IBIC 2019

International Beam Instrumentation Conference

Malmö, Sweden
8-12 September 2019

Characterization and first detection of beam losses with one detector of the ESS-nBLM system

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09/09/2019

Motivation & Context

nBLM Detectors

- Fast and Slow

Detector characte-rization

- MC results
- 1st beam loss detection

Conclusions

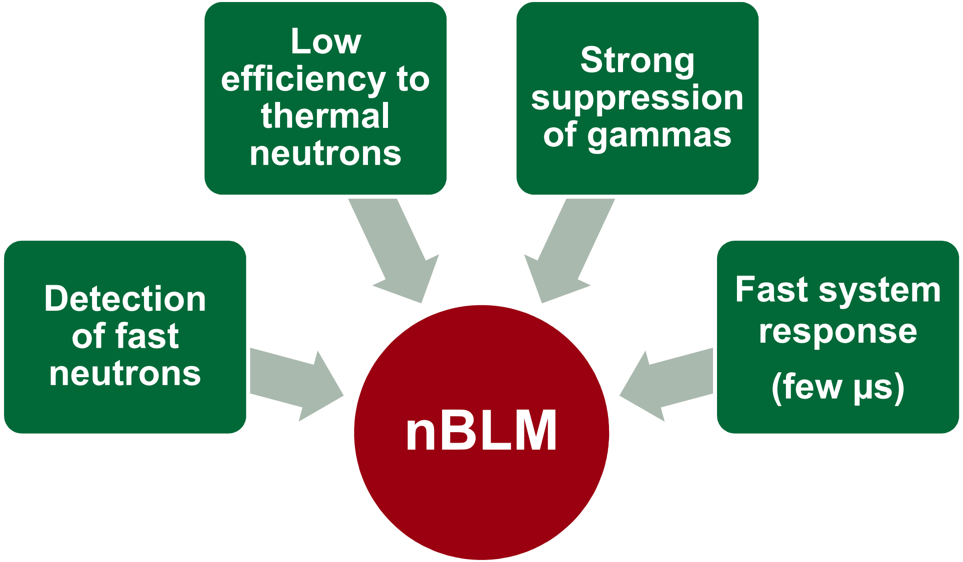
Why new Beam Loss Monitors (BLM)?

- To enlarge sensitivity at low energy regions of the accelerator
  - In new high intensity hadron linear accelerators even low energy beam could damage the accelerator or activate materials
  - Keep the loss <~ 1 W/m to allow hands-on maintenance
    - ESS 5MW → $2x10^{-5}$ /m of the total power (0.02 ‰)
- **Positioning of the BLM is important**
  - Different beam loss signature
  - At **low beam energy** only neutrons and photons can escape the beam pipe
  - Low rates since close to the reaction thresholds
  - RF x-rays represent a problem for loss measuring in linacs
  - Initial efforts at SNS to develop only neutron sensitive detectors

"…the x-ray component is quite significant and can be even greater than the loss itself. A detector that is sensitive to neutrons and not sensitive to x-rays could be a possible solution. Unfortunately it is hard to create such a detector that would work in analog mode."

A. Zhukov, WEYA2, PAC2013

NEUTRON BEAM LOSS MONITOR

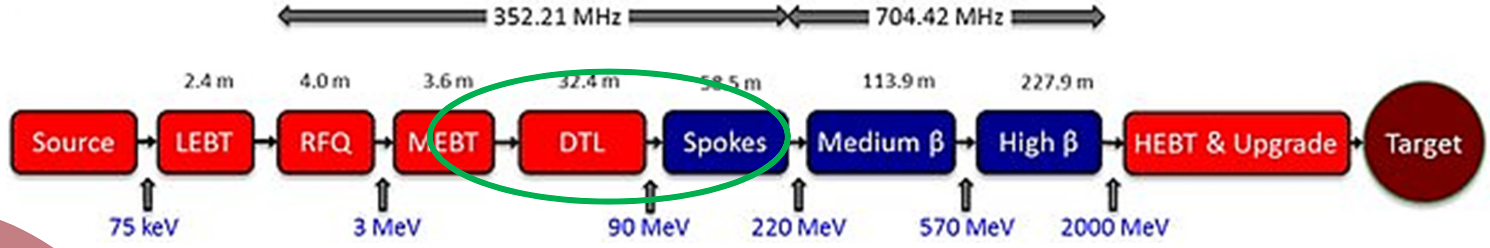


nBLM (*neutron Beam Loss Monitor*) →

- Fast neutron detector **based on Micromegas** (MMs) equipped with a combination of neutron convertors and moderators

CONTEXT: ESS-NBLM SYSTEM

- **Project: In-kind** contract between the European Spallation Source (ESS) and IRFU
  - Design, construction, test and delivery of 84 detectors by end 2019 + commissioning with commissioning of the machine
  - Part of the Beam Instrumentation systems of the ESS Accelerator (Lund, Sweden)
  - Dedicated mainly to the low energy region of the accelerator.



ESS-nBLM System

- Req. & spec. develop. : ESS
- Concept: CEA + ESS
- Detectors: CEA
- Gas System: CEA
- DAQ firmware: LUT
- Control System: CEA
- Installation: ESS
- Integration: CEA & ESS

ESS BLM system lead: *I. Dolenc Kittelmann*
CEA coordinator: *T. Papaevangelou*

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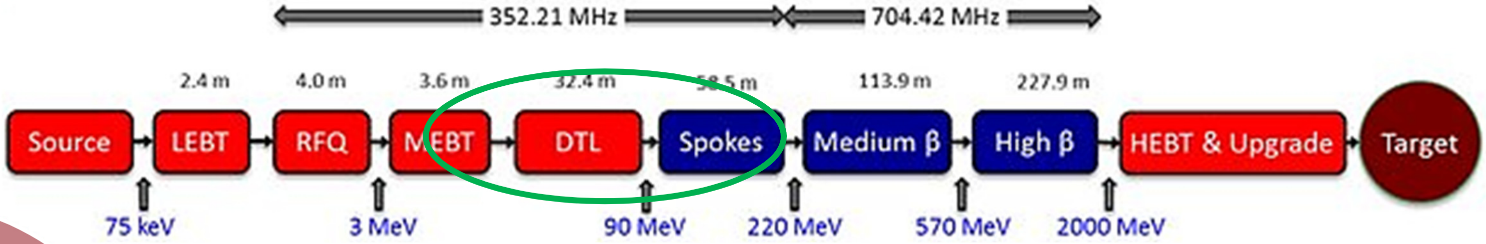

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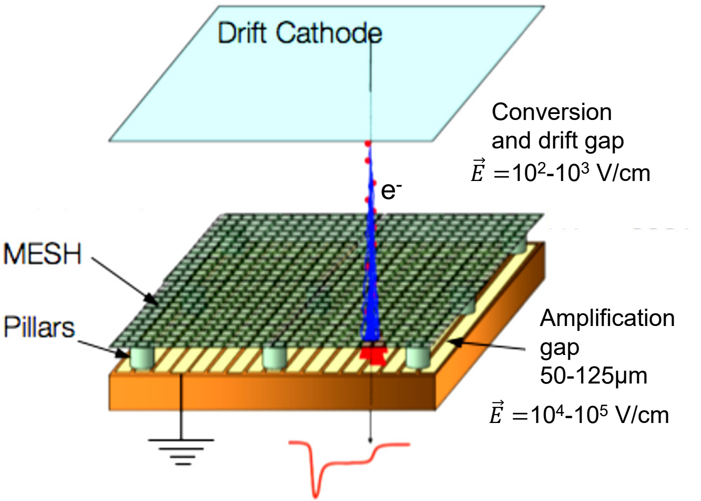
MicroMesh Gaseous Structures (**Micromegas**[1]) are an improved amplification structure to measure the ionization signal in a gaseous detector.

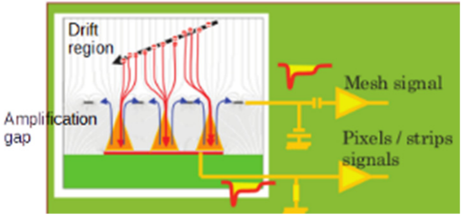
[1] Y. Giomataris, P. Rebourgeard, J.P. Robert and G. Charpak, "Micromegas: A high-granularity position sensitivegaseous detector for high particle-flux environments", Nuc. Instrum. Meth. A 376 (1996) 29.

- Two parallel plates:
  - A metallic micromesh suspended over an anode plane by insulator pillars
  - Defines two separate zones
    - Conversion zone: primary e^- are produced
    - Amplification zone: detectable avalanche is produced in the Micromegas

- Micromegas has high gain, fast signals, are rad. hard, robust and stable. They have been used in a large list of particle and nuclear physics experiments



To detect neutrons we need a neutron-to-charge particle convertor: it can be placed at the entrance of the conversion zone

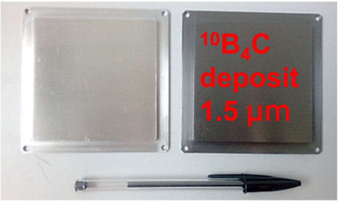


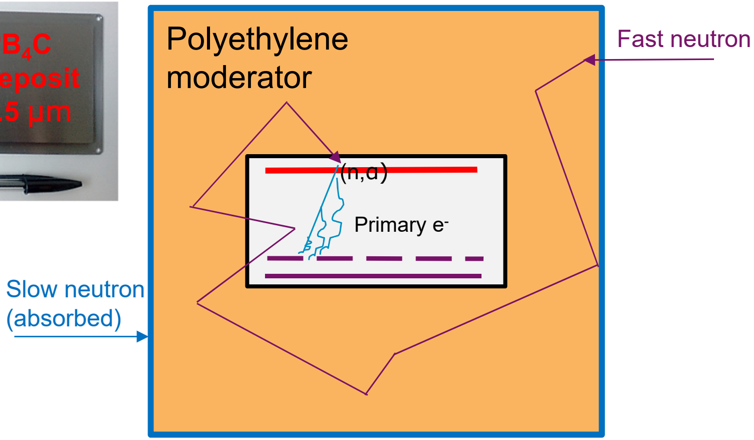
NBLM DETECTORS GEOMETRY

Two complementary modules with detector chamber identical, differences being:

- **neutron-to-charge particle convertor**
- **and the surrounding of the slow with absorber + moderator**

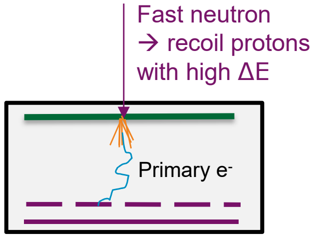
SLOW

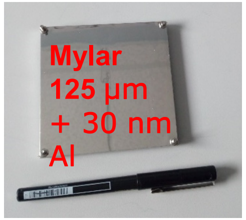




- Borated rubber (5 mm)
- Polyethylene (5 cm)
- Aluminium chamber
- **$^{10}B_4C$ deposited on Al**
- $He+CO_2$ gas
- MMs detector

FAST



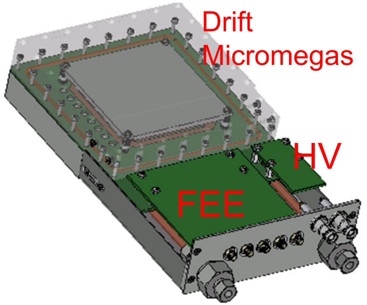


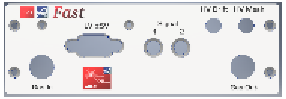
- Aluminium chamber
- **Plastic convertor on Al**
- $He+CO_2$ gas
- MMs detector

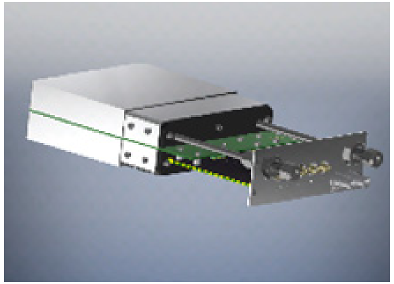
NBLM DETECTORS CHARACTERISTICS

	SLOW	FAST
neutron-to-charged particle convertor	B_4C	Mylar or Polypropylene
Reaction	$^{10}B(n,\alpha)^{7}Li$	(n,p)
Signal produced by	Fast neutrons after moderation	Fast neutrons
Detected energy	~constant for all initial neutron energy	Depends on initial neutron energy
Sensitivity	10^{-4} < En < 100 MeV	En > 0.5 MeV
Solid angle	4π	2π, n coming from the front only
Efficiency	~few $n \cdot cm^{-2} \cdot s^{-1}$	~10-100 times smaller
Response time	~200 μs	~0.01 μs
Objective	Monitoring of small losses	Fast detection (response in 5 μs) Fine structure of the lost
Shielding	Yes, for thermal neutrons	Not needed

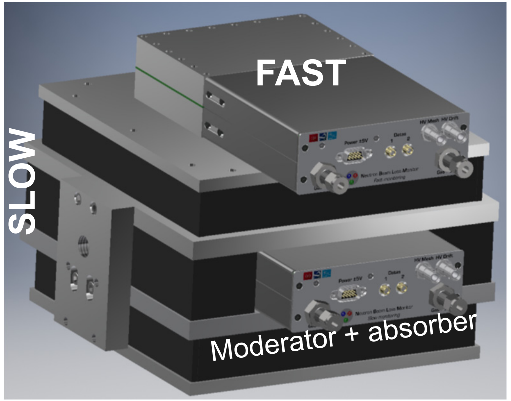
THE ESS-NBLM FINAL CHAMBERS





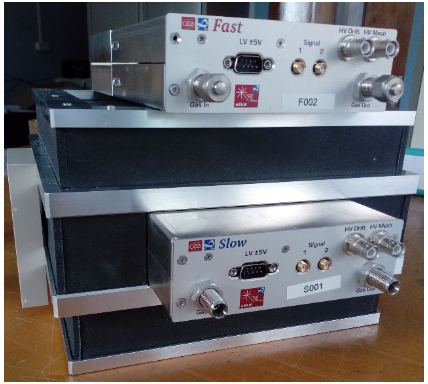


Chamber +
Faraday Cage ~ 20 x 15 x 2 cm^3



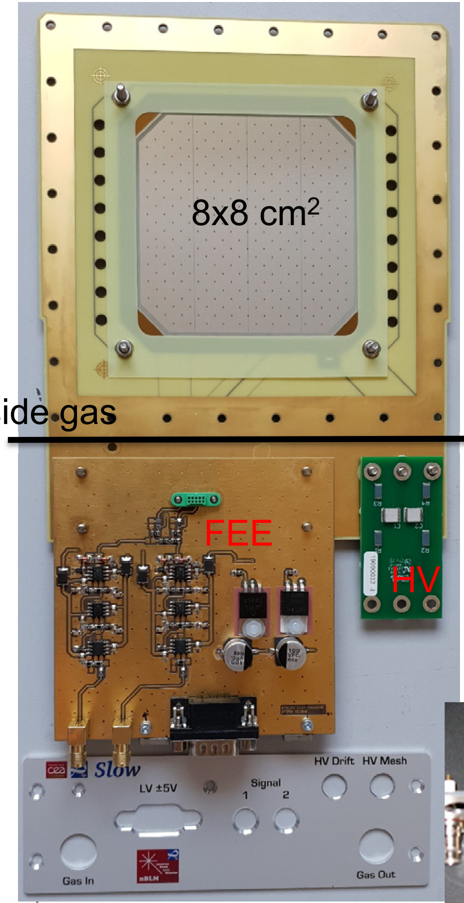
Assembly of a fast and a slow detector
size ≈ 20 × 25 × 25 cm^3 (~14 kg)

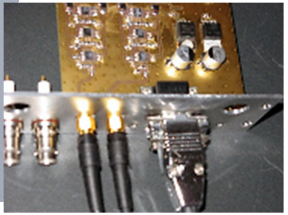
Moderator + absorber



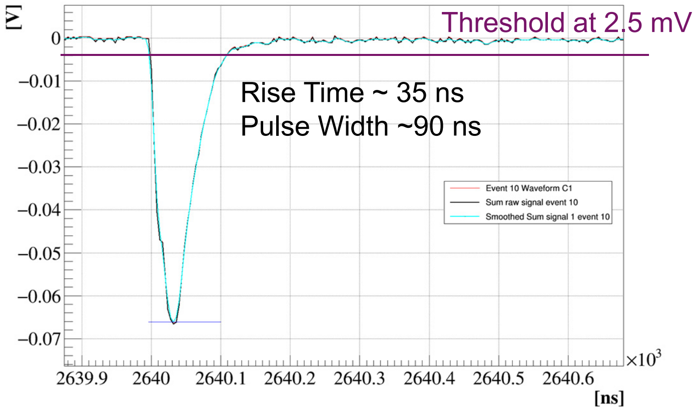
THE NBLM MICROMEGAS & FEE

- Bulk Micromegas (MPGD workshop at CEA/Saclay)
- Segmented in 4 sectors to accommodate for final rates
- Only one signal output (adding 1 to 4 segments together)
- Small drift gap: ~2 mm
- Operating in He+10% CO_2, 1 atm, circulation mode (1l/h/detector)
- FEE card and amplifiers designed at CEA
- Can operate in counting and charge mode



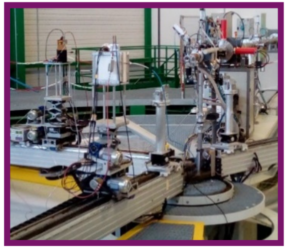
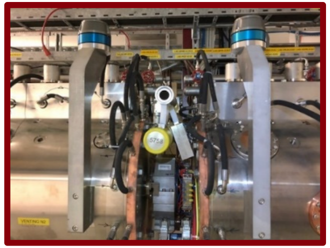
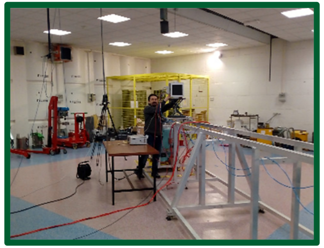


Single neutron acquired with the FEE final nBLM electronics at LINAC4



NBLM EXPERIMENTAL TESTS



July 2016

Kick-off

MC40- Cyclotron Birmingham, UK

Dec 2017

Correlation rate and intensity of the beam

IPHI, CEA, France

Jan. 2018

Time Response

AMANDE, IRSN France

Mar. 2018

- Calibration
- n/γ discr.

ORPHEE, CEA France

Apr. 2018

- Thermal neutrons

LINAC4 (CERN)

Nov-Dec. 2018

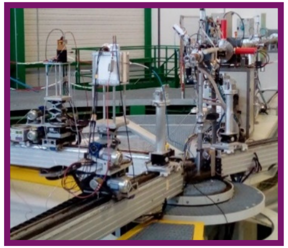
Real accelerator conditions

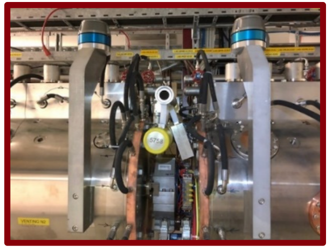
High intense n/γ sources, CEA France

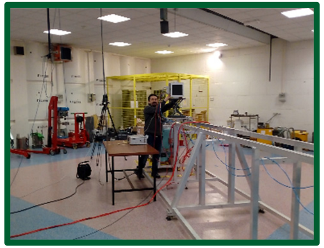
Feb. 2019

n/γ discrimination

NBLM EXPERIMENTAL TESTS







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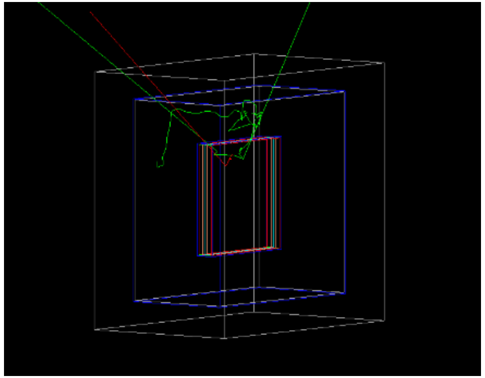
Paper under preparation

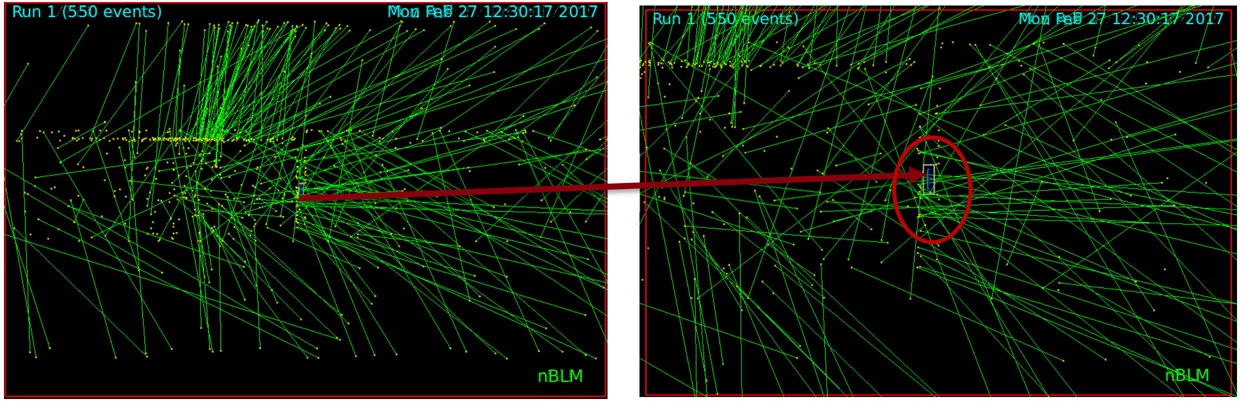
MONTE CARLO STUDIES

Monte Carlo simulations have been carried out in order to:

- Optimize the detectors features
- Estimate the expected response using as input data simulated by ESS-BI (I. Dolenc-Kittlemann) of normal, uniform and dramatic loss conditions



Simulations to study the geometry



Simulated dramatic loss at ¾ DTL1
Fast nBLM placed between DTL1 and DTL2

Simulations done in GEANT4

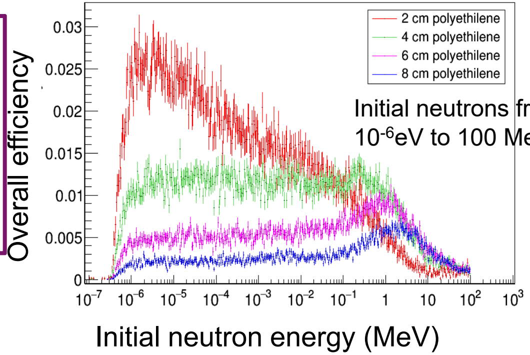
MONTE CARLO STUDIES

Monte Carlo simulations have been carried out in order to:

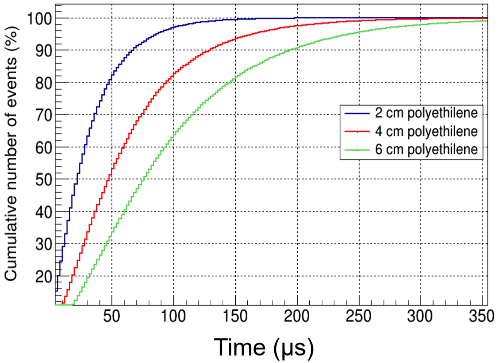
- **Optimize the detectors features**

Efficiency

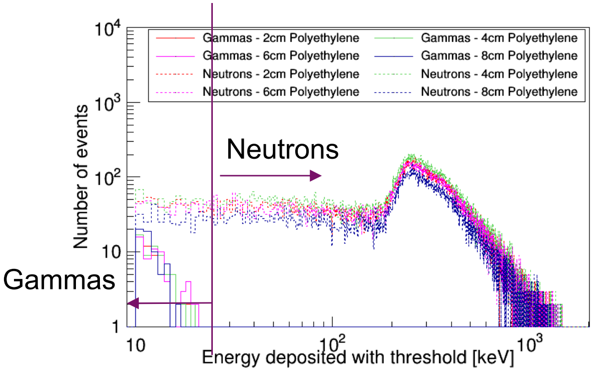
SLOW



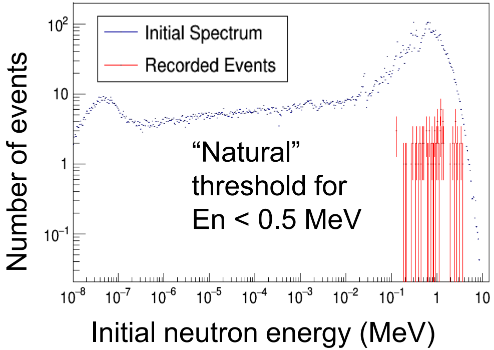
Time response

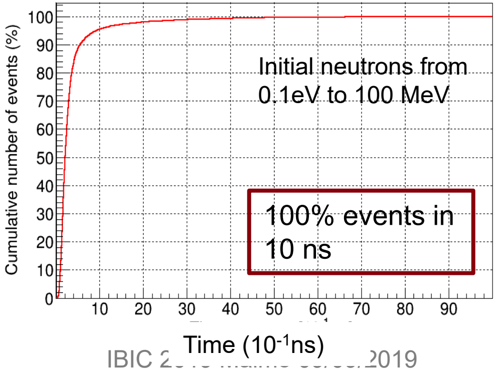


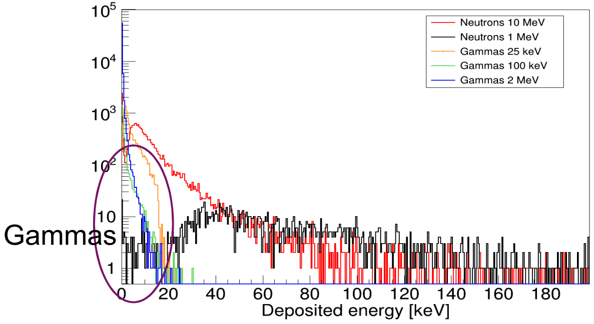
Gammas and neutrons response



FAST



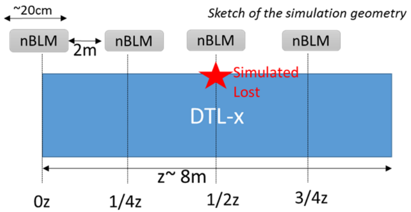




MONTE CARLO STUDIES

Monte Carlo simulations have been carried out in order to:

- **Estimate the expected response using as input data simulated in normal conditions and in the case of beam losses by ESS-BI (I. Dolenc-Kittlemann)**

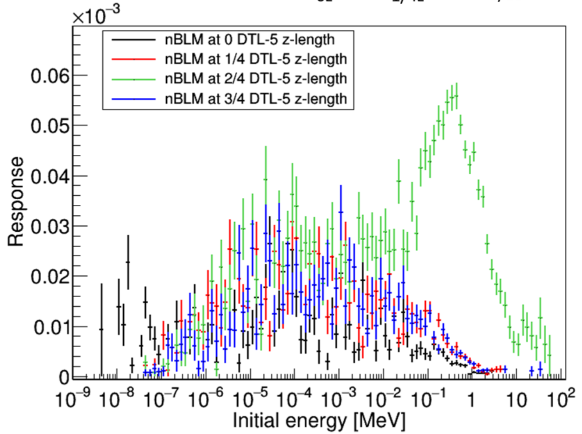


These simulations help to:

- Determine the distribution of detectors and the capability of the system to determine the position of the loss
- Preliminary estimation of the expected rates under different conditions.
  - Pile-up may be expected in case of fast big losses → system designed to transit from counting mode to current mode

Proton energy	Expected response for 0.01 W/m loss	Expected response "dramatic" accident
5 MeV	0.5×10^{-4} counts in 1 μs	54 counts in 1 μs
90 MeV	0.11 counts in 1 μs	7500 counts in 1 μs

Expected response obtained by MC simulations with Geant4



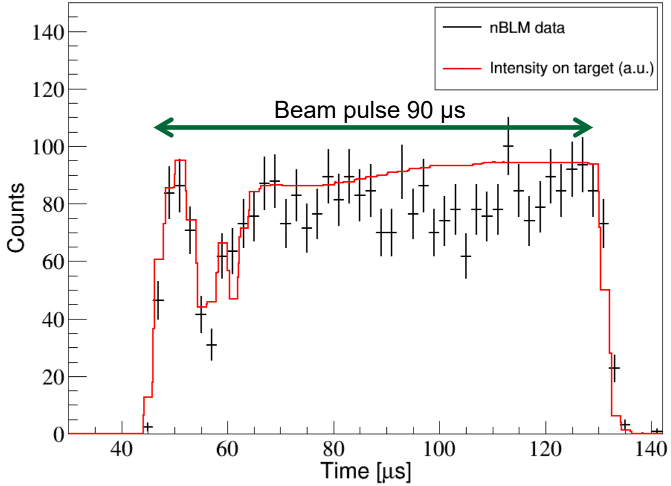
Response for the nBLM located at different positions along DTL-5 in the scenario where an accident happen in the middle of DTL-5. The green curve corresponds to the detector placed just on top of the lost.

EXPERIMENTAL RESULTS
NBLM TIME RESPONSE

IPHI 3MeV p beam
n produced with
Be target

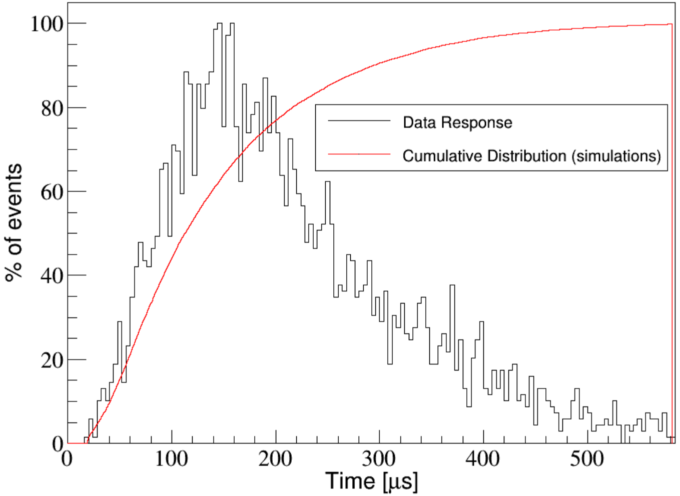
Data acq with a fast oscilloscope at 250 MS/s

FAST



- Immediate response
- Count rate in direct correlation with beam current intensity

SLOW



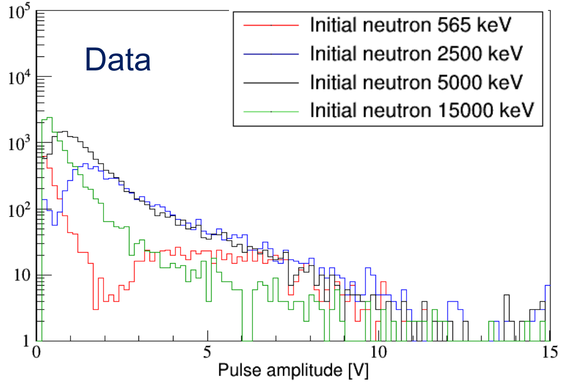
- Delay in signal: Convolution of moderation in polyethyelene + proton beam pulse duration (90 µs)
- ~ 200 µs from simulations for a instantaneous pulse

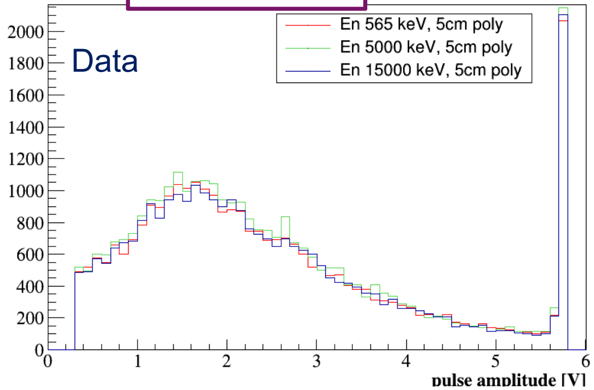
AMANDE monoenergetic neutron facility

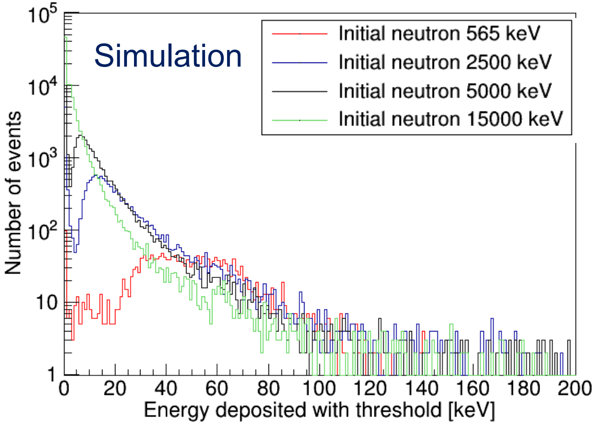
FAST

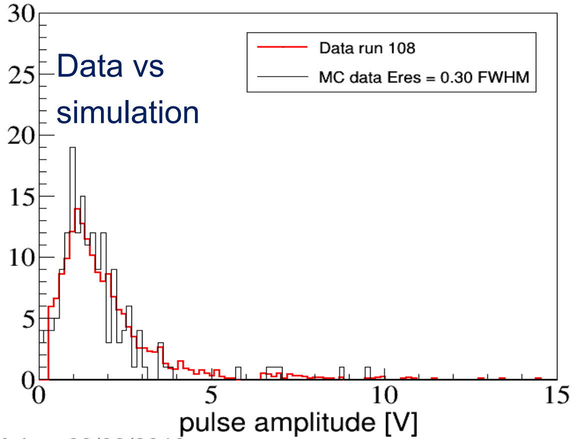
SLOW

Data acq with a fast oscilloscope at 250 MS/s







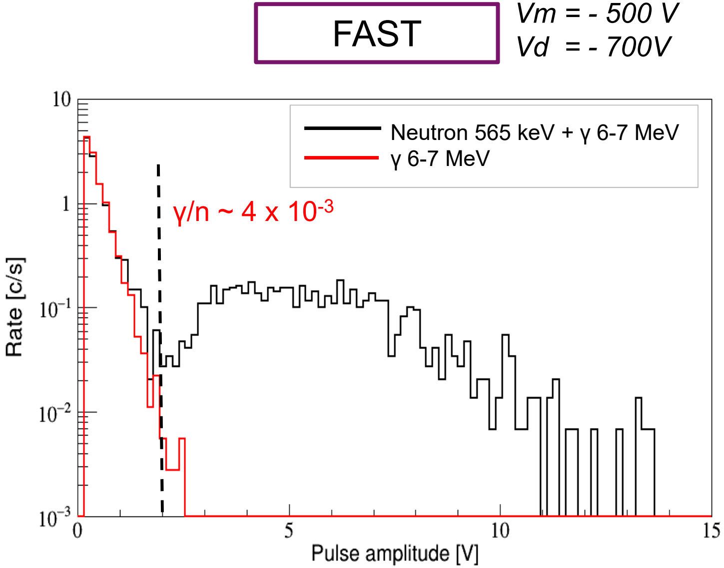


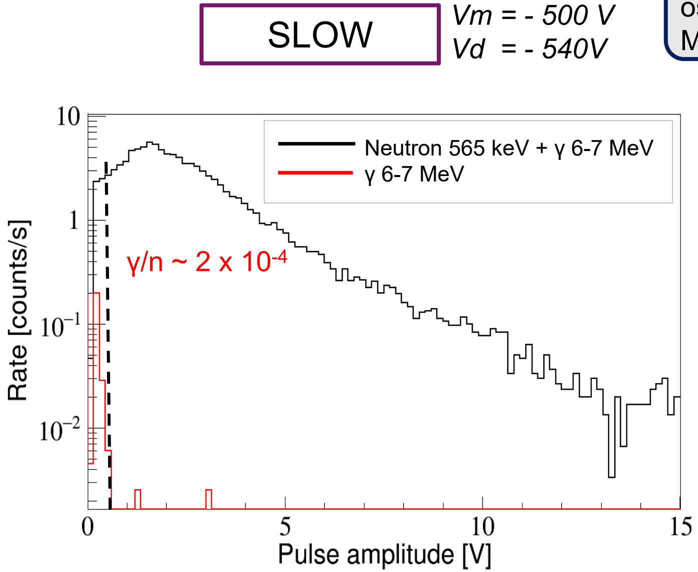
GAMMA/NEUTRON SUPPRESSION (I)

AMANDE monoenergetic neutron facility

Data acq with a fast oscilloscope at 250 MS/s

Using a charge amplifier





- Gamma/n difference based on the **difference ionization power of different particles** (electrons vs alpha/protons)
  - The choice of He gas enhances the suppression
  - Values are threshold and gain dependent
- Fast: non-monoenergetic beam will smear the response
- *Note*: Different drift distances (1.9 mm in fast / 0.4 in slow) in this case

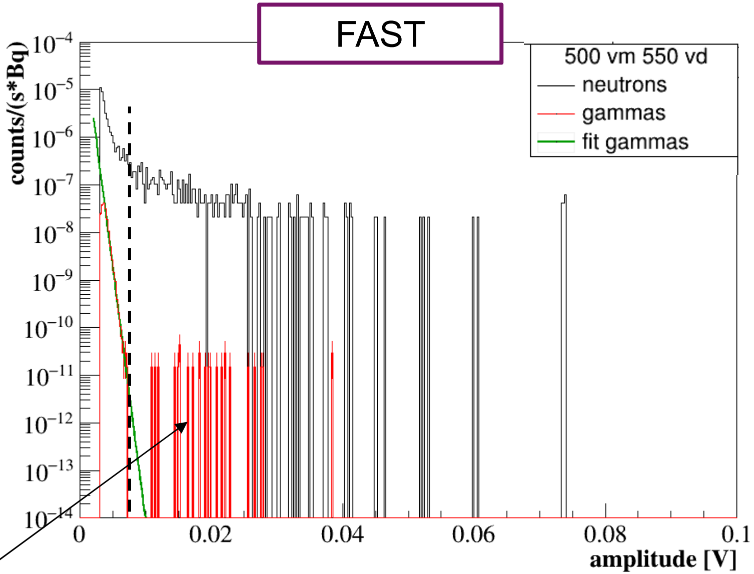
GAMMA/NEUTRON SUPPRESSION (II)

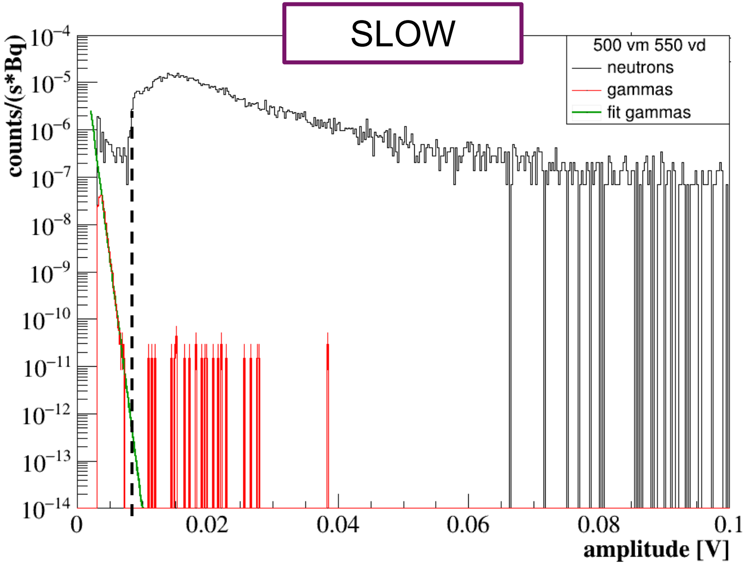
CEA Radioprotection Service

More data taken using radioactive sources: AmBe (n up to 10 MeV) and ^{60}Co (1.17, 1.33 MeV gammas)

Data acq with a fast oscilloscope at 250 MS/s

Using the final FEE card





Background from neutron source stored close by

- The gammas follow an exponential decay as was also observed in the simulations
- For an initial neutron spectrum with several energies the separation for the fast worsen
- In the case of the fast the discrimination is strongly dependent on the energy threshold

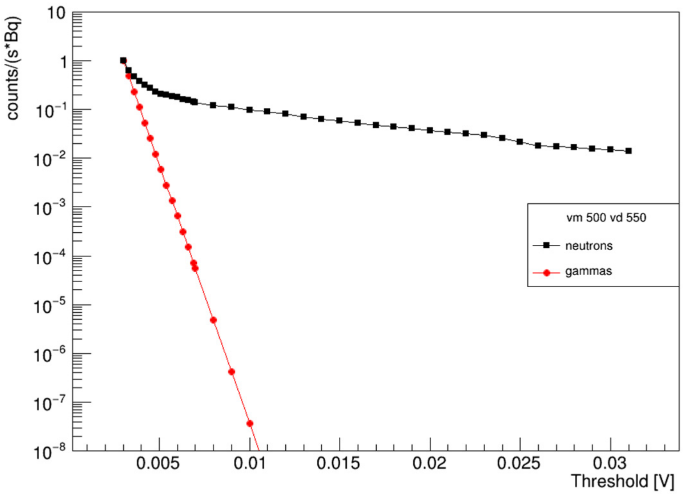
GAMMA/NEUTRON SUPPRESSION (III)

CEA Radioprotection Service

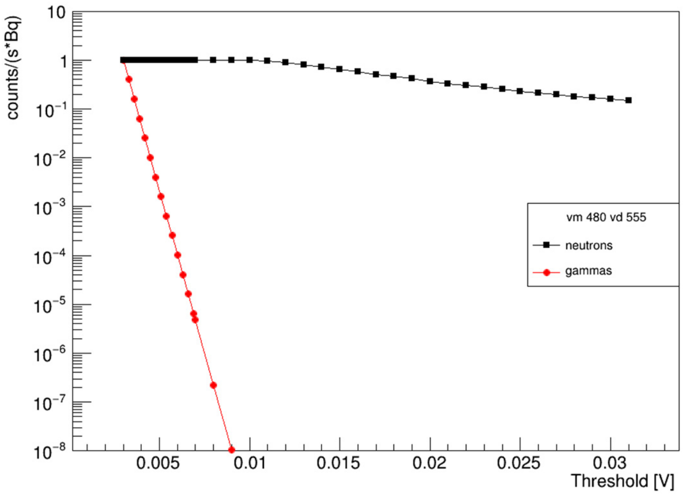
- In the case of the fast the discrimination is strongly dependent on the energy threshold
- A relative efficiency is computed for a range of energy thresholds

Data acq with a fast oscilloscope at 250 MS/s

FAST



SLOW



GAMMA/NEUTRON SUPPRESSION (III)

CEA Radioprotection Service

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Data acq with a fast oscilloscope at 250 MS/s

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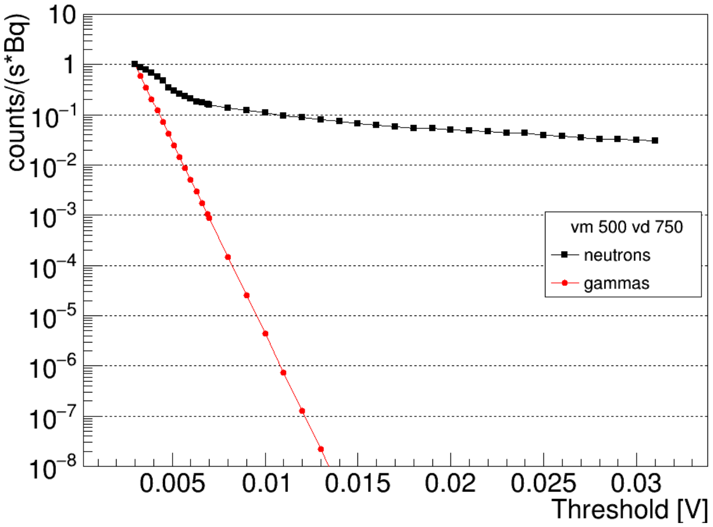

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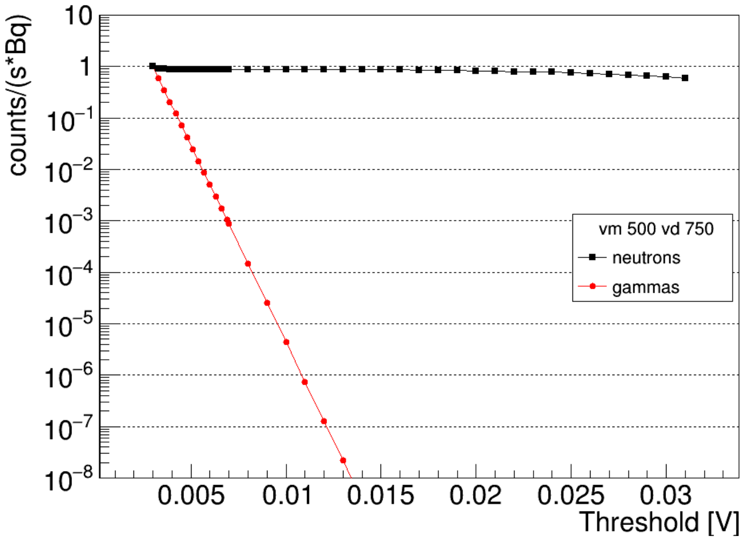


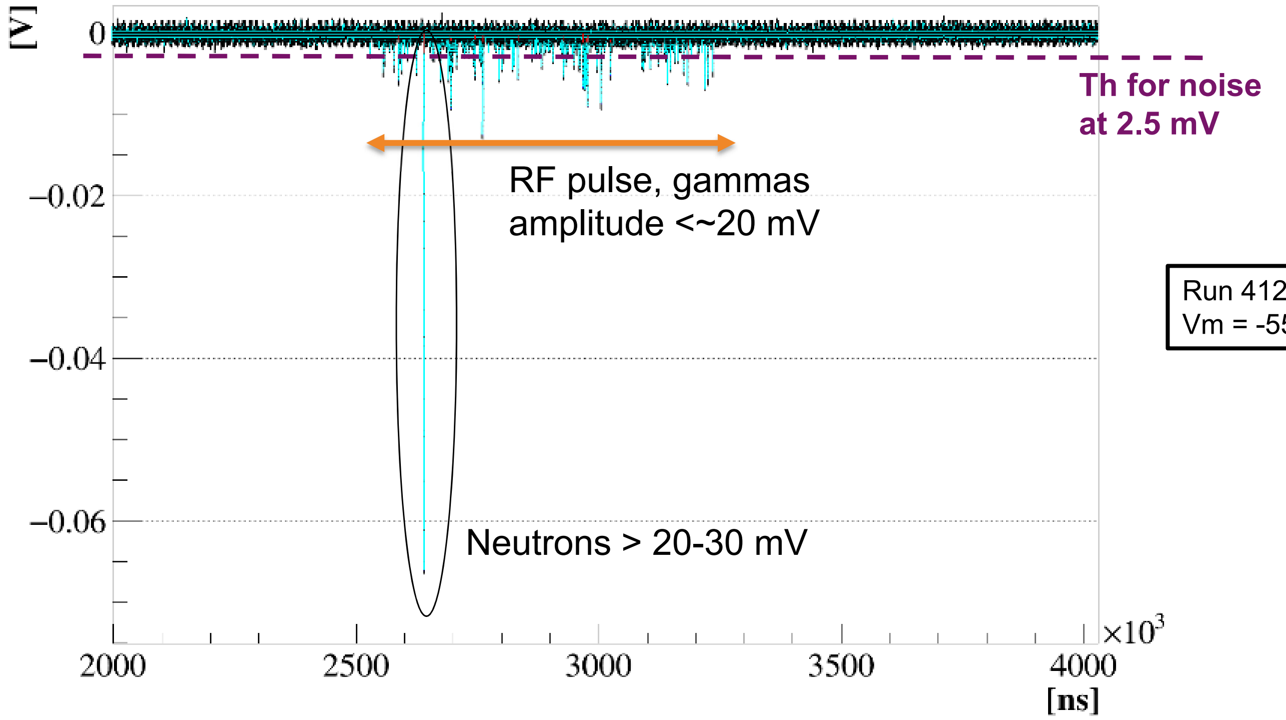
LINAC4 DATA

- **Fast nBLM module** installed between two DTLs at ~13 MeV proton region
- Final mechanics and electronics (*pre-series*)
- Gas: He + 10% CO_2
- Two data campaigns
  - November 2018
    - Understanding the detector
  - December 2018
    - Losses were produced

- Data taking with a fast oscilloscope
  - 250 Ms/s
  - Full bandwidth
  - With trigger of Linac4 also recorded

LINAC4 DATA

- Some history… Initially at Linac 4 we were detecting nothing so we increase the gain of the detector to force sparks to check detector was alive
- We start having events at 550V… ~50 -75 V higher gain than nominal

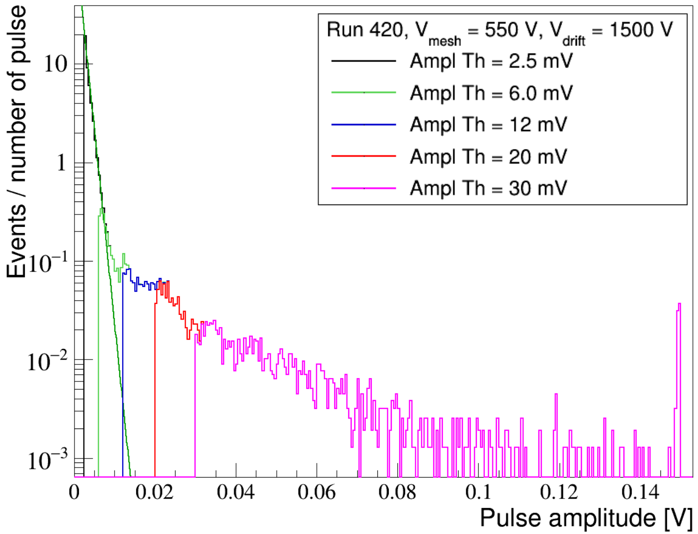


Run 412 – November 2018
Vm = -550V, Vd = -1650V

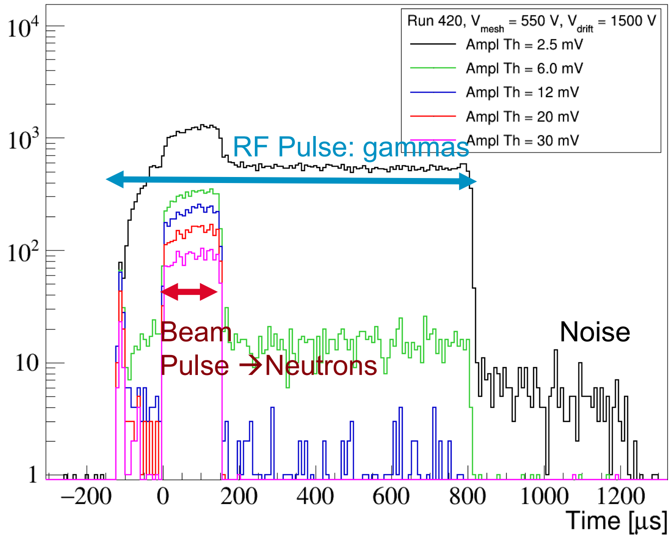
Run 420 – December 2018
Vm = -550V, Vd = -1500V

Observations in agreement with data acq. using the FMC
See poster MOPP022

Amplitude



Time distribution

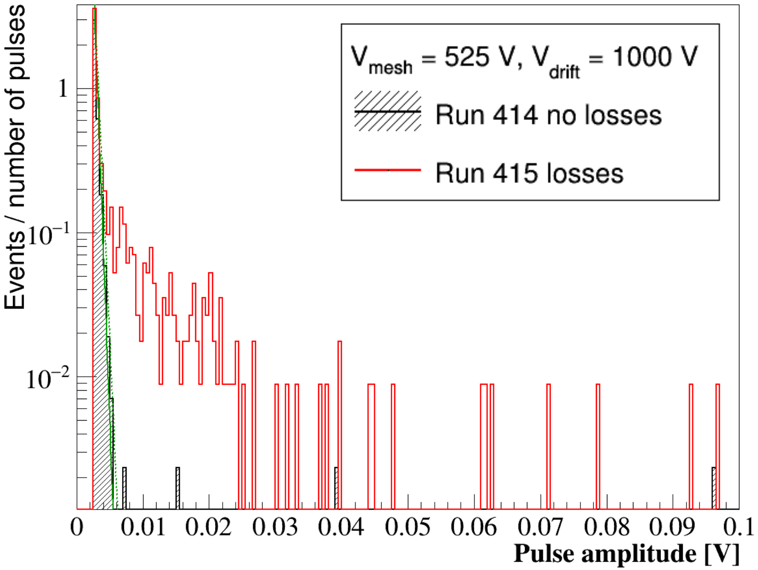


Applying amplitude cut, we recover the beam duration
→ Neutrons produced by beam
→ Gammas distributed all along RF pulse

LINAC4 DATA – PROVOQUED LOSSES

Vmesh = - 525 V
Vdrift = - 1000 V

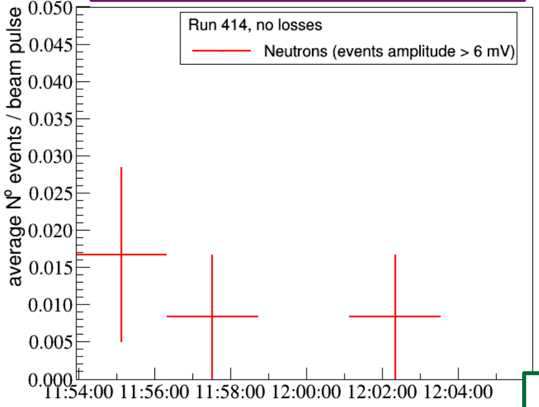
Amplitude



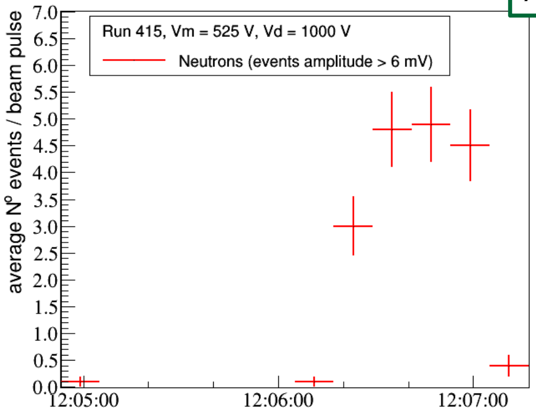
Run 414, No losses

Run 415 Losses

Average neutron rate

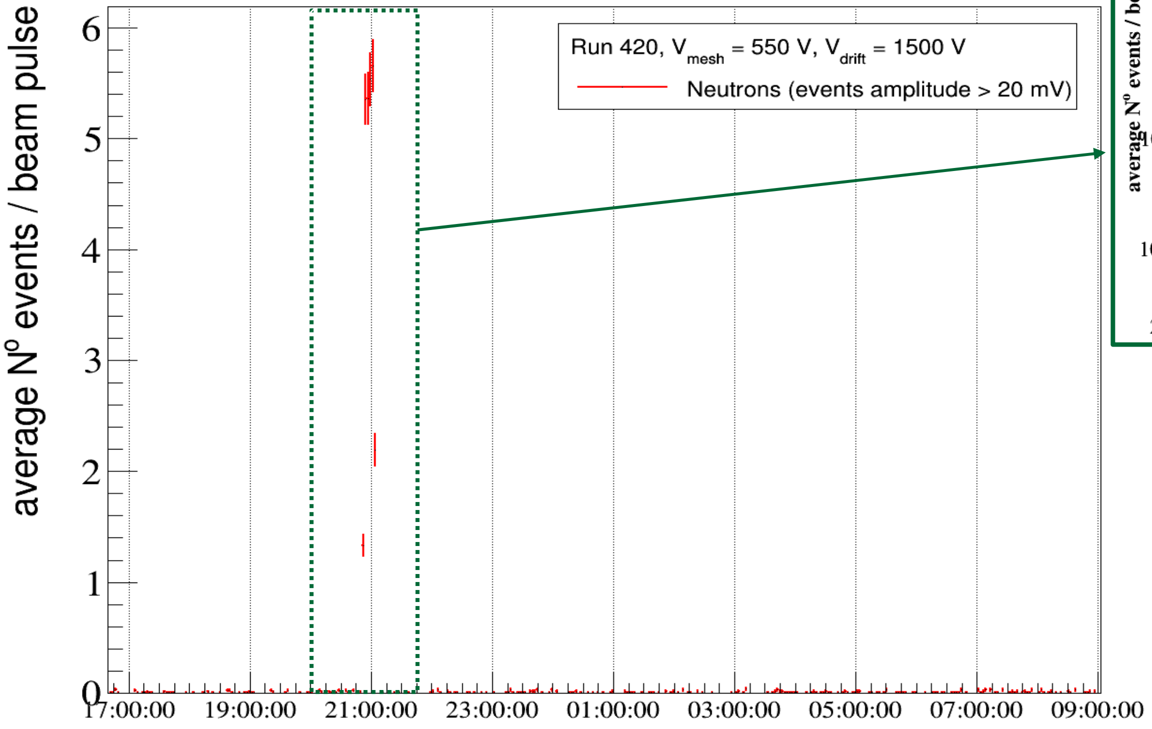


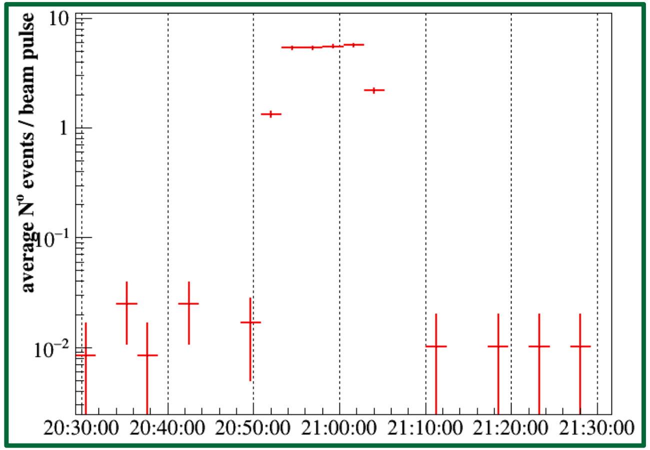
Neutrons
Ampl Th = 6 mV



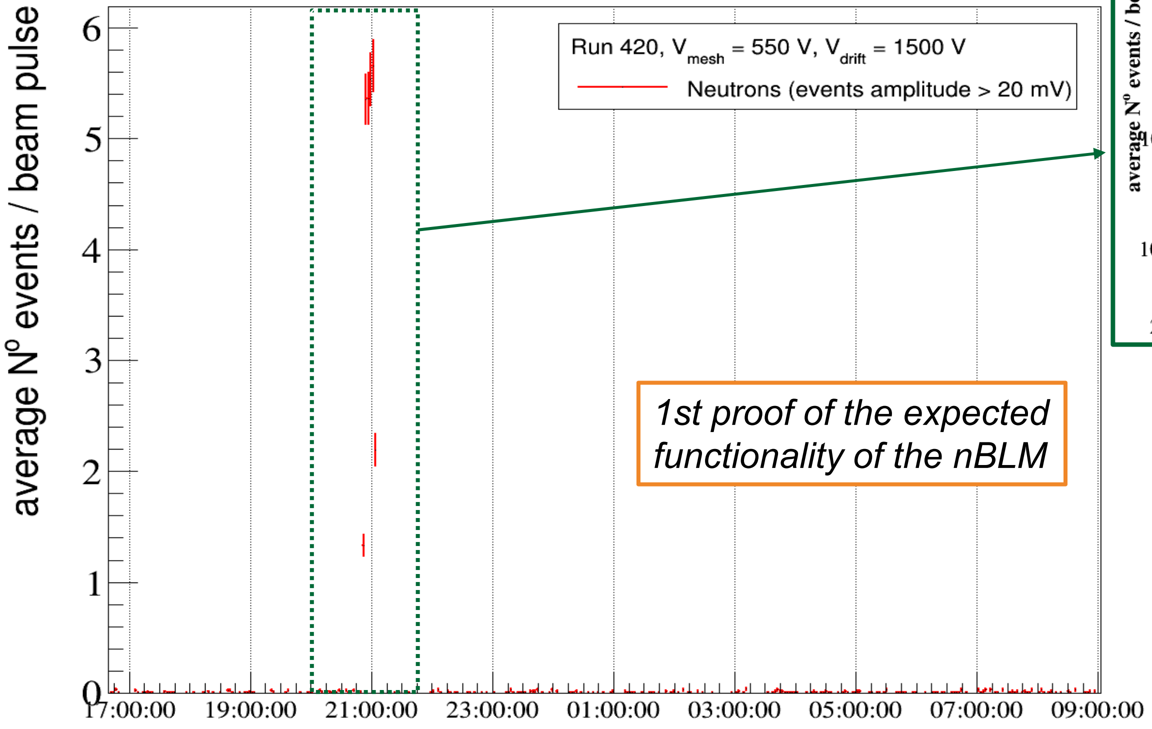
LINAC4 DATA – PROVOQUED LOSSES

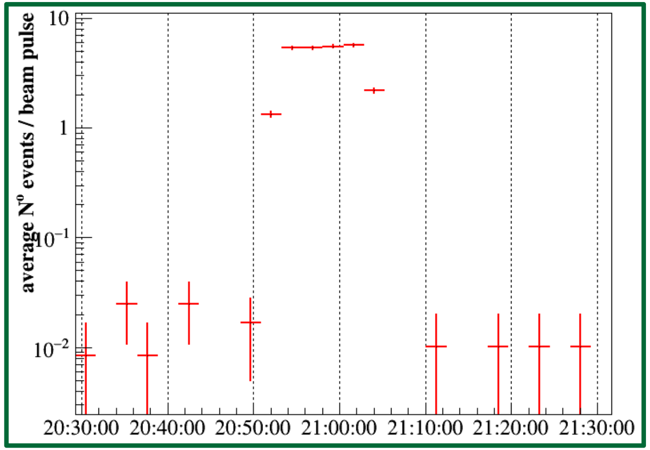
Run 420 – December 2018
Vm = -550V, Vd = -1500V





Run 420 – December 2018
Vm = -550V, Vd = -1500V





1st proof of the expected functionality of the nBLM

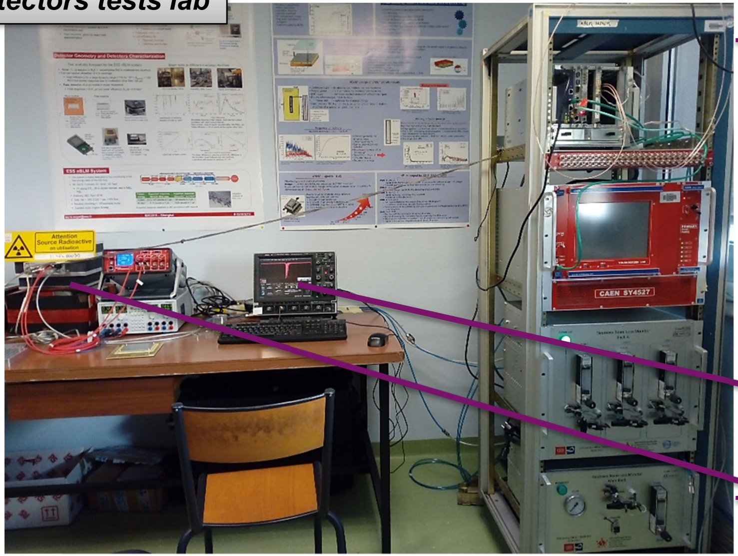
STATUS OF THE PROJECT

- Production of the detectors has started
- First 4 fully characterized
- First extra 8 modules expected before end Oct. 2019
- Control System and FPGA development almost finalized

Detectors Integration

Gas tests

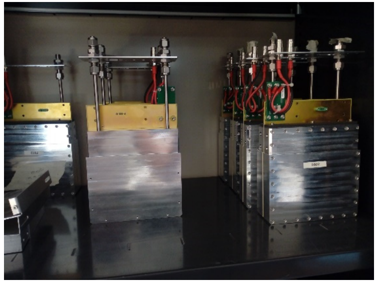
Detectors tests lab



Rack with (from top to bottom)
1. MTCA+FMC card
2. SY4527 CAEN Crate with the HV A7030 and LV A2519
3. Gas distribution chassis
4. Gas main control chassis

Neutron pulses

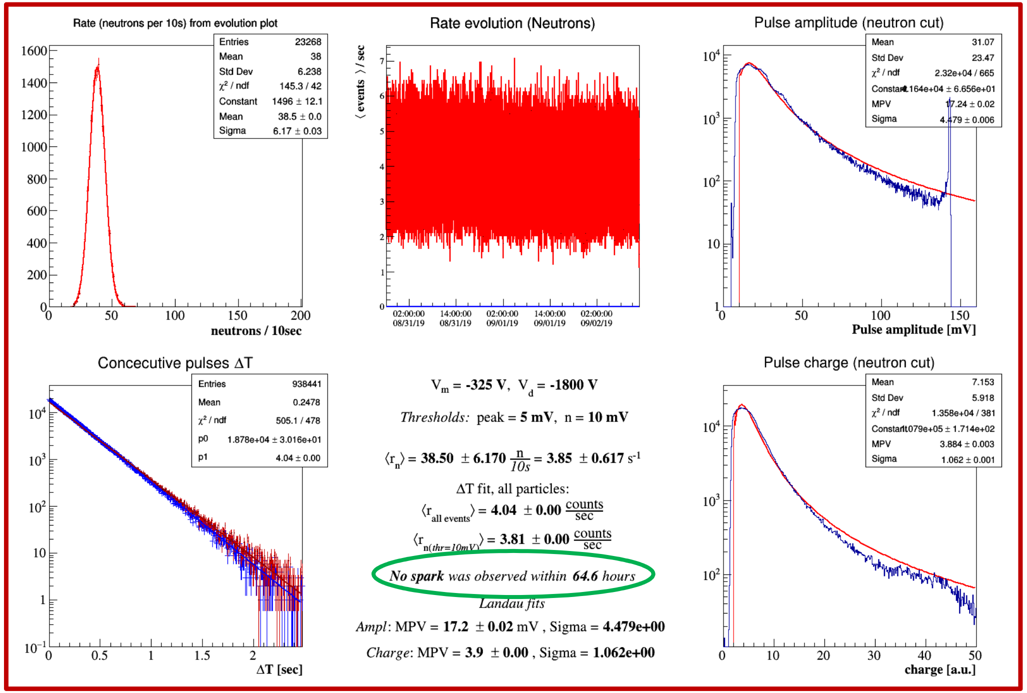
Slow module S002 under tests with a ^{252}Cf source (5-8 Hz)



Detectors mounted

STATUS OF THE PROJECT

- Production of the detectors has started
- First 4 fully characterized
- First extra 8 modules expected before end Oct. 2019
- Control System and FPGA development almost finalized



Detectors Integration

Gas tests

One of the outputs of the verification tests:

- Rate
- Rate evolution
- Amplitude distribution
- Charge distribution

Other include

- Amplitude stability
- Pedestal stability
- ToT, rise time, …

CONCLUSIONS

- New beam loss monitor based on **Micromegas** detectors
- Signal produced by fast **neutrons**, event by event detected
- Capable to **discriminate neutrons from x-rays event by event**
- Fast response and efficiency studied
- Clearly detect beam losses at LINAC 4
- Production project of 84 detectors system with ESS

The ESS-nBLM system team

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IRFU, CEA, UniversitéParis-Saclay, F-91191 Gif-sur-Yvette, France

E. Bergman, **I. Dolenc-Kittelmann**, F. Dos Santos Alves, C. Derrez, S. Grishin, K. Rosengren, **T. J. Shea**
European Spallation Source ERIC, SE-221 00, Lund, Sweden

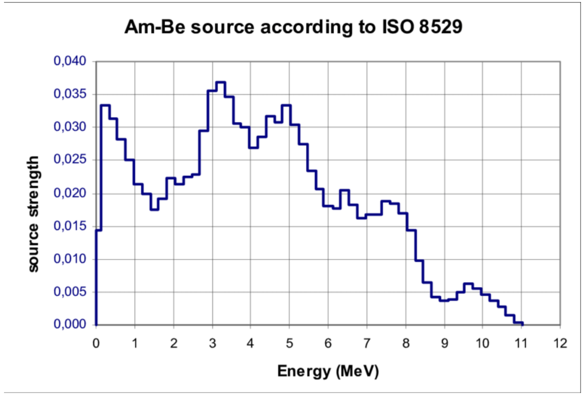
W. Cichalewski, **G. Jablonski**, W. Jalmuzna, R. Kielbik
Department of Microelectronics and Computer Science. Lodz University of Technology. Poland

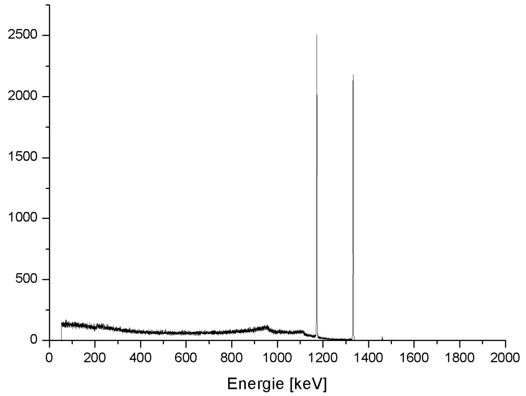
Thank you for your attention!

Back-up

More data taken using radioactive sources

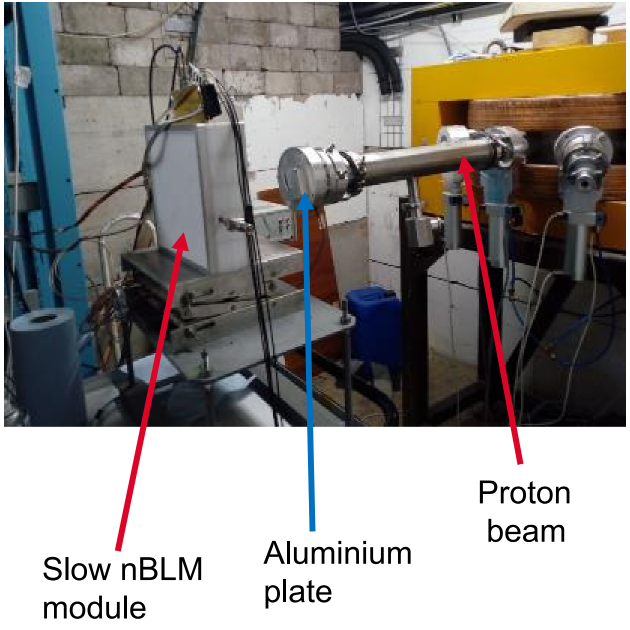
- Neutrons
  - AmBe 100 GBq
  - Fast and slow module
- Gammas
  - 60Co 8x10^10 Bq
  - With the slow detector only
- Data was taken at different field conditions with
- Gammas start to be detectable for Vmesh = 480 V
- Neutrons start to produce too much charge and sparks at ~ 510 V



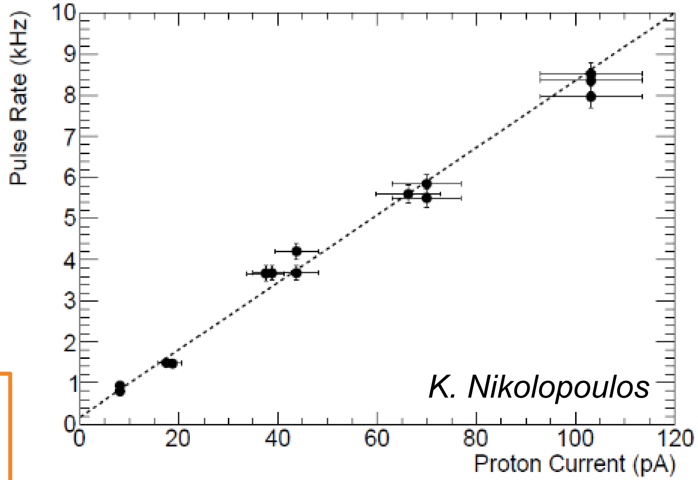


NBLM: CHARACTERISATION AT DIFFERENET IRRADIATION FACILITIES

MC40 Cyclotron (Birmingham University, UK):



- Medical synchrotron
- Protons up to 30 MeV
- Beam diameter ~1cm
- Continuum pulse
- Data taken at 28 MeV and different intensities
- Proton beam into Al plate ϕ=1cm

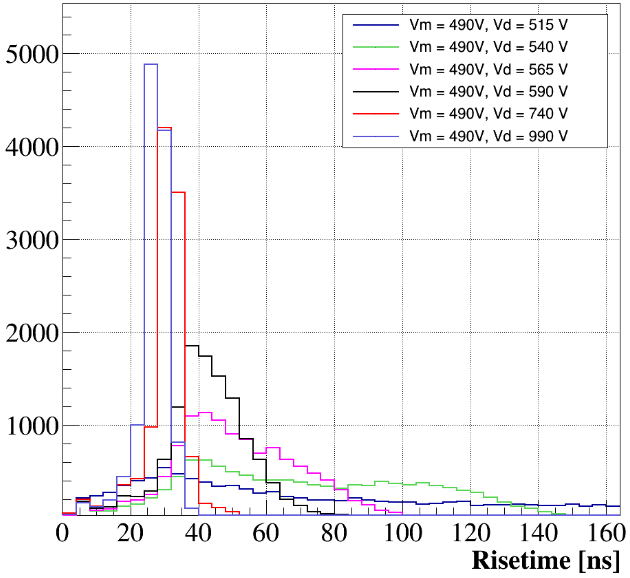


Correlation of the count rate with the intensity of the proton beam

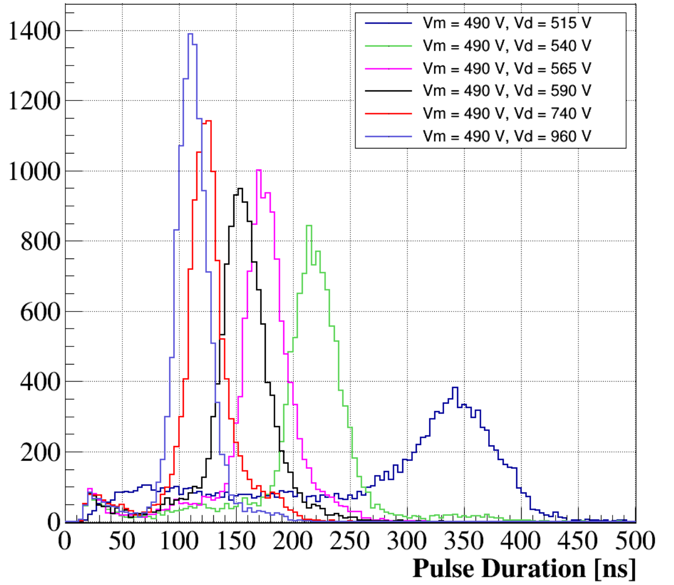
NBLM DATA – SIGNAL CARACTERISTICS

Dependency with drift voltage

Rise Time



Pulse width

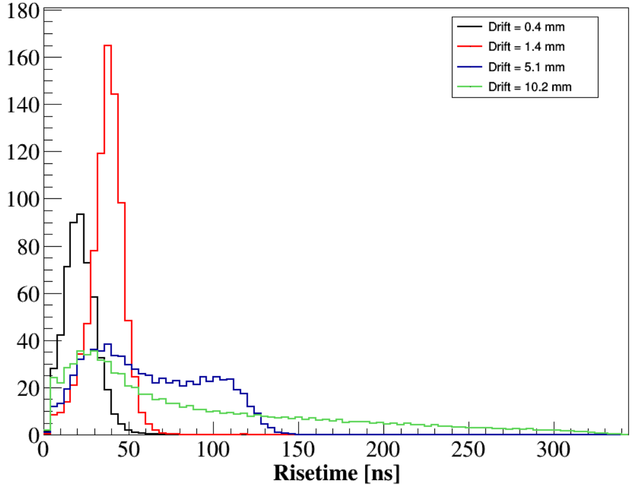


NBLM DATA – SIGNAL CARACTERISTICS

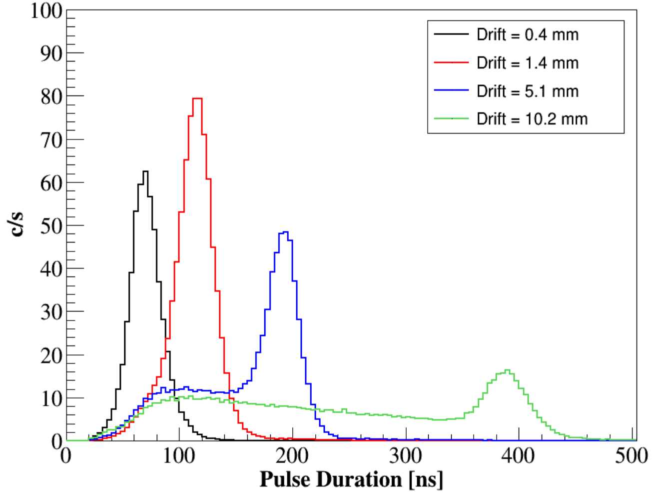
ORPHEE nuclear reactor LLB, CEA Saclay: 0.01 eV neutrons, flux 2×10^6 s^{-1} cm^{-2}

Dependency with drift distance

Rise Time

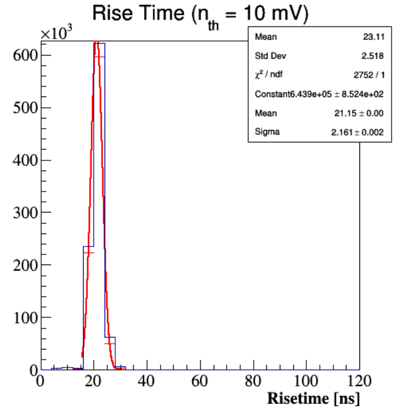


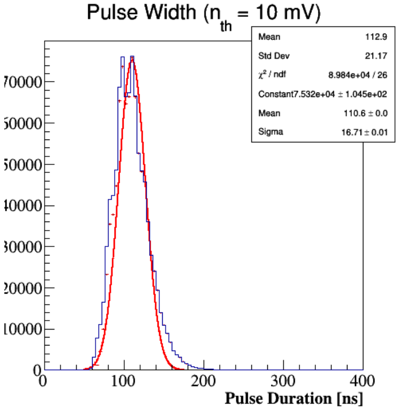
Pulse width

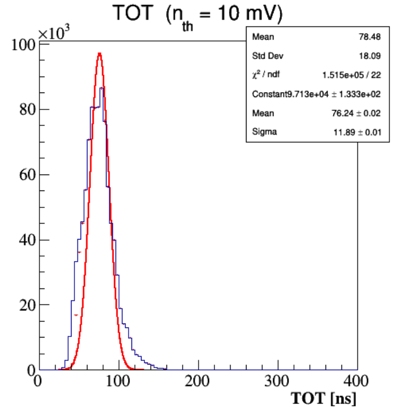


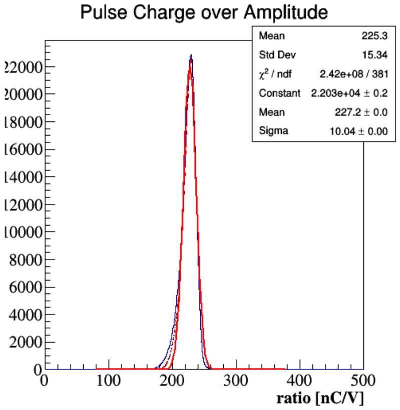
- Optimum **value ~2 mm**
  - Rise Time ~ 45 ns and very stable
  - Pulse duration ~ 60 ns → in 1µs ~ >10 pulses/window before pile-up (~10 MHz)
- Optimized to avoid also to be very close to sparking point

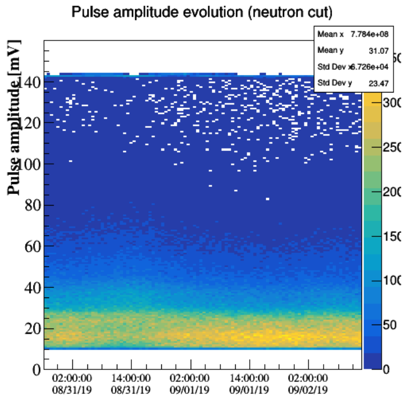
VERIFICATION TEST OUTPUT (I)

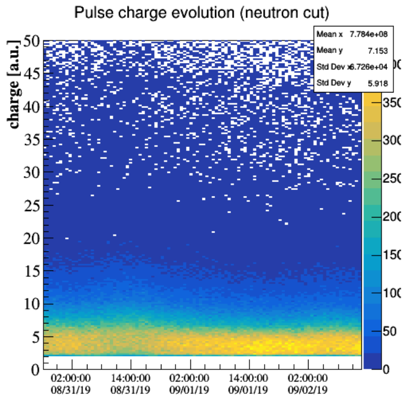




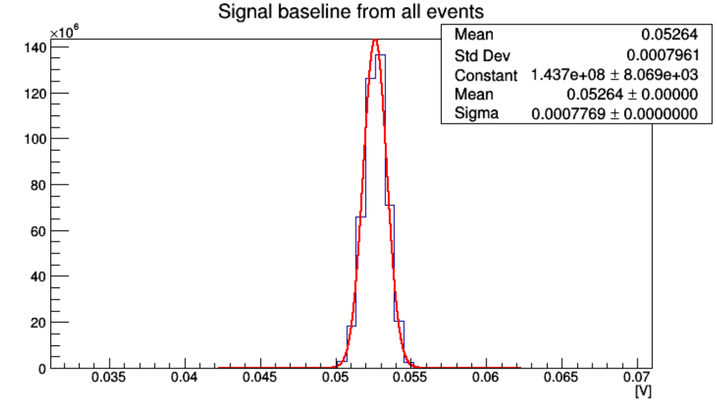


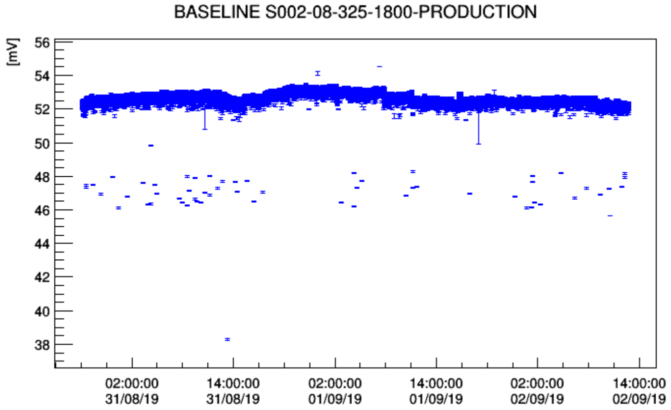


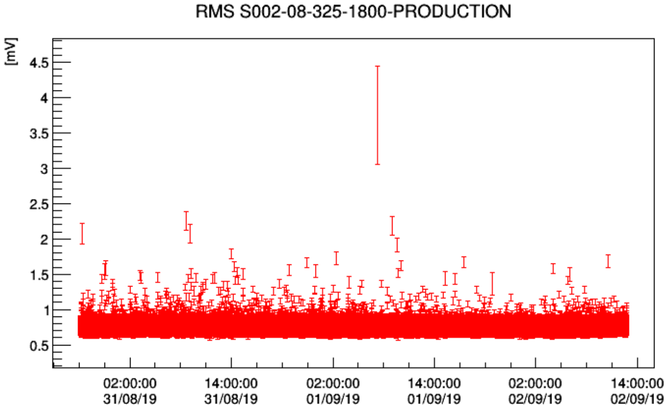


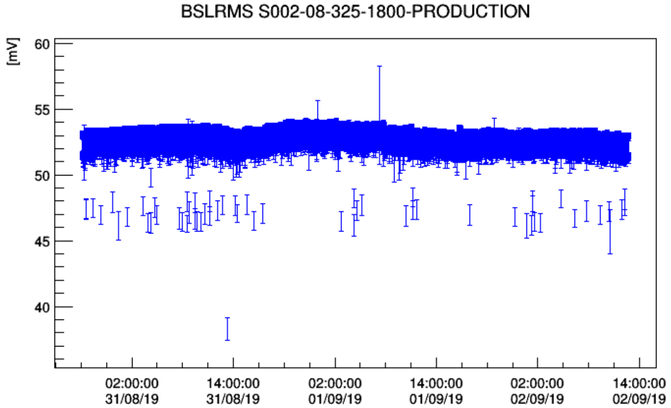


VERIFICATION TEST OUTPUT (II)

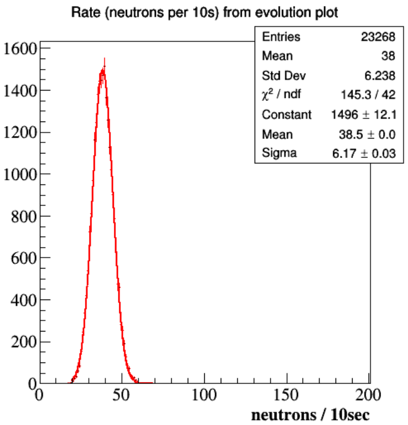


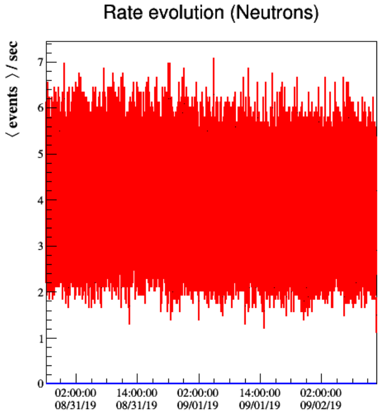


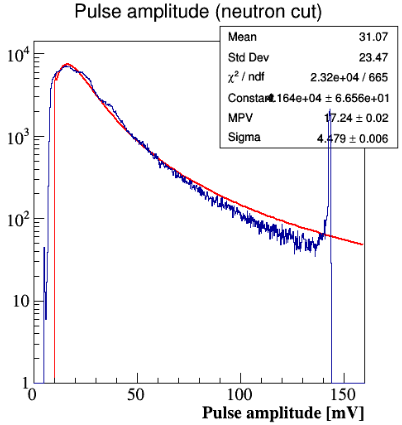


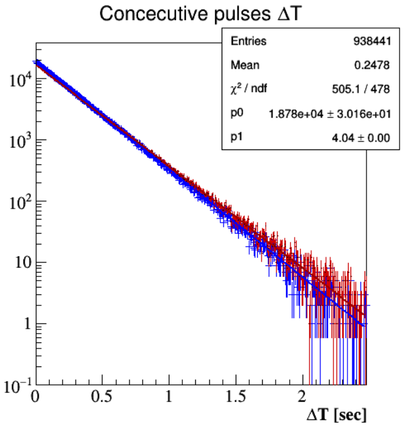


VERIFICATION TEST OUTPUT (III)









V_m = **-325 V**, V_d = **-1800 V**

Thresholds: peak = **5 mV**, n = **10 mV**

$\langle r_n \rangle = \mathbf{38.50} \pm \mathbf{6.170} \frac{n}{10s} = \mathbf{3.85} \pm \mathbf{0.617}\ s^{-1}$

ΔT fit, all particles:

$\langle r_{\text{all events}} \rangle = \mathbf{4.04} \pm \mathbf{0.00} \frac{\text{counts}}{\text{sec}}$

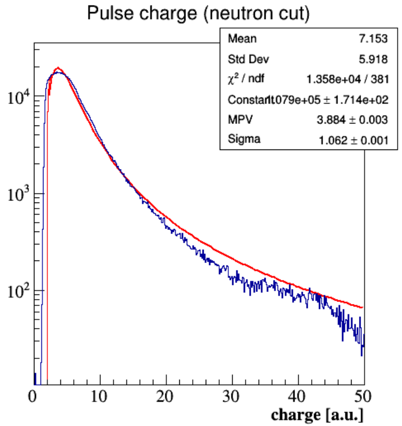
$\langle r_{n(thr=10mV)} \rangle = \mathbf{3.81} \pm \mathbf{0.00} \frac{\text{counts}}{\text{sec}}$

*No **spark** was observed within **64.6** hours*

Landau fits

Ampl: MPV = **17.2** ± **0.02** mV , Sigma = **4.479e+00**

Charge: MPV = **3.9** ± **0.00** , Sigma = **1.062e+00**



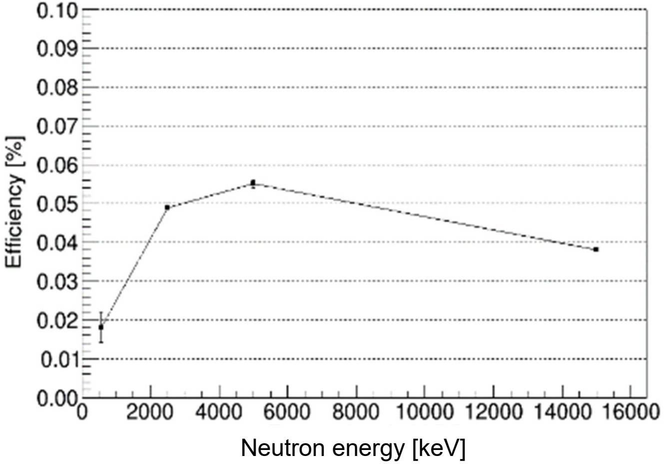
EFFICIENCY MEASUREMENTS

AMANDE monoenergetic neutron facility

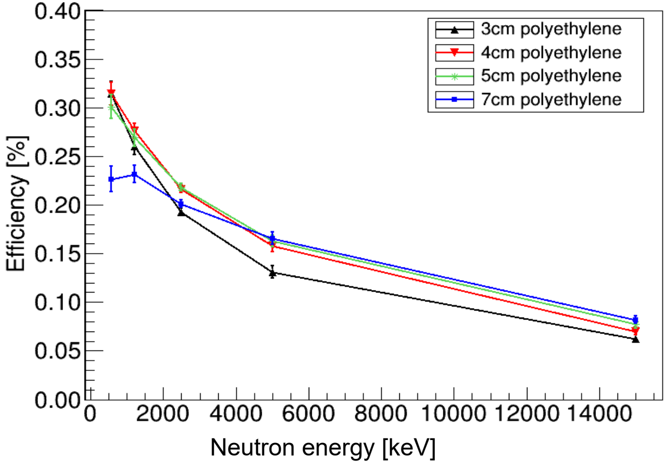
Data acq with a fast oscilloscope at 250 MS/s

Th at 0.30V = 52 keV

FAST



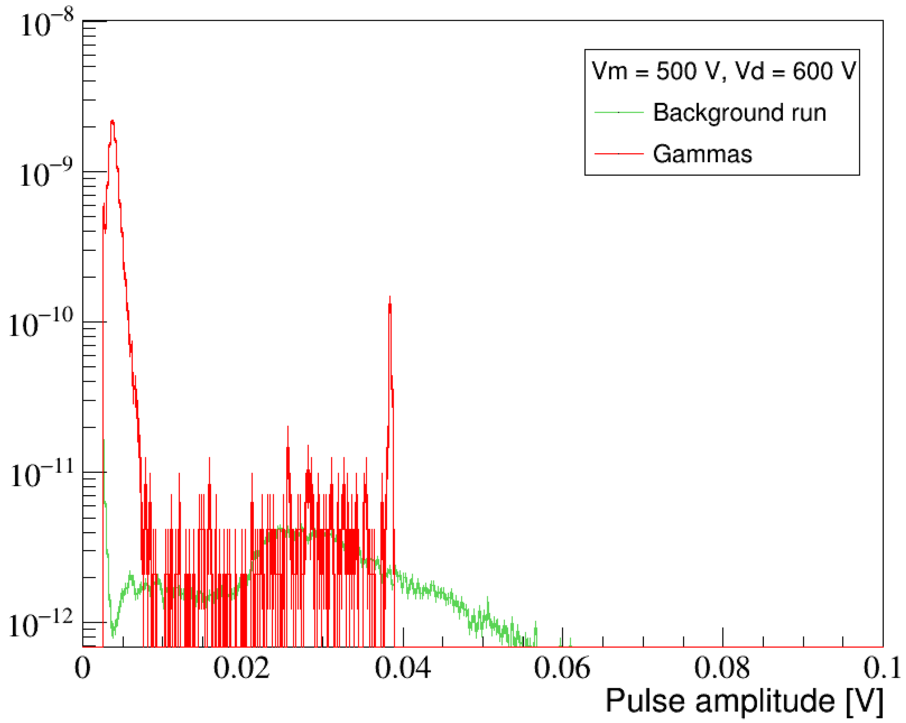
SLOW



- Efficiency strongly dependent
  - on threshold
  - on initial neutron energy
- Efficiency 5-20 smaller than slow module for monoenergetic beams

- Count rate of few /s for a neutron fluence rate of 1/s/cm^2

CEA Radioprotection Service



Neutron source was stored close by