ABSOLUTE CALIBRATION OF DEE VOLTAGE BY X-RAY ENDPOINT

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Abstract

We describe an X-ray technique for calibrating the rf voltmeters used to measure and stabilize the potentials of the dees in the M.S.U. cyclotron. The method is generally applicable and should be especially useful in cyclotrons which have multiple dees or which do not have separated turns.

1. Introduction

The Michigan State University Cyclotron has two weakly-coupled dees which can be operated either in phase or 180 degrees out of phase by adjusting the movable panels and the trimming capacitors to achieve a resonance in the desired mode. The modes are typically 200 kHz apart and about 8 kHz wide. The rf power is fed to the north dee only. The ratio of the amplitudes of the voltages on the north and south dees is varied by slightly detuning the south dee. Thus it is necessary to have a good measure of the relative dee voltage, and for this purpose we undertook to do a calibration of our dee voltmeters. In the X-ray technique described here the dee voltage is inferred from a measurement of the endpoint of the bremsstrahlung continuum, which corresponds to the peak dee voltage. It is possible to deduce the sum of the dee voltages from a measurement of the beam energy, the phase history and the number of turns. This will be shown to agree with the X-ray results.

2. Experiment

2.1 Detector Arrangement

Initially a Si(Li) X-ray detector (6 mm dia. Ortec model 7113-06275) was set up near a Plexiglass window (12 mm thick) in the cyclotron vacuum chamber. The X-ray continuum could be measured only at voltages above about 30 kV, mainly because signals became undectable in the background from room radioactivity at lower voltages. For this reason and also because of concern about distortion of the endpoint region of the spectrum from scattering, we inserted two 0.75 mm dia. thoriated tungsten filaments in the cyclotron, one under each dee, to provide controlled sources of electrons, as shown schematically in Fig. 1. A copper cap for the removable 6-inch steel plug in the lower yoke was modified to accept the filaments. One of the regular ion source filament leads was

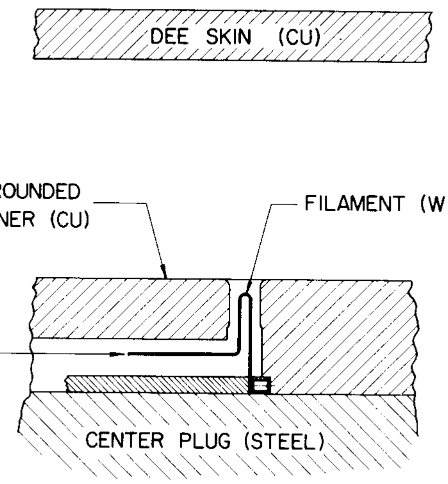

Fig. 1.--Layout of one electron source in the cyclotron. The support for the non-grounded side of the filament is not shown.

connected to each filament; the other end of each filament was grounded. This arrangement allowed remote switching from one filament to the other. The emission current could not be measured, however. In separate tests the filament emission was found to be about 2mA at a filament current of 40 A. Before the final data were taken the Plexiglass window was machined to a thickness of 2 mm in front of the detector.

At voltages above about 40 kV it was necessary to use a filter in front of the detector to prevent the counting rate from becoming excessive. The filters were mounted on a motor-driven wheel placed in front of the detector, which allowed selection of 7 different brass absorbers (from 0.13 mm to 1.70 mm thick), or no absorber, by remote control. The counting rate was always kept below 2kHz. Remote controls were not needed for radiation safety, but were used to speed up data collection.

2.2 Energy Calibration

Three typical spectra corresponding to different dee voltages are shown in Fig. 2. The energy scale was determined by measuring spectra from standard sources: ^{57}Co(6.4 keV, 14.39 keV, 122.19 keV, 136.31

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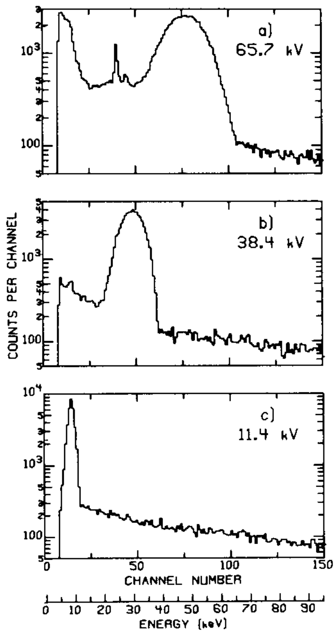

Fig. 2.--Typical X-ray spectra for three different peak voltages. The endpoint can be estimated to within about 1 channel (.639 keV). Absorber thickness: a) 1.1 mm; b) 0.25 mm; c) none. (See text).

keV) and ^{241}Am(59.51 keV). The copper K X-ray (8.5 keV) was also observed in most low-voltage spectra which required no filtration and this line was also included in the calibration. Also, the gold $K_{\alpha 1}$ and $K_{\alpha 2}$ lines (68.8 keV and 67.0 keV) from fluorescence of the gold layer on the X-ray detector were observed when the ^{57}Co source was used and were included in the calibration. Spectra from the ^{57}Co source recorded at various times during the experiment were used to check the energy calibration. The response of the detector was linear, with a standard deviation from the least squares straight line of 0.21 keV.

3. Data Reduction

Measurements were made at 10 frequencies from 14.3 MHz to 21.3 MHz. The endpoint was determined by visual inspection of plots, as in Fig. 2, and comparison with a background spectrum measured with the rf turned off. Notice that good statistics are necessary in the background in order to determine the end point, since no use is made of the intense part of the spectrum in the analysis. Each spectrum was accumulated in about 4 minutes.

The finite transit time for the acceleration of electrons across the dee gap reduces their maximum energy by an amount which is voltage- and frequency-dependent. Since the correction was only about 0.2% in the worst case, the correction was neglected.

X-ray end point measurements were made on one dee at a time with the other one always tuned to a lower voltage. A typical set of data for one frequency appears in Fig. 3. The rf voltmeters were assumed to be linear, which appears to be confirmed by the data, such as those in Fig. 3. There was no measurable dependence of the calibration on the mode (0° or 180°). The RMS deviation from the least squares line varied from 0.28 keV to 1.4 keV, with about 0.5 keV being typical.

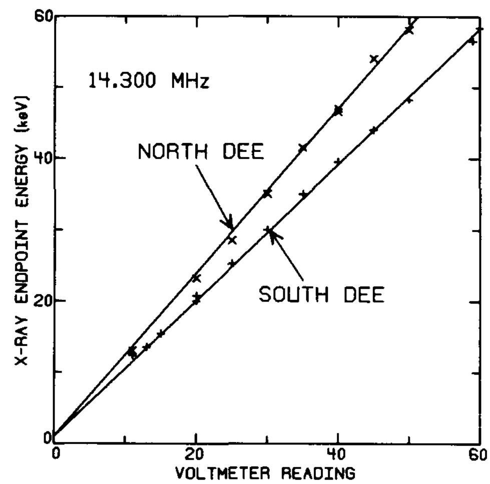

Fig. 3.--Calibration data for north and south dee voltmeters at 14.300 MHz. The straight lines are fitted by least squares. Standard deviations are 0.78 keV for the noth dee and 0.50 keV for the south dee. Note that the voltmeter reading is treated as dimensionless, so both the slope and the intercept of each line can be expressed in keV.

The parameters of the calibrations are shown in Fig. 4. One notices that the intercepts all fluctuate around the value +1 keV. The slopes show some significant differences in frequency response. Since non-linearity of the voltmeters is expected to show up most strongly at low voltages, this would primarily affect the intercept. Therefore the intercepts were all fixed at +1 keV and the fitting was repeated, with the result in Fig. 5. The essential features of the frequency dependence are unmodified, although the curves are a little smoother. We used these parameters to generate the calibration curves shown in Figs. 6 and 7. The points are calculated from the least squares straight lines. The curves are interpolated using a cubic spline function.

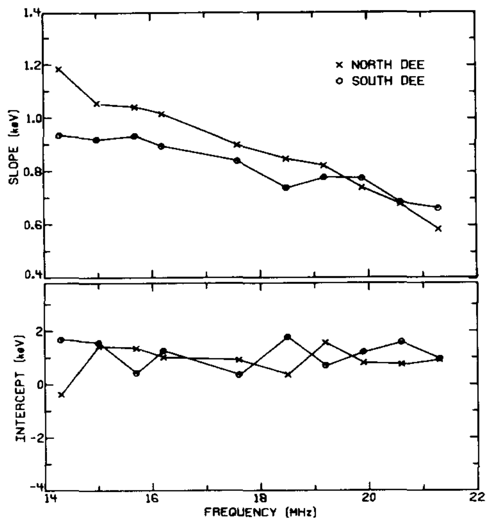

Fig. 4.--Frequency dependence of the voltmeter calibration parameters (slope and intercept of the linear fit). Both parameters were allowed to vary.

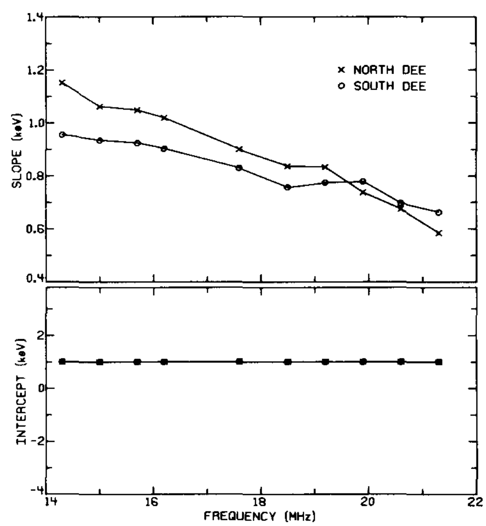

Fig. 5.--Same as Fig. 4, except the intercepts were constrained to be 1.0 keV and the slopes were varied.

4. Accuracy-Comparison with Turn Count

The number of turns the beam makes can be measured directly from a strip chart record of the differential probe current. If the beam phase is zero everywhere (peak energy gain), the number of turns is given by

$$N = \frac{E}{2Z(V_n+V_s)\sin(h69^\circ)}, \qquad (1)$$

where E is the final energy in keV, V_n and V_s are, respectively, the peak north and south dee voltages in kV, Z is the ion charge in electron charges and h is

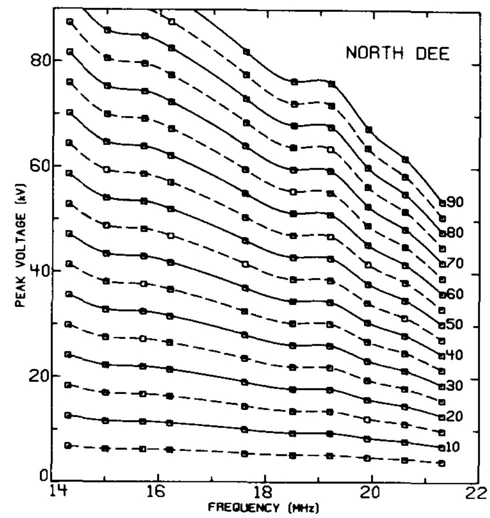

Fig. 6.--North dee voltage as a function of frequency with the voltmeter reading as the parameter (5 unit contours).

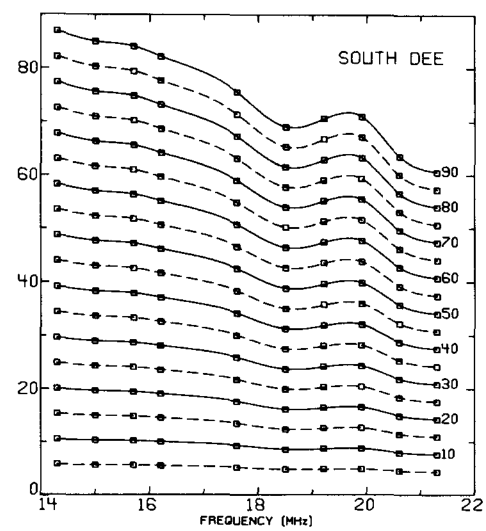

Fig. 7.--Same as Fig. 6 for the south dee.

the harmonic number. (The factor 69° is one half the dee angle). Table 1 compares the measured turn count with eqn. (1) for several different particles and energies. The discrepancies are 4% or less. If we attribute the entire discrepancy to non-zero phase, then $<\cos\phi>$, the average value of $\cos\phi$ is ≥ 0.96. Phase measurements made under conditions similar to those for the data in Table 1 suggest that $<\cos\phi> \simeq 0.98$, assuming $<\cos\phi>$ can be approximated by

$$<\cos\phi> = \frac{\int_0^{R_{max}} \cos\phi(r) \ r^2 dr}{\int_0^{R_{max}} r^2 dr} \ . \qquad (2)$$

We conclude that the absolute accuracy of the X-ray calibration technique described is better than 4% and is probably around 1% or 2% for voltages that are above 30 kV, corresponding to data in Table 1. By analyzing the fluctuations observed in the data we conclude that a single measurement of an endpoint is accurate to ±1 kV.

5. Acknowledgements

The mechanical design of the filament assembly was done by G. Stork. Parts of the apparatus were constructed by N. Mercer, P. Fighter and W. Harder. Dr. W.S. Chien helped make the measurements. We acknowledge with thanks their assistance in this project.

TABLE 1.--Comparison of turn count with prediction from the voltmeter calibration (eq.(1)). The harmonic number h=1 in all cases.

f [MHz]	E [MeV]	particle	Measured no. of turns	N
14.577	24	proton	204	196.4
14.998	76.6	$^3He^{++}$	170	164.3
16.132	30.3	proton	204	200.0
18.537	40	proton	216	209.8
20.241	48	proton	217	211.0