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Author
Clark, D.J.

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BEAM DIAGNOSTICS AND INSTRUMENTATION

D. J. Clark

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Methods of cyclotron beam development and diagnostics are described. Techniques for measuring the space, time and energy distributions of both internal and external beams are included. Emphasis is on the more recent methods commonly used at many laboratories.

Introduction

In the operation of the modern cyclotron, it is important to have adequate instrumentation in the internal and external beam regions. This is useful both for normal tuning of the beam and for diagnosing various cyclotron problems which arise (Fig. 1). Both visual and electrical observation techniques are useful. The traditional visual instrument is the eyeball (Fig. 2). More recently the telescope and then the TV camera have been used as visual tools (Fig. 3). Electrical readouts of currents, voltages, temperatures, pressures, etc. are also extremely useful. A recent survey by Richardson also discusses some of the techniques for investigating cyclotron beams.

Internal Beam Methods

Spatial Distribution

Cyclotrons report a variety of methods for observing the spatial distribution of the internal beam. Visual observation can be made of the ionization produced by the beam near the ion source, when large currents are being accelerated. Heating of dee and dummy dee carbon liners can also be observed in this case. Quartz plates or probes painted with phosphors can be moved radially to observe the beam distribution. Radiographs of probes exposed to the beam are also used.

The most common type of probe for beam current measurement is a single insulated electrode with a connection brought to the control room. An example of this "single finger" probe as used at the 88-inch cyclotron is shown in Fig. 4. It is of water-cooled copper construction, but some laboratories use aluminum because the radioactivity decays faster. Some laboratories cover the probe with a foil to intercept low-energy spurious beams.

When a sector-focused cyclotron is first tuned up, off-center or spurious beams are often observed. In order to tune up a properly centered beam, three probes spaced azimuthally around the machine are very useful. The most convenient probe locations for diagnostic work are at 120° intervals for a three sector machine. Probes between sections of the deflection system are useful also.

For the study of internal beam quality, shadow measurements can be made of one probe against another. This gives information about the radial amplitude of the beam. A useful type of probe for investigating radial beam quality and centering is a radial differential probe, or "DR" probe. A probe of this type used at the 88-inch cyclotron is shown in Fig. 5. The current collected on the inner finger of a DR probe in the Michigan State University cyclotron is shown in Fig. 6. Some runs with the DR probe in the 88-inch cyclotron, illustrating good and poor internal beam quality, are shown in Fig. 7. The periodic structure of Fig. 7(b) is typical of an off-center beam. Beam centering can be improved with this probe by tuning to minimize the fluctuations on the electrodes or maximizing the beam on the inner electrode at large radius. The value of the radial frequency, v_r, can be found from the spacing of the oscillations in Fig. 7(b). Some detailed analysis of probe measurements has been made by Lawson.

The axial distribution of the beam can be found visually with a phosphor probe, or by electrical readout from a multi-finger probe. A three-finger probe used at Berkeley is shown in Fig. 8. This probe was used to diagnose a problem in a median plane displacement in the 88-inch cyclotron. When the upper 8-in. pole plug was accidentally lowered 1/16 in., this probe indicated that the beam was low inside a 12-in. radius (Fig. 9(a)). The fault could be partially corrected by unbalancing trim coil no. 1 (Fig. 9(b)), but was later fully corrected by moving the plug back to its original position. The axial frequency, v_z, can be calculated from the periodicity of the curves of Fig. 9. Another useful probe is the "C probe" used at Berkeley. This consists of two electrodes above and below the beam which shadow the dee over the outer half of the acceleration region. They serve to protect the dee from beam and to give a current readout of beam which is high or low as a single-finger probe is withdrawn from the machine. Another useful technique is that of letting the beam burn its profile in a thin foil. Figure 10 shows an example of this for 30 MeV α-particles in the 88-inch cyclotron. The coupling resonance, v_f = 2v_z, is visible as a slight vertical blow-up. When enough beam hits the septum, a glow can be observed with a telescope or television camera. Figure 11 shows beam illuminating the radiation-cooled tungsten septum at the 88-inch cyclotron. This technique is very valuable in adjusting both the axial and radial beam distributions on the septum.
The measurement of the time, or phase, distribution of the internal beam is helpful in eliminating phase loss of the beam during acceleration. Display of internal beam pulses by direct current collection feeding a sampling oscilloscope was accomplished by Birmingham, Smith. In this method the current vs radius is measured at several dee frequencies near resonance with a single-finger probe (Fig. 12(a)). The break points of these curves are then used to plot the outer edges of the beam phase distribution (Fig. 12(b)). Results obtained from both positive and negative frequency deviations are quite consistent. The phase distribution of the internal beam can also be found from this data. A direct measurement of the internal phase distribution can be found from a plot of beam current vs frequency at a fixed radius (Fig. 13(a)). The slope of this curve gives the intensity distribution vs sin \( \phi \) (Fig. 13(b)).

Power Handling

In some of the new sector-focused cyclotrons several kW of beam power is present at full radius. Since the beam size at full radius is only several square millimeters, high power densities exist. Precautions must be taken to protect probes from burn-out. Most laboratories used water-cooled probes. Some also slant the surface with respect to the beam or sweep the beam across the probe. Livermore has made studies of power dissipation on water-cooled copper plates, reaching power densities of 71 kW per square inch. An Oak Ridge group has reached power densities of 71 kW per square inch by using swirling flow at high pressures and flow speeds. The usual water-cooled copper probe used in the 88-inch cyclotron (Fig. 4) will handle 3 kW of beam power. An experimental rotating tantalum probe in the 88-inch cyclotron is shown in Fig. 14. This was used with a beam power of 10 kW without water cooling. Performance would be improved when cooling is used. Birmingham uses a slanted water-cooled copper block to handle 12 kW of beam. Illinois uses a carbon block mounted on a cooled block with tungsten rods to absorb 14 kW of beam power.

External Beam Methods

Spatial Distribution

For observation of external beam spatial distribution, both visual and electrical methods are used. The traditional methods are the radiograph and photographic film exposure. Telescopes or television cameras are used to view the beam on quartz plates, and various phosphors such as zinc sulfide or vacuum grease. Electrical readout is obtained from various external beam probes. An example of a carbon block used to stop the total external beam in the 88-inch cyclotron is shown in Fig. 15. An air cylinder drive gives rapid insertion and removal from the beam pipe. A scanning pin plot from the University of Colorado cyclotron is shown in Fig. 16. A collimating slit used in the 88-inch cyclotron is shown in Fig. 17. Tantalum collimating slits for use at a radial focus are shown in Fig. 18. This unit with its "piggyback" quartz is used at Berkeley. A defocused beam on this quartz is shown in Fig. 19. A rotating wire scanner from ORIC is shown in Fig. 20. This unit gives an oscilloscope display at 60 cycles per second. Induction pickup coils are used by Argonne to monitor external beam position to an accuracy of 0.1 mm.

Time Distribution

Knowledge of the time distribution of the external beam is useful for diagnostic work and for coincidence experiments. A current collecting probe, induced probe or analyzing magnet can be used directly in the external beam, or the beam can be scattered into a detector and a coincidence method can be used. A recent measurement of the external beam pulses of the 88-inch cyclotron is shown in Fig. 21. These are single sweeps on an oscilloscope using a semi-conductor detector. The ripple on the beam is shown in this way. A fast Faraday cup used at ORIC gives sampling scope pictures as in Fig. 22. The probe is fast enough to show the fine structure of the phase distribution.

Energy Distribution

The energy of the external beam is measured by range in an absorber, by the kinematics or thresholds of certain reactions, and by the path taken by a particle in a known magnetic field of a bending or analyzing magnet. The energy distribution, or spread, is of particular interest for experiments. The energy distribution can be measured by sweeping the beam past a slit with an analyzing magnet, or by pulse height analysis of a semi-conductor detector looking at beam scattered from a thin foil. The semi-conductor method is relatively cheap, fast, and accurate. Figure 26 shows a spectrum of the full external beam of the 88-inch cyclotron measured with a Li-drifted silicon detector. The spread contributed by the detector and electronics is much less than the beam. Recently, Li-drifted germanium counters have given resolutions of 0.003% at 29 MeV for protons, so they could be used to study analyzed beams also.
Acknowledgments

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References

Notes:
Proceedings of the International Conference on Sector-Focused Cyclotrons, UCLA, 1962 is referred to as Paper Cl.
Proceedings of the International Conference on Sector-Focused Cyclotrons and Meson Factories, CERN, 1963 is referred to as Paper C2.
Proceedings of International Conference on Isochronous Cyclotrons, Gatlinburg, 1966 is referred to as Paper C3.
4. E. L. Kelley, Paper Cl, p. 35.
5. J. D. Lawson, (private communication).
FIGURE CAPTIONS

Fig. 1. (No caption).

Fig. 2. Visual methods of cyclotron diagnostics are very useful.

Fig. 3. Television monitors in control room of 88-inch cyclotron.

Fig. 4. Single finger probe used to measure internal beam intensity in 88-inch cyclotron. Material is chrome-plated, water-cooled copper.

Fig. 5. "ΔR" probe used on the 88-inch cyclotron. Material is water-cooled copper.

Fig. 6. Beam density distribution obtained with the inner electrode of a "ΔR" probe in the Michigan State University Cyclotron.

Fig. 7. Beam current vs radius on the two electrodes of a "ΔR" probe in the 88-inch cyclotron. 65 MeV α-particles with 44 kV on the dee. ΔR = 0.040 in. (a) beam started on center, giving good quality. Most of beam is on inner electrode at large radius. (b) beam started off center, giving poor quality. Over half of beam is on outer electrode at large radius.

Fig. 8. Three-finger probe used at the 88-inch cyclotron. Material is water-cooled copper.

Fig. 9. Runs with a three-finger probe at the 88-inch cyclotron. These show the median plane error caused by accidental displacement of the upper 8-in. center pole plug downward by 1/16 in. (a) trim coil No. 1 current = 0. (b) trim coil No. 1 upper winding current = -750 A, lower winding current = -480 A, giving partial median plane correction.

Fig. 10. Foil burn at full radius with internal beam of 88-inch cyclotron. 30 μA of 30 MeV α-particles. Material is 0.002 in. stainless steel.

Fig. 11. Television monitor showing deflector septum illuminated by about 1.5 kW of beam in the 88-inch cyclotron.
Fig. 12. Garren and Smith detuning method for calculating internal beam phase history for 130 MeV α-particles in the 88-inch cyclotron. (a) raw data is beam current vs radius at several frequencies. (b) phase history calculated from above data, compared to computer predictions.

Fig. 13(a). Internal beam current vs frequency for 65 MeV α-particles at a 30-inch radius in the 88-inch cyclotron.

Fig. 13(b). The slope of the data above is plotted showing the intensity distribution of beam vs $\sin \phi (\Delta f)$. The abscissa is calibrated using the $\Delta \sin \phi = 2$ length from 13(a).

Fig. 14. Rotating tantalum probe after a preliminary test without water cooling in the 88-inch cyclotron. Beam power was 10 kilowatts and rotation speed was 60 rpm.

Fig. 15. Graphite plate used to stop external beam of 88-inch cyclotron. Air cylinder drive is used.

Fig. 16. External beam scan using a pin on a fast chain drive at the University of Colorado cyclotron. Top scan is horizontal, bottom scan is vertical. 0.2 µA of 14 MeV protons. One large division = 1 cm on the horizontal scale.

Fig. 17. Collimator used to define the external beam radially at the 88-inch cyclotron. Material is graphite on a water-cooled copper frame. Width and center position are independently adjustable.

Fig. 18. Analyzing slit for external beam at the 88-inch cyclotron. Material is tantalum on water-cooled copper. "Piggy-back" quartz is useful for beam optics.

Fig. 19. Television picture of defocused external beam on a quartz plate at the 88-inch cyclotron.
Fig. 20. Spinning wire beam scanner used at ORIC to measure external beam distribution. Wire is 0.040-in. stainless steel. It spins at 60 cps, tracing a 4.5-in. diameter cylinder.

Fig. 21. Slotted plate method used to measure external beam emittance by Grunder, Selph, and Atterling at the 88-inch cyclotron.

Fig. 22. Slotted plate used for radial emittance measurement at the 88-inch cyclotron. Material is 1/8 in. tantalum on a water-cooled copper frame. Slots are 0.060 in., 0.020 in., and 0.010 in. width.

Fig. 23. Spots formed downstream from an array of 0.062-in. holes in a graphite plate in the external beam of the University of Colorado cyclotron. The detector is white spray paint on a microscope slide.

Fig. 24. Beam pulses from a semi-conductor probe in the external beam of the 88-inch cyclotron. The displays are single sweeps on a Tektronix 519 scope. 0.1 μA of 80 MeV α-particles. Time scale: 1 μsec/div.

Fig. 25. External beam pulse measured with a fast Faraday cup probe and a sampling oscilloscope by W. H. White at ORIC. Horizontal scale is 2 nsec per large division.

Fig. 26. Total external beam energy spectrum measured with a lithium-drifted silicon detector (supplied by the Goulding Nuclear Chemistry group) at the 88-inch cyclotron.
Beam Diagnostics & Instrumentation
"IT LOOKS LIKE IT'S THE FILAMENT."

Fig. 2
Fig. 5
Fig. 6
Fig. 7
Fig. 9
Fig. 12a-
Fig. 12b -

- Points deduced from I vs R measurements
- X Computer predictions
Fig. 16
Fig. 17
\[ \frac{dx}{ds} = \frac{x_2 - x_1}{l} \]

error in \[ \frac{dx}{ds} = \pm \frac{a + b}{2l} \]

**Fig. 21**
Fig. 22
Fig. 23
Fig. 25
Fig. 26

Counts per channel

Energy (channel number)

65-MeV $\alpha$ beam
$\Delta E = 150$ kV

$\Delta E$
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