A DIAGNOSTIC SYSTEM FOR OPTIMIZATION OF THE EXTERNAL BEAM QUALITY OF THE OAK RIDGE ISOCHRONOUS CYCLOTRON*

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Summary

The parameters of the external beam that are of prime importance to the experimenter are the emittance, energy spread, intensity of analyzed beam, and time structure. Diagnostic equipment has been developed for routine measurement and optimization of these parameters.

Emittance

The emittance area of a cyclotron beam is, for several reasons, one of its most important characteristics. Many experiments require a beam having a small emittance so as to reduce kinematic energy spread and thus enhance the resolution of the experiment. Knowledge of the emittance is essential to calculate the proper initial placement, and subsequently the current settings, of the beam transport magnets to obtain efficient transmission of the beam to the target. It is also important to be able to observe changes in emittance as cyclotron parameters are varied to optimize conditions for a given experiment. To meet these requirements an emittance measuring device was constructed and is used for optimizing beam conditions.

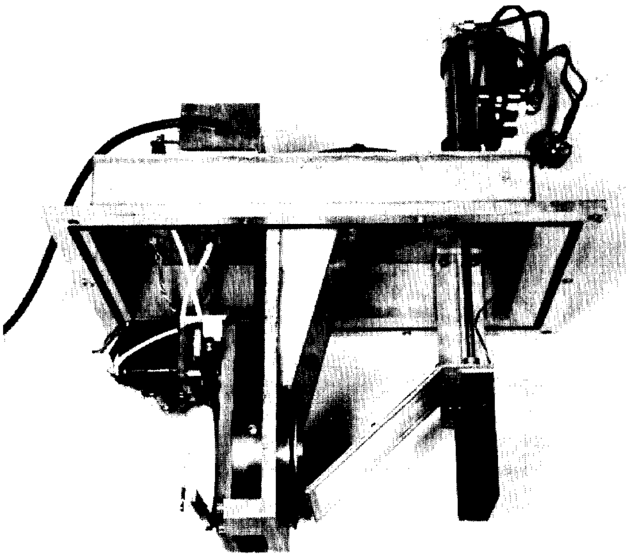

Fig. 1. Emittance measuring equipment. Beam direction is from left to right. All operations are remotely controlled except the rotation required to change from axial to radial measurements.

The device consists of a slotted zone plate for segmenting the beam, a scanning wire, a phosphor for observing the beam pattern, and a graphite beam stop. The scanning wire, phosphor, and beam stop are shown in Fig. 1. The zone plate is in a separate unit. All components can be remotely inserted and withdrawn from the beam path. The zone plate and the beam scanner can be easily rotated 90°, allowing measurement of both axial and radial emittance areas. The beam is scanned 61 in. beyond the zone plate, see Fig. 2. A radial scan of a 40-MeV proton beam from the Oak Ridge Isochronous Cyclotron (ORIC) is shown at the top of Fig. 2. The central slit is omitted to identify the center of the zone plate. With this device we find that for 40-MeV protons (100% current) the emittance of the ORIC beam is, at present, 67.9 mm-mrad radially and 31.4 mm-mrad axially, as shown in Fig. 3.

A phosphor placed directly behind the beam scanner provides a qualitative visual display of the beam illumination. The illumination of this phosphor by the axially and radially segmented beam can be viewed on a television monitor, as shown in Fig. 4. An unexpected but important benefit of the phosphor viewing was the detection of a slow radial oscillation (~ 5 to 10 H_z) in the beam. Oscillations are more readily observed when the beam is segmented by the zone plate than when the entire beam is viewed on the phosphor. Continuing improvement in regulation of power supplies for the dee voltage and the extraction system has reduced the amplitude of the oscillation.

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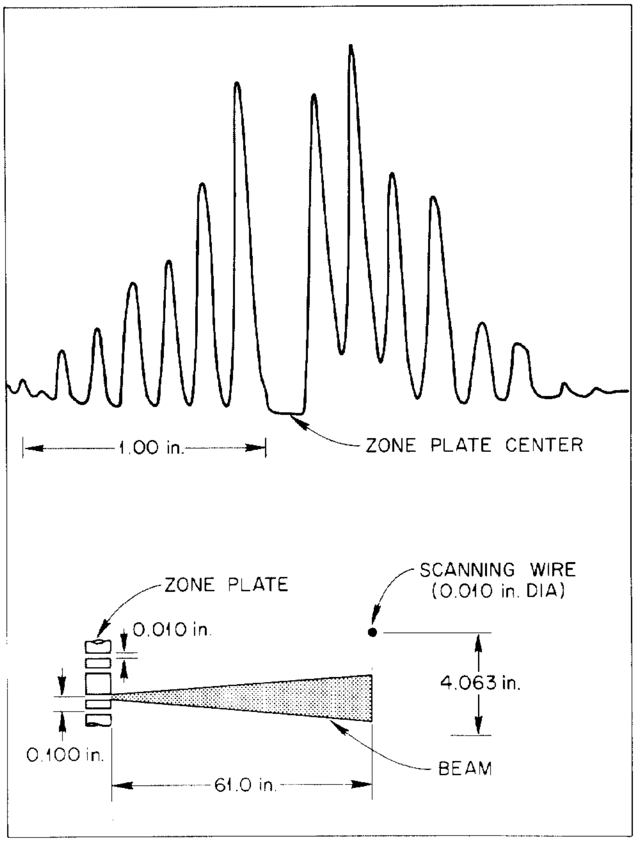

Fig. 2. Emittance measuring equipment schematic with typical radial scan for 40-MeV protons.

Energy Spread

The energy spread of the external beam is a function of several parameters and is a sensitive indication of the performance of the machine. For example, time variation in dee voltage or in magnetic field or non-optimized settings of these parameters can broaden the energy spectrum. An example of the wide variation in energy spread that can be obtained if careful attention is not given to tuning is shown in Fig. 5. These curves were made by slowly sweeping the beam across a 3.5-mm slit located in the focal plane of a 183-cm radius, n = 1/2 analyzing magnet. The control circuit of the analyzing magnet contains a motor driven potentiometer which, on command, will sweep the magnet current slowly through the range necessary to cover the full width of the energy distribution of the beam. An auxiliary output signal, proportional to magnetic field, drives the X-axis of a recorder. The beam current, as measured after the exit slit, is fed to the Y-axis. The simplicity of the system permits routine use.

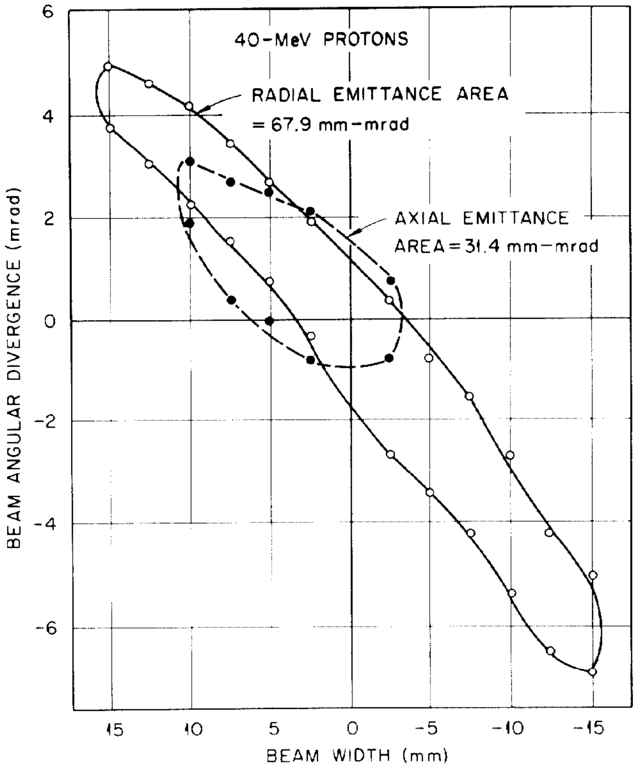

Fig. 3. Emittance for 40-MeV protons.

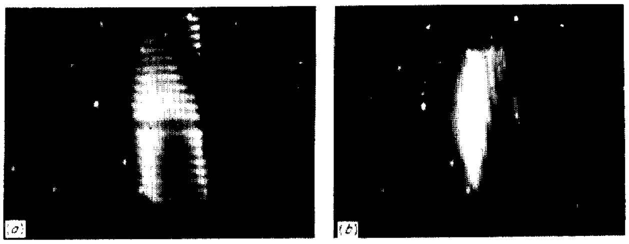

Fig. 4. Photograph of zone-plate shadows on a phosphor, as monitored on a TV system. The radial direction in the cyclotron is vertical in these pictures. The zone plate was rotated 90° from (a) to (b). The light dots are points of radiation damage on the TV camera.

Time Structure

A probe with somewhat unusual characteristics was required for investigating the microstructure of the external beam (the current-vs-time profile of beam bursts). A bandwidth greater than 500 MH_z is needed to resolve variations in the shape of pulses with periods less than 5 nanoseconds. For stability and reliability, a passive probe is desirable, and, for maximum usefulness, the probe should be compatible with

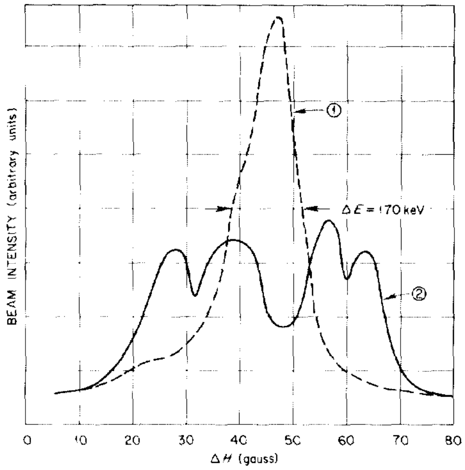

Fig. 5. Energy spread obtainable in ORIC with both normal (1), and poor (2) tuning.

modern electronics. Further, for maximum utility the probe should not interfere with the beam.

These considerations led to the design and construction of the device pictured in Fig. 6 and shown in cross-section in Fig. 7. Electrically, the probe is a piece of 50-ohm transmission line. Its impedance is near enough to 50 ohms, and sufficiently constant, so that spurious reflected signals are too low to be observed in normal operation. Mechanically, the device is two co-axial pieces of beam pipe. The inner pipe, the center conductor of the 50-ohm transmission line, is shielded from direct contact with the beam by a carbon collimator upstream from the probe. The inner and outer beam-pipe-conductors are bent out of the beam line and tapered to fit a commercially available 50-ohm vacuum connector.

The sensitivity of the probe is determined by its impedance and by its length, with maximum sensitivity for minimum length being obtained when the probe and a beam burst are the same length. Probe diameter is relatively uncritical as long as it does not approach probe length. In normal operation the beam does not strike the probe and is not affected in any detectable way by passing through the probe.

The system for measuring the beam microstructure consists of the 50-ohm probe, about 30 meters of low-loss 50-ohm coaxial cable, and a commercial sampling oscilloscope with various accessories. The oscilloscope has a vertical sensitivity of 2 mV/cm, which permits useful observation of beam currenst as low as one microampere. By the use of wideband amplifiers, beam currents as small as 50 nanoamperes can be measured.

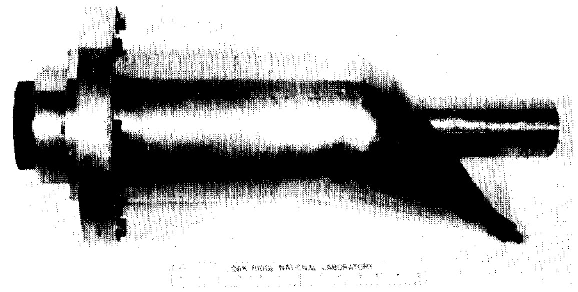

Fig. 6. 50-ohm capacitive probe.

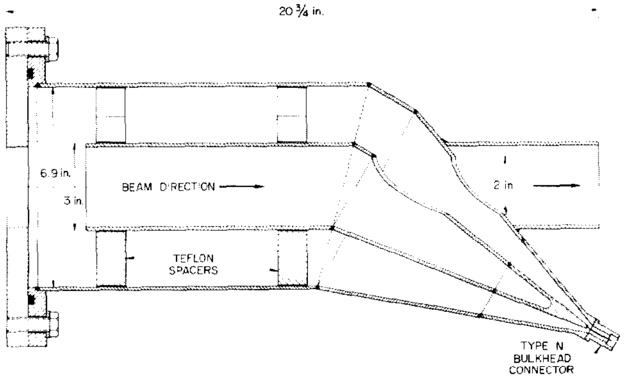

Fig. 7. Cross section of capacitive probe.

Typical data obtained by use of the 50-ohm probe system are shown in Fig. 8. The sampling oscilloscope trace in the upper right corner shows output from the probe, a voltage proportional to the rate of change of beam current during a beam burst. A smoothed, digitized version of the probe output is plotted, along with the computed microstructure curve. Since the probe output represents the time derivative of beam current, it is especially sensitive to microstructure asymmetry; the integrated microstructure curve is generated only when further data analysis is contemplated.

The pictures of oscilloscope traces shown in Fig. 9 illustrate some different beam conditions that can exist at ORIC. Picture (a) shows a beam which varies in amplitude by about 50%, but which has stable and symmetrical microstructure. The beam in picture (b) varies less in amplitude, but the microstructure of beam bursts is not symmetrical; this can be interpreted to mean that two time-separated sets of particles are extracted per rf cycle.

Picture (c) shows a relatively unstable beam with both amplitude modulation and varying microstructure. The predominant beam is primarily one peak (in time), but part of the time a second current peak of appreciable amplitude can be distinguished.

Picture (d) shows a very unstable beam produced by improper settings of cyclotron controls. The fluctuations in beam amplitude and variations in the time of arrival of the beam bursts indicate indicate that two distinct beams are present, an interpretation supported by the beam energy analysis shown in Fig. 5.

A radial scan of the internal ORIC beam with a differential probe taken in conjunction with Fig. 9b (but not shown) offers interesting support for the hypothesis that the two beams indicated by the 50-ohm probe also exist inside the cyclotron. The configuration of the scan suggests a major beam (large precessional peaks), accompanied by a minor beam (small peaks). The two beams have similar energies, but their radial and axial momenta could be sufficiently different to cause difficulty in transporting both beams through the external beam optics system.

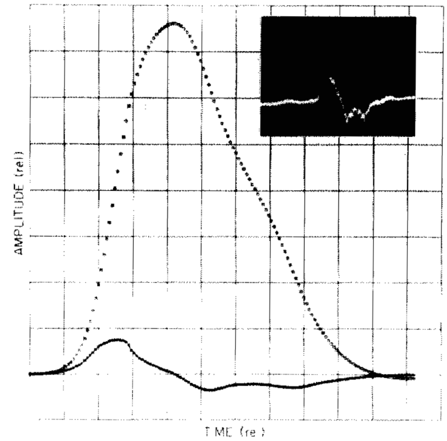

Fig. 8. Data from capacitive probe. The trace in the upper right corner is directly from the sampling oscilloscope. The upper curve is generated by a numerical integration of the original trace, after smoothing as shown in the lower curve.

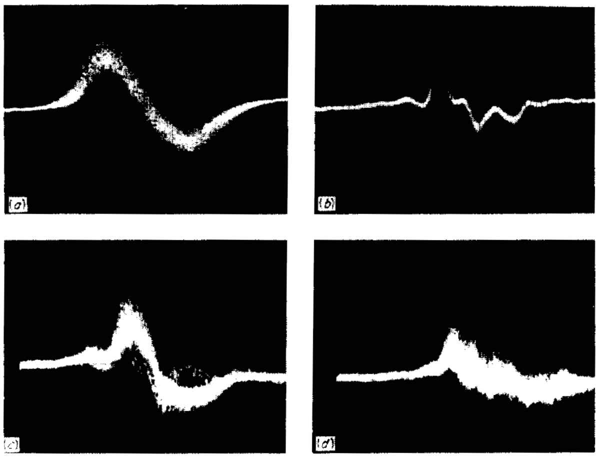

Fig. 9. Capacitive probe traces for various cyclotron conditions.

Conclusion

Development and use of the beam diagnostic system has contributed toward a better understanding of the operation of ORIC and is resulting in improved beam quality.