Document Type Document Template
Document Number ESS-0060903
Date Feb 20, 2020
Revision 0
State Released
Confidentiality Level Internal
Page 1 (16)

DETECTOR TECHNOLOGY REPORT FOR DIFFRACTION INSTRUMENTS DREAM, MAGIC, HEIMDAL

	Name	Role/Title
Owner	Werner Schweika	ICC Diffraction
Reviewer	Irina Stefanescu	Detector Scientist
Approver	Andrew Jackson	Acting Head Neutron Instruments Division

TABLE OF CONTENT........PAGE

LIST OF TABLES

No table of figures entries found.

LIST OF FIGURES

No table of figures entries found.

1. EXECUTIVE SUMMARY

The **ESS diffraction class instruments** [1] **DREAM** [2] and **HEIMDAL** are designed primarily for the purpose of powder diffraction, the instrument **MAGIC** using polarized neutrons is dedicated particularly for single crystal diffraction and for applications in the field of magnetism. However, the common use of large position sensitive area detectors enables all instruments for both, powder and single crystal diffraction. All three instruments make common use the same detector technology from the same company CDT Heidelberg, with mostly minor modifications the original "Jalousie" detector for the instrument POWTEX [3] at MLZ. Therefore, this report comprehends all three instruments.

The specific **detector technology** has been presented in the instrument proposals, which were approved and recommended by STAP and SAC to ESS. With TG2, scope setting and following TA, ESS and IK partner agreed on specifications, scope and budget.

The **current status** is that procurement is done for DREAM and MAGIC within budget, and now in progress for HEIMDAL. Manufacturing of detectors for DREAM is in progress, with deliveries and installation of detector elements starting March 2023 and completion in 2024. The MAGIC detector A is in preparation for the serial production of modules; detector B is already manufactured and complete with FAT. The readout electronics has been adapted to ESS specifications and applies for all detectors. The ESS backend master module is connected to the CDT front-end electronic. Finally, firmware integration has been completed and successfully tested establishing the data acquisition line for all CDT detectors to DMSC.

A common **challenge** for the diffraction instruments is the need for **high detector efficiency** with **time** and **2D spatial resolution** and **count rate capability** for Bragg diffraction. These characteristics should be competitive or superior to the **alternative ^{3}He-technology** to comply with the modelled diffraction pattern **for cases of high resolution as well as high intensity of ESS at full power**. To meet these requests as best possible, all detector elements are customized for each instrument.

The first comprehensive **verification of the Jalousie detector technology** was reported in 2014 with prototypes built for the POWTEX detector **[4].** Meanwhile, the POWTEX detector capabilities have been successfully demonstrated at the POWGEN-SNS [**5**], with new developments of advanced data analysis by 2D Rietveld refinement implemented in GSAS2 **[6].**

Detection efficiencies are reliably predictable and given by the amount of B-10 in the detector, i.e. by the number of coated cathode blades, the controlled thickness of the sputtered B-10 layers.

The typical process for all detectors for the ESS diffractometers is to start with the production of a "0-series" with a few modules, verifying the feasibility to meet specifications and to optimize the process for serial production, which then follows after successful review. This process includes careful investigation of issues, which so far has added acceptable time to development and leads to optimizations that benefit to the detector projects of all diffraction instruments.

There is a long list of **tests**, controls and quality assurance. Noteworthy, time and spatial resolution is determined by the geometry, confirmed by GEANT4 modelling **[7-9],** and verified using the DREAM mantle detector elements at the TRIGA reactor Mainz [10]. Functionality of a 12° endcap detector segment for DREAM is verified in an experiment at V20, HZB **[11].**

All targeted specifications are closely met.

Deliveries are in accordance with the instrument **schedules** for cold and hot commissioning. Projects run smooth and successful without notable **risks**.

2. INTRODUCTION

The instrument **DREAM** [2] is a general purpose powder diffractometer using thermal and cold neutrons. In backscattering world leading d-resolution is achievable. The detectors are arranged in Debye-Scherrer geometry around cylinder axis of the beam. 2D detector sensitivity and large detector coverage (in full scope) will allow for further for single crystal diffraction and texture measurements.

The instrument **HEIMDAL** is a thermal powder diffractometer. In full scope it will be complemented with a cold beam for SANS studies to cover multiple length scales. The diffraction detector is arranged in cylinder geometry around the vertical axis through the sample position with a radial collimator in front of the detector.

The instrument **MAGIC** is a single crystal diffractometer, using polarized neutron for applications in magnetism research. The detector geometry is similar to the one of HEIMDAL. There is an additional and smaller detector B for polarization analysis with wavelengths larger than 2Å.

The **chosen detector technology** is a multi-wire chamber. Neutrons are absorbed in ^{10}B layers, approximate 1µm thick and sputtered on Al-cathodes. The efficiency is determined essentially by the ^{10}B density and volume of the detector elements. The detector is segmented in a repeating modular structure, covering seamlessly a large solid angle and operated at ambient pressure. The detection efficiencies are typically specified to a minimum of ~56% at 1Å and increase for larger wavelength to ~80 -85%. With the volume depth and the large number of detection layers, the count rate capability is high, roughly scaling with the anode number, and ~30x higher than the rate capability of a ^{3}He-tube. This is important feature for single crystal diffraction at ESS. The neutron events are localized by coincidence of anode and cathode signals in the volume elements. Particular high spatial resolution in 2θ direction is achieved by inclined single-side coated cathode blades. The readout electronic, adapted to ESS specifications, makes event formation and connects to the master module of the ESS backend electronic.

3. REQUIREMENTS

General requirements and rationales.

Modular structures

- lower risk and impact of failure
- allow for early testing possibilities and cost-efficient serial production.

CE marking

Guarantee for 24 months after delivery of the detector system and SAT

Insensitivity to magnetic stray fields <0.1T, Report[12].

Readout electronics

confirm to ESS specifications, integrated in the ESS readout chain, not limiting the local and global count rate capability.

Detection efficiencies

are given by the amount of B-10 in the detector, i.e. by the number of coated cathode blades, the controlled thickness of the sputtered B-10 layers. In all cases, efficiencies are chosen higher than 50% at 1Å including any losses from structural material.

Resolution

of the detector is determined by geometric electrode structure through binning and has been designed to specifications as achievable within reasonable effort. Therefore, distance of the detector from the sample position has to be chosen appropriately with respect to experimental resolution, solid angle coverage and cost. TOF resolution is essentially determined by the binning size of the electrode grid structure provided with individual readout structure.

Solid angle coverage

is defined according to the ESS scope setting for instruments and TA.

Count rate capability

The requirements for time-of-flight Laue diffraction from single crystal are extreme and can be challenging to the count rate capability of any neutron detector, since it is determined by the recovery time for a single event. Therefore, the sample size should also be chosen reasonably small. For typical parameters of MAGIC at ESS, Bragg peaks will occur during short pulses (~150µs) with a 14 Hz repeat pattern. Compared to a continuous neutron beam, the time average efficiency of a detector is reduced by ~0.002. The detector should be state-of-the art. The detector has a count rate capability that is one order of magnitude higher compared to a conventional He-3 tube detector, simply because of the large number of effectively 7 wires in depth provided with separate readout for an infinitesimally thin beam. For a continuous beam, the detector will have a count rate capability of 500000 n/s with less than 10% dead time.

Intrinsic Background

At normal operational conditions with high voltage and counting gas, the background of the detector will be reasonably low according to the state-of-art. In normal laboratory environment without neutron beam the average detected background will be equal or better than observed with the state of art detectors. It will be less than 1 mHz per voxel for each detector module and accordingly that the integral background will also be less than the product of voxels times 1mHz.

DREAM total detector

	requirement	achieved	solution
Solid angle coverage	1.86 sr	2.16 sr	Jalousie detector, cost optimization
Background average	<1mHz/voxel	0.3mHz/voxel	

Count rate capability for Bragg diffraction should be as high as reasonably possible,
at least one order of magnitude higher than given by the alternative of single He-tubes.

DREAM mantle

Distance to sample > 1.1m

Δ2θ	=	0.29 degree FWHM	0.30 degree	7mm width, 256 cathode stripes
Δφ	=	0.69 degree FWHM	0.68 degree	11.4 mm cathode spacing
ΔTOF	=	7.3 mm FWHM	8.0 mm	10.7mm, 32 anode wires
efficiency 1Å	>=	55%	56%	1.1µm $^{10}\mathrm{B}_4\mathrm{C}$, 10 layers, 10° inclined

DREAM endcap

Distance to sample > 1.1m

Δ2θ	=	0.29 degree FWHM	<0.36 degree	10 mm anode wire pitch
Voxel size h	=	10 mm	10 mm	10 mm cathode spacing
ΔTOF	=	13-15 mm FWHM	13-15mm	cathode stripes
efficiency 1Å	>=	55%	60±0.4%	1.1µm $^{10}\mathrm{B}_4\mathrm{C}$, 12 layers, 10° inclined

DREAM high resolution backscattering and “nm-SANS”

distance to sample >2.5m

spatial resolution		8mm x 12.5mm		
“nm-SANS”				
efficiency 4Å	>=	82%		0.8µm $^{10}\mathrm{B}_4\mathrm{C}$, 12 layers, >1° inclined
high resolution backscattering				
efficiency 1Å	>	50%		0.8µm $^{10}\mathrm{B}_4\mathrm{C}$, 12 layers, >1° inclined

MAGIC

Converter coatings are arranged to have one coating layer in each voxel only in order to enhance spatial resolution. Detector depth is enlarged correspondingly to collect detection efficiency from nominally 10 Boron layers with 1.1µm coating thickness.

Solid angle coverage A) 48 degree vertical, 60 degree horizontal

B) 10 cm vertical, 120 degree horizontal

Detector A

used for time-of-flight single crystal diffraction and thermal neutrons (> 0.6.),
distance >1m to sample

Δ2θ = 2mm or 0.12 degree FWHM improved to 1 mm
Δφ = 0.32 degree FWHM
ΔTOF = 12 mm, accordingly 3µs at 1Å
efficiency 0.6Å > 40(−2)% including losses from structural material

Detector B

used for cold neutrons (>2.) and polarization analysis,
distance >1m to sample

Δ2θ = 2mm 1mm, change to 5 degree inclination
Δφ = 0.3 degree FWHM anode spacing
ΔTOF = 12 mm determined by 32 layers in 526 mm depth
efficiency 2-6Å >= 68 - 81% as calculated

HEIMDAL (not contracted yet)

Converter coatings are arranged to have one coating layer in each voxel only in order to enhance spatial resolution, similar to detector MAGIC A.

distance >0.8m to sample

solid angle coverage 110° horizontal, -22° to +22° vertical

Δ2θ = 1-2mm
Δφ = 7mm
ΔTOF = 10 FWHM mm, accordingly 3µs at 1Å
efficiency 0.8Å > 50%

4. TECHNOLOGY OPTIONS

CDT Jalousie detector

The detector is a multi-wire chamber. Neutrons are absorbed in ^{10}B layers, approximately 1µm thick and sputtered on Al-cathodes. The efficiency is determined essentially by the ^{10}B density and volume of the detector elements. The detector is segmented in a repeating modular structure, covering seamlessly a large solid angle and operated at ambient pressure. The detection efficiencies are specified to ~56% at 1Å and increase for larger wavelength to ~80 -85%.

The count rate capability is high, roughly scaling with the anode number, and ~30x higher than the rate capability of a ^{3}He-tube. This is important feature for single crystal diffraction at ESS. The neutron events are localized by coincidence of anode and cathode signals in the volume elements.

For DREAM, the detector has a cylindrical geometry around the beam axis, which adapts to the Debye-Scherrer rings. Near to the beam axis, forwards and backwards, detectors are placed at larger distance, which is beneficial for high resolution backscattering as well as for near small angle scattering down to 0.01Å^{-1}. Both sides of the cathodes of the DREAM detectors are coated. Particular high spatial resolution in 2θ direction is achieved by inclined single-side coated cathode blades, which is used by MAGIC and is planned also for HEIMDAL. These instruments have a different geometry arranging the detector elements around the vertical axis through the sample position. The difference in the detector geometry for the two powder diffractometers gives a complementarity which serves best for diverse needs of applications and user demands.

The readout electronic, adapted to ESS specifications, makes event formation and connects to the master module of the ESS backend electronic.

^{3}He detectors have been discussed as an alternative before proposing the instruments.

At that time, it was particularly difficult to get ^{3}He and cost estimates were significantly higher than for the chosen ^{10}B technology. Standard ^{3}He tube detectors are less performing in resolution and count rate capability. It was clear that such a choice would be taken only if severe problems occur with the preferred choice and additional contingency would be required.

Scintillator detectors have been considered in the previous POWTEX project. In our evaluation, this is a competitive technology with respect to spatial resolution, but less performing in respect to count rate capability and have the disadvantages of frames causing blind areas for scattering. The technology appeared as a second or third choice quality and would have required own developments by ESS or in-kind partners.

For considering any new ESS diffraction instruments, it could be interesting to compare Anger cameras and respective recent developments at SNS with the excellent performance of the chosen Jalousie technology.

5. DELIVERY PLAN

For all instrument detectors

CE certification	30.11.22	

DREAM

Mantle detector		
CTV, procurement	done	
CAD	done	
0-series		
Manufacturing	done	
FAT	done	
Neutron test TRIGA	done	
Review & optimization	done	
serial production		
FAT and delivery	02.03.23	
SAT	31.05.23	original target of contract 01.08.22

Endcap detector		
CTV, procurement	done	
CAD	done	
0-series		
Manufacturing	done	
FAT	done	
Neutron test V20 HZB	done	
serial production		
FAT and delivery	15.03.23	
SAT	01.06.23	original target of contract 01.08.22

Readout electronics		
Adaption to ESS specs	done	
Prototype	done	delivered to ESS
Serial production	done	
FAT	done	

Firmware	done	
HV and LV supply		
HV from Iseg	ordered	
HV cables & distribution	01.11.22	
LV from Kniel	paused	- wait for ESS confirmation

- High resolution backscatting detector and nm-SANS detector

CTV, procurement	done	
CAD	done	
0-series		
Manufacturing	in progress	
FAT	tbd	
<Neutron test not planned, module is similar to endcap detector element>		
Review & optimization	tbd	
serial production		
FAT and delivery	31.12.23 target of contract	
SAT	01.03.24 target of contract	

- Gas supply

Mass flow controllers	done
Switch to gas reserve	01.11.22

HEIMDAL

one type of detector module similar to MAGIC detector A,

less effort in prototyping required

Expected delivery	~ 2-y after contract, at least partial delivery for HC

MAGIC

- Detector A

CTV, procurement	23.07.2019	
CAD	done	
0-series		
Manufacturing	done	
FAT	ongoing	
Review & optimization	19.10.2022	
serial production		
FAT and delivery	1.12.2023	
SAT	1.02.2024	original target of contract 01.11.21

- Detector B

CTV, procurement	done	
CAD	done	
0-series		
Manufacturing	done	
FAT	done	
<Neutron test not planned, module is similar to endcap detector element>		
Review & optimization	done	
serial production		
FAT and delivery	done	CE pending
SAT	tbd	
Readout electronics	done	

- HV and LV supply

HV from Iseg	ordered	
HV cables & distribution	01.07.22	
LV from Kniel	paused	- wait for ESS confirmation

ESS detector group responsibility

Check and agree with specifications, participate in reviews, SAT, cold and hot commissioning, provide backend electronics, cooperate to connect assister firmware.

6. TESTING PLAN

Verification and validation

- Intermediate Design review (IDR)
  at completion of the 0-series and before serial production of a detector.
  Mechanical integration assured, CAD with interfaces communicated and agreed.

- **Factory acceptance test (FAT)**

- After the final assembly of a detector to an operable detector module, a final FAT will be performed. To this end, the detector system, equipped with readout electronics, will be flushed with a counting gas mixture. Once the oxygen content is sufficiently low for real neutron signal generation, the following tests are performed, taking advantage of the natural atmospheric neutrons continuously generated in our atmosphere by cosmic rays. Depending upon the size of the detector and the particular amount of ^{10}Boron converter coating present, a sizeable rate of real neutron signals may be detected: typically a rate of 1 Hz per detector module. It has been shown, that it is sufficient to go through the following characterizing tests:
- a) Electronics discriminator threshold scan. → Determination of optimum discriminator setting.
- b) HV scan of the detection plateau simultaneously for all anode wires and all cathode strips. This scan will take about two hours per data point due to the low count rate. Ramping through the HV in steps of 50 V will reveal the detection plateau and thus the optimized operating condition, where all neutrons are detected while yet the sensitivity to Gamma rays is negligible. → Determination of operating conditions
- c) Confirmation at operating conditions, that all anode as well as all cathodes are operative. This is done using a radioactive beta source and operating the detector well beyond the plateau. Scanning with the source across the device reveals immediately whether any individual readout channels, cathode- or anode-, stands out with too little sensitivity, which is an indication for a bad contact or a broken signal coupling capacitor. → Functional connectivity test. The mounting unit will pass the FAT only upon availability of all channels.
- d) Long term signal acquisition as homogeneity test. The mounting unit is operated over a period of one week at nominal operating conditions and this way reveals the homogeneity to cosmic ray neutron detection as well as background.
  e) Finally, the counting gas at the output of the mounting unit is fed to a high sensitivity oxygen gas analyzer.
  i) Verify the gas flow impedance of the input flow impeding capillary. All mounting units should behave similarly to within a margin of 20%.

- **Neutron acceptance test** should be performed for first modules of a series, if there are significant modifications compared to already existing and tested detector modules. Resourceful, detailed planning is required.

- **Site Arrival Inspection** (SAI) should include at minimum the following:
  - Visual inspection.
  - Inspection of shock watches

- **Site Acceptance Test** (SAT) should include, but is not limited to the following:
    - Visual inspection
    - Check protocol for initial operation.
    - Test functionality of power, gas flow, data readout.
      Prior to mounting of a module into its final position, a rough electrical connectivity test will be performed to make sure no wires have broken during transport, which would reveal itself in an electrical short of roughly 2 MOhms, corresponding to the in-line biasing resistors in the decoupling and filtering high voltage supply-line on the unit. A broken wire will need repair.
    - Test with background collected for 24h.
      The module is mounted into its final position and supplied with counting gas, power and high voltage. The same tests realized in the FAT will be redone on site using cosmic neutrons , or thermal neutrons at the site if available

QA purity of materials by supplier

Coating thickness and homogeneity by supplier QA

7. TESTING RESULTS

DREAM mantle detector

FAT passed [13]

Leakage tightness passed

HV plateau ~800V – 1050V

Intrinsic background and cosmic neutrons average. 0.06mHz / voxel

QA passed

Neutron test at TRIGA passed

Resolution Δ2θ 0.3 degree confirmed

Count rate capability – up 70kHz per anode no deviations from linearity visible

It occurred that one of the long mantle detector segments was found to be insufficient robust against HV short circuits. This issue was analysed in detail and a modification in the assembly of this detector type was introduced to assure robust operation [10].

Readiness for serial production [10]

The mantle detector was designed to closely meet the given resolution specifications and efficiency

$\Delta 2\theta$ = 0.29degree FWHM (achieved 0.30degree)

$\Delta\varphi$ = 0.69degree FWHM (achieved 0.68degree)

ΔTOF = 7.3 mm FWHM (achieved 8.0 mm)

$\varepsilon >= 55\%$ (achieved 56%).

DREAM endcap detector

FAT passed

stable operation, no anode wire nor cathode strip is missing

intrinsic background and cosmic neutrons 0.3mHz / voxel

HV plateau ~700V-900V , 3days counting all anodes

Leak-tightness passed

QA passed

Purity of $^{10}B_4C$ > 96% as certified by supplier

Nominal thickness of 1.1 µm by supplier

Radiation hardness of readout CIPix ASIC, confirmed operation up to an exposure of 4.8kGy

Neutron test at HZB Ref.11. passed

Functionality, xyz-voxel structure, time dependence, readout chain into final event data files

Mechanical integration into support structure

Resolution designed to specifications and theory, confirmed by neutron tests in Ref. 5,6,10

>60% efficiency at 1Å by design

Resolution specifications met by design

MAGIC detector B

- FAT passed
  - stable operation, no anode wire nor cathode strip is missing
  - intrinsic background and cosmic neutrons 0.3mHz / voxel
  - HV plateau ~700V-950V , >12h counting all anodes
  - Leak-tightness passed
- QA passed
  - Purity of $^{10}B_4C$ > 96% as certified by supplier
  - Nominal thickness of 1.1 µm by supplier

Validations

GEANT4 modeling of detector modules verifies the voxel positions and resolution Ref. 7-9.

GARFIELD modelling verifies and supports electric field design Ref.14.

Tests of the Jalousie detector concept

Efficiencies [4]

Absolute efficiency measurements with the ^{10}B based Jalousie detector with thermal neutrons 1.17Å at the instrument HEIDI – MLZ, published 2014.

Neutron test [5,6]

Powder diffraction and multi- dimensional refinement with the POWTEX Jalousie detector at the diffractometer POWGEN SNS.

[6] Report about the 2017 enterprise to operate one building unit of the final POWTEX detector at the neutron powder diffractometer POWGEN at the Spallation Neutron Source of the Oak Ridge National Lab, USA. As a result, we present the first angular- and wavelength-dependent data of the POWTEX detector, current data-reduction steps as implemented in Mantid and also multi-dimensional refinement results of two samples diamond and $BaZn(NCN)_2$ by use of the GSAS-II software suite.

Neutron test campaigns need huge human resources, time, and significant budget. They are strongly supported by the company but not part of the contract. During the transportation to SNS, the POWTEX detector was partly damaged, several 50g shock watches were triggered upon an accident. The good news is, the detector made of thin Al plates and its inner structure is surprisingly robust. With enormous efforts, the test campaign at POWGEN SNS and subsequent data analysis has been a full success.

8. RISKS

Currently no particular risks are identified.

9. REFERENCES

[1] KH. Andersen et al., The instrument suite of the European Spallation Source, Nuclear Instruments and Methods in Physics Research Section A957, 163402 (2020).
[2] W. Schweika et al., DREAM - a versatile powder diffractometer at the ESS, Journal of Physics Conference Series 746, 012013 (2016).
[3] A. Houben et al., New neutron-guide concepts and simulation results for the POWTEX instrument, Nuclear Instruments and Methods in Physics Research Section A680, p124 (2012).
[4] G. Modzel et al., Absolute efficiency measurements with the B-10 based Jalousie detector, Nuclear Instruments and Methods in Physics Research Section A743, p. 90 (2014).
[5] A. Houben, POWTEX detector test at POWGEN SNS, presentation to STAP Oct. 2019 https://indico.esss.lu.se/event/1544/contributions/11882/attachments/10372/17081/Andreas_Houben_POWTEX_detector.pdf
[6] A. Houben et al., POWTEX visits POWGEN, https://arxiv.org/abs/2110.12767
[7] I. Stefanescu et al., Neutron detectors for the ESS diffractometers, Journal of Instrumentation 12, P01019 (2017).
[8] I. Stefanescu et al., Performance study of the Jalousie detector baseline design for the ESS thermal powder diffractometer HEIMDAL through GEANT4 simulations, Journal of Instrumentation 14, P10020 (2019).
[9] I. Stefanescu, Detectors for the ESS diffraction instruments - where are we now –, presentation to STAP Oct. 2019 https://indico.esss.lu.se/event/1307/contributions/10048/attachments/9529/15095/DiffractionStapOct2019.pdf
[10] CDT, DREAM mantle detector serial production readiness report 02.12.2021.
[11] G. Kemmerling, M. Feygenson et al., DREAM detector test at V20@HZB, report to STAP Oct 2019. https://indico.esss.lu.se/event/1307/contributions/10057/attachments/9534/15088/DREAM_det_tests_STAP.pdf
[12] CDT report, Discussion magnetic field sensitivity 14.03.19.pdf
[13] CDT, FAT DREAM mantle detector T1.3 12.11.20.pdf
[14] I. Stefanescu, GARFIELD calculations for the MAGIC Jalousie detector

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue	Werner Schweika	13.06.2022
	updated	Werner Schweika	17.10.2022