A FLIGHT SIMULATOR FOR ELECTRON ACCELERATORS AND TEST FACILITIES

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Abstract

Next generation electron–positron colliders such as the FCC, CLIC and the ILC require high beam stability and small beam sizes to reach their target luminosities. Meeting these demands requires highly refined Beam-Based Alignment (BBA) techniques, supported by both precise simulations and experimental validation.

In this paper, combined simulation and measurement studies using a newly developed Flight Simulator tool designed to model realistic lattice imperfections, diagnostic performance, and apply corrections in electron accelerators and test facilities are presented. The framework incorporates magnet jitter, wakefield effects, and measurement noise, allowing detailed testing of dispersion-free steering and related BBA procedures. Complementary measurements performed at the Accelerator Test Facility (ATF) were used to benchmark the simulator and verify its predictive accuracy under varying operational conditions.

INTRODUCTION

The Accelerator Test Facility (ATF) is a linear electron accelerator developed to investigate beam dynamics and technologies relevant for future generations of linear colliders [1]. It is located at the Japanese High Energy Accelerator Research Organization (KEK). Commissioned in 1997, the ATF was initially designed to produce ultra-low emittance beams, a key requirement for projects such as the International Linear Collider (ILC). This objective was successfully achieved by 2001 [2, 3].

To further address the challenges associated with producing and measuring nanometer-scale beam sizes, the facility was upgraded in 2008 to include the ATF2 beamline [4]. Today, the ATF complex consists of an injector, a linear accelerator (LINAC), a Damping Ring (DR), and the ATF2 extraction and final focus beamline.

Electron bunches are generated by a Radio-Frequency (RF) gun, delivering charges ranging from 0.01×10^{10} to 1.0×10^{10} electrons per bunch at a repetition rate of 3.12 Hz. These bunches are accelerated to 1.28 GeV in an 88 m long LINAC before being injected into a 139 m circumference damping ring, where they are stored for 100 to 450 ms. During this time, synchrotron radiation reduces the beam emittance. The damping ring achieves a vertical normalised emittance below 10 pm, which is comparable to the requirements of the ILC Beam Delivery System (BDS) [5].

The electron bunches are then extracted using a kicker and transported through the extraction line, where they are focused and tuned to reach nanometer-scale beam sizes at the interaction point (IP). The ATF beam parameters are summarised in Table 1 and a schematic of the ATF and ATF2 beamlines is shown in Fig. 1.

Table 1: ATF2 Nominal Beam Parameters

Parameter	**Unit**	**Value**
Beam energy, E	GeV	1.3
Bunch population, N_b	electrons	10^{10}
Bunch length, σ_z	mm	7
Energy spread, σ_E	%	0.08
Normalized emittance, $\gamma\epsilon_{x,y}$	mm.mrad	5/0.03
Twiss β-function at the IP, $\beta^*_{x,y}$	mm	4/0.1
Beam size at the IP, $\sigma^*_{x,y}$	nm	9000/37

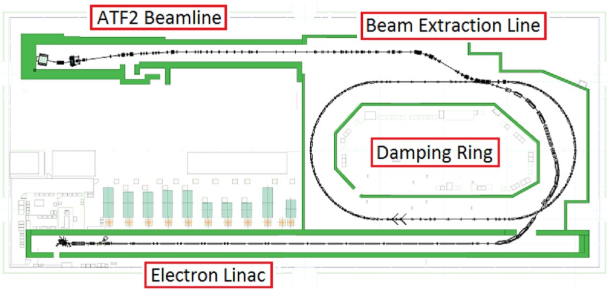

Figure 1: Schematics of the ATF/ATF2 beamlines.

The chromaticity of the ATF2 beamline has been designed to match the one of the ILC final focus system, leading to a target vertical beam size at the IP of 37 nm.

In recent operation, the ATF2 optics have been modified to use a horizontal beta-function, β_x, ten times larger than in the original design. This adjustment enhances the sensitivity to multipole field errors, bringing their impact closer to the tolerances expected for the ILC final focus system. This configuration is commonly known as the “10×1 optics,” reflecting the increased β_x while keeping β_y unchanged. The original configuration is known as the “1×1 optics.”

During the past several years, considerable effort has been dedicated to achieving the smallest possible beam size (Goal 1). A minimum vertical beam size of 42 nm was successfully measured in 2016 [6]. However, maintaining and consistently reproducing such performance has proven challenging due to various machine imperfections. In this context, beam-based alignment techniques, such as one-to-one steering, Dispersion-Free Steering (DFS), and Wakefield-Free

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Steering (WFS) are essential tools for correcting the beam trajectory and minimising the beam size at the IP.

RESULTS

The Flight Simulator is a unified toolbox to run beam-based Alignment (BBA) RF-Track simulations [7], measure several parameters (beam energy, beam charge, response matrices, orbits, emittance, etc.) and apply orbit corrections in different particle accelerators.

RF-Track is a particle tracking code developed at CERN for the design and optimisation of particle accelerators, combining high flexibility with fast simulation performance.

It can simulate the transport of particle beams with arbitrary energy, mass, and charge, including mixed beams, by solving fully relativistic equations of motion and accounting for spin polarisation. RF-Track models a wide range of physical effects, including space-charge forces in both bunched and continuous-wave beams, synchrotron radiation, wakefields, beam loading, intrabeam scattering, multiple Coulomb scattering, and inverse Compton scattering, with additional collective effects continuously being implemented.

The code supports the transport of single and multi-bunch beams through both conventional and advanced elements, including 1D, 2D, and 3D static or time-dependent radio-frequency electromagnetic field maps (standing and traveling-wave), as well as devices such as flux concentrators and electron coolers. RF-Track allows for overlapping elements and employs fast parallel algorithms. It can integrate the equations of motion either in space—well suited for ultra-relativistic regimes—or in time, which is more accurate for space-charge calculations. The transition between these integration schemes is handled automatically.

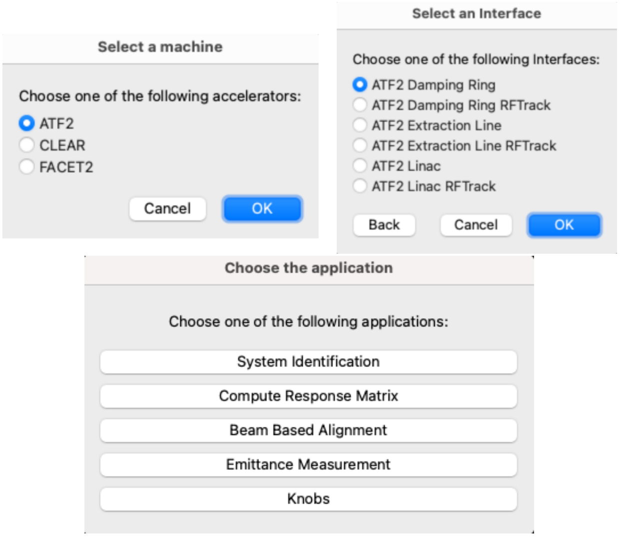
RF-Track is written in optimised, multi-threaded C++ and is available in two independent versions: one interfaced with Octave and the other with Python. Familiarity with either Octave or Python is recommended to fully exploit its capabilities.

Both the tool and its Graphical User Interface (GUI) are written in Python to make the tool user-friendly and easily tunable. The interface is quite simple: the user first selects the accelerator. Three choices are currently available: the Accelerator Test Facility (ATF) at KEK, the Facility for Advanced Accelerator Experimental Tests (FACET2) at SLAC, and the CERN Linear Electron Accelerator for Research at CERN (CLEAR). Then the user selects the part of the accelerator to study, for example: LINAC, Damping Ring or extraction line for ATF. The GUI cascade of choice windows is then shown as seen in Fig. 2.

The following tools are available for the Flight Simulator:

The System Identification

The System Identification tool or SysID is the interface to excite the orbit. A list of correctors and Beam Position Monitors (BPMs) can be selected/loaded/saved, a set of parameters can be set (amplitude of the initial horizontal and vertical kicks, target orbit excursion, number of cycles, etc.) and print the orbit for each excitation. The results are saved in separated files for further analysis. A screenshot of the SysID GUI used in ATF is shown in Fig. 3.



Select a machine

Choose one of the following accelerators:
● ATF2
○ CLEAR
○ FACET2

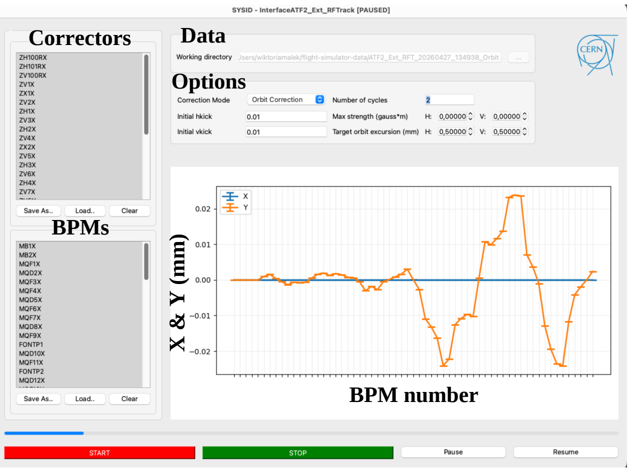
Select an Interface

Choose one of the following Interfaces:
● ATF2 Damping Ring
○ ATF2 Damping Ring RFTrack
○ ATF2 Extraction Line
○ ATF2 Extraction Line RFTrack
○ ATF2 Linac
○ ATF2 Linac RFTrack

Choose the application

Choose one of the following applications:

Figure 2: The Flight Simulator GUI cascade of choice windows.



SYSID - InterfaceATF2_Ext_RFTrack [PAUSED]

Working directory Jsers/wiktoriamalek/flight-simulator-data/ATF2_Ext_RFT_20260427_134938_Orbit

Correction Mode Orbit Correction
Number of cycles 2
Initial hkick 0.01
Max strength (gauss*m) H: 0,00000 V: 0,00000
Initial vkick 0.01
Target orbit excursion (mm) H: 0,50000 V: 0,50000

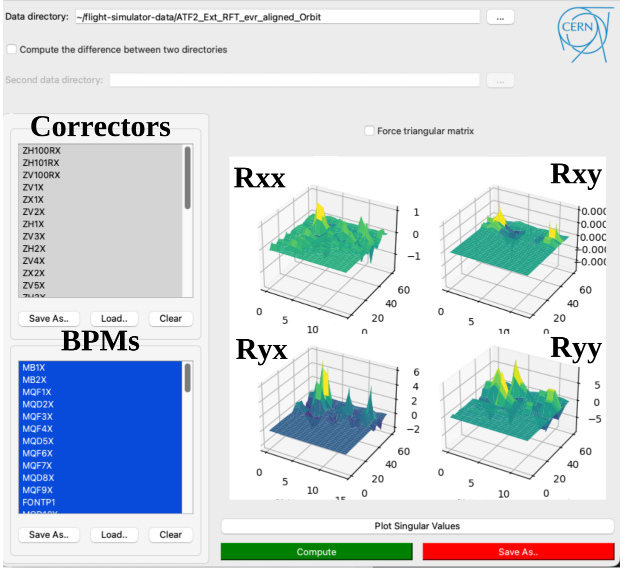
Figure 3: The Flight Simulator System Identification GUI.

The Response Matrices

The response matrices represent the impact of transverse kicks on the orbit measured at BPM positions. These matrices are $(N \times M)$ with N the number of steering magnets and M the number of BPMs. A subset of steering magnets and/or BPM can easily be selected in case of faulty equipments or targeted studies. An example of a response matrix calculation in the ATF2 extraction line is shown in Fig. 4.

The Beam-Based Alignment

Once the response matrices are calculated, several corrections can be applied using the BBA tool: one-to-one, DFS and WFS. The one-to-one correction minimises the orbit at BPM locations, DFS reduces the amplitude of the dispersion, and WFS mitigates the impact of intensity-dependent effects on the beam orbit. Together, these three corrections


Data directory: ~/flight-simulator-data/ATF2_Ext_RFT_evr_aligned_Orbit

☐ Compute the difference between two directories

☐ Force triangular matrix

Figure 4: ATF measured response matrices GUI.

play a significant role in reducing the beam size at the IP and increasing the luminosity. They can be applied either sequentially or simultaneously and are easily tunable through the interface thanks to several adjustable parameters, such as the weight of each correction, the number of iterations, the gain, and the maximum strength.

These corrections have demonstrated excellent performance at ATF, confirming the effectiveness of the implemented methods under realistic operating conditions. In the ATF LINAC, the application of the combined correction schemes led to a significant reduction of the dispersion by a factor of 6, while transverse wakefield effects were mitigated by a factor of 10, resulting in a noticeably more stable beam trajectory. The corresponding results, illustrating the evolution of the beam parameters before and after correction, are shown in Fig. 5.

In the ATF DR, where intensity-dependent effects play a particularly important role due to the beam dynamics and operating conditions, the corrections proved to be even more effective, reducing transverse wakefield effects by a factor of 15. This improvement highlights not only the efficiency of the correction algorithms but also the robustness and adaptability of the approach across different parts of the accelerator complex. The results obtained in the DR are presented in Fig. 6, clearly illustrating the strong suppression of orbit distortions and the overall improvement in beam stability after correction.

Previous DFS and WFS corrections showed excellent results in the ATF Extraction Line. These corrections combined decreased the vertical beam size at the interaction point of ATF2 by more than 15% and significantly increased the beam position and beam size stability [8, 9].

CONCLUSIONS

The newly developed Flight Simulator is a powerful tool to run RF-Track simulations and to apply several BBA corrections in three different accelerators. Both user-friendly and modular, the tool provides extensive flexibility to its users with dedicated GUIs and numerous variables to tune the corrections. The tool has given excellent results in the ATF. The DFS and WFS corrections lead to a clear improvement in beam stability across a range of beam energies and charges. In the ATF LINAC and the ATF2 beamline, the dispersion was reduced by factors of 5 and 6, respectively. The transverse displacement caused by intensity-dependent effects decreased by a factor of 5 in the LINAC, by a factor 15 in the DR and by about 30% in the ATF2 beamline. The Flight Simulator is not only useful for existing accelerators and test facilities but would also be an excellent tool to improve the quality and stability of future accelerators and colliders. New tools are being developed including an emittance measurement tool using quadrupole scans.

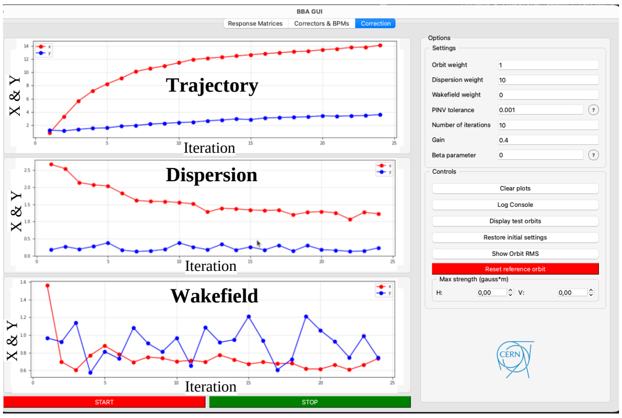

Orbit weight 1
Dispersion weight 10
Wakefield weight 0
PINV tolerance 0.001
Number of iterations 10
Gain 0.4
Beta parameter 0
Max strength (gauss*m) H: 0,00 V: 0,00

Figure 5: Simultaneous correction of the Dispersion and Wakefield in the ATF LINAC.

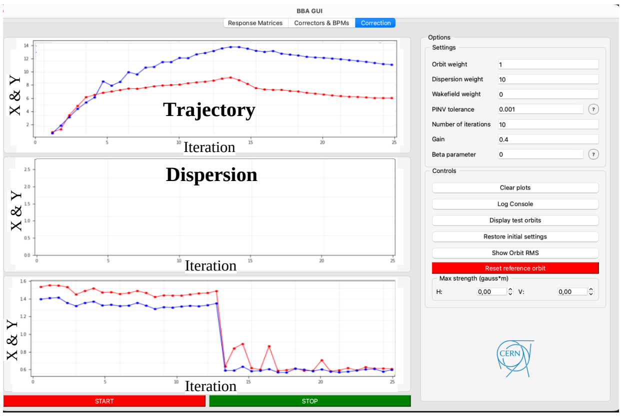

Orbit weight 1
Dispersion weight 10
Wakefield weight 0
PINV tolerance 0.001
Number of iterations 10
Gain 0.4
Beta parameter 0
Max strength (gauss*m) H: 0,00 V: 0,00

Figure 6: Wakefield correction in the ATF Damping Ring.

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