COLLECTIVE EFFECTS ANALYSIS FOR THE BERKELEY FEMTOSOURCE*

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Abstract

We present an overview of collective effects in a proposed ultrafast x-ray facility, based on a recirculating linac. The facility requires a small vertical emittance of 0.4 mm-mrad and is designed to operate with a “flat bunch” with a large emittance ratio. Emittance control from the electron source at the RF photocatode to the photon production chain of undulators, including understanding and mitigation of collective effects, is critical to successful machine operation. Key aspects of accelerator physics involved in beam break-up, coherent synchrotron radiation, resistive wall impedance and other effects have been addressed and reported here.

INTRODUCTION

The proposed LUX femtosecond X-ray facility [1] is based on a 600 MeV superconducting recirculating linac. It accelerates up to 2.5 GeV a 2 ps electron beam, which is subsequently used to generate ultra-short X-ray pulses. It is vital to preserve a small vertical emittance throughout the machine since the X-ray pulse duration is a function of the vertical emittance.

In this paper we investigate the three main mechanisms that can lead to a degradation of machine performance by emittance or energy spread increase: wakefields in the main linac and the preinjector; resistive wall impedance in the vacuum chamber; and coherent synchrotron radiation.

WAKE FIELDS

The performance of LUX depends on preservation of low vertical emittance through the linac and the arcs. The short-range transverse wake fields from the linac cavities are a potential source of vertical emittance growth, and the effects need to be carefully evaluated. The size of the transverse kick from the wake fields increases with increasing offset of the bunch from the axis of the cavity, so there are possible implications for the alignment of the cavities and orbit control.

It is possible to arrive at a semi-analytical estimate of the effects of the wake fields of the linac, as presented in [2]. However, a more complete investigation including the nominal bunch distribution and tracking through the arcs requires a tracking code. For the present studies, we have used MERLIN [3], which allows simulation of required effects. We also present some estimates of the influence of long-range wake fields on emittance growth.

Short-range wake fields

The present design of the linac uses the TESLA 9-cell, 1.3-GHz superconducting cavities. An analytical expression for the wake fields is reported in [4], while the lattice design used for the arc tracking can be found in [5]. For an exhaustive report of the technical details of the tracking, see [6].

To verify the wake field model in MERLIN, we first tracked a bunch with the nominal 2 ps bunch length, and (effectively) zero transverse emittance through four passes of the linac. In this case, the bunch was with a fixed vertical offset in each cavity, and the bunch was taken straight from the end of the linac on each pass and re-injected at the start of the linac: i.e. we modeled the effects of perfectly achromatic arcs with integer betatron phase advances. The results shown in Fig.1 are in very good agreement with our analytical model [2].

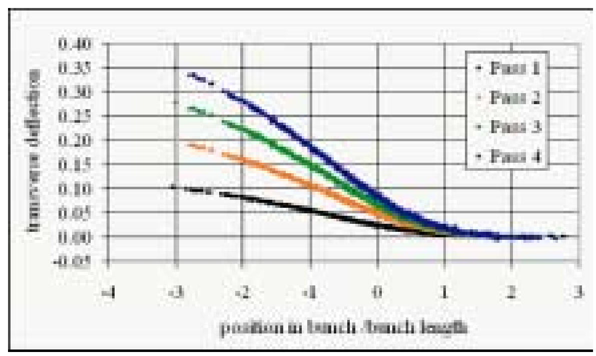

Figure 1. Transverse deflection of a 2 ps zero-emittance bunch, through four consecutive passes at constant vertical offset through the linac. Merlin tracking.

To estimate emittance growth from the wake fields in a linac with vertical cavity misalignments, we tracked a 10,000 macroparticle bunch with the nominal parameters specified in Table 1 from the entrance of the linac to the exit after the fourth pass. Vertical misalignments with a range of rms values (and a cut-off at 5 sigma) were applied to the cavities; the beam sees the same misalignments in the simulation on each pass. The cavity misalignments were the only imperfections applied to the machine; the arc optics and alignment were as designed. For large cavity misalignments, there is significant orbit distortion that is expected to lead to vertical emittance growth from coupling in the arc sextupoles.

Table 1: Bunch Parameters Used In Wakefield Simulations.

Initial bunch energy	120 MeV
Bunch charge	1 nC
Bunch length	2 ps
Energy spread	10^{-3}
Horizontal emittance (normalized)	20 µm
Vertical emittance (normalized)	0.4 µm

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No distinction was made between cryostats; in reality, cavity offsets are expected to be correlated according to which cryostat they are in. Since we find that the wake field effects for any reasonable cavity misalignments are so small, our conclusions are not likely to be affected by the fact that we have neglected this effect.

Results of tracking with the sextupoles turned on are shown in Fig. 2; results with the sextupoles off are shown in Fig. 3. The emittance growth with wakefields off is due to the deflecting kick from the cavity fringe fields. It appears that the wake fields themselves make negligible contribution to the emittance growth. The wake field cancellation resulting from the phase advance across the arcs can easily reduce the head-tail displacement by more than an order of magnitude; in which case, we would expect to see an emittance growth of the order 5% (tracking with an extreme rms vertical cavity misalignment value of 2 mm. The actual misalignment is about 0.5 mm instead).

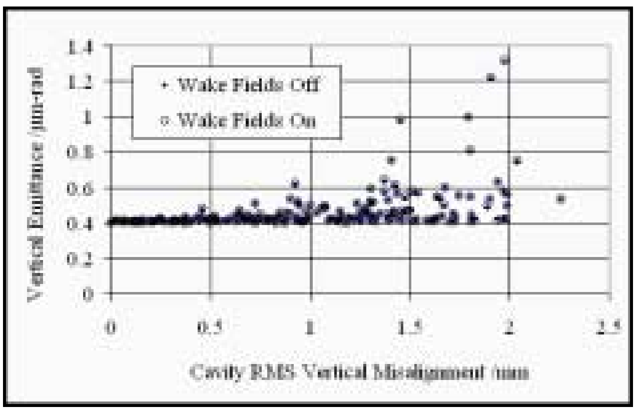

Figure 2: Results of tracking a nominal bunch from the first entrance of the linac through four passes (including the arcs) to the fourth exit from the linac. The arc sextupoles were turned on.

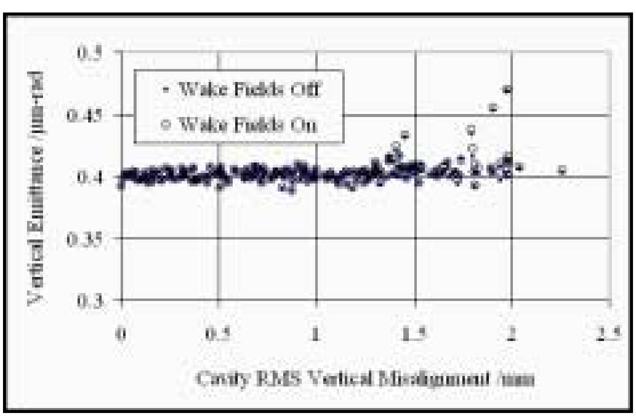

Figure 3: Results of tracking a nominal bunch from the first entrance of the linac through four passes (including the arcs) to the fourth exit from the linac. The arc sextupoles were turned off.

With the sextupoles turned on, any emittance growth from the wake fields is hidden by the very much larger emittance growth from the coupling. This should be easily fixed by proper orbit control and beam based alignment.

Long-Range Wake Fields

Since a bunch in LUX is recirculated four times through the main linac, we also investigate the influence of the transverse long-range wakefield on the bunch emittance. An estimate of the wakefield can be obtained by adding up the transverse wake from all the high-order modes of the 32 linac cavities. Figure 4 shows that the field amplitude decays by only a factor of 10 in the typical recirculation time of less than 1 µs. The long-range transverse wakefield is, in most cases, fairly constant over the bunch length and, therefore, its effect translates to a small additional displacement of the entire bunch (Fig.5), which does not affect the vertical emittance.

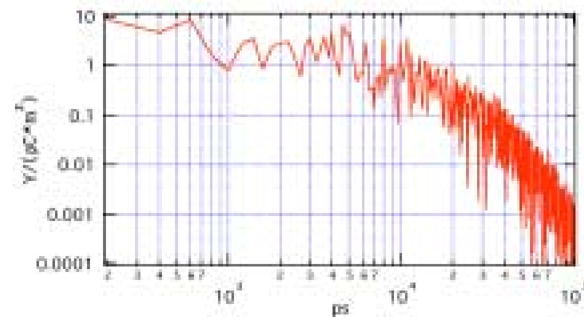

Figure 4: Long-range transverse wakefield with a 0.1% random detuning in the RF cavities HOMs.

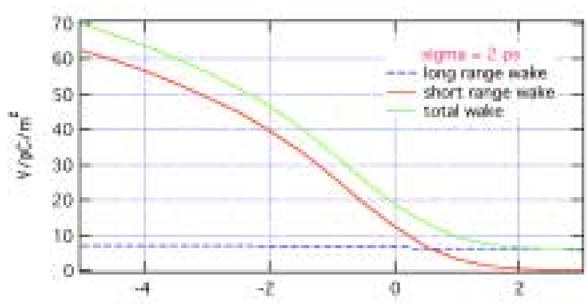

Figure 5: Total vertical displacement along a 2 ps bunch from short and long range transverse wakefields.

Resistive Wall Impedance

The resistive wall impedance also induces a vertical deflection along a bunch throughout the machine, which leads to a dilution of the vertical emittance. The resistive wall effects are worse at lower energies, for shorter bunches and for narrower apertures of the vacuum chamber. Figure 6 shows the oscillation of the bunch tail along the first arc for a beam pipe radius of 4.5 mm and an initial vertical offset of 100 µm. The tracking code results agree very well with a simple analytical model.

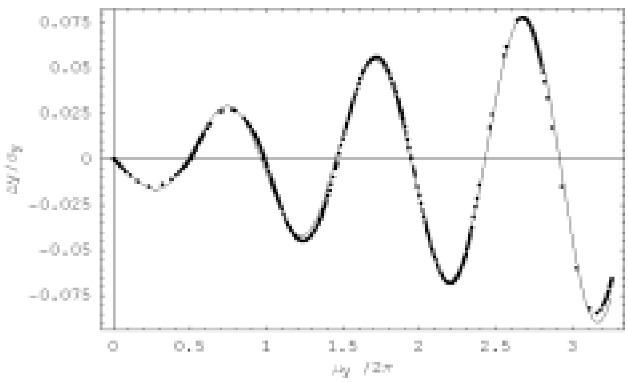

Figure 6. Vertical deflection of the bunch tail along an arc. Tracking (dots) and analytical model (solid line).

It can be seen that, even in this very conservative scenario, the resistive wall contribution is limited to less than 10% of the vertical beam size. This figure is expected to improve, as we expect to have an orbit control significantly better than 100 μm and larger beam pipes in most of the machine. The effects in the other arcs will be significantly smaller, because of the higher beam energy, so that we do not expect the resistive wall impedance to limit the performance of the light source.

COHERENT SYNCHROTRON RADIATION

Coherent synchrotron radiation (CSR) causes a variable energy loss along a bunch which, in turn, leads to emittance increase in the orbit plane. Since we have a relatively large horizontal emittance, the estimated small emittance growth does not seem to be harmful. Therefore, we are mainly concerned by the energy loss because of the resulting increase in the energy spread. CSR calculations are currently in progress.

Figures 7 and 8 show the tracking results [7] for a bunch with an assumed rectangular distribution in the horizontal emittance plane. It can be seen that, while CSR influences the bunch head and tail, the bunch core (90% of the particles) is relatively unaffected. Energy spread is controlled by careful design of the lattice [8].

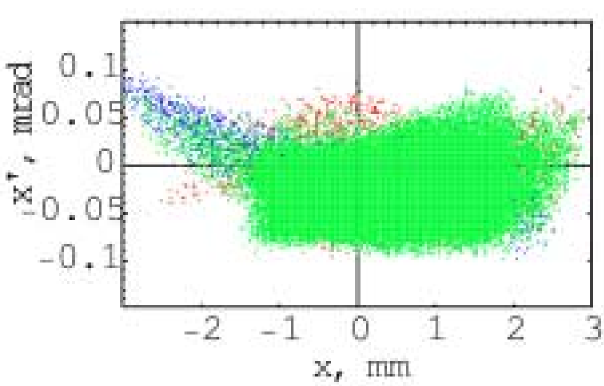

Figure 7: Tracking (***elegant***) of the horizontal emittance at the linac exit. Bunch core (green), head (blue) and tail (red).

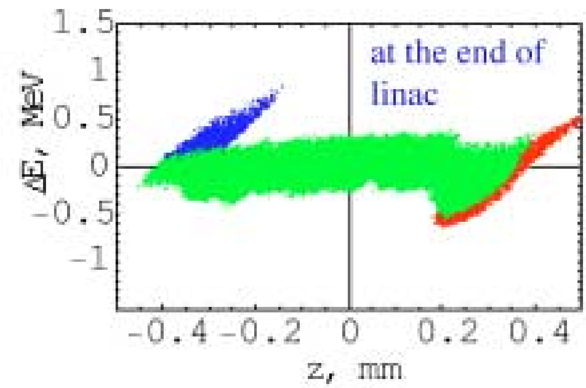

Figure 8: Tracking (***elegant***) of the energy spread at the linac exit. Bunch core (green), head (blue) and tail (red).

CONCLUSIONS

We have investigated several fundamental aspects of the beam dynamics in LUX. We are mainly concerned with the preservation throughout the machine of the vertical emittance and the energy spread, which are vital for the generation of ultra-short X-ray pulses. Our results show that, while one must always pay attention to these aspects in the design phase, they do not present insurmountable problems towards obtaining the machine design parameters.

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