DEVELOPMENT OF A SCINTILLATOR PROBE BASED ON FIBER OPTICS FOR RADIAL BEAM DIAGNOSTICS OF THE ION BEAM OF THE 88-INCH CYCLOTRON *

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Abstract

The complex 3-D magnetic field structure of the 88-Inch Cyclotron combined with the large number of tuning parameters such as trim coils, valley coils, the main field itself and the injection/extraction components makes it challenging to tune the Cyclotron. Furthermore, beam diagnostic devices to help tuning were limited to a stationary Faraday cup at the exit of the machine and a so-called Dee-probe which allowed for beam current measurements as a function of the turn radius. Motivated to improve the transmission of the Cyclotron due to misalignment of the ion beam in the center region and insufficient beam diagnostics, we have developed an optical beam viewer which we can move radially in and out of the machine. It allows us to image the beam cross section and its axial position with high spatial resolution as a function of radius. In this paper, we describe the mechanical development of the device which consists of a KBr scintillator disc, a fiber bundle and a digital camera and we present data from its initial commissioning.

INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley National Lab has been operating for more than 50 years, supplying numerous nuclear science programs with ion beams. More recently, two distinct user groups with very different beam needs have developed. The first group is composed of members of the National Space Security community who performs chip testing and requires low intensity beams of highly charged ions such as Xe^{43+}. The second is the Nuclear Science Community which requires medium charge states at relatively high intensities. For example, the heavy element research group has recently requested a $^{48}Ca^{11+}$ beam of 2 pμA. In order to meet these high current needs, a 4-year project was launched where the low energy injection beam lines and the Cyclotron center region were evaluated and upgraded. It became clear that in order to identify losses and increase the transmission of the Cyclotron, more detailed diagnostics were needed. Historically, a beam current readout of the inflector, a radial Dee-probe (a water cooled copper plate with a current readout) and a 3-finger probe were the only available diagnostic tools inside the Cyclotron. The 3-finger probe is composed of 3 segmented electrodes with individual current measurements that give a rough indicator of the axial beam position. However, there was no information about the beam shape and whether or not it was being clipped at some point along its trajectory. This led to the development of a radial scintillator probe to replace the 3-finger probe, which would give much more detailed information about the beam properties. The new probe utilizes most of the motion and vacuum components of the 3-finger probe which kept the amount of modifications at a minimum. The design and its implementation will be described in this paper.

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HARDWARE OF THE PROBE

The radial scintillator consists of three main components: The Scanner Head, a Fiber Bundle and the CCD camera which are all described below. A schematic view of the device is shown in Figure 1 and its technical details are summarized in Table 1.

Table 1: Specifications of the Essential Viewer Components

Camera:	Allied Vision Tech - GigE Manta
	1392 (H) x 1040 (V) pixels
	4.6 µm x 4.6 µm per pixel
	1/2" chip size, C-mount connectors
Fibers:	SCHOTT North America, Inc.
	10 µm mono-fiber size
	≈ 100 µm spatial resolution
Scintillator:	KBr from Alfa Aesar, 4mm thick

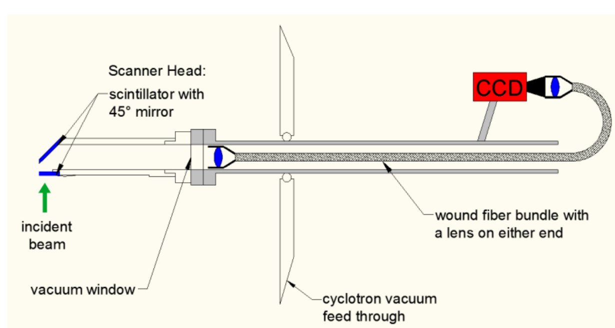

Figure 1: Schematic view of the radial scintillator probe commissioned at the 88-Inch Cyclotron at LBL.

Scanner Head

As shown in Figure 2a, the scanner head consists of a KBr scintillator from Alfa Aesar disc which images the beam and a 45 ° mirror projecting the image radially toward the lens of the fiber bundle. The two biggest problems during operation are (1) the degradation of the scintillator over time which leads to a reduction of the light yield with successive beam exposures and (2) the thermal expansion of the crystal and the resulting mechanical stress on it which can cause the crystal to shatter. While both issues are inherent to the design, they can be minimized by limiting the device's exposure to the beam. As Figure 1 shows, the 45 ° plastic mirror is beveled and its radial extent is the same as the scintillator. This was necessary in order to image the entire crystal but it also results in the mirror slightly being exposed to the ion beam. Therefore, the mirror surface gets damaged over time and has to replaced. For commissioning and calibration purposes we have neglected that issue but after using the probe for about 2 months, the mirror was too damaged to image the full area of the crystal.

Fiber Bundle

The fiber bundle is a custom design by SCHOTT North America, Inc. [1], based on our space constraints and optical specifications. It is built with clusters of 6x6 monofibers, where each mono-fiber has a diameter of 10 µm. For maximum usage of the camera's CCD pixels, the aspect ratio of the bundle is determined by the format of the CCD chip, in our case it is a 1/2 chip (4.8 mm x 6.4 mm). On one end, an objective lens projects the field of view (FOV) into the fibers where on the other end, a relay lens projects the image onto the CCD chip. As shown in Figure 2b, the connections between lenses, camera and the bundle are all done with regular C-mount connectors, making it easy to modify the system. With the current setup, we obtain a spatial resolution on the scintillator of approximately 100 µm over a total FOV of 36 mm (radially) x 47 mm (axially). To reduce the X-ray flux, the fiber bundle and the attached camera are located away from the Cyclotron mid-plane which made it necessary to have a flexible cladding. Furthermore, the presence of the strong Cyclotron main magnetic field made it necessary to design all components with either non-magnetic stainless steel or aluminum.

Camera

With a distance of about 50 m between the host computer and the device, we had to use a GigE camera (AVT Manta) because any other digital bus does not allow for such long cable lengths. We can adjust the camera exposure time and gain from the host computer which is important to achieve an optimal saturation of the chip and a reasonable signal to noise ratio. While the camera is housed in a 3mm thick lead box to reduce the X-ray flux to it, we still saw a significant radiation damage of the CCD pixels after a few weeks of operating the camera. This is also due to the neutron exposure to the camera as its physical distance to the Cyclotron extraction is only about 3 m.

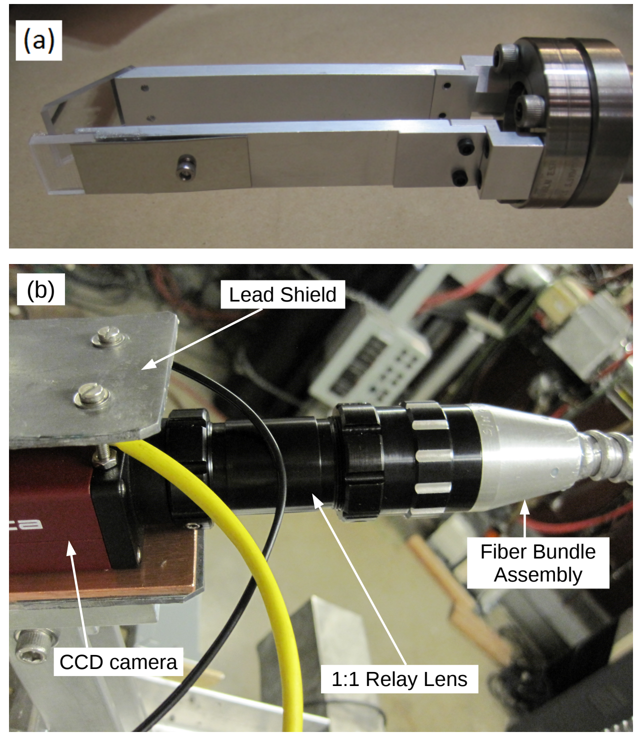

Figure 2: The two main components of the system: (a) Scanner Head with a steel mesh around the crystal for its charge neutralization. The mesh also provides mechanical support in case the crystal breaks. (b) The camera first connects to a relay lens and then to the SCHOTT Fiber Bundle; all connectors are C-mount.

CALIBRATION & INITIAL DATA

Since the scintillator probe was designed to measure the axial and radial position of the ion beam in the Cyclotron, we had to calibrate the device in order to know where the Cyclotron mid-plane is relative to the scintillator top and bottom edges. That axial calibration was done by taking the top- and bottom surface of the Dummy-Dee insert (described in more detail in [2]) as a reference mark. Here, the axial center of the insert is assumed to be aligned with the Cyclotron mid-plane and the position of the same was located with a high-precision scope. Relative to these marks, the vertical center of scintillator crystal was found to be roughly 2.3 mm lower than the Cyclotron mid-plane. That result is consistent with the fact that the top clearance between the scintillator and the Dummy-Dee insert is slightly reduced because of the fixture holding the Dummy-Dee insert in place. The radial position of the probe can be coarsely adjusted in real time from the control room. However, since we used the coarse motion system from the former 3-finger probe, the scintillator can only be positioned with a radial accuracy of approximately 0.5 cm.

A LabVIEW program controls the camera and saves the raw image whereas an offline Python script processes the data to crop the image, remove noise and overlay the reference marks mentioned above (Cyclotron mid-plane and

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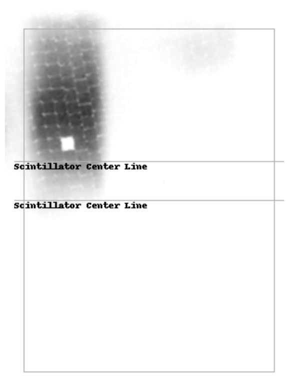
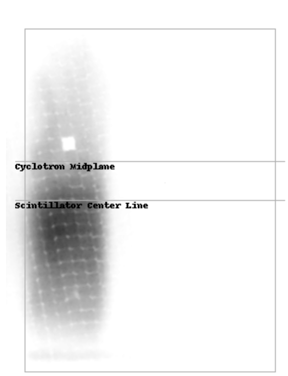
scintillator edges). Cropping becomes necessary if the scintillator surface does not fill the entire image size, leading to a significant portion of the image being dark. Figure 3 shows two images after they were processed by the Python script. The white rectangular area in the top left of each image is due to one damaged 6x6 mono-fiber cluster which occurred during the fabrication process. The gray box indicates the outline of the scintillator which was obtained by a separate calibration on the bench before the probe was mounted to the Cyclotron.

As the initial data set, a series of pictures was recorded, starting from a radius of about 9 cm (innermost position) in steps of approximately 0.5 cm out to a radius of 25 cm. Figure 3a shows the beam at a radius of about 20 cm and confirms that its trajectory is about 5 mm above the Cyclotron mid-plane during the first few turns which is caused by an offset of the main cyclotron magnetic field [3]. As the physical gaps are narrow in the axial direction near the Cyclotron center , beams that are away from the mid-plane are more likely to be clipped. The measurements taken with the scintillator are in agreement with beam current measurements which have indicated that a significant percentage of the transmission losses occur in the innermost 25 cm of the Cyclotron. As described more detailed in [2, 3, 4], the probe was then used to verify that unbalancing several of the trim coils can compensate for the offset of the main magnetic field and steer the beam back toward the mid-plane in order to increase the transmission of the Cyclotron. This can be seen in Figure 3b where the current in the bottom coil is about 193 A less than in the top coil.



(a) Trim coil 1 in balanced mode (Top and bottom coil each run 356 A).



(b) Trim coil 1 in unbalanced mode (193 A removed from the bottom coil).

Figure 3: The pictures are processed by a python script to crop them, remove noise and overlay reference marks. (a) shows the beam at r = 20 cm with trim coil 1 balanced and indicates that it is high relative to the cyclotron mid-plane while (b) beam at the same radius but with trim coil 1 unbalanced and therefore steering the beam down significantly.

CONCLUSION & OUTLOOK

As part of the high-voltage upgrade project, a radial scintillator probe based on fiber optics was developed and commissioned at the 88-Inch Cyclotron at LBNL. With the probe, an axial misalignment of the ion beam trajectory during the first 25 cm was found. Using the probe at several radial positions, we showed that with an unbalancing of trim coil 1, the beam can be steered back toward the mid-plane, therefore increasing the transmission. The following list describes some modifications we have planned for future designs making the probe more versatile and allowing for more qualitative beam diagnostic applications:

- The current design can easily be equipped with a hole mask in front of the scintillator crystal, turning the probe into a pepper-pot scanner for the Cyclotron. Having emittance data from inside the Cyclotron is essential for verifying particle tracking codes that have been developed and are described in [2].
- Some turns are only partially striking the scintillator while the remaining part makes one more turn and hits the scintillator at a larger radius. This results in multiple beam spots on the crystal which is hard to analyze. Therefore, shrinking the crystal in the radial direction would result in a much clearer dataset. For doing that, a more precise motion system with a sub-millimeter resolution will be necessary.

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