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PROBLEMS AND POSSIBLE SOLUTIONS FOR THE TRIUMF PROJECT

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Summary

Some of the design problems peculiar to TRIUMF are discussed. These problems arise from the large size of the magnet (4000 tons) and low average magnetic field which in turn are required by the necessity of avoiding electric stripping of the H⁻ ions. Gas stripping of the ions requires the low operating pressure of 4 x 10^{-8} torr. Problems arising from the acceleration on the 5th harmonic of the ion frequency and their relation to the unusually tight tolerances on the position of the accelerating electrodes are discussed. Some preliminary results of the magnetic field measurements are presented.

Introduction

At the 1965 meeting of the National Accelerator Conference at Washington, D.C., I gave an invited paper¹ comparing a number of possible accelerators in their performance as meson factories. These types of accelerators included:

The Sector Focusing Cyclotron (Mc²) The Negative Ion Cyclotron The Ring Cyclotron The Linear Accelerator The Separated Orbit Cyclotron

At that time the only project which had received approval was the ring cyclotron (SIN) at Zürich, Switzerland. Since that time approval has been given to the construction of a linac (LAMPF) at Los Alamos and later for a negative ion cyclotron (TRIUMF) at Vancouver, Canada. Recently, preliminary approval has been given for the construction of a linac near Moscow. Other papers at this conference will discuss the current status of SIN and LAMPF so I will confine my discussion to TRIUMF, which is based on a sector-focusing cyclotron accelerating H⁻ ions to intermediate energies.

As a meson factory, TRIUMF will have several important advantages:

- a) The energy will be continuously variable from 160 to 520 MeV.
- c) Two or more beams can be simultaneously brought out of the cyclotron at differing energies.
- c) The macroscopic duty factor of the beams will be 100%.
- d) Under certain conditions it will be possible to extract a raw beam from the cyclotron with an energy resolution FWHM of 0.01%.
- e) The capital cost is much less and the operating cost is lower than a linac of comparable energy.

The last point has assumed increasing importance in recent years. The details of the analysis of the costs of the actual construction of TRIUMF are given in a puper at this conference². The analysis indicates that the cost of the cyclotron plus shielding plus building to house the whole facility (including the experimental halls) has been \$20,000,000. This does not include the beam lines or other experimental facilities or the cost of development, models, etc.

Having pointed out the advantages to be expected from TRLJMF, it is my primary purpose in this paper to discuss some of the problems which have arisen in the design and construction of the facility, which has been described elsewhere³ ".

The H⁻ ion is a somewhat fragile entity with its second electron bound only with 0.75 eV. In order to preserve it until the desired acceleration has been achieved, two conditions must be satisfied. First, the chance of even a distant collision with a gas atom must be small - i.e. in the case of TRIUMF the effective background pressure in the acceleration chamber must be kept down to $4\,\times\,10^{-8}$ torr in order to keep the beam loss from this cause to 2%. Second, the maximum magnetic field must be kept fairly low. A magnetic field of 5.8 kG at 500 MeV transforms to the rest frame of the H⁻ ion as an electric field of 2.02 MeV/cm according to the relation ε = 0.3 $\beta\gamma B.$ The tunnelling effect of this electric field results in a lifetime for the loss of the extra electron of 70 µsec. With a maximum magnetic field of 5.8 kG and six-fold symmetry, the requirement of net axial focusing of the ions requires an azimuthal variation of the field such that the average field at the 500 MeV radius is 4.6 kG. This in turn requires a final radius of 310 in. and results in a magnet weighing about 4000 tons. A look at Figure 1 will give an impression of the size of the magnet - it shows most of the TRIUMF staff on the six-fold lower sectors in January, 1972.

The Magnet

As we see from Figure 2, which was taken early in the spring of 1972, the magnet is really composed of six separate magnets with common excitation coils². The erection of the magnet was completed in October, 1972, delayed 3 to 4 months by labour difficulties. The design of the magnet is also shown in Figure 3 and we see that some of the radial variation of the magnetic field, required to compensate for the relativistic increase of mass, comes from the variation of the thickness of the yoke with radius. This results in a saving in steel but also reduces the magnet efficiency to approximately 35%.

In developing the design of the magnet a 1/20 scale model was constructed and tested and then a 1/10 scale model was made according to scale drawings of those used for the full scale magnet. The agreement between the results of the two models was considered to be satisfactory to an accuracy of 12. The 1/10 scale model was constructed of plates of AISI 1006 steel of the same chamical analysis as the full scale magnet and with thickness of plates, etc. scaled down accordingly. Field measurements on the full scale magnet were carried out for about 3 weeks until the transformers on the power supply (purchased in the USA) burned out. This occurred in January, and so we have not yet been able to complete our measurements.

A quite surprising difference was found between the 1/10 scale model and the full scale magnet. In order to reduce the difference as much as possible, the model was allowed to deflect 0.06 in. (corresponding to 0.6 in. in full scale) whereas the big magnet should actually not deflect by more than 0.02 in.

Under these conditions, the comparison is shown in Figure 4a and Figure 4b. Figure 4a shows the rather surprising difference between the model and the big magnet in the radial variation of the azimuthal average of the magnetic field at equivalent excitations (ampereturns). Figure 4b shows the comparison of the axial frequency obtained after isochronizing the average field.

^eTRILME is a facility spensored by the University of Alberta, Simon Fraser University, University of Victoria and University of British Columbia and supported by the Atomic Energy Control Board of Canada.

We did not have sufficient time to trace down the reason for this discrepancy before the power supply failed. However, a comparison of the results from the flux coils shown in Figure 3 on the big magnet vs. the results from the model, indicates that there is almost 25% more flux flowing in the yokes near the centre for the big magnet. This is consistent with the main discrepancy in the two fields — i.e. an average field at low radii too high by approximately 100 G. The other discrepancy is a desirable one - i.e. the required excitation on the big magnet is perhaps 10% less in power than for the model. One possible explanation which we are investigating is that the permeability of the steel on the big magnet is better than on the model, possibly because of the difference in the treatment of thick and thin rolled plates. Our measurements indicate that we will cure the problem by winding bucking coils at the six points marked B-B' and adding 150 tons of steel to the yoke. This is being done while waiting for replacement transformers for the power supply.

RF System

The RF power required for operation of the resonator system at 100 kV across the tips of the segments is 1800 kW, including 200 kW of beam power. Figure 5 shows the divider and phaser which accepts the power from the intermediate power amplifier (IPA) and provides the proper impedance and phase relationships between the various amplifiers⁵. Flexibility in the combining of the outputs of the four power amplifiers is achieved by the combiners shown in the figure. In the case of combiner #1, the output of PA1 and PA2 will add at port #4 but will cancel at port #3, so that normally the power lost in the waster load is zero. On the other hand, turning off one of the amplifiers will result in the power being split between the useful load and the waster load. The same situation holds for combiner #3 except that in this case the output of all four amplifiers is combined.

Efficient transmission of the output of two, three or four amplifiers can be achieved by changing the configuration of the system. The system passes through the multipactoring region of the resonators on frequency synthesizer drive and then changes to the self-oscillatory mode. This mode will be followed during the first few minutes of operation while the resonator temperatures are changing, but when the frequency begins to stabilize, the operator will switch back to the synthesizer drive. Small changes in the frequency of the resonators can be effected by moving tuning plungers in the roots of the resonators. The resonator system is made up of 80 segments of which 40 (20 above the median plane and 20 below) form one side of the dee gap and the other 40 form the other side. The segments resonate at $\lambda/4$ of the 5th harmonic (23.1 MHz) of the ion frequency and develop a voltage difference of 100 kV between the tips or 200 kV across the dee gap (400 keV energy gain per turn). Notice that the segments will also resonate at $3\lambda/4$ of the 15th harmonic of the ion frequency. Thus flat-topping of the voltage wave comes naturally in this type of accelerating electrode geometry.

After an initial period devoted to elimination of parasitics in the amplifiers, the RF amplifier system was tested at full power (1800 kW) into a resistive load. Also an assembly of half of the resonators (40) has been tested in air up to the maximum voltage before onset of sparking. For the test the length of untured transmission line (Figure 5) was even longer than it will be in the operating condition.

At 50kV on the resonator tips, the input power required was 130 kW so that the voltage on the 500 untuned line was 3.6 kV. The voltage on the $3/2\lambda$ line varied from 20 kV at the peak to 4.6 kV at the coupling loop. Note that only one coupling loop is used, and

yet the voltage difference along the 50 ft length of dee gap was less than $\pm 5\%$. It is very gratifying to note that no parasitics raised their ugly heads during this test, and this gives us considerable confidence for the future.

Our experience on the Central Region Cyclotron indicates that capacitive coupling between the resonator banks is sufficiently good so that only one coupling loop is required for the whole cyclotron. One problem has shown up on the test which was not unexpected. Since the "bot" arm of a resonator segment must be self-supporting over a distance of 10 ft ($\lambda/4$), it must be rigid, which means it is susceptible to mechanical vibration. In the test, it was found that the natural frequency of the resonators varied over ±1.2 kHz in the 23 MHz due to a mechanical vibration at the resonator tips of $\pm .005$ in. This modulation is too large in the self-excited mode because TRIUMF operates on the 5th harmonic of the ion frequency, and it is too large in the driven mode because the Q of the resonators is >6000 and too much power would be required while the system was off frequency. The vibration appears to be due to noise in the water cooling system. The solution to this problem is twofold. First, a surge tank will be placed in the water line and second, some individual damping units will be applied to the resonators. Under test, these units have reduced the vibration amplitude by a factor of 10 but they will only be installed if they prove to be necessary.

Vacuum System

Figure 6 shows the bottom of the vacuum chamber being turned over after the cooling coils and the trim coils were attached. Last year the chamber was pumped down readily to 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 main pumping system consisted of cryopanels cooled by He gas at 20°K and shielded by panels at 80°K. The tests indicated that the cryopanels begin to pump within 30 min and cool to their working temperature in less than 2 h. The mechanical pumps bring the pressure down to 10^{-4} torr in 90 min and so that means 4 h total to achieve a pressure of 10^{-7} torr. One concludes that it will be quite feasible to defrost the cryopanels and return to operating pressure within the period of an 8 n maintenance shift. It also appears quite feasible to achieve the desired operating pressure of 4×10^{-8} torr. The noble gases and hydrogen will be pumped by turbo-molecular pumps and sublimation pumps.

The Central Region Cyclotron

The CRC consists of a prototype ion source and axial injection system and a full scale model of the central region of the cyclotron, capable of accelerating ions to 3 MeV. The injection system is 80 ft long and employs 50 electrostatic quadrupoles and 6 electrostatic 45° bending electrodes. The resonators (dees) which are used are full scale prototypes. On the basis of the performance of the CRC the following predictions can be made with confidence about the TRIUMF cyclotron:

- a) The resonators will operate without sparking at 200 kV dee to dee and the frequency and voltage constancy will be adequate.
- b) With the aid of chopper and buncher, 12% of the ions leaving the ion source can be accelerated to 3 MeV. Theoretical studies and previous experience indicate that the losses from 3 MeV to 500 MeV will not be very large.
- c) Good beam cuality can be maintained through the processes of injection and initial acceleration.

In the process of obtaining these assurances, however, a number of interesting problems have been encountered and overcome⁶. One problem was the comparatively large effect of a radial component B_r of the average magnetic field B on the axial displacement ΔZ of the equilibrium orbit at radius r. This is analogous to the displacement of the centre of oscillation of the weight on the end of a spring by an additional force and so we can write

$$\frac{\Delta Z}{r} = \frac{B_r}{B} \cdot \frac{1}{v_z^2}$$

where ν_{Z} is the axial focusing frequency due to both electric and magnetic forces and $\frac{1}{\nu_{Z}^{2}}$ represents the spring constant.

Thus for a given B_r , the displacement ΔZ at a particular momentum rB is some 25 times as great in TRIUMF as in an ordinary cyclotron with the same ν_Z because B near the centre is \sim 3kG. Additional coils are being placed around the upper and lower centre support structures shown in Figure 3 in order to reduce B_r to a negligible value. Asymmetric excitation of some of the circular trim coils can also be used for this purpose.

Another $problem^7$ arises from possible misalignment of the resonators forming the dee gap. Because the axial magnetic focusing is relatively weak near the centre of the cyclotron, the ions are susceptible to the net axial impulse given by crossing the electric lens of an asymmetric dee gap. The experimental results are discussed in a paper 6 at this conference. Ten pairs of correction plates above and below the median plane [as shown by Figure 1 in 6] were used to compensate for arbitrary misalignments set up in the resonators. The effect of the correction plates on the beam is shown in Figure 7. The uncorrected beam is shown in (a) where we see that the misalignment has had the effect of giving an upward impulse to the ions at 0° phase (largest radius) while the phases where the electric focusing is stronger (smaller radii) have been kept nearer the median plane. The corrections effected by successive correcting plates are shown in (b) and (c).

The injection system of the CRC is equipped with a chopper which can select particular phases of the injected ions. Since the electric lens focusing forces are paramount at small radii, the axial extent of the beam varies dramatically with phase as shown in Figure 8 after $2\frac{1}{4}$ turns. The extension of the phase acceptance, which will be available when 3rd harmonic RF is added, has been discussed⁸.

As a result of the use of trim coils to reduce $B_{\rm r}$ and the use of the correcting plates to compensate for resonator misalignment, the transmission of the beam through the first 6 turns contained in the CRC approaches 100%, as shown in Figure 9. This figure also shows the separation of the successive turns as recorded on a thin differential probe.

Orbit Dynamics

The low magnetic field in TRIUMF and the fact that the RF frequency is placed on the 5th harmonic of the ion frequency results in higher sensitivity to some distortions in the acceleration process. For example, acceleration on the 5th harmonic requires a five times greater accuracy in isochronization both in the radial variation of the magnetic field and the constancy of the field and applied frequency. For this reason, 54 circular trim coils are being provided. Also, in certain critical regions, the 1st harmonic⁹ in the magnetic field must be kept below 0.2 G. For this purpose 13 sets of harmonic coils are provided. The radiallongitudinal coupling effect is also more critical in the low energy region of TRIUMF than is ordinarily the case.

The External Beam Lines

In the initial operation of TRIUMF, two simultaneous lines of differing and variable energies will be extracted as shown in Figure 10. The more intense beam of 100 μ A will be used for meson production. One pion channel will have energy variable from 50 to 250 MeV with π^+ intensities at the exit of the channel of 3 to 30 x 10⁷ π^+ /MeV-sec. The intensity of the π^- beam will be down by one order of magnitude. From another target further downstream, a stopping π and μ channel will be taken off at an angle of 135° from the target. The number of μ^- mesons stopping in the secondary target from backward decay will be 1 x 10⁷ μ^+ /sec gm/cm².

The other proton beam line from the cyclotron will proceed into the proton hall where it will be divided alternatively into two lines, one with a maximum current of 10 μA and the other rated only at 0.1 μA . The latter will be used with a magnetic spectrometer and for coincidence experiments, while the former will be used with a liquid deuterium target as a source of polarized and reasonably monoenergetic neutrons.

Conclusion

Despite the technical problems described here, the labour difficulties in the construction industry which caused a delay of 4 months, and the burning out of the transformers in the main magnet power supply, which is delaying us by 3 months, we hope to accelerate a beam very early in 1974. The facility will be operated at an average of 1% of final intensity for the first 6 months and at 10% of final intensity for the second 6 months of operation. The experimental program will get under way as soon as a good beam has been successfully accelerated.

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Fig. 1. LOWER SECTORS OF MAGNET - JANUARY, 1972



Fig. 2. MAGNET YOKES COMPLETE & VACUUM CHAMBER INSTALLED - MARCH, 1972



Fig. 3. SECTION OF MAGNET SHOWING SUPPORT STRUCTURE ϵ LOCATION OF FLUX COILS AA' AND BB'



Fig. 4a. DIFFERENCE BETWEEN THE MEASURED AVERAGE MAGNETIC FIELD AND THE ISOCHRONOUS FIELD FOR THE MODEL AND THE BIG MAGNET







W4006

8€

1

450 kW

PA #4 (2) 4CW250,000A

30 kW



THE EFFECT OF THE CORRECTION IN COMPENSATING FOR THE RESONATOR MISALIGNMENT Fig. 7.



VARIATION OF THE AXIAL EXTENT OF THE BEAM WITH THE PHASE OF THE IONS Fig. 8.



Fig. 9. THE SHAPE OF THE BEAM PROFILE AT DIFFERENT AZIMUTHS FROM THE DIFFERENTIAL PROBE. THE TOP CURVE SHOWS THE TOTAL TRANSMISSION



Fig. 10. THE TWO EXTERNAL BEAM LINES AND THE PLAN OF THEIR INITIAL INSTALLATION