# An Insight into Radiation Tolerance of scCVD-DD First Irradiations with 26MeV p and ~20MeV n

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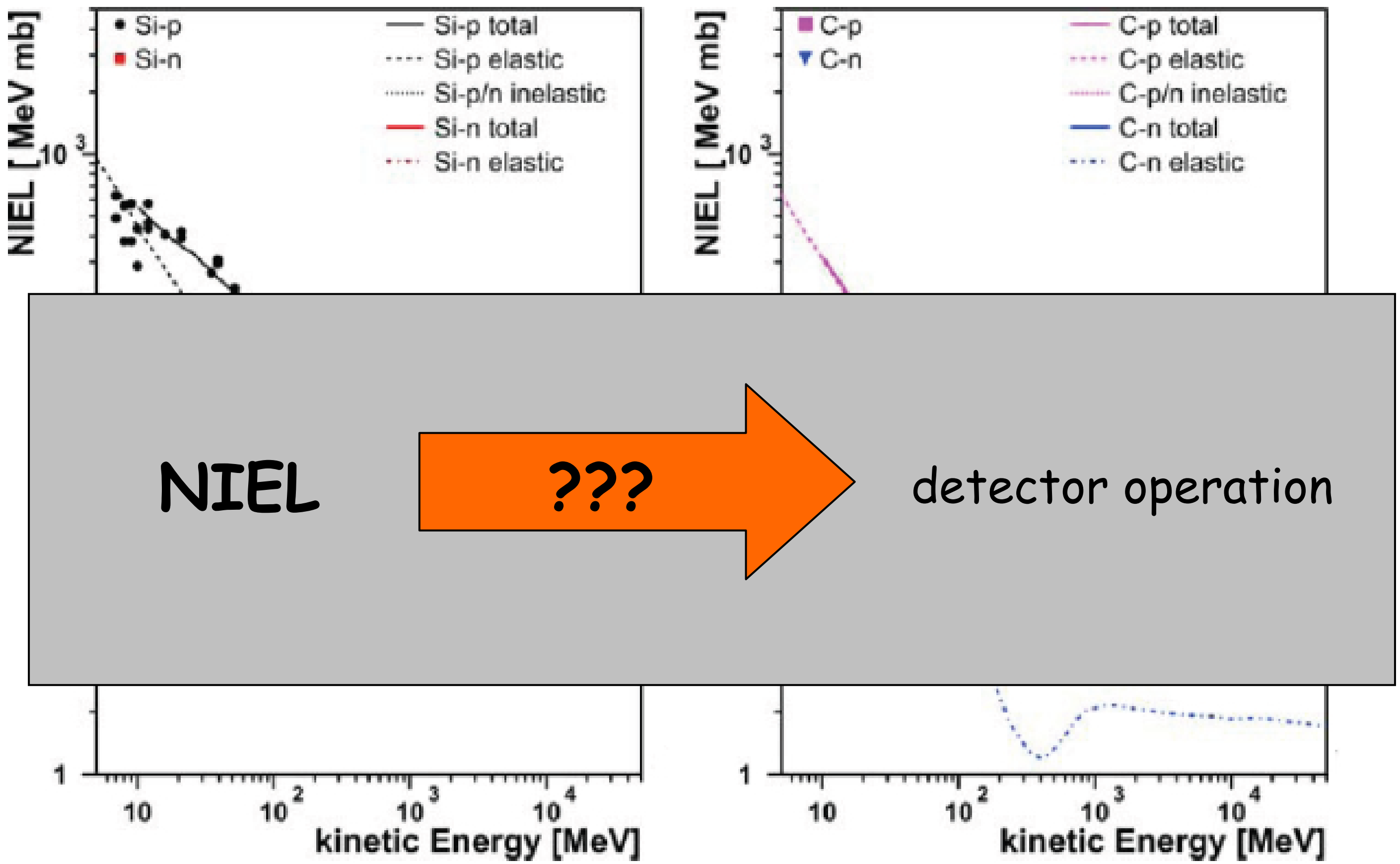
# Aim of the Study

Novel Radiation Hard(?) Diamond Detectors
for Hadron Physics

# OUTLINE

1. Introduction
   - Non Ionizing Energy Loss – NIEL
   - Radiation induced effects
2. Material and Methods
   - scCVD diamond
   - irradiation conditions – 26MeV p, ~20MeV n, on-line monitoring
3. Characterization
   - identification of radiation induced defects – optical characterization
   - dark current and TL
   - trapping time – TCT technique
   - trapping related phenomena – polarization, priming etc.
   - CCE and CCD of primed detectors
4. Summary
5. Outlook – How to proceed

# NIEL - Non Ionizing Energy Loss in Diamond



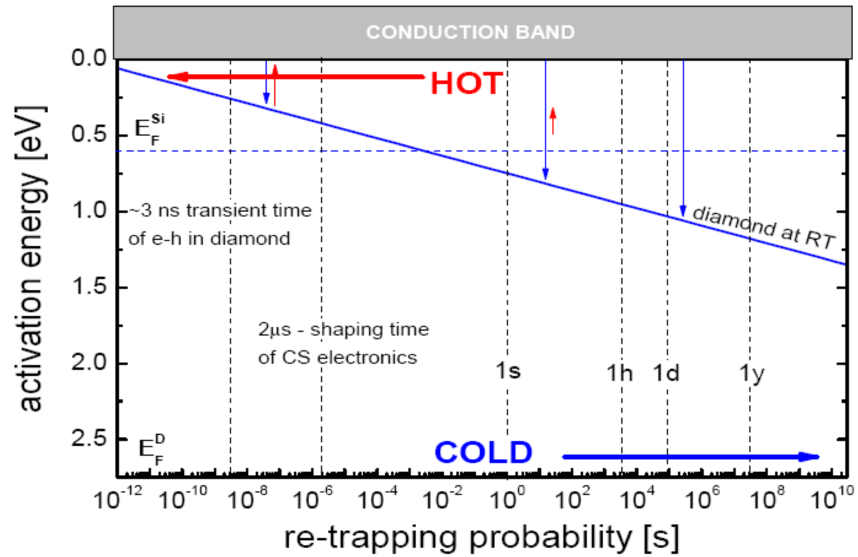

Radiation damage at LOW energy dominated by **elastic cross section**.
C-nuclei have factor two smaller Z than Si and higher displacement energy (≈40 eV **(?)** vs 20 eV)

Radiation damage at HIGH energy dominated by **inelastic cross section**.
C-nuclei smaller and more stable than Si. Diamond order of magnitude better than Silicon.

# NIEL – Radiation induced effects

## Silicon

- dark current → αΦ – NIEL scalable
- space charge → -βΦ – depletion voltage
- charge trapping → 1/τ – NIEL violation
- induced defects are mobile at RT - annealing




## Diamond

Gap ~5x silicon ~at RT Diam ~ Si at 60K

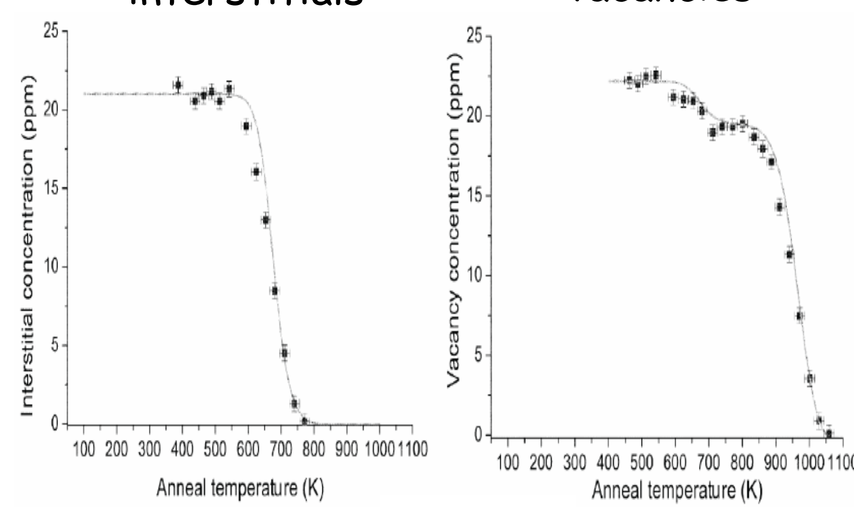
- dark current – none or decreases if present
- space charge – none(?)
- charge trapping – yes → space charge, pumping

Polarization

pumping, priming → 'Lazarus effect'

Induced defects are not mobile at RT
interstitials ~ 1.6 eV, vacancies ~ 2.3 eV

interstitials vacancies




M.E. Newton, 2002

# CCE and CCD

## CCE – charge collection efficiency $CCE = Q_{coll}/Q_{gen}$

$$Q_{coll} = Q_{gen}\, tau_{e,h}/t_{tr-e,h}\,(1 - \exp(-t_{tr-e,h}/tau_{e,h}))$$
$$Q_{gen} = \sim 36\text{e-h}/\mu\text{m} \times d$$

where $t_{tr}=v_{dr}/d$ and d-sample thickness in µm
- thickness dependent
- bias dependent

## CCD – charge collection distance

(averaged 'Schubweg' → e + h)

$$CCD = \mu_{e,h} \times tau_{e,h} \times E \text{ - ohmic transport}$$

better

$$CCD = v_{dr-e,h}(E) \times tau_{e,h}$$

at high E $v_{sat}$~constant

**$1/tau = 1/tau_{intr} + 1/tau_{rad-ind}$** and $1/tau_{rad-ind}=\beta\Phi$

Bad quality samples eg. pcCVD (or thin) appear more rad-hard when looking at CCE

# scCVD diamond

## Samples:

- single crystal CVD diamond – producer e6
- free standing thin films 3-5 x 3- 5 x 0.05 – 0.5 $mm^3$
- <100> oriented

## Atomic impurities:

- extremely low concentration of N (<5ppb) and B (<1ppb)

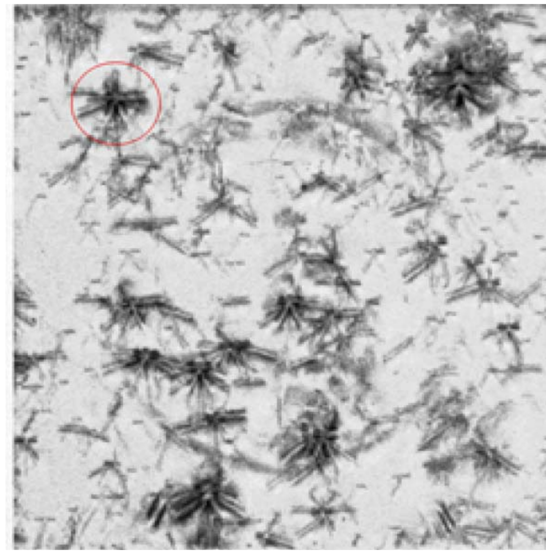
## Macroscopic impurities:

- most of the samples contains threading dislocations

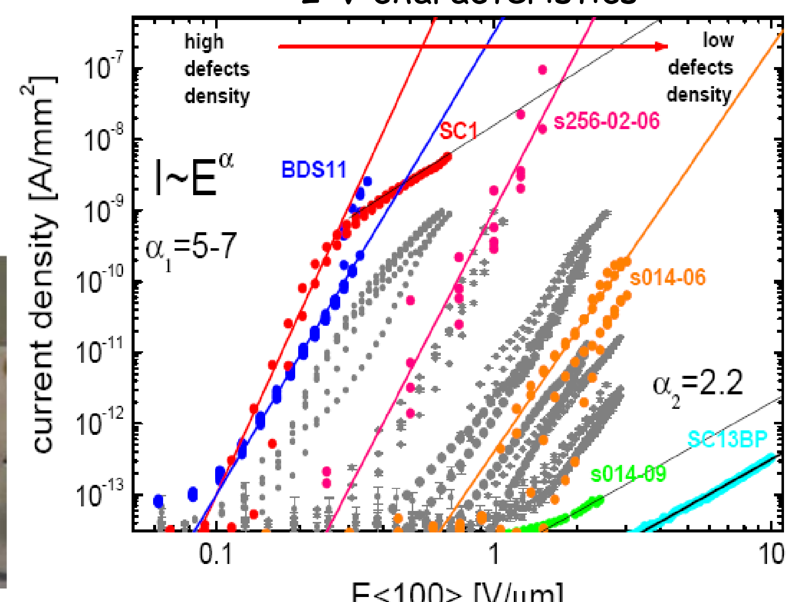
## Detector fabrication:

- cleaning and wet oxidation
- electrodes sputtering using shadow masks
- pad motive of 'sandwich' geometry
- Cr(50nm)Au(100nm)+annealing or Al(100nm)

X-ray topo



I-V characteristics



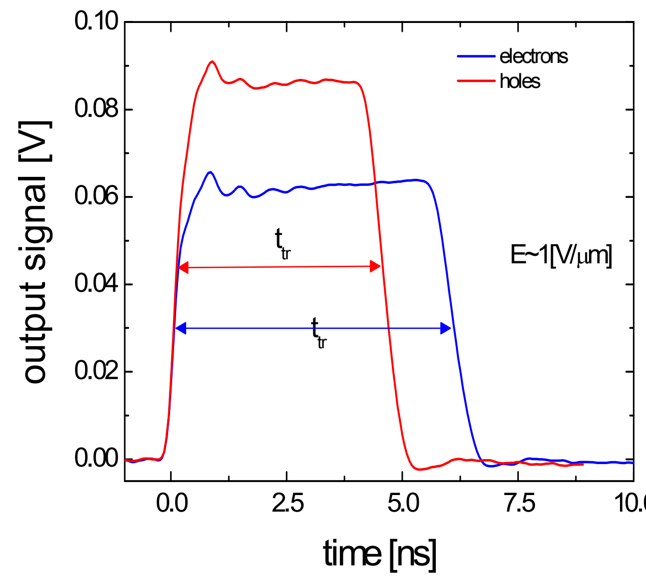
# scCVD diamond

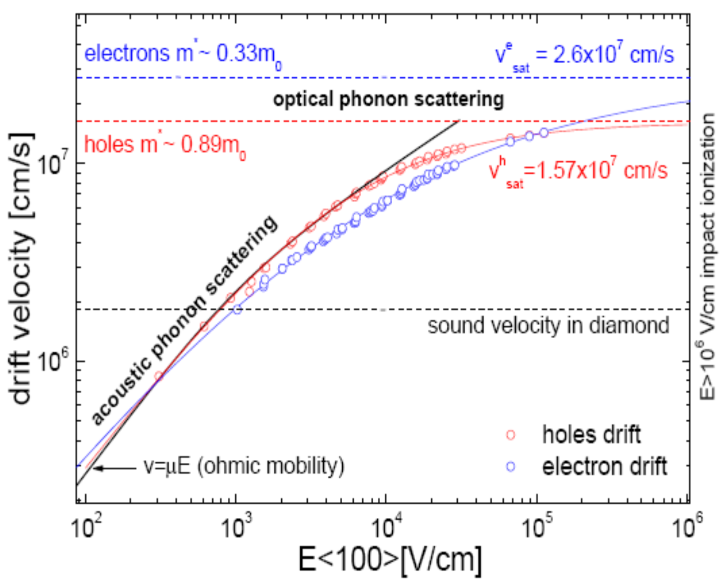
## Transport properties:

- can be operated at drift saturation velocity ~ 10 V/µm

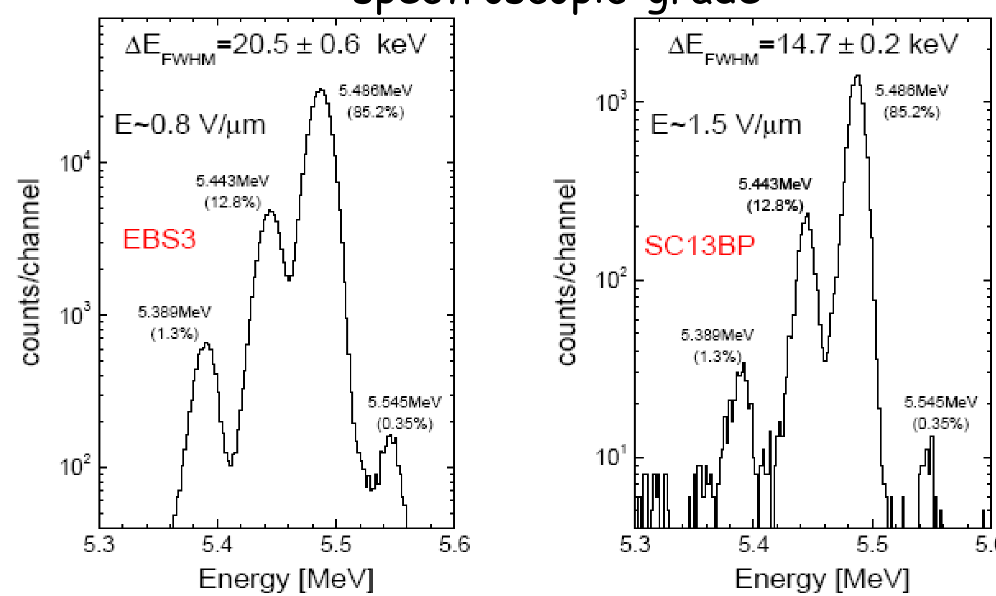
- velocities for e and h ~140 µm/ns @ 10 V/µm

- lifetime approaching 1µs → CCD approaching several cm



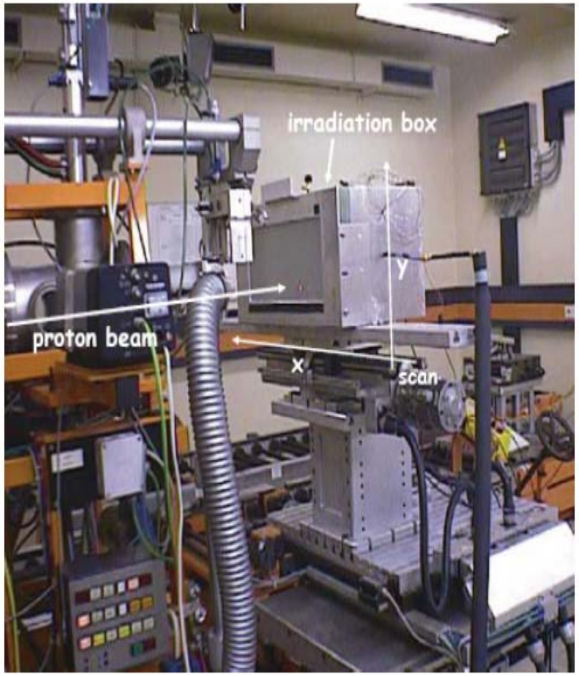

'spectroscopic' grade



# 26 MeV protons irradiation

Proton beam in Karlsruhe:

- 26 MeV
- beam current 500nA - 40μA
- beam radius 1mm – 1cm
- temperature ~-10 $^0$C (cold N2)
- time for 1e14p/cm2 on 12x12cm2: ~2min




Dosimetry well established (RD50 Si irradiation):
- initially calibrated
- nickel foil activation (dose verification if needed)

| sample | beam current [$\mu$ A] | irradiation time [min] | integral fluence $\Phi$ [26 MeVp/cm$^2$] scan integration | integral fluence $\Phi$ [26 MeV p/cm$^2$] Ni foil activation |
|---|---|---|---|---|
| BDS14 | 0.6 | 2 | $5.35 \times 10^{13}$ | $6.38 \times 10^{13}$ |
| EBS3 | 6 | 2 | $5.35 \times 10^{14}$ | $6.11 \times 10^{14}$ |
| BDS13 | 12 | 22 | $1.07 \times 10^{16}$ | $1.18 \times 10^{16}$ |
| s256-05-06 | 0.2 | $6 \times 3$ | $1.07 \times 10^{14}$ | - |

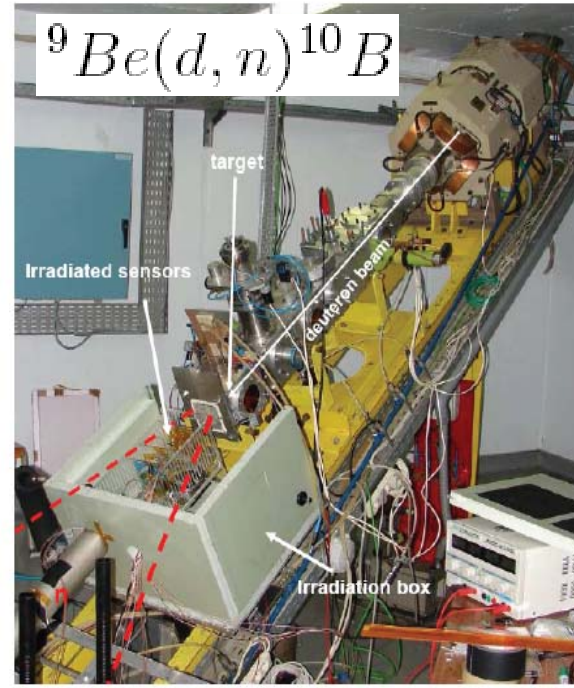
annealed Cr(50nm)Au(100nm)

# ~20 MeV neutrons irradiation

(thanks to Otilia Militaru)

High flux fast neutron line in Louvain-la-Neuve:

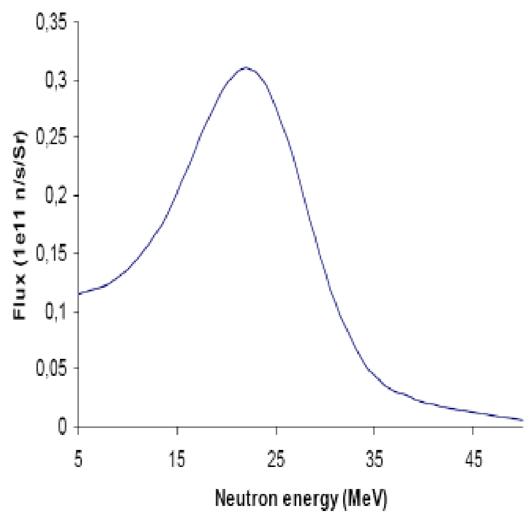
- ~ 20 MeV
- max. flux 6.6 x $10^{12}$ n $sr^{-1}$ $s^{-1}$
- contamination gammas~2.4%, charged ~0.03%
- temperature ~-10C (cold N2)
- irradiation time about 6h

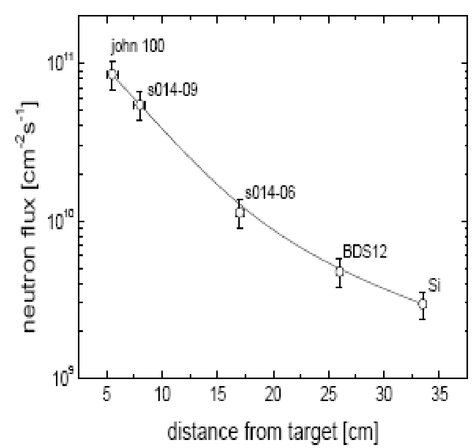



Dosimetry well established (RD50 Si irradiation):
- initially calibrated
- PAD (dose verification)

| sample | Integrated fluence | |
|---|---|---|
| | PAD dosimetry | current int. |
| BDS12 | $1.14 \times 10^{14}$ | $1.16 \times 10^{14}$ |
| BDS12 | $1.97 \times 10^{14}$ | - |
| s014-06 | $2.71 \times 10^{14}$ | $2.69 \times 10^{14}$ |
| s014-06 | $5.92 \times 10^{14}$ | - |
| s014-09 | $1.31 \times 10^{15}$ | - |
| john100 | $2.05 \times 10^{15}$ | $2.63 \times 10^{15}$ |

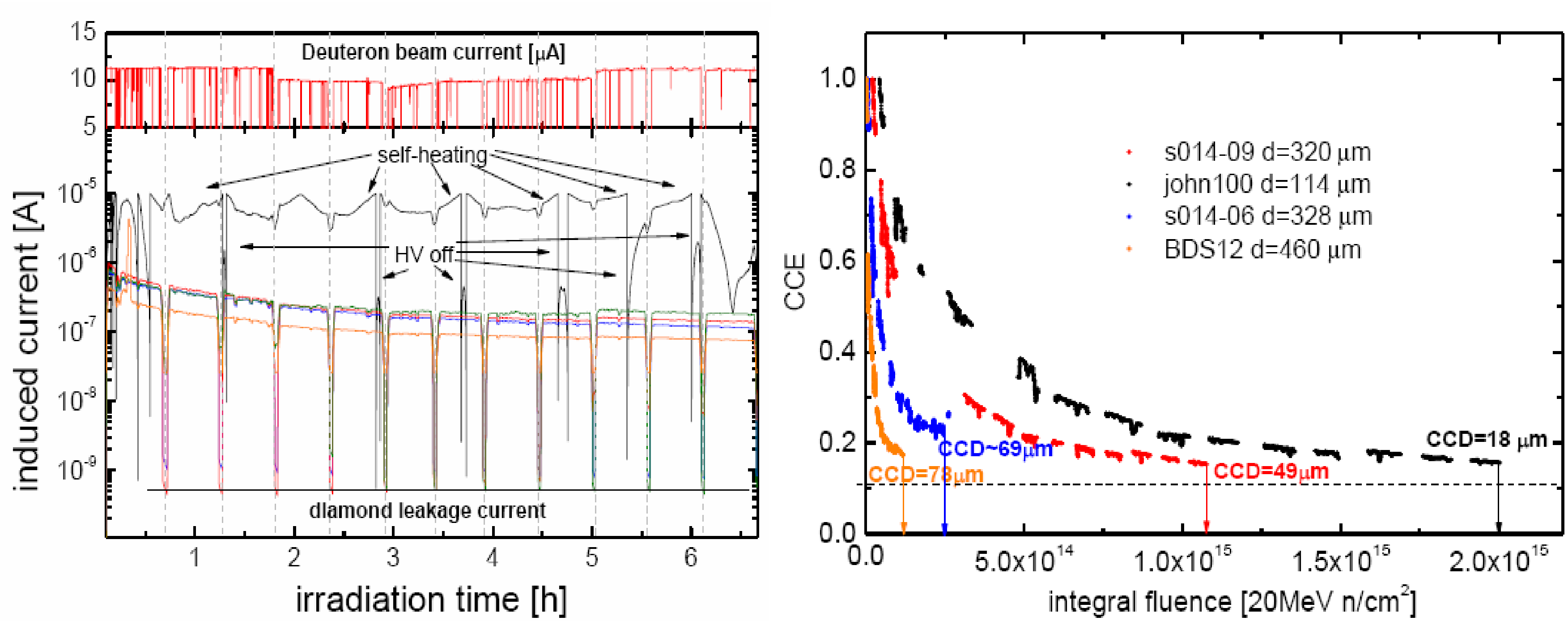
Al 100nm



# ~20 MeV n - on-line monitoring

- tunnel card developed for BML system of LHC (Steffen Mueller talk)
- biased detectors with DC current read-out
- Hammamatsu Si diode irradiated in parallel

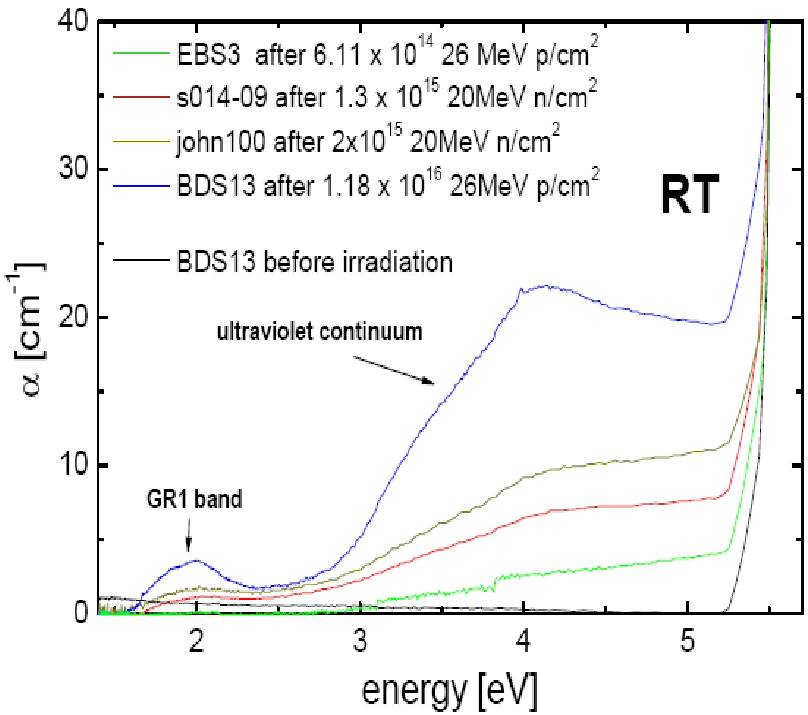


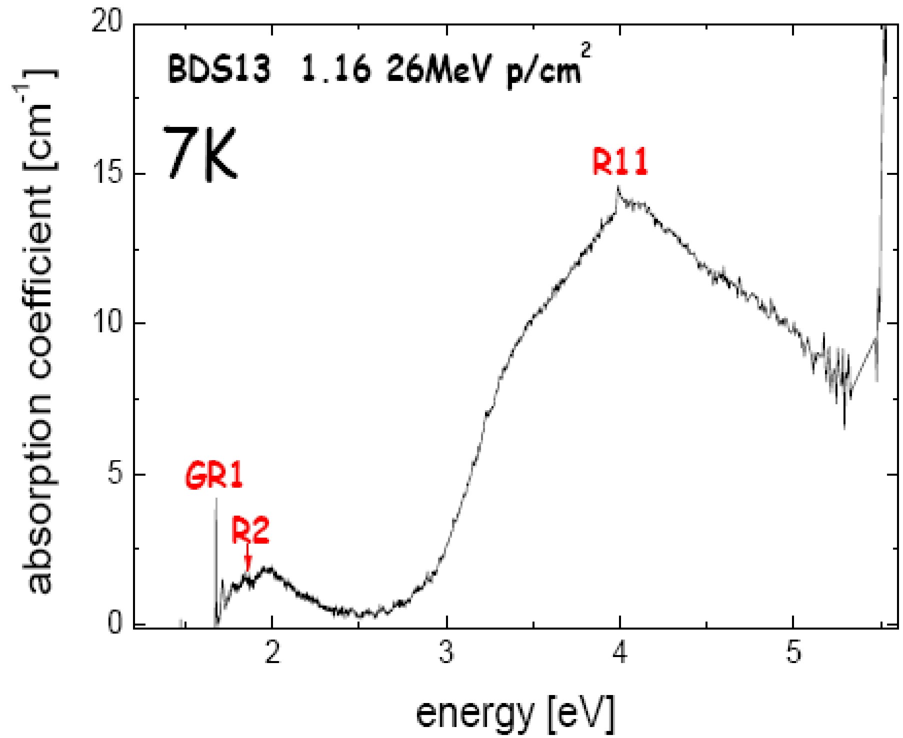

- drop of the current and unexpected low CCD/CCE (bias induced polarization)
- however.... beam induced I ~ two orders of mag. over the dark current
- Si → self-heating leads to thermal runaway

# Optical Absorbtion – 26MeV p irradiation

(thanks to Prof. Schwartz)

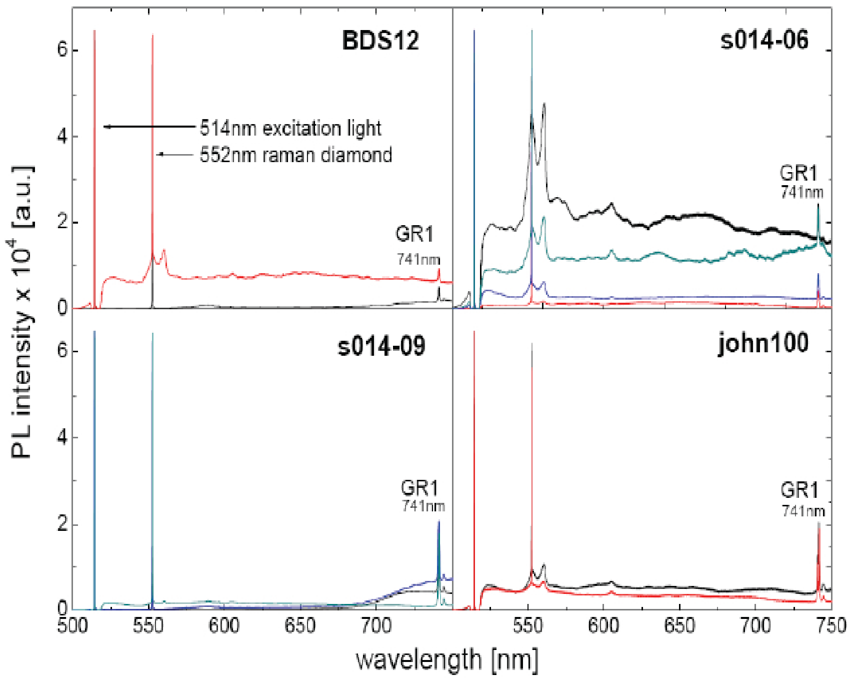
- low sensitivity but absolute estimation of the concentration of the defects possible
- RT and cryo measurements



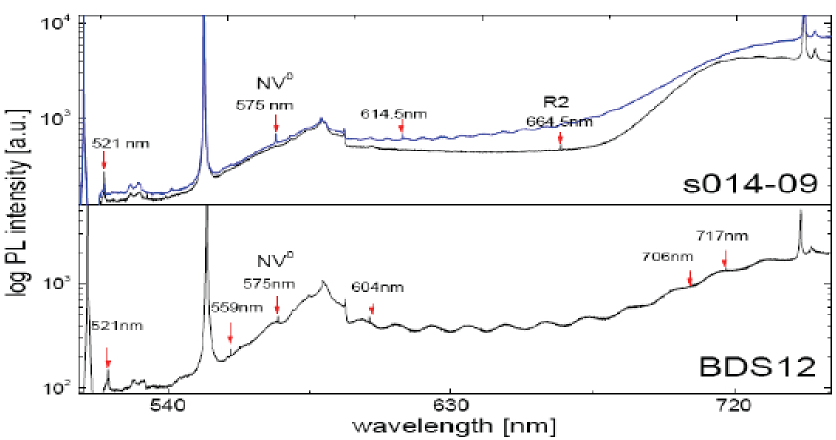



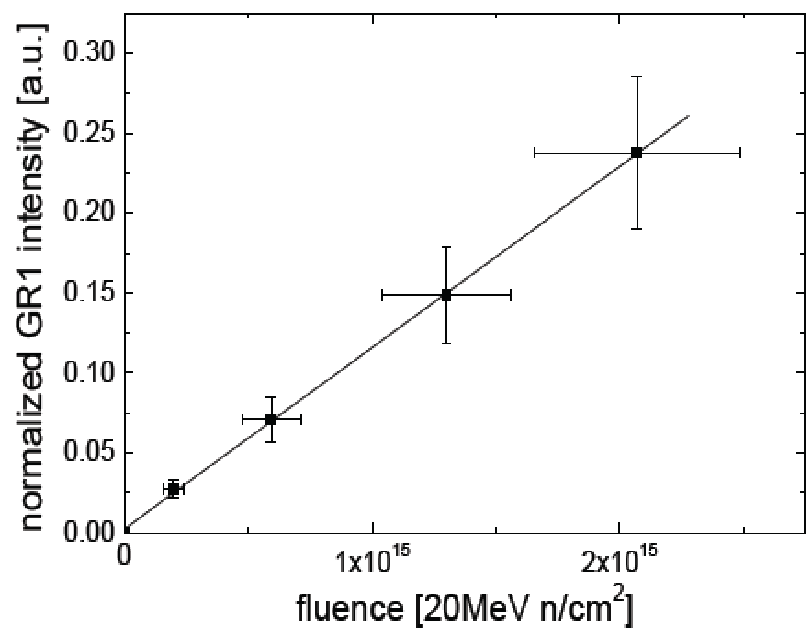

- only three ZPL; GR1-neutral mono-vacancy, R2, R11- split self-intersitial
- using ESR calibration constant of proportinality (Twitchen et al.) → ~$10^{17}$ $V^0/cm^3$
- about 20x lower than expected from NIEL

# Photoluminescence - ~20MeV n irradiation

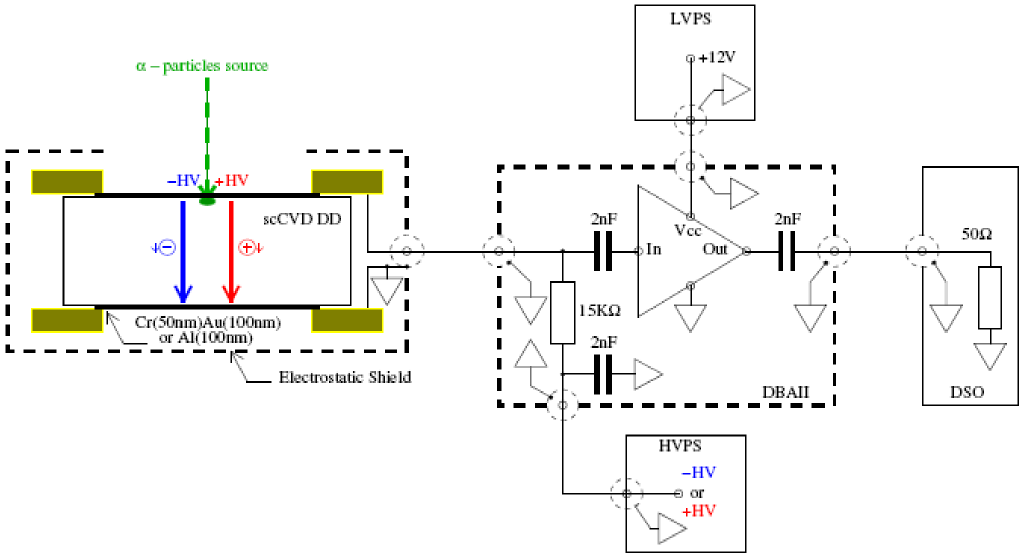



- high sensitivity but only relative comp.
- LNT measurements
- mainly GR1 (neutral mono-vacancy)
- residual defects ($NV^0$, R2, some others)
- linear introduction rate



# Electronic Characterization




## Transient Current Technique:

short range α-source (Am241-~5.5 MeV)

50Ω impedance DBA II, bandwidth **2.4 GHz**, gain ~120

Digital Scope, bandwidth **3GHz**, 20GS/s

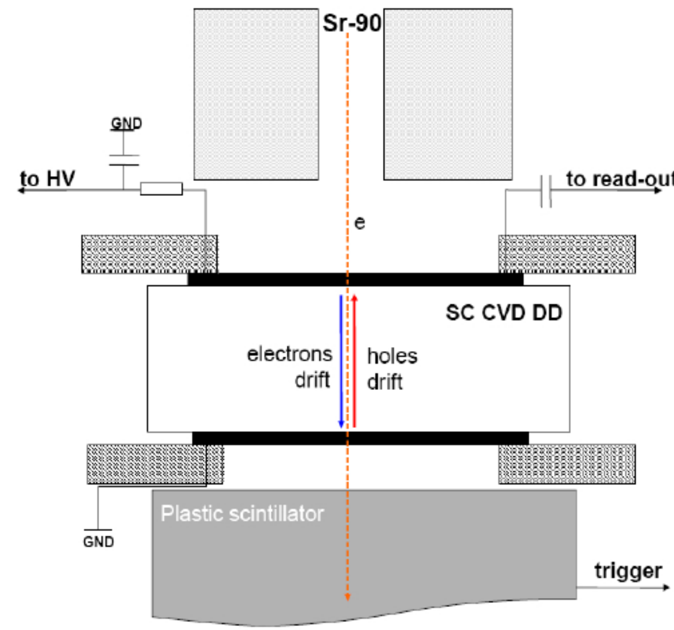
## Charge Collection Efficiency (primed state):

Sr-90 β-source – triggered Eβ>1.5 MeV – ~MIP eq.

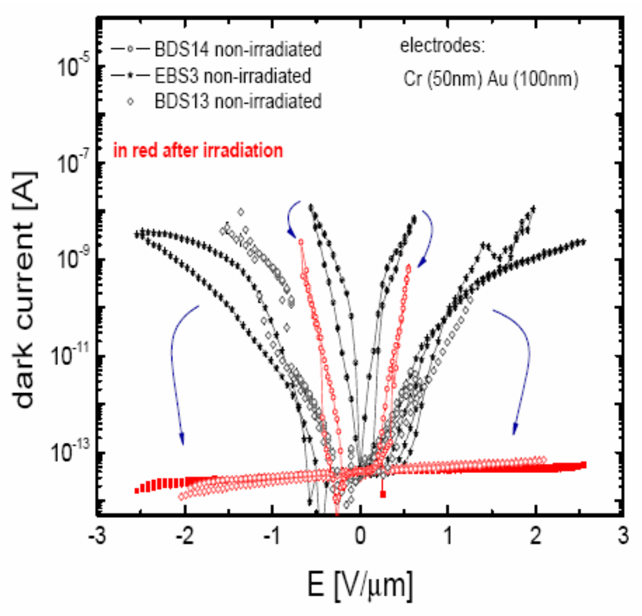
Low noise CSTA2 (Darmstadt) and A250CF (Amptek) preamplifier – shaping time 1μs

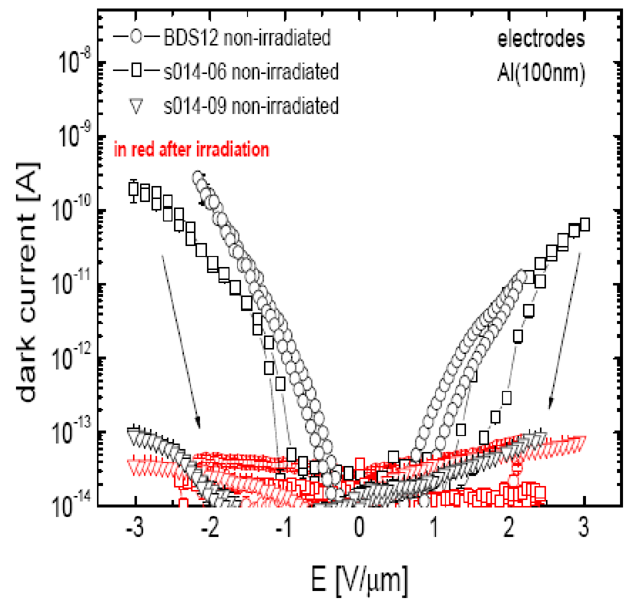
Classical electronics chain

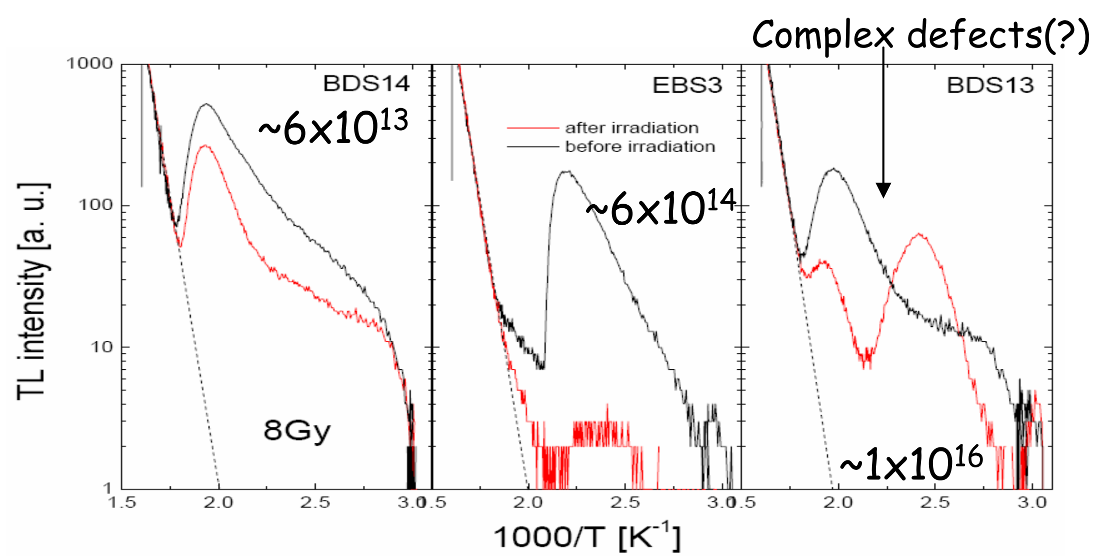
Cross calibrated pulser + Si detector (known ε)



# Dark Current and TL



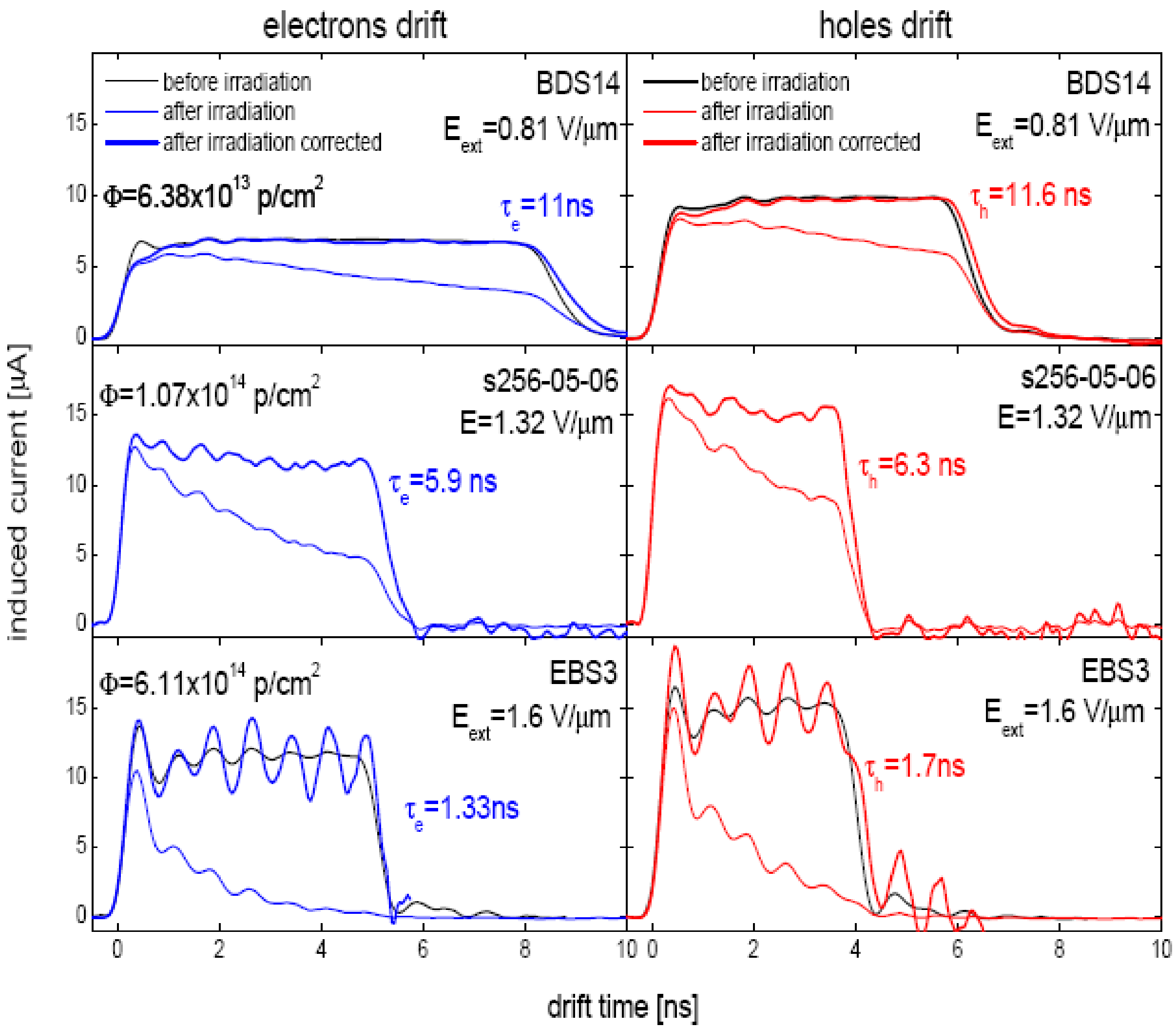



# Transient Current Signals

**26 MeV p irradiation ; Cr(50nm)Au(100nm) annealed electrodes**

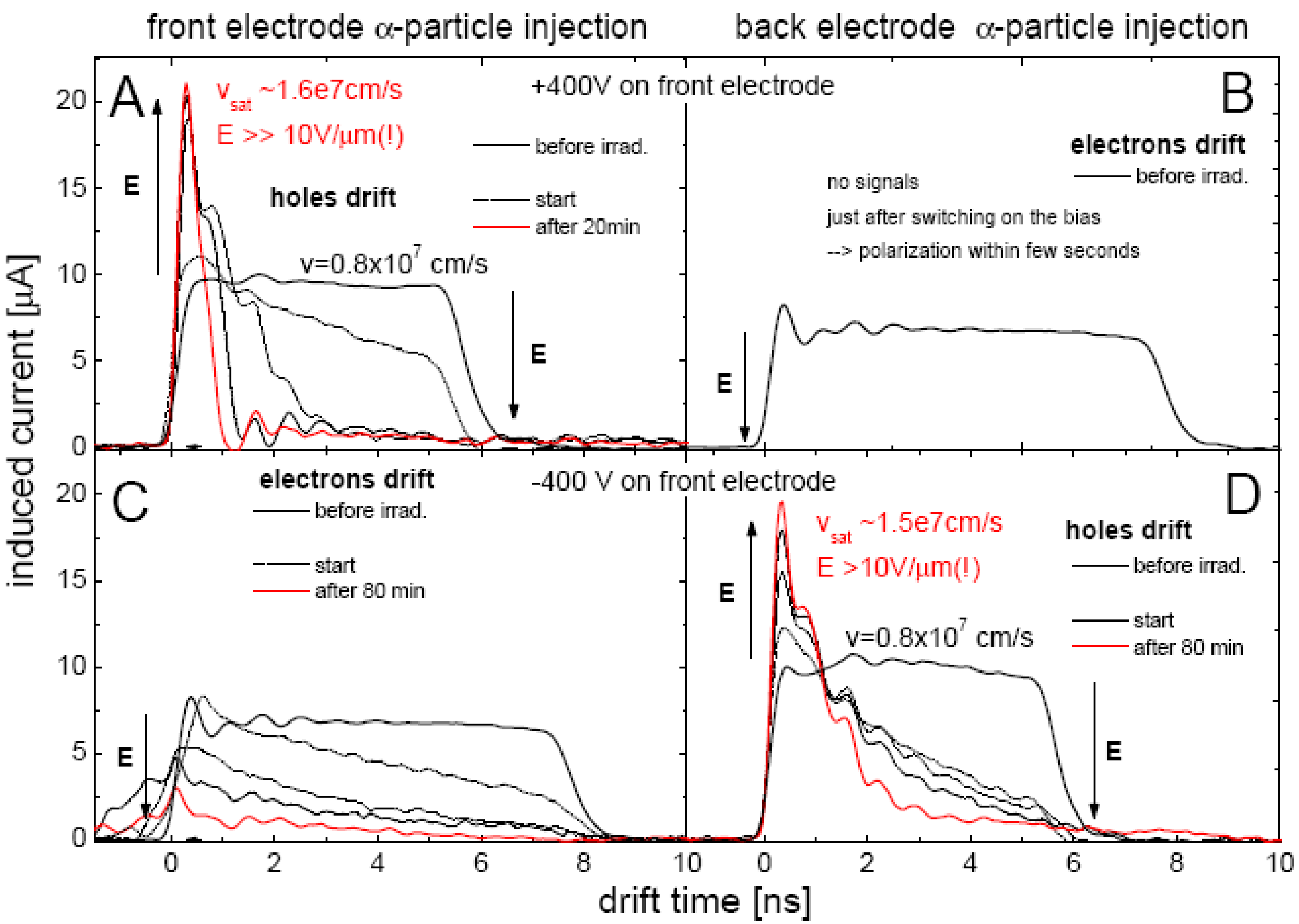
$$\int_{t=0}^{t=t_{dr}} I_{irr}(E,t)\,exp(t/\tau_{e,h})dt = \int_{t=0}^{t=t_{dr}} I_{vir}(E,t)dt$$




velocity didn't change
no additional scattering,
No space charge

# Bias-induced polarization

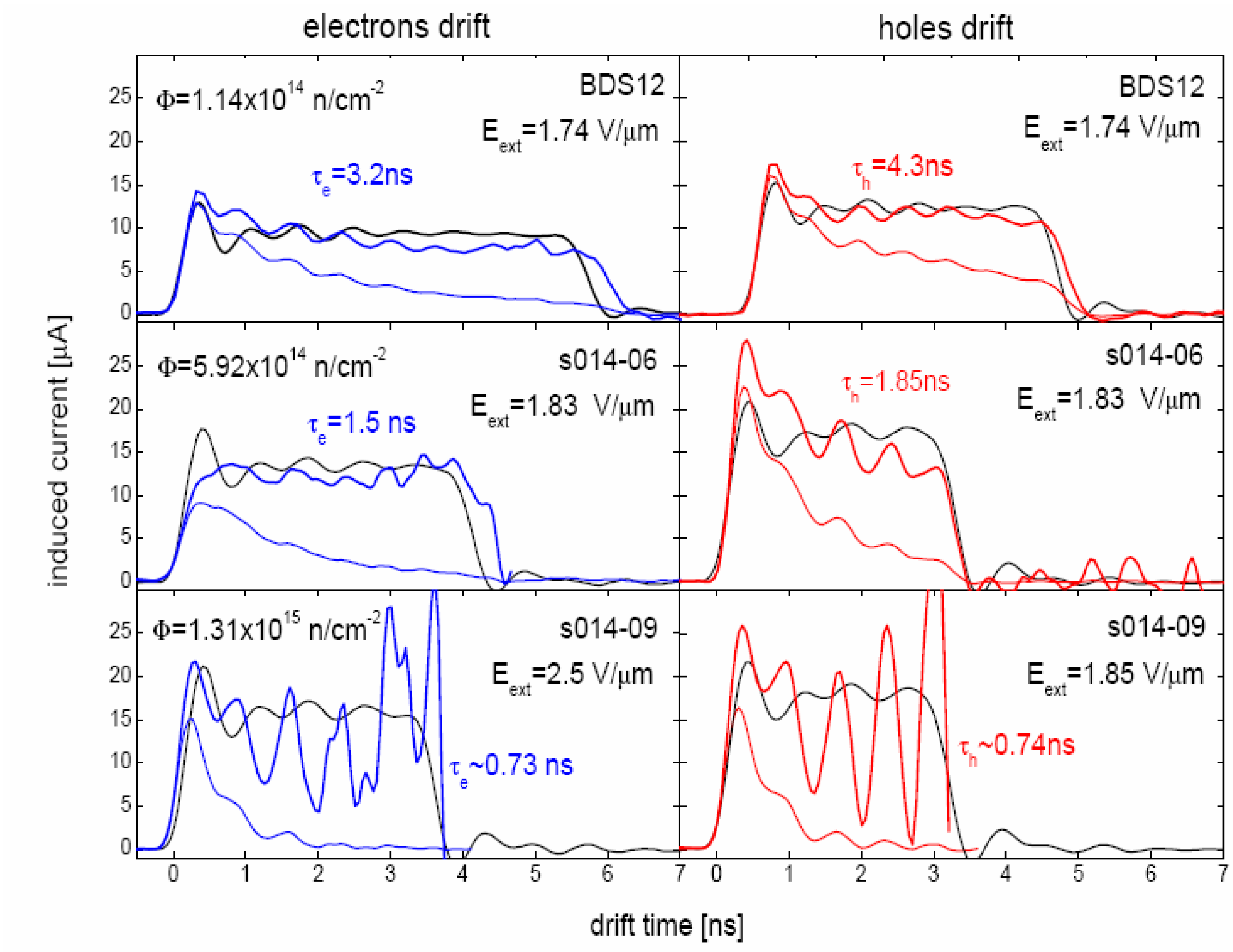
**20 MeV n irradiation ; Al(100nm)**




Similar effect observed in CdTe and irradiated cryo Si (reverse biased)

# Transient Current Signals

**~20 MeV n irradiation ; remetallized Cr(50nm)Au(100nm) annealed contacts**



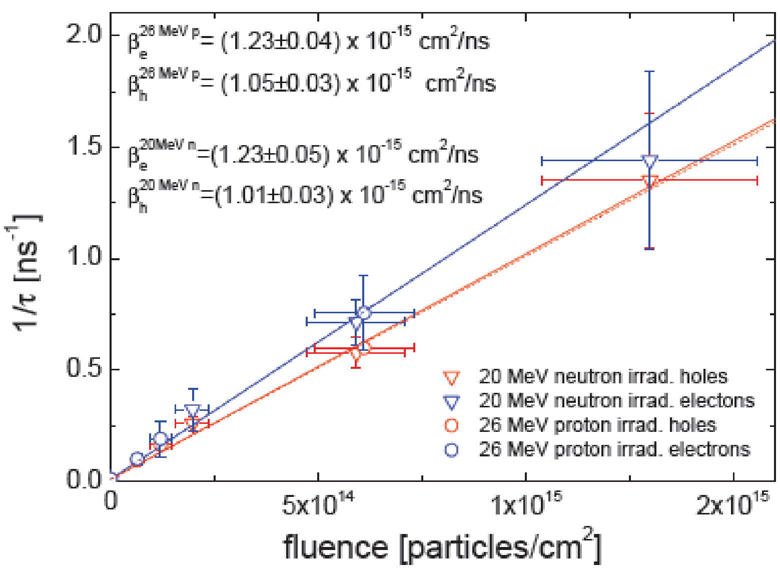
# TCT → trapping time (unprimed state)

$\beta_n=\beta_p$ - non-scalable with NIEL

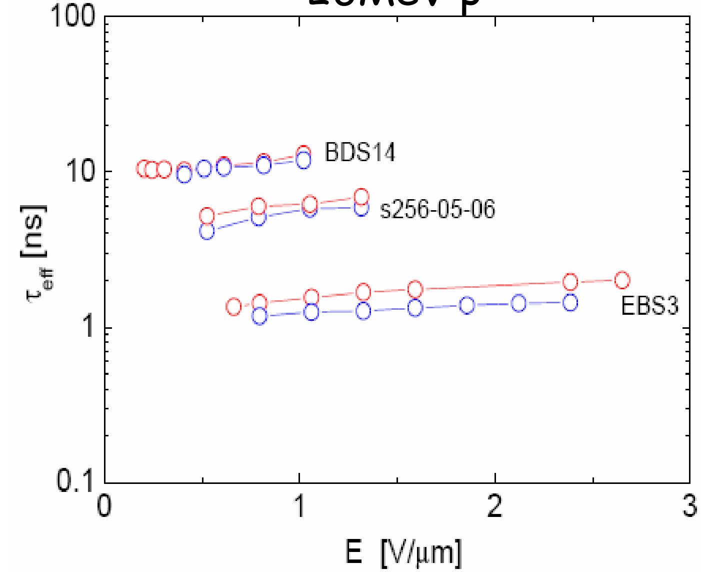
β - about twice higher than in Si(!) - no re-trapping

## $V^0$ cross-section for traping

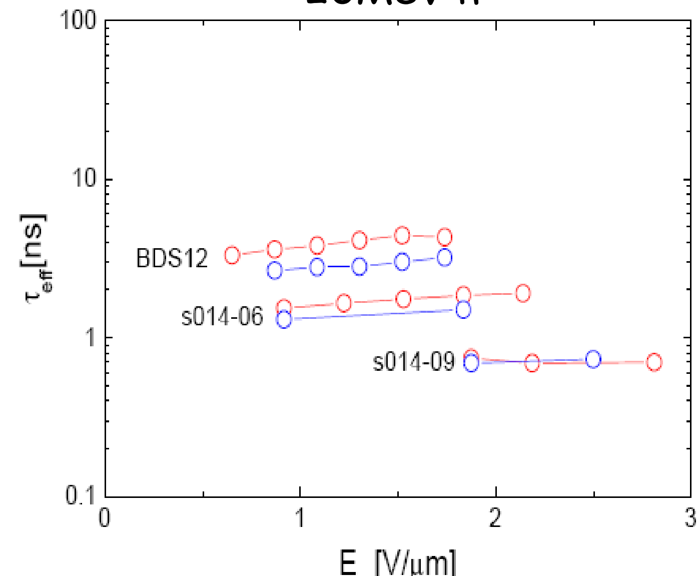
$$\tau_{e,h} = (\sigma v N)^{-1} \quad \sigma_{V^0} \approx 6\times 10^{-15}\ \mathrm{cm}^{-2}$$



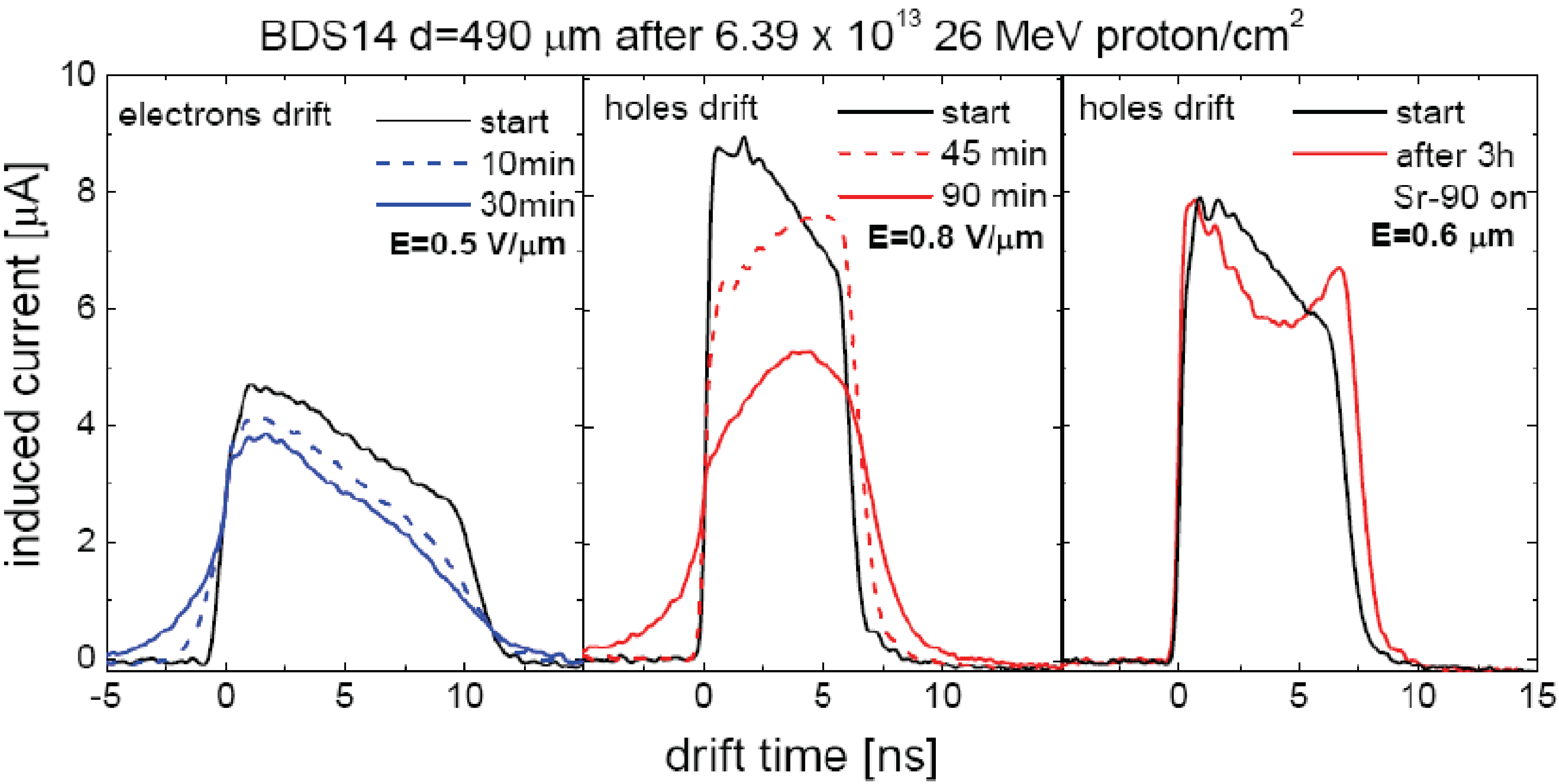

26MeV p




~20MeV n

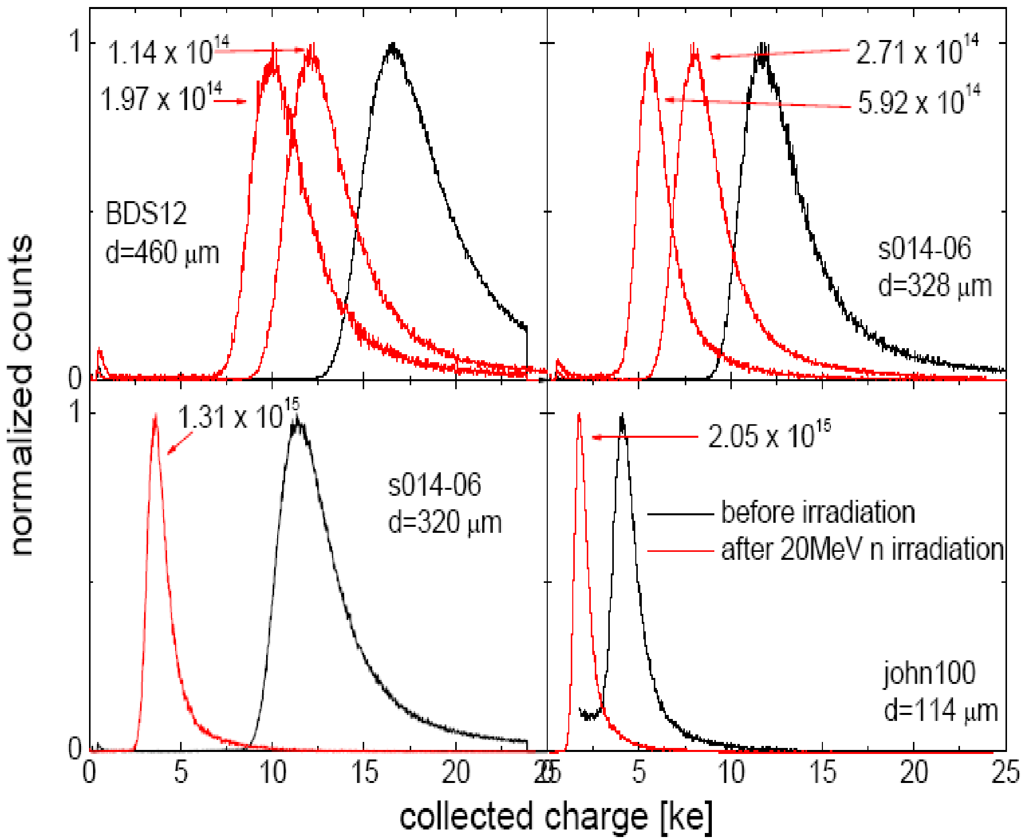


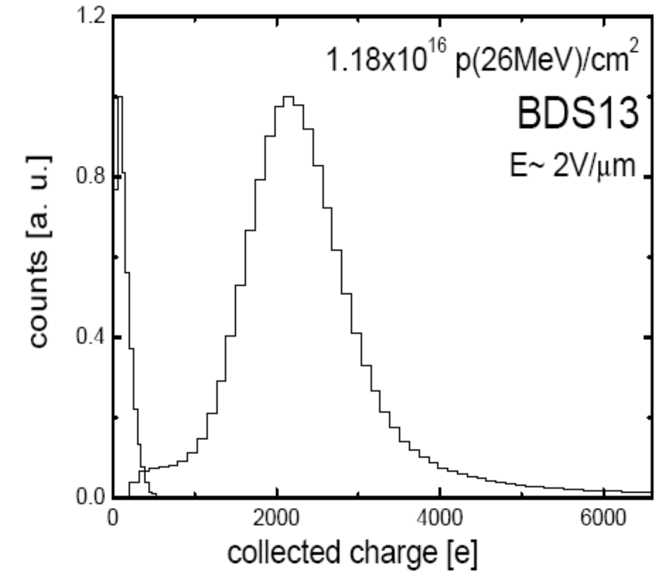
# TCT → trapping related effects

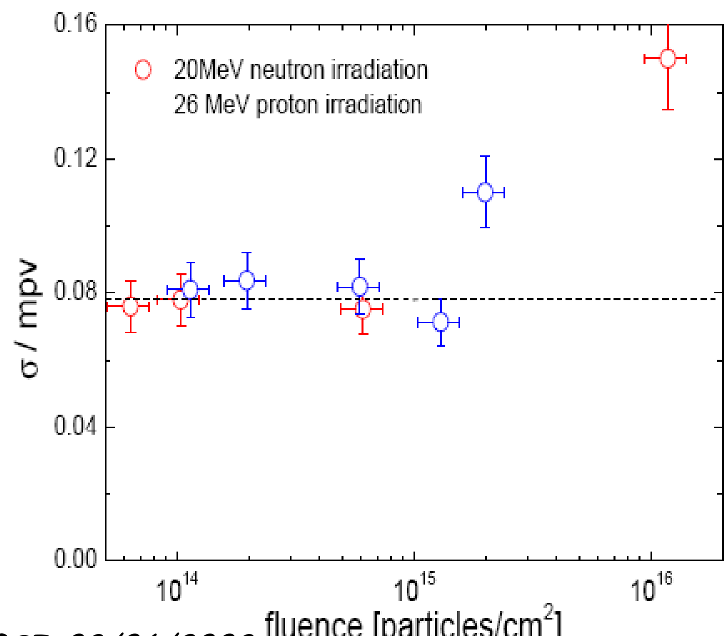



Stopped → polarization traversing→priming

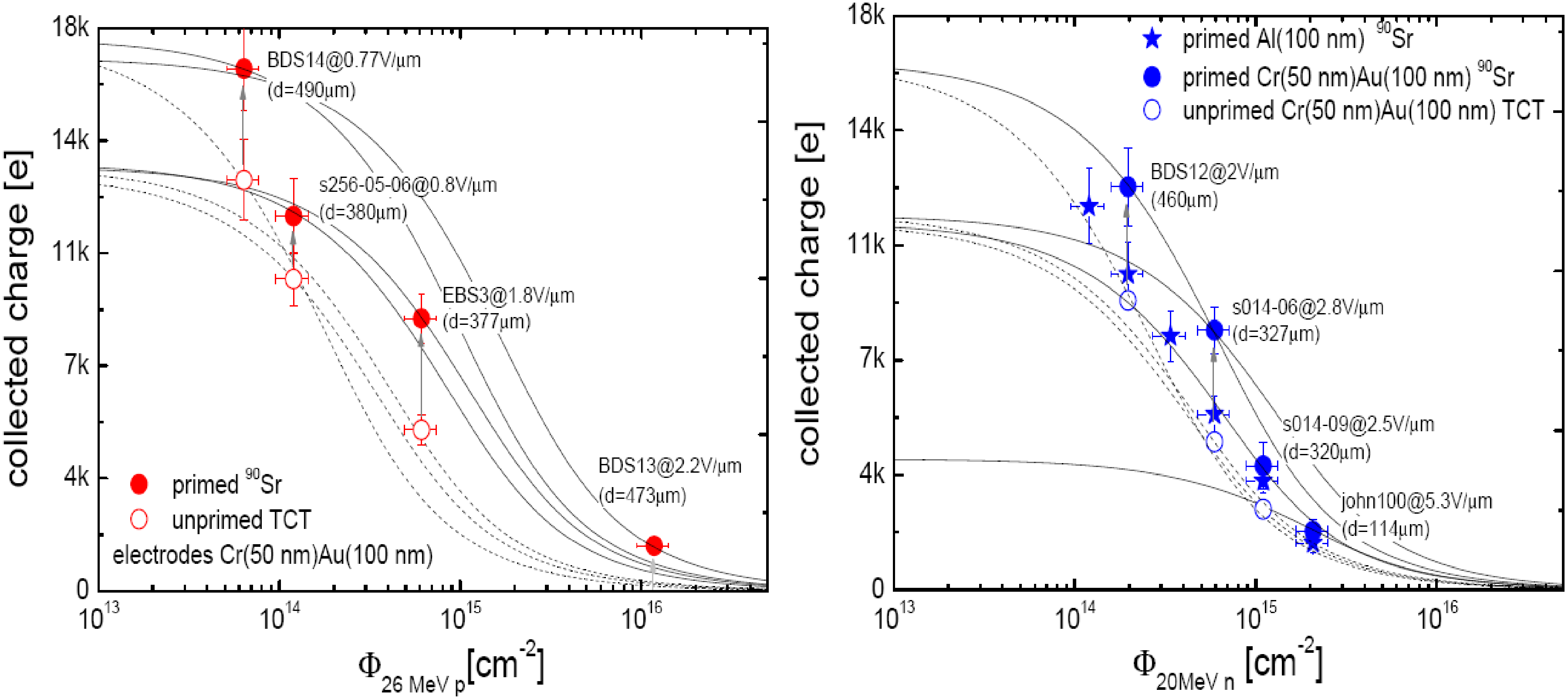
# Charge Collection for MIP



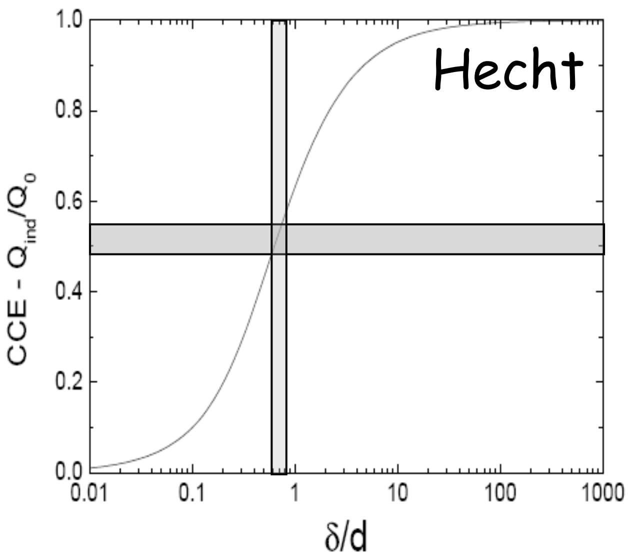



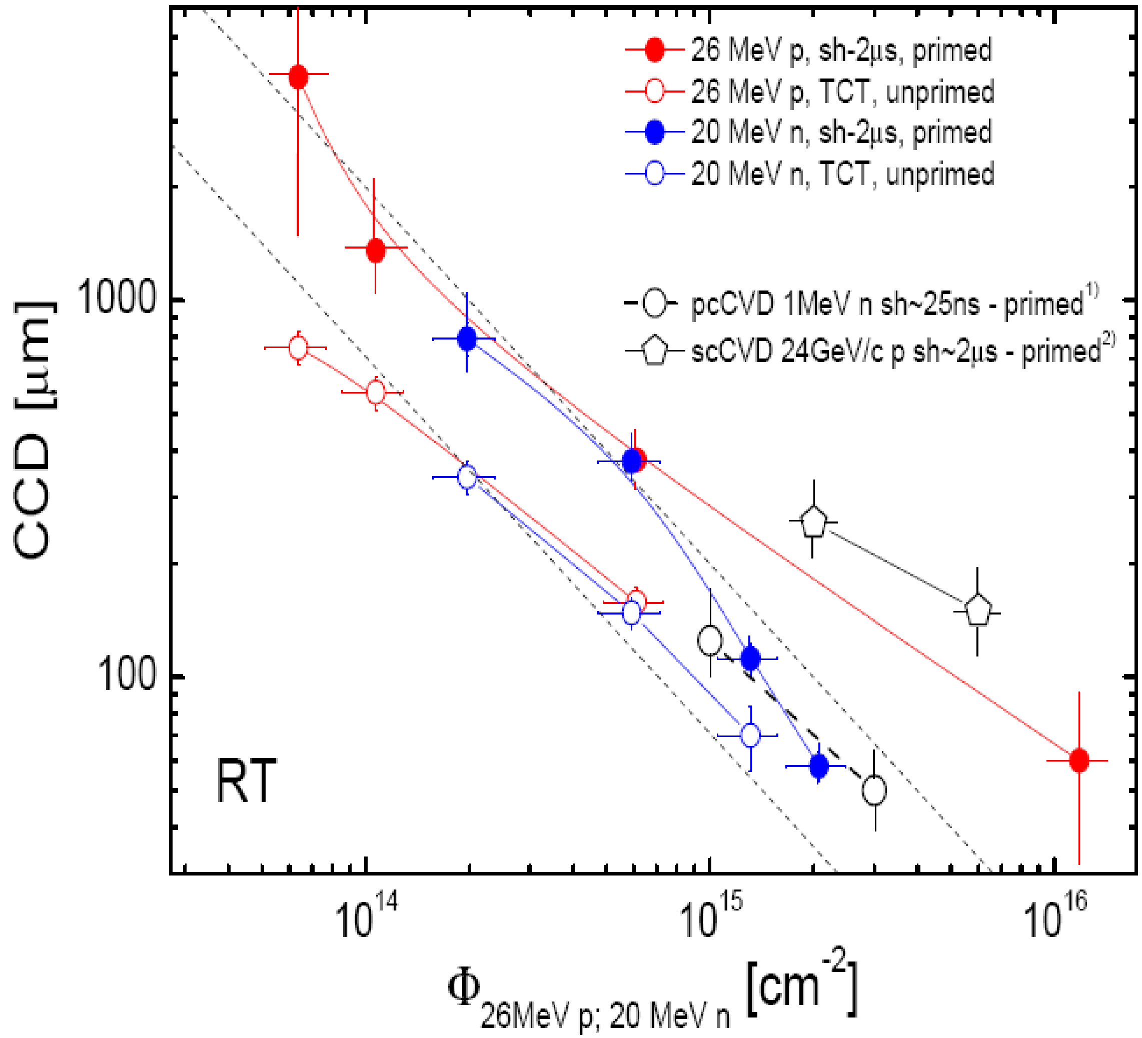
# Charge Collection




Are the detectors fully depleted?

# CCE → CCD


Hecht
CCE - Q_ind/Q_0
δ/d
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
100
1000


26 MeV p, sh-2μs, primed
26 MeV p, TCT, unprimed
20 MeV n, sh-2μs, primed
20 MeV n, TCT, unprimed
pcCVD 1MeV n sh~25ns - primed1)
scCVD 24GeV/c p sh~2μs - primed2)
CCD [μm]
1000
100
RT
10^14
10^15
10^16
Φ 26MeV p; 20 MeV n [cm^-2]

# Summary

We've damaged eight scCVD:

- no increase of the dark current after irradiation
- mainly neutral mono-vacancy (other complex defects(?))
- no space charge is observed after irradiation (CrAu electrodes)
- bias-induced polarization appears for samples metallized with Al
- no degradation of charge carriers velocity or mobility, only trapping
- effective trapping time proportional to the fluence
- equal $\beta$ for 26MeV p and 20MeV n – NIEL violation

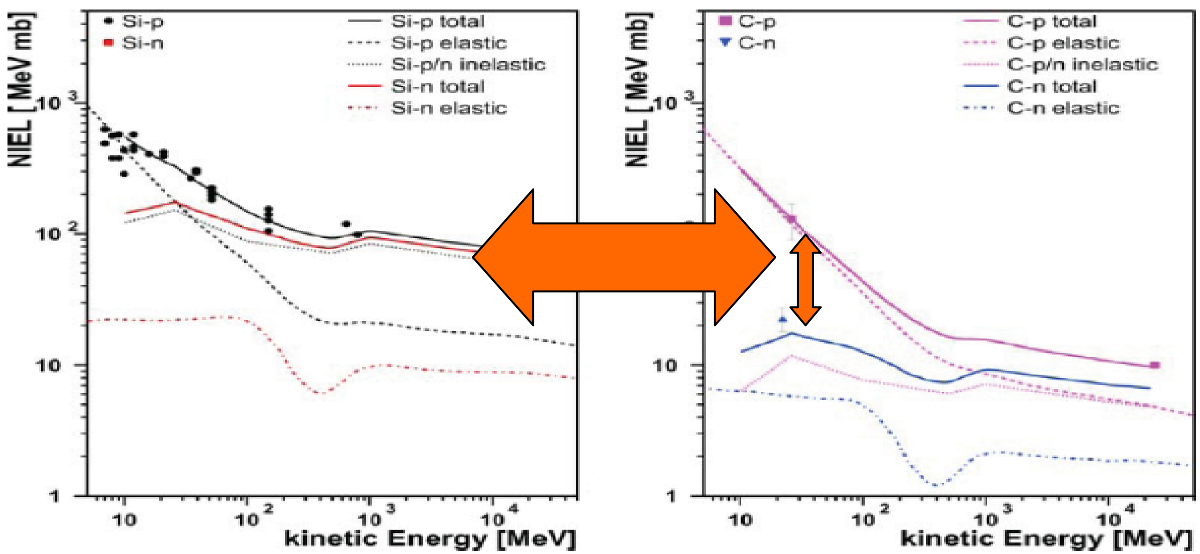
- after irradiation – priming and polarization phenomena are observed
- about x 2.3 increase in CCD of primed detectors
- shape of the Landau distribution remains constant (up to $10^{15}$) but MPV drops
- after $1.2 \times 10^{16}$ 26MeV/p well separated signal above the noise

- scCVD (as a material) is not less radiation hard than pcCVD

# Open questions

???

NIEL ⟷ detector operation




**During irradiation:**

- Self-annealing – is 43eV at RT valid?
- flux influence on self-annealing
- influence of biasing during irradiation

**After irradiation:**

- contacts influence – bias induced pol.
- polarization of primed detectors
- other defect – optically non-active
- light, temp sensitivity

How to compare with silicon?→ S/N, no cooling etc.

# Outlook or How to Proceed

NIEL verification:
- low fluence irradiation (<$5 \times 10^{14}$ part/cm$^2$) + TCT
- PL relative comparison of $V^0$ introduction rate (other defects)

Limits of diamond:
- more high fluence irradiations (>$10^{15}$ part/cm$^2$)

Contact influence:
- try various metallization to explore bias-induced polarization

Defects spectroscopy:
- TL and TSC – too deep levels (?)
- PL extended range
- others ...DLTS(?)

Numerical simulations:
-priming, polarization etc.

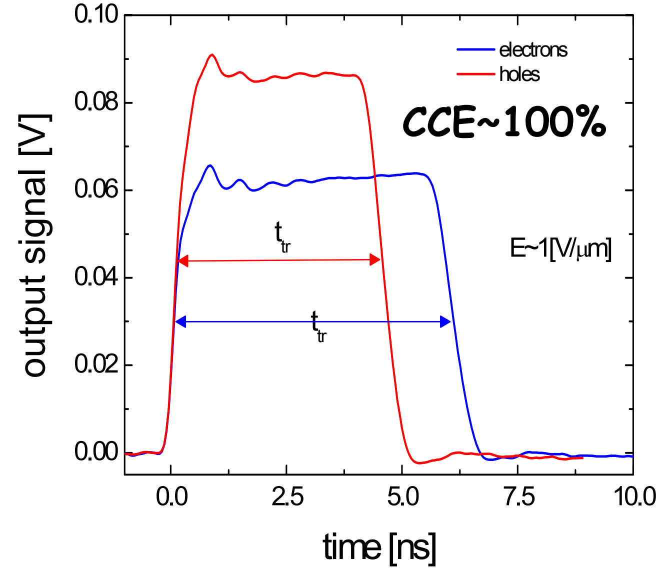
How to improve:
- injecting contact for irradiated detectors? (cryo Si CID)
- light illumination, temperature
- go 3D

# TRANSIENT CURRENT SIGNALS

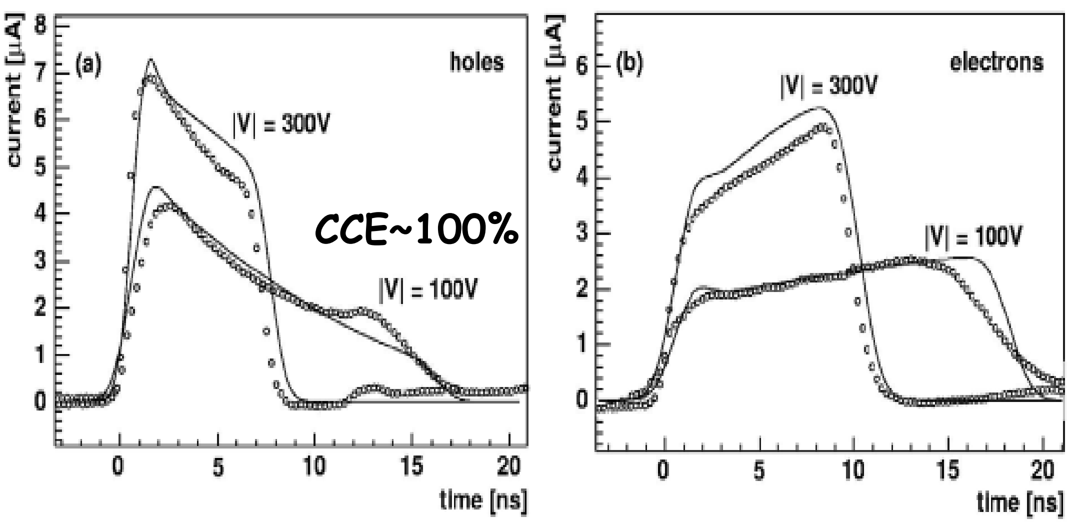
$$i(t) = Q_{gen}\frac{v_{dr}(E_{in})}{d}\cdot e^{-t/\tau_{e,h}}$$

$$Q_{col-e,h}(E) = \int_{t=0}^{t=t_s} i_{e,h}(E,t)\,dt$$

close to "IDEAL"

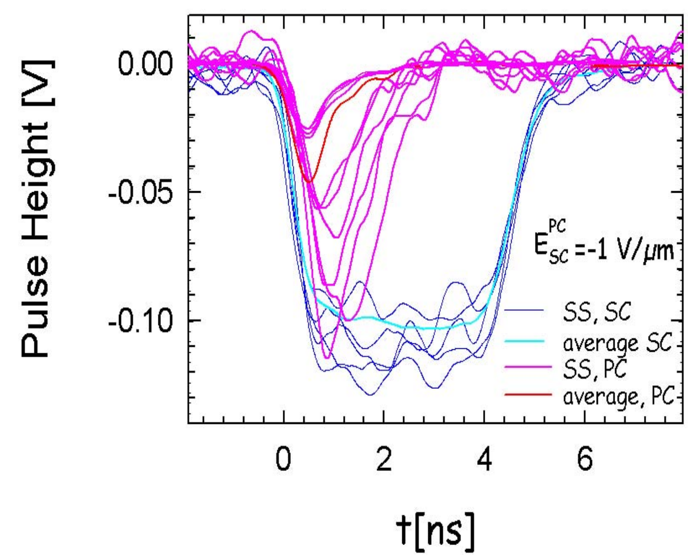



NEGTIVE SPACE CHARGE $(N_{eff}\sim 2.8\times10^{11}\ cm^{-3})$




H. Pernegger Journal of Applied Physics 97, 073704 (2005)

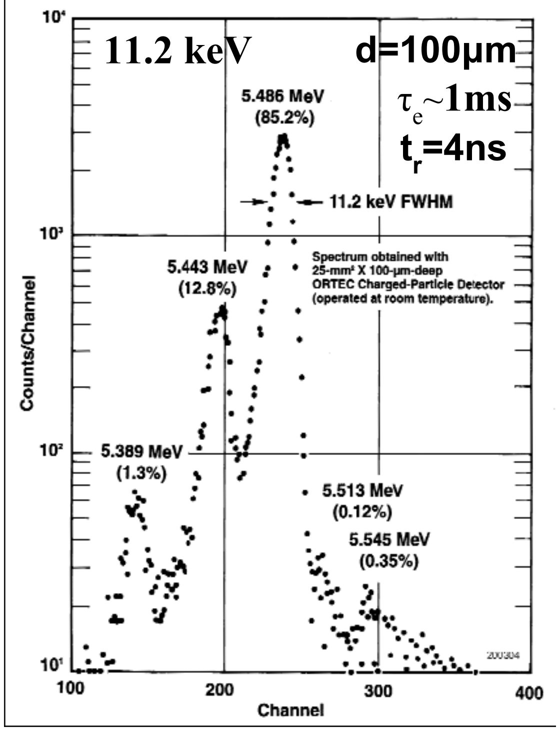
CHARGE TRAPPING



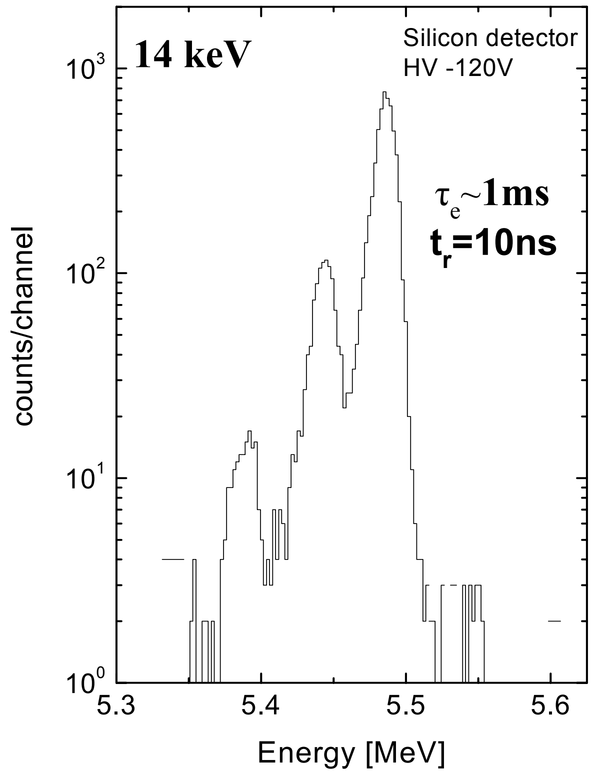
# APROACHING SILICON DETECTORS

$^{241}$Am α-particle spectrum measured using CS electronics

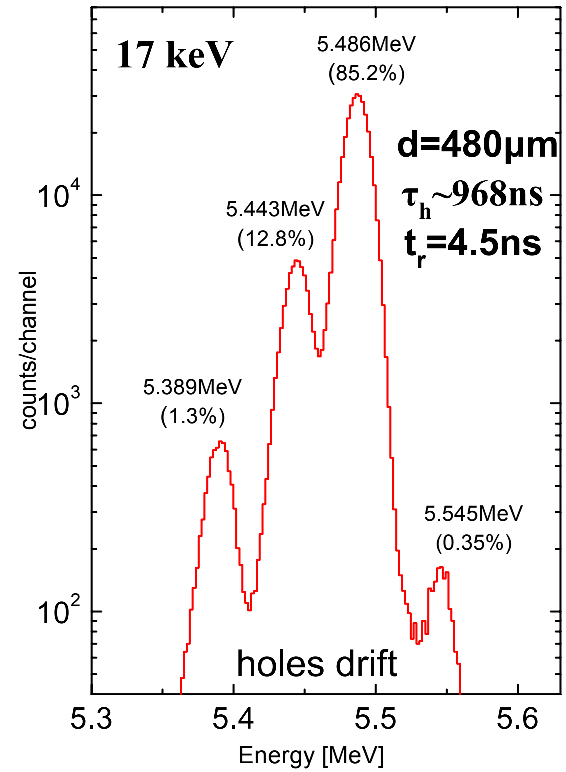
**ORTEC Silicon detector**




**"OUR" SILICON DETECTOR**




**SC CVD DIAMOND DETECTOR**




At **RT** resolution of Si detector is governed by **electronic noise** due to leakage current and capacitance

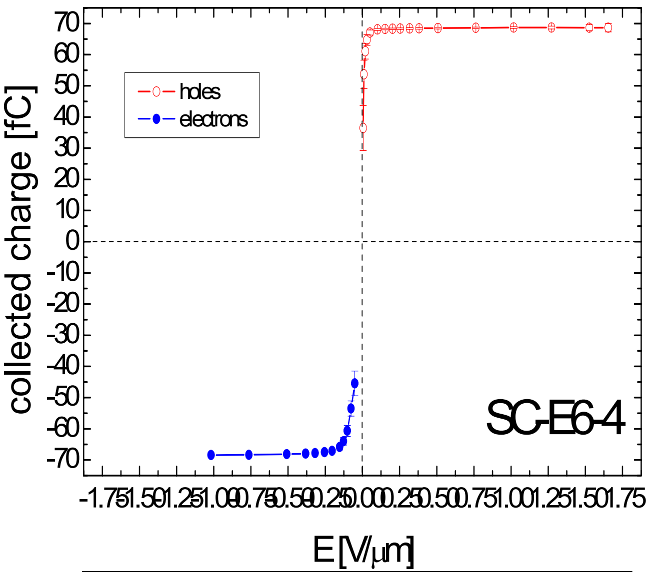
$$\Delta E = 2.355\sqrt{F E_0 \varepsilon_i + (\Delta e / 2.355) + a_1 E_0^{a_2}}$$

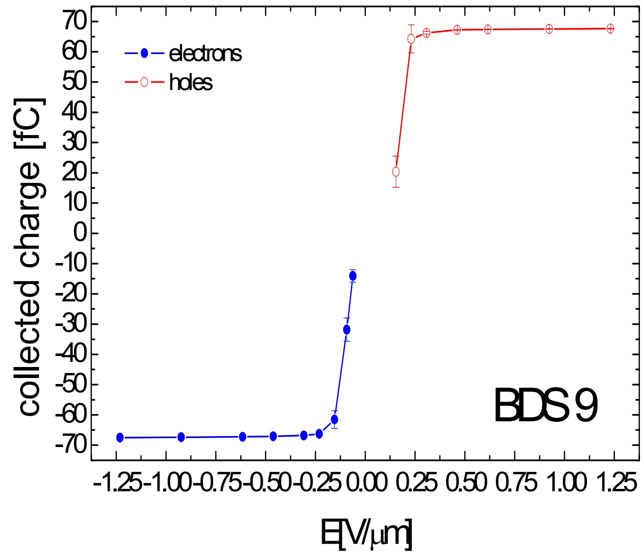
## REST OF THE SC CVD DIAMONDS(e OR h)

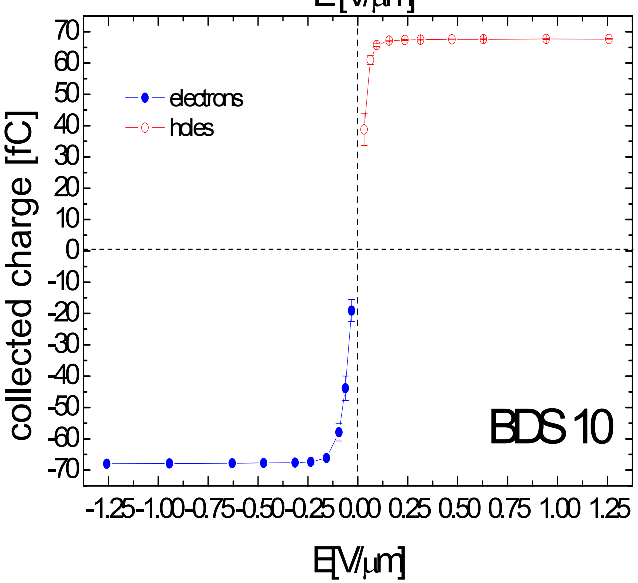
**ΔE(FWHM) < 25 keV**

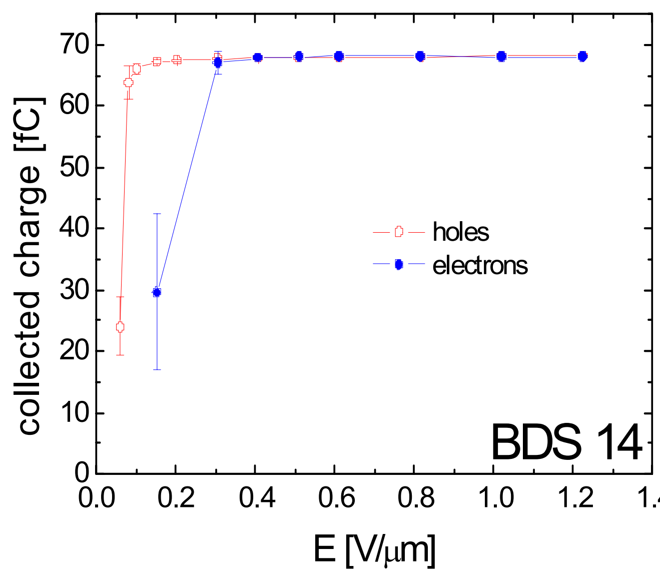
How to improve: grow better quality crystals or use thin detectors

# CHARGE COLLECTION - $Q_{col}$



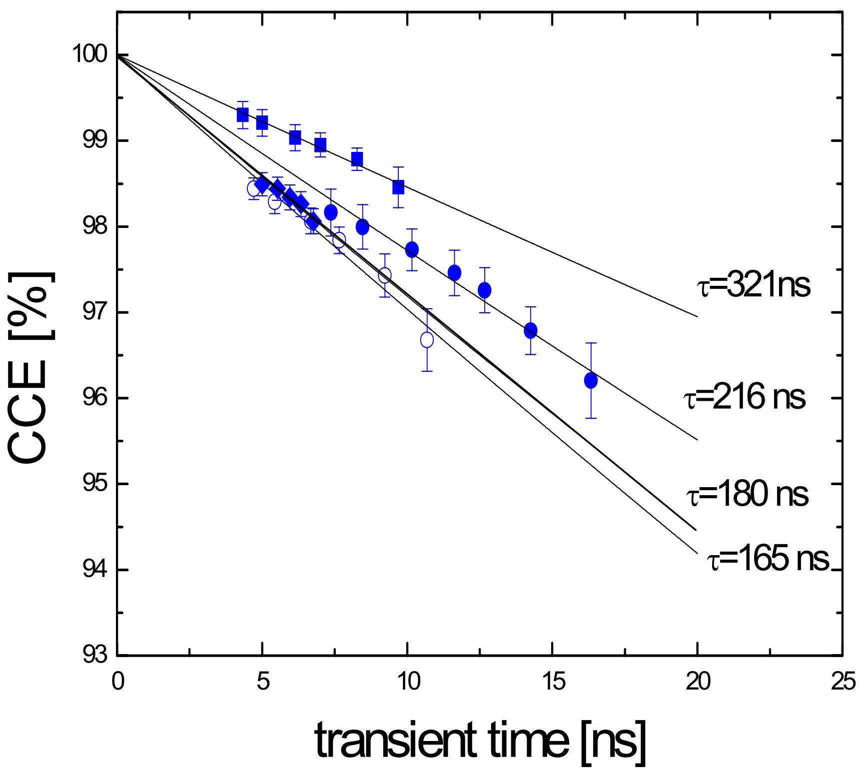



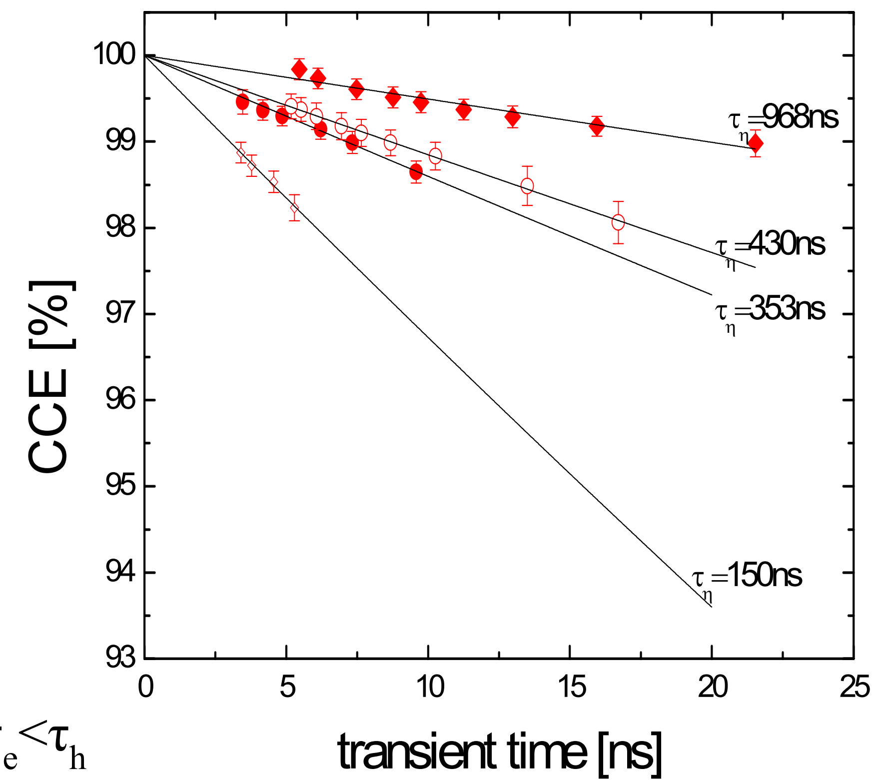
# LIFETIME, $Q_{gen}$ and $\epsilon_{avg}$

Hecht: $$CCE = \frac{Q}{Q_0} = (\tau_{e,h}/t_{tr}) \cdot \left(1 - \exp^{-t_r/\tau_{e,h}}\right)$$

**electrons**




**holes**




$\tau_e < \tau_h$

$\tau_e, \tau_h >>$ transient time

$Q_{gen}$=68.6 fC (±0.2) -->$\epsilon_{avg}$=12.8 (±0.05) eV/e-h

# IRRADIATION 26MeV PROTONS

Irradiation in Karsruhe with 26 MeV protons

Homogeneous energy deposition, dose well known

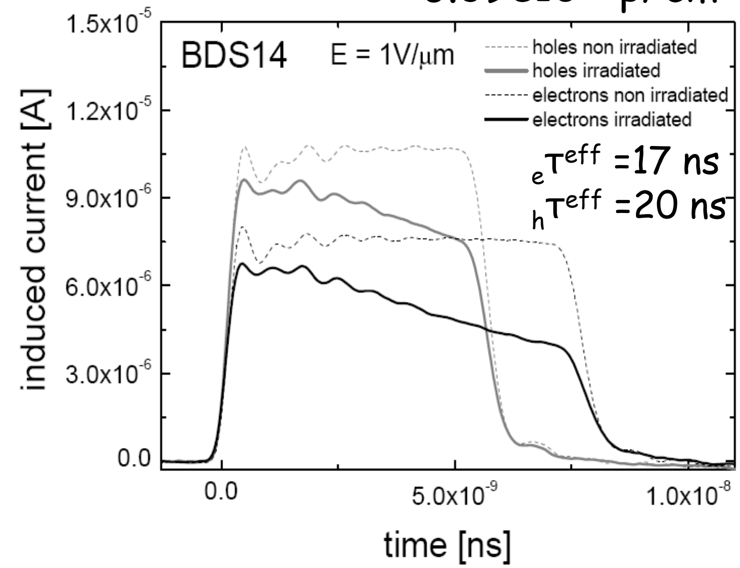
Optical Absorption spectra at 7K

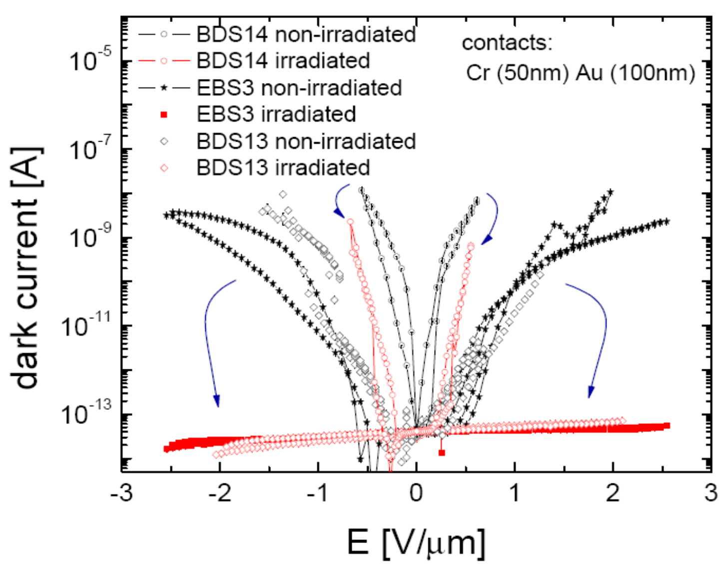
only GR1 and R11→ no other zero-phonon lines
e.g related to N, or aggregates

Leakage current decreases

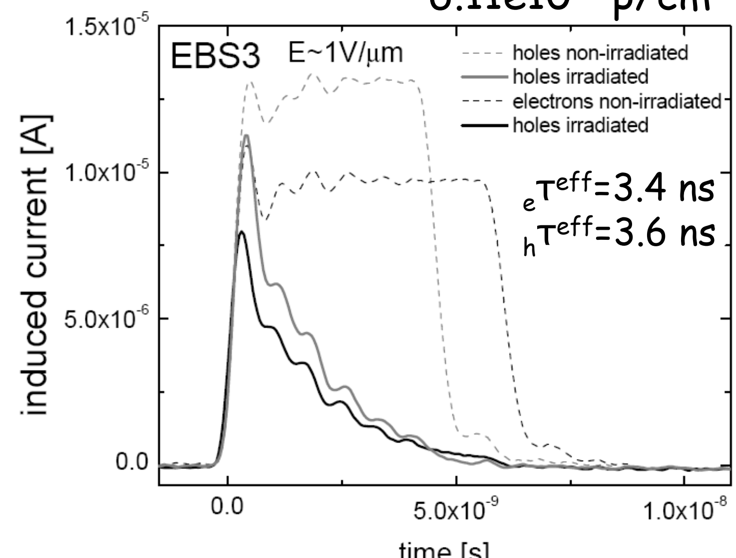
-Leakage current at the detection limit ($I<10^{-13}$ A/mm$^2$) up to 2V/μm

$6.39e10^{13}$ p/cm$^2$



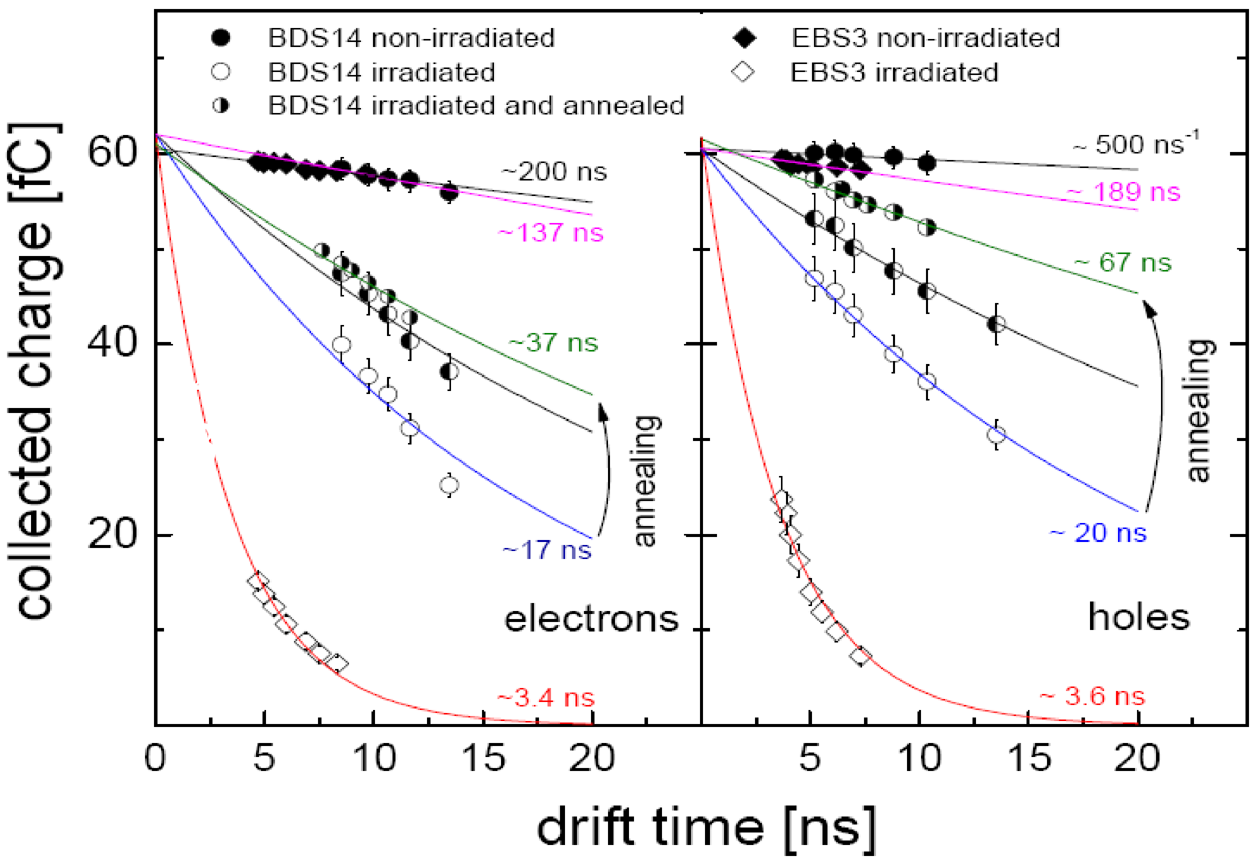




$6.11e10^{14}$ p/cm$^2$



# $\tau_{eff}$ – effective trapping time

$$Q_{coll} = Q_{gen} \cdot \exp\left(-\frac{t}{\tau_{eff-e,h}}\right)$$




a good parameter $\tau_{eff}$ ......
and even better one... $t_{tr}/\tau_{eff}$

# IRRADIATION 26MeV PROTONS

stopped particles → polarization

- pulse high decreases with time for alpha particles

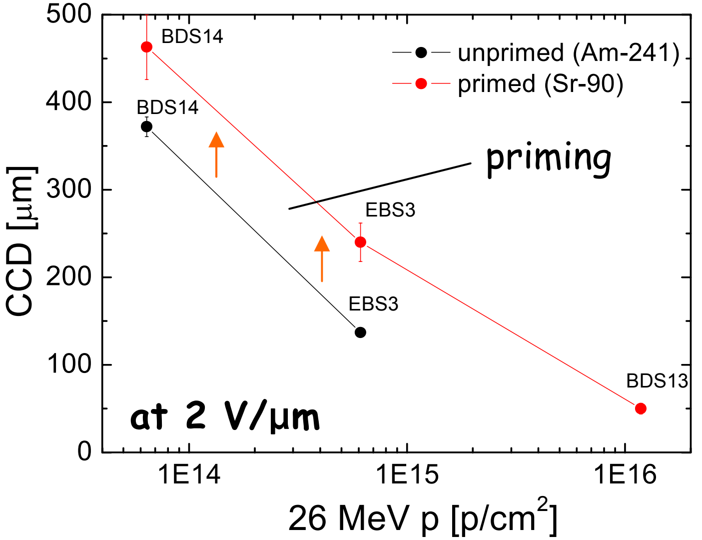
traversing particles → priming

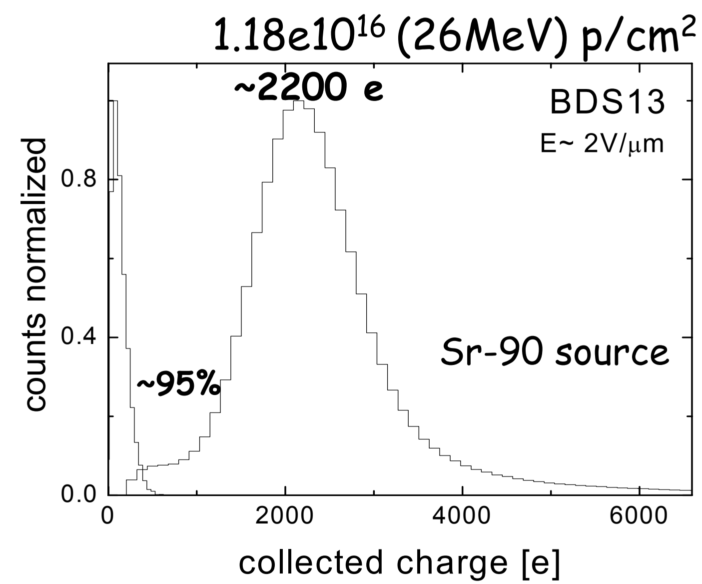
- stable operation
- CCE(CCD) increases due to deep traps filling

defects can be annealed

-about 70% (holes) 50%(electrons) electrically active defects annealed out after 3h at 1000C (sample BDS14)

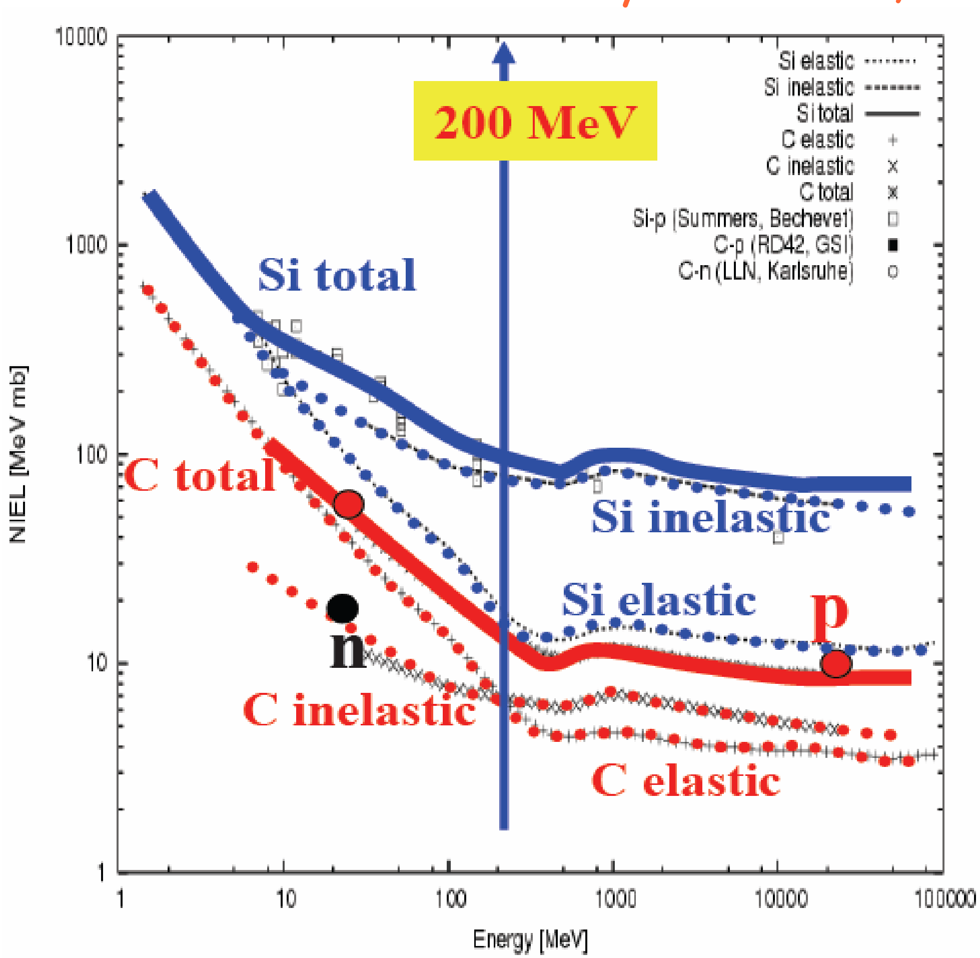
...obviously insufficient statistics
we need some more samples
to be destroyed !



# NIEL for DIAMOND

courtesy Wim de Boer, Univ. Karlsruhe




**Si**

| Z | Ions | NIEL |
|---|---|---|
| 14 | 417 | 4.2 |
| 13 | 910 | 9.06 |
| 12 | 1384 | 12.47 |
| 11 | 1021 | 8.86 |
| 10 | 1225 | 8.45 |
| 9 | 265 | 1.41 |
| 8 | 493 | 2.09 |
| 7 | 398 | 1.31 |
| 6 | 909 | 2.36 |
| 5 | 270 | 0.55 |
| 4 | 383 | 0.66 |
| 3 | 662 | 0.67 |
| 2 | 11152 | 4.4 |
| 1 | 46107 | 0.9 |
| Total | 6559 | 57.38 |

10 GeV protons

**C**

| Z | Ion | NIEL |
|---|---|---|
| 6 | 698 | 0.8 |
| 5 | 869 | 0.77 |
| 4 | 584 | 0.44 |
| 3 | 1133 | 0.55 |
| 2 | 10625 | 2.01 |
| 1 | 30465 | 0.24 |
| Total | 44374 | 4.81 |

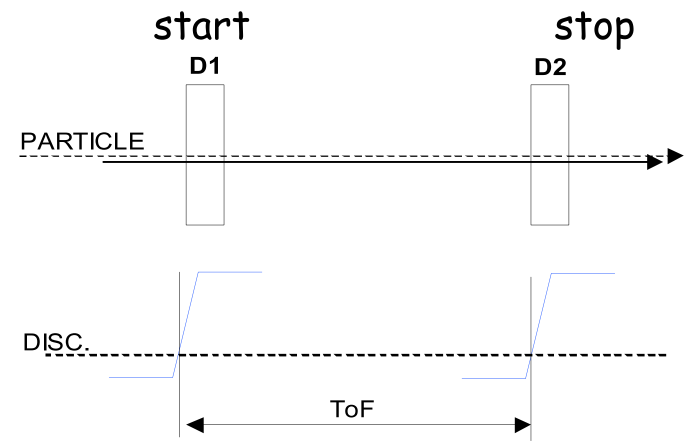
Radiation damage at LOW energy dominated by **elastic cross section**.
C-nuclei have factor two smaller Z than Si and higher displacement energy (≈40 eVvs20 eV)

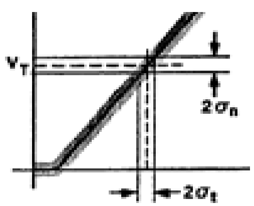
Radiation damage at HIGH energy dominated by **inelastic cross section**.
C-nuclei smaller and more stable than Si. Diamond order of magnitude better than Silicon.

# START DETECTOR FOR ToF SYSTEMS

**New RH and fast start detector needed**

## PRINCIPLE OF TIMING MEASUREMENT



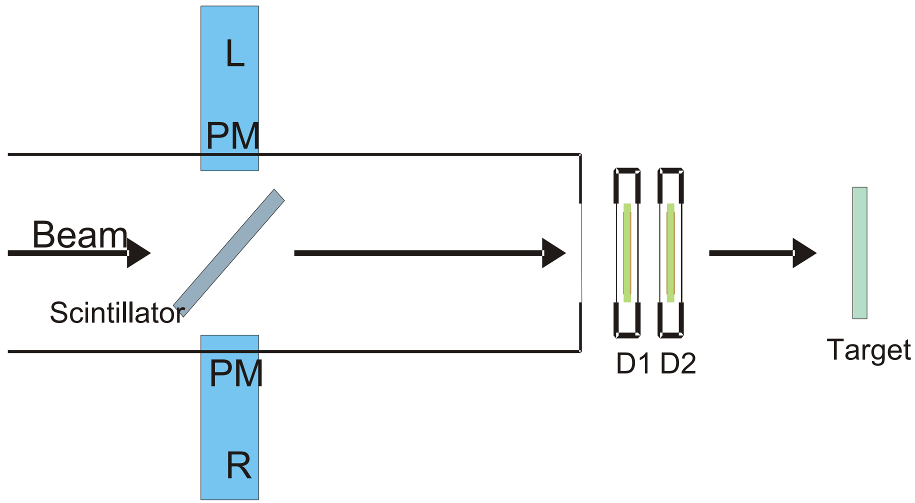



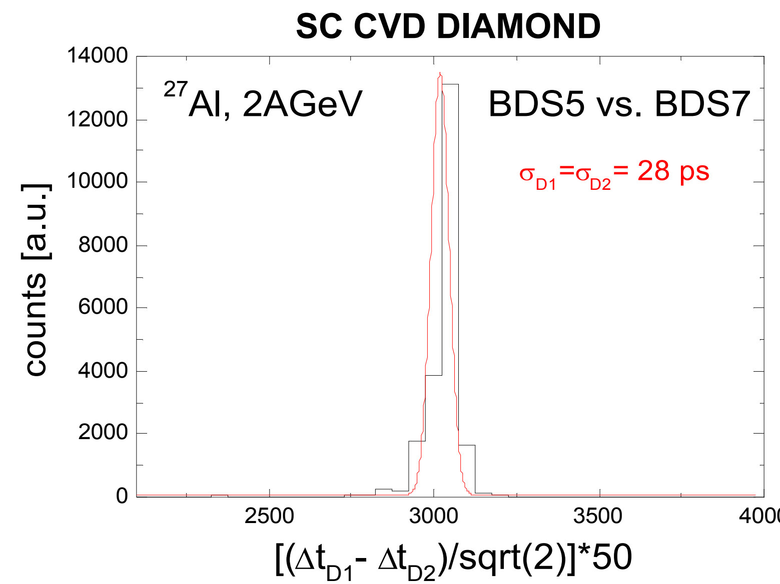
$$\sigma_{ToF} = \frac{\sigma_N}{\left.\frac{dV}{dt}\right|_{thr}}$$

**REQUIREMENTS FOR START DETECTOR:**

## $\sigma_{intr} < 50\text{ps}$

# RESULTS FOR $^{27}$Al 2AGeV - FoPi



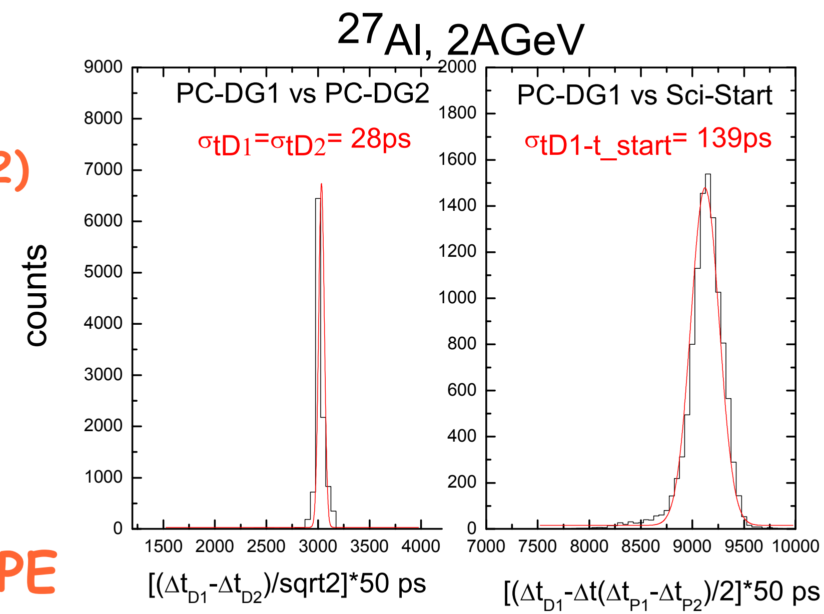




TIME DIFERENCE D1 vs D2

INTRINSIC RESOLUTION: $(\Delta t_{D1}-\Delta t_{D1})/sqrt(2)$

$\sigma_{intr}$= 28ps

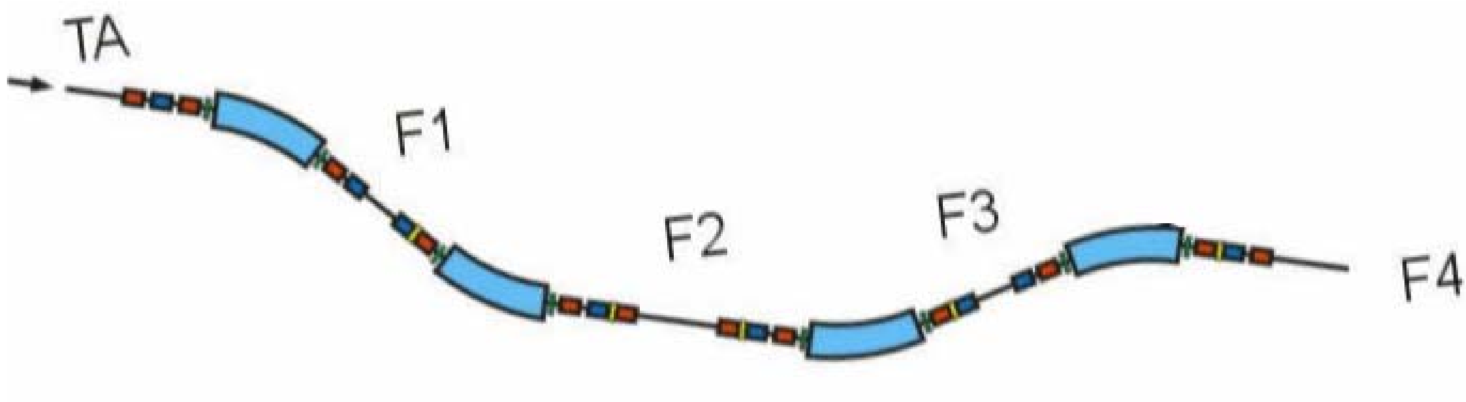
limited only by electronics (TDC 50ps/bin)

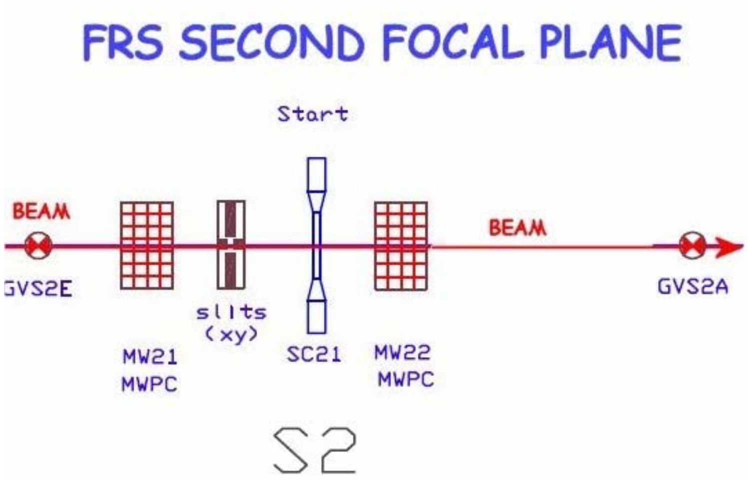


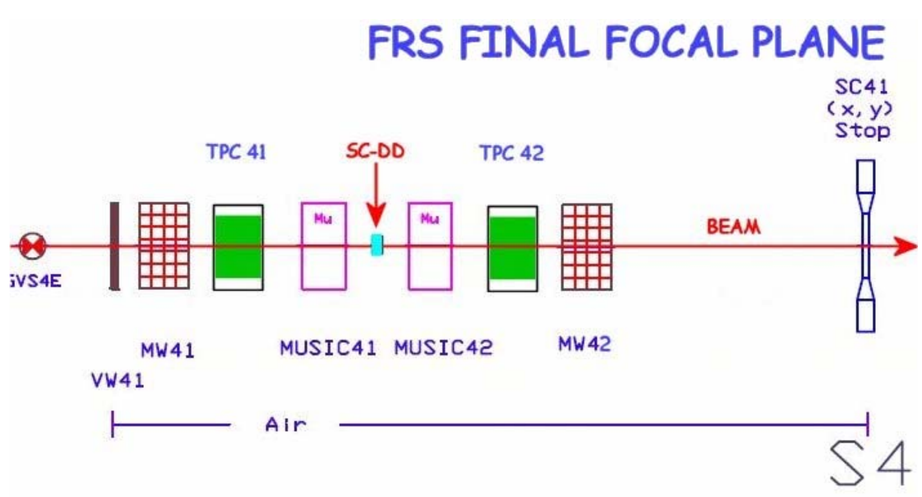

**poly CVD DIAMOND**

FOR MIP p SC DIAMOND ONLY HOPE

# FRAGMENTATION AT FRS OF GSI

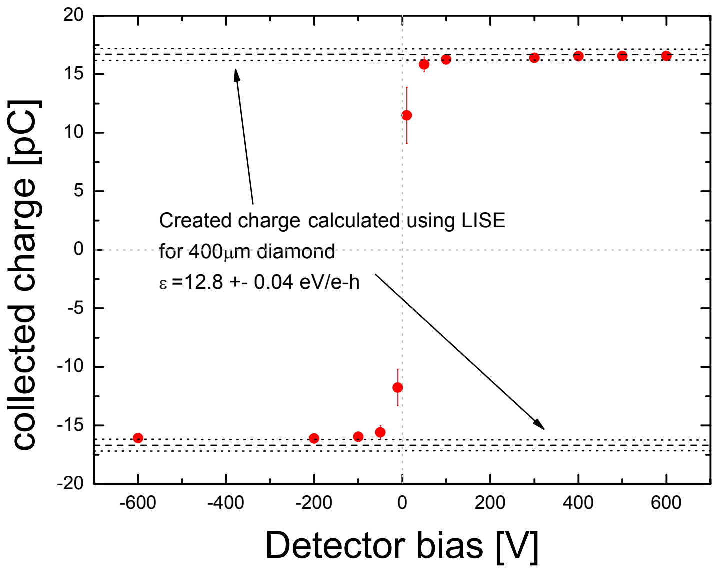


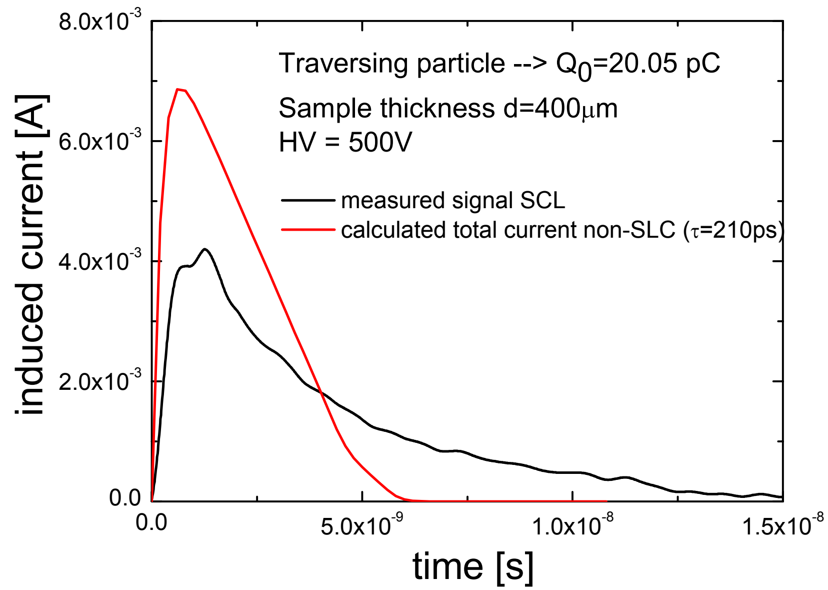



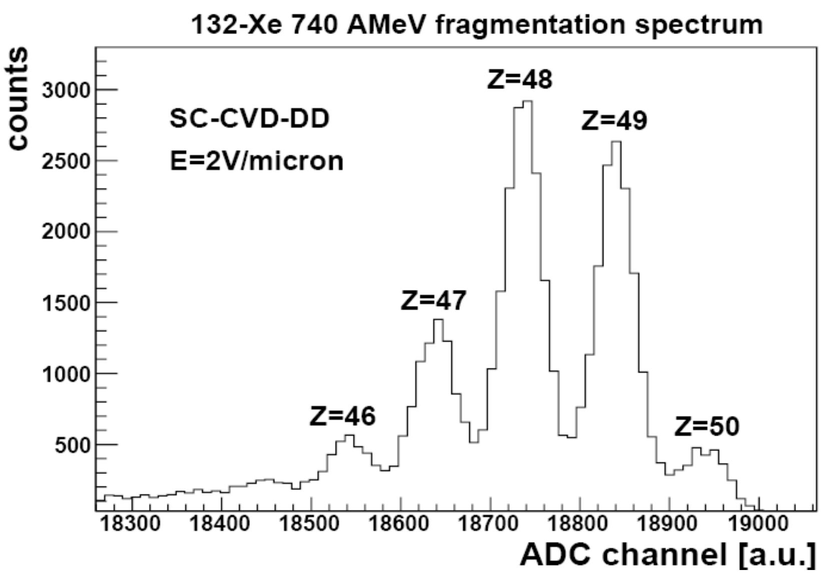



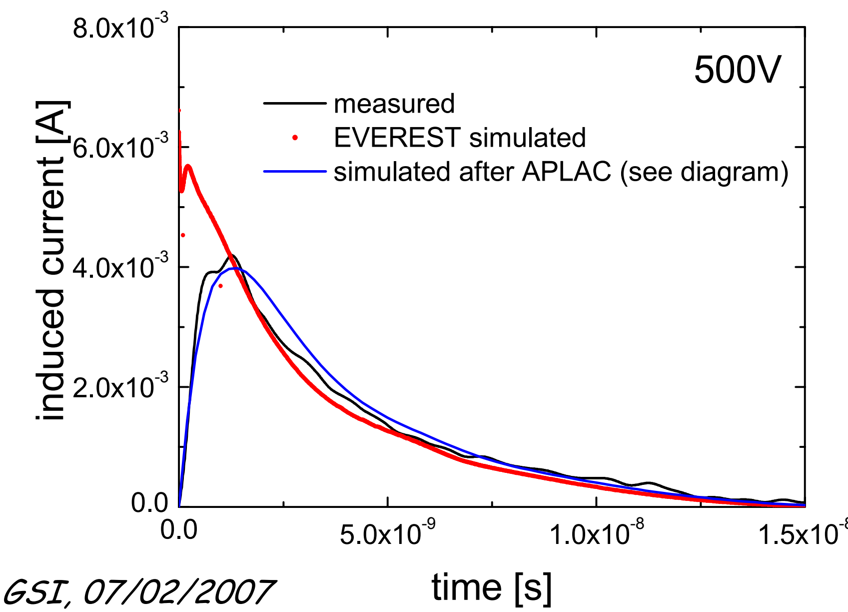

*PhD seminar at GSI, 07/02/2007*

# FRS - PRELIMINARY RESULTS



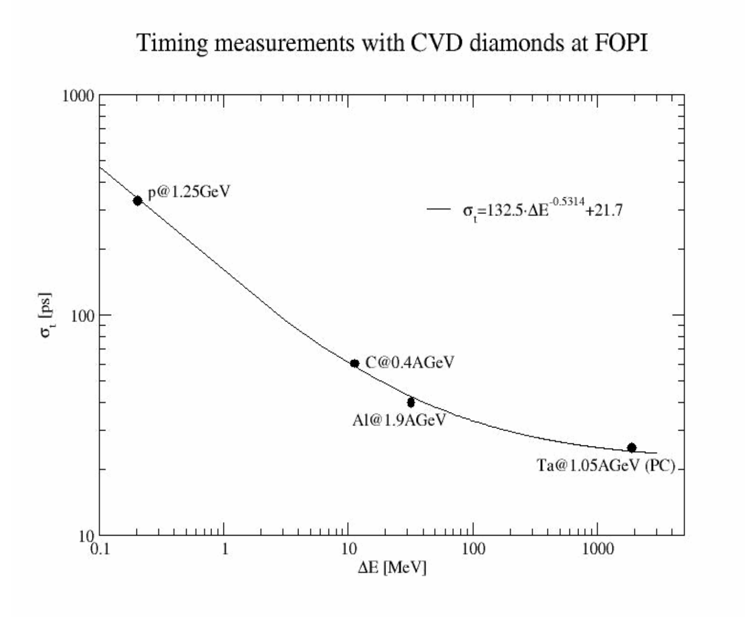




*PhD seminar at GSI, 07/02/2007*

# MORE DATA

## Relativistic protons (1-2 GeV) (timing)

- stable operation over a week (rates up to 1MHz)
- 100% separation from electronic noise (d=400μm)
- unsatisfactory timing → electronics development needed

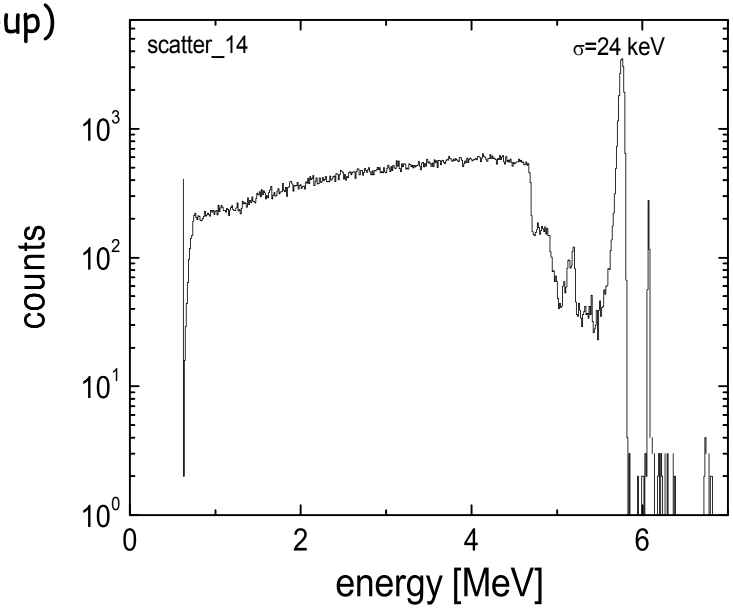



## Low energy (6 MeV/u) ions (p, He, Li) (timing, ΔE)

- good energy resolution ~1% (limited by experimental set-up)
- very good timing properties $\sigma^{intr}$ ~ 30ps

## Heavy ion beams Ta, Al, C, Ca (timing, ΔE) (FoPi)

- good energy resolution ~1%
- very good timing properties $\sigma^{intr}$~30 ps



# SUMMARY and CONCLUSIONS

## SC CVD Diamond as ΔE detector:

- lifetime of charge carriers >> transient time --> **CCE ~ 100%** at low E
- stable detection
- max. energy resolution **(17keV/5.5MeV)**
- **$\varepsilon_{avg}$ = 12.8 eV/e-h**

**homogeneous material suitable for energy loss spectroscopy**

## SC CVD Diamond as Timing detector:

- high mobility (**e- 1300-3100; h-2400 [$cm^2$/Vs]**)
- transient signals **1 ns/100μm**, uniform **$t_{rs}$<150ps**
- very good intrinsic time resolution (**$\sigma_{int}$~28 ps**) (heavy ions)

**fast device perfect for start detectors**

## Heavy irradiations with 26 MeV protons

- leakage current drops (no electronics noise), CCE drops, polarization and priming phenomena
- diamond is expected to be at least 10x more radiation hard than Si at higher energies

# OUTLOOK

**X-ray microbeam mapping at ESRF** – to find possible correlation with macroscopic defects (May'07)

**MIP timing** measurements with „stacked" diamonds using BB and fast CS electronics (May'07)

**Detailed radiation hardeness tests** -->irradiation with protons (26MeV) in Karlsruhe

fast neutrons in (~1MeV) Ljiubjana ( ~10MeV) Leuven

# PARTICIPANTS

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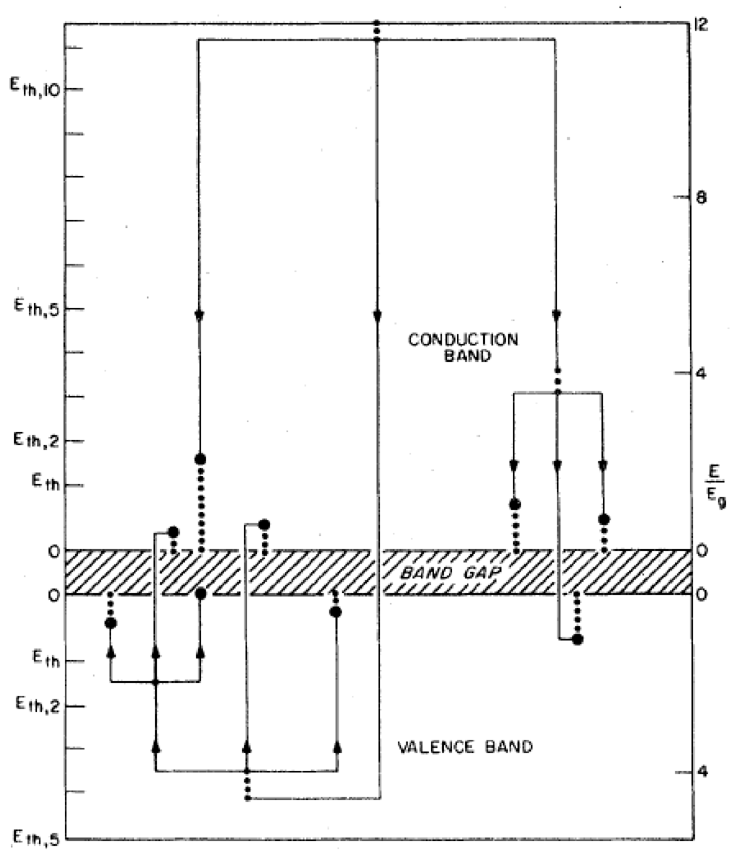
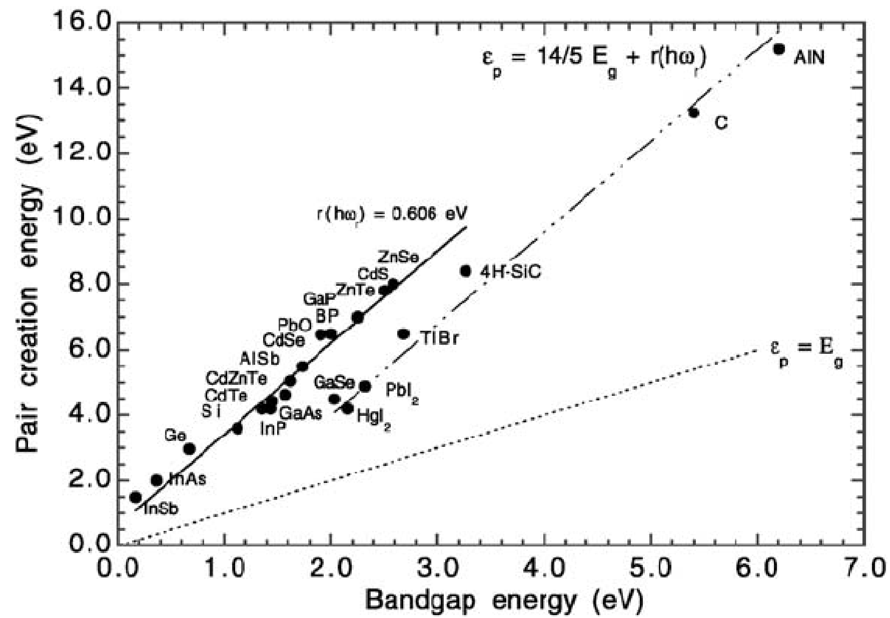
# ENERGY NEEDED TO CREATE e-h PAIR




Charge creation is not a random process

~~σ=sqrt(N)~~

σ=sqrt(F*N) – intrinsic resolution
where F<1 is the fano factor

Rule ~ 3x$E_g$ is not valid for diamond

Various values reported up to now for diamond:

From 19 eV/e-h → 13.1 eV/e-h

from calculation 11.8 eV/e-h diamond

general trend measured ε decreases when charge carriers liftime increases

# CCE mapping - ion microbeam at GSI