STRAY FIELD REDUCTION OF ALS EDDY CURRENT SEPTUM MAGNETS*

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Abstract

Stray field from an eddy current septum magnet adversely affects the circulating beam and can be reduced using several techniques. The stray field time history typically has a fast rise section followed by a long exponential decay section when pulsed with a half sine drive current. Changing the drive current pulse to a full sine has the effect of both reducing peak stray field magnitude by $\sim$3x and producing a quick decay from this peak to a lower field level which then has a similar long decay time constant as that from the half sine drive current pulse. A method for tuning the second half-sine (reverse) current pulse to eliminate the long exponential decay section is given. A method for halving the remaining brief peak is also given.

DESCRIPTION

Septum magnets are used for both extraction, and injection of beam out of, or into a storage ring, respectively. They are required to produce a uniform vertical magnetic field in a region immediately adjacent to the circulating beam, while maintaining a field-free region at the circulating beam. The septum functions as the field “divider’. The eddy current septum magnet design is favored for pulsed low duty intermittent extraction/injection, in contrast to direct drive septums having (typically water cooled) coils wound around the gap only, which are favored for high duty extraction/injection (both DC and pulsed). The eddy current septum magnet consists of a low inductance drive coil wound around a C-type core back leg; this assembly is then surrounded by a highly conductive shield box, including the ends. An unshielded back-leg wound C dipole would have a large stray field with flux emanating from all exposed surfaces, not just the poletips. By using a fast drive current pulse, this stray field dB/dt generates eddy currents in the septum and backplate which closely match the drive current, in reverse direction if there is sufficient septum thickness (typically >3 skin depths). The septum and backplate thus form a one turn transformer coupled coil, the net effect being to mimic a coil wound only around the gap. The shield must, at a minimum, “band” the core/coil assembly (on the horizontal plane), constraining the stray flux from the exterior faces of the core to pass inside the band. Typically, a half sine drive current time profile from a simple capacitor discharge circuit is used. Compared to the direct drive design, the eddy current design allows a thinner septum to be used, allowing closer proximity of the septum gap field region to the main circulating beam.

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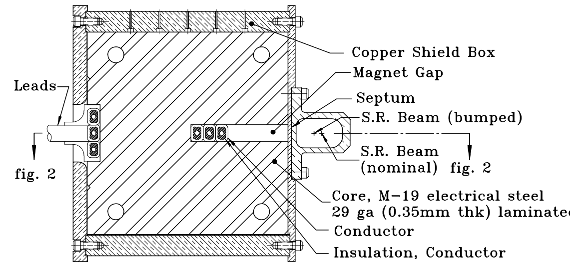

Figure 1: Thick Septum Cross-section

Stray Field Problem

The Advanced Light Source (ALS) utilizes a pair of eddy current septum magnets, a thick septum magnet, and a thin septum magnet, to extract the beam from the booster ring. A second pair, identical to the first, is used to inject the beam into the storage ring (fig. 2). The thick septum magnet[8] is a high field design (1.5 T max), with a laminated iron core, and 3 turn coil having a relatively slow 125 μsec drive current pulse (fig. 1), providing 10 deg. of bend. The thin septum magnet is a low field (0.5 T max) ferrite core magnet, with 1 turn coil, utilizing a faster 20 μsec pulse, providing 2 deg. of bend. The thin septum magnet’s faster pulse allows a thin, 1 mm thick copper septum to be used; the smaller skin depth, plus the addition of 0.5 mm of iron plating on the storage ring side of the septum prevent any significant stray field reaching the circulating beam. This is not the case with the thick septum magnet; although it has a thicker septum of 6.4 mm, a significant stray field integral along the circulating beam path of $\sim$170 G-cm peak is seen after injection, as evidenced by a horizontal beam displacement of 250 μm which adversely affects some users. This stray field takes approx. 100 msec to decay to negligible levels (B_y <1G). Currently the storage ring is filled at 1.525 GeV, once every several hours, so the stray field is tolerable. The ALS is now converting to ”top-off” mode [1][2][3] where beam is injected into the storage ring at the full 1.9 GeV energy every 20 sec. Under top-off mode, the stray field effect on the circulating beam would be larger and far more frequent, which is unacceptable.

Stray Field Reduction

The stray field, in both FEA simulations and in measurements, is time delayed from the main gap field, appearing only after the end of the half sine pulse. It is characterized as having a fast rise of $\sim$ 100 μsec, followed by a long decay “time tail”. Allowing the magnet current to progress through a full sine pulse (by adding a fly-back diode across

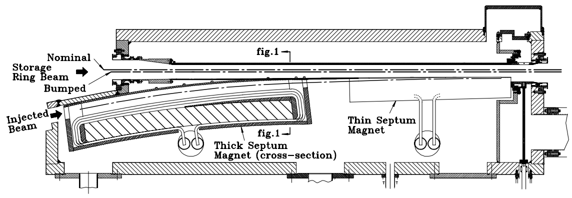

Figure 2: Injection Septum Magnet Layout, Top View

the SCR switch) both reduces the maximum stray field (by $\sim$ 3x) and creates a fast decay from this peak down to a level anywhere from 30% of the peak to zero (or less, in simulations), which then levels out and follows a slow decay of the same long time constant as the half sine case [7] [4]. This "plateau" field level is highly dependent on the ratio of the forward and reverse drive currents (resulting from drive circuit resistive losses). Another method for reducing stray field is to use ferromagnetic shielding between the septum and the storage ring beamtube [5] [6], which is effective but requires significant physical modifications.

Qualitative Description

Finite element analysis (OPERA-2D, transient solver) was used to simulate the thick septum magnet operation. The main drive current pulse is 5.3kV, producing +1.33 T maximum gap B field over a 125 μsec (half sine) period, and is the basis for simulations here. These results are compared to both field measurements using a (dB/dt) coil probe [3] made on a spare magnet, and to actual storage ring beam deflection measurements. For a half sine forward drive current pulse, $I_{for} = I_0 \sin(\omega t)$; $\omega t = 0 \rightarrow \pi$, the septum face $(x = 0)$ eddy current density is proportional to dB/dt (a cosine from $\omega t = 0 \rightarrow \pi$). As current diffuses into the septum, the area integral of the septum current density largely follows the drive current, (when all stray flux is contained within the septum). At the end of the half sine drive pulse, the net eddy current in the septum is close to zero, but the eddy currents, being temporally separated, are also spatially separated (while also diffusing together), and the current profile in a transverse direction forms a non-zero current dipole which creates a B field at the corner of the poletip. Figure 3 shows this flux and septum eddy currents at the end of the drive current.

A very similar distribution results after a full sine pulse, with reversed currents and fields. Figure 4 shows current density profiles across the septum thickness at various times after the ends of both half and full sine pulses (undamped drive current). Figure 7 shows B_y at the closest S.R bumped beam position, x=-2.1cm as a function of time for both half and full sine undamped pulses for the various cases presented here (B_{gap} positive). At the end of either pulse, the J profiles look very similar, however their evolution over time is very different as seen by the profiles at $t = 1.1$ ms (scaled here for clarity). For each half sine drive pulse there is a relative resistive decay between the plus and minus sections of the current dipole due to the

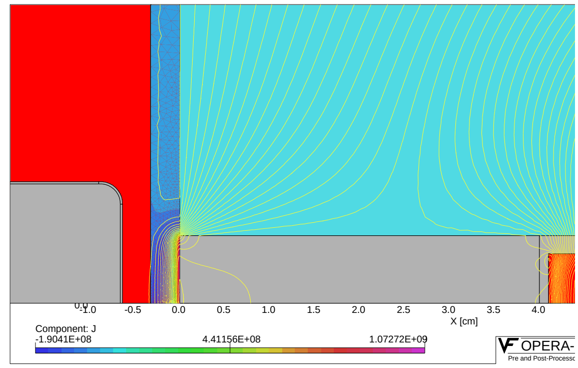

Figure 3: Flux and Eddy Current density(J) at ωt = π

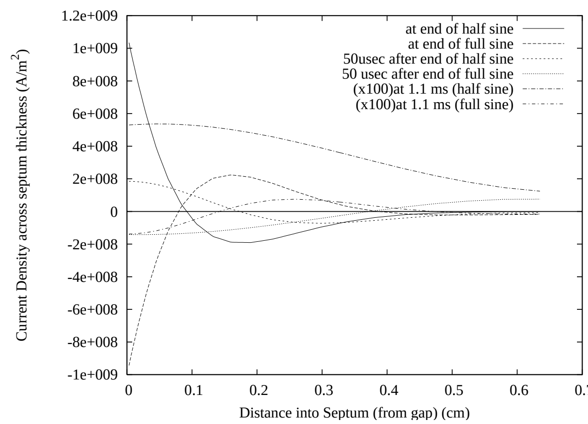

Figure 4: Septum Current Density, J

avg. time difference of t_d =82 μsec. There is also a relative resistive decay between the first and second half sine current dipoles due to the time separation of 125 μsec. The final residual septum current (after local variations have diffused together) links (with a corresponding back plate current) the entire magnet core and has a large inductance, and thus a slow decay. Using the straight line portion of the half sine decay plot on fig. 7 (characterized by high current density and thus larger losses) an exponential decay time τ = 9 msec is estimated for the residual current. Relative decay between the (+/-) current sections in each current dipole is 1.0% $(= 1 - e^{-\frac{t_d}{\tau}})$ and similarly, 1.5% between the two current dipoles. Summing (with eddy current sections listed backwards in time): for a half sine only drive pulse, $I_{r,hs} = I_0(-1.0 + 0.99) = -0.01 I_0$ and for an (undamped) full sine drive pulse, $I_{r,fs} = I_0((1.0 - 0.99) + 0.985(-1.0 + 0.99)) = 0.00015 I_0$ or a factor of (-67) reduction in I_r. The FEA simulated curves in fig 7 show a (-57x) reduction. The current dipoles, whose flux in freespace is very small, diffuse together quickly, as they simultaneously diffuse outward vertically into the septum.

The initial stray field direction appears to be dominated by the first half sine drive current direction, even though the septum eddy current profile reverses over a full sine drive current. In fig. 5 one can see that the original field direction is preserved at the left septum face even though

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the main bulk of the eddy current has reversed at the right face of the septum. Figure 6 shows the stray field integral along the S.R. beam path, both calculated (damped, where $B_{rev} = 0.92 B_{for}$) and back-calculated from measured 30 μm horizontal deflection of the beam from a comparative test [3] for both half and full sine pulses (0.67 G-cm/micron). Deflection data is low-pass filtered (60 Hz cut-off).

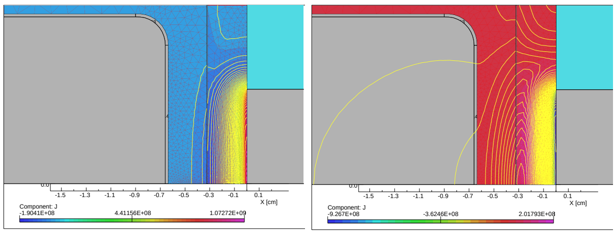

Figure 5: Flux and Eddy Current $\omega t = \pi$ (l), $\omega t = 2\pi$(r)

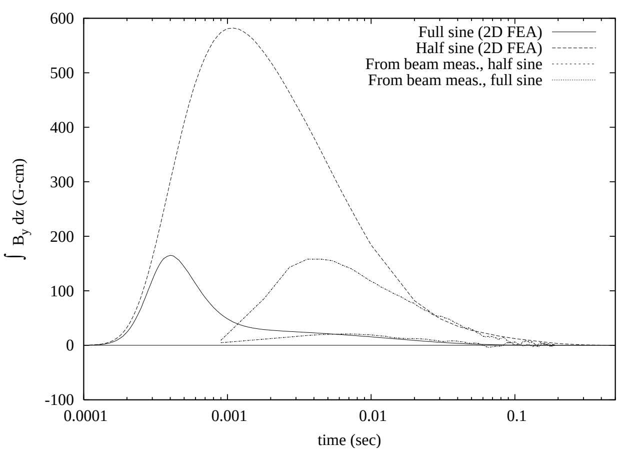

Figure 6: Stray Field Integral and S.R. Beam Deflection

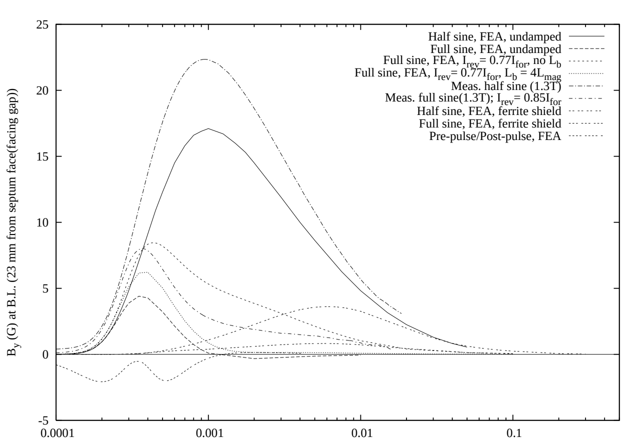

Figure 7: Stray Field @ closest S.R. beam position

Enhanced Full Sine Drive Current Pulse

An undamped full sine drive pulse allows the second half sine residual current to (more than) completely compensate that from the first half sine drive pulse. However, resistive losses in the drive circuit do not allow full current reversal; for the ALS, $I_{rev} = 85\% I_{for}$. The time tail is greatly reduced (compared to the half sine only drive pulse), but not eliminated at this damping factor. This reduction is sufficient to satisfy the requirements for ALS top-off mode, and the full sine drive pulse will be implemented. However, it is possible to reduce the stray field time tail to zero within 1 msec by boosting the reverse drive current I_{rev}. This boost can be provided by connecting a bypass inductor L_b in series with a reverse current blocking diode across the magnet leads. This allows some current to bypass the magnet during the main drive current pulse, thus boosting the reverse voltage on the capacitor (at $\omega t = \pi$). Figure 7 shows the FEA simulated stray field time history of a full sine drive current pulse, with $I_{rev} = 0.77 I_{for}$ in combination with $L_b = 4 L_{mag}$. The additional voltage required on the capacitor to provide this bypass current is ∼15 percent. Also for comparison, the effect of adding a 1mm thick ferrite shielding plate extending +/-5 cm in (Y) placed between the septum and the beamtube is shown in fig 7, for both half and full sine drive pulses. Finally, the effect of adding a “pre-pulse” half sine reverse current ($I_{pre} = -0.5 I_{for}$ of same frequency) immediately preceding an undamped full sine drive current, followed by a “post-pulse” half sine forward current ($I_{post} = 0.5 I_{for}$ of same frequency) is shown in fig 7.

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