A BEAM SCANNING DEVICE
FOR THE
UNIVERSITY OF MANITOBA
CYCLOTRON FACILITY

BY

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TABLE OF CONTENTS

ABSTRACT

This thesis describes the design and development of a beam scanning device over the period Spetember 1978 to February 1981 at the University of Manitoba 50 MeV cyclotron facility.

A review of the ways of imaging a proton beam is given, followed by design and construction details of a beam scanner.

A scanner now exists which can detect proton beam currents as low as 18 nano-Amperes from the cyclotron exit port and 1 nano-Ampere from the polarized ion source.

The scanner also has a unique feature in that it will give an intensity profile of a beam of low energy neutral particles.

ACKNOWLEDGEMENTS

I would like to thank all members of the technical staff of the Department of Physics most notably Alan McIllwain and Irv Gusdal for helping me set up and "de-bug" the scanner, Richard Hamel for designing and building the electronics and Jim Anderson and Tony Smith for designing the hardware and software respectively in the emittance measurement. All of their help is greatly appreciated.

Thanks too to my supervisor, Francis Konopasek, for his help during the course of my degree.

FIGURE CAPTIONS

CHAPTER 1

INTRODUCTION

INTRODUCTION

For precise alignment and guiding of sub-atomic particles along the beam lines of accelerators a monitor is necessary which gives information about the intensity and position of the beam.

Once beam width, displacement and divergence are known, beam optics can be set to guide as much of the beam as possible from accelerator to experimental area.

The project described in this thesis set out to build a beam scanner - a device which would give a cross-sectional view of the intensity of the charged particle beam and its displacement from the beam tube centre. A review of the various types of scanner that had already been built at various accelerating laboratories was undertaken and it was hoped to design a hybrid unit which would embody the best aspects of the various scanners.

The University of Manitoba cyclotron is a variable energy machine from 28-50 MeV with proton beam currents as high as 5μA. At the present time the cyclotron uses a screen system to image the position of the proton beam. Screens are injected into the line and viewed with a television camera. In the accelerating vault one camera can look at four screens shown in Fig. 1.1 but in the experimental area one camera is needed for each screen. A beam scanner in the position of a screen is cheaper and gives intensity information also.

A beam scanner has been developed which will monitor a 3mm wide beam down to 18 nano-Amperes and which can give an intensity profile of neutral particles. The estimated cost of construction and materials is $150.00 by Physics Department machine shop technicians, while a similar commercially available unit is quoted at $1,700.00. The basic criteria to be fulfilled by the scanner were:

(i) A real time output.

(ii) Negligible distortion on the particle beam.

(iii) Low cost.

(iv) Easy to maintain.

(v) Intensity profile as well as beam position output.

These factors are described in the chapters that follow together with a description of how the beam scanner built is incorporated into an emittance measuring device to measure the emittance of the beam from the cyclotron.

CHAPTER 2

DESIGN CONSIDERATIONS

SECTION I. A review of the types of scanners.

SECTION II. Secondary electron emission.

INTRODUCTION

Many types of beam scanner have been built, from simple photographic emulsions to complicated multi-motorised driven units. These have been described fully in the scientific literature.

It was proposed to study the various ways of obtaining information about an accelerated proton beam and to build a hybrid unit which would embody the best features of the different types of scanner.

A literature search was done and this chapter gives a review of the types of beam scanner, and a discussion of the reasons the scanner described in chapters four and five was designed.

The scanner designed works by utilizing the principle of secondary electron emission. Some of the aspects of this emission are described in Section II.

SECTION I. - A Review of the types of beam scanner.

There are many types of scanner and each has its own peculiarities but they fall into three basic categories:

(i) Non-intercepting types.

(ii) Those which stop or disturb the beam.

(iii) Intercepting types in which beam disturbance is negligibly low.

These will be discussed below.

(i) Non-Intercepting Types

Using magnetic induction techniques, a non-intercepting device finds the time average position of the beam at the Argonne National Laboratory cyclotron.[1] Two sets of detection coils determine the horizontal and vertical positions of the beam. Each set consists of two coils connected in opposition and symmetrically placed about the mechanical centre of the beam tube. The axes of the coils are located perpendicular to the direction of propagation of the beam. The coils are resonantly tuned to the frequency of the beam bursts from the cyclotron. The voltage induced per coil is given by:

$$e = \frac{K}{r} \frac{di}{dt}$$

where $i(t)$ -is the beam current.

r -is the effective distance from current filament to coil axis.

t - time

K - a constant

The magnitude and polarity of the induced voltage 'e' thus give the displacement of the beam and for two coils connected in opposition the voltage output would be zero for a beam at the centre of the beam tube. The detector can locate a beam current of 30 nano-Amperes with a positioning accuracy of 0.1mm with positioning accuracy decreasing for lower beam currents. However, this particular scanner gives no information on beam profile.

(ii) Types which Disturb or Stop the Beam

These types can be subdivided into those types which give beam profile or displacement measurement while the accelerating machine is running and those which require off-line analysis of an irradiated material as discussed below.

When a scintillating screen is placed in the beam, the rough dimensions of the beam can be seen as it strikes the screen. This is the system presently used at the University of Manitoba cyclotron, screens are inserted into the line via compressed air. In the accelerating vault a television camera looks at the desired screen by reflection in a mirror. The screens show displacement of the beam from the centre of the beam tube but again do not give a beam profile. When a screen is used the beam delivered to the experimental area is interrupted.

At the Stanford Linear accelerator,[2] a 1mm square molybdenum target is moved through the beam. The scattered beam produces an electromagnetic shower down the accelerator structure which is measured by a nearby ionization chamber. The resulting intensity gives a beam profile as the target is driven by motors in a Lissajous type figure of about 2.5 square centimeters. A complete scan takes approximately 20 seconds.

A further type used at the Radiation Centre of Osaka[3] monitors the profile of a beam as it leaves the exit window of a scanning linear accelerator. Some electrons are scattered through large angles as they leave the window; however, the beam profile of these electrons remains same. An array of thirty copper sensors is mounted at 40° around the exit window, the current produced by each of these is amplified and fed to a readout to display the beam profile.

The three types of monitor mentioned above operate when the accelerator is running. Other types will give a profile by examining a piece of material after it has been irradiated. An example of this is the irradiation of gold foil.[4] When bombarded with protons the foil becomes an X-ray source. After removal from the accelerator structure the foil is placed in contact with X-ray sensitive film. The developed film is scanned with an optical densitometer and the output intensity from the densitometer results in a beam profile.

In similar ways, ^{149}Terbium, an α particle emitter produced again by the irradiation of gold is scanned with an α detector and an array of γ ray active aluminium rods is scanned with a γ ray spectrometer to give intensity profiles which are the same as the cross-sectional intensity profile of the particle beam.

As a final example of this type of scanning method, thermoluminescent sheets when heated after irradiation give a light output across the sheet proportional to the intensity of the beam at each point.[5]

(iii) Intercepting Types

With these types of scanner the disturbance of the beam is negligibly low so that profiles may be observed as beam optics are changed without interrupting the beam incident on the target.

All of these types work by placing or passing a single wire or an array of wires through the beam. Secondary electron currents produced as the beam strikes these wires are amplified and read out to give position and profile data. The monitors fall into the subdivisions described below.

(a) Grids

Here a grid of wires is wound on a former in horizontal and vertical directions.[6,7] Each wire is insulated and the current produced in each wire as the beam strikes it is read out to give a histogram type profile. The grid of wires is injected into the beam line in much the same way as the screen system described above. The grid is removed when not in use to reduce heating of the wires.

(b) Plane Scanners

In an example of this type of scanner a single wire driven by a motor and pully system traces out an X-Y plane perpendicular to the direction of propagation of the cyclotron beam.[8] The wire moves in the X direction and the slowly changing current produced by the incident beam is amplified and recorded on a chart recorder or storage oscilloscope. When the X direction profile has been produced, a microswitch is activated to produce the Y profile. Another type used at the Oxford Tandem accelerator[9] uses a wire bent into a pentagon-like shape. Pivoted at one point, the wire vibrates rapidly through the beam. It is shaped in such a way that it gives the X and Y profiles on each passage through. The speed of the vibrations eliminates the need for a storage oscilloscope as used above, an ordinary oscilloscope will display the profile.

(c) Cylindrical Surface Scanners

These scanners form the bulk of beam scanners used at accelerator laboratories and are the only type of scanner manufactured commercially. They consist basically of a wire attached to an arm on a rotor. They scan on the surface of a cylinder the axis of which is perpendicular to the direction of propagation of the beam. Differences arise in the type of motor used to drive the scanner, for example a phase sensitive motor giving a real time output[10,11] or a stepping motor driven scanner giving a chart recorder, oscilloscope or computer graphics output.[12]

DISCUSSION OF SCANNERS

From the outset the criteria for the scanner were:

(i) To build a scanner that would give a real time output.

(ii) A scanner that would not interfere with or disturb the beam.

(iii) One that was as simple as possible to reduce maintainance.

(iv) Low cost.

(v) Must be able to give profile as well as displacement.

The monitors which stopped the beam were thus ruled out, so too was any type of scanner which required a storage oscilloscope such as a stepping motor driven wire scanner or a grid of wires. The final decision was between wire monitors which scanned on a plane and those which scanned on the surface of a cylinder.

The plane scanners have a "whipping" effect at the end of each scan and this can lead to a distorted beam profile indicating more or less intensity at a particular point on the plane of the resulting display.

The cylindrical surface scanners have two distortion effects. (a) The projection of the position of the wire onto a diameter of the circle in which it is moving gives simple harmonic motion rather than a linear motion, oscilloscope scanning is usually linear and this would result in some distortion of the observed profile. (b) The second distortion is that the scanner measures the intensity not on a plane but on the arc of a circle, thus there is an out of plane distortion which again affects the display.

SCANNER CHOSEN

Despite the two distortions mentioned above, a cylindrical surface scanner was chosen. The out of plane distortion is negligible for beam transport systems with focal lengths > 1.0m. The first distortion mentioned above has been overcome as described in Chapter 2 on the prototype scanner.

SECTION II. Secondary Electron Emission

Many types of beam scanner including the one described here rely on secondary electron emission to give a profile of a charged particle beam. The number of secondary electrons released as a wire passes through a proton beam is proportional to the intensity of the beam at every instant.

When the secondary electron current produced is collected and amplified for display, a cross sectional intensity profile of the beam results.

It is surprising that scanners using this technique work so well since, as described by Beck[13] the secondary electron emission efficiency given by:

$$\gamma = \frac{N_e}{N_i}$$

where N_e - is the number of secondary electrons produced

N_i - is the number of incident particles

is only a few percent when the incident particle are 50 MeV protons. The mechanism of secondary electron emission is described by Sternglass.[14] The most interesting and surprising finding is that the secondary electron emission efficiency does not depend on the work function, conductivity, or crystal structure of the metal used but is roughly constant at a particular energy of incident particle. Only secondary electrons produced near the surface i.e. within 10^{-8} to 10^{-9}m can escape from the wire and they leave with energies of 6-8 eV. The yield of these electrons is proportional to the energy loss of the incident particle. Since in wire scanners the wire has a negligible effect on the charged particle beam, the yield at 50 MeV is low. At lower energies the yield increases and is a maximum in the KeV range. These are the energies encountered in the ion source and as described in Chapter 5 the scanner output can be fed directly to an oscilloscope without amplification, since the secondary electron current is much higher.

For metals of low atomic number such as Beryllium and Lithium, an oxide coating increases the secondary electron yield and it has been found[15] that the increase continues with time of outgassing towards a limiting value many times the original yield.

For higher atomic number metals with an oxide coating the yield of secondary electrons decreases with time of bombardment and outgassing to that of a clean metal surface.[15]

In the scanner described in the next Chapter, steel, nickel-chrome and thoriated tungsten wires were tried as scanning wires. The size of the output signals was the same so steel was used for convenience.

CHAPTER 3

THE PROTOTYPE SCANNER

INTRODUCTION

As said in the design considerations, a rotating wire scanner was to be designed for the University cyclotron. This chapter describes mechanical and electronic details of the scanner, followed by modifications made as the development progressed.

Also discussed are the noise sources present and how they were reduced to a minimum.

I. MECHANICAL DETAILS

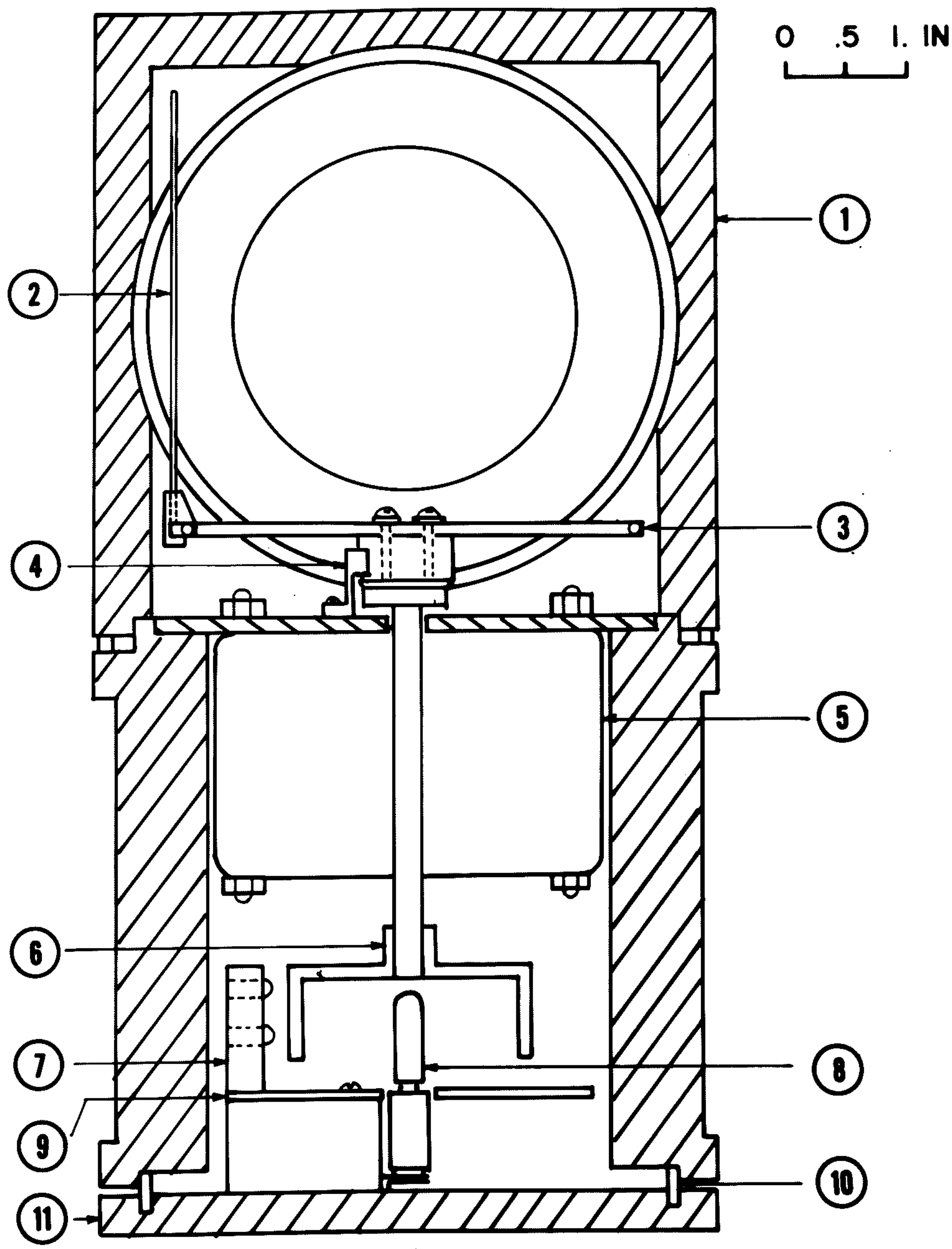
The design for the prototype scanner initially followed that of Bond and Gordon.[16] The scanner is shown in schematic form in Fig. 3.1.

A double shafted motor forms the heart of the scanner. The upper shaft carries the rotating arm to which the 1.0mm diameter steel scanning wire is attached, while the lower shaft carries an optical shaft position encoding device. The output of the shaft encoder gives information on the position of the wire in the beam tube.

(a) Motor

Since the motor was to operate inside the vacuum system a search of the motor literature was done to find the motor most suitable. This turned out to be a Singer-Kearfott company CT20173002 synchronous motor which had been tested at low pressures. However, the price for this motor was quoted at $340.00 each. To keep the price of the scanner as low as possible, tests were performed on a double shafted Electrohome SM418 motor similar to that found in small fans.

The motor in the scanner would operate only intermittently in use, however to see if heating of the motor would be a problem it was run in a vacuum of a few hundred microns for half an hour. The only cooling was by contact of the motor



.1 Prototype Scanner
matic.
andard 4" bean cube
anning wire
anning bar

4) Secondary electron pickup
5) Motor
6) Cylindrical encoder
7) Phototransistor assembly
8) Light source

9) Light baffle
10) 'O'ring vacuum seal
11) Base plate

with the floor of the vacuum chamber. The temperature of the motor reached 150° centigrade, only a few degrees higher than that obtained by running the motor in air for a similar period of time.

It was felt therefore that the only problem that would be encountered would be the outgassing of the lubrication of the shaft, this was to be solved by using nylon sleeve bearings. In fact over the time that the first scanner was used no problems with the motor bearings were encountered at all.

(b) Scanning bar and pickup

The prototype scanner used a brass rotating bar nine centimetres long with a hinged end. A spring would pull the wire out of the beam when the scanner was not being used. When the scanner was switched on, centrifugal force would lift the wire into an upright position. This is described further in the alignment of the scanner. A rotating contact made from phosphor-bronze formed the current pickup. Secondary electrons released from the wire result in an amplifier input current which is fed back down through the scanner housing to the input of the beam profile amplifier.

(c) Scanner housing

The scanner housing was made from aluminium except the base which was made from brass for easier welding. An auxiliary pumping port for the vacuum system was welded to the base plate but it was never needed since pumping of the scanner housing from the beam line was sufficient. The port was not included on further scanners. The scanner housing scanning bar and current pickup are shown in Fig. 3.2.

(d) Shaft encoding arrangement

A light "chopping" arrangement was used to encode the position of the shaft. A cylindrical drum was attached to the lower shaft of the motor, this drum was cut out in such a way that it would block light from a small 6 volt d.c. bulb to a pair of MRD-450 phototransistors for part of a revolution of the shaft. One phototransistor would be illuminated for half a revolution and blocked for the other half, giving rise to a square waveform output with the same frequency as the rotational frequency of the motor. The other phototransistor would be illuminated for only a fraction of a revolution giving rise to a 200μ second width pulse once every revolution of the motor. These outputs were used for shaft position and scanner alignment. The light encoding arrangement is shown in Fig. 3.3 where one can see the mounted phototransistors and cut-away drum.

(e) Alignment

The light encoding device gave outputs as shown in Fig. 3.4. If the oscilloscope controls are adjusted so that