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WAKEFIELD EFFECTS ON DARK CURRENT BUNCHES FOR LESA*

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Abstract

Alongside the new LCLS-II facility, a new electron beamline known as Linac to End Station A (LESA) is under construction at SLAC. LESA will use dark current from the new superconducting accelerator to search for MeV- to GeV-scale dark matter. To predict the behavior of the dark current in LESA, we must account for the effects of wakefields. In the conventional analysis of long-range wakefields, the bunches are both the sources and subjects of collective effects. Since the contribution of dark current to the wakefield is negligible, the dark bunches are passive recipients of the wakefield kicks. However, we also lose some simplifying assumptions. In contrast to the main bunches, which are generated at a low subharmonic of the RF frequency, dark current is generated on every RF cycle of the source cavity. The dark current bunches may also occupy a much larger proportion of each RF bucket. These complications lead to effects that are not seen in the main bunches, such as "beating" of the betatron amplitudes along the dark bunch train. In this work, we present the theory behind this interaction and apply it to LESA.

STEADY-STATE WAKEFIELDS

The Linac Coherent Light Source II (LCLS-II) RF photoinjector produces high-brightness electron bunches of up to 300 pC at a rate of 929 kHz, occupying one in 1,400 RF buckets of the 1.3 GHz linac. In contrast, the dark current that will be diverted to the Linac to End Station A (LESA) beamline [1, 2] is produced during every RF cycle via field emission from high-gradient surfaces in the accelerator cavities. Higher-charge bunches are also expected at the gun frequency of 185.7 MHz, the seventh subharmonic. Since their charge is very low, the dark current bunches do not produce significant wakefields of their own, but the wakefields produced by the main bunches that will be used for the LCLS-II free-electron laser (FEL) can produce strong wakefields that perturb the orbits of the dark current bunches.

To understand how the dark current bunches will be affected, we need to characterize the wakefields that will be produced by the main bunches. In a resonator of quality factor Q, shunt impedance R, and resonant frequency ω_r, the transverse wake function of order m at longitudinal position z relative to a delta-function impulse charge at $z = 0$ is

$$W_m(z) = \frac{R}{Q}\frac{c\omega_r}{\overline{\omega}} e^{\alpha z/c} \sin(\overline{\omega} z/c)$$

for $z < 0$ and zero for $z > 0$, where $\alpha = \omega_r/2Q$ and $\overline{\omega} = \sqrt{\omega_r^2 - \alpha^2}$. The longitudinal wake function is

$$W'_m(z) = \frac{R}{Q}\frac{\omega_r^2}{\overline{\omega}} e^{\alpha z/c}\left[\cos(\overline{\omega} z/c) + \frac{\alpha}{\overline{\omega}}\sin(\overline{\omega} z/c)\right]$$

for $z < 0$ and zero for $z > 0$, by causality [3]. Note that if we define $\phi \equiv \alpha/\overline{\omega}$, then the wake functions can be expressed as

$$W_m(z) = \frac{R}{Q}\frac{c\omega_r}{\overline{\omega}}\Im\left[e^{(\alpha+i\overline{\omega})z/c}\right]$$

and

$$W'_m(z) = \frac{R}{Q}\frac{\omega_r^2}{\overline{\omega}}\Re\left[e^{(\alpha+i\overline{\omega})z/c-i\phi}\right].$$

We can calculate the steady-state effective wake functions $W_{m,\infty}(z)$ and $W'_{m,\infty}(z)$ produced by an infinite train of identical bunches by summing their contributions. For a finite train of N bunches with period T, in the ultrarelativistic limit (so $v_z \approx c$),

$$\begin{aligned} W_{m,N}(z) &= \sum_{n=0}^{N-1} W_m(z - ncT) \\ &= \sum_{n=0}^{N-1}\frac{R}{Q}\frac{c\omega_r}{\overline{\omega}}\Im\left[e^{(\alpha+i\overline{\omega})(z-ncT)/c}\right] \\ &= \frac{R}{Q}\frac{c\omega_r}{\overline{\omega}}\Im\left[e^{(\alpha+i\overline{\omega})z/c}\sum_{n=0}^{N-1} e^{-(\alpha+i\overline{\omega})nT}\right]. \end{aligned}$$

The sum can be evaluated using the well-known fact that $\sum_{n=1}^{N-1}\zeta^n = (1-\zeta^N)/(1-\zeta)$, with $\zeta = e^{-(\alpha+i\overline{\omega})T}$.

$$W_{m,N}(z) = \frac{R}{Q}\frac{c\omega_r}{\overline{\omega}}\Im\left[e^{(\alpha+i\overline{\omega})z/c}\frac{1-e^{-(\alpha+i\overline{\omega})NT}}{1-e^{-(\alpha+i\overline{\omega})T}}\right].$$

Since $|\zeta| < 1$, the steady-state limit is

$$W_{m,\infty}(z) = \frac{R}{Q}\frac{c\omega_r}{\overline{\omega}}\Im\left[\frac{e^{(\alpha+i\overline{\omega})z/c}}{1-e^{-(\alpha+i\overline{\omega})T}}\right]. \quad (1)$$

A similar calculation, or simply taking the derivative of Eq. (1), yields

$$W'_{m,\infty}(z) = \frac{R}{Q}\frac{\omega_r^2}{\overline{\omega}}\Re\left[\frac{e^{(\alpha+i\overline{\omega})z/c-i\phi}}{1-e^{-(\alpha+i\overline{\omega})T}}\right].$$

As we would expect, the summation introduces a resonance via the denominator, exhibiting peaks whenever the mode frequency $\overline{\omega}$ is an integer multiple of the photocurrent bunch frequency $1/T$.

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LCLS-II SRF CAVITY DIPOLE MODES

The 1.3 GHz TESLA superconducting radio-frequency (SRF) cavities used in LCLS-II possess many dipole modes due to their nine-cell structure and the resultant mode splitting. The R/Q and Q values of the dipole modes up to 2.7 GHz are shown in Figs. 1 and 2, respectively.

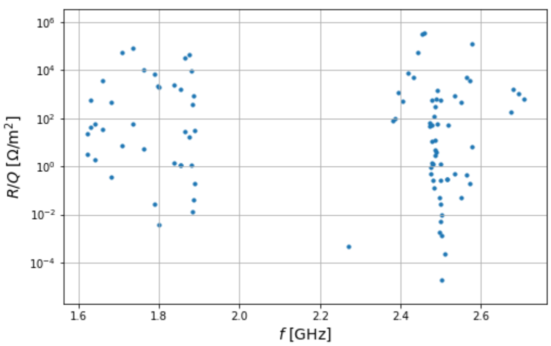

Figure 1: R/Q of the dipole modes.

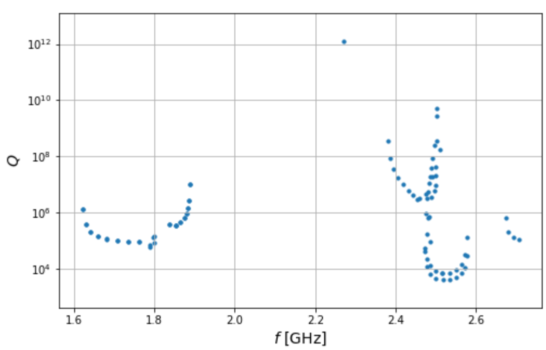

Figure 2: Q of the dipole modes.

Transverse Kicks on Dark Current Bunches

In the steady state, the kick seen by each photocurrent bunch approaches a fixed value depending on the amplitude and phase of the cumulative wakefield. In contrast, the dark current sees a wide variety of kick amplitudes from the wakefields. Figures 3 and 4 show the kick amplitudes seen by the dark current per millimeter of offset between the photocurrent bunches and the symmetry axis of the cavity for the 2.46 GHz dipole mode. Here, we assume that LCLS-II is operating at 929 kHz with 100 pC bunches. Since the LCLS-II beam exits the injector with 100 MeV of kinetic energy, the resulting transverse kicks, on the order of 10 V for a 1 mm offset, are quite small relative to the beam's longitudinal momentum. Therefore, we do not expect dipole wakefield effects to be problematic for LESA under ordinary circumstances.

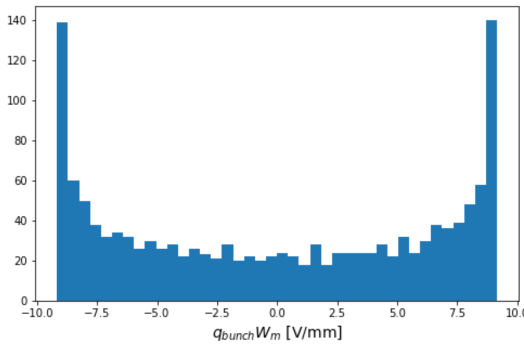

Figure 3: Distribution of kick amplitudes seen by the dark current bunches per millimeter of offset between the 100 pC photocurrent bunches and the beam axis for the 2.46 GHz dipole mode.

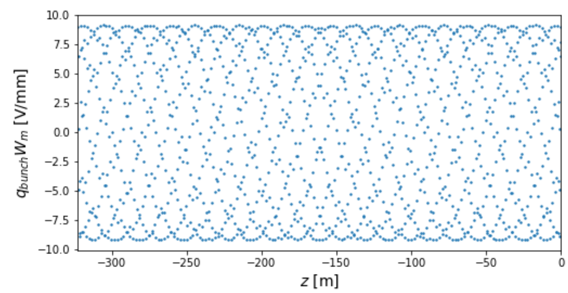

Figure 4: Beating of the kick amplitudes seen by the dark current bunches per millimeter of offset between the 100 pC photocurrent bunches and the beam axis for the 2.46 GHz dipole mode.

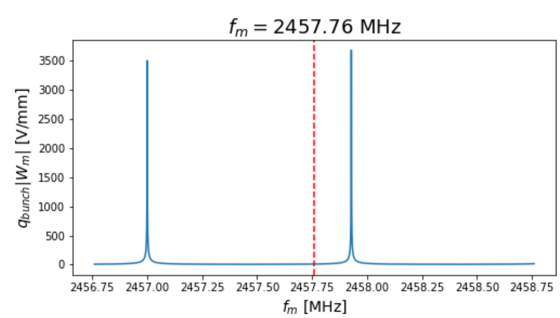

Figure 5: Resonant response of the mode with a numerically computed frequency of 2.46 GHz, marked with the dashed line, if the mode frequency varies by ±1 MHz. The peaks are spaced by the 929 kHz photocurrent bunch frequency.

Resonances

If all the mode frequencies were exactly those predicted in simulations, this would be the worst-case scenario. However, in practice, the dipole mode frequencies have an uncertainty on the order of 1 MHz, and will shift in frequency when the cavities are retuned. The most severe resonances can result in kick amplitudes as high as 3.7 kV per mm of offset. Fortu-

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nately, the highest-amplitude resonances correspond to high Q values. Consequently, the probability that a high-resonant-amplitude dipole mode frequency will coincide with a harmonic of the photocurrent bunch frequency is low. Even in the case that a troublesome resonance occurs, this resonance can be mitigated by detuning and retuning the offending cavity to shift the frequency of that mode. The highest-amplitude resonant peak is associated with the 2.46 GHz dipole mode. Its frequency response over a 2 MHz range, centered on the numerically computed mode frequency, is shown in Fig. 5.

CONCLUSION

The dark current bunches used for LESA are susceptible to deflection by dipole wakefields driven by the main beam. However, the likelihood that the wakefield amplitudes will rise to a troublesome level is low, and if this occurs, it can be mitigated by detuning and retuning the cavities. Due to the high Q of the most dangerous resonances, the photocurrent bunches would also see a large short- and long-range dipole wakefield in such a case, prompting a retuning of the offending cavity. In the absence of resonances, the amplitudes of the dipole wakefield kicks are insignificant in their effects on the dark current. However, the hollowed-out distribution of the wakefield-perturbed dark current may serve as a secondary indicator if a dipole mode is being driven near resonance. Therefore, observation of such a distribution in the dark current profile may aid in troubleshooting in the event that a nearly resonant dipole mode interferes with the operation of LCLS-II.

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