Micromegas for beam loss monitoring

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Motivation
• nBLM-ESS Project

nBLM Detectors
• Fast and Slow

Detector characterization
• 1st beam loss detection

Conclusions
Why new Beam Loss Monitors (BLM)?

- A need in the accelerator community:
- In new high intensity hadron linear accelerators even low energy beam could damage the accelerator or activate materials
  - Crucial to monitor **any small loss**
  - Keep the loss $\leq 1$ W/m to allow hands-on maintenance
    - ESS 5MW $\rightarrow 2 \times 10^{-5}$ /m of the total power (0.02 ‰)
- Positioning of the BLM is important
  - Different beam lost signature in different areas of accelerator
  - At **low beam energy** only neutrons and photons can escape the beam pipe
  - Standard used ionization chambers have little sensitivity in this area and are affected by RF emission.

…”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

Low efficiency to thermal neutrons

Strong suppression of gammas

Detection of fast neutrons

Fast system response (few µs)

nBLM

nBLM (neutron Beam Loss Monitor) →

- Fast neutron detector based on Micromegas (MMs) equipped with a combination of neutron convertors and moderators
**Project: In-kind** contract between the European Spallation Source (ESS) and IRFU

- Design, construction, test and commissioning of **84 detectors** by Nov 2019
- Part of the Beam Instrumentation systems of the **ESS Accelerator** (Lund, Sweden)
- Dedicated mainly to the **low energy region** of the accelerator.

### CONTEXT: ESS NBLM SYSTEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length (ms)</td>
<td>2.86</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>2</td>
</tr>
<tr>
<td>Peak current (mA)</td>
<td>62.5</td>
</tr>
<tr>
<td>Pulse repletion freq. (Hz)</td>
<td>14</td>
</tr>
<tr>
<td>Average power (MW)</td>
<td>5</td>
</tr>
</tbody>
</table>
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**nBLM-ESS System**

- Req. & spec. develop. : ESS
- Concept: CEA + ESS
- Detectors: CEA
- Gas System: CEA
- DAQ firmware: LUT
- Control System: CEA
- Integration: ESS
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Two complementary modules
Detector chamber identical
differences: neutron-to-charge particle convertor
and the surrounding of the slow with absorber + moderator

SLOW

Polyethylene moderator

FAST

Aluminium chamber
Plastic convertor on Al
He+CO₂ gas
MMs detector

Borated rubber (5 mm)
Polyethylene (5 cm)
Aluminium chamber
B₄C deposited on Al
He+CO₂ gas
MMs detector

n, γ

n, γ
<table>
<thead>
<tr>
<th></th>
<th>SLOW</th>
<th>FAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron-to-charged</td>
<td>$\text{B}_4\text{C}$</td>
<td>Mylar or Polypropylene</td>
</tr>
<tr>
<td>particle convertor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaction</td>
<td>$^{10}\text{B}(n,\alpha)^7\text{Li}$</td>
<td>(n,p)</td>
</tr>
<tr>
<td>Signal produced by</td>
<td>Fast neutrons after moderation</td>
<td>Fast neutrons</td>
</tr>
<tr>
<td>Detected energy</td>
<td>~constant for all initial neutron energy</td>
<td>Depends on initial neutron energy</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$10^{-4} &lt; \text{En} &lt; 100 \text{ MeV}$</td>
<td>$\text{En} &gt; 0.5 \text{ MeV}$</td>
</tr>
<tr>
<td>Solid angle</td>
<td>$4\pi$</td>
<td>$2\pi$, n coming from the front only</td>
</tr>
<tr>
<td>Efficiency</td>
<td>~few n·cm$^{-2}$·s$^{-1}$</td>
<td>~10-100 times smaller</td>
</tr>
<tr>
<td>Response time</td>
<td>~200 µs</td>
<td>~0.01 µs</td>
</tr>
<tr>
<td>Objective</td>
<td>Monitoring of small losses</td>
<td>Alarm (in 5 µs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine structure of the lost</td>
</tr>
<tr>
<td>Shielding</td>
<td>Yes, for thermal neutrons</td>
<td>Not needed</td>
</tr>
</tbody>
</table>
Assembly of a fast and a slow detector

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

Moderator + absorber

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

- 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
- FEE card and amplifiers designed at CEA
- Can operate in counting and charge mode

*Inside gas*

8x8 cm\(^2\)

FEE

HV

Single neutron acquired with the nBLM electronics

Threshold at 2.5 mV

Rise Time ~ 35 ns

Pulse Width ~90 ns
NBLM EXPERIMENTAL TESTS

July 2016
Kick-off

Dec 2017
Correlation rate and intensity of the beam

Jan. 2018
Time Response

Mar. 2018
- Calibration
- n/γ discr.

Apr. 2018
- Thermal neutrons

Nov-Dec. 2018
Real accelerator conditions

Feb. 2019
n/γ discrimination

MC40- Cyclotron, Birmingham, UK
IPHI, CEA, France
AMANDE, IRSN, France
ORPHEE, CEA, France
LINAC4 (CERN)
High intense n/γ sources, CEA, France
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Paper under preparation
**NBLM TIME RESPONSE**

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

**SLOW**
- Delay in signal: Convolution of moderation in polyethylene + proton beam pulse duration (100 µs)
- ~200 µs from simulations for a instantaneous pulse
EFFICIENCY MEASUREMENTS

FAST

Data

Simulation

SLOW

Data

Data vs simulation

1.0 \times 10^{5}
1.0 \times 10^{4}
1.0 \times 10^{3}
1.0 \times 10^{2}
1.0 \times 10^{1}
1.0 \times 10^{0}
1.0 \times 10^{-1}
1.0 \times 10^{-2}
1.0 \times 10^{-3}
1.0 \times 10^{-4}
1.0 \times 10^{-5}

Pulse amplitude [V]

Energy deposited with threshold [keV]

En 565 keV, 5cm poly
En 5000 keV, 5cm poly
En 15000 keV, 5cm poly

Data run 108
MC data E_{res} = 0.30 FWHM
EFFICIENCY MEASUREMENTS

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

- Count rate of few /s for a neutron fluence rate of 1/s/cm²
The choice of He gas enhances the suppression
Values are threshold and gain dependent
The difference in rate observed between fast and slow is due to different drift distance (1.9 mm in fast / 0.4 in slow)
LINAC4 DATA

- **Fast nBLM module** installed between two DTLs at ~13 MeV proton region
- Final mechanics and electronics (*pre-series*)
- Gas: He + 10% CO₂
- Two data campaigns
  - November 2018
    - Understanding the detector, test FEE in accelerator conditions…
  - December 2018
    - Losses were produced

- Data taking with a fast oscilloscope
  - 250 Ms/s
  - Full bandwidth
  - With trigger of Linac4 also recorded
LINAC4 DATA – PROVOQUED LOSSES

Run 414
No losses

Neutrons
Ampl Th = 6 mV

Run 415
Losses

V_{\text{mesh}} = -525 \text{ V}
V_{\text{drift}} = -1000 \text{ V}

Amplitude

Average rate
LINAC4 DATA – PROVOQUED LOSSES

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

average N° events / beam pulse

Neutrons
Uncorrelated neutrons
Sparks or recovery
LINAC4 DATA – PROVOQUED LOSSES

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

1st proof of the expected functionality of the nBLM
CONCLUSIONS

New application of Micromegas detectors

A lot of interest from the accelerator community

Detector concept, design, first prototypes and proof of concept in irradiation facilities in ~2 years

Proof fast response, n/g rejection and efficiency and FEE

Clearly detect beam losses at LINAC 4

Production project of 84 detectors system with ESS
Thank you for your attention!
Back-up
• 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

RF pulse, gammas amplitude <~25 mV

Neutrons > 30 mV

Run 412 – November 2018
Vm = -550V, Vd = -1500V

Th for noise at 2.5 mV
Applying amplitude cut, we recover the beam duration
→ Neutrons produced by beam
→ Gammas distributed all along RF pulse
Run 420 – December 2018
$V_m = -550 \text{V}, V_d = -1500 \text{V}$

Zoom of previous slide
Losses were produced btw 20:50 – 21:05
NBLM DATA – NEUTRON AND GAMMA SOURCES

**SLOW**

Lower gain (480 V)  
Higher gain (510 V)
NBLM DATA – NEUTRON AND GAMMA SOURCES

FAST

Vm = 490 V, Vd = 740 V, Fast
- Neutron source (run 616)
- Gamma source (run 630)
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 $\phi=1\text{cm}$

Correlation of the count rate with the intensity of the proton beam
Dependency with drift voltage

Rise Time

Pulse width

Risetime [ns]

Pulse Duration [ns]
ORPHEE nuclear reactor LLB, CEA Saclay: 0.01 eV neutrons, flux $2 \times 10^6$ s$^{-1}$ cm$^{-2}$

- Optimum value $\sim 2$ mm
  - Rise Time $\sim 45$ ns and very stable
  - Pulse duration $\sim 60$ ns $\rightarrow$ in 1$\mu$s $\sim >10$ pulses/window before pile-up ($\sim 10$ MHz)
- Optimized to avoid also to be very close to sparking point

Dependency with drift distance

Rise Time

Pulse width
Example of a pedestal distribution for one of the runs taken during the December 2018 campaign (left). (Right) The sigma of the pedestal distributions for different runs. Run 420 was when quite important beam losses were produced and this produced some sparks as explained in the text that broad the pedestal distribution.
SPARK IDENTIFICATION

- Identified pulse by pulse if
  - Sigma of baseline too large
  - Charge of pulse too large
Front end electronics for nBLM prototype

FAMMAS front-end module
(Fast Amplifier Module for Micromegas ApplicationS)

In few figures ...

- **Power supply**: +5V -5V
- **Consumption**: ≈ 50 mW
- **Input**: positive or negative
- **Noise**: 600 µV rms
- **Rise time**: < 1ns
- **Bandwidth adjustable up to** few GHz
- **Configurable gain, in these results** 40dB (equals x 100)
- **Very robust to sparks**
THE ACQUISITION SYSTEM

Fast acquisition

ICS standardisation for fast acquisition is based on:
- \( \mu \)TCA.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

- 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