SURVEY OF OPERATING SECTOR-FOCUSED CYCLOTRONS

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At the outset of this third conference on sector-focused cyclotrons, it is apparent that we are engaged in an enterprise which is successful, flourishing and full of portent for the future. In endeavoring to prepare a survey such as is implied by the title of this paper, some preliminary comments are in order. I have compiled information which has come to me through the graciousness and generosity of the directors and staff members of the respective cyclotron laboratories by many different routes : by personal contact, telephone, cable, letter, open literature, special reports, and perhaps even by rumor. The probability of errors in this process is very high and I apologize in advance to any group whose machine is inadvertently maligned or improperly reported. I should also point out that the bulk of the information I will present is at least a month old and in this rapidly moving field you will do best to consult with the many specialists who are present for more authoritative and more current data.

I have taken my task literally and will try to consider knowledge which has been gleaned from the operation of the machines. I will gloss over and essentially ignore the many beautiful and specialized design features of particular cyclotrons.

Overview of Progress

May I first summarize in a few sentences the essence of what appears to be the concensus of present experience, to be elaborated in the latter part of this paper and perhaps in much more elegant detail by subsequent speakers at this conference.

One. The achievement of isochronism has been accomplished without really too much difficulty. Computer techniques using reasonable but not impractically precise data give trim-coil current settings which readily take the beam to full radius.

Two. Data is now accumulating on the emittance of the internal and deflected beam. Beam quality is higher than many had expected and is genuinely competitive with other accelerator types.

Three. Wide range energy variation and rapid change of particle type are now accomplished. Small energy changes are made in seconds to minutes. Full-range energy changes or a type of particle change can be made in one half to two hours.

Four. Operation is very stable and parameter settings are almost shockingly reproducible from day to day.

(*) Operated for the USAEC by Union Carbide Corporation.

Machines now in Operation

There are, according to my best information, fourteen isochronous sector-focusing cyclotrons in operation, accelerating protons, deuterons or alpha particles, and one which accelerates electrons (if I may include this latter in order to utilize later some information which has been gleaned from it). These machines are listed in the approximate order of their achievement of operating status in Table I.

Table I

Isochronous Cyclotrons in Operation, April 26, 1963

Ion Machines (Place)	Date (Initial)	Sect.	Pole Dia (cm)	Beams measured at r max, Internal		External Beam	Orbits* at R max
				Max (MeV)	Other Beams (MeV)		
Delft	1958	4	85	12p			> 300
Urbana	1958	4	111	15p	4-15p	15p	> 100
Dubna	1959	6	120	13d			> 1000
Harwell	1959	3	56	3p			
Moscow	1959	3	150	32d	6p; 17, 29H_2; 35He_3	32d; 20H_2	> 160
Sea Island Conference							
Los Angeles	1960	4	125	50p	48H^-	48H^-	> 1000
Birmingham	1961	3	102	12d	11D^-	12d	> 400
Berkeley	1961	3	224	130α	25, 50p; 16, 33, 40, 65d; 25He_3 33, 65, 75, 80α	50p; 16-38d 33-75α	> 600
Oak Ridge	1962	3	193	90α	8, 12, 32p; 40d; 80α		> 500
Boulder	1962	4	132	28p	9-28p; 8-18H^-; 17D^-; 30α	8-18H^-; 9-28p	> 200
UCLA Conference							
Davis	1962	3	56	10p			> 100
Karlsruhe	1962	3	225	55d	55H_2; 50d		> 230
Ann Arbor	1962	3	211	40d	7, 12p; 15d	12p; 26d	> 150
Eindhoven	1963	3	130	20p	8, 14p	14p	> 400
Electron Machines				(keV)		(keV)	
Oak Ridge	1961	8	79	530		430	> 2600

* Usually limited by source geometry.

Note that various sector numbers 3,4, 6 and 8 are represented. The respective pole diameters are listed in centimeters. The largest is the new machine at Karlsruhe. The highest energy internal beam is the 130 MeV alpha beam at LRL. The most relativistic or highest energy per nucleon occurs with 50 MeV protons, UCLA and LRL. Nine of the cyclotrons now have deflected beams; some of them with many energies available. Electrostatic deflector efficiencies are in the range from 20-65%.

The newest comers are the last four on the chart, all having achieved operation since the UCLA conference a year ago. In the last column is calculated what data is available on the approximate turn or orbit number. As many observers have pointed out, the measurement of this quantity, usually by reducing the accelerating voltage until the beam vanishes, is obscured by the geometry of the source and accelerating electrodes. But the numbers are generally in the several hundreds of turns, which is very adequate for high-quality operation.

Isochronism and the Setting of Trimming Coils

The techniques used for setting trimming coils and thereby establishing the detailed shape of the magnetic field are generally unique to each cyclotron and its detailed design. Where calculated coil current settings have been computed, I believe that in nearly every case they have been adequate. Hand optimization has also been widely successful. It is clear that in most cases there are a large number of valid trim-coil current solutions. Some low energy studies made at Oak Ridge last summer on this point are illustrated in Table II. Here, five different sets of values arrived at by alternate methods are listed. Note that the polarity pattern is similar for all. The fact that the computer settings did not result in a full radius beam was traced to an operational error in setting the No 2 coil. Operation recently gives beam to full radius with unmodified computer settings for 8 MeV protons, for 90 and 80 MeV alphas and for 40 MeV deuterons, which were all the cases tried. Other laboratories in general have had similar results.

Table II

Values of current settings of the ORIC trim coils for 8 MeV protons determined by five alternative methods

	Optimized from			Computed		
	Beam Current	Phase Probe	Phase + Current	Direct	Exp Adj	Limit
Coil 1 (A)	+ 356	+ 371	+ 357	0	0	1080
Coil 2 (A)	- 529	- 540	- 560	- 465	- 424	900
Coil 3 (A)	0	+ 133	+ 104	+ 208	+ 123	801
Coil 4 (A)	+ 203	+ 86	+ 136	0	0	700
Coil 5 (A)	+ 120	+ 74	+ 68	+ 258	+ 303	675
Coil 6 (A)	+ 333	+ 333	+ 334	+ 162	+ 115	550
Coil 7 (A)	+ 314	+ 355	+ 347	+ 434	+ 436	550
Coil 8 (A)	+ 422	+ 439	+ 469	+ 515	+ 506	515
Coil 9 (A)	+ 183	+ 229	+ 285	+ 266	+ 280	490
Coil 10 (A)	- 445	- 415	- 435	- 470	- 461	470
Dee Voltage (kV)	15	10	10	12	12	
R_{max} (in.)	33	32	34	24	34	
Beam at R32" (μa)	65	100	180		110	
Beam at 20" (μa)	305	370	260		190	

Beam Emittance

Let me digress long enough to remind you of the most commonly accepted method of characterizing charge d-particle beam quality. In general, a beam will have a radial extent and an axial extent. The beam at each radial coordinate, for example, will have a distribution in angular divergence with maximum limits. It is conventional to plot the radial beam emittance in a phase space in which the distance from the central ray is the abscissa. Angular divergence limits are then plotted as the ordinates (these are proportional to the radial momenta). A vertical line in such space signifies a point source. A horizontal line indicates a parallel beam (zero angular divergence). The general shape of a beam is frequently roughly elliptical. The area is roughly π ab where a and b are the semi-major and semi-minor axes of the ellipse.

A typical plot for a d.c. accelerator, a von Ardenne source with 200 kV acceleration, is shown in Fig. 1. This was measured by McKever and Yokasawa of ANL. If the areas under the curves are planimetered, they turn out to be 46 π and 80.8 π mm mrad.

The emittance, as I have just described it, is invariant only at a fixed energy; to make meaningful comparisons of beam quality, the emittance at any two energies must be normalized to the same energy by a factor proportional to the momentum. This arises from the fact that the angular divergence is proportional p_r/p, and the apparent unnormalized emittance will always decrease as the energy increases. To adjust for this I have chosen to normalize all measurements to 50 MeV protons, the factors between this and 200 KeV protons is 16. The d.c. emittance, if measured at 50 MeV, would be 2.9 π and 5.1 π respectively. For 65 MeV alphas the factor is 1.8. Figures supplied by Teng of ANL give a 50 MeV linear accelerator radial emittance as 8.0 π mm mrad.

Some recent and very elegant measurements of Grunder and Kelley at LRL have determined 65 MeV alphas to be 16 π mm mrad, or 9.0 π adjusted to 50 MeV protons. Similar numbers have also been obtained by Allen at Urbana.

Measurements on the internal beam of the eight-sector electron machine give a value of 6.4 π as observed, or an adjusted value of 30 π mm mrad.

More details on these interesting measurements will be given in subsequent parts of this meeting.

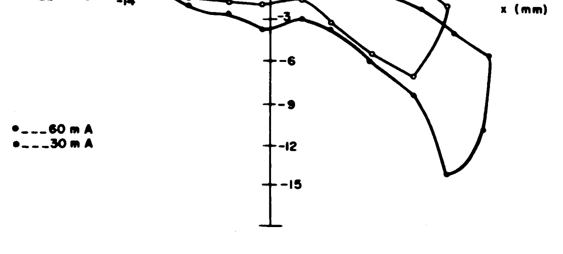

Fig. 1 Plot of emittance of beam from a von Ardenne source with 200 kV d.c. acceleration. The areas have been measured and found to be 46 π mm mrad for the 38 mA case and 80.8 π for the mA case.

Energy Definition

Up to the present only approximate measurements in the energy spread in isochronous cyclotron beams have been made. Estimates and preliminary measurements indicate that 1 to 5 turns may be deflected.

The associated estimate of raw energy spread of a few hundred kilovolt are consistent with this. The final energy definition available to the experimenter will then be a function of the resolution of the primary beam analysis system provide, although the intensity will be a sharp function of the initial energy spread. At least one installation, the group at Ann Arbor, is expecting to provide a system with $E/\Delta E = 8,000$ by using two magnets. For 40 MeV particles this system would give approximately a 5 kV width. Most of the groups will be providing substantially less analysis than this, but presumably precision work can be undertaken if high quality large radius magnets are provided.

Microscopic Duty Cycle

The isochronous cyclotron, in principle, has a large phase acceptance. An ideally isochronized machine could have a natural phase acceptance of 180°. It has been assumed, at least by some, from measurements on non-isochronous machines (with phase bunching operating at the center) that beams would be 20 to 40° wide. This would give a microscopic duty factor of about 10%. For many experiments this does not matter as there are some 10^7 or more beam bunches per second and counter random coincidences are very unlikely. However, a recent measurement at LRL (Grunder and Kelley) have shown that the acceptance is about 90°, and the corresponding microscopic duty factor is approaching 25%. Separate measurements by Powell at Birmingham show acceptance of greater than 70°.

Negative Ions

This survey would not be complete without some reference to the continuing beautiful work on negative ion acceleration. At UCLA the acceleration has been pushed to 40 to 50 MeV, with the final energy apparently limited by the onset of electric stripping. I understand that the point at which stripping is observed is consistent with the prediction of Judd in his post deadline paper appearing in the proceedings of the UCLA conference.

The Colorado group have pushed internal currents of negative ions up to 10 μA, with external currents to 2.5 μA. They are now developing a positive-voltage electrode so that external negative ion beams will, they hope, soon be available for use in research.

Negative deuterium ions have been accelerated at Boulder, at Birmingham and perhaps elsewhere.

Radioactivity and Radiation

As our new cyclotrons begin to operate at energies now far above the nuclear potential barrier for even the heaviest elements, the problem of radioactivity looms larger and ever more formidable. Initial experience indicates that radiation is indeed severe, almost frighteningly so, but perhaps in some ways it is turning out to more tractable than expected. The controlled focusing of these cyclotrons means that less beam is lost on the dees and on other components of the cyclotron. The targets, internal or external, and the cyclotron extraction septum are by far the most intense sources of radiation. To quote a few typical numbers : At UCLA, a few microampere of protons at 50 MeV give 50 R/hr of γ radiation inside the shielded vault. At LRL, 65 MeV alphas, 30 μA internal, 10 μA deflected, give 170 R/hr of fast neutrons near the target. At ORNL, 50 μA of 40 MeV deuterons gave 150 R/hr of fast neutrons 15 ft from an internal target. The residual radiation on shut-down in any of the above cases is a few R/hr close to the target or spetum. General room radiation on shut-down a few feet from the machine is a few mR/hr. Extrapolating these numbers to full operation, perhaps after a few minutes cooling, would yield 100 mR/hr general radiation with a few hot spots higher. A capability for changing targets remotely and perhaps a method for removing or changing the septum system may prove to be essential, and should solve the major radiation problems.

Variation of Energy

Many of the cyclotrons have wide range radio-frequency power generators and wide magnetic field adjusting capability. How have these systems worked out in practice? The answer is that, as far as time and the completion of systems has permitted testing, the energy variation has worked fully as well as expected. LRL has operated with external beams of 3 different particles at 3 energies each and with internal beams at 5 energies (4 particles). Colorado can work at any energy between 8 MeV and 24 MeV. ORNL has worked at 8 MeV protons and at 30 MeV, 80 MeV and 90 MeV alphas. For most machines, working at other values is purely a matter of motivation. In one eight-hour period recently, the LRL Staff changed particles and energies four times and did substantial experiments at each situation. Colorado moved, on one occasion, from 16 MeV to 20 MeV in about thirty minutes, with deflected beam in each case. They can make a 1% change in a few seconds, a 5% change in 2 minutes. Urbana works regularly at 4 to 15 MeV, extracted, with small frequency changes made in 5 to 30 min and large changes in 2 hours. Clearly an enormous and growing versatility is at hand.

This has been a brief summary of salient features of some of the first fourteen isochronous cyclotrons. At least 12 more machines are now abuilding; perhaps in two or three years we can hear another report on the performance of these yet newest and shiniest machines.

DISCUSSION

BLOSSER : Can you state the currents for these machines? Beam quality has little meaning unless the current is given; the phase-space area can be made anything one likes by appropriate slit settings.

TENG : The Argonne linac gives 10 to 15 mA at 8 π mm mrad radial phase space.

GRUNDER : The measurements for the 65 MeV α's were made with currents between 2 and 20 μA. We have made the interesting discovery that over this range the emittance stays constant. We suspect that the channel is limiting the emittance.

VERSTER : How do you define beam emittance in a cyclotron where radial and axial emittance may be different?

LIVINGSTON : The definitions correspond; available values for the other direction are not very different.

WIDERÖE : At what distance from the machines was the radioactivity measured?

LIVINGSTON : At UCLA the distance was about 2 m, at LRL less than 1m, and at ORNL about 5 m.

SCHMIDT : Were the measurements on microscopic duty cycle made on internal, external or energy-analyzed beams?

LIVINGSTON : The measurements at LRL were made on the internal beam.