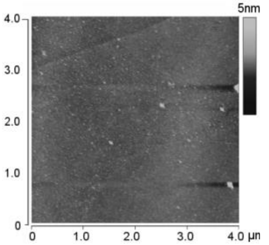
birefringence



white Beam X-ray Topographs



AFM



- Improved surface quality by ion-beam polishing, rms roughness < 1nm.

NoRHDia

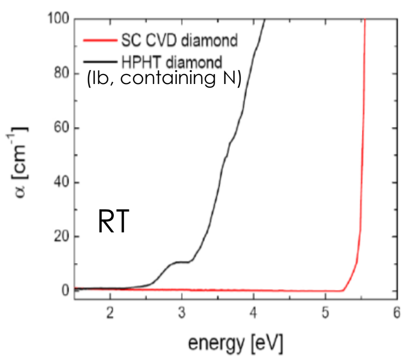
SCD bulk and surface defects

Michal Pomorski; Christoph Nebel; Annika Lohstroh

N deep donor (1.7 to 2 eV) @RT non-ionized

B acceptor 0.368eV

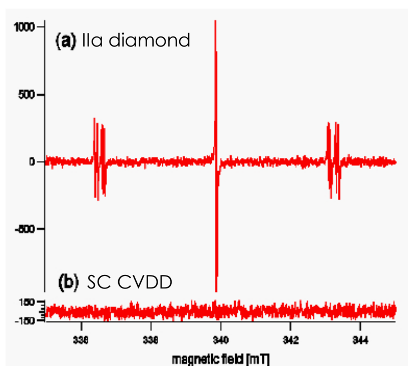
UV-VIS Optical Absorption



Nitrogen detection

➢ 2 eV photo-ionization

Electron Spin Resonance (ESR)

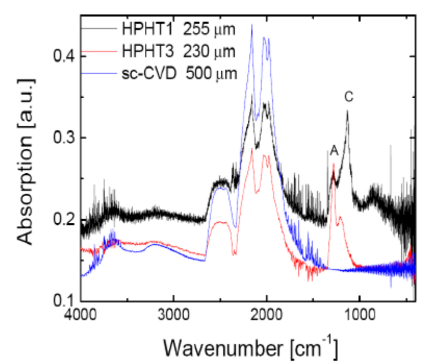


Nitrogen detection

ESR Signal

sensitivity < $10^{14}/cm^3$

IR Absorption



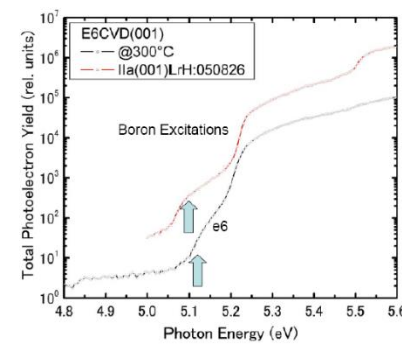
Nitrogen detection

sign of N: C or A centers

sensitivity 1ppm

TPYS

Total Photoelectron emission Yield Spectroscopy



Boron detection

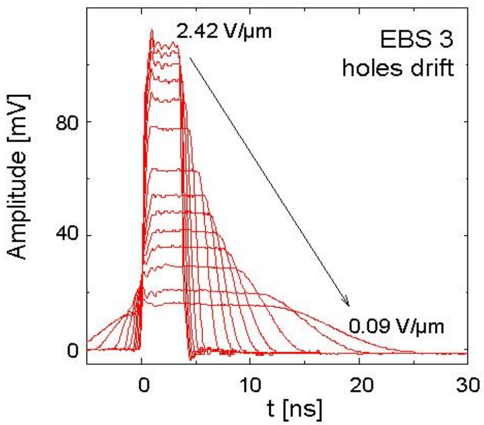
5.1 eV ; < 5.2 eV

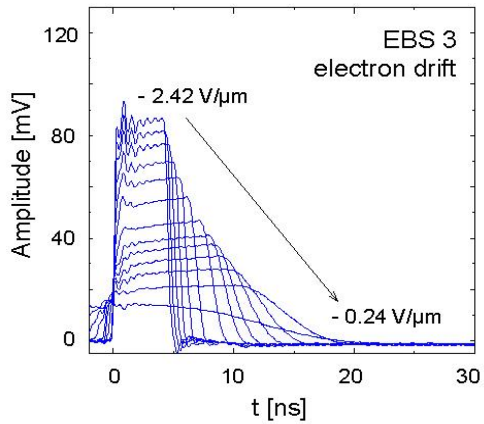
NoRHDia

Internal field profile, transport parameters

Michal Pomorski PhD Thesis (2008)

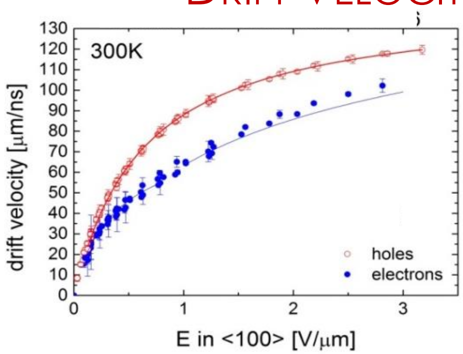
^{241}Am-α-SIGNALS AT INCREASING E_D

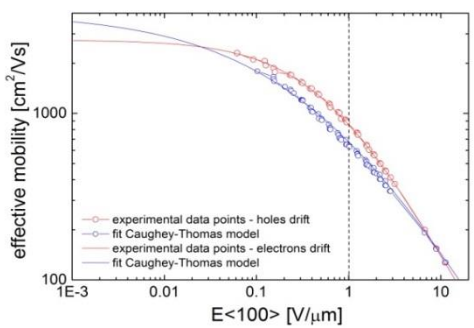




$$v_{dr}(E_D) = \frac{\mu_0 \cdot E_D}{1 + \frac{\mu_0 \cdot E_D}{v_{sat}}}$$

DRIFT VELOCITY, DRIFT MOBILITY





LOW-FIELD MOBILITY, SATURATION VELOCITY

	μ_0 [cm²/Vs]	v_{sat} [cm/s]
electrons	4551 ± 500	(2.63 ± 0.2) x 10^7
holes	2750 ± 70	(1.57 ± 0.14) x 10^7

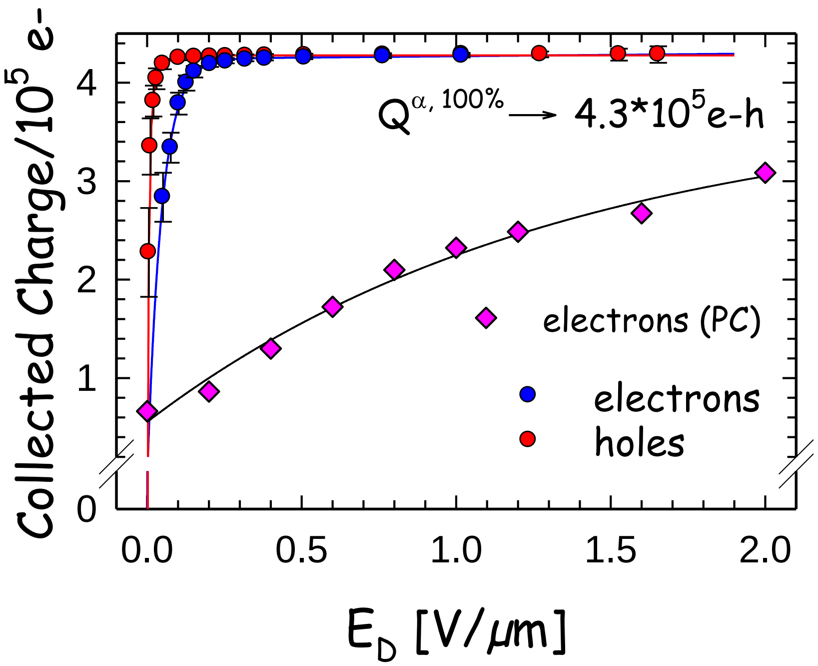
μ_0(e) controversial in literature:
Ok with Isberg, Pernegger;
Not with Tranchant et al.

NoRHDia

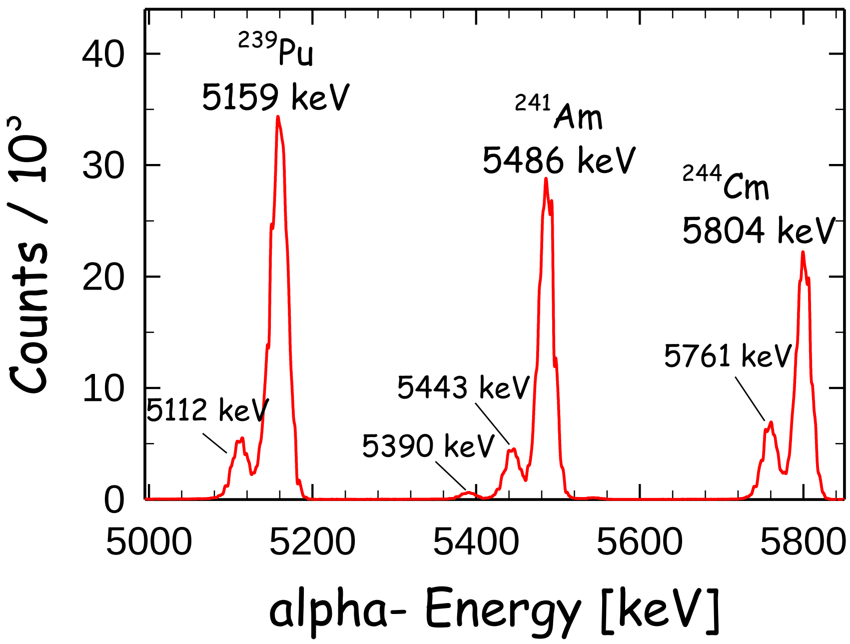
SCD – charge-collection properties

Low energy, stopped particles (single-carrier drift)

α-CCE ~ 100%; ε_{SCD} = 12.84 eV/e-h



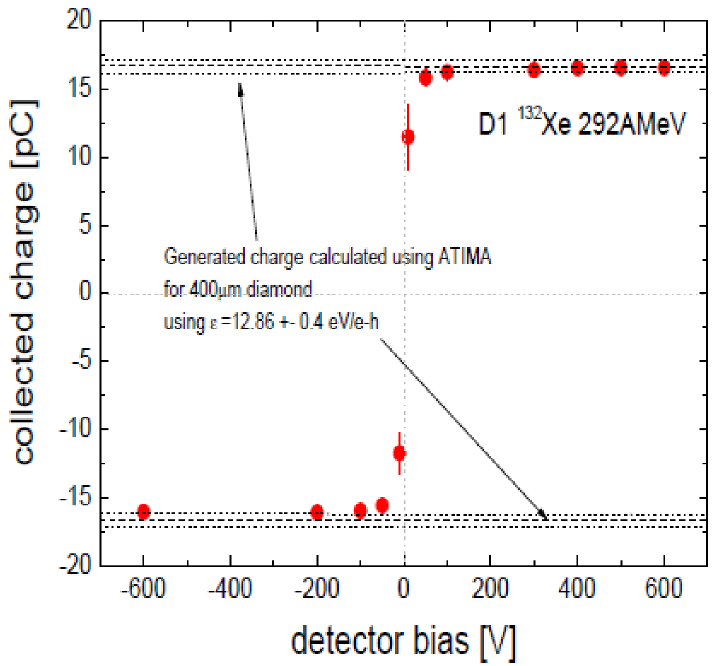
α - resolution dE/E = 0.003 ~ to Si (RT)



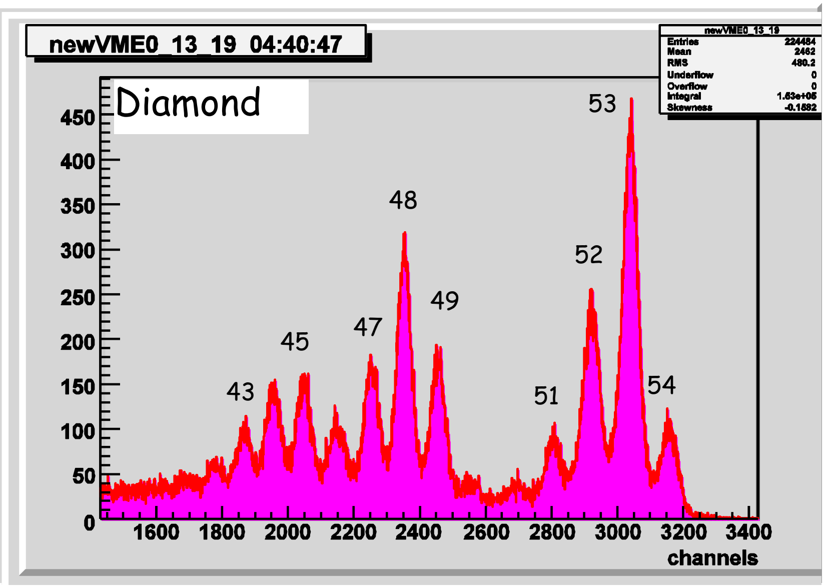
NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)



Online ^{132}Xe fragmentation spectra



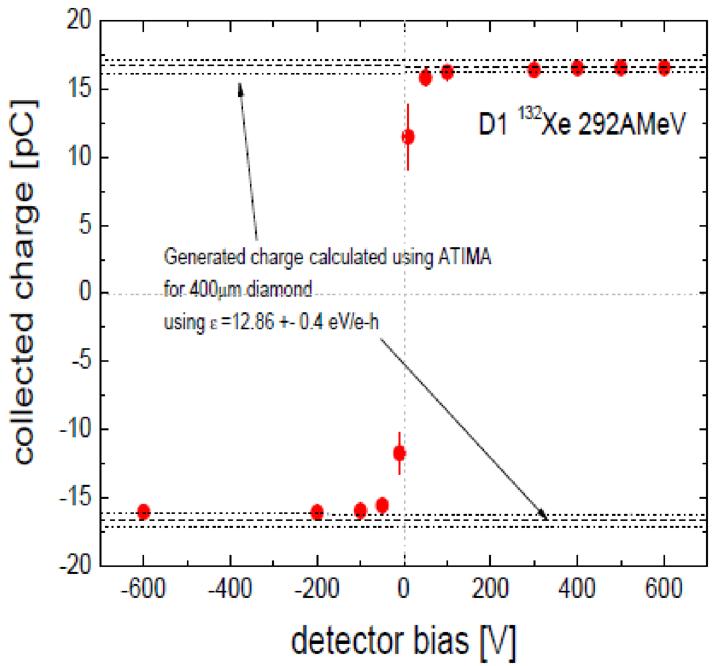
Ion Energy [ch]

No pulse-height defects in SCD (!)

NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)



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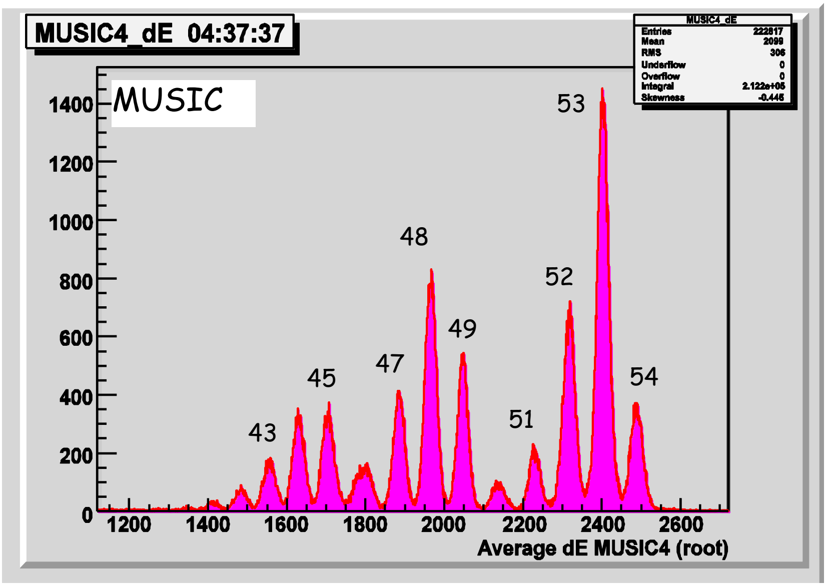


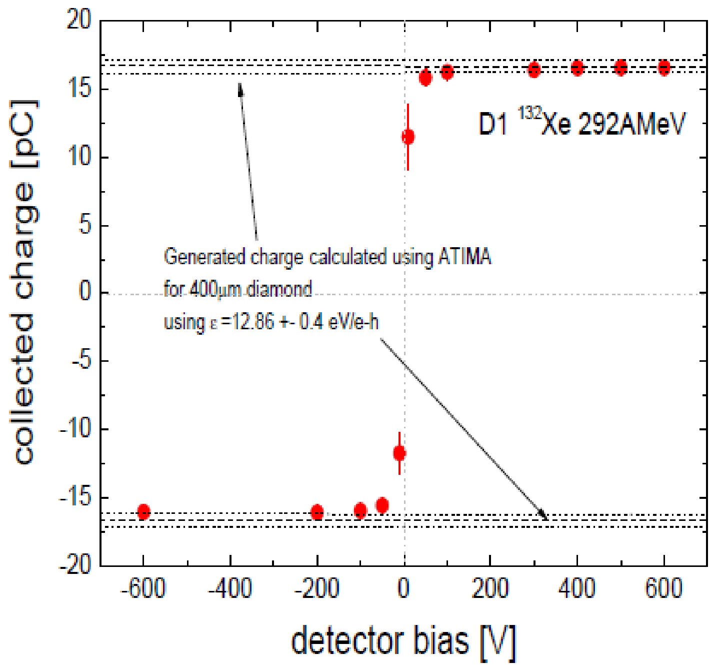
Ion Energy [ch]

Compare MUSIC data (!)

NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)



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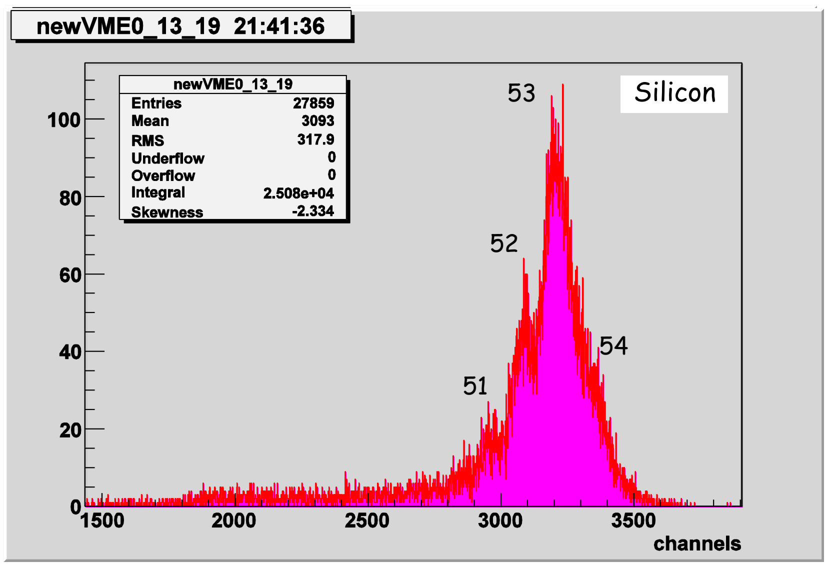


Ion Energy [ch]

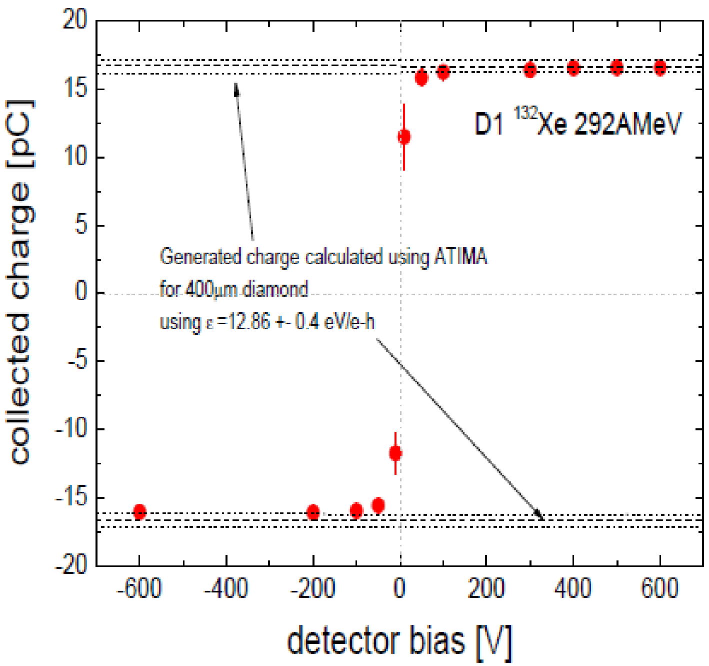
Compare Silicon data high range ….

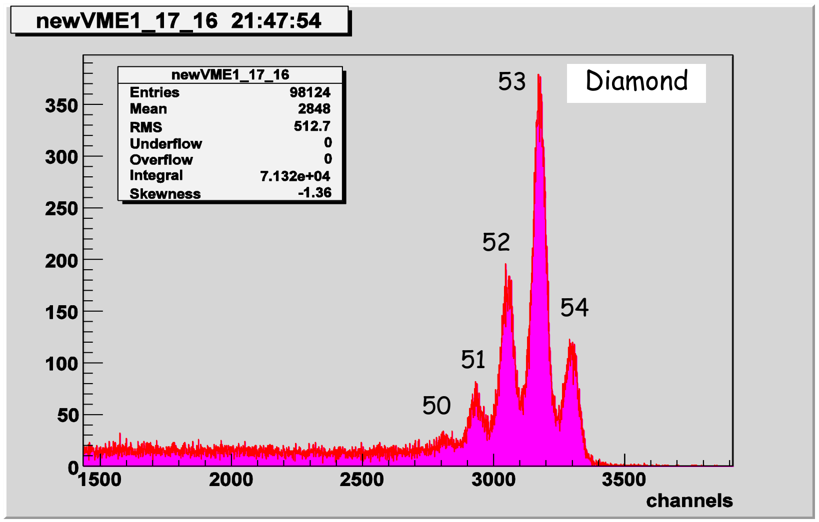
NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)

Online ^{132}Xe fragmentation spectra





Ion Energy [ch]

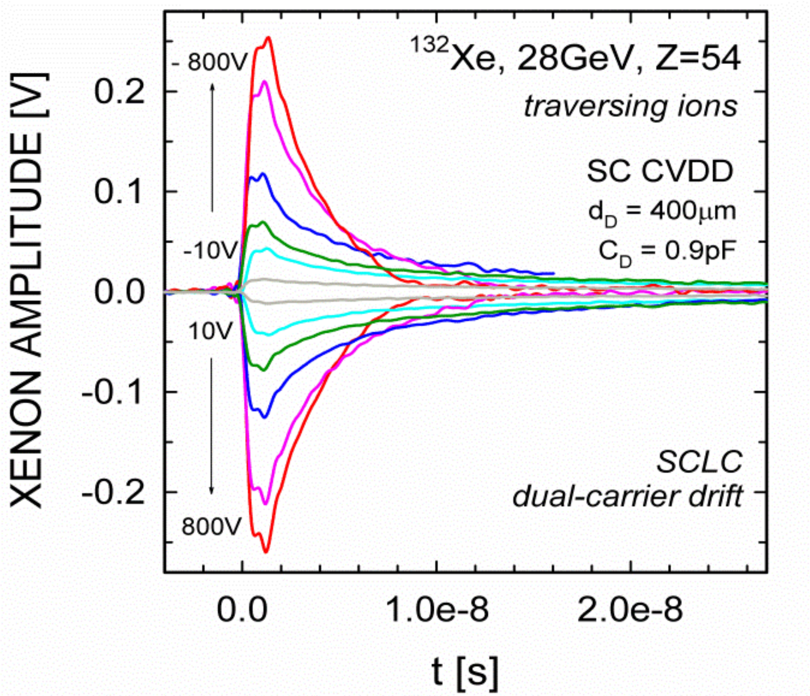
… with same range Diamond data (!)

NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)

Original (non amplified)
^{132}Xe-induced TC signals



Diamond in HI exp.: t_{decay} ~ 20-25 ns worse case

BUT << 1-2 µs shaping time of CSA

Silicon in HI exp. : t_{decay} ~ many µs up to ms

THUS: incomplete integration of charge

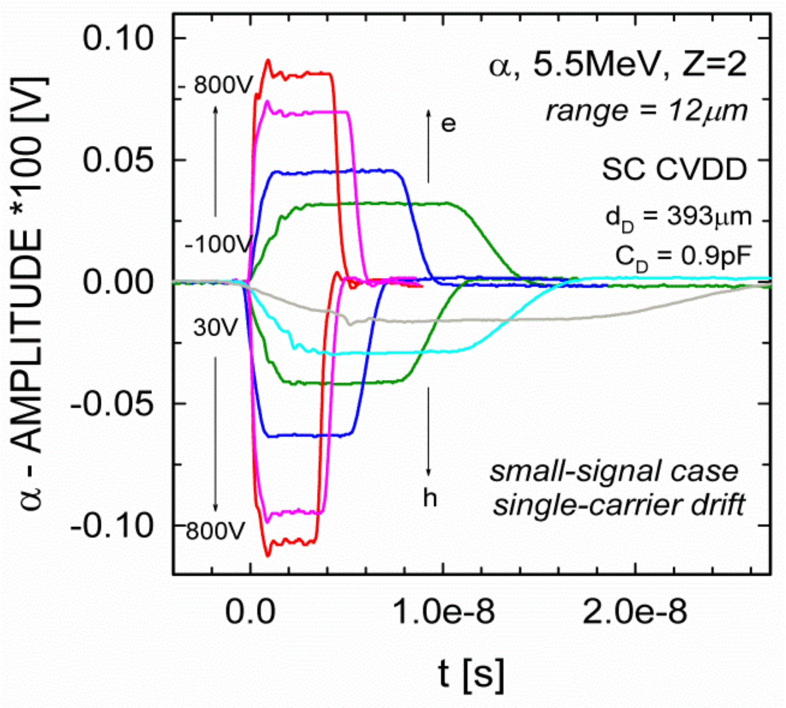
PH DEFECTS IN SI

NoRHDia

SCD – charge-collection properties

Relativistic particles (dual-carrier drift)

DBA
compare α - TC signals



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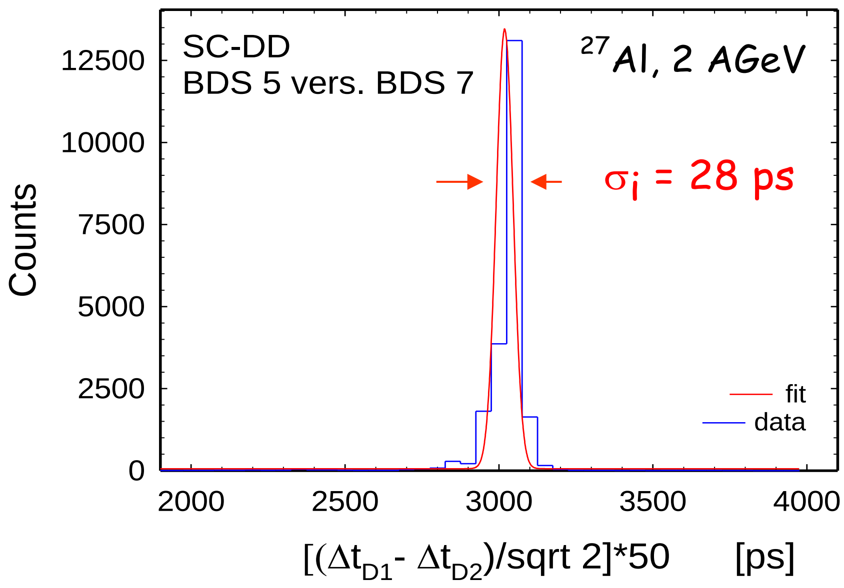
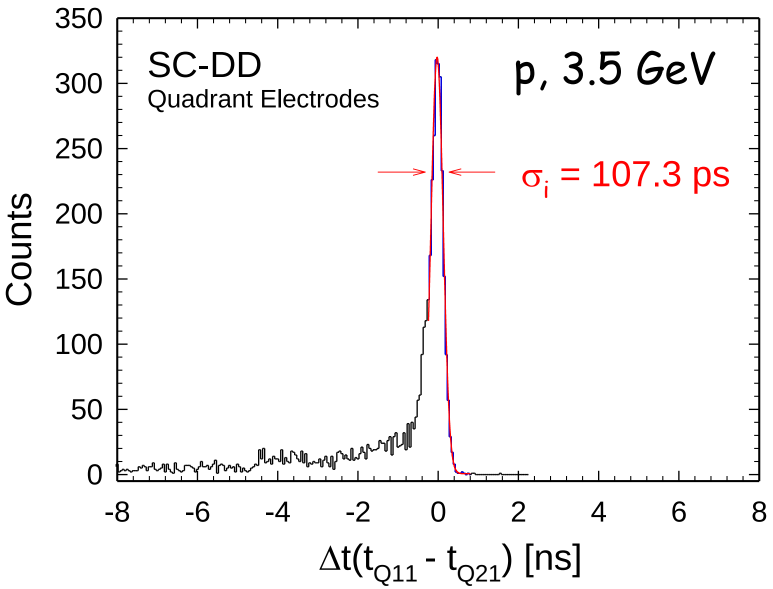
PH DEFECTS IN SI

NoRHDia

Intrinsic time resolution (σ_i)

The FOPI and the HADES Collaborations





limited by the electronic noise

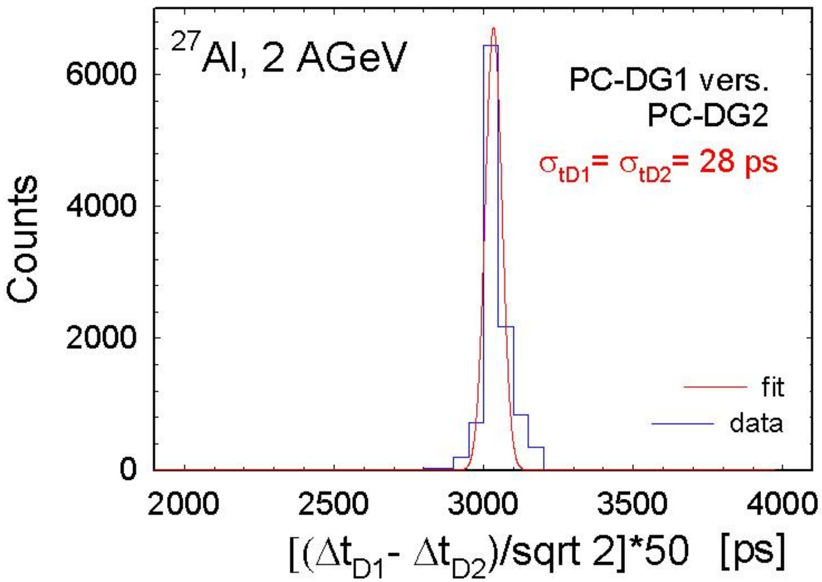
for MIP timing

SC CVDD the material of choice

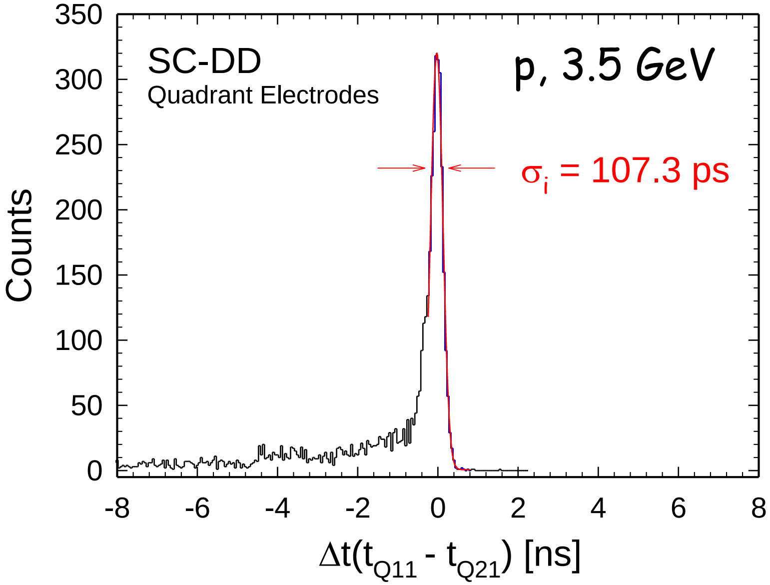
NoRHDia

Intrinsic time resolution (σ_i)

The FOPI and the HADES Collaborations



limited by the electronic noise



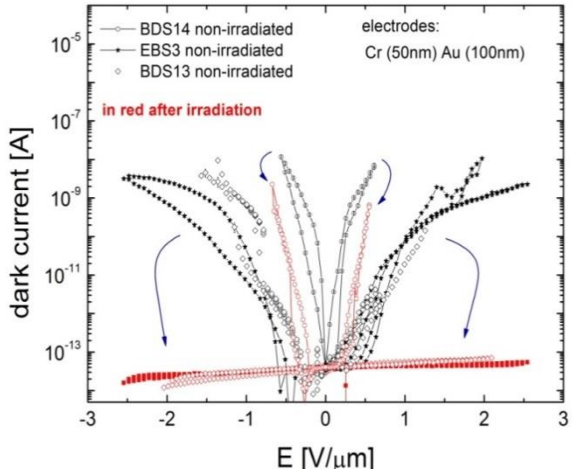
for MIP timing

SC CVDD the material of choice

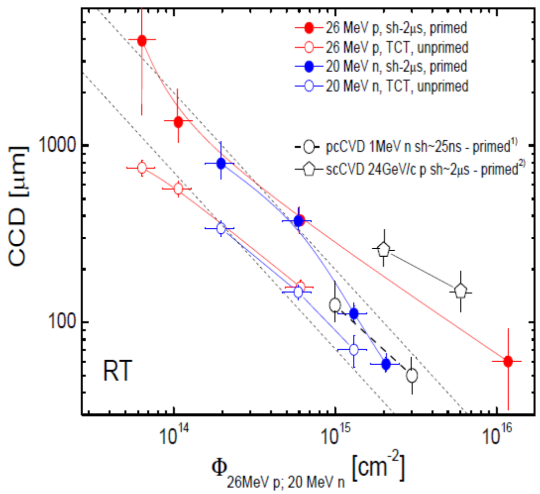
NoRHDia

SCD - Radiation Hardness

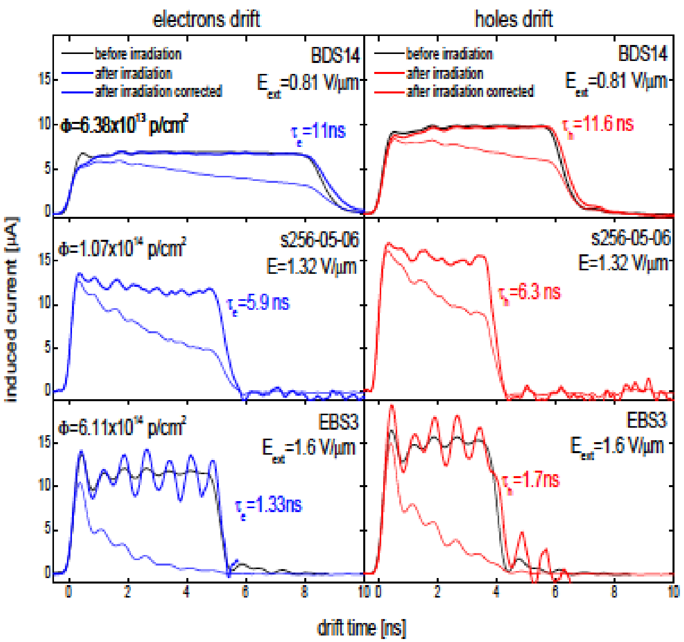
Michal Pomorski PhD Thesis (2008)



Compensation by V0 defects (deep donors)



Agreement with RD42

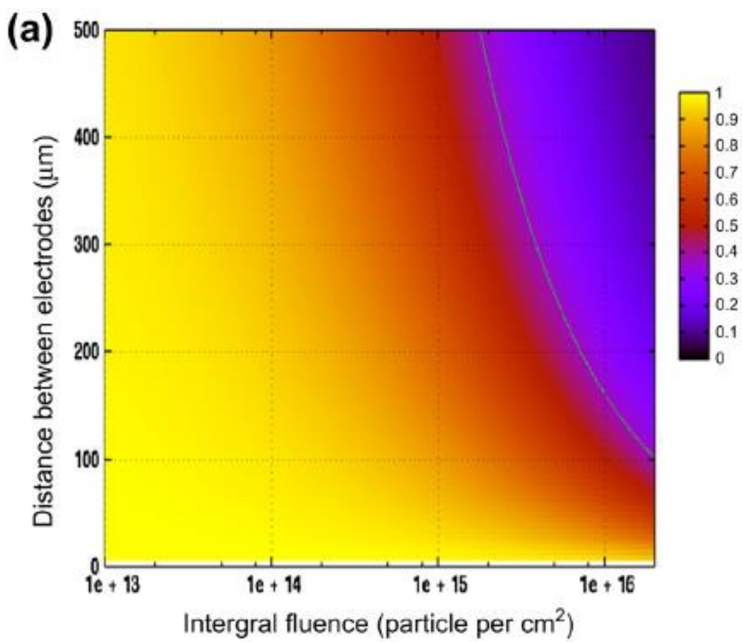


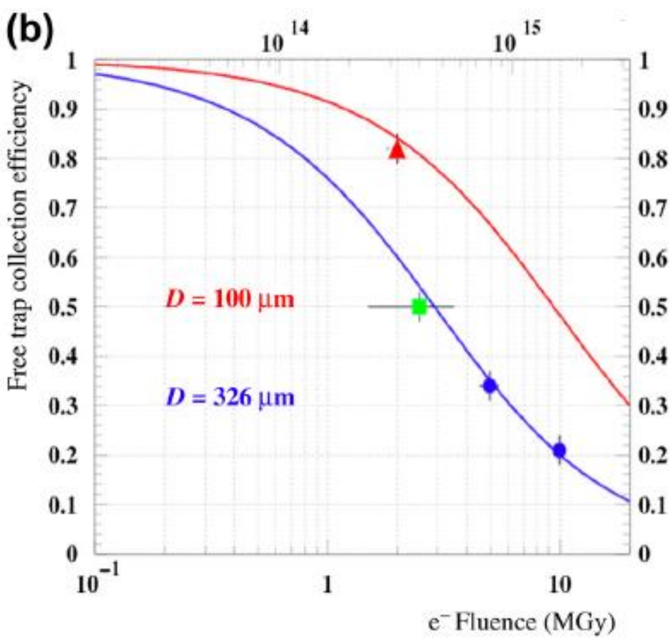
Indicating V0 production, Timing signal 'harder' than CCD

NoRHDia

Thickness dependence

Michal Pomorski thesis (left plot),
Wolfgang Lohmann, Sergej Schuwalow et al. (right graph)



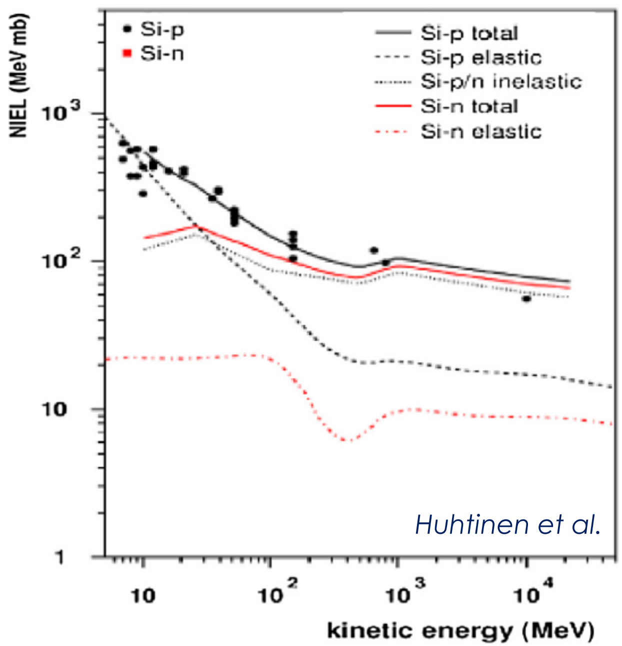


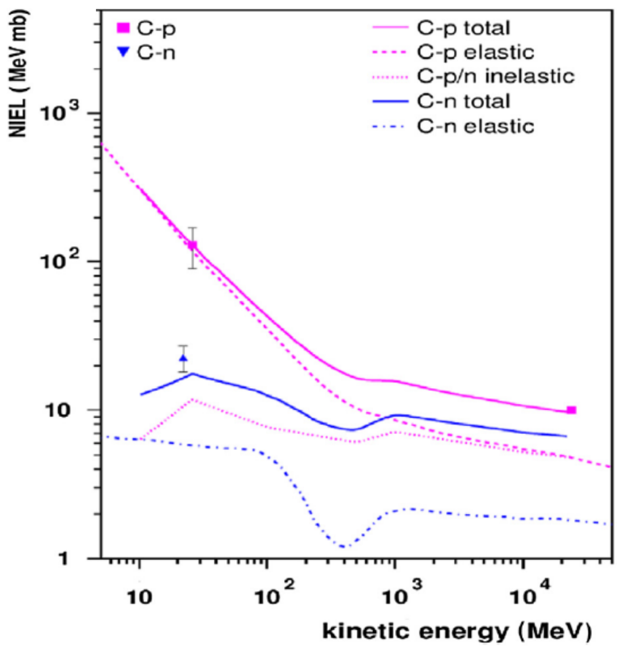
NoRHDia

SCD - Radiation Hardness

Wim de Boer et al. U Karlsruhe (2007)

NIEL hypothesis: Signal loss ∝ NIEL ∝ N_{def}





SRIM calculations

E > 100 MeV ⇨

Diamond > 10 x harder than silicon

E < 100 MeV ⇨

Diamond > ~ 3.5 x harder than silicon

SCD - Radiation Hardness

Steffen Müller, PhD Thesis, U Karlsruhe (2008)

Disadvantage ➡ NIEL hypothesis overestimates damage

- NEW MEASURE FOR RADIATION DAMAGE ➡ DISPLACEMENT PER ATOM (DPA)

“how often a carbon atom is displaced (on average) by incident particles”

- DPA is independent of the sample density and volume
- DPA is directly related to the production of Frenkel pairs (interstitial atom + vacancy)
- DPA distributions follow the characteristic shape of the specific energy loss along the path through the irradiated sample.

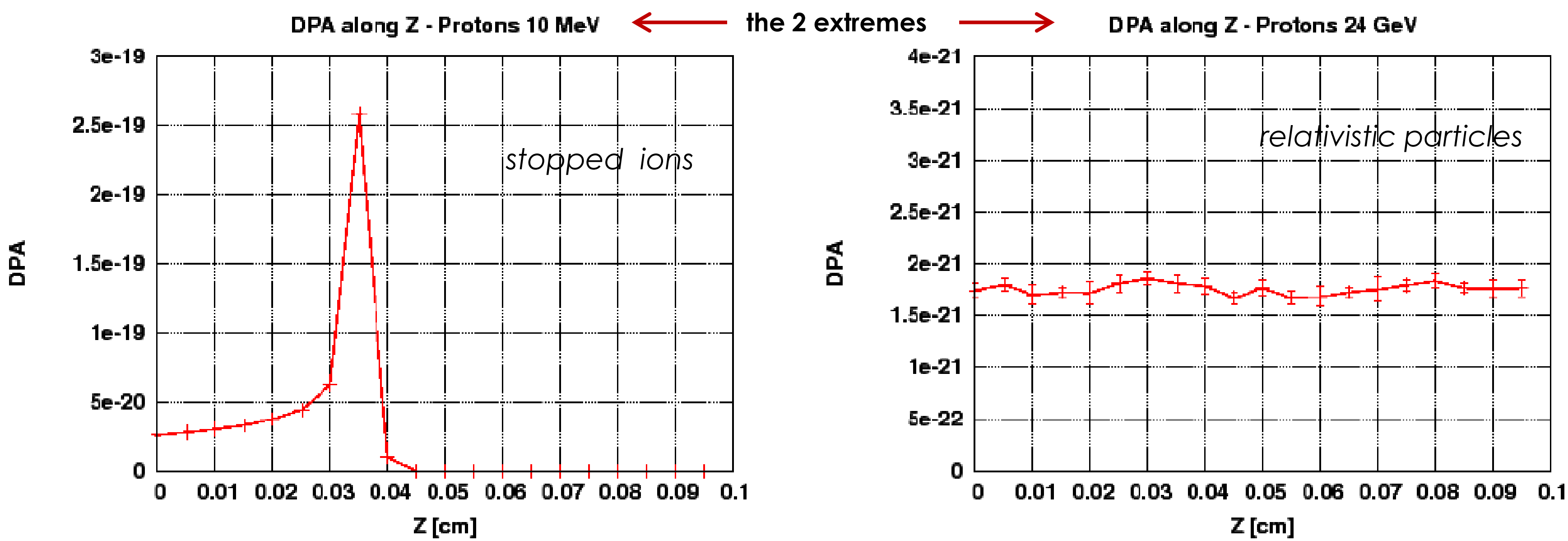
NoRHDia

SCD - Radiation Hardness

Steffen Müller, PhD Thesis, U Karlsruhe (2008)

Disadvantage ➡ NIEL hypothesis overestimates damage

- ❖ New Measure for radiation Damage ➡ Displacement Per Atom (DPA)

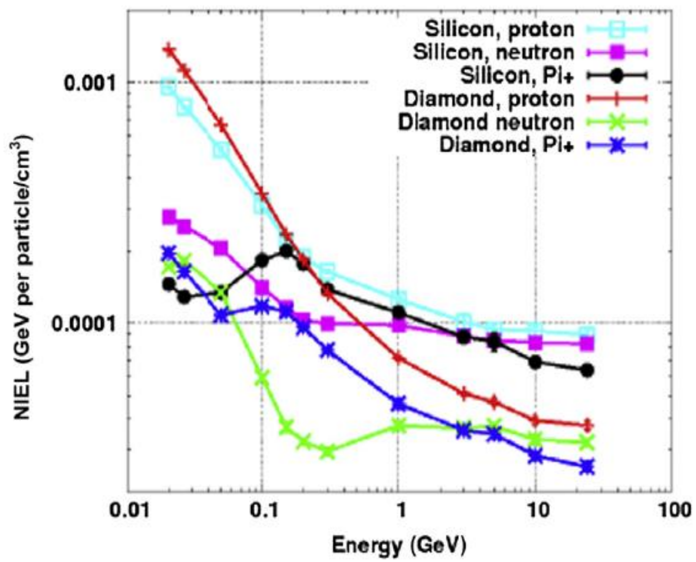


NoRHDia

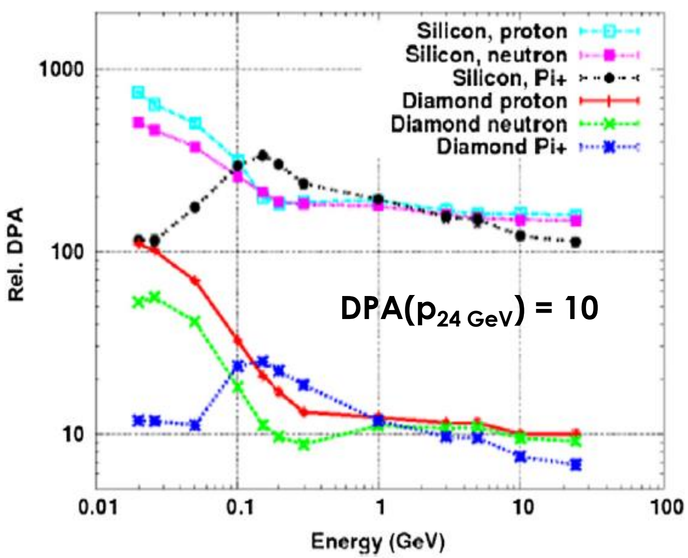
SCD - Radiation Hardness

Steffen Müller, PhD Thesis, U Karlsruhe (2008)

NEW NIEL SIMULATIONS for
DIAMOND & SILICON

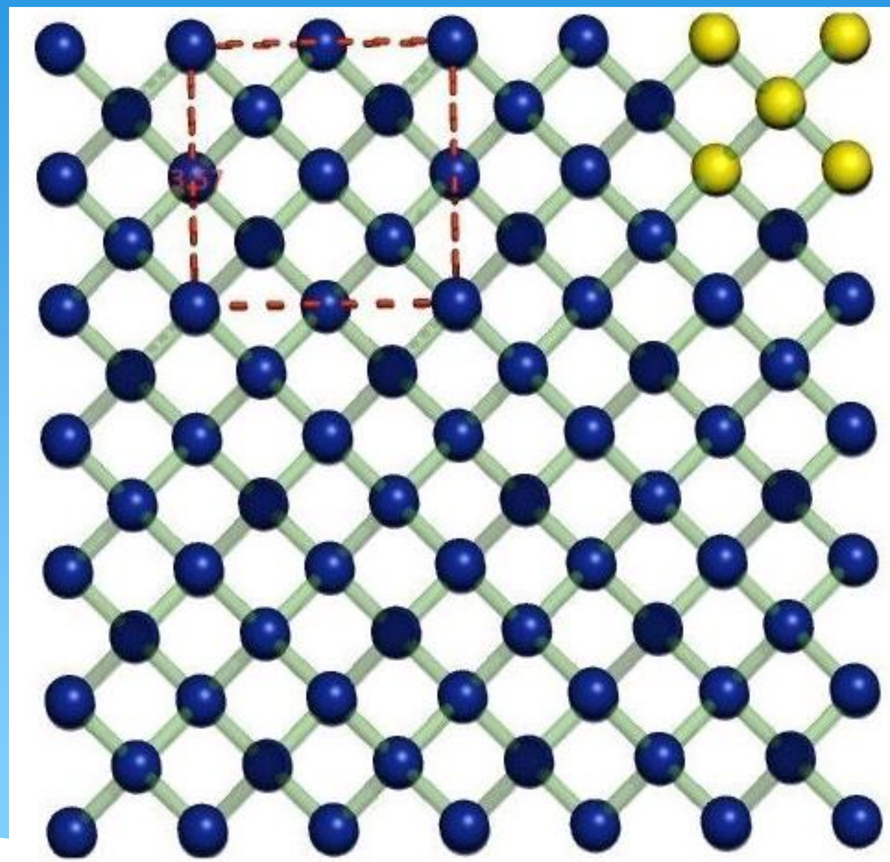


DPA SIMULATIONS for
DIAMOND & SILICON



NEW RESULTS FAVOUR DIAMOND → $D_{Si}(E)/D_{Dia}(E)$ ~15:1 at E = 24 GeV
,, ~ 6.7:1 at E = 20 MeV

CARAT



Advanced Diamond Detectors

CARAT Activities

CVD Diamond-on-Iridium (DOI)

TASKS

- Engineering of intrinsic DOI plates for detector applications
  - crystal growth and post processing; defect characterization
- Characterization of the electronic properties of DOI materials and sensors
- FEE developments
  - broadband amplifiers and discriminators – single-channel and ASICs - in particular, for fast MIP timing

Target ➡ Large-area, advanced-diamond strip sensors for tracking and ToF of HIs and MIPs

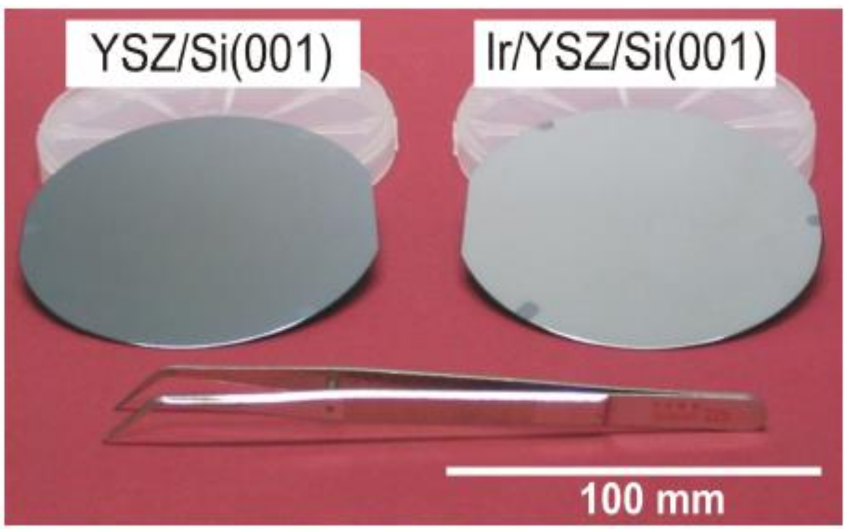
CARAT

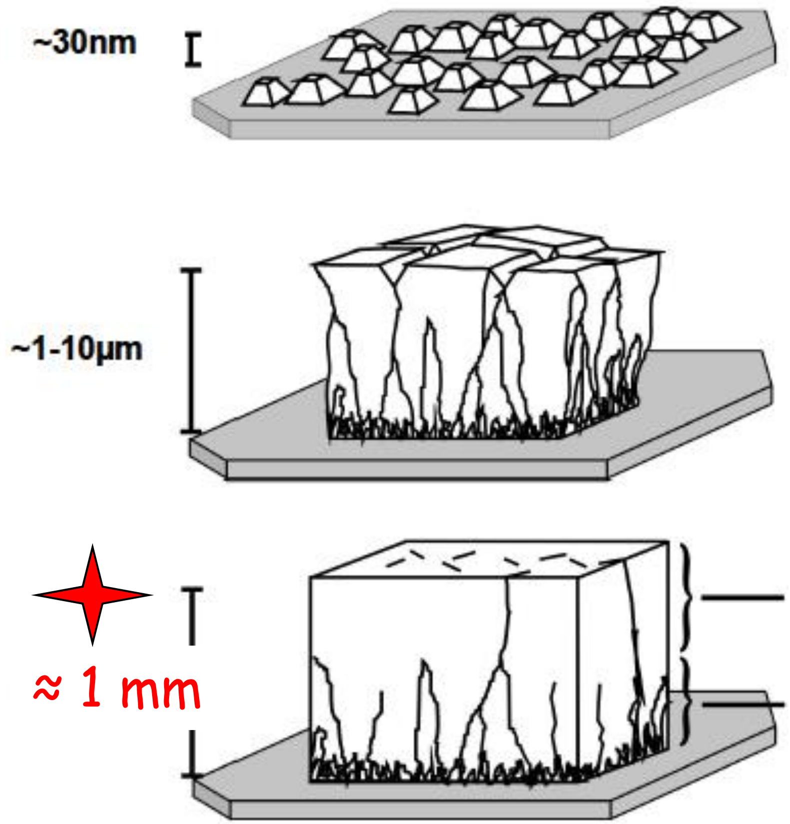
DOI growth for detector applications

Stefan Gsell et al., Appl. Phys.Lett. 84 (2004)

Wafer scale single-crystal diamond detectors by heteroepitaxy

on large-area multilayer substrates of Iridium top layers



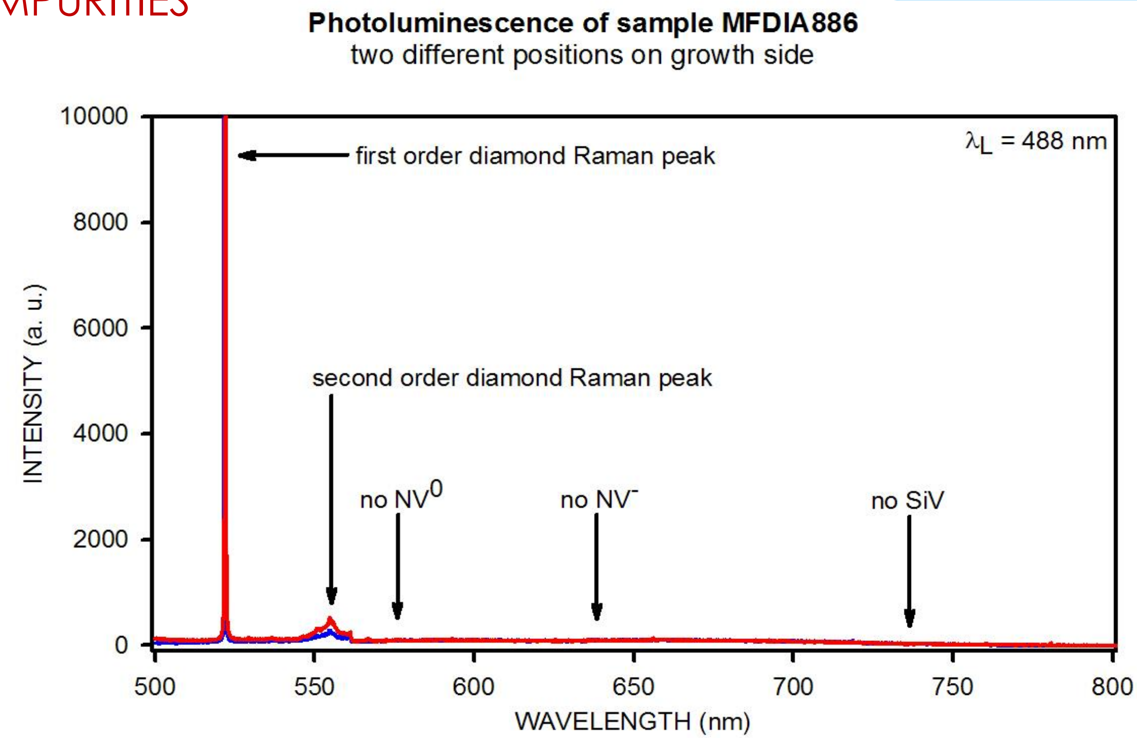


CARAT

DOI - Defect Spectroscopy

C. Stehl, M. Schreck, M. Fischer, S. Gsell

N and Si Impurities



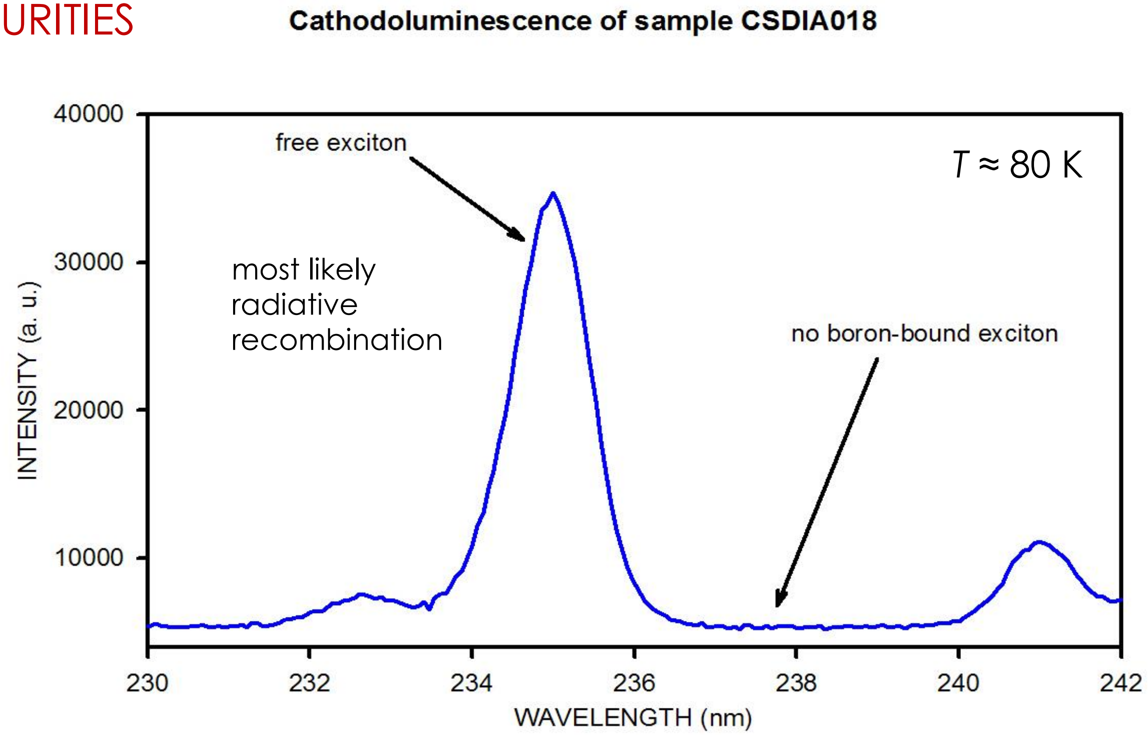
No SiV and NV_0 peaks visible

CARAT

DOI - Defect Spectroscopy

C. Stehl, M. Schreck, M. Fischer, S. Gsell

Boron Impurities



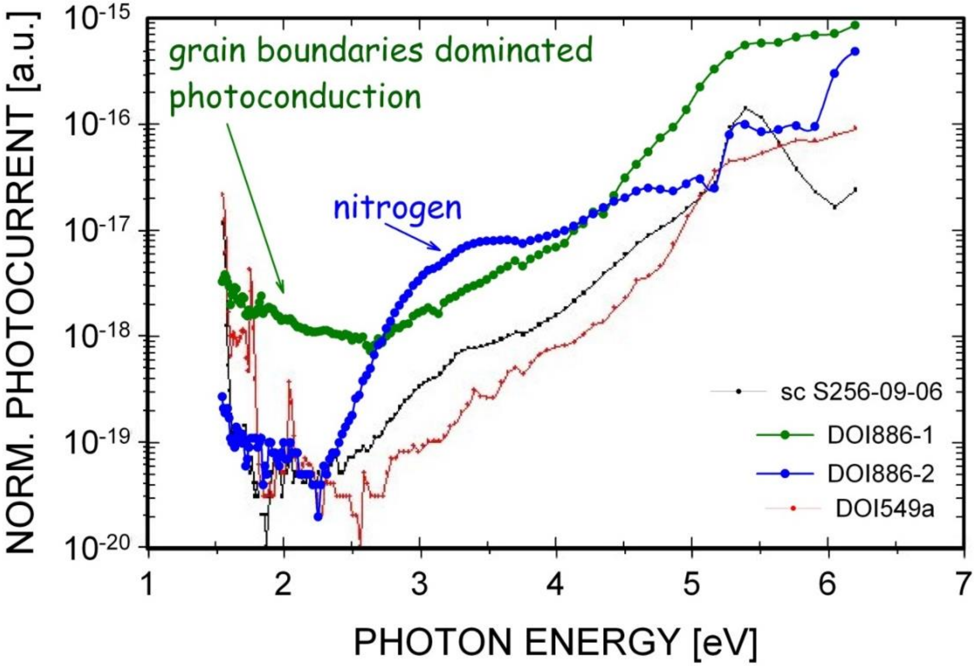
Boron concentration ≤ 1 x 10^{15} cm^{-3}

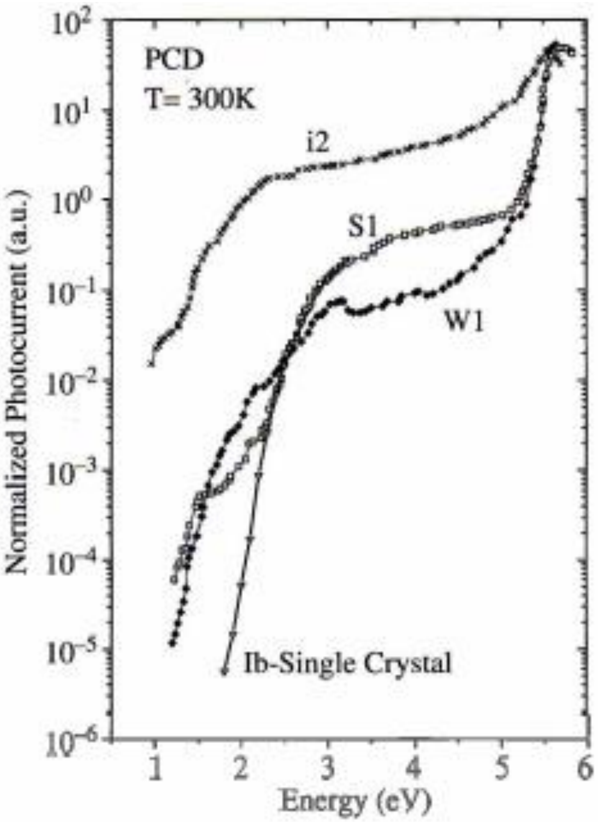
CARAT

DOI - Defect Spectroscopy

E. Layevski, C. Nebel (IAF,Freiburg)

Spectrally Resolved Photocurrents



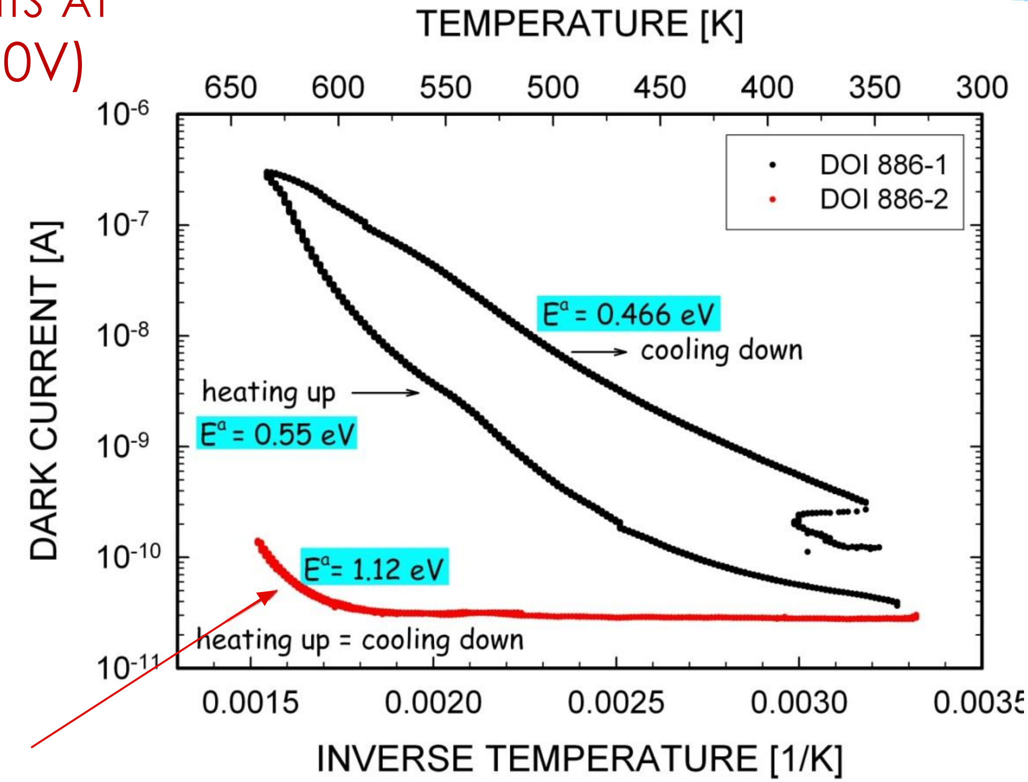


CARAT

DOI - Defect Spectroscopy

E. Layevski, C. Nebel (IAF,Freiburg)

THERMALLY ACTIVATED DARK CURRENTS AT LOW FIELDS (10V)



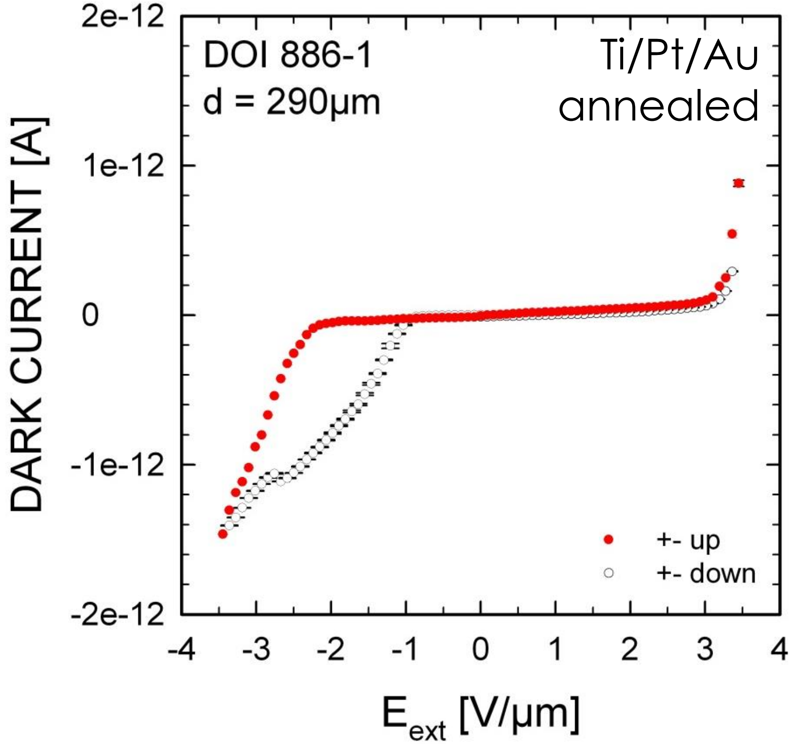
resistivity
too high

CARAT

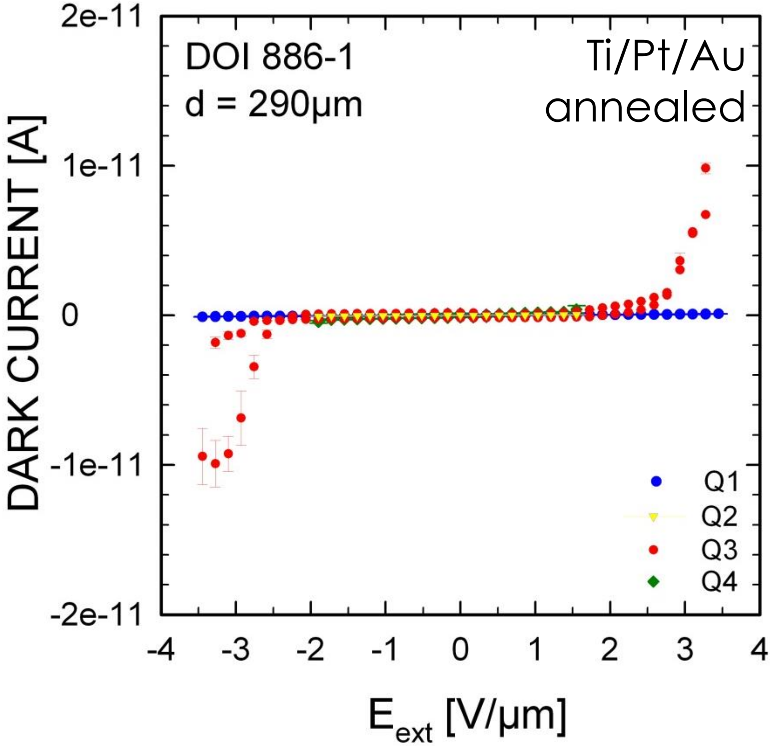
DOI - Dark Conductivity

M. Träger, S. Rahman (GSI)

SINGLE-CHANNEL SENSOR
DOT ELECTRODES



QUADRANT SENSOR
AREA HOMOGENEITY

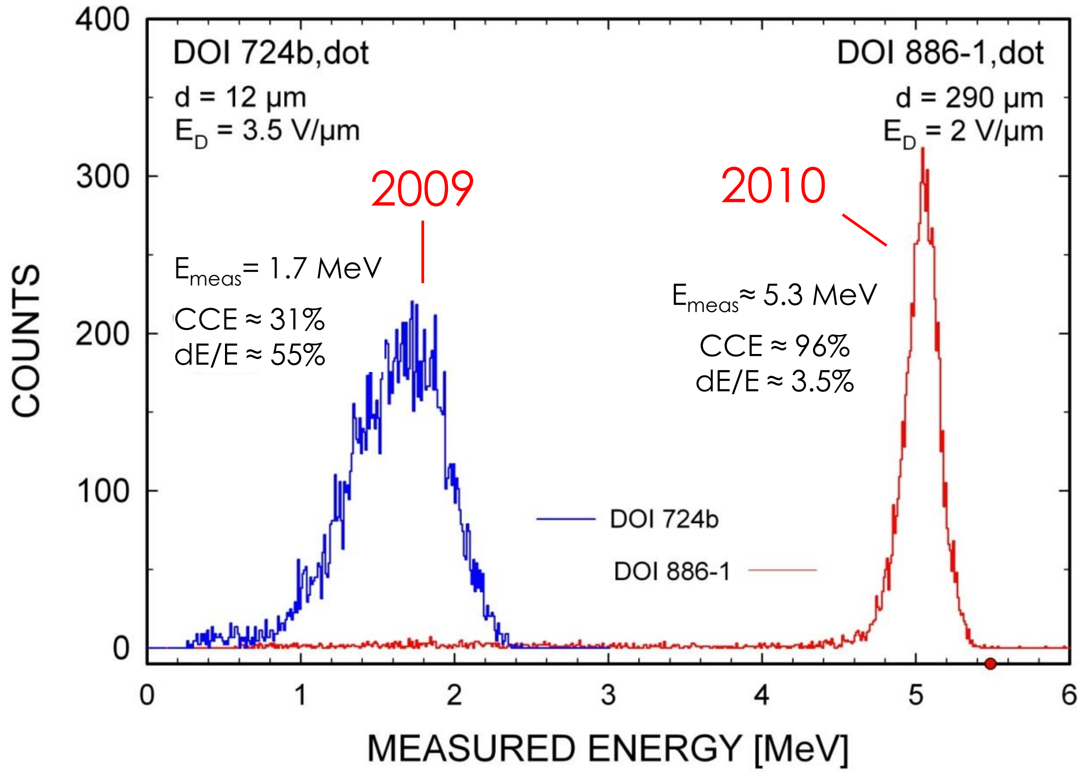


CARAT

DOI - Charge Collection Properties

M. Träger, S. Rahman, EBe (GSI)

- PROGRESS WITHIN ONE YEAR

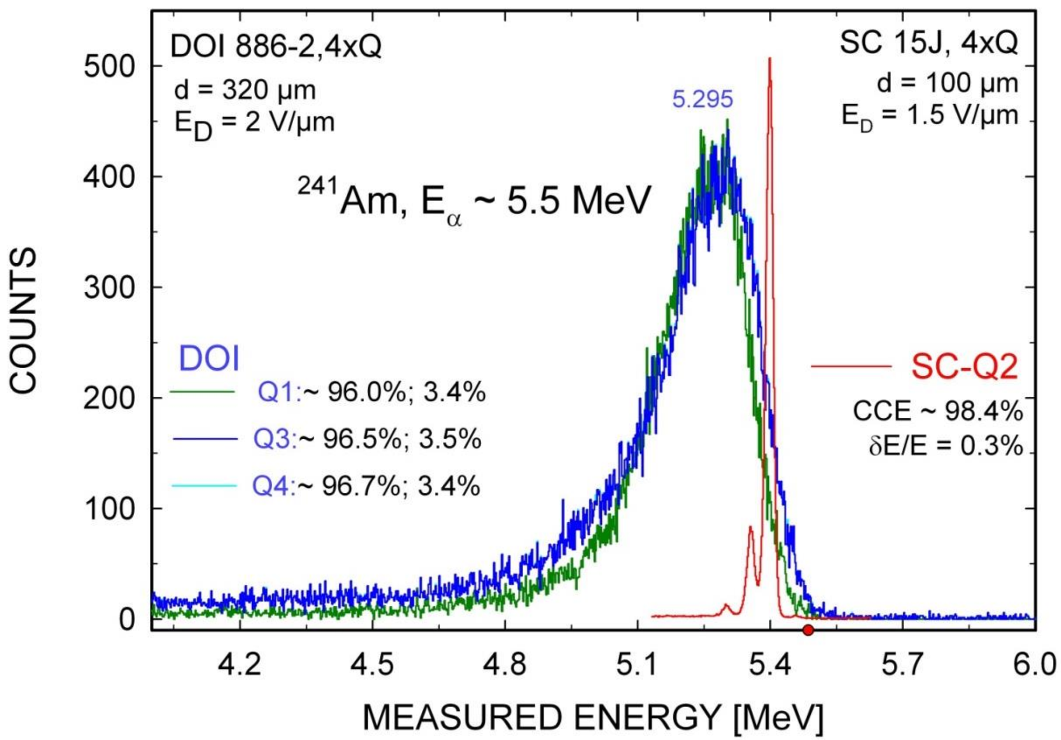


CARAT

DOI - Charge Collection Properties

M. Träger, S. Rahman, EBe (GSI)

Collection Efficiency and Energy Resolution



DOI vs. HSC CVDD (2010)

⬇

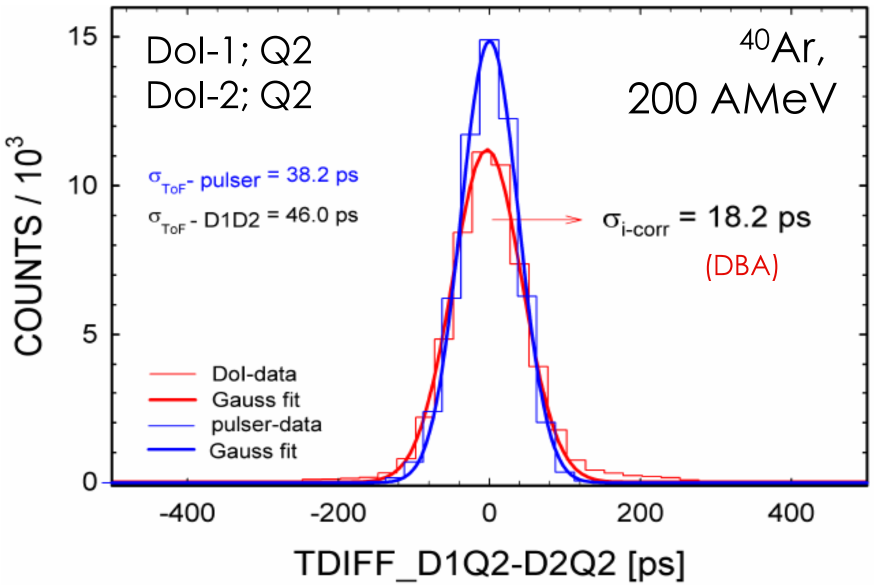
CCE lower by 2.5% only;
δE/E worse by 3%

CARAT

DOI - Timing Properties

P. Moritz, M. Ciobanu, W. Koenig, M. Träger
S. Rahman, C. Stehl, Ebe (GSI, UA)

Intrinsic Time Resolution and ToF Resolution



extended calculations and simulations

<u>M. Ciobanu</u> *et al., IEEE TNS 58 no. 4, 2073 (2011)*

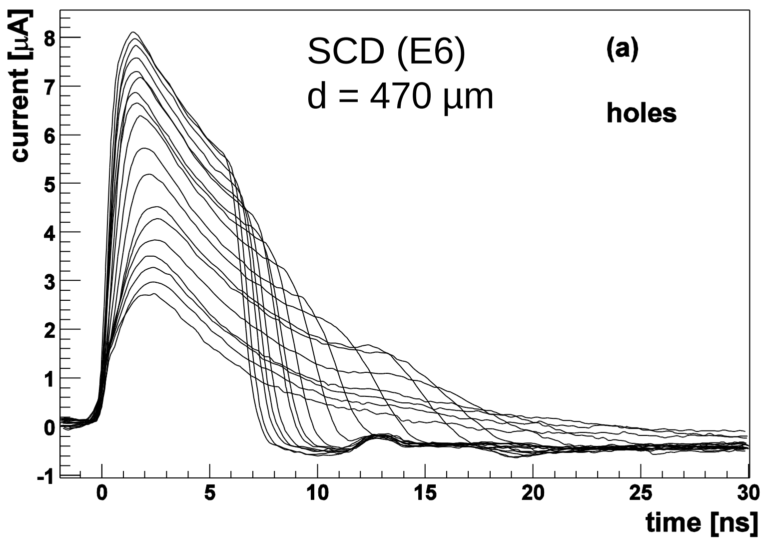
equal to PC and SC CVDD because limitation is due to the electronic noise

CARAT

Internal field profile, transport parameters

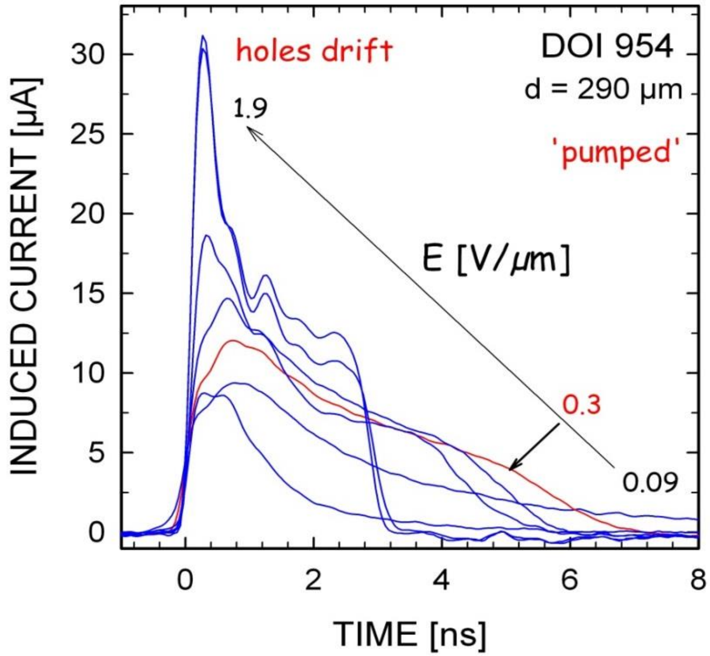
^{241}Am-α-TCT ➡ COMPARED

E6, Early Homoepitaxial SC CVDD(2004)



H. Pernegger, J. Appl. Phys. 97 073704 (2005)

UA, Early DOI (2011)



CARAT

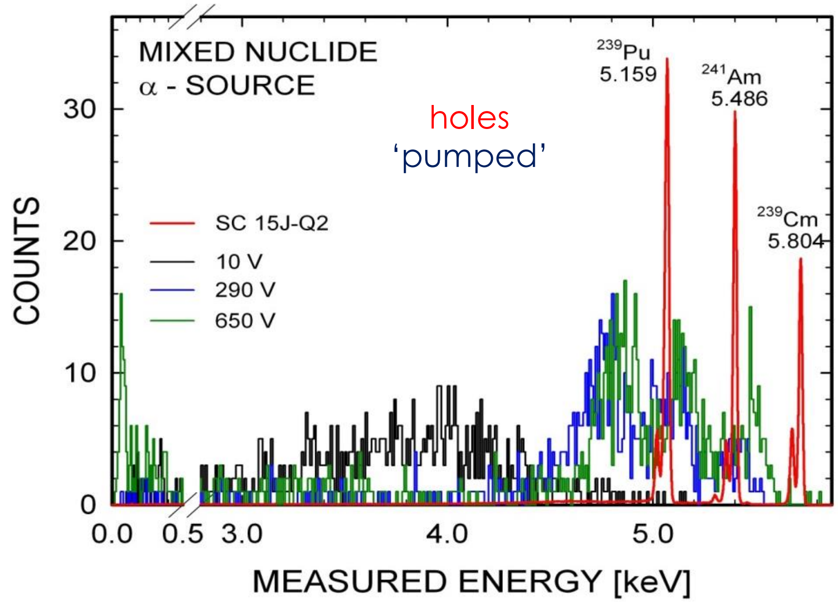
DOI– charge-collection properties

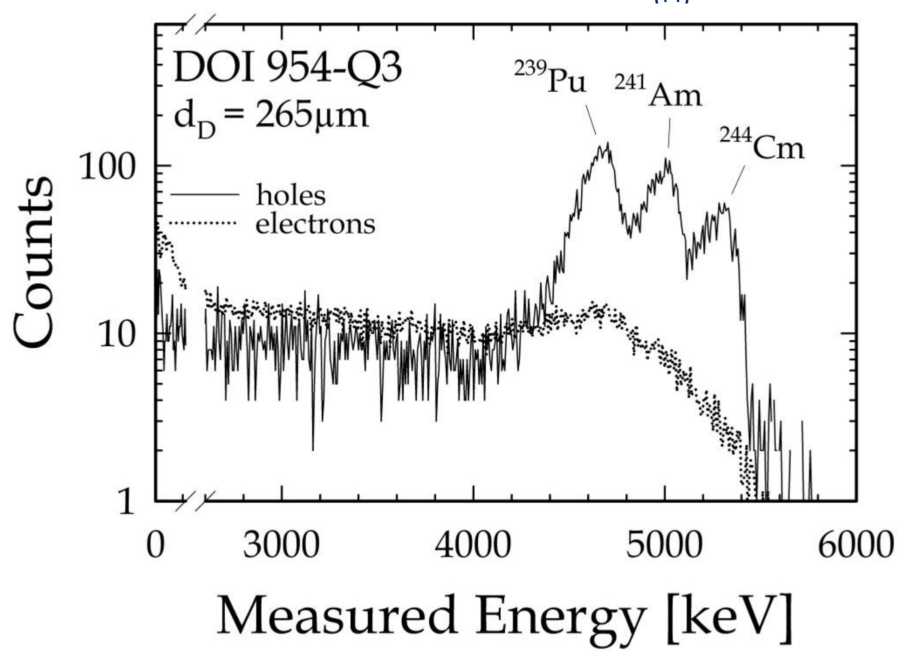
C. Stehl et al., Applied Physics Letters 103, 15190 *(2013)*

CCE and Energy Resolution

DOI (2011) ➡ $CCE_{(h)} \approx 93\%$

$\delta E/E_{(h)} \approx 1.5\%$





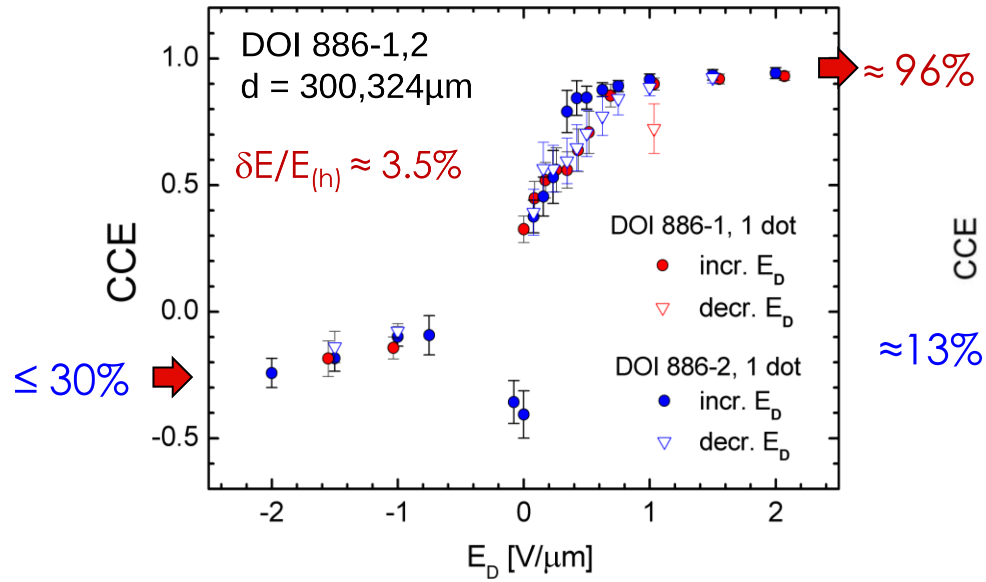
CARAT

DOI– charge-collection properties

Low energy, stopped particles (single-carrier drift)

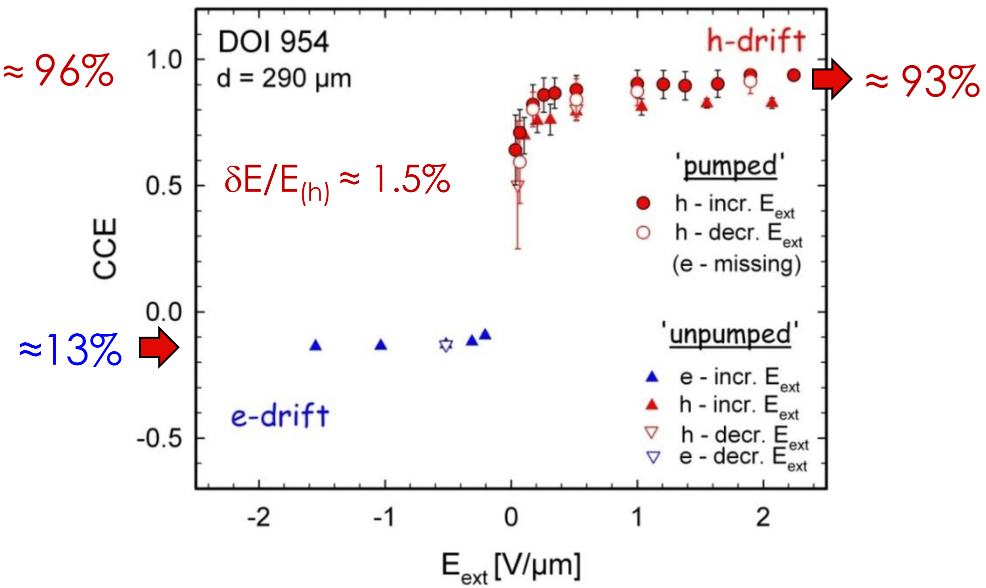
^{241}Am - α's - Collection Efficiency Plateaus

(2010)



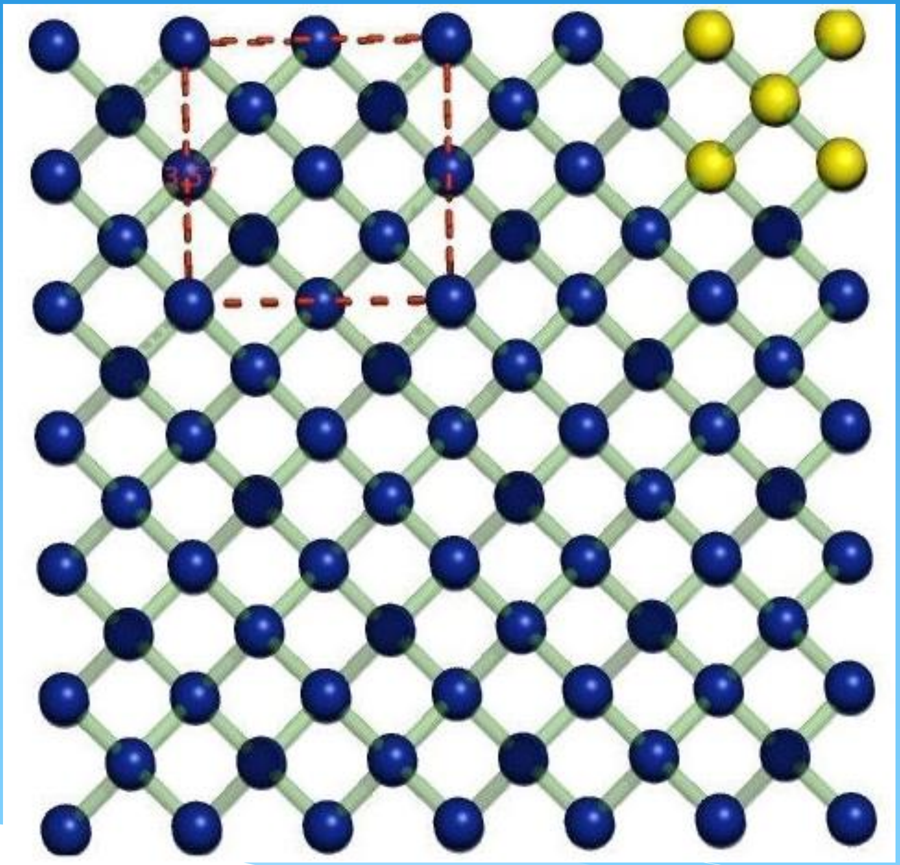
Higher fields needed to saturate

(2011)



Steep rise to CCE > 90%

ADAMAS



Advanced Diamond Assemblies

ADAMAS Activities

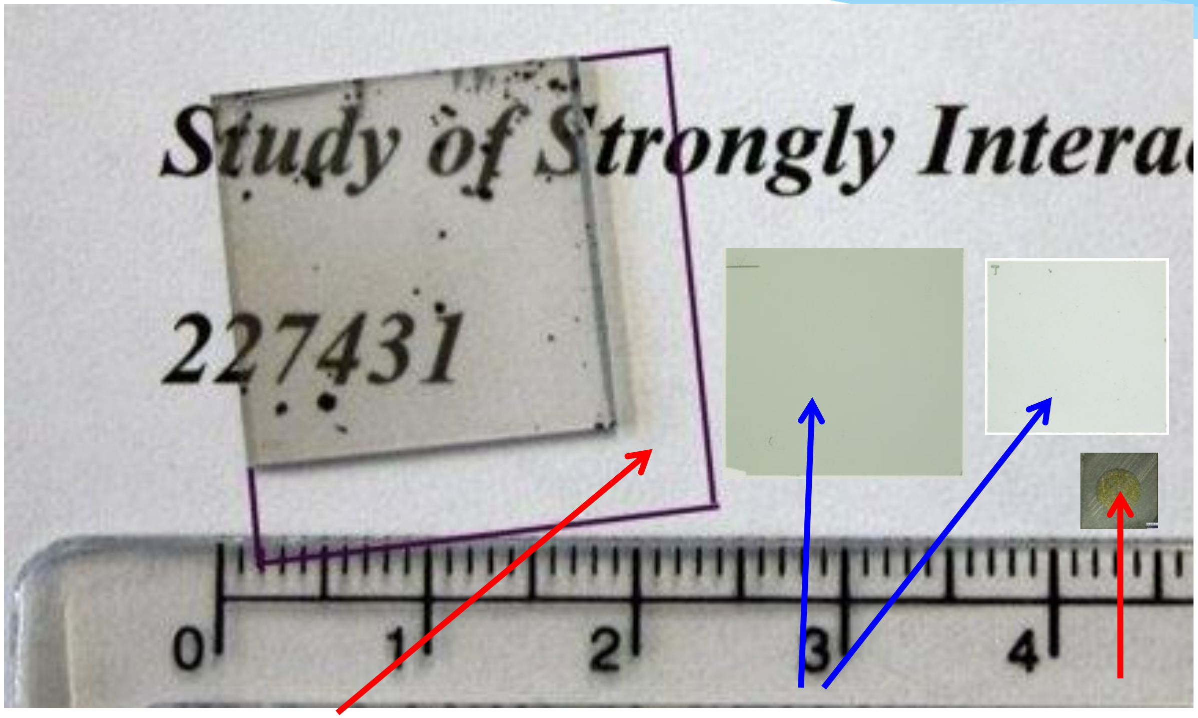
SC CVD Diamond-on-Iridium (DOI)

TASKS

- Engineering of Dia-on-Ir plates for sensor applications
  - further reduction of the dislocation density (particularly by ELO);
  - area enlargement
- Development of new pad assemblies with DLNBA
  - analytical description, simulations, and test of electronic and sensor design parameters
- Development of microstrip assemblies with PADI-8
  - double-sided strip motifs for differential readout

ADADAS

Status enlargement of the sample area

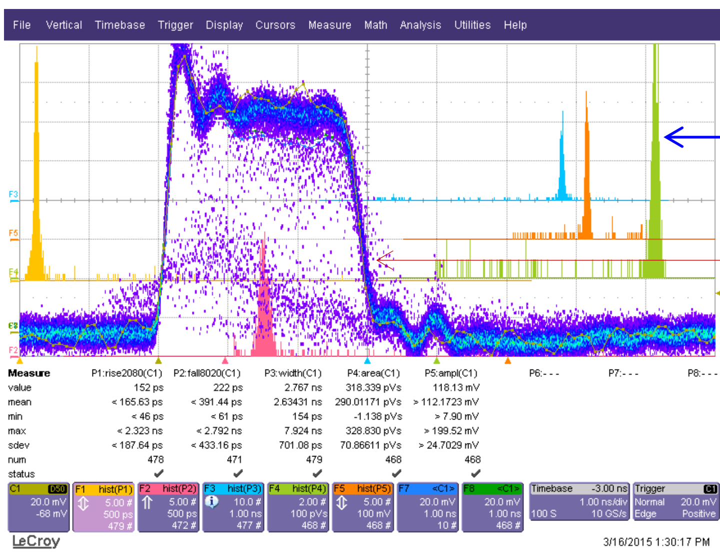


2014+ 2013 2011

ADAMAS

Internal field profile, transport parameters

DOI 2014 - TCT - ONLINE



NARROW SPECTRAL LINES

FULL CHARGE DRIFT
to the opposite electrode

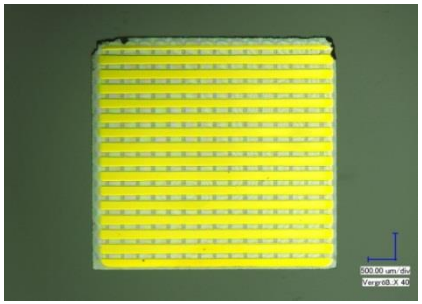
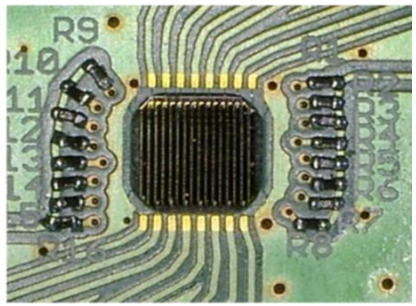
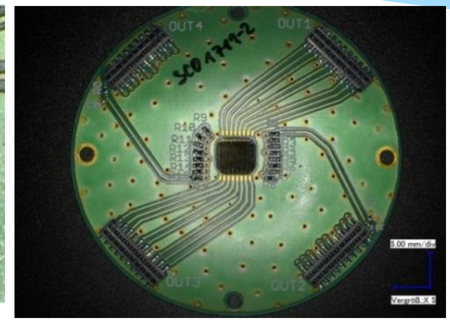
d_D = 300 μm

ADAMAS

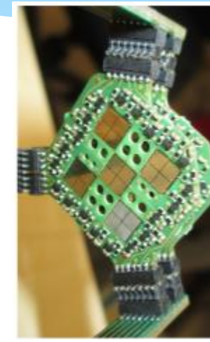
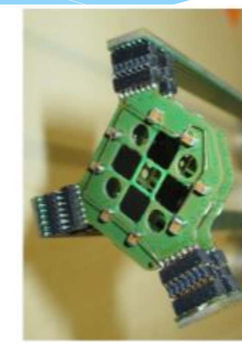
advanced strip/pad assemblies with PADI

J. Pietraszko for the HADES / CBM Collaboration

DOUBLE-SIDED MULTI-STRIP DIAMOND SENSORS

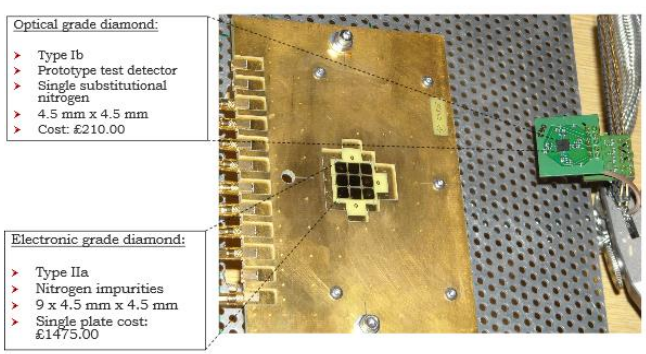




MOSAIC DD for MIPs

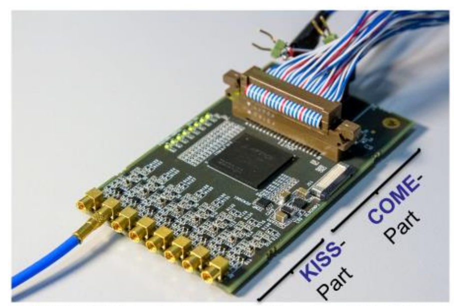



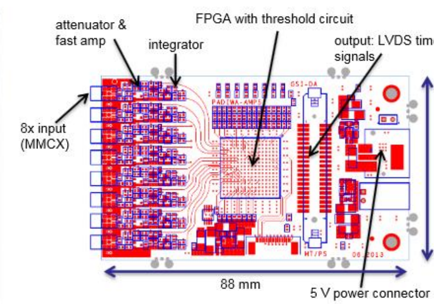
DD for SPACE RESEARCH and THERAPY

R. Pleskac for the BIO Collaboration



'COME & KISS QDC AND TDC for DD

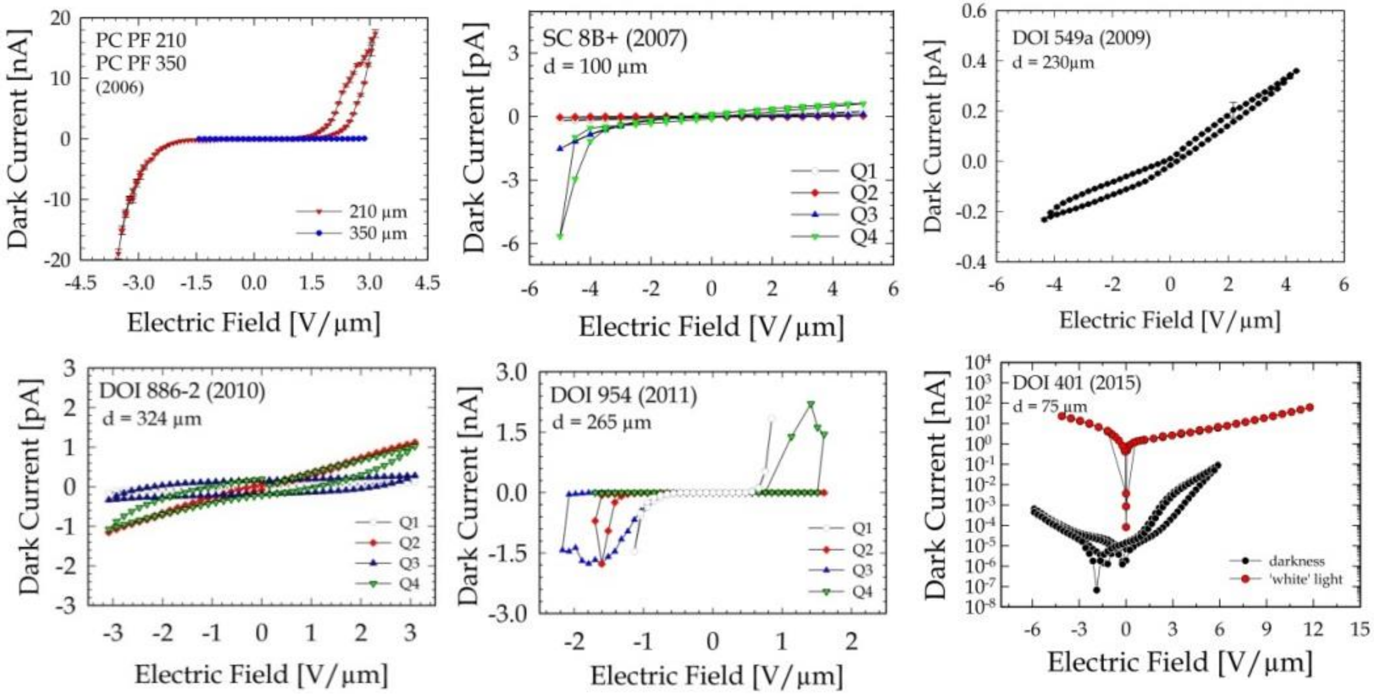




- 8 MMCX input channels → a least 24 TDC channels on TRBv3 needed
- Power supply: 5 V
- Time Precision: ~ 50 ps **(optimization ongoing!!!)**
- Relative charge resolution: < 0.5 % (for pulser signals >1 V, PadiWa-AMPSv1)
- Dynamic range: 250
- Max. rate capability: ~ 2 MHz **(optimization ongoing!!!)**
- *Max. data amount*: 50 MB/s
- *Universal applications*: read-out for: PMT, MAPD, diamond…

Comparison and Classification

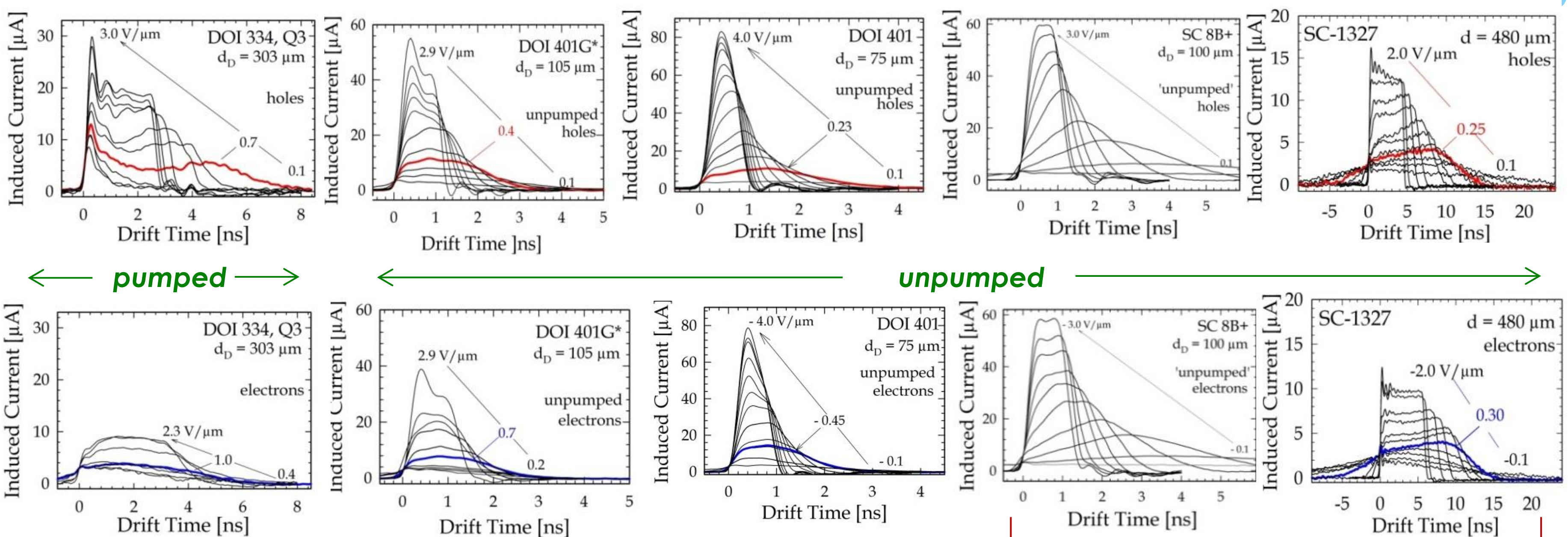
Dark Conductivity



Comparison and Classification

^{241}Am - α - TCT

DOI – improving reproducibility of hole drift

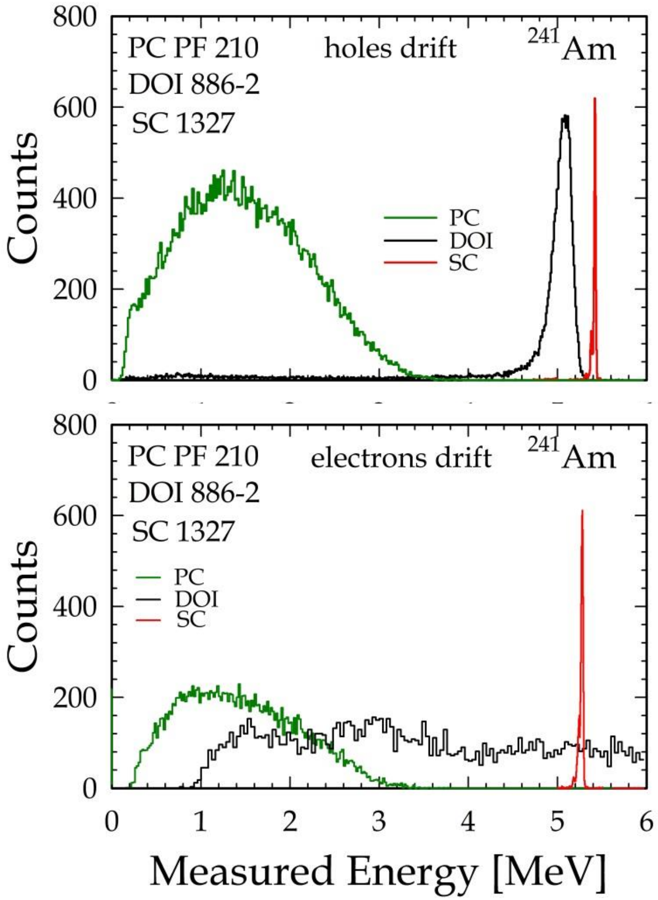


DOI - improving electron drift

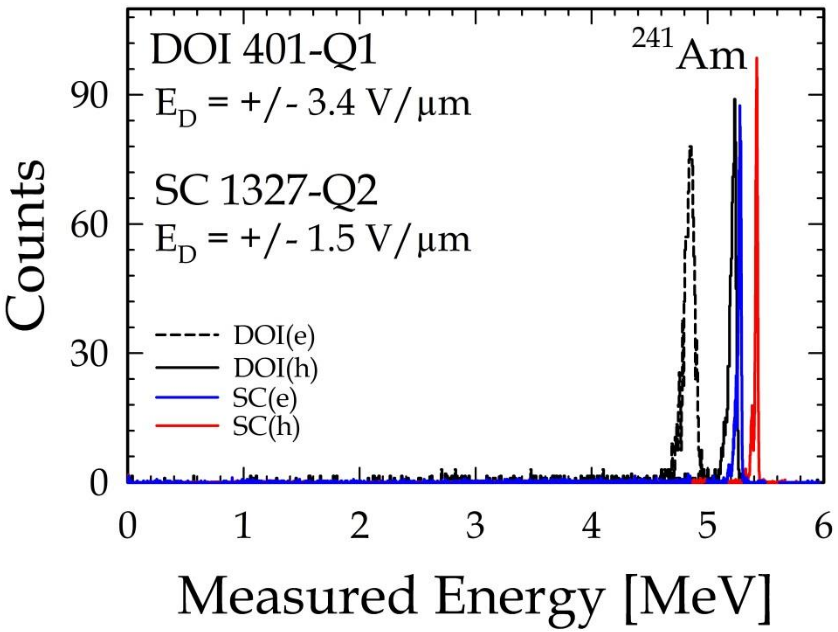
SCD – 100 µm (left plots) and 480 µm (right plots)

Comparison and Classification

Ion Spectroscopy (2010)



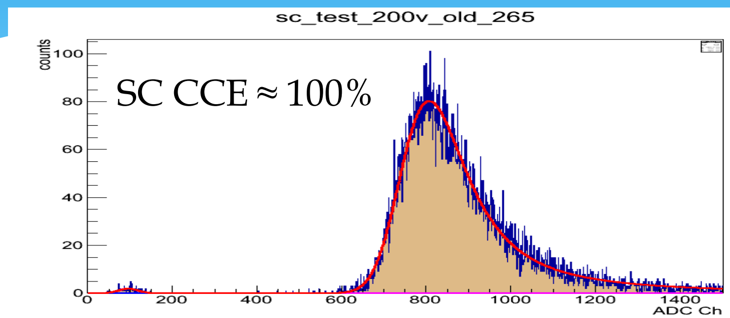
Ion Spectroscopy (2015)

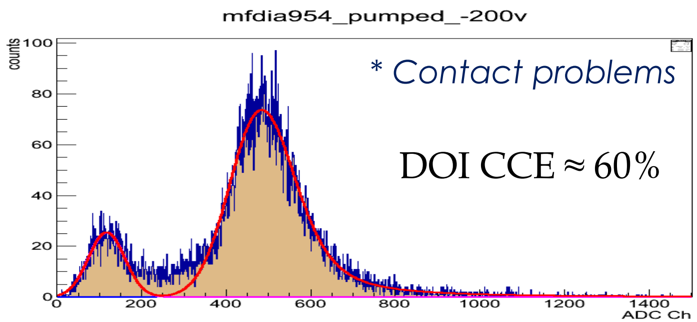


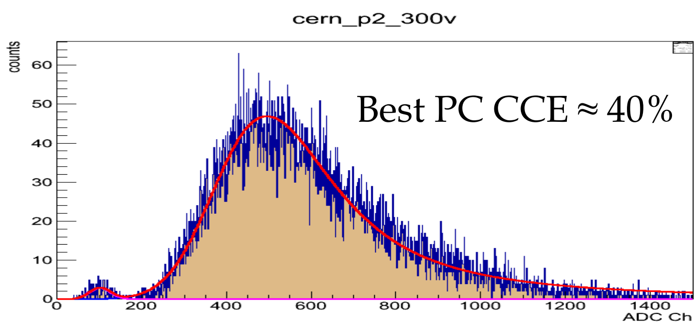
Comparison and Classification

MIP Efficiency

Konstantin Afanaciev, Wolfgang Lohmann, Sergej Schuwalow et al., DESY Zeuthen







DOI Dual-Carrier Drift

*to be confirmed**

new-data analysis ongoing

(p, 1 GeV; ^{90}Sr-β's)

CONCLUSIONS

HOMOSCDD BEST FOR BOTH

- Timing (incl. MIP) and Spectroscopy if SM areas acceptable

PCDD BEST FOR TIMING OF

- Swift Ions Heavier than ^{12}C
- No spectroscopy

DOI DD BEST FOR BOTH T & S

- Incl. large area detectors
- Slightly worse than HomoSCDD in high-resolution spectroscopy
- Need still some more R&D

OUTLOOK

NEW DIAMOND DETECTOR TECHNOLOGIES with DOI DIAMOND

- Large Area Continuous Position-Sensitive DD (ISS, CEA, GSI)
- 3D Diamond Detectors (CEA, UManchester)
- Silicon-on-Diamond (SOD) devices (UFlorence, GSI)

Thank You for your Attention !!