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ATF2-3 HARDWARE UPGRADE AND NEW EXPERIMENTAL RESULTS TO MAXIMIZE LUMINOSITY POTENTIAL OF LINEAR COLLIDERS

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Abstract

The ATF2-3 beamline is the only facility in the world for testing the Final Focus System (FFS) of linear colliders and is essential for the ILC and the CLIC projects. A vertical electron beam size of 41 nm (within 10% of the target), a closed-loop intra-bunch feedback of latency 133 ns, and direct stabilization of the beam position at the Interaction Point (IP) to 41 nm (limited by the IP BPM resolution) have all been achieved at ATF2. These results fulfilled the two main ATF2 design goals, but were obtained with reduced aberration optics and a bunch population of approximately 10% of the nominal value of 10^{10} electrons. Recent studies indicate that the beam degradation with the beam intensity is due to the effects of wakefields. To overcome this intensity limitation, hardware upgrades including new vacuum chambers, magnets, IP laser interferometer Beam Size Monitor (IP-BSM), cavity BPMs, wakefield mitigation station, as well as a comprehensive R&D program to maximize the luminosity potential are being pursued in the framework of the ILC Technology Network. This new R&D program focuses on the study of wakefield mitigation techniques, the correction of higher-order aberrations, tuning strategies, including AI techniques, as well as beam instrumentation issues for this type of collider such as the BPMs, advanced incoherent Cherenkov Diffractive Radiation monitor (iChDR), and fast feedback systems, among others. This paper summarizes the hardware upgrades, the R&D program and the experimental results of the Fall 2023-Winter 2024 campaign performed in ATF2-3.

INTRODUCTION

The FFS is one of the most complex subsystems of a linear collider. The design of such a system has been validated at the ATF2 beam line at KEK in Japan, which was constructed by an international ATF collaboration. There has been a continuous work from many labs, in ATF first and ATF2 after to get nanobeam sizes and its stabilization, but these results were obtained with reduced aberration optics and with a bunch population 10^9 electrons. To overcome this intensity limitation, since 2019 a continuous hardware upgrade program to mitigate the wakefields has been pursued. More recently a dedicated effort in the framework of the ILC Technology Network (WPP15) [1] is being made in this sense. In this paper we report about the recent hardware upgrades, the R&D program and the experimental campaign carried out at ATF2-3 in the last running period.

HARDWARE UPGRADES

Major hardware issues in the ATF2 beamline were identified in a comprehensive review realized in 2020 [2]. The ATF2-3 beam line upgrade is ongoing in the framework of the new Advanced Accelerator Element Technology Development (MEXT ATD) grant started in April 2023 and will continue over 5 years. Priority has been established, starting with IP-BSM laser, magnets and beam pipes. More in detail the most recent are:

Skew Sextupole Magnets

Four skew sextupole magnets are used in the ATF2-3 beamline to correct higher-order aberrations. These magnets were modified from those used at KEKB for studying the nonlinear optics correction, but the accuracy of the magnetic field was not sufficient for the ATF2 advanced correction needs. Four new skew sextupoles have been purchased in JFY2023, and will be installed in the summer 2024 shutdown.

Extraction Kicker System

The low-emittance beam needed to achieve the nanobeam sizes is generated by the ATF damping ring (DR) and sent to the downstream to the ATF2 beamline by means of an extraction kicker system. One of the potential sources of errors affecting the IP beam size is the nonlinear magnetic fields generated by the extraction kicker system. In order to mitigate this impact in a first phase a new ceramic chamber was fabricated in JFY2023 and will be installed in the summer 2024 shutdown. The inner diameter of the new ceramic chamber has been increased from 14 (DR vacuum chamber) to 20 mm. In a second phase a new kicker device fitting this new larger ceramic chamber will be installed and there will be tested with beam after JFY2025.

Magnets Movers Systems

Most of the magnets in the ATF2 FFS are positioned on a special kinematic mover that was originally developed at SLAC in the 1990s, for use at the Final Focus Test Beam facility [3]. The original system was equipped with a set of control hardware based on Computer Automated Measurement and Control (CAMAC) modules and custom-made motor drivers designed by SLAC. By rotating the cams, the center of the magnet can be precisely positioned both vertically and horizontally with a resolution of 1 µm. Additionally, the magnet can be rolled around the beam axis with a resolution of 50 µrad. However, over the years of operation, this system became outdated inefficient and unreliable, resulting in frequent crashes that caused delays in beam operation. To address this issue, a comprehensive control hardware upgrade is currently underway. The

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outdated centralized hardware will be replaced by a custom-made, fully distributed system consisting of individual control boxes for each magnet. The new system is designed in a modular manner, allowing for easy maintenance, expansion, and possible upgrades. In addition to the hardware, the control software has been fully upgraded, which includes motion control servers and a set of operator displays for controlling and monitoring every parameter in the system.

Timing System

The current ATF timing control system was built in late 1990s, and being gradually upgraded over time to introduce fiber-based signal distribution and EPICS based software controls. Until recent years CAMAC hardware controls most of the timing system. However, due to increased maintenance efforts and outdated CAMAC hardware it was decided to upgrade existing timing system with an event-based system. The new timing system generates event codes within an event generator (EVG) and distributes these codes with a scheduled delay to all local event receivers (EVR). The new timing system has been designed to take into account the 50 Hz AC power needed for the kickers system or the few milliseconds to build up power pre-trigger for the linac high-power klystron modulators, the RF gun, and the IP-BSM laser between others. Additionally, the implementation of a bucket selection algorithm is underway. Efforts to establish a reliable timing system at ATF and explore various solutions to enhance its robustness are ongoing.

Integrating Current Transformers

In order to improve the bunch charge and transmission measurement resolution, an upgrade of the ICTs DAQ system based on the digitizer system has been done. The upgraded system provides 3 times better bunch charge and transmission measurement resolution.

Cavity BPMs

The ATF2 CBPM system has been operating since 2010 and proven to be a reliable diagnostic with 20-30 nm resolution. CBPMs are mounted rigidly on magnets that in turn are mounted on transversal mover stages, which are used for CBPM calibration. The current system has certain limitations due to the large physical offsets exceeding the default range of ±100 μm and resulting in a reduced resolution of 200 nm to allow ±1 mm range. Additionally, the system is recalibrated at the start of each run week to compensate for phase drifts between position and reference channels and takes several hours. A new system actively pre-injecting burst RF oscillations directly into sensor cavities is under development to resolve these issues [4]. Injecting RF power in anti-phase with beam signals can compensate for static offsets. Using the same signals in-phase can help reduce the effects of drifts via no-beam calibration. The hardware challenges related to generation of beam arrival locked, phase coherent signals with high levels of control are currently being addressed in a proof of principle experiment.

R&D AND EXPERIMENTAL STUDIES

The new ATF2-3 R&D program focuses on the study of wakefield mitigation techniques, the correction of higher-order aberrations, the tuning strategies for long-tern beam stability including AI techniques, as well as the beam instrumentation. In the last running period, the main studies have been centred in:

Nonlinear Aberrations and Wakefields

Two kinds of studies have been pursued in the last experimental campaign. The first one consists of rotating the tilt angle of the laser interference fringe of the IP-BSM to investigate the impact on the beam tilt and the nonlinear distortion at the IP. The second one was dedicated to investigate the impact on the IP beam size due to the change of the beam orbit of the extraction section including the septum magnet. It was found that when the kicker angle is small and the beam passes close to the edge of the septum magnet, a nonlinear distortion of the beam at the IP was observed. An optimized beam extraction section trajectory minimizing this distortion was identified through these studies. In the next campaign studies to reduce the effect of higher order aberration will be made once the four new skew sextupoles will be installed in summer 2024.

An ATF2 wakefield model has been completed. Simulation and experimental results demonstrated that the effects are significant on the IP beam size. Efforts are being made to reduce such impact [11].

Machine Learning Studies

ML is being employed to optimize the beam operation in the all three major components of ATF-ATF2-3 complex: the linac, the DR, and the FFS. For instance, a successful linac tuning was obtained, resulting in a high intensity electron beam stored at the DR. After tuning, the electron intensity was increased from $3\ 10^9$ to $8\ 10^9$. For the FFS the ML tunning attempts were hindered by measurement fluctuations of the modulation, but some ML treatments and techniques enhanced the tuning's robustness. Concerning the DR, a study of emittance tuning has been realized. In a first step beam size minimization was successfully performed. However, β-function also became smaller, resulting in an increased emittance. To achieve the minimization of the emittance, it will be necessary to implement a simultaneous optimization of the β-function and beam size. This will be the subject of a subsequent investigation.

Incoherent Cherenkov Diffraction Radiation

iChDR is one of the most promising candidates for longitudinal profile measurements where SR is hardly or not at all exploitable, as in linear or extremely large circular accelerators. iChDR has been first observed in recent years, and models describing its basic properties exist [5-6]. To experimentally verify and validate for the first time such predictions, an experimental test was conducted at ATF2 [2]. The expected visible photon yield as a function of the distance from a fused silica (SiO2) (that we call 'Impact Parameter') are plotted in Fig. 1. The expectation from the 'non-stationary' model is higher by more than four orders of magnitude when compared to the 'stationary' one. However, there will also be contributions not only from iChDR but also from direct Cherenkov radiation (ChR) produced by halo particles directly traversing the radiator and producing a signal which exhibits many similar characteristics to the ChDR signal. These contributions from direct ChR are plotted as dashed curves. The green curve corresponds to a perfect Gaussian transverse distribution with a standard deviation of $\sigma = 10$ µm. The red curve represents a more realistic scenario with a typical halo distribution at ATF2, as measured in Ref. [4]. As visible in the plot, the particles in the beam's halo, producing direct ChR, have a photon yield comparable to that predicted by the non-stationary model. This finding suggests that directly measuring the photon yield of ChDR as predicted by the stationary model is not feasible with the current ATF2 beam parameters. However, there is still the potential to measure the light yield as predicted by the non-stationary model.

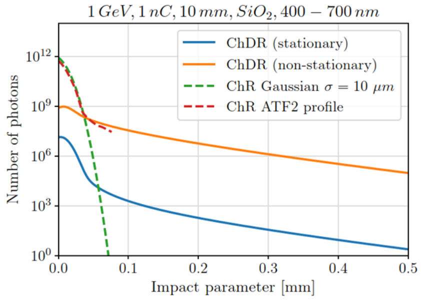

Figure 1: Expected number of photons from a SiO2 radiator of 10 mm length as a function of the impact parameter.

A preliminary test was performed in last experimental campaign by performing a single photon acquisition, as a function of the impact parameter at wavelengths of 800, 700 and 600 nm, the models predicting a larger yield for longer wavelengths. Contrary to expectations, no clear trend was observable, all wavelengths exhibiting a similar yield and a profile incompatible with ChDR emission models of Fig. 1. The signal levels extend to higher distances than expected from ChDR alone, hinting that the observed signal is affected by the presence of halo ChR. Reflecting on these results, we plan to repeat the experiment at with a re-designed setup, that is observing the ChDR emitted in the vertical plane with a redesigned Silica target.

Ultra-low β^* Studies

The ultra-low β_y^* optics of ATF2 is designed to have a chromaticity level similar to that of CLIC. Two shifts in December 2023 were allocated for this optics type, with the goal to upload and check the optics for the first time since March 2020. The optics was uploaded into the machine, and after orbit and dispersion corrections Final Doublet (FD) scans were performed. β_x^*/β_y^*=79 mm/76 µm (the target is 100 mm/25 µm) was obtained in the first attempt. A new optics was matched with MADX and SAD simulations and applied in the machine in the second attempt. β_x^*/β_y^*=85 mm/29 µm was measured, although it was noticed that the phase advance between the orbit feedback kickers and the IP was incorrect. Another optics was matched including the phase advance constraint but there was not enough time to verify the beta-functions at the IP.

FONT Feedback System

The highest resolution of the beam feedback system stripline BPMs reported to date in ATF2 is 157±8 nm, which was a beam intensity of 8.2 10^9 electrons per bunch. The most stable beam reported at the feedback BPMs themselves was a jitter of 340 nm at P2 and 270 nm at P3, which was achieved for a beam intensity of 4.5 10^9 [8]. As the corrected jitter is expected to scale as approximately $\sqrt{2}$ times the resolution, a minimum jitter of less than 250 nm should be possible with the current system. In the last experimental period, the aim of the beam feedback studies was to exceed the previous performance limit at higher beam intensity. The studies included an examination of factors that are expected to impact the resolution, such as the amplitude and phase of the local oscillator signals used in the front-end analogue processing, but to date no improvement on the previously reported feedback results has been achieved.

ILC CBPMs Studies

A prototyping study of an ILC CBPM re-entrant type [9] embedded in the Main Linac cryomodule with 1 µm resolution bunch-by-bunch, is under study. In a first phase a first prototype and its associated electronics readout system will be tested in the next experimental period in a dedicated experimental area of ATF complex in warm conditions. Cryogenic beam test will follow in a second phase.

FUTURE PERSPECTIVES

The results obtained in ATF2 in the last years have demonstrated that there is no showstopper for ILC FFS. Based on these achievements we have planned the next operation years of ATF2-3 with the main objective of deep in the understanding of luminosity optimization of the ILC.

ACKNOWLEDGEMETS

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