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MACHINE DEVELOPMENT AT THE BERKELEY 88-INCH CYCLOTRON

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Abstract

Machine development at the 88-inch cyclotron is described. Topics include instrumentation, deflector development, a radioactivity survey of the dee tank, and computer calculations on the gap-crossing resonance. Studies were made of external beam energy spread and pulse shape. Axial injection progress is described. Recommendations are made for design improvements on the 88-inch cyclotron.

General Development

Operation and machine development at the 88-inch cyclotron has been described previously.[1,2,3] Machine settings for new particle energies are being developed on a regular basis. The beams now available include protons from 10 to 55 MeV, α-particles from 15 to 130 MeV and He^3 from 10 to 145 MeV. Third harmonic acceleration is used for α-particles under 24 MeV and He^3 under 18 MeV. This mode runs well even though we do not use a dummy dee. Some high intensity runs showed that 5 mA of protons could be accelerated to a 5 in. radius, and the estimate is that about 3 mA would have reached full energy of 25 MeV if allowed to do so. This is in reasonable agreement with the calculated space charge limit.

Some modifications have been made to the machine and external beam line recently, as shown in Fig. 1. The three 120 degree probes are still available, and are useful for beam centering when first trying new modes of operation, such as third harmonic acceleration. The internal phase probe is no longer used. A radial probe line has been added at the "target probe" port to make "ΔR" measurements on the internal beam quality.[4] The new deflector, now in the beam testing stage,[5] is shown in place. Two TV cameras are used to view the ion source and deflector, and prove very useful to monitor source and puller problems, and beam distribution on the deflector septum. On the external beam line a radial steering magnet, and analyzing slits forming an object for the switching magnet have been added recently.

Before beginning testing on the new deflection system, the old system was optimized over a period of several years. The best figure for deflector transmission is 70% for 120 MeV α-particles. The average transmission is about 50% over all beams. There is usually about 10% loss at the coupling resonance just before deflection. Some septum development has been done to maximize its power handling, since high beam intensities are required for many of the several hundred isotope production runs per year. The best septum design thus far has been radiation-cooled 0.010 in. tungsten sheet with a 6 in. long tapered slot to match the beam profile. This design provides as much external beam current as several water-cooled copper designs which were tried, and is cheaper, less susceptible to damage, and more easily changed. The present external beam power available is about 3 kW, e.g., 150 μA of 20 MeV protons, with about 3 kW more dropped on the septum. Some studies are in progress on a possible water-cooled tungsten septum.

A radioactivity survey was made of the acceleration region in Nov. 1965 after a nine day shutdown, to determine the amount of activity which had built up during about 2 years of running with large beam intensities. These measurements are shown in Fig. 2. The deflector and moving probes were removed. The general βγ level is about 0.5 R/hr in the inner regions. However most work on this area can be done remotely from a location where the activity is about 100 mR/hr or less. Some hot spots appeared on the "C probe", which shields the dee from beam, and near the septum, where some material has been evaporated or sputtered. Comparison of these measurements with some made nine days earlier, showed that the activity had decayed about 30% during this time.

Some computer calculations have been made on the problem of the gap-crossing resonance pointed out by Gordon.[6] This effect is equivalent to a first harmonic in the magnetic field, and is produced by a "beat" of the 2-fold acceleration gap geometry against the three fold magnetic sector field of the 88-inch and many other cyclotrons. Figure 3 shows orbit center paths for accelerated beams with several starting phases. The gap crossing resonance causes the precession center to be off the magnetic center of the machine by about 0.2 in. With the starting conditions of Fig. 3(a), a center spread of about 0.2 in. is introduced into a beam with 50 degrees of phase spread. In Fig. 3(b), the particle starting in phase ($\phi_0 = 0$) was placed to approach the precession center at large radius. In this case the other phases diverged because of being too far off the accelerating gap, giving somewhat worse center spread than Fig. 3(a). This resonance appears to constitute a limitation on beam quality in this cyclotron, when a wide phase width is accelerated. Some possible remedies which are being studied are: use of the inner harmonic coils to compensate the effective error first harmonic, and displacement of the dee gap to coincide with the precession center.

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External Beam Studies

Measurements have been made of the energy and time distributions of the full external beam of the cyclotron. To measure the energy, lithium-drifted silicon detectors with associated electronics* were used. A gold foil was used on the beam line straight through the switching magnet, to scatter the beam 20 degrees into the detector. A pulse-height analyzer was used to display the spectrum. The contribution of detector and electronics to the energy spread was less than 10%. The time distribution of the beam was measured with a semi-conductor detector[7] placed directly in the beam on the same beam line.

The energy spectrum with the best cyclotron tuning is shown in Fig. 4. The full width at half maximum is 140 kV, or 0.22%, after correcting for detector and electronics. The energy spectrum for average cyclotron tuning is shown in Fig. 5(a). The spread is 0.4% FWHM. This is about equal to the energy gain per turn in the cyclotron. If the cyclotron is detuned, by changing the dee voltage by several hundred volts for example, a spectrum such as that of Fig. 5(b) can occur. The two energy peaks are believed to result from misalignment of the beam with the deflection channel, giving extraction from several precession cycles.

The beam time structure is shown in Fig. 6(a) for average cyclotron tuning, corresponding to the energy spectrum of Fig. 5(a). The pulse width is 30 degrees FWHM. For a detuned beam, corresponding to the energy spectrum of Fig. 5(b), the double-peak time structure is shown in Fig. 6(b). The phase width is 45 degrees. Sometimes three peaks are observed for detuned beams.

Some studies have been made on the sensitivity of the beam to instability of various machine parameters. Figure 7 shows the effect of dee voltage ripple on the energy spread of the external beam, for the condition of best tuning. Ripple was injected, and the cyclotron optimized for each measurement. The result shows that ripple should be kept less than 1%. Other measurements for cases other than optimum, and on beam optics for tightly collimated beams, indicate that the dee voltage regulation should be 0.1%. The stability of the dee frequency and the main magnetic field, including trim coil contributions, should be 0.002%.

The emittance of the external beam is about as reported previously,[2,3] 50 mm mr radially and 70 mm mr axially, including some measurement errors. The virtual sources are as reported.[3] With the small steering magnet added before the first quadrupole, all radial virtual sources can now be placed on the beam pipe center line.

*Supplied by the Lawrence Radiation Laboratory Nuclear Chemistry Instrumentation Group under F. S. Goulding.

Axial Injection Progress

During the past year axial injection studies for the 88-inch cyclotron have been in progress for use with a future polarized ion source. A bench test was set up, consisting of an ion source, a 5 foot long transport tube with electrostatic quadrupole focusing, and a probe for current measurement. Tests with this system served to test the initial components of an injection system, and helped to solve some of the problems of ion source optimization and quadrupole voltage supply leads. A test was then arranged to inject beam into the cyclotron through the upper pole. This was a preliminary test to study the problems and efficiency of the various components of the system. The normal ion source was removed for the test and replaced afterward.

The system tested is shown in Fig. 8. The ion source is a modified duo-plasmatron.* Three electric quadrupole doublets transport the beam down to the cyclotron center. The inflector is an electric mirror beneath a grounded grid, similar to the one used by Birmingham.[8] Frames were inserted in the dee and dummy dee to give the initial particle revolutions enough energy gain to clear the inflector. The frames did not have the grid wires used at Birmingham. Injection was on center through a one inch hole in a temporary eight inch diameter iron pole plug. The injection voltage was 15 kV and the dee voltage was 60 kV. This gives a ratio of 4/1 compared to the ideal ratio of 5/1.[9] This caused the initial orbits to be off center about 1/4 inch, and full power in the inner harmonic coils (15 gauss) had to be used to bring the beam back on center again. The beam intensities obtained were: 400 μA at the top Faraday cup, 130 μA at the inflector, 10-20 μA accelerated to 4 in. radius, 1 μA extracted of 30 MeV protons. The relatively poor transmission through the acceleration region and the deflector is due to poor beam quality caused by the off-center initial orbits.

The results of this test showed the weak points of the system as presently developed. The ion source will be modified to allow injection at energies of 10-15 kV. Studies will be made of optics problems in the quadrupoles and inflector region. Voltage holding problems of the inflector in the higher range of magnetic fields will be investigated.

Design Recommendations for Future 88-Inch Cyclotrons

The 88-inch cyclotron has proved to be a very sound design. It has produced external beams of the intensity and maximum energy predicted by its designers. Machine settings are repeatable after intervals of months or years. Energy is easily variable. The 8 inch pole plugs have proved very

*Provided by 90-inch cyclotron group, Lawrence Radiation Laboratory, Livermore.

valuable, both for accurate positioning of the ion source, and for easy conversion to an axial injection system.

In the light of several years of operational experience, there are some design modifications which one would make if the machine were built again, most of which have been or will be made on the present machine. The stability requirements on frequency, magnetic field, and dee voltage were mentioned in Sect. 2. Careful study should be made of the gap-crossing resonance, to minimize or cancel it out with center geometry or harmonic coils, since it appears to limit the ultimate quality of the internal beam with wide phase width. A large diffusion pump on the dee tank would ease the vacuum problems arising if a regenerator is used, or heavy ions are to be accelerated. The ion source could be put in from the bottom, leaving the top of the magnet free for axial injection equipment. A radial ΔR probe other than the usual high current probe used for measuring internal beam intensity (dee probe) is useful for optimizing internal beam quality. The original deflector design works very well, and we don't know yet how much improvement is possible with the new deflector. A radially focusing channel after the deflector would be helpful in bringing the beam out with small divergence. Radial and vertical steering of the external beam as it emerges from the cyclotron are useful for beam optics alignment.

Larger changes involving the rf system are the following. The vertical focusing built into the magnet is adequate for 70-75 MeV protons. The extraction system could extract this energy. So if the rf system went up to about 18.5 MHz, the cyclotron would be capable of producing this energy. A more difficult modification is that of adding some third harmonic to the rf voltage to give a "flat-top" on the rf wave. This could be done either by injecting the harmonic on the present dee, or by using a small additional dee or dees for the third harmonic. As suggested by others previously, this would combine the virtues of good beam quality with wide phase width, a significant step toward the "ideal cyclotron".

The question of depolarization of polarized ions during acceleration is one of interest for future designers. Recently some calculations were done by Baumgartner and Kim[10] using the actual operating magnetic fields for 10 and 55 MeV protons, and 65 MeV deuterons in the 88-inch cyclotron. The results show that the proton depolarization is less than 0.1%, and the deuteron depolarization is less than 1%. Thus there seems to be no problem in accelerating these polarized ions in the 88-inch cyclotron.

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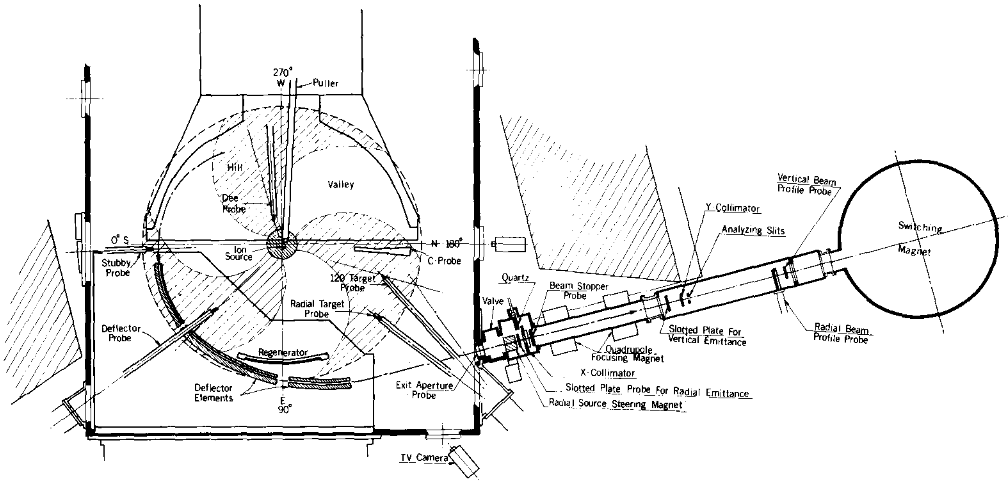

Fig. 1. Plan view of 88-inch cyclotron vacuum tank and external beam line.

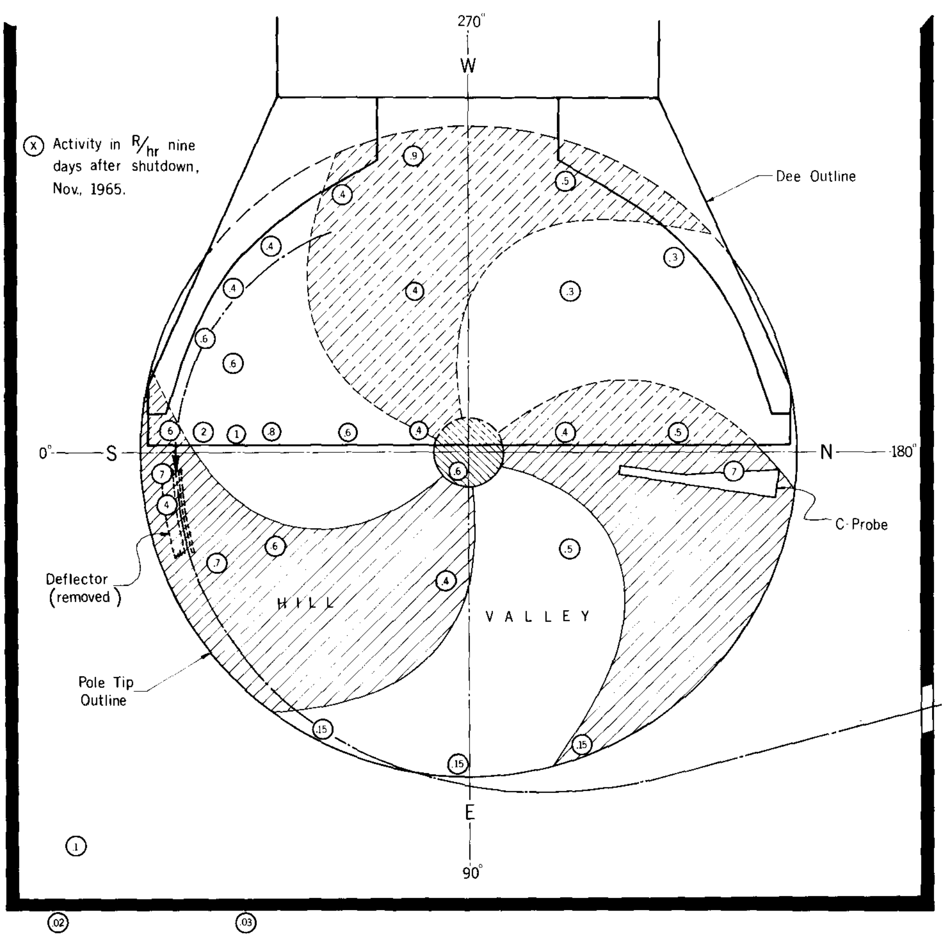

Fig. 2. Radioactivity survey of 88-inch cyclotron tank nine days after shutdown. The circled figures show the $\beta\gamma$ activity in R/hr. The deflector and moving probes were removed from the tank.

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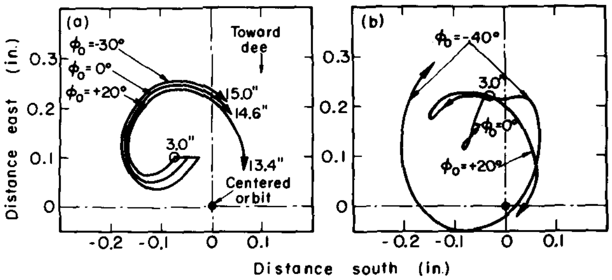

Fig. 3. Motion of orbit centers for 65 MeV α particles calculated with the general orbit code. Several starting phases are shown. Apositive phase means the particle lags behind the rf. (a) starting position adjusted to minimize center spread to about 0.2 inches. (b) starting position adjusted to bring the ϕ_0 = 0° particle to the precession center at 15 inches radius. Center spread is about 0.3 inches.

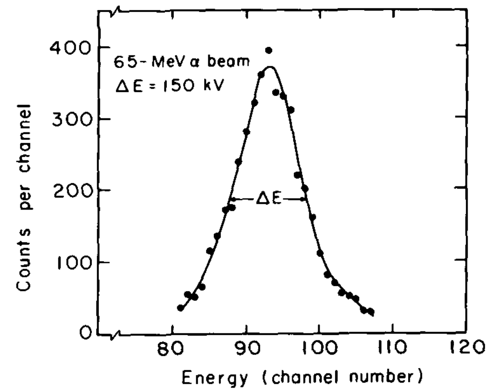

Fig. 4. Full external beam energy spectrum with best tuning conditions. 65MeV α-particles. 50% extraction efficiency. ΔE = 140 kV = 0.22% FWHM, after correcting for electronics spread.

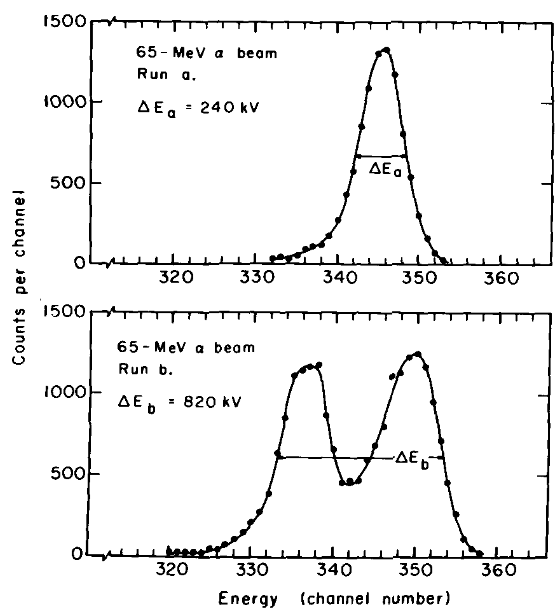

Fig. 5(a). Typical energy spectrum for 65 MeV α particles.

Fig. 5(b). Energy spectrum for 65 MeV α particles. Cyclotron detuned by changing dee voltage from optimum.

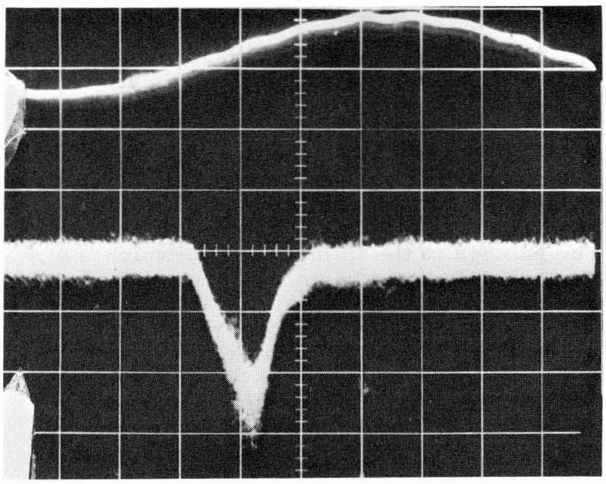

Fig. 6(a). Typical external beam pulse on sampling oscilloscope. Beam tuning same as Fig. 5(a). Phase width = 30 degrees FWHM.

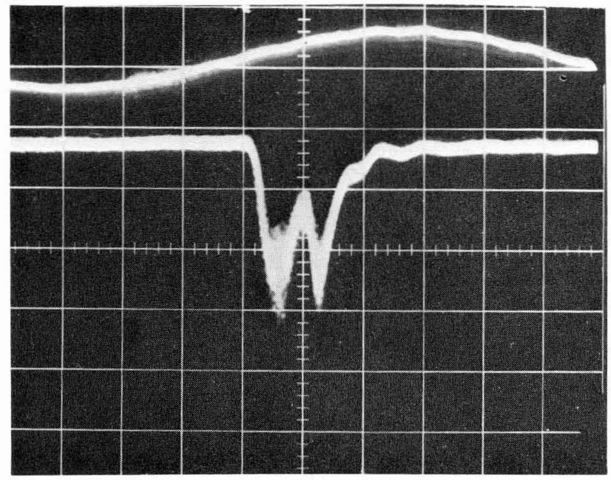

Fig. 6(b). External beam pulse with same tuning as Fig. 5(b). Phase width = 45 degrees FWHM.

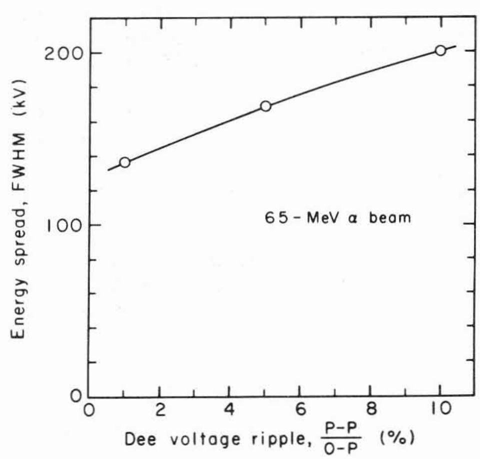

Fig. 7. Energy spread of 65 MeV α particle beam as a function of dee voltage ripple. The energy spread is full width at half maximum. The peak-peak ripple is divided by zero-peak dee voltage.

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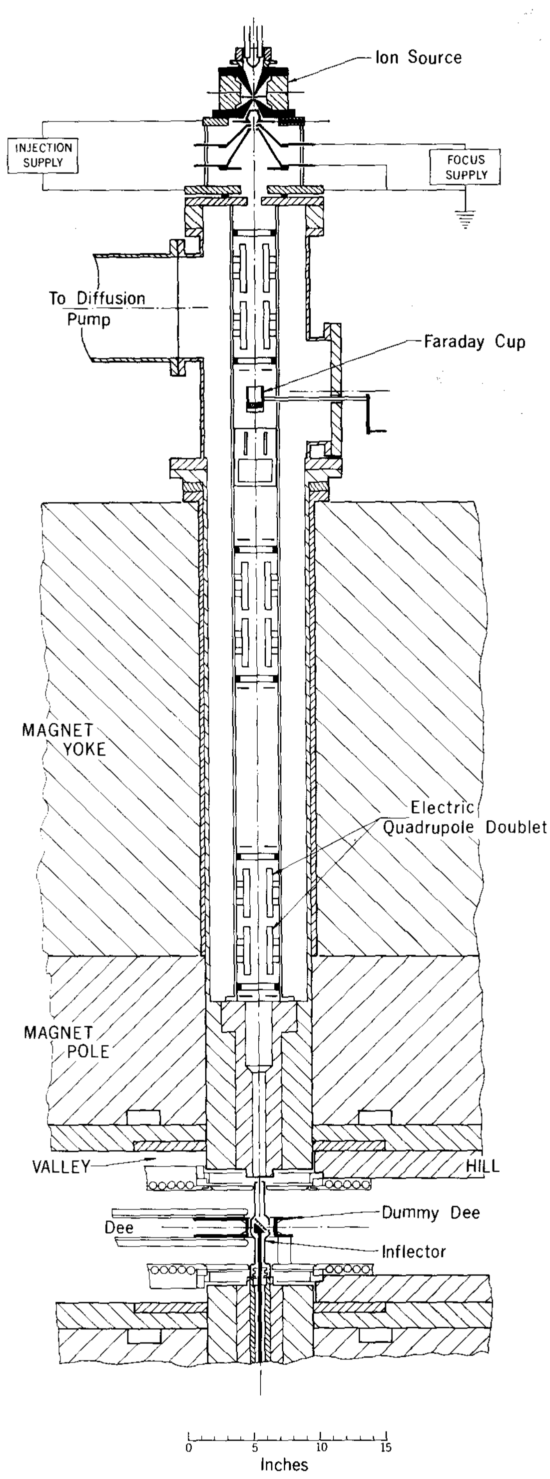

Fig. 8. Axial injection system used for a preliminary test in the cyclotron. Normal axial ion source was removed for this test and replaced afterward.

DISCUSSION

LIVINGSTON: What would be a reasonable performance of the axial injection system, after everything is optimized?

CLARK: Ultimately, we hope to reach the Birmingham performance, as far as efficiency goes. For beam intensity, I think 100 μA of internal beam would be reasonable. The limiting factor may be damage to the inflector grid, which intercepts some 20% of the beam.

PEEK: You were going to recommend some design features for future cyclotrons.

CLARK: Yes. This gap-crossing resonance seems to be a limitation on the ultimate internal beam quality. I think, in building a new machine, one should take a careful look at that, possibly look into optimizing it with respect to polar rotation, relative to the dee gap. This effect could be minimized that way; an alternative would be using four sectors instead of three.

HOLMGREN: Would the internal phase width of the beam be changed any with an axial injection system? Can you get any larger internal phase width?

CLARK: We did not measure the phase width, but one would expect phase widths up to 90°, as Bill Powell mentioned. Our normal phase width is about 60° internal; on extraction this reduces to 30 to 45°. I would expect an increase of, say, up to 90° internal.

HOLMGREN: How much of this loss of the extracted beam would you attribute to the space width that you may have introduced in the beam? Your extraction efficiency is relatively low, right now. You said you could optimize that by changing some of the other parameters. But would you still lose quite a bit of this beam just because of a larger space width, or can you extract a fair amount of it?

CLARK: Are you talking about the actual injection test?

HOLMGREN: Yes.

CLARK: That was a very rough test; the beam was off-center quite a bit for that particular test. With better values of injection energy, say 10 or 12 kV, instead of the 15 kV that we were using, I would expect much better centering of the internal beam, and a normal 50% extraction efficiency.

VAN KRANENBURG: If you added a dummy dee to your system could you improve the quality of the Berkeley cyclotron?

CLARK: Detailed studies of this were made by Willax during the design stage; he found that the beam quality was as good without the dummy dee as with it, in our particular case.

