CONSTRUCTION DETAILS OF THE TRIUMF H^- CYCLOTRON

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Summary

The TRIUMF cyclotron includes seven major components requiring large industrial contracts: the magnet cores, coils, D.C. power supply, vacuum chamber, support structure, RF resonators and RF power supply. The first five components are discussed, together with actual performance data. The RF components have been described recently[1] and will be installed in the cyclotron in about two months. The costs of these components plus associated building, engineering and inspection fees are given.

Introduction

The idea to build a cyclotron to accelerate H^- ions from 300 keV to 500 MeV[2 3 4] resulted in rather severe mechanical design problems caused by the large extraction radius of 780 cm. The conventional H shaped magnet would have been prohibitively costly, as may be deduced from the following table[5]:

Cyclotron	Extraction Radius [cm]	Steel Weight [metric tons]
Berkeley 184 in	208	3,600
Dubna	270	7,000
Leningrad	316.5	7,800

As the magnet steel is usually the largest single cost factor in a cyclotron, it was worthwhile spending the extra effort, both in model studies and mechanical engineering, to achieve a six-sector magnet design with a steel weight of only 3,600 metric tons. This is still considerably more than other cyclotrons, except those listed in the table.

The cyclotron is situated in a 30.5 x 30.5 m vault, which will eventually have 5.2 m thick concrete walls and a removable prestressed concrete beam roof of the same thickness. Its foundation consists of a monolithic concrete slab 3.30 m thick at the centre and 2.44 m thick at the periphery. The slab also supports 1,580 metric tons of heavy aggregate shielding, placed directly around the cyclotron.

The cyclotron is shown in figures 1 and 2. The right half of the picture shows the top section raised as required for installation and maintenance.

Magnet Cores

Magnet steel must be chosen for good magnetic properties, availability and economy. While high permeability is desirable, uniformity of magnetic properties throughout each sector, and from one sector to another, is the critical requirement. A low carbon steel, AISI 1006, with specified low limits on impurities, was chosen as meeting uniformity tolerances at a minimum cost premium. Use of fully killed steel, to minimise segregation throughout the ingot, also contributed to unformity. Plates, castings and forgings were considered but plate was chosen as most economical when construction was included[6 7].

Using plates rolled to good flatness tolerances, it was possible to construct the sectors as shown in figure 3, using flame-cut as-rolled plate. Only the pole pieces were machined. Each upper or lower yoke is composed of five sub-assemblies or blocks. Each block consists of a number of plates set side by side, bolted together tightly, and welded along their edges for rigidity. Block size was limited to 90 metric tons, to match available crane capacity. For each sector, upper blocks and pole pieces are bolted into a unit which can be elevated for maintenance. Lower blocks, poles and the vertical yoke are bolted into a unit, then mounted on the support columns.

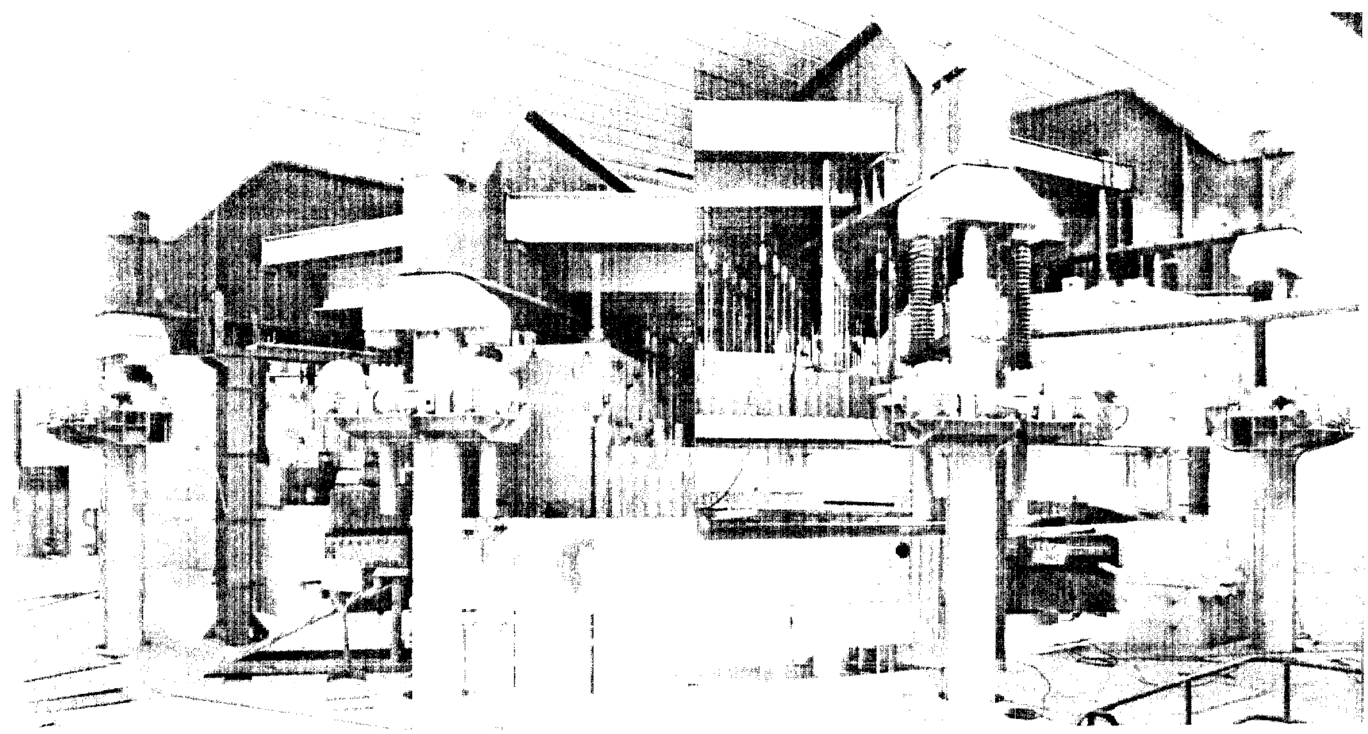

Figure 1
The cyclotron at the time of magnetic field measurements, January, 1973. Right of the centre the top section is shown elevated, revealing the field measuring arm.

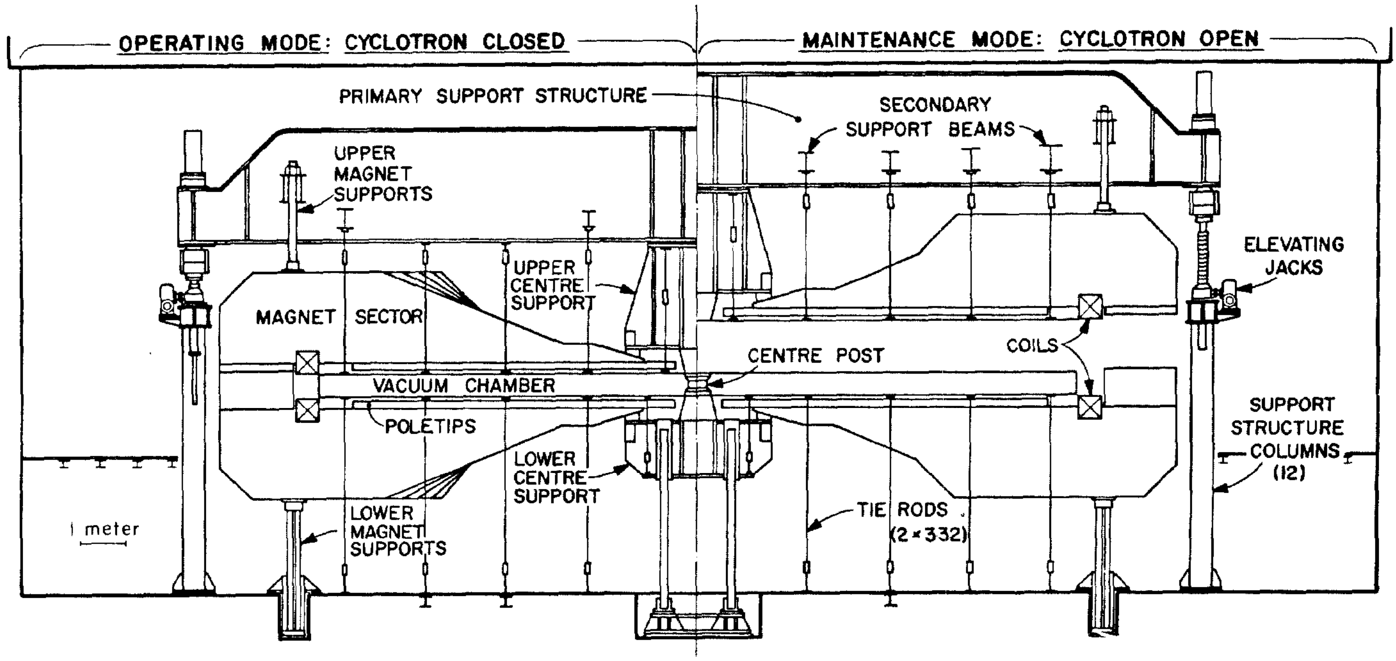

Figure 2
Cross section of the cyclotron

There are many holes through the pole plates and return yokes through which the tie rods pass, that connect the vacuum chamber lid and bottom to the support structure and to the floor. By spacing some of the 7.5 cm thick return yoke plates, 7.5 cm square holes were created in an inexpensive way. These holes allow enough room for the tie rods to move as much as 2 cm when the vacuum chamber expands during bake-out.

Each magnet sector was completely assembled at the manufacturers' to ensure that the exacting mechanical tolerances were met. It was then match-marked and broken down into its 22 component pieces. These were shipped in nine open rail cars installed with impact recorders to check the shipping instructions not to "hump" these cars. In Vancouver, delivery to the site was by truck.

The same nine cars and blocking were used for each shipment, which took 8 days, from Lauzon, Quebec to Vancouver. Including return of the empty cars, loading and unloading, a quick turn around time of one month per sector was achieved.

Magnet Coils

The six magnet sectors are excited by two common circular coils which are designed to give 800,000 Ampere Turns. Each coil has a cross section of 0.5 m x 0.5 m and a diameter of 18 m. Due to their size they could not be made as single units and transported to site for assembly. A conceptual design study[8] determined that the coils could be made in 60° segments and that the conductor material should be aluminum to minimise capital cost plus ten years power consumption cost. Subsequently it was established that the 60° segments should be joined together by welded inserts which would act as expansion joints and that only 15 turns would be used per coil to avoid a multitude of cooling connections in the restricted space available.

Each coil segment is made from 15 electrical conductivity grade extrusions each 2.95 cm x 47.75 cm laminated vertically. A conductor insulation wrap 0.44 mm thick was used and the conductors were further spaced by epoxy fibre-glass boards and sheet to give a conductor to conductor spacing of 3 mm. The epoxy was of the B staged Epoxy-Novalac type with NMA hardener. This assembly was cured to bond it together into a common mass. The segment was then protected by covering it with 6.5 mm aluminum plate epoxy bonded to the surface and joined at the corners by welded tabs. Conductor cooling is achieved by means of two parallel 12 mm diameter paths in each extrusion. The ends were plugged and welded and right angled connections were drilled. The ends of each conductor were cut to exacting tolerances and machined for welding with a J type groove. On site, each coil segment was installed and welded to the adjacent segment by means of V shaped connectors which also serve as flexible expansion joints.

In order to allow the upper coils to be elevated, a disconnect switch shown in figure 4 was installed. The switch uses 40 commercially available spring loaded contact fingers for each conductor. The mating surfaces are silver plated. The connecting part is guided into alignment by guide fingers which ensure initial alignment within 0.8 mm before entering the spring loaded contacts.

D.C. Power Supply

The power supply is rated at 110 V DC and 26,700 A. It is supplied at 12.5 kV, 3 phase and is composed of an isolating transformer, a primary regulating transformer, and a 12 phase delta-wye, delta-delta rectifier circuit. This is followed by a transistor pass bank which is the secondary regulator. The current is sensed by a water cooled shunt designed to give one volt output at full current. The current is maintained at 1 part in 10^5 over an eight hour period. The reference signal is derived from a digital source stable to 3 parts in 10^6. The variable transformer has proved to be unsatisfactory and will be replaced by an on-load tap changer capable of ± 15% voltage variation. When the supply is switched on, the magnet inductance limits the current build-up rate. This range is sufficient to cover voltage changes due to the coil temperature rise and uncertainty in the final current setting.

The buss connection to the power supply was made from the same conductor material as used for the coils. The assembly is braced to withstand short circuit currents and is protected by a sheet metal enclosure.

Vacuum Chamber

The 17.2 m diameter vacuum chamber is made of #316 stainless steel, chosen for its low permeability even after heating such as caused by welding. Chamber bottom and lid are made from plates, 250 cm x 620 cm x 2.2 cm thick, welded together using a full penetration submerged arc welding method.

The vertical side walls have a thin central section to reduce activation due to ions lost in the acceleration process. They are constructed as a ladder lying on its side with the 'side rails' made from 18 cm x 3.8 cm material and the 'rungs' from rectangular tubing, 11.5 cm x 3.8 cm x 0.3 cm wall. The latter is covered with a 0.125 cm thick sheet welded to the 'side rails'. This way the average wall thickness was reduced from 3.8 cm to 0.4 cm, while maintaining rigidity.

The location of the tie rod support points on the lid and bottom is determined by the maximum permissible deflection of the plate under vacuum, (0.125 cm). On this basis, 332 support points were required for a nominal 84 cm spacing.

The chamber lid seal consists of two polyurethane O-rings of rectangular cross-section. Since the radiation level of the seal will be about 50 Mrad/year, a seal life of at least 12 months at full operation is anticipated. Engineering studies to determine the feasibility of using a radiation proof remeltable metal seal, indicated that a very complicated and costly design would be required in order to cope with the thermal stresses during formation of the seal and bake-out of the chamber. Aluminum wire seals are used on all small flanges while the exit ports are sealed with Indium coated Inconel X C-rings.

Cooling coils are attached to all outside surfaces of the chamber by means of welded clips and soft solder. These coils are used for removal of the heat produced by the trim coils as well as for bringing the temperature of the chamber to 140°C in case bake-out of the

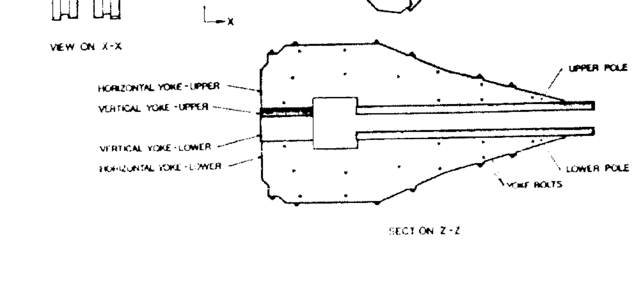

Figure 3
One of the six magnet sectors

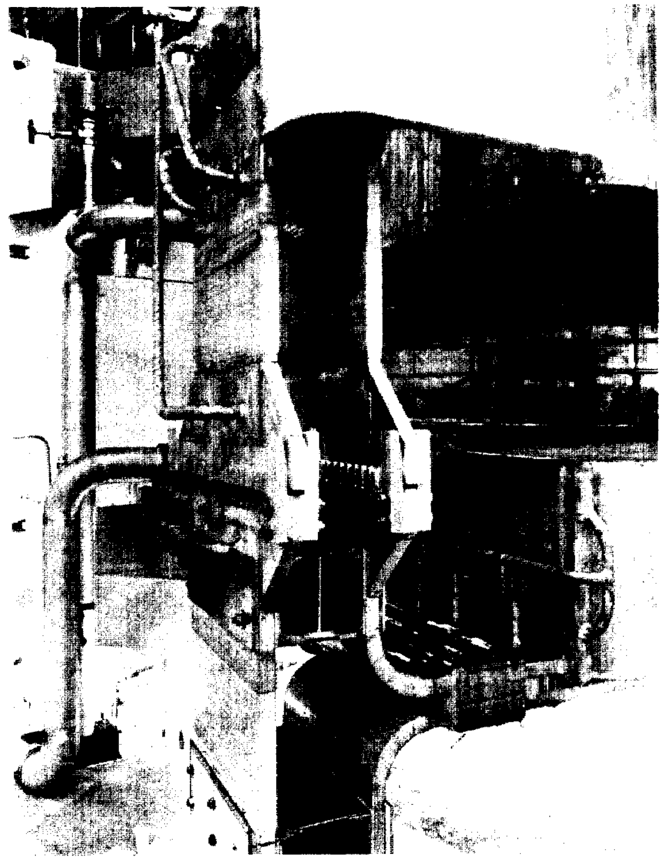

Figure 4
The disconnect between top and bottom coil

chamber is necessary. 55 sets of profile and 78 sets of harmonic coils are interspersed between the cooling coils mentioned above. These trim coils, made from magnesium-oxide insulated conductors are also secured to the outside of the chamber by means of tack welded clips. Cooling and trim coils as they appear on the chamber lid can be seen in figure 5.

Prior to installation the vacuum chamber was evacuated to 1.5×10^{-7} Torr. No leaks could be detected using a Helium leak detector with 10^{-8} Torr ℓ/sec sensitivity. The total leak rate, including outgassing, was 2×10^{-4} Torr ℓ/sec.

Support Structure and Elevating Jacks

During cyclotron operation the 2,500 metric ton atmospheric load is supported by the large 12 arm overhead structure and by means of numerous secondary beams and tie rods. An integral centre structure supports the tips of all 6 upper magnet halves, the dead weight and the magnetic load, and transmits this load, plus a portion of the atmospheric load, through a centre post in the vacuum chamber to a central column cluster below. The 12 outer ends of the overhead structure are supported by columns as shown in figures 1 and 2.

The lower support structure, illustrated in figures 2 and 6, consists of 6 central columns, plus 3 outer columns under each magnet sector. The system supports the cyclotron and accommodates normal expansion by column flexure while maintaining accurate component alignment. In the event of a moderate earthquake, column stiffnesses were chosen to permit relative motion between the cyclotron and its foundations with a reliable return to zero after such an experience.

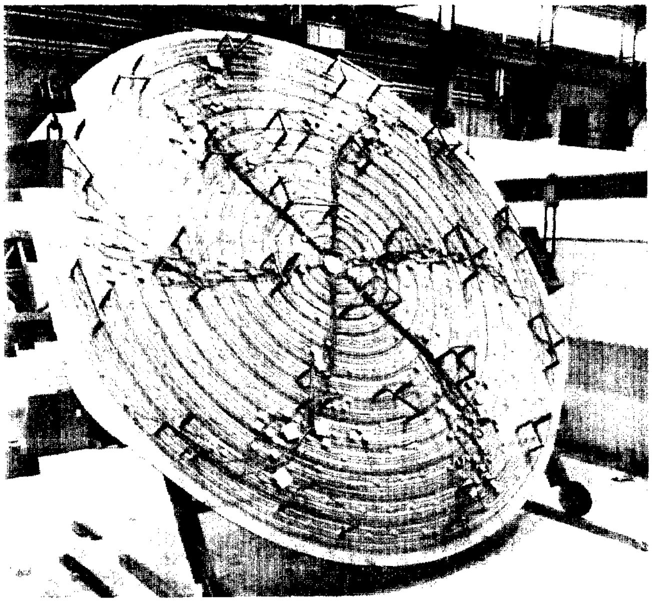

Figure 5
Trim and cooling coils on vacuum chamber bottom

This characteristic is supposed valid up to an earthquake strength of 0.1 g, a 1 in 100 year probability, but we have no experimental data as yet . . .

The 2,500 metric ton atmospheric load on the vacuum lid and the bottom is transferred via a total of 664 tie rods to the structure above and foundation below. Turn buckles for adjusting tie rod length are provided to level the tank and to permit accurate alignment of the resonators which are mounted on the tank inner surface.

With the cyclotron open, the overhead structure fully supports the upper magnet halves, about 2,000 metric tons, including chamber lid and magnet coils. Elevating is accomplished by means of 12 synchronized drive assemblies, each consisting of two 90 metric ton machine screw jacks, two 60:1 single worm gear speed reducers and a common 24 hp induction motor. Approximately 40 minutes are required for a full 1.22 m lift. The six sectors must be raised uniformly and the lifting points must be kept level within a tolerance of 1.55 mm, set by the stress level in the bolts joining the C and D blocks.

The angular location of the sectors is fixed by rigid guide columns fitted with spherical shell bearings. A 12.5 cm diameter spigot pin on each lower vertical yoke ensures that the upper and lower halves of the magnet cores are relocated within 0.25 mm.

The induction motors are synchronized by logic control. A 400 Hz synchro transducer is mounted at each of the twelve jacking points. The voltage output is proportional to the jack travel. The output from each station is compared with a common reference transducer and the difference voltages are used to control the drive motors in an on-off mode. Voltage comparators are set to give the following sequence of operation :

Equivalent distance between jack transducer voltage and reference voltage		Control action
limit		
a	0.125 mm	All motors shut off
b	0.25 mm	Drive brakes actuated
c	0.375 mm	Drive motor stopped
d	0.625 mm	Drive motor started
e	1.5 mm	All motors stopped

It is a feature of the system that the jack elevating speed is faster than the "reference" speed. During normal operation the jacking points are controlled within the limits d and c and operation has shown that the spread in travel is normally kept within 0.25 mm. The system is reversible and special logic is used to cross over the reference and signal voltages. It is necessary that the motors accelerate quickly because a one second delay is sufficient to shut down the whole system. The drives are automatically controlled except on an out of limit trip, when it is necessary to make a manual adjustment before the system can be started again.

Erection, Alignment and Deflection

The magnet cores, coils, vacuum chamber and support structure were erected in a double shift operation, which took 14 months. A detailed erection procedure had to be followed to save time and produce the required accuracy of alignment.

Both the magnet gap and the inner surface of the vacuum chamber are inaccessible for surveying when the cyclotron is in its closed condition. To achieve centring of the vacuum chamber, the inner surfaces were levelled under no load conditions and reference marks were scribed on the tie rods. Under vacuum, the tie rods were readjusted to bring the scribed marks into alignment.

The lid seal relies initially on an interference fit as shown in figure 7, aided eventually by the atmospheric load on the edge of the lid. There are no bolts. With the outer tie rods the lid periphery was adjusted to produce 4 - 8 mm interference on closing as designed. The lid is flexible enough to take this deflection. The seal proved to be vacuum-tight when closed the first time.

The support structure components and vacuum chamber tie rods have significant deflections during operating conditions compared to the non-operating modes. In order that the vacuum chamber is centred within the magnet gap and is flat over its inner surfaces when operating, these deflections were allowed for in the erection process.

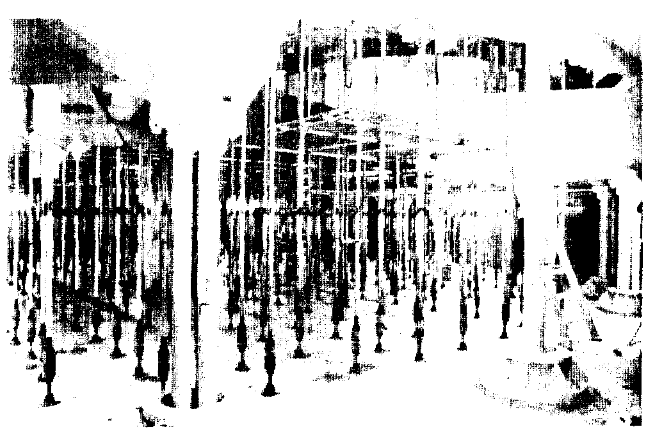

Figure 6
Lower support structure and tie rods

The most significant adjustment was to raise the centre of the magnet 2.5 mm relative to the outside with no vacuum load to compensate for the compression of centre supports under vacuum. The magnet gap varies by approximately 1 mm at the centre, due to the vacuum load. The major deflections are shown in figure 7. Changes in atmospheric pressure and temperature cause vertical deflections of the order of 0.25 mm. Similarly the addition of concrete shielding around the cyclotron will cause settlements of the order of 0.25 mm.

Cost

The table below lists the cost of the various major pieces of equipment discussed in this paper, along with the cost of installation and erection. The cost of buildings, services and shielding, shown for comparison, includes building space and some services for experimental facilities but shielding only for the cyclotron. Costs of the various remaining equipment, mostly built in-house, are shown in italics, as none of these are complete at this time and the figures shown are our best estimates to date. Associated costs, such as Consulting Engineers' and Inspection fees are also listed.

Development costs, such as beam dynamics studies, magnet model and centre region cyclotron model studies are not shown, and neither are the costs of commissioning and management. The table may therefore be used only as a useful guide to determine the replacement value of the facility.

Canadian k$	Contract plus extras	Owner supp'd equipmt	Total
Office, Lab & Workshop bldg	540		540
Excavation	181		181
Cyclotron foundtn & bldg substruc.	2,272		2,272
Main bldg steel superstructure	994		994
Cranes	209		209
Bldg finishes & machine services	1,388	492	1,880
Substation			410
Site improvements			50
Vault roof shielding			711
Remaining vault shielding			*359*
Cyclotron shielding			65
SUBTOTAL Bldgs, services & shielding			7,671
Site supervision and inspection			133
Engineers' fees			1,094
		Instln & erectn	
Magnet cores	3,176		
Magnet coils	594	887	6,229
Vacuum chamber	866		
Support and elevating structure	706		
Magnet power supply & busducts	283	24	307
Trim coils	63	90	261
Trim coil power supplies	108		
RF resonators			1,100
RF power supply + transmission	1,005	226	1,231
SUBTOTAL Major cyclotron contracts (a)			9,128
Site supervision and inspection			171
Engineers' fees			1,265
Vacuum pumping system			*337*
Ion source & injection system			*1,071*
Extraction and beam probes			*319*
Central control & safety system			*1,167*
Miscellaneous			*358*
SUBTOTAL "In-house" systems (b)			*3,247*
SUBTOTAL CYCLOTRON (a + b)			*12,375*

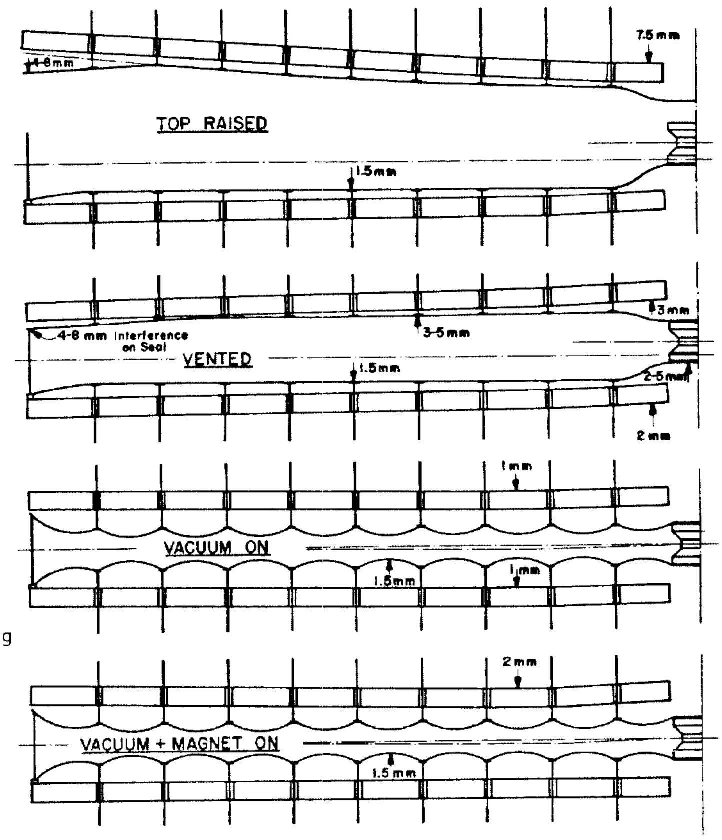

Figure 7
Vacuum chamber and pole plate deflections

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References

1 K.L. Erdman, R. Poirier, O.K. Fredriksson, J.F. Weldon and W.A. Grundman; Proc. Sixth Int. Cycl. Conf. (A.I.P. Conf. Proc. No. 9) 451 (1972).

2 E.W. Vogt and J.R. Richardson; I.E.E.E. Trans. Nucl. Sci. N.S.A. 13, 4, 262 (1962).

3 J.B. Warren; Proc. Fifth Int. Cycl. Conf. (Butterworths, London, 1971) 73.

4 J.B. Warren; I.E.E.E. Trans. Nucl. Sci. N.S. 18, 3, 272, (1971).

5 Appendix A; Proc. Sixth Int. Cycl. Conf. (A.I.P. Conf. Proc. No. 9) 451 (1972).

6 A.J. Otter, E.G. Auld, U. Kiesners and O.K. Fredriksson; Proc. Int. Conf. on Magnet Technology, Hamburg, 404, (1970).

7 TRIUMF Report, TRI-69-5, (1969).

8 TRIUMF Report, TRI-68-3, (1968).