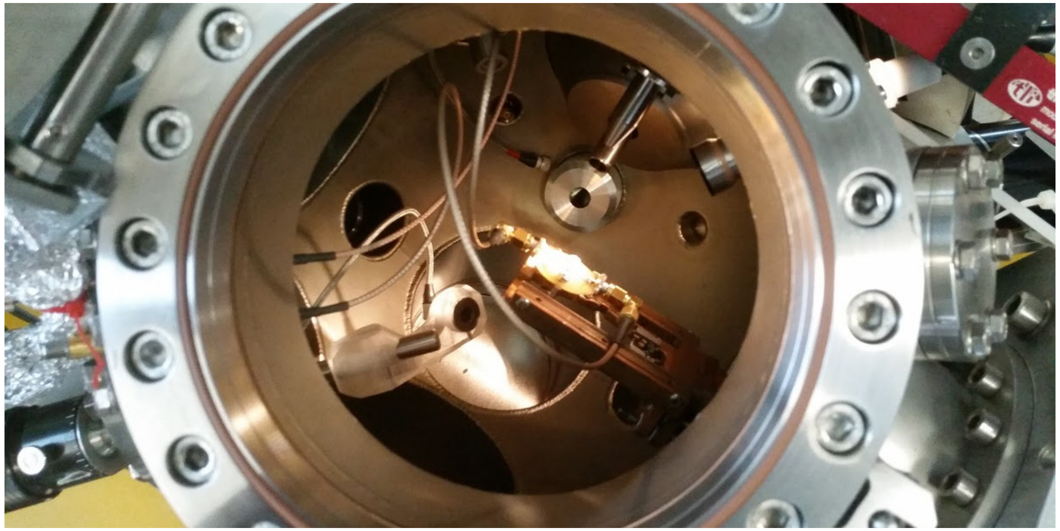
# Charge multiplication and signal recovery in thin diamond detectors

Natko Skukan

Ruđer Bošković Institute

Zagreb, Croatia



- **CO-AUTHORS**

*V. Grilj, M. Jakšić, I. Sudić*

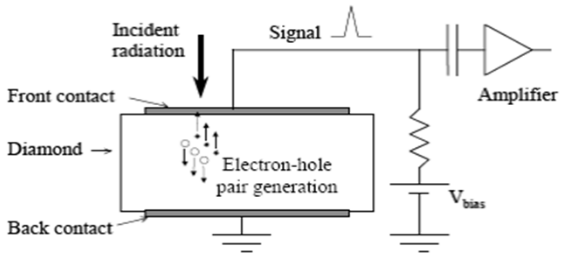
*M. Pomorski, P. Bergonzo, S. Saada*

*Y. Andoh, W. Kada, Y. Kambayashi*

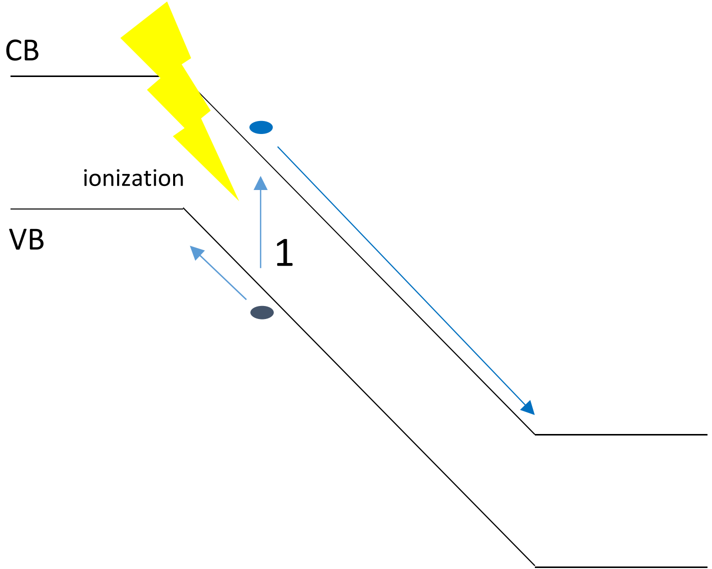
*T. Kamiya, T. Makino, T. Ohshima,*
*S. Onoda S. Sato*

- **CHARGE MULTIPLICATION**

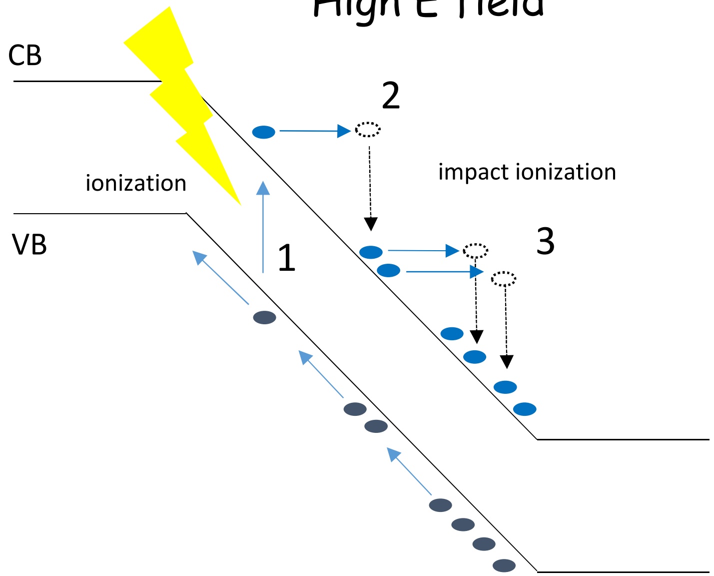
**internal gain**
**(solid-state proportional, Geiger counter)**




Low or moderate E field



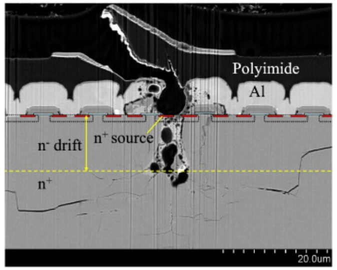

High E field



- **CHARGE MULTIPLICATION**

## Why it is interesting to investigate avalanche with diamond

- important physical parameters missing → high power electronics




Microelectronics Reliability 55 (2015) 1517–1521

- *Single event burnout in high power transistors (cosmic n at sea level)*

- experimental data (almost) not existing, mostly theoretical papers (several)

- New devices

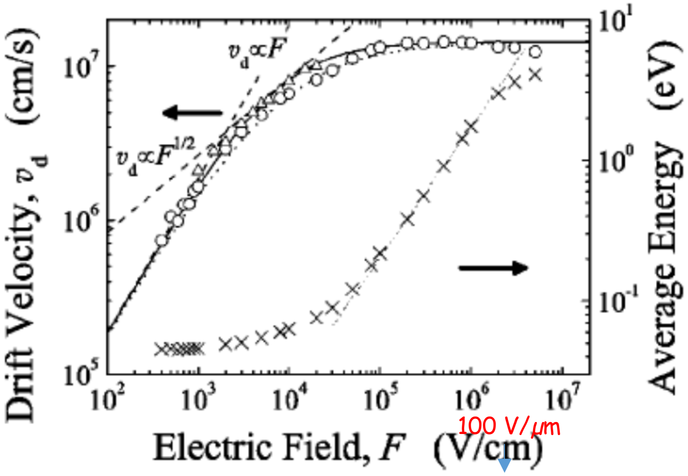
- diamond based APD (solid state – proportional, Geiger counters)

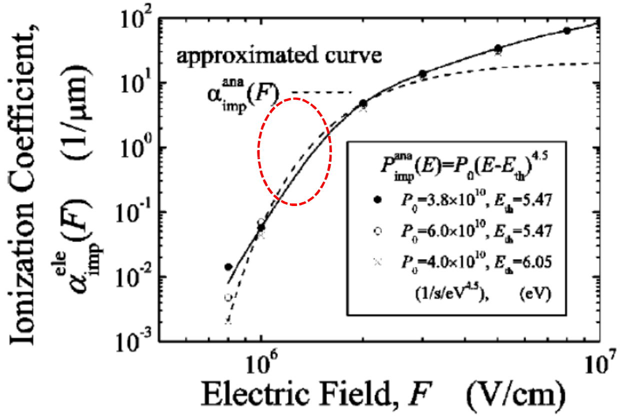
- True Radiation Hard Diamond Detectors

- **AVALANCHING IN DIAMOND**

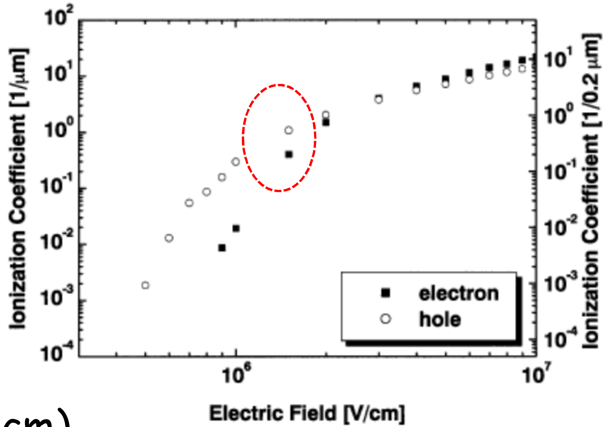
Watanabe, T., Masatake, I., Teraji, T., Ito, T., Kamakura, Y., Taniguchi, K. , Jpn. J. Appl. Phys. **40** (2001) L715-717.

<100> electrons




<110> electrons, holes



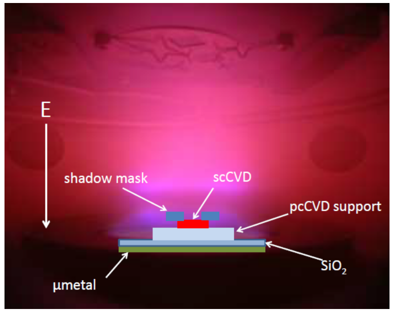

$$Q = \frac{Q_0}{1 - \int_0^d \alpha x dx}$$

α ~ 1/μm > 100 V/μm (1MV/cm)

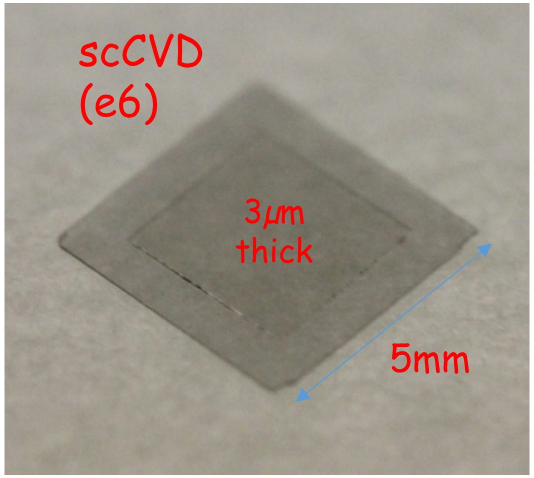
Threshold for impact ionization ~ E >100 V/micron (1MV/cm),
→ commercial scCVD plates: **500 μm** – 50 kV bias (hmmm…), **50 μm** – 5 kV bias (risky)

- **SCCVD DIAMOND MEMBRANES**

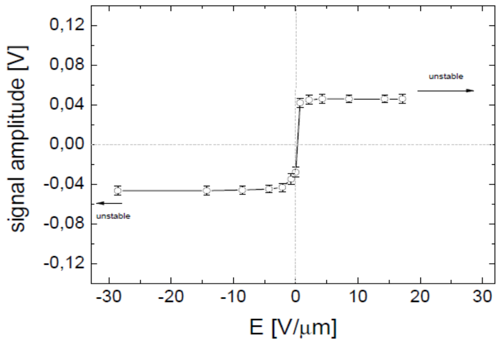

Ar/O plasma



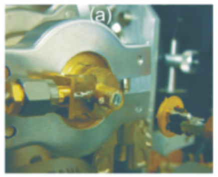

deep etching

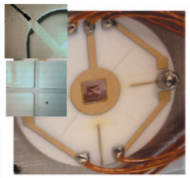



100%CCE@1 ppm [N]




: Appl. Phys. Lett. **103**, 243106 (2013); doi: 10.1063/1.4833236
: Appl. Phys. Lett. **103**, 112106 (2013); doi: 10.1063/1.4821035
*J. Synchrotron Rad.* (2014). **21**



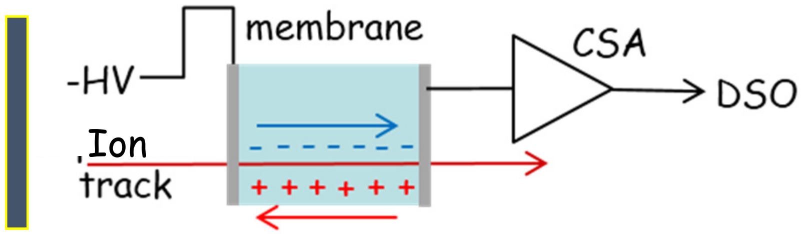



tender x-ray beam monitors ; active windows for external microbeams
bunch diagnostics for laser driven accelerators

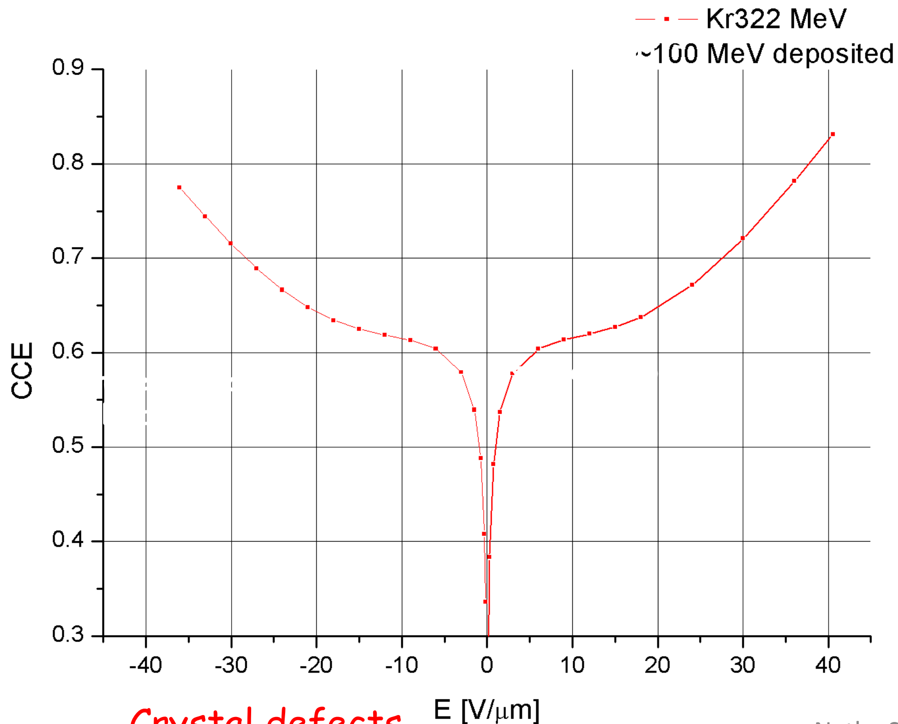
5 μm – 500 V bias (ok!) → a nice opportunity to try to study impact ionization

- **EXPERIMENTAL CHALLENGES – FIRST TRIES**

322 MeV Krypton beam at QST, Takasaki




- 6.7 μm thick membrane
- random irradiation
- SEU, well defined ΔE
- sandwich geometry → homogenous E




Crystal defects

- Tested only up to ~ 40 V/μm (270 V)
- Visible "exponential" increase with bias
- Heavy ion – "plateau" at ~60%- excitons?
- CCE still below 100%
- Not enough…

- **EXPERIMENTAL CHALLENGES – FIRST TRIES**

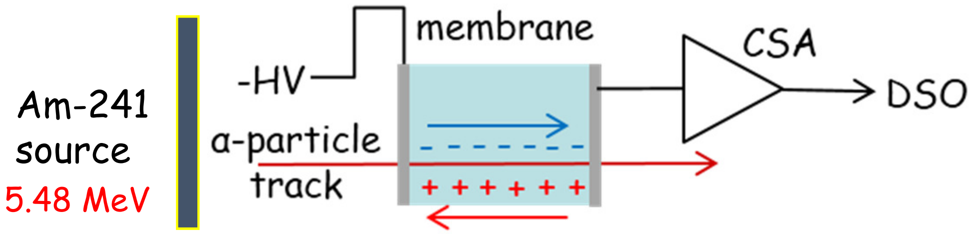
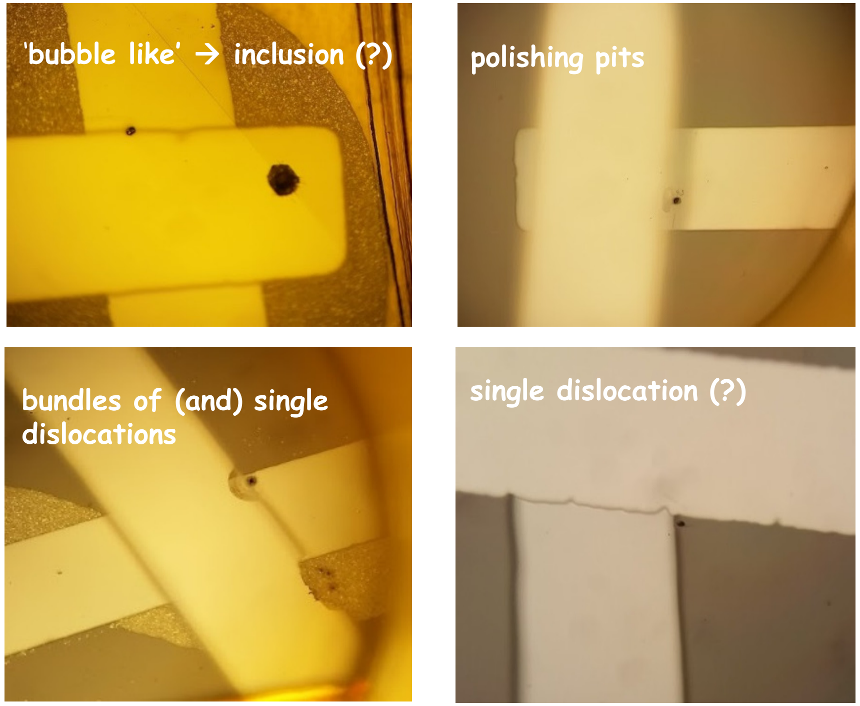



Table-top setup

- 3 μm thick membrane
- random irradiation
- SEU, well defined ΔE
- sandwich geometry
  → homogenous E

no multiplication up to 150 V/μm (~500V, 1.5 MV/cm) for 5.5 MeV α-particles

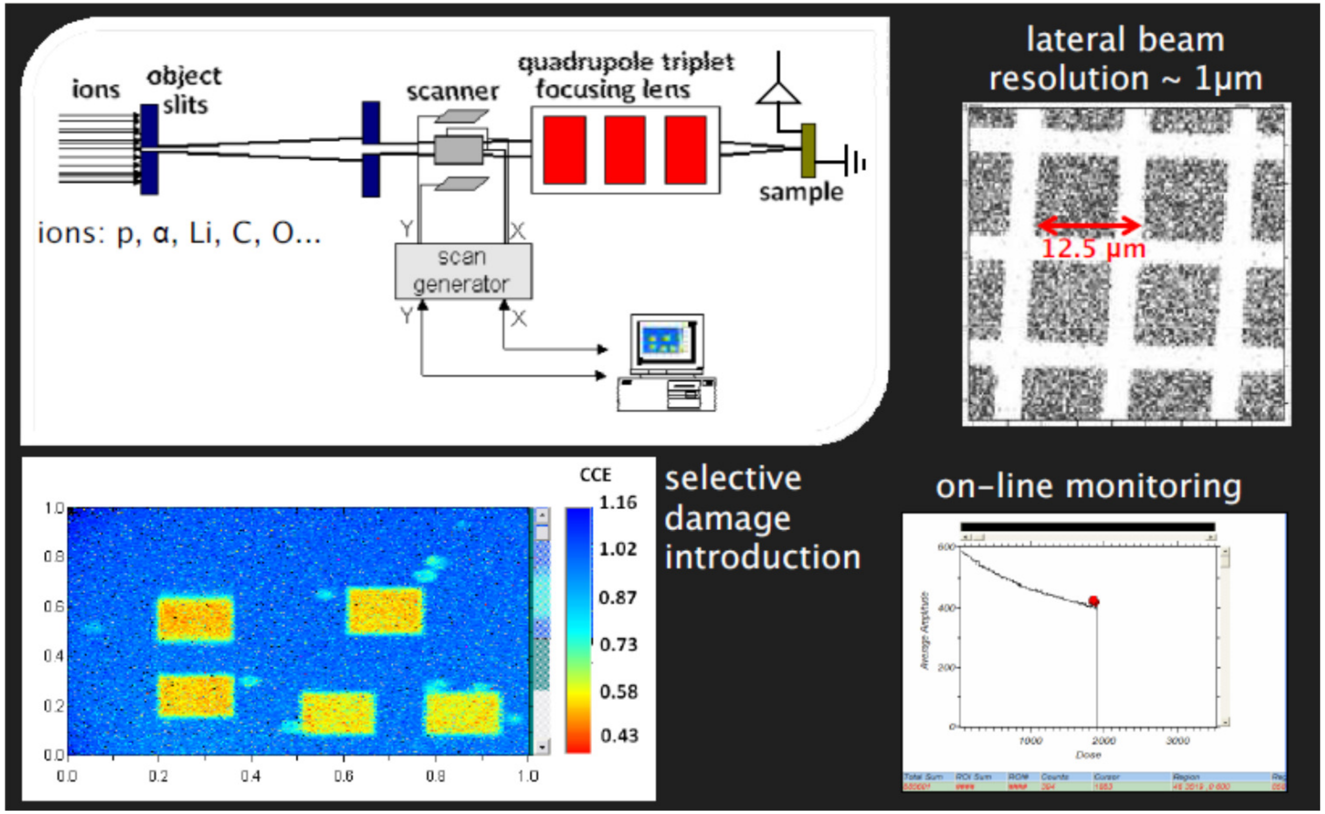



Crystal defects

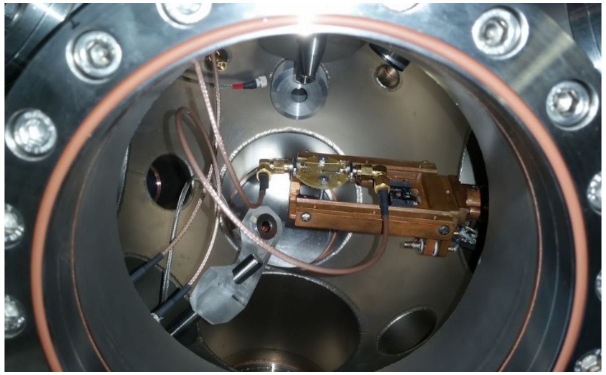
> 170 V/μm (~570V)

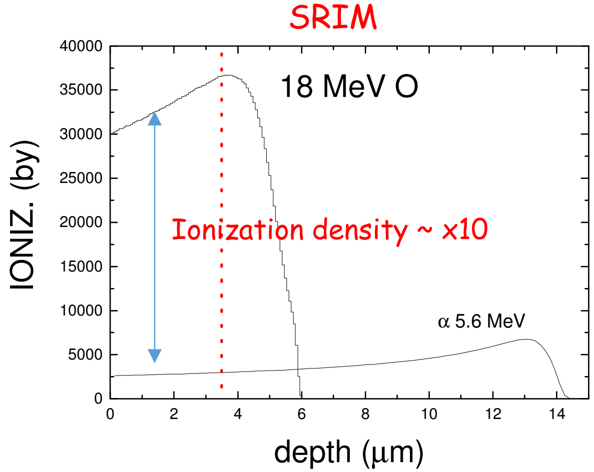
- **THE MICROBEAM IRRADIATION**

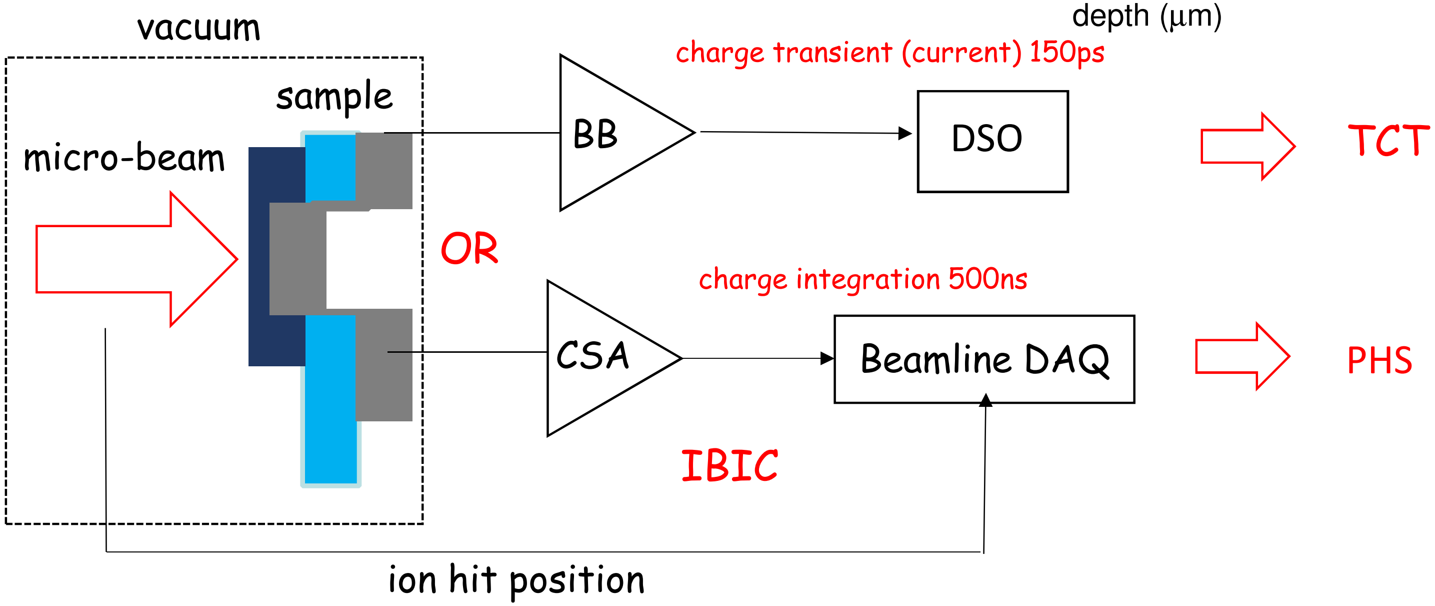
RBI, Zagreb, Croatia → 6 MV tandem accelerator Van de Graaff



- **CHARGE MULTIPLICATION – SET-UP @ IRB MICROBEAM**



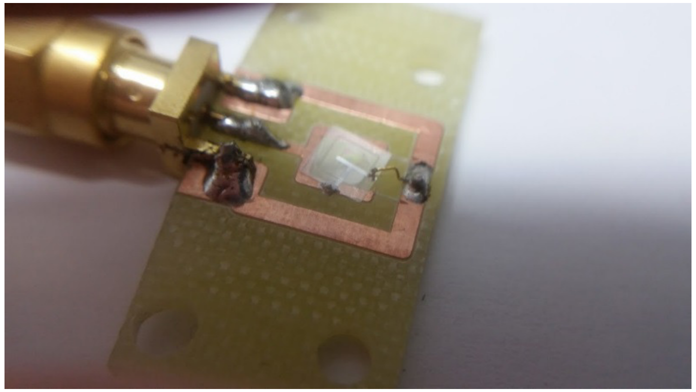


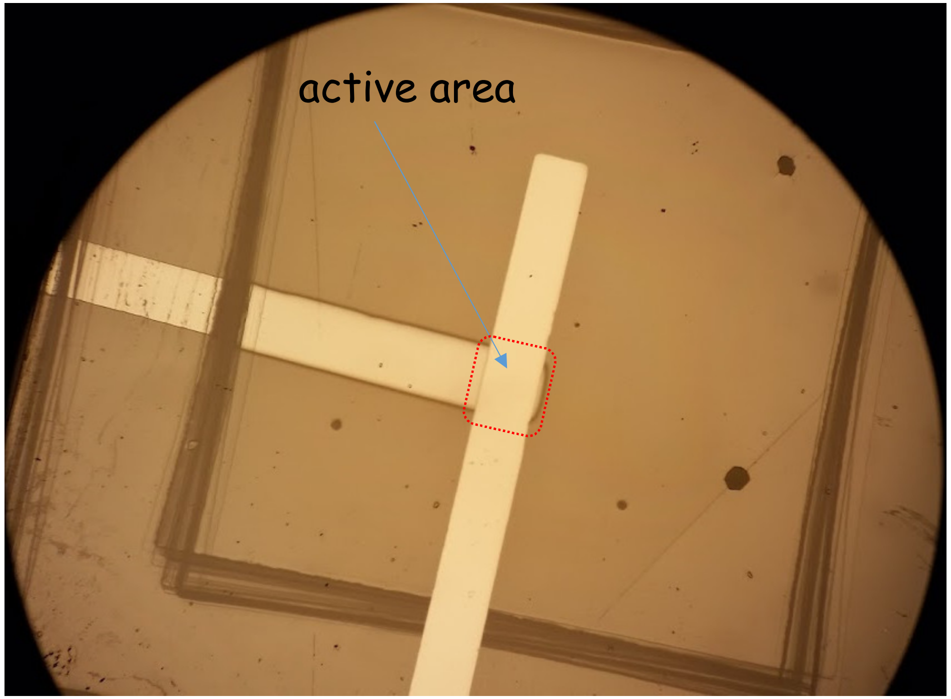




Natko Skukan, LIBI-RBI, ADAMAS 2016

- **CHARGE MULTIPLICATION – M-I-M MEMBRANE**

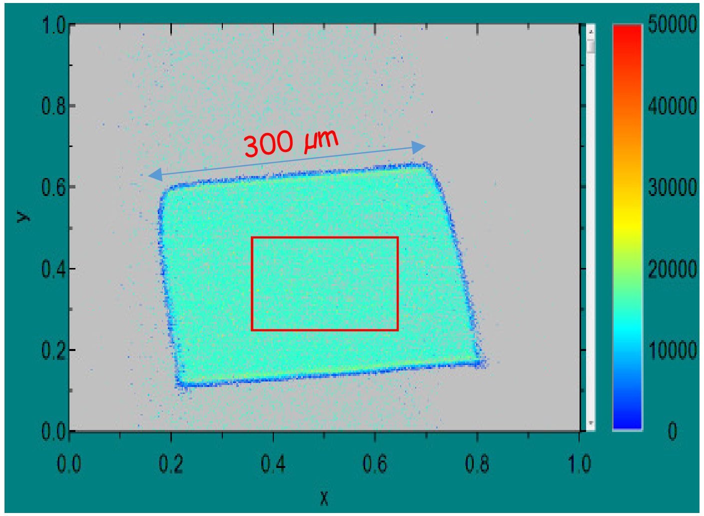
Sample: 4x4 mm 3.25 micron thick scCVD membrane e6 (<1ppm [N], <100>)



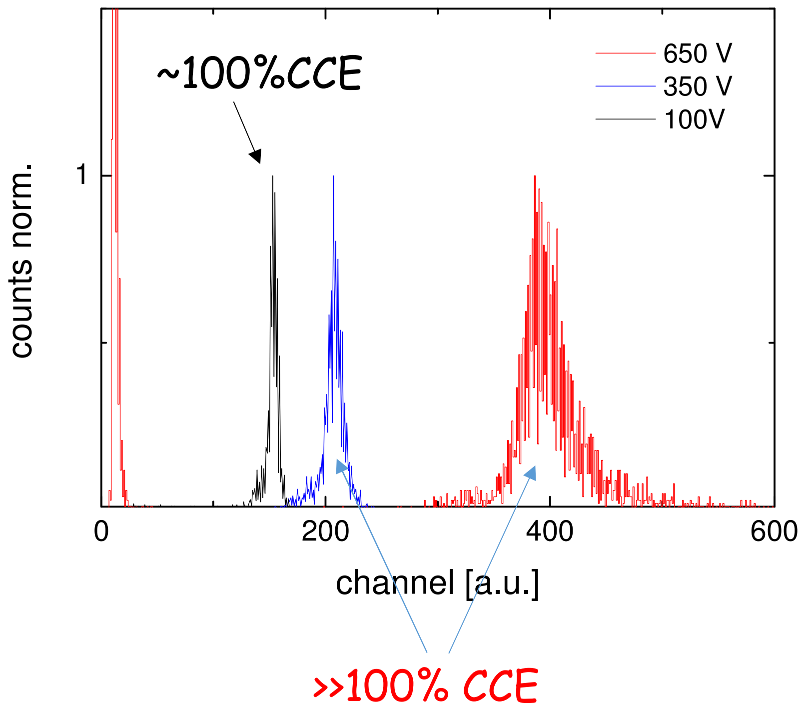


- **CHARGE MULTIPLICATION - PHS**

Full area amplitude map



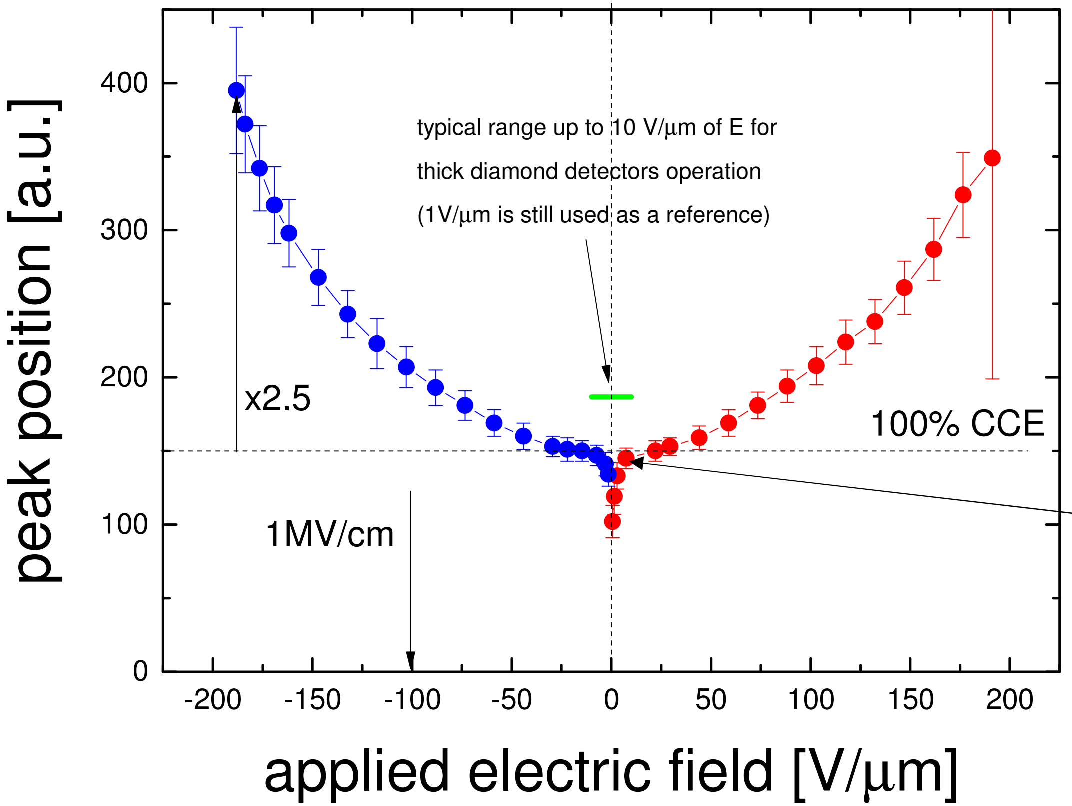

Corresponding PH spectra




[(DC) leakage current <1 pA]

- **CHARGE MULTIPLICATION – CCE VS E**

Results with 18 MeV O ions and charge sensitive electronics - CCE




Other ions also tested
Avalanche strongly depends on LET!

size of this point is larger that the range of E used
in most of the experimental papers
on charge transport in diamond

## • CHARGE MULTIPLICATION – IMPACT IONISATION COEFFICIENT

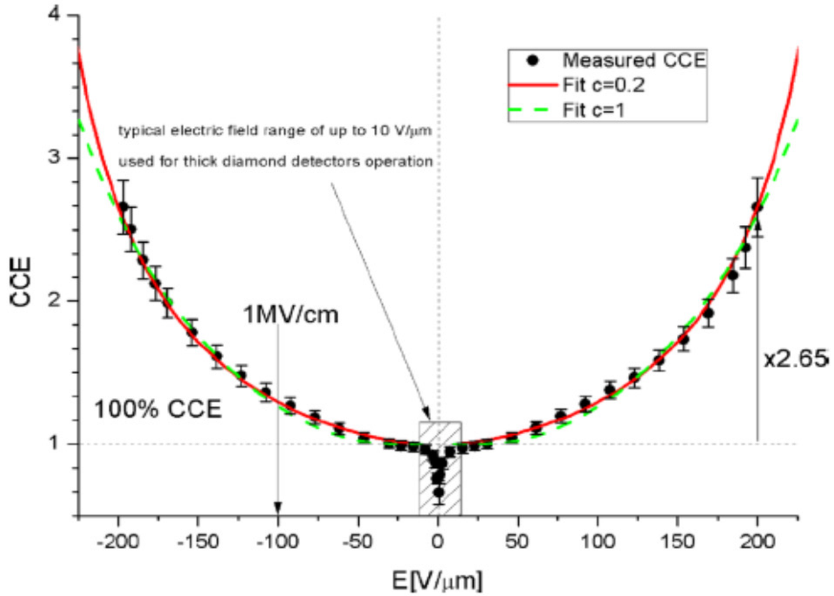
Chynoweth equation

$$\alpha = ae^{-\frac{b}{E}}$$

$$Q = \frac{Q_0}{1 - \int_0^d \alpha x dx}$$

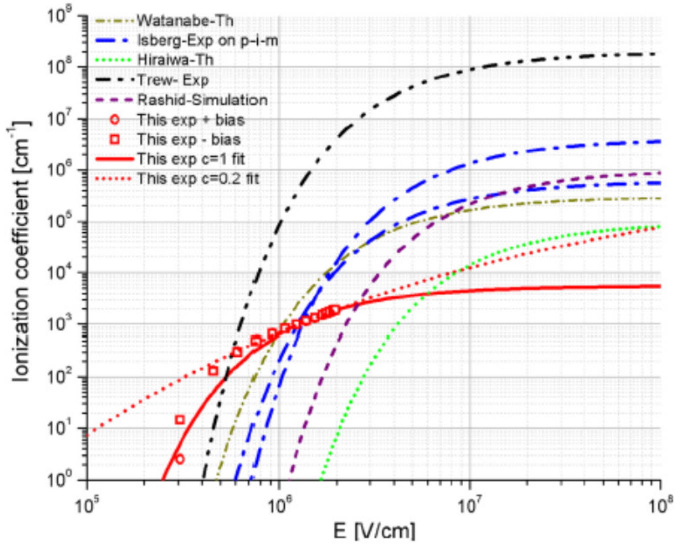
$$\alpha = ae^{-\frac{b}{(E)^c}}$$

$$\text{CCE} = \frac{1}{1-\alpha d}$$



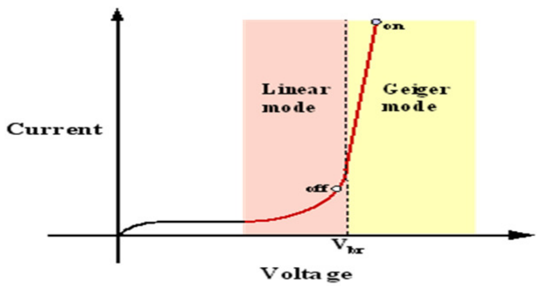

Geiger threshold: 363 V/μm 285 V/μm

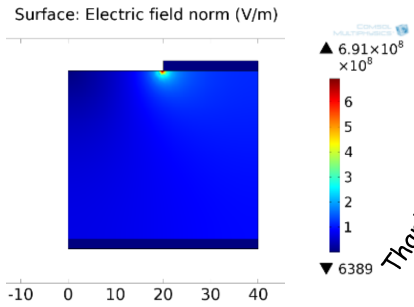
| a ($\mu m^{-1}$) | b (V/μm) | c |
|---|---|---|
| 0.56 ± 0.03 | 216 ± 9 | 1 |
| 180 ± 31 | 19.7 ± 0.5 | 0.2 |




Applied Physics Letters **109**, 043502 (2016); doi: 10.1063/1.4959863

- **CHARGE MULTIPLICATION – TOWARDS GEIGER MODE**

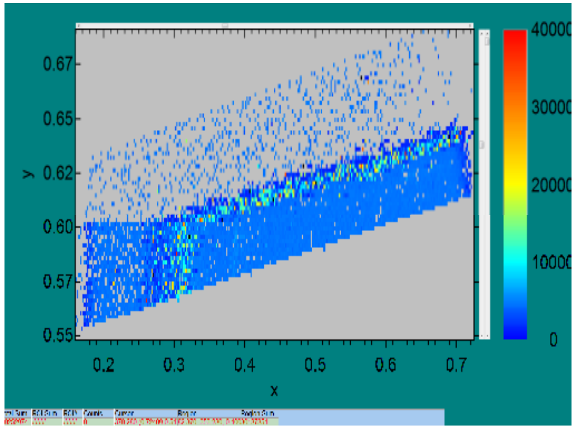


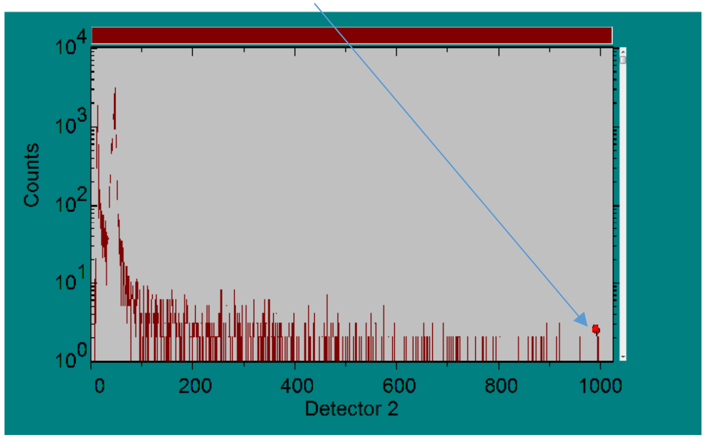




Thanks to Colin Delfaure!

@ -350 V (~100 V/μm → 1 MV/cm)

Hits at electrode border → up to x20 more charge



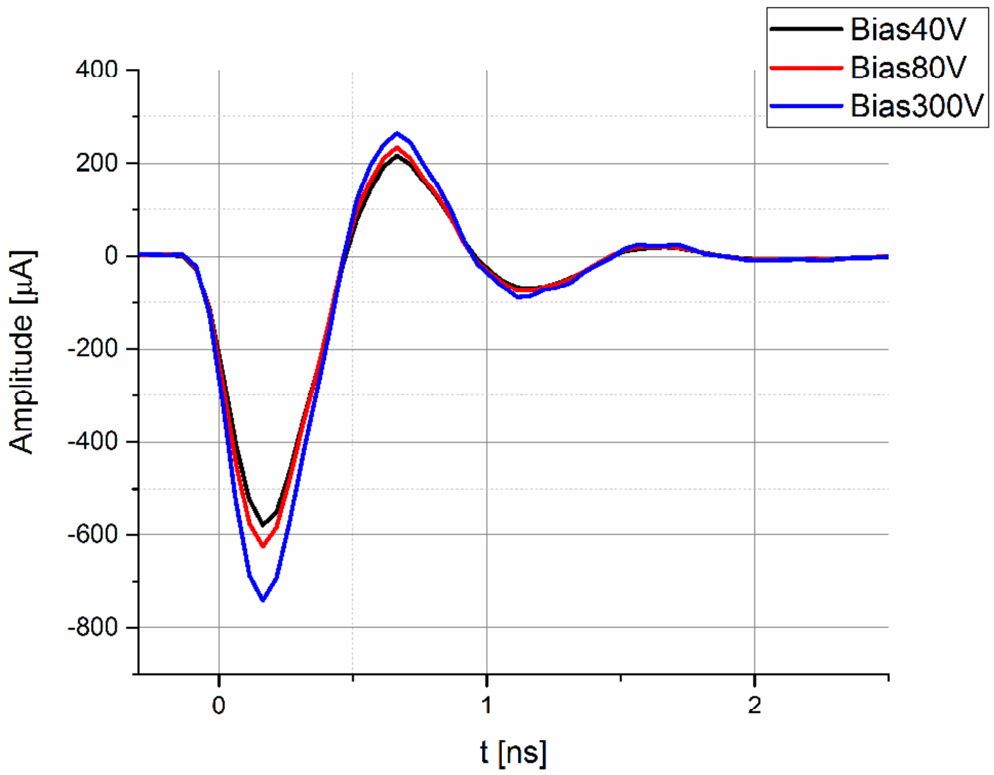




undefined field and limited area → only part of the charge cloud interacting

Typical R of CSA bias-T ~ 10MΩ – passive quenching of the avalanche

- **CHARGE MULTIPLICATION – TCT FAST READ-OUT**

Results with 18 MeV O ions and 50 Ω DSO read-out
(no amplifier was used)




Transient in 3.5 µm at > 30 V/µm

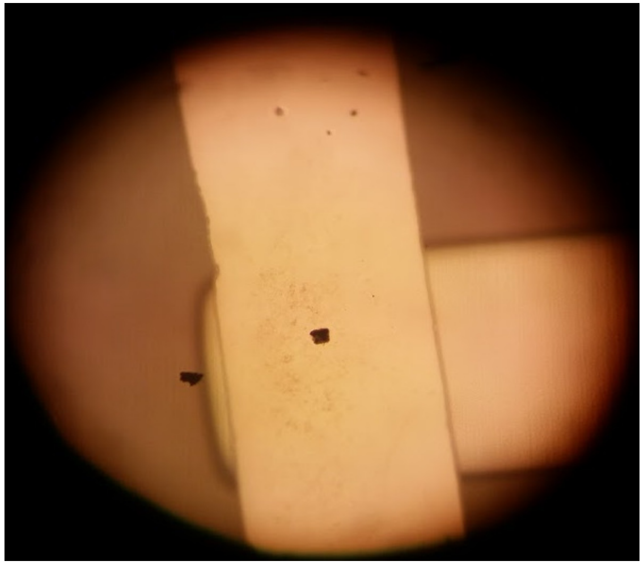
→ ~ 23 ps

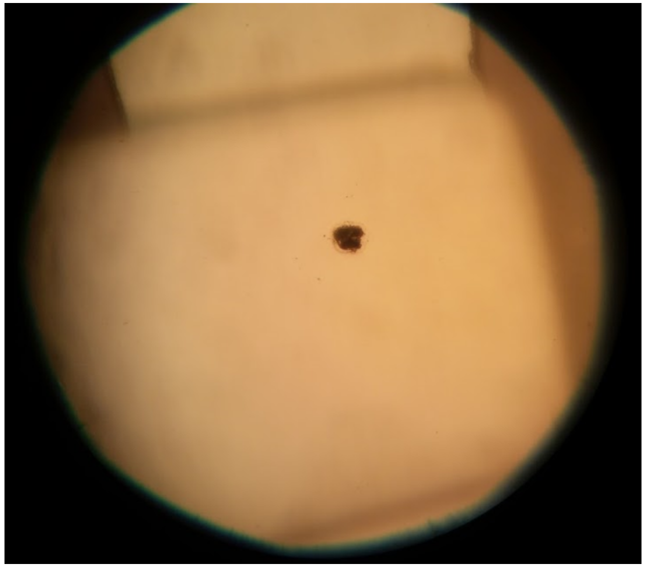
Measured risetime:

→ ~ 170 ps-
→ limitation of 2 GHz bandwidth;
→ Reflection at the feedthrough
→ But shape of the signal preserved

- **CHARGE MULTIPLICATION – THE END…**

@ ~ 650V (200 V/μm → 2 MV/cm)



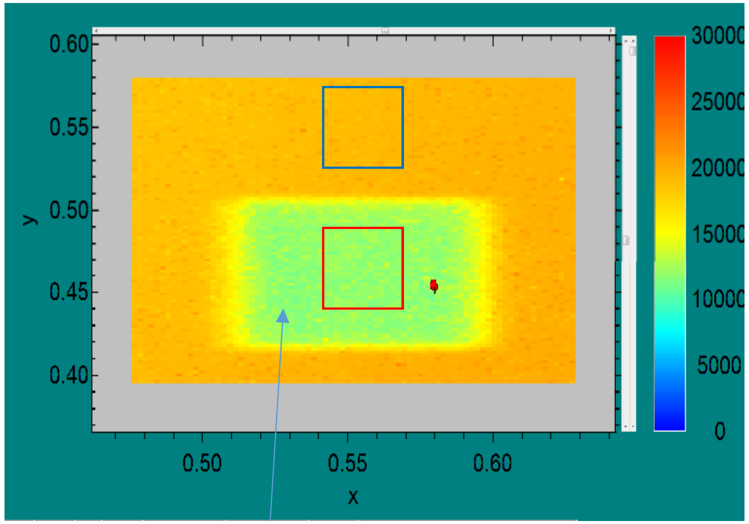


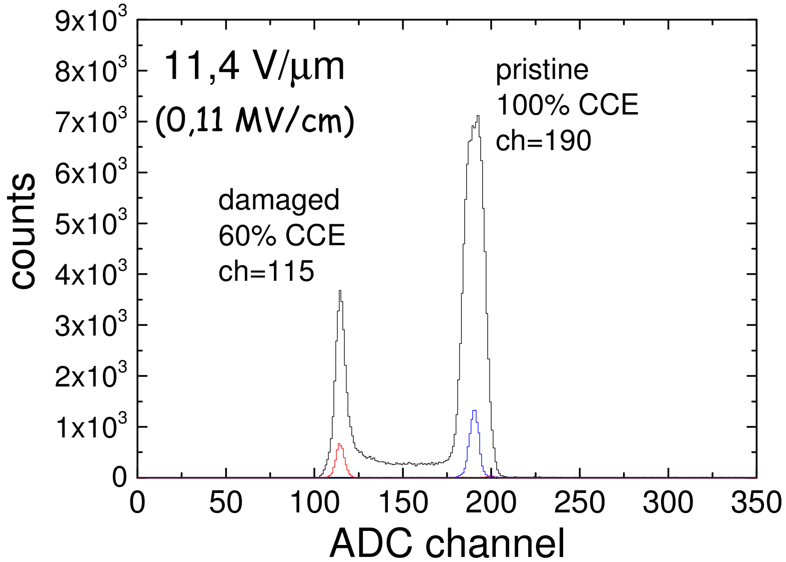
we need (structural) defects free diamonds
to study in more detail avalanche effect (…same for power electronics ..)

- **CHARGE MULTIPLICATION – THE END .. NOT REALLY !**

## First Application – True Radiation Hard Diamond Detectors

… membrane was re-metallized and send back to RBI for further measurements…



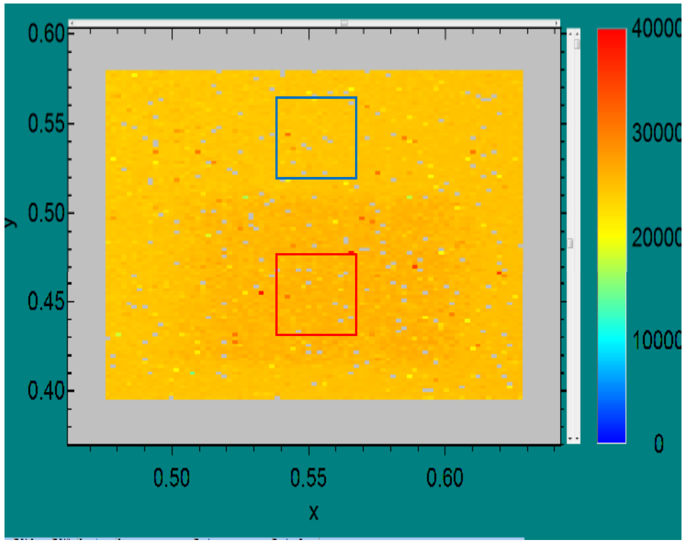



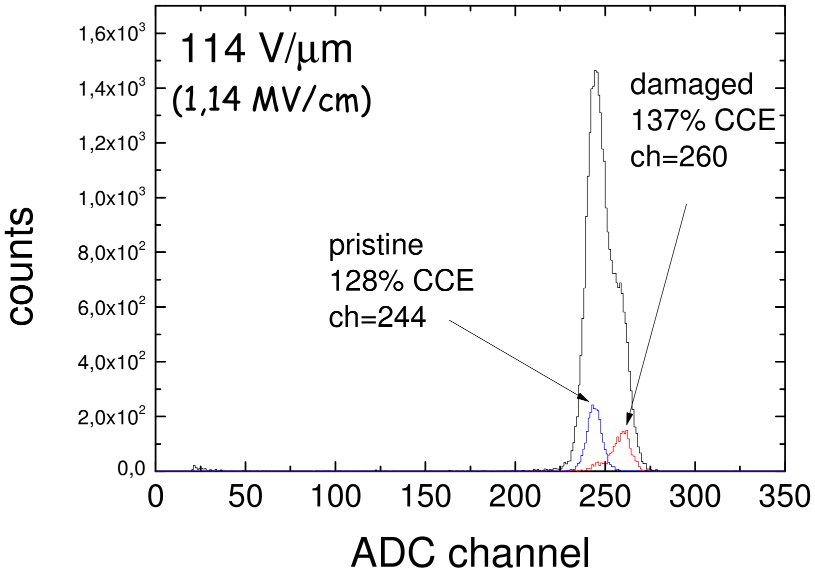

Region damaged with $1x10^{11}$ O (18 MeV) ions/$cm^2$

[creation of V0, deep trapping centres]
2.2*10^17 vacancies/cm^3 (SRIM).

- **CHARGE MULTIPLICATION – CCE RECOVERY**

First Application – True Radiation Hard Diamond Detector

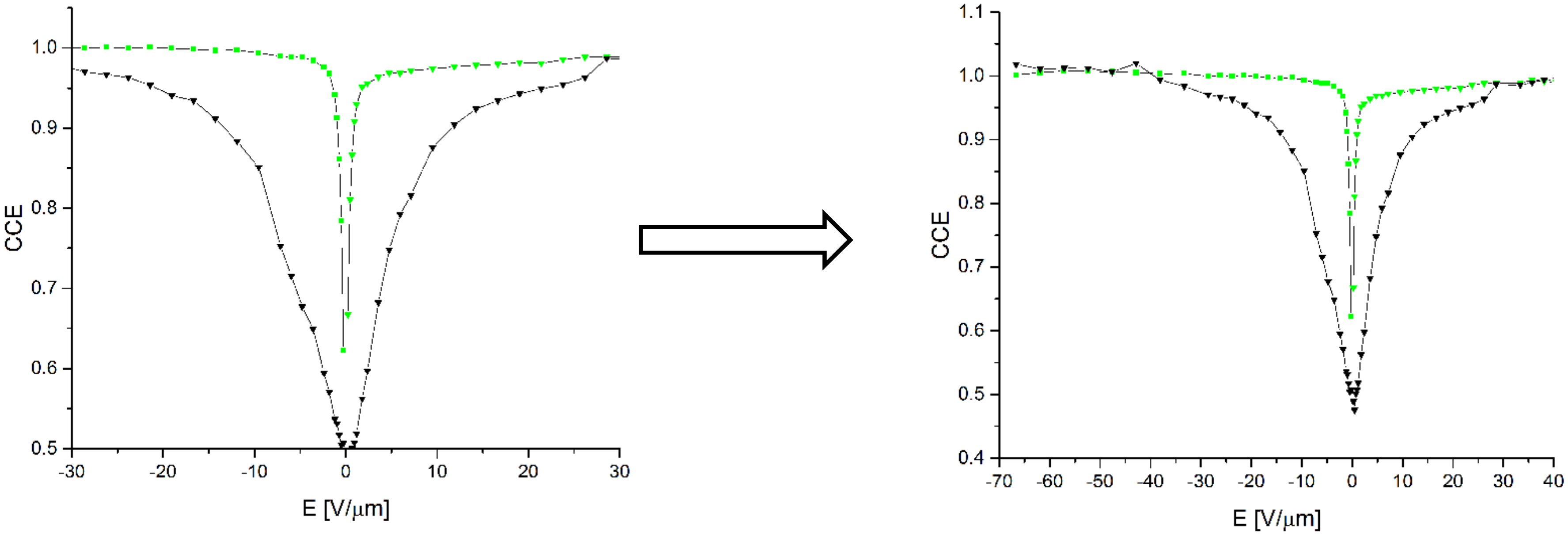



Complete recovery of CCE possible! (avalanching higher in damaged area)
[leakage current still <1 pA]

- **CHARGE MULTIPLICATION – CCE RECOVERY**

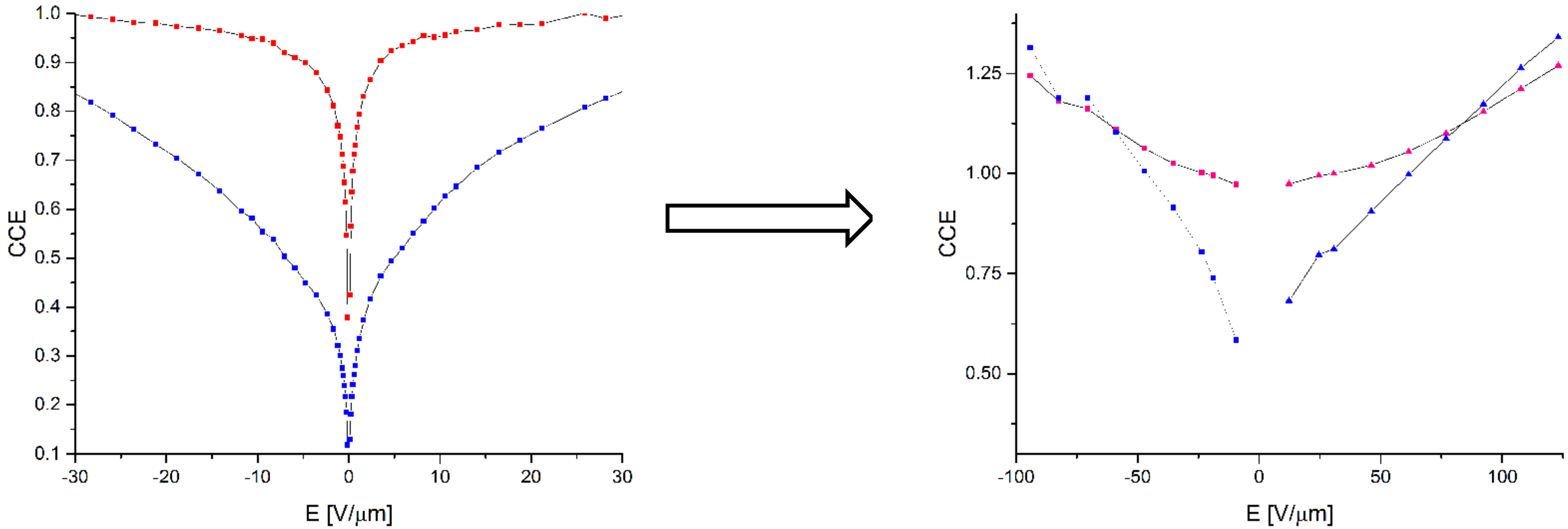
PROTONS-fast recovery & NO multiplication



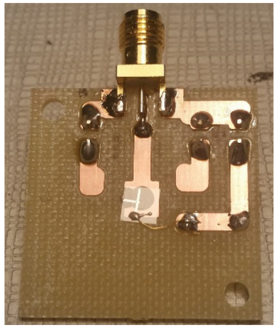
- **CHARGE MULTIPLICATION – CCE RECOVERY**

OXYGEN – High fields for recovery & multiplication!!!

Multiplication is higher in damaged areas



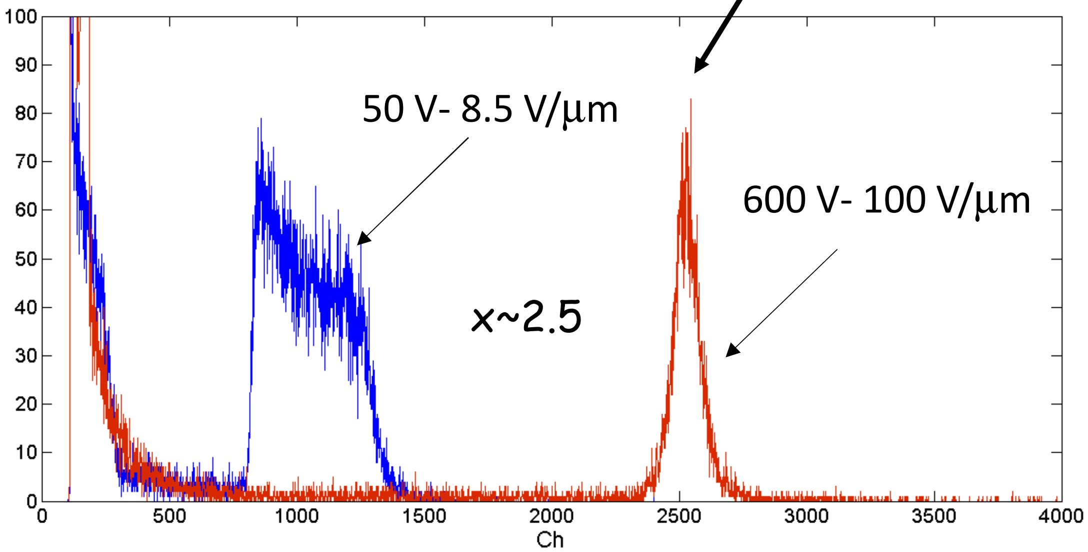
- **ANOTHER SAMPLE; HIGH LET BEAMS AT QST CYCLOTRON TAKASAKI, LAST WEEK; PRELIMINARY**

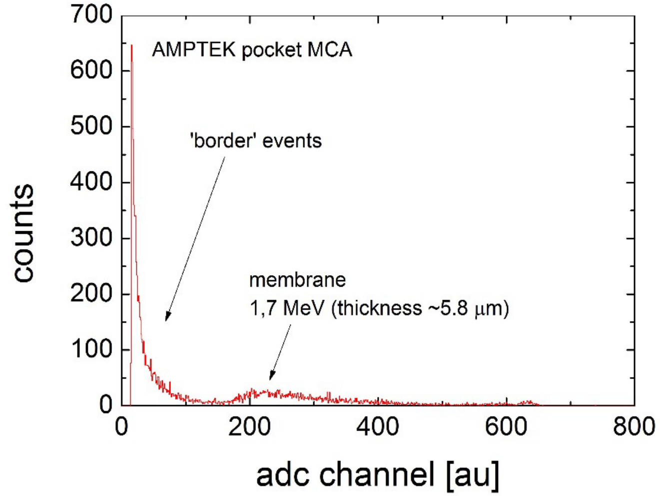


Cocktail beam
Xe 454 MeV
Kr 320 MeV
Ar 150 MeV
N 54 MeV

The peak shrinks as the multiplication is higher in thinner parts of the membrane!

Thickness measurement:
5.486 MeV $\alpha$ detection -telescope setup
- Bad thickness homogeneity

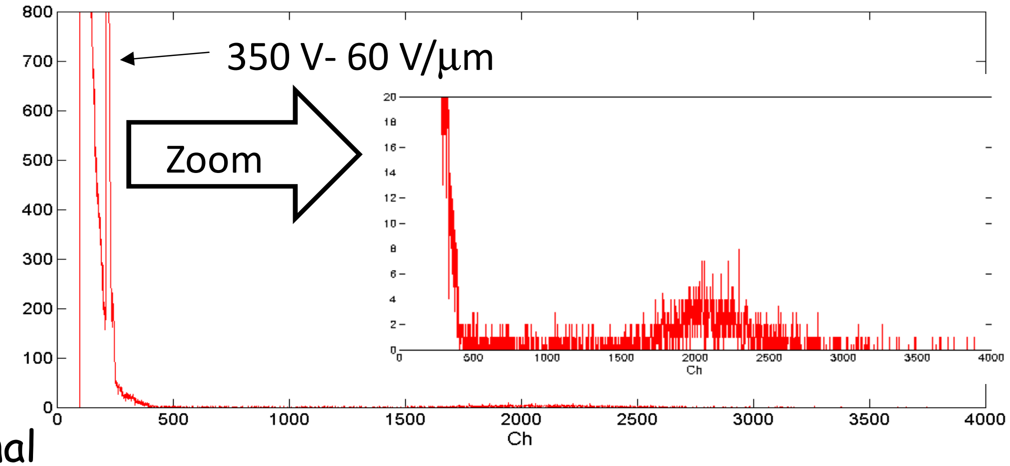



About 100 MeV deposited in the membrane

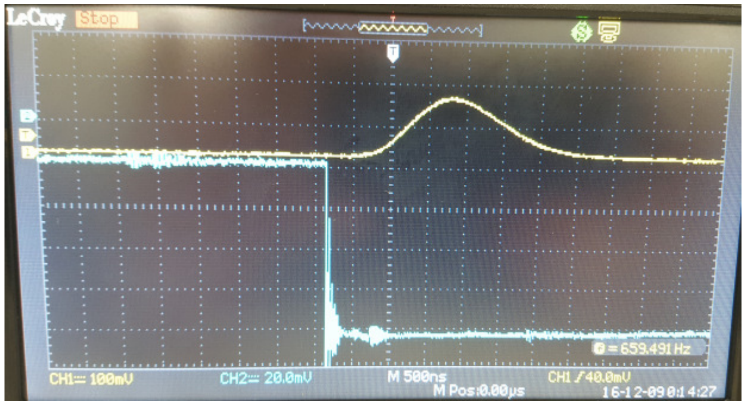
- **ANOTHER SAMPLE; GEIGER MODE, PRELIMINARY**

Cocktail beam
Xe 454 MeV
Kr 320 MeV
Ar 150 MeV
N 54 MeV

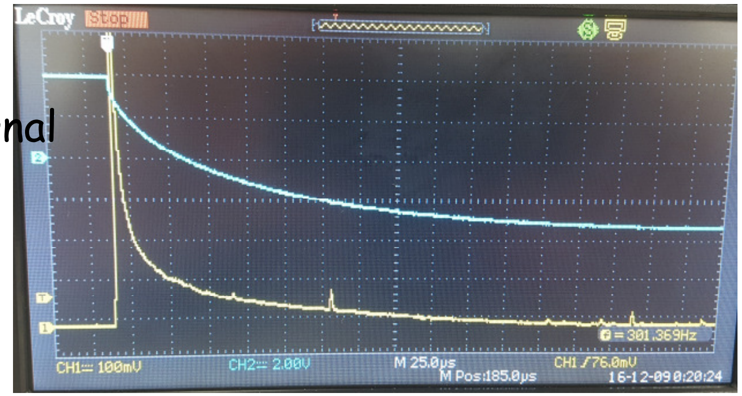



About 350 MeV deposited in the sample

Non Geiger mode:
Normal length f the signal
- 500 ns/div




Geiger mode:
Extended length of the signal
- 25 µs/div



- **SUMMARY AND OUTLOOK**

## CHARGE IMPACT MULTIPLICATION in scCVD DIAMOND:

- observed with 18MeV O (confirmed with Si, Ar and other HI down to C)
not seen for protons, α-particles, Li till 150 V/micron (1.5 MV/cm)

- Challenge: presence of structural defects (dislocations, inclusions, polishing)
- solid-state proportional and Geiger counters ahead …
- true radiation hard diamond detectors possible (thick detectors (?))

## OUTLOOK:

- Systematic study of impact ionization vs. LET with HI in intrinsic diamond (SG <1 ppm [N] ; EG < 1ppb [N], [B])

**!!! Thank you very much for your kind attention !!!**