RFTWEAK 5 – AN EFFICIENT LONGITUDINAL BEAM DYNAMICS CODE

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Abstract

The shaping of the longitudinal phase space in bunch compression systems is essential for efficient FEL operation. RF systems and self-field interactions contribute to the overall phase space structure. The design of the various facilities relies on extensive beam dynamics simulations to define the longitudinal dynamics. However, in everyday control room applications such techniques are often not fast enough for efficient operation, e.g. for SASE tuning. Therefore efficient longitudinal beam dynamics codes are required while still maintaining reasonable accuracy. Our approach is to pre-calculate most of the required data for self-field interactions and store them on disc to reduce required online calculation time to a minimum. In this paper we present the fast longitudinal tracking code RFTweak 5, which includes wakes, space charge, and CSR interactions. With this code the full European XFEL with a 1M particles bunch is calculated on the order of minutes on a standard laptop. Neglecting CSR effects this time reduces to seconds.

INTRODUCTION

RFTweak 5 is a fast tracking code for longitudinal phase space dynamics. A strong use case is the online setup of bunch compression in the control room during e.g. SASE tuning. The concept of the code is similar to LiTrack [1], which is written in MATLAB as well. RFTweak 5 includes effects of longitudinal wakes, space charge interactions as well as coherent synchrotron radiation (CSR) emission. While the underlying code is applicable to different electron linacs, the graphical user interface (GUI) of the code is build specifically for FLASH and the European XFEL. An example is shown in Fig. 1.

OVERVIEW OF THE TRACKING PROCEDURE

Beam-lines defined in RFTweak 5 consisting primarily of two different element types. Elements which keep the individual longitudinal particle position offset fixed while the energy is altered (Type 1) and the opposite in which the energy is constant and the position is modified (Type 2). Examples are RF structures or bunch compression chicanes respectively. We assume a sufficiently high beam energy to justify the assumption of fixed longitudinal position offsets in straight sections (Type 1 elements like drifts, quadrupoles, or RF structures). Furthermore, the assumption is made that elements with longitudinal dispersion (Type 2 like chicanes or energy collimator) consist purely of magnetic fields.

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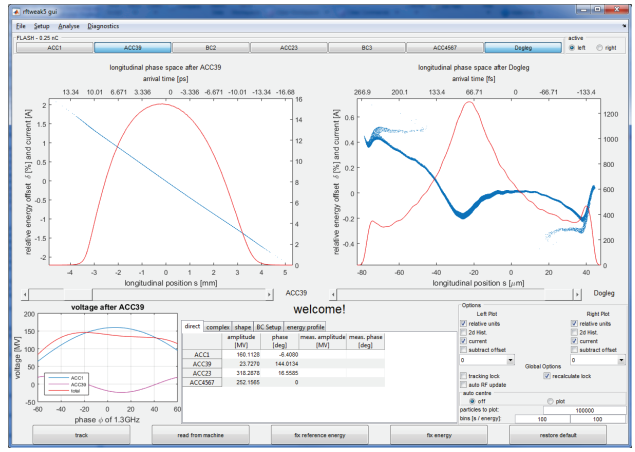

Figure 1: Layout of the main GUI for FLASH. Two phase space distributions are displayed at selected positions along the machine. Various options are available, like the display as point cloud or density histograms or the subtraction of polynomial offsets of various order. RF parameters of the linac can be entered by the user or read from the control system. Resulting voltage profiles after the lineariser cavities are directly displayed.

Self field interactions are neglected but CSR effects can be included as described later.

Both types of elements are described by the polynomial expansion

$$s^i_{n+1} = s^i_n + R_{56}\delta_{E_{i,n}} + T_{566}\delta_{E_{i,n}}{}^2 + \cdots \quad (1)$$

$$\delta_{E_{i,n+1}} = \delta_{E_{i,n}} + A + Bs^i_n + C{s^i_n}^2 + \cdots, \quad (2)$$

with the normalised energy offset $\delta_{E_{i,n}}$ of particle i at element n, some coefficients A, B, C representing longitudinal fields, and the longitudinal dispersion parameters $R_{56}, T_{566}, \ldots$.

In the first case the coefficients are obtained from a Taylor expansion of the longitudinal dispersion [2], in the latter the Taylor series expansion represents the longitudinal electric fields, e.g. the RF voltage.

Elements of Type 2 can include additional effects of longitudinal wakes. These wakes are either determined by geometry (e.g. cavities, changes in beam pipe diameter) or space charge. For FLASH and the European XFEL the geometric wakes are stored in a database [3]. In this database the integrated wakes per section are summarised as greens functions (wakes of an infinitesimal short bunch). Space charge wakes, which are dependent on the energy profile and the transverse beam dimensions, are summarised per section as well. These wake functions are calculated given

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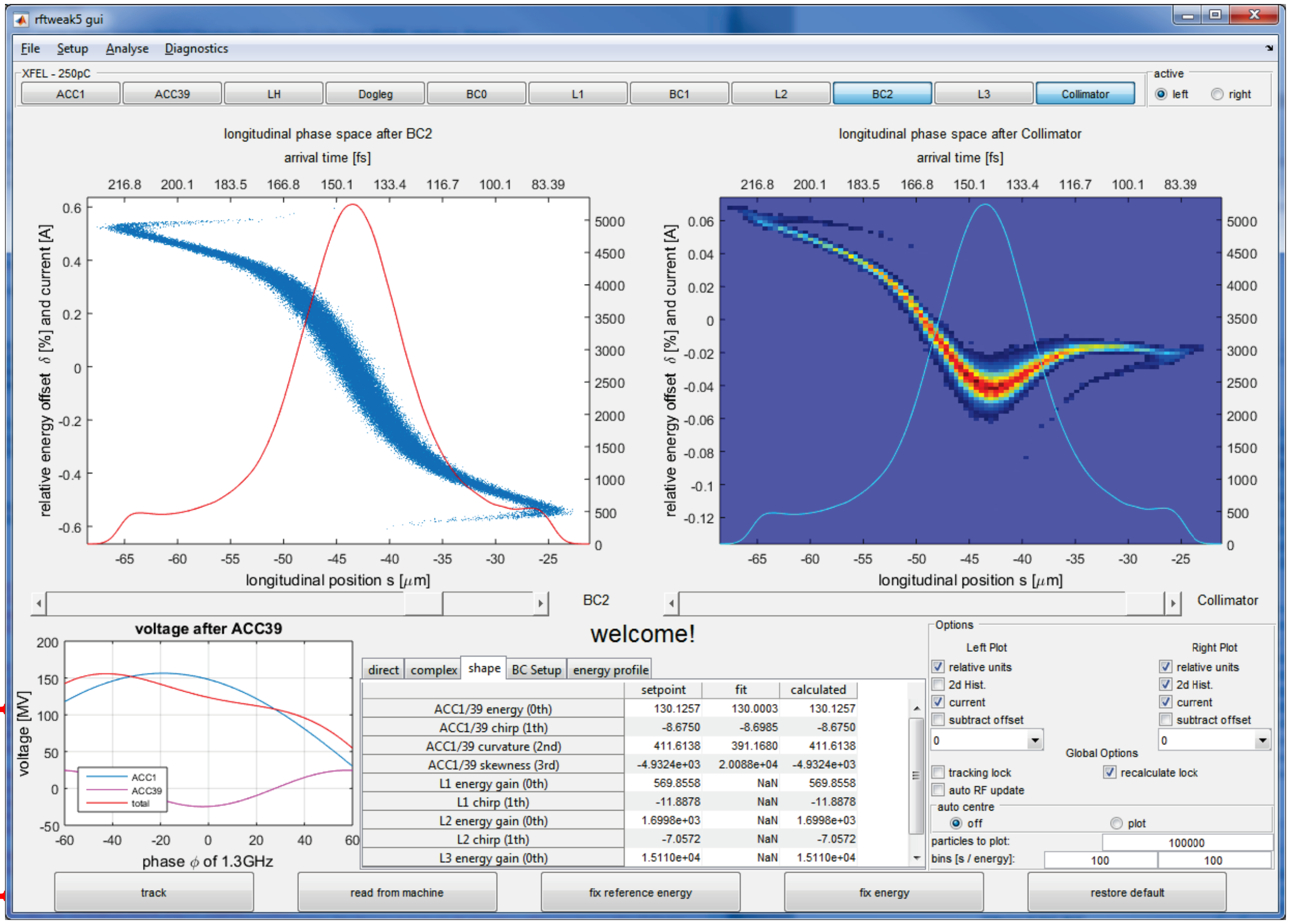

Figure 2: Layout of the main GUI for European XFEL. In this example RF parameters are controlled via abstract knobs corresponding to the desired shape of the longitudinal phase space for compression.

certain assumptions on the transverse dimensions from the design optics and a given energy profile. These wakes kernels are calculated before the actual tracking run, based on assumptions on the transverse beam size and a predefined energy profile. Wake fields, and the corresponding energy changes, are represented by a convolution of the sum of the wake-greens-functions with the actual longitudinal current profile.

Initial particle distributions are taken from ASTRA. From these 6D particle dumps only the longitudinal position and momentum information are directly used. Derived quantities like emittance or beam spot size are calculated and stored for later usage. The booster, ACC1 in the example of FLASH, is included in these ASTRA runs. To accommodate a variable setup of the booster in the code we apply the RF tracking first backwards to the entrance and then forward again.

To obtain CSR wakes in the relevant sections transverse phase space information are required. They are estimated from the initial particle distribution moments and linear transport from the start to the sections containing CSR effects. The tracking consists of a sequence of transport- and wake-steps. That transport is represented by 4D coefficients up to second order while the CSR wake kernels are taken from pre-calculated tables stored on disc.

Since these tables contain integrated wakes as well large transport steps, not necessarily smaller than the magnet dimensions, are possible. This allows for large tracking steps and thus efficient CSR calculations. The pre-calculation of these tables, however, can be very demanding. Especially since the tables need to be determined for each possible bending angle of the chicanes.

PROGRAM OVERVIEW

The principles outlined in the last section are combined into a MATLAB graphical user interface for use at the DESY FLASH and the European XFEL facilities. This graphical user interface was designed using the MATLAB datagui library developed at DESY [4].

The main functionality of the code is the ability to manipulate RF parameters of the machine and directly observe the resulting longitudinal profiles and phase space distributions, allowing for intuitive setup of bunch compression scenarios.

Bunch compression and the required shaping of the longitudinal phase space is not determined by individual RF stations voltage V and phase φ alone, but by an interplay of multiple stations. Therefore it is convenient to accept not only the voltage and phase of the individual stations

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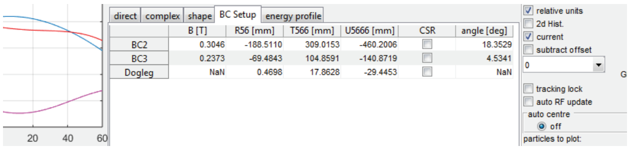

Figure 3: An example of the setup of dispersive sections. While the chicanes can be adjusted by the field, or bending angle, the dogleg or collimator sections are represented by the matrix elements. CSR calculations can be activated for each chicane individually.

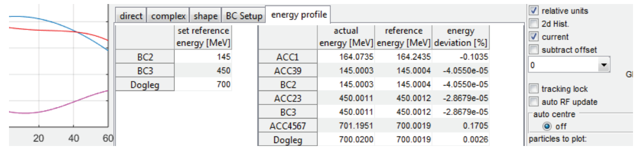

Figure 4: An overview of the energy profile in the currently selected model. On the left hand side the energies at the chicanes are defined as a basis for the wake table calculations. on the right hand side the actual profile is compared with these set values and the deviation is monitored.

as input parameters, as shown in Fig. 1. An obvious disadvantage of direct voltage and phase setup is the fact that each of these knobs changes the beam energy. However the compression is mostly tuned with a fixed beam energy at the chicanes while the chirp needs to be modified. Our approach here is to allow the user to set the RF not in Polar but in Cartesian coordinates, namely the real and imaginary part of $V \cdot \exp(i\varphi)$. The energy gain of a bunch is determined only by the real part while the imaginary part determines the chirp. This is equivalent to set a voltage V_0, the net energy gain, and to make the actual voltage a function of the phase as $V = V_0 / \cos(\varphi)$.

In general compression tuning is more involved than correcting the voltage for off-crest acceleration to maintain energy. The total, voltage especially of the booster and lineariser higher harmonic cavity, upstream each chicane is important. In [5] a model is developed which allows to calculate the required RF parameters resulting in desired phase space shapes, namely the polynomial expansion of the longitudinal position correlation upstream and after each chicane. In Fig. 2 the input mask of these parameters is shown. The user can set-up the linearisation of the phase space basically independent of the desired chirp. A later modification of the chirp maintains the shape of the current profile but changes the bunch length, which is very useful for FEL tuning or setup of seeding schemes.

Apart from the RF parameters the bunch compressor chicanes can be set-up or read from the control system (see Fig. 3). CSR interactions are activated for each chicane individually. Since the charge density is highest after the last chicane it is often accurate enough to only calculate the CSR effects optimising calculation time.

As mentioned above part of our approach for fast calculations self-field effects are treated by pre-calculated files stored to disc. As an example the CSR kernel tables for European XFEL are about 4 GB of data since data needs to be calculated for each bending angle and each chicane (in our case tables are calculated in 0.05 deg steps covering the corresponding bending angle range of the chicanes). Kernel files for the space charge and wake calculations (about 150 MB for European XFEL) are energy dependent, so they have, in contrast to CSR tables, be recalculated if the energy profile changes to obtain correct results. This calculations take about 2 minutes on a standard laptop, so they can in principle be recalculated "on-the-fly".

Since the RF parameters are meant to be modified we can not assume that the energy profile is constant. The tool is constantly calculating the deviation of the actual model profile with the set-values for the tables (see Fig. 4). We estimate that energy deviations up to about 5% are tolerable before the tables need to be recalculated. The GUI offers different methods to deal with larger energy deviations. Either the voltages are modified automatically in an iterative process that the beam energy matches the target values ("fix energy" button) or the target energy profile is set to the actual values, recalculating the tables ("fix reference energy" button).

SIMULATED DIAGNOSTICS

To further help the user in the control room setting up the machine actual diagnostic components are simulated.

An important tool is the use of a transverse deflecting structure (TDS) in combination with a spectrometer dipole to image the longitudinal phase space (see Fig. 5). The image is obtained from the 2D longitudinal phase space distribution using 6D transport between the deflector and the screen including the whole beam-line section. The missing transverse components are randomised based on the design Twiss parameters at the deflector assuming some user defined slice emittance. The effect of the transverse deflecting structure is included as a transport matrix [6]. As seen in Fig. 5 it is valuable to see how the resolution limitations of such measurements "smear out" the current profile to help understand high frequency excitations on the beam even if sharp edges are not visible in the TDS images.

Another important diagnostic are the bunch compression monitors (BCM). These diagnostics measure integrated intensity from coherent radiation to give a single number corresponding to the bunch length. Such devices are valuable for setup and feedback systems. In the GUI (Fig. 6) this number is calculated from the longitudinal profile following the methods outlined in [7].

The virtual diagnostics offered in the GUI are the spectra obtained from the synchrotron radiation cameras as seen in Fig. 7.

All the diagnostics are representing the actual diagnostics as much as possible. The image presented for the TDS measurements for example represent the same pixel size and chip dimensions, as well as the real RF power to streak conversion. Even the colourmap used in the control system

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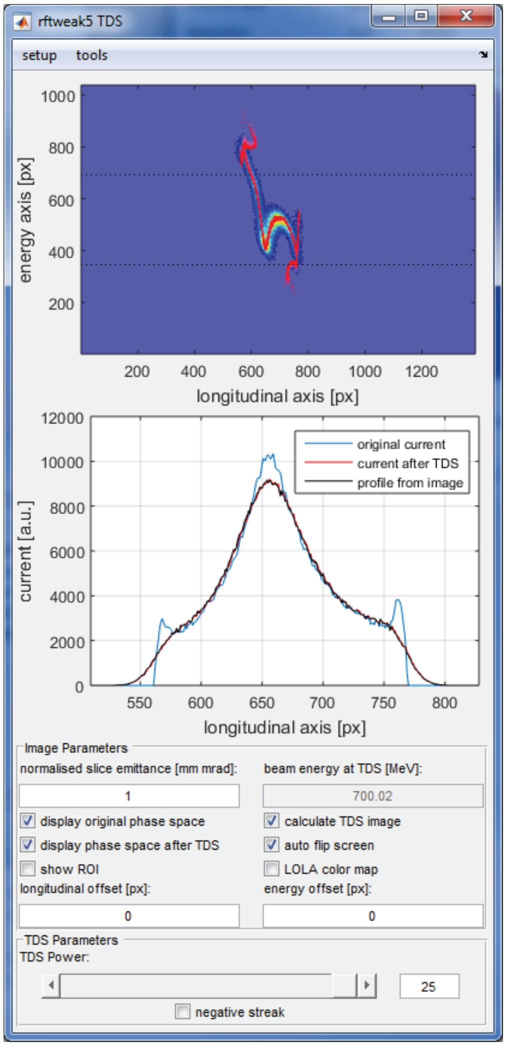

Figure 5: A simulated view of the LOLA transverse deflecting structure image for FLASH. The longitudinal phase space (red) is compared with the estimated image on the corresponding screen.

display can optionally be used. The BCM data are calculated using measured detector response data.

SUMMARY AND OUTLOOK

In this paper we presented a fast and efficient tracking tool for the longitudinal beam dynamics of electron linacs. Detailed GUI versions of the code were developed for FLASH and the European XFEL, but the code can in principle be applied to other machines as well. This tool is tested and in use at FLASH and intended as standard bunch compression setup aid at the European XFEL.

Pre-calculated wake kernel tables as well as a careful optimisation of tracking step size management allows efficient calculations on a time scale usable for control room applications. As an example the full European XFEL with 1 million macro-particles including geometric wakes, and longitudinal space charge is calculated in 5 seconds on a

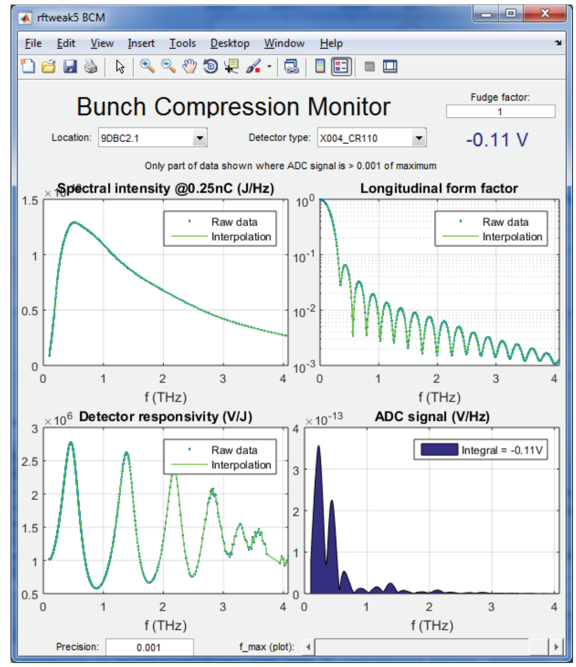

Figure 6: The expert GUI for the simulated bunch compression monitor (BCM) data. For the user the relevant number are the –0.11 V in the upper right corner, which corresponds to the actual ADC reading of FLASH in this example.

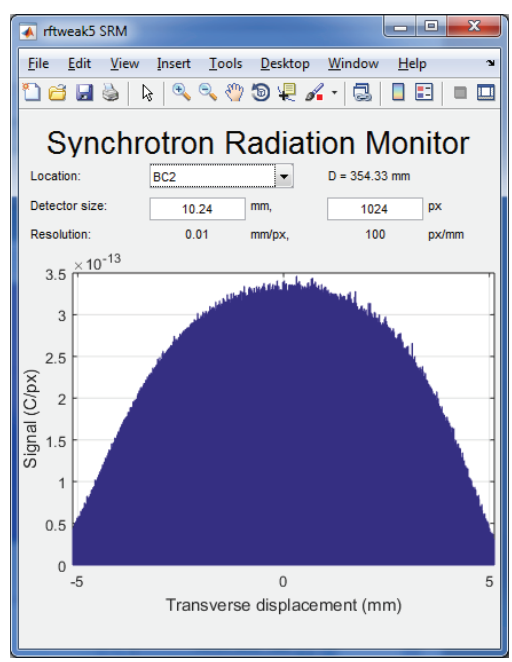

Figure 7: Beam energy spectra measured with the synchrotron radiation cameras in the chicanes are plotted for the chicanes as a tuning aid.

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standard laptop. Switching CSR interactions on increases the calculation time to the order of a minute.

In the future this project will be combined with our new project "XTrack", which is a full 6D fast tracking algorithm. We imagine that we set-up the compression in RFTweak 5 and transfer the data to the new code to obtain a full 6D phase space representation on the order of about 10 minutes at the undulators to judge FEL performance.

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