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STUDIES OF SINGLE AND MULTI-BUNCH INSTABILITIES IN LINACS USING RF-TRACK

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Abstract

In high-intensity linacs, bunch-to-bunch effects due to the excitation of short and long-range wakefields can lead to beam instabilities and beam breakup. Wakefields can be due to resistive or geometric effects excited in the RF structures or in the beam pipe. From version 2.3.0 onwards, the particle tracking code RF-Track has been modified to implement a multi-bunch beam model that simplifies and optimises the calculation of single and multi-bunch effects. The effect of wakefields on the beam is assessed by computing the action amplification due to incoming jitter. The jitter amplification due to multi-bunch effects is evaluated using a 1 GeV electron linac example.

INTRODUCTION

Linacs for high-energy physics colliders, medical applications, compact X-ray sources, such as Inverse Compton Scattering sources, and compact accelerator-based neutron production require high-intensity beams. When high-intensity beams are injected into linacs, intensity-dependent effects such as beam loading and short- and long-range wakefields in the accelerating structures must be considered. The effect of beam loading is primarily to reduce the effective accelerating gradient available in the RF structures as high-charge bunches travel through them. The effect of wakefields degrades the beam quality by causing transverse deflections, energy loss, emittance growth, energy spread increase and ultimately, beam breakup. In this paper, we focus on evaluating the effect of wakefields on beam jitter, both in single and multi-bunch operation, using the CERN tracking code RF-Track [1]. This code can also simulate the effects of beam loading, as presented in Ref. [2].

RF-Track v2.3.0

Initially developed for the design and optimisation of a medical proton and light ion linac [3], RF-Track has evolved over the years to extend its simulation reach and range of applications, becoming the primary design tool for many projects and studies: e.g., the “Deep Electron FLASH Therapy” (DEFT) facility [4], the positron sources of SuperKEKB [5], the CLIC and FCC-ee injector linacs [6, 7], Inverse Compton scattering sources [8], and the cooling channel of a future muon collider [9].

Up to version 2.3.0, RF-Track could only simulate single bunches. It was still possible to simulate bunch-to-bunch long-range effects using the standard trick of creating a single “super bunch” with all individual bunches suitably separated in time. This workaround, while working in some cases, introduced several inconveniences: it complicated the post-processing of the output data to separate the individual bunches; it undermined the simulation of single-bunch effects such as short-range wakefields or space-charge, whose algorithms are designed to operate in the short-range regime.

In version 2.3.0, the tracking core of RF-Track has been rewritten to handle multi-bunch beams rather than single bunches, introducing the new object `Beam`. In RF-Track, a “Beam” is a set of single bunches that the user can specify individually at arbitrary distances from each other. The main innovation and benefit of the new object is that it allows a specialised implementation of long-range collective effects for multi-bunch beams. For example, specific single-bunch effects such as space charge are applied to each bunch individually, while bunch-to-bunch effects such as long-range wakefields can be computed considering the large spacing between bunches using a dedicated long-range algorithm. In addition, accessing information about each bunch and analysing the results after tracking is now much easier. The new “Beam” model also increases flexibility, for example, by allowing the user to simulate bunch trains where some bunches are single particles while others are multi-particles, thus speeding up simulations where one needs to focus on a specific bunch. Moreover, the bunches can be arbitrarily and irregularly spaced, have different charges and even be of different species.

It should be noted that these changes have been implemented to maintain backward compatibility with older simulation scripts, so when the user is working with single bunches, RF-Track behaves in the same way as in previous versions.

Example of Beam Definition

The following lines provide an example declaration of a train consisting of 30 equally spaced bunches:

```
% Define a bunch
bunch = Bunch6d(mass, charge, q, phase_space);
% Define the train structure
num_of_bunches = 30; % train length
bunch_spacing = 1/3 * ns; % bunch spacing
% Define a beam
B0 = Beam(bunch, bunch_spacing, num_of_bunches);
```

If “LINAC” is an arbitrary beamline, then `B1 = LINAC.track(B0);` is the outcoming train, where `B1{1}` is the first bunch, `B1{2}` is the second, etc.

JITTER AMPLIFICATION

Single-bunch Short-range Wakefields

A detailed explanation of the Wakefield models implemented in RF-Track was presented in Ref. [10]. The effect of short-range wakefields on a bunch, in addition to introducing correlated energy spread and slice emittance growth, is also to deflect the centre of mass of the bunch outwards in the transverse plane, effectively increasing the amplitude of any incoming betatron oscillation. If the oscillation is due to an incoming beam jitter, short-range wakefields can thus lead to jitter amplification, which might have a detrimental impact on the downstream accelerator sections. In this section, we outline a robust method to evaluate the jitter amplification factor of a beamline.

The jitter amplification factor can be calculated analytically using a point-like bunch approximation and making other simplifying assumptions, as described for example in Ref. [11]. However, an accurate estimate of the effect taking into account the full 6D dynamics of the bunch particles can only be obtained by computer simulation. As a robust technique to evaluate the jitter amplification factor, we propose to transport a set of bunches through the beamline, each starting from a different position in the canonical phase space $x - P_x$, drawing an ellipse, and then to evaluate the ratio between the area of the ellipse at the end of the beamline and the initial one. This ratio is the jitter amplification factor.

An interesting consideration about the jitter amplification factor is that, for oscillations reasonably within the beamline aperture, it is independent of the amplitude of the incoming beam offset, making it a fairly general and practical estimator.

In the case of a purely linear system with no wakefield effects, the area of the initial and final ellipses would be equal and the jitter amplification factor would be 1. In the presence of short-range wakefields, the area is increased at each structure, and so is the jitter amplification factor.

We use an X-band linac from 100 MeV to 1 GeV, consisting of a regular FODO lattice with four RF structures between two consecutive quadrupoles, as an example. The main parameters of this setup are listed in Table 1. The RF structure used is based on the design described in Ref. [12], and the short-range wakefield model used is based on the approximation proposed in Ref. [13]. Figure 1 shows the ellipse at the beginning and at the end of the X-band linac, together with the ellipses obtained when the simulation of the short-range wakefields has been switched on and off. When wakefield effects are off, the area of the initial and final ellipses are identical.

Figure 2 shows the jitter amplification along the linac. When the wakefield effects are switched off, the ellipse area along the linac is very well preserved, and the jitter amplification remains constant and equal to 1. When wakefield effects are on, one can see an increase in the jitter amplification and its dependence on the focusing strength of the lattice. Stronger focusing helps reduce the jitter amplification factor.

Table 1: Parameters of the Example Linac

Parameter	**Value**	**Units**
Initial energy	100	MeV
Final energy	1000	MeV
RF frequency	11.9942	GHz
Accelerating gradient	60.7	MV/m
Structure's length	21.2	cm
Iris aperture	6.3– 4.7	mm
Total number of structures	72	#
Bunch charge	1	nC
Bunch length	300	µm/c
Initial energy spread	0.1	%
Normalised emittance x/y	1	mm.mrad
Nb. of bunches per train	30	#

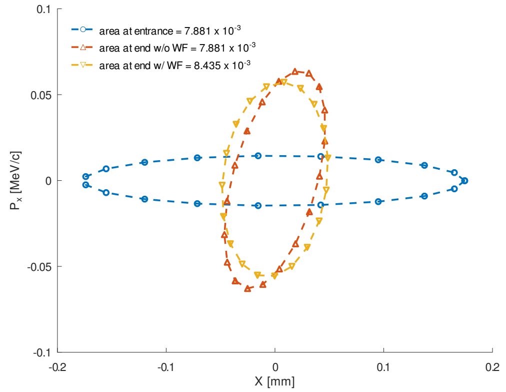

Figure 1: The circles indicate the phase space coordinates at the linac start. The triangles show the corresponding coordinates at the linac end: without wakefields (triangles pointing upwards) and with wakefields (triangles pointing downwards). The ratio of the areas of the triangle ellipses to the circle ellipse is the jitter amplification.

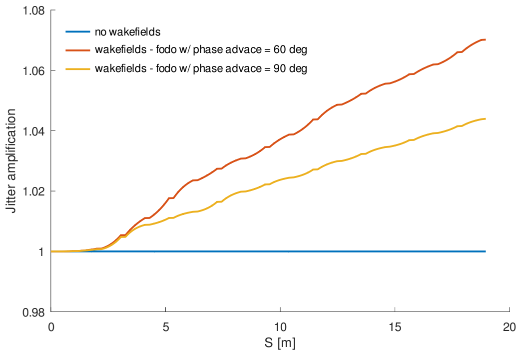

Figure 2: Evolution of the jitter amplification along the 1 GeV linac, due to single-bunch effects, as computed by RF-Track.

Multi-bunch Long-range Wakefields

When trains of tens or hundreds of bunches are accelerated, high-order modes (HOM) excited by the beam and trapped in the RF structures can persist long enough to cause bunch-to-bunch effects, such as strong transverse deflections leading to an increase in the projected emittance or even beam breakup. Techniques such as detuning and damping can reduce the amplitude of the HOMs at the cost of a more complex RF design and manufacturing. Complementary, stronger optics can also help reduce the effects of HOMs at the cost of an increased number of quadrupoles and greater chromatic effects. The optimal solution to fulfil the beam requirements is a compromise between RF and beam dynamics constraints, which is usually achieved by combining the different techniques.

A practical method used in CLIC and other projects with critical beam stability requirements is to damp the HOMs so that each bunch excites a wake that affects only its immediately following bunch [14]. Beam dynamics simulations are then used to evaluate the strongest kick that can be sustained before the performance requirements are exceeded. Focusing on the kick “at the next bunch” allows one to abstract from the spacing between the bunches and focus on the maximum kick strength alone.

As an example, we consider the case where all bunches along the train enter the line with the same offset. This is usually called “coherent” jitter. Figure 3 shows the results of a transverse wakefield scan performed in RF-Track. It is customary to perform these calculations assuming point-like, rigid bunches, as this approximation matches the assumption made when using analytic estimates. The simulation confirms that no jitter amplification occurs when the excited kick “at the following bunch”, W_t, is zero – as expected.

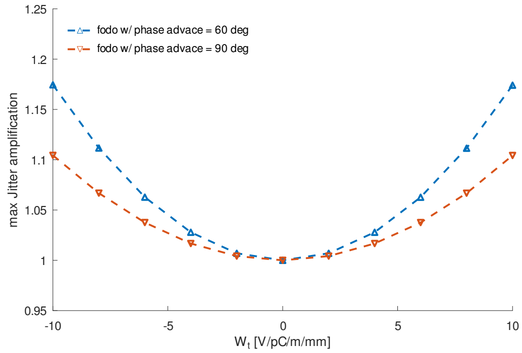

Figure 3: Multi-bunch jitter amplification due to long-range wakefield effects, as a function of the strength of the kick exerted by each bunch on its immediately following bunch.

Since RF-Track can simulate beam elements with any number of overlapping collective effects active per element, using the new `Beam` definition, it is easy to perform a multi-bunch simulation where each bunch along the train is represented by a full 6D particle distribution, and where short- and long-range wakefield effects are active simultaneously. Figure 4 shows the results of a W_t scan in this case. The simulation shows that the jitter amplification factors due to short- and long-range wakefields add up and that both effects must be considered. This plot provides tolerances for the RF design, as it sets the threshold for the strongest sustainable kick that can be excited in the structure. The jitter amplification experienced by each bunch in the train for the largest kick strength, $W_t = 10$ V/pC/m/mm, is shown in Fig. 5.

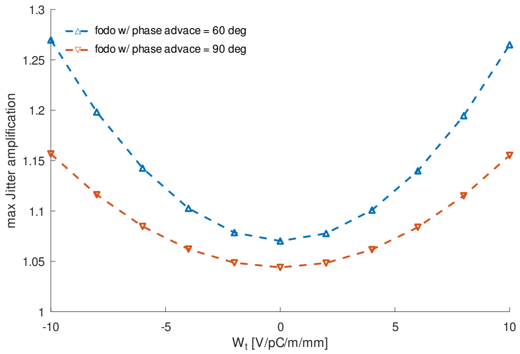

Figure 4: Multi-bunch jitter amplification due to short- and long-range wakefield effects simultaneously.

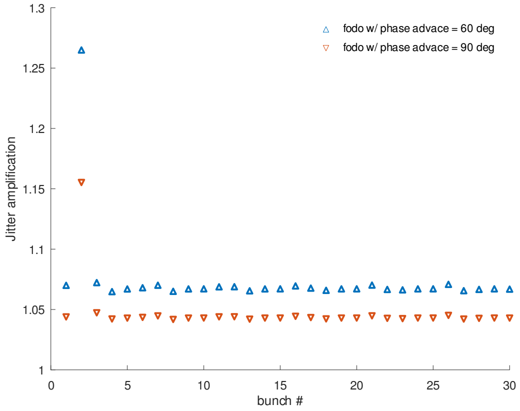

Figure 5: Multi-bunch jitter amplification along the train. Since the long-range wakefield affects only “the following bunch,” the amplification factor de-coheres rapidly.

Simulation Speed

The simulation of 30 bunches with 1’000 particles per bunch, with short- and long-range wakefields applied in each of the 72 linac accelerating structures over ten kicks, took about 10 seconds on an ordinary laptop. Each point in all figures, except for Fig. 1, was evaluated by tracking 16 trains to paint the phase space ellipse.

CONCLUSIONS

This paper describes a new beam model implemented in RF-Track to ease the definition, manipulation, and simulation of multi-bunch beams in the presence of collective effects. It also presents a robust method to assess the impact of short- and long-range nonlinear effects on the beam jitter, such for example as wakefields. Compared with analytic methods presented in the literature, this method is more general, as it applies to multi-particle non-Gaussian bunches and to wakefield-dominated beamlines. This new beam model enhances RF-Track’s simulation reach and improves the dialogue between beam dynamics and RF design by allowing the inclusion of complex beam dynamics requirements already in the design process.

REFERENCES

[1] A. Latina, “RF-Track Reference Manual”, CERN, Geneva, Switzerland, 2021. `doi:10.5281/zenodo.4580369`

[2] J. Olivares Herrador *et al.*, “Beam loading compensation in charge-varying scenarios with RF-Track”, presented at the 32nd Int. Linear Accel. Conf. (LINAC’24), Chicago, IL, USA, Aug. 2024, paper MOPB041.

[3] S. Benedetti, A. Grudiev, and A. Latina, “High gradient linac for proton therapy”, *Phys. Rev. Accel. Beams*, vol. 20, no. 4, p. 040 101, 2017. `doi:10.1103/PhysRevAccelBeams.20.040101`

[4] C. Rossi *et al.*, “The deep electron FLASH therapy facility”, presented at the 32nd Int. Linear Accel. Conf. (LINAC’24), Chicago, IL, USA, Aug. 2024, paper WEYA002, this conference.

[5] F. Alharthi *et al.*, “Benchmarking the FCC-ee positron source simulation tools using the SuperKEKB results. Benchmarking the FCC-ee positron source simulation tools using the SuperKEKB results”, *J. Phys.: Conf. Ser.*, vol. 2687, no. 2, p. 022 010, 2024. `doi:10.1088/1742-6596/2687/2/022010`

[6] Y. Zhao, H. Bajas, S. Döbert, A. Latina, and L. Ma, “Optimisation of the CLIC positron source”, in *Proc. 12th Int. Particle Accel. Conf.*, Campinas, Brasil, May 2021 (online). `doi:10.18429/JACoW-IPAC2021-WEPAB014`

[7] Y. Zhao *et al.*, “Optimisation of the FCC-ee positron source using a HTS solenoid matching device”, in *Proc. 13th Int. Particle Accel. Conf. (IPAC’22)*, Bangkok, Thailand, Jun. 2022, pp. 2003–2006. `doi:10.18429/JACoW-IPAC2022-WEPOPT062`

[8] V. Musat *et al.*, “A compact water window X-ray source based on inverse Compton scattering”, in *Proc. 15th Int. Particle Accel. Conf. (IPAC’24)*, Nashville, TN, USA, May 2024, pp. 441–444. `doi:10.18429/JACoW-IPAC2024-MOPG76`

[9] B. Stechauner *et al.*, “Comparison of tracking codes for beam-matter interaction”, in *Proc. 14th Int. Particle Accel. Conf.*, Venice, Italy, May 2023, pp. 921–924. `doi:10.18429/JACoW-IPAC2023-MOPL165`

[10] A. Latina, “Update of the tracking code RF-Track”, in *Proc. 12th Int. Particle Accel. Conf. (IPAC’21)*, Campinas, Brasil, May 2021 (online), pp. 4180–4182. `doi:10.18429/JACoW-IPAC2021-THPAB203`

[11] D. Schulte, “Multi-Bunch calculations in the CLIC Main LINAC”, in *Proc. Particle Accel. Conf. (PAC’09)*, Vancouver, BC, Canada, May 2009, pp. 4664–4666. `https://accelconf.web.cern.ch/PAC2009/papers/fr5rfp055.pdf`

[12] W. L. Millar *et al.*, “High-power test of two prototype x-band accelerating structures based on SwissFEL fabrication technology”, *IEEE Trans. Nucl. Sci.*, vol. 70, no. 1, pp. 1–19. `doi:10.1109/TNS.2022.3230567`

[13] K. L. F. Bane, “Short range dipole wakefields in accelerating structures for the NLC”, Stanford Linear Accelerator, Stanford, CA, USA, Rep. SLAC-PUB-9663, LCC-0116, Mar. 2003.

[14] A. Grudiev and W. Wuensch, “Design of an x-band accelerating structure for the CLIC main linac”, in *Proc. 24th Int. Linear Accel. Conf. (LINAC’08)*, Victoria, BC, Canada, Sep.-Oct. 2008, pp. 933–935. `https://accelconf.web.cern.ch/LINAC08/papers/thp062.pdf`