Optimisation of the cyclotron central region for the nuclear physics user*

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ABSTRACT

Beam requirements for high quality nuclear physics experiments are reviewed along with features of central region arrangements for preferentially transmitting particles satisfying the requirements. With such a central region, phase widths of 1·5° can be achieved and such phase widths in conjunction with good stabilising circuits lead to highly monochromatic beams. (External beam energy spread 0·04% *FWHM* at MSU.) Such systems also give 100% extraction efficiency and high transmission through external analysis systems. (Total transmission of 20% at MSU for 1 in 6000 energy resolution and emittance of less than 1 mm mrad.)

1. INTRODUCTION

Modern nuclear physics is a science of detail in which significant experiments are concerned in almost every case with careful determination of the individual properties of particular nuclear quantum states. Such experiments require very monochromatic beams in order to separate close lying quantum states, with good collimation in order to precisely study spatial details of the states. Desired beam currents are generally modest—usually in the range 50-500 nA on target—the limitation on current coming in most cases from the data processing system. Frequently the nuclear characteristics of greatest interest are rare phenomena and the cleanness of the setup is of great importance in separating the desired results from background phenomena.

Relative to these nuclear physics requirements, the cyclotron in its normal condition is a very intense, rather imprecise beam source. This mismatch is generally corrected by means of a beam analysis system which transmits a precisely defined sub-section of the beam to the user. The remaining beam (typically 90-99% of the total) is stopped and in so doing intense radiation and residual acitivity are produced along with intense thermal heating, all of which lead to substantial problems. Moreover these problems are all in principle unnecessary—the external analysis system is selecting a certain volume in phase space which (as a result of the character of the equations of motion) must have

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uniquely originated in a corresponding phase space volume at the centre of the cyclotron and therefore the function of the external analysis system could have been accomplished by an equivalent phase space selection in the centre of the cyclotron, but with the problems of radiation and residual activity eliminated and the problems of thermal heating greatly reduced. While such a central region system in principle exists, none such has yet been totally realised in practice, although great progress has been made. The situation is reviewed in this paper.

2. SYSTEM REQUIREMENTS

In nearly every case energy resolution is the primary factor determining the accelerator requirements for a given nuclear experiment. The nuclear physics itself gives no universal criterion for adequate resolution since the separation of nuclear quantum states rapidly approaches zero as the excitation of the nucleus is increased, with heavy nuclei far from closed shells as the most severe case. The accelerator is, however, never the sole factor in determining the energy resolution of an experiment—energy loss and straggling in the target and energy resolution of detectors are other very important effects and the accelerator system is therefore completely adequate whenever its contribution to the resolution is small compared to other factors. This is still a complicated criterion with many variations depending on the conditions of particular experiments. At our laboratory for example most physics users at present specify 1 in 3000 for the beam energy spread, a few ask for 1 in 6000 and on rare occasions 1 in 10 000 is used.

Emittance requirements generally follow from the energy requirement via the combination of slit size and useful aperture of the analysis system or, for light targets, from kinematic broadening due to the combination of the spot size on target and the finite angular spread of the beam and detector. The emittance in the scattering plane (normally the radial plane) contributes linearly to the energy spread whereas the perpendicular emittance (axial) gives a quadratic contribution—hence an axial emittance substantially larger than the radial emittance is usually acceptable. The actual value of the emittance necessary for given resolution is determined by the physical size of the analysis system and the scattering chamber. We have for example at MSU an unusually compact analysis system[1] (magnets weighing only 7 tons)—1 in 6000 resolution with this system requires 0·5 mm entrance and exit slits and for lowest aberrations the divergence is limited to 2 milli-radians (mrad), therefore yielding 1 mm mrad for the required emittance. If this system were twice as large in all dimensions and with all fields reduced to half, it would have exactly the same resolution with 1·0 mm slits and 2 mrad divergence and therefore an emittance two times larger could be allowed. (The larger analysis system would of course be more expensive and would require more space—ergo for specified energy resolution a cyclotron with good emittance can work with a smaller analysis system and thus achieve a significant cost saving.) In a similar fashion the size of the scattering chamber fixes the target-detector distance and therefore the target spot-size and divergence required to reduce kinematic broadening to a specified level. In the MSU set up, which is fairly typical, these various factors lead to requirements of 1 mm mrad and 3 to 5 mm mrad for the radial and axial emittances respectively in a normal high-resolution experiment.

The final beam property to discuss is the duty-cycle, a parameter frequently misunderstood (and even more frequently weighed with exaggerated importance).

As is well known, an isochronous cyclotron normally produces a continuous train of nanosecond pulses separated in time by about 50 ns. Therefore to slow equipment the cyclotron appears to yield a continuous beam (100% macro-duty-cycle) whereas to fast equipment it appears to yield a sharply pulsed beam (1-3% micro-duty-cycle). For fixed experimental requirements (specified pileup probability, true to accidental ratio, etc.) the duty-cycle then in a complicated way determines the running time required to obtain a given result. The complexity arises from the fact that the quantity of significance, the running time, is an involved mixture of the characteristics of the accelerator and the detection system with wide variations in the characteristics of the latter quantity depending on the experiment. The present highest resolution detection system for example consists of a magnetic spectrograph with photographic plates, an arrangement whose performance is completely independent of duty-cycle. Running time for such arrangement is determined entirely by the accelerator luminosity.
Less well recognised is the fact that the wide class of direct reaction spectroscopic experiments [(p, d), (d, p), (p, t), (^{3}He, d)... etc.], is independent of a cyclotron type micro-duty-cycle since the counting rate is controlled by the data processing time for an event, a time interval of order tens of microseconds. (Very sharp beam microstructure can often in fact be a positive advantage in such experiments, the timing information allowing particle identification in a single detector in lieu of the conventional two detector $dE/dx, E$ system and thereby yielding improved energy resolution due to decreased surface loss and dead layer effects.) A good duty-cycle is of most benefit for the various multifinal particle experiments such as (p, 2p), (p, p$'\gamma$), etc. Even for such experiments as these the detector is however also of key importance. At present, for example, the best resolution for both γ-rays and high energy protons is obtained with germanium detectors—these detectors have a charge collection time of about 10 ns and therefore the advantage of a true DC beam relative to cyclotron pulsing is of order 5 to 1 rather than the 50 : 1 or 100 : 1 which the acceleration duty-cycle alone would imply. (A further consequence of this property of germanium detectors is the fact that for such experiments a cyclotron with very short, sub-nanosecond pulses is completely equivalent to a machine with normal 2-3 ns pulses or to a possible 'flat-topped' machine with 8-10 ns pulses, since the germanium charge collection time in every case makes it impossible to separate two events from the same cyclotron pulse.) The class of experiments for which long duty-cycle is of greatest advantage reduces then to experiments studying multi-particle final states using fast detectors—certainly an important class of experiments but nevertheless a small part of contemporary nuclear experimentation. In summary then, good duty cycle is an important and valuable attribute but in most experiments of much less importance than energy resolution. Since the cyclotron involves a fundamental conflict between duty cycle and energy spread it is in most circumstances best to favour energy resolution. (Leaving the choice of good duty-cycle or high energy resolution as a free option for each user is of course the obvious ideal solution.)

3. DESIGN CONSIDERATIONS

3.1. *Energy spread*

Since the acceleration in a cyclotron comes solely from the rf system,[2] the energy spread in the beam must come from some variation in the relationship of the beam to the rf. In actual fact, the energy spread of a cyclotron beam is dominantly a result of three effects, namely: (a) time fluctuations in the amplitude of the dee voltage, usually called 'rf ripple', (b) the fact that all particles do not cross the accelerating gaps at the same time, the distribution of the particles relative to the rf being referred to as the 'phase width' of the beam, and (c) time fluctuations in either the rf frequency or the magnetic field either of which will produce a 'phase shift' of the beam relative to the rf and hence a change in acceleration. The first and last of these factors, the stabilisation of the rf voltage, the rf frequency and the magnetic field are engineering problems whereas restriction of the beam phase width is an orbit dynamics problem. As regards the engineering problems—modern techniques readily allow the stabilisation of magnetic fields to levels of 1 part in 100 000 and of rf frequencies to 1 part in 1 000 000 (using an MOPA system). With such stabilisation the contribution to the beam energy spread from factor (c) above is negligible. Stabilisation of the rf voltage has proved much more difficult. Levels of 2 to 6 in 10 000 have been achieved in our laboratory after long effort[3, 4]—1 in 10 000 is believed possible. Even at these levels the rf voltage is still the dominant factor in the beam energy spread when a good phase selection system is in use and our engineering colleagues are hence accordingly urged to press on further with their already highly productive efforts on voltage stabilisation.

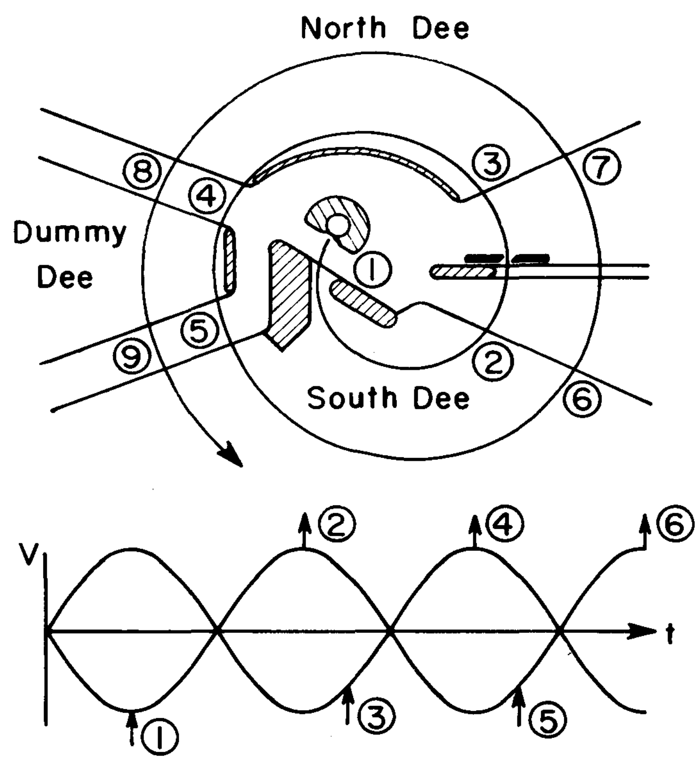

Fig. 1. Top–schematic drawing of central region arrangement in the MSU cyclotron including computed central ray trajectory for the first two turns. Bottom–voltage vs time for the two dees with numbered arrows indicating the phase relationship of successive accelerations

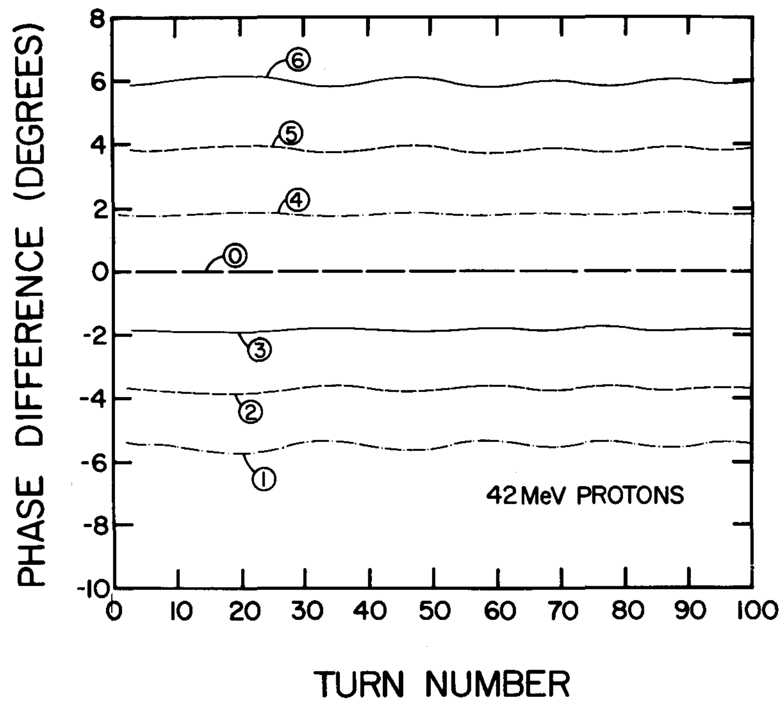

Fig. 2. Phase difference, $\varphi_i - \varphi_o$, vs turn number for a family of central rays. Ray o leaves the source at $\tau_o = -28°$, rays 1, 2 . . . 6 leave the source at $\tau_o = -34°, -32°, -30°, -26°, -24°$, and $-22°$ respectively

Finally let me consider the problem of limiting the phase width of the beam or 'phase selection' as it is usually called. Phase selection via the phase dependence of the electric focusing forces was suggested a number of years ago by Hagedoorn[5] and extensively studied.[6] To my knowledge there have however as yet been no experimental studies of the performance of such systems. Recently at MSU we have installed a very effective radial motion phase selection system—since this system has not been discussed elsewhere I will describe it in some detail here.

The essential feature of the system is a phase dependent centring error the origin of which can be qualitatively understood from Fig. 1. Our cyclotron like most recent cyclotrons has the puller extended à la W. I. B. Smith[7] in order to place the ions initially at a positive phase. The most intense beam group crosses the source to puller gap effectively at zero phase and enters the south dee. Due to the puller offset the south dee on the first turn is essentially 180° in length and so the particles also leave this dee at zero phase as indicated by the '2' on the right of Fig. 1. But now the flight path to the north dee entry at '3' is only about 45° and so particles enter this dee at a time when the voltage is rapidly changing. Since this gap is increasing the energy by about 40%, there is a large shift in the effective orbit centre and due to the rapidly changing voltage this shift has a strong phase dependence thus producing a phase dependent centring shift. At later gaps such as 5, 7, etc., the shift is alternately decreased and increased but since the energy increase on gap 5, 7, etc., is 20%, 12%, . . . etc., the large shift at gap 3 is never compensated. A following slit system arranged to require centring will then act as a phase selecting system.

The phenomenon is depicted quantitatively in Figs 2 and 3 which show results of numerical orbit tracking. For these figures a 'central' ray and six

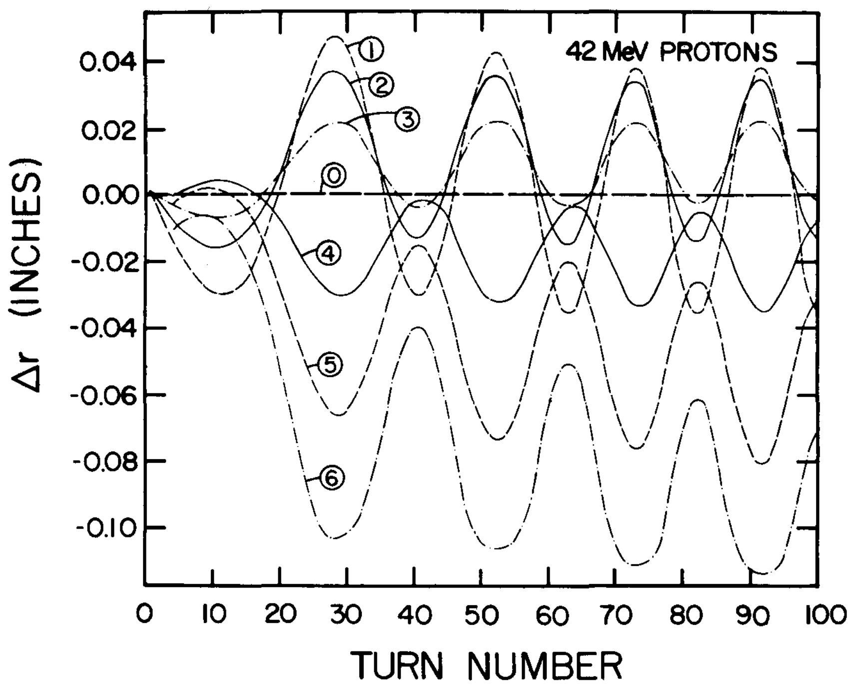

Fig. 3. Radius difference, $r_i - r_0$ *at* $\theta = 180^\circ$ *vs turn number for the same family of rays as in Fig. 2*

'displaced' rays have been tracked, the displaced rays differing from the central ray in that they leave the ion source in successive two degree steps earlier and later than the central ray. In Fig. 2 the phase difference between the central ray and the displaced rays is plotted vs turn number. The difference in starting time is seen to result in an almost exactly identical difference in phase showing that a structured central region has essentially no phase grouping. Fig. 3 is similar to Fig. 2 except that the radius difference between the displaced rays and the central rays is plotted rather than the phase difference. In marked contrast with the phase difference the radius difference is sharply structured, the structure repeating periodically with the precessional frequency in the manner characteristic of a centring error. For phase selection a slit placed at the antinode of this spacing modulation will clearly be the most effective, i.e. in the vicinity of turn 28 for the rays shown here.

We have not as yet however looked at the complete problem—a real source has both a finite size and a finite divergence and all of the rays shown in Figs 2 and 3 originated at the centre of the source moving straight ahead. A study of rays displaced in initial position from the rays of Figs 2 and 3 so as to represent the finite source aperture produced results essentially identical to Figs 2 and 3

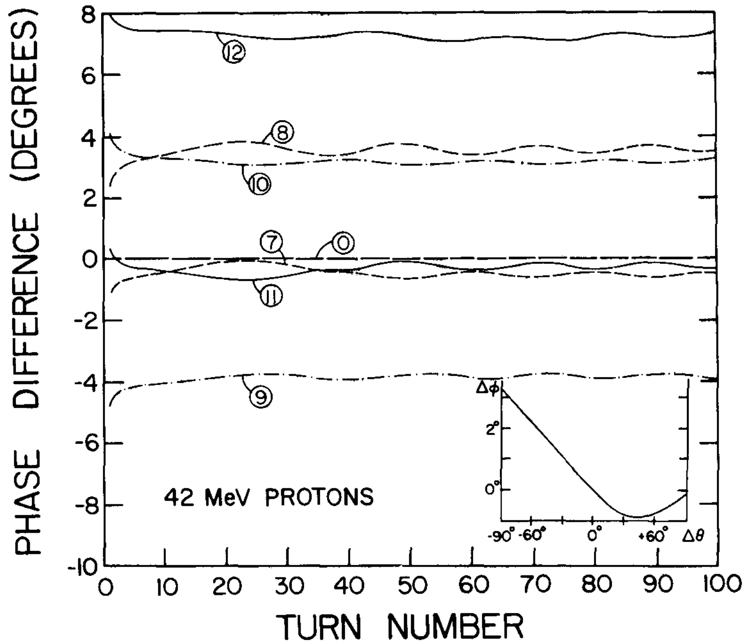

Fig. 4. Phase difference, $\varphi_i - \varphi_o$, vs, turn number for a family of rays leaving the source at ±90° to the central ray direction. Ray o is the same as in Fig. 2, rays 7, 8, . . . , 12 have r_o = − 32°, −32°, −28°, −28°, −24°, and −24° respectively with positive initial P_r for odd numbered rays and negative for even numbered rays. Initial energy 20 eV. See text for discussion of inset

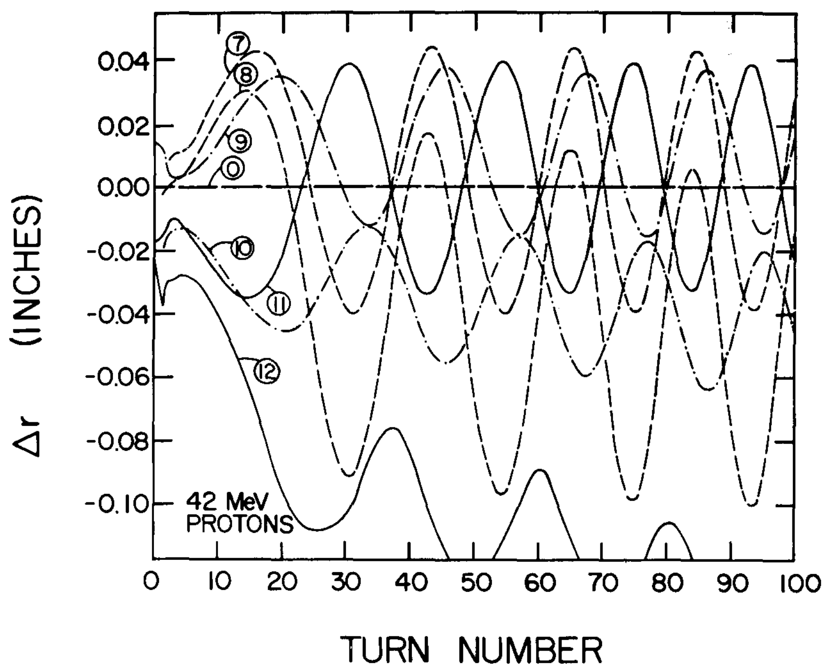

Fig. 5. Radius difference, $r_i - r_o$, at θ = 180° vs turn number for the same family of rays as in Fig. 4

and so no figures showing these results are included herein. In contrast a study of rays initially diverging from the source showed marked differences—these results are shown in Figs 4 and 5. The most important new phenomenon is the strong phase shift which occurs on the first half turn for the ray whose initial divergence carries it to the inside of the turn. The shorter path length causes this ray to be displaced in phase by about 4° for the maximum divergence case selected. The phenomenon is also strongly non-linear as can be seen from the inset in Fig. 4 which gives the phase shift $\Delta\varphi$ vs the divergence angle $\Delta\theta$. Another important feature to notice in Fig. 5 is the fact that rays of given phase come to a focus in the vicinity of turn 23 and are thoroughly scrambled near turn 28, i.e. the effective centring error is phase shifted relative to that for rays leaving the source with no divergence, and an additional slit will hence be necessary for best phase selection.

Experimental data showing the performance of such a system is given in Fig. 6 which is a plot of γ-ray intensity vs time for the beam on the internal probe of the cyclotron. The two curves are with 0·5 mm slits on the 18th and 28th turns 'in' and 'out' (in our cyclotron these slits are controlled by a console switch and can be inserted or removed in about 1 s). With the slits 'in' the pulse width is 0·2 ns *FWHM* corresponding to 1·4 rf degrees. With the slits down the phase width is 3·4 ns *FWHM* corresponding to 23 rf degrees. Using the

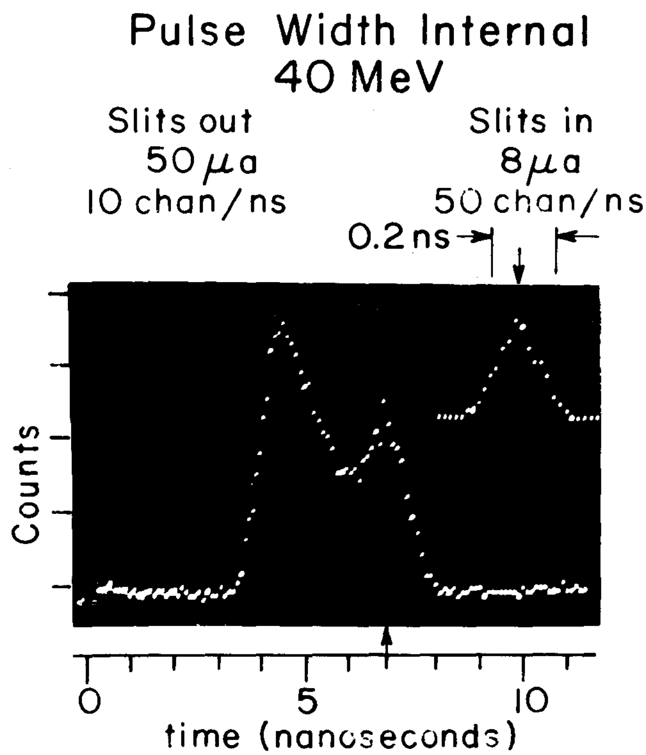

Fig. 6. γ-ray yield vs rf time for beam hitting the internal probe, the main curve being with the 18th and 28th turn slits out, the inset at the upper right with the slits in (on a five times magnified scale). The largest observed current transmitted by these slits is 15 μ A, the narrowest time group 0·15 ns FWHM *(R. St. Onge, private communication).*

phase slits and adjusting the field or frequency so that the phase group is on the average on the top of the rf wave, the contribution to the energy spread from the phase width is reduced to about 1 part in 14 000. With improved rf amplitude control, beams of 1 in 10 000 energy precision should hence be attainable.

3.2. *Emittance*

Comparing the desired emittance values (Section 2) with the natural characteristics of the cyclotron we immediately note that the emittance requirement should be easy to achieve, at least in principle, since the specification is essentially identical to the measured emittance of a cyclotron ion source (after correcting for the energy difference between the cyclotron external beam and the d.c. acceleration used in the source studies). Fig. 7 and Table 1, for example, show

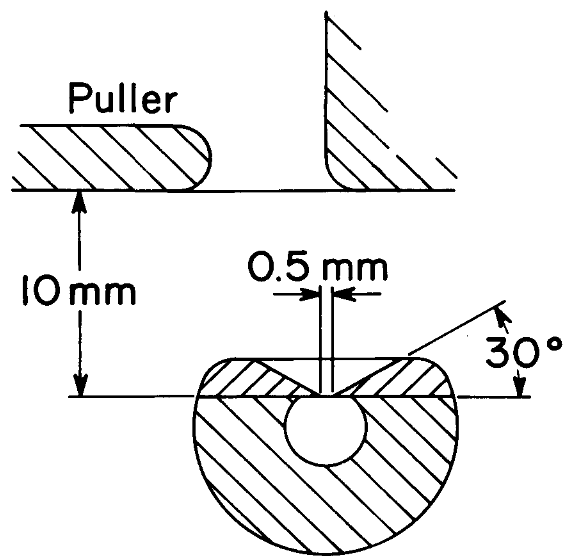

Fig. 7. Median plane cross-section view of the source-puller geometry employed by D. A. Cluxton (ref. 8) in most recent MSU d.c. ion source emittance measurements. The major design change from previously studied sources is the use of a knife edged tantalum extraction slit in place of the previous square edged graphite slit

source geometry and a summary of the most recent emittance data from the MSU source testing facilities.[8] Since the data are taken at 35 keV the inferred emittances at 40 MeV for a 3 A arc would be about 0·9 mm mrad radially and 3·0 mm mrad axially for 90% transmission. These values are adequate for energy resolutions of up to 1 in 10 000 even with a relatively compact analysing system.

The d.c. source emittance data lead to an interesting speculation as to the origin of the 10–50 mm mrad radial emittance observed in many cyclotrons. It seems unlikely that the ion source emittance is significantly different from machine to machine since the studies of both Mallory[9] and Cluxton[8] show no strong geometry effect. In the acceleration process the radial phase space area

Table 1. SUMMARY OF EMITTANCE DATA FROM MOST RECENT MSU DC ION SOURCE TESTS—D. J. CLUXTON (REF. 8). ION SOURCE SLIT 0·5 mm WITH 30° RECESS AS IN FIG. 7. GAS FLOW 1·5 cc/min. EXTRACTION VOLTAGE 35 kV. CURRENTS IN MILLIAMPS UNLESS OTHERWISE INDICATED.

Arc		*Radial emittance*					*Axial emittance*				
Current A	volts	*100%*		*Reduced area*			*100%*		*Reduced area*		
		mm mrad	cur.	%	mm mrad	cur.	mm mrad	cur.	%	mm mrad	cur.
1·0	100	48	0·9	96	36	0·86	114	0·9			
2·0	125	41	1·1				207	1·1	61	32	0·85
3·0	150	69	3·2	96	34	3·1	245	3·2	82	89	2·7

should be essentially preserved due to Liouville's theorem and the generally weak coupling of the radial motion to either the axial or longitudinal motion. Also, the typical cyclotron is a highly linear device over distances of the order of turn widths and it is therefore unlikely that the phase space area of a well centred beam will be enlarged by non-linear mixing of filled and unfilled regions. The dominant phenomenon producing the emittance enlargement appears in fact to be a combination of the mixing of radial phase space regions in multi-turn extraction combined with an experimental inability to distinguish between emittance and dispersion. Figs 8 and 9 show results of a computer study illustrating the phenomenon. Central rays have been tracked from the ion source

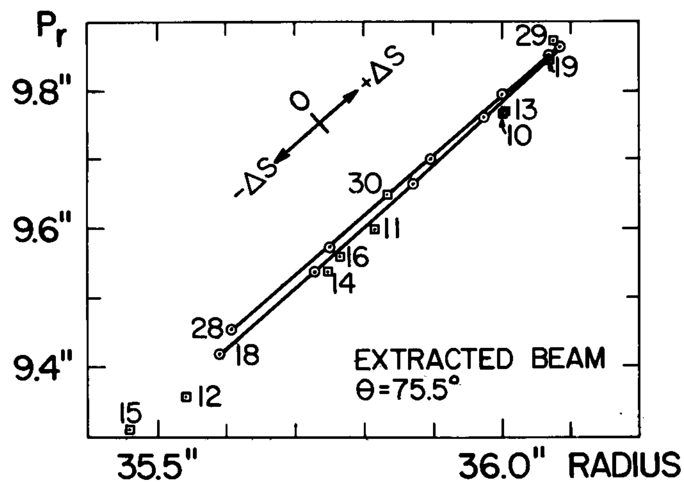

Fig. 8. Graph of radius vs radial momentum in the extracted beam for rays leaving the ion source at rf times as labelled (all times are negative). The circled points joined by the line entered the deflector on turn 212, and are at 1° intervals in τ_0. Other rays entered the deflector on turns as follows: $|\tau_0| = 10° \rightarrow 217$, $= 11° \rightarrow 216$, $= 14° \rightarrow 214$, $= 29°, 30° \rightarrow 213$

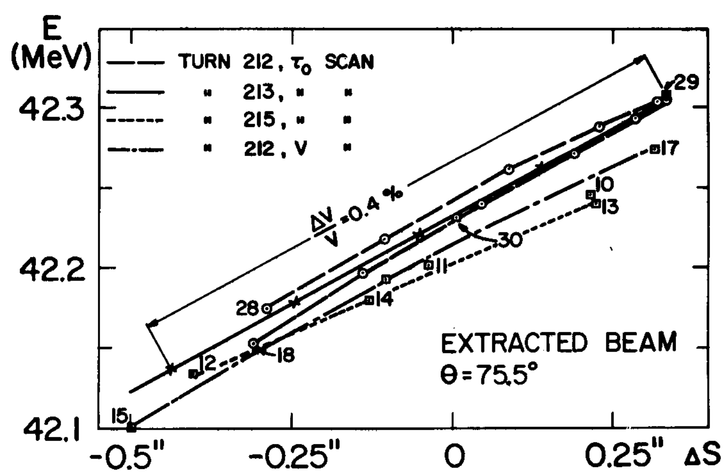

Fig. 9. Graph of final energy vs position on dispersion curve S (defined in Fig. 8) for the same rays as in Fig. 8 plus a group of rays run at various rf voltages with τ_0 fixed at $-23°$

through the cyclotron and deflector and out into the fringe field for various initial phases and rf voltages. Points are labelled to indicate the initial τ_0 (minus signs omitted). The dominant feature of these results is very strong dispersion—for a given turn the position of the final point varies smoothly up and down the r, P_r line in very direct relation to the final energy. Fig. 9 shows this even more directly, the results from Fig. 8 being replotted as Energy vs a co-ordinate S giving the position along the dispersion line. Note from the Figures that when an energy difference sufficient to permit an additional turn builds up, a distinct shift in the location of trajectories occurs. Multi-turn extraction hence will be expected to yield a larger emittance than single turn extraction even for a very well centred beam such as in these calculations (design ray centred to ±0·2 mm).

Results of experimental studies of the external beam distribution are shown in Fig. 10. The results agree very closely with the behaviour expected from the computer studies, namely that the total length of the distribution is dominantly a result of dispersion (in this case the energy spread being almost entirely a result of rf voltage ripple). Using computer results to separate the emittance and dispersion, one obtains the results shown at the right of the figure. The resulting radial emittance value is 0·7 mm mrad which is in reasonable agreement with the 0·9 mm mrad expected from the d.c. source studies. Corresponding experiments on the axial emittance give a measured value of 5·0 mm mrad which is likewise in reasonable agreement with the figure of 3·0 expected from the d.c. studies. The cyclotron beam is thus inferred to be inherently very well collimated but

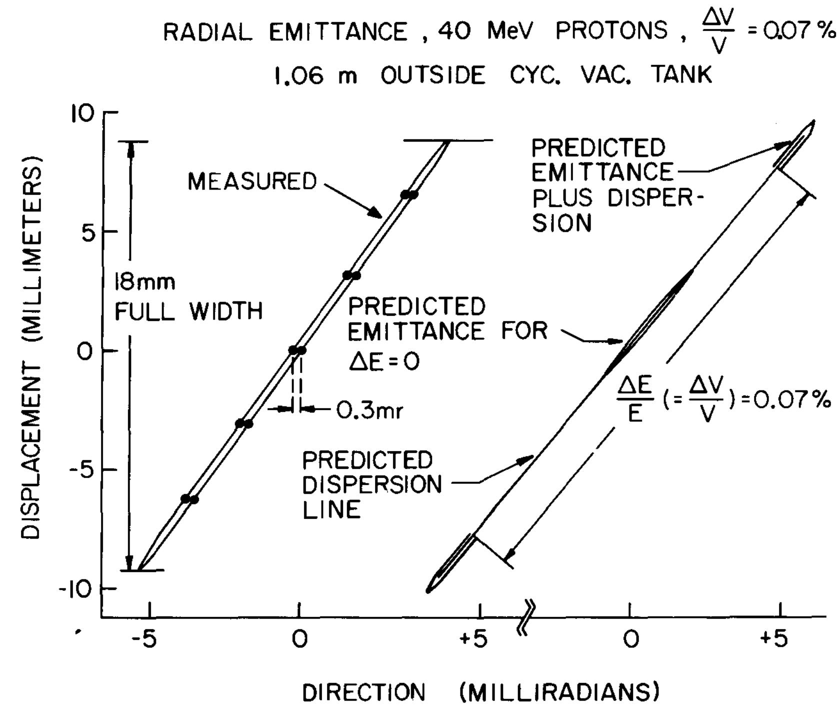

Fig. 10. Right–measured radial distribution of the cyclotron external beam (100% of beam). Left–computer calculation of expected beam distribution due to combined emittance and dispersion

with energy and radial position varying slowly in time in accord with the rf voltage ripple.

To further test the validity of the dispersion-emittance separation two additional tests were made. In the first of these the rf ripple was doubled by reducing the gain of the rf voltage feedback loop and the data of Fig. 10 were remeasured. The length of the distribution (along the dispersion curve) increased by ~ 80% without detectable change in the width (perpendicular to the dispersion curve) as the analysis would predict. In the second test the beam analysis system was set up for 1 in 6000 resolution and the beam reaching the target was measured as a function of the aperture of a radial slit located at the edge of the cyclotron at the position of the emittance measurements. Results of this experiment are shown in Fig. 11. One sees that the beam satisfying the 1 in 6000

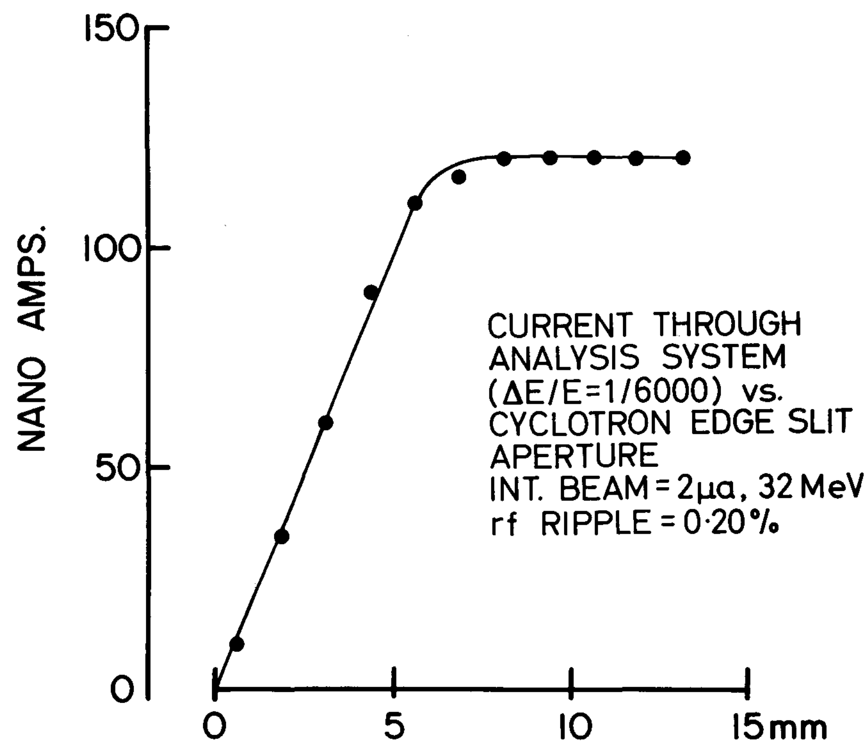

Fig. 11. Current transmitted through a 1 in 6000 energy analysis vs the aperture of a slit located at the position of the emittance measurement of Fig. 10

energy requirement comes entirely from the centre 6 mm of the beam at the fringe field location in excellent agreement with the expectation from Figs 8 and 10.

While similar calculations or experiments for other cyclotrons are not available, the basic nature of the phenomena make it likely that these results are widely valid, namely that the external beam of any cyclotron is in fact a very small pencil of essentially the same phase space area as observed in source studies and moving in time on a nanosecond scale for the phase distribution and a milli-second scale for rf voltage or magnetic field variations. As these time variations are removed the spatial size of the external beam shrinks and approaches the value expected from ion source studies.

3.3. Duty-cycle

For experiments with high energy resolution a cyclotron has inherently a low microscopic duty-cycle. The origin of this phenomenon can be understood by looking at Fig. 12 which shows final energy for central rays leaving the ion

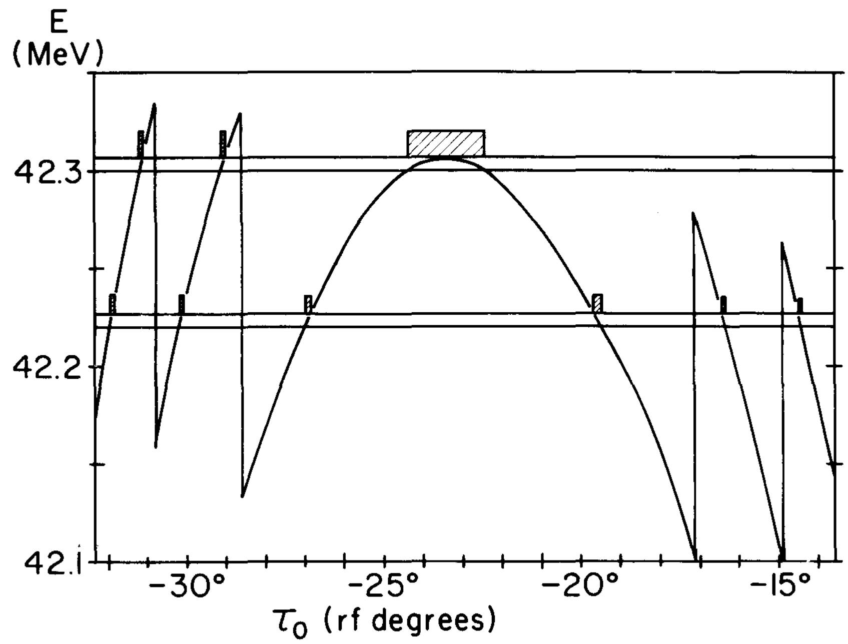

Fig. 12. Final energy vs initial time for a family of central rays tracked from ion source to extraction. The upper pair of horizontal lines mark off a 1 in 6000 energy interval with the bite positioned for maximum transmission and duty-cycle. The shaded areas mark the time intervals when beam would be transmitted. The lower pair of horizontal lines show the effect of a mis-set energy analysis on the time distribution which also is equivalent to the effect of a change in the rf voltage

source at initial rf times (τ_0) as indicated on the horizontal axis. The curves are parabolic in form, the energy maximum at $\tau_0 = -23°$ corresponding to the ray which is on the average exactly centred on the rf wave. When the maximum radius particles reach the deflector, they are sliced off–particles earlier and later make an additional revolution and are then themselves sliced off, etc. The total resulting energy distribution vs time for the extracted beam is then as shown, i.e. a central parabolic section and successive sawtoothed satellites. If this beam is fed to a beam analysis system set for 1 in 6000 (and with the system tuned for maximum transmission) the beam transmitted will be that corresponding to the shaded areas on the upper energy band in the figure. Immediately one notes that nearly all of the shaded area (~5/6) comes from the parabolic section of the distribution. Hence after energy analysis the beam will be sharply pulsed even though the phase distribution in the cyclotron may have been very broad.

If the effect of rf ripple is included the curves in Fig. 12 move up and down in time while the energy selection band stays fixed–this will then give an apparent smearing out in a beam time distribution taken over an extended time, but this is in fact a false indication of duty-cycle improvement–any position of the energy distribution curve relative to the energy acceptance bite other than that indicated for the upper band of the figure in fact gives even sharper pulsing and lower duty-cycle than the case shown. (Schematically this can be understood by thinking of the energy acceptance interval as shifted say to the lower band in Fig. 12–the pulses are clearly sharper and the duty-cycle lower but because the pulses occur at a different time relative to the rf, a time-of-flight spectrum as normally taken will be broadened and thus falsely indicate an improved duty cycle.)

Results of an experimental study of the beam time distribution following energy analysis are shown in Fig. 13. As in Fig. 6 curves are shown with the phase selection slits both 'in' and 'out' but now the two distributions are essentially identical thus confirming that the beam analysis system transmits essentially the same particles as the phase slits. This result is also confirmed by observations of the transmitted beam current. Beam actually reaching the target

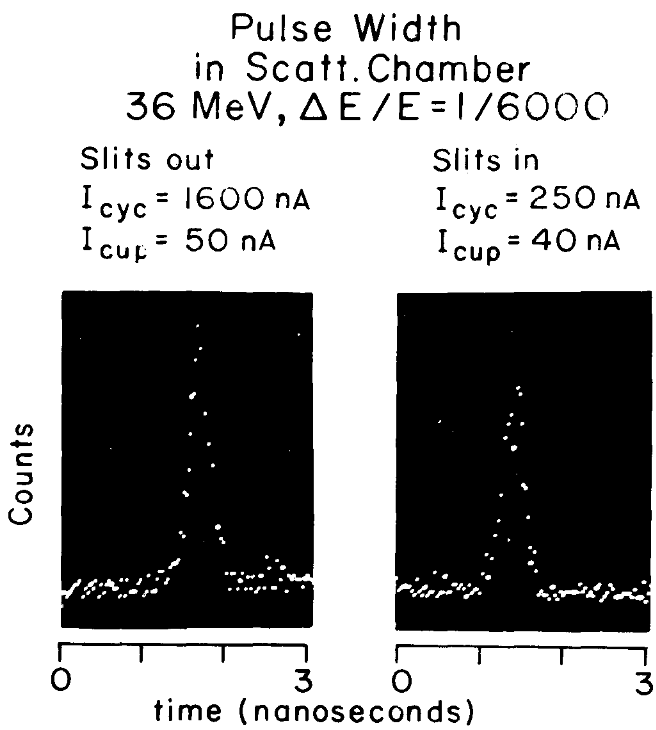

Fig. 13. γ-ray yield vs rf time for beam reaching the scattering chamber after 1 in 6000 energy analysis with the 18th and 28th turn phase selection slits in and out. Removing the slits greatly reduces the transmission efficiency from cyclotron centre to scattering chamber without appreciably improving the scattering chamber duty-cycle even though the internal beam duty-cycle has broadened in the manner indicated in Fig. 6

is essentially independent of the slits' up or down condition. Using the slits thus removes beam which would eventually be lost but before it has received enough energy to produce radiation or radioactivity.

4. CONCLUSIONS

Carefully stabilised cyclotrons and external analysis systems can furnish precise particle beams well matched to the needs of contemporary nuclear physics experiments. If the cyclotron central region is carefully arranged most of the beam which fails to satisfy the analysis requirements can be removed in the central region. Using such a system (and with good stabilising circuits on the magnet and rf) the MSU cyclotron has produced beams with energy spread of 0·04% *FWHM* and with the external analysis system set for 1 in 6000 resolution; 20% of the beam leaving the cyclotron central region is transmitted all the way to the user's scattering chamber 30 m away. The system also easily gives 100% transmission through the cyclotron and 100% extraction efficiency. Activation problems are therefore minimised.

I am indebted to M. M. Gordon for many helpful discussions, to D. A. Johnson for carrying out the computer work and to R. St.Onge and W. P. Johnson for planning and setting up the time-of-flight apparatus.

DISCUSSION

Speaker addressed: H. G. Blosser (MSU)

Question by M. L. Mallory (ORNL): How much time do you allocate for accelerator research?
Answer: Four hours per day from Monday to Friday is normal.

Question by M. E. Rickey (Indiana): With regard to the 2 in 10^4 dee voltage stability, is it the dee voltage itself or simply the dee voltmeter which is held to this precision, since the voltmeter is usually less reliable than this figure? It is my understanding that it is the voltmeter output which is regulated.
Answer: It is the voltmeter which is regulated to 2 in 10^4. We have in progress an independent test of the voltmeter using the spatial position of the extracted beam as the absolute reference. A false signal in the voltmeter could readily be responsible for the energy spread being larger than expected (4×10^{-4} instead of $2{\cdot}5 \times 10^{-4}$).

Question by A. A. Kolomensky (Lebedev Insitute): Can you summarise the data about the influence of space charge (or beam current) on the energy spread. I mean especially the experimental data?
Answer: Gordon will duscuss this in his paper (p 305 below)

Question by J. A. Martin (ORNL): You say that the phase width of the beam is about 1·5°. Is the phase of the rf voltage appropriately stable?
Answer: It is difficult to comment. Experimenters have runs several hours long with a scattering chamber 100 ft from the cyclotron. Using the rf for timing they obtain a time resolution of 0·5 ns.

Second question by J. A. Martin: Is there any difficulty in readjustment of the slits on turns 18 and 28 when the energy of the beam is changed or when α-particles or deuterons are accelerated?
Answer: This is not a problem. We have ¼-in adjustment for each slit but we do not need to change their position over the whole first harmonic energy range.

Question by D. J. Clark (Berkeley): In your very nice high resolution work with $\Delta E/E = 1/6000$, how much beam can you get on target and how much do you expect to get with better dee voltage regulation?
Answer: With an internal current of 750 nA we get 20% transmission to the scattering chamber when the analysing system is set for 1/6000 and 1 mm–1 mrad. With 6 μA we get 10% transmission. We have not tried higher currents to the scattering chamber but the phase slits will pass up to 15 μA and all of this can be extracted from the cyclotron.

REFERENCES

1. Mackenzie, G. H., Kashy, E., Gordon, M. M., and Blosser, H. G., *I.E.E.E. Trans. Nucl. Sci.* **NS-14, 3,** 450, (1967).
2. The discussion in this paper neglects 'space charge' acceleration effects. This important topic is treated in a separate paper. Proceedings of this conference, p. 305 by M. M. Gordon.
3. Johnson, W. P. and Sigg, P. K., *I.E.E.E. Nucl. Sci.* **NS-16, 3,** 492, (1969).
4. Sigg, P. K., private communication.
5. Hagedoorn, H. L., private communication.
6. Blosser, H. G., Gordon, M. M., and Reiser, M., CERN 63-19, 193, (1963).
7. Smith, W. I. B., *Nucl. Instr. Meth.* **9,** 49, (1960).
8. Cluxton, D. J., Michigan State University Report **MSUCP-25,** (1969).
9. Mallory, M. L. and Blosser, H. G., *I.E.E.E. Trans. Nucl. Sci.* **NS-13, 4,** 163, (1966).