Harmonic operation of the Harwell variable energy cyclotron

E. J. Jones and K. J. Howard
A.E.R.E., Harwell, England

Presented by K. J. Howard

ABSTRACT

The currents accelerated on different harmonic modes have been compared and it was found that operation on the seventh harmonic is possible with the existing open centre geometry of the Harwell Variable Energy Cyclotron. Using the measured threshold voltage for acceleration the effective gap factor for the first gap crossing has been calculated and compared with theory.

1. INTRODUCTION

To cover the wide ranges of energy and ion required by users of the Harwell Variable Energy Cyclotron (V.E.C.), operation on modes higher than the fundamental is necessary. A demonstration of the various regimes of harmonic operation is given in Fig. 1, which is an abridged version of a nomograph used on the V.E.C. Harmonic operation has associated with it a number of problems, the most serious of which is the fact that when the accelerating voltage is a high harmonic of the fundamental, the transit time of the ion across the accelerating gap (at small radii) becomes comparable with the period. This results in a much reduced energy gain (small gap factor) or even a condition where there is no acceleration (gap factor <0). For the V.E.C. the gap factor problem is not significant until the fifth harmonic mode, and therefore third harmonic beams such as low energy helium, 38 MeV Ne^{3+} and 22 MeV C^{2+} ions, have been in regular use for some time. Some future beams however will entail operation on fifth, seventh or higher harmonics, and in view of this a short study has been made of the feasibility of such operation, and this will now be described.

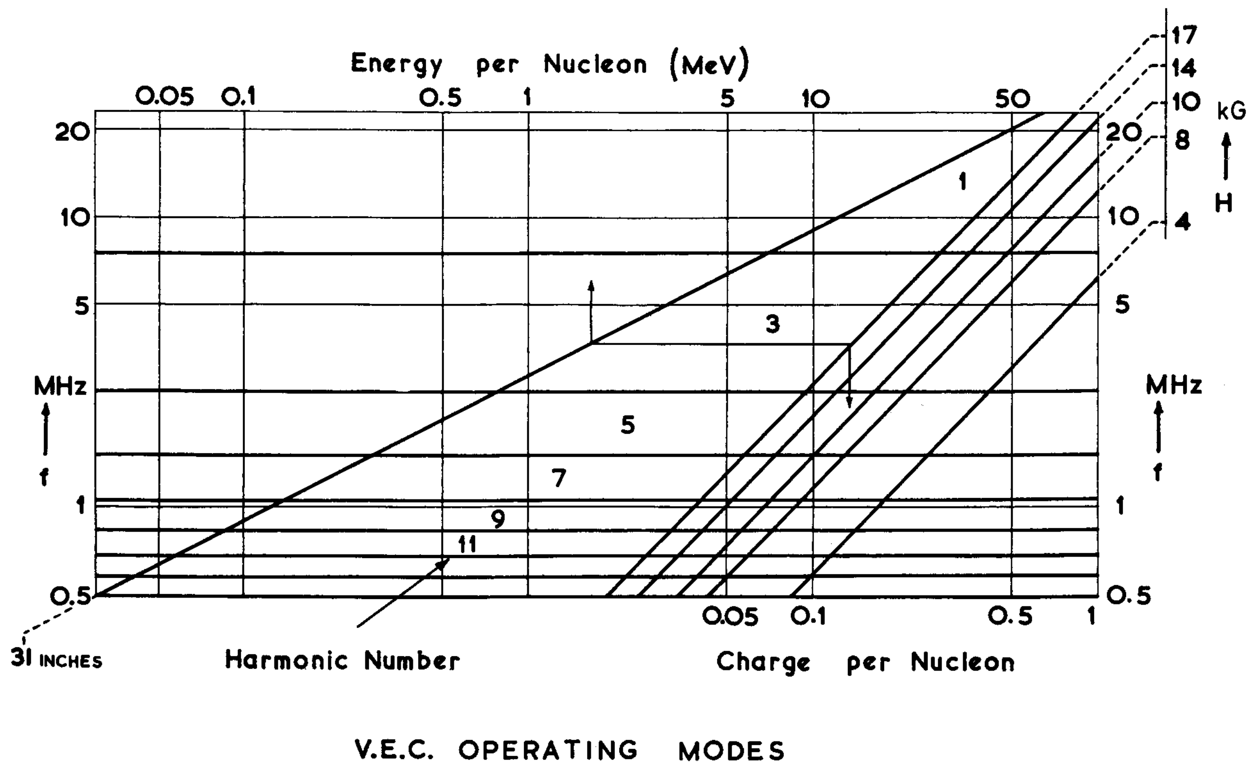


Fig. 1. The ion rotation frequency and mean magnetic field at a given radius are related to the energy and charge per nucleon by a horizontal tie line, e.g. for an energy of 1·5 MeV per nucleon at a radius of 31 in (787·4 mm) and 0·15 charges per nucleon the rotation frequency will be 3·4 MHz with a mean magnetic field of 15 kG

2. EXPERIMENTAL STUDIES OF HARMONIC OPERATION

2.1. *Preliminary measurements on fifth and seventh harmonic modes*

Some measurements were made two years ago on the acceleration of doubly and singly charged nitrogen ions on the fifth and seventh harmonics respectively. It was found that with the dee voltage significantly higher than a certain threshold value, beams of useful intensity (of the order of μA) could be accelerated to full radius in each case. The intensity was critically dependent on the settings of the 'inner' orbit coil currents, a feature which is not experienced on fundamental operation. These two effects are, of course, direct results of the reduced gap factors and will be discussed shortly. It is sufficient at this stage to observe that despite the relatively open accelerating structure of the V.E.C. (see Fig. 2), operation up to the seventh harmonic is quite practicable.

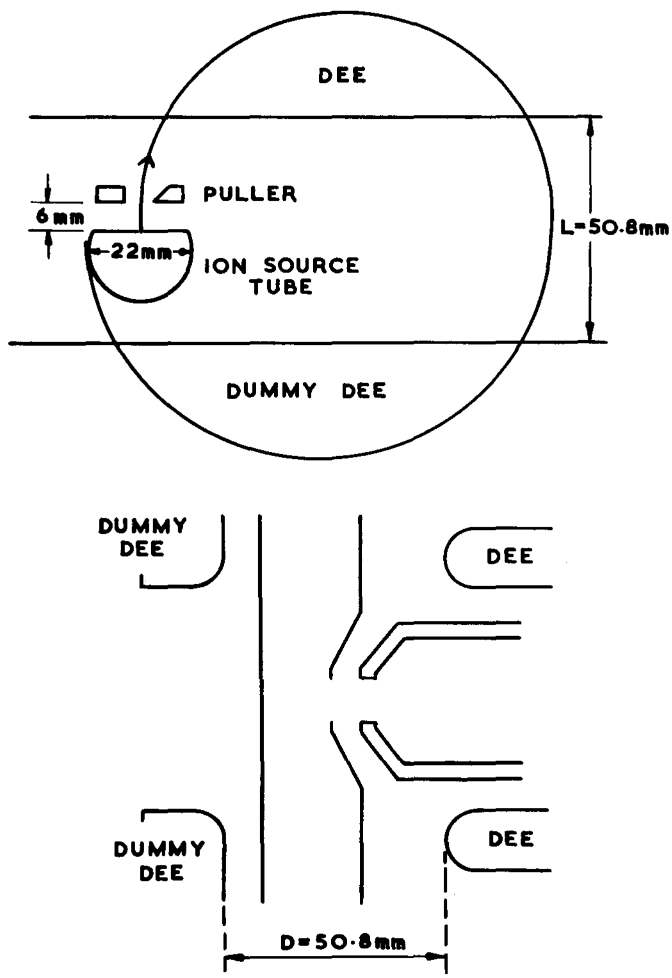


Fig. 2. V.E.C. centre geometry

2.2. *Direct comparison of various harmonic modes*

A useful measure of the feasibility of harmonic operation is the relative fraction of the beam accepted for harmonic acceleration compared with say, fundamental operation. It must, however, be borne in mind that for a given dee voltage, as the harmonic mode of operation is increased (because of decreasing charge to mass ratio N/A) the radius of the first turn also increases, which results in a compensating effect on the gap factor. In order, therefore, to obtain realistic lower limits for the relative efficiencies of the harmonic modes, comparisons have to be made at the appropriate crossover conditions (N/A the same for both modes). For example, to compare third and fifth harmonics, it is necessary in the case of the V.E.C. to take an ion beam whose maximum energy is 7·5 MeV ($\times N$) where N is the charge state of the ion. Similarly, first and third, fifth and seventh harmonics can be compared using beams of maximum energy $24N$ MeV and $5N$ MeV respectively.

The experimental procedure adopted was roughly as follows. Taking the comparison of third and fifth harmonic operation as an example, the first step was to establish stable conditions (especially with respect to the ion source) for a 7·5 MeV He^{+} beam with a radio frequency of 11·52 MHz, corresponding to a third harmonic. Measurements were then made of beam current for different dee voltages. On completion the frequency was changed to 19·21 MHz corresponding to the fifth harmonic, and the beam current measurements repeated.

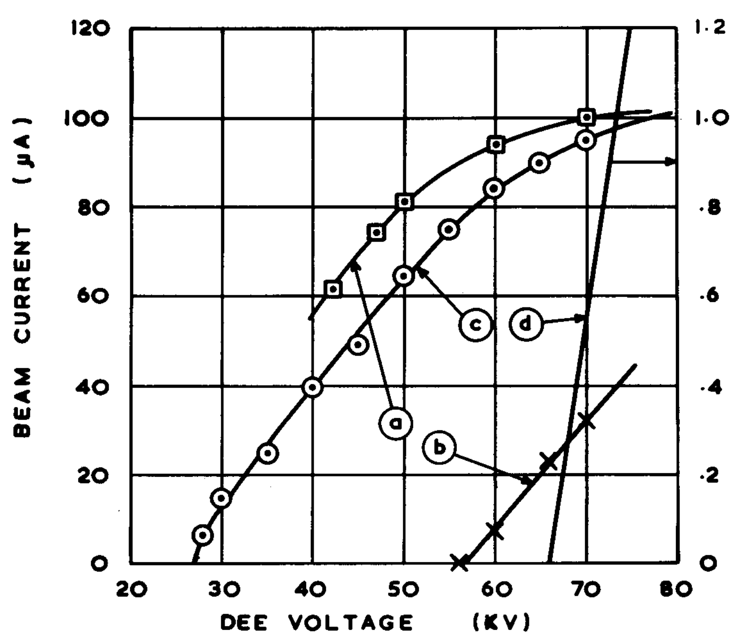


Fig. 3. Beam current vs dee voltage for various harmonic modes
Curves (a) Fundamental, (b) Third harmonic — 14 MeV per unit charge maximum energy
(c) Third harmonic, (d) Fifth harmonic — 7·5 MeV per unit charge maximum energy

Due to a shortage of time, direct comparison of fifth and seventh harmonic operation was not possible at this stage, and therefore, in order to derive a figure for comparison it has been necessary to use earlier measurements, one on a krypton beam (which had the appropriate energy) and the other on the 3 MeV nitrogen beam already reported in section 2·1.

3. DISCUSSION OF MEASUREMENTS

3.1. *Relative efficiencies of first, third, fifth and seventh harmonic acceleration*

From the measurements given in Fig. 3, Table 1 has been compiled giving the lower limits to the expected fraction of beam accelerated for various harmonics, for a fixed dee voltage of 75 kV. The figure of 2×10^{-3} for the seventh harmonic is probably uncertain by a factor of two or three.

Table 1

Harmonic mode	1	3	5	7
Fraction of current accepted	1	0·4	0·01	0·002

3.2. *Estimates of gap factors for threshold measurements*

Taking the centre geometry of the V.E.C. given in Fig. 2, the following expression can be derived, relating the threshold dee voltage V_0 to the gap factors on the first turn.

$$g_1 = \sqrt{\left(\frac{g_0\, E}{e\, V_0}\right)} \cdot \frac{r_s}{r_{\max}}$$

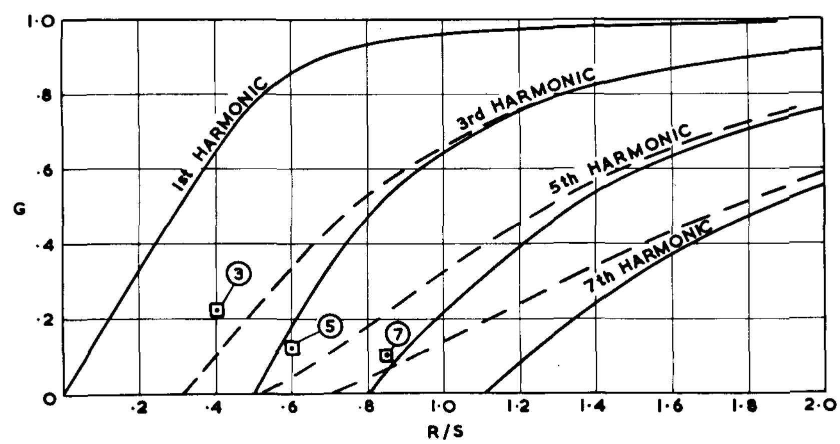
where
g_1 = gap factor between dee and dummy dee
g_0 = gap factor between puller and ion source
E = energy of ion at maximum radius $r_{\max}$
r_s = radius of ion source tube.

Values of g_0 have been calculated for the conditions which applied during the measurements and found to be 0·8, 0·7, 0·75 for the third, fifth and seventh harmonic cases respectively. Using these values and the measured threshold voltages, the following values for g have been obtained: third harmonic: 0·22; fifth harmonic: 0·12; seventh harmonic: 0·1.

3.3. *Comparison of measured and calculated gap factors*

In Fig. 4, gap factor curves are given for various harmonics.

The values of g, of the previous section are also shown (as single points) and it will be observed that in all three cases the practical values are larger than



Solid curves: Simple formula

$$G = \left(Sin \frac{nS}{2R}\right) \Big/ \frac{nS}{2R}$$

Dotted curves: Formula used by Fremlin et al

$$G = \frac{J_0 \left(\frac{nL}{2R}\right)}{cosh \left(\frac{nD}{2R}\right)}$$

where S = L + D
n = *the harmonic number (1, 3, 5, etc.)*
R = *mean radius of curvature of the ion path*
L *and* D *are the width and height of the accelerating gap and are shown on Fig. 2*

Fig. 4. Gap factor curves for different harmonic modes

those predicted even by the refined formula of Fremlin *et al.*[1] It is, moreover, salutory to note that the simple formula for gap factors would rule out harmonic operation above the third for the present centre geometry of the V.E.C. In view of the results obtained it is clear that one cannot apply this formula for low gap factors (<0·2). The factor of two difference between the measured and calculated values of g using the more accurate formula is probably reasonable.

4. FURTHER BEAM OBSERVATIONS

4.1. *Field fitting tolerance*

It has already been mentioned that the intensity of the accelerated beam was sensitive to the setting of the 'inner' orbit coil currents. This is probably due to the fact that with small gap factors in the central region there are rapid changes of ion phase, and also the acceptable deviation of the field from the isochronous value (deliberately introduced to give vertical focusing) becomes rapidly less.

4.2. *Quality of accelerated beam*

For most third harmonic beams the quality is not substantially worse than for fundamental beams with the result that good extraction is obtained.

On the fifth and seventh harmonic beams, however, there is considerable deterioration in beam quality. For example, the best extraction efficiency is only about 20% to 30% for the fifth harmonic beam investigated and about 10% for the seventh harmonic beam.

5. CONCLUSIONS

From the short study that has been carried out it is evident that harmonic operation up to the seventh is feasible without any modification to the accelerating structure, provided a reduction of the order of 1/500 in intensity can be compensated by increased ion source output. By reducing the central gaps by a factor of two say, operation on harmonics as high as the ninth can be envisaged.

The recent installation of an axial injection system should improve harmonic operation a little, but even in this case to achieve really efficient operation on harmonics beyond the third a tightening up of the central geometry will be necessary.

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REFERENCE

1. Fremlin, J. H., Gent, A. W., Petrie, D. P. R., Wallis, P. J., and Tomlin, S. G., *J. Inst. Elec. Engrs.* **93, Part IIIA,** 890, (1946).