POLITECNICO DI MILANO

# A neutron detector for pulsed mixed fields:

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The problem is known since the forties. In 1948 C. H. Westcott [2] reported “*A feature common to all machines giving particles of the highest energies is that their output is not continuous, but occurs in bursts or 'pulses' separated by relatively long intervals during which the machine gives no output…The pulsed nature of the source is of no consequence when it is used to manufacture radioactive isotopes, ….There remains, however, a large field of investigation where quantitative results are of importance and where methods involving electrical counting of the instantaneous products of the reaction are pre-eminently*

There are plenty of practical situations with particle accelerators used for both scientific and medical applications [3], where the time structure of the secondary stray radiation limits the use of active monitors. Usually the time duration of a single burst can range from few µs to about 1 ms with a typical repetition rate in the range 10 Hz – 100 Hz [4,5,6]

[3] S. Agosteo, Radiation Measurements 45 (2010) 1171-1177

[4] Klett, A., Leuschner, A., IEEE 2007 Nuclear Science Symposium & Medical Imaging Conference, Conference Records, Oct 27-Nov 3 2007, Honolulu, Hawaii, USA.

[5] CERN-DGS-2012-036-RP-TN, Environmental measurements and instrument intercomparison around the PS accelerator complex.

[6] W.A. Barletta, Nuclear Instruments and Methods in Physics Research A (2010) 618 69–96

# Pulsed neutron fields (PNF)

It is well-known that neutron detectors, based on neutrons counting, generally suffer from dead-time effects and have strong limitations when measuring in pulsed radiation fields.

This is a major issue at particle accelerators, where pulsed neutron and gamma fields are present because of beam losses at e.g. targets, collimators and beam dumps.

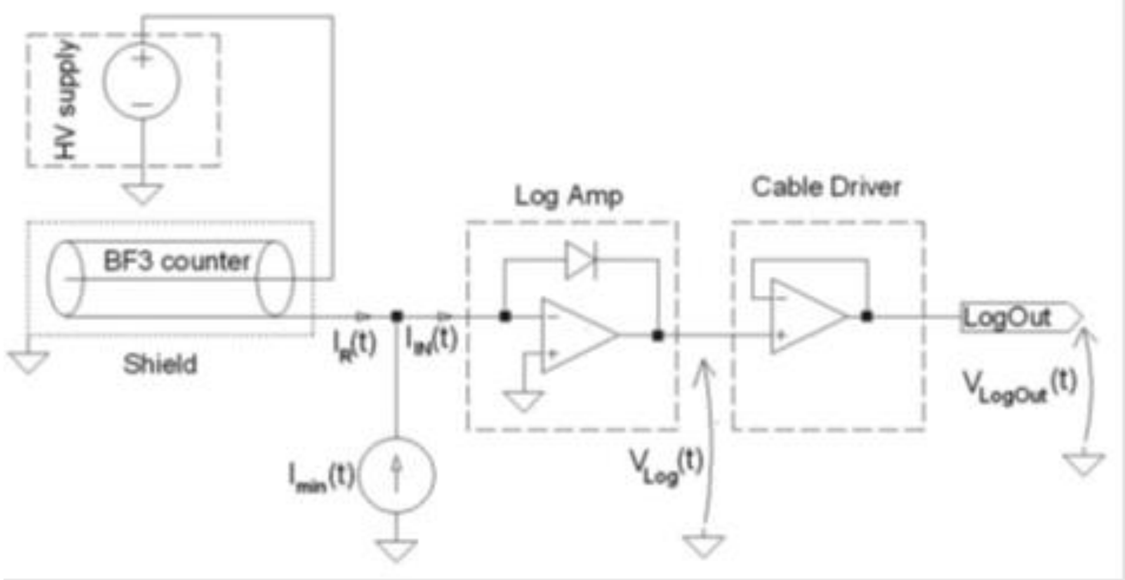
# Pulsed neutron fields (PNF)

An ideal neutron survey meter for PNF should meet the following requirements:

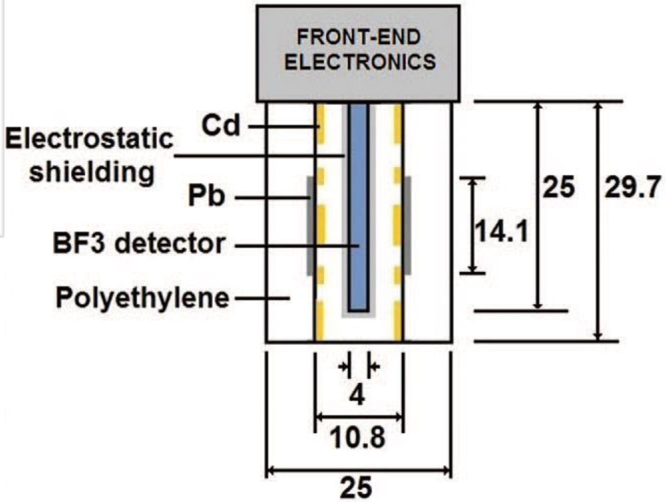
1. capability to withstand very high instantaneous neutron fluxes with little or no saturation;
2. sensitivity comparable to that of commercially available rem counters;
3. capability to measure correctly the intensity of a single neutron burst;
4. capability to reject the photon contribution that accompanies the neutron field.

At present there is no instrument capable to fulfill all the requirements

LUPIN (Long interval Ultra wide dinamic Pile-up free Neutron detector)



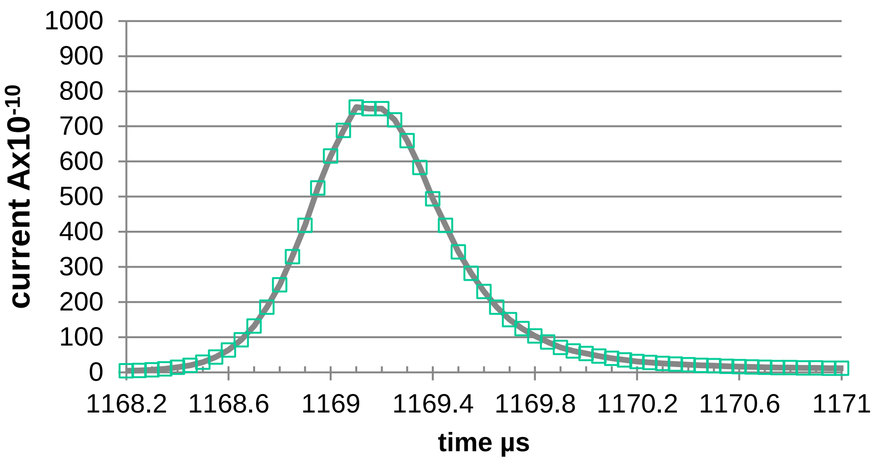

The BF3 detector is placed inside a cylindrical polyethylene moderator

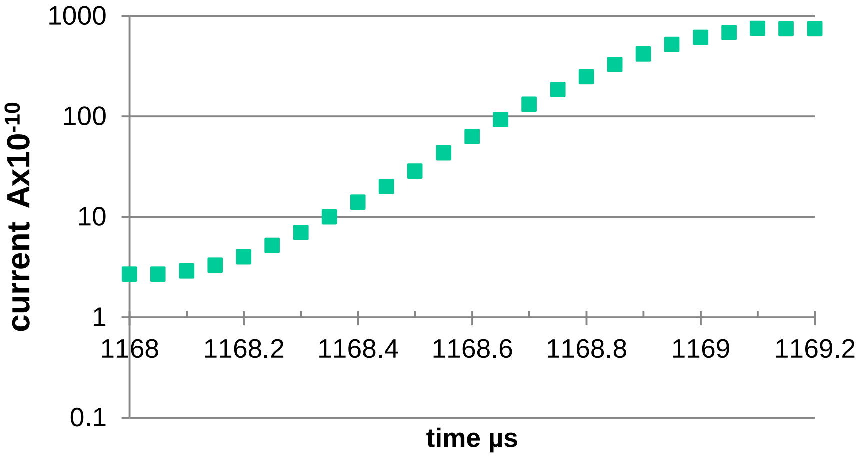


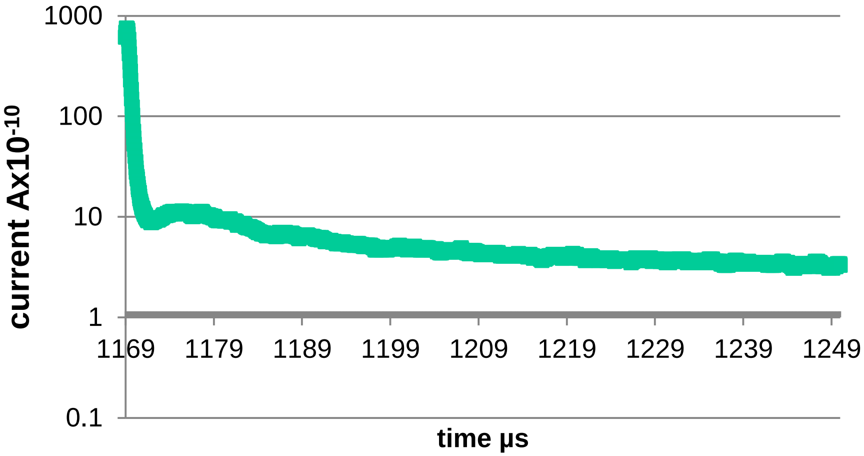

The signal LogOut is acquired with an ADC (10 MHz) and processed via software (current integration over a user settable timebase). The system measures the charge generated by a neutron interaction

# The LUPIN output pulse

Example of a neutron current pulse

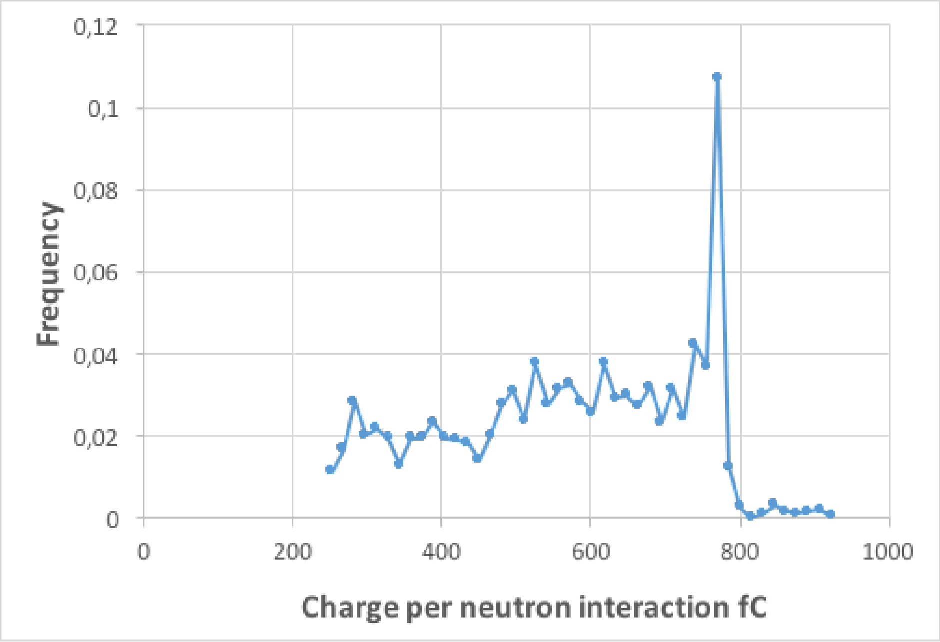


# Charge calibration

The charge calibration is the measurement of the mean collected charge (MCC) expected from a single neutron interaction, expressed in fC/n




The total charge, measured during the interaction of a radiation burst involving several neutron interaction, divided by MCC is the number of neutron interactions

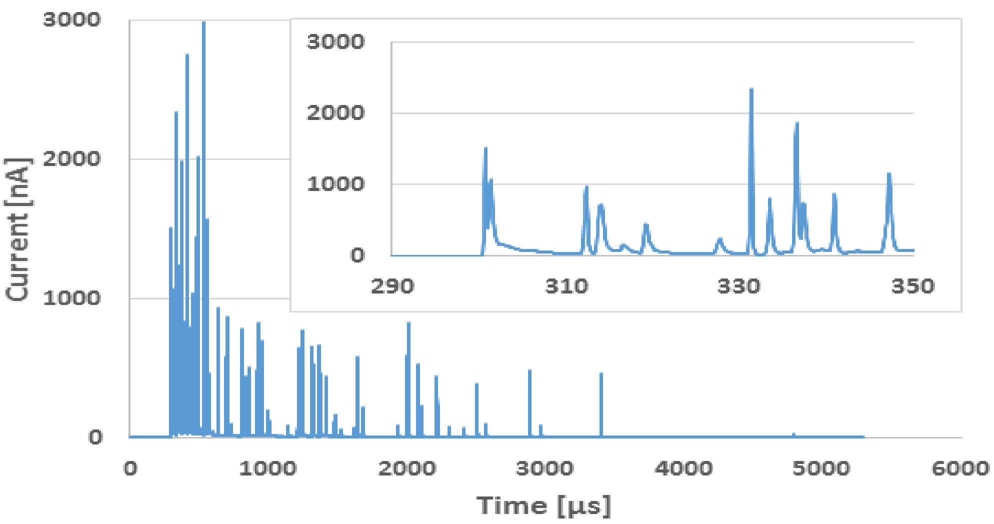
BF£ counter MCC = 570 fC  with HV=1180V

# Signal analysis

The current profile produced by a neutron burst interaction is shown on the right. The number of interacting neutrons N can be calculated using the following equation:

$$N = round\left(\frac{\sum_{i=1}^{n} I_n \cdot \Delta t}{MCC}\right)$$

In the example N=107, integrating over 4ms.




About 50 neutron interactions occur in about 300 μs, corresponding to an interaction rate around 170 kHz.

The sensitivity of the LUPIN in terms of ambient dose equivalent H*(10) is 2.17 $\pm$ 0.22 count per nSv.

The acquisition shown in figure corresponds a burst intensity of 49 nSv

$$MCC = 570 \pm 10\ fC$$

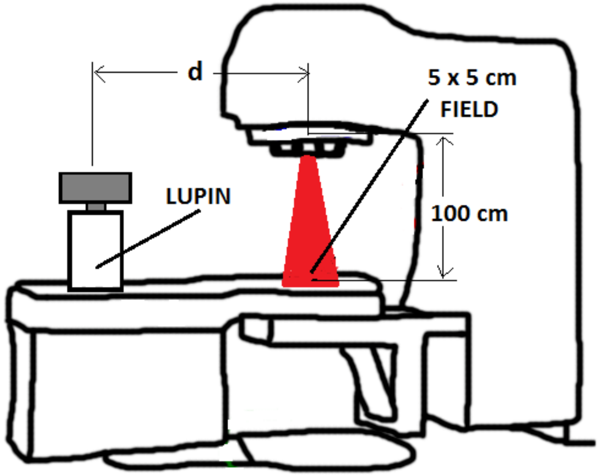
# Measurement at S. Raffaele hospital

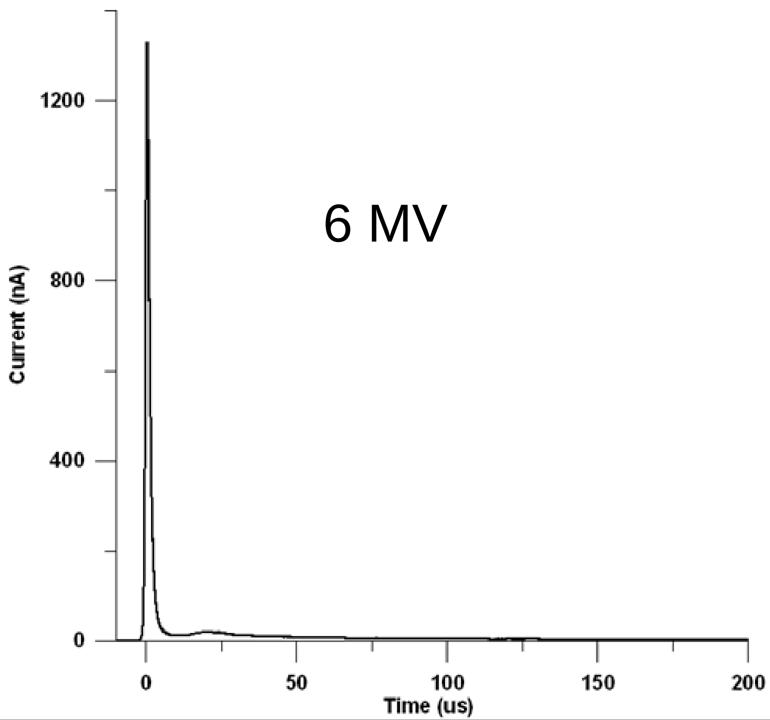
Electron radiotherapy LINAC: Varian Clinac® DHX - Dual energy

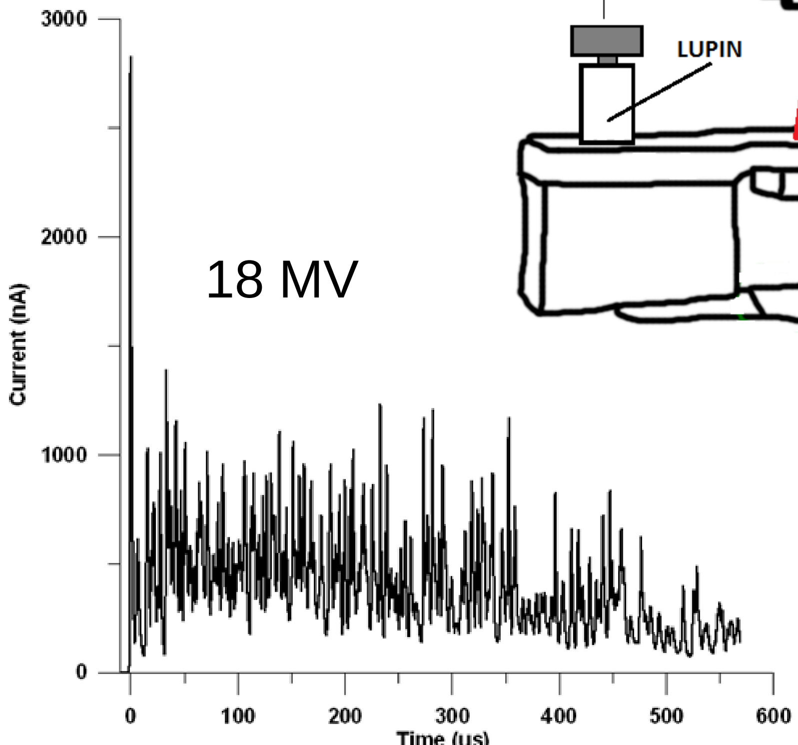
beam directed on the treatment couch, irradiation field of 5 x 5 $cm^2$.

The detector was placed on the therapy couch at 100 cm from the isocenter.

LINAC was operating 6 MV or 18 MV.



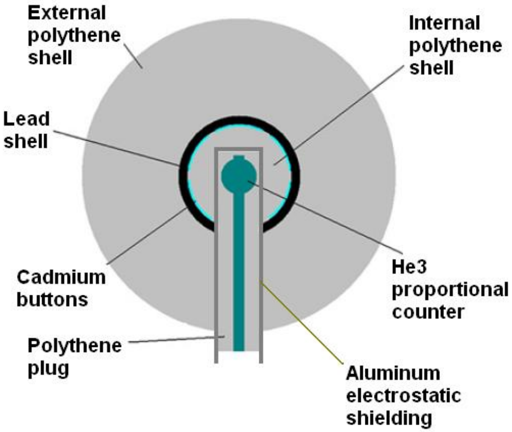



# Conclusions

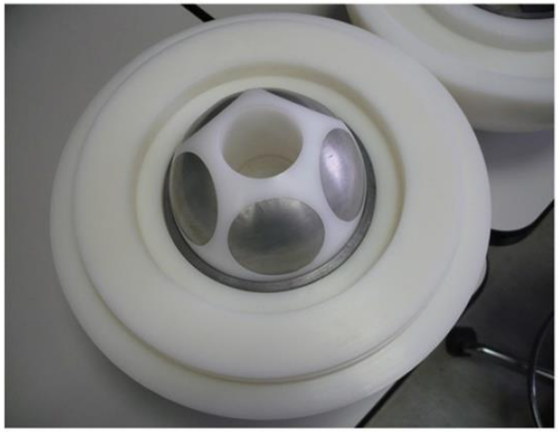
A number of developments are planned (and most of them implemented) to improve the performance of the LUPIN.

1) a reading in terms of ambient dose equivalent would be desirable, to employ the instrument as a rem-counter. This implies the use of a specific moderator that is still being designed.
2) the behavior of the detector needs to be analyzed over a wide range of burst intensities in order to evaluate the linearity of its response.
3) improvements on the detector sensitivity, on the isotropy of its response and on the signal analysis process can be achieved by employing a $^3He$ proportional counter and by optimizing the electronics.

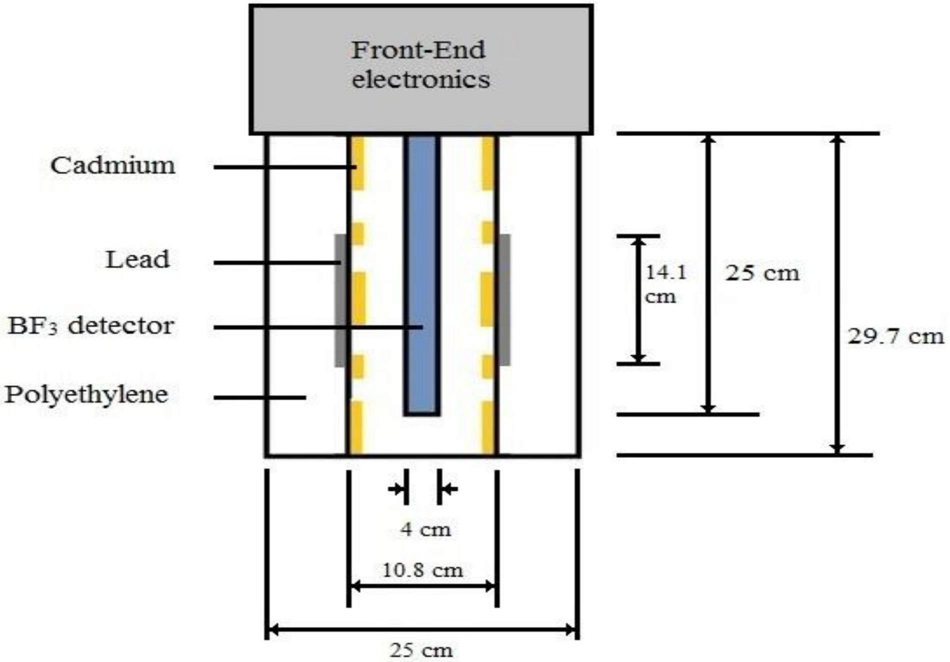
# LUPIN He-3



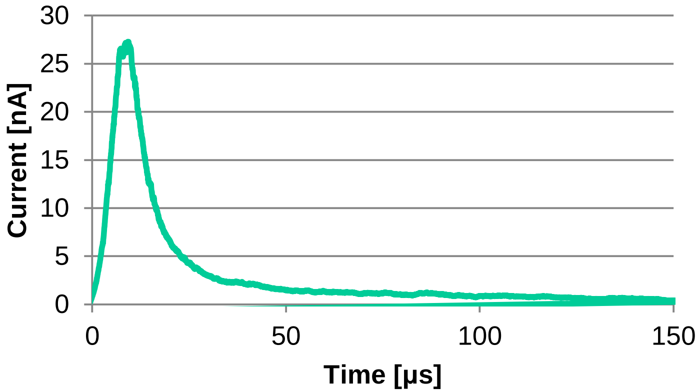
External polythene shell
Internal polythene shell
Lead shell
Cadmium buttons
He3 proportional counter
Polythene plug
Aluminum electrostatic shielding

# LUPIN BF3

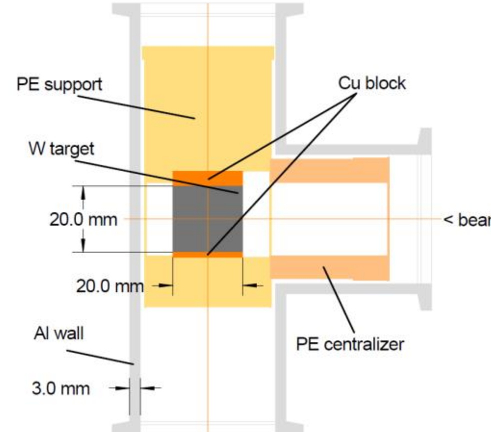


Front-End electronics
Cadmium
Lead
BF3 detector
Polyethylene
14.1 cm
25 cm
29.7 cm
4 cm
10.8 cm
25 cm

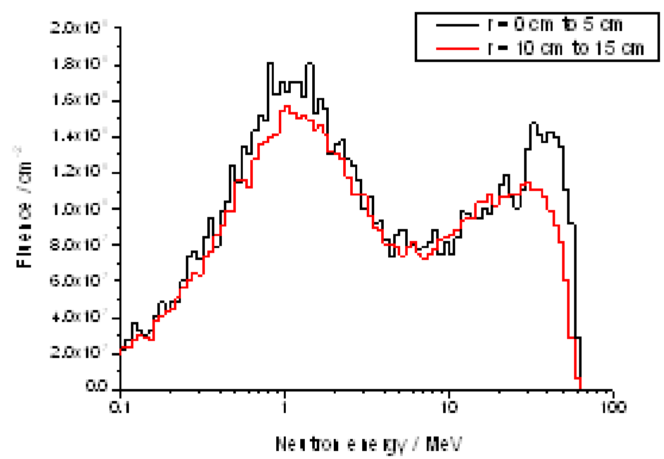



Current [nA]
Time [μs]
30
25
20
15
10
5
0
0
50
100
150

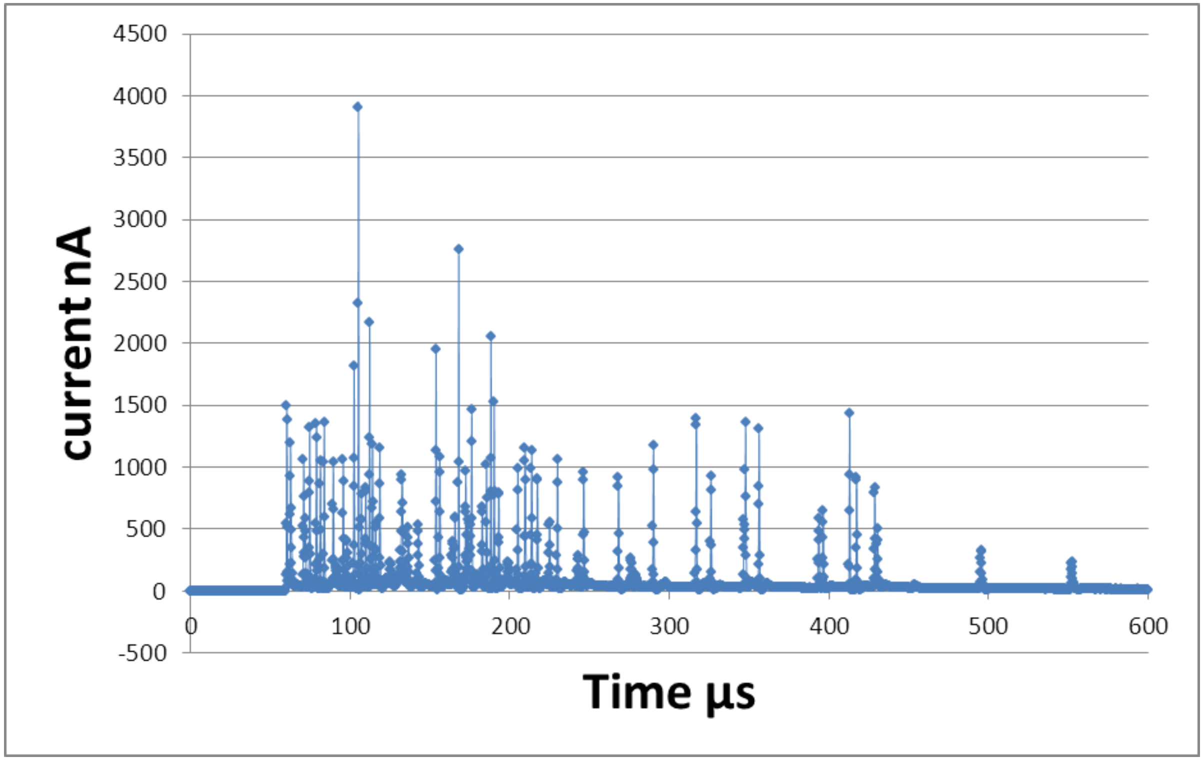
# Test at HZB  68 MeV protons on W




The proton beam is delivered in burst with duration of 1 µs, 10 µs, 40 µs

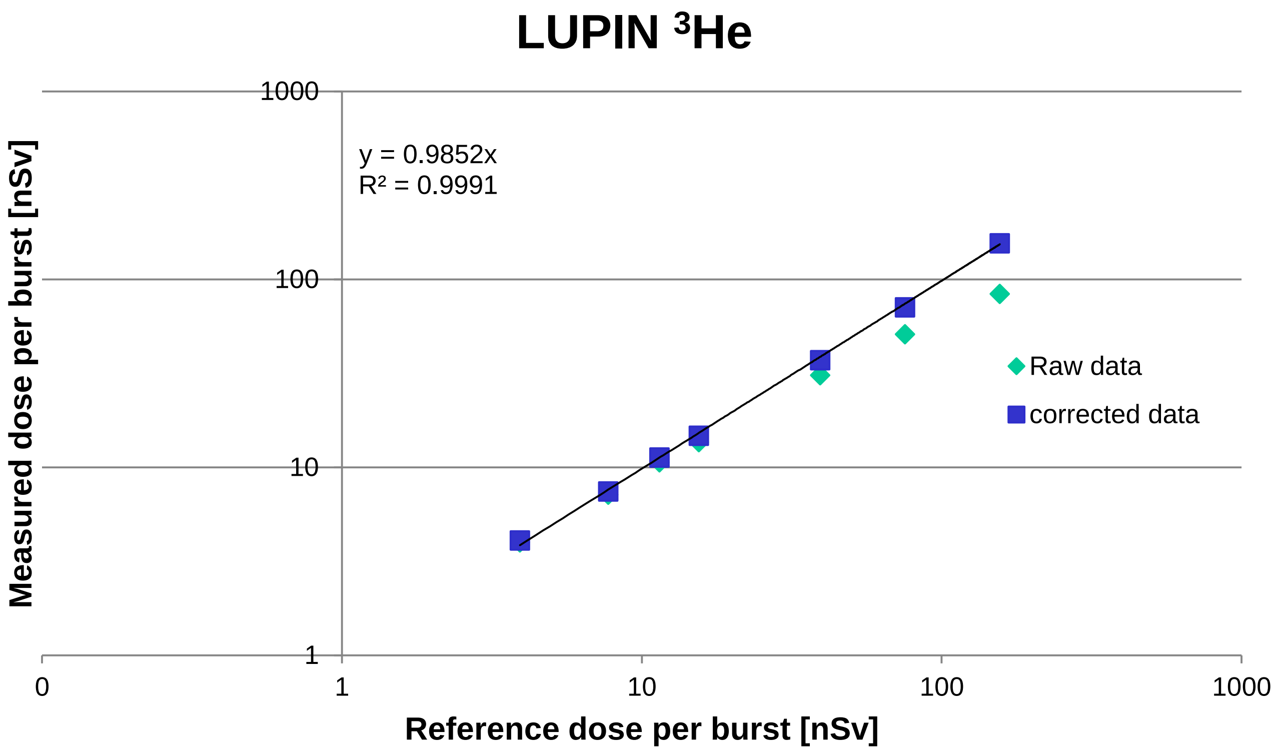


# LUPIN output signal resulting from a neutron burst 1µs long

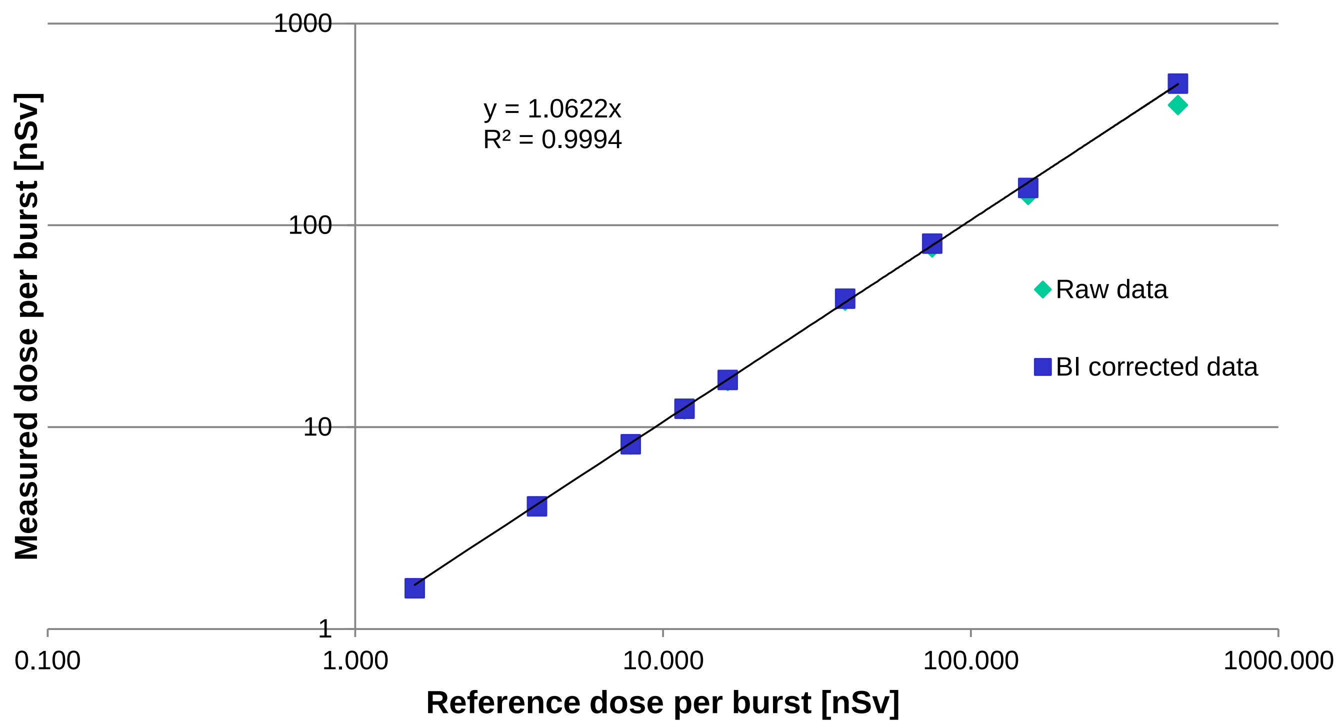


# Test at HZB 68 MeV protons on W

| Setting number | Ion current [pA] | Burst current [nA] | Burst length [μs] | Burst charge $Q_i$ [fC] | Reference burst yield [nSv per burst] | Average dose rate [μSv·h$^{-1}$] | Burst dose rate [Sv·h$^{-1}$] |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 5 | 1 | 5 | 0.077 | 27.72 | 0.28 |
| 2 | 1.5 | 15 | 1 | 15 | 0.231 | 83.16 | 0.83 |
| 3 | 3 | 30 | 1 | 30 | 0.462 | 166.32 | 1.66 |
| 4 | 5 | 50 | 1 | 50 | 0.770 | 277.2 | 2.77 |
| 5 | 10 | 100 | 1 | 100 | 1.540 | 554.4 | 5.54 |
| 6 | 25 | 250 | 1 | 250 | 3.850 | 1386 | 13.86 |
| 7 | 50 | 500 | 1 | 500 | 7.700 | 2772 | 27.72 |
| 8 | 75 | 750 | 1 | 750 | 11.550 | 4158 | 41.58 |
| 9 | 100 | 1000 | 1 | 1000 | 15.400 | 5544 | 55.44 |
| 10 | 250 | 250 | 10 | 2500 | 38.500 | 13860 | 13.86 |
| 11 | 500 | 500 | 10 | 5000 | 77.000 | 27720 | 27.72 |
| 12 | 1000 | 1000 | 10 | 10000 | 154.000 | 55440 | 55.44 |
| 13 | 3000 | 800 | 40 | 32000 | 492.800 | 177408 | 44.35 |

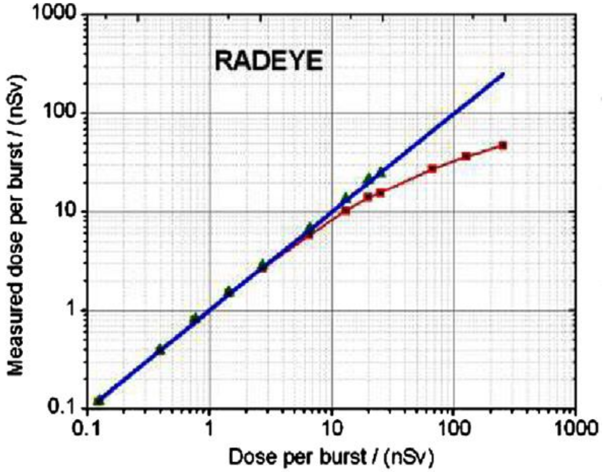

LUPIN ³He
y = 0.9852x
R² = 0.9991
1000
100
10
1
0
1
10
100
1000
Measured dose per burst [nSv]
Reference dose per burst [nSv]
Raw data
corrected data

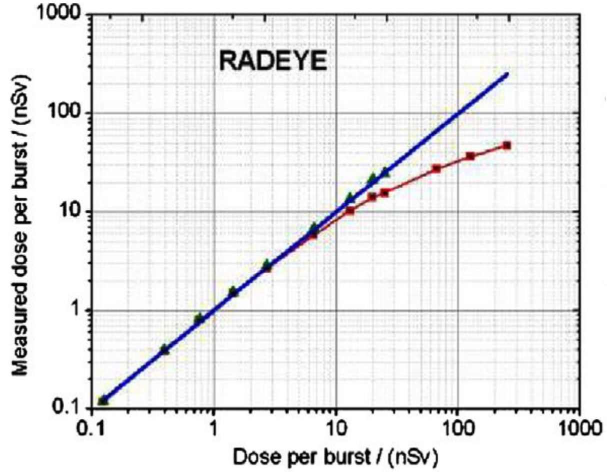
# LUPIN $BF_3$

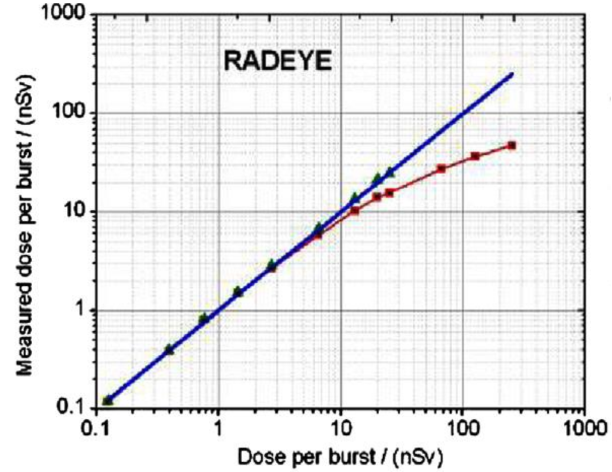


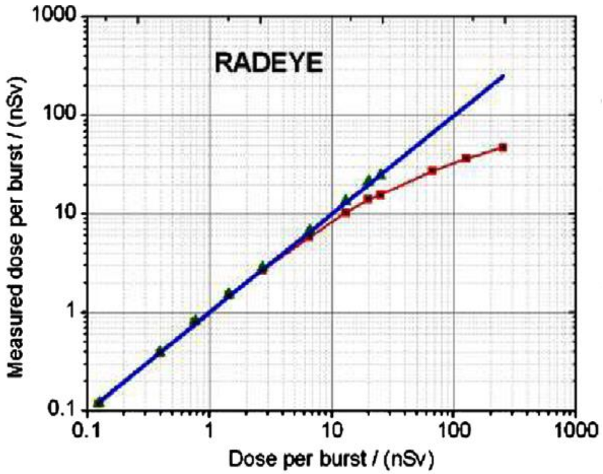
y = 1.0622x
R² = 0.9994
1000
100
10
1
0.100
1.000
10.000
100.000
1000.000
Measured dose per burst [nSv]
Reference dose per burst [nSv]
Raw data
BI corrected data

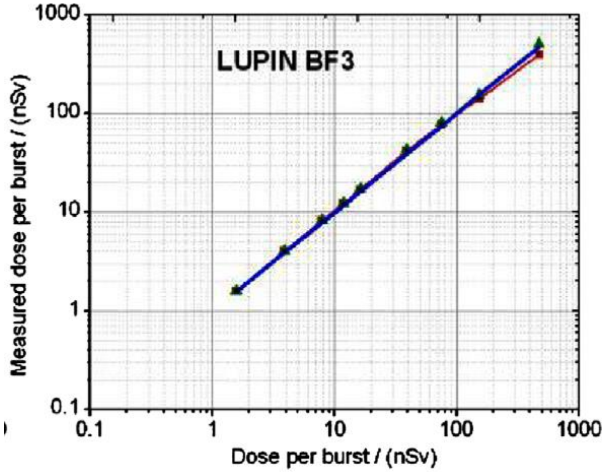
# Instruments comparison

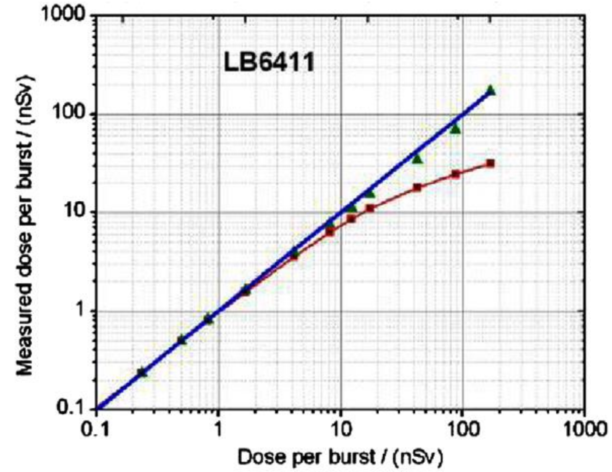


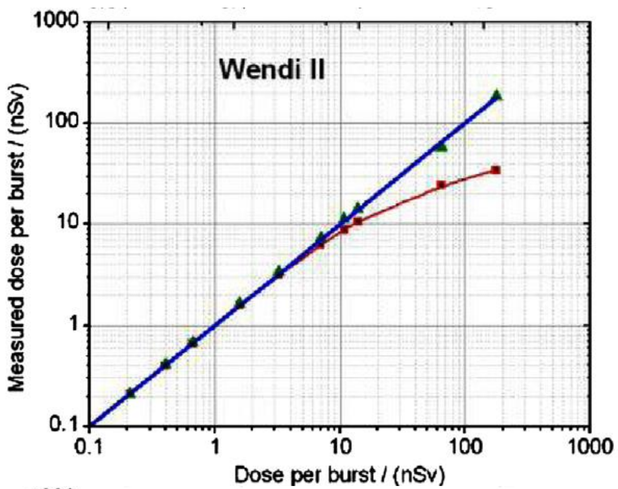



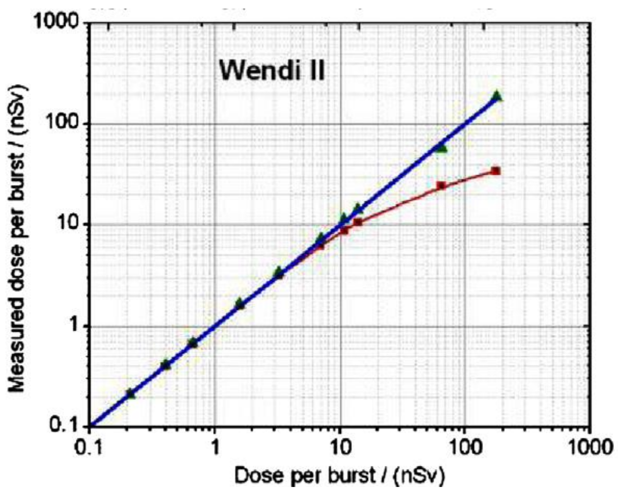



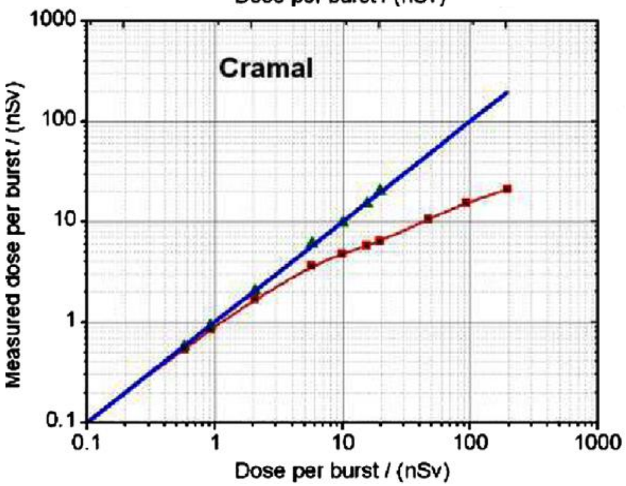



# Instruments comparison



# Space charge effect

The lack of linearity for the LUPIN is due to the space charge effect that shields electrostatically the inner anode producing a decrease in the multiplication factor.

The different behavior of the  two LUPIN version is in the different geometry.

The small detector has an higher charge density

# Neutron photon discrimination

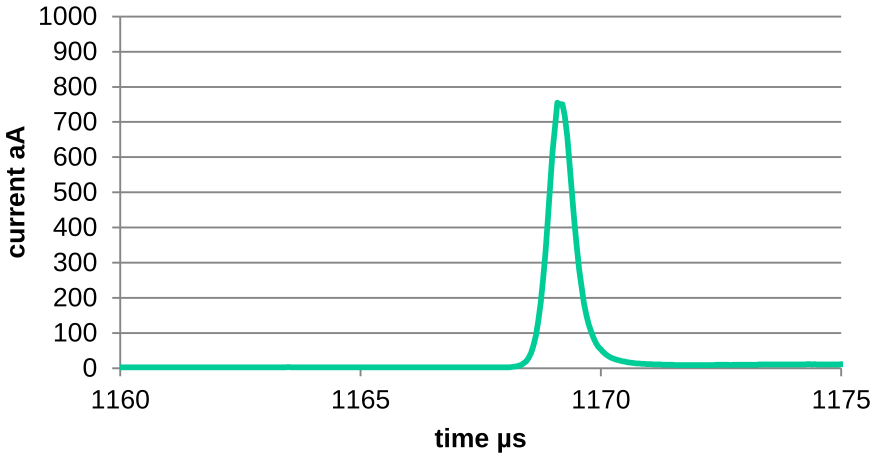
There are two possible scenarios

1) A mix and steady photons + neutrons field
2) A mix and pulsed photons + neutrons field

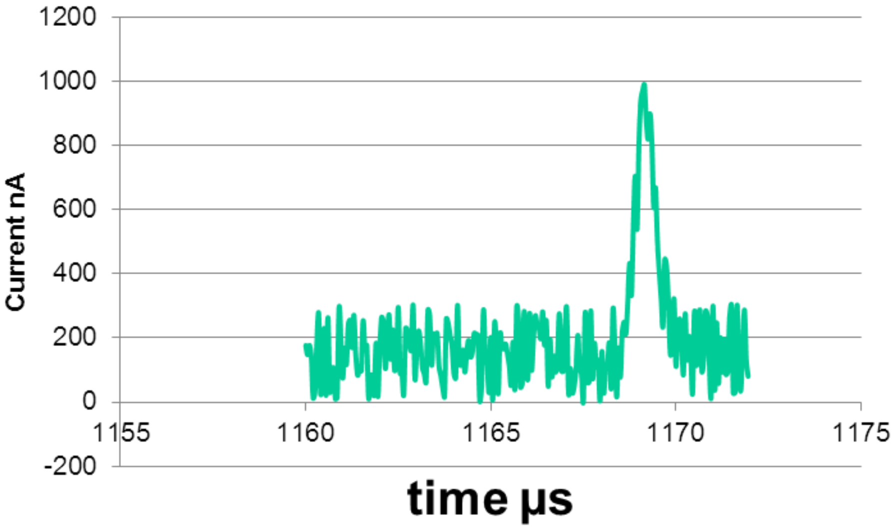
The techniques to cope with the two situations are different

# mix and steady photons + neutrons field

Neutron pulse without photon field



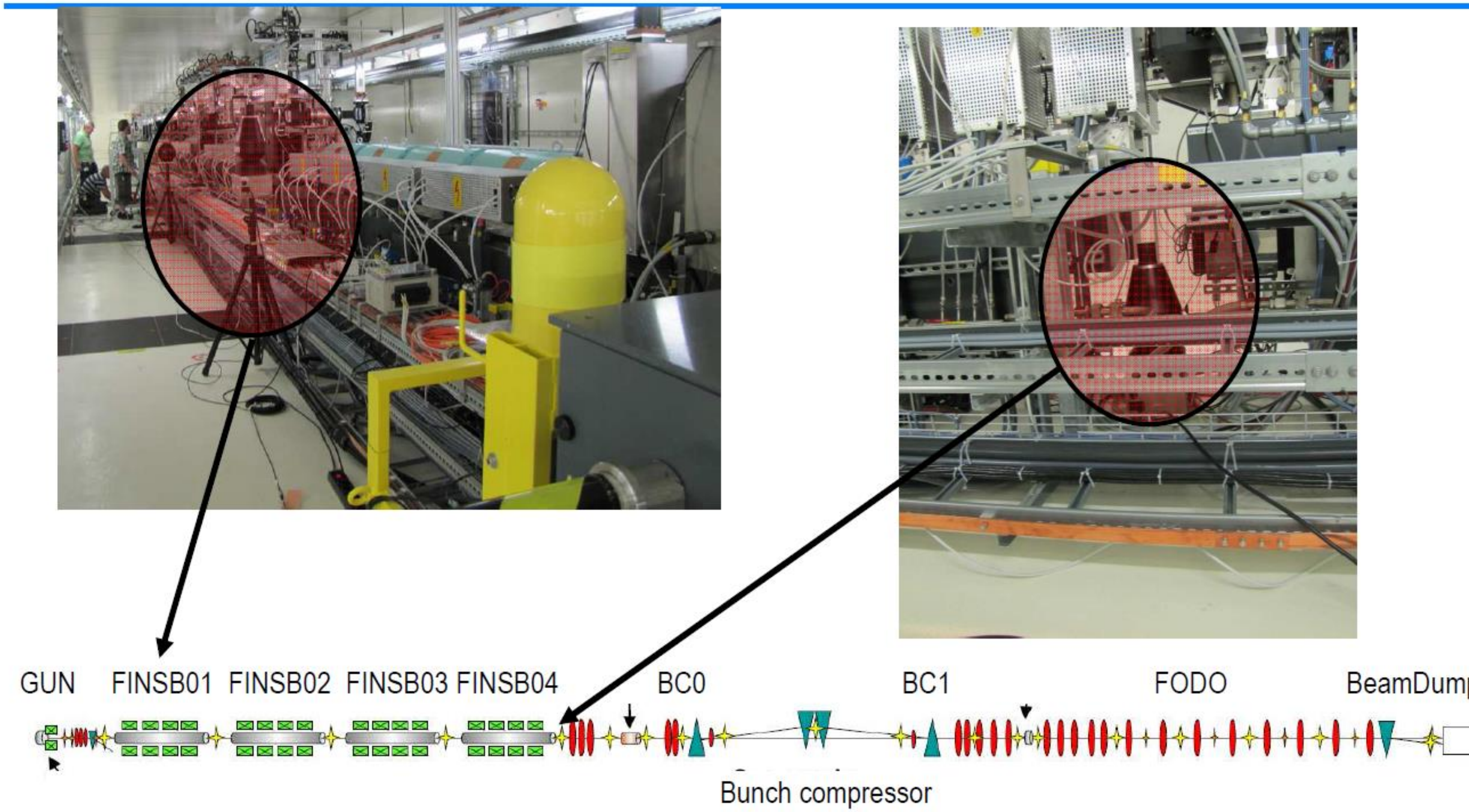

Neutron pulse photon field




The technique is to acquire the baseline variation using a pre-trigger

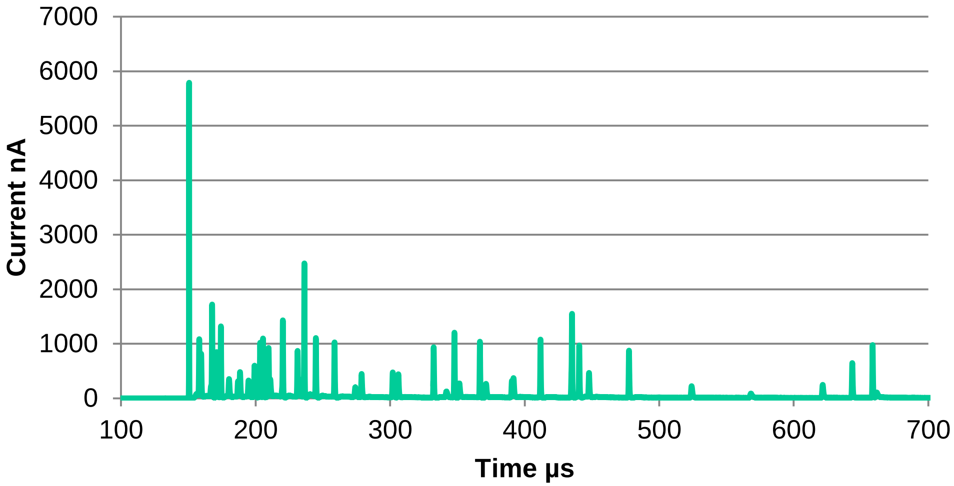
# mix and steady photons + neutrons field

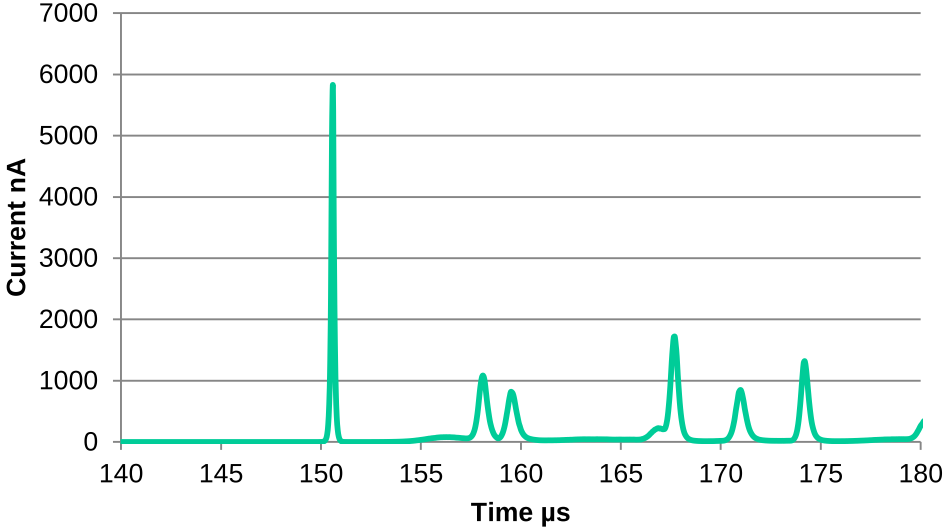
## Normal Operation: Measurement Positions 1




- Beam height
- Distance to Beam Line ~ 1 m

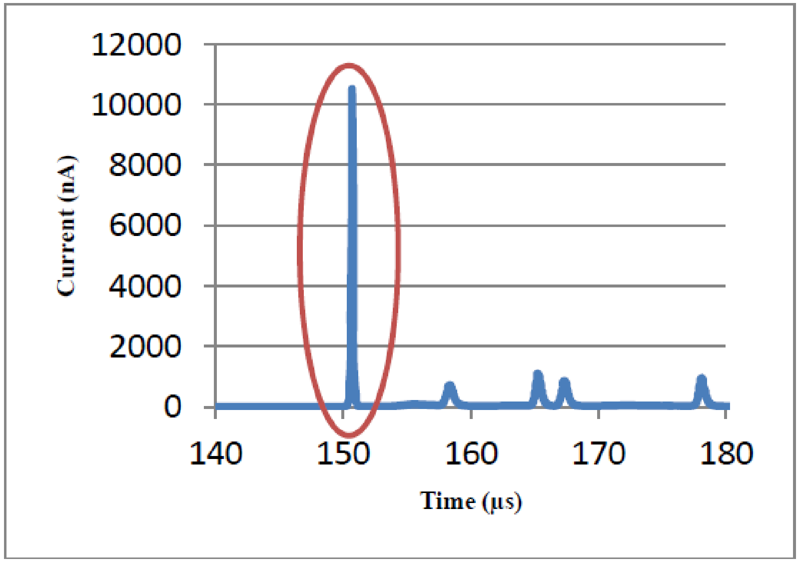
# mix and steady photons + neutrons field

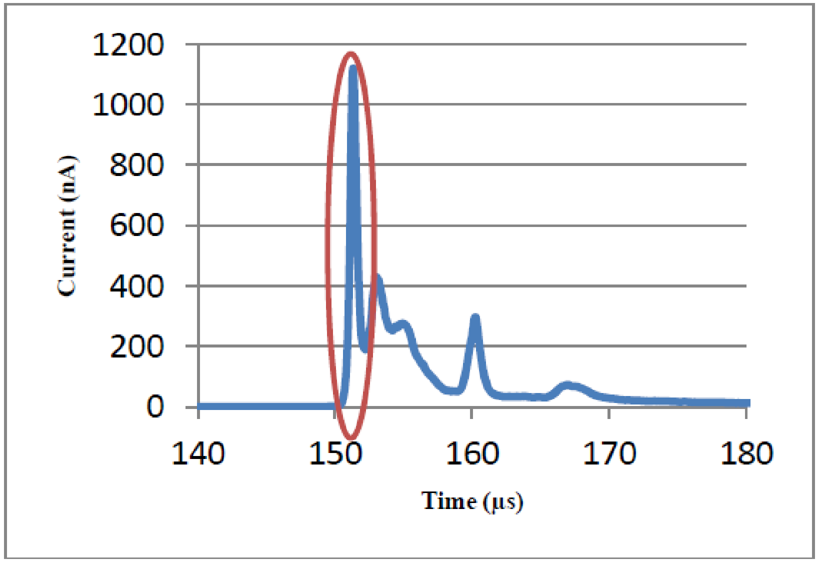


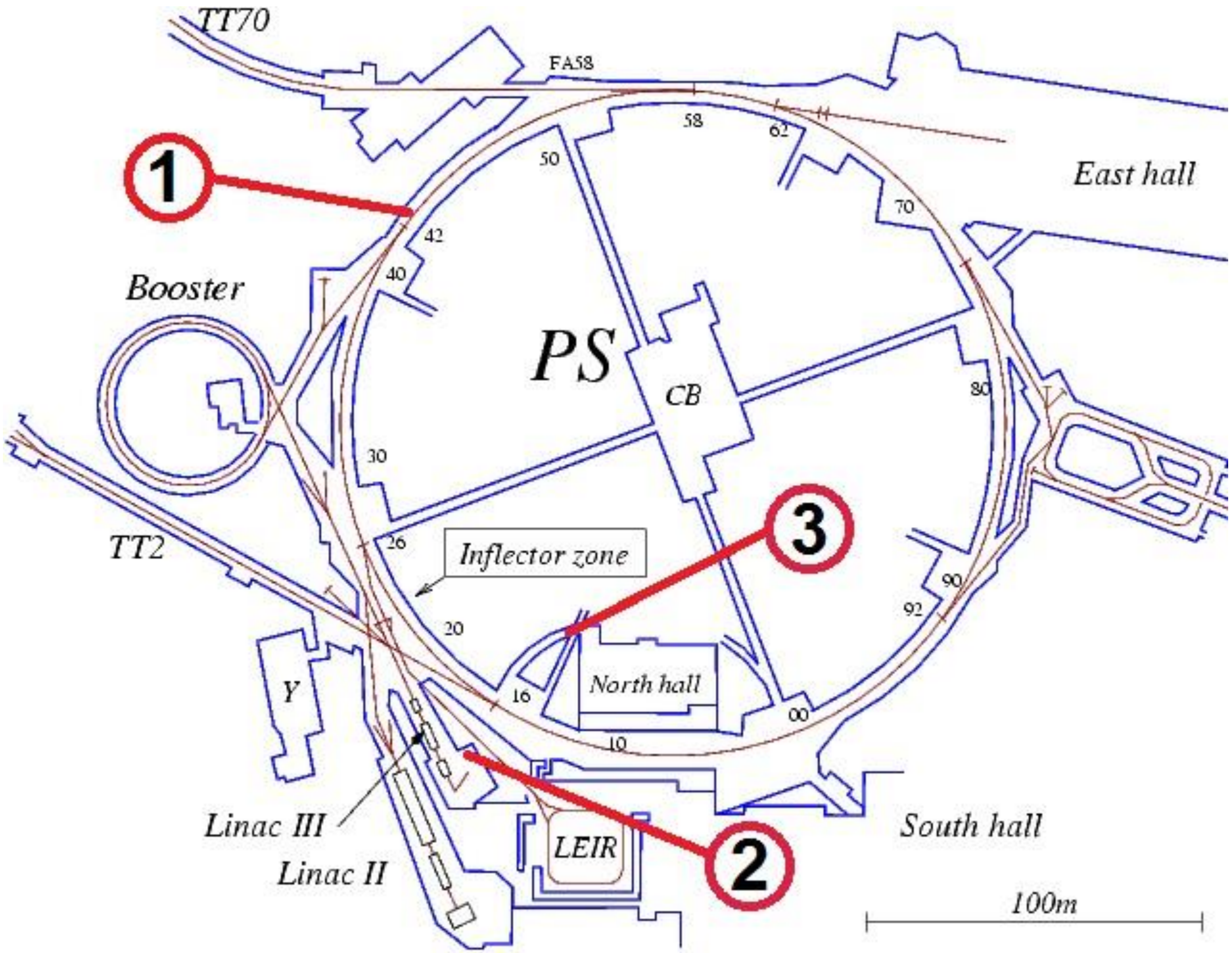
# mix and steady photons + neutrons field

Figure 1 Example $BF_3$ (Left) and 3He (Right) current plot including gamma contribution (circled in red)

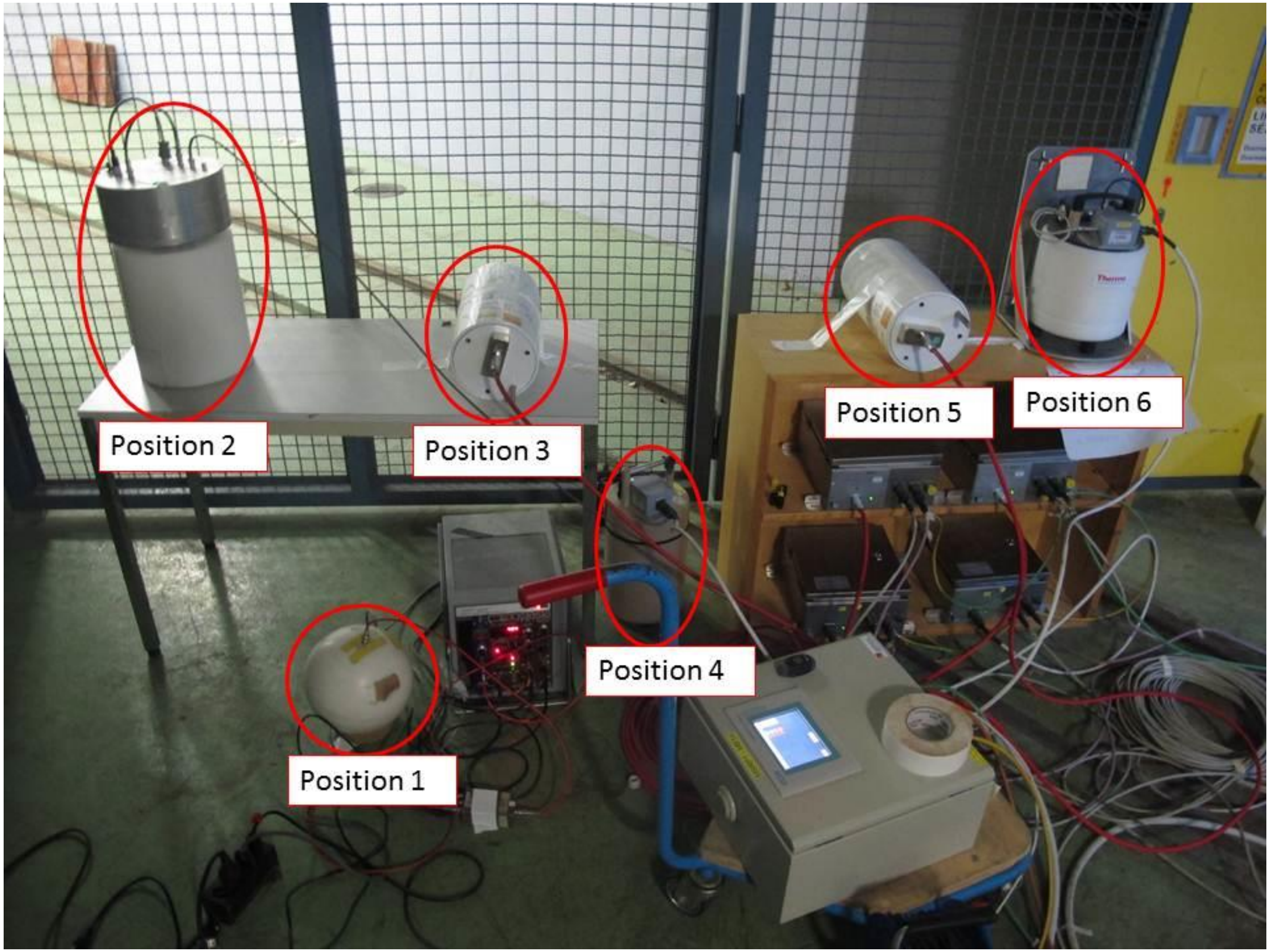


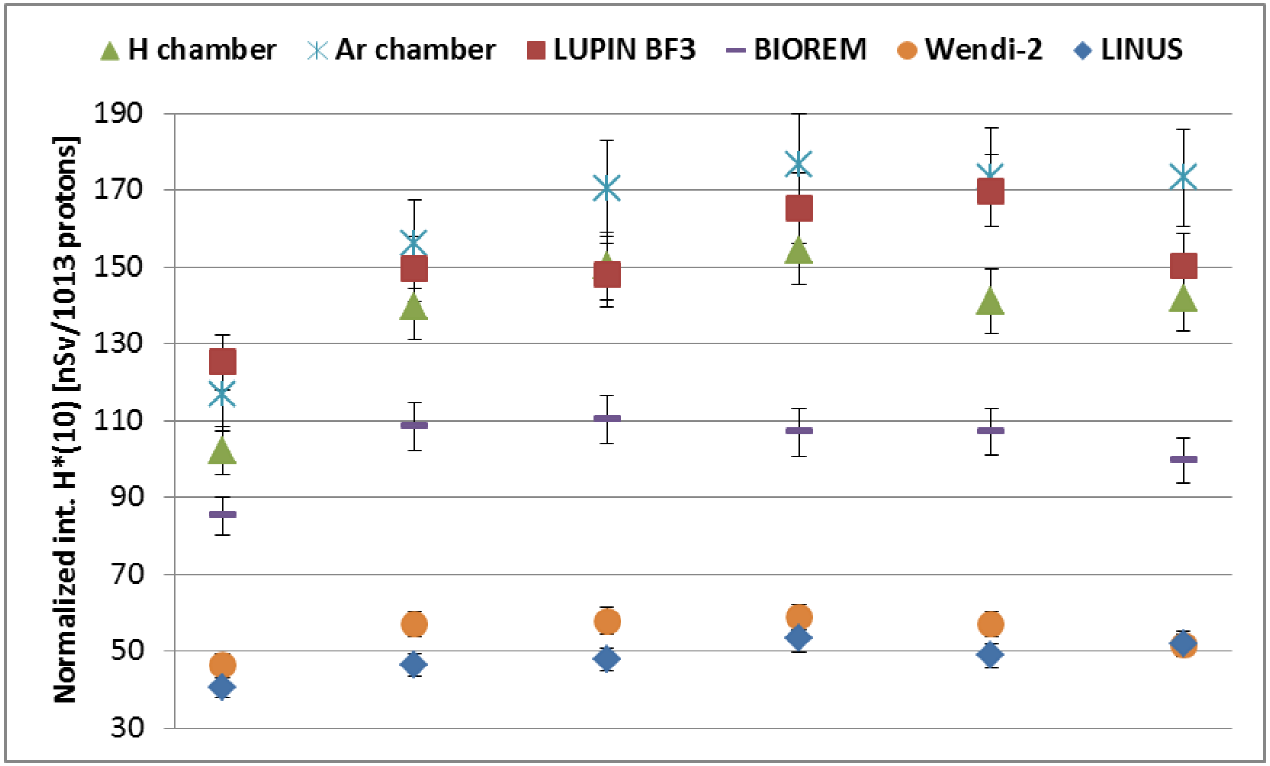
# Instruments comparison at CERN PS



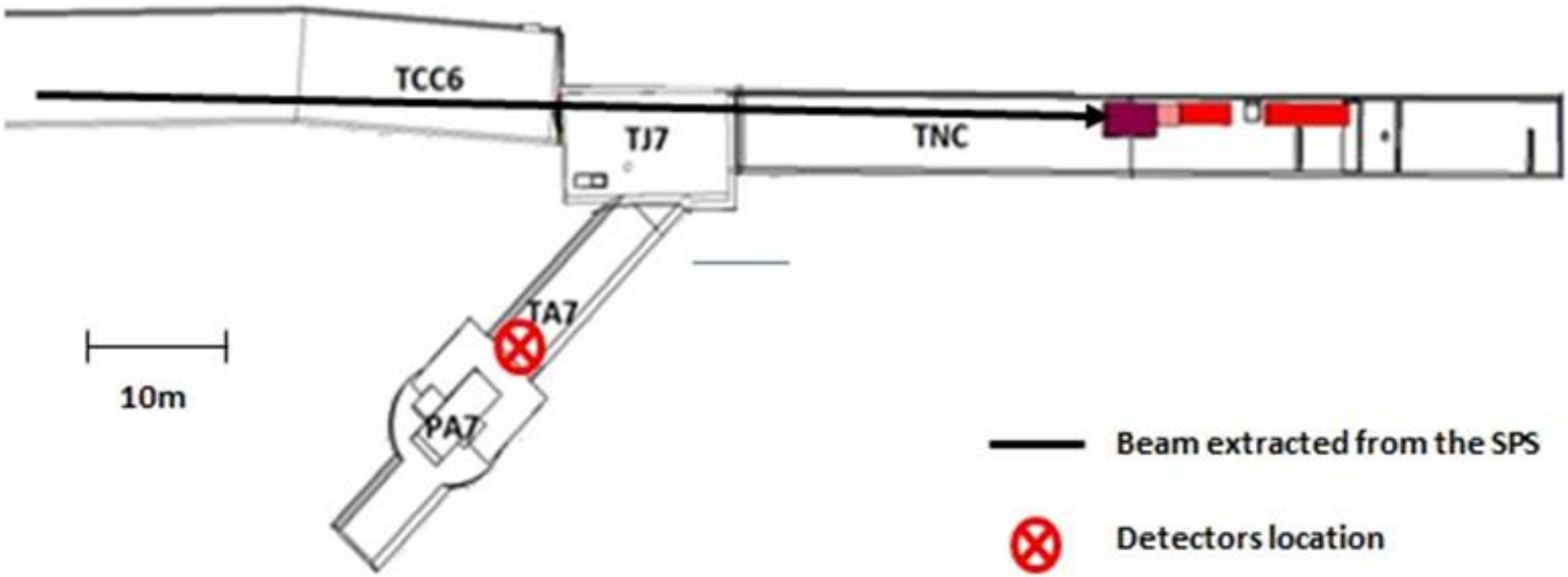
# Instruments comparison at CERN PS



# Instruments comparison at CERN PS

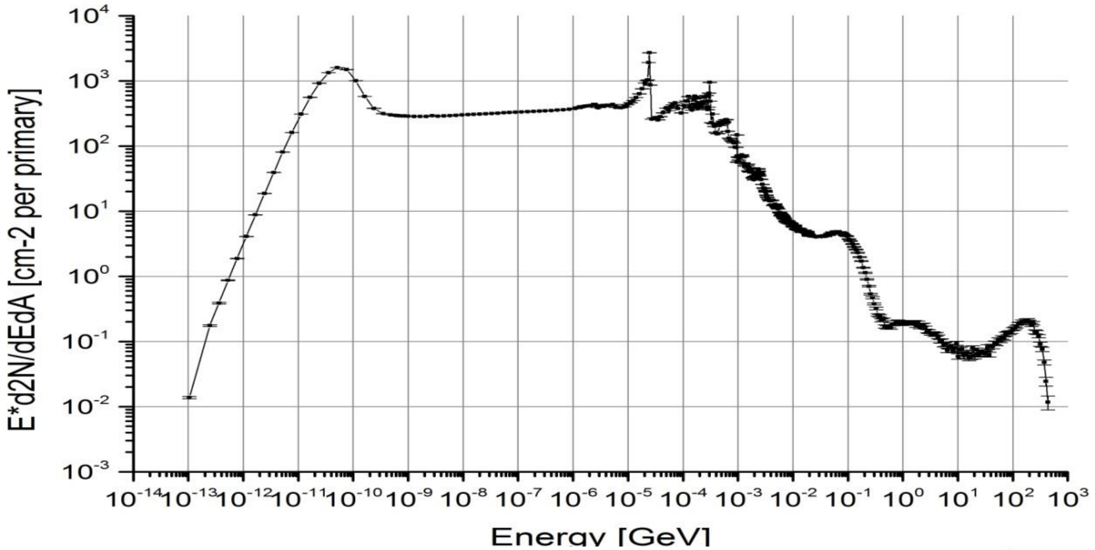


# Instruments comparison at CERN IRADMAT

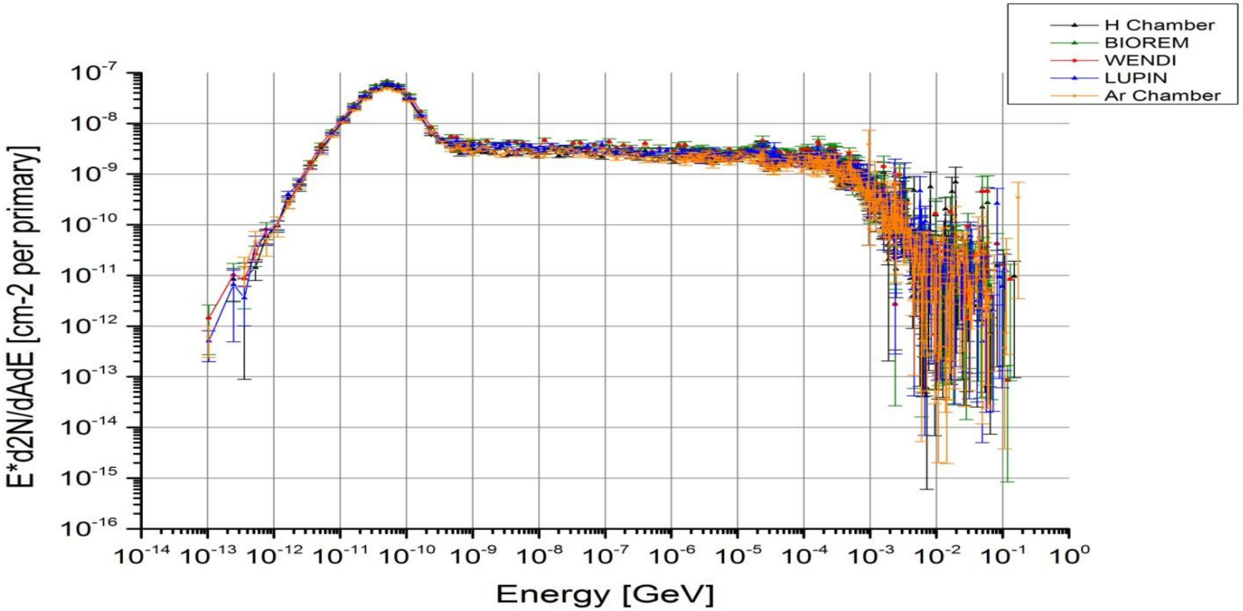


# Instruments comparison at CERN IRADMAT

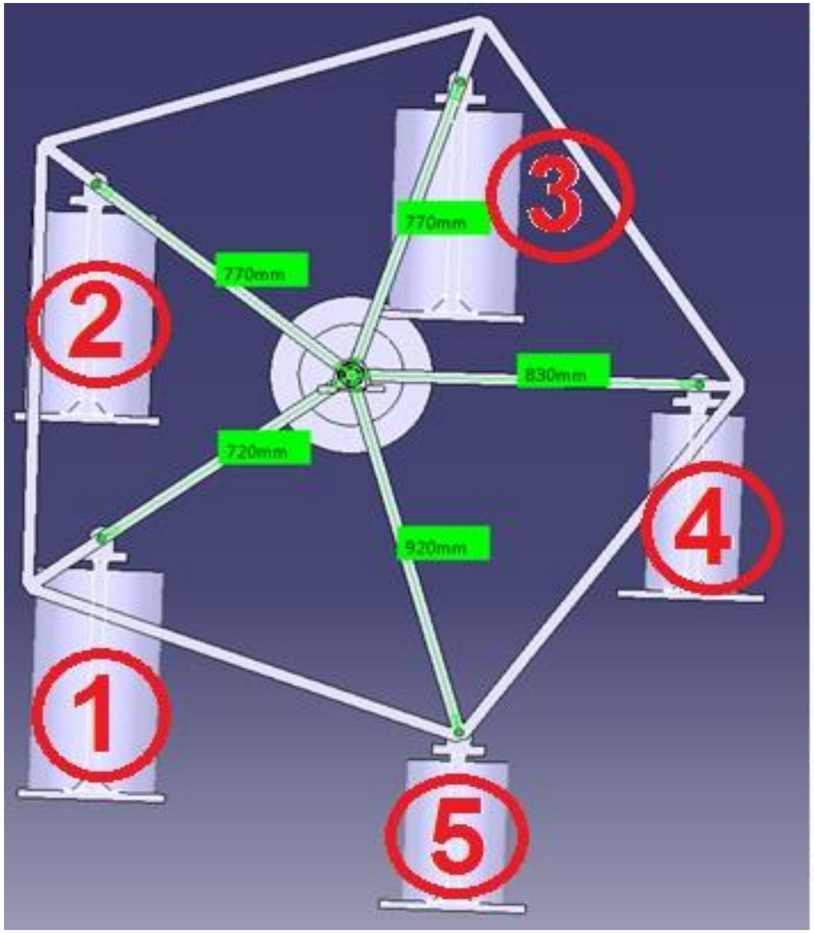
Two meters upstream the target

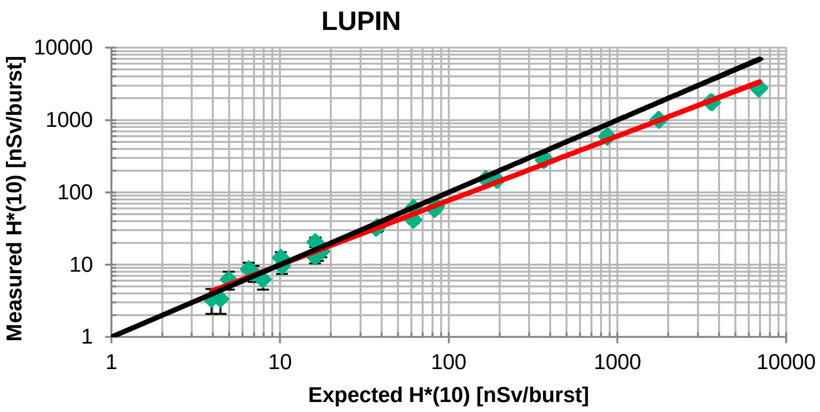


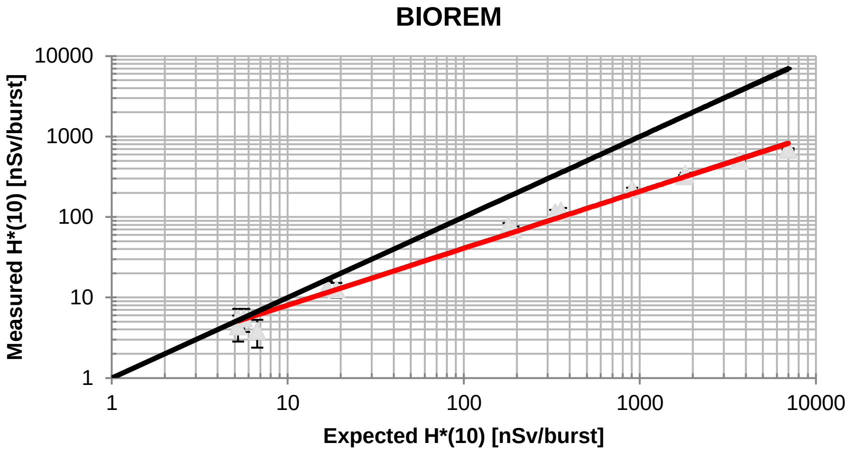

Instruments position

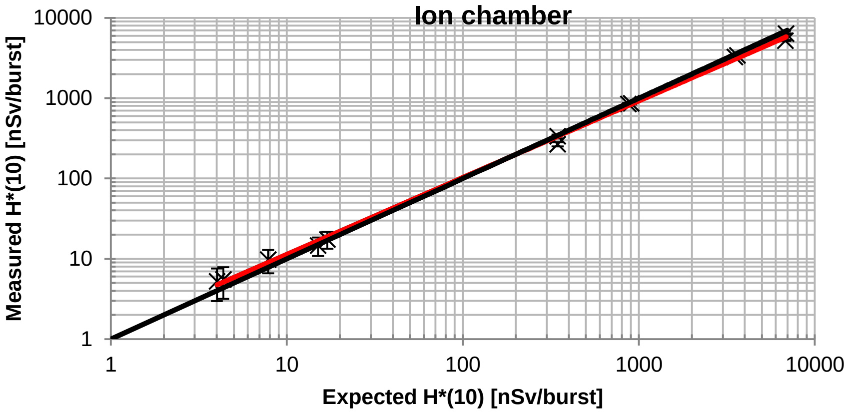


# Instruments comparison at CERN IRADMAT





LUPIN
Measured H*(10) [nSv/burst]
Expected H*(10) [nSv/burst]
1
10
100
1000
10000


BIOREM
Measured H*(10) [nSv/burst]
Expected H*(10) [nSv/burst]
1
10
100
1000
10000


Ion chamber
Measured H*(10) [nSv/burst]
Expected H*(10) [nSv/burst]
1
10
100
1000
10000

# ASTRID and ASTRID2 accelerators at ISA

at ISA, Aarhus, Denmark, around the ASTRID and ASTRID2 storage rings.

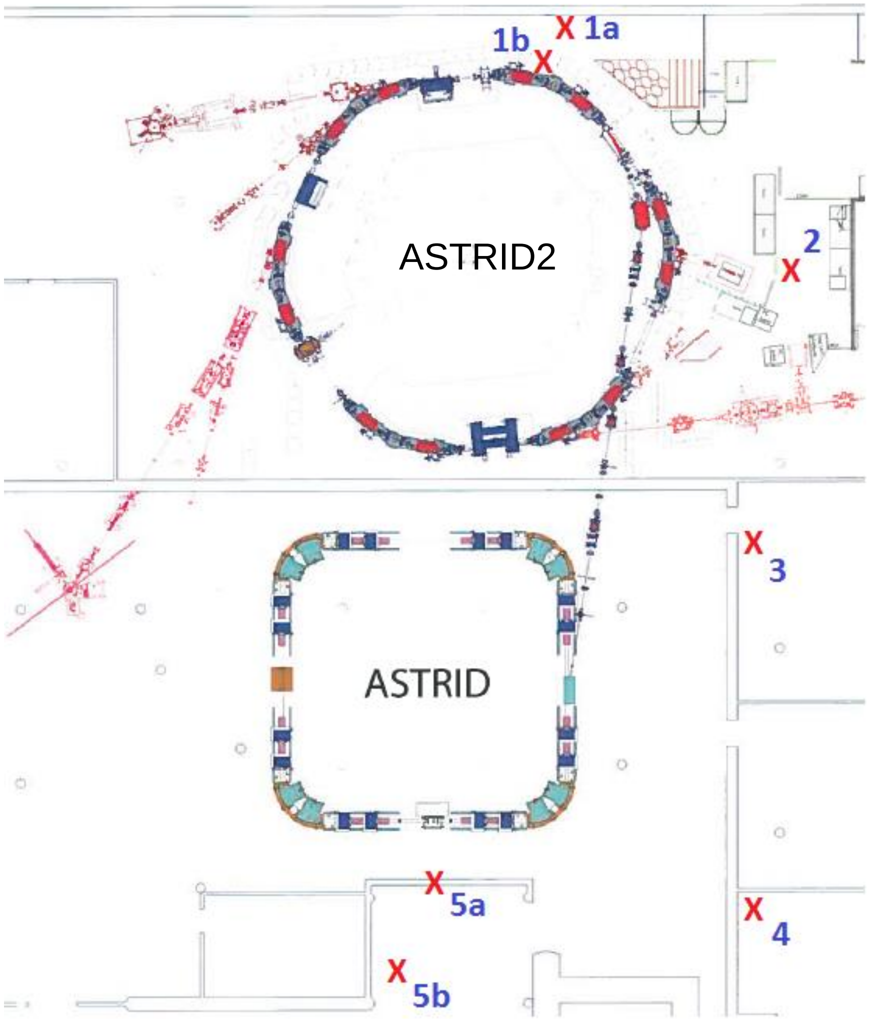
ASTRID is a 40 m long electron storage ring that has operated since 1990. It operates as a 580 MeV electron storage ring, injected from a 100 MeV racetrack microtron.

**ASTRID2** is a 45.7 m circumference storage ring located next to ASTRID that operates at 580 MeV.

ASTRID is used as an injector for ASTRID2 (one injection every 150-200 s, slow extraction mode), which maintains an almost constant circulating current fluctuating around 200 mA.

In ASTRID, a fast injection mode can also be operated, with an injection frequency from the microtron of 2 Hz.

Measurement of neutron H*(10) rate in 7 selected positions around the storage rings.



# Result of the measurements

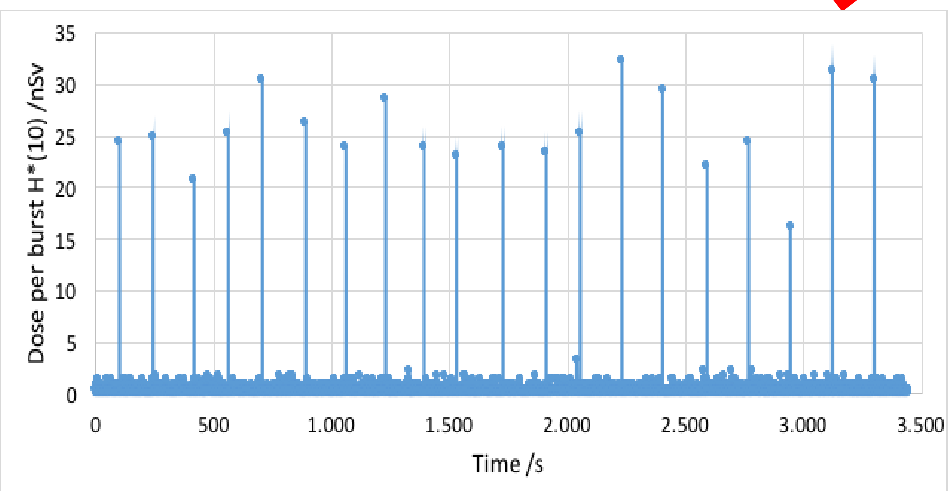


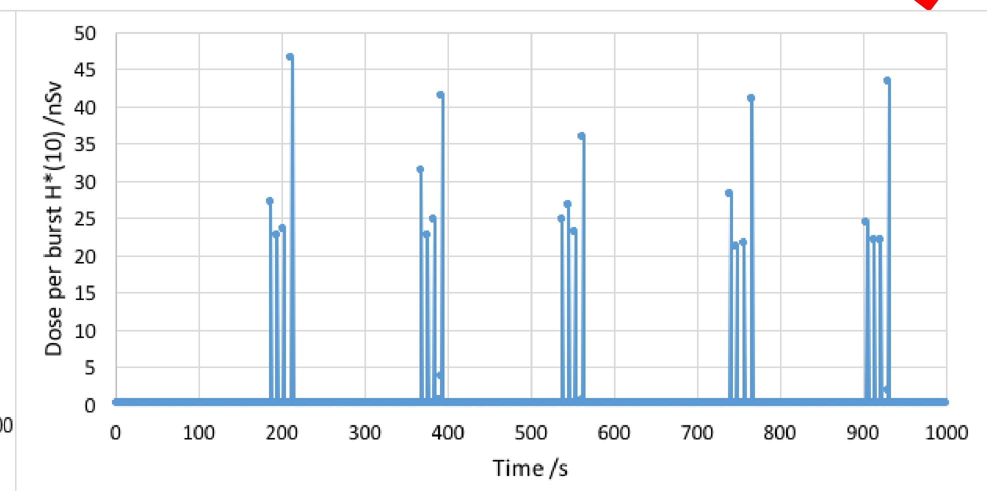
| Position | Extraction | H*(10) per burst [nSv] | Average H*(10) rate [µSv/h] |
|---|---|---|---|
| 1a | Slow | 5.6 | 0.37 ± 0.11 |
| 1b | Slow | 31.7 | 1.6 ± 0.2 |
| 2 | Slow | 1.9 | 0.26 ± 0.08 |
| 3 | Slow | 2.8 | 0.08 ± 0.01 |
| 3 | Fast | n.a. | 2.5 ± 0.8 |
| 4 | Slow | n.a. | 0.005 ± 0.001 |
| 4 | Fast | n.a. | 0.15 ± 0.05 |
| 5a | Slow | 27.7 23.3 23.5 43.7 | 2.4 ± 0.3 |
| 5a | Fast | n.a. | 405 ± 63 |
| 5b | Fast | n.a. | 41.5 ± 10.1 |

10 mHz

Fast extraction 2Hz

The dose per burst is not measured for fast extraction mode (n.a.) because the dose is sampled every second

# Open question

Can the LUPIN be of any interest for measuring stray neutron around medical facilities? i.e. activities related to the WG9?

# Space charge effect

In case of intense burst the charge generated inside the proportional counter can shield the electric field causing a decrease in multiplication factor with a consequent underestimation of the charge

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A novel technique for compensation of space charge effects in the LUPIN-II detector

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[c] Fondazione CNAO, via Caminadella16, 20123 Milano, Italy

# Space charge effect

$$M = \exp\left[\frac{V}{\ln\frac{b}{a}}\frac{\ln 2}{\Delta V}\cdot ln\left(\frac{V}{K * p * a * \ln\left(\frac{b}{a}\right)}\right)\right] = \left(\frac{Q}{e}\right)\cdot\left(\frac{W}{E}\right)$$

$$M' = \exp\left[\frac{V-\delta V}{B}\cdot\ln\left(\frac{V-\delta V}{C}\right)\right]$$

$$\delta V = \frac{E}{W}\cdot\frac{eb^2}{\mathrm{Vol} * 4\varepsilon_0}\cdot N_i\cdot M'$$

$$M' = \frac{1}{\exp\left[-\frac{V}{B}\ln\left(\frac{V}{C}\right)\right] + \frac{D}{B}\cdot N_i\cdot\left[1+\ln\left(\frac{V}{C}\right)\right]}$$

$$D = \frac{E}{W}\cdot\frac{eb^2}{\mathrm{Vol} * 4\epsilon_0}$$

# Space charge effect compensation

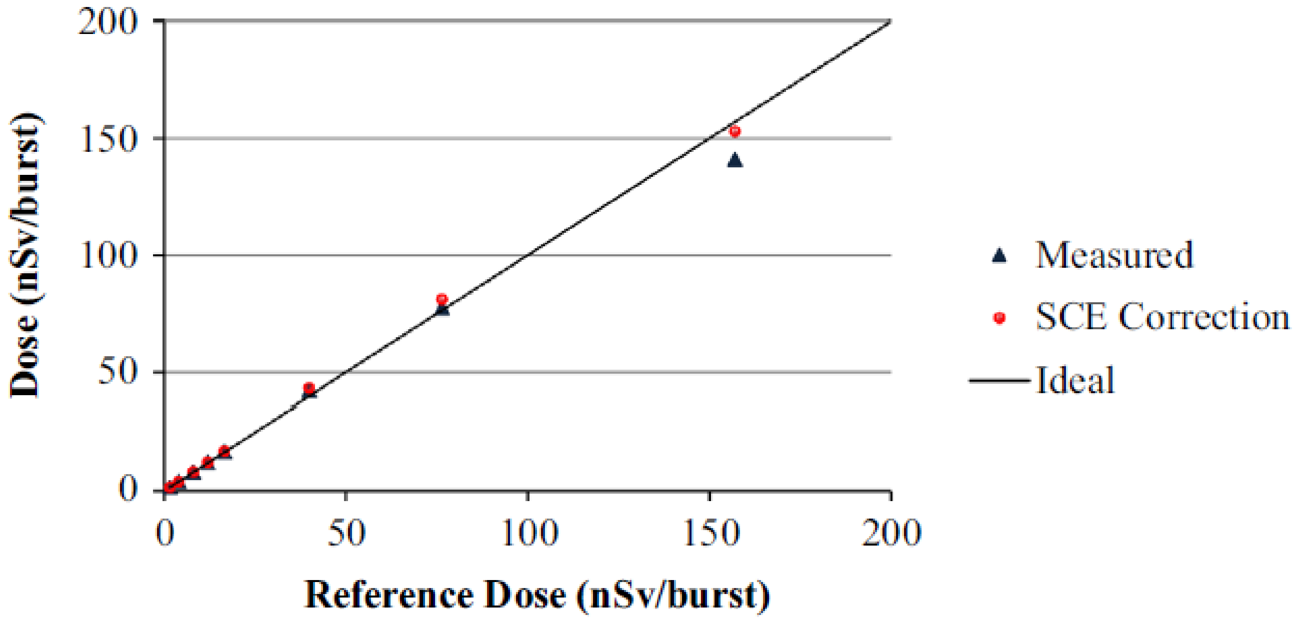


**Fig. 4.** Improvement of detector performance due to SCE compensation of HZB data.

# Space charge effect compensation

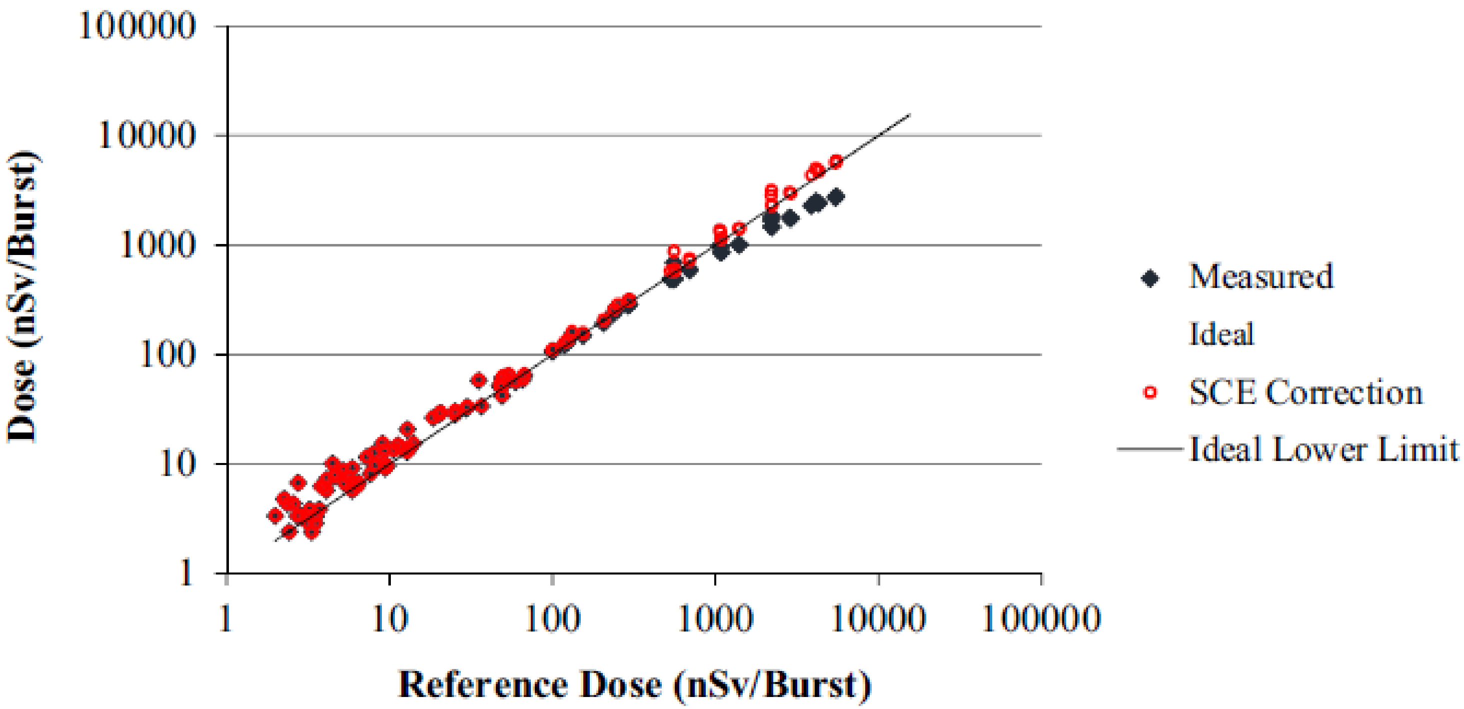


**Fig. 6.** Improvement of detector performance due to SCE compensation of HiRadMat data.