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61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

Daejeon, Korea, 17-22 June, 2018

ESS nBLM: Beam Loss Monitors Based on Fast Neutron Detection

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CEA DEDIP

- detector design and production (42 slow and 42 slow detectors)
- gas system design & fabrication
- Part of DAQ control hardware (FE digitizers, HV and LV PS)

CEA DIS

- Monitoring and control system for the prototype
- data processing functionality related algorithms

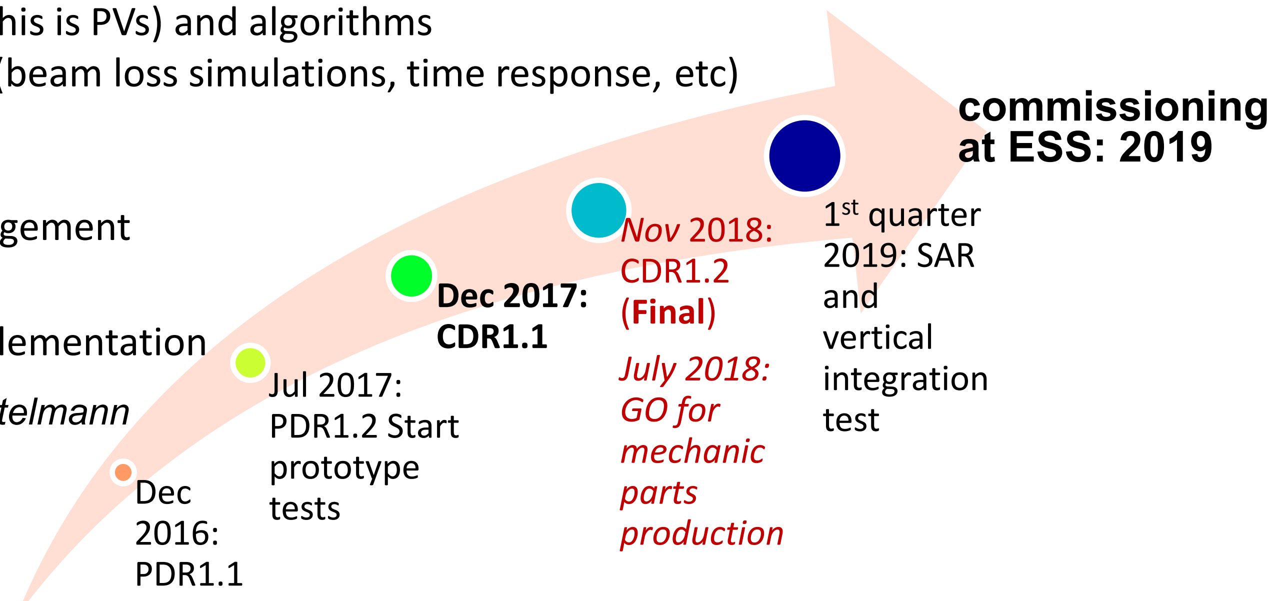
ESS BI

- system architecture and layout
- data processing and protection functionality related algorithms
- monitoring variables (in epcis this is PVs) and algorithms
- development of requirements (beam loss simulations, time response, etc)
- gas lines 3d model
- installation
- coordination and project management

Lodz University, DMCS

- FPGA firmware design and implementation

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



Why a new BLM

Challenges:

- RF cavities emit γ-rays. Those γ's may pose a problem to BLMs
- In the case of high intensity but low energy regions of an accelerator charged particles and γ's do not even exit the accelerator vessel
- Continuous monitoring of small losses is needed (0.01 W/m)

Signature of beam loss: **fast neutrons**

➔ Thermal neutrons can come from moderation inside the walls, so must be rejected

➔ Gamma's and X-rays present during normal operation, so the detector must be insensitive to them

A new BLM should be:

- sensitive enough to very small losses
- fast enough to react on "catastrophic event"
- appropriate for *high particle rates*
- reliable on long term
- radiation hard

"…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."

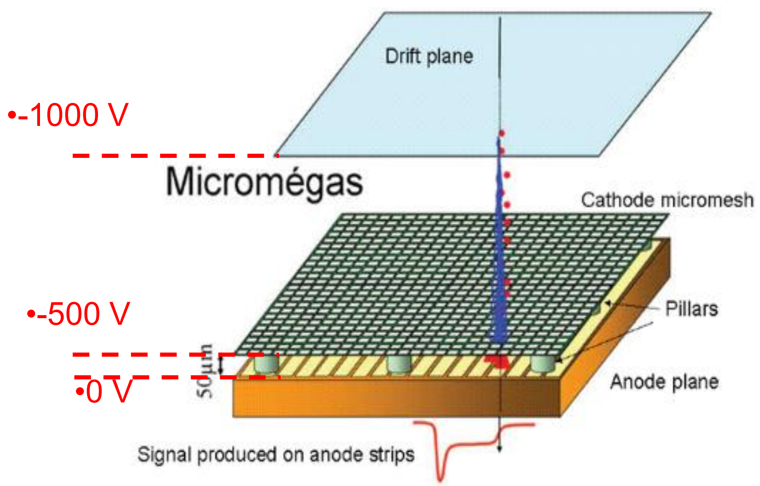
A. Zhukov, WEYA2, Proc. PAC2013, Pasadena, CA USA

The "ESS nBLM" concept

Micromegas detector equipped with combination of appropriate neutron convertors & moderators

The **Micromegas** detector

- Multi-Pattern Gaseous Detector, invented in 1995 at CEA Saclay[1]
- Parallel plate detector with a thin metallic mesh dividing the gas volume in 2 parts:
  - drift region (1 to 100 mm) → E ≈ 100 V/cm
  - amplification region (30 to 150 μm) → E ≈ 100 kV/cm
- Grounded read-out: conductive strips connected to FEE
- Pillars are used to reinforce the response uniformity



Small amplification gap:

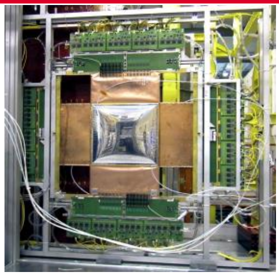
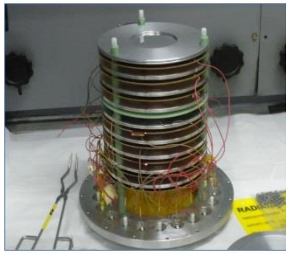
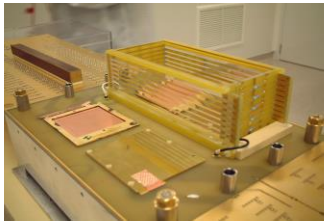
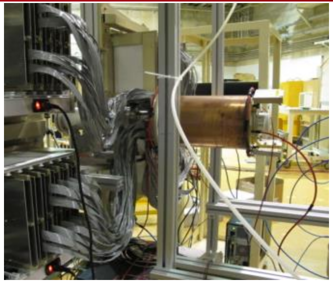
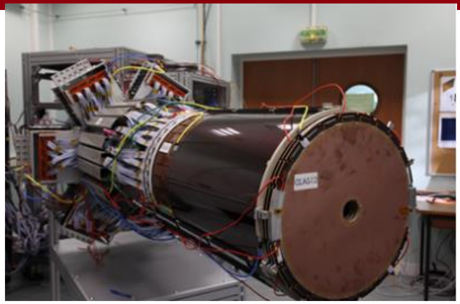
- very strong and uniform electric field with low voltages → high gain / discharges non destructive
- single stage of amplification → fast signals
- fast ion collection → High rates (~10^6 s^{-1} mm^{-2})
- radiation hard

MPGD fabrication techniques → towards industrialization:

- Easy to manufacture at low cost & big surfaces

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

MICROMEGAS APPLICATIONS: PARTICLE & NUCLEAR PHYSICS EXPERIMENTS AND MORE

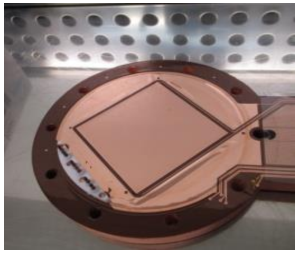






COMPASS NTOF KABES/NA48 MINOS CLAS12

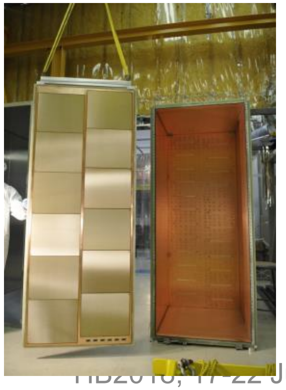
1996 2000 2001 2003 2009 2014 2015 2017 2018

Micromegas Invention

CAST



T2K

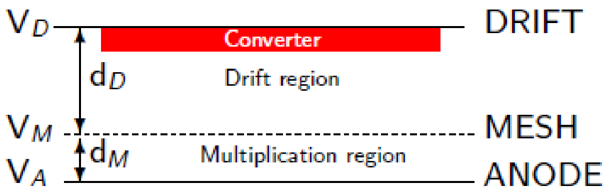


ScanPyramids

ATLAS-NSW

Neutron detection ➔ *neutron-to-charge converter*

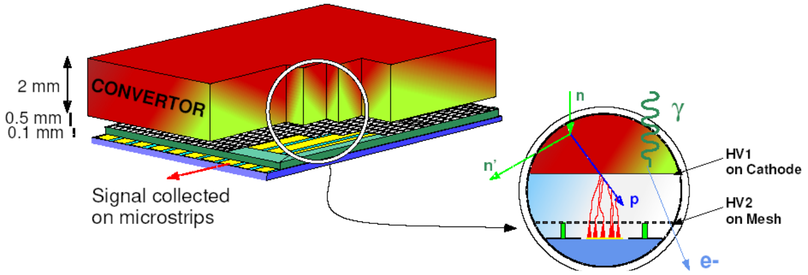
- Solid converter: thin layers deposited on the drift or mesh electrode (^{10}B, $^{10}B_4C$, ^{6}Li, ^{6}LiF, U, actinides…)
  - Sample availability & handling
  - Efficiency estimation
  - ✗ *Limitation on sample thickness from fragment range ⇒ limited efficiency*
  - ✗ Not easy to record all fragments



In use at nTOF, CERN, since 2001 for neutron beam flux and profile monitoring

- Detector gas (^{3}He, BF_3…)
  - Record all fragments
  - No energy loss for fragments ⇒ reaction kinematics
  - No limitation on the size ⇒ high efficiency
  - ✗ *Gas availability*
  - ✗ Handling (highly toxic or radioactive gasses)

- Neutron elastic scattering
  - ➢ gas (H, He)
  - ➢ solid (paraffin etc.)
    - ✓ Availability
    - ✓ High energies
    - ✗ Efficiency estimation & reaction kinematics

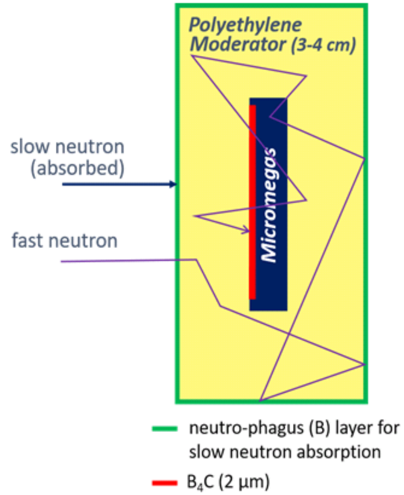


DEMIN Micromegas for the MegaJoule program
https://doi.org/10.1016/j.nima.2005.11.184

2 types: “slow” & “fast”

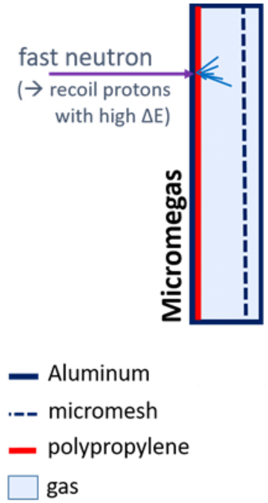
➔ “slow” detector (MM + B_4C) capable of monitoring fast neutron fluxes ~ few n · cm^{-2} s^{-1}

- Neutron converter: 0.2 – 1.5 µm $^{10}B_4C$, $^{10}B(n, \alpha)^7Li$ reaction
- Tuneable efficiency (converter thickness, segmentation, natural boron) max factor: 7×4×5 = 140
- Detection of fast neutrons after moderation in polyethylene (5 cm)
- Thermal neutron absorber (5 mm borated rubber)
- 4π acceptance
- Time response ~ 200 µs



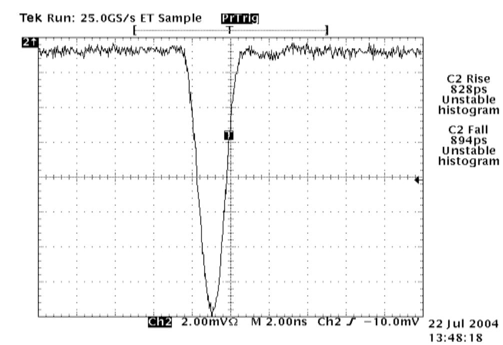
➔ “fast” detector (MM + H-rich target) appropriate for high flux - high energy neutrons

- Neutron converter: 125 µm Mylar, aluminized (50 nm)
- Insensitive to thermal neutrons
- High particle fluxes
- Fast time response ~0.01 µs
- Directional
- Lower detection efficiency (~100 times smaller)

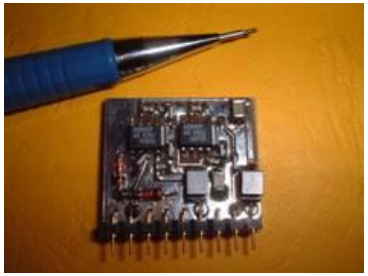


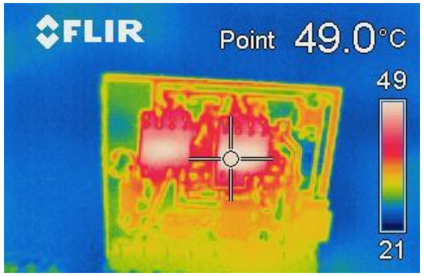
THE nBLM MICROMEGAS

- Common design for fast and slow detectors
  - ➔ Different convertors, the slow surrounded by moderator
  - ➔ Standard "Bulk" Micromegas, segmented in 4 pads (can be read individually or as one)
- FEE electronics: FAMMAS[1] preamplifiers (*Fast Amplifier Module for Micromegas ApplicationS*)
  - ➔ integrated on the board for the prototypes
  - ➔ as mezzanine card for the production
  - ➔ Radiation hardness: test planned @MC40 cyclotron Birmingham U.
    - LV : + 5V -5V
    - Consumption ≅ 50 mW
    - Noise: 600 µV rms
    - Risetime: < 1ns

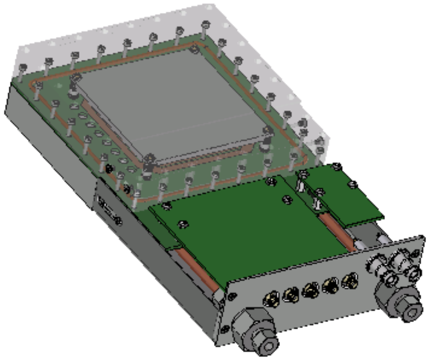


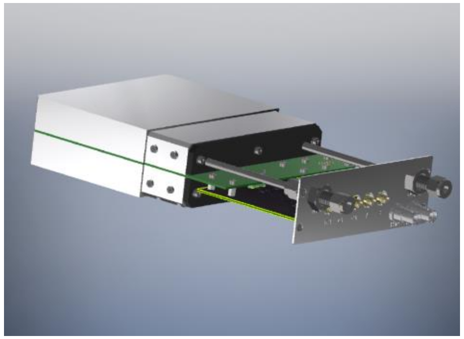
[1]P. Legou, "Beam Spectrometers using Micromegas in Time Projection Chamber mode", in Proc. HB2006, Japan 2006.

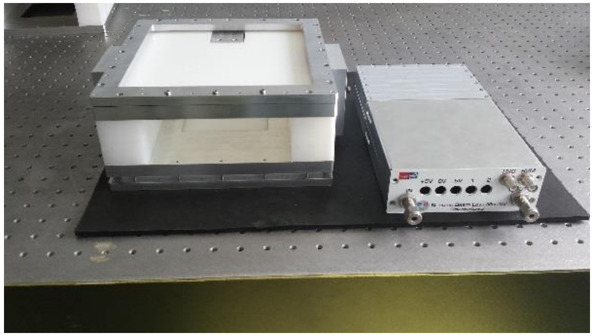




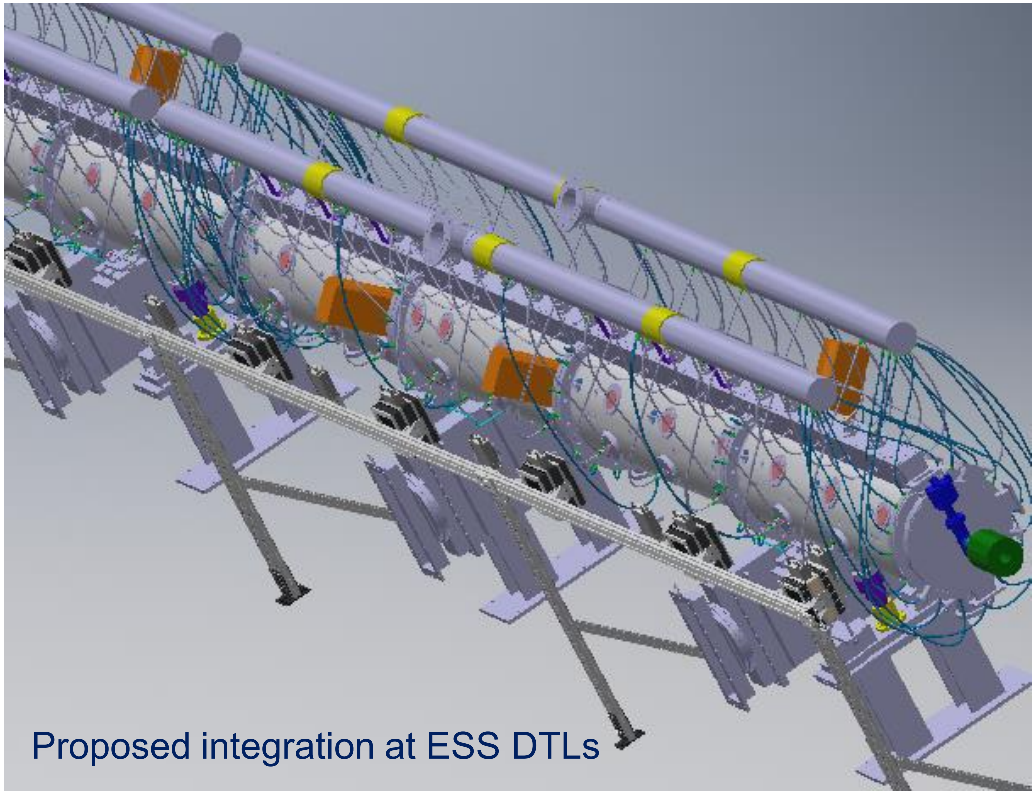
THE nBLM CHAMBERS







Assembly of a fast and a slow detector
size ≈ 20 × 25 × 25 cm^3 (~10 kg)



Proposed integration at ESS DTLs

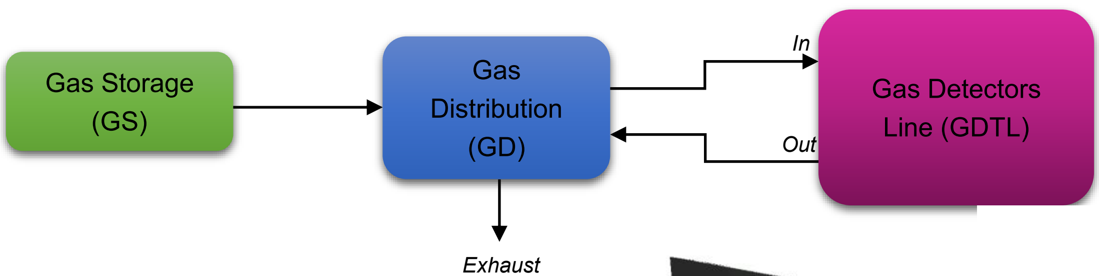
nBLM Gas System

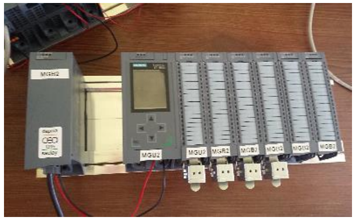
Detectors are designed to operate in semi – sealed mode, however for long term stability some gas recirculation is necessary. The nBLM Gas System:

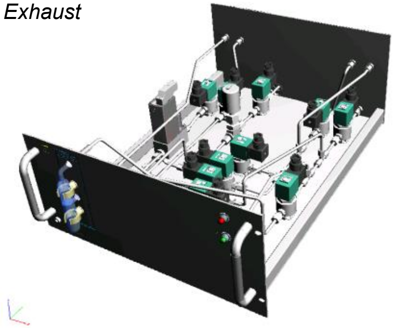
- Provide a constant flow of 0.2 - 2 l/h of **He + 10% CO_2** @ 1bar in 6 independent gas lines
- Each line feeds a group of detectors in series
- PLC Control / Monitoring of flow IN – flow OUT of each line ➔ assure tightness & gas quality
- Report system health status to EPICs GUI

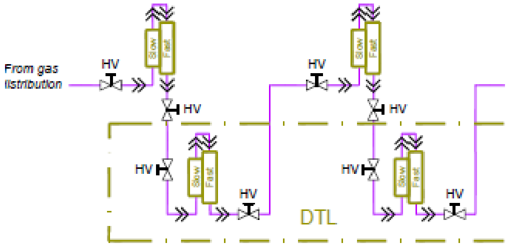
The need for gas recirculation complicates the system. However:

- The detectors can keep operating stably for hours if gas recirculation has stopped
- Gas is non flammable, redundant gas storage design
- Manual bypass for all controllers is possible in case necessary

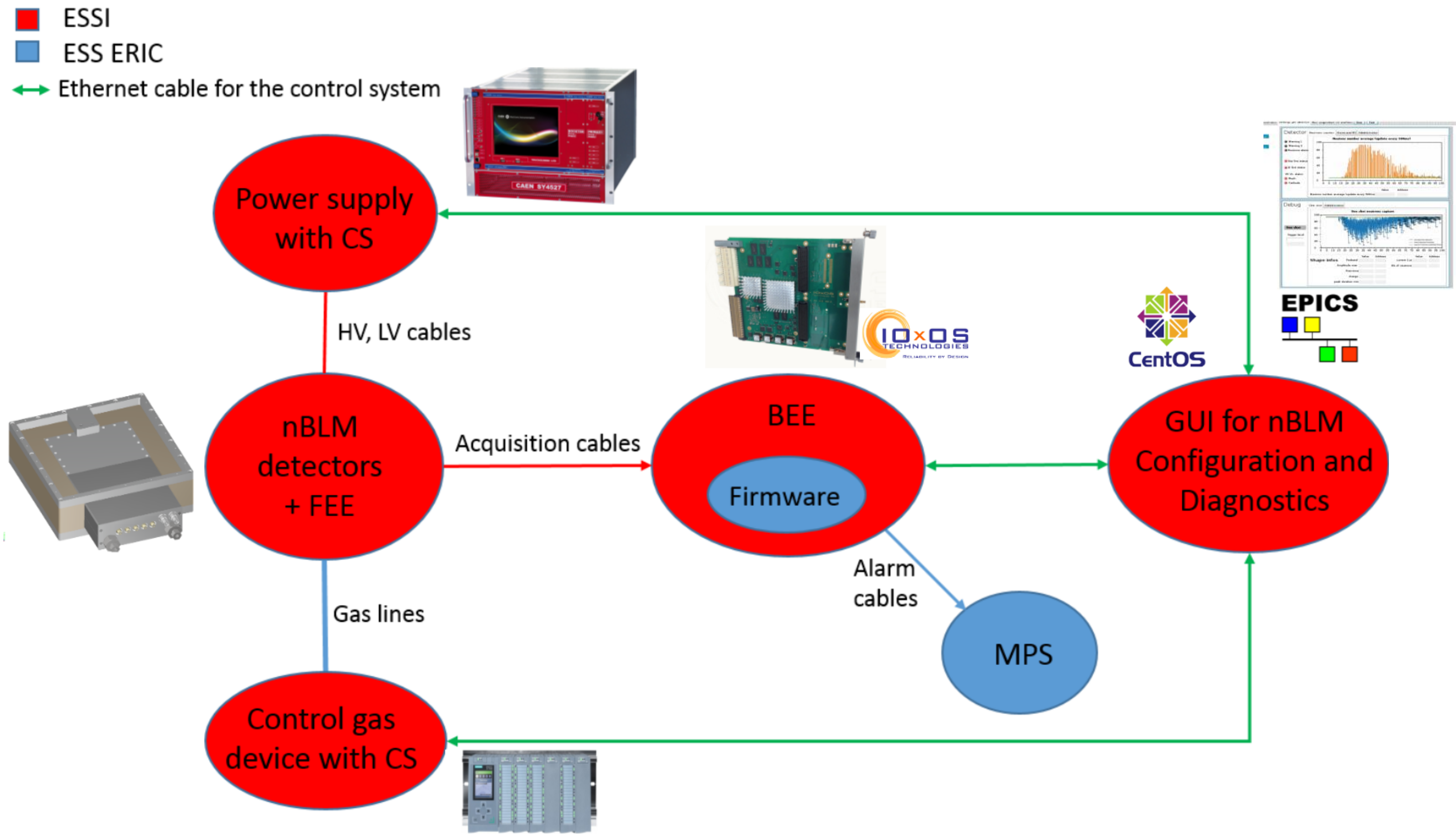








CONTROL SYSTEM ARCHITECTURE



THE ACQUISITION SYSTEM

➢ **Fast acquisition**

ICS standardisation for fast acquisition is based on:

- µTCA.4
- IOxOS CPU IFC_1410
- IOxOS ADC_3111 FMC boards
    - Total 16 cards (128 channels)
    - Input voltage range is -0.5V to 0.5V
    - Sampling frequency of 250 MSamples/s

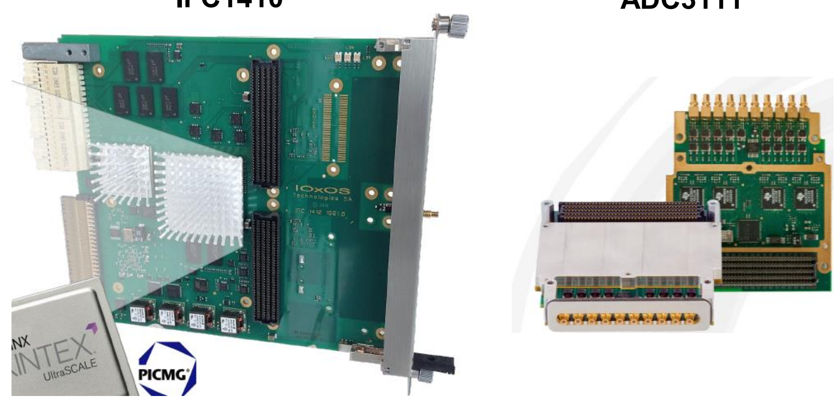
➢ **FPGA firmware**

The FPGA will have the following tasks:

- Detection of neutrons and counting. Automatic switch to current mode.
- Beam Permit signal to the Beam Interlock System
- Acquire post-mortem data
- Provide debug and diagnostic data
- Provide oscilloscope functionality
- Generate warnings/health status of subsystems

BEE boards

IFC1410 ADC3111

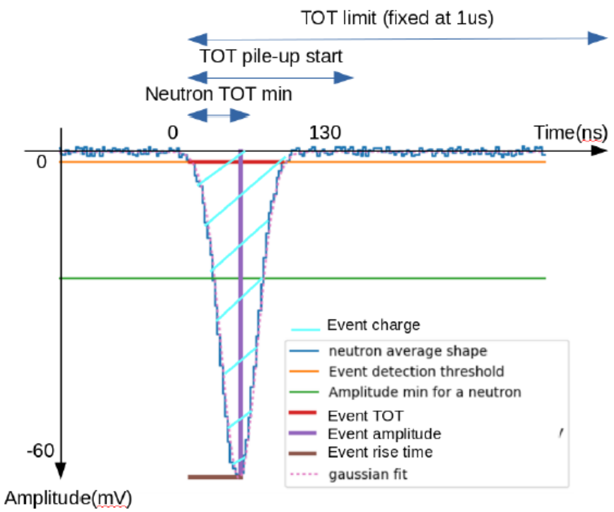


- Only one ADC3111 FMC per IFC1410 board
- Pairs of fast and slow acquisition for software architecture convenience.
- Cross detector pairs on different ADC3111 modules to avoid blind regions in case of card failure

Acquisition logic

- FMCs provide data continuously, every ns
- The algorithm compares the values to a threshold
- When trigger, pulse parameters are provided (TOT, amplitude)
- Neutron to gamma discrimination is based on amplitude threshold
- The number of neutrons per μs and the total charge (integral) is provided
- When pileup observed counting is based on charge

  ➔ The pulse charge distribution from neutron events has a constant shape. The mean value can be used to calculate the average number of neutrons
- Continuous integration is equivalent to current mode (1 reading per μs)
- Self - calibration of pulse amplitude and pedestal runs to check stability



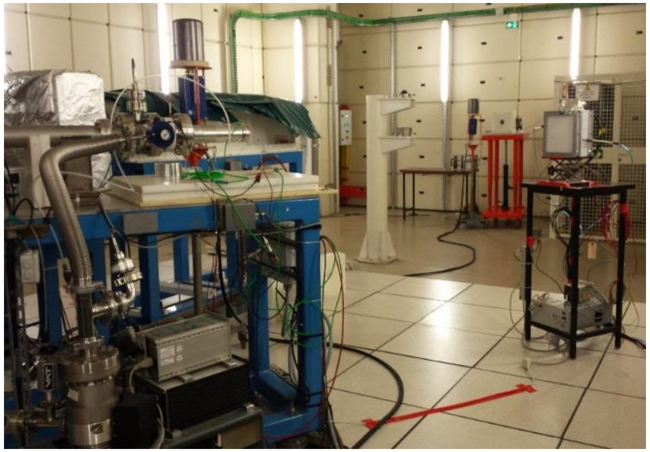
DETECTOR PERFORMANCE

- The ESS nBLM is a system under development
- The commissioning of the ESS linac is planned to start in 2019 and the actual condition (particle yields, background, E/M noise etc) are unknown
- As a result, the performance of the nBLM detectors is not known can only be estimated by:
  - MC simulations of loss scenario (ESS)[1] and of the detector response (Saclay)[2]
  - Detector characterization measurements in neutron and gamma ray facilities
  - Measurements at similar facilities for proof of principle and sensitivity estimation

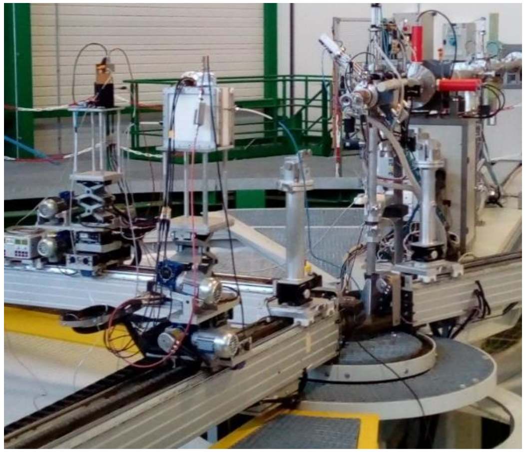
[1] *I. Dolenc Kittelmann, "Report on the MC simulations for the ESS BLM", ESS, Lund, Sweden, Rep. ESS-0066428, Dec. 2016.29*

[2] *L. Segui, "Monte Carlo results: nBLM response to EES beam loss scenarios", CEA Saclay, France, Rep. CEA-ESS-DIA-RP-0023, July 2017*

Beam tests at different irradiation facilities so far



IPHI CEA/Saclay
3 MeV p on Be target and Al endcap

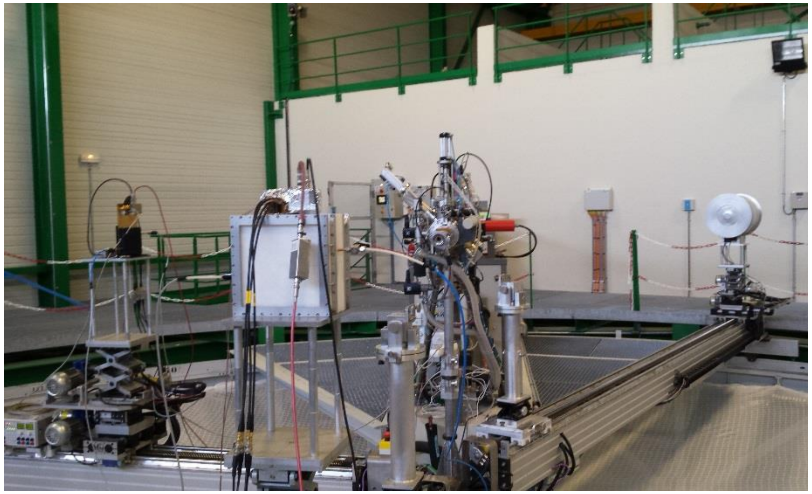


AMANDE, IRSN,Cadarache
Monoenergetic n or γ+n yields

MC40, Birmingham, UK
28 MeV p on Al target

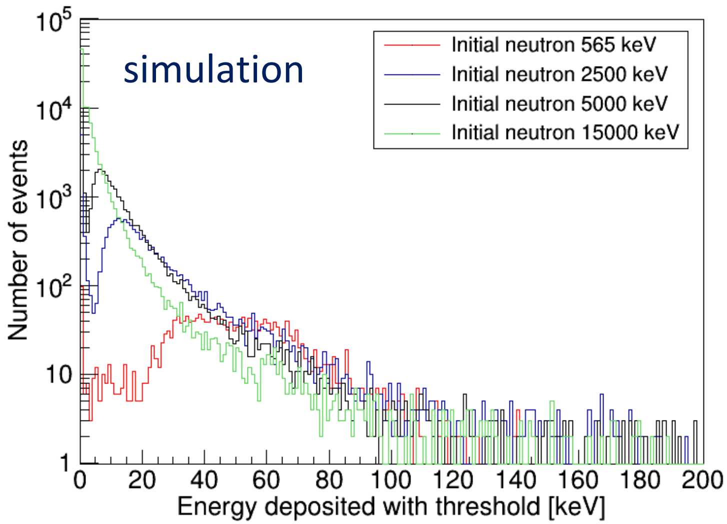
Tests at AMANDE

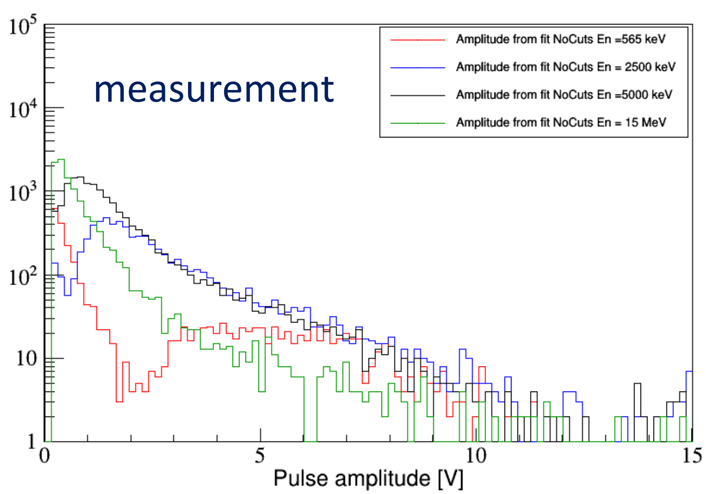
- Both slow and fast prototypes were tested at the following neutron energies: *565 keV, 1.2 MeV, 2.5 MeV, 5 MeV, 15 MeV*
- Varied the thickness of the polyethylene moderator of the slow detector between *3 – 7 cm*. The neutron convertor was *1.5 μm* $^{10}B_4C$, placed at *0.4 mm* from the mesh
- Tested two convertors for the fast detector: *100 μm Mylar* and *1 mm polypropylene*. Both samples had a layer of *50 nm Al* and were placed at *2 mm* distance from the mesh
- The 565 keV field is produced using a *LiF* target ➔ contamination by 6-7 MeV gammas from $^{19}F(p,\alpha\gamma)O^{16}$ of ~equal flux. Using an AlF_3 target instead only gamma field
  ➔ **measure γ/n suppression**.
- A shadow cone used for backscatter suppression. IRSN reference detectors for the flux.
- Acquisition with digital oscilloscope ➔ possible to detect beam fluctuations



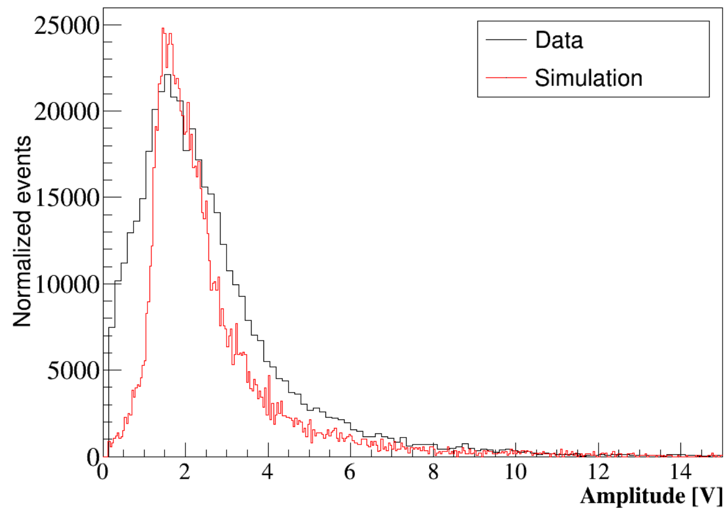
SIMULATION VALIDATION

Fast detector





Slow detector

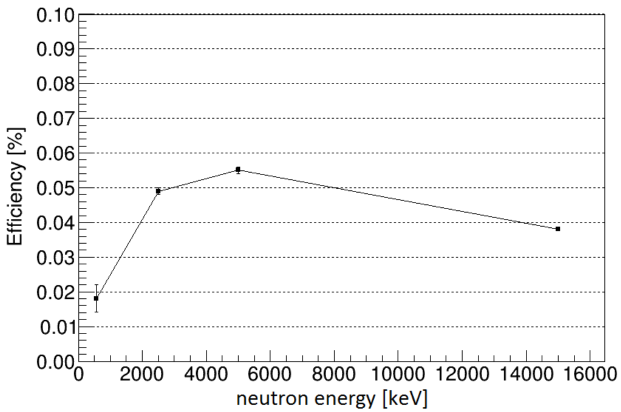


- Good agreement with simulation
- Pulse amplitude spectrum of slow detector independent with neutron energy
- Energy calibration possible for both detectors thanks to the peaks

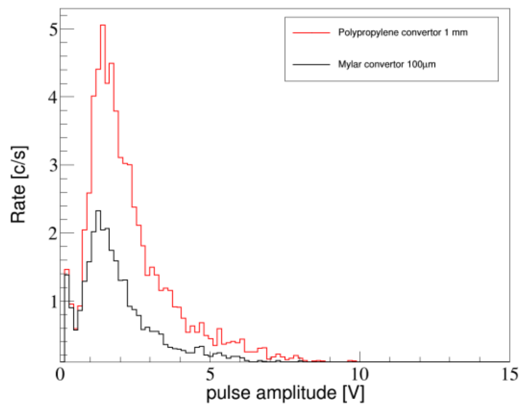
DETECTION EFFICIENCY

Fast detector

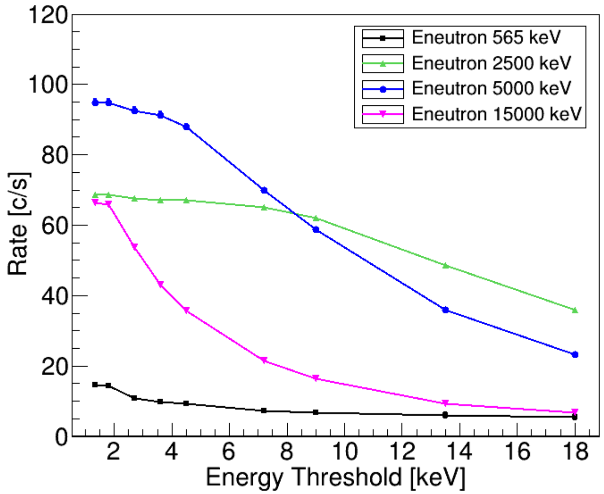
Dependence with neutron energy



Mylar vs Polypropylene



Dependence amplitude threshold



Double efficiency when 1 mm polypropylene is used instead of 100 µm Mylar.

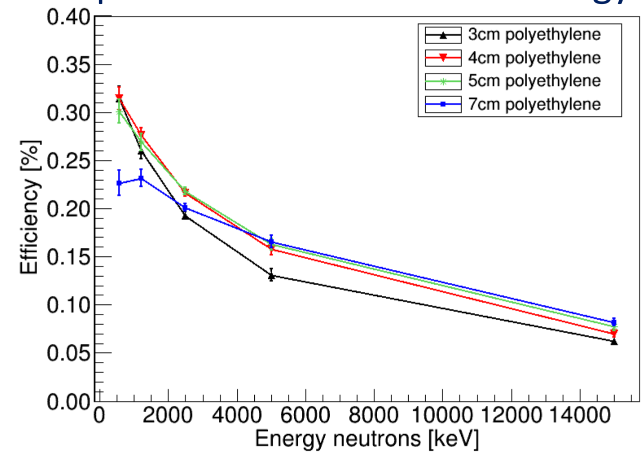
However, we choose the **Mylar** due to the **stability** of the metallization, sacrificing a factor 2 in count rate.

For the slow detector the area of the moderator is used for the calculation (25×25 cm²)

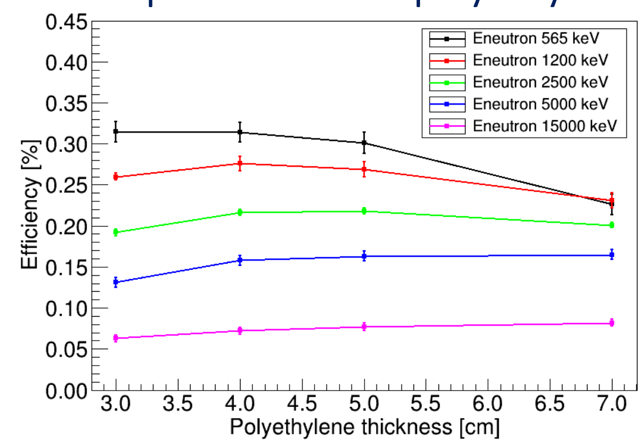
While for the fast the active zone (8×8 cm²) !

Slow detector

Dependence with neutron energy



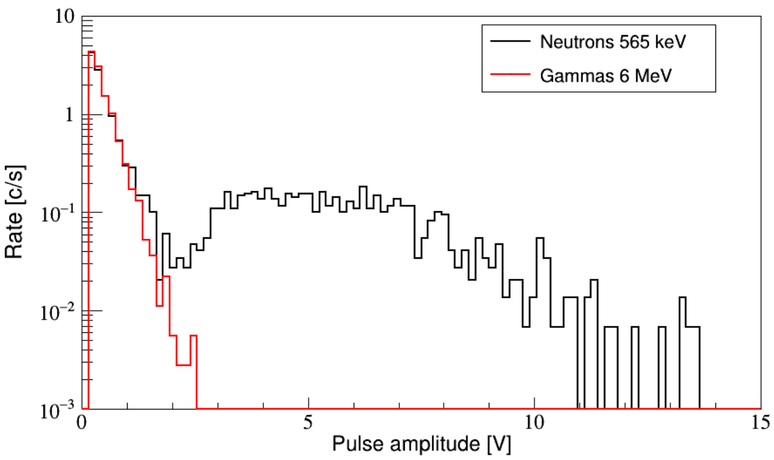
Dependence with polyethylene



Moderator thickness chosen for final detector: **5 cm**

GAMMA TO NEUTRON SUPPRESSION

Fast detector

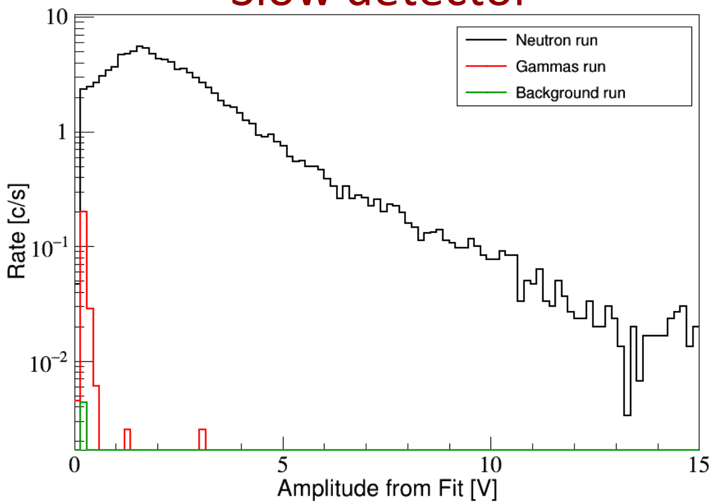


Applying an amplitude cut at 2 V ➔

γ/n relative sensitivity = 3.5 × 10^{-3}

higher threshold ➔ complete suppression

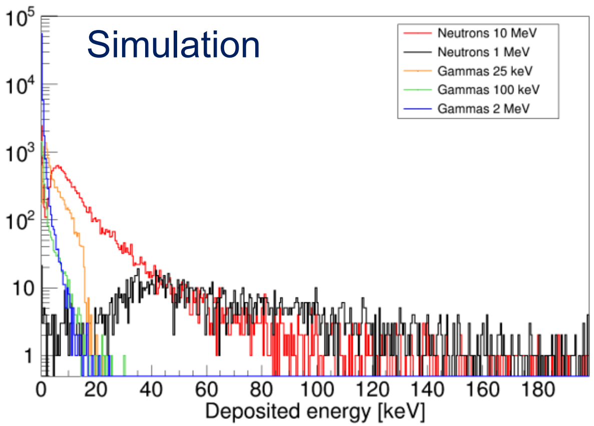
Slow detector



Applying an amplitude cut at 0.3 V ➔

γ/n relative sensitivity = 1.8 × 10^{-4}

Possibly the two events are environmental neutrons!



- The lower efficiency to gammas is due to the difference in the **ionization power between ions and electrons**.
- The choice of **He gas** enhances the suppression
- In the case of the slow detector the suppression is stronger due to :
  - α or ^{7}Li ions instead of protons of fixed energy
  - Smaller drift gap (0.4 vs 2 mm)

Tests at IPHI

Tests for future neutron facility SONATE: *3 MeV protons on Be* target

Use of polyethylene and borated plastic blocks for beam moderation and / or collimation

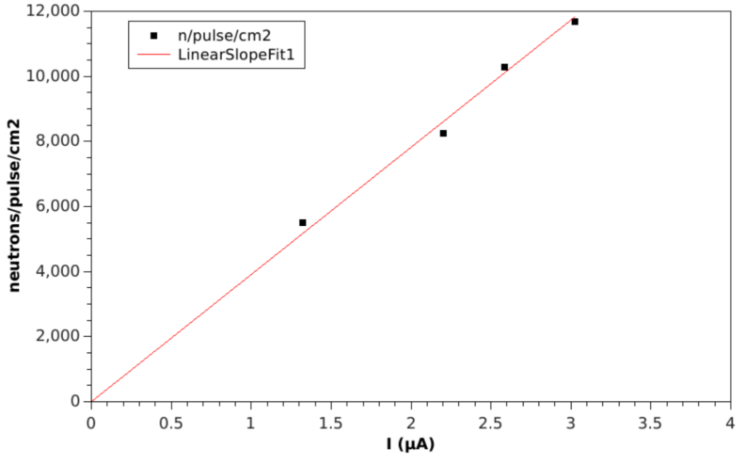
Pulsed beam, duration *90 ns*, repetition rate *1Hz,* intensity *1.3 – 3.2 μA*

Tested both detectors with same configuration as in AMANDE

Data also taken when Be was replaced by a Ni Faraday cup for other experiments (drop in neutron flux by factor 100). Main goals:

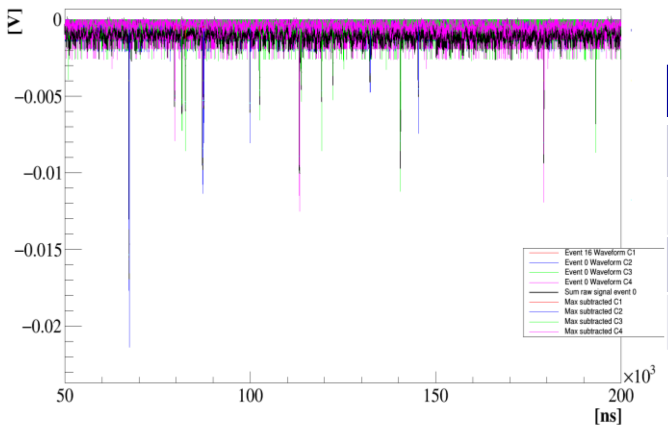
- Study the neutron yield
- Test of Front-End Electronics
- Develop the analysis algorithm for the FPGA
- Study the timing response

Count rate vs beam current

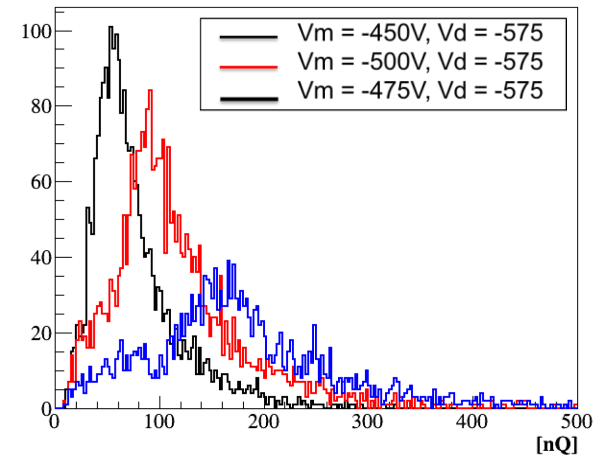


- The 4 segments were recorded independently by a digital oscilloscope at 250 MS/s
- Instantaneous rate high enough to reach the limit of **current mode.** *Detector stable*.

Run with Ni

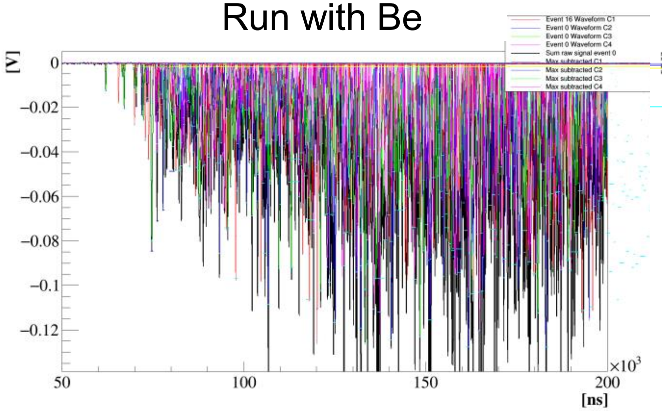


	Rate [c/p]	RateQ [c/p]
Sum	34.	34
C2	12.	11.
C3	10.	10.
C4	7.	6.

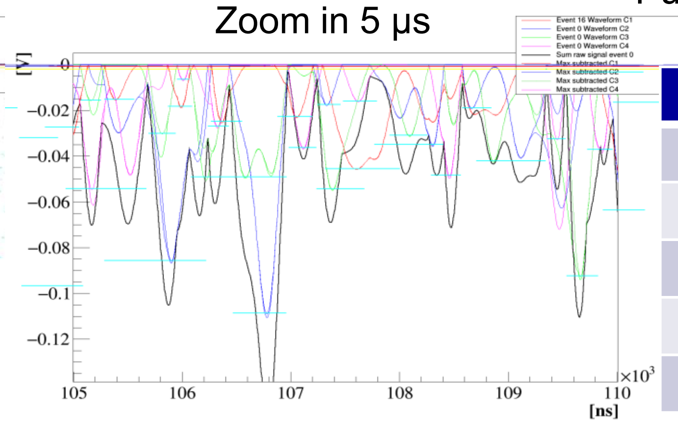


Pulse Charge from low intensity run

Run with Be



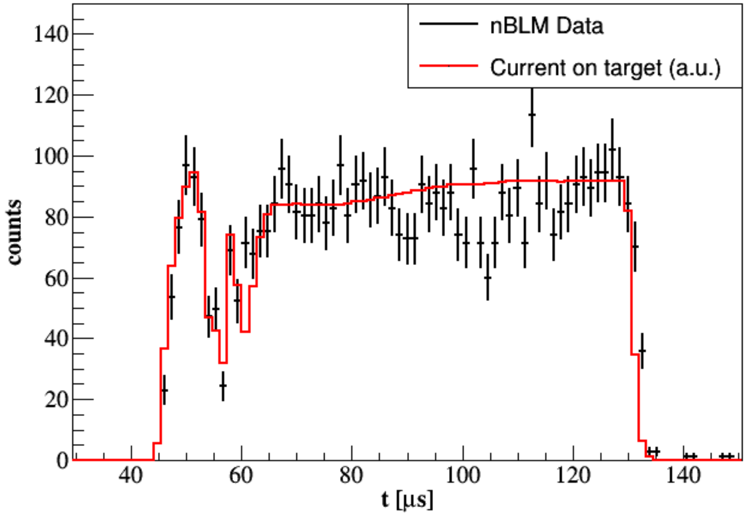
Zoom in 5 μs



	Rate [c/p]	RateQ [c/p]
Sum	241	2318
C1	511	794
C2	518	783
C3	521	730
C4	473	816

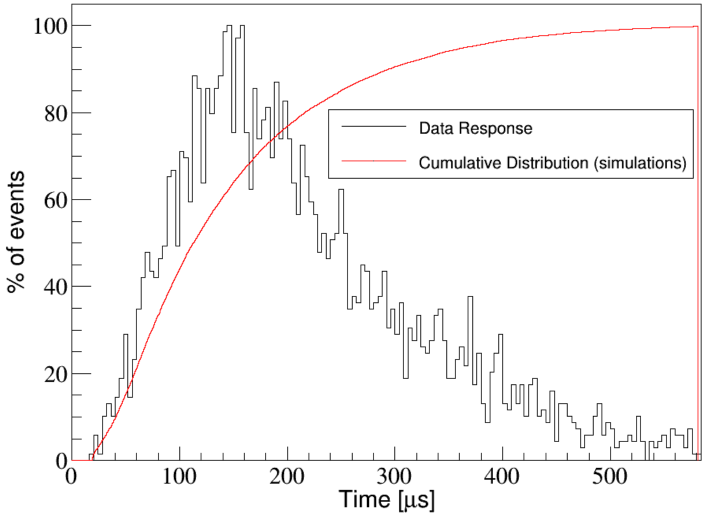
TIMING RESPONSE

Fast detector



- immediate response
- count rate in direct correlation with the intensity of the beam current

Slow detector



- due to moderation time most of the events are recorded with a delay of 100-200 µs.
- in agreement with simulation
- higher efficiency ➔ a significant number of the events (~5% of the total) will be register within the first 5 µs, so possible to use for early warning

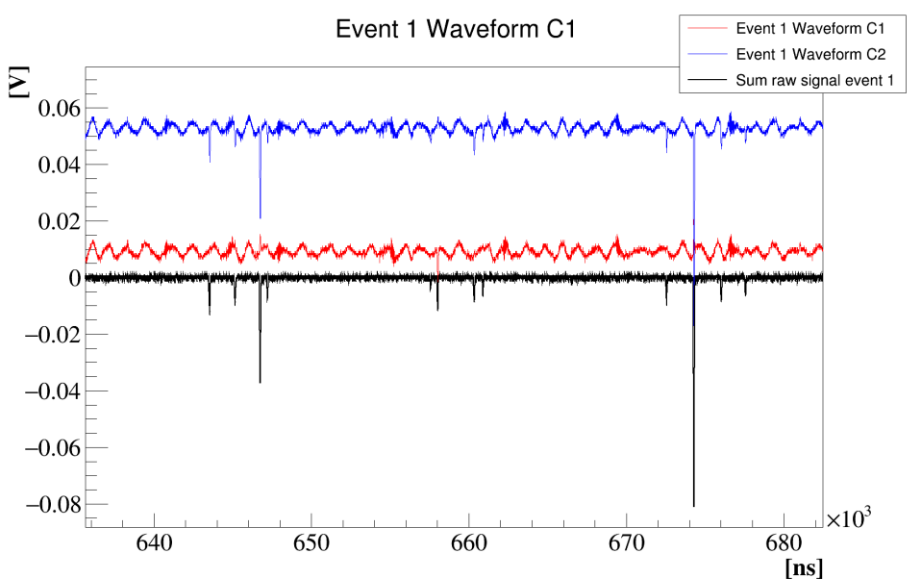
NOISE REJECTION

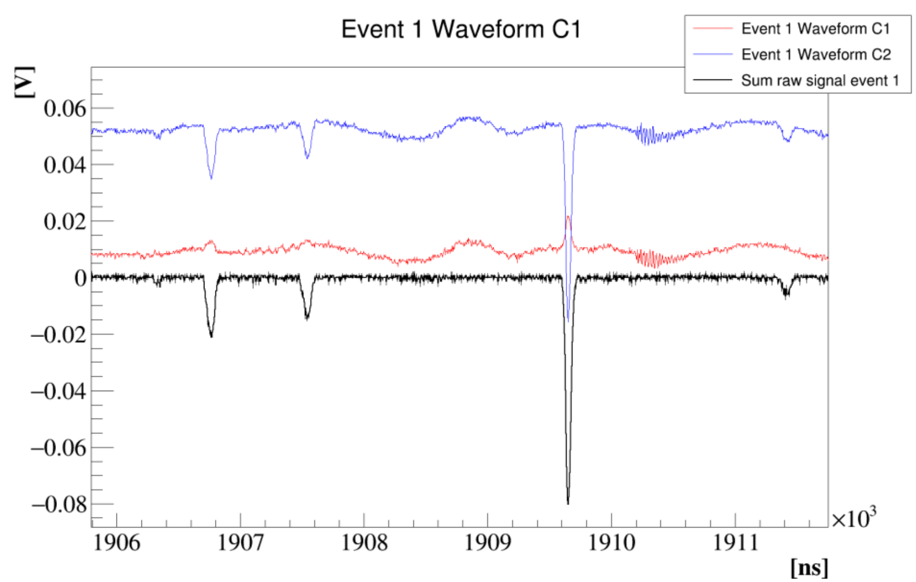
Special care is taken for the design of the detector grounding, Faraday shielding and cabling.

FEE with low noise components and proper choice of power supplies, filters and buffers.

Furthermore: FEE cards equipped with 2 identical amplifiers each, with all channel connection combination possible. This could allow in case of extreme conditions:

- ➢ Common mode noise suppression in-flight by subtraction channel by channel at the same FMC (double amount of signal cables and FMC channels)
- ➢ In case gamma background too high ➔ continuous signal, no threshold discrimination: Possible to mask part of the converter: this part of the detector will be sensitive only to gammas and subtraction of the gamma continuous can be done channel by channel



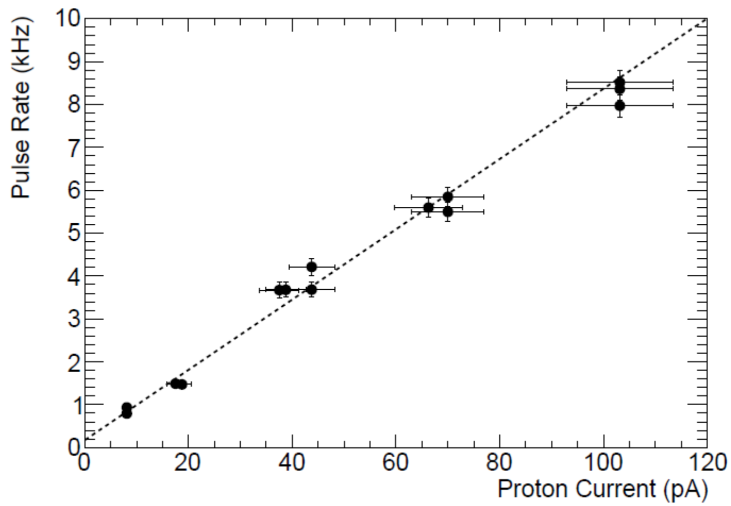


Other tests

MC40 cyclotron , Birmingham Un. UK

28 MeV p on Al plate. To follow:

- More materials relevant to the ESS linac
- FEE irradiation



ORPHEE nuclear reactor LLB, CEA Saclay

0.01 eV neutrons, flux $2\times10^{6}\ s^{-1}\ cm^{-2}$

- Analysis ongoing
- Stable operation with high current (up to 600 nA), no discharges
- Verified that 5 mm Borflex absorbs completely the thermal neutrons
- study the detector operation parameters (B4C thickness, drift gap, operating voltages) to optimize signals (duration, amplitude etc.)

Planning

- **CEA Saclay SPR:** 110 GBq AmBe, Co, Cs sources
- **CERN GIF++:** gamma irradiation
- **CERN Linac4:**
  - ➔ Install a detector in the hall (without interfering!) in Aug 2018.
  - ➔ Profit from September's run to test response, backgrounds, BEE (possible) in most similar(?) conditions available to the ESS linac

Summary

Project: development of neutron based BLM for ESS with Micromegas readout

- Kick-off → 7/2016
- CDR2 → scheduled on Nov. 2018, commissioning of first detectors planned for spring 2019

Fast/Slow nBLM (to get almost all neutrons)

- sensitive to low losses (aim: 0.01 W/m)
- timing → <15 ns / 200 μs
- intrinsically reduced γ sensitivity → 0.3 % -> 10^{-5}

- nBLM may work in 2 modes, since expected rates are difficult to estimate
  - neutron counting (< 10^6 cts/s)
  - current
  - gas → 90% He + 10% CO_2 → installation of a gas system
- Electronics
  - FEE pre-amplifiers (high BW, low noise, gain=34) with common mode noise rejection capability
  - FPGA for data processing (real-time waveform analysis for counting mode)

Tests in several facilities verify the behavior predicted by the simulations. More tests to follow and analysis to be completed in order to predict the sensitivity in ESS linac conditions.

Thank you for your attention!

T_0: June 1st 2016

T0 (1. June 2016)

6 months

Activties:
1. Detector design (MC sim.)

PDR-1 (end of Nov. 2016)

6 months

Activties:
1. Prototype manufacturing
2. Initial electroncis design

To deliver at PDR-1:
1. Documention on the detector design.
2. Report on plans for the protptype (design, planned tests)

PDR-2 (end of May 2017)

5 months

Activties:
1. Inital prototype tests
2. Completion of electroncis design

To deliver at PDR-2:
1. Documention on the inital electronics design.

CDR-1 (end of Oct. 2017)

5 months

Activties:
1. Final prototype tests.
2. Completion of the FPGA firmware
3. Completion of the SW development for the control system.
4. Completion of the gas& filtering system design.

To deliver at CDR-1:
1. Report on the intial prototype tests with suggested changes to the system design as the outcome of these tests.
2. Documention on the completed electronics design.

CDR-2 (end of March 2018)

5 months

Activties:
1. System component manufacuring/procurement
2. Vertical integration test of the system (for 1 unit)
3. Delivery of the system to ESS

To deliver at CDR-2:
1. Report on the final prototype tests with suggested changes to the system design as the outcome of these tests.
2. Documention on the completed FPGA firmware development.
3. Documention on the SW development for the control system.
4. Documention on the gas& filtering system.

SAR (end of Sept. 2018)

To deliver at SAR:
1. Documentation on "as-bulit" sysetem.
2. System installation and commissioning instructions
3. Calibration, opertaion and maintainence manuals.

Installation and comiss. start (27. Nov. 2018?)

? months

Activties:
1. Support with installation and commissioning

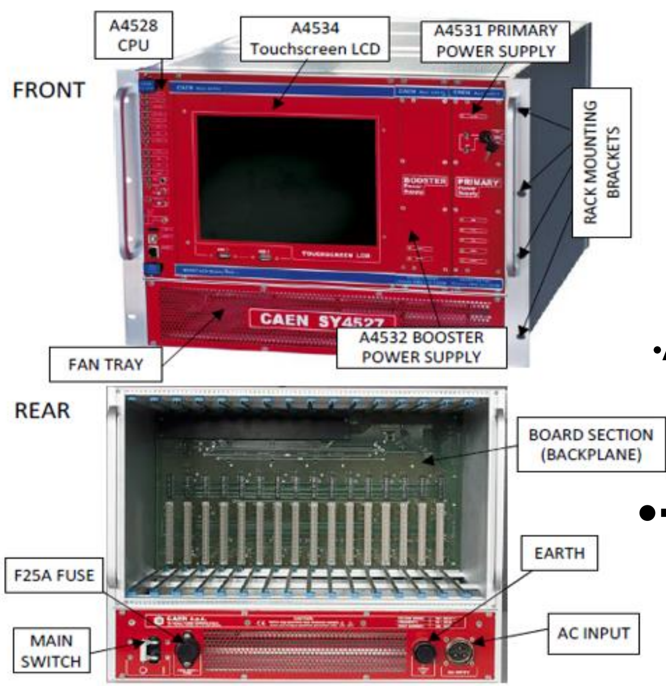
Installation and comiss. end (Dec. 2018?)

Handover to ESS

Commissioning: Spring - Fall 2019

- HV and LV crate

SY4527

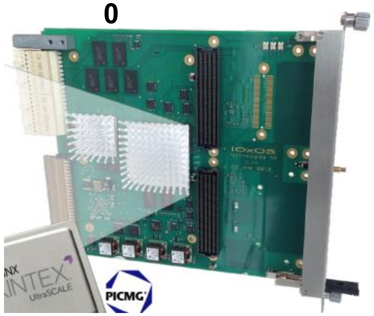


- A7030 + A2519

- +

- BEE boards

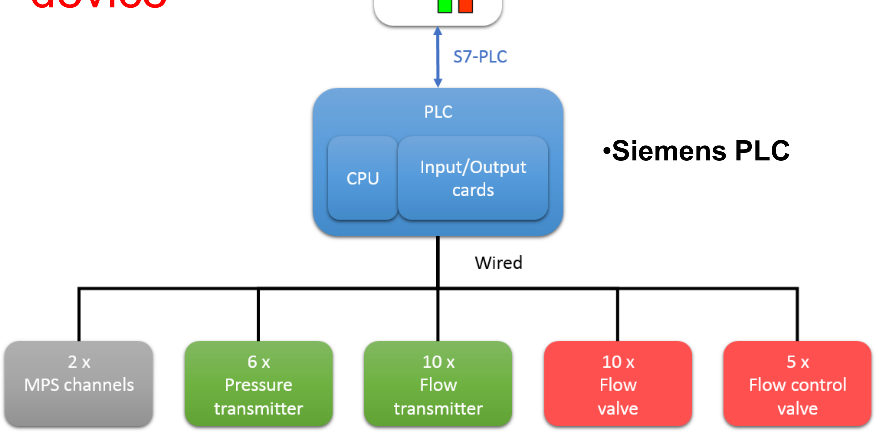
- IFC1410

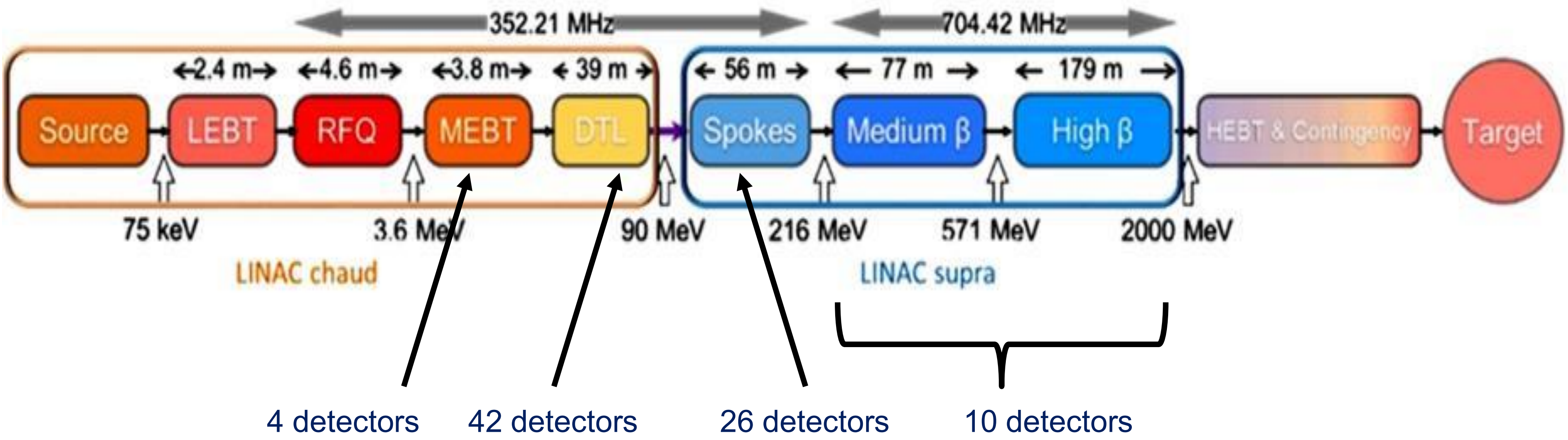


- ADC3111

- Gas
- device

- IOC
- Kontron IPC
- Siemens PLC




352.21 MHz
704.42 MHz
2.4 m
4.6 m
3.8 m
39 m
56 m
77 m
179 m
Source
LEBT
RFQ
MEBT
DTL
Spokes
Medium β
High β
HEBT & Contingency
Target
75 keV
3.6 MeV
90 MeV
216 MeV
571 MeV
2000 MeV
LINAC chaud
LINAC supra
4 detectors
42 detectors
26 detectors
10 detectors