

INSTALLATION AND FIRST TESTS OF A HIGH BRIGHTNESS BEAM TEST FACILITY FOR ERL APPLICATIONS AT INFN-LASA *

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Abstract

A High Brightness Beams Test Facility (HB²TF) has been funded in 2023 at the INFN-LASA laboratory in Segrate (Italy). The Test Facility will allow us to perform developments in ERL design and to carry out experiments with a high current CW electron beam in frontier areas of accelerator physics.

In this paper we will report on the status of the project and discuss the first tests underway on the main elements involved and available.

INTRODUCTION

The High Brightness Beams Test Facility (HB²TF) at the INFN-LASA laboratory, in Segrate (Milan, Italy) will allow to perform developments in the injector field and to carry out experiments with a high current CW electron beam in frontier areas of accelerator physics. The Test Facility setup comprises a high-performance laser driven DC Gun followed by a normal conducting RF buncher acceleration section to provide 0.8 MeV, 2.5 mA CW electron beam. The facility has been conceived as the first stage of a more complex ERL Linac injector design, named BriXSinO [1], that foresees a second buncher and a SC booster linac able to increase the electron energies up to 4-10 MeV, maintaining beam current up to 2.5 mA, followed by a SC accelerating linac (the ERL) which will allow to reach up to 45 MeV.

The HB²TF goals will provide experimental confirmation of the capability to generate high brightness beams at very high repetition rate (about 100 MHz). The beam dynamics studies that will be applied in HB²TF aim to verify the possibility to inject such a beam in a further stage of acceleration suitable for an ERL advanced experiment. The availability of a Test Facility which would be able to operate for long periods to test all the novelties in this design will be a relevant event in the technological and scientific panorama of the area.

The following section will summarize the characteristics of the main components currently undergoing commissioning, highlighting their specific features and the related design choices.

MAIN PARAMETERS

The design of the first section of the HB²TF facility follows a classic approach to electron beam injectors intended for use in an ERL facility. Essentially, it is based on a DC

gun, which utilizes a photocathode excited by a UV laser. The goal is to generate electron bunches of charge up to 100 pC, which, after emission, enter a solenoid to focus them, compensating for natural beam divergence and “space charge” effects in this low-energy region. Because electrons are still at a relatively low energy—a few hundred keV—immediately after emission from the cathode, they spread out quickly; the solenoid provides axisymmetric magnetic focusing to counteract this expansion and tune the emittance oscillations following emittance compensation scheme [2].

Two normal-conducting sub-harmonic bunchers, following a novel layout, have been planned to shape the beam in a suitable way for entry into a superconducting booster.

The frequency of 1.3 GHz is adopted for the SC linac booster, while for BD motivation [3] the frequency of the bunchers is set to 650 MHz, i.e. a sub-harmonic.

Due to budget constraints, the facility currently under construction will be completed up to the first buncher, even though the design of the subsequent elements—both in terms of beam dynamics and technology— of the second section are already included.

BEAM PHYSICS

The HB²TF beamline follows a new design for an ERL injector (or merger) capable of providing high-brightness beams at a relatively low energy of about 4.5 MeV. This machine is designed to work with different starting parameters; however, considering a maximum average current of 2.5 mA, the following simulation has been performed with a bunch charge of 100 pC, which corresponds to a repetition rate of 25 MHz. Although this machine can reach a maximum repetition rate of 100 MHz, we have opted for a single-bunch reference simulation where space charge plays a main role. This choice is conservative and addresses one of the key points in ERL injector optimization, i.e., coping with high-brightness beams still dominated by space charge at the ERL–linac injection, thus representing a challenging optimization.

This design is innovative because it uses two bunchers at the sub-harmonic frequency of 650 MHz to gently compress the beam while accelerating it in a distributed beam gymnastics scheme [3]. The choice of a longer RF bucket allows the trapping of longer, cigar-like electron bunches with lower charge density, resulting in lower final emittances. Additionally, the use of two bunchers provides

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better control over longitudinal bunch compression. The injection phases of the two bunchers are not set at the RF zero-crossing, allowing simultaneous acceleration to mitigate space-charge effects and bunching to increase the final beam brightness.

The behavior of the main beam parameters has been simulated using the ASTRA [4] code and optimized with the GIOTTO code [5,6]; RF-Track and COMSOL have also been employed for comparison and cross-check purposes [7]. The optimized main beam parameters are shown in Fig. 1, and the values at 4.5 MeV, at the exit of the line, are well suited for injection into the ERL. The 100 pC bunch, with a rms length of 1 mm, maintains a peak current below 12 A, an ideal value for entering a dispersive section and transporting the beam to the ERL main axis while preserving emittance. The very low energy spread of 0.07% is optimal for containing chromatic effects [8]. At the injector exit, the normalized emittance of 0.9 mm·mrad is lower than what is required to drive light sources such as FEL or ICS radiators.

The acceleration section performances here reported refer to an updated design for the BriXSinO injector. The first design foresaw the presence of three 2-cell SC cavities, bERLinPro-like. A recent revision, aimed at reducing complexity and costs, foresees an architecture based on two cavities: a single-cell cavity and a 7-Cells modified Tesla-like cavity.

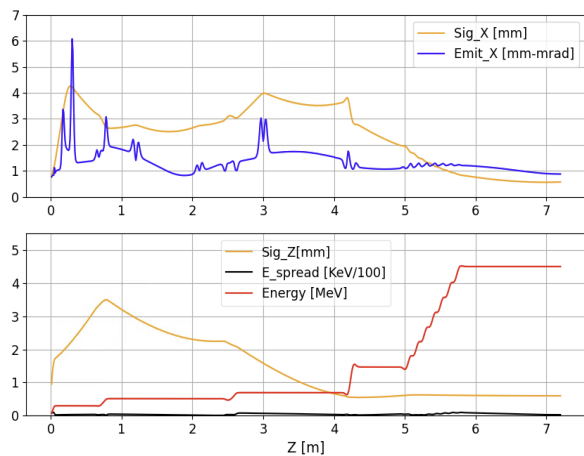


Figure 1: The upper plot shows the beam envelope (yellow) and normalized emittance (blue). The lower plot shows the bunch length (yellow), the energy spread (black), and the energy gain (red).

PHOTOCATHODE

The INFN Cs₂Te photocathodes have been selected as the HB2TF electron source, due to their photoemissive properties at 254 nm such as high Quantum Efficiency (QE) ($\geq 10\%$) and high QE spatial uniformity, low dark-current and thermal emittance (divergence 0.5 mm mrad) and, long operative lifetime [9]. Among their excellent results, remarkable is the QE and the operative lifetime, also in CW regime (1 MHz) [10]. Cs₂Te are deposited on INFN-type Mo plugs in the photocathode laboratory at LASA, and, after their characterization, they are transferred to the

HB²TF DC Gun using an UHV suitcase and handled in a transfer chamber connected to the DC Gun.

DC GUN

A DC gun is a robust and well-developed solution when high repetition rates are required. In HB²TF we based our design on the “inverted insulator” scheme developed at JLAB [11]. The mechanical structure was the result of a fruitful collaboration with JLab and the SAES Getters RIAL Vacuum company and it’s now in the assembling phase (See Fig. 2). We achieved an improved symmetry of the electric field (cylindrical symmetry of the inner vacuum chamber), a better vacuum level and quality by combining NEG and NexTorr solutions and compatibility with the INFN photocathodes and related manipulation systems.



Figure 2: Status of the vacuum system and DC gun chamber installation in May 2026.



Figure 4: Spherical cathode with inserted the INFN photocathode plug.

The spherical cathode with the INFN photocathode plug installed is shown in Fig. 4.

The high voltage to the photocathode is provided by a 350 kV-3 mA XP Power power supply. A high pressure tank PED compliant, suitable for operation up to 9 bar in

N_2 , has been built to contain the multiplication column and hence reduce the footprint of the installation.

LASER SYSTEM

The optical system is designed to excite the photocathode for electron bunch generation. The light source is a 1035 nm mode-locked Yb laser (Orange, Menlo Systems) delivering 10 W average power at 92.857 MHz with 190 fs pulses. The pulses are temporally stretched to 440 ps using a Chirped Volume Bragg Grating (CVBG) [12].

A 100 mW fraction of the beam is transported through a ~ 140 m polarization-maintaining fiber to the optical laboratory hosting the HB²TF experiment. There, the signal is pre-amplified to about 1 W in a Yb-doped PM fiber stage and further amplified up to 60 W using an NKTaeroGAIN-BASE-1.2 fiber amplifier [13].

Frequency conversion from the infrared is employed to generate the fourth harmonic at 258.75 nm for photoemission, using a 10 mm LBO crystal for second harmonic generation and three 1.5 mm BBO crystals for fourth harmonic generation, yielding up to 21.5 W and 4.5 W, respectively. The repetition rate is controlled via a Pockels cell, while temporal and spatial pulse shaping are achieved using a stacking technique [14] and a π -Shaper [15]. Beam pointing stabilization on the photocathode ensures a closed-loop stability better than 5 μ m.

At present, the system has been realized and validated up to the amplification stage, which meets the design specifications. The second harmonic generation and subsequent ultraviolet conversion stages are currently under completion and optimization.

THE BUNCHER RF SUBSYSTEM

The two bunchers designed for the HB²TF test stand took inspiration from the structure used in cERL [16] and scaled down in frequency. The electromagnetic studies have been carried out using as a first tool the Superfish code and the detailed behavior has been optimized using Ansys HFSS (see Fig 5).

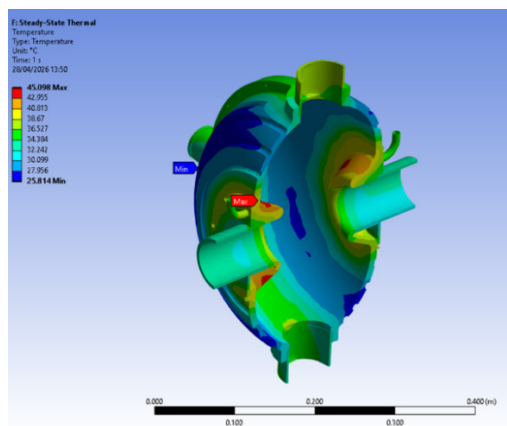


Figure 5: First buncher cavity thermal analysis at nominal gradient.

The cavities have been machined from bulk copper pieces using a high-precision lathe and the resulting two main halves will be brazed. The cooling channels have

been inserted in the outer shell of the cavities and they are able to remove all the thermal power expected delivered by the nominal RF field, about 10 kW. The cooling circuit comprises an external thermo-chiller (model HRS 150-WF-40 from SMC company) for each cavity.

A compact power coupling loop has been also designed, able to withstand powerful incident power and transition with minimal footprint to the 3" 1/8 RF coaxial line., it is now in the machining phase. Figure 6 shows a section drawing of the structure as installed in the buncher cavity. Cooling channels pass through the loop body and allow for its thermalization, the ceramic window is also easily reachable for an optional, outer cooling system.

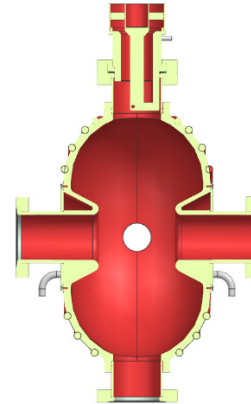


Figure 6: Power coupler loop and transition to RF coaxial line.

The RF amplifier to drive each buncher has been specified and commissioned to an external Italian company. A detailed description is available in [17] at this conference.

A compact LLRF module has been specified and has been awarded to the same company.

The two systems will be delivered by the end of May 2026 and the LLRF has been extensively tested using a different RF chain with excellent results.

A synchronization module has been internally developed to link together the main RF frequency (both 650 and 1300 MHz) and the timed operations of the laser subsystem. The module has been laboratory tested and it is installed on the experiment.

RADIOPROTECTION AND RADIATION MONITORING

A radiation detection system has been designed based mainly on 3 devices: a radiation detector monitor (model AT1123 from Atomttx), a Beam Loss Monitor (model Libera BLM with Scintillator EJ200 from Instrumentation Technologies) and a small network of LND model 712 Geiger detectors particularly suited to monitor the X ray emissions during the conditioning activities of the copper RF structures.

3 mm lead foils have been installed around the test facility to provide local shielding and the 3 monitor system have been interlocked to a FPGA based system which will provide a control system aimed to guarantee safety for the equipment and the persons involved.

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