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THE MAIN MAGNET POWER SUPPLY FOR AN ION RAPID CYCLING MEDICAL SYNCHROTRON

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Abstract

The ion Rapid Cycling Medical Synchrotron (iRCMS) collaboration is proposing to build a state-of-the-art proton and carbon accelerator for irradiation of cancer tumors. This paper describes the proposed Main Magnet Power Supply of the Medical Synchrotron. This power supply is a current regulated, two quadrant dc to dc converter series resonant, running at 60 Hz, and rated at 2700 Amps, +/-1000 Volts. The power supply will generate a current of the form Im(t)=Idc-Iac cos(2 π f t), where Idc=1394 Amps, and Iac=1050 Amps. The current of the power supply at beam injection is about 360 Amps and the current at extraction is about 2500 Amps. Six capacitor banks will be used in series with the 24 magnets of the Synchrotron, one capacitor bank for every four magnets. Also six bypass chokes will be used in parallel with the capacitor banks, necessary to bypass the dc current around the capacitor banks. This resonant power supply is the most economic system, where energy can be exchanged between the magnets and capacitors, with the power supply providing the losses.

THE MAIN MAGNETS

The circumference of the proposed iRCMS, is 53.56 meters. The main magnets will be combined functioned magnets and the total number of magnets will be 24. It is proposed that originally this Synchrotron will run at 30 Hz, expandable in the future to 60 Hz. As a result the magnets and the power supply should be designed to run at both frequencies 30 and 60 Hz with minimum future modifications. Four magnets will be built using the same girder, creating a module. The total number of modules will be 6 as shown in Figure 1. The total magnetic length of a 4 magnet module will be approximately 6 meters long. There are 2 different designs of the main magnets currently being investigated, regarding power losses and optimum cooling. An 8 turn per pole magnet, and an 11 turn per pole magnet. Both designs are air cooled. The maximum current of the 8 turn per pole magnet, will be 2444 amps and the maximum current of the 11 turn per pole, magnet, will be 1745 amps. It was calculated that the inductance of the 8 turn per pole 4 magnet module, was approximately 8.25 mH and the inductance of an 11 turn per pole 4 magnet module, was approximately 15.5 mH.

THE POWER SUPPLY

The power supply will generate a current of the form Im(t)=Idc-Iac cos(2 π f t), where Idc=1394 Amps, and Iac=1050 Amps for the 8 turn per pole magnet design and Idc=982 Amps, and Iac=764 Amps for the 11 turn per pole magnet design. Based on this it was determined that a conventional current regulated power supply connected in series with the 24 magnets, of the 8 turn per pole type, would require +/-10 KV for 30 Hz operation and +/-20 KV for 60 Hz operation. As a result a resonant power supply was chosen because the voltage required, as it will be shown, was approximately +/- 300 volts for the 8 turn per pole magnet design at 30 Hz, and +/- 500 volts at 60 Hz. These voltages for the 11 turn per pole magnet design, were calculated to be +/360 volts for 30 Hz operation, and +/650 volts for 60 Hz operation. A block diagram of the resonant power supply and the magnet connections is shown in Figure 1.

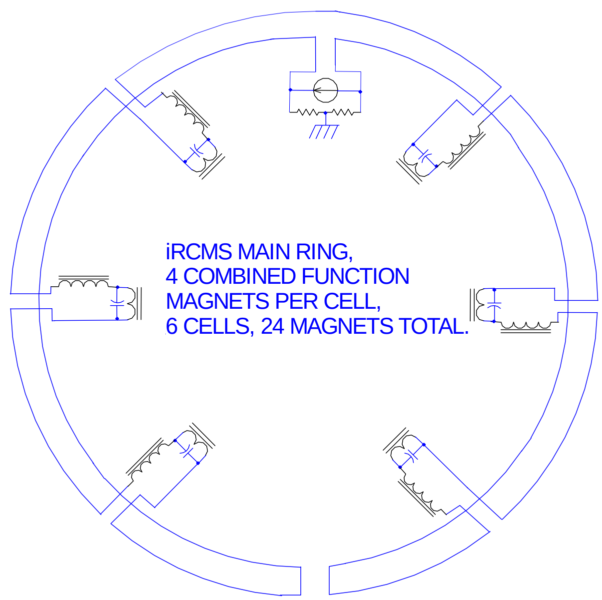

Figure 1: Power supply, magnet cell, block diagram.

There is a capacitor bank in series with a 4 combined function magnet module, and a choke in parallel with the capacitor bank. Since the required magnet current has a dc offset, the choke is used to pass the dc magnet current to the next 4 magnet module. Based on information we have from power supply manufactures, we could use one power supply with the power electronics specified for higher voltage to be able to run at 60 Hz for an additional 10% higher cost from the beginning. This power supply would run at 30 Hz originally, and later to run it at 60 Hz, we could replace only the transformer. If however the budget is very tight at the beginning, then we first specify one power supply for 30 Hz operation and later we purchase another supply connected in series with the first one, so we could run at 60 Hz. The equivalent circuit of one, 4 magnet cell is shown in Figure 2.

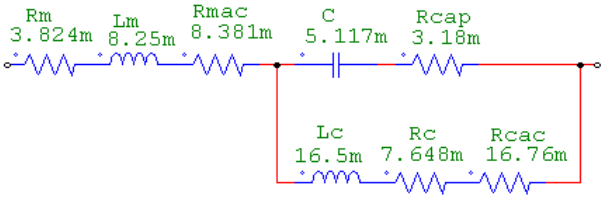

Figure 2: Four magnet cell for 30Hz

Rm is the dc resistance per 4 magnets. Lm is the inductance of the 4 magnet cell. Rmac is the ac resistance per 4 magnets due to copper, core and beam pipe, Eddy current losses, at 30 Hz. C, is the capacitance of the capacitor bank for every 4 magnets, to resonate at 30 Hz. Rcap is the ac resistance of the capacitor. Lc is the inductance of the choke. Rc is the dc resistance of the choke. Rcac is the ac resistance of the choke due to Eddy current losses at 30 Hz. The transfer function of the four magnet cell G(s), is given by the formula,

$$G(s) := \frac{\left(\frac{1}{s\cdot C} + Rcap\right)\cdot(s\cdot Lc + Rc + Rc\_ac)}{s\cdot Lc + Rc + Rc\_ac + \left(\frac{1}{s\cdot C} + Rcap\right)} + (s\cdot Lm + Rm + Rm\_ac)$$

We know that, for a current regulated supply driving a four magnet cell, 1/G(s)=I(s)/V(s) in Laplace transform. I(s) is the power supply current, V(s) is the power supply voltage. Also we know that Y(f)=20log(1/G(f)) is the gain of the transfer function 1/G(f). Figure 3 shows the gain of the transfer function 1/G(f) of the 4 magnet cell.

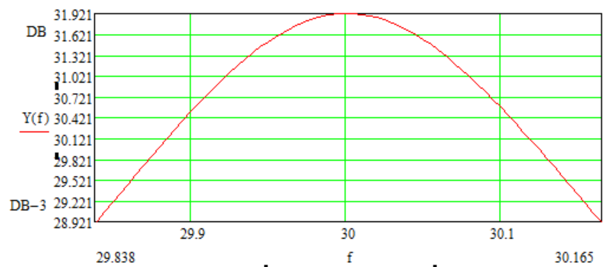

Figure 3: Four magnet cell 1/G(f), Gain in db around 30Hz

Note that the Q of the four magnet cell is given by the formula Q=30/(30.165-29.838) and it is equal to 91.7.
Also the gain and phase, of the four magnet cell 1/G(s) transfers function, is shown in Figure 4. The power supply current and voltage, driving 6 four magnet cells as shown in Figure 1, are shown in Figure 5. Vrps(t) is the power supply voltage and Ima(t) is the power supply current.

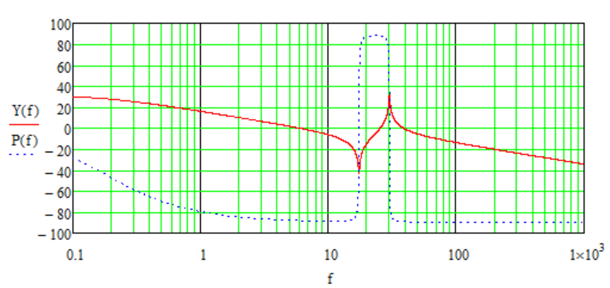

Figure 4: Four magnet cell 1/G(f), Gain in db, and Phase in degrees, 30Hz

This is the power supply needed to drive the main magnets of the iRCMS at 30 Hz, with the 8 turn per pole magnet design. Based on this, it seems that a 0 to 2600 amps +/- 300 volt, two quadrant switch mode power supply should be adequate. The specification of the current regulation of such a supply is 0.1%.

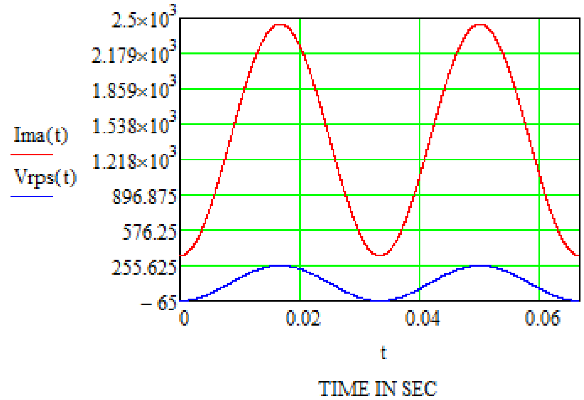

Figure 5: PS voltage and current 30 Hz, 8 turn per pole magnet.

It was calculated that the inductance of the 4 cell magnet, will be changing from 8.4 mH to 8.1mH from 318 amps to 2444 amps respectively. As a result the inductance chosen to resonate at 30 Hz was the midpoint of 8.25 mH. This way the power supply should have enough voltage not to come out of resonance. The voltage drop across the four magnets is shown in Figure 6.

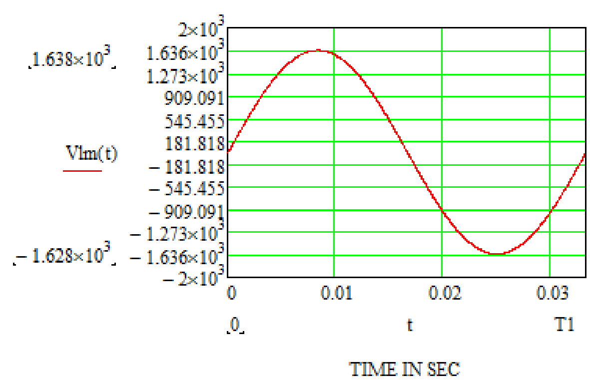

Figure 6: Four magnet module voltage drop in Volts, 30Hz

Based on this, the maximum voltage to ground any magnet can see will be 1638 volts, with the power supply grounded in the middle.

PARAMETERS FOR 30, 60 HZ OPERATION

Tables 1,2,3 show all the parameters for 30 and 60 Hz operation based on the magnet type.

Magnet	Lm(mH)	Lc(mH)	Rm(mO)	Rc(mO)	Rmac(mO)	Rcac(mO)	C(mF)	Rcap(mO)
30HZ,8 turns/pole	8.25	16.5	3.824	7.648	8.381	16.762	5.1175	3.13
60HZ,8 turns/pole	8.3	16.6	3.824	7.648	24	48	1.2717	6.27
30HZ,11 turns/pole	15.5	31	8.124	16.248	9.467	18.934	2.7238	5.88
60HZ,11 turns/pole	15.5	31	8.124	16.248	38	76	0.681	11.72

Table 1:

Magnet	Icap_peak(A)	Ick_peak(A)	Q	Vcap(V)	Vmag_ac(V)	Vmag to grnd(V)
30HZ,8 turns/pole	1573.997414	1919	92	1632.015	1632.015	1632.015
60HZ,8 turns/pole	1573.496301	1919	85	3283.812	3283.812	3283.812
30HZ,11 turns/pole	1144.306452	1363.6	111	2229.86472	2229.86472	2229.86472
60HZ,11 turns/pole	1144.306452	1363.6	92	4459.72944	4459.72944	4459.72944

Table 2:

Magnet	Imag_peak(A)	PS(+/-V)	PS (A)	PS (Kwpeak)	E_Cap(Jules)
30HZ,8 turns/pole	2444	400	2600	1040	6815.205852
60HZ,8 turns/pole	2444	600	2600	1560	6856.510129
30HZ,11 turns/pole	1745	475	1900	902.5	6771.891155
60HZ,11 turns/pole	1745	730	1900	1387	6771.891155

Table 3:

Icap_peak, is the capacitor bank peak current. Ick_peak, is the choke peak current. Imag_peak, is the peak magnet current. Q is the Q of the system. Vcap, is the capacitor peak voltage. Vmag_ac, is the peak ac voltage of the 4 magnet module. Vmag to grnd, is the maximum voltage to ground of a 4 magnet module. PS(+/-V), is the maximum and minimum power supply voltage. Note 150 volts have been added to calculated power supply voltages for regulation, and resonant drifts, due to capacitance, inductance variations. PS(A), is the maximum power supply current. PS(Kwpeak), is the maximum power supply power in KW. E_Cap, is the energy of the capacitor bank. All the parameters of Tables 2 and 3 are based on two different types of simulations, one using MathCAD 14 software, and two using a simulation program called PSIM 9.0. Note that the power supply needed to run the 8 turn per pole magnet design at 30 Hz would be rated at +/-300 Volt, 0 to 2600 Amps, and to run at 60 Hz it would be rated at +/-500 Volts, 0 to 2600 Amps. Also the power supply needed to run the 11 turn per pole magnet design at 30 Hz would be rated at +/-360 Volt, 0 to 1900 Amps, and to run at 60 Hz it would be rated at +/-650 Volts, 0 to 1900 Amps.

PROTOTYPE RESULTS

A prototype was made using a bipolar current regulated supply rated at +/-50 volts, +/-25 Amps. This supply drove a magnet cell similar to the one shown in Figure 2, at 60 Hz. The cell parameters were Rm=415mOhms, Lm=23mH,Rmac=0.67Ohms,C=0.613mF,Rcap=14.3mOhms,Lc=23mH,Rc=415mOhms,Rcac=0.67Ohms. Figure 7 displays the power supply voltage and current at 60 Hz. Figure 8 displays the measured gain of the open loop transfer function of the supply. Note the phase of the open loop transfer function never exceeded -90 degrees. The bandwidth of the closed loop transfer function, for the current regulated supply was measured to be 340 Hz. It was observed as expected, that changing the current frequency for a fixed resonance, the power supply voltage was increasing. Thus it is important, that if we keep the current frequency constant for the iRCMS supply, to have enough voltage from the supply, to compensate for inductance, capacitance drifts.

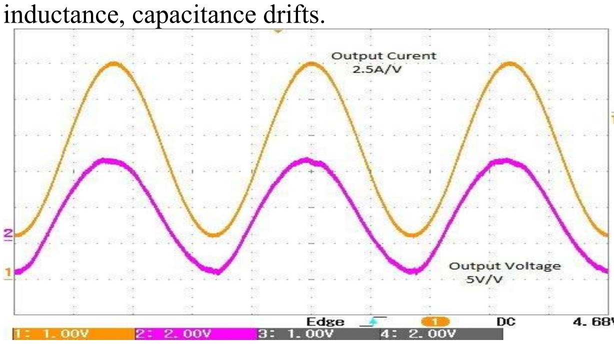

Figure 7: Prototype power supply voltage & current

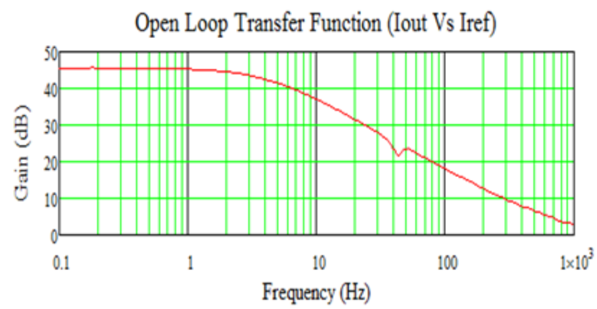

Figure 8: Current gain of PS open loop transfer function.

CONCLUSION

It seems that based on the above simulation and prototyping such a system is realizable. The Fermi Lab Booster Synchrotron main magnet power supply is of similar topology as the proposed one, for iRCMS, running at 15 Hz. There are however, some issues we need to address. Simulations show that the inductance of the 4 magnet module is moving as a function of current. It will be changing from 8.4mH to 8.1mH from the lowest current to the highest respectively. We need to simulate this using a variable inductor as a function of current, to better understand the power supply voltage requirements. Also the calculated Q of our system varies from 92 to 111 based on the magnet design. We need to make a prototype magnet and run it at resonance for both 30 and 60 Hz, so we can study any unexpected problems.

ACKNOWLEDGMENTS

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