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EVALUATION OF PULSED SEPTUM LEAKAGE FIELDS AND COMPENSATION FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The Advanced Photon Source Upgrade (APS-U) will use on-axis horizontal-plane injection with a pulsed septum. Pulsed leakage fields are a concern as they will cause transient beam motion and emittance dilution. In this paper, we describe results of modeling the effect of such leakage fields on the beam. We also evaluate methods of compensating for the leakage fields, including the limited time response of correction elements. Several septum drive-pulse shapes are considered and compared.

INTRODUCTION

Recently a decision was made to use horizontal-plane injection for the APS Upgrade [1], owing the anticipated difficulty of ensuring sufficiently low vacuum pressure in the stored beam chamber for the DC Lambertson septum [2,3] needed for vertical-plane injection [4]. Part of the decision process was evaluation of leakage fields from both septa, i.e., DC leakage for the Lamberston [5] and pulsed leakage for the horizontal septum. In this paper, we present simulations and analysis for the latter.

MODELING OF THE SEPTUM

The design of the APSU septum, Fig. 1, is similar in design to the existing APS septum currently in operation [6]. The 17-mm magnet gap was selected to meet the beam stay clear requirements. The septum magnet core is curved to match the injected beam path, which allows maintaining a 15.89-mm gap width throughout the entire length of the magnet, to minimize the inductance. The septum thickness at the downstream end is 3 mm, but greater at the upstream end owing to the curvature of the magnet. The design main field is 1.42 T with a total (straight) length of 1.493 m.

Magnet modeling with OPERA [7] was performed on short models to save on calculation time, reduce complexity, and help with issues on meshing, conceptualization, and prototyping. Magnetic field, thermal, voltage, and force data for a full-length model were extrapolated from the data obtained from the short models. Multipoles for the full-length model leakage field at the center of field free tube were extrapolated from the short models to give an upper bound field map at a reference radius of 10 mm. The dipole field at the stored beam position will be less than 30 μT m. Several possible drive current timelines were studied. Minimum and maximum timelines were specified as power supply design criteria to limit the maximum voltage, leakage field, temperature rise, and forces.

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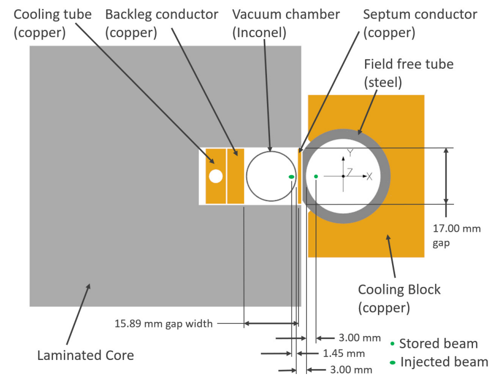

Figure 1: Cross-section of the APS-U 1.4-T pulsed septum magnet.

TRACKING METHODS

The septum leakage field extends over about 100 ms or nearly 30,000 APS-U turns. Since we track 48 bunches of 1000 particles to ensure realistic sampling of the leakage waveform, tracking studies are potentially very time-intensive. To address this, we used the `ILMATRIX` element in `elegant` [8,9], which provides fast simulation of storage ring lattices, including chromatic- and amplitude-dependent tune and lattice function variation. The data that configure `ILMATRIX` are obtained from tracking, including chromatic tune variation up to third order in δ and amplitude variation up to second order in the invariants. Synchrotron radiation effects are also included using a lumped approach using the `SREFFECTS` element with `COUPLING=1` to reflect the intended working configuration of APS-U. Using an initial model for the septum leakage field, we compared `ILMATRIX` results to element-by-element tracking results, finding that `ILMATRIX` accurately captures orbit changes and emittance increases due to decoherence, while reducing run time by a factor $\sim 10^4$.

BEAM DISTURBANCE AND COMPENSATION

Initially, the septum was driven by a half-sinusoidal waveform. Figure 2 compares emittance predictions with and without leakage field, showing that the disturbance for the initial septum model peaks at 5% and lasts about 10 ms, which exceeds our goal of a less than 2% increase.

Inspection of the leakage field revealed that rapid changes at the terminus of the half-sinusoidal pulse, so we tried a revised pulse shape with a smoothly-tapered termination, as shown in Fig. 3. This significantly reduced high-frequency leakage components, as Fig. 4 shows. This in turn reduced

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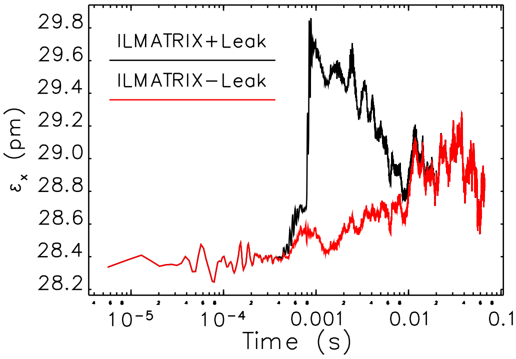

Figure 2: Comparison of horizontal emittance evolution with and without septum leakage field from initial model.

the emittance disturbance (Fig. 5), due to eliminating a short spike in the centroid (Fig. 6).

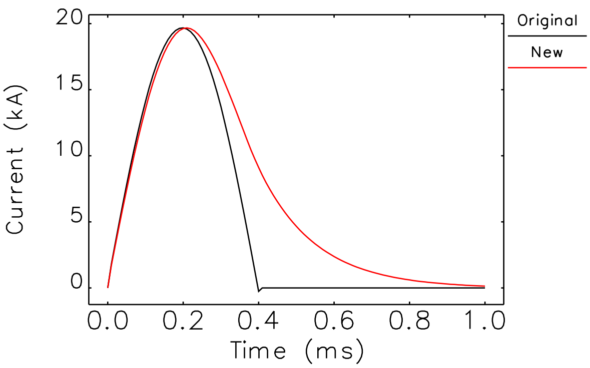

Figure 3: Comparison of original and revised septum drive pulses.

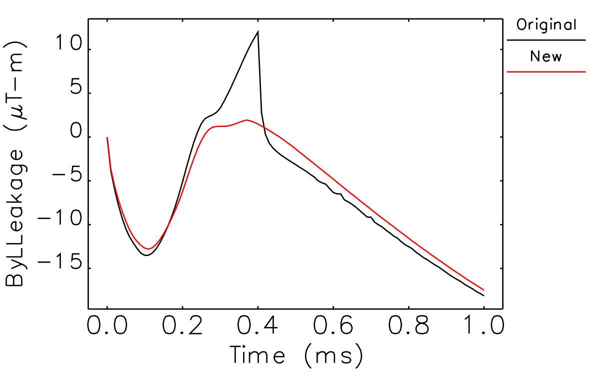

Figure 4: Comparison of leakage field for original and revised drive pulses.

Since the leakage field effects are larger than acceptable, we modeled compensation, starting with an inverted replica of the leakage field, which provides perfect correction. Assuming power supplies that can provide the needed waveforms, we must still impose a 10-kHz low-pass filter to include the effect of the magnet and vacuum chamber [10]. In addition, we modeled a stair-step drive with a 22.6-kHz update rate, intended to emulate using feedforward [11] in

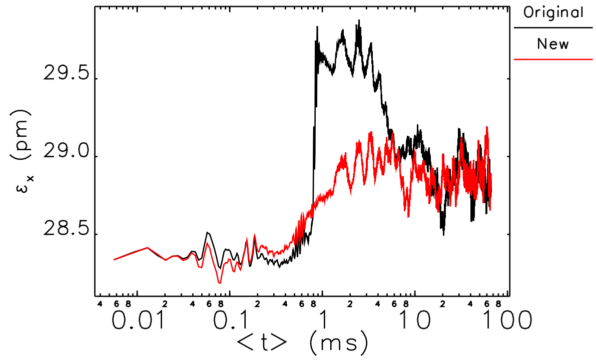

Figure 5: Comparison of emittance for original and revised drive pulses. The time axis is offset by 368 μs.

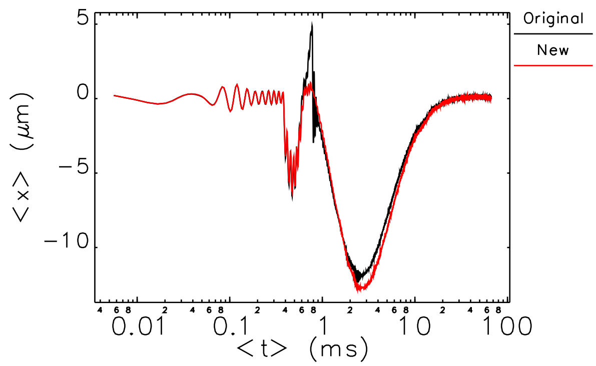

Figure 6: Comparison of centroid for original and revised drive pulses. The time axis is offset by 368 μs.

the fast-orbit feedback system [12]. As Fig. 7 shows, either method is effective in suppressing the relatively slow effect of the post-pulse leakage field on the orbit. Both are also somewhat effective in suppressing beam motion during the pulse. The stair-step method performs worse and does not achieve the 10% goal.

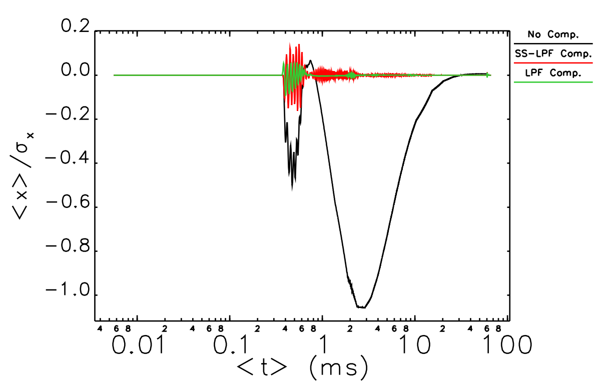

Figure 7: Comparison of centroid change without compensation to results with two compensation methods.

Figure 8 confirms the inferiority of the stair-step replica, showing that it actually makes the emittance worse. This may be a result of high-frequency changes in the centroid introduced by the steps, as evident in Fig. 7. In contrast, with

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the simple low-pass filtered replica, the emittance increase is well under the 2% goal.

In addition to the tapered half-sinusoid, a decaying, multi-cycle drive current was also investigated. While slightly better in the absence of compensation, it proved harder to compensate because the frequency had to be increased in order to reduce power dissipation in the magnet.

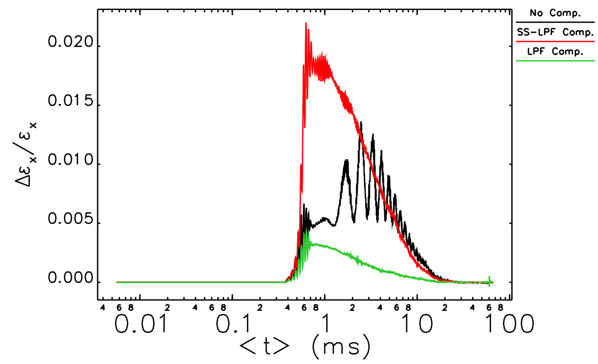

Figure 8: Comparison of emittance change without compensation to results with two compensation methods.

NONLINEAR DYNAMICS

Because the injected beam nearly fills the accceptance, which itself is limited by nonlinear dynamics, another potential impact of the leakage field is reduced injection efficiency. We modeled this using time-dependent integrated multipoles (up to 20 pole) implemented with `elegant`'s `MULT` element for a time duration of 200 ms—long enough for the fields to decay more than an order of magnitude. The time-dependence was imposed using the `modulate_elements` command.

The need to simulate 54,000 turns using element-by-element tracking means we must limit the number of particles to achieve practical run times, even using parallel tracking. Using a uniform 6d distribution over $\pm 4\sigma$ with gaussian weights gave high sensitivity to tail losses with only 1000 simulation particles. We performed simulations for 100 post-commissioning ensembles [13], with 30 injected beam shots per ensemble. As Fig. 9 shows, there is very little change in the expected loss fraction due to leakage fields.

POWER SUPPLY

The power supply for the APS-U septum is similar to that for the present APS storage ring thin septum [14], which uses a DC power supply to charge a capacitor bank. When the SCR is triggered, the capacitor bank discharges through the inductance of the magnet, forming an L-C circuit with a resonant half-period of about 400 µs. This produces a half-sine current waveform that ends abruptly when the current comes to zero, since the SCR cannot conduct reverse current.

As noted above, this sudden end of the current waveform causes a spike in the leakage field seen by the stored beam,

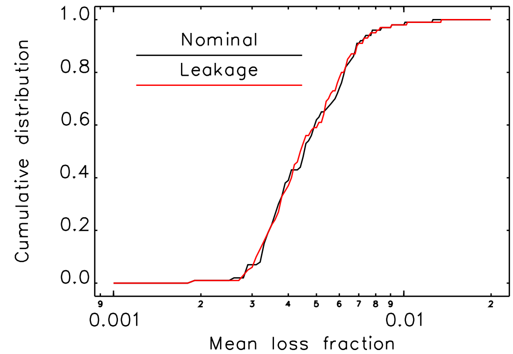

Figure 9: Cumulative distributions of injection efficiency with and without time-dependent septum leakage multipoles.

which can be avoided by making the current go to zero in a gradual fashion. This can be accomplished by adding a damped free-wheeling circuit to the output of the power supply, as shown in Fig. 10. The free-wheeling circuit consists of a diode and resistor. The diode is in off state before the current reaches the peak and, therefore, does not affect the current shape. When the current starts to drop, the voltage across the septum becomes negative and the diode starts to conduct. This shunts the current through the resistor, creating a damped, series L-R circuit. The resistor value will be chosen to achieve the desired tapered waveform.

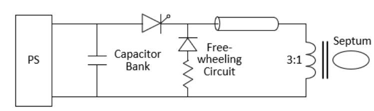

Figure 10: Schematic of septum power supply.

CONCLUSIONS

APS-U will use horizontal-plane on-axis injection with a 1.4-T pulsed septum magnet. The high field and small emittance raises concerns about leakage fields, which have been estimated using OPERA. We evaluated beam motion and emittance increase using particle tracking, concluding that a tapered half-sinusoidal waveform gives smoother time-dependence of the leakage fields, allowing compensation using fast steering magnets. The correctors must be driven with arbitrary function generators, rather than feedforward, in order to meet requirements.

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