mu2e 2427
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Optimization of RF Modulated Magnets for Secondary Extinction 2

Abstract: I discuss the relative advantages of different frequency operation of the radio frequency modulated magnets (aka AC dipoles) for the mu2e extinction channel and a plan to optimize the beam.

Doc-db 1063-v1, *Optimization of RF Modulated Magnets for Secondary Extinction*, presented a two-frequency (at 2 and 3 times the bunch frequency) magnet system that satisfies the physics objectives of the RF modulated magnets in the extinction insert. That memo lists some advantages of the system relative to the Fermilab scheme with magnets operating at 1/2 and 17/2 times the bunch frequency.

1. Relatively small frequency range with similar power at each frequency.
2. Ability to use each magnet in a modular system at either frequency.
3. Reduced peak voltage with respect to the Fermilab scheme.
4. Lower power dissipation than in the Fermilab scheme.
5. Probably identical power supplies for all magnets.

The two schemes operate with filled bunches at different points on the RFMM phase: the UCI scheme on the maximum and the Fermilab scheme on the zero field point. In the UCI case, it is likely that one or two very small trim magnets will be necessary to compensate for slow drift of the peak field; these could also be operated in a DC mode with a field integral of ~250 Gm to offset the RFMM deflection, making the two options equivalent in terms of the rest of the beam-line.

We now have a test magnet that can be operated at frequencies spanning the full possible operating range for the two schemes. This allows a much more flexible approach to optimizing the beam. For example, if a larger magnet gap is possible in one of the schemes, this would allow either more safety with respect to beam losses or a redesign of the beam to reduce costs by running the extinction insert at a higher value of β.

This note provides a tool to quantify the operating parameters (voltage, current, etc.) of the two schemes and to suggest a set of measurements that would provide input on some assumed numbers and validate the model. The actual numbers (e.g. for the magnet inductance or operating current) are likely only approximate, but the comparison of different schemes is probably quite good.

The results in the note are based on an ELEKTRA model of an RFMM for MECO. Chuan Chen, who did the study, gave a brief description of the model in a talk that is attached to this document. Briefly, the calculation assumed a particular Mn-Zn ferrite (MN8CX from Ceramic Magnetics, Inc.) optimized for the proposed frequencies and a strip-line conductor to reduce local fields in the return. The model used the ferrite material's conductivity and assumed a relative permeability of 1000, whereas the actual material had a value close to 3000 below 1 MHz, decreasing to

1000 at ~2.5 MHz. Using the actual permeability at the operational frequency would give slightly different results.

Figure 1 is from a spreadsheet that calculates the resonant circuit parameters using as input the performance of the magnet from the ELEKTRA model. The more darkly shaded cells contain the input parameters; others are calculated by the spreadsheet. The essential part of the ELEKTRA calculation is determining the inductance and current required to get a given peak field. The values of these parameters for a magnet without a ferrite yoke are also given in the spreadsheet. Finally, the spreadsheet calculates the capacitor parameters to get the appropriate resonant frequency and the total real resistance for the desired Q value (100). The code and model for the ELEKTRA calculation is no longer available.

Table 1 The table is a spreadsheet that calculates the parameters of an RFMM appropriate for MECO. More heavily shaded cells are inputs; other cells are calculated. The peak current for the given geometry and field is calculated using the Elektra code.

	MECO			
Beam Parameters	**Air return**		**Ferrite return**	
Beam momentum	8000	[MeV/c]	8000	[MeV/c]
Angular deflection	0.0014	[radian]	0.0014	[radian]
Harmonic	1		1	
Harmonic	741,000	[Hz]	741000	[Hz]
Magnet Parameters				
Number of modules	5		5	
Module length	1.00	[m]	1	[m]
Module gap	0.10	[m]	0.1	[m]
Current sheet width	0.13	[m]	0.13	[m]
Module width	0.10	[m]	0.1	[m]
Peak field	0.0075	[T]	0.0075	[T]
Peak current	1285	[A]	480	[A]
Peak magnetic flux Φ	0.00075	[Tm^2]	0.00075	[Tm^2]
Peak $d\Phi/dt$	3476	[Tm^2/s]	3476	[Tm^2/s]
Peak inductor voltage				
Module Inductance	5.81E-07	[H]	1.56E-06	[H]
Maximum stored energy	0.48	[J]	0.18	[J]
Maximum stored energy	0.4797		0.1792	
Skin depth	7.66E-05	[m]	7.66E-05	[m]
Bulk resistivity	1.72E-08	[Ωm]	1.72E-08	[Ωm]
Conductivity	5.81E+07	[$\Omega^{-1}m^{-1}$]	5.81E+07	[$\Omega^{-1}m^{-1}$]
Resistivity	2.25E-04	[Ω/square]	2.25E-04	[Ω/square]
Resistance	0.0018	[Ω]	0.0018	[Ω]
Permeability	1.26E-06	[H/m]	1.26E-06	[H/m]
Capacitor Parameters				
Required capacitance	7.94E-08	[F]	2.97E-08	[F]
Permittivity	8.85E-12	[F/m]	8.85E-12	[F/m]
Gap	0.005	[m]	5.00E-03	[m]
Area	44.9	[m^2]	16.8	[m^2]
Maximum stored energy	0.48	[J]	0.18	[J]
Resistor Parameters				
R_{eff} for Q=100	0.0043	Ω	0.0115	Ω
Dissipated power for Q=100	3555	W	1328	W
	741000	Nominal bunch frequency		

To calculate operating conditions for other magnets, I have scaled the results of this model as follows. Dimensional arguments show that the inductance is proportional to the area perpendicular to the current loop and inversely proportional to the gap; this follows from treating the magnet essentially as a single turn solenoid and neglecting edge effects. Hence, we can get the approximate value of the inductance by scaling from the inductance calculated for the MECO version. By equating the energy expressed in terms of the inductance and current ($E = ½ LI^2$) and in terms of the magnetic field and volume ($E = ½ B^2V$), we can then calculate the current for any value of the field. Once the current and inductance are known, the induced EMF can by calculated from the time derivative of the magnetic flux ($\mathcal{E}=-d\phi_B/dt$). This would be the potential seen across the inductor and capacitor.

Examples of magnet operating parameters are given in Table 2. In these examples I have used a gap that is twice that proposed for mu2e in order to take a more conservative approach to beam losses and radiation damage and/or allow a higher β in the extinction region. For the UCI scheme, two magnets are run at 1.2 MHz with a peak field of 31 Gauss, and 4 are run at 1.8 MHz with a peak field of 28 Gauss, as discussed in mu2e-1063. The stored energy in each magnet is about 0.005 J and the maximum voltage across the magnet (and capacitor) is 2300 and 3100 V for the two types of magnets. The peak currents are 40 and 35 Amperes. Assuming a Q value of 100, about 80 W is dissipated in each module. If the gap is equal to that in the CDR, the peak voltage remains the same and the stored energy and peak currents are both lower by a factor of two.

For the Fermilab scheme, I assume that the two frequencies use the same total magnet length (perhaps not optimal) with peak fields given by 14 Gauss (5.1 MHz) and 236 Gauss (0.3 MHz). Again I assume a gap twice that in the CDR and calculate peak currents of 18 and 303 Amperes and peak voltage of ~4500V in each magnet. At a Q value of 100, the dissipated power is 64 W and 1074 W for the 5.1 and 0.3 MHz magnets, respectively. With the nominal gap of 1 cm, the peak currents and dissipated power would be a factor of two lower. The very large power is due to the fact that there is a very large field between pulses, this being inherent to the technique of operating with bunches on the magnets' zero crossings.

I propose that we use the prototype magnet to make the following measurements at frequencies of 0.3, 1.2, 1.8, and 5.1 MHz.

1. Peak magnetic field vs. magnet current up to whatever power is available.
2. Peak magnet voltage under the conditions as in 1.
3. Power dissipated in the circuit; allows calculation of Q.
4. Width of the resonance curve by measuring the field vs. frequency; allows calculation of Q.

The measurements should be compared to an ELEKTRA (or equivalent) model of the magnet prototype. This would allow a more reliable extrapolation to possible modifications to the magnet to optimize the beam performance.

If the magnets can be run at a full range of frequencies, the motivation for an early decision on the mode of operation is mostly to allow modifications of the beam-line

to reduce costs (i.e. with higher β) and to allow power supplies to be designed and costed.

Table 2 The table is a spreadsheet that calculates the parameters of RFMMs that are appropriate for mu2e. The values are scaled from those calculated with an Elektra model of one of the models proposed for MECO. The shaded cells are entries. In this example, I have chose a gap that is twice that proposed for mu2e.

	mu2e				
Beam Parameters	UCI 1	UCI 2	FNAL high	FNAL low	
Beam momentum					
Angular deflection					
	2	3	17/2	1/2	
Frequency	1200000	1800000	5100000	300000	
Magnet Parameters					
Number of modules	5	5	5	5	
Module length	1	1	1	1	input parameter
Module gap	0.02	0.02	0.02	0.02	input parameter (twice the fermilab value)
Current sheet width	0.13	0.13	0.13	0.13	not relevant (only for calculating real resistance)
Module width	0.1	0.1	0.1	0.1	width in bend plane
Peak field	0.0031	0.00275	0.0014	0.0236	input parameter
Peak current	40	35	18	303	calculated from inductance and stored energy
Peak magnetic flux Φ	0.00031	0.00028	0.00014	0.00236	calculated from width, length, field
Peak dΦ/dt	2337	3110	4486	4449	calculated from frequency, peak magnetic flux
Peak inductor voltage	2337	3110	4486	4449	calculated as L dI/dt (check)
Module Inductance	7.78E-06	7.78E-06	7.78E-06	7.78E-06	scaling from meco
Maximum stored energy	0.0062	0.0049	0.0013	0.3580	scale from meco w ferrite, B^2*V = 0.5LI^2
Maximum stored energy	0.0062	0.0049	0.0013	0.3580	0.5*L*I^2
Skin depth	7.66E-05	7.66E-05	7.66E-05	7.66E-05	from meco, unchanged
Bulk resistivity	1.72E-08	1.72E-08	1.72E-08	1.72E-08	from meco, unchanged
Conductivity	5.81E+07	5.81E+07	5.81E+07	5.81E+07	from meco, unchanged
Resistivity	2.25E-04	2.25E-04	2.25E-04	2.25E-04	from meco, unchanged
Resistance	0.0017	0.0017	0.0017	0.0017	from meco, unchanged
Permeability	1.26E-06	1.26E-06	1.26E-06	1.26E-06	from meco, unchanged
Capacitor Parameters					
Required capacitance	2.26E-09	1.01E-09	1.25E-10	3.62E-08	calculated from frequency, inductance
Permittivity	8.85E-12	8.85E-12	8.85E-12	8.85E-12	
Gap	0.005	0.005	0.005	0.005	
Area	1.3	0.6	0.1	20.4	
Maximum stored energy	0.006	0.005	0.001	0.358	
Resistor Parameters					
R_{eff} for Q=100	0.0933	0.1400	0.3967	0.0233	
Dissipated power for Q=100	74	88	64	1074	
	600000	Nominal bunch frequency			

Additional studies of the beam performance would be very useful. One such study is to look at the beam transport downstream of the extinction insert as a function of field in the RFMM over its full range of values. This would tell us where beam is dumped as a function of time and allow a convolution of the time structure of the RFMM field with the calculated time structure of the beam into the extinction insert. This would inform both the calculation of the extinction and the calculation of radiation loads downstream of the insert. For example, it would tell us whether the very large field between pulses in the Fermilab scheme has any value in terms of

extinction performance and whether the relatively lower field in the UCI scheme presents any problems.

We propose that the UCI group can help with these studies by contributing to the magnet test setup, participating in the measurements, contributing to the modeling of the magnet, and contributing to studies of the proton beam transport.