Radiation monitoring with diamond sensors for the Belle-II vertex detector

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Outline

- The SuperKEKB collider
- The Belle II detector

introduction

- The Radiation monitoring system
- Diamond sensors

why

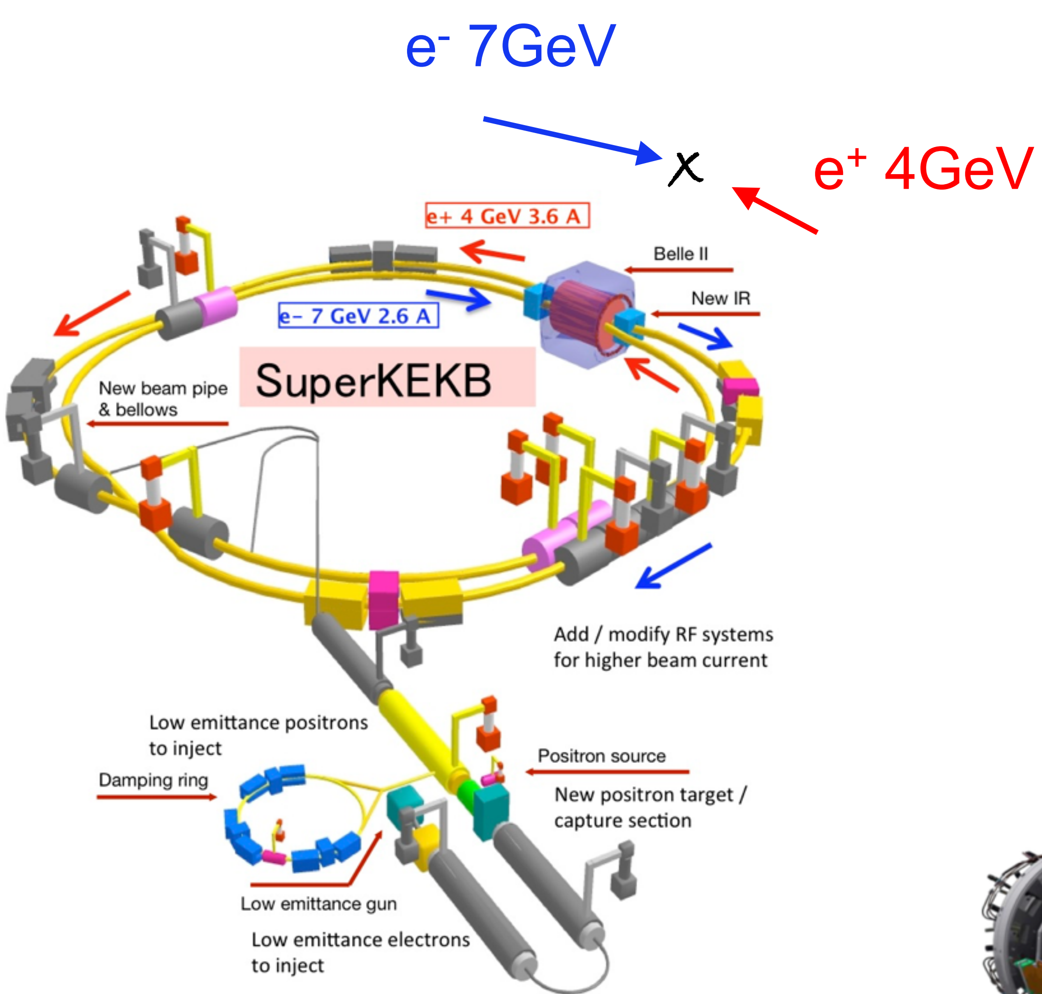
- Calibrations and characterization

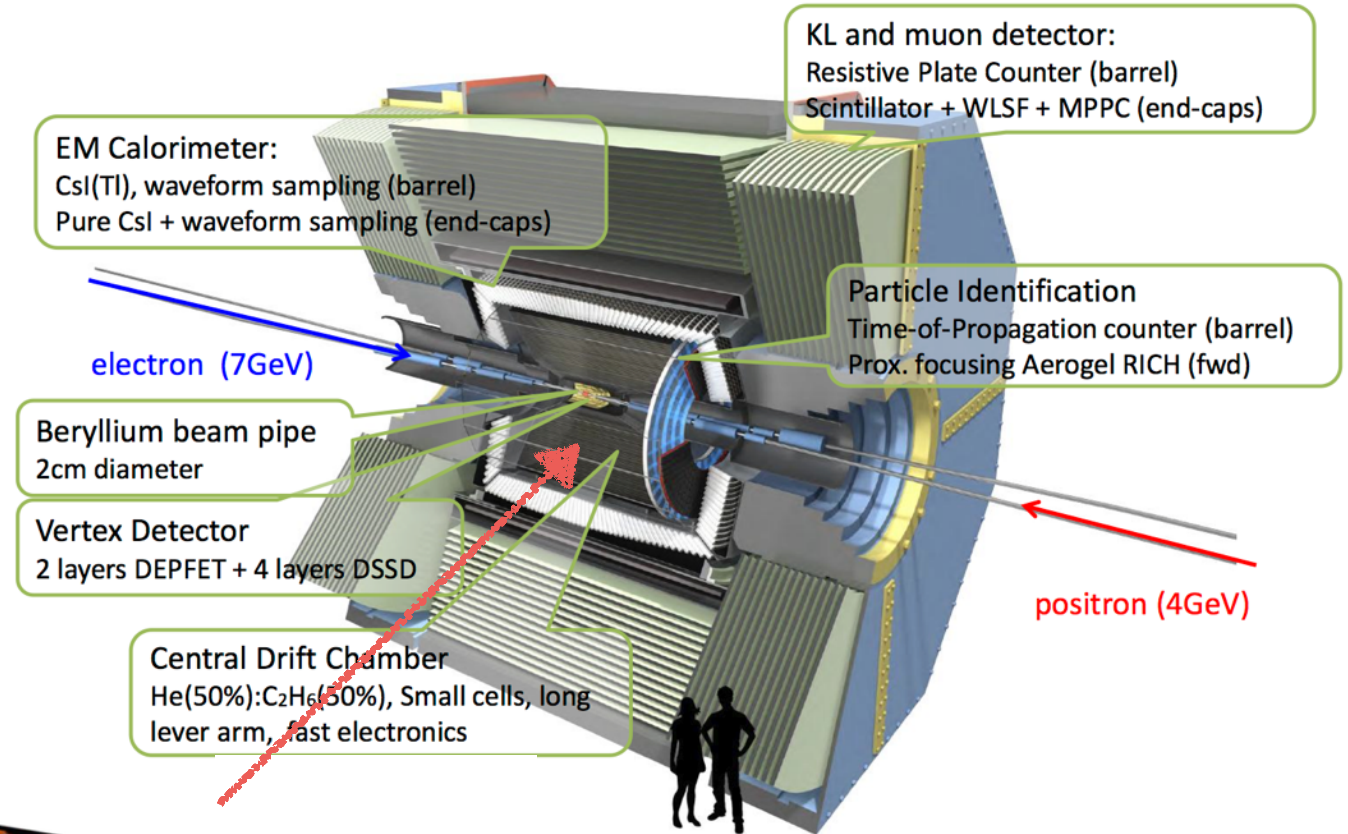
how

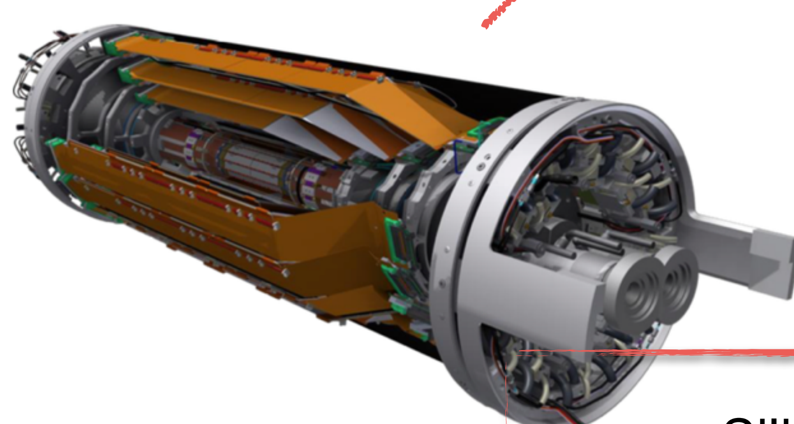
- First commissioning of SuperKEKB

results

(An example)







- Doubled beam currents
- Reduced beam spot size

L_{peak}: 8x10^{35} cm^{-2}s^{-1} (40 x KEKB)

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

Vertex Detector

- Silicon Vertex Detector:
  4 layers of double-sided Si strip detector
- Pixel detector:
  2 layers of DEPFET pixels

Radiation monitoring system

Large radiation doses expected

in 10 years:

15/18 Mrad on pixels

10 Mrad on the silicon vertex detector

→ need to monitor radiation occurring in the inner silicon detector

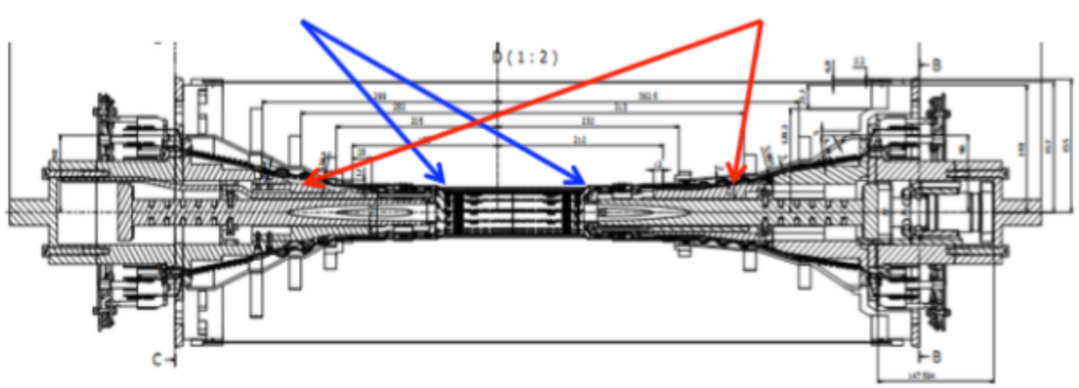
Requirements:

Radiation monitoring

- sufficiently accurate measurement of instantaneous and integrated dose

4 + 4 sensors
PXD-beam pipe

6 + 6 sensors
close to SVD L3 support rings



Deliver beam abort signal

- large increase in backgrounds

→ "fast" abort trigger system

- lesser increase in backgrounds

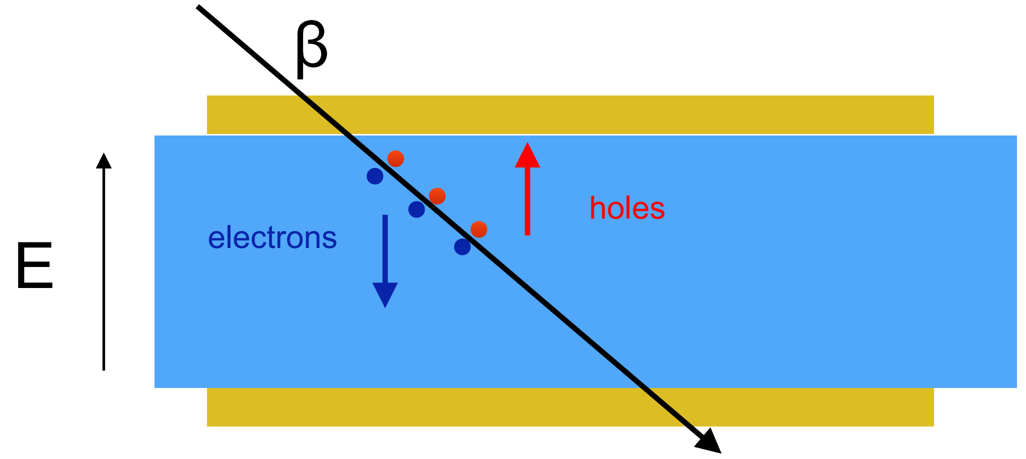
→ "slow" abort trigger system

use 20 single crystal diamond sensors

Why diamond sensors?

requirements

- Response time for fastest beam abort trigger: 10 μs
- Response time for slow beam abort trigger: >10 s
- Precision on instantaneous dose rate: 50.0 mrad/s for fast abort; 5.0 mrad/s for slow abort



work as an ionization chamber

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

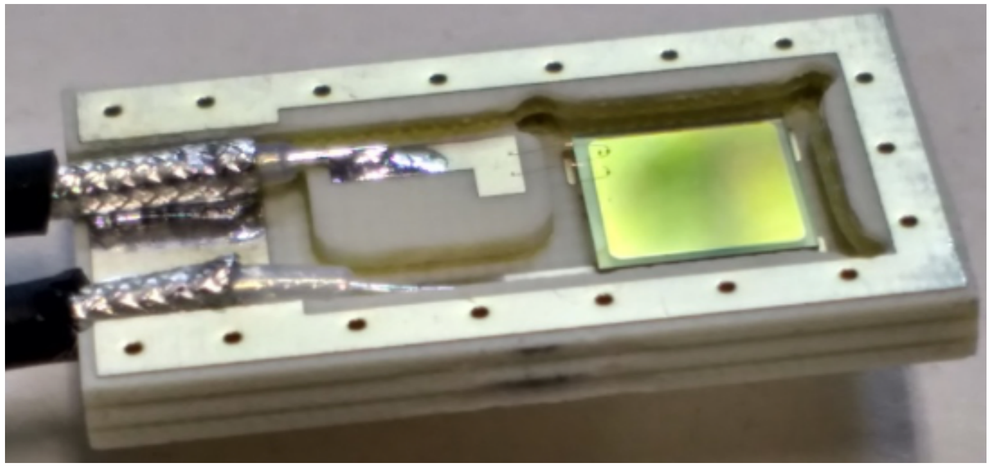
- wide band gap (5.5 eV)
- high displacement energy (42 eV)
- extreme thermal conductivity (2000 W m^{-1} K^{-1})
- high mobility for holes (1200 cm^2 $V^{-1}s^{-1}$) and electrons (1800 cm^2 $V^{-1}s^{-1}$)

1- Strong resistance to radiation and temperature

2- No need for darkness, pn junction or cooling

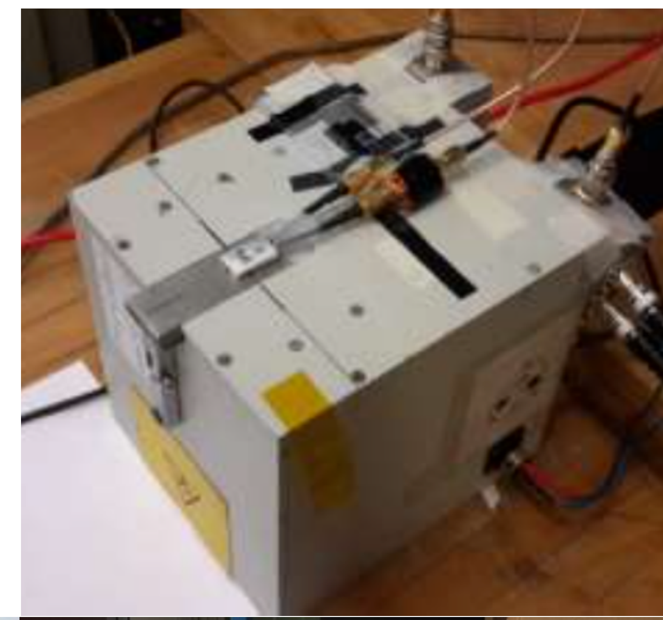
3- Ultrafast charge collection due to high drift velocity

Tests and calibrations



- the metallised diamond crystal is first glued on the printed circuit support

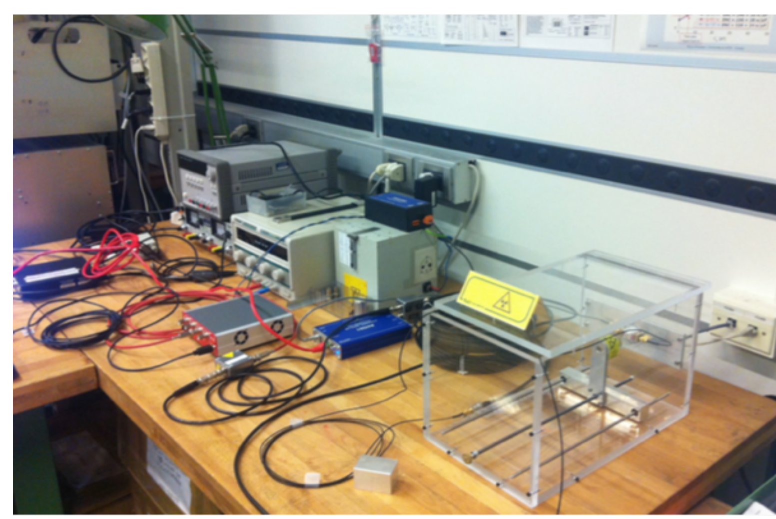
- the upper electrode is wire bonded

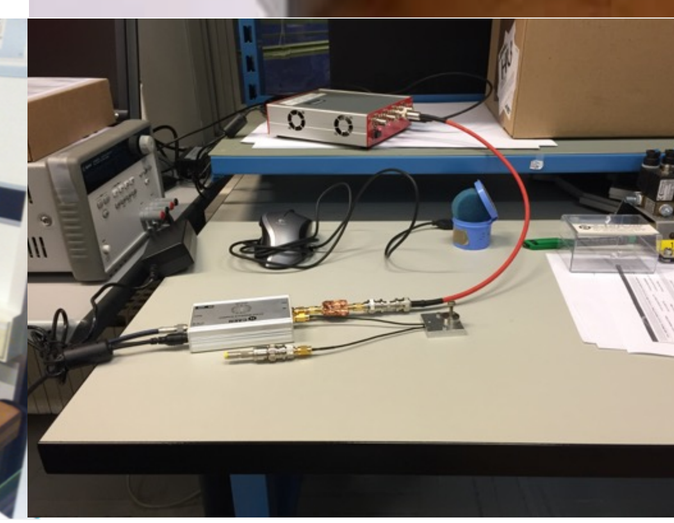


(0) Preliminary test: dark I-V characteristic:

Dark currents below the pA range at typical O(100V) operation voltage

- stability with time
- uniformity
- charge collection efficiency
- conversion from current to dose rate



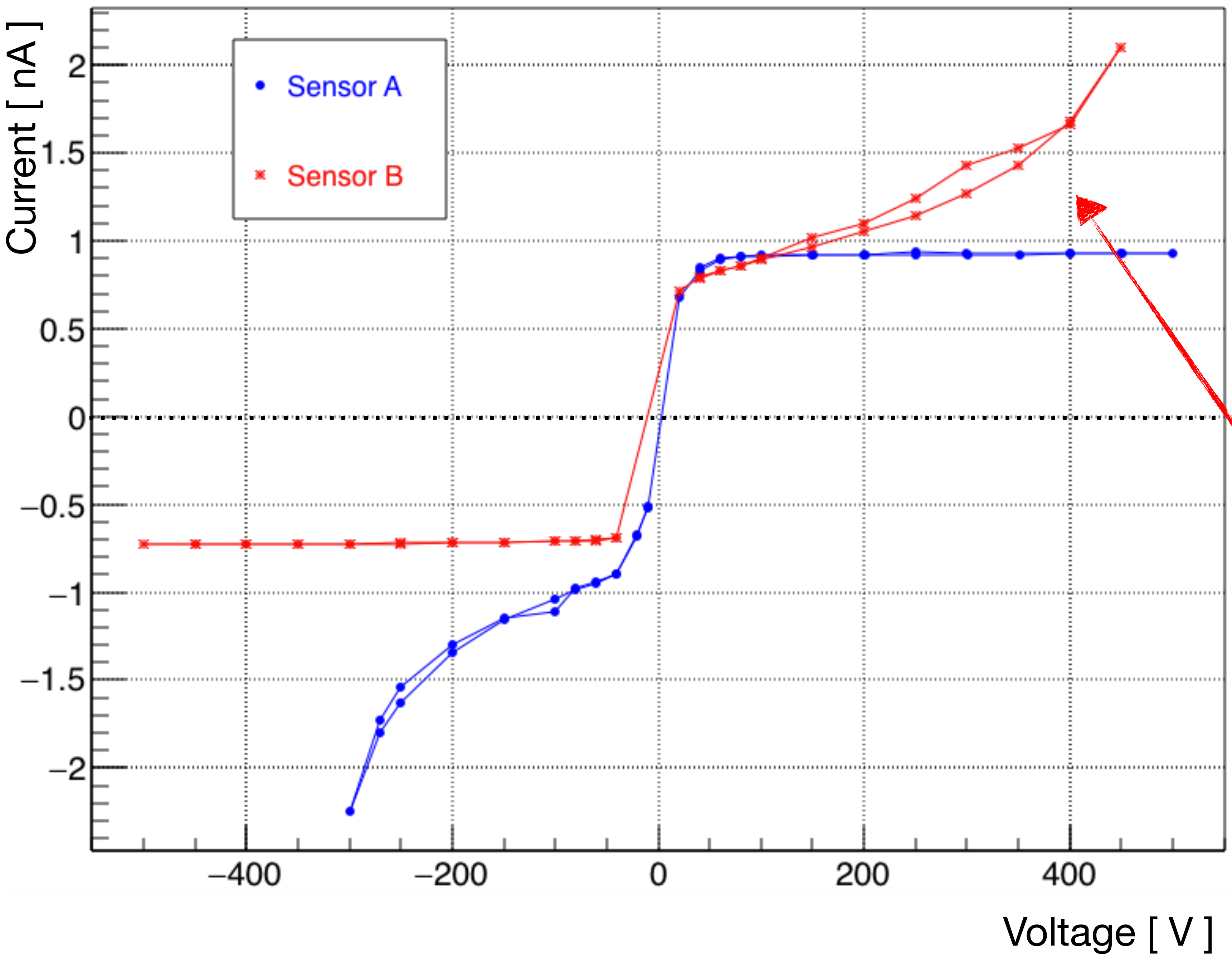


I-V with β ^{90}Sr source

I-V characteristic (just an example)

2 single crystal CVD diamonds with metalization (Ti + Pt + Au)

source-sensor distance fixed at 2mm



Different behaviour observed for each diamond sensor

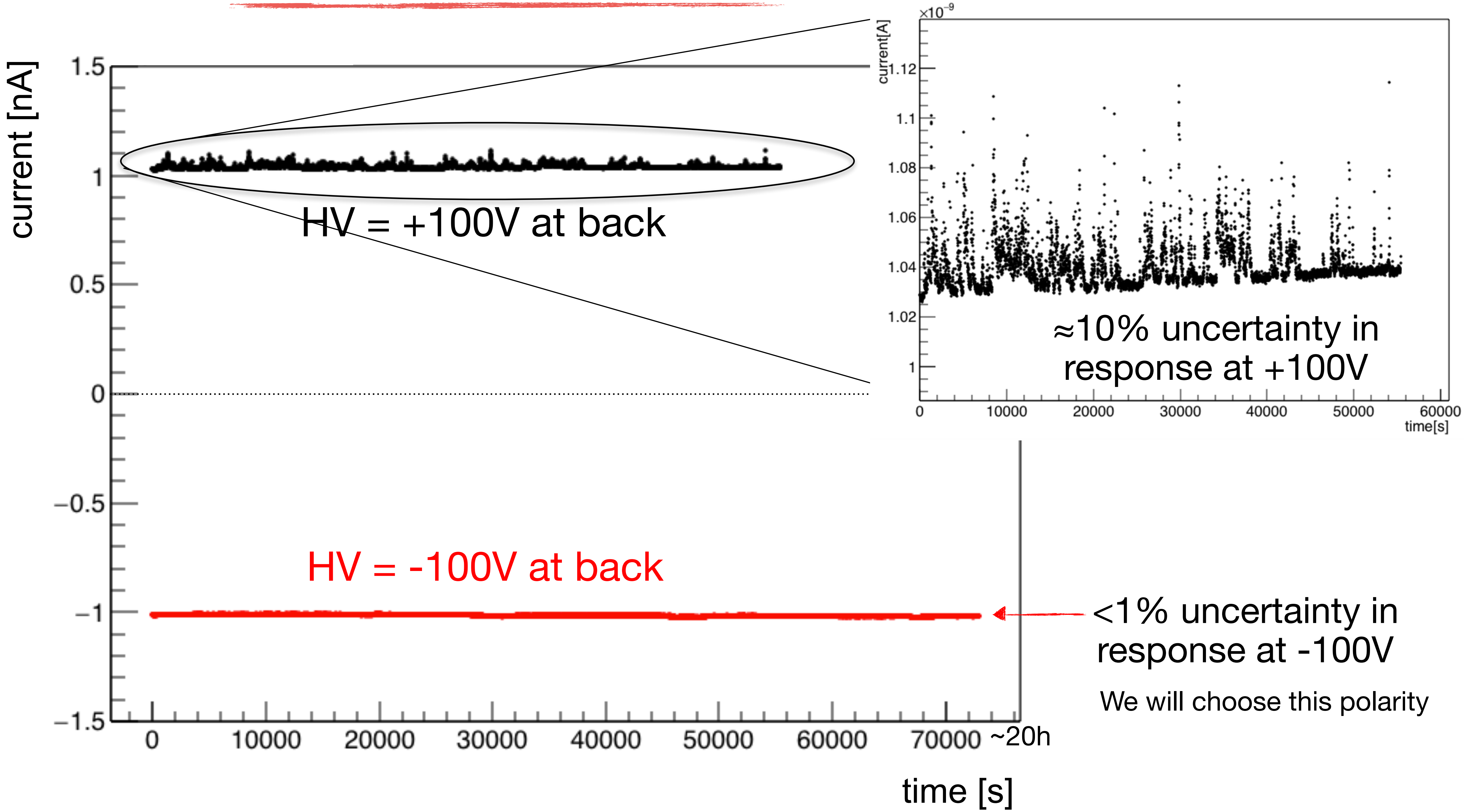
hysteresis loop in some sensors

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

Stability

Check stability as diamonds will record dose for years

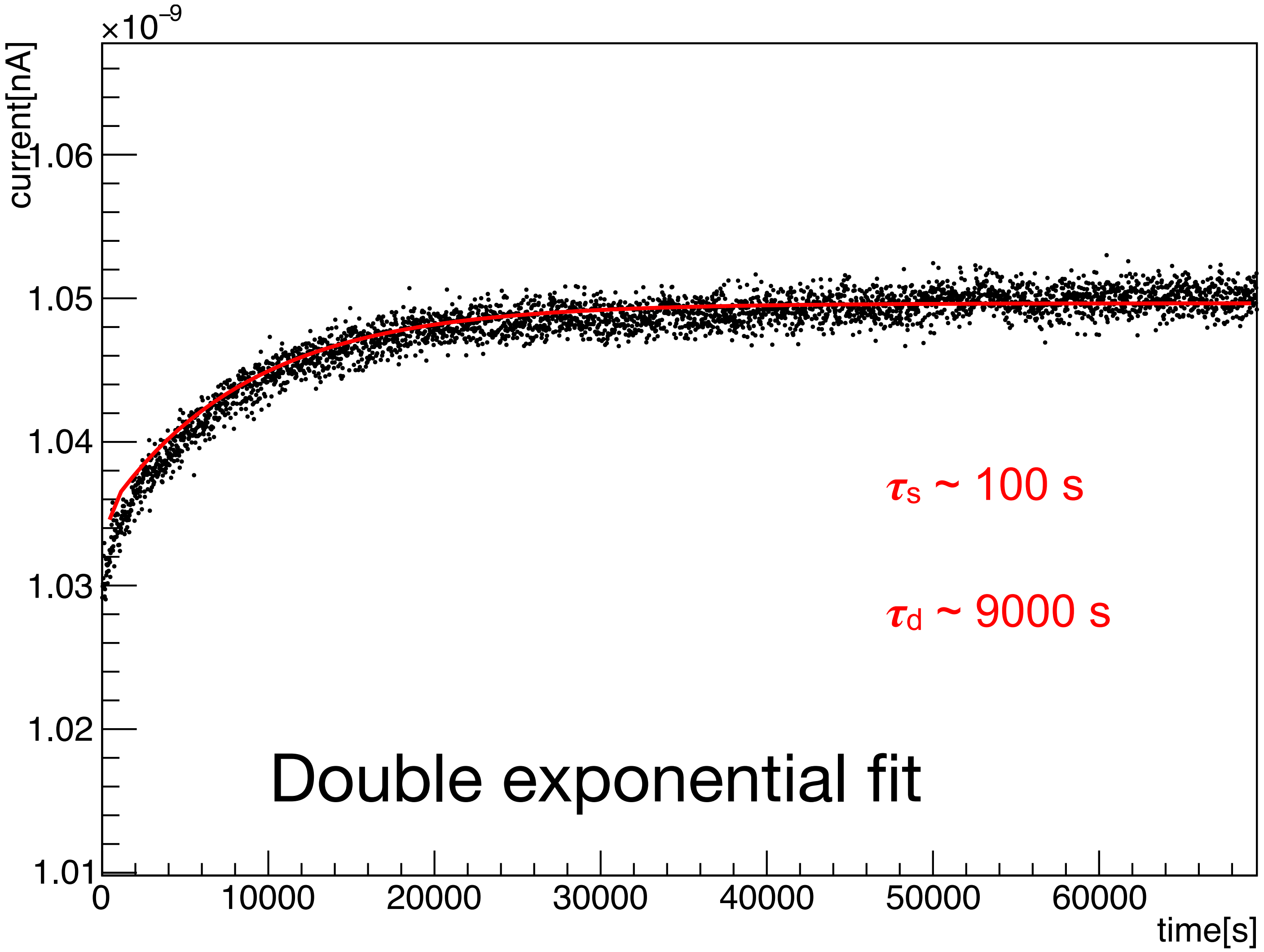
same diamond with different polarity



<1% uncertainty in response at -100V

We will choose this polarity

Transient



stability is reached after a transient

→ presumably due to traps in the crystal

Asymptotic state: both shallow and deep levels completely filled

Shockley-Hall-Read theory for impurity levels as trapping centres.

Two different types of traps:

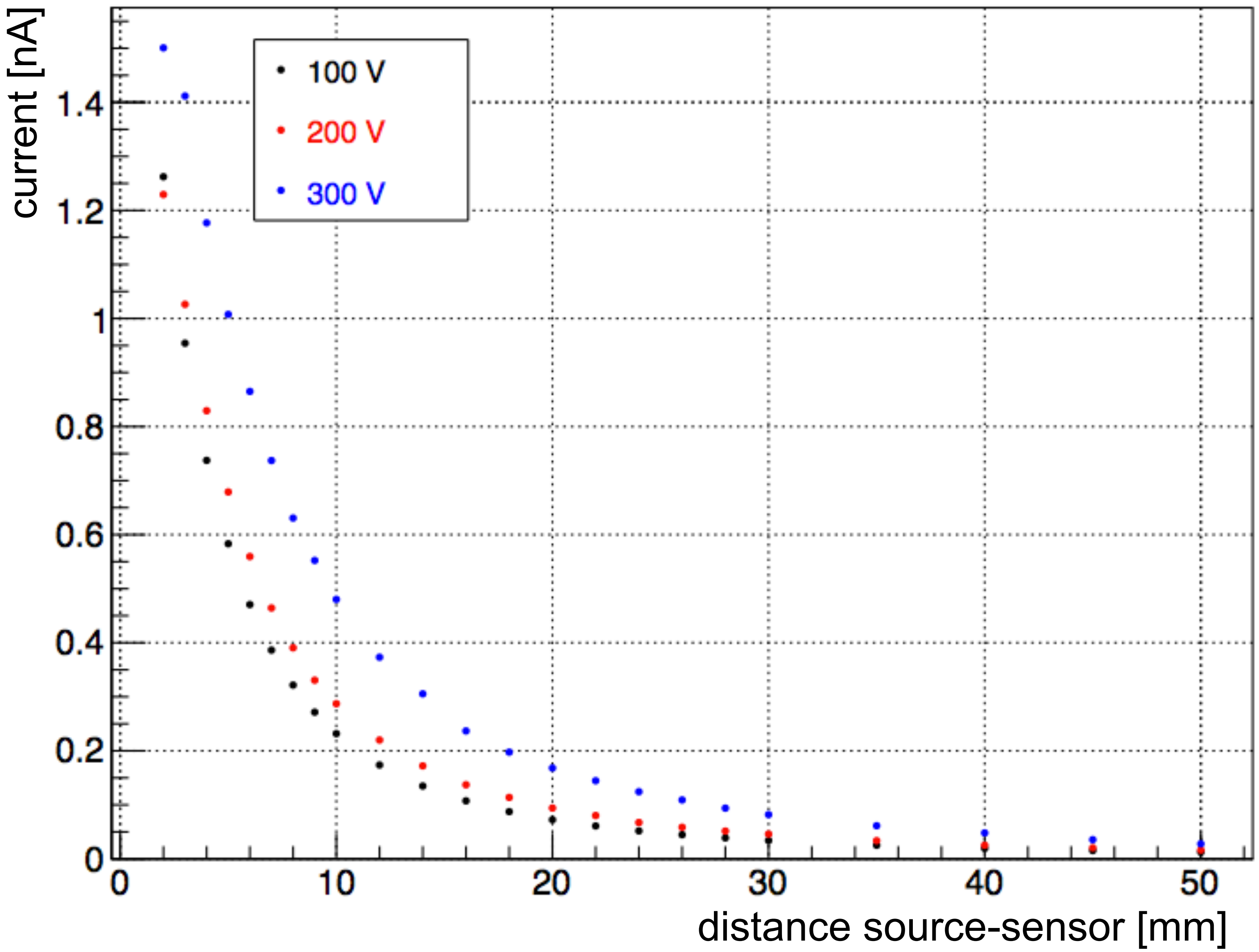
- shallow traps
- deep traps

τ_s → time constant associated to shallow traps

τ_d → time constant associated to deep traps

inferred from the fit

Dependence on β source distance



Response as a function of the distance between the source and the sensor depends on HV bias

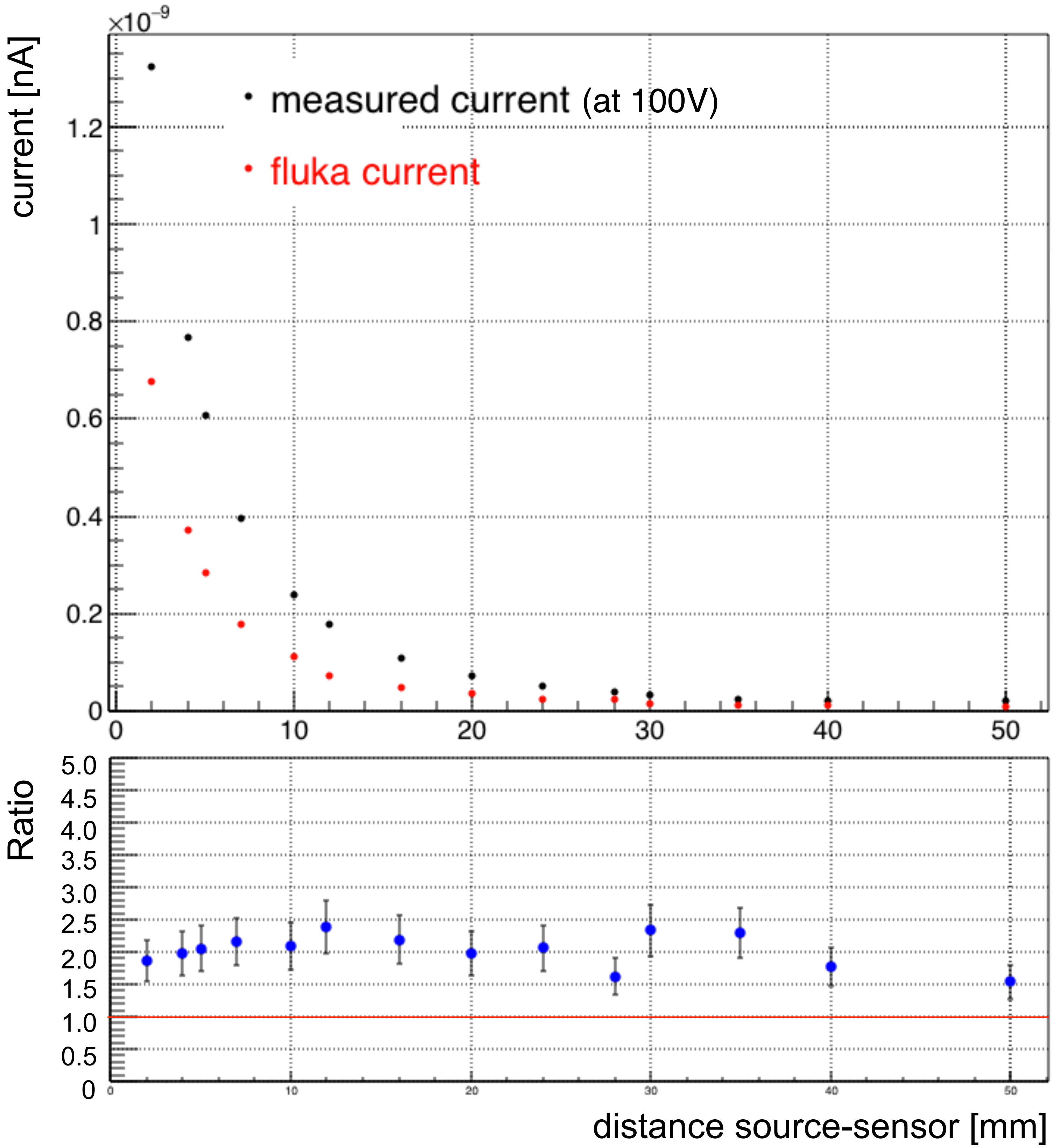
→ photoconductive gain

due to ohmic contact between electrodes and diamond → charge injected from the electrode

current-to-dose conversion requires knowledge of the photoconductive gain

Use FLUKA to compare with measurement and infer the gain for each diamond

Comparison with FLUKA



current decreases approximately with the inverse square of the distance

→ agreement with simulation

measured current > simulated current

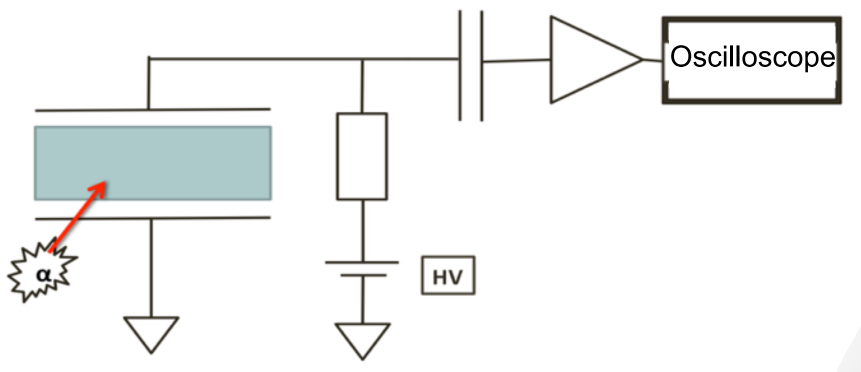
→ photoconductive gain (at 100V)

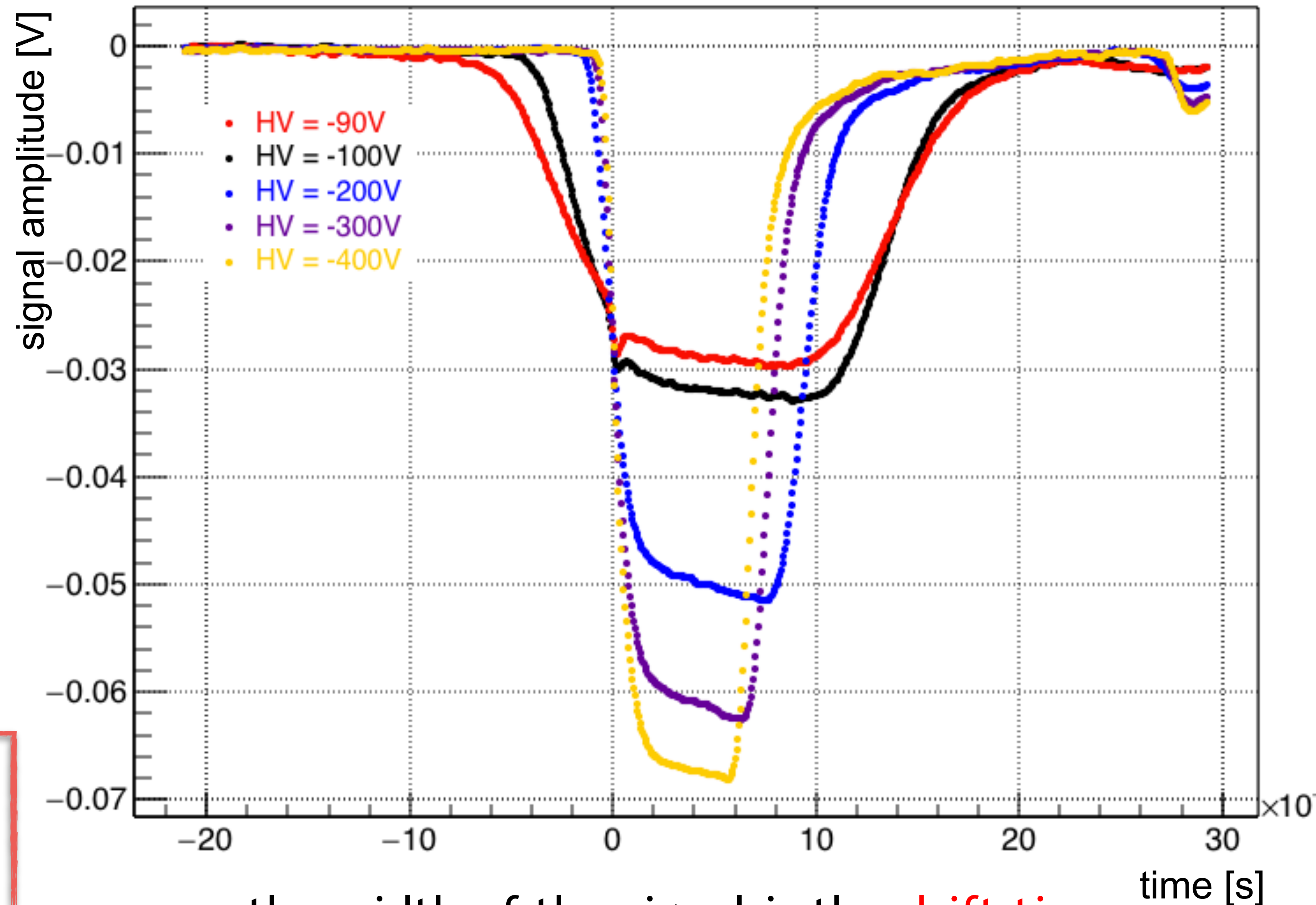
photoconductive gain

$= I_{meas}/I_{FLUKA}$

TCT with Alpha source

(TCT = Transient Current Technique) α source: 241-Am, 55kBq





square pulse →

check of the uniformity of the electric field in the diamond bulk

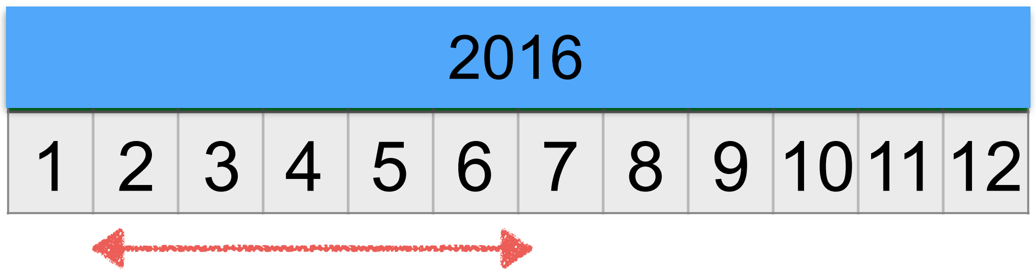
pulse area constant from -90V up to -400V

→ Fully efficient from -90V (CCE ~ 100%)

the width of the signal is the drift time of charge carrier

it decreases consistently with the bias applied

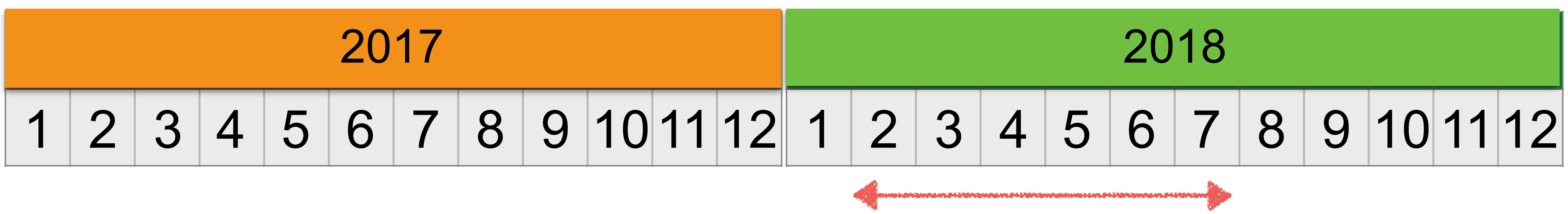
Commissioning schedule



4 diamonds installed
on the beam pipe

Concluded !

Phase I (no Belle II detector)



8 diamonds
will be installed

Phase II (BELLE II detector without VXD)
First collisions

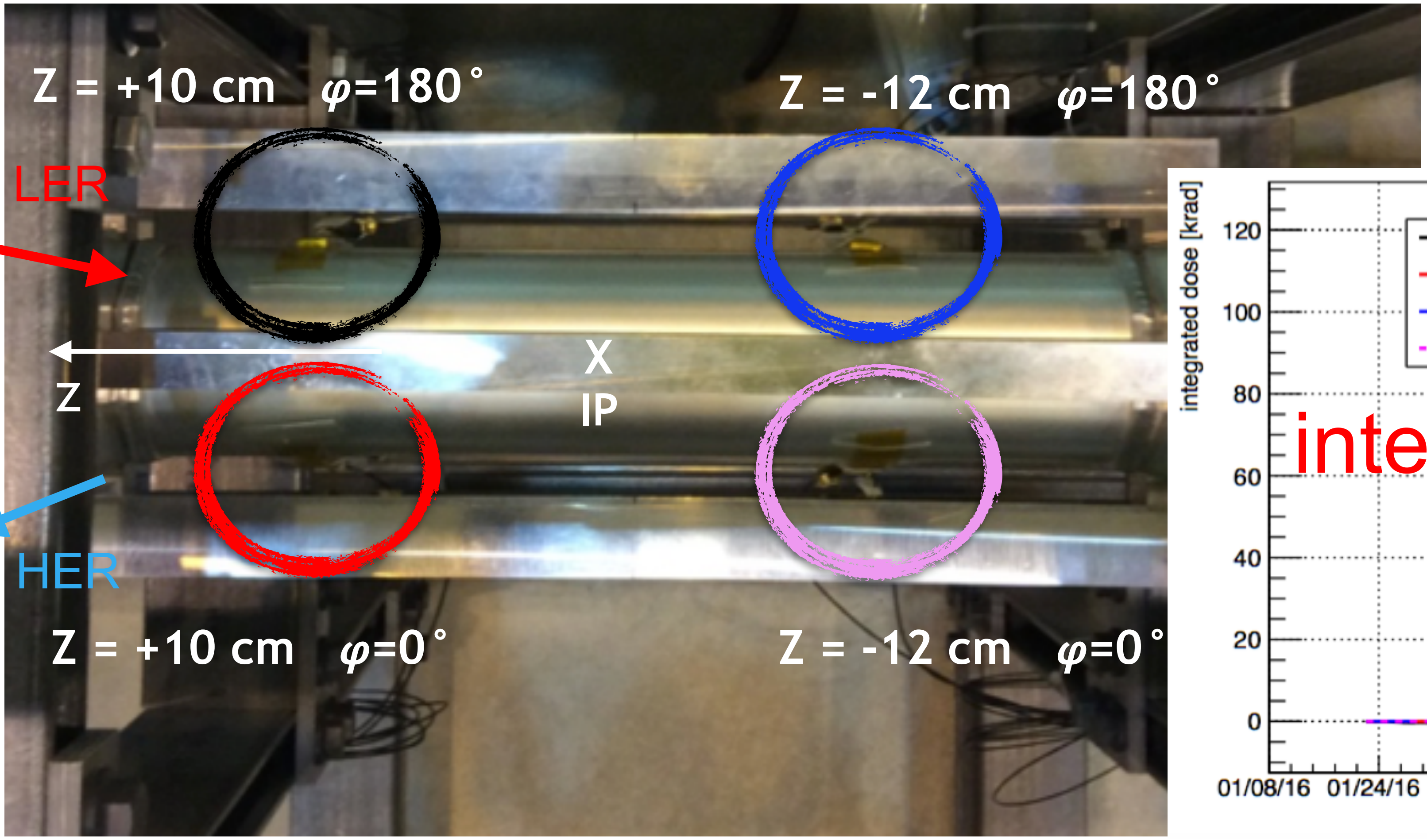
20 diamonds
will be installed

Phase III (full BELLE II detector)

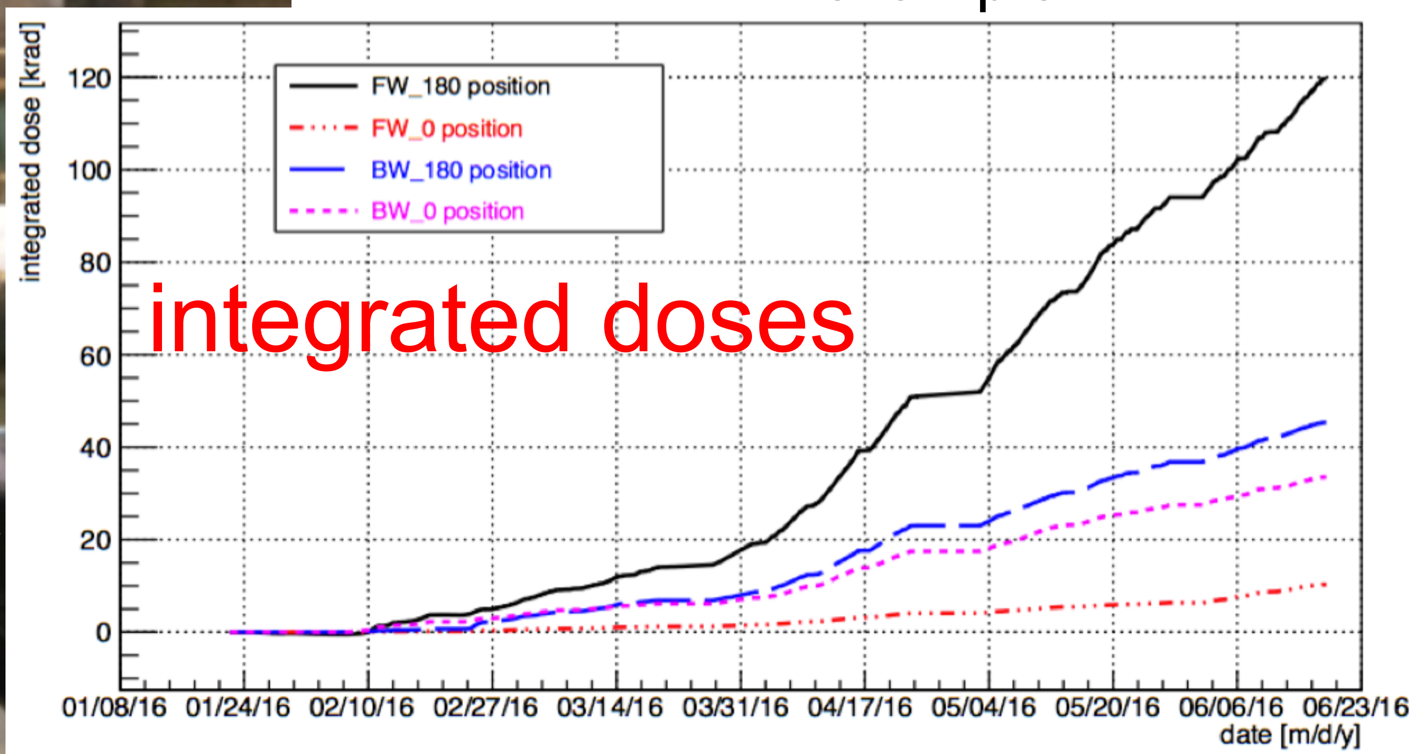
Phase I SuperKEKB commissioning

Four diamonds installed on the pipe for beam-radiation measurement

- first test and calibration of diamonds sensors in realistic conditions to prove proper operations and check precision for fast and slow aborts
- first measurement of beam-induced background in SuperKEKB to provide valuable feedback for validating background simulations



An example



Summary

- 40x increase in superKEKB luminosity
  → High instantaneous/integrated radiation doses for the inner silicon detector

- use 20 single crystal diamond sensors to monitor radiation.

Complete characterization:

→ • dark current
→ • stability with time
→ • uniformity
→ • charge collection efficiency
→ • photoconductive gain
→ • conversion from current to dose rate

- 4 sensors and electronics prototypes installed in the first SuperKEKB commissioning phase.
  - Measurements of all primary beam backgrounds and integrated dose measurement

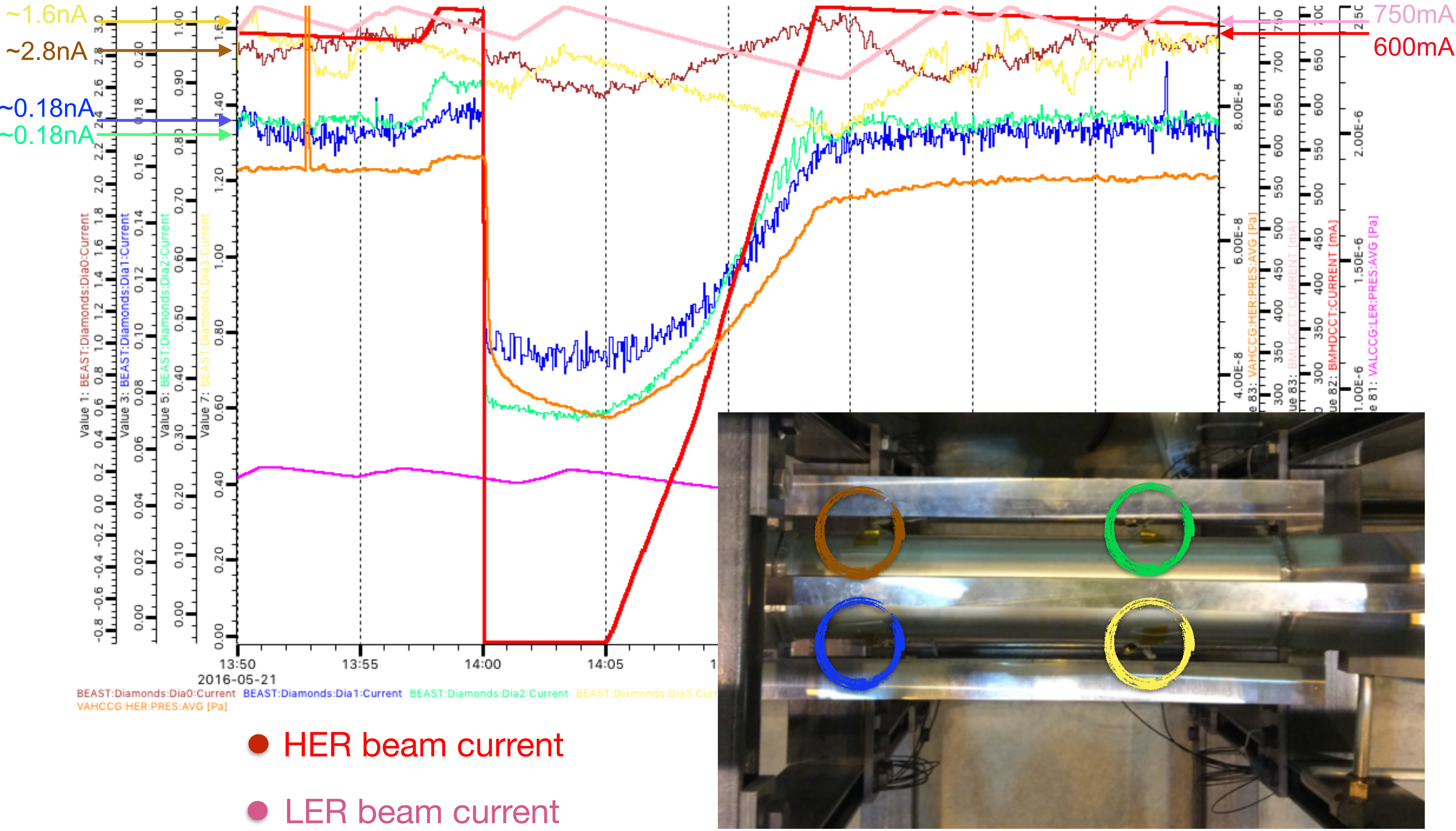
- First test and calibration on diamond and readout electronics done. Precision (0.5 nA on the shortest 10μs time scale) OK for reliable fast and slow aborts for phase 2/3

Development of beam abort in next commissioning phase (02-2018 → 07-2018)

BACKUP

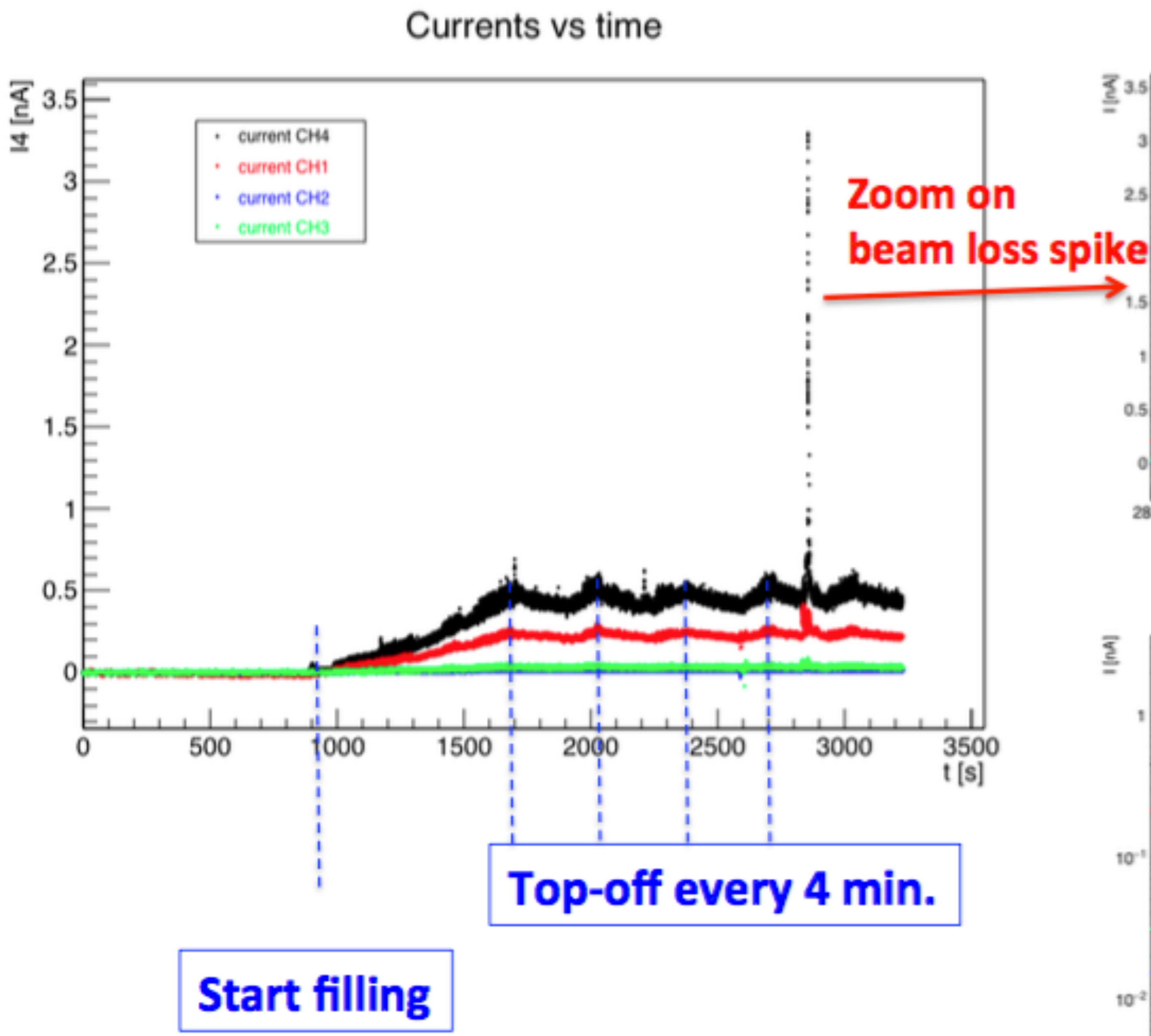
Specification	Value
Number of radiation sensors	20
diamond sensor size	5 mm$\times$5 mm$\times$500μm
maximum coax. cable length from sensor to electronics	$3 + 40$ m
sensor current/dose rate conversion factor	$1 \div 10$ nA/(mrad/s)
sensor current measurement sensitivity	0.01nA
sensor current measurement range	$1 \div 10$mA
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	$1 \div 10$ 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	$0 \div 5$ mA
for typical diamond sensors (slow aborts):	**Value**
current measurement, precision (time scale 1 s)	< 1 nA
response time	$> 1 \div 100$ s
current range	$0 \div 15$ μA

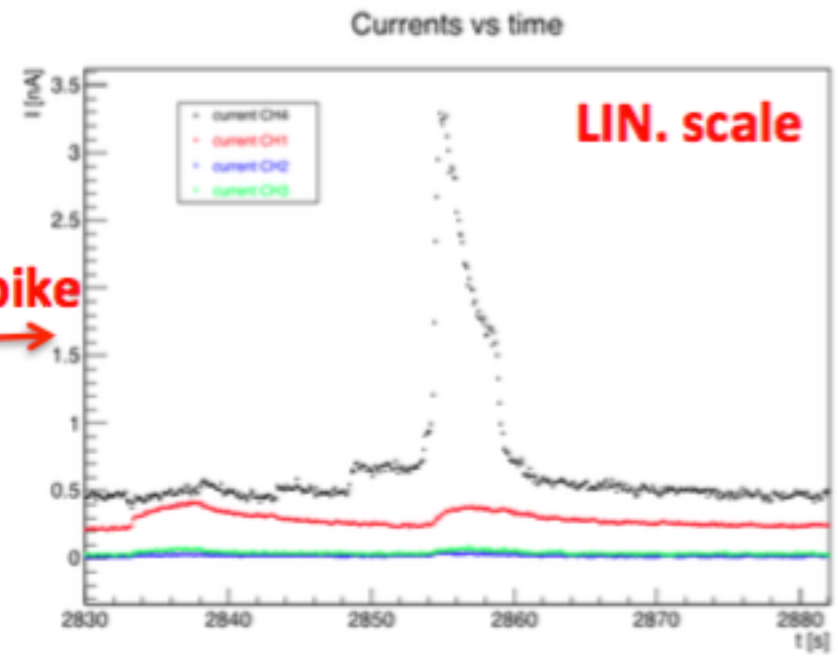
Diamond sensor response

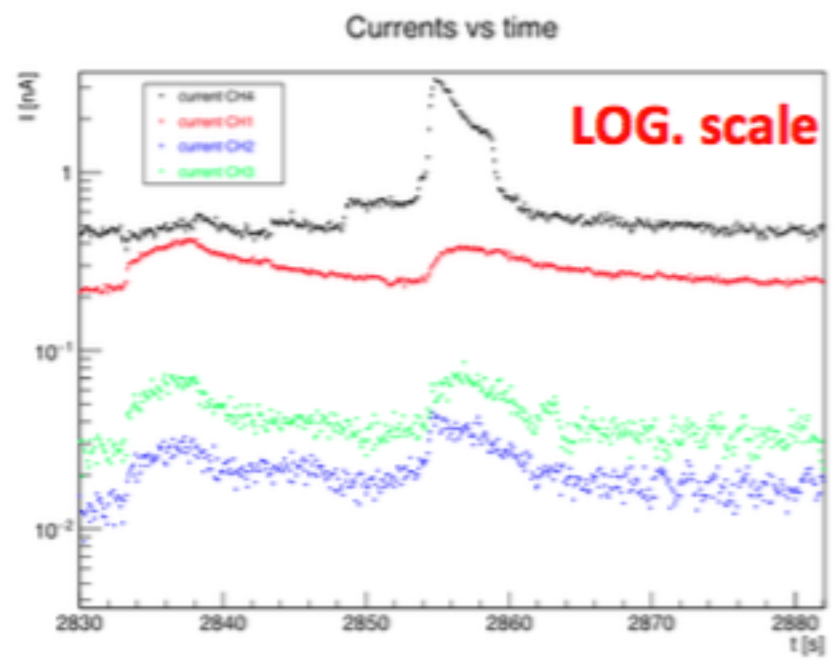


- HER beam current
- LER beam current

First signals

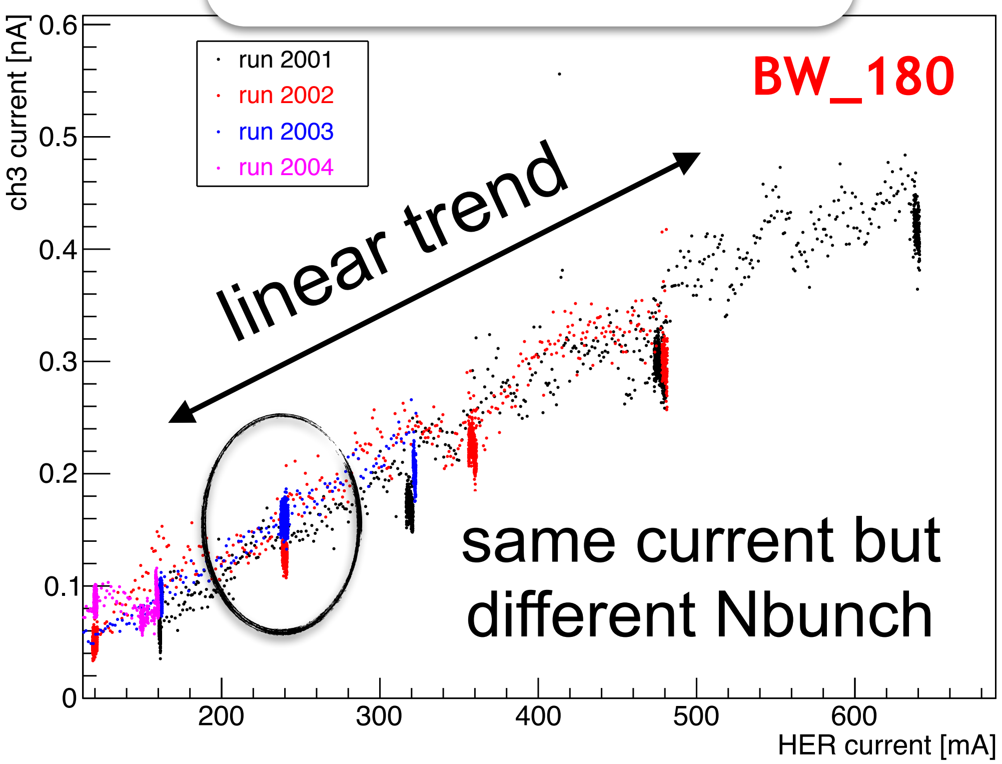




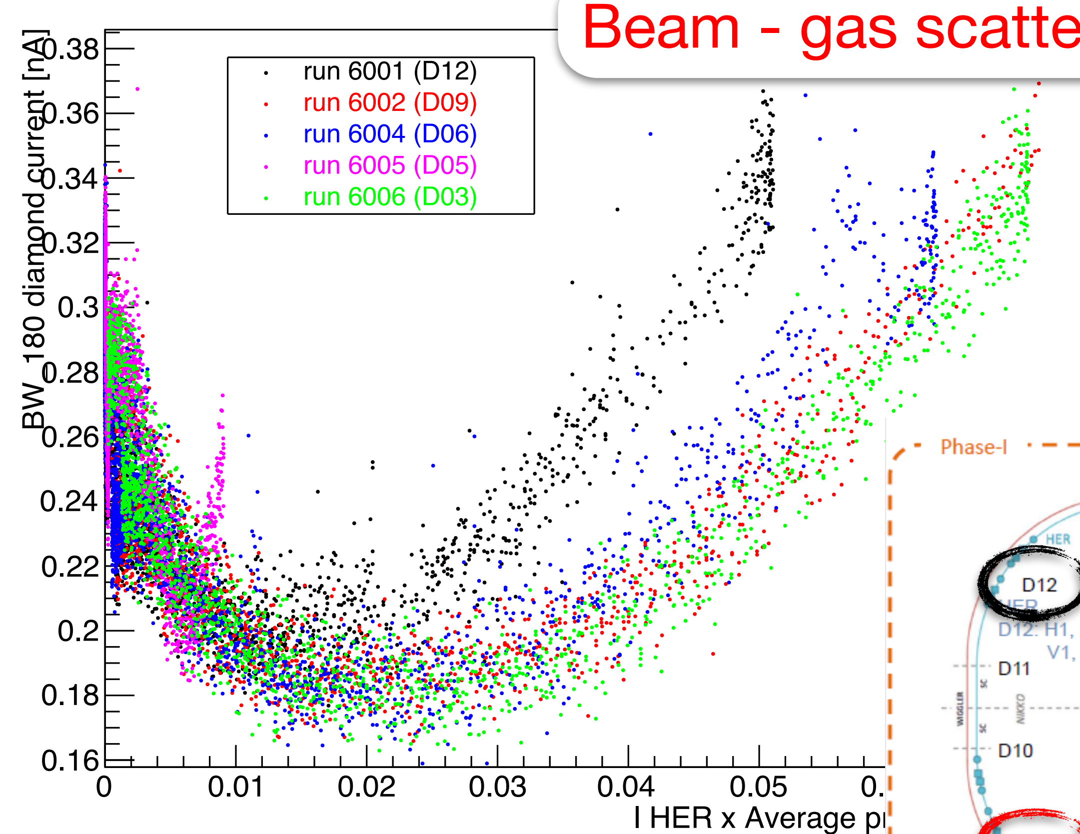


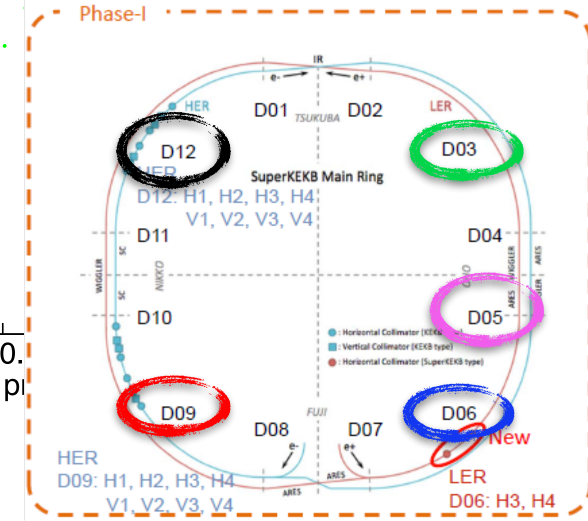
Background Studies

Current scan

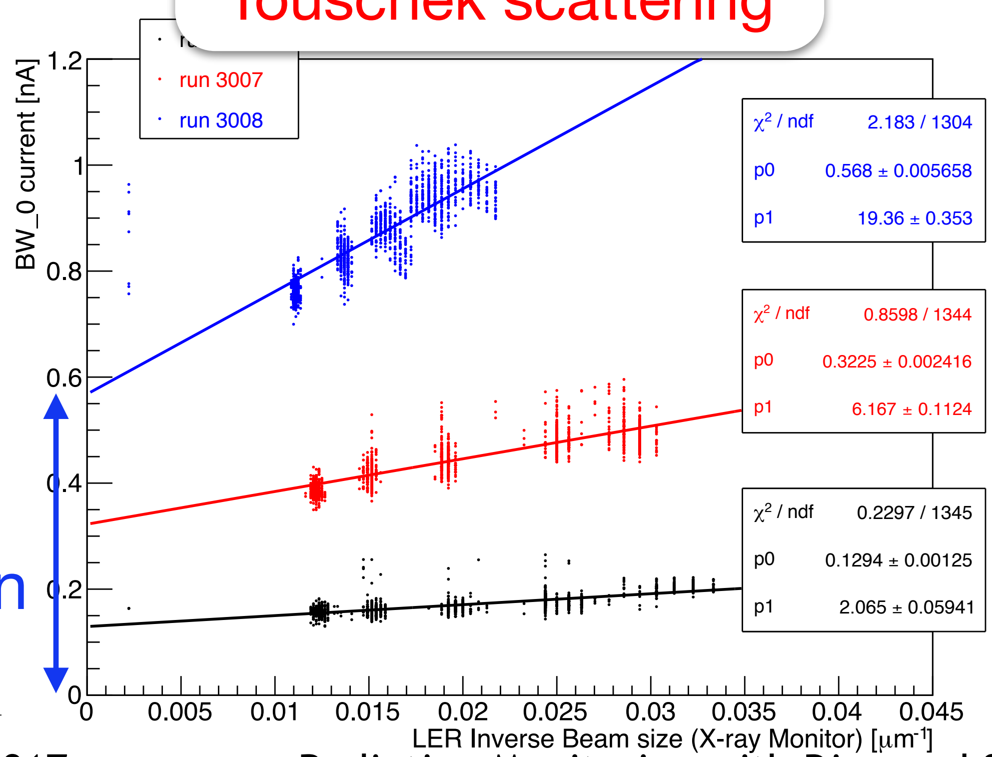


Beam - gas scattering





Touschek scattering



beam gas contribution

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

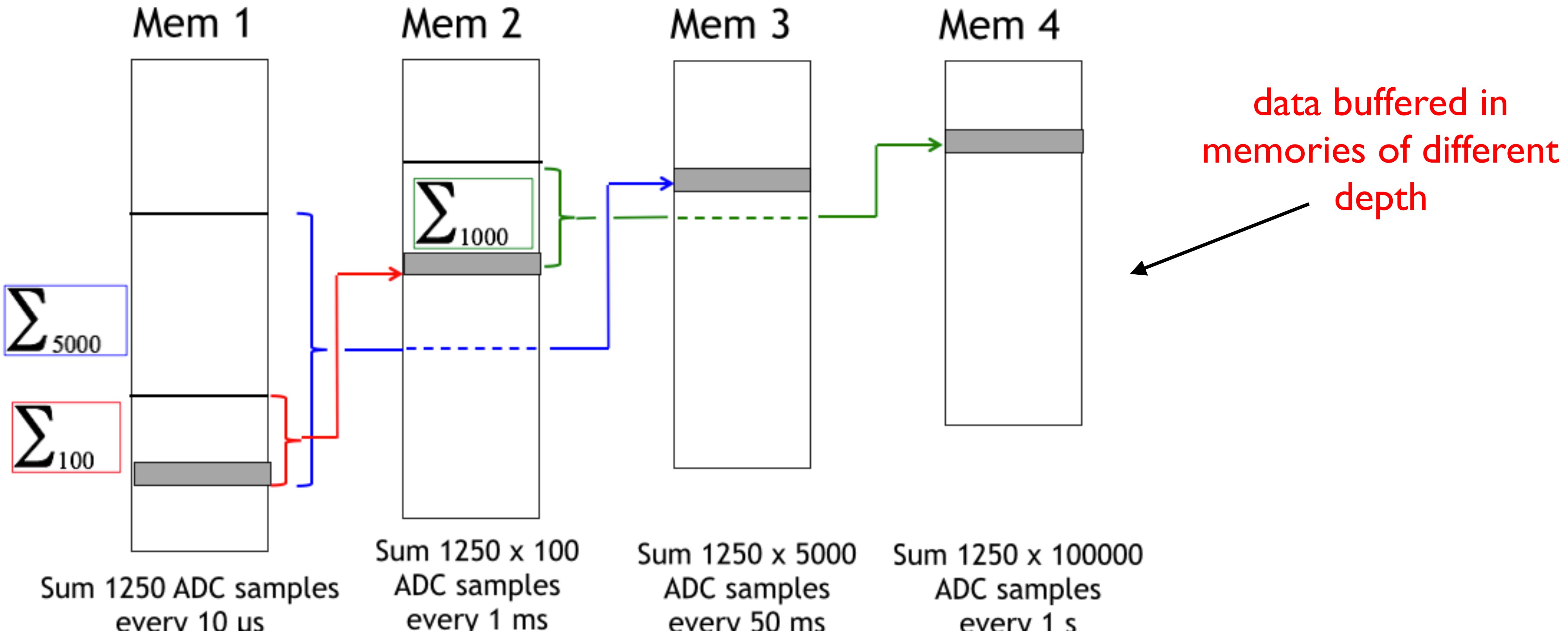
Beam abort thresholds (1/2)

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"



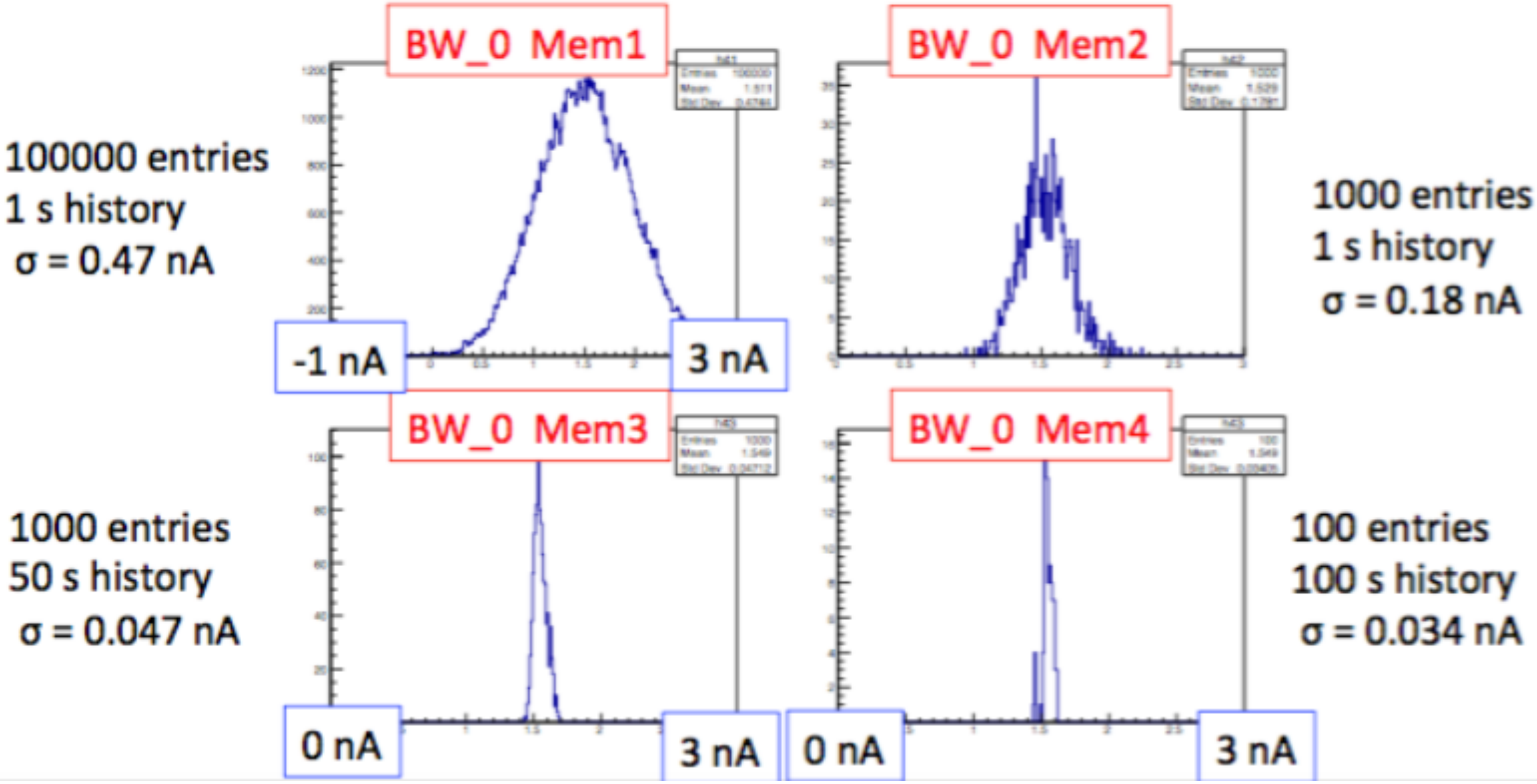
Beam abort thresholds (2/2)

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

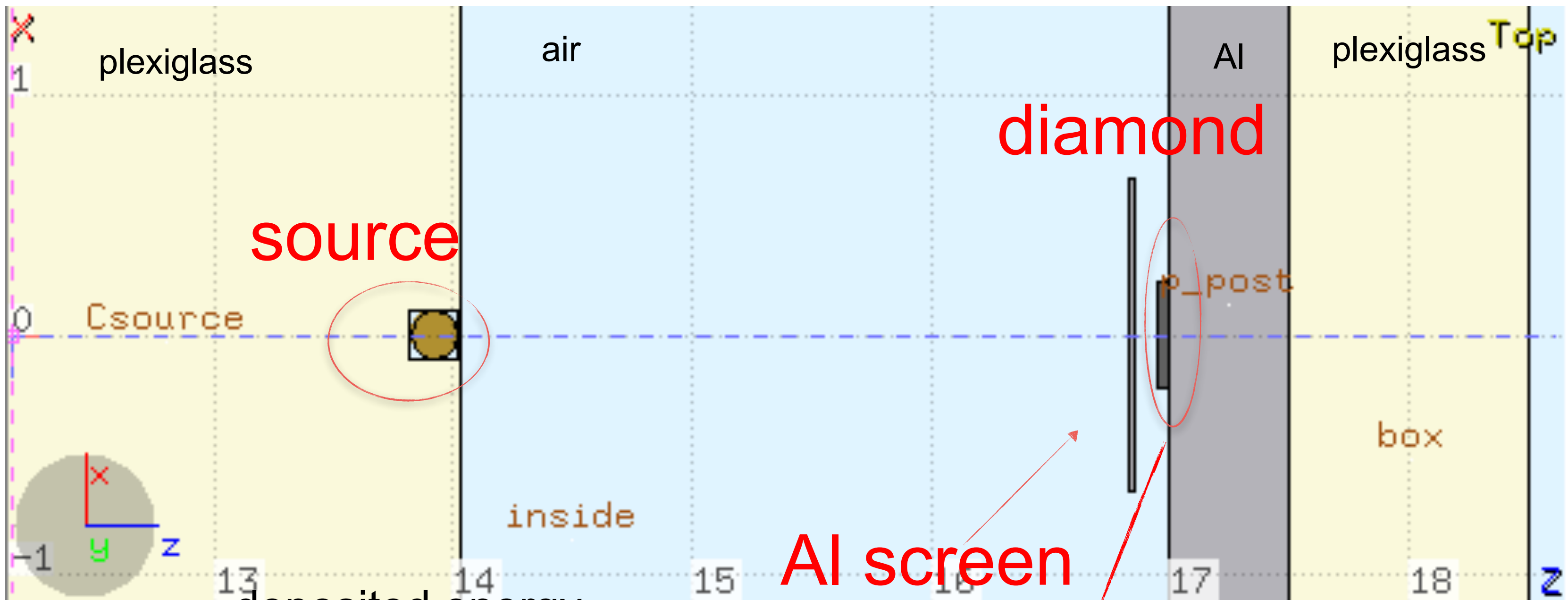
Noise decreases with increased averaging, from about 0.47 nA to < 0.04 nA

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

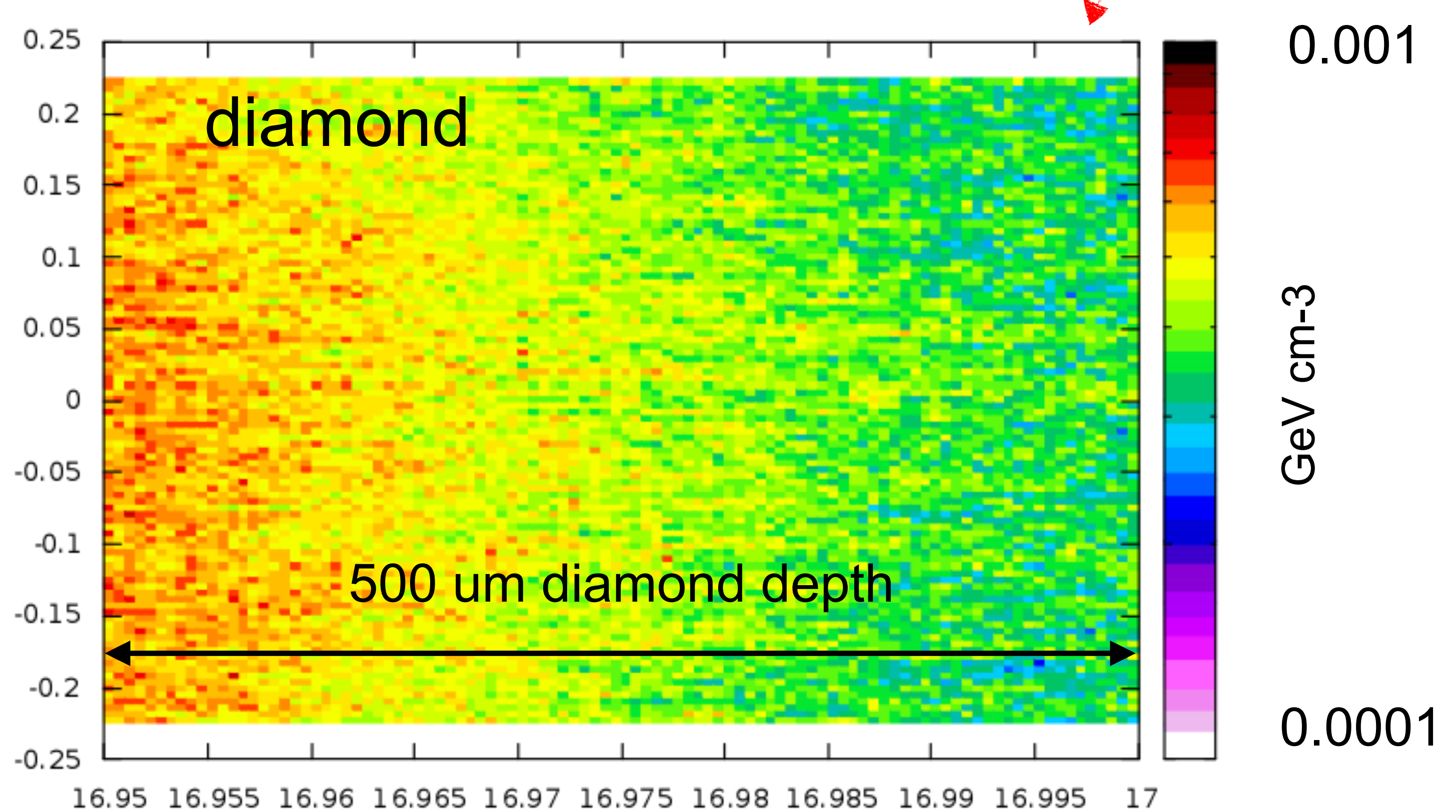


FLUKA

simplified geometry:



deposited energy

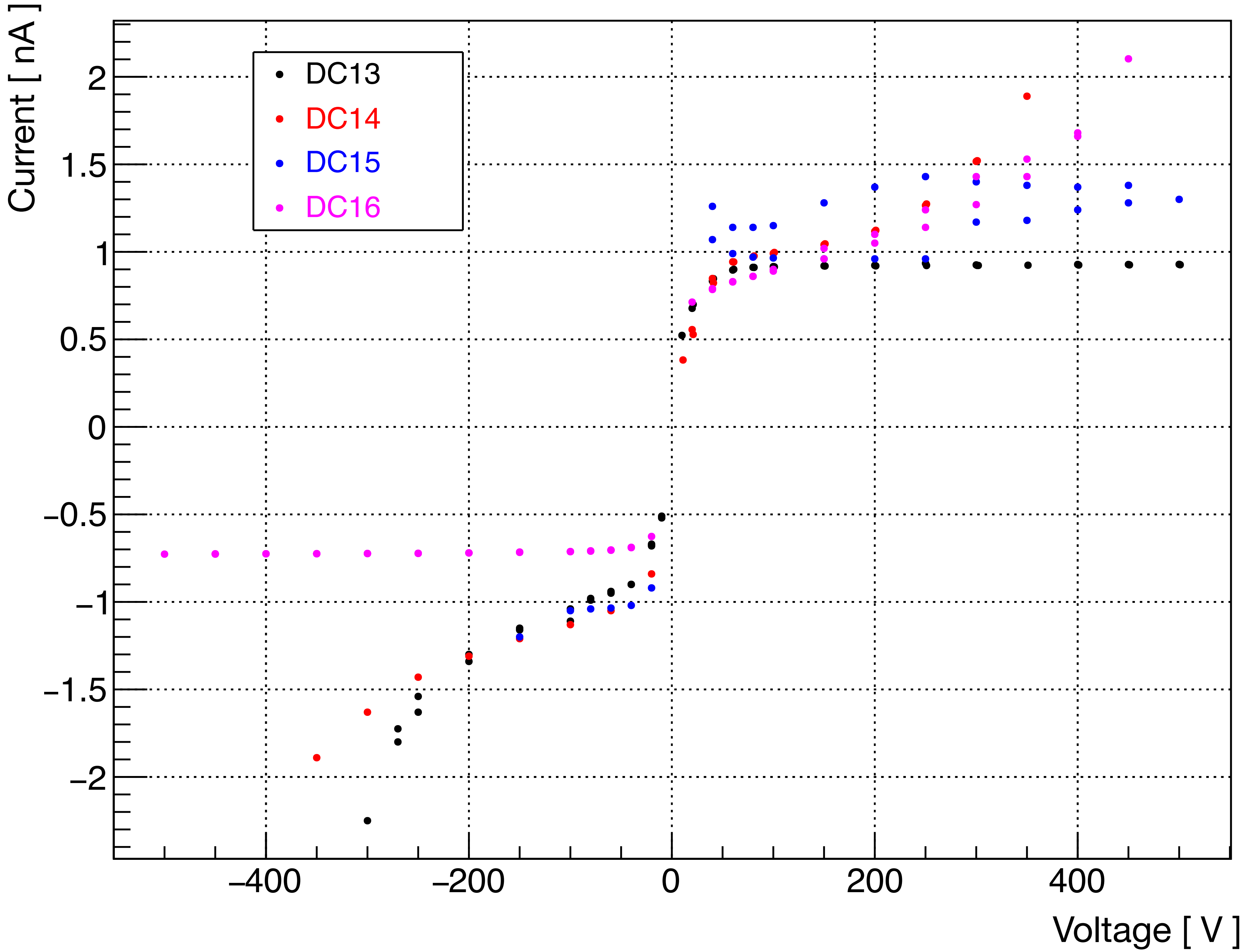


photoconductive gain = I_{meas}/I_{FLUKA}

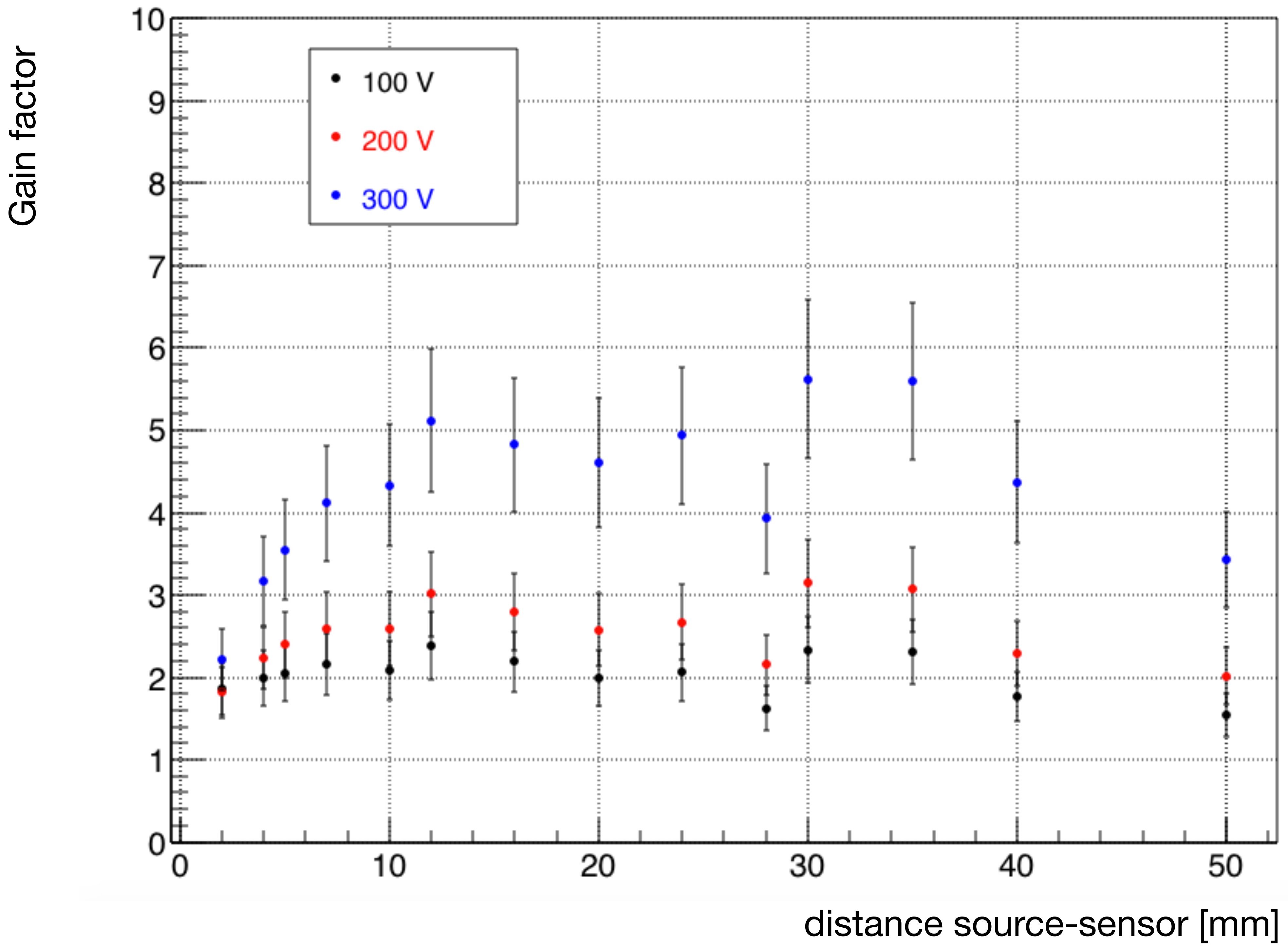
assuming:

- deposited energy equal in simulation and measurement
- $CCE_{FLUKA} = 1$, $CCE_{meas} = 1$
- no photoconductive gain in simulation

IV characteristic



Photoconductive gain

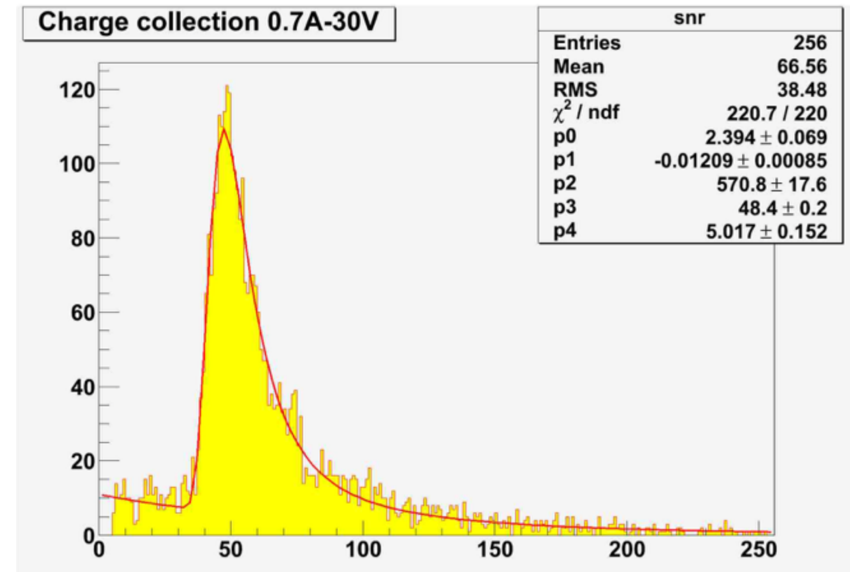


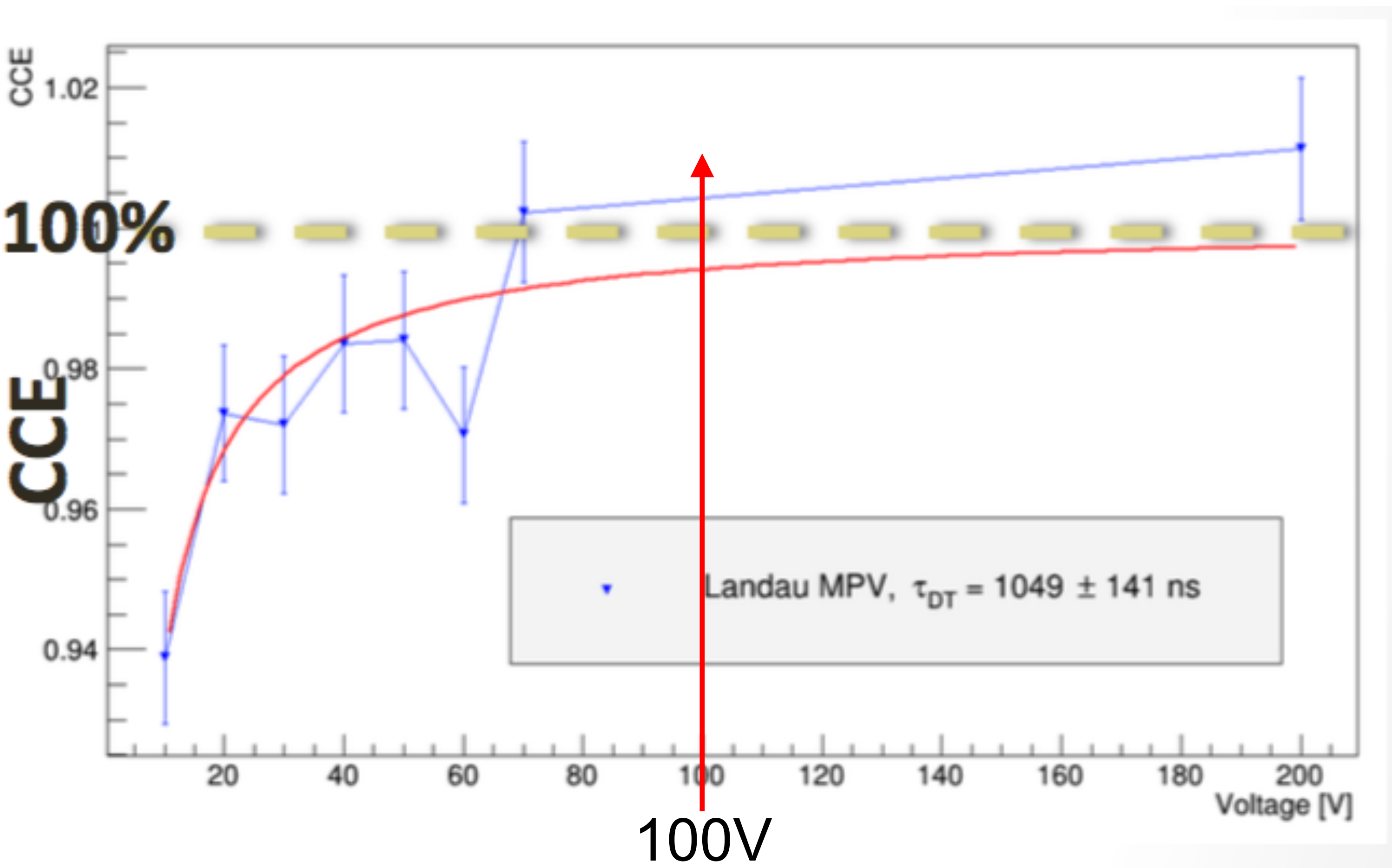
Charge Collection Efficiency

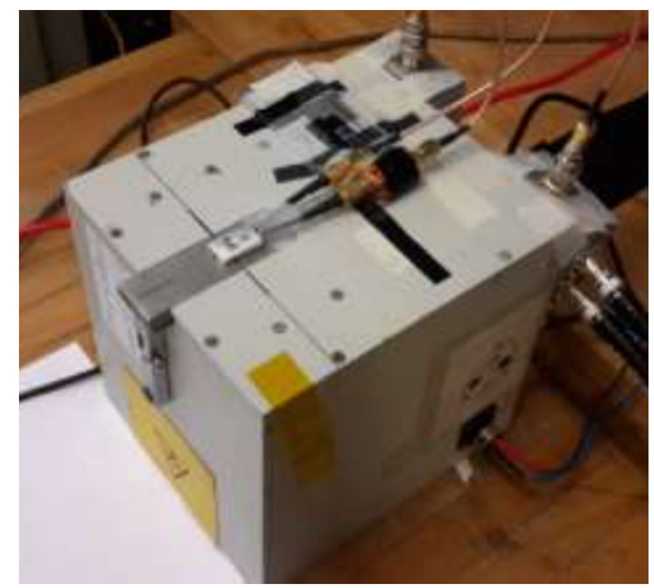
Example: DM5, CCE ≈ 100%

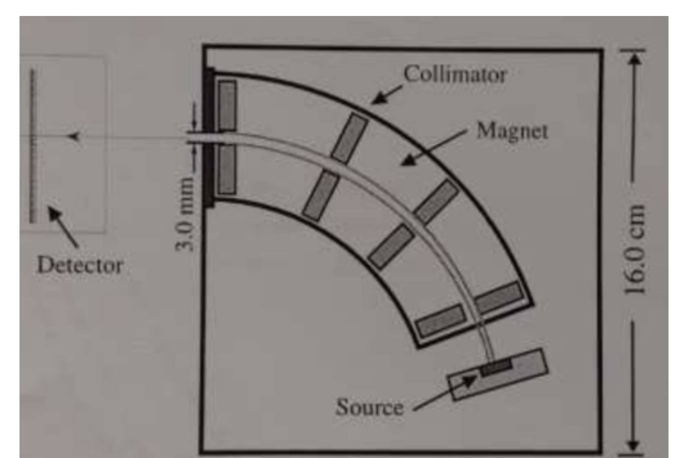
Landau Most Probable Value (MPV) vs HV ➔ Charge Collection Efficiency

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









Current-dose calibration factor (1/2)

Reference: With β ^{90}Sr source at 18 mm distance -> FLUKA vs measurement

We measure currents -> we need a conversion factor from current to dose

FLUKA

- RE (Released Energy) = 3.25 GeV/s
- Assuming:
  - $CCE_{FLUKA}=1$
  - $E_{e\text{-}h} = 13$ eV

predicted current

=1

$$I_{FLUKA} = \frac{RE_{FLUKA} * q_e}{E_{e\text{-}h}} \; CCE_{FLUKA} * (G_{PC})_{FLUKA} = 40 \text{ pA}$$

generated charge

conversion factor eV->J

$$Dose = \frac{RE * 1.6\ 10^{-19}}{M} = 1.47 \text{ mrad/s}$$

mass (Kg)

predicted dose rate

$$\boxed{(Dose/I) = \frac{1.47 \text{ mrad/s}}{0.04 \text{ nA}} = \frac{37 \text{ mrad/s}}{\text{nA}}}$$

dose - current conversion factor

Current-dose calibration factor (2/2)

We measure currents -> we need a conversion factor from current to dose

Measurements

Photoconductive gain = I_m/I_{FLUKA}

I(pA)	@-100V	@+100 V	G_{PC-}	G_{PC+}
Fluka*	-40	+40		
DM4	-850	+660	21.25	16.5
DM5	-460	+180	11.5	4.5
DC3	-230	+340	5.75	8.5
DM7*	-130	+340	3.25	8.5

measured current

$$\underbrace{I_m}_{\text{measured current}} = \text{generated charge} \; \underbrace{CCE_{exp}}_{=1} \; G_{PC,exp}$$

assumption: equal to generated charge FLUKA

$$\boxed{\text{Dose (mrad/s)} = \frac{I_m\,(\text{nA})^{*}\ 37\ \text{mrad/s/nA}}{G_{PC}}}$$

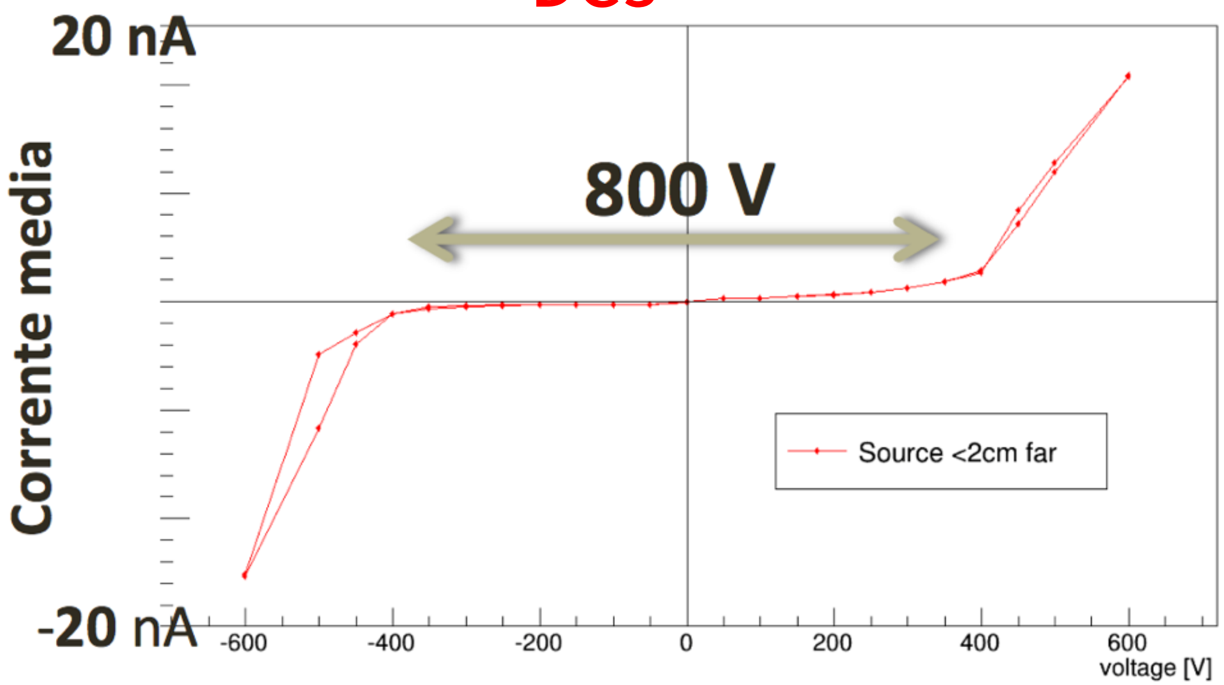
DOSE RATE

Systematics

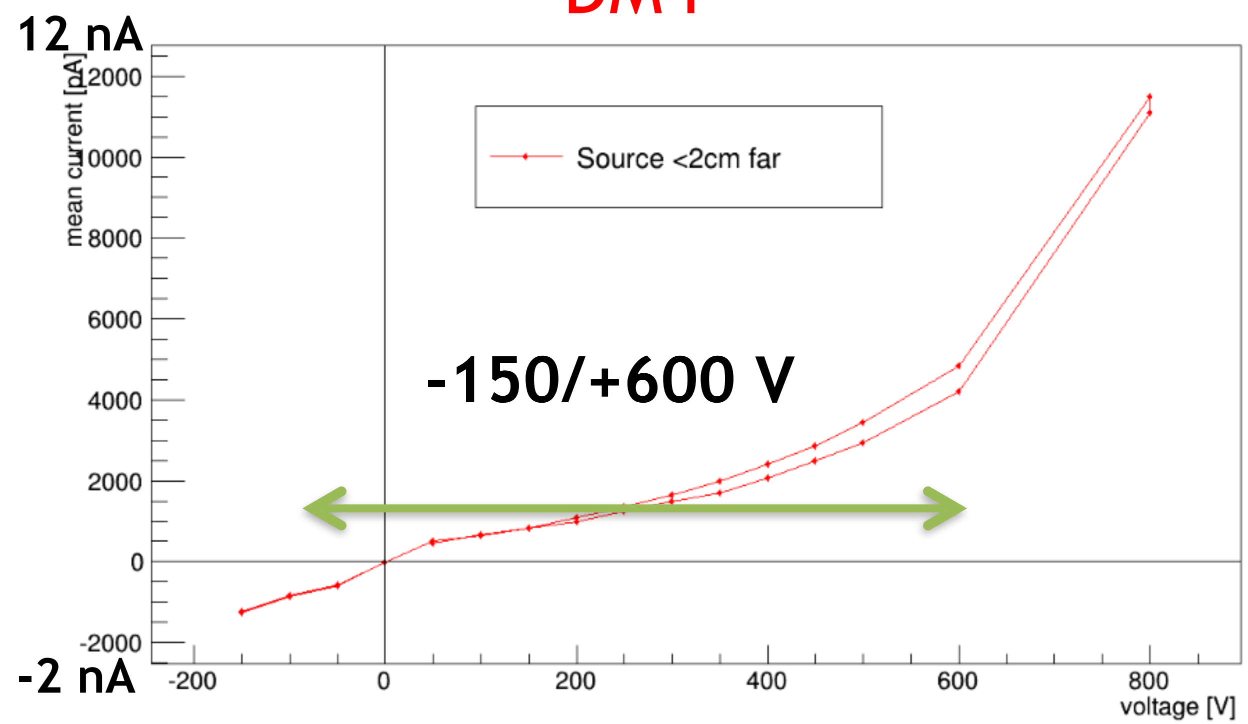
- Source distance -> 11%
- Diamond Active Volume-> 10%
- Source activity -> 7%
- Electronics Offset drift ~ 2%
- HV effects order 1%
- Priming/pumping effects (initial stability)<10%
  (long term < 1%)
- FLUKA simulation -> 1 %

I-V with β ^{90}Sr source (d=18mm)

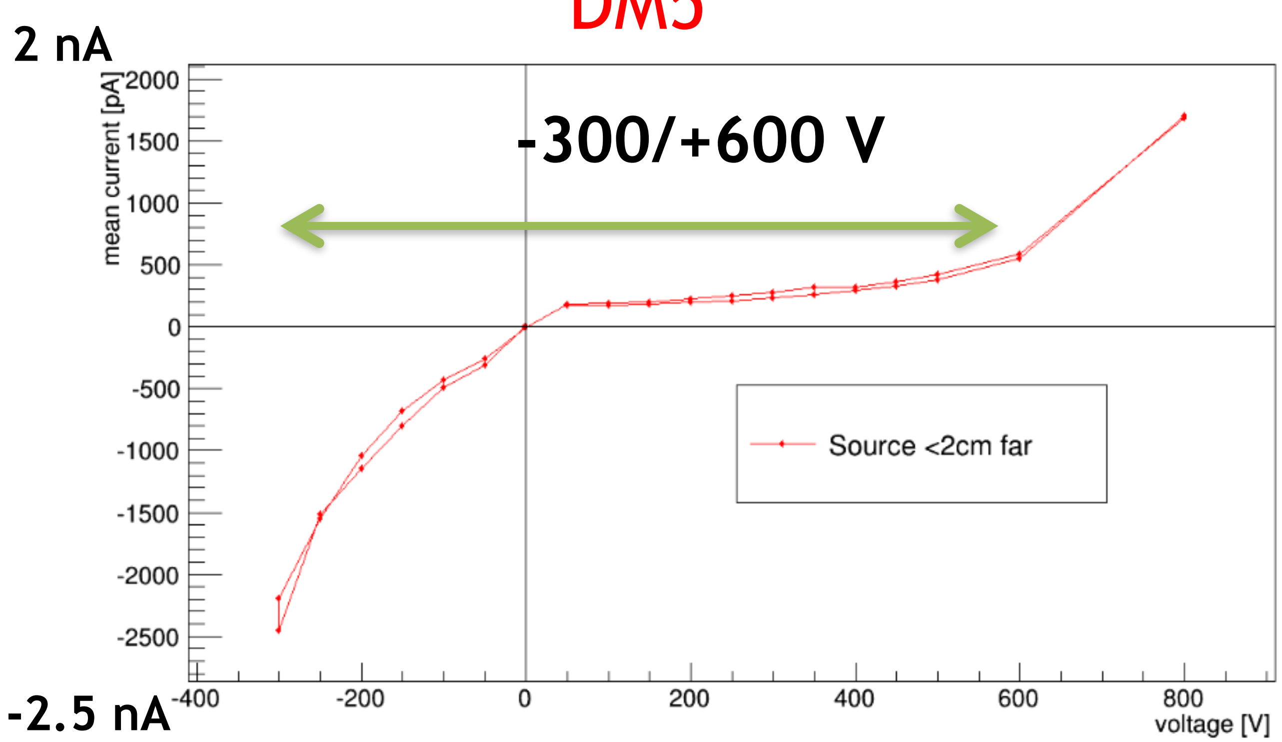
DC3



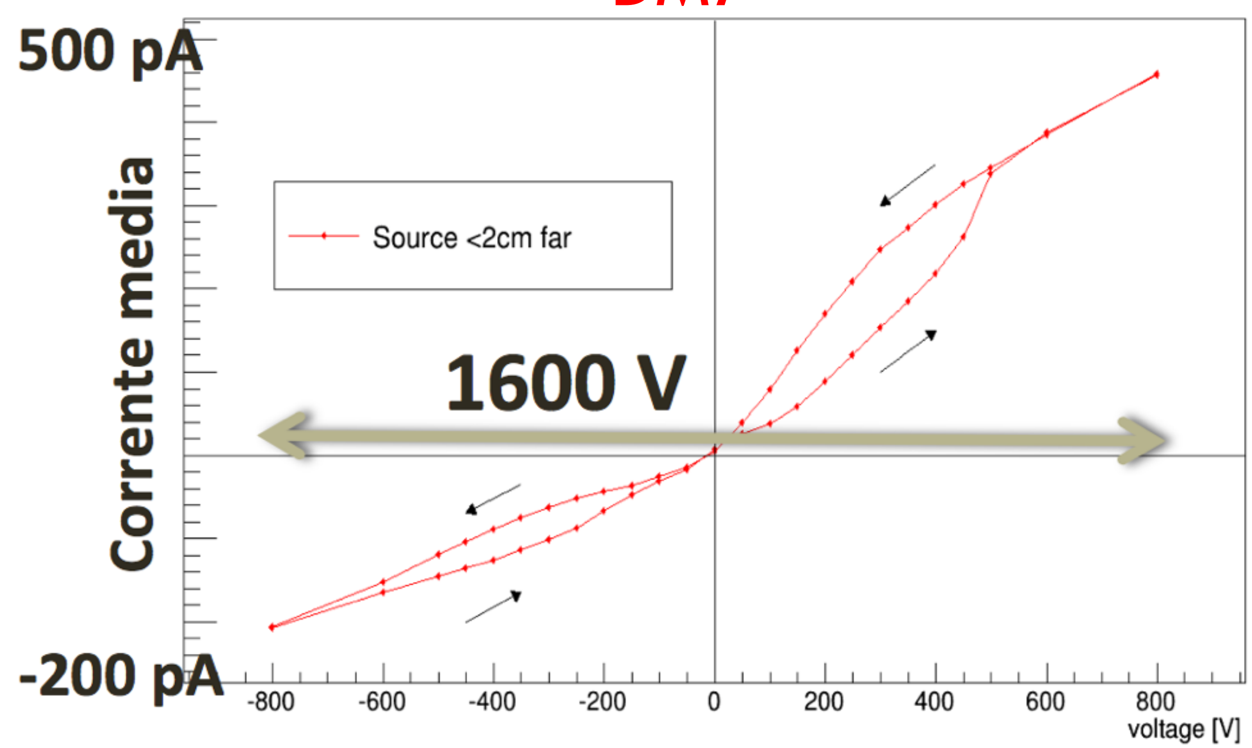
DM4



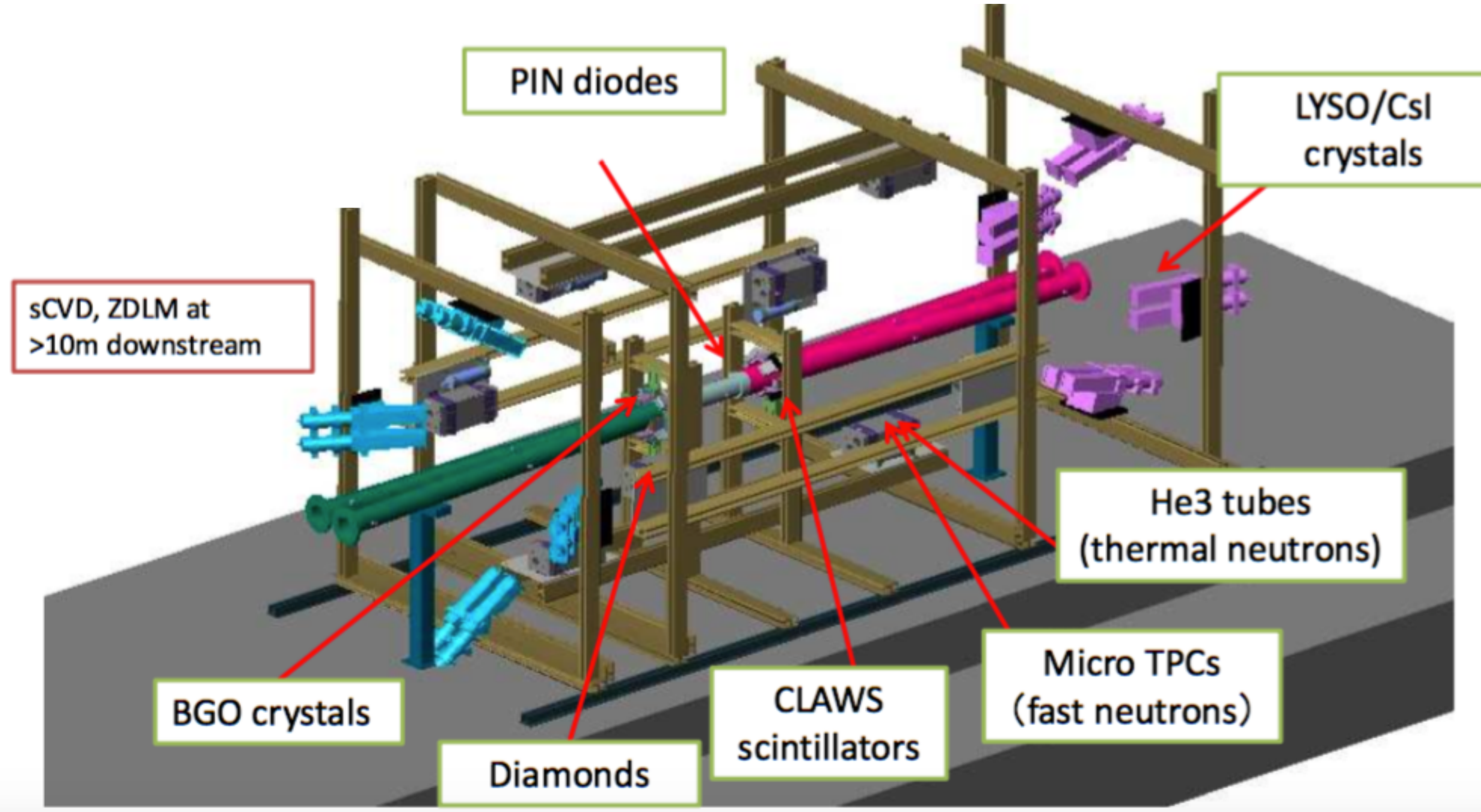
DM5



DM7



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