# Synthetic diamonds for heavy-ion therapy dosimetry

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# Outline

**Why CVD diamonds?**

**Motivation & Aim**

Online monitoring → High-speed single-particle beam monitor

Offline monitoring → **T**hermo-**L**uminescent **D**etector

**Detectors, Electronics and Equipment**

**Principles of operation**

**In-beam tests - results and discussion**

**Summary and Outlook**

# Why CVD Diamond? – Beam Monitor Concepts

- High drift velocity + short charge lifetime
  - short pulses (ns) ‘’rise time & duration’’
  - good time resolution for high-speed counting
- „Simple“ operation because of broad 5.5 eV band
  - gap no cooling or pn junction is needed
- Radiation hard ~$10^{15}$ particles/cm$^2$
- Carbon low Z=6
  - beam quality preserved
  - biocompatible
- Actual size possible up to 12 cm ø wafers (nanoCVD larger size possible)

# Motivation & Aim

**Online** monitoring High-speed single-particle beam monitor

Avoid the need for daily calibration of the gaseous monitor detector in terms of ‘particles per monitor unit’

Measure intensity & structure of the extracted beam by **counting individual particles** close to the **GHz/channel**-range

**Offline** monitoring Thermoluminescent diamond detector

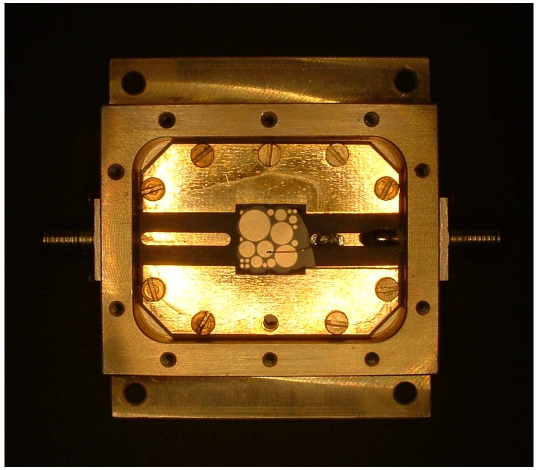
Dose verification after irradiation

Mostly outside the beam (Dose ≈ 0) → very sensitive material needed

Standard TLD material (**LiF**) shows low efficiency to HI - **fast local saturation**
→ CVD better candidate?

# Detectors & Parameters

| Sample name | Size [mm²] | Thickness [µm] | # Pad | Pad size [mm²] |
|---|---|---|---|---|
| B | 20 × 20 | 95 | 16 | 17.64 |
| D1 | 10 × 10 | 100 | 21 | 2.01 |
| D2 | 10 × 10 | 100 | 21 | 8.04 |
| S6 | 10 × 10 | 500 | 1 | 63.6 |
| L3 | 10 × 10 | 124 | 1 | 63.6 |
| NCD | ~ 1.2 | 60 | 21 | 4.15 |



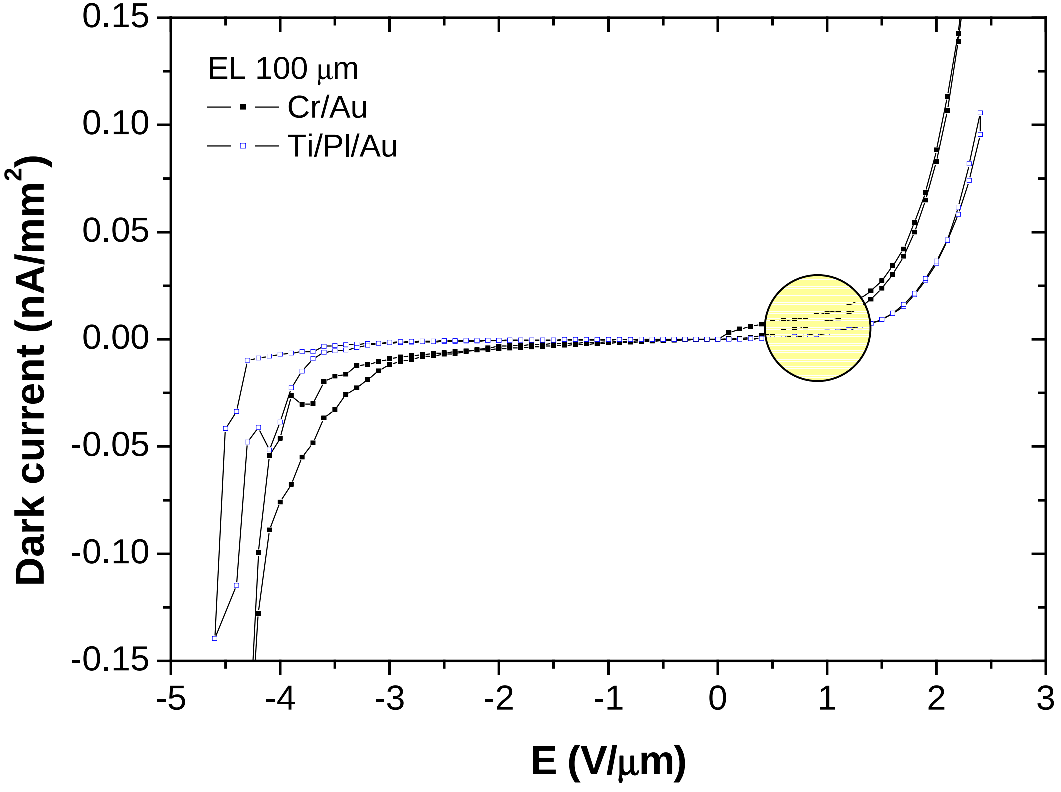
Pixel area: 0,2 – 16 mm$^2$

| Sample name | Size [mm²] | Thickness [µm] | Producer |
|---|---|---|---|
| TM | 3.6 × 3.6 | 385 | e6 |
| PC | 3.6 × 3.6 | 359 | e6 |
| OP | 3.6 × 3.6 | 355 | e6 |
| EL | 3.6 × 3.6 | 370 | e6 |
| BEL | 3.1 × 3.1 | 560 | LUC Belgium |
| HPHT1 | 10.38 | 255 | IMP Russia |
| HPHT2 | 7.84 | 359 | IMP Russia |
| HPHT3 | 6.63 | 230 | IMP Russia |

# Detectors & Parameters

I-V characteristics (D1 , D2)

Electric field = 1V/µm



# What about fast read-out electronics?

**Already existing fast "commercial" electronics**:

**DBA – Diamond Broad-Band Amplifier** → designed specially for diamond at GSI

- Various types : DBA II;  III ; IV
- Low noise, remote controlled gain for DBA III  and IV
- Analogue output signal,
- Band width 2.3 - 2.1 GHz

☺ Quite good for heavy ion (high signal)  beam monitoring
☹ Only single channel read-out
☹ Pick-up noise relatively high

**Development of new fast multi-channel electronics**:

**NINO** card → prototype designed for ToF ALICE project,

- Differential read-out of 24 channels per card
- Digital signal

Modifications:

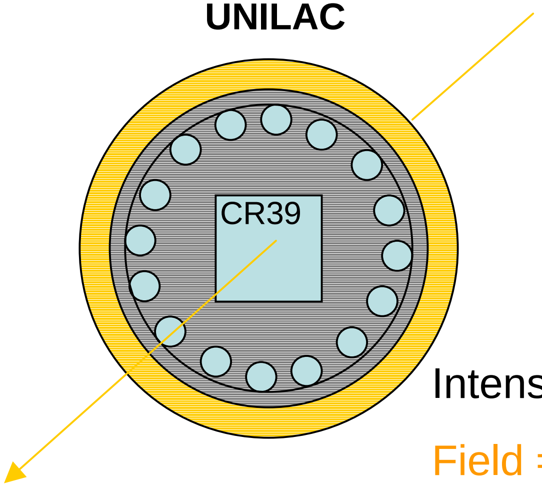
☺ Differential input → elimination of pickup noise
 -  Further modification in progress

# Experiments & Beam Parameters

| | SIS | | UNILAC | |
|---|---|---|---|---|
| **Energy** | 80-430 MeV/u | $^{12}C$<br><br>Therapeutic conditions –<br>Scanning beam | 11,4 MeV/u | $^{12}C$, 10.2 MeV/u<br>$^{48}Ca$, 8.3 MeV/u<br>$^{54}Cr$, 7.6 MeV/u<br>$^{152}Sm$, 5.8 MeV/u<br>…<br>… |
| **Beam size** | 4 -10 mm (FWHM)<br>3 × 3 $cm^2$<br>10 × 10 $cm^2$ | | 45 mm Ø | |
| **Intensity** | $10^6$ -$10^8$ ions/second<br>2.8×$10^4$ -2.6×$10^7$ ions/$cm^2$ | | $10^4$-$10^5$ ions/second/$mm^2$ | |
| **Operation** | Transmission mode | | Stopping mode | |
| Aims | Feasibility test | | | |
| DBA | Reduce pickup noise | | bipolar | |
| NINO | 1.test unipolar | | bipolar | |

# Setup

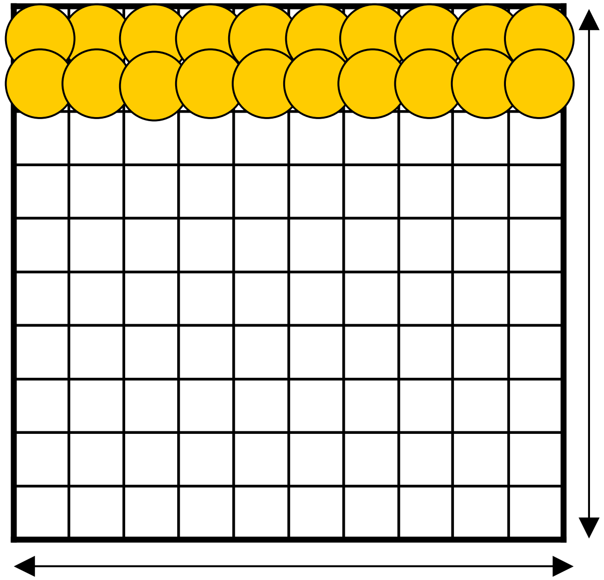
**UNILAC**




Intensity = const (x,y)

Field = 16 cm$^2$

**SIS**

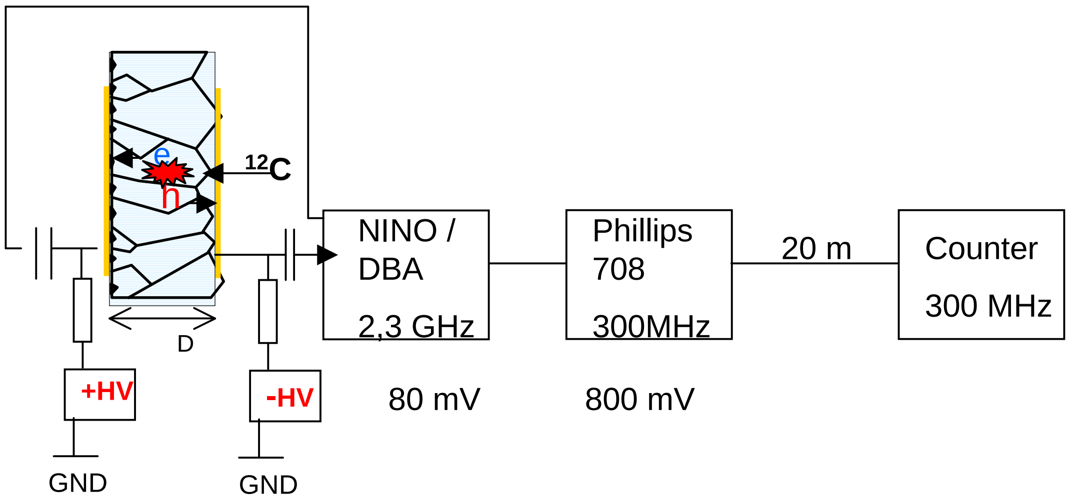


Intensity ≠ const

Field = 9 cm$^2$

256 irradiation points

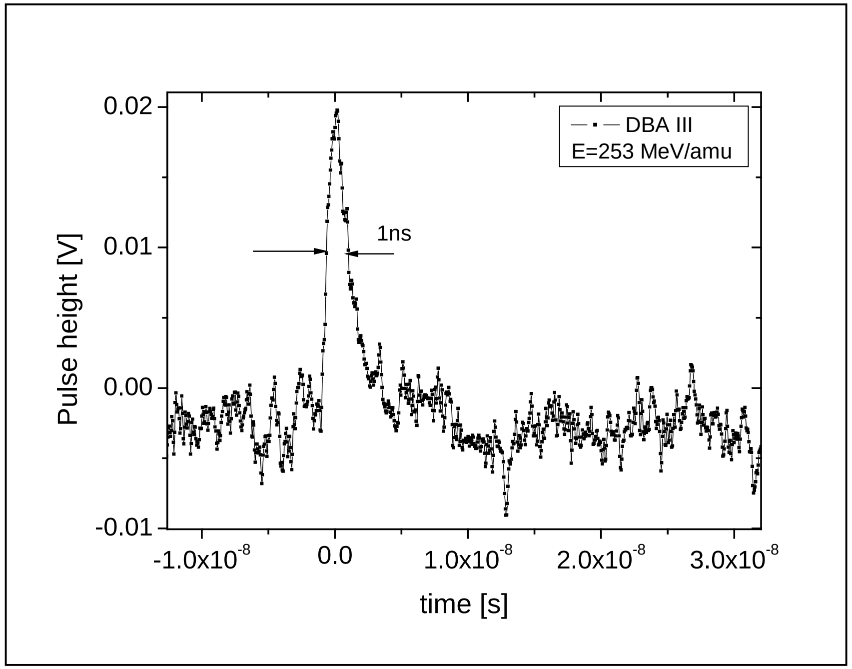
Ø 2,2 – 8,8 mm

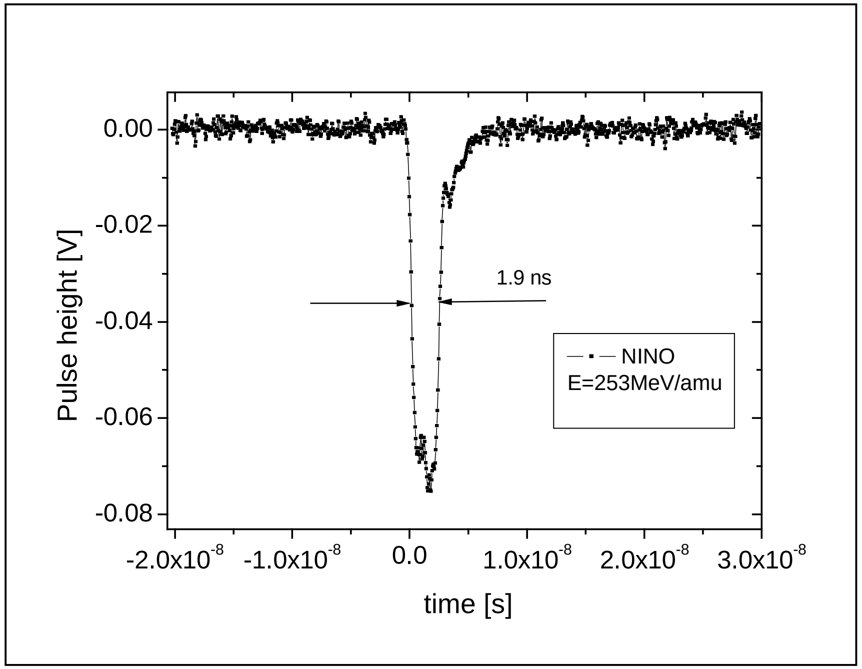


# Results

**16 Pixel detector** 150µm $^{12}C$ E=253 MeV/u SIS

1st beam time – set-up of first electronics with unipolar readout



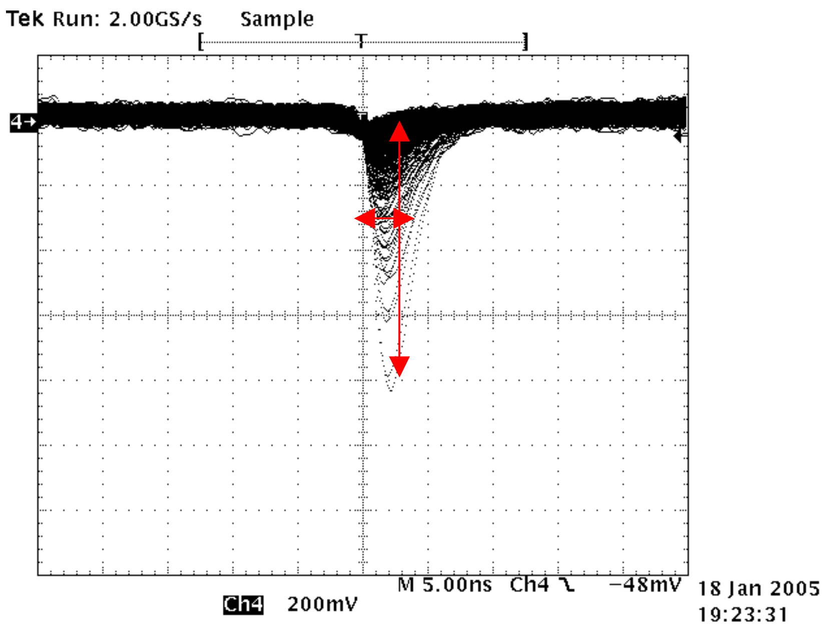

High pick-up noise with DBA III, better for NINO (even with unipolar input)

# Results

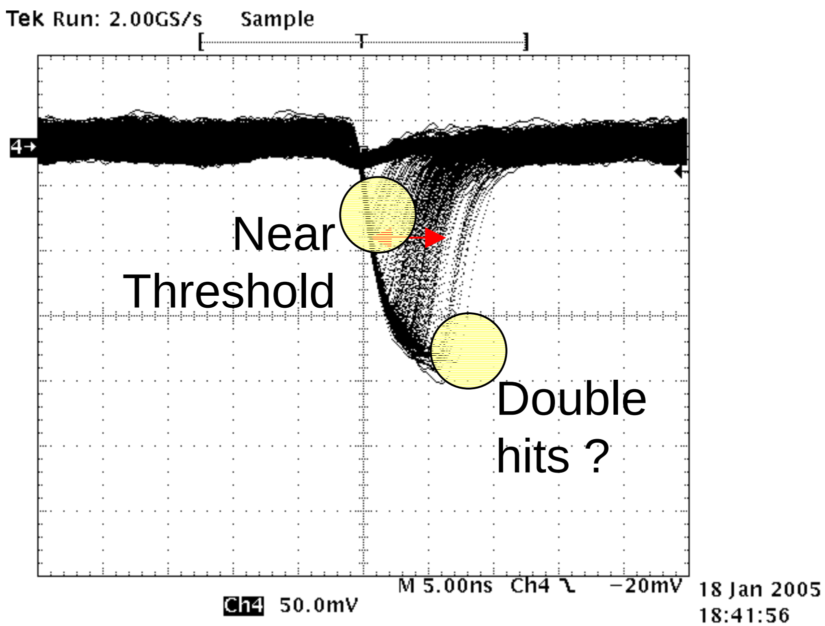
**16 Pixel detector** 150µm $^{48}Ca$ E=8,3 MeV/u UNILAC

Single shots, unipolar read-out

DBA IV




NINO

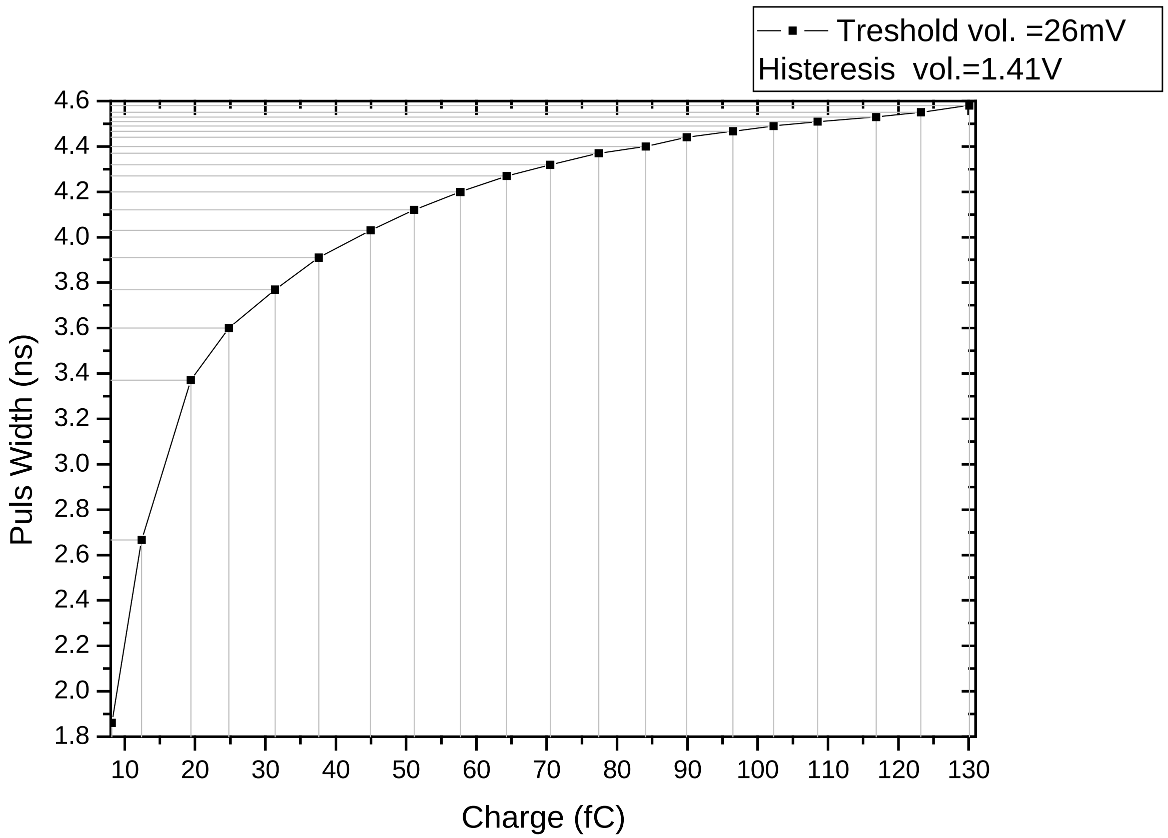



Pulse area ~ $Q_C$

Pulse with ~ $Q_C$

# Results

Pulse width – charge dependency for adapted NINO



# Results

**1 Pixel L3-GSI** 124µm $^{12}C$ E=10,2 MeV/u UNILAC

NINO card

20mV Threshold

-Pulse splitter used
→½ original signal from NINO


← Original signal

← Digital signal after Philips 708 discriminator

30mV Threshold

# Results

**1 Pixel L3-GSI** 124µm $^{12}C$ E=10,2 MeV/u UNILAC

**Double pulse width** **Only 1 pulse is counted** **→ Pileup problem**


| Measure | P1:fall(C2) | P2:ampl(C2) | P3:widn(C2) | P4:rise(C2) | P5:width(F1) | P6:widn(C2) | P7:widn(C3) |
|---|---|---|---|---|---|---|---|
| value | 1.221 ns | 1.371 V | 5.772 ns | 816 ps | 403 ps | 5.772 ns | 9.134 ns |
| mean | 1.67336 ns | 1.34428 V | 4.30110 ns | 1.35013 ns | 462 ps | 4.30110 ns | 7.22394 ns |
| min | 132 ps | 158 mV | -400 ps | 134 ps | 4 ps | -400 ps | -376 ps |
| max | 331.612 ns | 1.638 V | 36.037 ns | 317.028 ns | 2.2 ns | 36.037 ns | 42.581 ns |
| sdev | 6.32162 ns | 181.93 mV | 2.31745 ns | 7.57374 ns | 393 ps | 2.31745 ns | 5.41167 ns |
| num | 14.338e+3 | 1.533e+3 | 21.343e+3 | 14.436e+3 | 2.500e+3 | 21.343e+3 | 20.263e+3 |
| status | | | | | | | |

NINO card

Digital signal after Philips 708 discriminator

Original signal

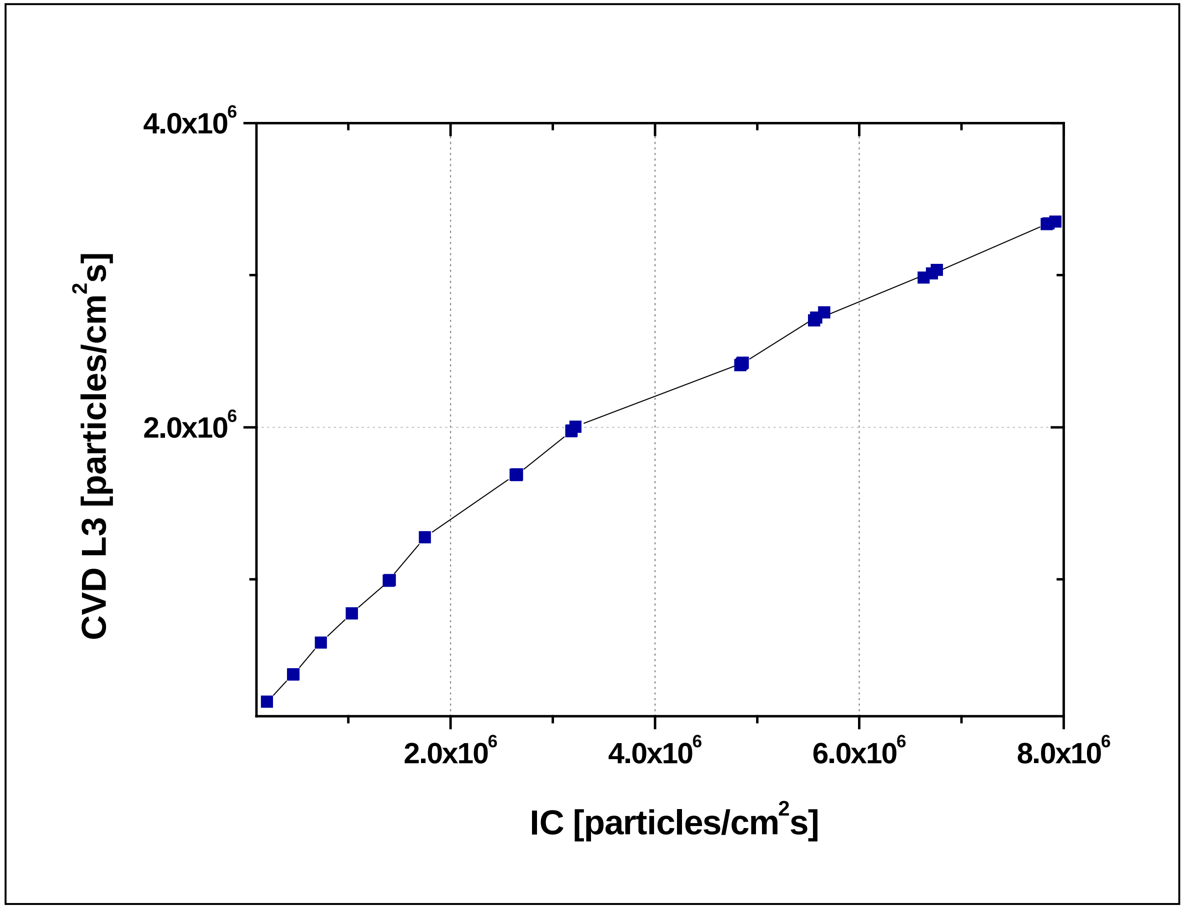
Th=30mV

-Pulse splitter used

→½ original signal from NINO

# Results

**1 Pixel L3-GSI** 124µm $^{12}C$ E=10,2 MeV/u UNILAC




NINO card

30 mV threshold

Phillips 708

300 MHz discriminator

30 mV threshold

→ Too large pixel

→ Multi hits

# Results

**Single Pixel detector** L3 GSI 124µm $^{152}$Sm E=5,8 MeV/u UNILAC


Moving baseline

→ Loss of counting rate (?)

→ Baseline restorage needed

Discriminator Threshold

Trigger Threshold

# Results

**Pixel detectors D1, D2** 100µm $^{12}C$ E=80-430 MeV/u SIS


D1 detector

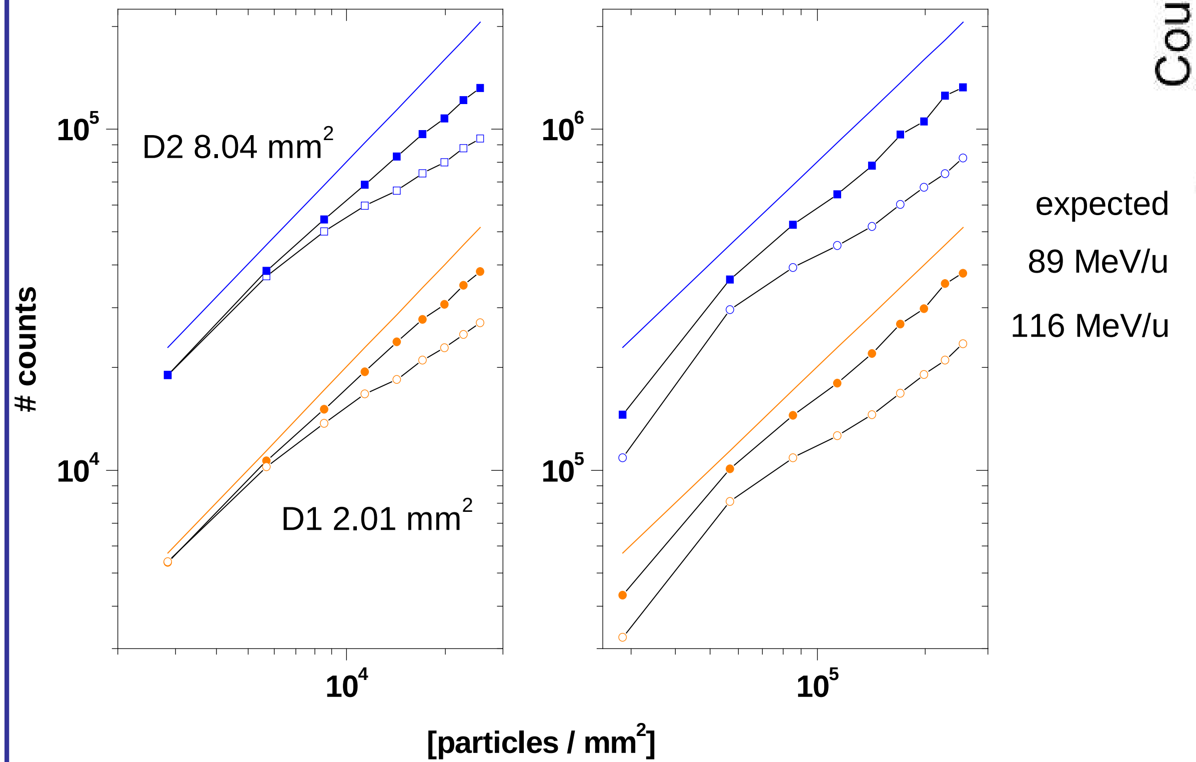
Pixel area=2.01mm$^2$

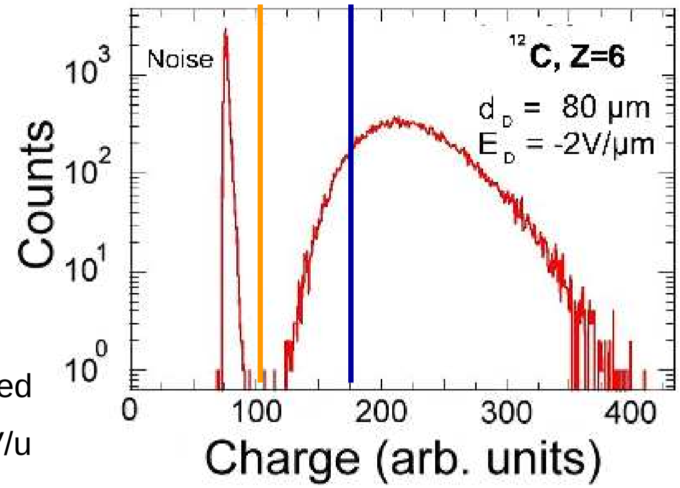
D2 detector

Pixel area=8.04mm$^2$

# Results

**Pixel detectors D1, D2** 100µm $^{12}C$ E=80-430 MeV/u SIS



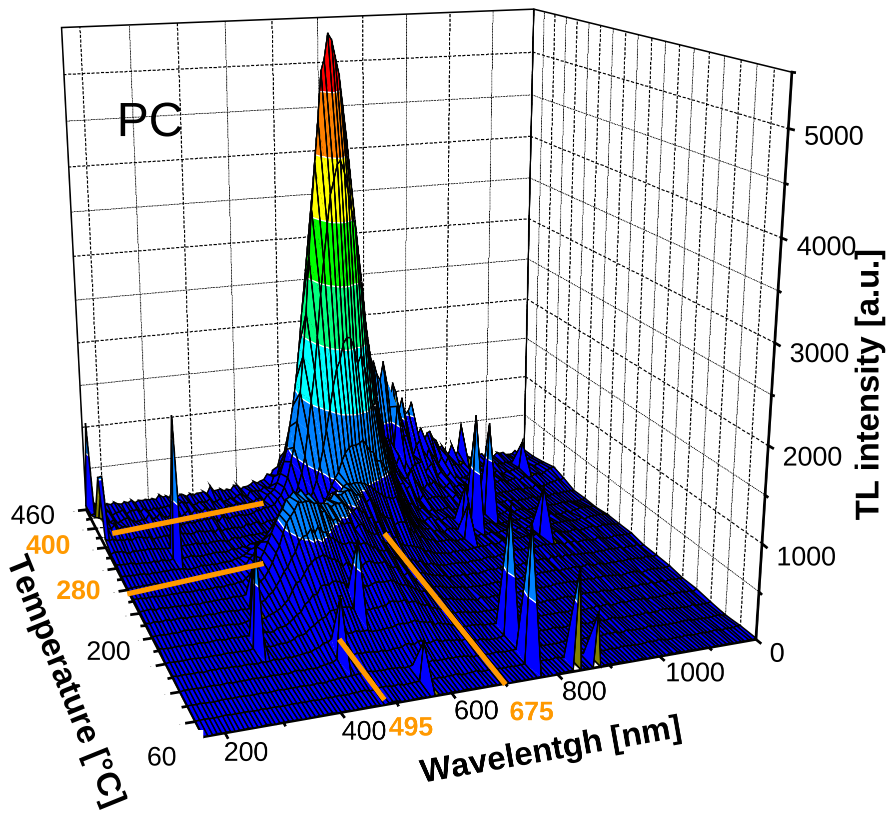



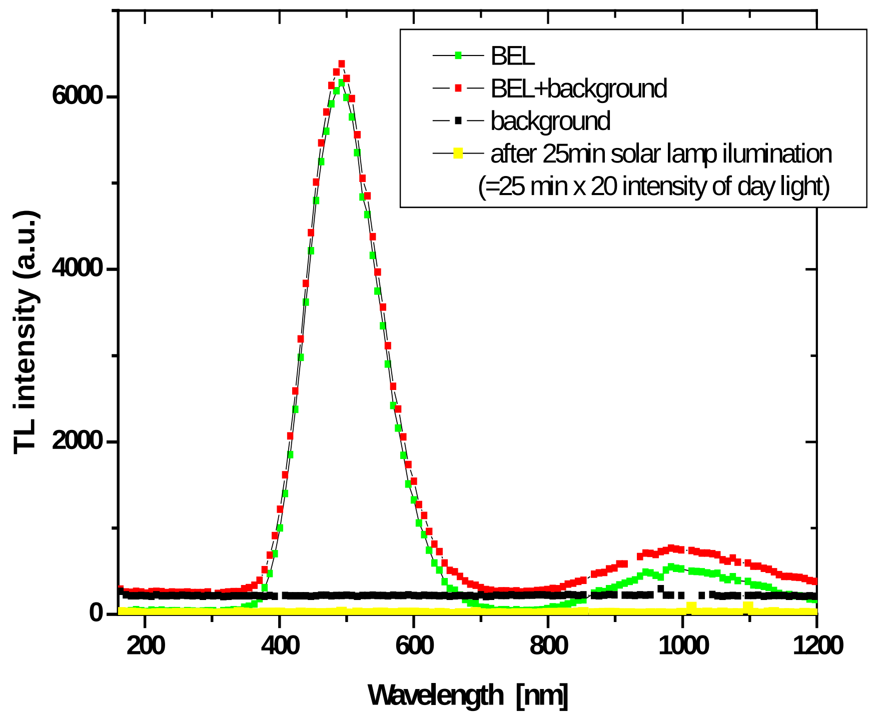

→ Missing counting efficiency due to electronics

# Optical measurements

Emission spectra of IMO and PC samples after 1.2 kGy  X-ray irradiation

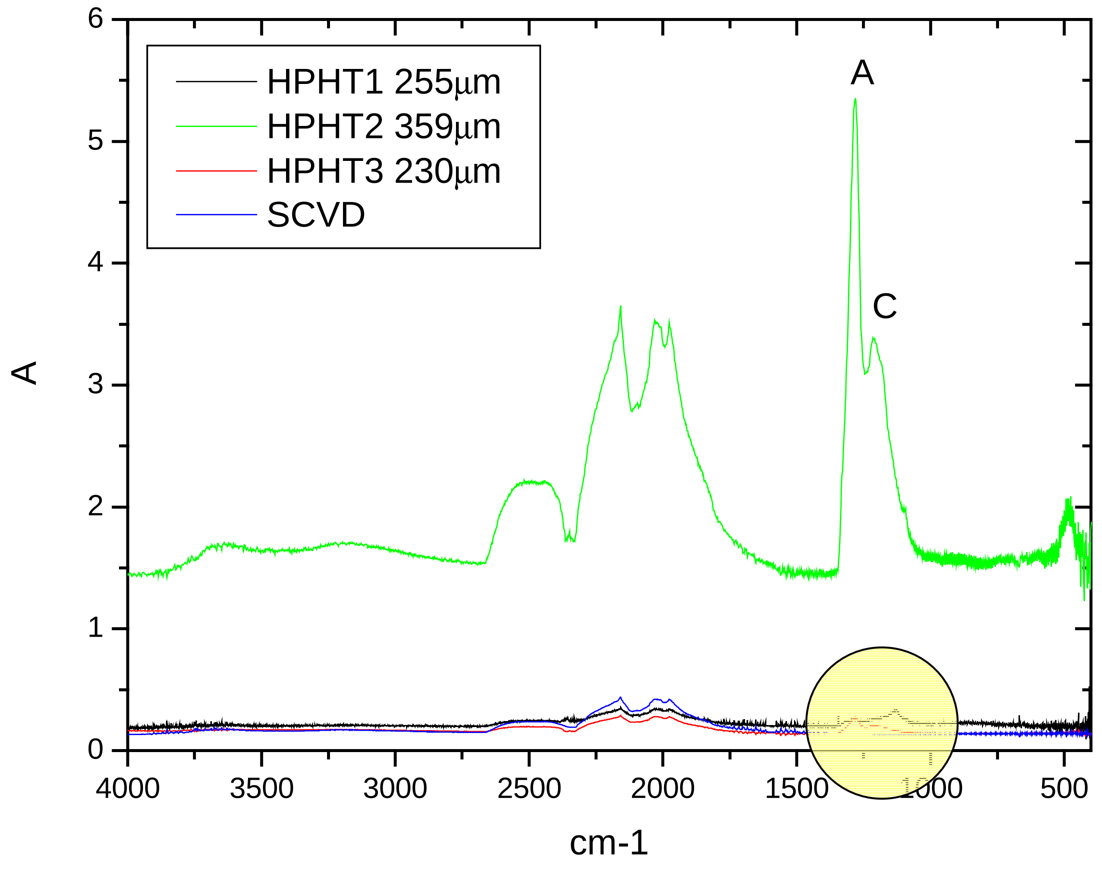
HR= 2 ℃ / sec



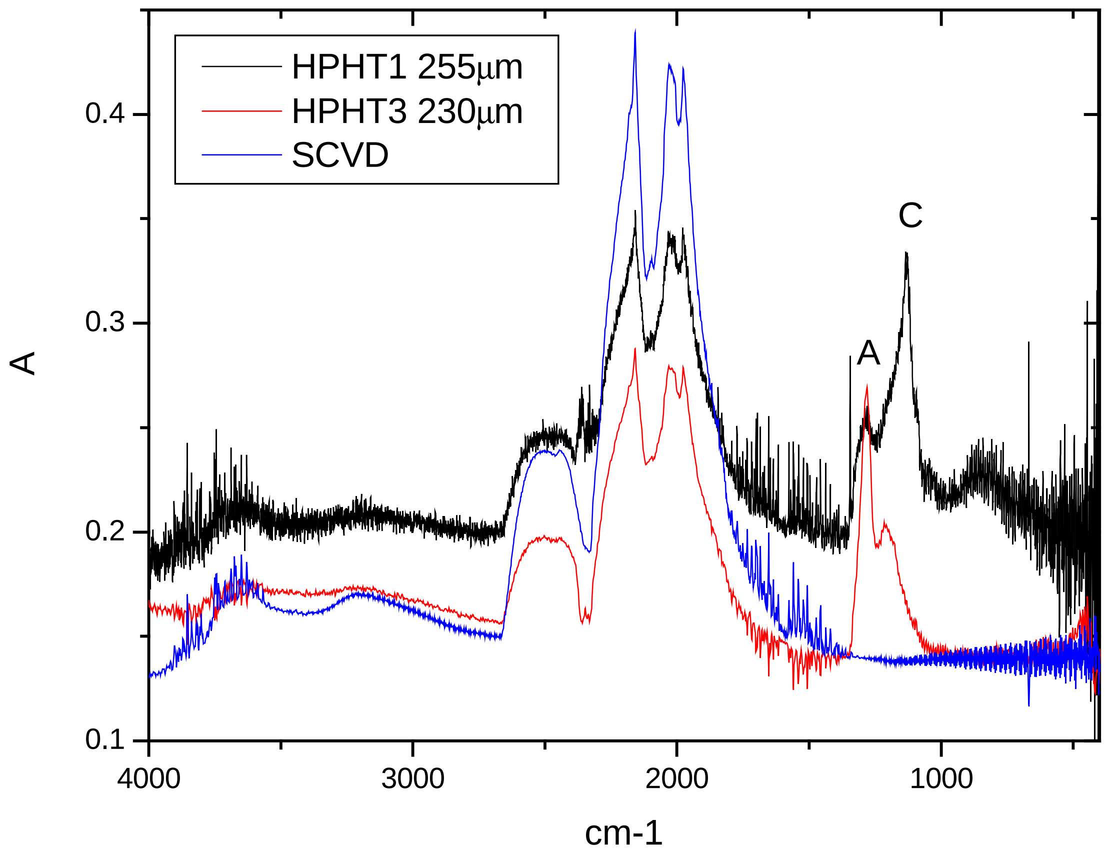
# Optical measurements

IR absorption spectra of 3 different HPHT samples



# Optical measurements

IR absorption spectra of 3 different HPHT samples



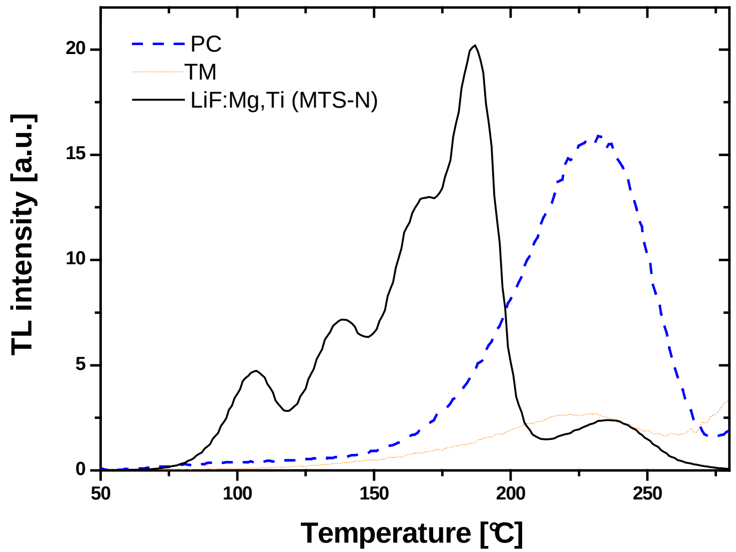

→ Nitrogen pairs "A" dominant in TL

→ SCVD not useful for TL

# Offline monitoring - TLD

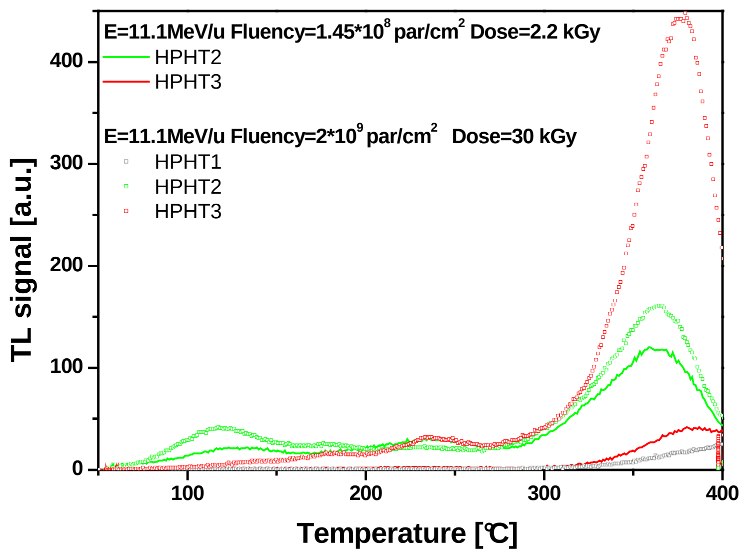
Typical TL glow curves

irradiation with C ions (350MeV/u)
Dose up to 2 Gy



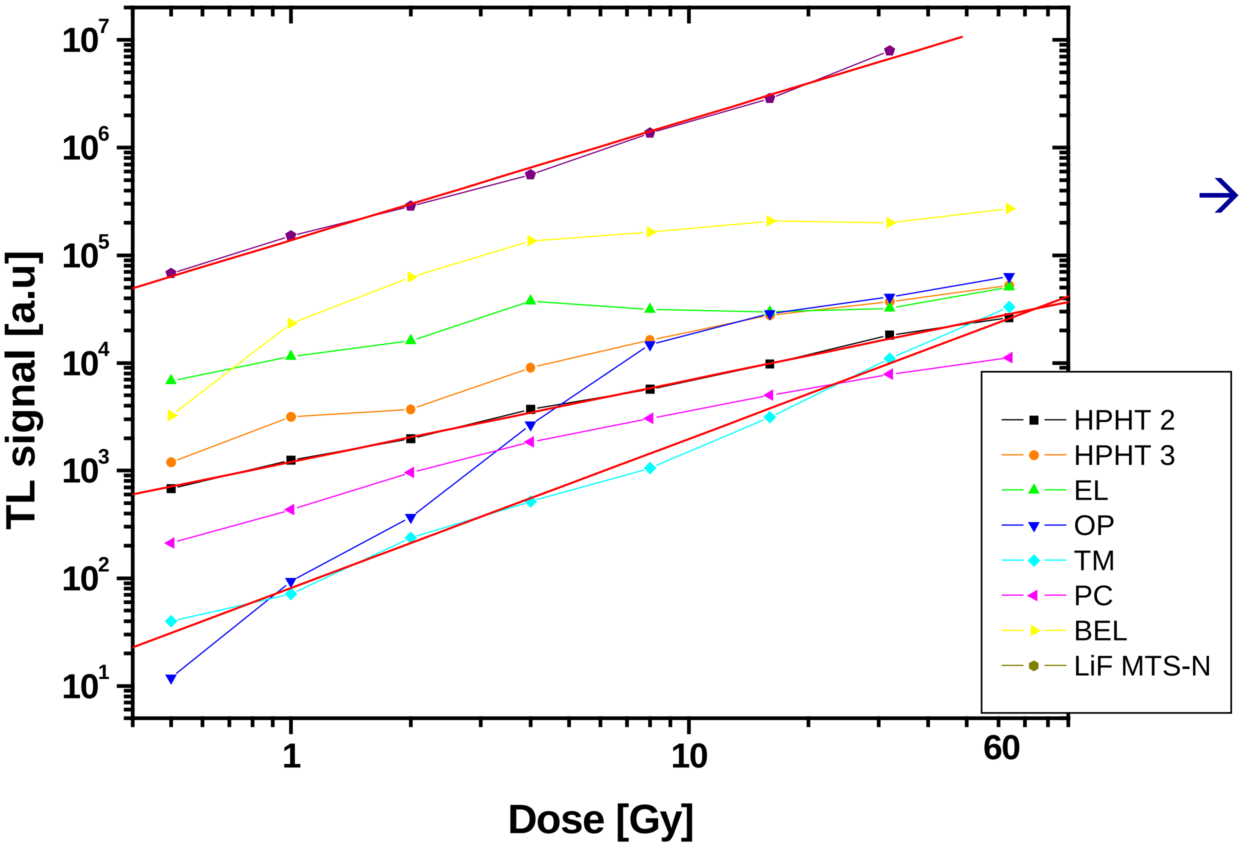

3 HPHT diamond detectors

irradiation with Au ions (11.4MeV/u)
dose 2.2 kGy and 30 kGy



# Offline monitoring - TLD

Linearity test with X-rays




→Good up to **60 Gy**

**TM, PC, HPHT**

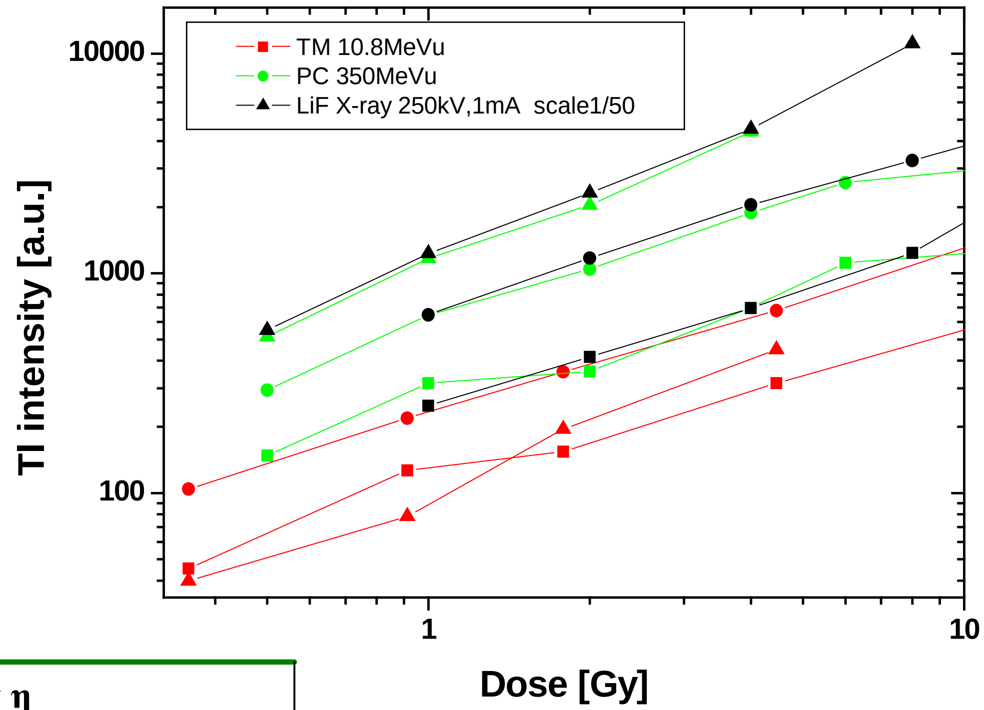
# Offline monitoring - TLD

Efficiency of pCVD diamonds and LiF (MTS-N) detector for different species and energy regimes

**Efficiency**

The efficiency η was derived according to equation (1) where TLHI and TLX are the integral light sum of detectors irradiated with heavy ions (HI) and X-rays (X) respectively.

$$\eta \equiv \frac{(TL_{HI} / D)}{(TL_X / D)} \cdot 100\%$$




| | Efficiency η | |
|---|---|---|
| Sample type | 350 MeV/u | 11.4 MeV/u |
| PC | 100% | 32% |
| TM | 100% | 41% |
| LiF (MTS-N) | 100% | 9% |

**!** Efficiency of TL diamond detectors to HI better than for standard TLD material

# Summary & Outlook (online)

- Various poly-CVD diamond detectors tested
- First results on NanoCrystalineDiamond sample

- Various ion spezies & energies used
- Fast single channel & muliti-channel electronics tested

- Achieved promising results for online beam-diagnostics for HI

- double hits (UNILAC) → more & smaller pixels
- Results depending on detector quality → investigation on detector 'grade', preparation, contacts
- electronics noise limits resolution → bipolar readout (NINO) necessary, work on DBA
- best choice: SC CVD membrane < 100µm, 200 × 200 $mm^2$

# Summary & Outlook (offline)

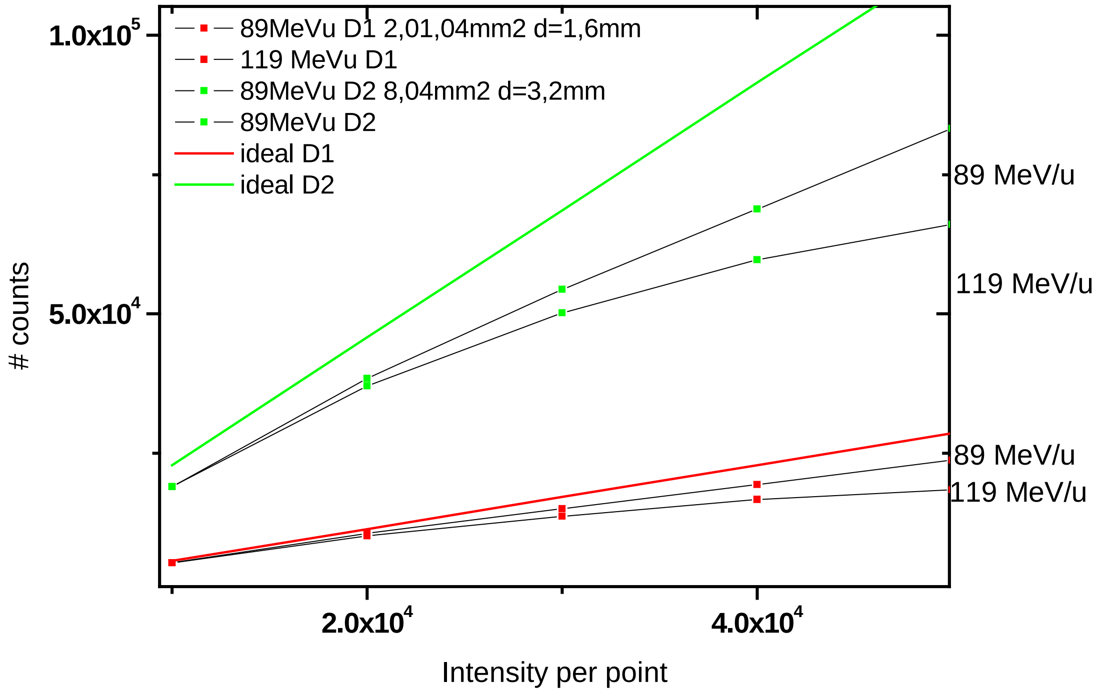
- Various poly-CVD and HPHT diamond detectors tested
- Different ion spezies & energies used
- Readout done with commercial equipment → optimization of annealing- & readout-parameters & procedure necessary

- Achieved very promising results for offline beam-diagnostics for all measured HI

  - Efficiency higher than for LiF
  - Linearity up to 60 Gy → detailed investigations on dose- & dose-rate dependency necessary
  - Results depending on detector quality → investigation on different batches & ‘grades’ necessary
  - Results scatters in one batch → dependency on history, annealing needed
  - Best results with material grade PC and TM → more investigation with different ion species end energies
    → investigation of mixed field conditions

TSC investigation planed

# Results



1.0x10^5
5.0x10^4
# counts
2.0x10^4
4.0x10^4
Intensity per point
89MeVu D1 2,01,04mm2 d=1,6mm
119 MeVu D1
89MeVu D2 8,04mm2 d=3,2mm
89MeVu D2
ideal D1
ideal D2
89 MeV/u
119 MeV/u
89 MeV/u
119 MeV/u