Radiation monitoring and beam abort for the Vertex detector of Belle II at SuperKEKB

Outline:

Belle II at SuperKEKB and its radiation monitoring system
Characterization of CVD diamond sensors used as radiation monitors
Preliminary results from first commissioning phase

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Belle II

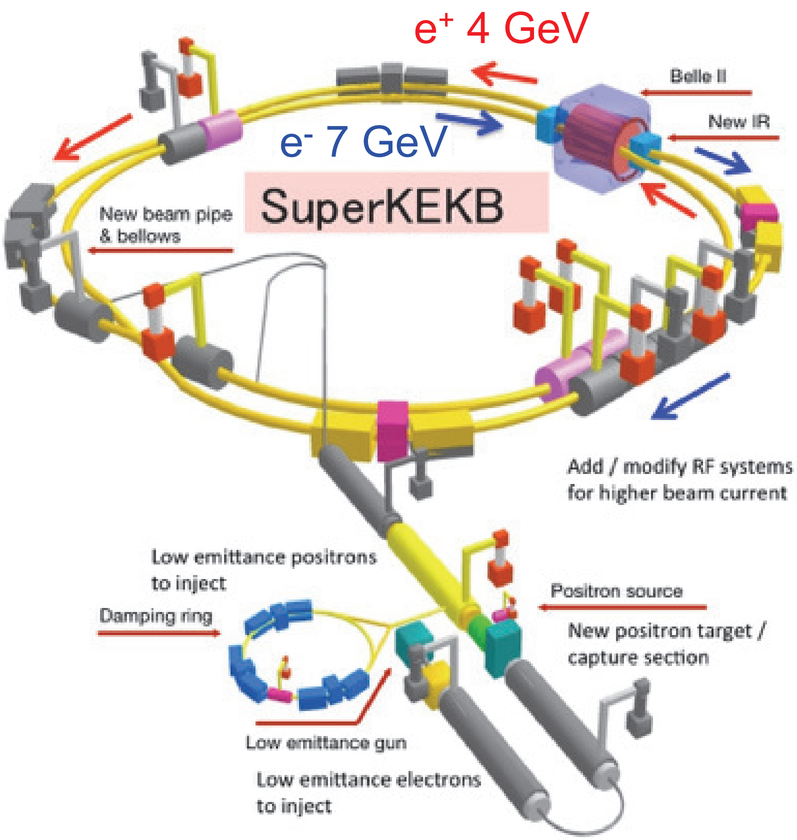
SuperKEKB & Belle II

- Reduced beam spot size
- Doubled beam currents

L_{peak}: 8×10^{35} $cm^{-2}s^{-1}$ (40 x KEKB)

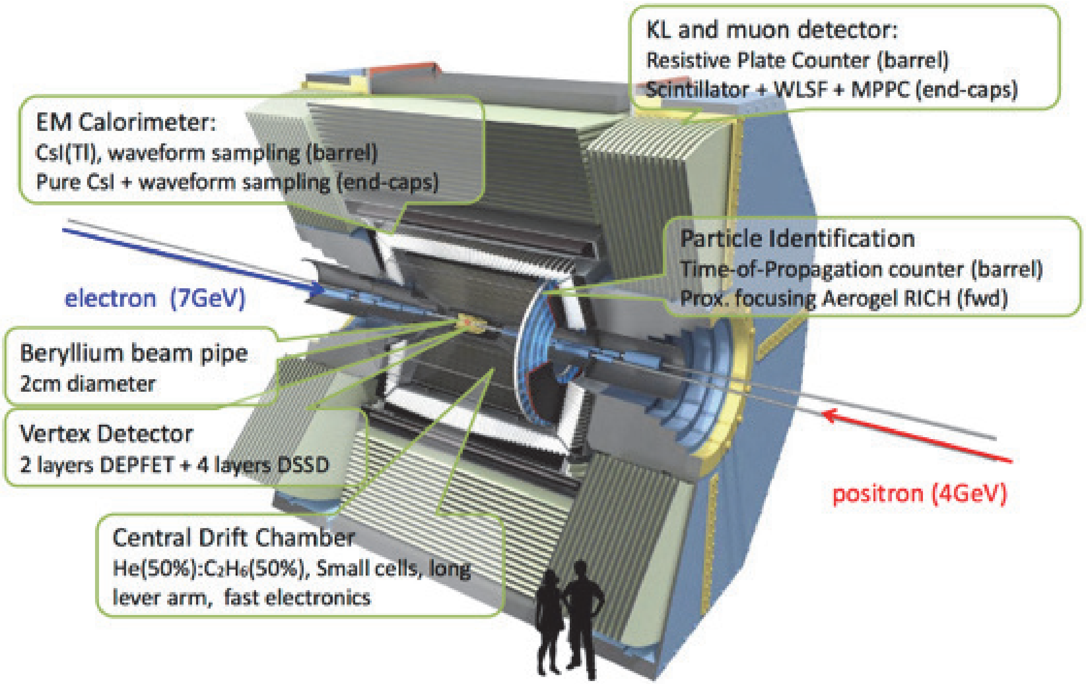
L_{int}: 50 ab^{-1} by 2025 (50 x KEKB)

Large radiation doses expected



$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Belle II Detector



Radiation monitoring system

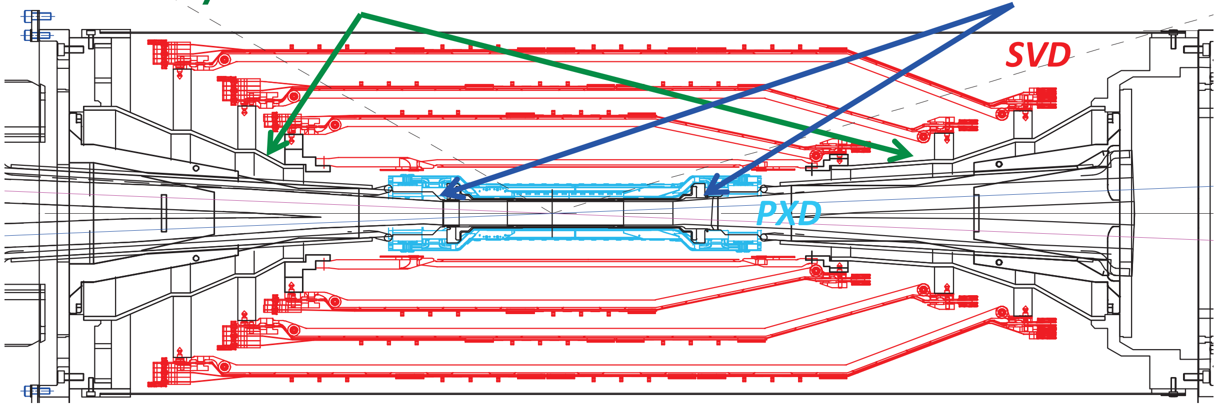
Need of radiation monitoring

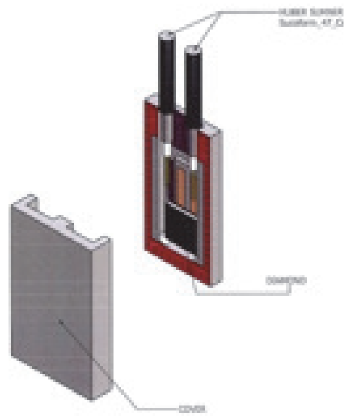
- First vertex detector layer at 1.4 cm radius (Depfet pixels)
- Severe beam-induced bkg & radiation doses mainly from low energy **e^- e^+ γ**
- Background sources: **e^+e^- pair** production in γγ scattering, **radiative Bhabha**, **Touscheck, off-momentum** particles from beam-gas, Synchrotron radiation
- 20 single crystal CVD diamond detectors

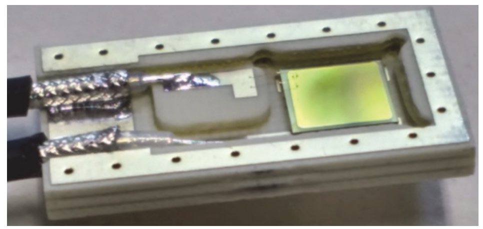
Installation locations

6 + 6 diamond sensors
SVD Layer-3 and -4

4 + 4 diamond sensors
PXD-beam pipe

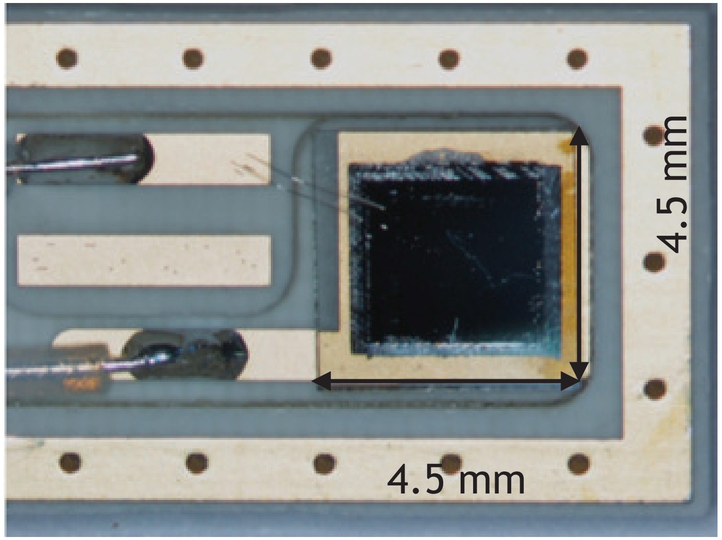






Long (30 m) coax cables direct connect HV and signal to a remote read-out electronics

Radiation monitoring system



20 s-CVD diamond sensors

Volume:
(4.5 x 4.5 x 0.5) mm^3

Specification	Value
Number of radiation sensors	20
diamond sensor size	5 mm×5 mm×500μm
maximum coax. cable length from sensor to electronics	3 + 40 m
sensor current/dose rate conversion factor	1 ÷ 10 nA/(mrad/s)
sensor current measurement sensitivity	0.01nA
sensor current measurement range	1 ÷ 10mA
normal frequency of current sampling	100 kHz
depth of buffer memory for specific events (aborts etc)	600 ms
normal frequency of data recording on slow control DAQ	1 ÷ 10 Hz
response time of fastest (hardware) beam abort trigger	10μs
response time of slow (software) beam abort trigger	> 10 s
instantaneous dose rate sensitivity	1.0 mrad/s
integrated dose overall relative uncertainty	5%
for typical diamond sensors (fast aborts):	**Value**
current measurement, precision (time scale 1 ms)	10 nA
response time	up to 10 μs
current range	0 ÷ 5 mA
for typical diamond sensors (slow aborts):	**Value**
current measurement, precision (time scale 1 s)	< 1 nA
response time	> 1 ÷ 100 s
current range	0 ÷ 15 μA

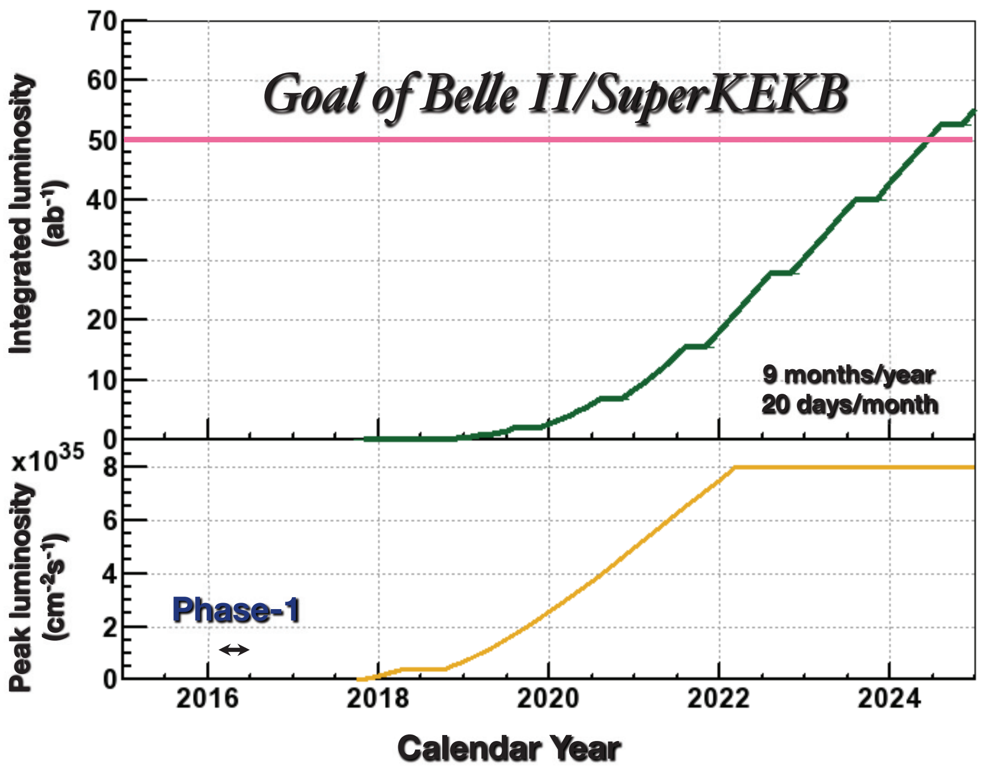
Radiation monitoring

- sufficiently accurate measurement of instantaneous and integrated radiation dose

Deliver beam abort signal

- large increase in backgrounds
  → "fast" abort trigger system
  - instantaneous dose precision 1mrad/s
  - response time 10 us
- lesser increase in backgrounds
  → "slow" abort trigger system

SuperKEKB luminosity projection

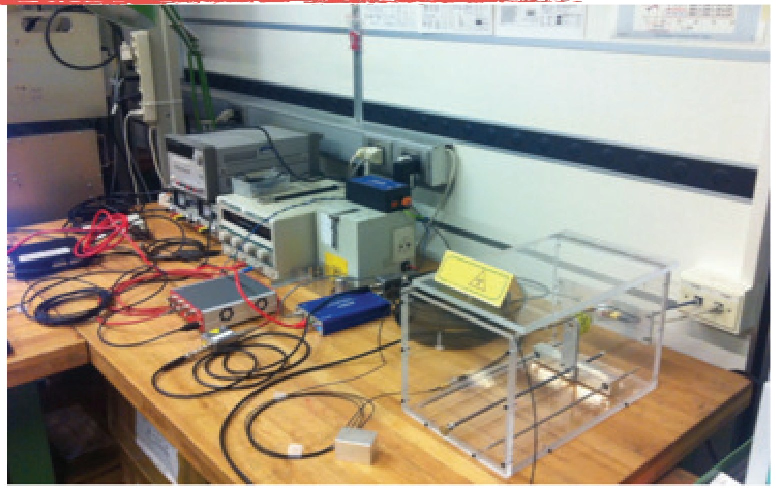


Three phases:

1. Feb-Jun 2016: first beams, no collisions, no Belle II; specific bkg detector → first 4 ◇'s
2. End 2017: 4 months commissioning first collisions, Belle II det. without VXD → 8 ◇'s
3. End 2018: Physics → full radiation monitoring system with 20 ◇'s

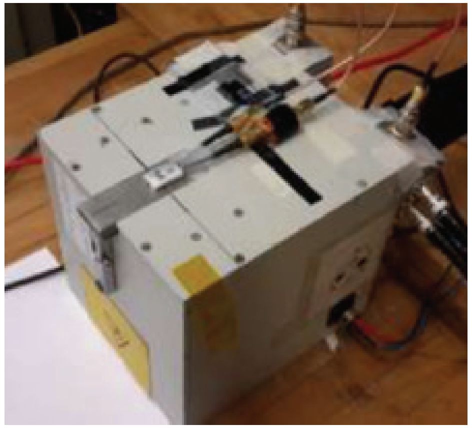
CVD sensors: tests and calibrations

(0) Preliminary test: dark I-V characteristic



(1) Measurements with β ^{90}Sr source

- I-V characteristic
- current as function of the source-sensor distance



(3) Measurement with single electron
(1-2 MeV, source ^{90}Sr + magnet):

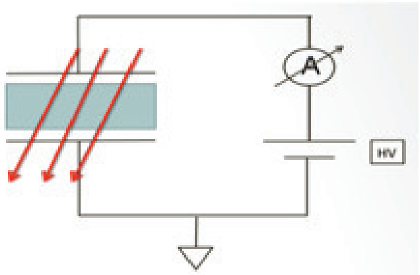
- charge collection efficiency measurement

(4) TCT measurement with α source

- check for the uniformity of the material

I-V with β ^{90}Sr source (d=18mm)

I-V characteristic

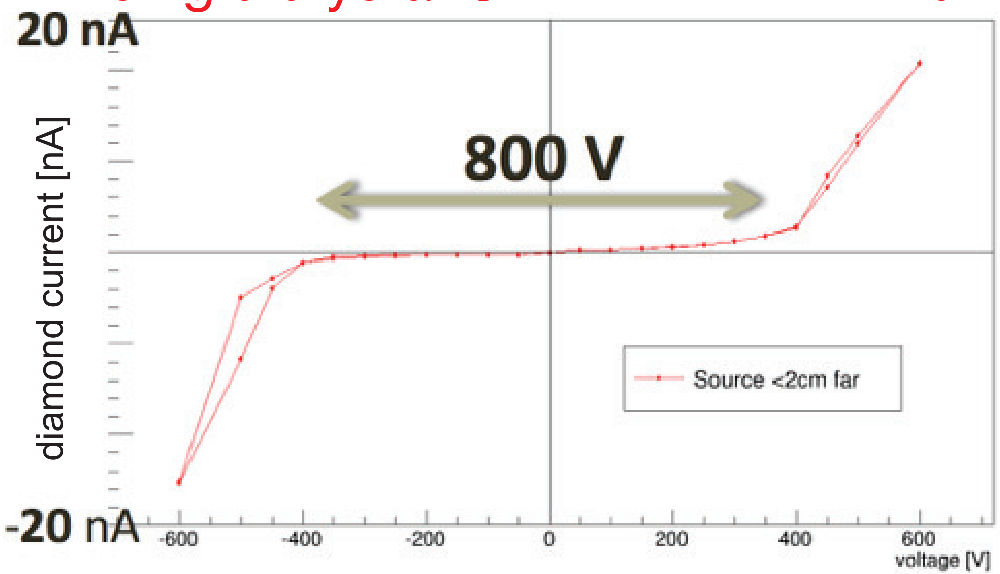


Three different types of diamond sensors tested:
- single crystal CVD with Ti+Pt+Au metallization from Cividec
- single crystal CVD with Al metallization from Micron
- poly-crystal CVD with Al metallization

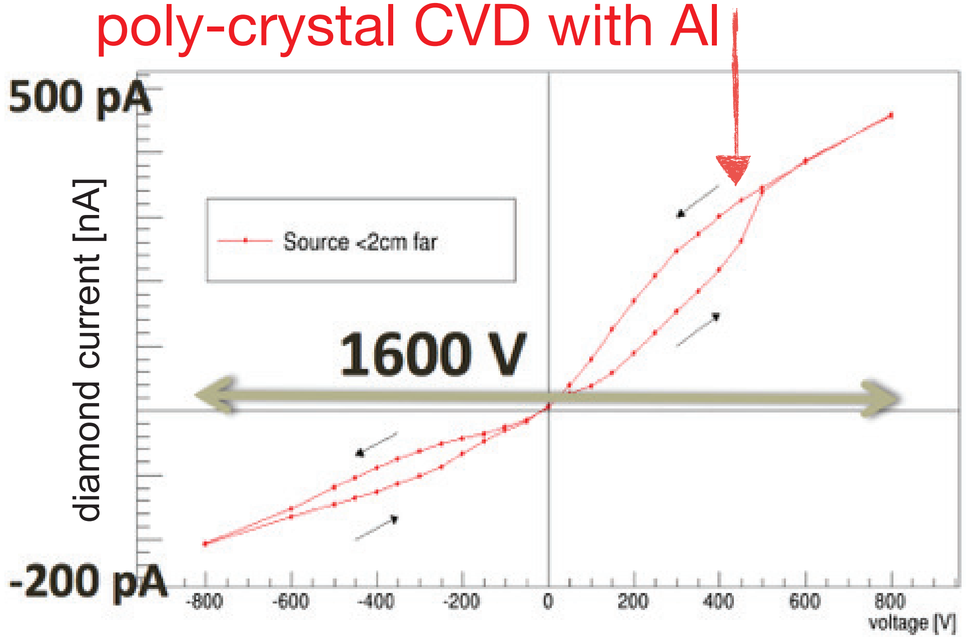
→ **very different behaviour observed:**
I'll show only the extreme cases

deep levels act as centers to capture or emit majority carriers during the charging or discharging process

single crystal CVD with Ti+Pt+Au

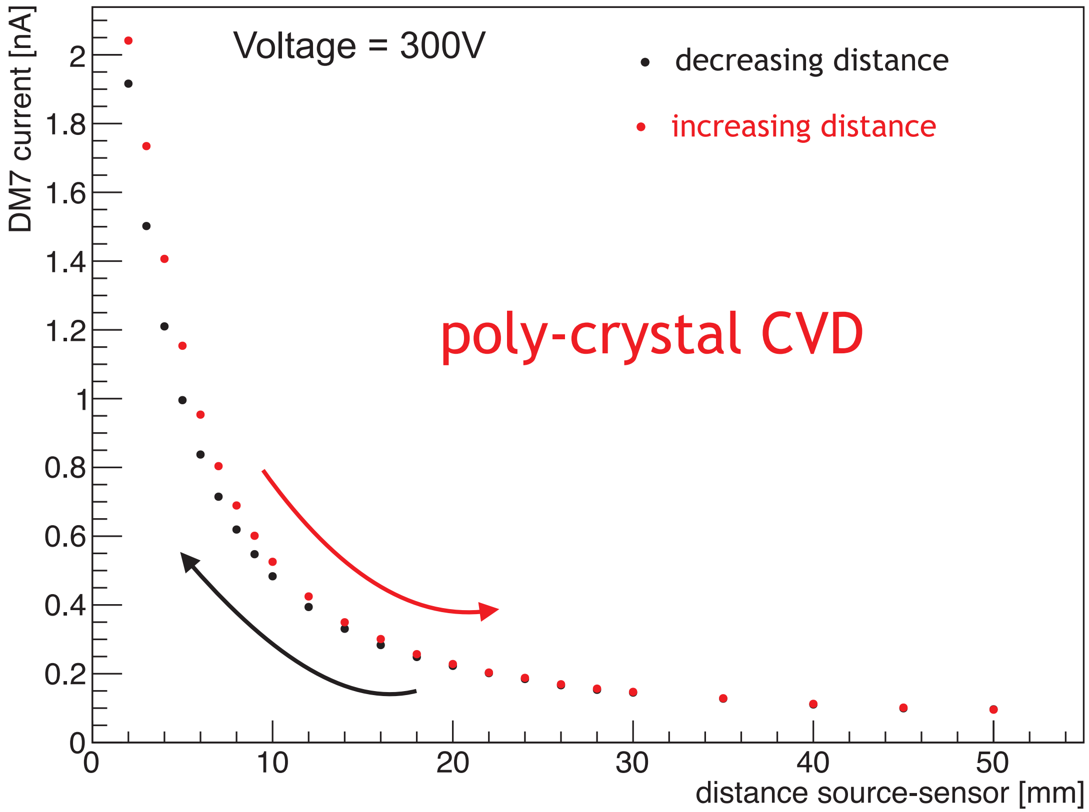


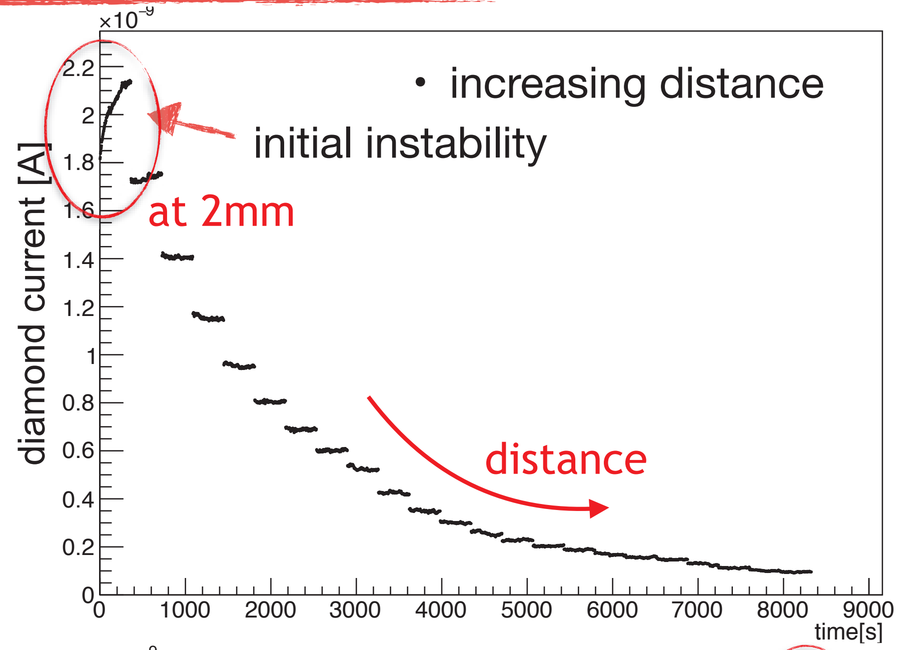
poly-crystal CVD with Al

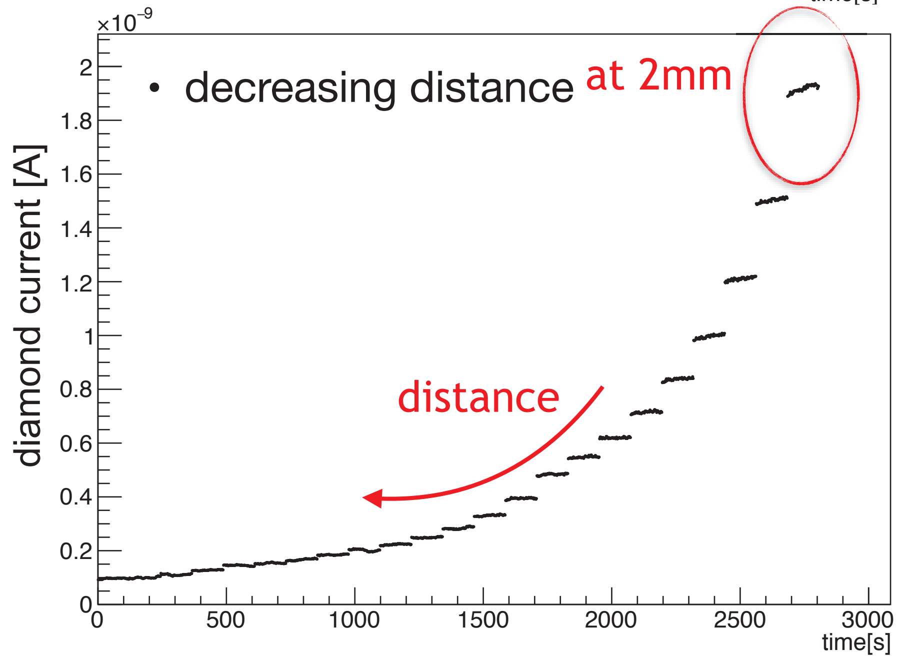


Current vs source distance

Current as function of the source-sensor distance







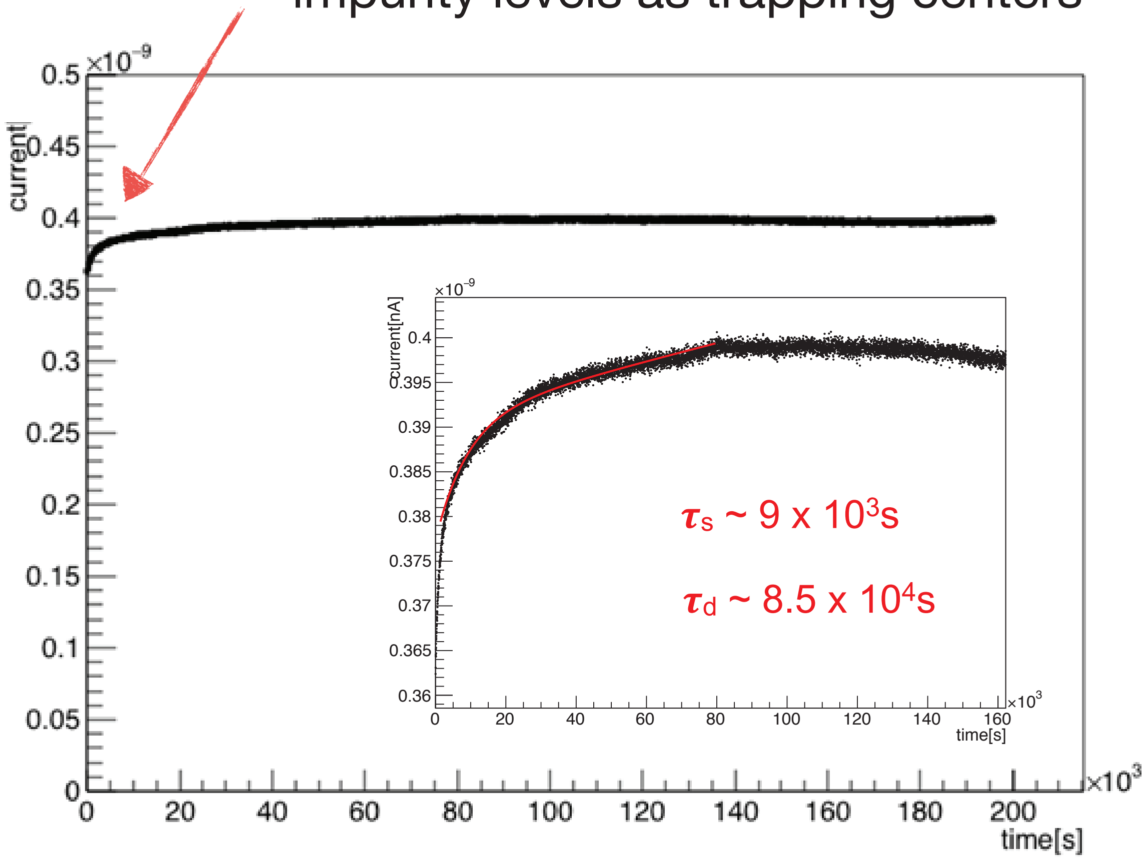
The coexistence of two different current values at low distances indicates that the values of current are not taken at steady state

Stability measurements

Measurement as function of time

Exponential trend

→ Shockley-Hall-Read theory for impurity levels as trapping centers



Two different types of traps:

- shallow traps
- deep traps

Steady state: both shallow and deep levels completely filled

fit function

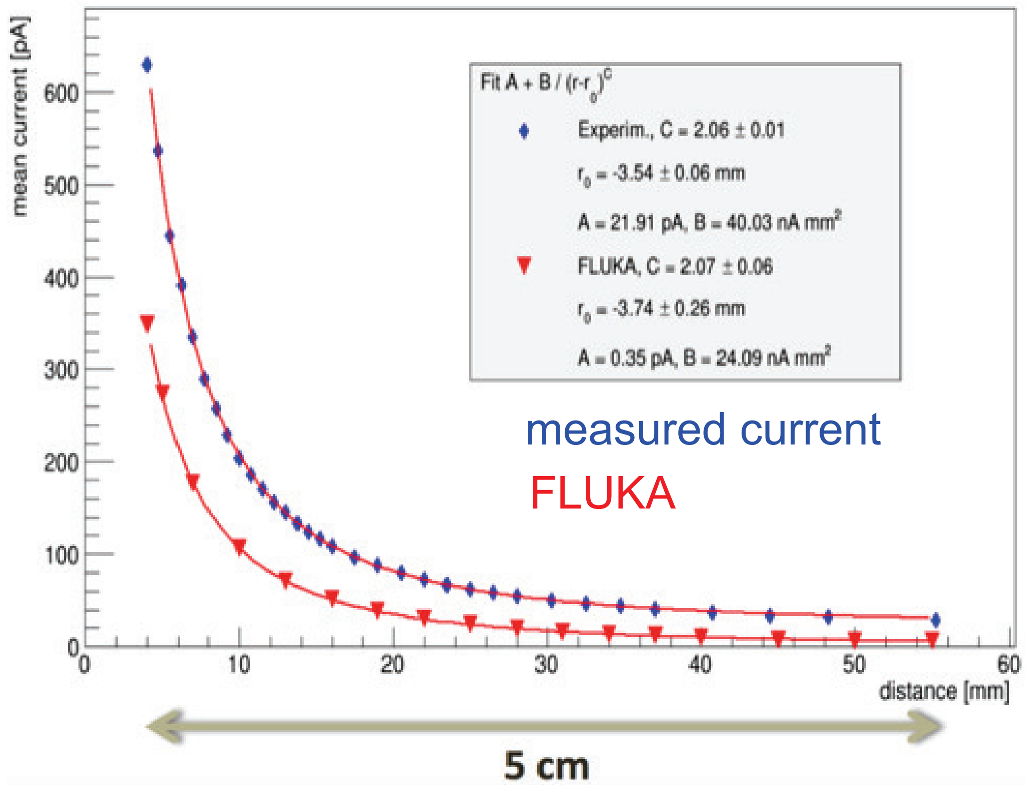
$$I(t) = I_0 \left[1 - w_s e^{-t/\tau_s} - w_d e^{-t/\tau_d}\right]$$

τ_s → time constant associated to shallow traps

τ_d → time constant associated to deep traps

Comparison with FLUKA simulation

Current as function of the source-sensor distance



predicted current

$$I_{FLUKA} = \frac{\Delta E/\Delta t * q_e}{E_{e-h}} \; CCE_{FLUKA} * (G_{PC})_{FLUKA}$$

CCE_{FLUKA} =1

$(G_{PC})_{FLUKA}$ =1

generated charge

A simplified geometry implemented:

4.5 x 4.5 x 0.5 mm^3 diamond detector fixed on a steel wall and screened by Al (13 x 20 x 0.2 mm^3)

- ☑ current decrease approximately with the inverse square of the distance
  → agreement with simulation
- ☑ measured current > simulated current
  → photoconductive gain

To convert the current measurements into dose rate measurements we need to know the value of the photoconductive gain

Photoconductive gain

Photoconductive gain due to ohmic contact between electrodes and diamond

→ Charge injected from the electrode

measured current

I_{meas} = generated charge $CCE_{exp}\, G_{PC,exp}$

assumption: equal to generated charge FLUKA

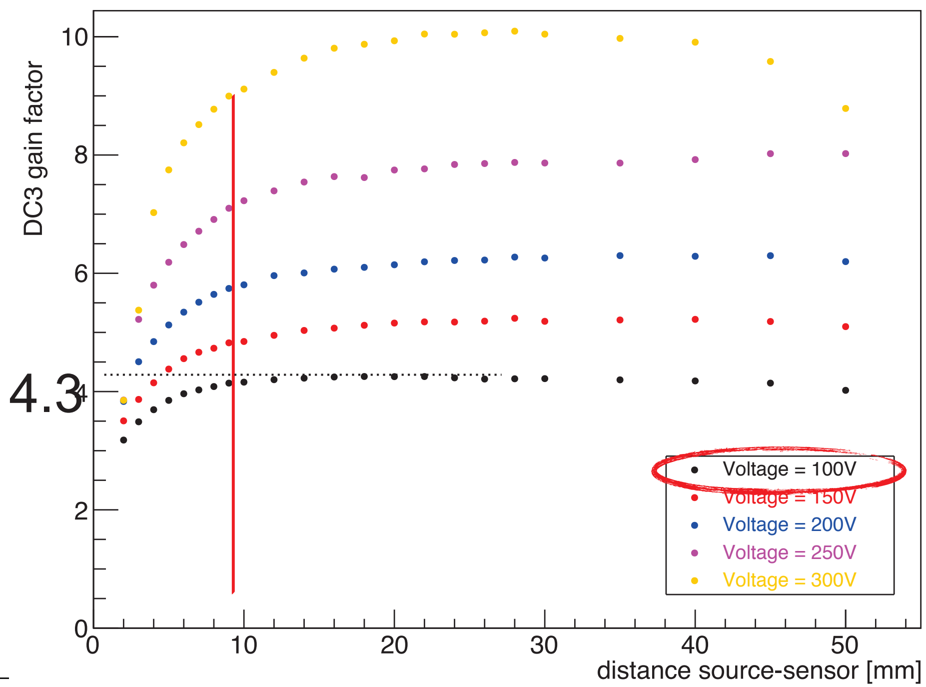
CCE measured for each diamond sensor

~1

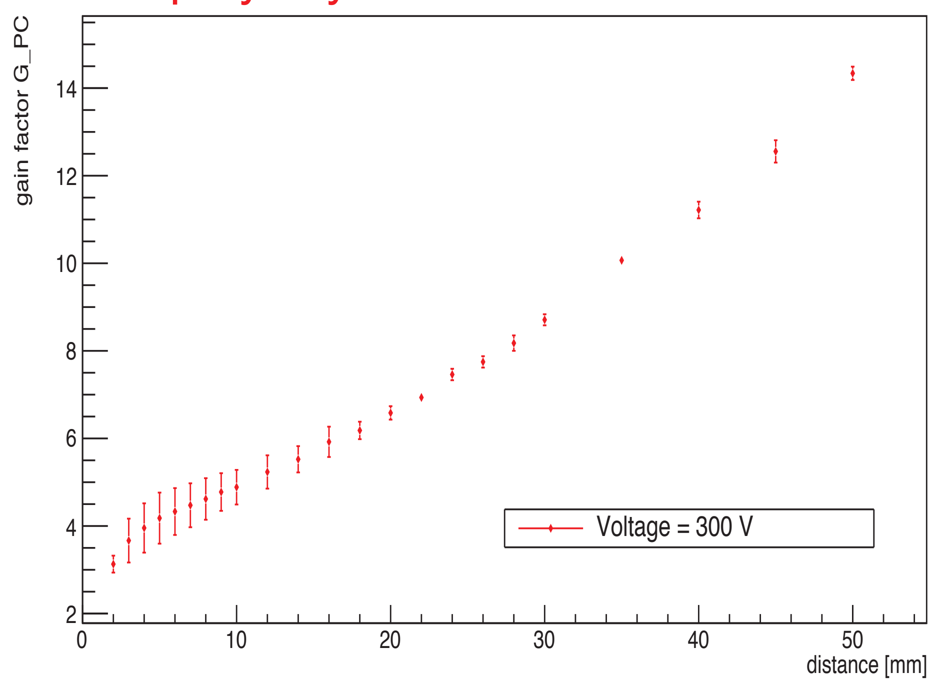
$$\frac{I_{meas}}{I_{FLUKA}} = \frac{CCE_{meas} * (G_{PC})_{meas}}{CCE_{FLUKA} * (G_{PC})_{FLUKA}} = (G_{PC})_{meas}$$

=1 =1

single crystal CVD



poly-crystal CVD

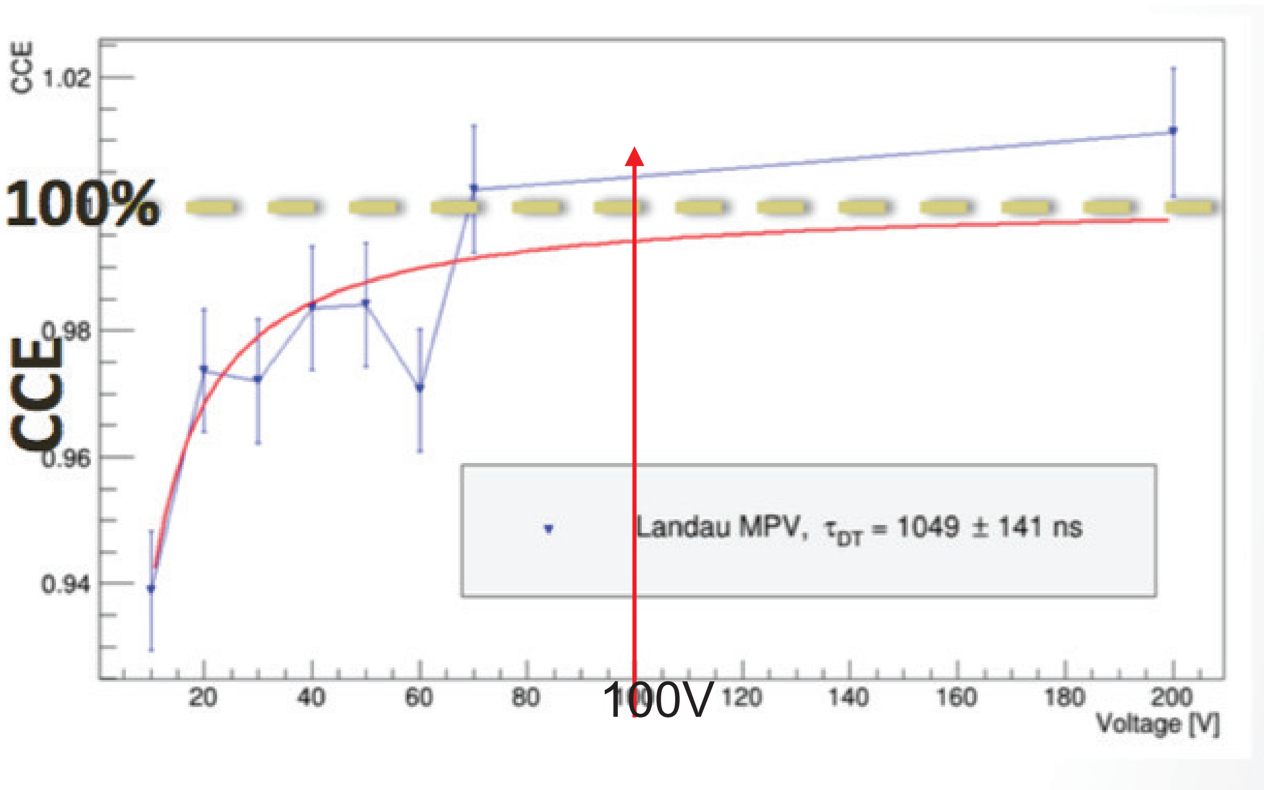


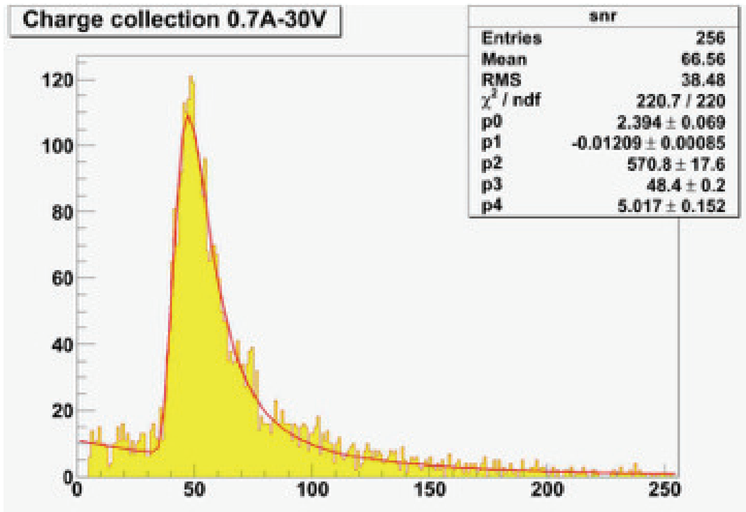
Charge Collection Efficiency

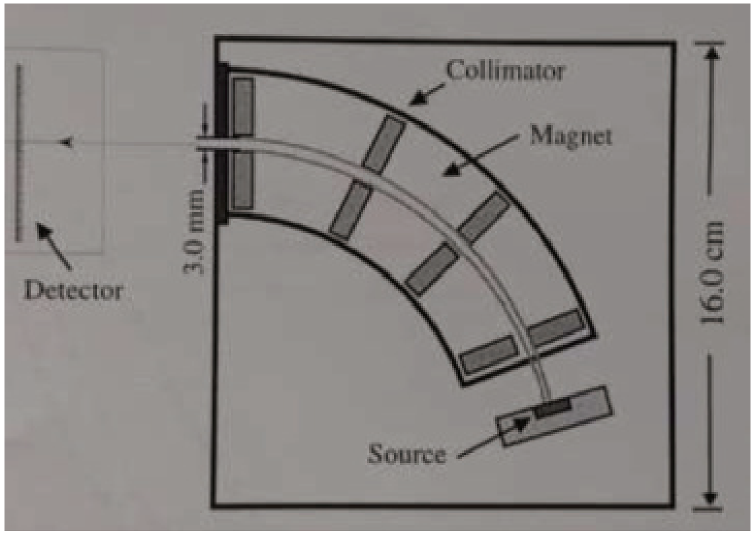
Example: DM5, CCE ≈ 100% @ 100V

Landau Most Probable Value (MPV) vs HV ➔ Charge Collection Efficiency

$$CCE = \frac{Q_{\text{collected}}}{Q_{\text{generated}}} = \frac{v_{dr}\tau}{d}\left(1 - e^{-\frac{d}{v_{dr}\tau}}\right), \qquad v_{dr} = \mu\frac{V}{d}$$

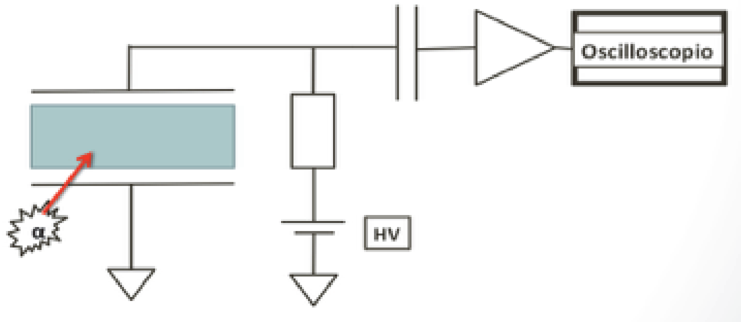


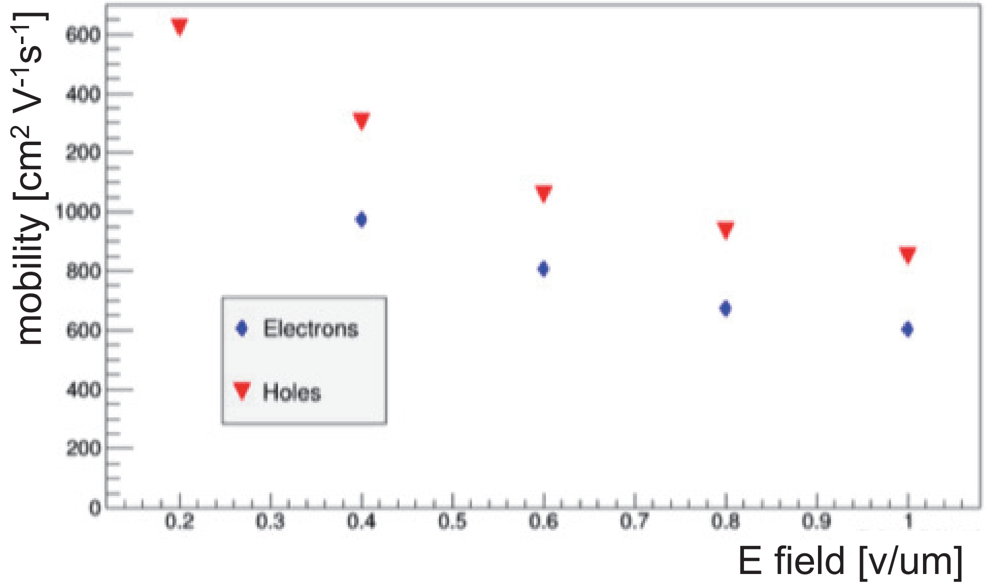




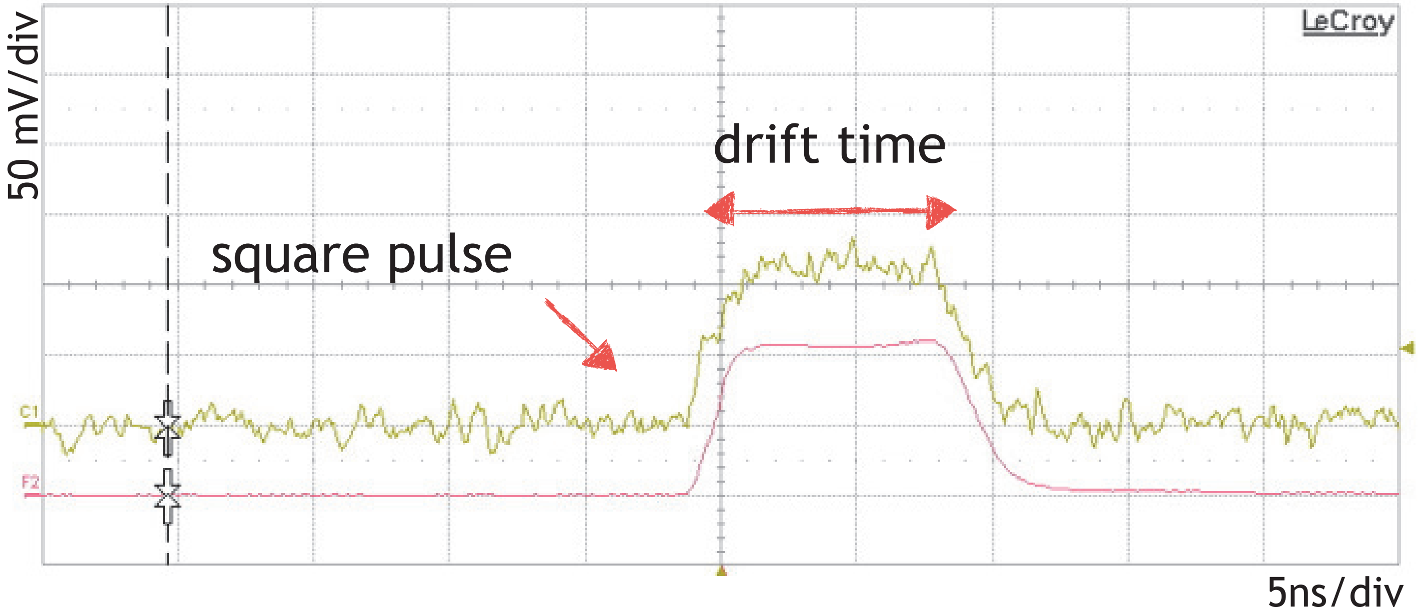
TCT with α source

(TCT = Transient Current Technique)



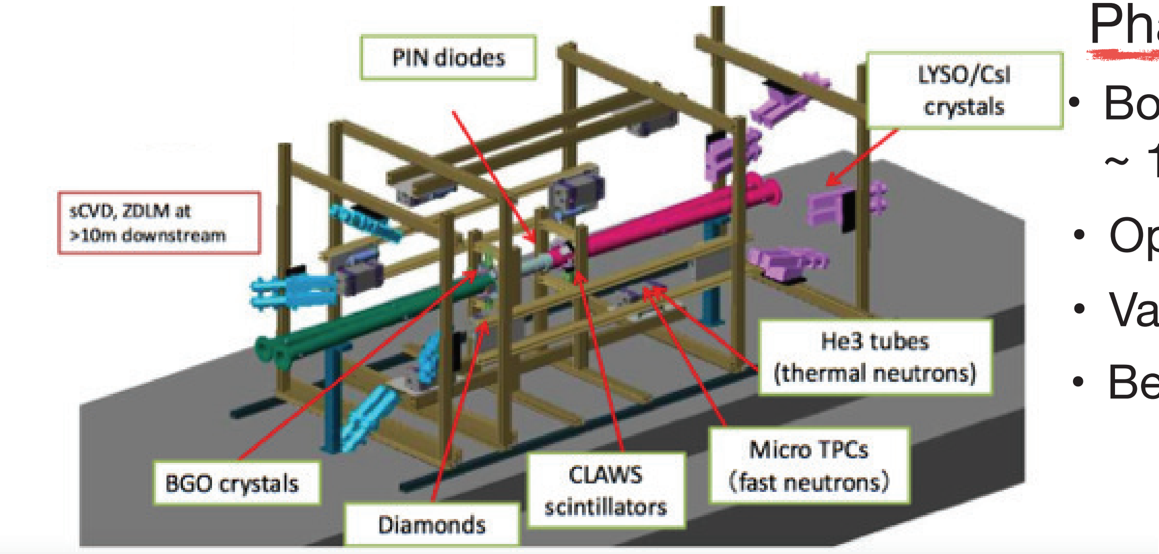


α source: 241-Am, 55kBq



- measure mobilities of electrons, holes
- check of the uniformity of diamond

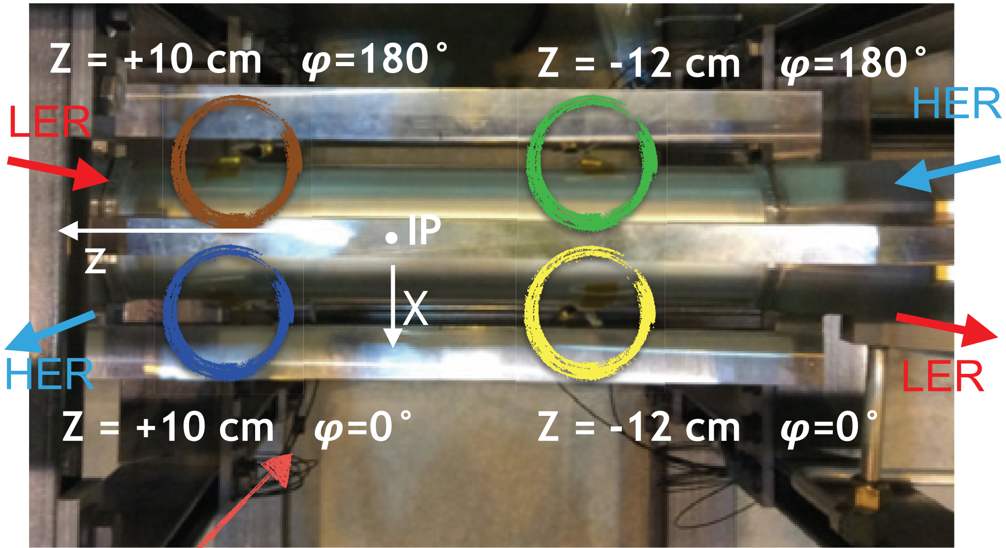
Phase I SuperKEKB commissioning



Phase 1 (from February to June 2016)

- Both beams commissioned, currents up to ~ 1 A, without collisions
- Optics study
- Vacuum scrubbing
- Beam backgrounds study

- Since Background simulations have large uncertainties: measurements near IP
- First measurements of SuperKEKB injection background
- Test and calibration of diamond sensors. Precision (0.5 nA on the shortest 10µs time scale) OK for reliable fast and slow aborts for phase 2/3



4 diamonds installed in this phase

Diamond Sensors in BEAST phase1

LER only: 2.5 nA
HER only: 0.1 nA
LER+HER: 2.6 nA

FW_180 (PV Dia0)
DM7 Z = +10 cm

LER only: 0.3 nA
HER only: 0.4 nA
LER+HER: 0.7 nA

BW_180 (PV Dia2)
DM5 Z = -12 cm

some uncertainties on the position dominated by (0,0,0) position

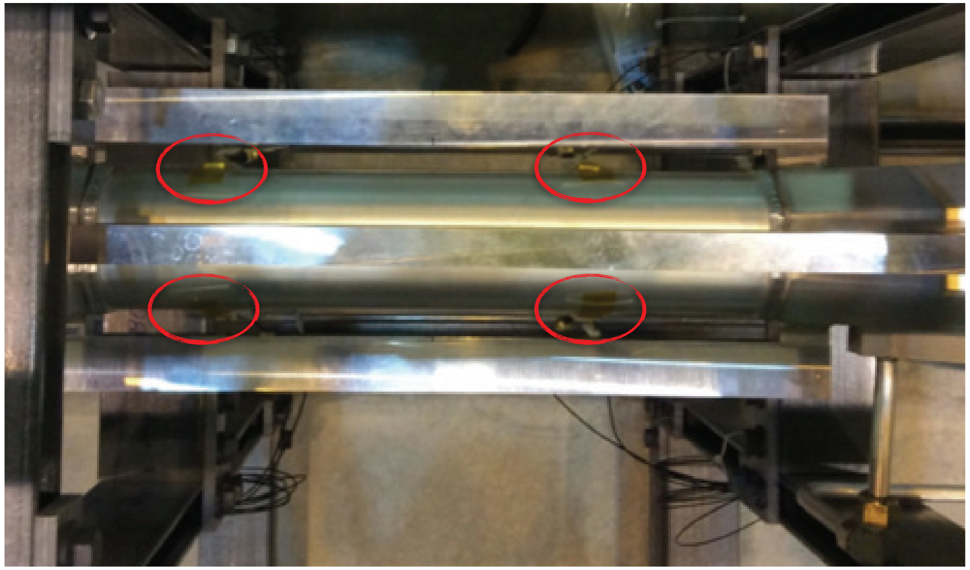
Δz = +/- 2 cm

Δy = +/- 1 cm

LER

z

HER



HER

LER

- DC3: *sCVD*, CIVIDEC metallization (Ti + Pt + Au)
- DM4, DM5: *sCVD*, Micron metallization (Al)
- DM7: *pCVD*, Micron metallization (Al)

FW_0 (PV Dia1)
DC3 Z = +10 cm

LER only: 0.08 nA
HER only: 0.08 nA
LER+HER: 0.16 nA

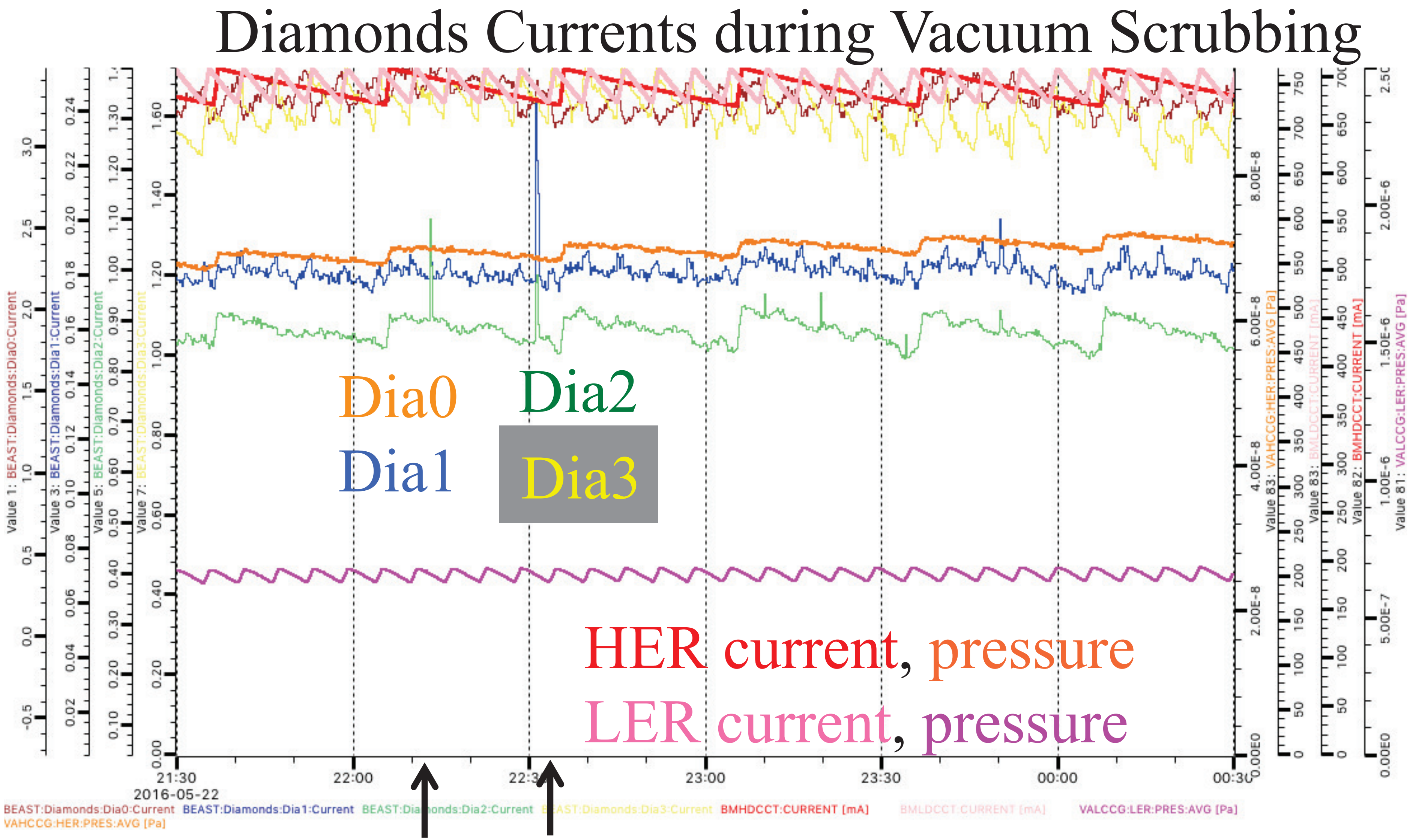
BW_0 (PV Dia3)
DM4 Z = -12 cm

LER only: 1.2 nA
HER only: 0.1 nA
LER+HER: 1.3 nA

1 nA -> 2 - 8 mrad/s

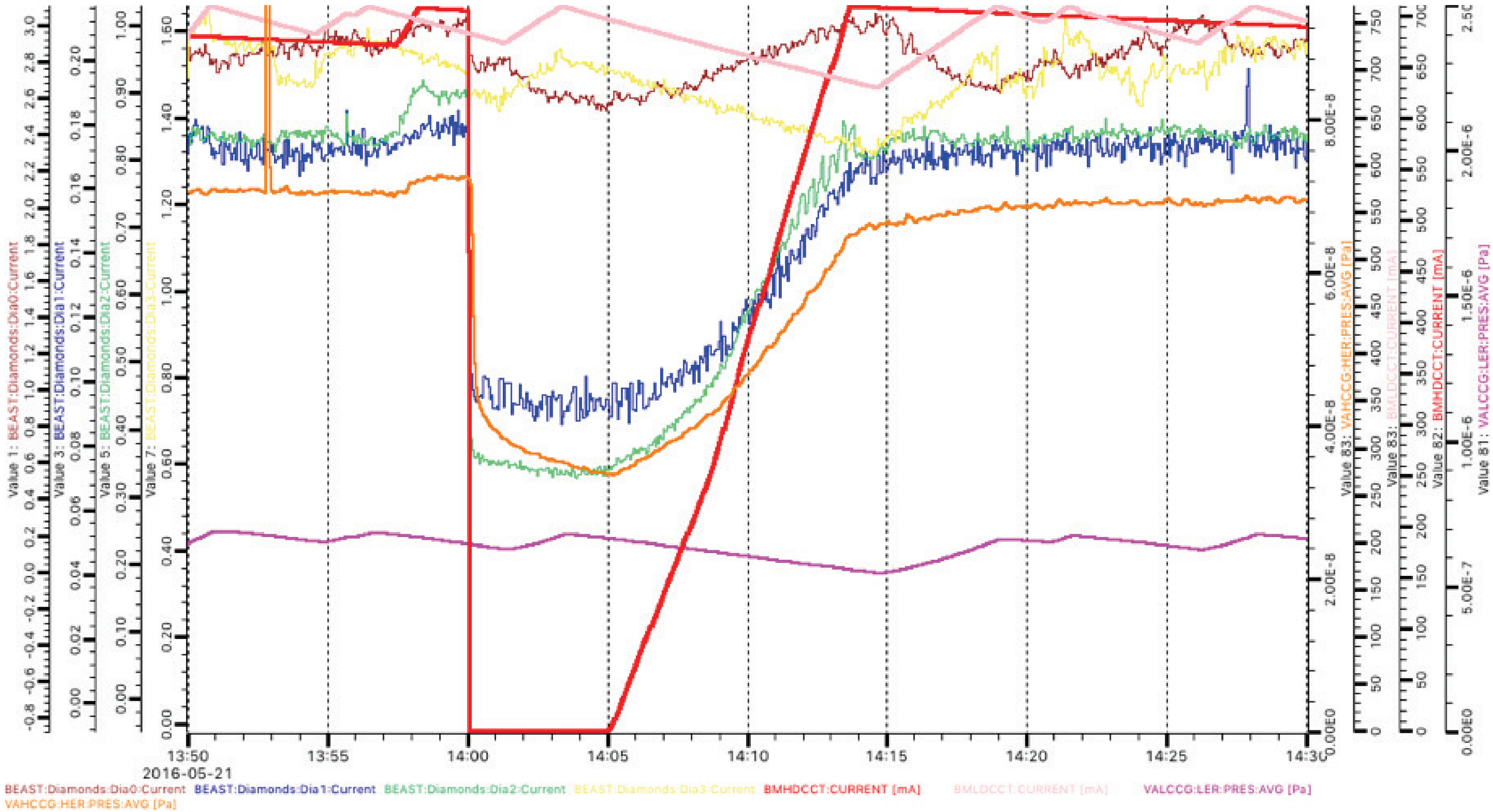
Volume: (4.5 x 4.5 x 0.5) mm^3

Diamond sensor response



Occasional spikes in coincidence with other detectors

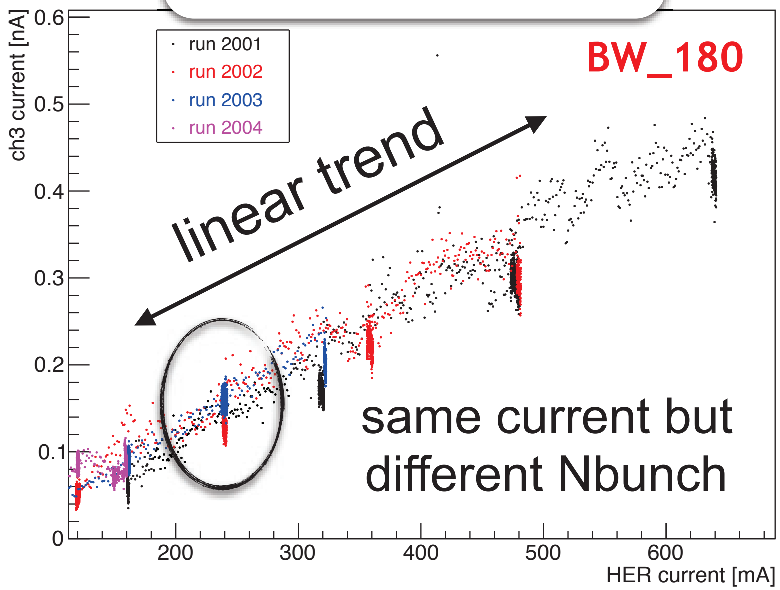
Diamond sensor response



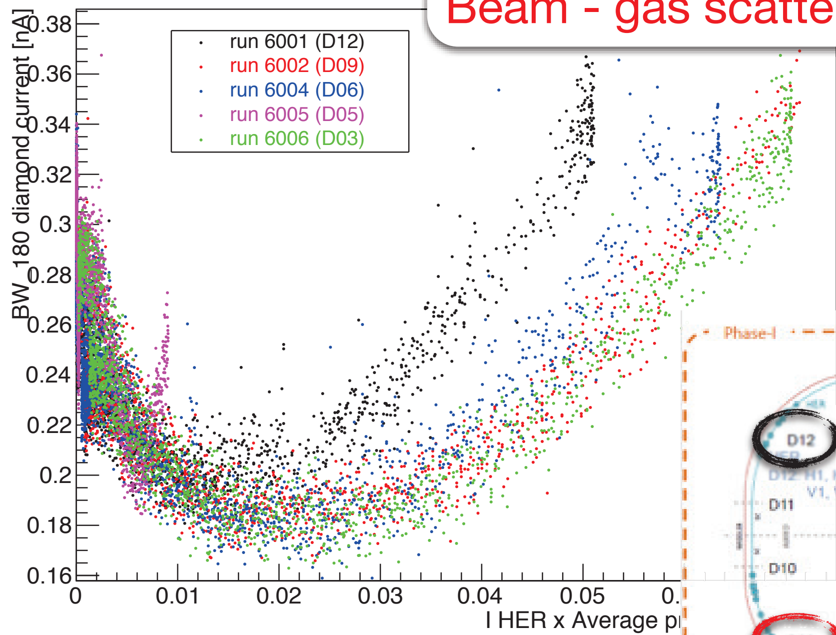
- HER beam current
- LER beam current

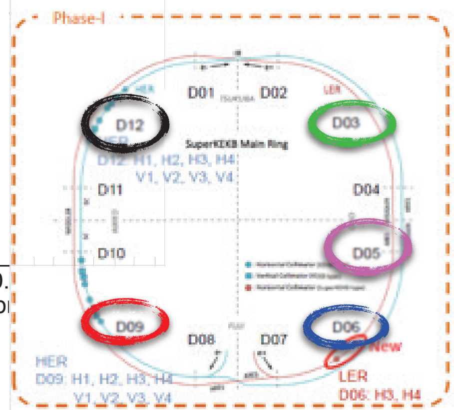
Background Studies (preliminary)

Current scan

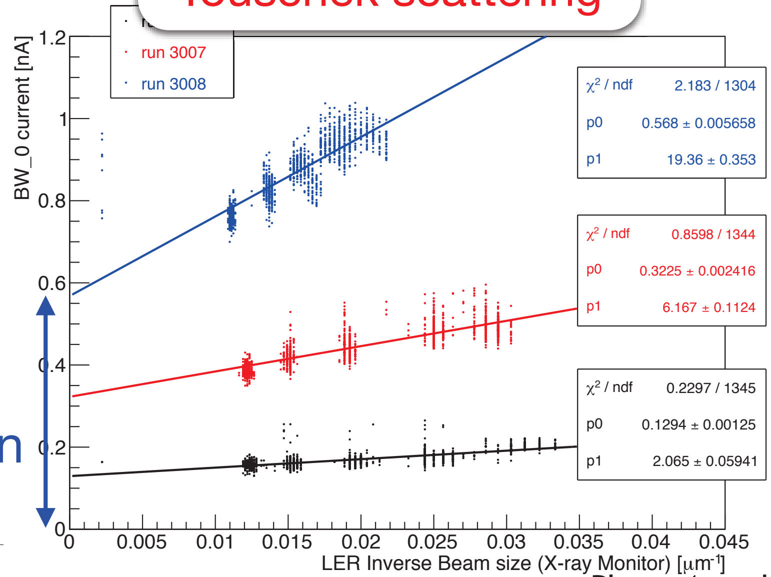


Beam - gas scattering





Touschek scattering

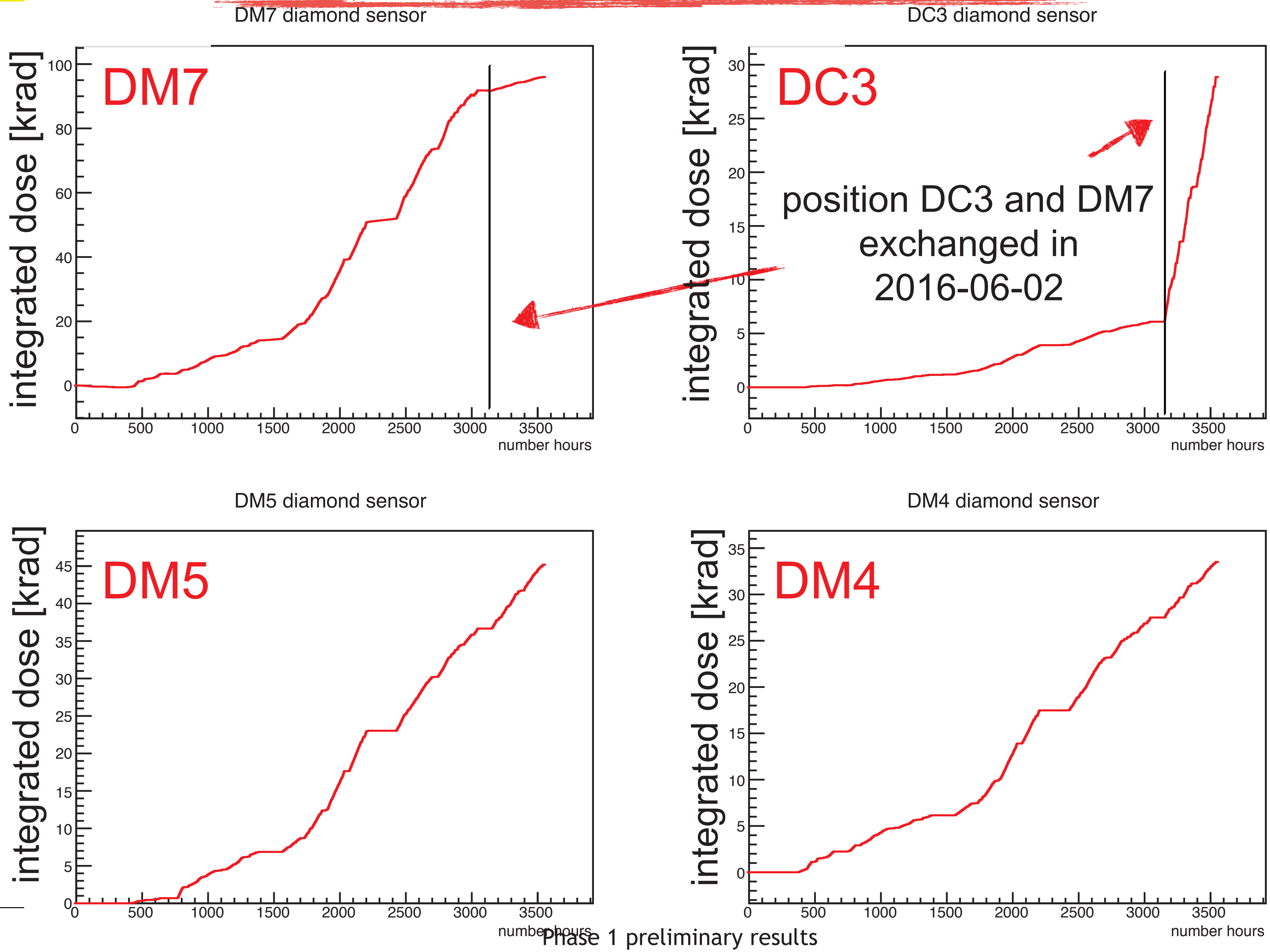


beam gas contribution

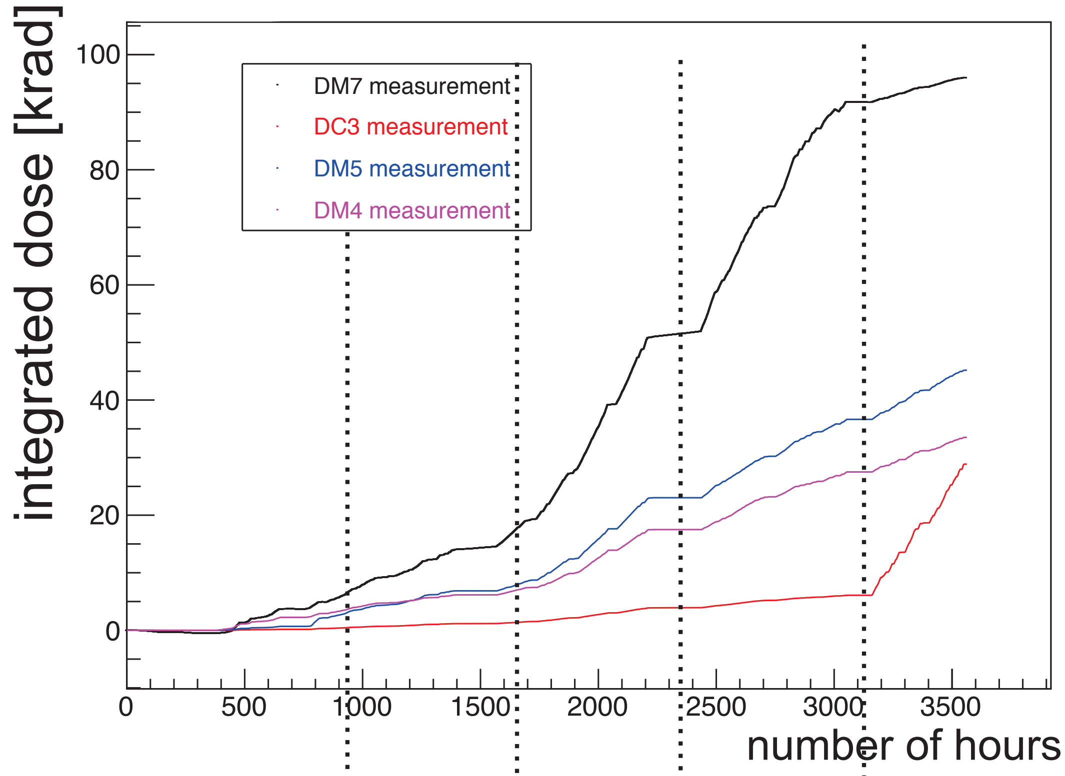
Diamond current vs inverse beam size:
Linear fit, intercept
→ extrapolation to pure beam-gas contribution

Phase 1 preliminary results

Integrated dose (1/2)



Integrated dose (2/2)

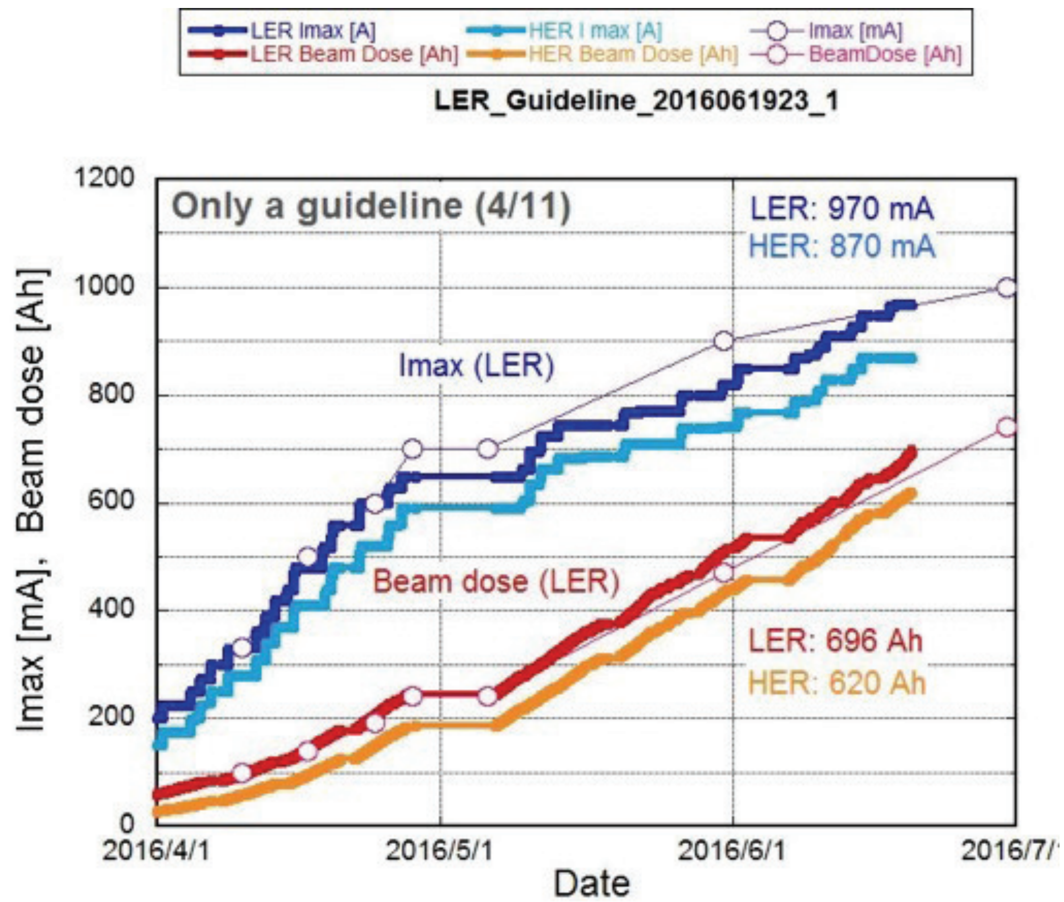


~2016-03-01

~2016-04-01

~2016-05-01

~2016-06-01



relative systematic error on integrated dose related to calibration uncertainties ~ 20/30% (to be refined)

Conclusions

- SuperKEKB: 40-fold increase in luminosity over KEKB
  → High integrated dose expected

- Radiation monitoring system: 20 s-CVD diamond sensors

- Diamond calibration:
  → dark I-V characteristic
  → I-V curve with β ^{90}Sr source
  → current vs β ^{90}Sr source distance
  → CCE measurement
  → TTC measurement
  → photoconductive gain

- 4 diamond sensors and electronics prototype installed in the first SuperKEKB commissioning phase. Phase I success:
  - Measurements of all primary beam backgrounds

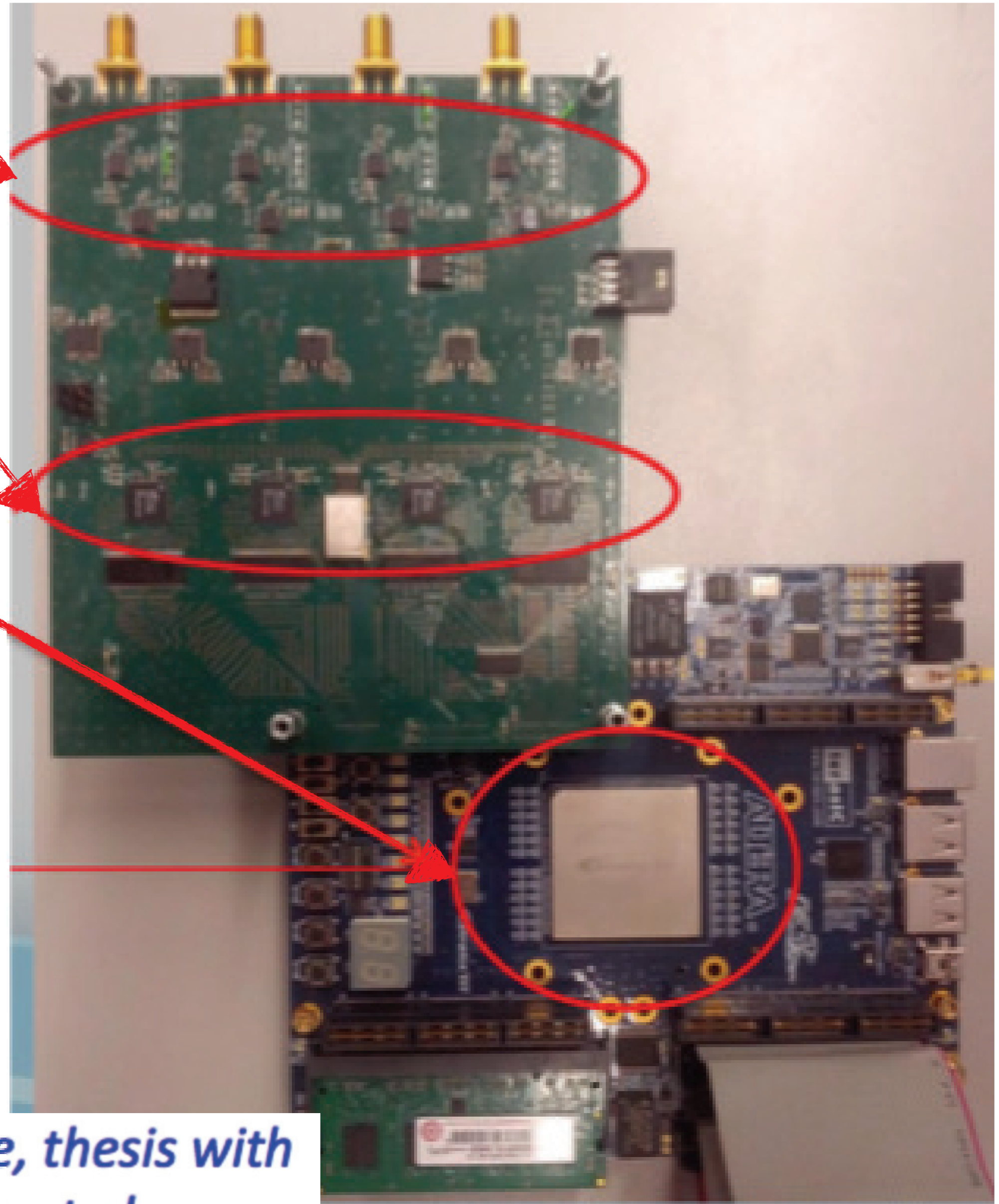
- First test and calibration on diamond and readout electronics done. Precision (0.5 nA on the shortest 10μs time scale) OK for reliable fast and slow aborts for phase 2/3

Development of beam abort in next commissioning phase (11-2017 —-> 6-2018)

BACKUP

Electronics prototype

- Analog front-end picoammeters
  - transimpedance amplifiers
  - 16-bit ADCs, 130 MHz oversampling
  - 2 selectable current ranges
- Digital section: Stratix III FPGA
  - Running averages (4 levels)
  - Programmable abort thresholds, depending on machine status
  - Timing and Control
- External RAM, Ethernet
- DAC for HV module control



F.Vulpone, thesis with G.Cautero et al.

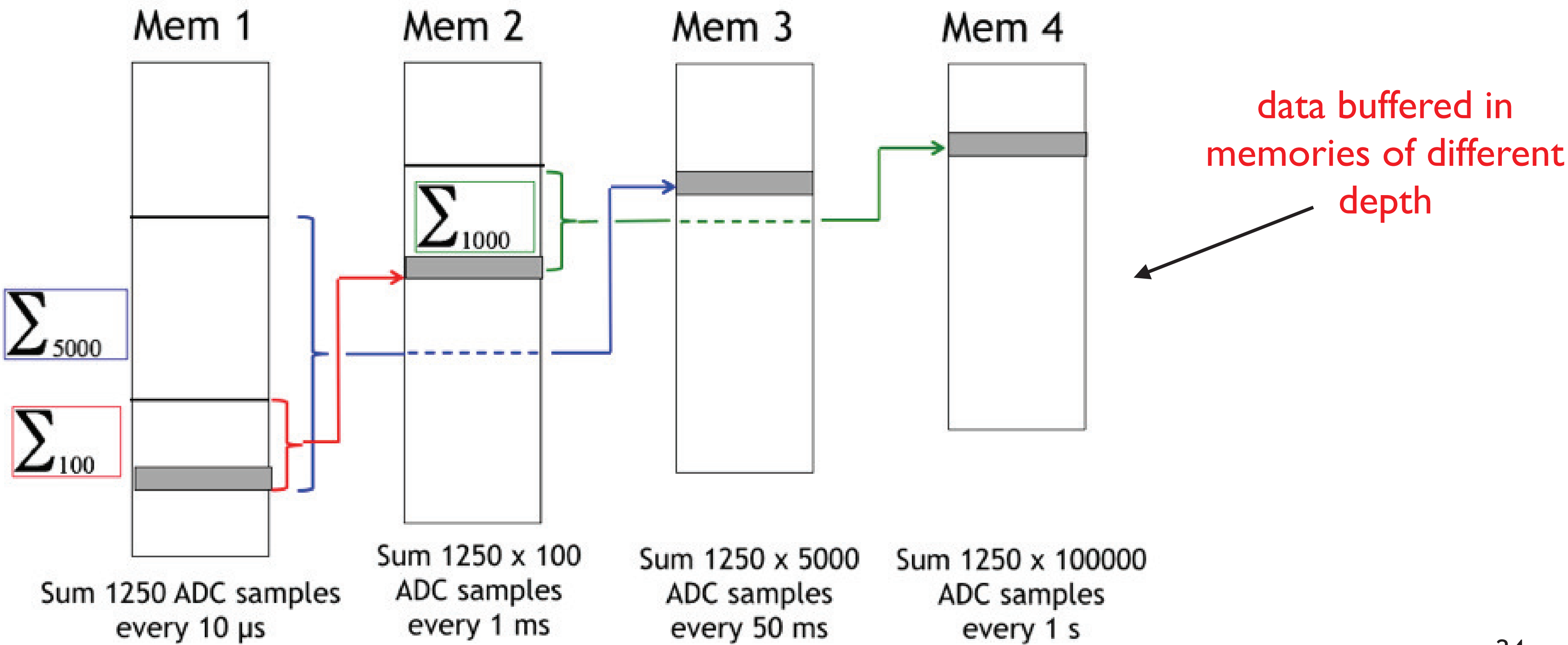
Beam abort thresholds (1/2)

Preliminary study from diamond sensors

Diamonds: Abort Buffer Memories

- diamond current will be sampled and digitized at 100kHz
- several levels of running averages are computed providing an effective digital filter

Present configuration of revolving Abort Buffer Memories
to be improved with really "running sums"



Beam abort thresholds (2/2)

Buffer memories: snapshot example

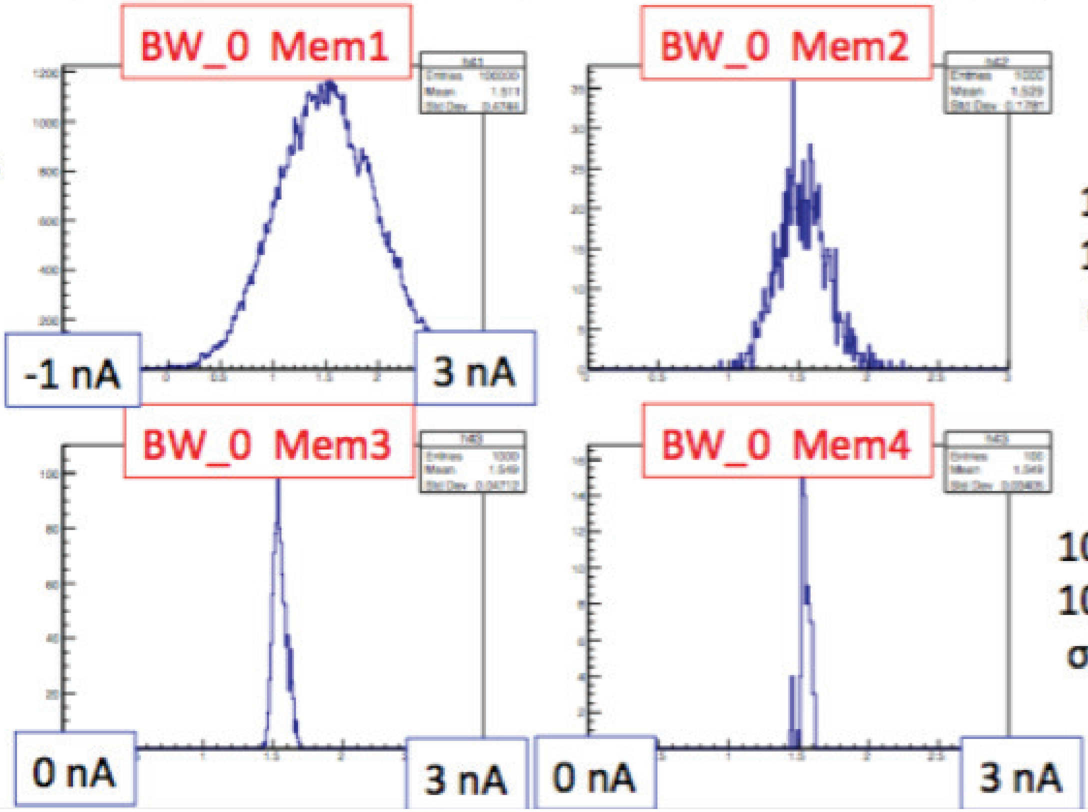
Example of snapshot of Buffer Memories (Mem1 to Mem4) for Dia3 = BW_0 in stable beam conditions, with average I(BW_0) = 1.5 nA

Noise decreases with increased averaging, from about 0.47 nA to < 0.04 nA

OK both for fast (10 μs) and slow (> 1 s) beam aborts with appropriate thresholds

100000 entries
1 s history
σ = 0.47 nA

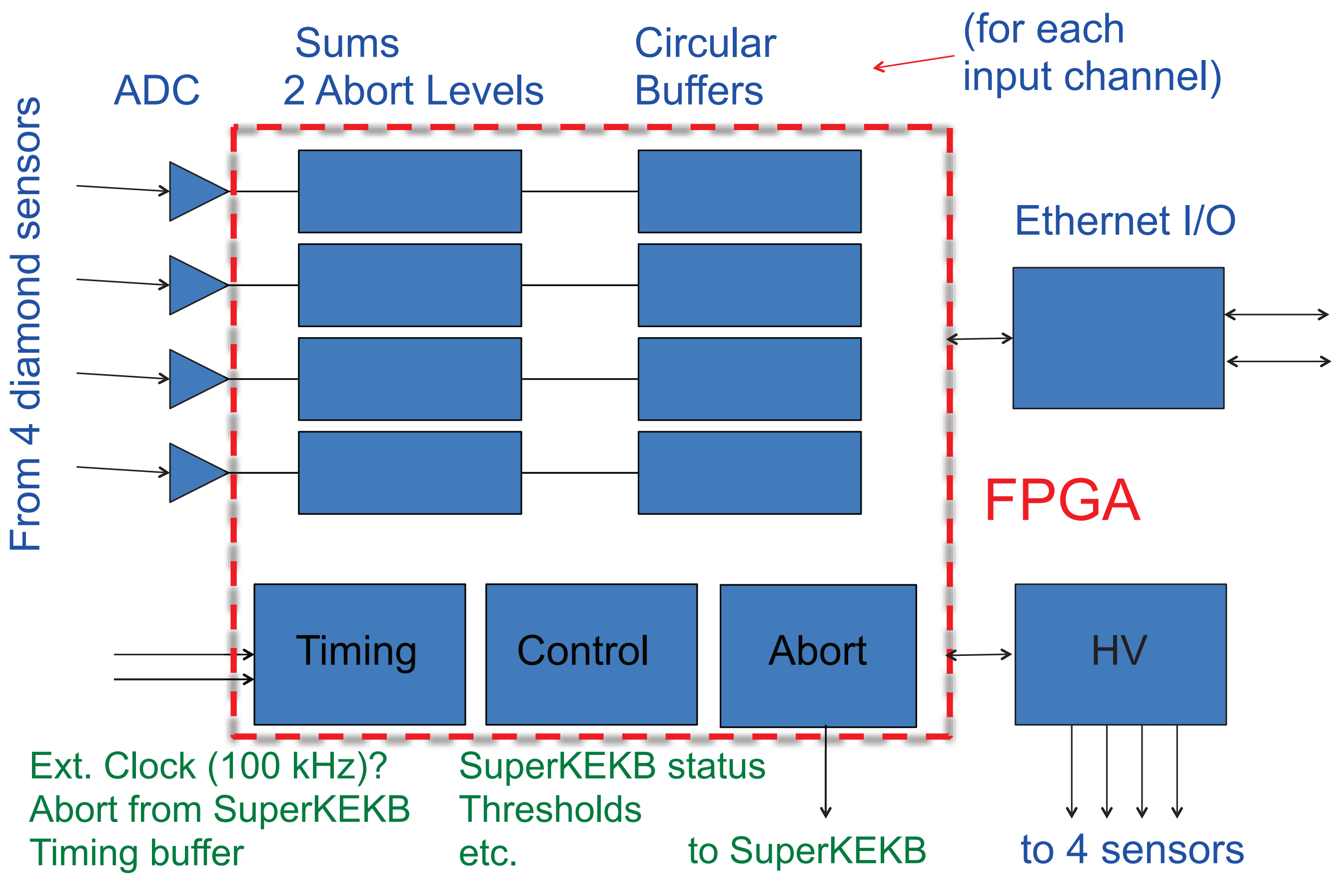
1000 entries
1 s history
σ = 0.18 nA



1000 entries
50 s history
σ = 0.047 nA

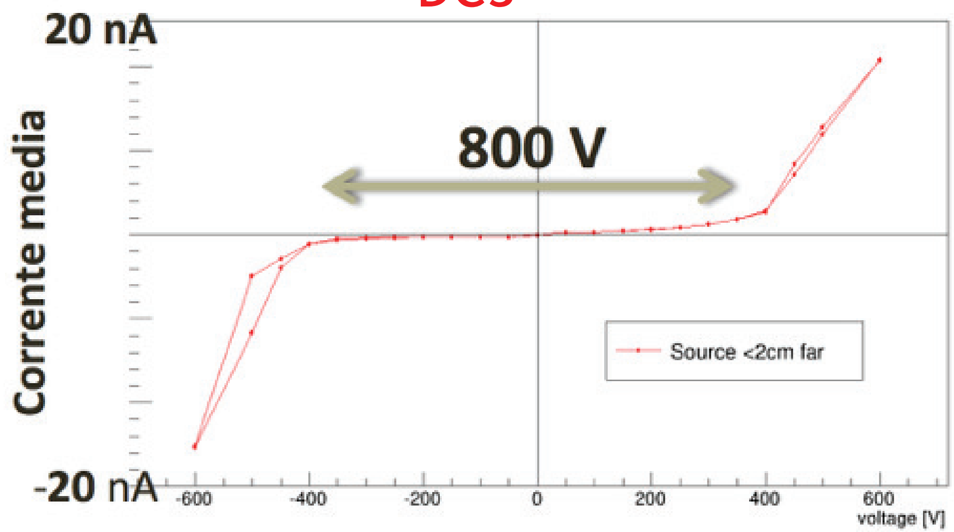
100 entries
100 s history
σ = 0.034 nA

Rad.Mon+Abort, 4-channel Box

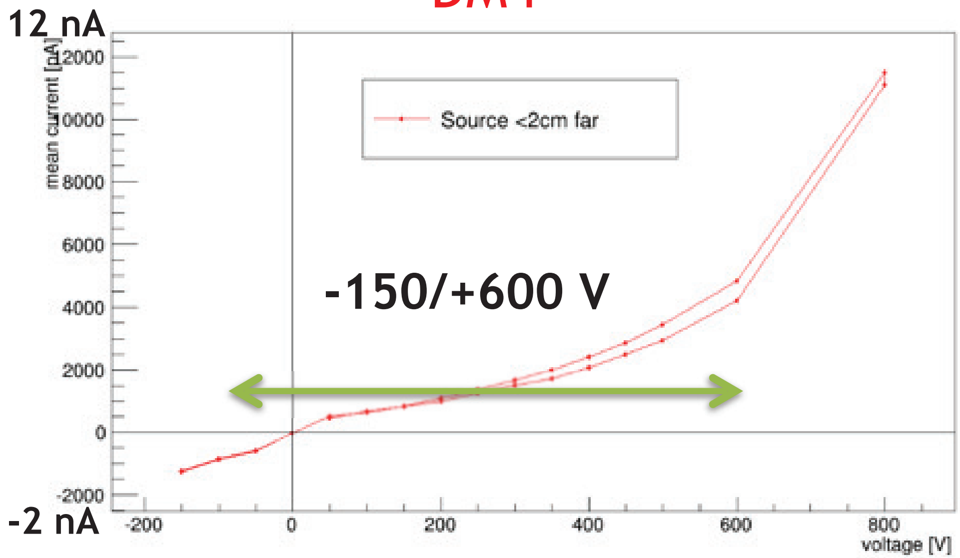


I-V with β ^{90}Sr source (d=18mm)

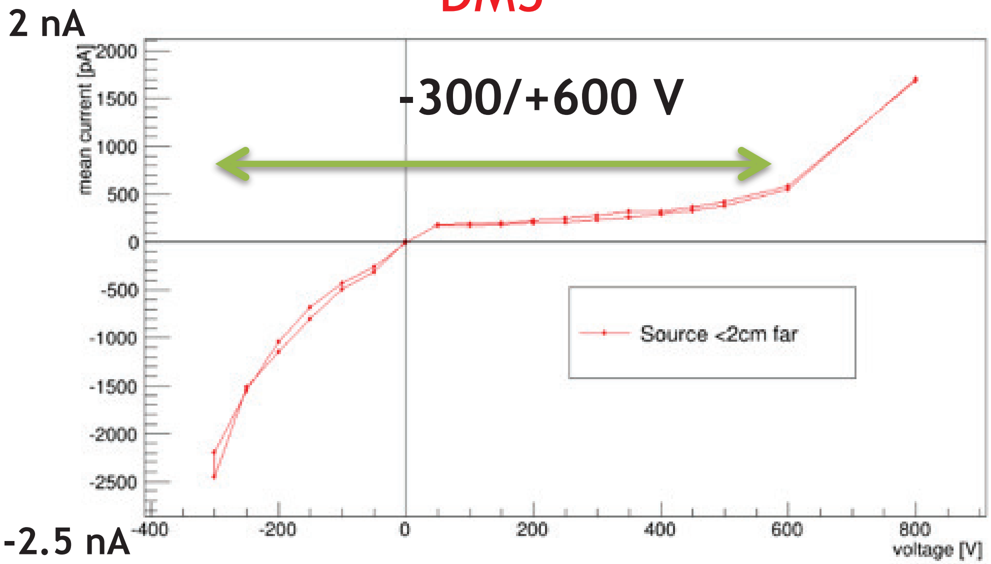
DC3



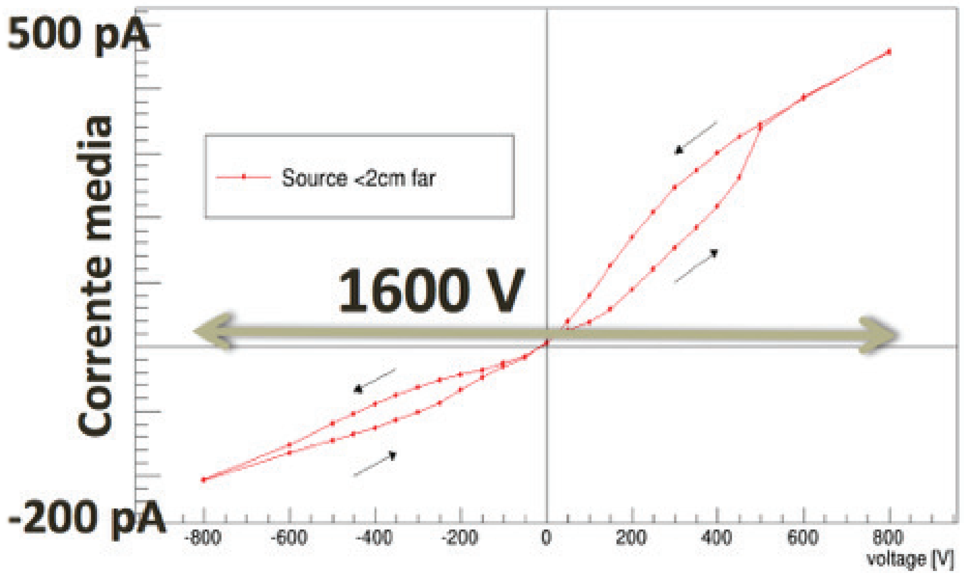
DM4



DM5

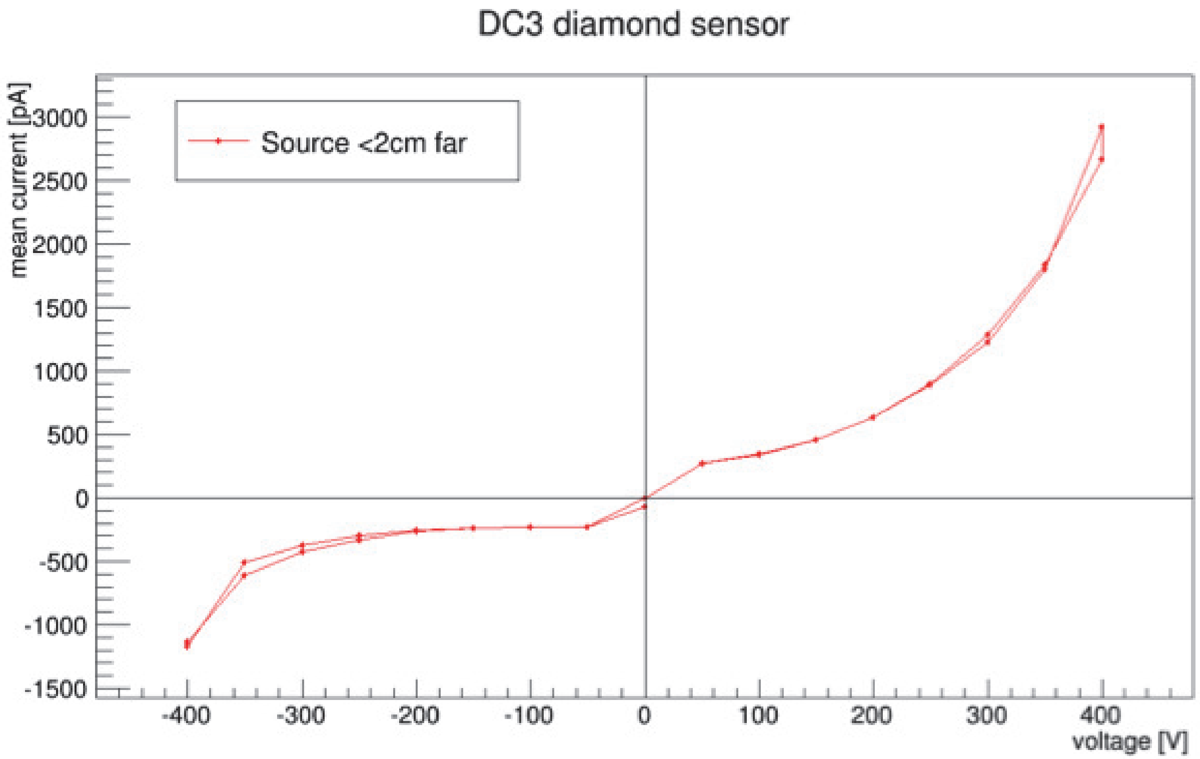


DM7



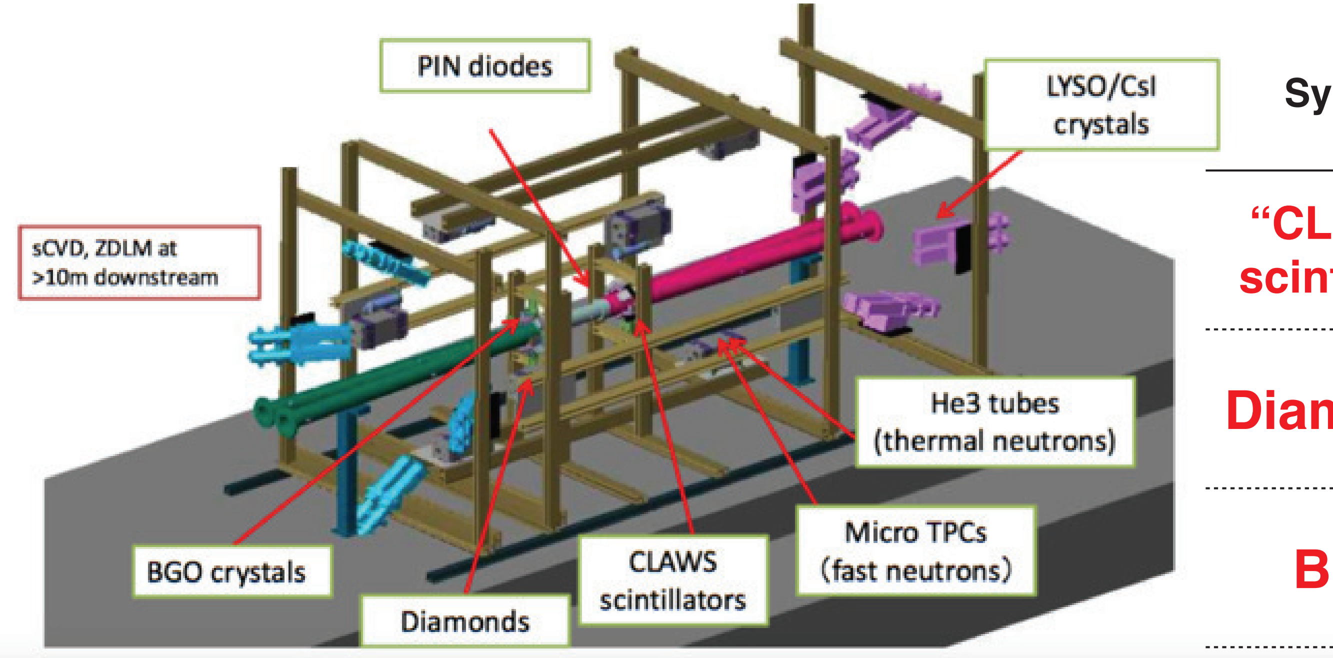
I-V with β ^{90}Sr source (d=18mm)

DC3 sc-CVD from Cividec:
zoom without breakdown zones



DC3 sc-CVD from Cividec:
Most stable from the first prototypes
No discharges and reproducible results
Now γ irradiated 20 MRad (to be tested)

BEAST sensors



System	Detectors installed	Measurement
"CLAWS" scintillator	8	injection backgrounds
Diamonds	4	ionization dose
BGO	8	luminosity
Crystals	6 CsI(Tl) 6 CsI 6 LYSO	EM energy spectrum
He-3 tubes	4	thermal neutron flux
Micro-TPCs	2	fast neutron
PIN diodes	64	neutral vs charged radiation dose

- Since Background simulations have huge uncertainties: measurements near IP
- First measurements of SuperKEKB injection background
- Test and calibration of diamond sensors Precision (0.5 nA on the shortest 10μs time scale) OK for reliable fast and slow aborts for phase 2/3

First signals