The Cyclo-Graaff, concept and practice

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Presented by F. O. Purser

ABSTRACT

The design aims and performance of the Cyclo-Graaff accelerator are discussed. Energy spread from the 15 MeV injector cyclotron has been reduced to 15 keV and reliable operation of the accelerator combination has been attained. Output pulse time structure has been studied and proven useful as a tune up aid. Indications that the external beam from the cyclotron can be used to provide a feedback signal for further energy spread reduction are presented.

1. INTRODUCTION

The Cyclo-Graaff is of course a new combination of accelerators rather than a new machine in itself. Both the compact isochronous cyclotron and the tandem accelerator are, individually, well proven accelerators with well known capabilities and limitations. The Cyclo-Graaff project is an attempt to use the strong points of the tandem accelerator to offset corresponding limitations in the isochronous cyclotron and vice versa. By so doing we have achieved a very flexible accelerator at a modest cost when compared with other accelerators presently operating or planned to operate within our energy range.

The principal design aim of the project has been to utilise the economically obtained beam intensity and energy available from the compact cyclotron to extend the useful range of the FN tandem to include the 15-30 MeV energy region. If one disregards the rather standard problem of matching the emittance of the cyclotron beam to the acceptance of the tandem with an appropriate combination of lenses, only one serious characteristics mismatch is encountered. Practically any competently run tandem will produce beams whose inherent energy spread is less than 0·02%. On the other hand a cyclotron whose external beam has an energy spread before magnetic analysis of less than 0·2% is a very well behaved cyclotron indeed. A large portion of our work, therefore, has been directed toward methods of minimising the inherent energy spread of the

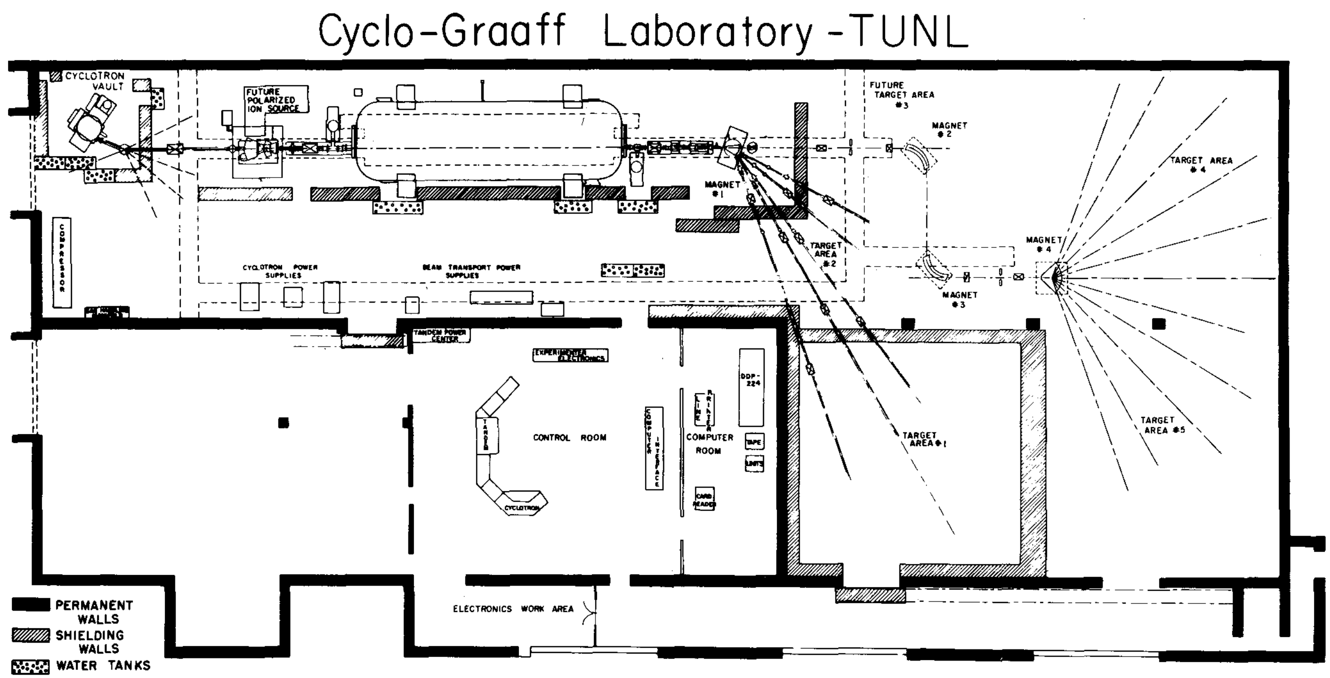

Fig. 1. Plan view of laboratory level. The enclosure shown around the injector cyclotron is completely roofed with pre-cast concrete beams, thus creating a separate cyclotron vault within the accelerator bay

cyclotron beam and thus reducing this mismatch at the 15 MeV transition point of the Cyclo-Graaff. Any slow changes in cyclotron output energy are completely cancelled by the tandem without a loss of target beam intensity.

2. PHYSICAL PLANT AND EQUIPMENT

Our physical plant is shown in Fig. 1. The cyclotron has been placed in one corner of the large accelerator bay principally to ease the radiation shielding problem. As shown it is surrounded by 2 ft thick walls of concrete block and water tanks and the enclosure is roofed with 1 ft thick reinforced concrete beams thus creating a separate cyclotron vault within the accelerator bay. The other shielding walls shown adjacent to the tandem and analysing magnet are also composed of 2 ft × 3 ft movable concrete blocks stacked to a height of 14 ft and have proven quite adequate with only a minimum of additional local shielding in doorway areas.

The basic components of the Cyclo-Graaff in use are a 15 MeV fixed energy A.V.F. cyclotron produced by the Cyclotron Corporation of Berkeley, California, and a standard High Voltage Engineering Corporation FN tandem accelerator. The cyclotron utilises an external negative ion source with ions being introduced into the central region by axial injection and inflected into the median plane by an electrostatic mirror. The source is capable of producing up to 2·4 mA of H^- ions. Since it is a fixed energy machine both isochronism and the necessary azimuthal field variation can be obtained by shaping the iron alone without the additional cost and operational complications added by field trim coils. Of course the fixed energy reduces the cost and complexity of the rf system drastically. The 17 keV injection energy and the phase space acceptance of the axial channel also tend to reduce the criticality of central region design in that a relatively rigid and well defined beam is presented to the first acceleration cycle. Beam extraction from the cyclotron is accomplished with harmonic coils and an electrostatic deflector.

Modifications to the FN tandem for use with the Cyclo-Graaff have been minimal. In order to accommodate a 3 in aperture magnetic quadrupole triplet in the standard low energy extension, the source box and table have been moved a total of 2 ft farther from the low energy base plate. In addition, the ¼ in diam. gas stripper canal in the terminal has been replaced by one with 5/16 in diam. These changes have produced only one perceptible change in normal tandem operation: beam transmission through the tandem during tandem operation alone appears to be improved when we use the magnetic triplet instead of the einzel lens supplied by HVEC with the machine.

At the present time we are utilising four experimental stations in target area 1. Magnets 2, 3, 4 are now due for delivery in early November when target areas 4 and 5 will be opened. This magnet system operates in either a high resolution mode or a near achromatic mode and because of its arrangement offers a number of interesting control possibilities with the two accelerators which we will investigate on delivery. Ultimate energy resolutions from the magnet system alone in target area 4 should be less than 5 keV at 30 MeV.

In Cyclo-Graaff operation the external beam from the cyclotron is analysed by a 20° inflection through a circular pole magnet and then focused onto a set of input collimators by a magnetic quadrupole triplet. The input collimators are two 0·100 in circular apertures separated by 8·0 in and represent the upstream image of the tandem gas stripper canal. The beam through these collimators is then focused onto the tandem stripped by a second quadrupole triplet located in the tandem low energy extension. With this optical arrangement essentially all of the beam transmitted by the collimator is subsequently accelerated and transmitted to the output slits of the analysing magnet.

3. CYCLO-GRAAFF DEVELOPMENT

At Triangle Universities we are not cyclotron people *per se* and our approach to this project has been to treat the cyclotron simply as an additional ion source, one of three which shortly will be in use for the tandem accelerator. We have avoided detailed orbital calculations as much as possible and began with the assumption that we had a reasonably isochronous, reasonably well behaved cyclotron and have in general measured and calculated only those average beam characteristics necessary for our purposes. It should be added at this point that one of the reasons we have been able to get away with so casual an approach has been the existence of a body of very fine detailed work, accomplished by cyclotron experts, which has made possible our understanding of the effects of various cyclotron parameters upon the average properties which interest us. In particular the published work of Dr. Blosser's group at MSU has been helpful.

In any ion source one seeks the following characteristics.

(1) High luminosity or a reasonable beam intensity concentrated within an acceptable phase space area.
(2) Minimum inherent energy spread due to the source alone.
(3) Predictability of all performance characteristics.
(4) Reliability of performance.

Our cyclotron, as delivered, filled the first of these requirements very well. With small extracted beams the measured emittance was less than 15 × 15 mm-mrad and beams of 10 μA or greater appear to lie within a phase space area of less than 30 × 30 mm-mrad which is well within the acceptance of the tandem. Consequently our principal post delivery work has concentrated upon the last three characteristics, energy spread, reliability, and predictability of performance.

Let us now consider the energy spread mismatch referred to earlier. In an ideal cyclotron the energy spread of a single turn arises of course from the sinusoidal nature of the accelerating voltage and the finite angular spread of the phase packet accelerated to full radius. The one obvious way to improve this energy spread is to reduce the size of the phase packet accelerated. One method of doing this is to limit the accelerated beam internally with a slit or set of slits and at present on our cyclotron rf phase limitation is accomplished with one 0·040 in movable slit located on the third or fourth orbit and one 0·125 in movable post located usually between the twelfth and fifteenth turns. With this arrangement we have been able to reduce the accelerated angular acceptance from its normal 25–30° to the neighbourhood of 5°. The locations and widths of these slits are decidedly non-optimal as yet in that with the present locations we are sacrificing too much of the beam we would like to extract as well as that portion lying outside the desired phase area. There is some indication from the orbit profile that our outer post is in a region where particles of differing phase tend to have small radial separation and that we would benefit greatly by moving it 1 in farther out to the vicinity of the thirtieth orbit. However, this move cannot be made until the presently uncooled post is replaced by one which is water cooled. Maximum internal beam current circulating before phase limitation ranges from 40 to 70 μA depending upon target beam requirements.

The degree to which phase limitation is profitable in reducing the time averaged energy spread of the external beam is determined primarily by the degree of dee voltage ripple present. The increase in extracted energy spread due to dee voltage ripple arises from two sources. The first of these involves of course only the time dependent increase and decrease of mean proton energy caused by the varying dee voltage effect upon protons occupying a restricted rf phase spread. Thus, if the dee ripple is 0·1%, and the final energy is 15 MeV, then dee ripple will introduce an additional 15 keV in the width of the time averaged energy spread.

A more serious situation with respect to dee ripple arises when internal phase limiting is insufficient and the final phase selection of the extracted beam is accomplished to some degree by the extraction channel width. In this case, dee voltage ripple actually changes the rf angular spread and make-up of the extracted phase packet as a function of time and can introduce much more serious effects upon beam energy spread.

There is a critical qualitative difference between these two cases. In the first the mean energy of the extracted beam changes coherently with the dee voltage ripple as a function of time while the instantaneous energy spread remains relatively constant. Since this ripple frequency is generally slow, one may then hope to eventually remove this component of the average energy spread by operations external to the cyclotron. In the second case, on the other hand, the instantaneous energy spread may be greatly increased while the mean extracted beam energy can show little change or is incoherently related to the dee ripple as a function of time.

A basic criterion thus for achieving minimum energy spread and the possibility of external energy homogenisation of the cyclotron beam is to limit the phase internally so that the dee voltage ripple cannot substantially change the phase history of the extracted pulse. This is simply a requirement that the time averaged energy spread of the internal phase packet which is accelerated to extraction radius must be less than the effective energy acceptance of the extraction mechanism.

An indication of behaviour of this type may be seen in Fig. 2, which shows comparative traces of the dee voltage envelope and the output of a difference amplifier driven from a set of beam limiting slits located externally to the cyclotron. The upper half of the figure represents a condition of insufficient phase limiting by the internal slits while the lower half shows the results of correct positioning. The right hand spectra in both cases are measurements of the time structure of the extracted pulse. The time scale is 50 pico seconds per channel. Dee voltage ripple for this test was 0·2%. A prerequisite for utilising a signal of this nature for energy control is that there be no transverse beam motion at the slits which is not due to energy fluctuations. A new deflector supply with the capability of accepting a feedback signal for beam position control is being built to eliminate this possible source of error.

Measurement of the time structure of the extracted pulse has proved to be an extremely useful diagnostic tool to aid cyclotron tuning which bears strongly upon the predictability requirement previously mentioned. These measurements are made with commercially available time-to-amplitude converters. A crossover discriminator triggered from the radiofrequency provides the stop signal and gammas from the external collimation system detected in a small NATON-136 scintillator provide the start signal. Time resolutions as low as 300 ps FWHM

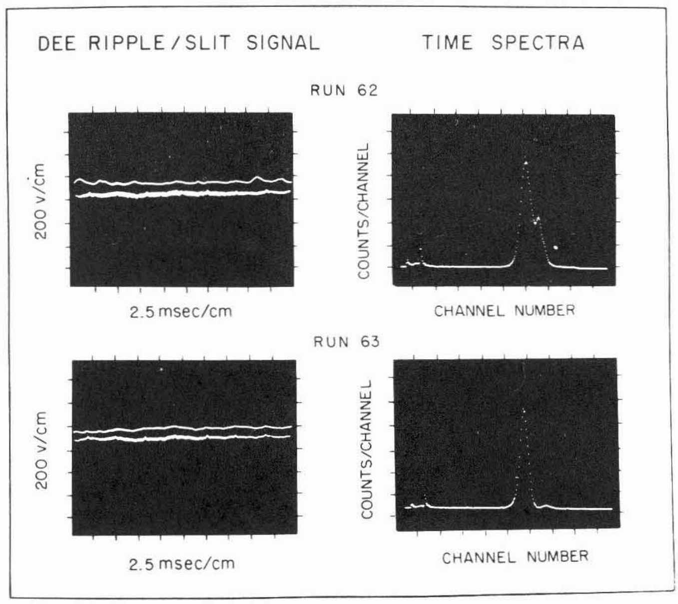

Fig. 2. Dee voltage ripple effects. The upper of the dual traces shown in the left hand figures is a difference signal from external beam limiting slits. The lower of the traces is the dee voltage envelope. The scale for the pulse time spectra on the right is 50 ps per channel

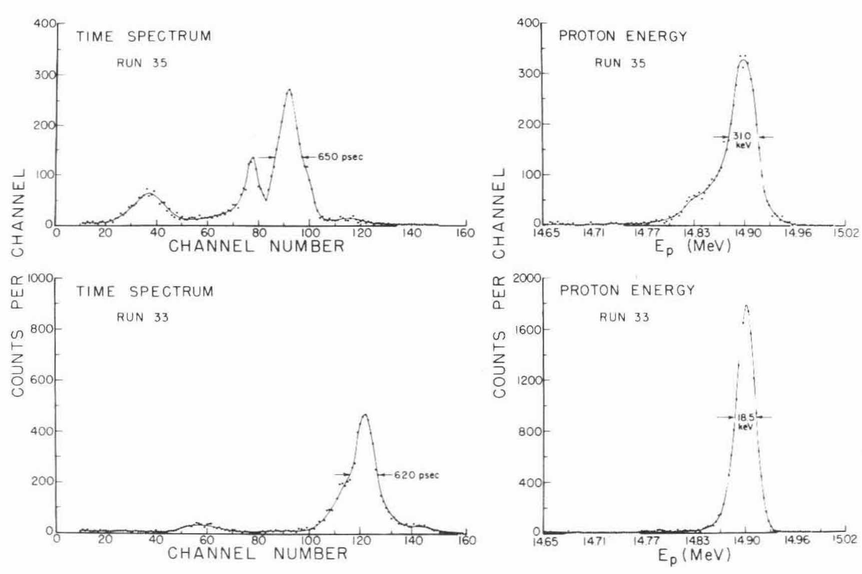

Fig. 3. Beam energy and time structure. Study of the pulse time structure of the extracted beam has proved to be a useful tuning aid

have been observed. Fig. 3 shows two representative measurements made prior to injection into the tandem. In the upper half of the figure the time structure shows clearly that several different bursts are being extracted, since for this run the internal slits were deliberately mispositioned. The energy spectrum on the right was obtained by measuring the energy of protons elastically scattered from a thin gold foil with a cooled surface barrier detector. The energy spectrum indicates a relatively large energy spread and shows structure also.

In the lower half of the figure, the internal slits have been more properly positioned to select phase effectively. The extracted beam time structure has cleared up nicely, though some signs of structure are still visible, but the effect upon the energy spectrum is marked. Widths shown for the energy peaks have been roughly corrected for the effects of detector and electronic resolution.

The principal advantage of time monitoring is that it can be accomplished continuously without interfering with the extracted beam. Our cyclotron has a tendency to detune with time as various components reach stable thermal, electronic, and mechanical equilibrium at different times. By monitoring the time structure, one may keep the energy spread continuously tuned to a minimum. Our experience has been that tuning is adequate when the time structure shows basically only one peak. So long as the width of this peak is less than one ns minor fluctuations in width are of only secondary influence upon net energy spread.

In the first year of operation we have experienced several cyclotron mechanical failures, generally associated with inadequate cooling water flow to various components. When these problems are thoroughly shaken out we have every reason to believe that the cyclotron will prove as reliable as more common tandem sources. In the most recent week of operations, the Cyclo-Graaff was in use for six days with the cyclotron being turned down only to change experiments. After a warm up period of approximately 8 h, the cyclotron requires minor tuning at intervals of 2-3 h. This degree of stability is most satisfying.

4. CYCLO-GRAAFF PERFORMANCE

The maximum beam current which has thus far been injected and accelerated has been 1·8 μA measured at the high energy end of the tandem. I might say that this occurred during a test of laboratory radiation levels. Since all of the work presently in progress involves detection of charged particles, most experimenters can tolerate only 100–200 nA of beam current in their target chambers before counting rate difficulties become serious.

The terminal response of the tandem with the Cyclo-Graaff beam has shown some improvement over normal tandem operation. Fig. 4 indicates the comparison. The improvement is probably due to the increased radiation level in the vicinity of the high voltage terminal which produces increased ionisation of the insulating gas and leads to improved corona response. The normal absence of ionising radiation associated with the use of inclined field accelerating tubes has proved to be a mixed blessing and has led HVEC to make provision for the installation of a high intensity γ-source inside the pressure tank for their higher energy machines. Our injection energy seems to sidestep this problem rather neatly. In operation we monitor the radiation adjacent to the terminal and can easily determine from this source alone when the injected beam wanders and take corrective measures.

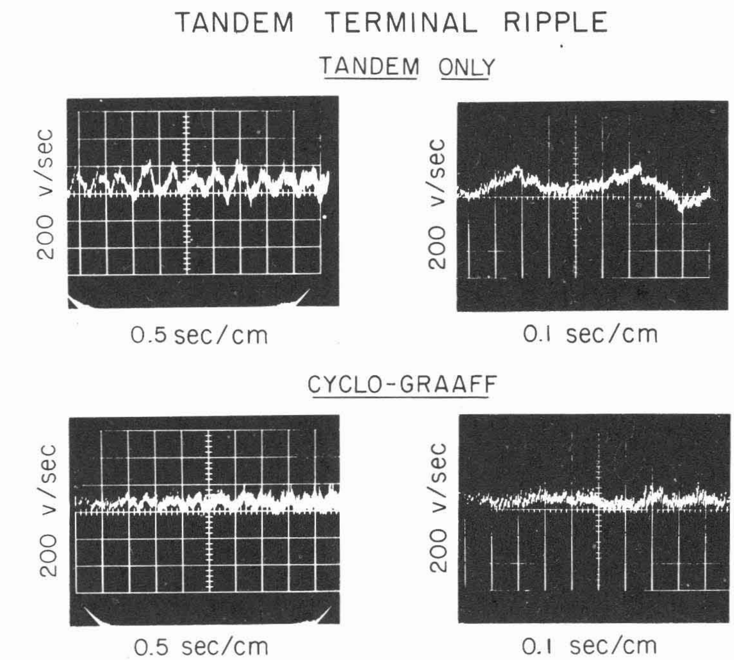

Fig. 4. Tandem high voltage terminal response. Terminal ripple measured at the capacitive pick up appears improved for Cyclo-Graaff operation over that found during normal tandem runs

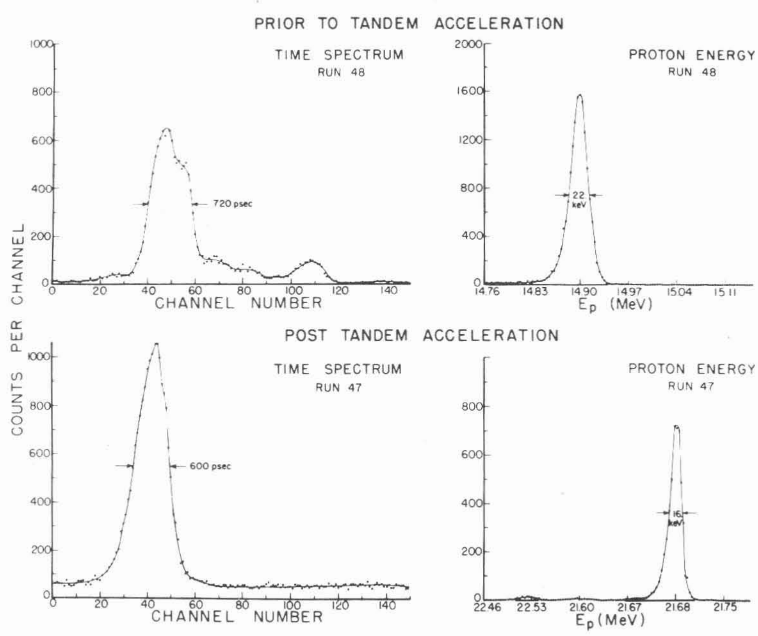

Fig. 5. Cyclo-Graaff beam energy and time structure. For this measurement considerable improvement in energy homogeneity was apparently found after transmission through the tandem. If not due to detector variations, it was probably caused by energy selection at the tandem stripper canal

Fig. 5 shows the time structure and energy spread of the Cyclo-Graaff beam measured before and after tandem acceleration. The measurements in the upper and lower halves of the figure were made in quick succession to eliminate the effect of possible changes in cyclotron tuning. The post tandem measurements were made in a scattering chamber located on the 52° port of the analysing magnet and with the slit settings used, the energy resolution of this magnet is more than 75 keV. It is possible that some energy selection was accomplished at the input to the tandem stripper or at the 0·060 in input collimator to the scattering chamber. The time structure measured at the scattering chamber would indicate that any such selection was accomplished elsewhere. The post tandem energy spread is most probably a conservative estimate as only a minimum detector resolution has been assumed. It might be pointed out that for beams of this quality we are very near the limit of the effective resolution of the detector system used. At this limit small changes in system resolution

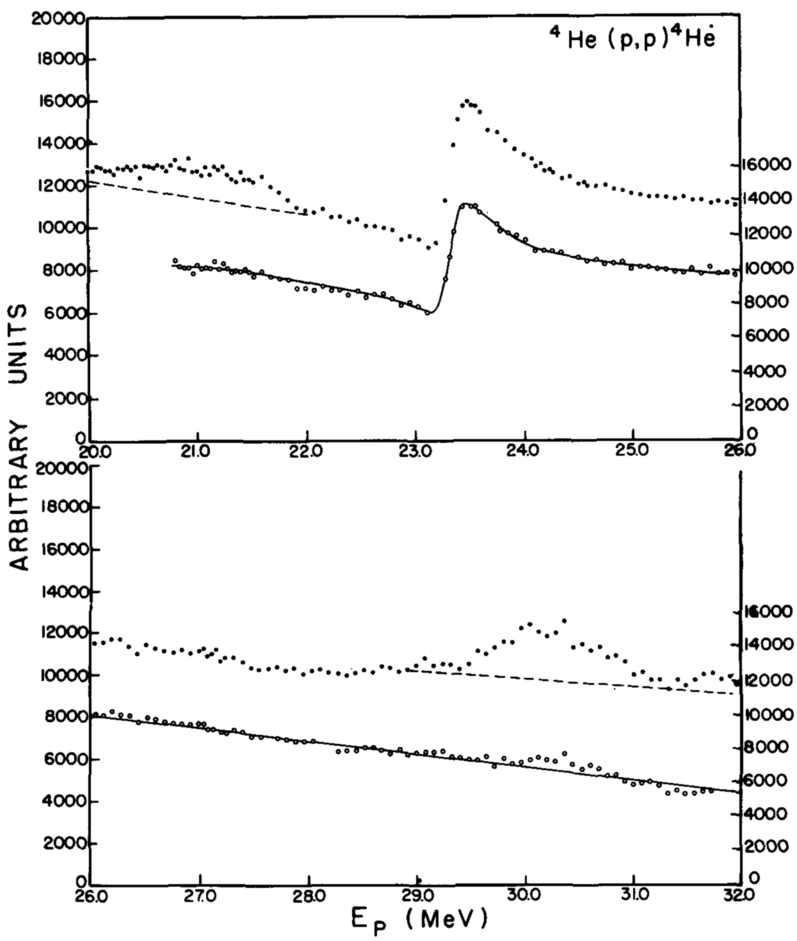

Fig. 6. Cyclo-Graaff sample data. The solid circles above are raw data and the open circles have been corrected for background. Data for excitation curves of the nature shown which require practically continuous exact energy changes can be accumulated rapidly and accurately with the Cyclo-Graaff

caused by slightly different operating conditions will indicate quite large changes in beam energy spread which may not be real. On the day following the measurements shown in Fig. 5 the resolution of the same detector system was measured with the tandem beam and yielded a value of 25 keV. One of the first undertakings for the high resolution analysing system when delivered will be to measure the energy spread of the Cyclo-Graaff beam under varied tuning conditions.

Fig. 6 is a sample of the type of data that can be accumulated rapidly and accurately with the Cyclo-Graaff. This excitation curve was run from 20 to 32 MeV in 80 keV and 40 keV steps during 14 operating hours. I do not believe that the ease and rapidity with which exact energy changes of this nature can be accomplished can be equalled by most variable energy cyclotron installations. The major time delay in energy changes with the Cyclo-Graaff involves data output rather than machine tuning. This run was primarily an accelerator demonstration run and mean energy spread of the proton beam was probably 50 keV or more as the data were taken before we had learned to use the phase limiting slits correctly. This probably had little effect upon this experiment as the energy loss in the gas scattering cell was close to 150 keV. Since this experiment the scattering chamber geometry has also been changed and the large backgrounds indicated by the solid circle data in Fig. 6 are no longer with us.

5. EVALUATION AND FUTURE

One lesson learned thus far in the Cyclo-Graaff project has been the absolute necessity that all power supplies associated with the cyclotron and intervening beam transport equipment be stabilised and ripple free to the maximum extent possible. Fully half of our effort to achieve the higher resolution desired is a result of inadequately stabilised supplies which have required alteration or replacement.

We have not thus far seen any reliable improvement in the cyclotron beam energy spread as a result of transmission through the tandem; however, we do have good indication that such improvement is possible through use of a feedback signal derived from the cyclotron beam. Our first approach will be to apply this correction signal to the present dee voltage regulator. A second possibility requires increasing the frequency response of the tandem itself by applying the correction signal directly to the stripper. Obtaining a response at this point adequate to handle the 360 cycle per second dee voltage ripple appears quite feasible.

One of the improvements to be considered is the addition of another dee between the two present dees to be operated at the third harmonic of the fundamental radiofrequency. Generally rough calculations indicate that one could alternatively achieve either 6–10 times as much beam with the same energy spread as is available at present or that one could achieve 6–10 times better spread with the same beam. Installation of a third harmonic dee would probably require concurrent installation of a set of tuneable beam centring coils to counteract the first harmonic kick associated with the unequal voltage gains at the two gap crossings in this configuration, but nothing in the proposal seems technically impossible or even very difficult.

In conclusion we believe that the Cyclo-Graaff concept has proven itself and has much to recommend it. We expect to compete on more or less equal terms not only with MP type tandems but with double MP installations such as is being built at Brookhaven National Laboratories. The cost difference is impressive in a time of research budget retrenchment.

DISCUSSION

Speaker addressed: F. O. Purser (Duke University)

Question by C. Mayer-Böricke (K. F. A. Jülich): How much beam intensity do you lose with the monochromator system?
Answer: With the present energy spread of the beam of 15 keV one would expect to lose approximately two-thirds by transmission through the final magnet system operated in the dispersive mode. If the dee voltage ripple contribution is nullified one might expect transmission of 50% or better.
Question by A. A. van Kranenburg (N. V. Philips): Would you comment on the absolute intensities that were reached with this configuration?
Answer: With 300 μA of d.c. beam injected approximately 40 μA are accelerated by the radiofrequency. Of this from 5 to 12 μA are accelerated through the phase limiting slits, dependent upon target beam current and energy spread requirements. At the present time our extraction efficiency is a low 30%.
Question by J. Warren (UBC): What has your experience been with source lifetimes?
Answer: Source lifetime is of course controlled by filament lifetime, and for the currents presently required filaments are lasting approximately 100 operating hours. At somewhat lesser current levels we have obtained lifetimes of approximately 200 h.