Performance of H^-/D^- Cyclotron Using Internal Source

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Abstract

Over the past ten years, several models of H^-/D^- compact cyclotrons using internal source have been constructed and put into routine operation. This paper reports the performance of some of these machines. Detail description on individual cyclotron is omitted in order to give space for discussion on the design guideline and the criteria which warrant the high beam currents capability. It has been found that the design of the ion source and the central region (beam centering, axial focusing strength, puller voltage and RF phase acceptance, etc.) together with the design of the vacuum system determine the initial beam current capability. Subsequently, the magnet phase profile (energy gain per turn), magnet optics quality and the vacuum characteristics dictate the beam survival before extraction. Finally, the required beam quality after charge exchange in turn influences the design of the magnet structure. A thorough understanding on these coupled relationships between critical parameters is essential for the successful design of this type of cyclotron.

I. INTRODUCTION

Compact H^-/D^- cyclotrons in the 10-40 MeV range are widely used today for commercial isotope production and for PET scanning system in hospitals. Two types of these cyclotrons co-exist, namely, those that use an H^-/D^- cusp source with external injection and those that use an internal H^-/D^- source. At TRIUMF, both types are in operation at their peak performance, about 450 μA for the former and 240 μA for the latter. The H^-/D^- cyclotron using an internal source suffers from higher gas pressure thus higher stripping loss. The limited output from the internal source and the lower dee voltage used confine the beam current capability to about one-half of that obtainable from an external source system. However, these compact cyclotrons do find their usefulness in many medical facilities needing only 50-200 μA external beam currents. The compact internal source technology has been transferred through the authors of this report to several cyclotron manufacturers and about 30 H^- or H^-/D^- cyclotrons using such source are in service today worldwise. These models are: CP-42 series including H^-/D^- CP-45, 11 MeV H^- RDS, 10 MeV H^-/5 MeV D^- Cyclone 10/5, 18 MeV H^-/9 MeV D^- Cyclone 18/9 and the 16.5/8.5 H^-/D^- cyclotron. Detail description of these cyclotrons has been reported elsewhere.

II. PERFORMANCE

External Beam from Sample H^-/D^- Cyclotrons

Facility	Beam Energy (MeV)	Target Curr. (μA)	Max. Ext. Curr. (μA)
TRIUMF CP-42	42 H^-	200	240
	30 H^-	240	300
M.D. Anderson CP-42	42 H^-	100	200
Amersham CP-42	42 H^-	200	240
	30 H^-	200	300
UCLA CP-45	45 H^-	100	150
	23 D^-	50[p]	
CYCLONE 10/5	11 H^-	50	90
	5.5 D^-	40	80
CYCLONE 18/9	18 H^-	50[p]	(250)[a]
	9 D^-	50[p]	(160)[a]

p Projected
a at r = 10 cm

The external beam current available with various models are summarized in the table above. For CP-42 series 200 μA can be achieved throughout. Up to 300 μA has been obtained at 30 MeV at Amersham and at TRIUMF Applied Program facilities. Fig. 1 shows a section of recording of such event. Fig. 2 shows the recording of the endurance test for a CP-42, performed at Berkeley TCC for 100 hours uninterrupted extraction of 200 μA at about 38 MeV. Three attempts were made resulting a total of 300 hours of running such high beam power. Except for initial tuning at the begining of the test, the entire operation was uneventful. As can be seen from Fig. 2 that the arc current and vacuum were unchanged for the entire test. The RF amplifier was finetuned by operator about once per hour. Typical crowbar rate was about 2 per hour. As for the Cyclone 10/5 , the routine beam requirement is only 50 μA. The maximum achievable amounts to about twice as high, so the routine requirements are easily met.

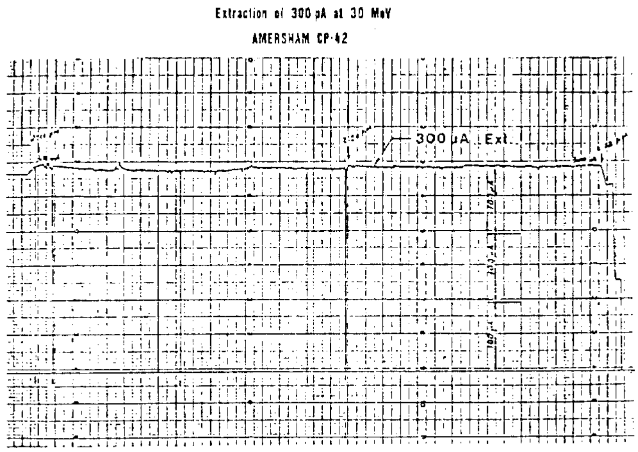

Fig. 1. Record showing the extraction of 300 μA at 30 MeV from the Amersham CP-42.

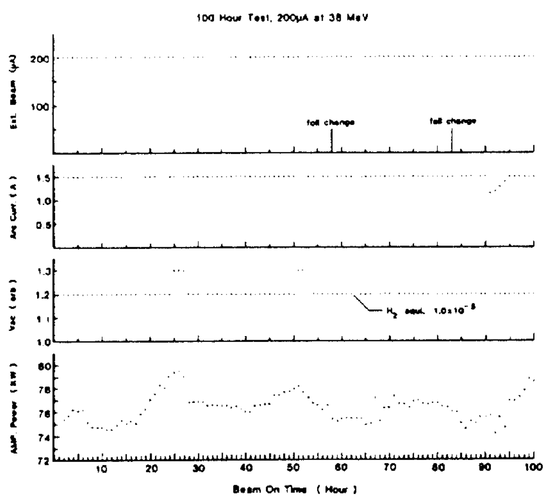

Fig. 2. Time dependence of cyclotron parameters over a period of 100 hours during high current extraction.

III. PHASE WIDTH and MAGNETIC FIELD

Since the extraction efficiency is always 100%, the emphasis of H^- cyclotron design is actually on the internal beam capability. As we shall point out later, within the present internal source technology the H^-/D^- ion density per unit RF phase is low in comparison with the corresponding proton beam. Ehlers [1] stated that the H^- ion density is emission limited, and that the intensity remains constant above 8 kV DC. This means that for cyclotron RF extraction the H^- beam current will be linearly proportional to the phase width achievable. One faces the problem of how to optimize the phase width for the initial acceleration and how to maintain it until extraction.

For the first requirement, several contributing techniques can be utilized:

–Make the threshold dee voltage lower but operate the cyclotron at higher voltage if possible. Beam centering must be optimized.

–Minimize axial phase selection by using phase lagging and a proper cone field.

–Optimize the axial opening in the central region and make use of optimal electric focusing.

–Precision alignment of dee structure and ion source with respect to the magnet median plane. Also precision alignment of magnetic field symmetry about the geometrical mid-plane.

As for the second requirement, a very flat phase profile corresponding to a conservative energy gain per turn should be obtained. The designed or actually attainable energy gain per turn should be higher than the value used for the profile calculations. In addition, the best achievable vacuum should be provided. Fig. 3 shows the phase history in sinϕ for three CP-42 cyclotrons.

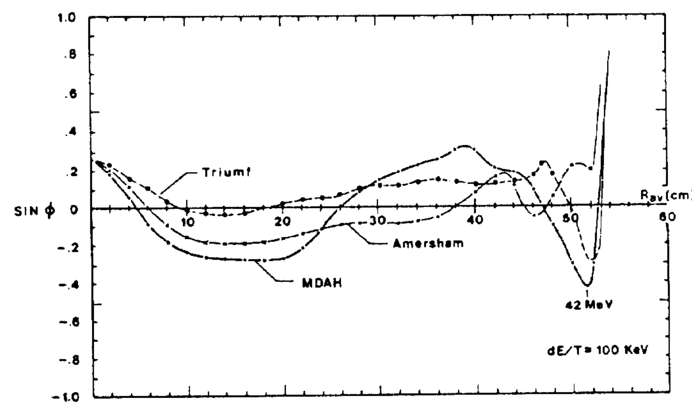

Fig. 3. Comparison of phase profiles in sinϕ between 3 CP-42 cyclotrons.

As can be seen in Fig. 3 that the magnet of Amersham CP-42 has the best field among these three whereas the one of M.D. Anderson the worst. Test records showed that extraction of 200 μA at 42 MeV was relatively easy with the Amersham CP-42. No phase loss was observed when the matching RF frequency was found and used. In contrast, the same extraction test at MDAH was quite difficult. Although the extracted beam currents met the specification, the dee voltage and arc current required were much higher than those used for other CP-42s. Due to some difficulty in the dee supporting insulators, users of these cyclotrons reduce the dee voltage subtantially making the energy gain per turn down to about 70-80 kV. The actual phase profiles will be much inferior to those shown in Fig. 3.

The charateristics of a resonance curve, I(beam) vs. I(mag), has been exploited to measure the phase width at low energy. An example is shown in Fig. 4(a). The flat top region of the bell shape curve (solid) corresponds to the excursion of sinϕ of the beam bunch within the ± 1 boundary, while the fall-off slope represents the excursion out of the boundary. Since the total $\Delta\sin\phi$ is equal to 2, wider the width of the fall-off narrower the flat top. The $\Delta\sin\phi$ the beam occupies is larger. Furthermore, since $\Delta\sin\phi$ is invariant for an ideal phase profile, the ratio of fall-off width to flat top width should be the same for all radii.

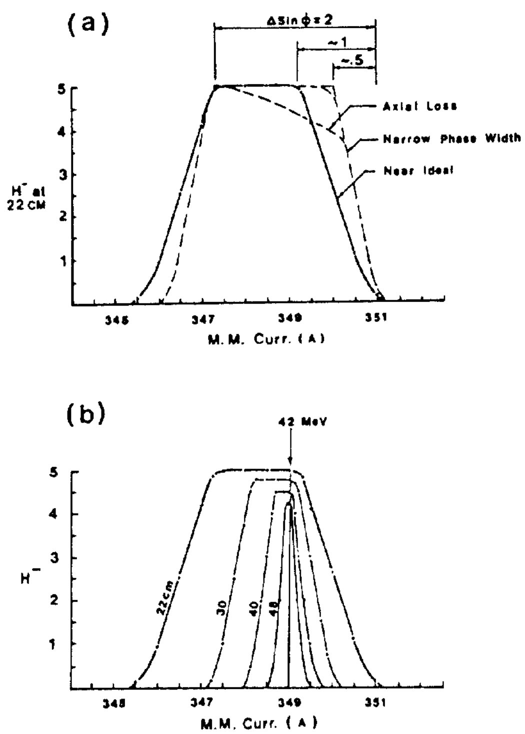

Fig. 4. Use of resonance curves for (a) central region and (b) phase profile optimization.

The quality of the resonance curve reflects the quality of the axial focusing at the initial stage of acceleration. A sloped top (dashed) indicates that axial loss occurs as the beam getting more phase advanced and being axially selected. The near ideal curve was obtained after various efforts to improve the axial focusing strength has been made following the guideline described earlier. The width of $\Delta\sin\phi$ occupied by the beam was also optimized to about one. The inferred phase width was about 60°.

A family of resonance curves at various radii can be plotted against a fixed RF frequency as shown in Fig. 4(b). This plot can be used to identify the extend of phase loss, gas stripping loss and axial loss. A number of these plots against a banwidth of RF frequencies using an optimal dee voltage should be obtained in order to select an operating frequency which gives the best phase profile available.

IV. ION SOURCE and CENTRAL REGION

The performance of the internal H^-/D^- source has been reported at the 1992 cyclotron conference. The optimum ion output and gas efficiency have been obtained by source parameter optimization coupled with the central region optimization described in the last section. The coupled relationship between the source and the central region is also greatly improved. For example, four dimensional position adjustments optimize the initial orbit, the ion transit time from the source slit to the puller. This feature can also reduce the space-charge effect, minimize the initial vertical oscillation amplitude. The surface betweem the source and puller was shaped to provide axial electric focusing for the low energy ions during the first crossing. The careful surface treatment allowed a higher RF field between the gap without excessive flashovers. The sum of all these efforts provided us the beam capability of 600 μA H^- at r=15 cm (3.5 MeV). Routinely available beam currents has been about 450-500 μA with a lower dee voltage at a less than ideal condition.

V. SUMMARY

The capability of extracting 200-300 μA of proton beam from a compact H^-/D^- cyclotron has been demonstrated. However, the highest potential for D^- beam was not explored except at low radius. The routinely available D^- currents at present is 50-100 μA from a somewhat compromised system. Due to limited space for writing, the importance of gas loading, cyclotron tank pressure and gas stripping loss were not discussed here. Reducing the gas loading into the acceleration chamber remains the greatest challenge for the internal H^-/D^- source designers, but it also possesses the highest potential for improvement. In summary, the reported results were obtained with cyclotrons lacking either magnet profile perfection, or optimal dee voltage capability. It is possible that 450-500 μA of H^- can be accelerated to higher energy, say 30-40 MeV, with an internal source cyclotron if all deficiencies are removed, as this has been done in the case of external H^-/D^- source cyclotrons.

VI. ACKNOWLEDGEMENT

The authors of this paper wish to thank Drs. M. Finlan and D. Lewis of Amersham International; J. Burgerjon, R. van den Elzen and J. Lofvendahl of TRIUMF applied Program; Dr. A. Zermeno and C. Brown of M.D. Anderson Hospital for their efforts and assistance in performing the tests for CP-42. Special thanks go to Drs. Y Jungen and S. Laycock, H. Marie and M. Abs of IBA; Dr. S. Lindback and J. Bergstrom of Scanditronic for adopting the internal source techniques and their invitation to join the efforts in making their cyclotrons work. The teaching of H^- acceleration from TRIUMF; the encouragement from Prof. Vogt, Drs. G. Dutto and P. Schmor of TRIUMF/UBC are greatly appreciated.

VII. REFERENCES

[1] Ehlers, K.W., " Design consideration for high intensity nagetive ion source", Nuc. Instr. and Method, 32, (1965) p.811.