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A HIGH BRIGHTNESS BEAM TEST FACILITY FOR ERL APPLICATIONS

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Abstract

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

THE PROJECT PURPOSE

High-brightness electron beam source is a critical element in the path to the success of upcoming projects, such as linac-based light sources and industrial-scale UV lasers. This paper will present and discuss the main elements related to the development of a High Brightness Beams Test Facility (HB^{2}TF) at the INFN-LASA laboratory, in Segrate (Milan, Italy). The Test Facility 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 1 MeV, 5 mA CW electron beam. The facility has been conceived as the first stage of a more complex ERL Linac injector design that foreseen a SC booster linac able to increase the electron energies up to 5-10 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 HB^{2}TF goals will provide the experimental confirmation of the capability to generate high brightness beams with high current and at very high repetition rate. The beam dynamics studies that will be applied in HB^{2}TF are aimed 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 Beam Physics

The HB^{2}TF beamline follows a new design for an ERL injector capable of providing high brightness beams at a relatively low energy of about 4.5 MeV. This design is innovative because it uses two bunchers instead of one and employs a 650 MHz rf frequency instead of the commonly used 1.3 GHz [1, 2]. The choice to use a longer rf bucket allows for the trapping of longer cigar-like electron bunches having lower emittances. Additionally, the use of two bunchers provides better control over longitudinal bunch compression. The injection phases of the two bunchers are not at the rf zero-crossing, allowing for acceleration while mitigating space-charge effects and bunching to increase the final beam brightness.

Main Parameters

HB^{2}TF is based on a DC-gun with a maximum acceleration field of 350 kV/m. However, we have chosen to work at 300 kV/m to be conservative. Downstream of the DC-gun, the two RF sub-harmonic bunchers are set with a maximum peak field of 2.7 MV/m. The apparatus under development currently ends with the second buncher. In our simulations, we considered an RF SC linac booster that accelerates the beam to 4.5 MeV. This value is ideal for low energy injection in ERLs and provides adequate mitigation of space charge effects. Laser pulse shaping data, charge extracted, used in this study are reported in Tab. 1, along with other main data for the simulated working point (WP). Tab. 1 includes also the WP for the injector booster, which actual design is based on three 2-cell SC cavities bERLinPro like [3].

Table 1: Main parameters related to the Injector

Q_b [pC] = 50; σ_x [μm] = 650; τ_{laser} [ps]; = 18 ps (rise-time=1ps)
DC-gun: ΔV=300 kV/m
The two Bunchers: E_p = 2.7 MV/m
Φ_{inj_1} = -31°, Φ_{inj_2} =-35°
SC inj. booster (three two-cells): E_p = 11.5 MV/m
Φ_{inj_1} = -25°, Φ_{inj_2} = 21°, Φ_{inj_3} = 0.0°

Defined Working Point

The behavior of the main beam parameters simulated using the ASTRA code [4] is shown in Fig. 1. The upper plot shows the beam envelope (yellow) and normalized emittance (blue). The lower plot shows the bunch length

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(yellow), the energy spread (black), and the energy gain (red). Upstream the vertical dashed line is the BD of HB^{2}TF, downstream is the BD up to the injector end [5]. The final beam parameters at 4.5 MeV are well-suited for injection into the ERL. The bunch with 50 pC and 1 mm rms length maintains a peak current below 10 A, an ideal value for entering a dispersive path and bringing the beam to the ERL main axis while preserving emittance. The very low energy spread of 0.07% is optimal for containing chromatic effects [6]. At the injector exit, the normalized emittance of 0.7 mm mrad is lower than what is required to drive light sources such as FEL or ICS radiators.

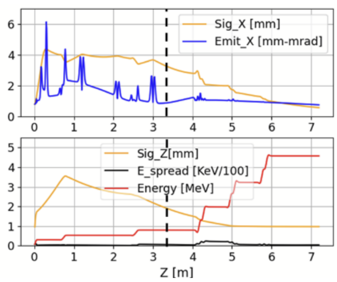

Figure 1 - Main beam parameters up to the end of HB2TF beam line (dashed vertical line) and after.

Table 2: Main Beam Parameters at the injector end

σ_x[mm]	σ_z[mm]	$\varepsilon_{n,x}$ [mm-mrad]	E [MeV]	ΔE/E [%]
0.6	1	0.7	4.5	0.07

THE BEAM SOURCE

Photocathode

Cs_2Te photocathodes will be the electron source for HB^{2}TF, since their photoemissive properties at 254 nm as high Quantum Efficiency (QE) in UV range (≥ 10%) and high spatial uniformity, low dark-current and thermal emittance (divergence 0.5 mm mrad), long operative lifetime [7] makes them the best choice for this application. Among the excellent results, remarkable is the QE and the operative lifetime, also in CW regime (1 MHz) [8]. Cs2Te layers are deposited on INFN-type Mo plugs in the photocathode laboratory at LASA, a leading lab for these devices, and, after their characterization, they will be transferred in the HB2TF DC Gun by our UHV suitcase.

DC Gun

A DC gun provides a robust and already well-developed solution with proven and well documented successful operations at high repetition rate. Our reference solution is the “inverted insulator” design developed at JLAB [9]. Based on this design, we are actively collaborating with JLAB and SAES Getters company to improve the UHV chamber design towards an improved symmetry of the electric field (cylindrical symmetry of the inner vacuum chamber), a better vacuum level and quality (NEG and NexTORR solutions are under investigation) and, a compatibility with photocathode transfer system developed at INFN for cathode exchange and manipulation. Fig. 2 shows a sketch of the chamber. Vacuum and electrostatic simulations will be used to validate this improved design. On the complementary infrastructures, the HV power supply has been already ordered and we are in a well advance phase on the procurement of the inverted insulator, High Voltage resistor, HV cables and, SF6 tank and handling system as well as on the ancillaries parts.

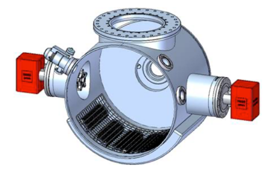

Figure 2: Sketch of the design of the UHV DC Gun vacuum chamber.

Laser System

The aim of the optical system (see Fig. 3) is to excite the photocathode for the generation of the electron bunches. The main oscillator, model Orange from the Menlo Company, is a 1035 nm mode-locked Yb laser with a 92.857 MHz repetition frequency, 10W of mean power and a pulse duration of 190fs. The light pulses outgoing the oscillator are temporally stretched by a Chirped Volume Bragg Grating (CVBG) up to 440 ps [10], with a spectral width of 2.8 nm. After this stretching stage, the laser beam is divided in two lines by a beam splitter (BS): a small portion (100 mW) is coupled into a fiber (about 140m long) and the remaining power (about 2 W) is dedicated to another part of our laser system.

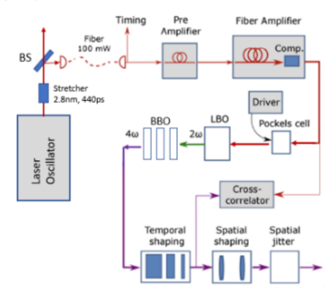

Figure 3: The laser subsystem.

The 100 mW laser pulses that arrive with the optical fiber are pre-amplified to about 2 W, exploiting a first fiber amplification stage based on a polarization-maintaining (PM) Yb-doped fiber, then to about 60 W, exploiting a second amplification stage based on the NKT aeroGAIN-BASE-1.2 fiber amplifier [11]. Starting from the IR light at 1035 nm, the 4th harmonic at 258.75 nm is generated to obtain pulses suitable for the photoemission process. This task is performed using a Lithium tri-borate (LiB3O5) 10 mm long and three BBO (BaB2O4) crystals 1.5mm long for the second (21.5W) and fourth harmonic generation (4.5W), respectively. The repetition rate of the laser pulses is controlled by a Pockels cell from kHz up to the repetition rate of the oscillator. The stacking method [12] is exploited to get a 18 ps rectangular pulse with about 1 ps rise and fall time. The so-called pi-Shaper will be used instead for the spatial shaping [13]. Finally, spatial stabilization of the pulses on the photocathode target is performed providing a

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closed-loop stability lower than 5 μm. The laser oscillator, the power amplifier, the Pockels cell the temporal shaping and spatial stabilization system of the spot on the photocathode are already present in our laboratory.

THE BUNCHERS SUB-SYSTEM

Bunches need to be compressed to shorter length after the gun, before entering the BriXSinO SC Booster. As the beam is still non-relativistic at this point, the simplest method of bunch compression is the velocity bunching for which we choose sub-harmonic bunching solution, using two $\beta < 1$, 650 MHz spherical reentrant shape copper cavities. The beam energy before entering the first cavity is 300 keV and 638 keV before entering the second.

Buncher Cavity Electromagnetic Design

The buncher cavity has been designed by employing Superfish code and Ansys HFSS commercial electromagnetic simulator, using as a reference the cERL buncher cavity design scaled from the original 1.3 Ghz frequency [14]. Table 3 summarizes the main electromagnetic and design parameters for the two buncher cavities. The structure, with radius R_c = 170.12 mm and total length L_c = 324.24 mm, is visible in Fig. 4.

Table 3: Buncher Cavity Main Design Parameters

	Buncher 1	Buncher 2
f_0 (π-mode) [MHz]	650.35	
β (v/c)	0.74	0.906
Input beam energy [MeV]	0.3	0.638
E-field ampl. [MV/m]	2.7	
Cell per cavity	1.0	
Active cavity length [m]	0.171	0.209
Cavity quality factor Q_0	3.2×10^4	3.67×10^4
Ext.quality factor Q_{ext}	3.02×10^4	3.24×10^4
R/Q [Ω]	195.7	223
Geometry factor G [Ω]	211	244
E_{pk}/E_{acc}	3.07	3.88
B_{peak}/E_{peak} [mT/(MV/m)]	0.96	0.96
B_{peak}/E_{acc} [mT/(MV/m)]	2.94	3.73

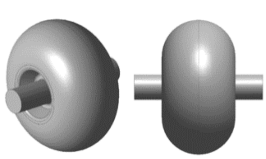

Figure 4: Buncher cavity geometry.

A first analysis has been performed by employing the Eigenmode solver, with the objective to verify the correctness of the results in terms of operating frequency and electric field of the employed TM010 mode. Then, a coaxial coupler, working in the 3 1/8” standard, has been designed to feed the cavity. The coupling is magnetically performed through a loop, that extends from the coupler inner conductor, which can be rotated (with respect to the cavity axis) to obtain the desired coupling factor, or βcoup.

Mechanical Modelling and Thermal Analysis

We are planning to machine the cavity made from bulk copper. It is possible to fabricate it in two halves with a high-precision lathe machine. The two parts will be brazed in a high-temperature furnace. The cooling channels can be inserted in the outer shell of the cavity. We have started the thermal analysis with the CST code. The average RF power to be dissipated by the cavity walls is considered to be 10.3 kW. The channels inner diameter is 1.5 cm. We considered a water flux of 10 l/min and water temperature of 30 °C. The simulation output is given in Fig. 5, which shows the temperature distribution inside the copper with a hot spot of 45.2 °C. The temperature gradient of about 15 °C will produce a frequency shift of about 187 kHz, which can be corrected with the tuning in-vacuum plunger.

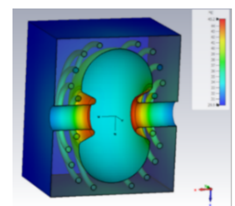

Figure 5: CST thermal analysis of the buncher cavity.

RF power plant preliminary design

The beam loading of the buncher cavities is negligible, as the RF power is almost all dissipated in the cavity walls. The power budget to feed the buncher is reported in Table 4 for the case of E_z max = 2.7 MV/m, so far considered in the beam physics simulations. For the power amplifier we have chosen a modular, expandable Solid-State Amplifier (SSA) solution. Coaxial cables are preferred over waveguides: 3 1/8” cables will be used. The possibility to embed the LLRF controls inside the SSA is also under study. Final forward power will be defined by the SSA modularity.

Table 4: Power for the two Buncher Cavities

	E_z max = 2.7 [MV/m]	
	SHB 1	SHB 2
Beam power [kW]	2	2
Cavity power [kW]	11	14
Total power [kW]	13	16
+15% margin	15	18.4
FW power – 4 kW SSA [kW]	16	20
FW power – 5 kW SSA [kW]	20	20

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