A CCD Camera Probe for a Superconducting Cyclotron

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Abstract

The traditional internal beam probes in cyclotrons have consisted of a differential element, a wire or thin strip, and a main probe with several fingers to determine the vertical distribution of the beam. The resolution of these probes is limited, especially in the vertical direction. We have developed a probe for our K1200 superconducting cyclotron based on a CCD TV camera that works in a 6 T magnetic field. The camera looks at the beam spot on a scintillating screen. The TV image is processed by a frame grabber that digitizes and displays the image in pseudocolor in real time. This probe has much better resolution than traditional probes. We can see beams with total currents as low as 0.1 pA, with position resolution of about 0.05 mm.

Introduction

The standard beam probe for the K1200 cyclotron consists of a beam current measuring device that gives limited information on the vertical beam distribution. The probe head is made of three copper leaves separated by small insulating spacers in the vertical direction. The height of each leaf is approximately 6 mm. The probe thickness in the beam path direction is such that it stops completely most of the heavy ions in the energy range of our cyclotron, but not so for lighter ions. The only information that we obtain with this probe is the total current as a function of radius. This is probably enough to study vacuum loses and tune the beam through resonances by maximizing the transmitted beam current, but very little can be learned about beam dynamics. Several attempts have been made at other laboratories to obtain more information on the internal beam, but these techniques all have limitations [1, 2].

After our successful experience with the use of scintillators and a frame grabber to tune and study external beams [3] and similar experiments at other laboratories [4, 5, 6, 7], we decided to look into the possibility of building a beam probe physically compatible with the present current probe that could include a TV camera to look at a phosphor covered plate. This new kind of internal beam probe was then developed for the K1200 cyclotron. It consists of a small TV camera that looks at the image produced by the beam hitting a phosphor covered plate. The small size of the camera allows it to be placed close to the screen. The image gives a detailed view of the current density in r and z, with position resolution of about 0.05 mm. Total beam currents below one electrical pA are easily analyzed. This probe opens new possibilities for the study of internal beam dynamics and allows tuning very weak beams, below one pA.

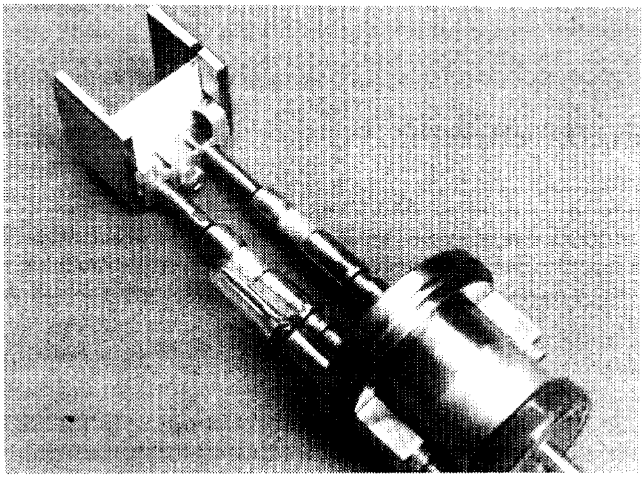

Figure 1: Close up view of the probe head before welding to the vacuum tube. The support for the scintillating plate is seen on the upper left. The plate is held in a groove by springs. The two supports are the electrical connection to the beam current monitors.

TV probe

The desire to make the new probe and the standard probe interchangeable, so as to use the same hardware for the drive presents severe restrictions on the physical dimensions. The space is limited to a tube of 1.25 inches diameter that is inserted in the median plane between the two sections of the superconducting coil.

Two major concerns were the possibility of radiation damage to the camera and the high magnetic field (6 T) in which the camera must work. The simplification offered by inserting the camera close to the plate, compared to

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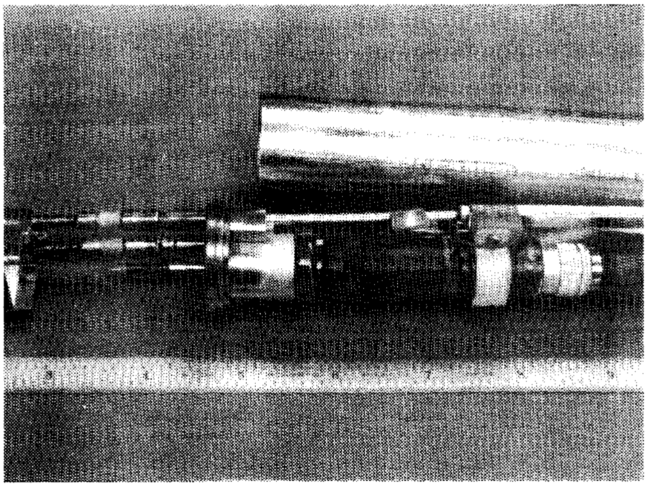

Figure 2: TV camera positioned behind the window as it would appear inside the stainless steel tube that is positioned above.

using an optical system with its associated loses, induced us to design and build the TV probe. We chose an ELMO 102BW camera after testing it in a magnetic field because of its small size and image quality.

Figure 1 shows a close up view of the probe head, while Figure 2 shows the TV camera placed behind the head next to the stainless tube that encloses the system. The ruler is marked in inches. The phosphor plate is removable, allowing an easy change of the phosphor if needed. The probe removal and reinsertion in the cyclotron can be done under vacuum in a period of 30 minutes. The screens are produced by spraying ZnS[8] phosphor with Krylon as a binding agent.

The two insulators that support the head are hollow, and a conducting rod traverses to carry the current signal to the beam current monitors (BCMs). We have had difficulties reading beam currents below 100 pA, but a beam current below 1 pA gives an easily viewable light output for the TV camera and produces no radiation damage to the CCD. We have noticed permanent radiation induced damage for currents above 1 nA. This threshold depends on the ion and its energy. But for the cases that we have tested this seems to happen at least 100 times above the currents that we would normally use for TV viewing. The tuning is normally performed with attenuators inserted in the injection beamline. These screens[9] which are available with different combination of transmissions, down to 10^{-7}, sample the beam over the complete phase space, rather than just collimating it. In the regime of negligible space charge, the small amount of current that is injected, is then representative of the total beam; the attenuator thus provides complete control of the beam intensity hitting the probe. Once the beam is tuned, the probe is retracted and the attenuator screens adjusted to match the experiment requirements. Working with low current allows the probe to run with no water cooling, which lowers the electrical noise. The ability to tune beams with very low intensities will allow us to accelerate to higher energies ions that are produced in limited quantities in the ion source. Modern 4π detector experiments require low intensities and can make use of these weak high energy beams.

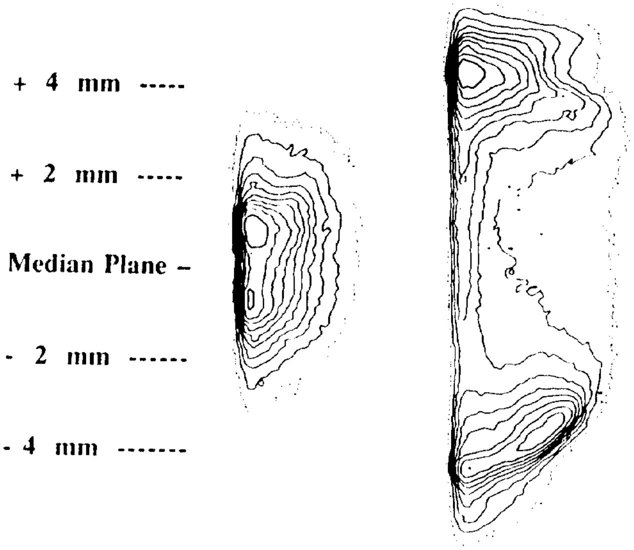

Figure 3: Contour plot of light intensity on the scintillator for a He beam of 40 MeV/u. The probe is at a fixed radius (0.83 m), just outside the $\nu_r = 2\nu_z$ coupling resonance. The plot on the left corresponds to a centered beam, while the one on the right is from an off-centered beam.

The glass dome visible at the lower left in figure 1 is used to insert an illuminating optic fiber. The purpose is to inspect the condition of the screen in case there are doubts about its integrity.

The RS170 TV signal from the camera can be sent directly to a B&W monitor or to the frame grabber [3] which displays the intensity levels displayed in pseudocolor on a color monitor in real time. Figure 3 shows an example of the equicontours of the light intensity for two different centering coil values with the probe at a fixed radius. The beam probe was placed just beyond the region of the $\nu_r = 2\nu_z$ resonance. This coupling resonance transfers energy between the horizontal and vertical oscillation planes. Most of our beams have to cross this resonance, and severe losses can occur if the beam is not centered when crossing it. As the figure shows, the probe picture gives a dramatic visualization of the increase of the vertical oscillation between the centered beam (left picture) and an off-centered beam (right). These pictures were digitized from a video tape recording. Digitizing from a recorded image introduces some noise that is not present when capturing frames from a live image.

Figure 4 shows five intensity contour plots taken at approximately 2.5 mm increments apart in radius, with the innermost at a radius of 0.52 m. The $^4He^{2+}$ beam had an energy of approximately 10 Mev/u at this radius. The vertical oscillation of the beam about the median plane is clearly visible . Part of the beam hits the probe plate, and part continues for one more orbital revolution before hitting the plate. By then its vertical position has changed.

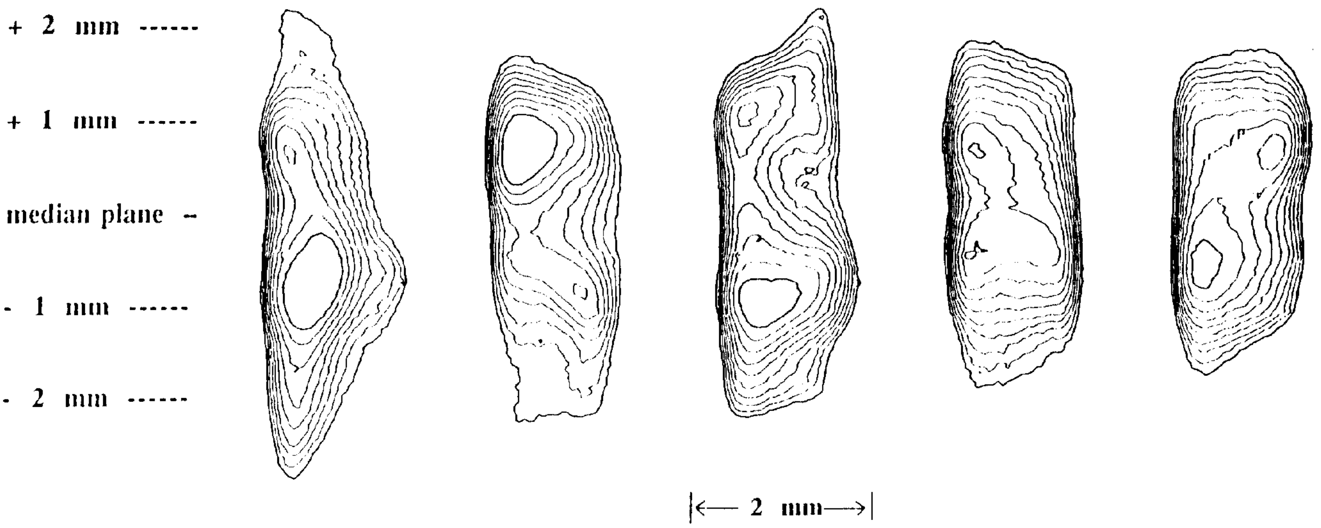

Figure 4: Contour plots at five radii showing the vertical oscillation of the beam around the magnetic median plane. See text for more details.

As the vertical focusing frequency $\nu_z \approx 0.4$ for this beam, it takes 2.5 orbital revolutions for one complete vertical oscillation.

The width of the beam trace in radius must be equal to the radius gain per turn for a centered beam. The calculated radius gain per turn is approximately 1.5 mm, in good agreement with the observed beam width. If there are fluctuations on the beam width when scanning the probe radially, that must be taken as an indication of off-centered beam. This is a very useful diagnostic in cyclotrons with closely separated turns, where it is difficult to detect the orbit precession from the turn pattern. It is possible to imagine a control program that analyzes the beam pattern and decides to change the centering coil and the dee voltages to center the beam automatically. The pictures observed during the probe motion remind us of the time exposure of a moving quartz plate shown by Kelly during the early operation of the LBL 88-inch cyclotron[10].

Conclusions

The detailed information that the new probe gives in the r and z planes with very low noise expands enormously the work that can be done in comparing with orbit tracking simulations. A rich new field opens to us with this new diagnostic tool.

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