DANFYSIK

Danfysik 2016

Detailed Design Report

Raster scanning magnet system for ESS

DDR
Rev B
DF project no 502446

DANFYSIK A/S
Gregersensvej 8
DK-2630 Taastrup, Denmark

www.danfysik.com
danfysik@danfysik.dk
☎ +45 7220 2400

Preparation/Review	Signature	Date
Author: Nils Hauge Amir Anari	NH AANA	2017-02-27
Check: Christian Glarbo	CGPE	2017-02-27
Approved by: Christian Glarbo	CGPE	2017-02-27

Revision History Log:

Date:	Rev.:	Init:	Changes:
2016-12-22	A		Initial version
2017-02-15	B		Update after Critical Design Review at ESS

Reference Documents

[1] "Contract concerning the delivery of the raster scanning magnets for the ESS project", AU, 31/5/2016
[2] "Appendix 1: Technical Specification", AU, March 2016
[3] "Conceptual Design of Raster Scanning System", AU, 17/02/2015
[4] "Technical Description and Compliance Matrix", DF, 20/04/2016
[5] "502446 DDR-RSMS-MPS RevA", DF
[6] "502446 DDR RevA", DF

See all DDR documents in [6].

Abbreviations

[AU]	Aarhus University
[DF]	Danfysik
[ESS]	European Spallation Source
[RSMS]	Raster Scanning Magnet System
[RSM]	Raster Scanning Magnet
[PSU]	Power Supply Unit

Content

1. Introduction

The following document is a detailed design report describing the design figures for the 502446 raster scanning system. The main goal of this document is to settle the magnetic and mechanical design of the magnets, vacuum chambers and support structure.

2. System description

The Raster Scanning Magnet System (RSMS) consists of two girder sections each having four raster scanning magnets (RSM) together with a ceramic vacuum chamber system. All magnets are identical in construction, however the orientation is pairwise 90° rotated in order to enable both vertical and horizontal scanning of the beam. The configuration of each girder section is mirrored so the following configuration is obtained [HHVV] [VVHH]. Each girder sections are supported by two legs. The main assembly of one girder is shown in Figure 1.

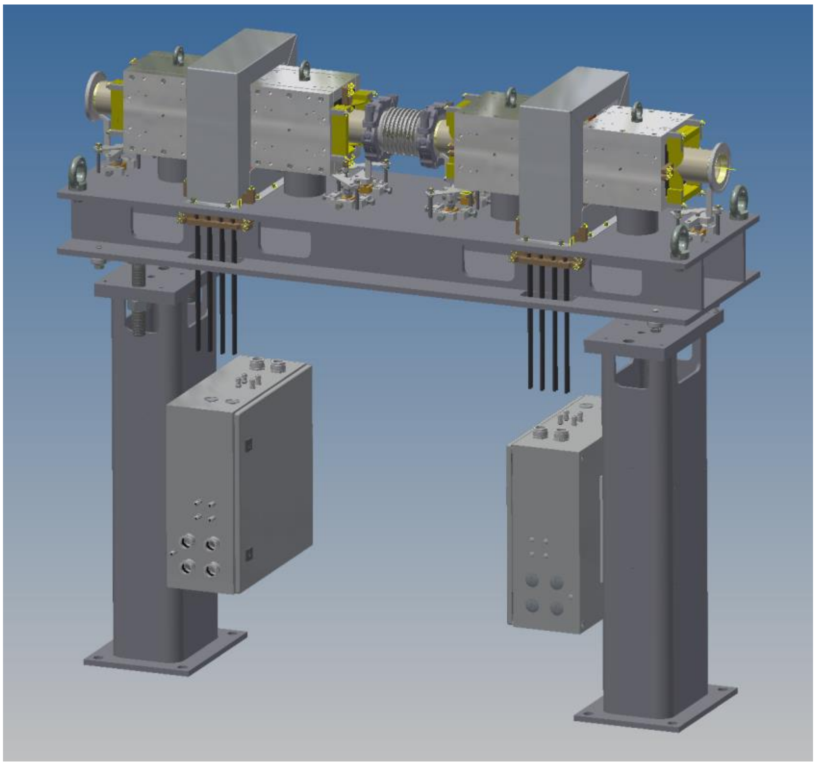


Figure 1: Main assembly of the RSMS

To produce the scanning field a fast scanning power supply for each magnet in used. The power supplies (PSU's) produce triangular shaped currents by applying square wave voltages onto the magnets. The frequency is 40 kHz for the horizontal oriented magnets while 29 kHz for vertical oriented magnets. All power supplies will be constructed identically while the scanning frequency being configurable within these two settings. The system is designed for a lower frequency of 10 kHz.

The magnets and power supplies are separated by 35 meters of cable. The power supplies are situated in a radiation free zone (green zone) while parts of the magnet system can be experience intense neutron radiation.

The operation of the system is controlled by the ESS timing event receivers which also broadcast the timing signals for the raster system. The operation is monitored by the ESS Fault Detection Unit

(FDU) using the interlock readback signals from the PSU. Furthermore, an integrated B-dot coil in the magnets is used to monitor the field waveform variation.

The following chapters provide design details of the subcomponents in the magnet system.

3. Raster scanning magnets

In the following the Raster Magnets will be described in details.

3.1. Magnet Description

The Raster Scan Magnets (RSM) are ferrite core based and of Window Frame (WF) type. This is the most efficient type of magnet for this operation. The coils are of saddle shape type and made from solid OF-HC copper sheets. The coils are vacuum resin impregnated with G11 support structures for ground insulation and alumina charged for improved thermal conductance. The coils are air cooled and each has a 60°C NC thermal switch for over temperature detection.

An aluminium housing supports the ferrite core plates and hold them in position by clamping. The coils are fastened at the extremes to the housing and are free floating inside the magnet. The coil uses bus bars to connect to the power cables. The connections are shielded.

A Bdot loop is included in the magnet for monitoring the field waveform (dB/dt).

A set of alignment fiducial holes is located at the magnet housing top plate. The top plate also has room for a precision level gauge.

The following table summarises the main magnet parameters:

Parameter	**Symbol**	**Value**
Nominal Field	B_0	±0.0167 T
Maximum Field	B_{max}	±0.0171 T
Minimum Field	B_{min}	±0.0011 T
Effective length	L	300 mm
Field waveform		Triangular shape
Waveform frequency H (V)		40 (29) kHz
Nominal Current	I_{nom}	332 Amp
Maximum Current	I_{max}	340 Amp
Minimum Current	I_{min}	23 Amp
Max. Magnet Voltage	U_{max}	427 V
Magnet Resistance	R_{AC}	9 mOhm
Magnet inductance, incl connections	L	7.8 μH
Pulse length	T	3.57 ms
Repetition rate		14 Hz
Max Power dissipation	P	17 W

Table 1: Summary of magnet parameters

3.2. Magnetic calculations

Both 2D and 3D magnet calculations have been performed for the RSM. The 2D calculation has been used to evaluate eddy currents and proximity effects in the coil section. The 3D calculation has been used to find the magnetic effective length and stored energy for inductance calculation. The integrated field homogeneity is found to be 1%, well within the specification of 10% in 30x30 mm^2 good field region, see also Figure 4 below.

Using the transient module in Opera 2D, eddy current and proximity effects has been evaluated. A quarter section has been used due to symmetry along vertical and horizontal mid planes. It is seen in Figure 2 and Figure 3 that the current density is higher close to the magnet gap. The current flows mainly (70%) within the first 0.2 mm, while the skin depth of copper at 40 kHz is 0.33 mm. This must be considered when defining the AC resistance and heat losses in the coil, see also section 3.3. In the evaluation of the magnetic forces in the transient analysis the integrated coil forces were found to be less than 2 N per coil section.

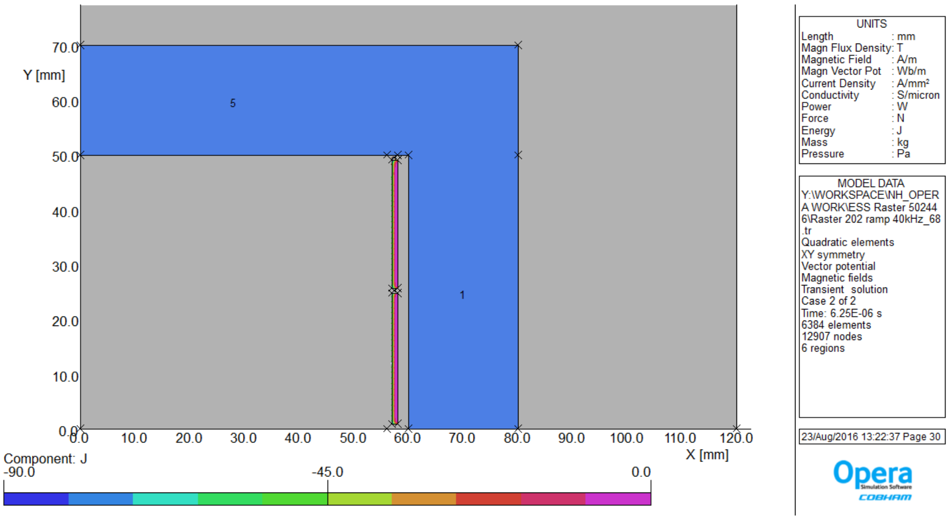


Figure 2. The 2D model, one quarter of the section.

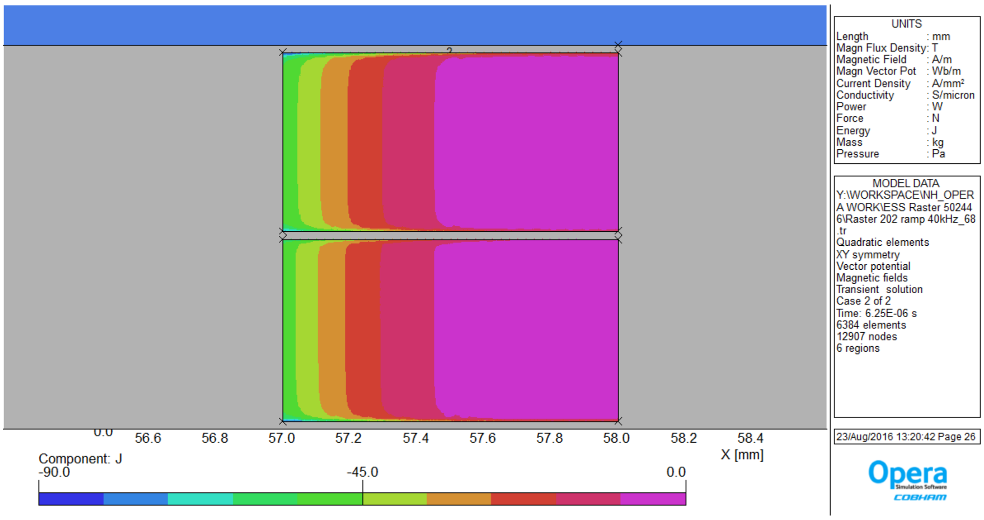


Figure 3. Exaggerated figure of the coil showing current density distribution.

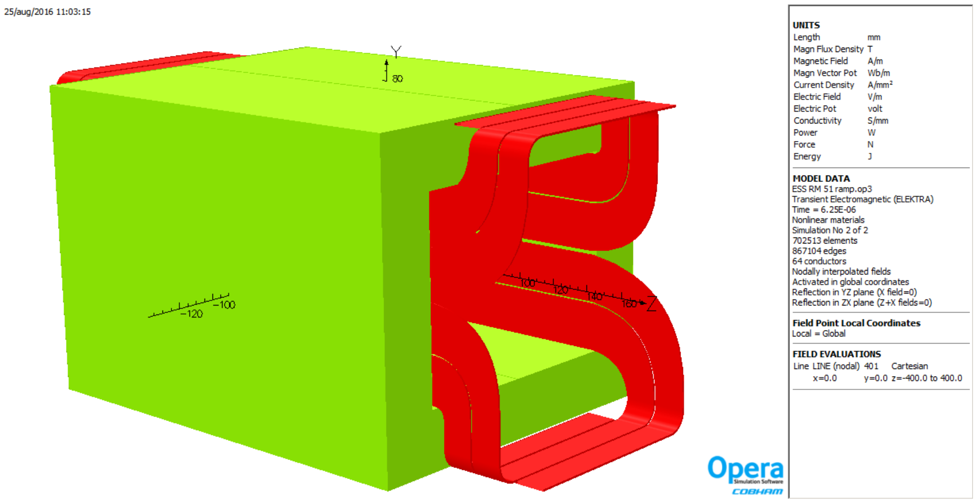


Figure 4. The 3D model with true coils

From the 3D calculations the stored energy can be used to find the total inductance of the magnet. The inductance is found to be larger than the analytical calculation. In the model the coils have been modelled with end connections, these have only the half current due to the overlap. The connections to bus bars will be at the vertical center plane of the magnet.

In the model the magnetic length is found to be 300 mm for a 230 mm ferrite core length, see also Figure 6.

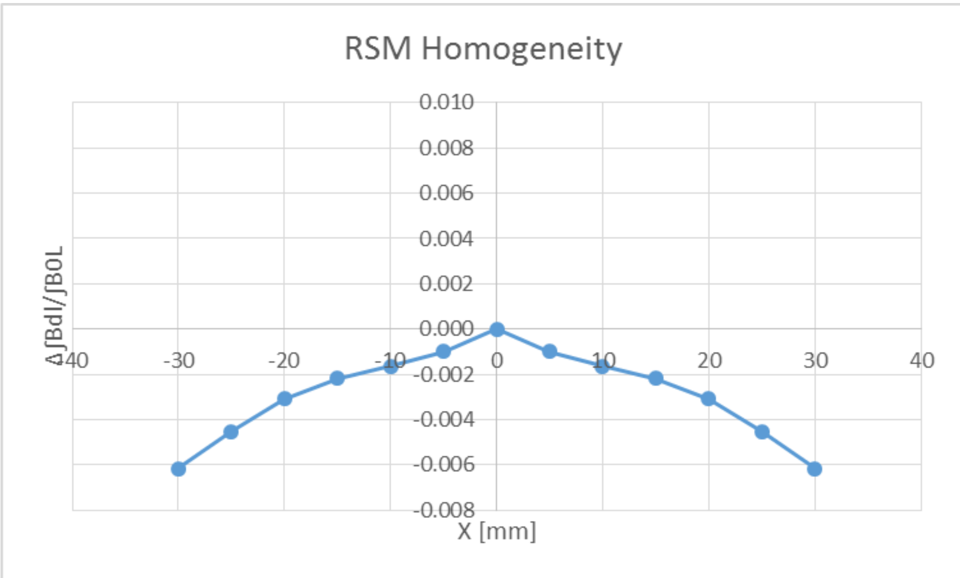


Figure 5. The integrated field homogeneity

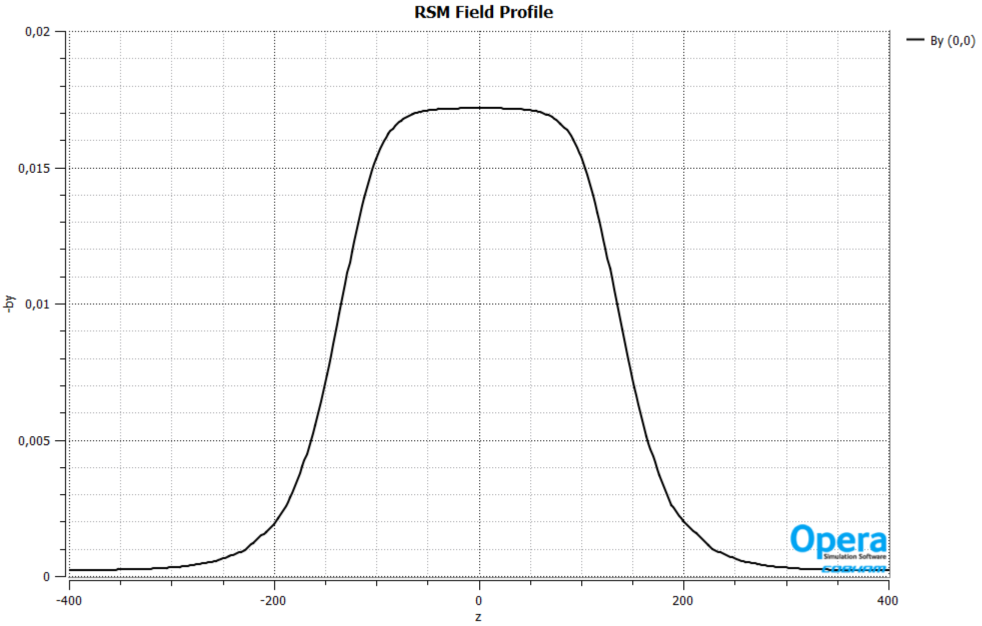


Figure 6. Field profile at 340 Amp

3.3. Thermal calculation

Using the average current skin depth (0.33mm) in the coil the thermal load can be calculated. The calculations are based on maximum current and full duty. Moreover the main part of current only run at one side of the conductor facing the gap due to the induction law. It is found that the maximum power in the coils is 17 W. The average current density in the coil calculated from the power is 1.8 Amp/mm^2 . This is a rather high figure that under normal circumstances would give a rather large temperature rise.

From the 2d calculation a Power/unit length of the RSM coil section can be calculated, this is found to be 0.333 W/mm. Assuming the same load on the full length coil and a average resistivity of 0.0172 µΩ*m (20°C), a total of 300 W is dissipated in the magnet. With a duty of 5% the power this is only 15W.

The 2d calculations show a slightly lower power than the analytical power calculation since it uses resistivity properties at 20°C while the operating temperature is expected to be 30-40°C. If compensating the copper resistivity with its temperature coefficient the results become close. The RSM coil cross section is high and tall and has a large surface area vs its volume which makes air convection cooling efficient.

3.4. Coil assembly

The coil will be made from solid OF-HC copper sheets and then will be bent to form a saddle-shape; the coils will be vacuum resin impregnated with radiation resistant CTD101K inside a mould. The resin will be charged with alumina powder for enhanced thermal conduction. In order to improve mechanical properties, G11 Etronax pieces are added to the vulnerable areas and the spaces between each loop will be filled with G11 Etronax pieces.

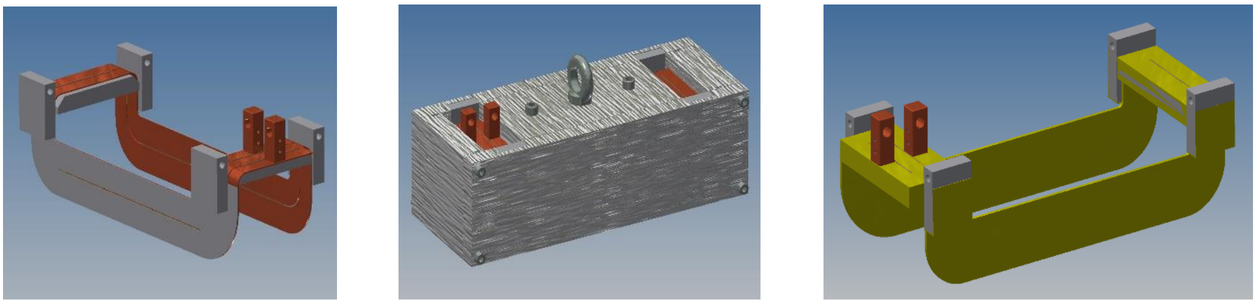


Figure 7: Bent coil and G11 pieces (left), mold (middle), final coil (right)

3.5. Magnet yoke assembly

Ferrite yoke cores are made from four ferrite plates held in position by clamping, see Figure 8. The exertion of clamping force will be done using springs on 2 sides of the core assembly. Two of the ferrites are constrained by the coil edges and other two are constrained by the Bdot holders (longitudinally) and constrained by friction forces in the transverse direction.

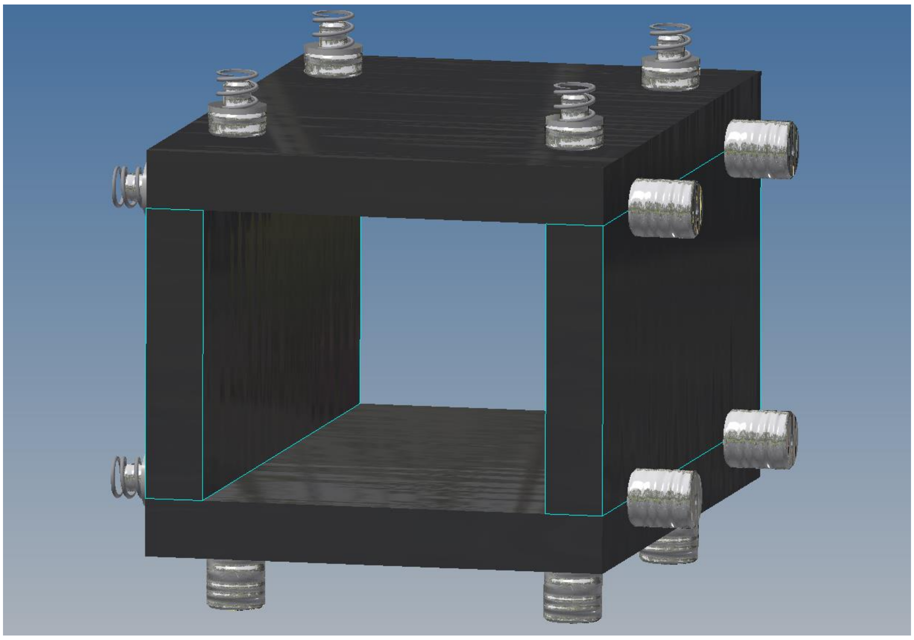


Figure 8: Clamped ferrite core assembly

The clamped ferrite core assembly and impregnated coils will be assembled inside the aluminum housing. The aluminum housing keeps the ferrite core fixed and the two coils will be fastened to the aluminum yoke using screws. On all outer surfaces, there are 4 threaded holes for mounting on girder, one threaded hole for lifting with eye-screw and 4 alignment fiducial holes.

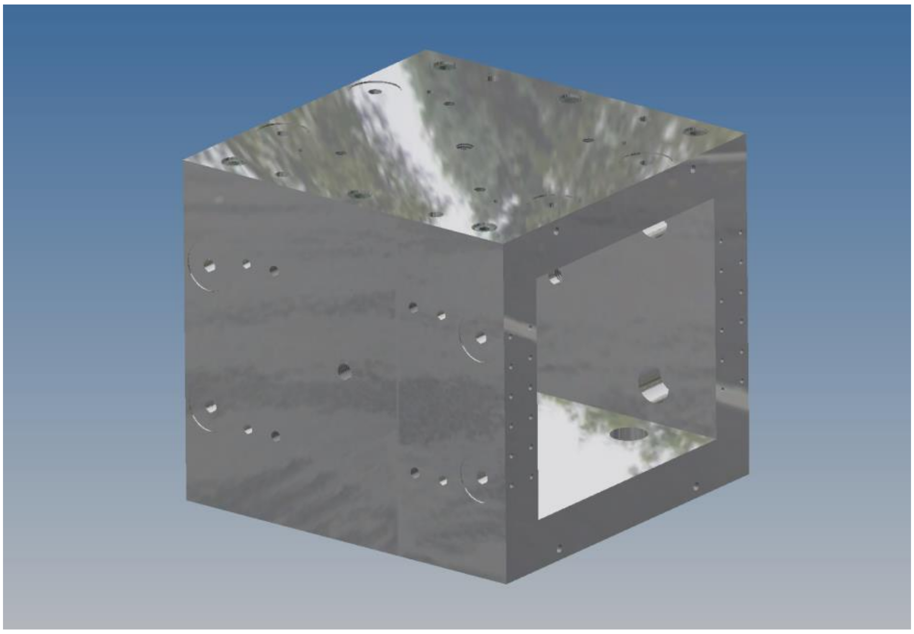


Figure 9: Aluminum housing assembly

3.6. Magnet assembly

The RSM assembly consists of:

1. Saddle shape type coil assembly
2. Ferrite core
3. Aluminum housing
4. Bdot loop
5. Bus bars
6. Thermal switches

The RSM is shown in Figure 10.

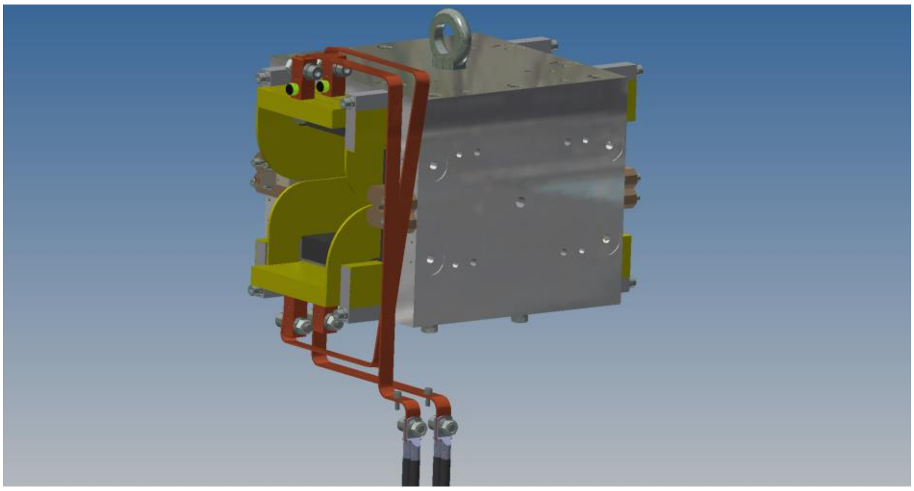


Figure 10: Raster scanning magnet

One Bdot loop is installed in each Raster magnet and can be used to monitor the field waveform. The Bdot loop is made out of insulated copper and rounded over one of the ferrite plates and hanged to the aluminum housing using arms made from G11 etronax.

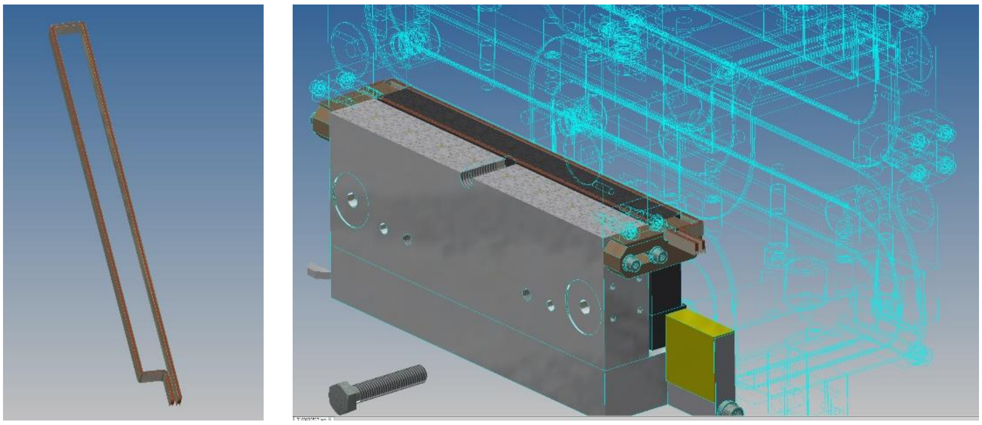


Figure 11: Bdot loop (Left) and cross section of the raster magnet at its assembly position (Right)

4. Vacuum chamber

The magnet vacuum chambers will be made from a circular ceramic tube. The ceramic length will be long enough to accommodate two magnets including their fringe fields, approximate 800 mm long. The inner diameter is 80mm and outer 90 mm. Ceramic to metal joints will be made as brazing transition pieces, these will be welded to the flanges. The flanges are Quick Conflat flanges for fast opening and closing of the connections. The ceramic will be prepared for internal Ti coating by adding 5mm metallization on the internal at each end.

The ceramic vacuum chambers will have adjustable support connections to the girder section. One end will be fixed while the other is floating to accommodate differences in thermal expansions.

Bellows will be hydro formed thin walled sections with welded Quick Conflat flanges. The inner diameter of the bellow section will be larger than the opening in the flanges.

All vacuum parts will be made to UHV standards, all metal sealed flanges and materials. The He leak rate will be tested to 1E-10 mbar ltr/s. The ceramic chambers will be tested for outgassing properties, the specification call for 1E-10mbar/ltr s cm^2.

The design and manufacturing shall follow the guiding rules listed in the following European Spallation Source official documents:

- ESS-0012894, ESS Vacuum Handbook Part 1 – General Requirements for the ESS Technical Vacuum System
- ESS-0012895, ESS Vacuum Handbook Part 2 – Vacuum Equipment Standardisation
- ESS-0012896, ESS Vacuum Handbook Part 3 – ESS Vacuum Design & Fabrication
- ESS-0012897, ESS Vacuum Handbook Part 4 – Vacuum Test Manual

4.1. Ceramic vacuum chamber

The vacuum chamber assemblies consist of: cylindrical ceramic chamber (Al_2O_2), brazed transition pieces made from NiFe alloy, and welded quick CF flanges on both ends. The vacuum chamber has quick CF 100 flange on both ends. The ceramic pieces will be prepared for a possible metallization of its interior by having the metallization for brazing extended on the inner surface by 4-5mm.

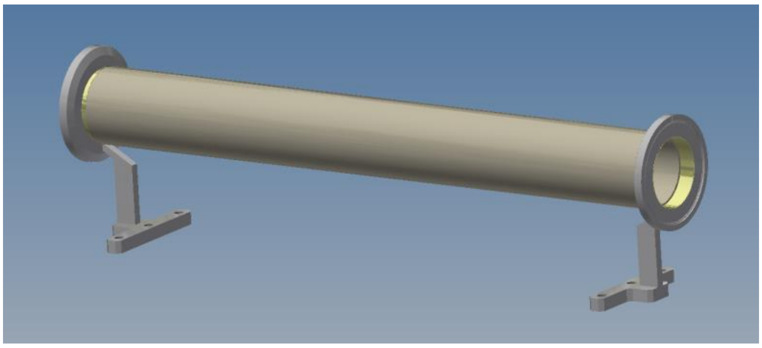


Figure 12: Vacuum chamber assembly

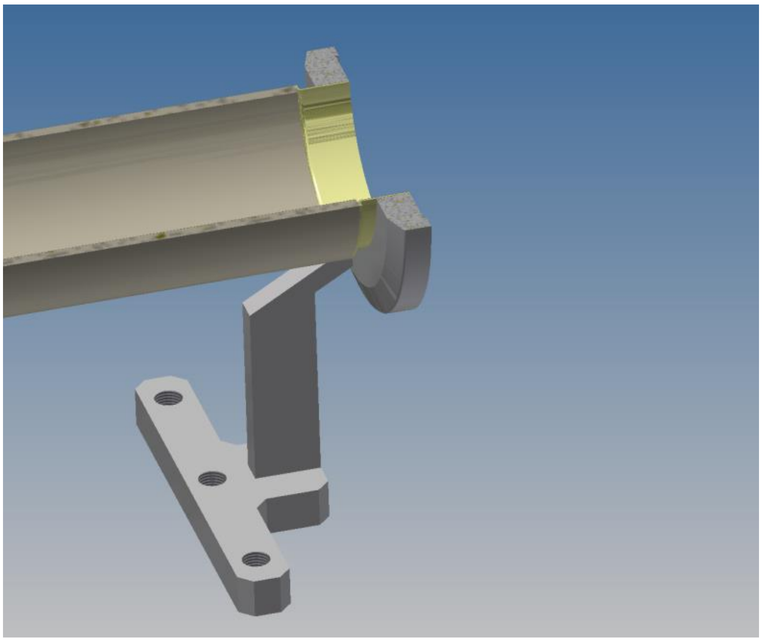


Figure 13: Section view of vacuum chamber ends

4.2. Bellow section

Two vacuum chambers will be coupled to each other using a hydro-formed flanged bellow and coupling will be done using quick clamps. The inner diameter of the bellow section is dia120mm.

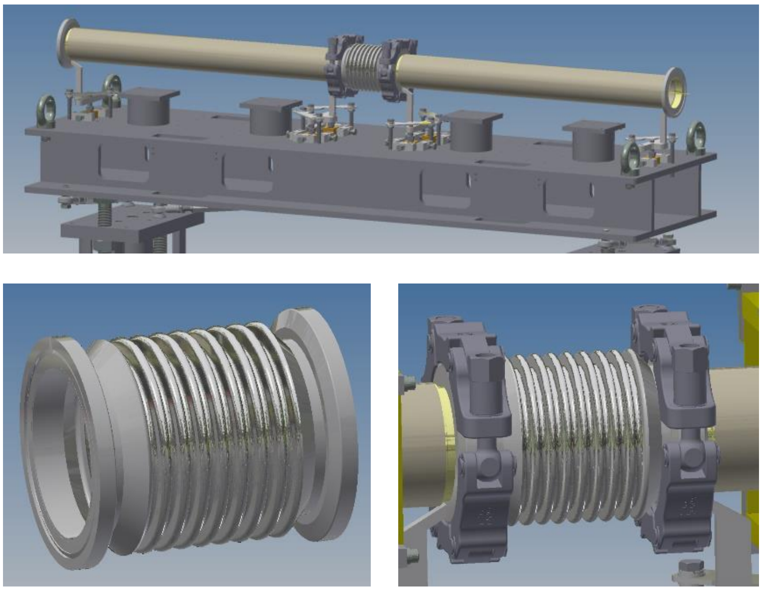
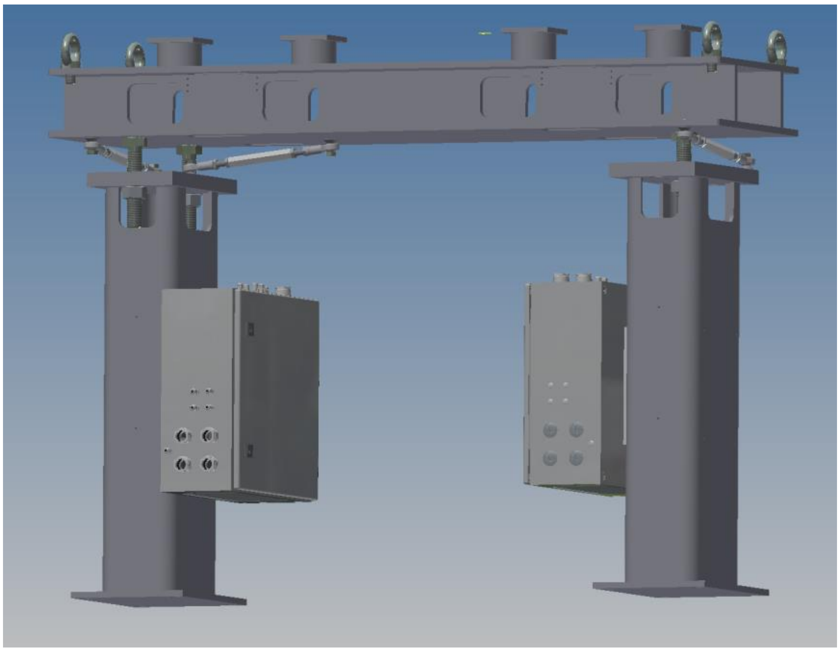


Figure 14: Coupling of vacuum chambers using quick clamps and bellow

5. Support structure

5.1. Mounting on supports

Four raster magnets, vacuum chamber alignment parts, vacuum chamber tie-down structure, bus bar terminals and shield will be mounted on a girder which is suspended over two legs. A combination of three screws and three turnbuckles provide six degree of freedom for alignment of the girder. Two connection boxes will be mounted on the inner surface of support legs and cables will be routed to them.



The magnets will be fixed mounted on the girder section within machining tolerances. The magnet to magnet alignment is trusted to be within the specification. During assembly the magnet to magnet alignment will be checked within a girder section. Final alignment of the four magnet girder section will be done by the girder.

The vacuum chamber will have an adjustable fixed end at the girder extremes while the inner ends will be floating in the length direction. The bellow section closes the vacuum section.

Along the side of the magnets power connections are located. Bus bars is used to connect the coil leads with the cables. Bus bars will be screwed to a terminal made from G11 Etronax. The connections and bus bars are shielded by a fixed but removable common cover. The bus bars are shown in Figure 15 with the cover removed.

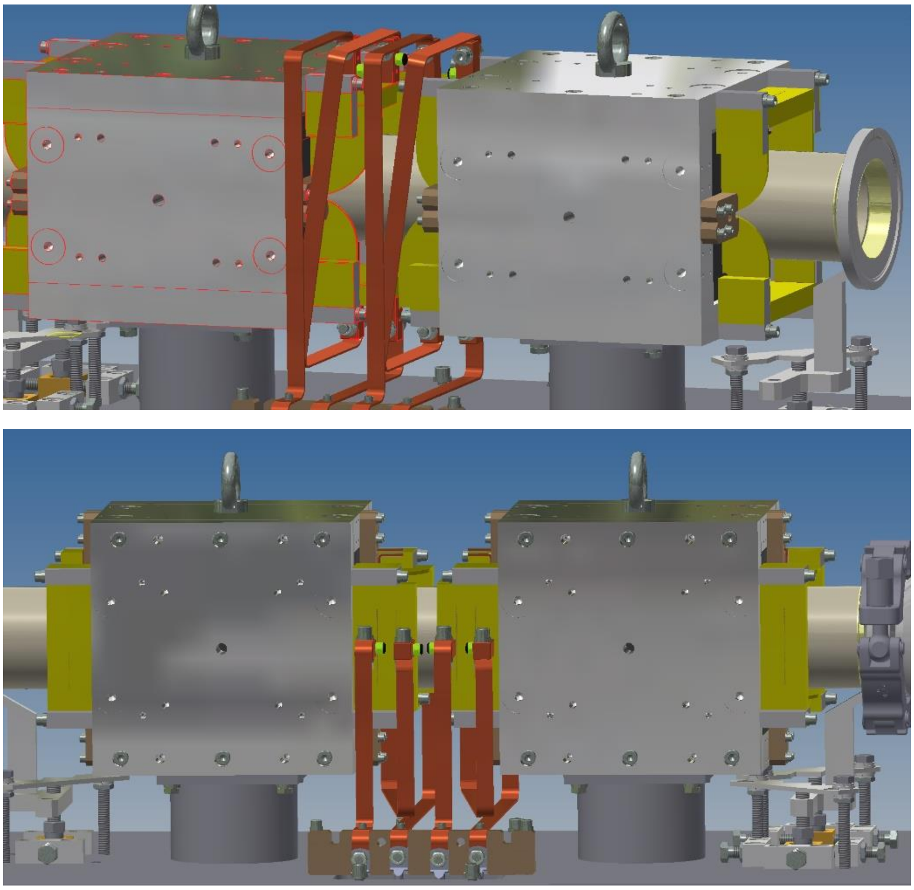


Figure 15: Bus bar connections for the raster magnets

5.2. Alignment

The magnets are pre-aligned on the girder section along with their vacuum chambers. The adjustments are done by a three axis turnbuckle system, a total of ±25 mm horizontal range and ±35 vertical range. The range has been reduced from the specified ±50 mm due to the availability of the used links.

The nominal height of 1500 mm is found at first, then angular alignment to ±0.1° (pitch/yaw/roll) and then transverse adjustments. The height, angular and transvers alignment are checked and finally adjusted in a few cycles. The alignment is checked with a laser tracker and precision inclinometer. There will be four alignment fiducial holes on each magnet.

6. Interface specification

Mechanical interface to ESS is found to the connections to adjacent vacuum chambers and support attachment to the floor. The vacuum chamber flanges are Quick Conflat DN100 that connects to the diagnostic box placed between the two girder sections. The outer flange connections are Quick Conflat DN160 that connects upstream and downstream of the RSM system. The Quick Conflat flanges are within standard range from MKT (Mechanische Komponenten Tschann GmbH, Germany). See also Layout drawing 7103033532. The total length flange to flange on a girder is 1791 mm.

The attachment to the floor is made with M12 anchor screws through the support legs foot plate. The nominal beam height is 1500 mm.

A thermal switch is attached to the coil for thermal detection. The switches are series connected on each magnet coil and are of NC type and is an interlock circuit to each PSU. The opening temperature is 60°C.

The Bdot loop monitor the field waveform (dB/dt) during operation. If a single turn loop is mounted around one ferrite return leg then the voltage would be:

$$U = \frac{L \cdot W}{2} \cdot \frac{\partial B}{\partial t}$$

Where L is the effective length and W the effective width of the magnet, respectively. At 40 kHz operation at full current of 340Amp the voltage from the loop is ±51 V. Ideally the voltage has a square waveform.

6.1. Cable connection

The cables from the power supply end close to the floor level at a connection box mounted at the support leg, see also Figure 1. There will be two connections at each end of the support. The connection box includes a matching circuit of a capacitor and resistor, see [5]. The resistor is clamped to the support leg for heat transfer. From the connection box two + two short transition cables bring the power to the power connection on the girder. The cables are long enough to allow final alignment of the girder sections. The cables are 16 mm^2 each. The cables are easily exchangeable in case of degradation due to radiation and maintenance.

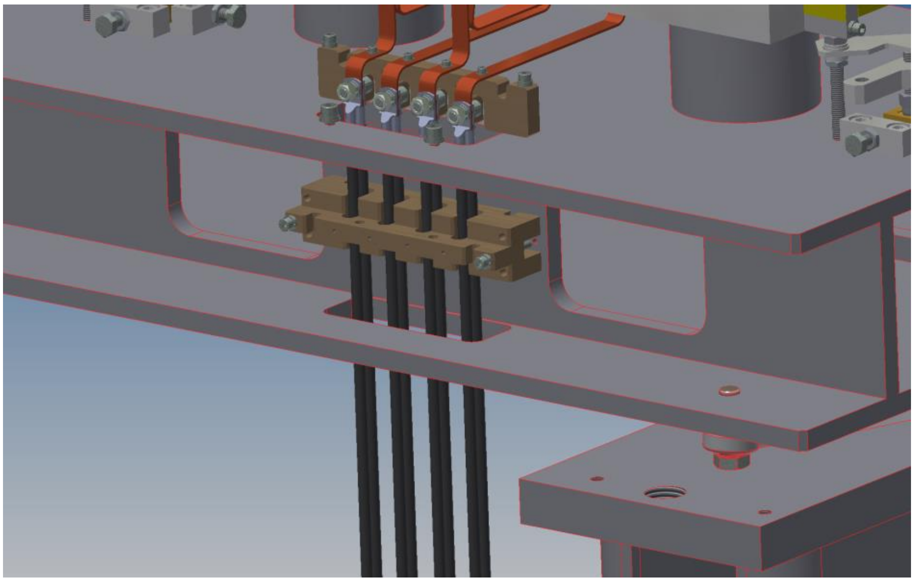


Figure 16: Bus bar termination and cable holders

7. Tests and Measurements

7.1. Mechanical

All critical dimensions and geometrical tolerances of parts and assemblies will be measured and documented. The measurements will be made using standard workshop calibres and gauges. In addition a measuring arm will be used for the geometrical tolerances. A visual inspection of all parts and surface conditions will be conducted. Critical components to be measured are:

- The ferrite plates and assembled yokes
- The Coils
- The Vacuum Chambers and bellow sections

Signed protocols will be used during production and assembly.

7.2. Electrical

The coils will have their DC resistance measured. After epoxy impregnation the high voltage insulation to ground and inter turn insulation will be tested. The high voltage holding will be 2 kV and inter turn voltage will be 500 V/turn.

The coil to ground high voltage insulation will be tested on the assembled magnet to 1 kV. A dc-resistance and inductance measurement will be made on the assembled magnet. A standard LCR meter will be used for this measurement.

7.3. Vacuum

The ceramic vacuum chambers and bellow sections will He leak tested to 10^{-10} mbar.ltr/s using a standard oil free leak detector. In addition a thermal outgassing test will be conducted to show a

<$5*10^{-9}$ mbar.ltr/s.cm^2. An oil free vacuum pumping station with a turbomolecular pump will be used for this test. A RGA is available in this pumping station.

7.4. Magnetic

The magnets can only be magnetic measured with their dedicated power supplies. The magnet transfer functions will be measured within the operational ranges using a full length strip line probe. The probe is 700 mm long and covers the full magnet length and end fringe fields. Thus the full magnetic strength is measured. The probe will also be used to find the integrated field uniformity within the good field region. An oscilloscope will be used to analyze the probe voltages.
The signal on from the Bdot coil will be measured as well to verify that the Bdot signal does indeed reflect the magnet field and that the Bdot signal quality is acceptable.

During the magnetic testing a full power test will be conducted to measure the thermal properties of the coils.

8. Recommended spare parts

Part	**Quantity**	**Comment**
Cable between connection box and bus bars	32	Cables may be exposed to radiation causing degradation. The cables are easily exchangeable causing minimum down time. The radiation resistance of the XLPE insulation is 10^6Gy according CERN data.
Coils	2	May be exchanged in case of long term degradation of epoxy
Ferrites, horizontal	2	Ferrites do not degrade. Ferrites are fragile and could potentially be damaged during exchange of a coil
Ferrites, vertical	2	See above
Vacuum chamber	1	