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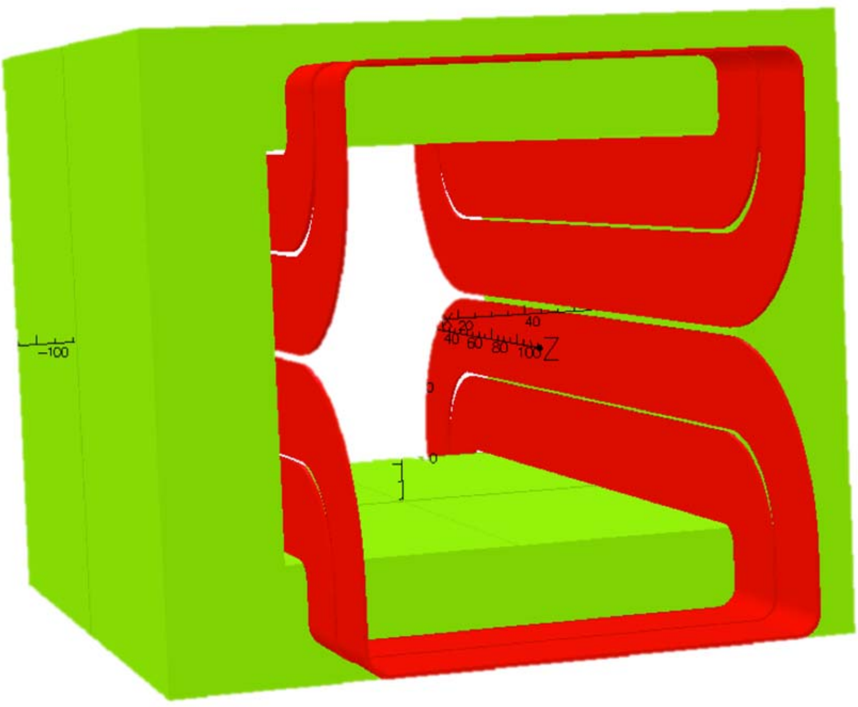
Conceptual Design of Raster Scanning System



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1 Introduction

1.1 Abstract

This document describes a conceptual design for the Raster Scanning Magnets and Magnet Power Supply to be used for the target raster scanning system at ESS.

The scope only deals with the preliminary conceptual design and specifications of the magnet and MPS units. None of the units are standard delivery and it is foreseen much more effort shall be put into the final specification, conceptual and detailed design before the raster scanning system can be made ready for production.

The cable specification connecting RSM and MPS is not yet completely finalized and it is an important parameter for designing the MPS to its actual load.

It is anticipated a trigger signal to the MPS is required for initiating each scanning sequence.

1.2 Reference Documents

Raster magnet power supply presentation slides "Preliminary Feasibility

Assessment of Power Converters and Magnets for Beam Raster System" Written by Carlos A. Martins from ESS, Accelerator Division.

File: "RasterPowerConvertersMagnets.pdf"

1.3 Abbreviations and Definitions

DF	Danfysik A/S
MPS	Magnet Power Supply
RSM	Raster Scanning Magnets
W,D,H,	Width, Depth, Height
IGBT	Insulated Gate Bipolar Transistor
HW	Hard Ware
SW	Soft Ware
FPGA	Field Programmable Gate Array

2 SS Raster Scanning Magnets (RSM)

2.1 Basic Magnet Concept and Specification

The raster scanning magnet system will scan a proton beam ranging from 0.6GeV to 2.0GeV (future upgrade to 2.5GeV). Four horizontal and four vertical scanning magnets are required in the ESS Beam Expander System. The present proposal include up to 2.5 GeV beam energy with contingency such that one power supply can be off in each direction. The operating range of the power supply is limited such that for low energy scanning only one plus one magnet is running.

The four plus four magnets are all identical. A pair of magnets with same polarity shares a ceramic vacuum section. The magnets run with a triangular pulse shape of up to 40 kHz. The operating frequency requires NiZn ferrites with high permeability and resistivity. The air cooled coils requires special attention to reduce eddy current heating.

The most favorable magnet topology is a Window Frame(WF) yoke. The ratio between useful aperture and magnet aperture can be practically 1 if a narrow coil is used. WF magnets uses saddle shape coils in order to get the coil transition from one side to the other away from the aperture. The conductor distribution in the magnet aperture defines the field homogeneity and need to be carefully designed. Figure 1 shows a draft magnet proposal.

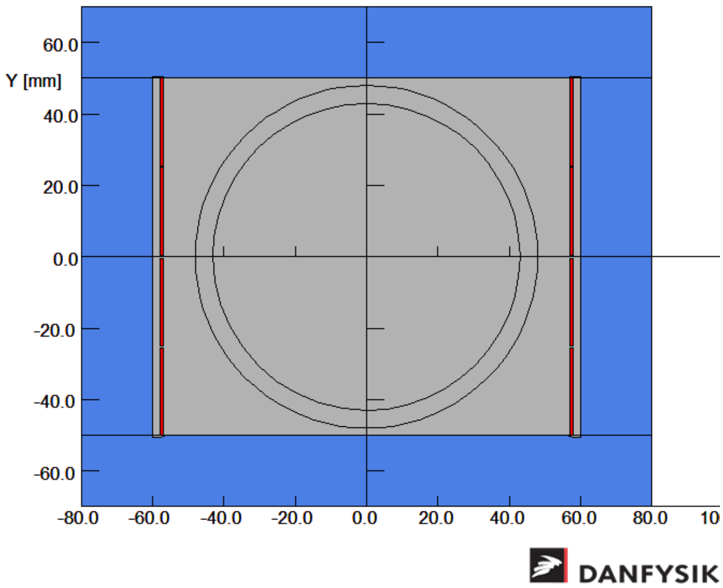

Figure 1. Cross section view of the WF magnet with circular ceramic vacuum chamber.

The coils need to be self-supported in the magnet aperture. The stiffness of the coil must withstand Lorentz forces under ramping and at the same time being able to be cooled by air convection only. It is the intention to make the coil from a water-jet cut HCOF Copper plate of 1mm thickness (skin depth of Copper is 0.5mm @ 40 kHz). The plate can be bent to its saddle shape, glass-fibre epoxy reinforcement added and insulated. Figure 2 shows a corner of the magnet and the coil configuration.

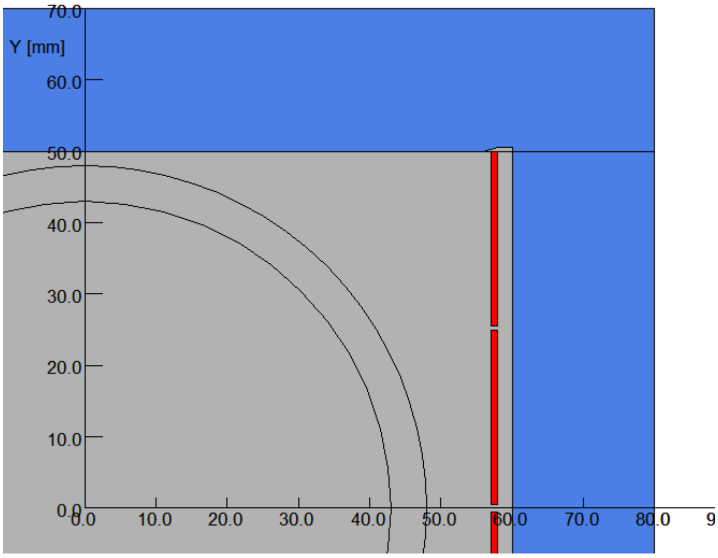

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Figure 2. Close up of a quadrant of the magnet. Two turn coil and a shim in upper corner are seen (in total 2 times two turn coils).

A suitable ferrite for the magnet yoke is CMD5005 from Magnetic Ceramic. The yoke length is assumed to be 200mm and the thickness 20mm. The ferrite blocks can be divided for manufacturing purposes.

2.2 RSM specifications

The following table summarizes the proposed magnet specification:

Nominal Field	B_{nom}	:	0.0106	T
Maximum Field	B_{max}	:	0.017	T
Maximum Strength	∫ Bdl	:	0.005	Tm
Magnet Length	l_{eff}	:	300	mm
Nominal Bend Angle	φ	:	0.12	mrad
Maximum Bend Angle	φ	:	0.26	mrad
Magnet Aperture	HxV	:	100x100	mm
Free Aperture	HxV	:	ø80	mm
Magnet Total Inductance (connectors included)	L	:	6.6E-06	H
Total resistance	R	:	0.0021	Ohm

Pulse Shape		:	Triangular	
Maximum Current	I_{max}	:	340	A
Nominal Current	I_{nom}	:	213	A
Repetition rate	F	:	14	Hz
Pulse length, linear ramp	t_{ramp}	:	6250	ns
Peak Field Amplitude Stability		:	±1%	
Timing jitter	t_j	:	<10	ns
Voltage, excluding cable drop	U_{mag}	:	363	V

2.3 Magnetic calculations

A 3D calculation has been performed to analyze the field integral and homogeneity of the proposed magnet. The model is shown below in Figure 3 including the thin conductor saddle coils. The proposed yoke length of 200 mm results in an effective length of 270 mm, the yoke must then be 230 mm long to have an effective length of 300 mm. The magnet total length including the coil transition is 330mm.

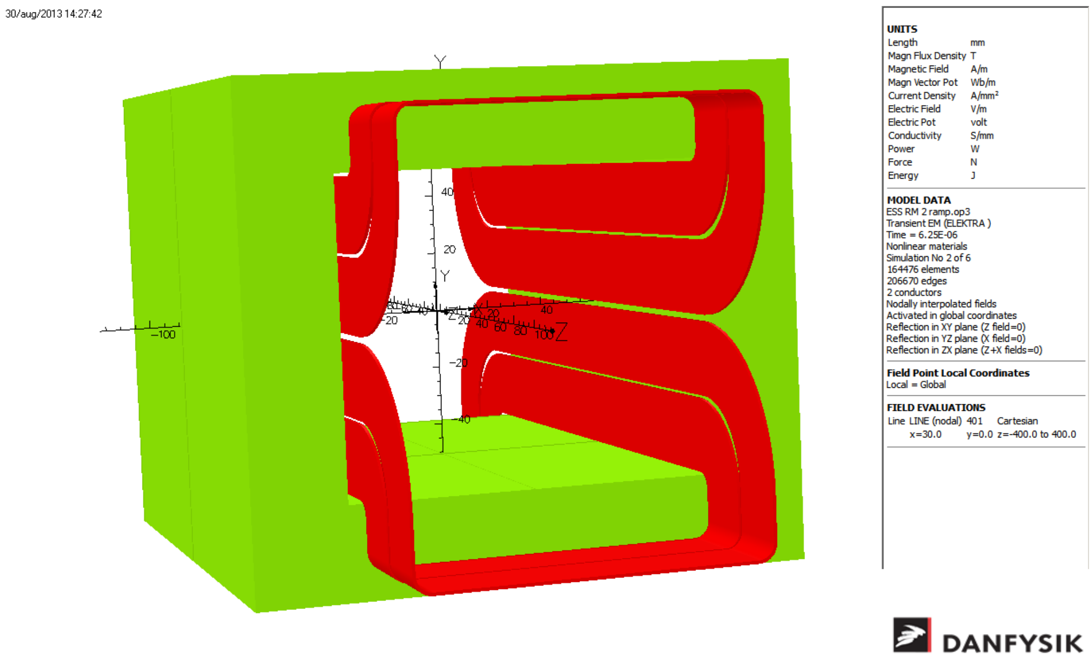


Figure 3. The 3d model.

The 3D model was made without any shimming of the poles(close to the coil), the analysis show that there is no need for shimming, see also Figure 4 below.

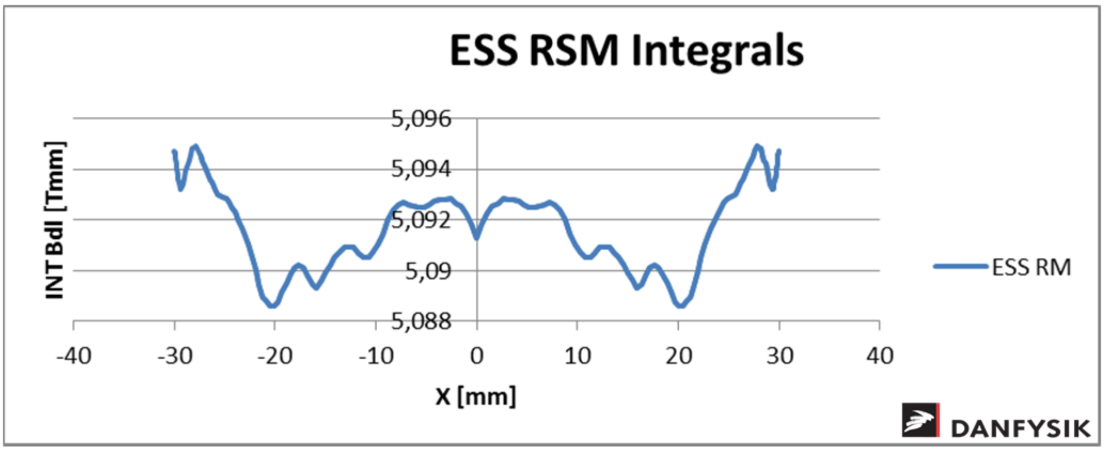


Figure 4. Field integrals on R=30mm.

2.4 Power and Thermal load on the coils

The maximum instant peak power in the magnet is 250W at I=342Amp. The triangular current shape reduce the power by a third, the average power is 83W. The duty is 3.57ms and 14Hz repetition gives 4W. The 2D transient calculation suggests there is an additional 60% power loss in the coils which includes eddy current losses and unevenly distributed current. The total power loss in the magnet is 7W. This load can be dissipated through air convection, there is no need for additional cooling. The 40 kHz scanning rate is not a limit and the frequency could be twice.

The 2D calculations also show that the force on one coil section in the magnet gap is <2N. The coil is not self-supported by itself but must have reinforcement. It is suggested to include G11 plates (glass fiber epoxy) within the epoxy impregnation that can be used for coil support. The epoxy should be radiation resistant and alumina charged to improve its resistance and thermal conductivity.

2.5 Ceramic Vacuum Chamber

A long circular ceramic vacuum chamber is proposed. Ideally the ceramic length should include two magnets and their fringe fields. However the fringe fields reach far out from a large magnet gap and a compromise should be made. Since the two magnets have same polarity they can be close. It is suggested to have 120mm separation (yoke to yoke) between the two magnets. Then a ceramic length of 860mm can be used, which is commercially available (Friatec, Germany). The ceramic thickness can be no less than 5mm. The transition to stainless steel Conflat flanges is made with a NiFe alloy(Kovar), brazed to the ceramic and welded to the flanges. The ceramic interior may have a Ti coating (a few hundreds nm) to avoid charge build up by the beam and reduce RF leaking.

2.6 Diagnostic Bdot

A Bdot loop can be included in the magnets for diagnostics. There are several options to achieve this. A single wire loop around one return ferrite, a loop around one coil or a loop insert in the magnet gap.

3 Magnet Power Supply Specification

3.1 MPS Output data

Output current: ±340A pp, adjustable 10%<Io<100% local or remote set able with an accuracy better that 0.5%.
Output voltage: ±650V pp @ 30m cable & ±575V pp @ 20m cable, adjustable from 50 to 750V
Output frequency: 40 KHz (increased specification from 20 KHz)
Output accuracy: ±1% Calculated from peak value including DC asymmetry. This include also accuracy and stability
Duty cycle: 5%
Pulse duration: 3½ms
Pulse repetition: 14Hz
Efficiency: >65%
Cooling: Air cooled

3.2 Load data

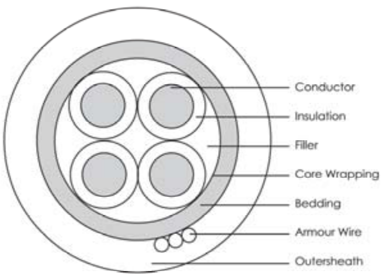
Magnet inductance: 6.6µ
Magnet resistivity: 2mΩ
Cable length: 20m or 30m between MPS and RSM. Note: All parallel load cables must have exactly the same length.
Cable type: Two Draka cables FXQJ-CU EMC -35mm^2 or equal in parallel shown in Figure 5, see also section 3.2.1.
Cable resistivity: 250µΩ/m @ 31°C.for a CU cable with four paralleled 35mm2 conductors.
Note: 1 meter to and from the load equals 2 meters of total conductor distance.
Cable Capacitance: 560pF/m for two cables in parallel (Cable type dependent, must be verified)
Cable Inductance: 190nH/m for two cables in parallel (Cable type dependent, must be verified)
Skin effect on cable: Driving the cable with 40 kHz skin effects has to be taken into consideration calculating the actual cable resistance.
At 40 kHz the skin depth is $\sqrt{(2\cdot\rho/(\omega\mu))}$ = 0.33mm. With a conductor diameter of 6.7mm results in an increased cable resistance of R_{AC}/R_{DC}= 5.5. Due to each conductor is made out of minor non isolated cupper wires the actual surface is a bit higher offering a better ratio, but in other case the proximity effect will decrease the ratio. As the last two effects have a minor influence, they will not be taken further into consideration.

3.2.1 Choice of cable:

For cable between power supply and magnet different types might be considered.

I. Litz wire
II. Coax cable
III. 4 core wires

Figure 5. Possible cross section of power cable.



Ad I. Litz wire for high currents in longer lengths is hard to get. Bundling them to minimize the total cable inductive value is also very difficult.

Ad II. Coax cable for high currents is expensive and is, due to its larger diameter, difficult to bend, which may complicate the installation.

Ad III. Four core wires are available from many manufactures. Its four conductors form a sort of a quadrupole layout, which minimizes the cable inductance. Adding several four conductor cables in parallel is not only providing Litz wire benefits but also reduces the overall cable inductance.

Further calculations in this document are based on using two four conductor cables in parallel. At final design it can be investigated if an overall better solution can be achieved by adding further four conductor cables.

4 MPS system design

This chapter describes the system design of the raster scanning magnet power supply.

4.1 Operation

The scanning power supply will be designed to drive a magnet with triangle current synchronized to an external clock reference.

4.2 MPS Principle Block Diagram

In Figure 6 the MPS is described by a main principle block diagram consisting of the following blocks:

- Input converter
- Output converter
- Control electronics

Each block is detail described below.

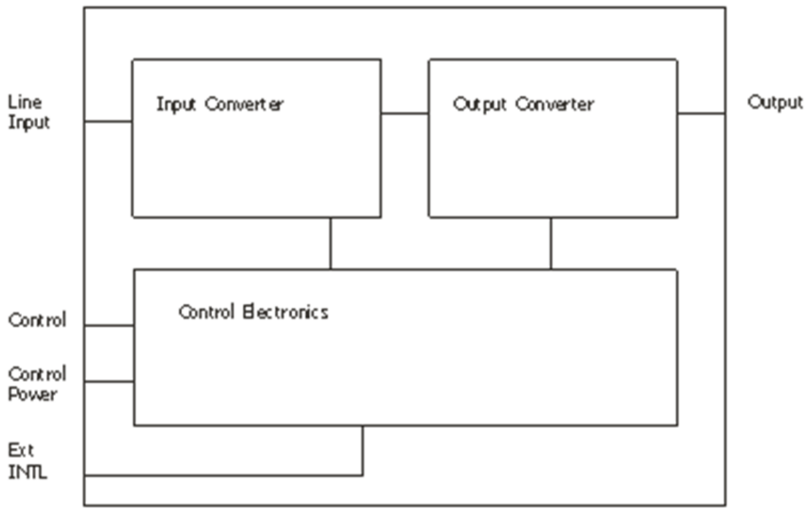


Figure 6. MPS principle block diagram

4.3 Input converter

The task of the input converter is to transform the incoming line voltage to a DC-link voltage suitable for the output
To calculate the required power demand the power losses of each major component are considered.
The required power of the input converter is expected to be:

Peak power PWPE=340·750=255KW
Power losses during pulse train:
- PW_{load} = $(340/\sqrt{3})^2 \cdot 2 \cdot 10^{-3}$=77W (Triangle current shape)
- PW_{cable} = $(340/\sqrt{3})^2 \cdot 0.25 \cdot 10^{-3} \cdot 30 \cdot 5.5$ =1590W
  (Factor 5.5 is due to the skin effect, see section 3.2)
- PW_{filter} = $½ \cdot 33 \cdot 10^{-9} \cdot 750^2 \cdot 2 \cdot 40k$=743W
- PW_{IGBT} = $(340/\sqrt{3}) \cdot 4 \cdot 2$=1570W (4=$VCE_{SAT}$)
- $\sum PW_{losses}$ = 77+1590+743+1570=3980W
Power average PW_{AV}=3980·5/100≈200W

Safety margin on the input converter size is stated later in this chapter.

The input power demand can be provided by designing the input converter as a capacitor charge power supply capable of delivering charging currents up to at least $200/750\cdot((1/14)/((1/14)-3.5\cdot10^{-3}))>280mA$.

The specification of capacitors and charge energy can be calculated as follows.
The requirement of 1% accuracy specifies that the supply voltage may not to change more than 1% or 7½V.
Drawing 3980W from the 750V requires 5.3A. With this current demand, the 7½V voltage drop and the 3½ms operation time leads to the capacitor size being calculated to $5.3/7.5\cdot3.5\cdot10^{-3}\approx2500\mu F$.
The energy drawn is $½\cdot2500\cdot10^{-6}\cdot(7502-(750-7.5)^2)\approx 14J$. This energy has to be restored before the next pulse train, which means that the capacitor charge power supply must be capable supplying $14/(1/14-3.5\cdot10^{-3})$=206J/sec. or in other terms a charging current of around 206/750=275mA (Which fits well with the previous current demand calculation above)

Sufficiently safety parameters should be added to the above calculated parameters. It is advised to add 50% for the capacitor value and 100% for the output power capability of the capacitor charge power supply.

In addition of delivering power to the DC-link, the input converter has also to perform the task of turning the main power ON and OFF and to generate an interlock if input voltage and currents are outside specified limits.

To ensure the desired peak current, the output voltage of the capacitor charge power supply must be adjustable from the control electronic. This is further described in the chapter control electronic.

4.4 Output converter

The task of the output converter is to convert the DC link power to the desired triangle shaped load current. The technique for this conversion is described below.

A conventional current regulated power supply is not suitable due to the high output frequency. An integration of the output converter with the load is therefore necessary, which is described further below.

Applying DC voltage to an inductor (inductive load) the current will increase given by the formulae $I_L=1/L\cdot\int V_L\cdot dt$ where I_L is the magnet current and V_L is the voltage across the magnet. With a constant voltage applied across the magnet the current will change linearly with time. The needed voltage can also be expressed by $V_L=L_L\cdot dI_L/dt + R_L\cdot I_L$.

With $L_L=L_{MAG}+L_{CALBE}$ and $R_L=R_{MAG}+R_{CALBE}$

$$V_L=(6.6+0.19\cdot30)\cdot10^{-6}\cdot(340-(-340))/(1/(40\cdot10^{3}\cdot2))+(2+0.25\cdot10^{-3}\cdot30\cdot5.5)\cdot340=684V$$

Note: Charge current from -340A to +340A

Note: The above calculation takes only the inductive and resistive parts into consideration, in practice internal voltage drops e.g. across the IGBT switches must be added, therefore the small difference between the above figure and the specified power supply output voltage.

The resistive voltage drop will be $I_L\cdot R_L$ or $340\cdot(2\cdot10^{-3}+0.25\cdot10^{-3}\cdot30\cdot5.5)=14.7V$, which is less than 3% of the total charge voltage and can therefore compensated with a slightly higher DC link voltage. The un-linearity this resistive value leads to have no practical influence on the raster pattern.

The power loss can be estimated as the output current times internal voltage drops added with switching and filter losses. The majority of the voltage drops is due to the IGBT's plus cable. Implementing the suggested soft switching nearly will eliminate the switching losses. The estimated power budget can be seen in chapter 4.3

With the calculated power losses of 180W air cooling is possible..

Figure 8 illustrates a proposed conceptual design of the output converter. Note the IGBT's are simulated as switches.

Due to the high switching frequency the cable must be calculated as a transmission line with the right cable parameters, and matching filters must be added to avoid ringing and reflections.

Output filter controlling the rise and fall time into the cable should also be implemented. This can be integrated in a soft switching technique reducing overall power loss.

In the circuit schematic (Figure 8) an automatic OFFSET/SYMETRY and GAIN adjustment is implemented. This is necessary due to only slightly component miss match may lead to out of specification outputs. Grate care must also be taken in start timing to avoid asymmetry.

Great care to the life time of the IGBT's has to be taken as the required pulse operation will cause thermal cycling. It is therefore suggested to use 900A IGBT's e.g. FF900R12IP4D, which can be seen on Figure 7.

Figure 7, FF900R12IP4D 900A IGBT

4.4.1 Output converter Frequency

The calculated output converter is optimized for a current triangle frequency of 40 kHz with a 3.5msec. pulse duration and a repetition rate of 14Hz.

Changing those parameters affects following other parameters:

<u>Triangle frequency</u>

- 40kHz. To 20kHz. Possible, but new DC-link voltage prediction must be given
- 40kHz. To 80kHz. Not Feasible. This would require
  - Twice the DC-link voltage
  - >2KV IGBT's (3.3KV standard) It is to be investigated, if this IGBT is able to do the high switching frequency?
  - More volume (only two MPS per rack)
  - Stronger capacitor charge supply
  - Bigger capacitors
  - Four times the power loss in filters
  - Nearly double the price

<u>Repetition frequency</u>

- >14 Hz. Possible but will require

o Stronger capacitor charge supply

- <14 Hz. Possible

Pulse train duration

- >3.5 msec. Possible but will require
  - o Stronger capacitor charge supply
- <3.5 msec. Possible

4.4.2 Output converter Simulations

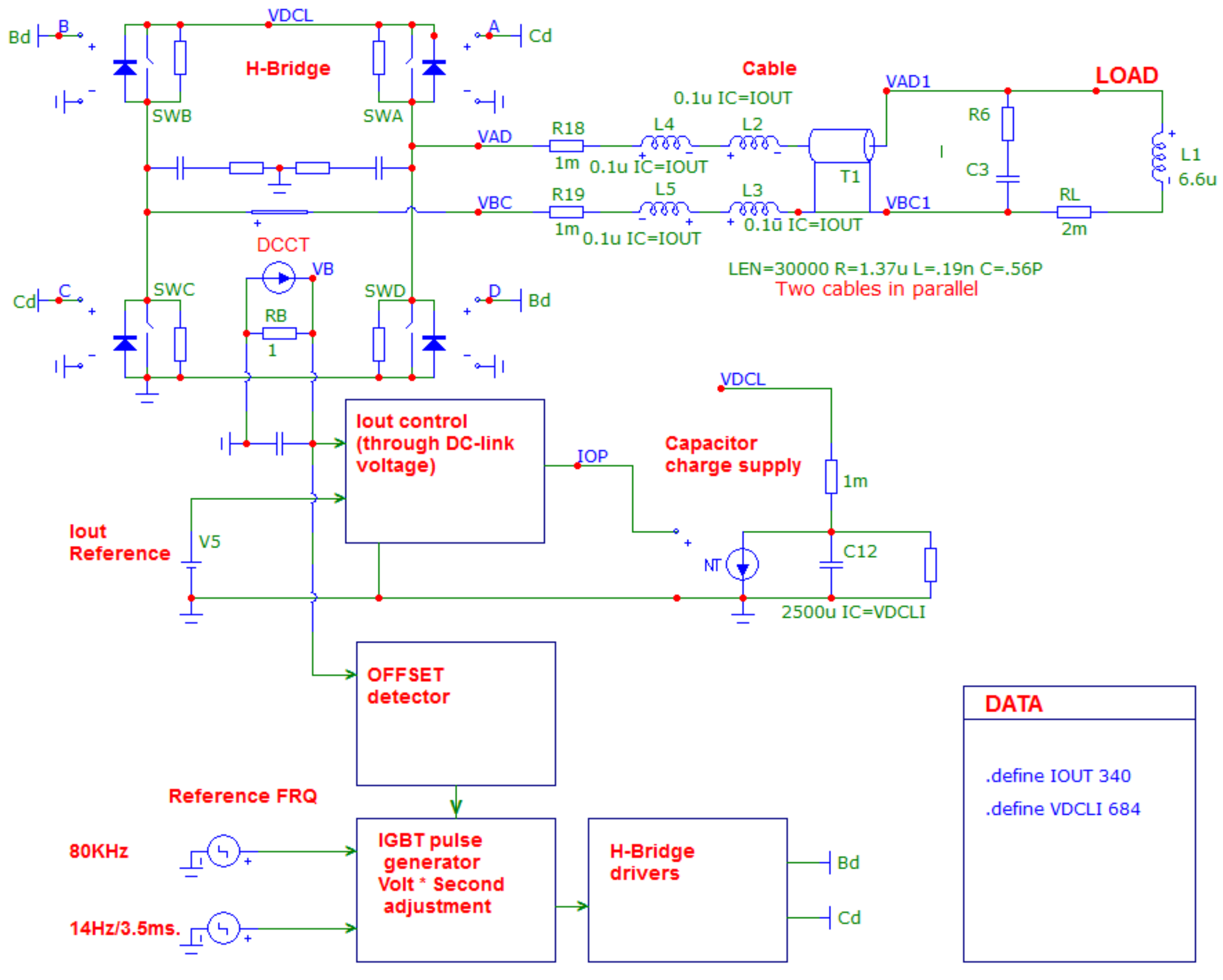


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Figure 8, Preliminary conceptual schematics of output converter

Figure 9 below shows simulation traces of the output converter. Please refer to the schematic in Figure 8 for trace references.

Be aware of the unavoidable distortion at the triangle top and bottom due to the cable transmission behavior.

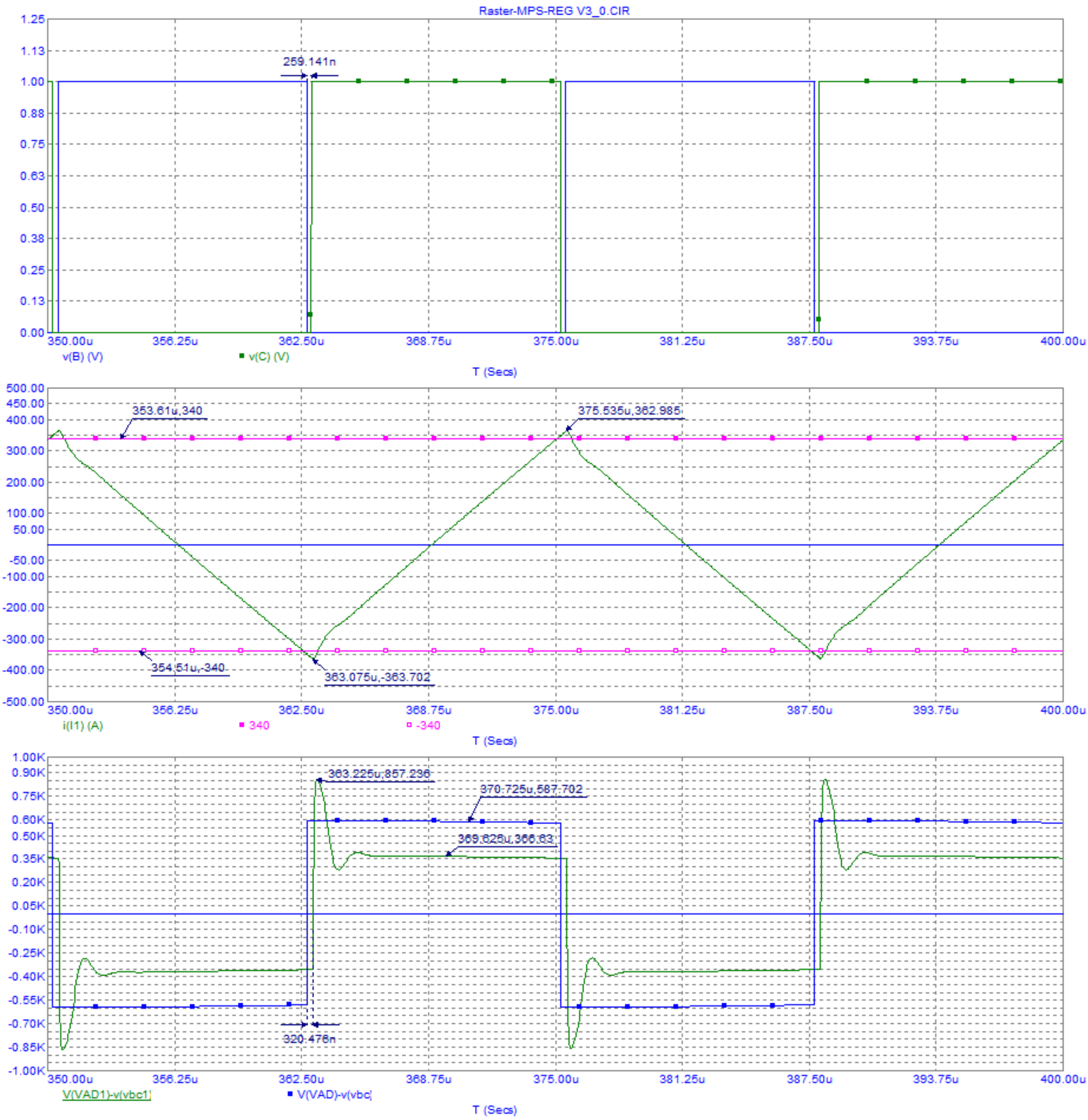

Figure 9. Simulation results

4.5 Control Electronic

The control electronic can be divided into two major blocks

1. User control, parameter supervision and interlock handling
2. Regulation control

4.5.1 User Control

The user control circuit must support both locally and remotely operation to turn the power supply ON and OFF, read status, interlocks and parameters and to set the peak output current within a certain range. For better service as many as possible status and interlock signals must be provided.

Following user control signals must be provided:

- 80 kHz clock reference through a fast and noise insensitive fiber optics transmission. (Twice the triangle frequency.)
- 3.5 msec. pulse with a repetition rate of 14Hz through a fast and noise insensitive fiber optics transmission. (Pulse train duration)
- RS-xxx or Ethernet communication

A more detail specification on the user control circuit has to be described at later stage.

4.5.2 Regulation Control

Due to the high frequency it is not possible to control the triangle pulse shape on the fly. After applying the DC-link voltage onto the load then the current wave form is only shaped through physical laws by the load and the cable parameters. Two things though can be slowly regulated.

1. Output Peak current
2. Output current DC offset (symmetry)

1) The DC link voltage sets the peak output current given that the load parameters and the frequency are constant.
   Adjusting the output current can therefore be made by adjusting the DC-link voltage thereby ensuring the next current pulse train peak values to be more accurate.
   A feed forward regulation scheme can provide a new DC-link-voltage set value to the capacitor charge supply after each pulse train. The new and next set value is calculated by an FPGA digital control circuit based on the measured peak currents during previous pulse train. After some pulse train the desired peak value will be achieved within specification.

2) To ensure that the DC offset current through the magnet is zero then the positive volt second product must be equal to the negative. Skew due to delay times in IGBT's and control circuits may quickly generate a DC offset. The peak symmetry must be measured and the difference adjusts the positive volt time second product of the square wave. It will take few pulses before the symmetry is within specification.

The used cable length must be known to the FPGA for a quicker feed forward prediction to the digital regulation loop.

4.6 RSM-MPS Block Diagram

Figure 10 to the right shows a more detail block schematic of the Raster Scanning power supply.

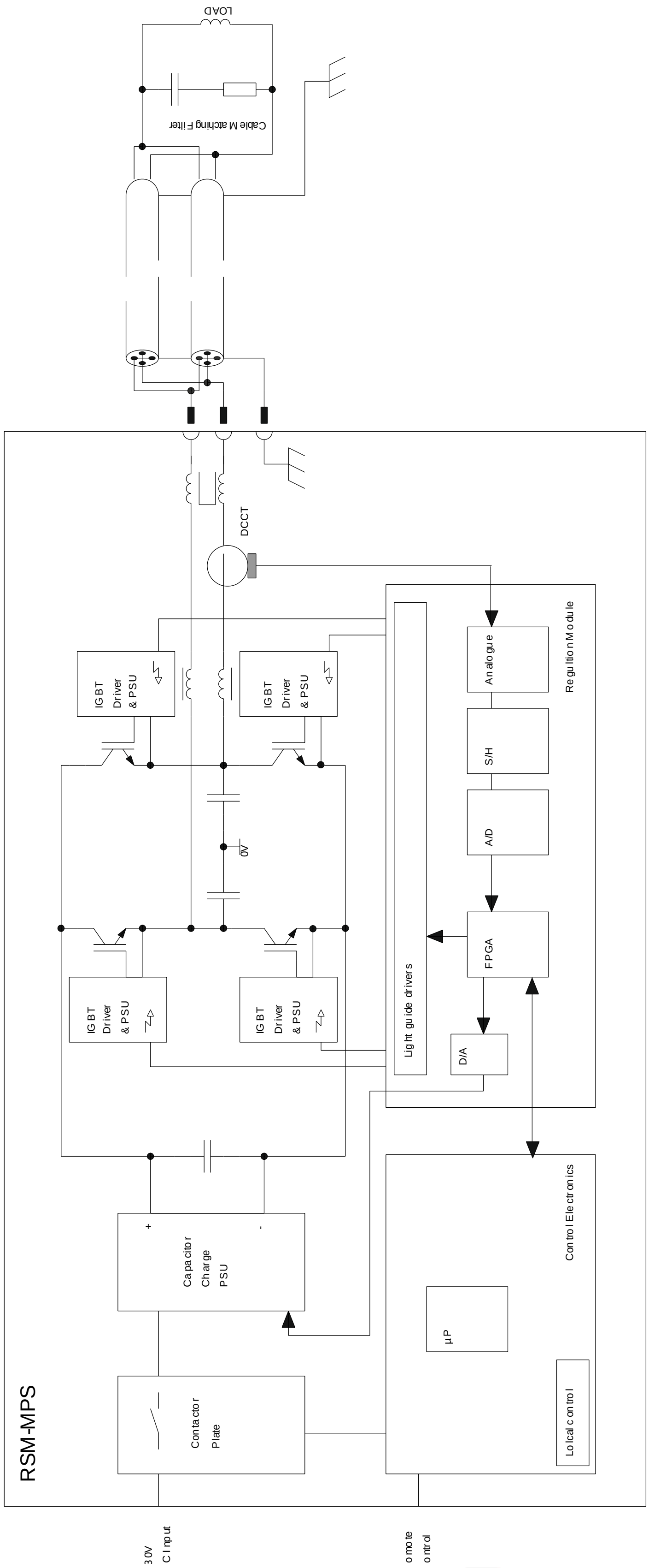

Figure 10, block schematic of the Raster Scanning power supply

4.7 RSM-MPS Mechanical layout

The RSM-MPS can be built in in a 19” rack system containing four power supplies.

Each power supply consists of three 19” units containing following elements:

- Control Electronics with local control 2U height
- Input and Output converter 4U height
- Charge power supply 2U height

Access to the power supplies and the connections between the elements is from the back of the cubicle.

5 Summary

A preliminary conceptual design study has been performed for a raster scanning magnetic system to be operated at 40 kHz for scanning a proton beam ranging from 0.6 to 2.0GeV including future upgrade to 2.5GeV. The main focus has been on the technological feasibility on realizing magnets and magnet power supplies. The aim of this study has been to evolve conceptual designs of magnet system and magnet power supply for a raster scanning system. The study has not considered how the proposed concepts can be produced. It is recommended to make a pilot system to disclose modifications required for producing the required system and to prove long term stability.

A proposal for Raster scanning magnets have been evolved for the required operational and magnetic specifications. NiZn ferrites have been selected for yoke material to comply with operational frequency and a special coil design has been evolved amongst others to facilitate maximum aperture and maximum reduction of eddy current. The 40 kHz scanning rate is not a limit for the magnet.

The Magnet Power Supplies can be realized to operate the proposed magnet system for the given specification. The proposal reveals realization to be far more complex than a traditional DC or slow ramping power supply used traditionally in particle accelerators, but applying the latest achievements for power devices (IGBT’s) and FPGA digital control a solution will be within reach of realization. A study has been performed on possible cable types and characteristics for initially to select a feasible cable type. The result of this study has been taken into account when simulating the proposed concept.