A TWO HARMONICS CIRCUIT FOR THE POWERING OF THE VERY FAST RCS (RAPID CYCLING SYNCHROTRON) OF THE MUON COLLIDER ACCELERATOR*

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Abstract

This paper analyses the application of a two harmonics circuit with additional active filter for the powering of the four RCS stages of the muon acceleration to the ultimate 10 TeV energy level.

INTRODUCTION

Acceleration for a muon collider needs to be extremely fast to ensure efficient transmission of the decaying beams, with acceleration times ranging from hundreds of microseconds to few milliseconds. One of the proposals for such a machine is centered around a rapid cycling synchrotron (RCS), a hybrid lattice of cells with alternating superconducting and resistive dipole magnets. Resistive magnets will swing from negative to positive field level (more than 3600 T/s), while the superconducting magnets provide a field offset. The resistive magnets need to be supplied with extremely high peak power levels, in the order of few tens of GW, to provide the necessary magnetic field variations. A preliminary configuration for the RCS involves the use of four rings to accelerate muons from an initial energy of 63 GeV to a final energy of 5 TeV (Table 1). There are many examples where RCS are used for the production of high intensity proton beams. These include facilities such as BESSY II in Berlin, ISIS in Oxford, Desy II in Hamburg, and others. In such systems, the Bref has a pure sinusoidal shape and the acceleration is performed during the period corresponding to half a sinusoidal portion with a frequency ranging from a few Hz to few tens of Hz (see Fig. 1 blue curve). The resonant circuits employed in these applications are predominantly continuous, with the "White circuit" being one of the most well-known and widely utilized topology [1].

Nevertheless a quick look at Fig. 1 is sufficient to realize that in the case of the muon accelerator it is not possible to use a continuous resonating scheme like the "White" circuit.

$$E_{gapB_{max}} = \frac{B_{max}^2}{2\mu_0} L_m h_{gap} w_{gap} \tag{1}$$

$$E_{totB_{max}} \approx 1.5 E_{gapB_{max}} \tag{2}$$

$$P_{max} = \frac{2E_{totB_{max}}}{\frac{T_{ramp}}{2}} \tag{3}$$

To estimate the required peak power for a linear B-field acceleration profile, one can use the preliminary design values reported in Table 1. Using Eq. (1) and (2), it is possible to estimate the total magnetic energy in the gap of a dipole magnet. B_{max} is the peak of the magnetic induction reference in the gap, L_m is the total length of resistive magnet and h_{gap}, w_{gap} are the respective gap dimensions. The total energy stored in the magnet is typically 1.5 to 2.5 times this value, depending upon its design (Eq.3 with T_{ramp} equal to the time to go from $-B_{max}$ to $+B_{max}$).

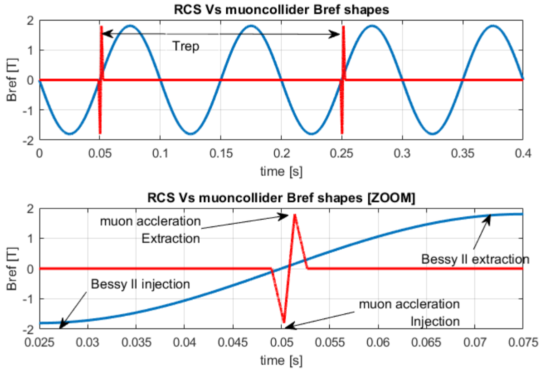

Figure 1: "Standard" sinusoidal shape RCS vs muon collider acceleration. The DC component of the BessyII circuit has not been represented here.

Table 1: RCS Tentative Dimensioning for 10 TeV CoM collider [2]

Parameter	**RCS1**	**RCS2**	**RCS3**	**RCS4**
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
Res. mags Lm [km]	3.65	2.54	4.37	20.38
Binj in gap [T]	0.36	-1.8	-1.8	-1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	100	100
Dipoles Gap h [mm]	30	30	30	30
Dipoles Egap@Bext [MJ]	14.1	9.8	16.9	78.8
Dipoles Etot@Bext [MJ]	21.2	14.7	25.3	118.2
Dipoles Pmax [GW]	121	54	43	74

In the ideal scenario where there is a perfectly linear ramp (see Fig. 1 red curve), Eq. (3) can be utilized to calculate the peak power that must be provided to the magnets. Results of the calculation for each RCS are presented in Table 1. The calculated peak power values are extremely high and have an impact on the possible topologies of the powering system and also on optimization of the acceleration profile.

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In the following paragraphs, we explore the different ways in which the Bref can be shaped and the resulting impact on the dimensioning of the powering system. The proposed power converter topology consists of a two-harmonics resonant circuit with the addition of an active filter (AF), as shown in Fig. 5. In this circuit, the magnetic field is generated through the joint action of a free discharge from both first and second harmonic branches, complemented by the action of an active filter connected in series.

SHAPING THE MAGNETIC FIELD REFERENCE RAMP

To investigate the effects of the reference field shape, we developed a program that generates Bref as a sum of algebraic functions. Specifically, we selected a sequence of sinusoidal, parabolic, cubic, parabolic, and sinusoidal functions, which we collectively refer to as the SPQPS reference. The three main parameters, or variables, defining Bref are illustrated in Fig. 2 and include:

- Brefdot -> derivative at Inj and Extr
- Bmax->Max and min values of Bref
- Tpre->pre-oscillation time

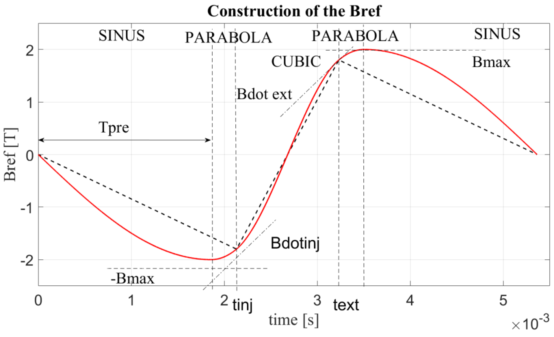

Figure 2: Construction of the Bref using the three parameters

Once these parameters are fixed, the program automatically calculates the parameters of the resonating circuit required to generate the SPQPS Bref, as shown in Fig. 2. These parameters include:

- $C1, C2, L1$: The circuit components values
- v_{C10}, v_{C20}: The initial conditions for C1 and C2
- v_{AF}: The contribution of the Active Filter

Figure 3 provides an example of the effects of changing the Brefdot $k\frac{B_{ext}-B_{inj}}{t_{ext}-t_{inj}}$ (left) and Bmax (right) parameters of the Bref shape. In both cases, the comparison is made against the same case, where the Brefdot is kept very high (k=95%) and the Bmax =1.82T. When a low Brefdot (45% in Fig. 3) is selected, the contribution of the AF is strongly reduced at the cost of a higher harmonic content in the Bref. If the Bmax is increased, a better Bref shape is obtained with a smaller cost in terms of AF power, but the peak current in the magnets is increased and saturation is reached (see middle row in Fig. 3). In Fig. 3, it is observed that variations in Brefdot and Bmax parameters result in an automatic increase in the discharge's total duration. This behavior can be attributed to the methodology employed for generating the SPQPS Bref, which aims to optimize the evolution of the free circuit to match the desired SPQPS Bref while minimizing the contribution from AF.

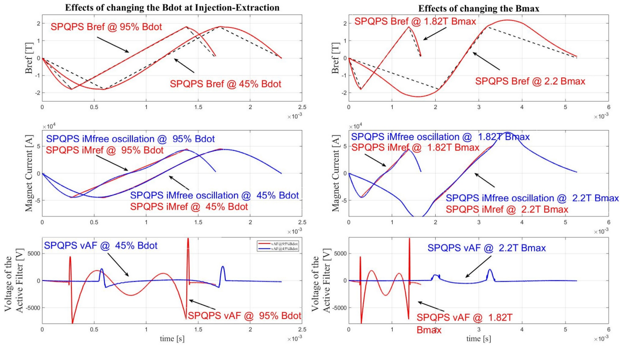

Figure 3: Left: Variation of Brefdot; Right: variation of Bmax.

The best shape for Bref not only depends upon the powering system but also strongly impacts magnet and RF design. Resistive magnets may have to support higher maximum current with consequences on losses, iron saturation, and electrodynamics forces. RF is directly impacted by the derivative of Bref, as this basically dictates the shape of the average accelerating gradient. Fig. 4 shows the comparison between a perfectly linear Bref ramping profile and one with harmonics. Although the ideal profile would be perfectly linear, a certain amount of harmonic content in the magnetic field can be tolerated at a price of an increased peak RF voltage [3].

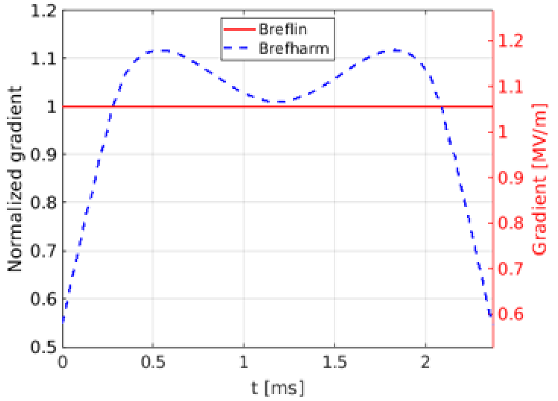

Figure 4: Comparison of RF accelerating gradient with linear vs harmonic Bref ramp.

RESONANT POWER SUPPLIES FOR FAST RAMPING RCS

Due to the high peak power required by the fast Bref, resonant power converters are a natural choice. In general, power from resonant discharge is considered much more cost-effective than that from switching power converters, which rely on an increasing number of active switching devices to condition currents and voltages. This advantage is even more pronounced when accelerating muons, due to the extremely low ramping times and high peak power involved.

Figure 5 presents the general schematic of the two-harmonic circuit, which is based on similar systems that were widely used (especially in the past) for pulsed power converters driving bumper and septum magnets [4].

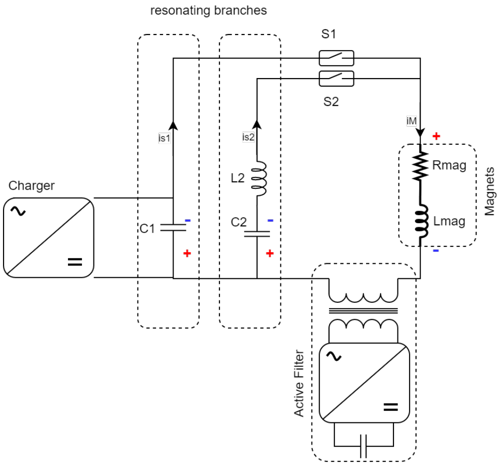

Figure 5: Proposed two harmonic resonant circuit.

The operation involves two contributions: two charged capacitor banks (C1 and C2 in Fig. 5) discharge into the magnet load, providing a fundamental and a second harmonic field. An additional power converter, the Active Filter, corrects the natural oscillation waveform to approach the desired Bref. One of the advantages of the circuit is that, after a complete oscillation, the system returns to its initial conditions. Only the losses have to be replenished by the charger before a new cycle can be executed. Furthermore, the two switches S1 and S2 can be opened with no current once the cycle is completed. Fig. 6 shows a complete oscillation cycle of the circuit. The first row compares the ideal linear Bref with the SPQPS one. The second row shows the harmonic current contribution from each branch. The third row compares the voltage across the magnets with that provided by the active filter. The fourth row shows the dynamic of the C1 and C2 capacitors voltages.

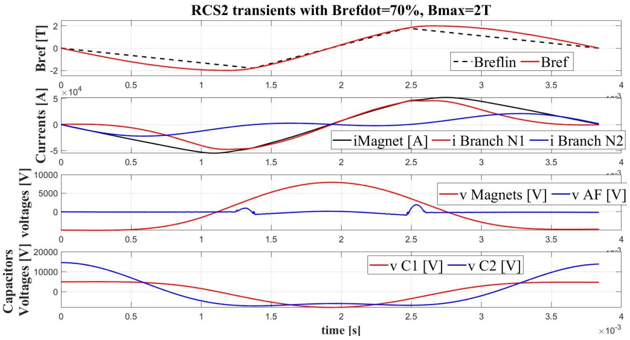

Figure 6: Full oscillation of the two harmonic circuit.

PRELIMINARY RESULTS FOR THE MUON RCSS POWERING

We have run the computer program with different values of the Bref parameters and reported the results in Table 2. The table reports two calculated cases. On the left the case where no compromises are taken on the Bref and a linear profile is pursued. On the right in underlined font, a Bdot of 70% and a Bmax of 2T are considered (simulated, for RCS2, in Fig. 6). The second case greatly reduces the power requested by the active filter even tough it requires higher energy (and cost) circuit components. The overall solution cost would most probably be smaller because resonating power is cheaper than active one. In addition the use of an higher Bmax allows the pure oscillating solution (i.e. without any active filter action) to be closer to the desired linear solution.

Table 2: RCS Tentative Dimensioning Powering System (Quantities are per Sector)

Parameter	RCS1	RCS2	RCS3	RCS4
Nsector	200	200	200	200
Mag curr [kA]	44 55	45 55	45 55	45 56
Mag power [MW]	954 437	419 193	338 155	623 280
Mag nrg [kJ]	115 141	80 98	137 165	640 758
Caps NRG [kJ]	308 274	213 192	366 337	1740 1713
L2 NRG [kJ]	97 55	67 39	115 76	524 517
AF power [MW]	839 193	358 89	290 84	680 216
caps surface [m2]	31 28	22 19	37 34	176 173
L2 surface [m2]	4 2	3 2	5 3	23 22

Table 2 also provides a rough tentative estimation of the square meter of land required for the capacitors and the L2 inductance with preliminary numbers estimated in [5].

CONCLUSION

The present work reports on the preliminary sizing of a powering system for the RCS stages of a muon accelerator. The calculations presented in this paper have been obtained using an iterative MATLAB script. Although the results are preliminary, the script provides a valuable insight into the topology, space requirements and dimensions of the individual components of the circuit. Moreover, during the course of our analysis, we attempted to evaluate a rough cost estimate of the proposed solution. Our findings revealed that the active filter plays a crucial role in determining the overall cost. Our calculations, while very approximate, suggested that exploiting the resonance at the maximum level, and leaving the role of "minor corrector" to the "classic" power electronics, could lead to a more cost-effective solution. Further research is necessary to gain a better understanding of the active filter's topology and the optimal way to employ it. Additionally, alternative powering schemes should be investigated to strike the right balance between the overall cost and the harmonic content of the magnetic field reference.

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