Extraction performance of the Harwell variable energy cyclotron

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ABSTRACT

Over 50 different beams ranging from protons to neon ions with 10 to 1 energy coverage have now been developed to meet the demand of users of the Harwell V.E.C. With such a wide spectrum of beams there are naturally variations in their orbital characteristics which in turn are reflected in the extraction performance. For most beams the extraction efficiency is greater than 50%; exceptions are some of the harmonic beams where only about 30% has been obtained. It should be pointed out that these figures apply for a simple puller and ion source geometry with no defining slits and a variable orbit operation.

Substantial improvements in extraction are obtained by using a defining slit in the central region. For example, 70% efficiency can be achieved routinely on a large number of beams, whilst 80 to 90% has been measured with very careful tuning up of machine parameters.

The septum part of the extractor consists of a readily detachable tungsten foil of thickness 0·5 mm with a V-shaped slot to assist power dissipation. The maximum power dissipation is estimated at about 2 kW. Over the past 12 months during which there has been extensive running with powers of about 1 kW, it has not been necessary to replace the septum.

The maximum voltage gradient on the extractor channel is about 120 kV/cm and although difficulty was experienced in voltage holding during the first year of operation, this has now been overcome by hard chromium plating of the copper electrodes.

1. INTRODUCTION

Extraction from the Harwell Variable Energy Cyclotron is by means of precessional extraction and an electrostatic deflector. The extraction system has to handle a very wide range of beam conditions (see Table 1) including harmonic modes of operation and consequently there are variations in extractor performance. Various factors which influence extraction will now be discussed.

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Table 1. TABLE OF EXTRACTED BEAMS AVAILABLE UP TO JUNE, 1969

Particle	*Approx. energy* (MeV) *at extraction radius*			*Notes*
H^+	7		27	
	10		35	
	13		40	Currents limited by permissible
	17		43	dissipation on extractor (~1·5 kW)
	20		46	
	24		48	
			53	
H_2^+		5		Third harmonic
		12·5		Third harmonic
D^+	15		30	
	17·5		32·5	
	20		36	
	22·5		40	
	27		42	
$^3He^{2+}$		28		
		39		
		53		
		73		
		83		
$^4He^{2+}$		25		Third Harmonic
	30		60	
	35		65	
	40		72	
	45		80	
	52		84	
	53			
$^4He^+$		6		Third Harmonic
		7·2		Third Harmonic
		7·5		Third Harmonic
		8		Third Harmonic
		9·3		Third Harmonic
		11		Third Harmonic
		12·1		Third Harmonic
C^{2+}		22		Third Harmonic
C^{3+}		24		Third Harmonic
C^{4+}		88		
		118		5 μA extracted
C^{5+}		175		0·08 μA extracted
N^+		3		Seventh Harmonic
N^{2+}		7		Fifth Harmonic
N^{4+}		98		
N^{5+}		150		2 μA extracted
O^{4+}		32		Third Harmonic (~10 μA extracted)
$^{20}Ne^{3+}$		20		Third Harmonic (~10 μA extracted)
		38		
$^{20}Ne^{4+}$		65		Third Harmonic (7·5 μA extracted)

2. DESCRIPTION OF THE EXTRACTION SYSTEM

2.1 *Electrostatic deflector*

A full description of the beam deflection system for the V.E.C. has been given by Randle.[1] The system consists essentially of a two channel electrostatic deflector of 108° total length. The first channel 48° long has an earthed electrode of tungsten with provision for readily removing the first 125 mm section (the septum). The high voltage electrode is made of water cooled copper. In the second channel both electrodes are made of copper with water cooling and are curved vertically to give a horizontally focusing electric field.

2.2 *Magnetic channel*

Even with focusing in the second deflector channel the beam dispersion is large, and studies were made during the design stage of various horizontal focusing devices, the final choice being a magnetic channel. Initial commissioning was carried out without the channel however and as subsequent operation has shown that for a majority of beams the loss between the extractor and the main beam transport system does not exceed 25%, permanent installation of the channel has not been considered urgent.

When the channel was tested it was found to give more than sufficient reduction in beam width, but to require moving radially for different beams. It has been modified to give less focusing and operation at a fixed position, and will be tested when convenient.

3. EXTRACTION EFFICIENCY

3.1 *General discussion*

Although the theoretical analysis of the deflector carried out by Mayhook[2] was based on the condition of a beam entering the deflector with completely incoherent radial oscillations, it soon became evident in practice that precessional extraction by means of a controlled amount of coherent radial oscillation gave a higher extraction efficiency. A detailed study comparing theoretical predictions with practical results has not been carried out, but by examining the performance over widely different conditions some useful observations can be made.

In resonant precessional extraction, that is, extraction after the $\nu_r = 1$ resonance, the internal beam is on centre right up to the extraction region and beam quality is maintained as there is no increase in incoherent radial oscillations from precessional mixing. Another advantage of this mode of extraction is that precession is only required over a fraction of a cycle and therefore is not ultra sensitive to the applied first harmonic or the dee voltage, and gives rise to stable extracted beams. A problem which does arise, however, is the production of the optimum magnetic field fall off in the extraction region, which satisfies simultaneously both the ν_r and phase slip requirements.

An alternative to extraction after the $\nu_r = 1$ resonance is to extract before the resonance. In this case the coherent radial oscillation required for precessional extraction is best produced by a first harmonic operative over the last quarter of the radius. To start the radial oscillations at the centre has the disadvantage of increased sensitivity of extraction to machine parameters.

3.2 *Results for the V.E.C.*

Although the aim has been to use the $\nu_r < 1$ mode of extraction whenever possible, for some beams successful extraction is more readily achieved with the $\nu_r > 1$ mode.

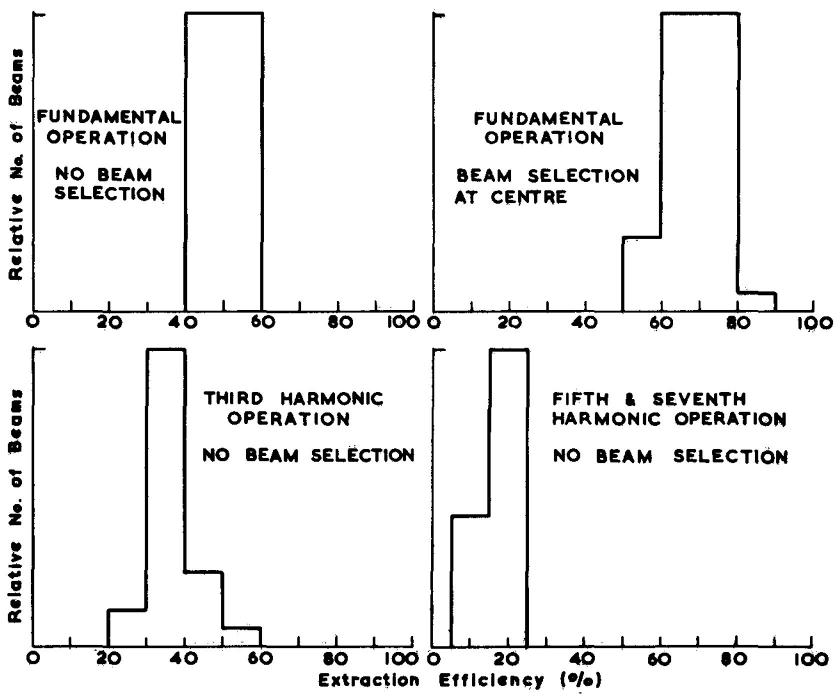

Fig. 1. Extraction efficiency distributions for various operating modes

Fig. 1 shows the extraction efficiencies obtained for various conditions. It will be observed that the efficiency for fundamental operation is on the average about 50%, third harmonic operation 40%, and for the fifth and seventh harmonics much lower, 20% and 10% respectively. Although there is apparently on the average a fall in extraction efficiency even for third harmonic, it should however be noticed that an efficiency of greater than 50% has been obtained on two third harmonic beams and one would therefore conclude that there is no significant deterioration in beam quality for third harmonic operation. However when we consider fifth and seventh harmonic beams, there is undoubtedly a considerable deterioration in the internal beam quality (oscillation amplitudes of about 25 mm have been observed) and therefore poor extraction efficiency is to be expected. Fig. 2 shows some typical plots of the current on a probe as a function of radius.

The sudden fall off of current at around 750 mm corresponds to the extractor intercepting the beam. The sharpness of this interception is a good

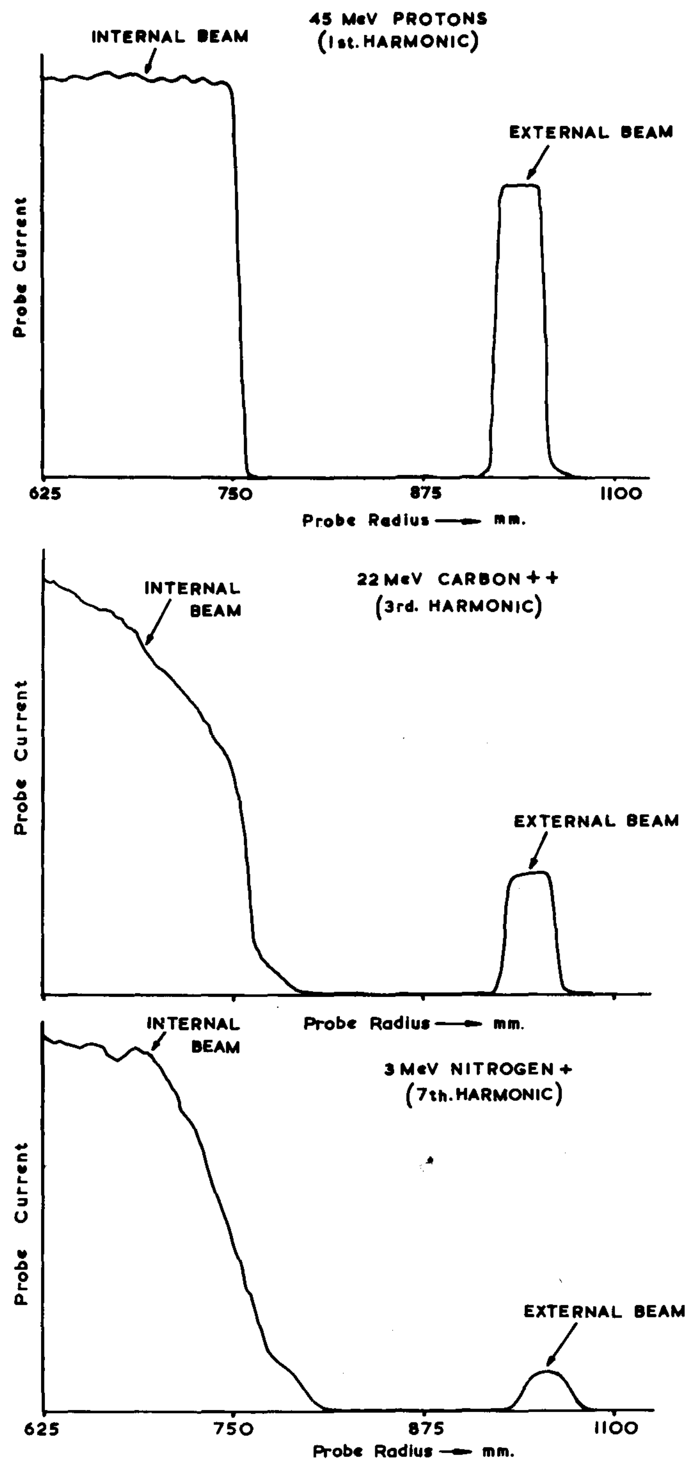

Fig. 2. Typical current vs radius plots (probe has a radial extent of 25 mm)

measure of the quality of the beam entering the deflector and the resultant extraction efficiency. The contrast between the first and the seventh harmonic beams is very marked.

3.3 *Improvements in extraction efficiency*

Marked improvement in the extraction efficiency of most fundamental beams can be obtained by beam selection using a single slit near the centre. The intensity is reduced to between one-third and one-tenth depending on which turn is limited by the slit. In practice that slit position is chosen which gives the maximum extraction efficiency. The improvement obtained is shown in the top right-hand histogram of Fig. 1. Extraction efficiency of 70% can be routinely achieved, whilst with careful tune-up 90% has been measured. The beam selection by the slit is two fold, firstly, the phase width is reduced by a factor of approximately two and secondly, a certain range of radial oscillations is rejected.

In Fig. 3, some typical shadow plots are given for the two conditions, with and without beam selection. From these plots oscillation amplitudes have been determined as described by Bennett *et al.*[3] The selective effect of the slit is demonstrated, even though in the case chosen, an off-centre component of oscillation was used.

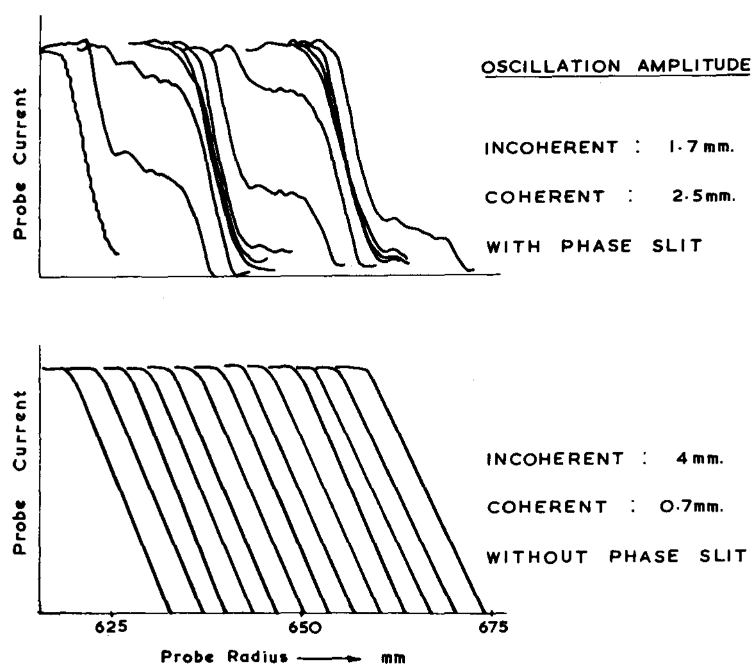

Fig. 3. Shadow plots for the determination of oscillation amplitudes (taken at 3 mm radial intervals)

4. FURTHER PERFORMANCE FACTORS

4.1 *Power capacity of the septum*

Up to the present no modifications have been made to the septum to improve its power capacity, which is estimated at between 1·5 and 2 kW. As discussed in the previous section, improvements in the extraction efficiency have been achieved with the result that the present limit in intensity of the external beam (e.g. 40 μA for 50 MeV protons) set by the septum exceeds the intensity required in most experiments.

Although there has been very little operational experience at the higher powers of 1·5 to 2 kW, over the past 18 months there has been regular use with powers of about 1 kW and under these conditions there has not been a single septum failure.

4.2 *Voltage Holding*

During the first year of running much trouble was experienced through the deterioration with time of the voltage holding of the extractor channels. It was observed that good voltage holding which could be restored by mechanical cleaning of the electrodes, would deteriorate with cyclotron running at such a rate that after about three months, cleaning would again be necessary to restore the top end performance (120 kV/cm). Cleaning by electrical discharge or ion bombardment was not successful.

As a positive attempt to lessen the problem of deterioration, chromium plating of the electrodes was undertaken. Operation over the 18 months since this change was made has shown little, if any, deterioration in voltage holding.

4.3 *Vertical steering in the second channel*

It was mentioned in section 2 that the second channel has curved electrodes to give radial focusing. The resulting vertical defocusing will cause vertical steering of an off axis beam, with its consequent problems. To minimise the steering it is therefore important that the second channel be positioned accurately (better than 0·5 mm) with respect to the median plane.

5. CONCLUSION

The results obtained on the V.E.C. show that versatility and good extraction performance can be obtained simultaneously and furthermore, that the latter can be markedly improved with little additional complexity.

The authors wish to acknowledge the careful work of the operating team during both beam development and routine operation of the cyclotron.

DISCUSSION

Speaker addressed: E. J. Jones (Harwell)

Question by J. A. Martin (ORNL): Would you please state the size of the radial aperture of the slit used on the 1st half-turn at the centre of the VEC?
Answer: The radial aperture is 0·080 in.

REFERENCES

1. Randle, T. C., N.I.R.L./R/86, S.R.C. Rutherford Laboratory, England (1965)
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3. Bennett, J. R. J., Coupland, J. H., Jones, E. J., Lawson, J. D., Mayhook, A. R., Randle, T. C. and Trew, D. H., RHEL/R/135, S.R.C., Rutherford Laboratory, England (1966)