Ideas about measuring short range wake fields in accelerating structures for high-energy and free-electron laser linear accelerators

V. Ziemann, R. Ruber
Department of Physics and Astronomy
Uppsala University

Abstract

We discuss two methods that hold the promise to measure extremely short range wake fields on the sub-ps time scale.

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1 Introduction

Linear accelerators used in high-energy physics, such as the Compact Linear collider CLIC [1], or to drive a free-electron lasers, such as SwissFEL [2] or MAX4 [3], require very short electron bunches with a time duration in the 10 to 100 fs range, corresponding to a length of 3 to 30 μm. Acceleration structures, filled with microwaves in the GHz range, are used to bring the electrons to their final energy. The geometric dimension of these structures is rather small in order to achieve efficient transfer of power to the beam. But the proximity of the walls causes the electrons to excite electromagnetic fields that disturb other electrons, either those following a distance behind, called long-range wake fields, or even the electron within the same bunch, called short range wake fields. It is those fields that act within the duration of a single electron bunch, that we intend to determine because they can ruin the beam quality.

The wake fields operate both in the direction of propagation (longitudinal wakes) which typically cause the beam to loose energy, and in the transverse direction, where the bunch receives a transverse deflection. Note that the wake fields are caused by the interaction of the bunches with the acceleration structure. The longitudinal wakes cause an increased momentum spread in the bunch that can transform into increased bunch length which spoils the performance of the accelerator. Equally the transverse forces can cause oscillations of the center of mass of the bunch or an increase in the transverse beam size and the emittance. Both are undesirable effects and potential limiting factors for the performance of the linear accelerator used in free-electron lasers or high-energy physics.

To assure that future accelerators can fulfill their performance goals a detailed understanding of the limiting factors is mandatory. Recently a collaboration to study X-band technology for free-electron lasers has been established to study the design and special requirements. Among the expected advantage of X-band technology is the high achievable gradient which makes it possible to build shorter accelerators and operate them at higher repetition rates compared to conventional normal conducting accelerators. The limiting factors of commercially available RF sources have been addressed and they are available from two companies, CPI and Toshiba. The detailed study of the breakdown phenomena is of high importance for high-energy accelerators like proposed for the future CLIC collider, but of less importance for FEL accelerators as they would include a relatively small amount of structures and might operate at relatively lower gradient (order of 70 MeV/m) and pulse length. One remaining outstanding question of high importance that could possibly limit the usage of X-band structures are short range wake fields. We therefore investigate methods to measure these short range wake fields in accelerating structures for high-energy and free-electron laser linear accelerators.

2 Previous Work

The long-range wake fields can be directly determined in the ASSET facility [4, 5] at SLAC, where both electron and positron bunches are available that are injected into the linear accelerator with a varying temporal distance and then the effect of the leading bunch

on the trailing bunch can be detected by using a long part of the accelerator following the tested acceleration structure as diagnostics to determine the change of trajectory of the trailing bunch. Even early prototypes of CLIC structures were analyzed there [6, 7].

The short range wakes that operate within the bunch cause the center of mass of the bunch to lose energy (which heats the walls). This is called the loss factor and can be observed in circular accelerators as a shift in synchronous RF phase, because the RF system has to replenish this. The transverse fields kick the beam transversely and one needs to observe a change in the beam position downstream of the structure. Experiments of this type were done in Argonne National Laboratory [8] with the aim to study two-beam acceleration methods. Another experiment aimed at implementing a two-beam acceleration scheme using wake fields was done at DESY in the 1980s and is discussed in ref. [9]. The length scale addressed in the above experiments is a ps or longer and we intend to measure at least one order of magnitude better.

A direct measurement of the ultra-short range wake fields at a sub-ps time scale, either longitudinal or transverse, has not been undertaken to our knowledge.

3 Two Ideas to Measure the Short Range Wakes

We intend to measure the short range wake fields with beam. The range of the wake fields is on the order of less than one mm and follows approximately the dependence [10, 11] of $W \propto \exp\left(-\sqrt{s/s_0}\right)$ with s_0 on the order of or even below $1\,\mathrm{mm}$, corresponding to about $3\,\mathrm{ps}$. We foresee two complementary ways to accomplish this

1. Inserting an unpowered structure into a synchrotron light source with a retractable manipulator. This addresses the loss factor and the transverse kick.

2. Producing two short consecutive ultra-short electron bunches using a modified version of the slotted-foil technique used a LCLS [12, 13]. The first bunchlet generates the wake and the trailing bunchlet witnesses the fields and needs to be analyzed in an extremely high-resolution spectrometer.

3.1 Ring-based

In modern synchrotron light sources the diagnostic system, especially the beam position monitor system permits to detect micron-size motion of the beam's center of gravity. Moreover, the radio-frequency system is usually equipped with high accuracy phase and amplitude control. We foresee a system in which the device under test (DUT), the accelerating structure, is pre-aligned on a manipulator that can insert it into the path of the beam. The experiment would start with an extracted DUT and the ring will be set up probably with a moderate stored current and a single bunch for stable operation. After which the orbit and the synchronous phase will be recorded. Then this beam will be dumped and the DUT is inserted. Upon injecting beam with the same properties as before again the orbit and the synchronous phase are recorded a second time. Injecting

into a ring with a small aperture DUT is feasible considering that top-off operation with narrow gap undulators is feasible. The difference in phase is related to the energy loss factor of the structure and the change in orbit due to the transverse wake fields. Finally the transverse position of the DUT in the beam can be varied and changes in the orbit can be observed. Fitting a linear dependence should give the transverse kick factor for a single bunch. Repeating similar measurements with a bunch train would address the long range wakes and might be interesting to do as well.

The important question to establish the feasibility of the method is related to tolerances. The longitudinal loss factor of a CLIC structure is about $1\,\mathrm{kV/pC}$ for very short bunches and depends on the bunch length σ_z approximately as $\sigma_z^{-1/3}$. We estimate that bunches in the ring have a length of $4.4\,\mathrm{mm}$ and the loss factor is probably a factor 5 to 10 less for these long bunches. We assume $0.1\,\mathrm{kV/pC}$ per structure. It needs to be compared to the loss due to synchrotron radiation, which is the dominant factor to determine the phase of the beam. For a $3\,\mathrm{GeV}$ ring with a bending radius of $10\,\mathrm{m}$ the losses due to synchrotron radiation are $720\,\mathrm{kV/turn}$ and for a bunch of $100\,\mathrm{pC}$ the ratio of loss factor and synchrotron losses are around $1.5\,\%$, which should result in a visible change of the phase. A higher current which should be feasible in most rings is beneficial. Observing the synchronous phase as a function of time the natural losses allow us to observe and determine the charge dependence. Comparing the phase change while varying the RF amplitude permits us to determine the bunch length dependence of the loss factor.

The transverse kick in a CLIC structure is on the order of $6\,\mathrm{kV/pC\,m}$ [11] for a 44 micron long bunch and a structure $0.25\,\mathrm{m}$ long. The data in [11] follow the scaling law $k_\perp = 1.9\,\sigma_z^{2/3}$ with the bunch length. Extrapolating, a bunch of length $\sigma_z = 4.4\,\mathrm{mm}$ will experience a kick on the order of $120\,\mathrm{kV/pCm}$. In that case a rather large structure offset of $1\,\mathrm{mm}$ will lead to a transverse kick of magnitude $12\,\mathrm{kV}$ for a $100\,\mathrm{pC}$ bunch. Comparing with the beam energy of $3\,\mathrm{GeV}$ this will cause minute deflections in the micro-radian range which in turn cause rather small changes on the orbit in the range of a few microns, assuming typical beta function values of $10\,\mathrm{m}$. This is somewhat marginal to state that this will be reliably done, though with some effort it is probably measurable. An advantage is that rings have a large number of position monitors and the large number can be used to fit the orbit change to a deflection at the location of the DUT. In this way a substantially better resolution of the kick should be possible.

Details for a specific ring must be worked out. But we conclude that these measurements are within reach to determine the longitudinal loss factor of CLIC structures and possibly even the transverse kick factors.

3.2 Two bunchlets

In order to directly observe the effect of a leading bunchlet on a trailing witness bunch we need to first create such a pair, send it through the DUT and then analyze the trailing bunchlet. First we consider the creation of bunchlets which is inspired by the slotted foil method used at LCLS [12] to generate bunchlets with small emittance that participate in the FEL process in order to reduce the number of radiating modes. Using V-shaped slits
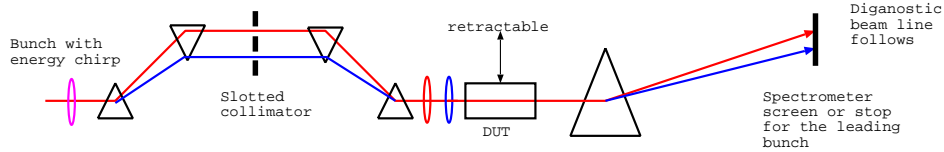
Figure 1: The chicane with the collimator.

allows to create two low-emittance bunchlets following each other. We propose to use the same method at a low energy of 10 MeV and replace the foil by a V-shaped collimator inside a chicane. The collimator should be thick enough to stop the intercepted electrons and the slits must be chosen such that the resulting bunchlets have sufficient intensity while being short enough not to overlap longitudinally after the second leg of the chicane. The method is illustrated in Fig. 1 where a bunch with a correlated energy spread or chirp (by running the bunch off-crest) enters at the left as the magenta bunchlet and the different energies follow a path length according to their energy; the high energy particle's path is shorter. The collimator in the middle of the chicane selects two energies. After the chicane we have two bunchlets with two energies that follow each other. The dynamics of the system was analyzed in [13] with the result that the rms bunch length σ_s of each bunchlet is given by

$$\sigma_s \approx \frac{1}{|Dh|}\sqrt{D^2\sigma_\delta^2 + (1 + hR_{56})^2[w_x^2/3 + \varepsilon\beta]} \tag{1}$$

where $D \approx L\phi$ is the dispersion of the chicane, L the distance between the dipoles and ϕ the bending angle of the chicane dipole. $h \approx 10/\mathrm{m}$ is the energy chirp from accelerating the bunches off-crest and $R_{56} \approx 2L\phi^2$ is the phase slip factor of the chicane. Note that at the low energy the length $\tilde{L}$ of the chicane contributes to the R_{56} by adding $\tilde{L}/\gamma^2 \approx 0.01\,\mathrm{m}$ which is on the order of $10\,\%$ of the contribution from dipoles. w_x is the width of the collimator slit and ε, β are the emittance and beta function at the slit. σ_δ is the uncorrelated energy spread and it limits the achievable length of the bunchlets. The temporal or longitudinal separation between the bunchlets is given by

$$\Delta z = \frac{1 + hR_{56}}{|Dh|}s_x \tag{2}$$

if s_x is the separation between the two slits. Inserting values of slit width of $w_x = 0.3\,\mathrm{mm}$ and separation of $s_x = 1\,\mathrm{mm}$ and furthermore assuming the beam parameters given in table 1 we find that the dispersion at the slit is $D = 0.24\,\mathrm{m}$, the R_{56} is $0.11\,\mathrm{m}$ and the rms width of the beam at the slit due to the chirp is $W_x = 5.7\,\mathrm{mm}$. This results in the length of the bunchlets to be $\sigma_s \approx 19\,\mu\mathrm{m}$ or about $50\,\mathrm{fs}$ and the separation is $\Delta z = 52\,\mu\mathrm{m}$ ($150\,\mathrm{fs}$) per mm slit separation. The distance between bunchlets can be adjusted by making the slit separation variable. Two vertical slits are arranged almost parallel, but with a small angle relative to one another. Then, moving the collimator vertically will adjust the location where the beam intercepts the slits and will vary the bunchlet separation. The

Table 1: Input parameters for the chicane.

Quantity	Symbol	Value	Unit
Energy	E	10	MeV
Relative momentum spread	σ_p	10^{-4}	
Bunch length	σ_z	3	mm
Normalized Emittance	ε_n	1	mm-mrad
Beta function	β	1	m
Energy chirp	h	-8	1/m
Length between dipoles	L	1	m
Angle	ϕ	13.6	degrees
Beam width at slit	W_x	5.7	mm
Slit width	w_x	0.3	mm
Slit separation	s_x	1	mm

Table 2: Output parameters for the chicane.

Quantity	Symbol	Value	Unit
Compresssion	$1/(1 + hR_{56})$	10	
Bunchlet length	σ_s	19	μm
Bunchlet separation	Δz	50	μm (for s_x =1 mm)
Bunchlet intensity	f	2	% of initial charge

minimum length of the bunchlets can be affected by increasing the chirp h slightly, which reduces the length of the bunchlet down to $12\,\mu$m. Else the lower limit is determined by the incoherent momentum spread σ_p and improving it to 10^{-5} would result in a slightly reduced bunchlet length of $\sigma_s \approx 15\,\mu$m. This would require, however, a high-performance photo injector. More optimization is certainly needed.

We need to note that the charge in the bunchlets is drastically reduced due to the heavy collimation. We can estimate the fraction f of the total beam that passes through one slit to be $f = w_x/\sqrt{2\pi}W_x \approx 2\,\%$. Or, in other words, only about two percent of the total current populates the bunchlets. This might cause intensity problems for the diagnostic system. Note also, that varying the separation of the slits moves the slits away from the center of the distribution and will cause some variation of the intensity. This can be calculated and taken into account in the analysis.

Once we have two consecutive bunchlets following one another with a variable distance we propose to pass them through an accelerating structure mounted on a retractable system, that allows to place it into the beam's path and manipulate its transverse position with micron precision. Comparing the energy of the second bunch with respect to the first with acceleration structure in or out of the beam line will give a measure of the

magnitude of the wake field. Moving the structure transversely and observing changes in the relative position of the two bunchlets on a screen will give information about the transverse wakes. We consider it essential to have the structure retractable in order to compare the in and out configuration without changing any other accelerator parameter. The latter would introduce systematic changes in the orbit that would swamp the minute signals we can expect from the very low-intensity bunchlets with charges of only a few pC. Increasing the slit width w_x helps somewhat. Its effect on the bunch length can be alleviated by fine-tuning $1 + hR_{56}$ as can be seen in eq. 2.

In this scenario we have very short bunchlets and the loss factor of the the acceleration structure is close to the maximum value of $1 \, \text{kV/pC}$, such that a $10 \, \text{pC}$ bunchlet will cause up to $10 \, \text{kV}$ energy loss for the trailing bunchlet. Considering the beam energy of $10 \, \text{MeV}$, we will expect a change of relative momentum of up to 10^{-3}. Detecting this reliably would require a spectrometer with a resolution an order of magnitude better, thus we aim for $\delta p/p \approx 10^{-4}$ provided that we can start with bunch intensities from the electron gun on the order of $1 \, \text{nC}$.

The transverse deflection experienced by the trailing bunchlet due the transverse wakes is on the order of $3 \, \text{kV/pCm}$ using the above scaling with 2/3 power of the kick factor, we find that a $10 \, \text{pC}$ bunchlet receives a transverse kick of $30 \, \text{V/mm}$ and that translates into an angle of $3 \, \mu\text{rad}$, causing $30 \, \mu\text{m}$ position changes at monitors located at positions with beta functions on the order of $10 \, \text{m}$. This should be measureable using high-resolution cavity-based position monitors and using several, say 10, in a row in a dedicated diagnostic beam line will improve the resolution of the deflection by a factor of 3. It remains to separate the two bunchlets, since we only want to find the position of the trailing bunchlet. This can be achieved in a dipole magnet, where the leading bunch, that already initially has higher energy is deflected less and can be taken out by a septum magnet or a collimator, whereas the trailing bunchlet continues on to the diagnostic beam line, probably FODO, with many position monitors.

4   Conclusion

It appears that directly measuring short-range wake fields of accelerating structures is difficult, but marginally feasible. We can either use the superb diagnostic in a ring or creating a bunchlet doublet to excite and probe the wakes, both longitudinally and transversely. In any case do we have to remotely insert the structure into the beam line to compare the in- versus the out-configuration, otherwise systematic differences will spoil the realiability of the measurement.

Since future linear accelerators will require smaller longitudinal and transverse sizes in order to achieve their performance goal which, at some point will be limited by short range wake fields. Since accelerators get more expensive with every generation, experimental test to complement and benchmark numerical simulations are necessary to ensure that the performance of the accelerator is guaranteed.

The results in this note are indicative that using one or both of the suggested exper-

iments are promising, though rather demanding and cutting-edge, and we plan to study their feasibility further of a rather by at least one order of magnitude in accuracy. In that process we need to identify suitable accelerators and probably need some moderate diagnostics for a proof-of-principle test.

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