# BrightnESS

## Building a research infrastructure and synergies for highest scientific impact on ESS

## H2020-INFRADEV-1-2015-1

## Grant Agreement Number: 676548

**Deliverable Report: D4.2 “Counting rate capability”**

# 1 Project Deliverable Information Sheet

<table>
<tr><td rowspan="8">BrightnESS Project</td><td colspan="2">Project Ref. No. 676548</td></tr>
<tr><td colspan="2">Project Title: BrightnESS - Building a research infrastructure and synergies for highest scientific impact on ESS</td></tr>
<tr><td colspan="2">Project Website: https://brightness.esss.se</td></tr>
<tr><td colspan="2">Deliverable No.: 4.2</td></tr>
<tr><td colspan="2">Deliverable Type: Report</td></tr>
<tr><td>Dissemination Level: To EC</td><td>Contractual Delivery Date: 31.07.2016</td></tr>
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<tr><td colspan="2">EC Project Officer: Bernhard Fabianek</td></tr>
</table>

## 2 Document Control Sheet

| | | |
|---|---|---|
| Document | Title: BrightnESS_Deliverable_4.2 – Counting rate capability | |
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| | Approved by | BrightnESS Steering Board |

## 3 List of Abbreviations

| | |
|---|---|
| BNC | Budapest Neutron Centre |
| ESS | European Spallation Source |
| FEE | Front-End Electronics |
| ILL | Institut Laue-Langevin |
| LU | Lund University |
| MWPC | Multi-Wire Proportional Chamber |

## 4 List of Figures



## 5 Contents

# 6 Executive Summary

This deliverable, “Counting rate capability”, is part of the task 4.2 “The Intensity Frontier”. It aims to report the rate capability of the technology used for the Multi-Blade detector.

The Multi-Blade is a $^{10}B$-based detector conceived to face the challenge of the counting rate capability arising from the neutron reflectometry at the European Spallation Source (ESS). The current detector technology, based on $^{3}He$-based detector, is reaching fundamental limits in counting rate capability and position resolution. [Cam+11] The problem with count rates is a general one, and the ESS solution could potentially be applied to existing instruments at other neutron sources. [PHW14]

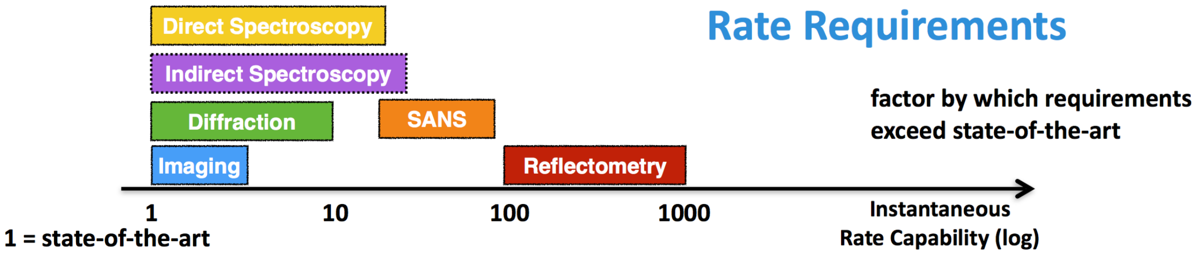


*Figure 5.1. Requirements challenge for detectors for ESS. Figure from [Hal].*

The work on the Multi-Blade began in 2011 at the Institut Laue-Langevin (ILL) where two technology prototypes were built and tested showing promising results. [Pis14] The European Union is now sponsoring the Multi-Blade detector through the BrightnESS project [ESS] that aims to realise detectors optimised for these high rates.

The Multi-Blade design has been improved since the beginning of BrightnESS as part of task 4.2. A new demonstrator has been built and tested within the collaboration of ESS, Lund University (LU) and the Wigner Research Centre for Physics, Hungary. It has been shown that aside from the improvement in counting rate capability, the Multi-Blade design also decreases the spatial resolution by about a factor three over state-of-the-art $^{3}$He-based reflectometer detectors. These and other results including the path ahead for this project will be presented. The Multi-Blade design is the one favoured as a development path to be pursued for reflectometry at ESS.

At present, a data rate of 40 kHz/mm2 is achieved. This result is already very close to the desiderata target of 100 kHz/mm2 and it is a factor 100 above the state of art of the available technology (300Hz/mm2). Calculations indicates that this design is capable of reaching the given goal.

# 7 Report on Implementation Process and Status of Deliverable

The new Multi-Blade demonstrator built in 2015 (in the following MB-15), has been tested and fully characterised. As far as the "counting rate capability" is concerned, tests were performed at the Budapest Neutron Centre (BNC) reactor in Budapest, Hungary in March and May of this year.

According to [Ste+16], we define:
**Global time-averaged detector rate,** $\bar{R}_g$**,** as the total number of neutrons per second recorded by the whole detector;

**Local time-averaged detector rate,** $\bar{R}_l$**,** as the total number of neutrons per second recorded in a detector channel or per area;

**Global instantaneous peak detector rate,** $R_g$**,** as the highest instantaneous neutron count rate on the whole detector;

**Local instantaneous peak detector rate,** $R_l$**,** as the highest instantaneous neutron count rate on the brightest detector channel or blade.[1]

We also define **Flux capability,** *F***,** of the detector as the maximum flux on the active surface of the detector that can be sustained without losing data. In general,

$$F = R_{max} \times \epsilon_{det}^{-1}$$

where $\varepsilon_{det}$ is the efficiency of the detector.

Reflectometry is a technique which reflects the incoming neutron beam into a narrow reflected line. Additionally, as ESS is a pulse spallation source, this means that the instantaneous rate is much higher than the time averaged rate. Therefore, the critical performance characteristic for a reflectometry detector is the local instantaneous peak detector rate and its corresponding local instantaneous peak flux capability.
Given the geometry of the detector, we expect no limitation to the counting rate capability from the *space charge effect* [And+09] of the Multi-Wire Proportional Chamber (MWPC); we aspect limitations from the double pulse time resolution of the used electronics.

The present Front-End Electronics (FEE) used on the detector, is made of a preamplifier stage, followed by an analogue shaper. The shaper is providing a signal with a length of ≈ 500 ns; this limits the maximum counting rate of the electronics to ≈ 1MHz per channel. Practically as not all signals are equally distributed in time, a general rule of thumb [Kno10] is a factor of 10 less, i.e. ca. 200 kHz per channel. This capability of the technology exceeds the design goal of 100 kHz. With improved FEE and shorter shaping time, this can be as low as 100 - 200 ns; thus there is potential to improve further beyond this number. Therefore, the capability of the technology meets the design goal.

As a summary of the results of the tests performed in Budapest, the local counting rate capability of the MB-15 is proved to be as good as 16.7 kHz/*ch* and the extrapolated global rate along a single wire is up to about 47.6 kHz/mm. These measurements showed no signs of signal saturation and were limited by the maximum beam intensity available from the neutron source. Even if these limits are already beyond the state of art of the available

[1] At pulsed sources, the instantaneous rate could be more of an order of magnitude higher than the average rate as the neutron emission is concentrated in short bursts. The knowledge of this rate is important in determining whether a detector technology is suitable to be utilised for a specific application has impact on the design of the detector and electronics.

technology, the actual limit of this detector is above the limitation set by the neutron beam available.

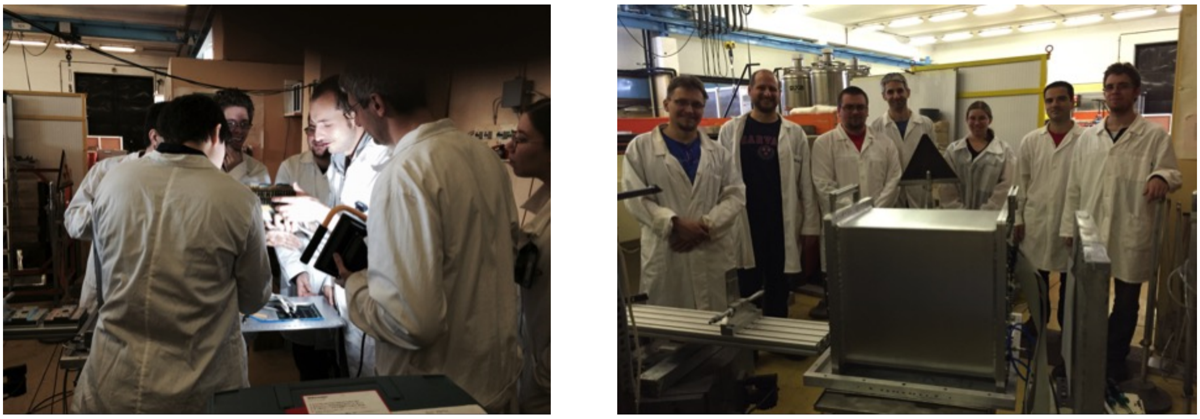

*Figure 6.1. Pictures during the tests at the BNC reactor in Budapest. Tests on the rate capability were performed in March and May 2016 (picture on the left and on the right respectively).*

# 8 Technical Content

The requirements for the reflectometry instruments at ESS ask for a counting rate capability of the detector better than 100 kHz/mm2.

| Instrument | | area $(mm \times mm)$ | $\Delta x$ $(mm)$ | $\Delta y$ $(mm)$ | global rate $(s^{-1})$ | local rate $(s^{-1}mm^{-2})$ |
|---|---|---|---|---|---|---|
| ESTIA [EST13] | min | $500 \times 170$ | $\leq 2$ | $\geq 2$ | - | - |
| | ideal | $500 \times 500$ | $\leq 0.5$ | $\geq 0.5$ | $\sim 10^7$ | $3 \cdot 10^4$ |
| FREIA [FRE13] | min | $500 \times 500$ | 8 | 1 | - | - |
| | ideal | $500 \times 500$ | $\leq 8$ | $\leq 1$ | $\sim 5 \cdot 10^5$ | $\sim 3.5 \cdot 10^3$ |
| THOR [THO13] | min | $500 \times 500$ | 2 | - | - | - |
| | ideal | $500 \times 500$ | $\leq 2$ | - | - | - |
| VERITAS [VER13] | min | $500 \times 500$ | 2 | 2 | - | - |
| | ideal | $500 \times 500$ | $\leq 2$ | $\leq 2$ | $5 \cdot 10^5$ | $5 \cdot 10^2$ |

*Table 7.1. Detector requirements, for both ideal-world and minimal requirements, in terms of detector active area, spatial resolution, global and local rates for reflectometer proposals at ESS. Table from [PHW14]*

This is the goal the Multi-Blade is aim at and we can state that we are approaching it.

The Multi-Blade detector is a stack of Multi-Wire Proportional Chamber (MWPC) (see Figure 5.1) operated at atmospheric pressure with continuous gas flow (*Ar/CO2 80/20* mixture).
The Multi-Blade is made up of identical units, called cassettes. Each cassette holds a blade (a substrate coated with $^{10}B\ ^{4}C$) and a two-dimensional readout system, which consists of a plane of wires and a plane of strips. Each $^{10}B\ ^{4}C$-converter (blade) is inclined at 5 degrees with respect to the incoming neutron beam. The inclined geometry has two advantages: the neutron flux splits among many wires (the local counting rate capability is increased) and the spatial resolution improved. Moreover, the use of the $^{10}B\ ^{4}C$ conversion layer at grazing angle also increases the detection efficiency. The increase in counting rate capability is not only expected because of the inclination but in the Multi-Blade design the neutron conversion medium and the detection medium are distinct and this allows for a flexibility in the optimisation process. E.g. the MWPC geometry can be altered to improve the counting rate capability without any change in the efficiency. Differently in an $^{3}$He-based detector the two media are the same and this optimisation is more complex.

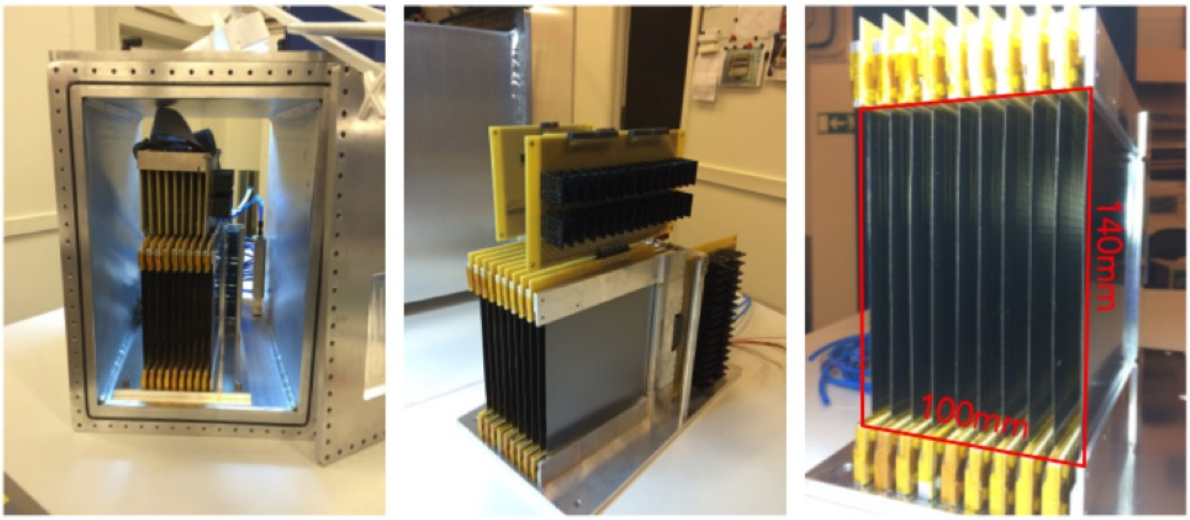


*Figure 7.1. Pictures of the Multi-Blade MB-15 detector: the 9 units (cassettes) assembled and placed in the gas vessel and equipped with the front-end electronics.*

The response of the detector [MPona] and its homogeneity [MPonb] has been measured. An example of these results is shown in Figure 5.2. A borated sheet containing shaped cuts, is placed on the entrance window of the detector. Any incoming neutron will be absorbed by the sheet, with the exception of the one in correspondence of the cuts. As shown, it is possible to reconstruct the image of the word ESS by analysing the data from the detector.

The counting rate capability is measured using a collimated beam. A spot of approximately 3 x 3mm is obtained and the rate of the illuminated channel is plotted against the intensity of the beam. As shown in figure 5.3, even without the usage of any absorber, the detector does not show any sign of saturation. The same measurement is repeated illuminating a full wire (vertical slit). As shown in figure 5.4, the detector was able to sustain the maximum rate available at the beam line, without showing any sign of saturation. The counting rate capability of the Multi-Blade MB-15 is proved to be as good as 2 kHz/mm2 and extrapolated up to about 40 kHz. Future tests will be performed on this prototype and on the next one (the MB-16). The future tests will involve more intense neutron beams in order to measure and verify the limits of the detector technology.

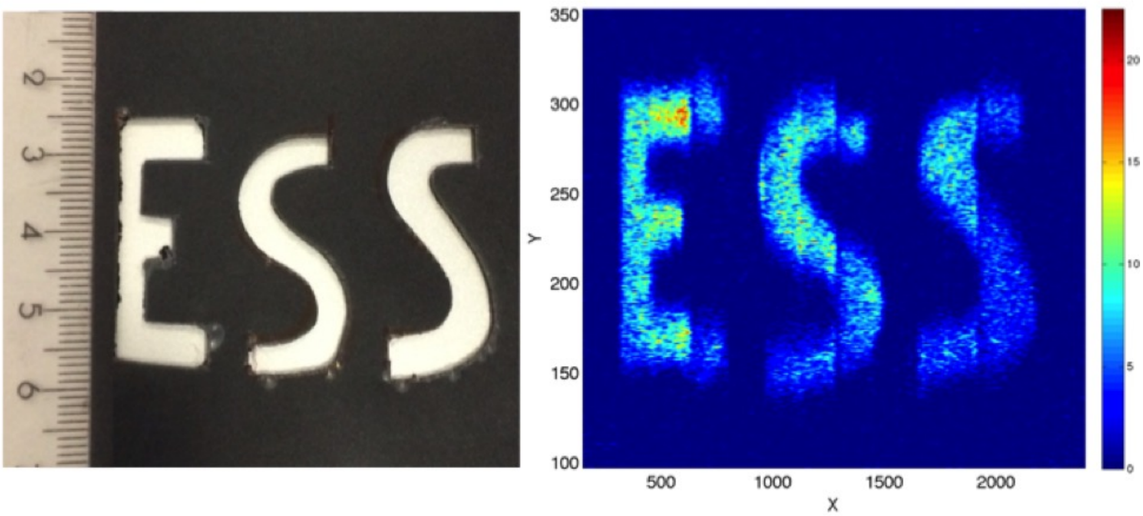


*Figure 7.2. An example of the response of the MB-15 detector. A borated sheet (on the left) has been placed on the entrance window of the detector to reproduce the word ESS. On the right the reconstructed image from the detector.*

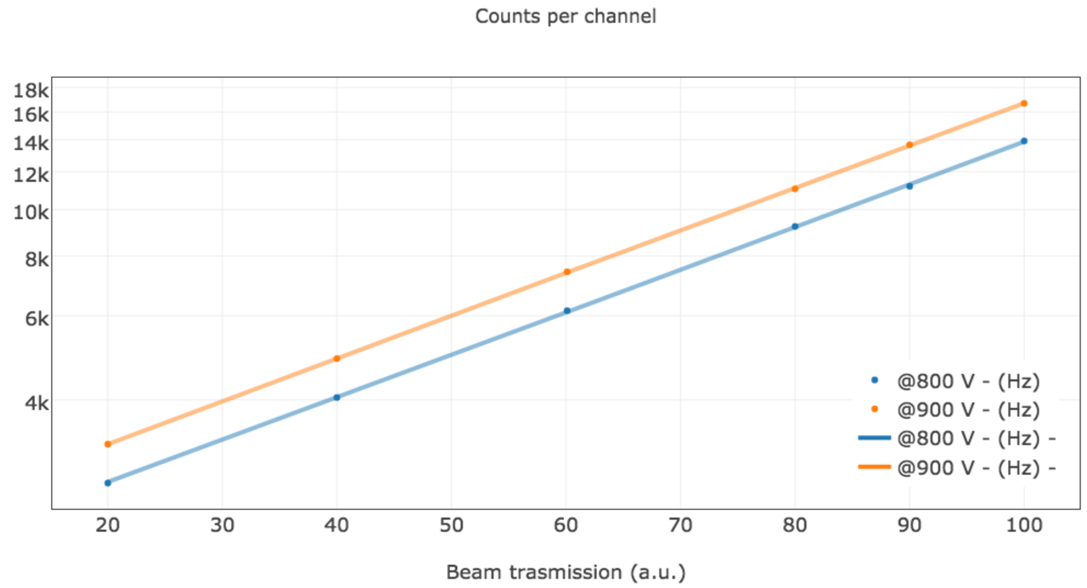


*Figure 7.3. The counting rate of the Multi-Blade MB-15 detector as a function of the beam transmission measured at the BNC reactor in Budapest. The counts have been recorded changing the transmission of the beam in order to identify any saturation due to the rate. In this plot, the beam was concentrate in a spot of approximately 3 x 3mm.*

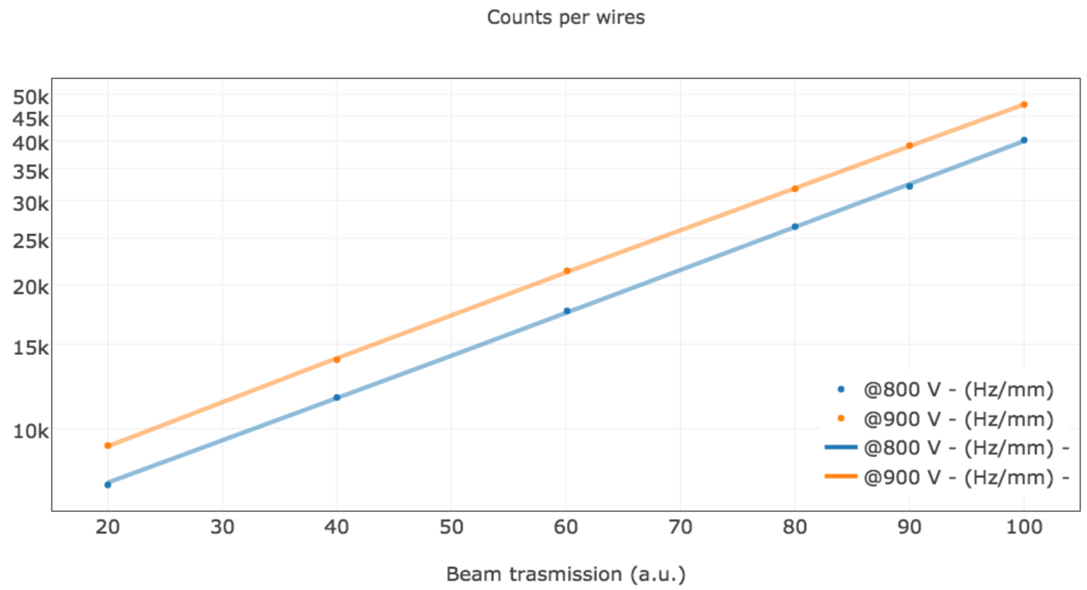


*Figure 7.4. The counting rate of the Multi-Blade MB-15 detector as a function of the beam transmission measured at the BNC reactor in Budapest. The counts have been recorded changing the transmission of the beam in order to identify any saturation due to the rate. In this plot, the beam was concentrate in a vertical slit of approximately 3 x 10mm.*

# 9 Conclusion

The Multi-Blade aims to answer the challenge of high instantaneous neutron flux that will be present at the European Spallation Source. The initial concept developed at ILL, France, has been improved and a new prototype, the MB-15, already shows promising results. Measures of the counting rate, show that the detector has a very good capability compared with the current used technology having already measured rates up to ≈ 50 kHz per channel. Calculations show that the detector design is capable of exceeding the target intensity for the reflectometry applications at ESS. Realising the intensities that will be produced at ESS during test beam conditions is a challenge with present sources.
Since the actual limit of this detector is beyond the limitation set by the available neutron beam, further tests will be performed involving more intense beams to verify this. Moreover, a new prototype is at present under development, in order to explore different solutions for the mechanics and the electronics. The design, construction and performance of the MB-15 prototype are presently being summarised for a future journal publication on this topic.

# 10 Bibliography


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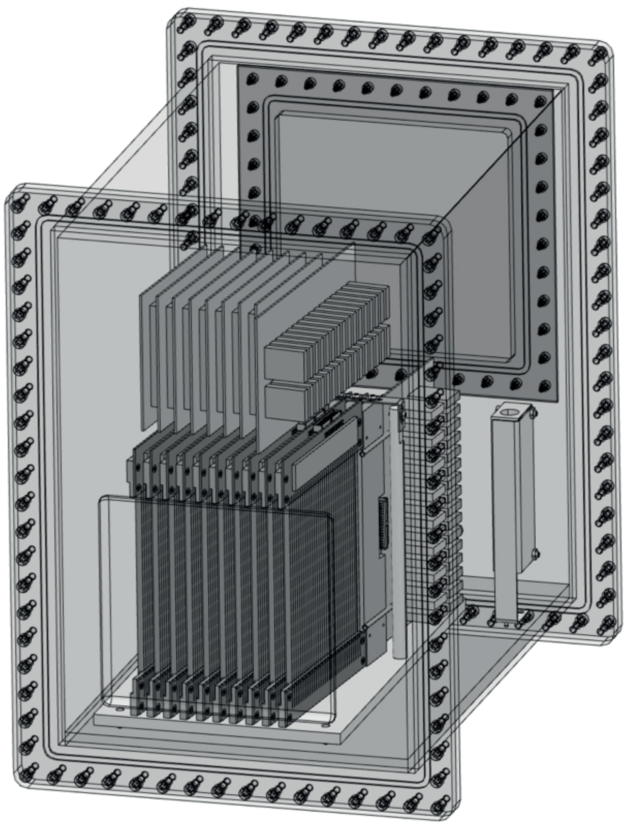
[VER13] VERITAS. "Vertical Sample Reflectometer. ESS Instrument Construction Proposal". In: (2013)


A publication about the progress made from the beginning of the BrightnESS and including the results obtained about the performance of the Multi-Blade detector (response, homogeneity, counting rate capability, etc...) is at present under preparation and will be soon submitted to a journal which allows Open Access format and also submitted to the arXiv preprint server.

EUROPEAN
SPALLATION
SOURCE

# Multi-Blade:
# Boron-Based Neutron Detector for Reflectometry Applications



September 2016

# The Concept

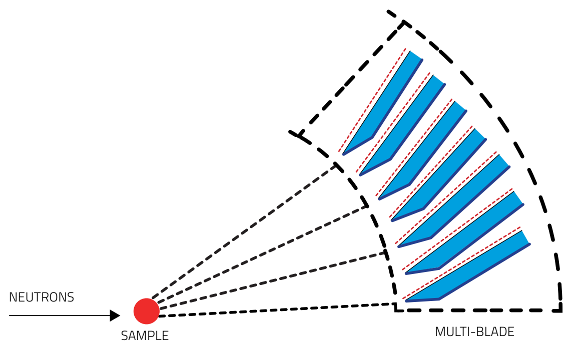
The Multi-Blade is a boron-based neutron detector developed for Reflectometry applications. It consists of a stack of Multi Wire Proportional Chambers (MWPC) operated at atmospheric pressure with continuous gas flow (Ar/$CO_2$, 80/20 mixture). This implies that cost-effective materials can be used in the detector and that it can be easily operated in vacuum tanks.

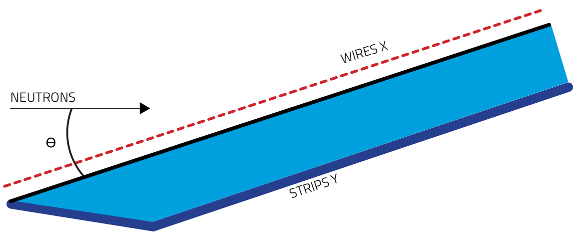
The Multi-Blade is made up of identical units, called cassettes. Each cassette holds a blade (a substrate coated with $^{10}B_4C$) and a two-dimensional readout system, which consists of a plane of wires and a plane of strips. Each $^{10}B_4C$-converter (blade) is inclined at 5° with respect to the incoming neutron beam.

The inclined geometry has two advantages: the neutron flux splits among many wires, which results in the increase of the counting rate, and the spatial resolution is improved.

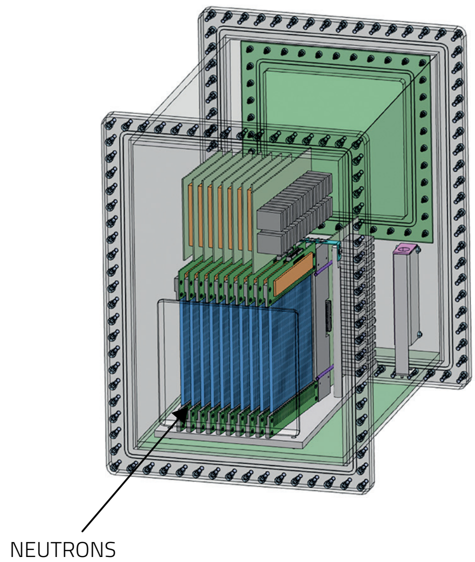
## Key Features:

- Optimised for Reflectometry applications
- Beyond state-of-the-art spatial resolution
- High counting rate capability
- Full integration into ESS systems

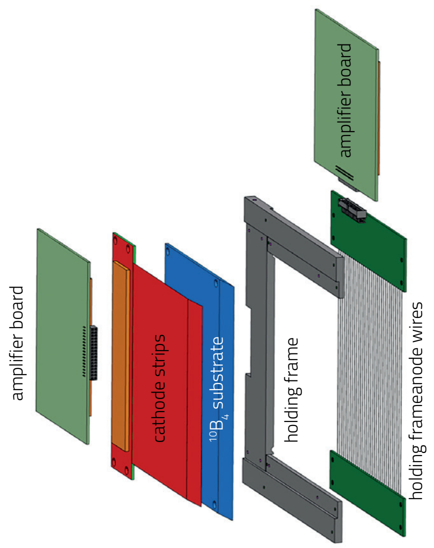



## Full Multi-Blade 3D CATIA model




## Exploded view of a cassette



# The Technology

The idea of the Multi-Blade detector derives from a similar concept published in 2005 (NIM A 554 (2005) 392) by a team at the Institut Laue-Langevin (ILL). At ESS, the work on the Multi-Blade began in 2011, within the FP7 CRISP project at the Institut Laue-Langevin (ILL) where two technology prototypes were built and tested showing promising results.

## Challenges:

### High Counting Rate Capability

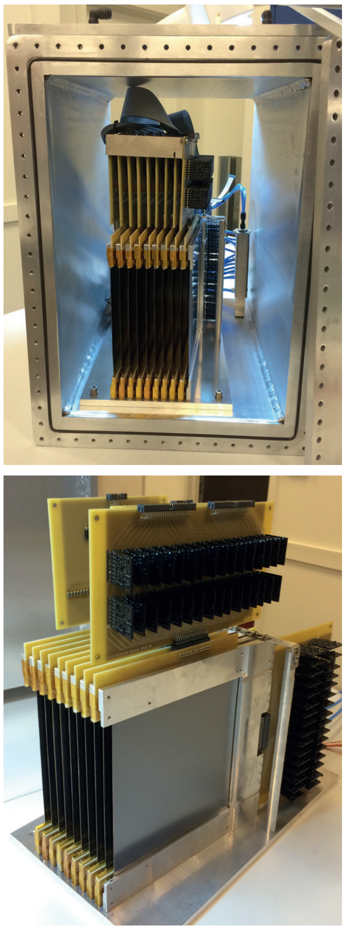
The instantaneous neutron flux on detectors at ESS will be without precedent and neutron reflectometers are the most challenging instruments.
The expected peak instantaneous local flux at the detector for the reflectometers is about $5\times 10^5$/s/mm$^2$.

### High Spatial Resolution

A spatial resolution of ca. 1mm is required, primarily for angular-dispersive measurements, and for off-specular and grazing incidence SANS (GISANS) experiments and all reflectometers.
Current state-of-the-art technology reaches about 1.5mm, to be improved by a factor of 3.

### Uniformity in modular design

The Multi-Blade prototype has a modular design. This requires that some effects must be avoided in order to guarantee a uniformity response in the detector. The effects to take into account are, among others, the overlap between different substrates, coating uniformity and substrate roughness.



FIRST PROTOTYPE BUILT AT ILL (2009)

# Related Publications


**Detector Design**

- F. Piscitelli, J.C. Buffet, J.F. Clergeau, S. Cuccaro, B. Guerard, A. Khaplanov, Q. La Manna, J.M. Rigal, P. Van Esch. "Study of a high spatial resolution 10B-based thermal neutron detector for application in neutron reflectometry: the Multi-Blade prototype", Journal of Instrumentation 9, P03007 (2014); doi:10.1088/1748-0221/9/03/P03007; arXiv:1312.2473v1.
- F. Piscitelli "Boron-10 layers, Neutron Reflectometry and Thermal Neutron Gaseous Detectors", University of Perugia (2014)
- F. Piscitelli et al., "Analytical modeling of thin film neutron converters and its application to thermal neutron gas detectors", JINST 8, P04020 (2013), arXiv:1302.3153

**Coatings**

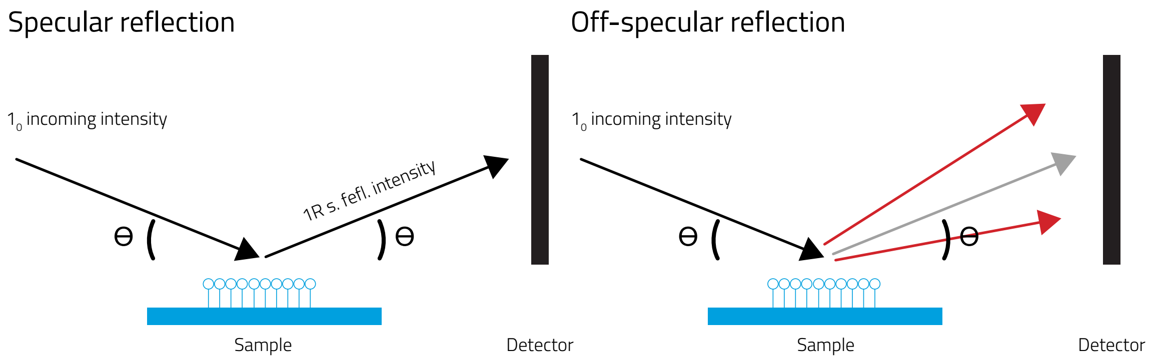
- C. Höglund et al. "B4C thin films for neutron detection", Journal of Applied Physics 111, 104908 (2012); doi:10.1063/1.4718573.
- C. Höglund,K. Zeitelhack, P. Kudejova, J. Jensen, G. Greczynski, J. Lu, L. Hultman, J. Birch, R. Hall-Wilton. "Stability of 10B4C thin films under neutron radiation", Radiation Physics and Chemistry 113 , 14-19 (2015); doi:10.1016/j.radphyschem.2015.04.006.

# Applications for Reflectrometry Instruments

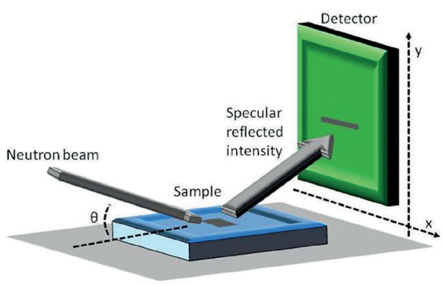
The Multi-Blade technology is developed for the detectors in ESS Reflectometry instruments and could be applied to other detectors.

The Reflectometry technique, consisting in reflecting neutrons off the surface of a material or tissue, allows scientists to learn about the density, thickness and roughness, and magnetization of a thin film surface at the boundary and its surrounding environment. Thanks to the high brightness and unique time structure of neutrons delivered by ESS source, the performance of reflectometres will be one to two orders of magnitude over instruments in current operation. The instruments will allow to follow kinetics with sub-second resolution.

## Instrument Requirements

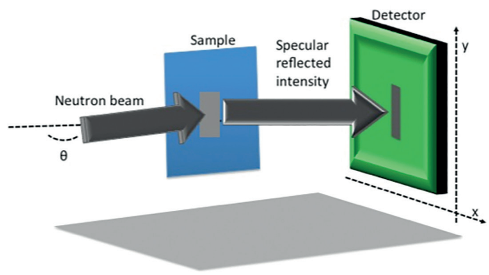



The ESS Reflectrometry Instruments are FREIA (the Fast Reflectometer for Extended Interfacial Analysis) and Estia, a polarised focusing reflectometer for small samples.




FREIA

**Horizontal Reflectometer**
(FREIA)
Suitable for liquids
(limited angular range)




Estia

**Vertical Reflectometer**
(ESTIA)
Not suitable for liquids
More versatile (wide angle range)

FREIA and Estia will require better position resolution and higher rate capability in comparison to existing detector technologies.

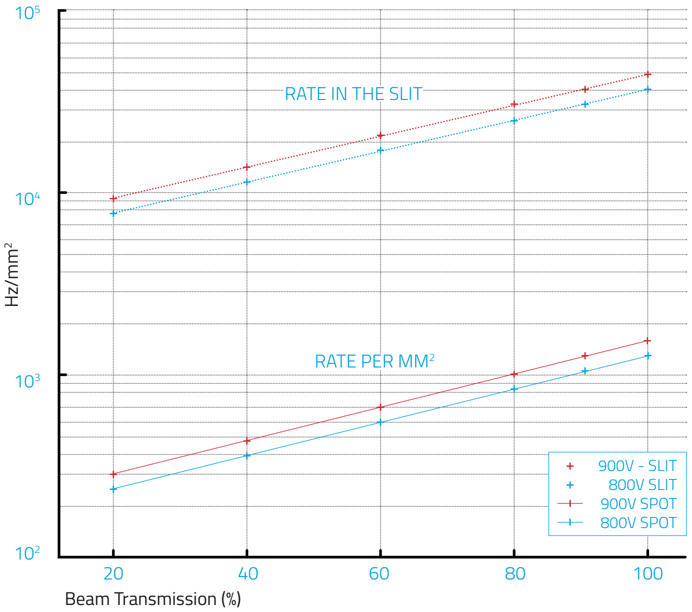
| | Freia | Estia |
|---|---|---|
| Max local rate | $10^5$ n/s/Å/mm$^2$ | - Conventional refl $10^5$ n/s/Å/mm$^2$<br>- High intensity mode $10^4$ n/s/Å/mm$^2$ |
| Spatial resolution | 4 mm x 1 mm | 3 mm x 0.5 mm |
| Self-scattering | $10^{-4}$ | $10^{-4}$ |

# Latest performance of Technology Demonstrator

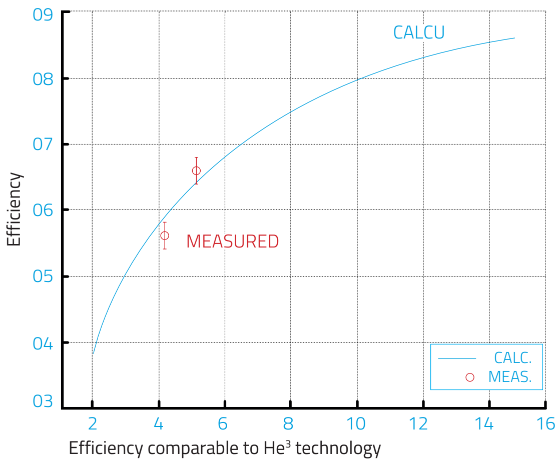
The latest tests – performed at the Budapest Neutron Centre (BNC), Hungary, in June 2016 – based on a number of characterisations (including measurements of the efficiency of a detector whose blades are tilted at a 5° angle) showed:

- An efficiency of about 45% thereby reaching the pre-defined goal of 40% above 2.5 Å.
- The 5° tilt of the detector increased the available surface area with which a traveling neutron can interact. This contributed to the improvement in counting rate capability of the demonstrator.
- Counting rate of the beam of 2 kHz per mm$^2$ without the occurrence of saturation.

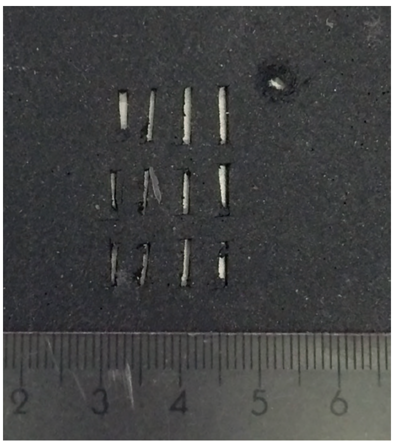
## Counting rate capability

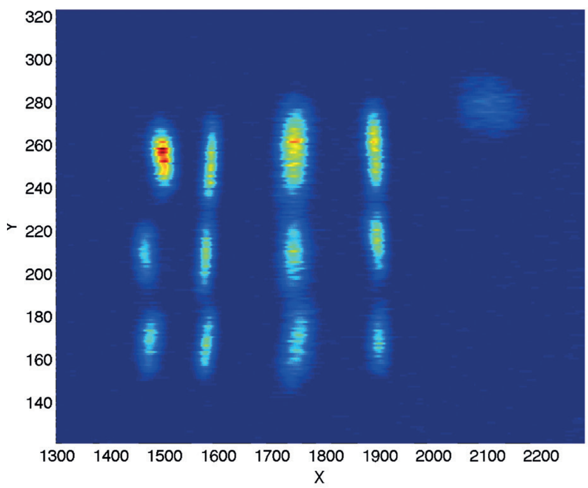



## Efficiency




Assuming that the same charge of the slit concentrated in 1 mm$^2$, the rate is above 40KHz/mm$^2$.
There is no space charge saturation observed up to ~ 2kHz/mm$^2$.



# Detector Technology Features

## Performance table with comparison

| | **Multi-Blade Detector** | **Closest version (FIGARO -ILL)** |
|---|---|---|
| Efficiency | Measured 53% at 4.1 Å abd 60% and 5.1 Å (>45% at 2.5 Å) | 63% at 2.5 Å |
| Spatial resolution | X 0.3 mm<br>Y 2.5 mm | 2 mm<br>7.5 mm |
| Size | X 100 mm (final detector 400 mm)<br>Y 140 mm (400 mm) | 500 mm<br>250 mm |
| Gamma sens. | $10^{-7}$ (as for $He^3$) | $10^{-7}$ |
| Cassette overlap | 0.7 mm gap 50% loss (goal 0.4 mm) | 0.5 mm Al-wall between tubes |
| Local Reate capability (1/mm2) | Measured and no limit found up to 20KHz | 1kHz |
| Scattering | $10^{-4}$ | $10^{-2}$ |

## Coatings for Multi-Blade

| | |
|---|---|
| Coating | $^{10}B_4C$ |
| Purity | 80 % 10B |
| Thickness | 6 µm |
| Substrate format | 2x140x160 mm |
| Substrate material | Al |
| Product capacity | 0.2 $m^2$/run |

## Electronics for Multi-Blade

| | |
|---|---|
| Pre-amplifiers | VMM ASIC |
| TDC | 2 types available: TOF/normal |
| Number of pixels | 0.8 MPix for 10x40 cm detector area |
| Number of channels | 800x x 800y |
| Time channel width (forTOF) | 1 µs |
| Remote control | EPICS/Ethernet |
| Measurement Data Transfer | BDI/Ethernet |
| Event data stored for each neutron | |
| Full integration into ESS DMSC and ICS fra-mework | |

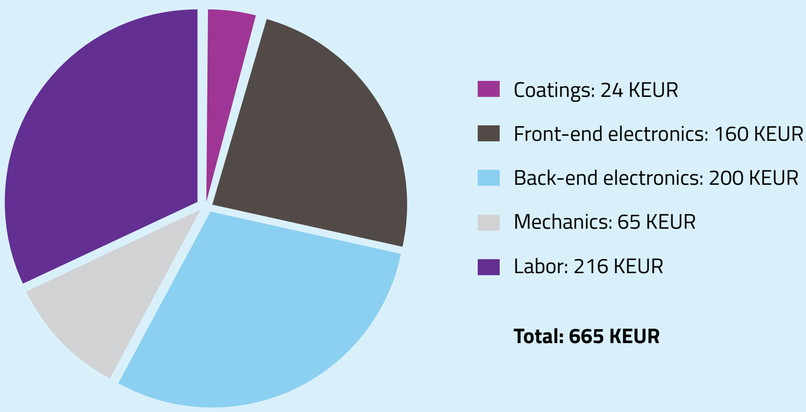
# Schedule and Cost of a Turnkey Multi-Blade Neutron Detector

## Schedule (*Indicative*)

| | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|
| Detector Construction | Jan-Dec | Jan-Dec | Jan-Dec | Jan-Dec |
| Final Design Verification | Jan-Jul | | | |
| In-Kind Contracts | Aug-Dec | | | |
| Coatings | | Jan-Jul | | |
| Mechanics | | Jan-Jul | | |
| Assembly | | Aug-Dec | | |
| Testing | | | Jan-Jul | |
| Final Electronics Design | Jan-Dec | Jan-Jul | | |
| Electronics Production | | Aug-Dec | | |
| Electronics Testing | | | Jan-Jul | |
| Detector Integration and Calibration | | | Aug-Dec | |
| Installation and Commissioning | | | | Jan-Jul |
| Detector Ready for Neutrons | | | | Jan-Jul |

## Cost (*Indicative*)

The following benchmark cost includes Design, Installation, Commissioning and Manpower. It refers to a 100 x 400 mm detector based on an up-scaling of the 2015 demonstrator model.




# Terms and Conditions:

This Detector offer is based on 'turnkey' delivery, including installation, delivery and cold-commissioning of the Detector on the instrument. The Detector has an expected lifetime of 10 years.
This document is intended only as an example offer for in-house production for ESS instruments.
For more details, please contact the ESS Detector Group.

# The Collaboration

The Boron-based Neutron Detector is a technology developed by the ESS Detector Group in collaboration with the Wigner Research Centre for Physics in Hungary, Lund University (LU) and Linköping University (Li) in Sweden.

This R&D project is part of BrightnESS (WP 4.2: Neutron detectors – The intensity frontiers).

It is anticipated that this collaboration will oversee the production and delivery of the Detectors.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