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# Implications of long-range wakefields on multi-bunch beam dynamics in the ILC with a new low surface field superconducting cavity

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ABSTRACT

This article focusses on a beam dynamics study for the linacs of the ILC. In particular, the impact of long-range transverse wakefields on the beam quality is studied for the case in which the ILC would be built using the new low surface field (NLSF) superconducting cavities. This presents an alternative design to the baseline TESLA-style cavities. The progress of the beam down ~10 km of each linac is simulated using the tracking computer code PLACET. In addition, the results of an analytical matrix method, in which the beam is subjected to identical wakefields from each cavity, are also presented. Both systematic and random errors, arising as a natural process during fabrication, are implemented in the beam tracking study. The latter source of error is found to be beneficial, as emittance dilution is reduced due to the beam receiving non-coherent kicks.

## 1. Introduction

We explore beam dynamics in high gradient superconducting radio frequency (rf) cavities. These are intended to be used for the international linear collider (ILC) [1] and also for light source applications such as European XFEL [2]. This linear collider is designed for electron–positron collisions at an initial centre of mass energy of 500 GeV with a peak luminosity of $2\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the baseline design. This also provides a path for a future upgrade to 1 TeV [1] in order to facilitate new physics regimes to be explored. The collision energy at the interacting point (IP) is achieved by accelerating the beams through a combined length of 23 km of linacs. The superconducting technology utilised entails a long bunch train (~1 ms) in which the majority of the rf power goes into acceleration of the beam (and little is lost to the cavity walls). However, a not inconsiderable amount of energy is required to cool the cavities down to cryogenic temperatures (2 K)—and this of course impacts the overall rf efficiency of the collider. The baseline design includes 2625 bunches, each of which is spaced from their immediate neighbours by 369 ns. Each bunch consists of approximately $2\times10^{10}$ particles. A short summary of the key beam parameters used in this study is provided in Table 1 (selected parameters taken from [2]).

The wakefields in the superconducting L-band cavities are diminished compared to normal conducting counterparts. This is due to the larger apertures (the iris radius is ~35 mm compared to typical X-band cavities which have a corresponding average iris radius of ~4 mm). As a result, the alignment tolerances in the ILC cavities are considerably relaxed compared to their X-band counterparts [3].

In addition to the ILC baseline TESLA cavities, there are several designs [4], which have focussed on enhancing the accelerating gradient, with a view to reduce the overall footprint of the collider. These new designs have the potential to reduce the overall cost of the collider. The approach focussed on in this work, is the new low surface field (NLSF) [5] design. This design provides minimum surface electromagnetic fields whilst allowing sufficient coupling between all cells in each 9-cell cavity—such that fabrication tolerances are acceptable [5].

We track the beam down each linac, consisting of ~11 km of cavities, and monitor its progress under the influence of self-excited long-range transverse wakefields. In our detailed simulations we confine ourselves to studying the impact of injection offsets on the emittance dilution. We then contrast the emittance dilution in the NLSF design to that of the TESLA-style design. Both systematic and random frequency errors are included in this study—both of which will inevitably occur as a result of fabrication of ~16,000 cavities.

An overview of the rf design of the NLSF cavity is described in [5]. The next section provides a summary of extant tracking codes together with a description of a matrix-based analytical approach. This enables a rapid determination of the beam quality. The

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**Table 1**
Selected beam parameters in the ILC main linac [1].

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Initial beam energy, $E_0$ | 15 GeV | Initial horizontal emittance, $\gamma\epsilon_x$ | 8.4 μm |
| Final beam energy, $E$ | 250 GeV | Final horizontal emittance, $\gamma\epsilon_x$ | 9.4 μm |
| Particles per bunch, $N_e$ | $2\times10^{10}$ | Initial vertical emittance, $\gamma\epsilon_y$ | 24 nm |
| Bunch spacing, $t_b$ | 369 ns | Final vertical emittance, $\gamma\epsilon_y$ | 34 nm |
| Bunch train length, $t_t$ | 969 μs | Vertical beam size, $\sigma_y$ | 1.6 μm |
| Number of bunches, $n_b$ | 2625 | Initial energy spread, $\sigma_E/E$ | 1.5% |
| Bunch length, $\sigma_z$ | 300 μm | Final energy spread, $\sigma_E/E$ | 0.10% |

penultimate section focuses on a beam dynamics study in which tracking results are presented. The final section provides concluding remarks on the suitability of the NLSF cavity for linear collider applications, from a beam dynamics perspective.

## 2. Beam dynamics analysis

### 2.1. Overview of beam dynamics study

Here we analyse the dynamics of beam dilution due to long-range transverse wakefields. In particular we contrast the beam dynamics issues in the baseline cavities to those in the NLSF-style cavities. The latter cavities have resulted from an optimisation process in which various geometrical parameters were varied. A number of potential candidates arose from this optimisation process. However, in this work we focus on the NLSF cavity, which is most practical from a fabrication perspective and in particular in terms of cleaning the surface of the cavity [5]. We track the complete ILC bunch train down the linac to the IP.

There are several codes available to conduct a beam dynamics tracking study and in the next section we discuss their applicability and merits.

### 2.2. Overview of beam dynamics tracking codes for linear collider applications

Over the course of a few decades, several computer codes have been developed to track the progress of charged particle beams under the influence of rf magnetic and electric fields. Provided the beams are accelerated to relativistic velocities, these codes are able to neglect space charge forces, and this is of course readily achieved after 0.5 MeV for electron acceleration. However, longitudinal and transverse kicks imparted to the beam motion by self-excited wakefields are included in all codes developed for linear collider applications. Here we provide a few remarks on the salient features of some important beam dynamics effects which are included in current and in recent past, codes in usage—MERLIN [6], LIAR [7], Lucretia [8] and PLACET [9], in particular. Each of these codes were developed at different scientific laboratories as a tool to solve specific beam dynamics problems for linear colliders. It is interesting to note that initially there were significant discrepancies seen in comparisons between several of these mainstream codes [10].

Two beam representations are generally used: firstly, the sliced beam representation, where each bunch is longitudinally divided into slices. Each slice contains a small number of macroparticles, which have a fixed longitudinal position $s$ but their energies can differ; secondly, the beam is modelled as a large ensemble of Gaussian distributed single particles.

The first representation is beneficial as it allows the tracking time throughout the rf structures to be minimised. Indeed, the computation time scales are in direct proportion with the square of the number of particles. However, provided only two orders of transverse degrees of freedom are needed to represent interaction sextupoles, octupoles and other higher order multipoles, a sliced beam is sufficient and we utilise this method in our simulations.

One of the popular codes for beam dynamics simulations in linear colliders, and indeed for hadron colliders, is MERLIN (which is written in the computer language C++) developed by N. Walker. This code has already been used extensively to simulate beam dynamics in the main linac, beam delivery system, bunch compressor and the damping rings for the ILC. It includes methods for specifying and applying a wide range of alignment, field and diagnostics errors. MERLIN supports both beam representations. Short-range wakefields are included with the kick applied at the exit of each rf cavity. Long-range wakefields are implemented and their effects have been studied to understand the impact of wakefields and beam halo in collimation systems for both lepton and hadron accelerators.

The Linear Accelerator Research (LIAR) simulation programme was written in the FORTRAN computer language by several accelerator physicists, initially based at the SLAC National Accelerator Center, to study beam dynamics, tuning and beam instrumentation algorithms for the Next Linear Collider (NLC) and Japanese Linear Collider (JLC). The beam representation used in the LIAR code is based on the macroparticle description. In this representation all macroparticles are monoenergetic and have distinct $z$-positions. Since the DIMAD [11] tracking engine has been integrated into LIAR, the second beam representation is also available to the user of the code. It has been successfully used and verified for start-to-end simulations of the NLC and also for TESLA-style cavities and for the ILC.

Lucretia is a Matlab based simulation package written in C++ for the study of single-pass electron beam transport systems. This code extends LIAR's capabilities to include realistic simulations of accelerator operations, tuning, and stabilisation. This code is suitable for simulating the operation of bunch compressors, linear colliders, beam delivery systems and linac-driven free electron lasers. Luctretia tracks only single particles beams. Rf cavities support single bunch wakefields as well as multi-bunch transverse wakefields. Since its early beginning it has been collectively improved over the years by several scientists in addition to the original author, P. Tenenbaum. It has been benchmarked against several codes—and in particular has been shown to be in excellent agreement with LIAR.

The tracking code Program for Linear Accelerators Correction Efficiency Tests (PLACET) was originally developed by D. Schulte to study beam dynamics and tuning of the drive beam decelerator of CLIC [12]. Since its inception in 1998 this code has been significantly improved [13,14] due to the increasing demand from growing community of users in framework of the CLIC and ILC projects. Originally written in C, PLACET is now entirely written in C++ and is a stable and mature tool for simulating both beam transport and orbit correction in electron–positron linear colliders.

PLACET is an open-source code, which relies on open-source components. Its interface is based on both Tcl/Tk and Octave, which provide flexibility in programming of complex beam dynamics simulations. It is relatively efficient, fully programmable, modular and allows the implementation of 4-D and 6-D tracking. During tracking PLACET can switch between the two beam representations, which allow beams in electron–positron linear colliders to be simulated from the exit of the damping rings to the IP. PLACET can be used to simulate element misalignments, ground motions, and arbitrary failures. It has tools to study beam-based alignment of non-linear optical systems and higher order imperfections in magnets. It simulates single-particle, collective, single and multi-bunch effects such as incoherent and coherent synchrotron radiation, short- and long-range wakefields [15], and collimator wakefields [16].