APERTURE TEST FOR INTERNAL TARGET OPERATION IN THE JLAB HIGH-CURRENT ERL*

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Abstract

A high current beam transmission test has been successfully completed at the JLAB FEL Facility, culminating in very low-loss transmission of a high current CW beam through a small aperture simulating the configuration of an 10^{18} cm^{-3} internal gas target proposed for the DarkLight experiment [1]. In order to meet the technical challenges, minimal beamline modifications were made to create a machine configuration that is substantially different from those used in routine UV or IR FEL operation. A sustained 8 hour high power beam run was performed, with clean transmission through a 2 mm transverse aperture of 127 mm length. A beam size of 50 um (rms) was measured near the center of the aperture. Experimental data from a week-long test run consistently exhibited beam loss of only a few ppm on the aperture while running 4.5 mA current at 100 MeV – or nearly 0.5 MW beam power. This surpassed the users' initial expectation and demonstrated a unique capability of an ERL for this type of experimental configuration. This report presents a summary of the experiment, a brief overview of our activities, and outlines future plans.

INTRODUCTION

With the successful completion of recent IR and UV upgrade, JLab FEL is now capable of providing users with high average power femtosecond laser pulses with unprecedented wavelength tunability from VUV to THz. As the only currently operating FEL based on a CW superconducting energy recovering linac (ERL), the facility not only remains unique as an FEL driver [2, 3], it has also drawn significant interests in new physics experiments involving interaction of MW electron beam with thick gas targets such as DarkLight experiment to search for dark force particles.

The proposed DarkLight experiment requires sophisticated detectors and a windowless gas target embedded in the magnetic solenoid with multi-stage differential pumping system. A key pending question then was if it was possible to achieve the stringent electron beam specifications and background conditions necessary to carry out the experiment. In other words, people needed to know if the JLab FEL electron beam could be tightly focused to a tiny spot and cleanly transported through certain narrow target area, and if noticeable, how much beam loss and radiation there would be. An experiment to demonstrate the suitability of JLab FEL machine for the DarkLight experiment was therefore proposed and later successfully implemented in summer 2012, which will be reported in this paper.

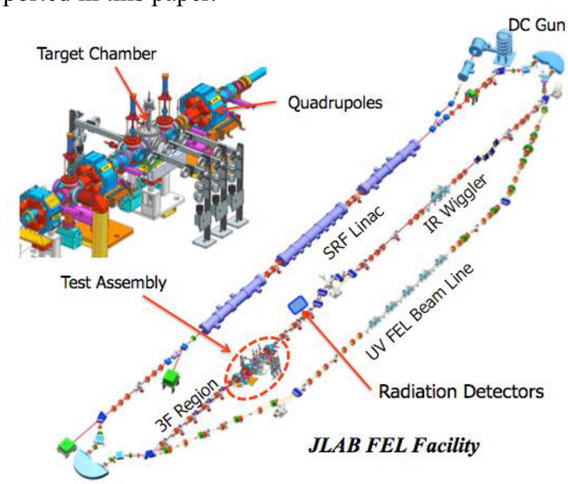

Figure 1: A schematic of the JLAB FEL Facility showing the ERL accelerator, IR and UV FEL beamlines, the proposed beam transmission test experiment assembly and its location. The location of the radiation detectors is also shown.

Specifically, the purpose of the test is to transmit a 100 MeV high-current electron beam cleanly through a 2 mm diameter hole (127 mm long) in an aluminum beam tube block simulating operation of the gaseous hydrogen target proposed for the DarkLight experiment. In addition, it is desirable to characterize photon and neutron radiation backgrounds produced during beam transmission through the hole in order to design the DarkLight detector. Knowledge of the radiation background is necessary to ensure the DarkLight's tracking detectors are able to operate successfully in the FEL tunnel.

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EXPERIMENTAL SETUP

Although JLab FEL has gained extensive experience in the machine design and operation and had in place the necessary beam controls to deal with halo along the beamline, the proposed aperture test requires a quite different machine configuration and beam specifications with longer bunch length, sub-mm beam size, ~10^{-5} beam loss through a 2 mm diameter beam tube of 127 mm length, and as much sustained beam current as possible. To make this test possible, the machine needs to operate with a “cross-phased” tuning instead of the nominal “off-crest” configuration routinely used for FEL operation. In this case, the beam is phased on the rising part of accelerating RF field waveform in the first and the third super-conducting cryomodules, and on the falling portion of the field waveform in the second module, resulting smaller momentum spread and a longer bunch. The detailed machine design is described elsewhere [4].

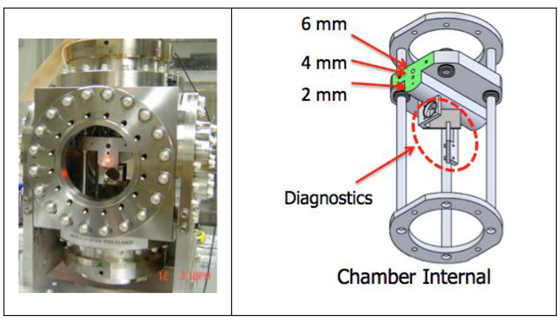

Figure 2: Left: A photo of the target chamber with three beam tubes and diagnostics seen from an open side port. An aligning laser beam spot can be seen on the 2 mm hole. Right: 3D illustration for the internal components and mechanical structure of the target.

There are several locations along the beamline that have been considered for this test, and it is desired that both beam-halo and emittance be eventually measured at a preferred experimental location, i.e., the UV wiggler pit or its close vicinity. However, an opportunity exists in a shorter term with lower cost to validate the beam halo and emittance with relatively minor modifications in the 3F region on the IR beamline. This choice has the added advantage of performing initial halo studies in the most operationally flexible and heavily instrumented region of the JLab FEL facility. Although this location is not where the DarkLight experiment is eventually intended to take place, the measurement will provide valuable experience and data needed for a preliminary beam analysis, uncover potential effects that may be seen in the final location, and thus inform the design of the beam line to the DarkLight detector in the UV section of the ERL accelerator. Fig. 1 is a schematic of the JLab FEL Facility and the locations of the proposed test and the radiation detectors. The transmission experiment assembly, the section of the modified beamline in 3F region, is also shown.

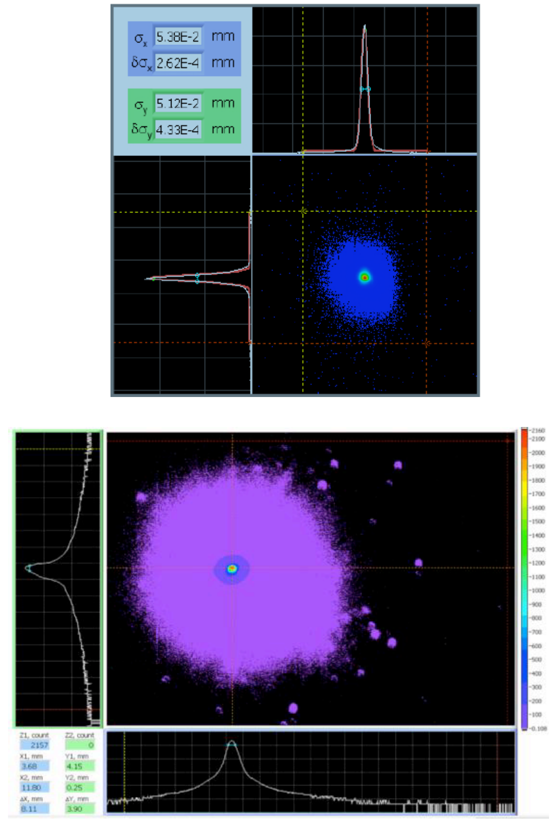

Figure 3: Top: measured beam transverse profile by using the OTR beam viewer. The beam size is ~50um (rms) based on best Guassian fit to the horizontal and vertical projections. Bottom: a high dynamic range beam profile measured with Ce:YAG showing beam halo around the core (vertical scale is logarithmic).

To meet the stringent requirement of the beam specifications and the machine operation schedule, moderate modification on the beamline was made, including installation of target chamber, additional steering dipoles and diagnostics in the 3F region to provide the requisite orbit and envelope control, and two extra correctors to control the orbit into or out of the test assembly. The target chamber consists of an aluminum beam tube block and internal diagnostics including a Si OTR viewer and a Ce:YAG scintillator, all attached together and horizontally aligned to the longitudinal center of the tubes, as shown in Fig. 2, the beam block is driven by a step motor to vertically move the tubes and diagnostics in or out of the way of traveling electron beam. A RTD on top of the beam block measures the temperature changes during the test. The target chamber were surveyed and assembled together with other external components in a lab before integrated into the beamline. High precision alignment was achieved with the help of a Faro arm device. The final alignment of the diagnostics was performed by threading a laser beam mode-matched to the e-beam envelope in the beam tube region. During the survey, we found the effective aperture diameter of the smallest tube is less than 2 mm, close to 1.8mm.

Among other beam parameters, the transverse beam size and the low intensity halo around the bright core are the most important information to this test, essential diagnostics therefore need to be in place. As illustrated in Fig. 2, a 100 micron thick Ce:YAG crystal is attached and longitudinally aligned to the center of the beam block for halo measurement. The scintillation signal was captured simultaneously by two CCD cameras through an optical imaging system. Setting different exposure time on the cameras and numerically combining the two individual images produces a high dynamic range beam profile [5]. A measurement is shown in Fig. 3 indicating a dynamic range on the order of 10^5.

In addition to the halo monitor, an OTR viewer (Si wafer) was installed in a similar way beneath the beam block, also aligned to the longitudinal center of the beam tube block, to measure and monitor the beam size during machine tune up. This viewer, together with one standard OTR beam viewer upstream and one downstream of the target, provides effective means to control beam orbit and envelope. A beam profile measured with the center OTR viewer shows a tiny 50um rms beam size (Fig. 3). It should be noted that the beam has to be run at a low current mode for such kind of diagnostics.

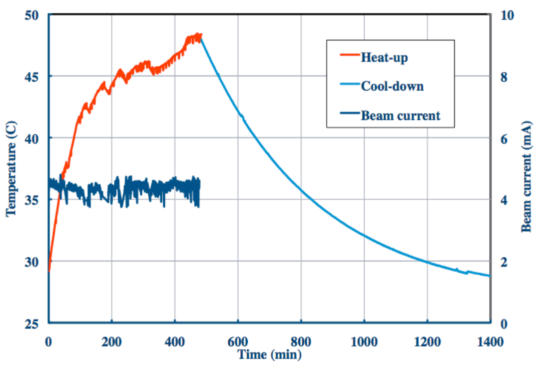

Figure 4: Beam block temperature and beam current vs. run time when transmitting a 4.5mA/100MeV beam through the 2 mm hole. After the beam is turned off, a cool-down curve is recorded and shown here.

TEST RESULTS AND ANALYSIS

We started with low duty-cycle beams and tried different bunch charges for minimum beam loss during machine optimization. The maximum beam current allowed was 4.5 mA (75 MHz, 60 pC/bunch) due to a damaged component in the injector. Both temperature and radiation data were recorded when running full 450 kW CW beam through different beam tubes. Significant temperature rise was observed with beam running through the beam tubes, in particular with the 2 mm hole, as seen in Fig. 4. Using both the heat-up and cool-down data we analyzed the deposited beam power into the beam block as a function of time, as shown in Fig. 5. The variation of the deposited power is primarily due to the machine instability caused by some aging components and the extreme ambient temperature encountered on the day of the test. The average beam loss (the ratio of the deposited power over the initial beam power) is about 3ppm, and the minimum is less than 2 ppm. It has to be pointed out that this beam loss includes the combined contribution directly from the beam halo and resistive wall heating. We estimated about 0.5 W or 20% of the deposited power is from the Wakefield. Further analysis also indicates that about 50% of the electrons hitting the tube wall may have escaped through the back and side of the block [6].

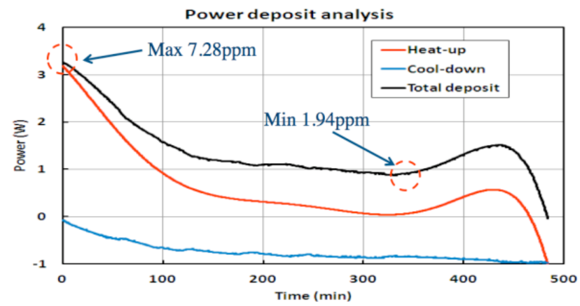

Figure 5: Analysis of beam power deposited into the beam block through 2 mm beam tube test based on data in Fig. 4.

SUMMARY

A sustained 8 hour high current beam transmission test through a narrow aperture is implemented successfully. Experimental data consistently indicates that a 100 MeV electron beam of 0.43 MW average power can pass cleanly through a 2 mm diameter aperture of 127 mm length with an average beam loss of only about 3 ppm. This level of losses is acceptable for the DarkLight experiment and the beam backgrounds generated are manageable. Although the test has demonstrated the suitability of JLab FEL in the proposed DarkLight experiment, we believe significantly better performance is expected in future by running ERL machine at lower charge/high repetition rate, replacing aging components, upgrading gun and by employing suitable collimators upstream of the target interaction region.

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