OPERATING EXPERIENCE WITH THE UNIVERSITY OF COLORADO CYCLOTRON (*)

J.J. Kraushaar, D.A. Lind,
M.E. Rickey and W.R. Smythe
University of Colorado
(Presented by D.A. Lind)

Operating experience with the University of Colorado cyclotron has been obtained during irregular operation over the past year, first with acceleration of H^- ions and deflection by stripping and then acceleration of protons with electrostatic deflection. Operation has been limited to machine tests except for a few bombardments and some runs for testing solid state counters in a scattering chamber.

The main magnet supply has consistently demonstrated stability to 1 in 3×10^4. The sense of the main field can be reversed in about 10 min. from the control room. The shim-coil supplies use 64 pass transistors in an emitter follower configuration with fixed voltage control of the bases but no current feedback. Reversing is done by means of a patch panel. The supplies provide 400, 500, 750 and 750 A respectively, regulated to 0.5 percent. Most of our other magnet supplies are based on the same principle. A central field coil and a set of valley coils are also provided. Partial harmonic control can be achieved by the valley coils. Thus far we have never used them for that purpose.

The master-oscillator, power-amplifier system using capacity coupling to the dee has fully satisfied our expectations. There has been no trouble from parasitic oscillations, or multipactoring.

The system in its present form is particulary simple. The tuned-plate circuit of the final stage was eliminated and the coupling capacitor is now a fixed capacitor which gives proper coupling over the entire frequency range of 7.5 to 21.3 Mc/s. The use of a fixed-voltage power supply for the output stage of the power amplifier has proven satisfactory. Although we initially installed a triggered spark gap crowbar circuit in this power supply, we are now using only a series resistance to protect the tube; the crowbar circuit was disconnected. The movable short using finger stock mounted on water-cooled copper pieces has caused zero down time since installation, at current densities to 100 A/in. A recent inspection showed no discoloration or other evidence of heating of the finger stock.

An automatic voltage control circuit was recently installed; it compares a rectified signal from the dee volt-meter pick-up with the d.c. level set by the dee

(*) This work is supported by the U.S. Atomic Energy Commission under contract AT(11-1)-535

voltate potentiometer at the control desk. It amplifies the error signal and applies it to the screen grids in the low level stages of the power amplifier to change the gain of the amplifier. The system works well and appears to stabilize the dee voltage to better than a part in one thousand. It removes ripple produced by the final stage power supply and the 60 cycle filament voltage, as well as from other sources that might be present in the power amplifier.

Our original system for coupling between power amplifier and the dee involved a tuned circuit at the plate of the output tube, a transmission line, and a variable coupling capacitor. Trouble was experienced with both variable vacuum capacitors and mica capacitors in the resonant plate circuit. For this reason a revision of the plate circuit was made which eliminated the tuned circuit. This new circuit has proven very satisfactory. It consists of a fixed coupling capacitor, a transmission line approximately 6 ft. long between capacitor and the tube, and an RF choke to feed d.c. to the tube. The arrangement is illustrated in Fig. 1a. Figure 2 shows the voltage step-up ratio, as a function of frequency as obtained with the arrangement shown in Fig. 1d. It is interesting to note that for frequencies above 13.2 Mc/s there is a voltage node on the transmission line. This frequency was determined by shorting the cyclotron end of the transmission line and measuring the resulting resonant frequency of the transmission line loaded with the tube capacitance. Since the most RF power is required at the high frequencies, the fact

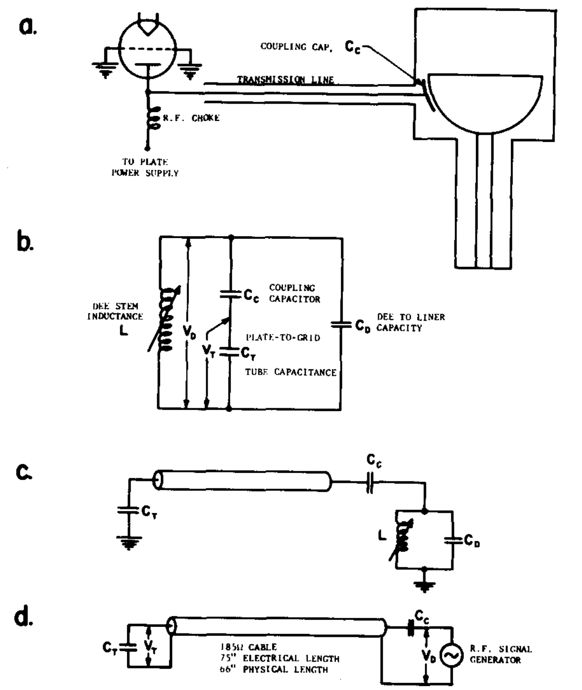

Fig. 1 Electrical equivalent of final RF stage circuit.
a. Actual circuit.
b. Simple equivalent circuit. This approximation ignores the effect of inductance in the transmission line. The ratio of dee voltage to tube voltage is independent of frequency, in this approximation.
c. Equivalent circuit, including the effect of the transmission line.
d. Circuit employing a signal generator, two trimmer capacitors, two vacuum tube voltmeters and an appropriate length of RG 114/u cable to measure the voltage step-up ratio as a function of frequency.

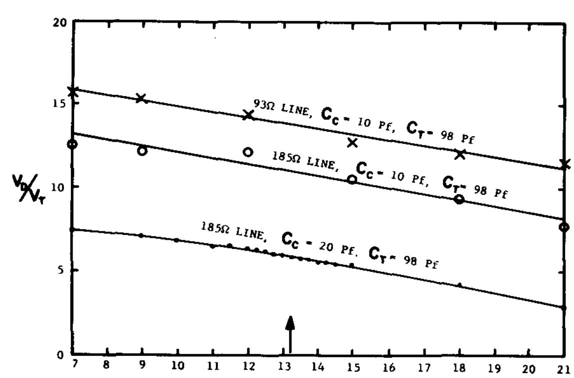

Fig. 2 Values of dee voltage to tube voltage ratio as a function of frequency. The data was taken with the arrangement shown in Fig. 1d. Above 13.2 Mc/s there is a voltage node on the 185 ohm line, but the voltage step-up ratio is well behaved.

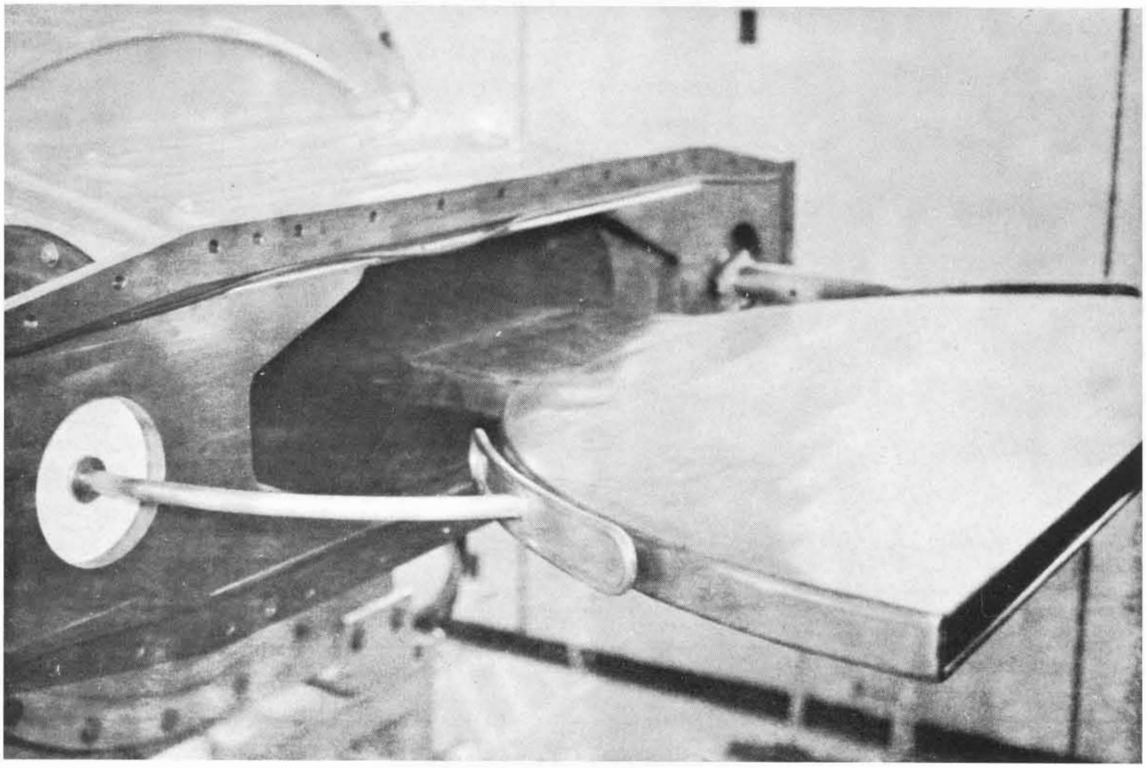

Fig. 3 Photograph showing the RF window, the coupling capacitor and the dee.

that the RF voltage on the tube decreases somewhat at lower frequencies, for a fixed dee voltate, is not harmful.

The coupling capacitor, shown in Fig. 3, has the positive d.c. plate voltage on it, which makes it possible for electrons to oscillate near it in the magnetic field and to migrate until they hit the RF window. Damage of the alumina insulator has been attributed to this cause. Although the window has not failed, we plan to install an electron dump.

Table I lists the parameters for typical operation of the capacity-coupled plate system. It was not operated below 9.5 Mc only because the frequency-doubling circuits following the master oscillator were not trimmed for the low frequencies. The important parameters are the tube-to-dee step-up ratio $V_D/1.41V_T$ and the final stage power, $i_p V_T (75\ \mathrm{kV}/V_D)^2$. This quantity is in error because it is assumed that the final stage conducts only at the peak of the plate voltage swing.

The experience with this RF system indicates that, for the power levels required in this machine, it is possible with the new power tetrodes and commercially available amplifiers to build a system requiring no tuning of intermediate stages. Our experience indicates that elaborate crowbar protection is also unnecessary.

It is worth noting that the vacuum system has performed very well. Pressures indicated by the gauges at the high vacuum pump manifolds range from 5×10^{-7} to 1.5×10^{-6} mm. With normal gas flow at the ion source these pressures rise only slightly. This good vacuum has made possible the good RF operation and the deflector operation for both positive and negative potentials.

The deflector and magnetic channel are shown in Fig. 4 with the external beam

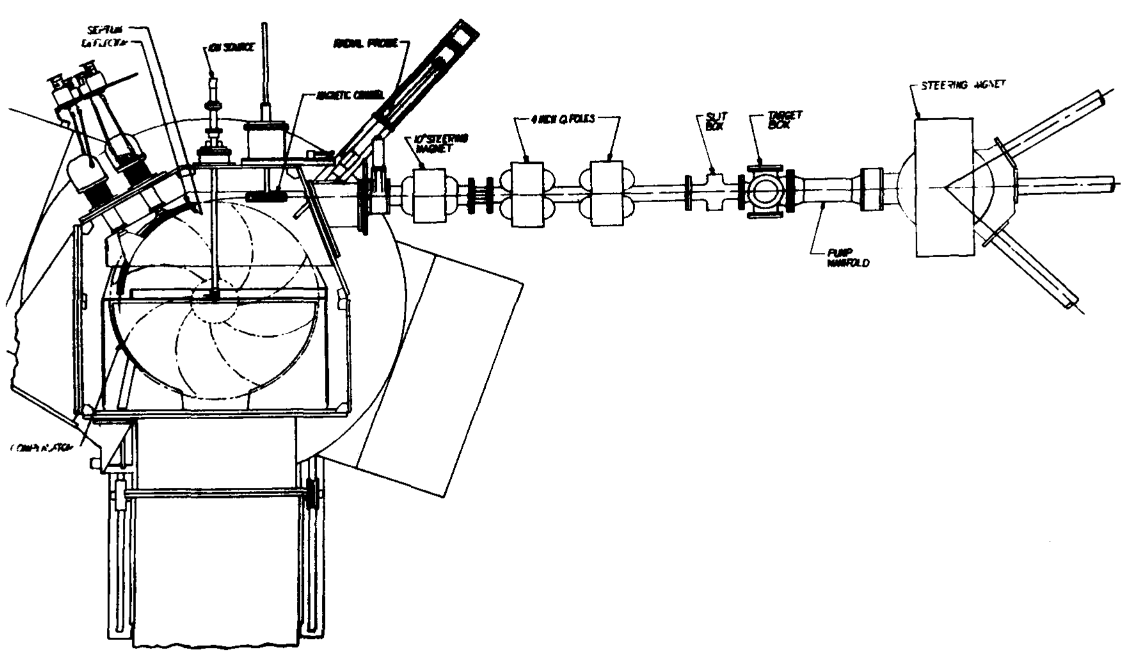

Fig. 4 Layout of the deflector and external beam handling system within the cyclotron vault.

Table I

Typical Operation - Capacity Coupling, Untuned Plate Circuit

Short position	0000	100	200	400	610	800	1000	1200	1400	1696	2000	2400
OSC	226	353	456	616.5	742	830	906	968.5	44	177.5	291.2	413
Freq (Mc/s)	21.31	19.78	18.55	16.62	15.12	14.06	13.15	12.40	11.75	10.95	10.26	9.52
ip (5681) (A)	4.5	4.9	4.75	4.95	4.2	3.9	4.1	3.7	3.9	4.0	4.1	3.3
ip (4cw) (A)	1.2	1.1	1.05	1.0	- -	1.0	1.0	.95	.9	0.9	0.95	.77
V_D (peak) (kV)	37	43	40	48	52.5	55	60	60	64	73	75	68
V (Trans.) (kV)	2.7	2.07	1.85	2.3	2.4	2.5	2.54	2.6	2.73	3.2	3.4	3.0
V (Drive 5681) (V)	405	437	458	430	- -	363	450	357	340	350	340	308
V (Drive 4cw) (V)	143	146	156	172	- -	115	118	115	110	115	125	96
Step-up ratio*	9.7	14.7	15.3	14.8	15.5	15.5	16.7	16.3	16.6	16.1	15.6	16.0
Power** (kW)	49.9	29.5	31.0	27.8	20.5	18.1	16.3	15.1	14.6	13.5	14.0	12.0

* The tube-to-dee step-up ratio is $V_D/1.41V_T$.

** The power, $i_pV_T(75\ kV/V_D)^2$, is approximately proportional to the power required to produce V_D = 75 kV, (error is due to change in the plate current wave form).

steering system. As shown, the magnetic channel is inserted through the 8-in. port. The extraction port can be displaced sideways to accomodate either a deflected beam or one stripped out of the machine. The 10° magnet permits steering the beam through the quadrupoles to the slits. The switching magnet provides for momentum analysis at slits located within the shield wall on the beam deflected 45° to the right.

The septum and deflector are both articulated to provide separate in-out and rocking motions. In addition the complete assembly can be displaced parallel to the tank wall; thus the entrance to the deflector channel can be positioned at radii between 22.8 and 24 inches. The septum is insulated to permit a control voltage up to 20 kV for steering purposes to be applied. At negative potentials the deflector stands off 80 kV and at positive potentials it has withstood 60 kV. An electron dump for the deflector is provided.

Operating experience has been under a considerable variety of conditions. No careful tests were made on isochronization and the effects of various trim coils. In fact, it is easier to tune up the machine by using the motor-driven probe and observing beam current as a function of radius for various coil-current settings than to refer to the computer programs. Some rather crude comparisons of beam variation with radius as a function of the magnetic field profile were made. Also, a very little work was done with a resonant beam-current probe to measure the phase. The results of these tests only substantiated what seemed to be indicated by other observation. Since adequate dee voltage (up to 90 kV) has always been available, there never was an urgent need to make studies of phase history or threshhold. An artificial threshhold is introduced by using a graphite flag along-side the ion source to define the central orbit. This made a considerable reduction in the amount of spurious beam when H^- ions are accelerated. The one surprising feature of operation with internal beams is the ease with which they can be tuned and the relative insensitivity to settings of the various shim coils. Shim coils do make an improvement but the settings are not critical and the beam has been brought out to 24 in. (23.6 in. is the design radius) without difficulty.

The behavior of the system, including the electrostatic deflector, from 9.95 Mc up to 16.5 Mc was explored in detail. No mechanical adjustments were needed over this range. Internal beams at 19.6 Mc have been brought out to extraction radius. We have experienced considerable difficulty holding the ion source output down to 10 to 20 microamperes.

Beam quality: No careful measurements have been made. With negative ions a crude investigation of vertical and radial oscillation was made by examining the ray pattern. The resultant circle of confusion at the waist had a diameter of about 3 mm. The angle corresponding to the cone of divergence (full width) is about 0.02 rad; this gives a radial luminosity of 60 mm mrad with a beam current of 2.5 μA. Observations of the errosion of the graphite beam current probe indicate that vertical excursions of about 2 mm might exist. There is a high degree of coherence in the beam, as indicated by the distinctly separate turns stripped or deflected out. A measurement of beam quality was made on the 18.9 MeV electrostatically deflected beam. The result indicates a radial phase-space area of 34 mm mrad for about 2 μA of deflected beam. This beam is limited by the deflector channel.

Energy definition: If separate turns are discernable in the external beam the energy resolution must be better than one percent. An attempt to measure this by elastic scattering of 7.6 MeV protons gave a result less than 130 keV. The sharpness of magnet tuning and dee voltage control indicates that the energy resolution should be very good.

Energy variation: The system has been operated over a frequency range of 9 to 21 Mc/s. We have changed the frequency over small increments (about 0.5%) with the compensator drive without turning the RF off. Large changes are made in 2 to 4 minutes. Reproducibility of settings is excellent. Changing particles takes 5 to 10 min. and changing from positive to negative ions about 20 minutes. The pre-set oscillator frequency is stable to 0.003%. All fine tuning is done with the magnet control.

Extraction efficiency: With the electrostatic deflector the efficiency runs about 10 to 15 percent. The configuration was originally set up to get a beam on the first tests and has not been changed; the efficiency can certainly be improved.

Time structure: The time structure of the internal beam was determined by making the beam probe a resonant structure at 2 f. A measure of the phase slip was made but further work was not carried out. We have also looked at the time structure of neutron pulses produced by the external beam. They were certainly bunched to 10% of the RF period.

Stability and reliability: All settings are very reproducible. The RF system was turned off for entry to the vault and, on switching on, the deflected beam appeared. Controls behave in a consistent and reproducible manner. Start-up time is limited by the RF system warm-up time; otherwise a beam can be obtained in 5 minutes.

Table II lists a series of typical operating conditions. The frequency is the best index for the operating conditions. The energy was determined at two different settings by copper-foil irradiation; other energies are computed by the frequency settings. Other ions have also been run only to verify that no special difficulties exist on changing from one ion to another. A rather small beam of D^- was obtained at 17 MeV and alphas were obtained at an energy of 30 MeV.

Table II

Recent Measurements with Protons

Frequency (Mc/s)	Beam Energy (MeV)	Beam Current (μA)	Radius (in.)
9.95	6.8	700	22
		0.25(neg)	extracted
10.87	8.2	0.1 (neg)	extracted
11.68	9.5	0.28(neg)	extracted
13.08	11.8	0.14(neg)	extracted
13.08	11.8	25-50	22
		5	extracted
15.1	15.8	100	22
		2.5	extracted
16.5		23	22
	18.9*	2	extracted
18.44	23.8	30	21
19.6	23.5*		22.5 (uncertain)
19.6	26.6	50	23.6

* The beam energy was determined on these runs by activation of copper foils. Other energies are computed from the frequency setting.

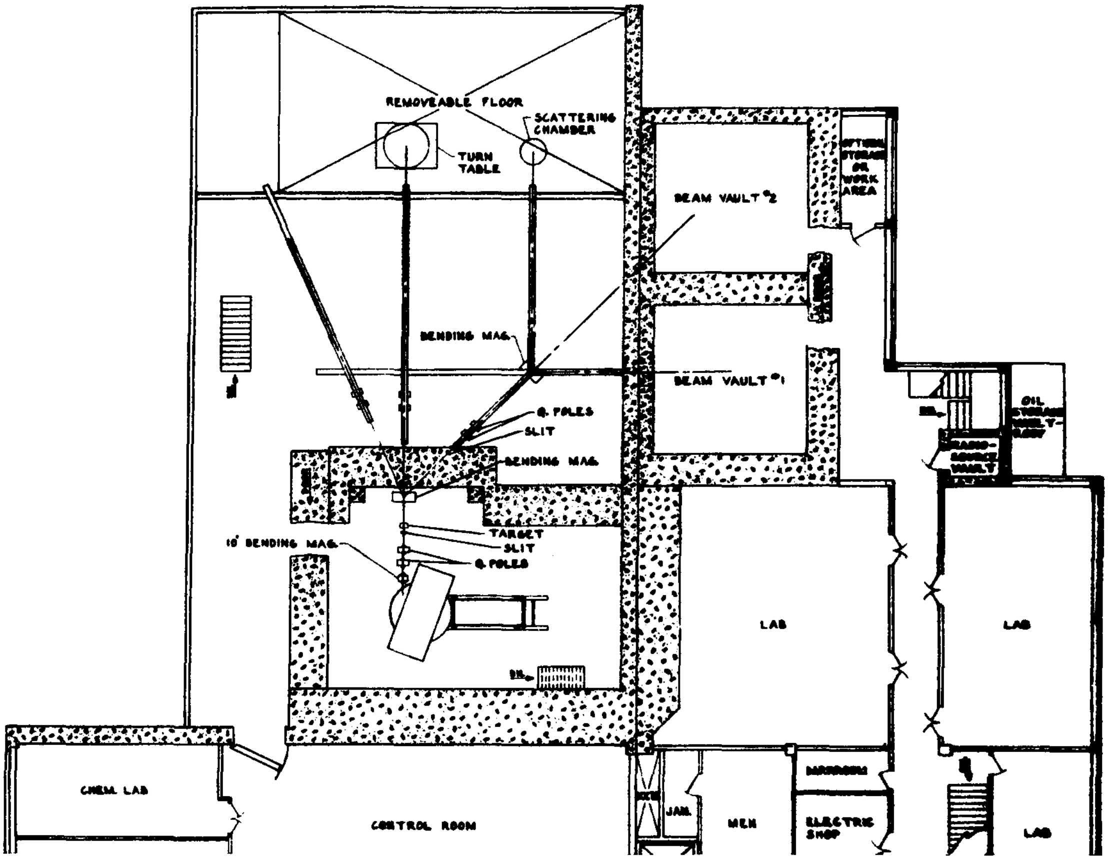

Fig. 5 Layout of the experimental area showing the disposition of the cyclotron, control room and experimental area. The part of the building to the right of main experimental area and cyclotron vault is under construction.

Figure 5 shows the layout of the cyclotron and experiment area, including the new addition under construction. That part of the building to the right of the main experiment area is being added to provide several shielded experiment vaults and space for the mass separator[1] and beta spectrometer[2]. All beam plumbing is suspended from I-beams overhead. The structure is also rigid enough to suspend quadrupole magnets and other incidental beam handling equipment. Other details regarding the machine are to be found in the proceedings of the UCLA conference[3].

References

1. The Colutron, a Zero Deflection Isotope Separator, L. Wahlin, University of Colorado Nuclear Physics Lab. Report OCOL 516 (1963).
2. A.A. Bartlett et al., Nucl. Instr. and Meth. 17, 188 (1962).
3. D.A. Lind et al., Nucl. Instr. and Meth. 18,19, 62 (1962).
   D.A. Lind et al., Nucl. Instr. and Meth. 18,19, 129 (1962).
   Rodman Smythe, Nucl. Instr. and Meth. 18,19, 582 (1962).

DISCUSSION

KHOE : How do you measure the beam quality?

LIND : We use a diaphragm with an array of holes and place photographic paper about 6 ft from the diaphragm. The positions of the spots show, then, the slope and the size of the beam.

KHOE : What is the effect of scattering if the beam hits the edge of a hole?

LIND : There was perhaps some effect. This was a rather crude measurement; certainly it has to be refined to get better results.

TENG : Do you have any measurements of the negative-ion beam intensity as a function of radius? Do you see any break-up of the negative ions?

LIND : As I remember, we saw no attenuation in the negative ion beam as a function of radius; our tank pressure is very low. Experimental facilities are now available to measure electrostatic stripping of the negative ions and to measure cross-sections by back scattering, charge exchange, and so forth. This will be done within the next two months.

BROBECK : What are the deflector and dee gaps, to ground?

LIND : I think that all sparking occurs from the deflector to the septum. This gap varies from about 5 mm at the entrance to about 10 mm at the exit. Incidentally, with regard to the beam quality, it is certainly true that our beam is highly collimated by the deflector-septum arrangement.

BLASER : Did you try to produce neutral hydrogen atoms?

LIND : Not yet; this will be done with the external beam.