DEVELOPMENT OF ADVANCED BEAM HALO DIAGNOSTICS AT THE JEFFERSON LAB FREE-ELECTRON-LASER FACILITY*

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Abstract

High average current and high brightness electron beams are needed for many applications. At the Jefferson Lab FEL facility, the search for dark matter with the FEL laser beam has produced some interesting results [1], and a second very promising experiment called "DarkLight", using the JLab Energy-recovery-linac (ERL) machine has been put forward [2]. Although the required beam current has been achieved on this machine, one key challenge is the management of beam halo. At the University of Md. (UMD) we have demonstrated a high dynamic range halo measurement method using a digital micro-mirror array device (DMD). A similar system has been established at the JLab FEL facility as a joint effort by UMD and JLab to measure the beam halo on the high current ERL machine [3]. Preliminary experiments to characterize the halo were performed on the new UV FEL. In this paper, the limitations of the present system will be analyzed and a discussion of other approaches (such as an optimized coronagraph) for further extending the dynamic range will be presented. We will also discuss the possibility of performing both longitudinal and transverse (3D) halo measurements together on a single system.

INTRODUCTION

Beam-halo in a high current ERL machine can be a serious issue for some applications such as the proposed "DarkLight" experiment, which requires that the low intensity distribution be less than 10^{-4} of the core's intensity. To measure the low intensity distribution around the bright core of the electron beam presents technical challenges due to the very high contrast or dynamic range that is required. There are different ways to perform a high contrast electron beam halo measurement. The conventional scraping collimator and wire scanner [4, 5] have provided good contrast (up to 10^6) but involve the direct interaction of insertion devices with the electron beam and therefore prevent full beam operation during the measurement. Although good progress has been made in the development of laser wires, the contrast still needs significant improvement in order to be acceptable for measurements up to the 10^4 level.

The concept of the coronagraph has been long proved by numerous studies and tests in astronomical research. In the accelerator community, beam-halo studies have also been going on for a long time. KEK followed an internal-mask scheme with a Lyot stop and produced very encouraging results by using Synchrotron radiation (SR) light. At the JLab FEL, our near term goal is to use a modified existing phosphor-screen halo monitor for lower current beams while developing new non-interceptive systems for both high current ERL beam studies, and applications such as beam-target interactions. We are especially interested in learning the source of the beam-halo on our ERL machine and in finding an effective way to suppress it. In this paper, we will present the on-going activities and our near term goals related to these measurements.

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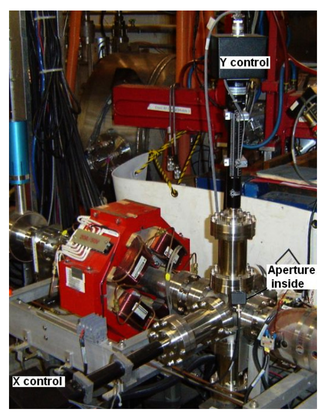
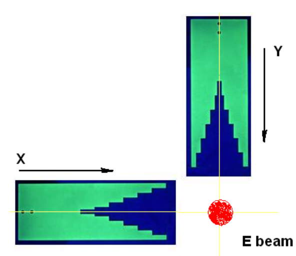
SYSTEM DEVELOPMENT

Presently, there are two different beam-halo measurement systems under development and test at the JLab ERL FEL facility, as discussed below.



(a)



(b)

Figure 1. (a) A picture of the installed jaw-plate halo-monitor. (b) Diagram showing the basic principle of the variable aperture formed by two jaw-plates crossing to each other.

Interceptive Beam Halo Monitor

The first one is a beam-scraping based system located near the injector in the FEL vault. As shown in Fig. 1(a), this is an interceptive beam profile monitoring device which consists of stepped jaw-like plates (Fig. 1(b)) controlled by two 6" stepper motor driven actuators. The plates are made of 1/16" aluminum machined in steps of 10mm x 5mm (on each side). When the two jaw-plates move in and cross each other, a variable aperture forms and closes down to intercept a different part of the electron beam. When inserted all the way the plates close off the beam path completely. The beam image, produced by the phosphor material on the jaw-plates when illuminated by the electron beam, is captured by a camera for data acquisition. For spatial calibration of the camera, an additional UV LED is installed on the side. The position is calibrated against external indicators (steps per mm) and the device is fitted with IN/OUT limit switches. Radiation monitors such as beam-loss monitors and PMTs can also be used for detection of the intercepted beam. We are planning to move this system to a new location upstream of the IR FEL wiggler for detailed beam-halo measurements, including bench-mark tests of the system itself in regard to the ultimate limit on the acceptable beam current and dynamic range. An obvious disadvantage of this system lies in its interceptive nature.

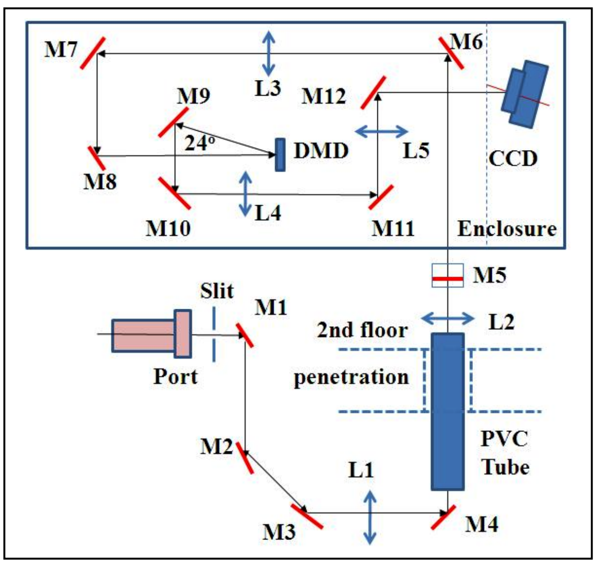


Figure 2. Schematic of the optical transport for beam imaging with SR light. M, mirror. L, lens. M5 is a 45° reflector that bends the beam by 90° from the vertical to the horizontal plane. M1 through M4 are in the electron beam radiation area.

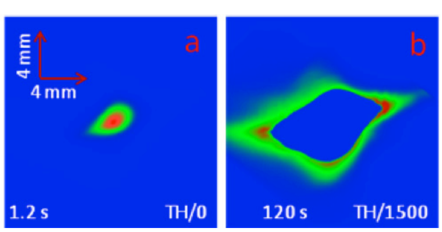


Figure 3. Measured beam images, (a) Original beam without applying the DMD mask, (b) After the beam core is masked by the DMD. TH refers to mask threshold setting. Camera integration time (in seconds) is marked on the lower left corner. Also see [3] for more details.

Non-interceptive Beam Halo Monitoring System

The second system is a non-interceptive system based on the micro-mirror-array coronagraph concept [6, 7]. The electron beam profile is imaged through a 12-meter optical transport using the synchrotron radiation (SR) light parasitically generated from the 135MeV electron bunch passing through a magnetic dipole. Fig. 2 is the schematic of the optical transport designed for image relay and magnification adjustment. The whole system is pre-aligned with a laser beam and fine adjustment is achieved with remotely-controlled motorized mirrors (M1, M2, and M4) when the SR light is available. One key element here is the DMD that kicks out the bright beam core while leaving the low intensity beam halo to be detected by the CCD camera. Very low intensity beam halo distribution can be measured by setting the proper threshold of the core intensity to be blanked out, the integration time on the camera, and the use of neutral density (ND) filters.

Figure 3 presents preliminary data, which were taken recently when the JLab ERL machine ran with 1ms macro-pulses at 60Hz, a 4MHz micro-pulse repetition rate, and 60pC charge in each micro-bunch. Notice the revealed halo distribution in Fig. 3(b) when the DMD mask is applied, which could not be seen without application of the mask as shown in Fig. 3(a). The analysis shows a dynamic range of 10^4 is achieved with the present experimental conditions.

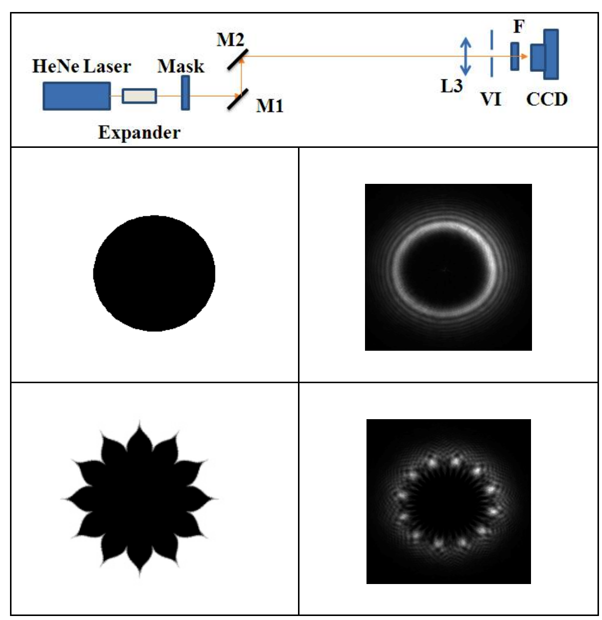


Figure 4. Top: optical layout of measurement. Mask pictures and images for contrast measurements. Middle: Sharp-edge mask, Bottom: 12-petal mask. M, mirror. L, lens. F, ND filter. VI, variable iris.

Our measurement contrast may be affected by several factors including stray light, broadband SR light dispersion, image smearing along the arc orbit, and diffraction. With proper shielding, using band-pass filters, and background subtraction, the first two factors can in principle be suppressed to a negligible level. The image smearing induced by the electron orbit can be minimized with an angle-limiting slit, or completely eliminated by working with edge radiation. However, diffraction by the hard edge of the mask may cause considerable artifacts on the low intensity halo, which appears to be on the order of 10^{-4}. For example, taking a close look at Fig. 3(b), the (higher intensity) red color area along the mask boundary is likely due to the diffraction effect. This kind of issue has been an active research subject in astronomical and space program studies in search of faint planets near bright stars. It has been theoretically proved that certain types of petal-shaped masks can be adopted to suppress the diffraction down to the 10^{-10} level [8]. We have performed a test with simple petal masks as shown in Fig. 4. The light source was an expanded HeNe laser beam, the flower-like mask was made of black paper, 16 mm in diameter with 12 identical petals. We used the same 16-bit cooled CCD camera as was used for the previous SR light measurements. The distance from mask to the camera was about 10 meters. The dark shadow formed by the mask had a contrast (with respect to that without mask) in a 3 mm diameter center area of 2.5×10^{-3} for the sharp-edge mask and 1.3×10^{-5} for the petal-mask. This indicates that a significant difference can be made with petal masks, as expected. High contrast measurements may thus be achieved if the low intensity beam halo is imaged into the dark shadow area. It should be pointed out that this simple test has not yet been fully optimized. The actual contrast for the petal mask could be much higher if the scattered light were further reduced, and if a better geometric precision on the mask pattern could be guaranteed. Since the biggest advantage of using the DMD over a conventional mask is that in principle a mask with any arbitrary shape can be easily made, it will be interesting to see how the real performance of a DMD enabled petal mask will turn out in this regard. An experiment is under way with the DMD and will be reported later when the result becomes available.

Longitudinal Halo Measurement

In addition to the spatial beam halo, as has been discussed above, another very important aspect about the high current beam is the low amplitude temporal distribution before and after the main pulse, which is suspected to be a few picoseconds (ps) to tens of ps in the case of the JLab ERL. The temporal halo is definitely not desired and may limit high current operations of the machine. The exact cause of the temporal halo is not quite clear and its behavior has not been well studied so far. A deflecting cavity is a very powerful tool for tracking temporal halo, but limited by the maximum acceptable beam current. Streak cameras have also been used for temporal measurements for a long time. With many SR light ports available around accelerators such as our ERL machine, non-interceptive realtime monitoring of the temporal characteristics of high current electron beam can be readily implemented by fast streak cameras [9]. As a matter of fact, the higher electron beam current provides stronger SR light and therefore makes such measurements easier.

A streak camera in lieu of the CCD camera, combined with the coronagraph technique such as the mask method we presented earlier in this paper, can reveal a high contrast 3D electron beam profile. In streak camera applications, only a slice of the incoming beam is permitted into the front slit in order to achieve high temporal resolution. The challenge with this new proposal is that the whole beam image brought to the front slit of the streak camera needs to be scanned over the slit without causing unacceptable time delay along the beam propagating direction. This can be accomplished by either an optical scanner that produces a flat focal plane or simply slowly scanning the streak camera head. Of course, the robustness of this method highly depends on the software and data acquisition system needed to effectively process the experimental data and reconstruct a whole 3D profile. We are planning to integrate a femto-second streak camera with the newly established DMD optical transport for a demonstration of a complete 3D high contrast beam profile measurement in near future.

SUMMARY

We have presented our efforts and activities in measuring the high current electron beam halo at the JLab FEL facility. The preliminary results from a non-interceptive system have been analyzed and an approach for further improving the contrast has been discussed. We have also described a plan to implement a high contrast 3D beam profile measurement by combining the current SR optical system with a fast streak camera.

ACKNOWLEDGEMENTS

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