THE PRESENT STATUS OF TRIUMF

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ABSTRACT

The current status of the TRIUMF project is described. Erection of the cyclotron magnet is virtually complete, including the support structure which raises and lowers the upper half of the magnet. The vacuum chamber has been tested, with cryopumping enabling a pressure of 10^{-7} Torr to be achieved within a few hours. The final design pressure of 4×10^{-8} Torr looks easily achievable. The resonators, operating on the fifth harmonic of the ion frequency are undergoing manufacture. The radio-frequency amplifiers have been tested and appear to be capable of delivering the 1600 kW of 23 MHz power required for operation at 200 kV between the "dees". The initial version of the ion source and injection system has been tested and the H^- beam has been injected into the full-scale model of the central region of the cyclotron.

The use of a sector-focusing cyclotron accelerating H^- ions to intermediate energies was one of four early suggestions for an accelerator to serve as a meson factory.[1] This suggestions is now being realized in TRIUMF and the facility has been described several times.[2-4] The purpose of this present report is to describe the status of TRIUMF as of July 1972.

MAGNET

A very large magnet is required to accelerate H^- ions to 500 MeV without undue electric stripping. With the maximum magnetic field less than 5.8 kG the final orbit turns out to have a mean radius of 310 in. and the amount of steel required in the magnet is somewhat over 4000 tons. An impression of the size of the magnet can be gained from an examination of Fig. 1, which shows most of the main-site staff of TRIUMF on the sixfold lower sectors as of January 1972. Fig. 2 shows an earlier stage of construction and gives more details of a lower sector. By March 1972 the vacuum chamber was resting on the lower magnet sectors, and the upper sectors were being emplaced as shown in Fig. 3. In this picture one can also see the ends of two of the upper coil segments in the lower left and lower right. Since the coils are over 50 ft in diameter, they could not be transported to the site as circles. They were divided into six segments which are welded together at the site. In the picture one sees the ends of two of these segments, consisting of 15 slabs of aluminum 1 × 19 in. with two cooling channels of 0.5 in. diam in them. The required current per turn is 27,000 A and the DC power will be 2.9 MW. Separate treated

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water systems are used for the aluminum and copper cooling. Fig. 4 shows the 180-ton support structure which is used to raise and lower the upper half of the magnet and the top of the vacuum chamber.

Some measurements have been taken of the settling of the large concrete slab (approximately 9 ft thick and 70 ft in diameter) on which the magnet rests. Over a period of two months under the total load of some 4500 tons, the slab has apparently settled fairly uniformly by a fall of an average of 0.02 in. This movement will be monitored from time to time but it appears to be of no particular concern for the operation of the facility.

It is estimated that the major shimming program for the magnet will require at least three months. The effects of various shims have been studied on the 1:10 scale model, and a computer program is being developed which it is hoped will speed up the shimming process. Although satisfying the requirements of isochronism is relatively straightforward, the axial focusing is affected in rather complex ways by the addition of various shims. The flip-coil technique has been adopted for the main measurement of the magnet field. A radius arm 27 ft long has been constructed, carrying 105 flip coils, and positionable with an accuracy of 0.010 in. Approximately 80 integrating circuits will be used. The position of the magnetic median surface will also be determined by the technique developed at TRIUMF[5] although flip coils will also be used here instead of Hall plates. Preliminary tests have indicated that the magnetic median surface can be determined with an accuracy of 0.030 in.

THE RADIO-FREQUENCY SYSTEM

This system is described in detail in another paper in this conference.[6] The requirements to be satisfied are 100 kV to ground at each resonator tip with an amplitude stability of ± 2.5 parts in 10^5 (for eventual separated turn acceleration) and a frequency stability of ± 7.5 parts in 10^8 at 23.1 MHz (the fifth harmonic of the ion frequency). As discussed below, flat-topping of the voltage wave is very desirable to improve phase acceptance and beam quality. This requires up to 100 kW of 69.3 MHz power to give a total power from the system of 1650 kW.

The available DC power is 2.6 MW at 20 kV which can feed into 8 tubes of type 4CW250000. The excess RF power available may be useful in punching through the multipactoring region. After getting through the multipactoring region the system switches from the power amplifier to the self-excited mode. This mode is followed during the short time required for the resonators to come to temperature equilibrium and then it reverts to the power amplifier mode where the frequency is determined by the frequency synthesizer source.

The resonators or "dees" are designed to resonate at $\lambda/4$ of the fifth harmonic of the ion frequency, or $3\lambda/4$ of the 15th harmonic of the ion frequency. Flat-topping of the voltage wave using the third harmonic of the fundamental RF is a natural development in this accelerating electrode geometry.

Fig. 5 shows a typical resonator segment, utilizing a copper-aluminum 'roll-bond' material with the copper as the conductive surface. Each segment is 193 in. long, 32 in. wide and 6.5 in. high. Model tests showed an expected heat loss of 12 kW per segment, but the flexibility in the shape of the cooling pattern allows temperature differences to be maintained at less than 5°F. The 'roll-bond' panel floats on a large aluminum extrusion, and thermal deflections are minimized by expansion compensating supports between the panel and structure. A shorting plane connects the two arms of the resonator segment. It contains two tuning pockets for adjusting the inductance of the segment. Mounting hardware for the segments is designed to be compatible with remote installation and removal. This will be required after the cyclotron has operated for some time at full intensity and has become radioactive.

VACUUM SYSTEM

Extreme care must be used in the fabrication of a vacuum chamber some 56 ft in diameter and 18 in. deep if it is to maintain a vacuum of 4×10^{-8} Torr. The TRIUMF chamber was welded up out of 10 ft by 20 ft sheets of 7/8 in. thick type 316 stainless steel. The welds were inspected and checked by 100% X-ray examination. The side walls are 1.5 in. thick with a 1/16 in. thick section 4 in. high in the central region to reduce the residual radioactivity. The side walls were curved to the 28 ft radius by a technique of differential heat treatment. The tank bottom, lid and side walls have a total of 208 ports, ranging in diameter from 1 in. to 12 in. and sealed with covers and 2S aluminum wire gaskets 0.162 in. diam. The top and bottom of the vacuum chamber are shown in Fig. 6 before the side walls were welded on to the bottom. Note the outgassing and cooling tubes and the trim and harmonic coils. Fig. 7 shows the bottom of the chamber being turned over before attaching the side walls.

Before the vacuum test, the interior of the chamber was blasted with glass beads (20μ) to remove scale and peen the surface. This was followed by hand washing with methanol to remove dust and grease. For the evacuation trials the top was sealed with a double Buna-N O-ring, but in actual use a more radiation-resistant organic-based material will be used.

The vacuum system[7] employed in the tests consisted of a roughing system of four mechanical pumps in parallel backing a small blower which in turn backed two larger blowers in parallel, a cryopumping system, and an auxiliary pumping system. The cryogenerator was a Philips Model B-20 with a capacity of 100 W at 20°K and about 1400 W at 85°K. Helium gas at 20°K was conducted by an insulated transfer line to cryopanels inside the vacuum chamber. The cryopanels consisted of two one-inch stainless steel tubes at 20°K surrounded by panels of copper at 80°K in such manner that there was no direct line of sight from the 20° surface to any surface except that at 80°K. The total length of the panel was 40 ft. This provided an effective pumping area of 1.2×10^4 cm^2 at 20°K and 7.4×10^4 cm^2 at 80°K. Assuming a sticking factor of 50%, the pumping speed for air was 80,000 ℓ/sec and for water was 5×10^5 ℓ/sec. The auxiliary pumping system is required to pump non-condensable gases such as hydrogen, and for the test consisted of two 10 in. diffusion pumps. No diffusion pumps will be used in the final system.

A helium leak detector was used to check for leaks. In the hundreds of feet of welding the only leak found was one along a side wall diaphragm. Some leaks were found in the aluminum gaskets but these were successfully sealed by tightening the flange bolts.

By calibrating the through-put of the leak detector with a moving oil drop it was determined that the total outgassing rate of air from the chamber after 18 hours was 2×10^{-4} atm - cm^3/sec.

The tests have shown that the mechanical pumps will reduce the tank pressure to 10^{-4} Torr in 90 min, at which point the cryogenerator would normally be turned on. Although troubled by a helium leak in the cryopanel, the test readily achieved a pressure of 1.5×10^{-7} Torr. A mass analysis showed that the partial pressure of nitrogen was less than 10^{-8} Torr. The cryopanels begin to pump within 30 min and cool to their working temperature in less than two hours. Thus in operation the tank pressure should be reduced to the order of 10^{-7} Torr in four hours. One concludes that it will be quite feasible to defrost the cryopanels and return to operating pressure within the period of an 8-hour maintenance shift.

The final vacuum system for the cyclotron is shown in Fig. 8. It differs from the system used in the tests in that the auxiliary pumping system contains no diffusion pumps but instead consists of a combination of turbo-molecular pumps for the noble gases and titanium sublimation pumps for hydrogen. The turbo-pumps must be shielded from the magnetic field.

BEAM PROBES

The extraction foil, or stripper, which strips the two electrons off the H^- ions so that the beam comes out of the cyclotron into the meson hall will be a carbon foil of approximately 0.001 in. thickness.

For mechanical reasons, the stripper will hang into the beam plane from a foil cartridge which holds six replacement foils. It will have quasi-radial movement sufficient to cover an energy range from 165 to 500 MeV with beam currents of 100 μA at maximum energy. It is expected that a foil will last at least a week at this current.

The beam desired in the proton hall will be down in magnitude at least a factor of ten below that in the meson hall, because of shielding requirements. When the factor becomes greater than 100, a wire stripper of carbon 0.001 in. diam is necessary for the second beam in order to achieve stability.

The extraction probes are shown as numbers 1, 2, 3 and 4 on Fig. 9. The other probes, used for beam diagnostics, are also shown in the figure. Probes 5 and 6 in the figure are high-energy current probes, where the stripped electrons are measured, while probes 7 and 8 are low-energy current probes, where the total charge is measured. Probes 11 and 12 are centring or shadow probes, used for orbit centring and also for measuring the RF distribution along the dee gap. A number of phase probes will also be used.

There will be a number of adjustable slits and flags which will be used to control the phase and emittance of the beam. Their position will range in energy from 4 to 30 MeV.

THE CENTRAL REGION CYCLOTRON (CRC)

The CRC was built to combine a number of prototype tests. These included:

1. Development of an external H^- ion source and injection system
2. Mechanical and electrical testing of the resonator structure
3. Testing of magnetic field measuring techniques
4. Actual testing by injection of the H^- ions and acceleration over five or six turns.

These requirements meant that the CRC would be an accurate full-scale replica of the central region of the large TRIUMF cyclotron. The result is undoubtedly the most expensive 3 MeV cyclotron that has ever been built! However, the results and the experience gained have been well worth the time and money, and they are described in another paper.[8]

STUDIES IN BEAM DYNAMICS

The effects of resonances on the TRIUMF beam quality have been studied.[9] In accordance with previous discussions, it was found that TRIUMF is approximately a factor of ten more sensitive than most cyclotrons to the presence of a first harmonic in the magnetic field. Detailed orbit calculations have shown that 0.2 G first harmonic produces a serious effect on the radial amplitude, but that the effect can be reduced to a negligible value by use of the harmonic coils being installed on the vacuum chamber. It was also found that the tolerances on the first harmonic twist in the median plane due to the $\nu_x-\nu_z=1$ resonance are not too difficult to satisfy while in the neighbourhood of the $\nu_x=1.5$ resonance the gradient of the third harmonic must be less than 0.2 G/in.

One of the tolerances which has been investigated in the last year has been the effect of dee or resonator axial misalignment[10] on the beam quality. Fig. 10 shows the effect of a 1 mm misalignment from symmetry in which diagonally opposite resonators are either elevated or depressed with respect to the median plane. There is an axial impulse given to the ions by the asymmetric electric lens of the resonator edges, and this persists to large radii for phases such as 0 deg (where the electric focusing force is small). For positive phases (ions lagging behind the RF wave) the electric focusing is large and the oscillating amplitude is held to small values. On the other hand, when the misalignment is such that the resonators on one side of the gap (say) are depressed with respect to the other side of the gap, the resulting oscillation amplitude is relatively independent of the electric focusing or phase of the ions.

Since these alignment tolerances are rather difficult to achieve and maintain at the end of the long resonator arms, an alternative scheme for compensation has been devised, involving insulated plates above and below the median plane at DC potentials up to 3000 V. The beam itself will be used as the signal for compensation.

The effects of the third harmonic when optimized to produce a broad phase acceptance (as distinct from the condition required for separated turn acceleration) are shown in Fig. 11. Here we see the shape of the RF wave, the energy gain per turn and ν_z^2 as a function of phase. It can be shown that the electric focusing depends simply on the rate of change of the energy gain with phase. In the expression for the normalized resonator voltage $V/V_0 = \cos\phi - \varepsilon\cos(3\phi + \delta)$ the optimum phase acceptance occurs at $\varepsilon \simeq 0.24$ and $\delta \simeq -25$ deg.

Although the macro-duty factor for TRIUMF will be 100%, we are also interested in the micro-duty factor and in particular the factors which influence it.[11] Fig. 12 shows the expected phase acceptance for two cases; Case 1 applies where there is only the fundamental of the RF (fifth harmonic of the ion frequency) and Case 2 where there is also the optimum component (described above) of the third harmonic RF. The selection phenomena are as follows:

1. Ions must clear centre post
2. Ions must end up in orbits centred to 0.04 in.
3. Effect of radial-longitudinal coupling should be maintained less than 0.01 in.
4. Vertical acceptance must be achieved with and without space charge.

The net effect of 1, 2, 3 and 4 above is shown as the acceptance of the cyclotron and shows a micro-duty factor up to 20% with the third harmonic.

The schedule for completion of the cyclotron previously indicated November 1973 as the beam-on time. However, recent industrial strife in British Columbia has delayed this date by several months. The facility will be operated at an average of one per cent of final intensity for the first six months and at 10% of final intensity for the second six months of operation. In addition to the probes shown in Fig. 9, the external beam after momentum dispersion will be used to measure the energy spread of the beam and thus the amplitude of radial oscillations as shown in Fig. 13.

REFERENCES

1. J.R. Richardson, Nucl. Instr. & Meth. 24, 493 (1963)
2. E.W. Vogt and J.R. Richardson, IEEE Trans. Nucl. Sci. NS-13, 4, 262 (1962)
3. J.B. Warren, Proc. Fifth Int. Cyclotron Conf. (Butterworths, London, 1971) 73
4. J.B. Warren, IEEE Trans. Nucl. Sci. NS-18, 3, 272 (1971)
5. G.H. Mackenzie and J.R. Richardson, Nucl. Instr. & Meth. 87, 319 (1970)
6. K.L. Erdman, R. Poirier, O.K. Fredriksson, J.F. Weldon and W.A. Grundman, Paper H11 this conference
7. D.C. Healey and D.A. Axen, private communication (1972)
8. E.W. Blackmore, G. Dutto, M. Zach and L. Root, Paper D4 this conference
9. J.L. Bolduc and G.H. Mackenzie, Paper M10 this conference
10. M.K. Craddock, G. Dutto and C. Kost, Paper M5a this conference
11. G. Dutto, C. Kost, G.H. Mackenzie and M.K. Craddock, Paper M5b this conference

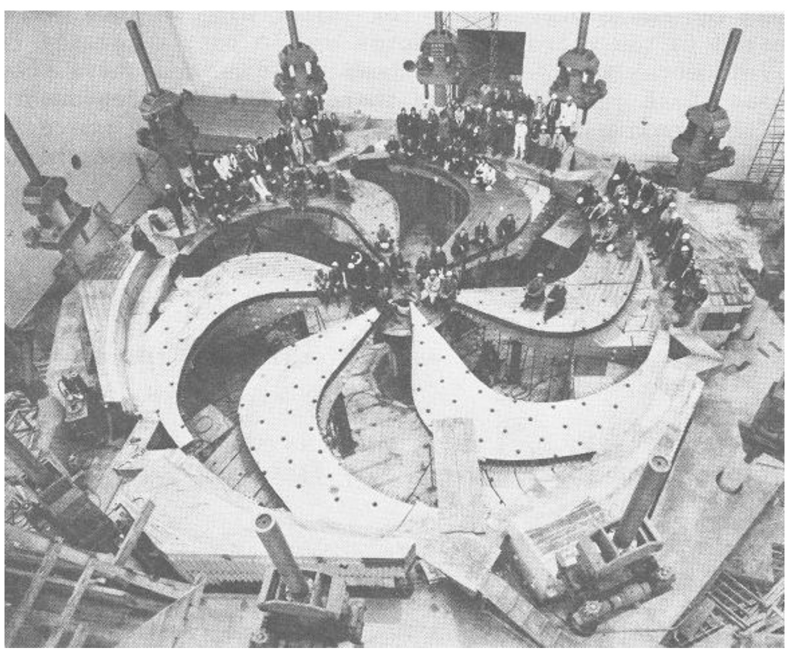

Fig. 1. Lower sectors of magnet with TRIUMF staff - January 1972

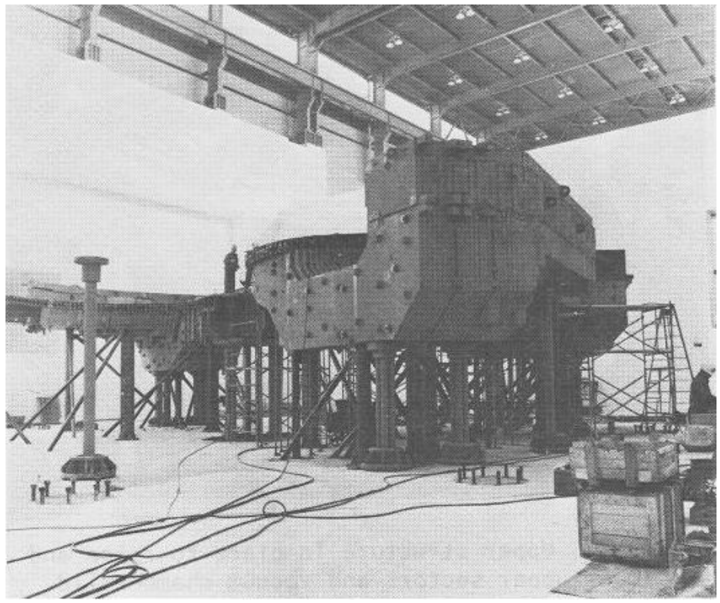

Fig. 2. Lower sector of magnet
Fall 1971

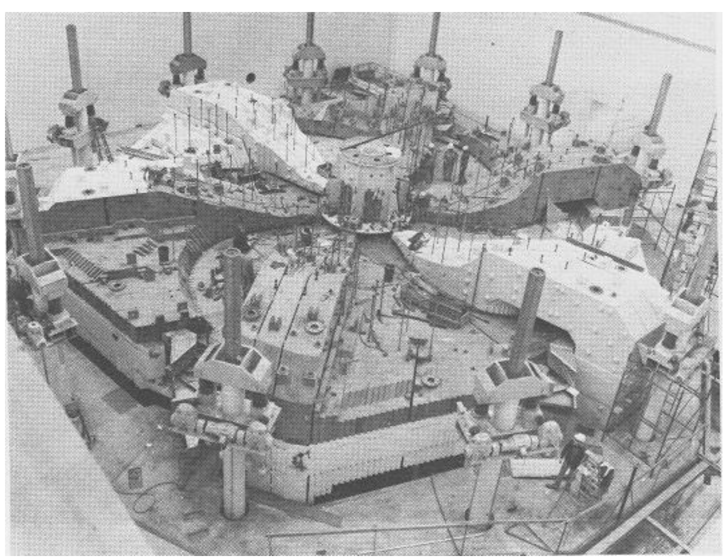

Fig. 3. Upper sectors being emplaced
March 1972

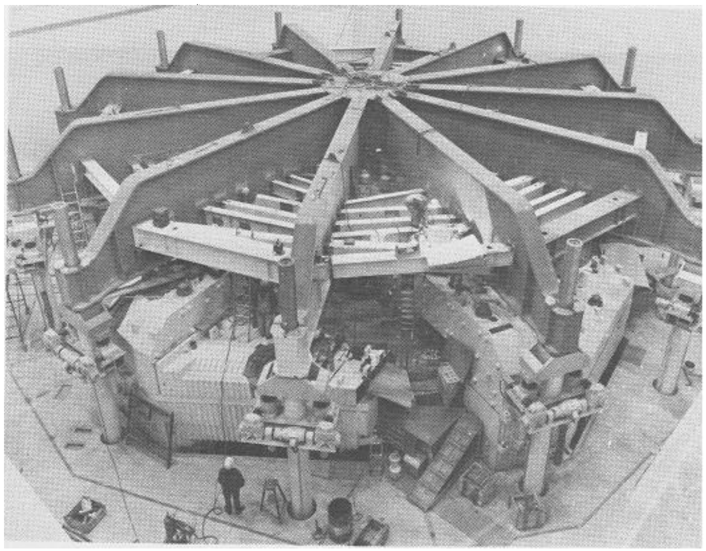

Fig. 4. Upper structure in place to raise and lower upper sectors and vacuum chamber lid

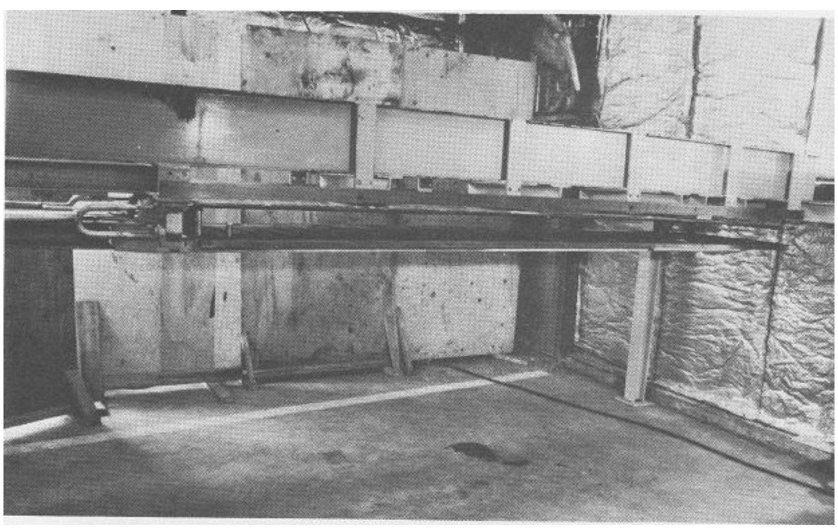

Fig. 5. Resonator segment

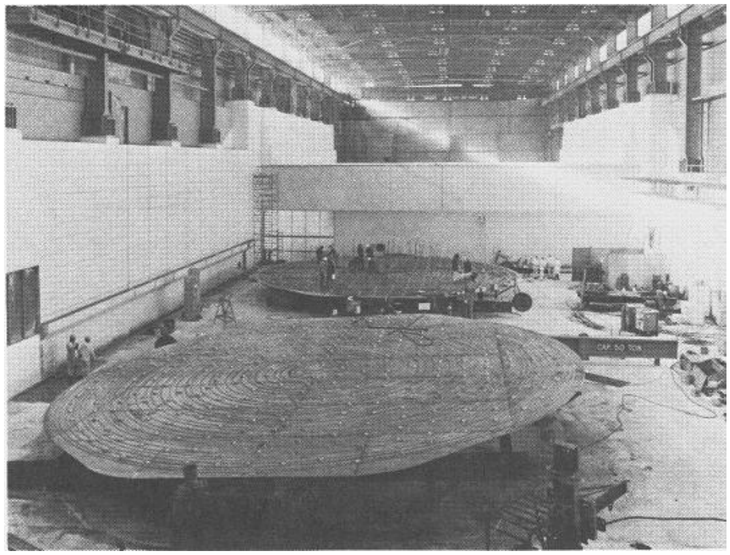

Fig. 6. Top and bottom of vacuum chamber

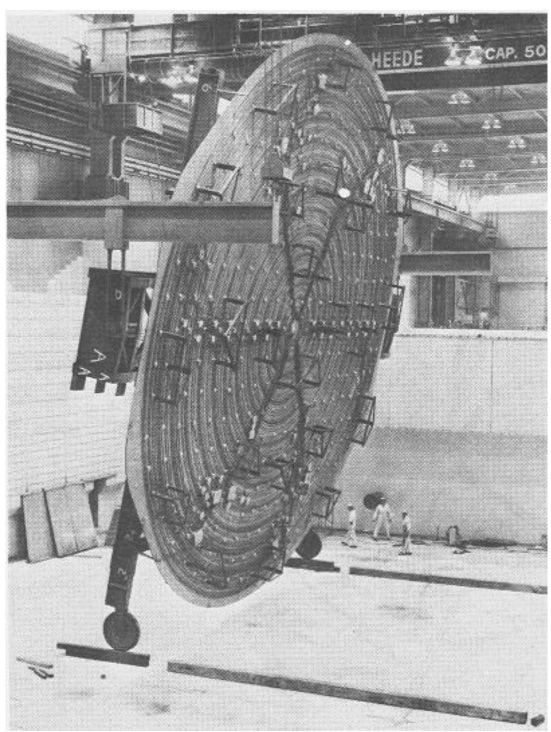

Fig. 7. Turning over the bottom of the vacuum chamber

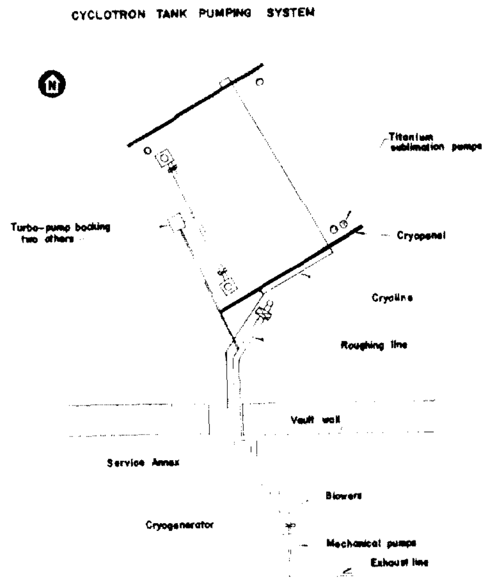

Fig. 8. Vacuum system for the cyclotron

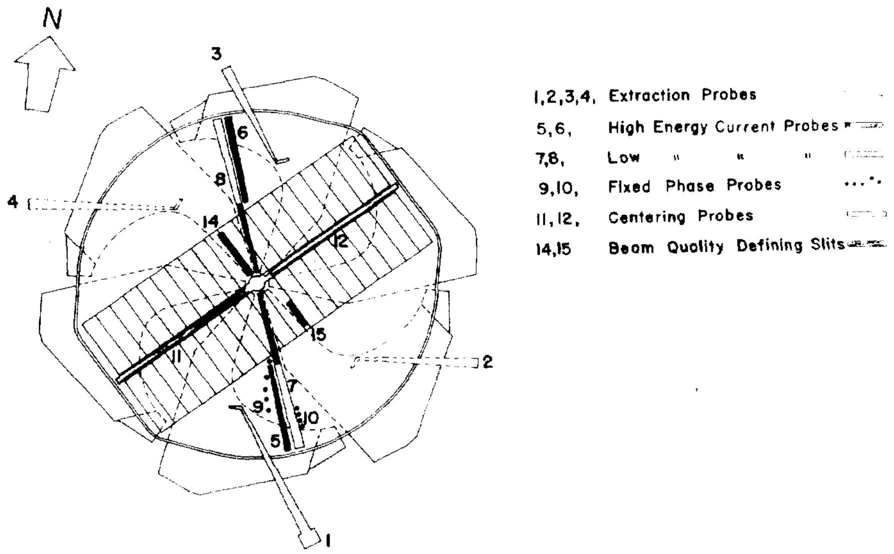

Fig. 9. Beam probes for initial operation of the cyclotron

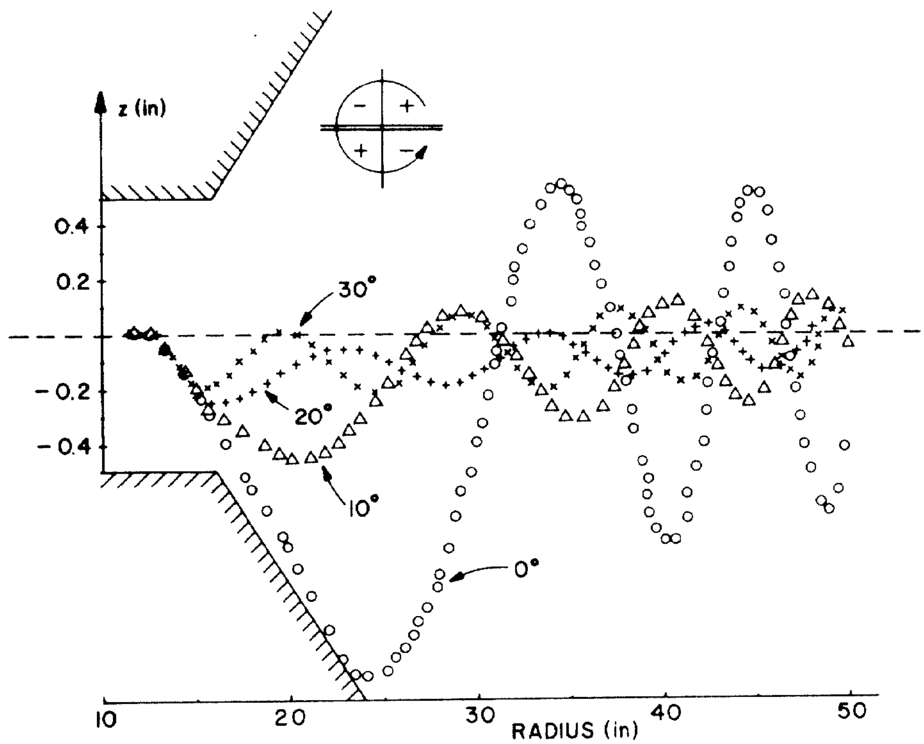

Fig. 10. The effect of a 1 mm misalignment of the resonators on the axial motion of the ions

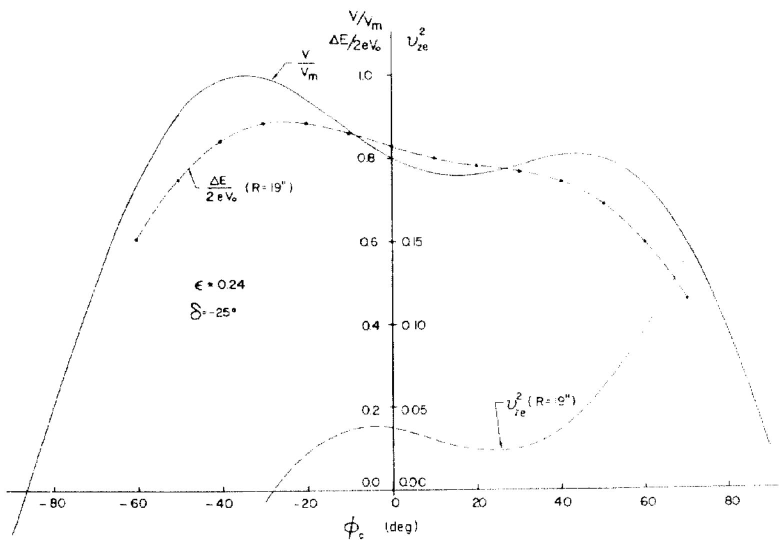

Fig. 11. The shape of the RF wave, energy gain per turn, and ν_z^2 as a function of the phase

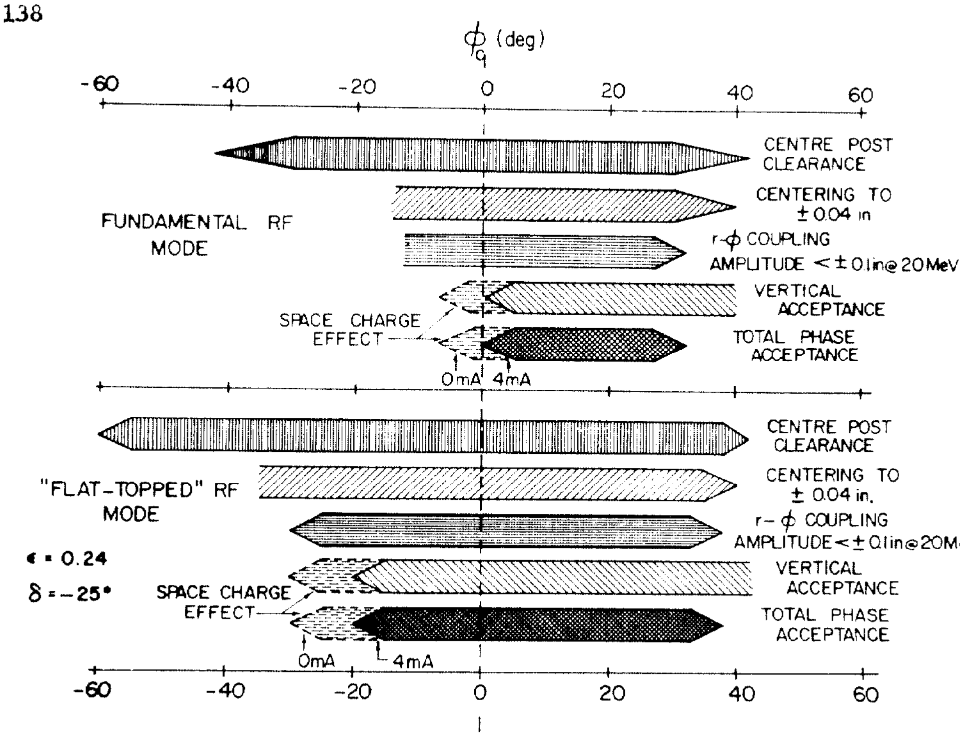

Fig. 12. Expected phase acceptance without and with the third harmonic of the RF

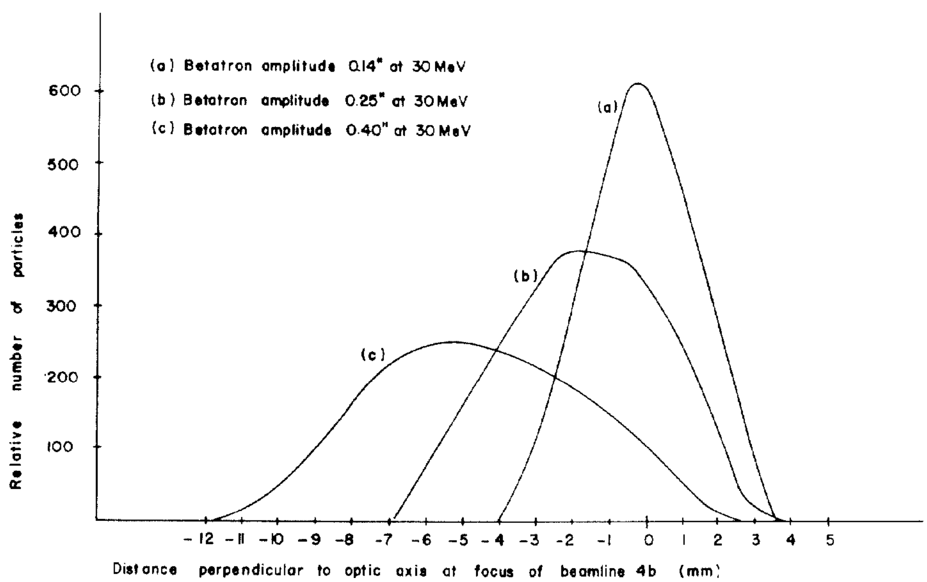

Fig. 13. Use of external beam in measuring radial betatron amplitude at 500 MeV

DISCUSSION

RESMINI: How was the space-charge effect on the acceptance estimated?

RICHARDSON: Werner, would you answer that.

JOHO: We just used the Reiser formula from the Gatlinburg Conference for the transversal space-charge.

WEGNER: With the thin walls on your vacuum chamber what equilibrium-induced activity do you expect?

RICHARDSON: We expect an equilibrium-induced activity down by just about a factor of 10 from what Michaelis showed--primarily due to the increased size, 56 ft in diameter instead of 200 cm.

WEGNER: How high would the radiation level be?

RICHARDSON: Something of the order of 5 to 10 R/h.

RAINWATER: You have a series of resonators that run along--you couple them to one and you believe they will couple to each other. This would be for the fundamental, but you are indicating that somewhere near the centre you have a particular 3 x frequency, which used to be called second harmonic and I gather people now call it third harmonic, and it is in the particular phase. Do you really have some feeling of certainty as to how this propagates throughout the system? Do you have to feed it somewhere? Apparently you are relying on the fact that these are basically the same. It isn't obvious to me how this coupling throughout the system works, and in particular what would happen to these 3 x frequency phase and amplitude relative to the fundamental. Can you comment on this briefly?

RICHARDSON: Well, the situation as far as the fundamental goes we are very sure of. The coupling is very good from resonator to resonator and, say, from top to bottom. No problem there. I agree there are problems on the third harmonic. It isn't as simple as just putting it on, because as I said there is this business of tuning the individual resonators, with these little pockets near the root. This can very likely have a different effect on the third harmonic than on the fundamental, so I think it is likely that we are going to have to put in some additional little bumps or vanes, which will take care of this problem. The amount of third harmonic power involved is 100 kW vs the 1600 kW of the fundamental. Perhaps Karl Erdman might like to comment on that?

ERDMAN: I can answer that with respect to the third harmonic: we modelled this with a half-scale resonator system made of plywood with copper surface sheeting. Our voltage droop as far as the resonators were concerned--first harmonic droop from the centre of the resonator to the outside edge--was something like 1% max, due to non-uniformities.

The third harmonic was about 3% from the outside to the middle. This is well within tolerances. We are allowed something like 1% per meter of resonator width, as far as the beam dynamics are concerned, in terms of actual energy resolution. So the whole thing has been modelled and the phase control circuits checked at half-scale, which was at 50 Mc and 150 Mc.

JUDD: I would like to make one comment about the 100 days. Apparently you don't work at night. I am put in mind of the request at the Bevatron some years ago when time was scheduled in 12-hour increments called periods; Prof. Owen Chamberlin and his colleagues requested a run of 80 periods and it was granted. They were asked how they wanted it and the reply was: "40 days and 40 nights--we want a flood of beam!"

I would like to ask you one other question, based on long past history. How many knobs have you demanded on this machine?

RICHARDSON: I have been trying to minimize it. Actually, there are quite a few, quite a few.

JUDD: I was told there might be 50 in the control station.

RICHARDSON: That's right.

JUDD: Which means you have only gone up 25% in 22 years!