INTERNAL BEAM DYNAMICS STUDIES WITH A TV PROBE

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ABSTRACT

We have developed an internal probe for the K1200 Superconducting Cyclotron based on a TV camera and scintillator. This probe provides a detailed picture of the internal beam with a resolution of 0.05 mm. The low intensity sensitivity of this probe (1 epA) has helped in the tuning of low intensity beams. The processing of the TV signal with a digital frame grabber allows a real time pseudocolor display and a fast quantitative analysis. We have studied several beam dynamics problems (resonance traversal, radial and vertical beam centering, etc.) and simulated them with particle orbit integration codes and transfer matrix codes. Comparisons with tape recorded pictures that show extremely intricate behavior are presented.

1. INTRODUCTION

Our laboratory has successfully used scintillators and a frame grabber to tune and study external beams.[1] This experience convinced us to look into the possibility of building a beam probe physically compatible with the present current probe (utilizing the same drive) 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.[2] 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 new probe has been in use for more than a year, giving a very satisfactory performance, and allowing us to measure beam parameters that were unavailable before its commissioning. After the publication of the report previously mentioned[2] we learned of the previous use of a TV camera in a separated sector cyclotron.[3]

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2. PROBE DESIGN

One of the major difficulties in designing a median plane probe for a superconducting cyclotron like ours is the small space available in the penetrations through the coil cryostat. This 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. Figure 1 shows a sketch of the probe head showing the scintillating plate, viewing window and TV camera. The scintillating surface is obtained by spraying ZnS on an aluminum plate. This plate slides between two clips that allow for its fast replacement. Figure 2 shows a close up of the probe head before assembly.

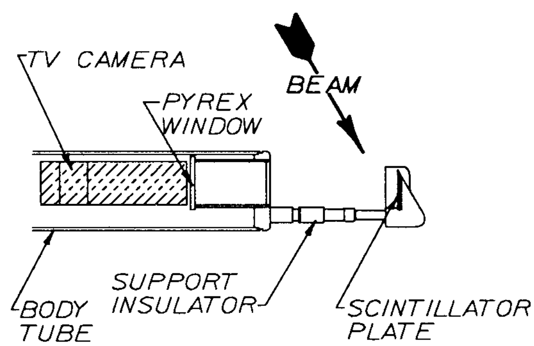

Figure 1. Sketch showing the head of the TV probe. The angle the beam makes with the scintillating plate changes between 35 and 65 degrees.

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

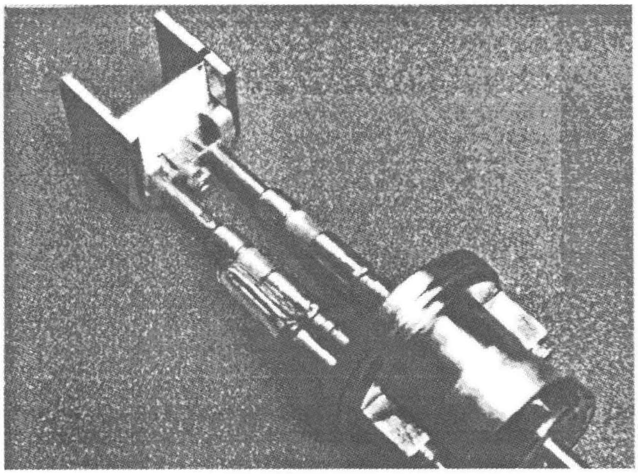

Figure 2. Close up view of the probe head before welding to the vacuum tube. The support for the scintillating plate is seen on the upper left. The plate is held in a groove by springs. The two supports are the electrical connection to the beam current monitors.

Figure 3. These two beam snapshots were taken at a radius of 0.51 m (left) and 0.52 m. The total vertical height as determined by the lowest contour line is 8.5 mm. It clearly shows the vertical oscillation of the beam and the radius gain of the beam between turns, for example on the left contour plot. The left edge of each contour plot corresponds to the edge of the scintillating plate, while the right edge is determined by the radius gain per turn and centering error.

3. MAIN APPLICATIONS

3.1. Correction of Vertical Oscillations

The first observation made with the probe showed us that the beam was not on the median plane but oscillating around it by as much as 2 mm. Considering that the beam size was close to 1 mm the oscillation was an important part of the effective beam size. Since then we have introduced an asymmetric current supply to the top and bottom trim coil 0, that together with a variable vertical positioning of the inflector allows us to correct this vertical oscillation. The original current probe did not have enough resolution to detect this error. Figure 3 shows an example of a beam off the median plane.

3.2. Radial Centering

If the beam is centered, the width of the beam trace seen on the probe should be equal to the radius gain per turn and approximately constant in a small region of radii. If instead the beam is off-centered, the beam width will appear to fluctuate when moving the probe radially. We have written a program to use the TV probe to center the beam automatically. The program searches in the phase and amplitude of the first harmonic bump used to center the beam until the beam width observed in a radius range is constant. The program has control of the probe and the harmonic coils. The process takes approximately 12 minutes and converges in most cases. It must check that the beam does not disappear because of RF sparks or similar problems.

3.3. Detailed Beam Dynamics

For the first time we could obtain really detailed information on current density as a function of r and z, much more than any differential probe could give us before. The quality of the beam and halo formation can be studied during the acceleration process. We found that one of the most interesting phenomena was the crossing of the $\nu_r = 2\nu_z$ resonance. This study will be the topic of the next section.

4. OBSERVATIONS OF THE RESONANCE CROSSING

The K1200 cyclotron beams cross the $\nu_r = 2\nu_z$ resonance between 0.65 cm and the extraction radius of 1.00 m, depending on the ion energy and Q/u. The losses are minimized by crossing the resonance with the beam centered. This is normally possible unless the resonance crossing occurs after the $\nu_r = 1$ resonance, just before extraction.

The photographs of the TV probe scintillator shown here were obtained during a run of $^4He^{1+}$ 40 MeV/u. The calculations described later were performed for the same ion and energy conditions.

Figure 4 shows two snapshots of the TV screen that displays the TV probe signal. We combine the video signal from the probe with computer generated text. The computer displays the radius that the probe is at on the lower left (in inches) and up to three parameters and their names on the upper left. These parameters can be selected from the whole data base available to the control system. In the pictures displayed we are showing the magnitude and phase of the centering bump provided by trim coil 1. The normal beam size is smaller than what is displayed on the left portion of the figure. The beam has been off-centered on purpose to show the effect of

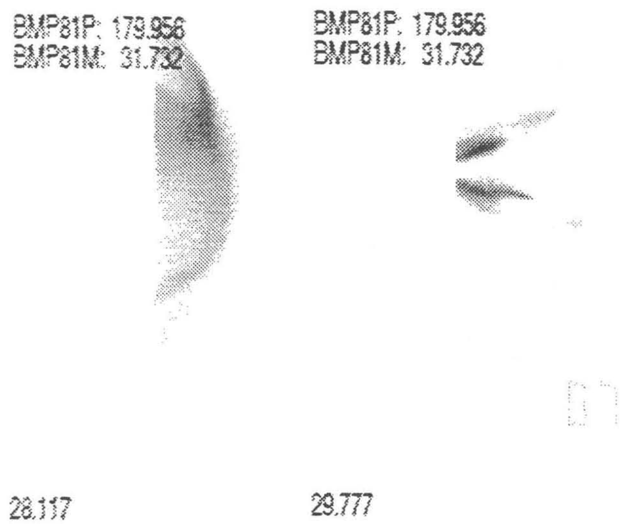

Figure 4. Two snapshots of the TV screen showing the beam spot during the crossing of the $\nu_r = 2\nu_z$ resonance. The height of the beam spot on the left is approximately 13 mm. See text for more explanations.

the resonance. The beam height of the left picture is 13 mm.

The most surprising observation, when looking at the probe move out in radius, is the formation of arcs like the one observed on the picture on the left, and the jets observed on the picture on the right in Fig. 4. We decided to simulate the orbit dynamics and probe interception of the beam to verify that those structures could be predicted by our orbit codes.

5. SIMULATIONS OF THE RESONANCE CROSSING

The simulation of the TV probe observations involved several steps. First we used our code Z3CYCLONE[4)] to track five different central rays from the inflector to a radius of about 10 cm. In this code the electric field is calculated in a 3D grid from potential data calculated with the relaxation code RELAX3D.[5)] The five different rays were spaced 8 degrees in RF time between them to simulate the phase acceptance of the central region. A first harmonic imperfection was introduced as generated by trim coil 1. From a radius of 10 cm to approximately 70 cm the central rays were tracked with the code SPIRAL GAP that uses a delta function approximation for the energy gain at each gap on the six spirals.

At a radius of 70 cm (just before the resonance) we started the tracking with SOMA,[6)] a second order matrix code, populating with 2000 particles an elliptical (eigenellipse) phase space around each central ray in (r, p_r) and in (z, p_z) for a total of 10000 particles. We selected a gaussian distribution, relatively flat, where the edge density was 70% of the central density. The central rays have centering errors from 2 to 7 mm.

We modified SOMA to give us the (r, z) intersection with the path of the TV probe. This data file giving the intersection of each particle in each turn with the probe path is analyzed later with another program that keeps track of the intersections with the probe to check that a hit is the first one or if a previous turn already was intercepted (and consequently lost).

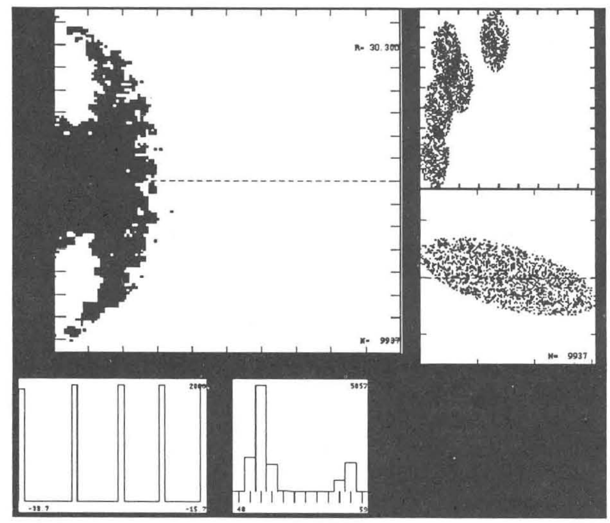

Figure 5. Snapshots of the computer screen showing the display of the probe simulation with characteristics similar to the picture observed on the left of Fig. 4. See text.

Figure 5 shows a black and white snapshot of the computer screen where the large graph on the upper left represents the (r, z) diagram of where the beam hits the scintillator at a given radius. The sharp edge on the left represents the edge of the scintillator. We can see the similarity between this simulation and the observation on the left section of Fig. 4. The graph on the upper right shows the population at the start of the SOMA calculation in (r, p_r) and in (z, p_z) under it. The two graphs at the bottom show the phase distribution (five equal bars in the histogram) and a histogram with the turn number (from the beginning of the SOMA calculation) when the particle strikes the phosphor screen. The two groups of turns agree with a ν_r value close to 1.10.

The program allows us to select an area on the screen, see Fig. 6 (area fenced in by the dashed polygon), and then gives us the initial conditions, phase and turn distribution of that group of particles. As we can see the bulk of the particles in the fenced area forming the large circular arc away from the median plane come from the ellipses with larger centering error.

Figure 7 show a different radius plot where we have selected to show only the particles that populated the ellipse around the central ray with larger centering error (compare with the initial (r, p_r) distribution of Fig. 5). The (r, z) plot shows the jet structure observed on the right hand side picture of Fig. 4.

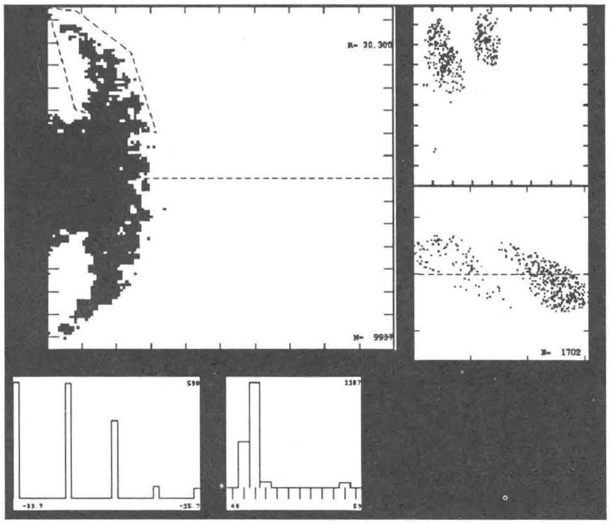

Figure 6. Snapshots of the computer screen showing a fenced area (dashed polygon) and the initial conditions and turn distribution of the selected particles.

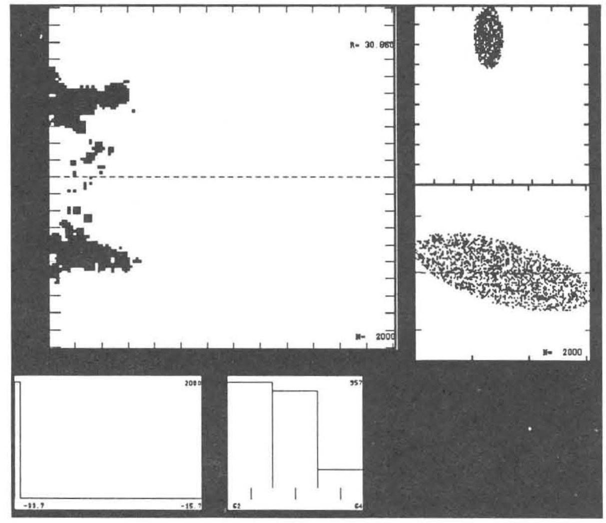

Figure 7. Snapshots of the computer screen showing the jet structure similar to the observed on the right picture of Fig. 4.

6. CONCLUSIONS

We have shown some of the applications we have found for a TV based internal beam probe in our K1200 superconducting cyclotron. Centering of the beam in both vertical and radial direction is now possible with great accuracy. The study of resonance crossing and comparison with simulated probe traces shows very good agreement on the structures observed.

7. REFERENCES

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