UK Atomic Energy Authority

Supply of Additional Polychromators for the Thomson Scattering diagnostic on the COMPASS-U tokomak

UKAEA Technical Proposal

Abstract
This document outlines the technical components of the UKAEA's proposal for the design, manufacture and supply of polychromators to the Institute of Plasma Physics of the Czech Academy of Science. In this document we aim to demonstrate how the UKAEAs extensive experience puts us in an ideal position to deliver this contract by meeting the requirements.

Executive Summary

United Kingdom Atomic Energy Authority (UKAEA) welcomes the opportunity to provide its expertise to deliver Polychromators to Institute of Plasma Physics of the CAS.

UKAEA has significant Thomson scattering polychromator experience developed through our on-going work at MAST over the last 20 years. Polychromators were built in house at UKAEA for Edge and Core Thomson scattering diagnostics on MAST and UKAEA supplied designs to get similar units built at COMPASS in the Czech Republic and TCV in Switzerland. The polychromator design has been developed with each generation for improved performance and manufacturability.

The polychromator design proposed for COMPASS-U will be based on the latest version developed by UKAEA. The key elements of the proposed polychromator design are:

- **Modular and Compact:** Each polychromator occupies 2U within a 19" rack;
- **Energy Efficient:** Each polychromator uses [redacted];
- **Enclosed:** Polychromators are designed not to have be opened once sealed. No internal calibrations or adjustments are required;
- **Thermally Stable:** Built in temperature compensation;
- **Optically Uniform:** The same fibre bundle image is presented to each interference filter;
- **Reliable:** 130 polychromator units operated over the last 15,000 discharges on MAST without any single unit failure;
- **Accurate:** [redacted]re key to obtaining good plasma profiles. The low systematic errors achieved by this design are evidenced by the good profiles produced (see section 8).

The selected project team brings together a wealth of experienced UKAEA resources to deliver the required Polychromators.

With our experience, we believe that we are very well positioned to deliver high quality polychromators.

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1 Background and Expertise

UKAEA has extensive experience in producing polychromators for Thomson scattering systems, developed over 22 years, this work encompasses design, manufacture and installation activities. The proposed polychromator design has been developed and improved over a number of generations by our team at UKAEA, improving the performance and manufacturability with each generation. A brief timeline of relevant projects that UKAEA has been involved in are provided below and summarised in Table 1, excluding those relating to commercial contracts 2022 – 2024.

2003 – MAST Core

A Core Thomson scattering system with 19 spatial points was in operation on MAST containing the first generation of 5 polychromators of those proposed for this project.

2005 – MAST Edge

An Edge Thomson scattering system was built with 8 new polychromators and a modified optical interference filter design optimised for the plasma edge.

2007-2009 – MAST Core Upgrade

A large Core Thomson scattering upgrade with 125 additional polychromators was built and installed on MAST.

This new generation of polychromators was specifically designed with mass production in mind due to the large number. The modifications to this generation were:

- New mechanical chassis components developed for ease of manufacture and alignment.
- Modifications to outer 19” casing to cater for large numbers of polychromators being manufactured.
- New Electronics to remove ‘peak overshoot’ observed due to detector impulse response.

These 125 polychromators were assembled in house at UKAEA and forms a good model for the JT60-SA project. The time from commissioning of the project to delivery of polychromators took approximately 1 year.

2012 - TCV

Polychromator optics and chassis design supplied to TCV in Lausanne, who replicated this design for their system. Due to their data acquisition system, they chose to use a different electronic design.

2017-2019 – MAST-U X-point

A further 10 units were built for the MAST-U X-point Thomson scattering system as part of the enhancements project. These featured:

- Improved optical filters and design with a focus on improved rejection of the laser line. Due to geometry of the collection optics of this diagnostic, laser wavelength rejection is a key parameter.
- Chassis modifications, in particular with a modification of angle on the final filter to allow measurements to low electron temperature.

2022 - 2024 Commercial contracts for the supply of Polychromators

61 units were built for 6 separate commercial contracts with specific contract quantities ranging from 5 to 29 units

There are now a total of 148 polychromators operational on MAST-U based on various generations of this design, some have been in use for >19 years. During this time there has been no failure of produced polychromators. By this we mean that while some failures have been observed in both Avalanche Photodiodes (APDs) and Circuit boards during the assembly process (<1%) once the boxes are sealed the manufactured polychromators have been 100% reliable.

Table 1 – Generation of UKAEA polychromators

[redacted]

2 Proposed Polychromator Design

The proposed polychromator design is based on that of an existing UKAEA design, an example of which is shown in Figure 1. We envisage supplying the sealed polychromator units and that the polychromators will not have to be opened during their working lifetime. However, [redacted]

[redacted]

[redacted]

[redacted]

The optical layout of a polychromator is shown in Figure 2 from an input fibre bundle, through [redacted]

[redacted]

Image on the filters:

[redacted]

Coating of Optics:

[redacted]

3 Compliance to customer requirements

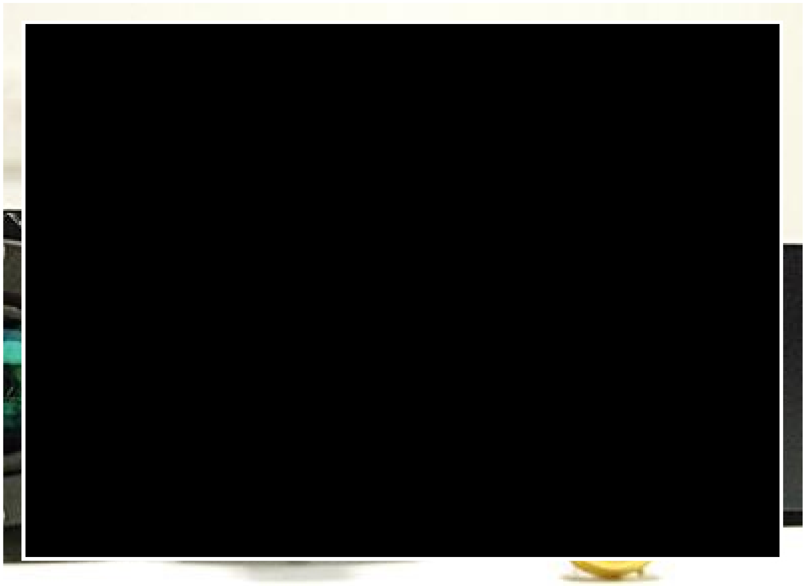
We confirm that our bid and offered Polychromators will fulfil all of the requirements contained in the Technical Specification and the Contract. Further to this we can answer "yes" to the specific requirements listed in the table below which has been copied from document CU_DIAG-010-011_PTD_Annex No.1 – Technical Specification_Polychromattors.

No.	Name of the requirement	Description of the requirement	Seller´s confirmation
1	Number of spectral channels	6 active channels (with BP filters and APD detectors) + 0^{th} channel (passive for laser line rejection)	Yes
2	Laser line rejection of filters in channels 1-6	OD5 or better (rejection of the filter itself, not including the effect of 0^{th} channel)	Yes
3	Laser line rejection by channel 0	Laser line (at 1064.1 nm) intensity shall be "dumped" in the 0^{th} channel, with filter absolute transmissivity >90% (best effort for >95%) – see chapter 5.4	Yes
4	Reflectivity of filters outside BP	>98% in range from 670 nm to 1070 nm	Yes
5	Optical filters absolute transmittance inside BP	>90% (with best effort for >95%)	Yes
6	Filters technology	Hard coating manufacturing technology	Yes
7	Filters optical and mechanical backward compatibility	Diameter 31.7 mm, clear aperture >29 mm, 2 mm thick substrate. Mounted in a ring with outer diameter 33.7 mm. Angle of incidence is 4.5°, cone half-angle 2°. See chapter 5.3.	Yes
8	Overall optical transmission from fibre bundle to detector	>55% for all channels (with best effort for >60%)	Yes
9	APD active area diameter	at least 1.5 mm	Yes
10	APD sensitivity	APD is suitable for wavelengths 670 nm - 1064 nm and has quantum efficiency of the APD at least 85% at 900 nm and 40% at 1060 nm (see chapter 5.6).	Yes
11	APD gain temperature compensation	The output signal of each channel is stabilised in the operational temperatures range, the stability is below 3% for +/-3°C variation. Each APD integrated circuit package has an on-board temperature sensor for this gain compensation. (see chapters 5.6 and 5.9)	Yes
12	Electronics bandwidth	Overall bandwidth (-3dB) of the electronics (on the fast output) is higher than 16 MHz and lower than 75 MHz	Yes
13	Polychromator sensitivity	Overall sensitivity of the polychromator from the detector, including the subsequent electronics, shall be at least $2 \cdot 10^6$ V/W at 900 nm and $1 \cdot 10^6$ V/W at 1060 nm on the output (while fulfilling the requirement on the dark noise)	Yes
14	Dark noise	Overall dark noise lower than 2 mV at 100 MHz measurement bandwidth, assuming the dynamic	Yes

		range is +/-5 V (if the dynamic range is different, the requirement shall be scaled accordingly)	
15	Fast and slow outputs	Each spectral channel has two electronic outputs, with high-pass and low-pass filters (see chapter 5.8)	Yes
16	Potential later upgrade of 0th channel	The design allows potential later installation of an APD detector with coupling optics for measurements on the 0th channel (which are not part of the tender). There is a spare channel on the electronics board and fast/slow output connectors for this purpose.	Yes
17	Option to measure full bandwidth signal	Possibility to bypass the high pass filter on the fast output (see chapter 5.8)	Yes
18	Polychromator layout	All channels (filters and APDs, where applicable) are on the same side of the polychromator, the side with the fibre bundle input.	Yes
19	Etendue	The polychromator accepts 3 mm fibre bundle with F/1.75 on input and maintains the etendue through the polychromator.	Yes

4 Detector

[redacted]



[redacted]

[redacted] *PCB.*

5 Electronics

5.1 Pulse Response

[redacted]

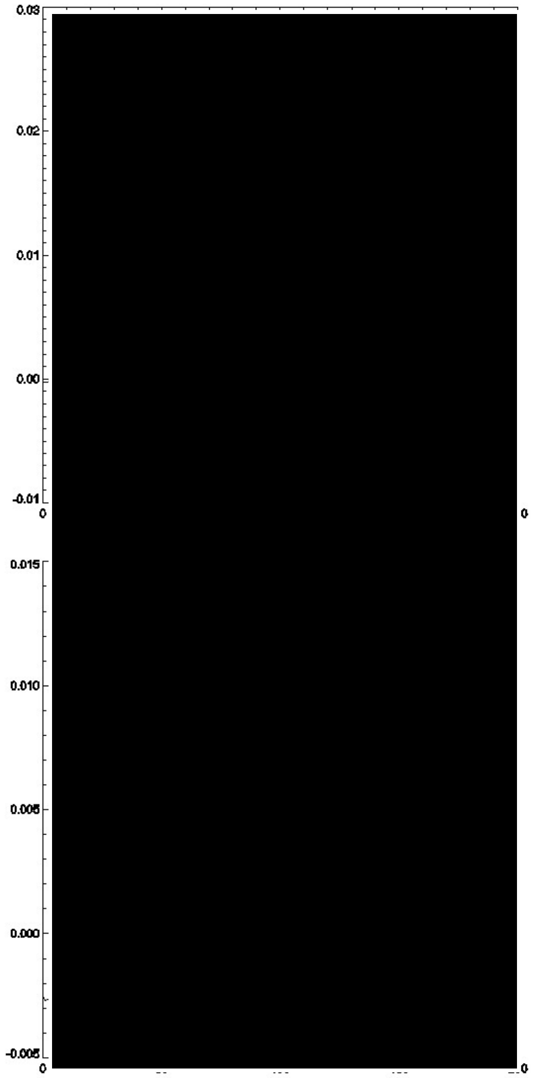


Figure 5 – [redacted]

5.2 [redacted]

[redacted]

[redacted]

[redacted]

5.3 Variable Gain

[redacted]

[redacted]

5.4 Specifications

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6 CE Marking and Safety

The polychromators will be supplied CE marked. No other electrical safety standard shall be applied, for example American standards.

The polychromators will be supplied in closed boxes. It is not anticipated by us that the purchaser shall open the boxes. If they do so, it is entirely at their own risk.

UK Atomic Energy Authority

CE - DECLARATION OF CONFORMITY

Manufacturer:	UK Atomic Energy Authority Culham Science Centre Abingdon Oxfordshire OX14 3DB United Kingdom
Product name:	PL-YU Thompson Scattering Polychromator
Product Reference:	DR0011392
Technical File Location:	TF-0000166 (address as above)

We hereby declare that the equipment detailed above satisfies all relevant provisions of the following EU directives:

- 2014/35/EU – Low Voltage Directive
- 2011/65/EU – Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive
- 2014/30/EU – Electromagnetic Compatibility Directive

In case of any modification of the equipment, not being agreed upon with us, this declaration becomes invalid.

Issued on: 15/09/2023

The following harmonized norms, national standards and technical specifications were applied:

- BS EN 61010-1:2010+A1:2019 *"Safety requirements for electrical equipment for measurement, control, and laboratory use-General requirements"*
- BS EN 61326-1:2013 *"Electrical equipment for measurement, control and laboratory use – EMC requirements."*

Place:
Culham Science Centre

Name, function, and signature of the responsible person:

15/09/2023
Emily Harford – Principal Engineer for the Design Authority – UK Atomic Energy Authority

7 Cubicle Installation

The MAST core Thomson scattering diagnostic has 130 polychromators in total, 5 re-used from an existing installation and 125 custom built.

The image in Figure 8 shows on the left-hand side 8 cubicles each 47U high and each containing 3 groups of 5 polychromators and related digitisers. Each cubicle has a local electrical distribution on the back with 8 way socket strips for each set of five polychromators. The optical fibres are fed in to the cubicle from the top and feed to the polychromators from the left-hand side of the cubicle with a dedicated hole drilled for each fibre. These images are provided for information only as a potential installation configuration.

[redacted]

Figure 8 – Cubicles of Polychromators for MAST Core Thomson scattering system.

The proposed polychromator dimensions are 2U high fitting in a 19” rack. The depth of the polychromators is compatible with a standard 19” rack.

The same external package is proposed for both the polychromators.

8 Low Systematic Error

One of the key important measures of success for polychromators is that they have low systematic error in measurement of electron temperature and density. This is driven by uniform wavelength channel sensitivity across polychromators as far as is possible and any sensitivity variation being reflected accurately in the polychromator spectral calibration. This will result in accurate measurement of electron temperature and density with low point to point scatter in observed profiles and good ability to analyse the data obtained. Through the successive generation of polychromators built at UKAEA, we have been able to optimise the design to provide very low systematic error. This is illustrated by Figure 9 showing profiles obtained on MAST during a pellet injection.

[redacted]

9 Spectral Calibration

Careful measurement of the spectral sensitivity, i.e. spectral calibration, is critical for obtaining the accurate electron temperature. [redacted]

List of Equipment used for Spectral Calibration

[redacted]

[redacted]

UKAEA has software specifically made for the polychromator calibration, written with Python. [redacted]

[redacted]

[redacted]

Based on the filters specifications, the spectrometers can easily be calibrated by absolute calibration in Raman. This calibration has been successfully deployed on MAST for a number of years.

[redacted]

Figure 13

10 Factory testing and inspection

Component Testing

Each sub-component of the polychromators and alignment monitors must be inspected to ensure high quality polychromators are produced. During the component assembly process or manufacture, essential properties of the power supply unit such as DC outputs for the amplifiers and high voltage sources are measured. Similarly, during mechanical assembly each optical sub-component and assembly are checked via steps such as back illumination and transmission measurements where appropriate.

Assembly Testing

Once the polychromator is assembled, but not yet sealed, a number of checks need to be performed. These checks include observation of fibre bundle image on the optical filter and setting of the amplifier jumpers and output capacitor jumpers for each wavelength channel. To verify all steps have been appropriately completed a suitable checklist will be completed for each polychromator. A sample of such a checklist is shown in Figure 14.

Electrical Safety Testing

After completion of the assembly testing and Electrical Safety test is completed. These checks confirm the polychromator is safe to operate from an electrical safety perspective. A sample of this checklist is appended to this document, see section 18 Appendix 1 - Electrical Safety Checklist

Functional Testing

Once the assembly is finished and the polychromator is sealed every polychromator goes through a further set of tests. These final checks verify the responses of the high frequency and low frequency channels for the pulse input and sinusoidal wave input and include a spectral calibration as described in Section 9. A sample of this checklist is shown in Figure 16.

These functional tests checklists are added to the assembly test checklists to verify they are completed and once finalised each polychromator has its own effective '*Polychromator Passport*'.

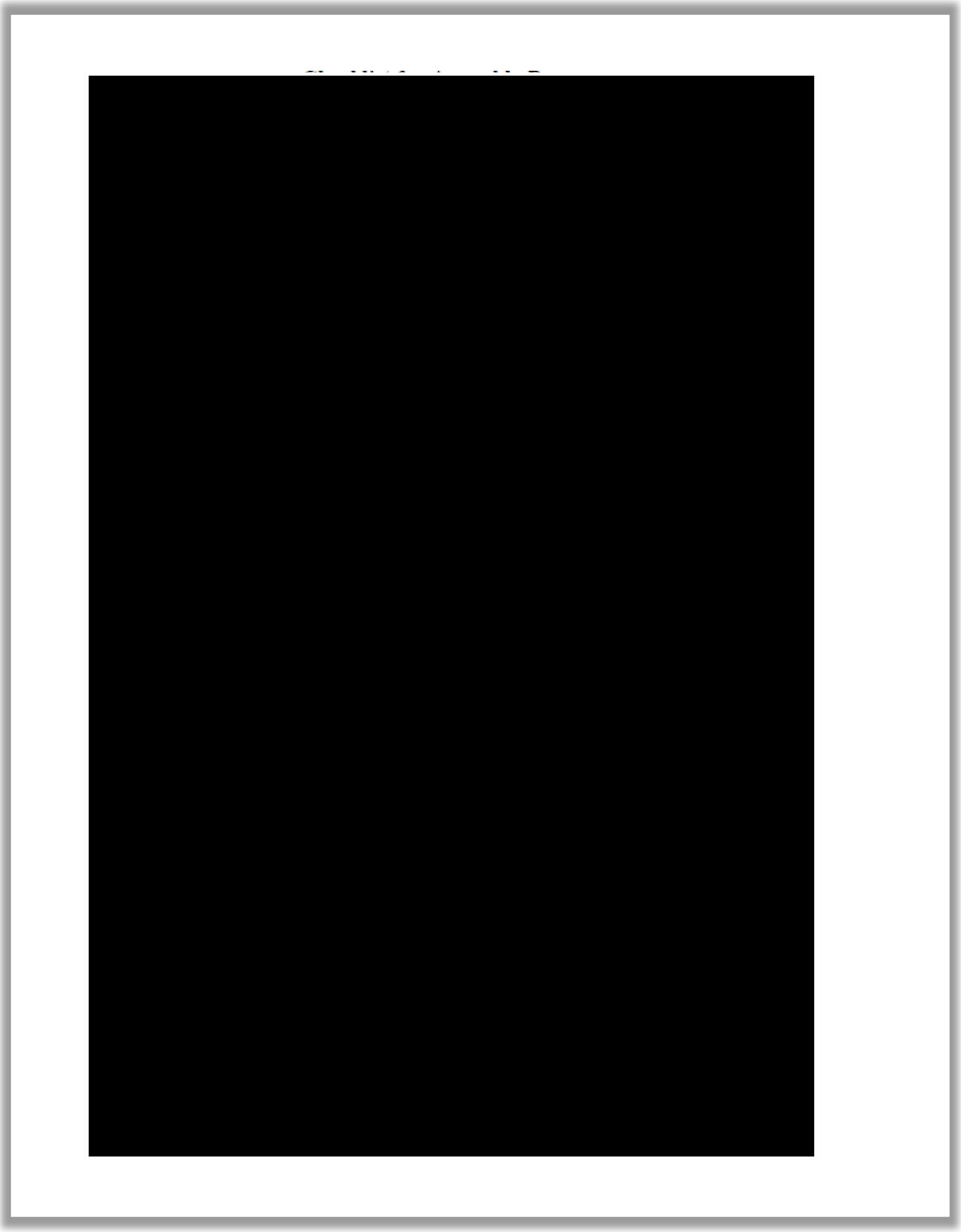

[redacted]

Figure 14 – Examples of checklist for Assembly Testing of a polychromator

[redacted]

Figure 15 – Examples of checklist for Functional Testing of a polychromator.

11 Acceptance Testing

Customer Factory Acceptance Testing (FAT) at UKAEA Culham site is possible and we will be able to accommodate this.

If required, we are also able to support any Site Acceptance Testing (SAT) at the customers location.

12 Filters

The filters wavelengths requested can be supplied. The responsibility for the specification of the filters central wavelength and bandwidth, and hence electron temperature sensitivity range, must finally reside with WEST. However, we at UKAEA are happy to advise.

Four our Polychromators, we have previously purchased and used all the filter wavelengths specified.

[redacted]

13 References

"Design of a new Nd:YAG Thomson scattering system for MAST" R. Scannell, REVIEW OF SCIENTIFIC INSTRUMENTS 79, 10E730 (2008)

"A 130 point Nd:YAG Thomson scattering diagnostic on MAST" R. Scannell, REVIEW OF SCIENTIFIC INSTRUMENTS 81, 10D520 (2010)

14 Organisation Chart

[redacted]

Project Manager

Responsible for driving the project and project governance

UKAEA Procurement Group

Support the project with all high value procurement activities

UKAEA Quality Group

Support the project with any quality assurance activities

Technical Lead

Expert in the design, assembly, testing and use of the polychromator offering technical support as required to the rest of the project team

Mechanical/Optical Build – Team Lead

Building of mechanical housing and optical elements.

Electrical Build – Team Lead

Responsible for electrical assembly and testing of the completed polychromator

Manufacturing Services Group

Responsible for the manufacture of the bespoke metalwork used in the optical assembly

15 Acronyms

APD	Avalanche Photo Diode
FWHM	Full Width at Half Maximum
IDC	Insulation Displacement Contact
ITT	Invitation to Tender
MAST	Mega Amp Spherical Tokamak
PCB	Printed Circuit Board
TCV	Tokamak à configuration variable
UKAEA	United Kingdom Atomic Energy Authority
CWL	Central Wavelength
BW	Bandwidth

16 Case Study 1: Manufacture of Polychromators for X-point Thomson Scattering diagnostic

[redacted]

The manufacture of 10x polychromators for an X-point Thomson scattering system was completed in March/2018 (internal reference numbers 501-510). These were procured, assembled, manufactured and tested in house and were designed to measure in the low Temperature region.

The filters used for this system were, in order of placement in the polychromator:

Table 2 – XTS polychromator filter layout

[redacted]

The successful implementation of this project is indicated by the spectral calibration shown above in figure 17.

17 Case Study 2: Manufacture of Polychromators for Divertor Thomson Scattering diagnostic

[redacted]

Eight polychromators, internal reference # 201-208, were built by modifying existing edge Thomson scattering polychromators. This was completed in September 2018 as evidenced by the above photograph and signed off internally at that date as part of the B2M18 milestone. Two existing filters were retained from the existing polychromators and three new filters inserted specifically for the scattered spectrum expected in the Divertor region.

Table 3 – XTS polychromator filter layout

[redacted]

The filters on the 'red' side of the laser wavelength were installed to provide redundancy and improve immunity to any divertor line emission that might occur during radiative detachment experiments, as well as measure non-Maxellian velocities.