Evaluation of the Factory Acceptance Test of the ESS Raster Scanning Magnet System Pre-Series

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Abstract

This note is to provide an executive summary of the Factory Acceptance Test (FAT) results that are documented in test reports [1]. The note will discuss system shortcomings and their potential impact, but also add an impartial layer, *i.e.* convey impressions of the system FAT performance as perceived by the Aarhus University (AU) team to the future system owners.

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1 Introduction

The FAT of the pre-series took place at Danfysik during November 2017 with AU and European Spallation Source (ESS) representatives being present for two days at the end of the period, November 29–30. The visit included

- Visual inspection of magnets, power supplies, termination box, support stand.
- Review of FAT test reports for power supplies and magnetic measurements. The results were scrutinized and in a few cases more detailed or alternative testing methods were requested. Along with a few demonstrations of the key FAT measurements, these were conducted by the Danfysik technicians while supervised by the future system users.
- Training on how to operate the system, both locally and through a remote line.
- Inspection and confirmation of interfacing parts of the Raster Scanning Magnet System (RSMS).

It should be noted that the FAT and demonstrations were not conducted on the fully assembled system in its intended application, in particular

- Magnets and termination box were not mounted on the girder, which excluded testing of internal mechanical interfaces and alignment capabilities.
- The power supplies were not tested in parallel operation but only sequentially, which excluded direct testing of synchronisation, combined heat load and subsequent cooling needs.

It was estimated and agreed that these test simplifications were not likely to affect the general system performance and indirect measurements or deductions would suffice. Additionally, the simplifications would be remedied and fully explored during the imminent Site Acceptance Test (SAT) in Aarhus.

2 Comments to the FAT reports of the supplies

The FAT test reports of the supplies [1] contain descriptions of the procedures and equipment used to test the supplies. For each Test Step (TS), acceptance criteria and results are presented and have the values agreed upon by Danfysik and AU. Briefly described, the FAT programme tests included detailed system functional tests, both at high and low combinations of current amplitude and raster frequency, safety measures like grounding, high-voltage isolation, earth leak test, system self-protection measures (system interlocks, over-frequency), and remote control. Long-term raster waveform stability was also tested to some extent, $\simeq$ 8 hours, although more detailed long-term testing would be a key element of the SAT.

As documented in the FAT reports, both supplies pass almost all the acceptance criteria and the main focus will here be on the few TSs which apparently failed and their significance.

2.1 Current Waveform Parameters

The current waveform was measured using a DCCT enclosing a single power cable conductor core close to the magnet. The signal was measured using a oscilloscope, often set to infinite trace persistency to perform long-term stability testing of parameters.

Frequency / kHz	Magnet #	Set current / A	Magnet current / A
40.000	16653	310.1	329.0
	16654	306.9	326.3
10.000	16653	322.6	328.6
	16654	317.6	323.9

Table 1: Magnet current amplitudes found to yield integrated magnetic fields of 5.01 mT.m. The values found are to be compared with the model prediction of 332 A.

2.1.1 Absolute amplitude accuracy, TS 2.10

The absolute accuracy of the current amplitude, FAT Test Step (TS) 2.10, was measured to 3.2% and 3.0% for the supplies 1700703 and 1700704 [1], respectively, which is notably larger than the specified <1%. According to the manufacturer, there are two effects that are believed to cause an output current slightly larger than the set point

Power cable discharge: the power cables will continue to discharge energy in the magnet a bit longer than the supply actually does.

Peak detection: the inter-burst regulation loop relies on peak detection in the current waveform using an internal DCCT in the Output Crate. During the FAT, the amplitude accuracy error was studied and found to exhibit a frequency dependence, specifically the error would be larger at the higher frequencies. It is believed that the current peak detection scheme is challenged at the highest current slopes, dI/dt, *i.e.* at a combination of high current amplitudes and raster frequency.

Calibrated strip line probes were used to find the magnet current set points leading to an integrated dipole field of 5.01 mT.m while measuring the current with a DCCT near the respective Raster Scanning Magnets (RSMs). The empirically found values are presented in Tab. 1 and are to be compared with the model prediction of 332 A. It is clear that the amplitude set point tends to underestimate the true current—measured near the magnet—in particular at the higher raster frequencies, cf. the explanations previously presented.

It should be noted that the effects observed above should not change with time and can be mitigated by a calibration of the RSMS while looking directly at the beam response, a non-zero transverse centroid position at a downstream location. Additionally, a constant raster amplitude error of the order of $\simeq$ 3% is not considered noticeable by Beam Interceptive Devices (BIDs).

2.1.2 Stability, TS 2.12

Contrary to the impression one may get from the comment of FAT TS 2.12, the system stability was not tested while undergoing significant environment changes, *e.g.* thermal cycling. The system was operated in a standard lab environment over the course of the 8 hour stability test[1] at 340 A (100%), 40.000 kHz, 14 Hz trigger, cf. FAT TS 142 of [1]. The DCCT signal was displayed with infinite persistence on an oscilloscope zoomed in on the last positive current peak of the burst. The 99% peak-to-peak variation is 1.1% and 1.2% for report 1700703 and 1700704 [1], respectively, *i.e.* very close to the specified $\pm$0.5%.

[1]For one supply, the testing was limited to 4 hours.

The long-term amplitude stability defines the sharpnes of the raster pattern outline, when averaged over several bursts. This distribution is however to be convoluted with a two-dimensional Gaussian distribution that represents the unrastered beam size. This distribution is significantly wider, having a ratio of the RMS beam size to the nominal raster amplitude of $\gtrsim 20\%$. The slightly larger value of the raster amplitude stability is thus considered to be indiscernible in the delivered beam distribution and the performance result was accepted during the FAT.

2.1.3 Offset, TS 2.13

The current DC offset is measured as half of the difference between the positive and negative peak height of a single pulse, 2 ms into the burst. The acceptance criteria is set as $< 1\%$ DC offset which would correspond to a beam displacement of $\lesssim 0.6$ mm at the target. The relative offset error is in the test data seen to increase with raster frequency, and only one supply exceeds the criteria, only at the highest raster frequency (40 kHz), with a relative offset of 1.3%, cf. report 1700703 [1]. In other respects, it has been seen that the peak detection circuits are less accurate at the highest frequencies. The present result may thus be a result of the finite accuracies of the two distinct peak detection circuits, positive and negative.

Based on the beam response evaluation above, the tolerance exceedance should only have a minuscule effect, and the recommendation is to approve the performance. The second supply does not fail this test step.

3 Additional Measurements

3.1 Stray Field Extent and Impact

The range of the RSM fringe field is considered important for two reasons:

- The AC stray field could disturb other instruments in the vicinity of the RSMS, *e.g.* beam instrumentation.
- A ceramic chamber is used in the RSMS to avoid resistive losses due to eddy currents in conductors. Such losses would not only lead to heating of components, but could potentially overload the power supplies. The ceramic chamber has, however, a finite length and there will be metallic parts at either end of the ceramic chamber.

The stray field extent will thus have to match the modelled values to be consistent with the system design choices, *e.g.* length of ceramic chamber. The stray field magnitude was measured using a crude $\simeq 1\ \text{cm}^2$ handheld wire as a pickup loop, sensitive to time-varying magnetic fields like the Bdot loops of the RSMs.

The pickup loop was held in a horizontal plane, *i.e.* sensitive to the vertical component of the field only, $\propto dB_y/dt$. This should also be the dominating field component when held near the vertical center axis of the magnet, the nominal beam height. The measured signals can be seen in Tab. 2. This data is in Fig. 1 visually compared with simulated data that is traced from a plot in the RSMS Detailed Design Report (DDR) [2]. In both cases the data represents values on the beam axis that are normalised to the value at the magnet center. The measured values correspond very well with the modelled field shape, when considering that the relative data tracing error becomes significant at the lower field values.

Position from magnet center / mm	Peak voltage / mV
0	291
140	143
200	32.0
400	0.74

Table 2: Magnetic field profile data as measured on beam axis using a pickup loop.

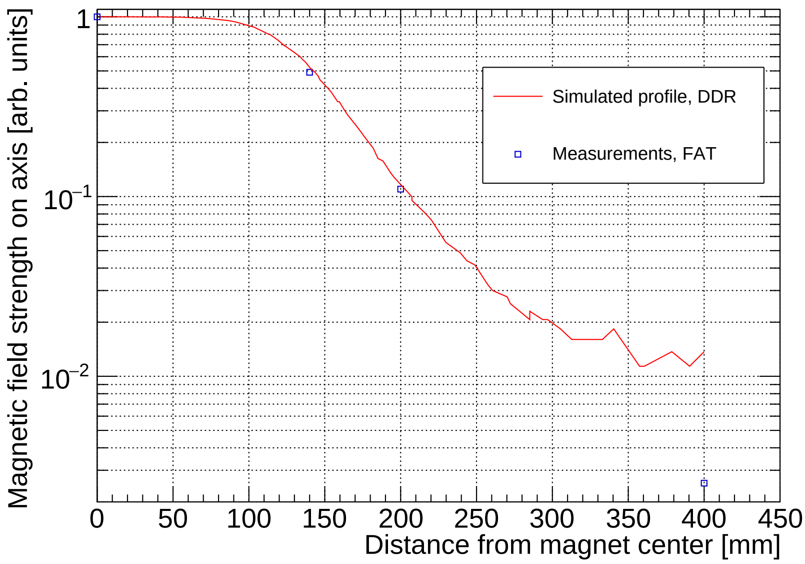

Figure 1: A comparison of the field profiles found in the DDR simulations and FAT measurements, cf. Tab. 2.

As a final way of ruling out any detrimental impact of having metallic parts on the beam axis in the vicinity of the RSMs, one of the system's metallic Quick-Conflat end-clamps was placed about 20 mm longitudinally from the coil edge (similar to the final location of this clamp). The supply was set to operate at 340 A (100%), 40.000 kHz, 14 Hz trigger for about 30 min. At this point, no noticeable heating of the clamp was found and the RSMS had delivered bursts, apparently not additionally burdened by the clamp.

4 Conclusion

Within the first few days of December 2017, the RSMS pre-series was fully accepted for delivery to AU. The minor system caveats found during the FAT would either have diminishing impact on the system performance or would be examined closer during the SAT.

The FAT program has been found to also in practice cover the system well, and a very similar FAT is anticipated for the full-scale system. In some cases, the TSs could here be reduced in numbers and complexity, now being more familiar with the system. Additional test series should on the other hand consider the increased unit quantity, added dimension (*e.g.* confirm the relative roll of horizontal and vertical RSM pairs on the same girder), *etc.*.

5 Acronyms

AU Aarhus University

BID Beam Interceptive Device

DDR Detailed Design Report

ESS European Spallation Source

FAT Factory Acceptance Test

RSM Raster Scanning Magnet

RSMS Raster Scanning Magnet System

SAT Site Acceptance Test

TS Test Step

References

[1] Danfysik, H. D. Thomsen, and S. P. Møller, "Factory Acceptance. Test Procedure For ESS RSMS-PS Serial No. 1700703 and 1700704," tech. rep., ESS, 2017.

[2] Danfysik, H. D. Thomsen, and S. P. Møller, "Detailed design report. raster scanning magnet system for ess," tech. rep., ESS, 2016.