USE OF AN ISOCHRONOUS CYCLOTRON FOR NEUTRON TIME-OF-FLIGHT EXPERIMENTATION

H. A. Howe, A. Svanheden, and M. Reiser

U. S. Naval Radiological Defense Laboratory
San Francisco, California 94135

SUMMARY

The design of the U. S. Naval Radiological Defense Laboratory's (USNRDL) cyclotron for the production of subnanosecond, high intensity, charged particle beam pulses for neutron time-of-flight experiments, is described. Klystron bunching of the extracted cyclotron beam is possible for short bunching path lengths between cyclotron and target but it demands a beam of large energy spread -- greater than 1%. A method of linearizing the effect of the sinusoidally varying, accelerating potential is described, and it is shown that klystron beam bunching is possible with reduced beam energy spread. It is seen that the cyclotron competes with single stage, dc accelerators for neutron time-of-flight experimentation and will furnish large beam currents at higher energies in excess of the beam currents contemplated for the dc tandem machines.

INTRODUCTION

Neutron energy measurement techniques have always been among the most difficult in nuclear physics. Since the neutron carries no charge, its energy is not easily determined by measuring the energy released in its interaction with matter. For some time the most successful neutron energy determinations have utilized the measurement of the neutron time of flight over a fixed path. An attractive method of measuring the neutron flight time has employed short bursts of neutrons which are later detected at some distance from the source. A review of neutron time-of-flight techniques by Neiler and Good[1] has described experiments using dc accelerators and cyclotrons as neutron producers. Neutron energy measurement in the MeV range requires neutron bursts less than several nanoseconds long, and such short bursts are produced by pulses of charged particles impinging on a neutron producing target. The formation of short pulses of charged particles from the cyclotron, suitable for neutron time-of-flight measurements, is the principal subject of this paper.

A list of important characteristics of charged particle beams used to furnish neutron bursts includes: a short pulse length of 1 to 5 nanoseconds, a pulse repetition rate less than 2 Mc/sec, an average current of at least 20 μA, an energy spread of less than 1.0%, a diameter less than 0.5 cm, and a total divergence less than 6°. During the time between pulses the accelerator must produce little background which would interfere with the neutron detector measurements. At the U. S. Naval Radiological Defense Laboratory a tritium target will be used which yields monoenergetic neutrons between 1 and 12 MeV from a 2 to 14 MeV primary proton beam.[2]

THE CYCLOTRON

The naturally pulsed beam of the cyclotron, with peak currents of 40 mA, is well suited to furnish short, intense beam pulses. Typically the cyclotron beam pulse length varies from 2 to 10 nsec at a repetition frequency of 30 to 4 Mc/sec. To conform with neutron time-of-flight requirements it is desirable to reduce both the beam pulse length and repetition frequency.

Figure 1 is a schematic view of the accelerating region of the 70-inch, sector-focused cyclotron being constructed at NRDL. This cyclotron utilizes a magnetic field of four-fold symmetry and two 35° dees located in opposing valleys. For the acceleration of low energy protons, i.e., 1.6 to 16 MeV, the proton cyclotron frequency varies from 3.5 to 11 Mc/sec; however, the dees operate on the third harmonic at frequencies from 10.5 to 33 Mc/sec. For 16 MeV protons, 100 kV will be applied to the dees yielding a 320 kV energy gain per turn with 50 turns for complete acceleration.

Figure 1 shows protons, supplied by the source, accelerated through a slot in the puller which is attached to the dee. Spurious beam -- that varying greatly in starting condition from the acceptable beam -- is intercepted by the "beam stopper probe."

The beam then encounters the "phase selector slit" which, as the name implies, selects or transmits that part of the beam which has an rf phase contained within a well-defined interval. The phase selector slit can be positioned to accept rf phase widths from 10° to 30°. Extensive computer study has determined a central-region geometry which is capable of producing high quality beams, radially and axially, with very small intrinsic energy spread as described in another paper at this conference.[3]

The beam pulse train then proceeds to the "beam pulse selector" which is capable of transmitting selected, single, beam pulses for further acceleration. The beam pulse selector utilizes a deflector with a dc bias voltage which normally deflects the beam axially into the dee and dummy dee. Transmission of single beam pulses is accomplished by momentarily cancelling the dc deflector bias as discussed in another paper at this conference.[4] It is advantageous to employ beam pulse selection at the center of the cyclotron, before acceleration, instead of outside the cyclotron, after acceleration, in order to reduce the internal beam thereby reducing the radiation background between beam pulses.

It is planned that the NRDL cyclotron will be capable of accelerating 16 MeV protons with beam pulse lengths of 25° rf phase, or 2 nsec, at a reduced beam pulse repetition frequency as high as 0.3 Mc/sec.

The internal beam will be extracted with a magnetic peeler-regenerator system which deflects the beam into a magnetic channel. Radial overlapping of successive turns of the internal beam would cause individually accelerated beam pulses to be preceeded and followed by satelite pulses after extraction. No beam overlapping will occur in the NRDL cyclotron because of the large fractional energy gain per turn, yielding an 0.3 inch radial gain per turn and the use of orbit precessional motion which, for three inch radial oscillations, increases the radial separation of successive orbits further to 0.7 inches at extraction.

KLYSTRON BEAM BUNCHING

The extracted beam pulse of 25° rf phase length represents a 2 nsec pulse for 16 MeV protons and 10 nsec for 1.6 MeV protons. This is about a factor of 3 too large for neutron time-of-flight spectroscopy and some means must be found for pulse compression. There are two general methods commonly employed. The first is the Mobley technique which forces particles at the front of the beam pulse over longer paths to the target than those at the rear so that all parts of the pulse arrive simultaneously. The second is the klystron technique which decreases the velocity of the particles at the front of the beam pulse and increases the velocity at the rear so that all particles arrive at the target simultaneously.

Because the accelerating fields in a cyclotron are time varying, variations in particle energy along the beam pulse are correlated with the particle position, and it is our purpose to consider the use of this correlation to produce klystron bunching. At a given instant, picture a reference particle within a beam pulse traveling with a velocity, v, to a target at a distance, L, see Fig. 2. The condition for klystron bunching requires that particles located within the pulse, a distance, x, from the reference particle arrive at the target at the same time, or, that the fractional difference in the velocities equals the fractional difference in the distances to be traveled, i.e., $\Delta v/v = - x/L$. For the cyclotron, $x = R\Delta\theta$, where R is the beam extraction radius and $\Delta\theta$ is the azimuthal position with respect to the reference particle, with the positive sense taken in the direction of beam travel. Therefore, the klystron condition for the bunching of a cyclotron beam is,

$$\Delta v/v = -(R/L)\Delta\theta \tag{1}$$

The energy gain of a charged particle traversing a dee of azimuthal extent, α, with an applied voltage, $V = V_0 \sin n\omega t$ is,

$$E_\delta = 2V_0 \sin(n\alpha/2) \cos n(\omega t + \delta), \tag{2}$$

where ω is the particle cyclotron frequency and δ is the particle azimuthal position when the applied dee voltage passes through zero. Now, if we consider δ the position of a reference particle in a beam pulse, the energy gain of any other particle, located at a central azimuth, $\Delta\theta$, from the reference particle will be,

$$E_\delta(\Delta\theta) = 2V_0 \sin(n\alpha/2) \cos n(\omega t+\delta+\Delta\theta). \tag{3}$$

Expansion of Eq. (3) in powers of $\Delta\theta$ about the reference position, δ, assuming two dees and N turns yields

$$\frac{E_T(\Delta\theta)}{E_T(0)} = \frac{E_T(\Delta\theta)}{4V_0 N \sin(n\alpha/2)\cos(n\delta)} = \Big[1 - n\tan(n\delta)\Delta\theta - \frac{n^2}{2}\Delta\theta^2 + \frac{n^3}{6}\tan(n\delta)\Delta\theta^3 + \frac{n^4}{24}\Delta\theta^4 \ldots\Big] \tag{4}$$

Equation (4) represents the fractional energy gain for which the reference particle is accelerated with constant δ. However, in the case of a magnetic field that is not quite isochronous, the reference position will vary for each turn defining different δ's. But since the sum of sine waves of different phase is still a sine wave one can assume an effective δ for which Eq. (4) still applies and in this case δ is given by,

$$\tan(n\delta) = \sum_i^N \sin(n\delta_i) \Big/ \sum_i^N \cos(n\delta_i) \tag{5}$$

For small values of $\Delta v = v(\Delta\theta) - v(0)$ we have

$$\Delta v/v = (1/2)(\Delta E/E) = (1/2)(E_T(\Delta\theta) - E_T(0))/E_T(0) = (1/2)\Big[(E_T(\Delta\theta)/E_T(0) - 1\Big] \tag{6}$$

Substituting Eq.(4) in Eq. (6),

$$\frac{\Delta v}{v} = \Big[-\frac{n}{2}\tan(n\delta)\Delta\theta - \frac{n^2}{4}\Delta\theta^2 + \frac{n^3}{12}\tan(n\delta)\Delta\theta^3 + \frac{n^4}{48}\Delta\theta^4 \ldots\Big] \tag{7}$$

The klystron condition, Eq. (1), can be satisfied only for small $\Delta\theta$, hence, neglecting the higher-order terms, one obtains

$$\tan(n\delta) = (2/n)(R/L). \tag{8}$$

Introducing this into Eq. (7) one can write

$$\frac{\Delta v}{v} = \Big[-\frac{R}{L}\Delta\theta - \frac{n^2}{4}\Delta\theta^2 + \frac{n^2}{6}\frac{R}{L}\Delta\theta^3 + \frac{n^4}{48}\Delta\theta^4 \ldots\Big]. \tag{9}$$

Equation (9) expresses the fractional particle velocity distribution in a beam pulse which has been accelerated with the reference particle position, δ, chosen to insure bunching for small $\Delta\theta$. The first, or linear term, expresses complete klystron bunching which represents the fractional velocity difference required to move a particle from its initial position within the pulse, $\Delta\theta$, to the reference position upon its arrival at the target. The non-linear terms can be considered to represent additional displacement of the particle away from the reference position to the particle's final position in the compressed beam pulse. Since the quadratic term is larger than the other non-linear terms some reflection will show that a pulse defined between extremities at $\pm\Delta\theta$ is compressed to an equivalent angular width given by the sum of the non-linear terms for which the argument $+\Delta\theta$ or $-\Delta\theta$ yields a maximum.

One defines the beam pulse compression factor, C, as the ratio of the compressed pulse width to the uncompressed pulse width or,

$$C = \mathrm{Max}_{\pm} \left| \left(-\frac{n^2}{4}\Delta\theta^2 + \frac{n^2}{6}\frac{R}{L}(\pm\Delta\theta)^3 + \frac{n^4}{48}\Delta\theta^4 \ldots\right) \Big/ \frac{R}{L}(2\Delta\theta) \right|$$

or

$$C = \left[\frac{n^2}{8}\frac{L}{R}|\Delta\theta| + \frac{n^2}{12}\Delta\theta^2 - \frac{n^4}{96}\frac{L}{R}|\Delta\theta|^3 \ldots\right] \qquad (10)$$

The compressed pulse length, w_c, is the product of C and the initial pulse length, or

$$w_c = (R2\Delta\theta) = (1/4)\, L\, (n\Delta\theta)^2 \qquad (11)$$

where terms in C of higher order than the first have been neglected. Since the rf phase acceptance angle, $n\Delta\theta$, can be varied over only a limited range, the compressed pulse length, w_c, can be reduced only through a reduction in the klystron bunching path length, L.

However, the energy spread of the beam caused by klystron bunching imposes severe restrictions on the design parameters. From Eq. (1) one derives half the energy spread of the pulse

$$\Delta E/E = (1/2n)\,(R/L)\,(n\Delta\theta)\,. \qquad (12)$$

For a realizable rf acceptance phase, $n\Delta\theta \approx 1/5$, or 12°, and a required energy half width, $\Delta E/E < 0.5\%$ Eq. (12) indicates that $L/R > 20/n$. However, substitution of this value of L/R into Eq. (10) demonstrates that only a beam pulse compression factor of 1/2 is possible for $n = 1$ and compression is impossible for $n > 1$.

ENERGY GAIN LINEARIZATION

In order to obtain klystron compression, the linearization of the particle energy gain as a function of particle position, $\Delta\theta$, has been investigated. If an accelerating field, operating at a harmonic of the main dee system rf frequency, is added to the acceleration region of the cyclotron, the quadratic non-linearity in the particle energy gain can be eliminated. Therefore, it was decided to include a small linearizing, accelerating electrode in the cyclotron tank, see Fig. 1, of angular extent, α_q. Assume an applied voltage, $V = V_{qo} \sin q\omega t$ and consider the azimuthal position of the electrode center line variable, to be defined in terms of δ_q, the angle between its center line and the reference particle at $t = 0$. The calculation proceeds with the power series expansion of the sum of the main dee system voltage gain and the linearizing electrode voltage gain. The coefficient of the quadratic term can be forced to vanish for a minimum voltage on the linearizing electrode when $\delta_q = 0$, that is, when the reference particle receives maximum energy from the linearizing electrode. The condition for cancellation of the quadratic term then determines the ratio of the amplitudes of the energy gains of the main dee system to the linearizing system, or

$$E_\delta(0)/E_q(0) = -q^2/n^2 \qquad (13)$$

and the klystron bunching condition for small $\Delta\theta$ becomes

$$\tan(n\delta) = (2/n)(R/L)(q^2-n^2)/q^2\,. \qquad (14)$$

The expression for the fractional change in velocity along the pulse now becomes

$$\frac{\Delta v}{v} = \left[-\left(\frac{R}{L} - \frac{rq}{2}\frac{n^2}{q}(q\epsilon)\right)\Delta\theta + \frac{1}{6}\left(n^2\frac{R}{L} - \frac{rn^2q}{2}(q\epsilon)\right)\Delta\theta^3 + \frac{rn^2}{48}(n^2-q^2)\,\Delta\theta^4 \ldots\right] \qquad (15)$$

where $(-q\epsilon)$ represents the "wandering" or gradual shift of the linearizing rf phase relative to the main rf system and $r = q^2/(q^2-n^2)$.

The compression factor, C, is calculated as before

$$C = \left[\frac{r}{2}\frac{n^2}{q}\frac{L}{R}(q\epsilon) + n^2\left(1 - \frac{rq}{2}\frac{L}{R}(q\epsilon)\right)\Delta\theta^2 + \frac{q^2n^2}{96}\Delta\theta^3 \ldots\right] \qquad (16)$$

For the NRDL cyclotron we set $q = 3n = 9$ and $L/R = 20$. Assuming $r \approx 1$ the compression factor is

$$C = 10(q\epsilon) + (9 - 100(q\epsilon))\Delta\theta^2 + 9.6\Delta\theta^3 \ldots \qquad (17)$$

Equations (16) and (17) indicate that very little non-linearity remains and the main obstacle to large pulse compression is the experimentally unavoidable fluctuation in the phase between the main small rf system and the linearizing rf system, $(-q\epsilon)$. For the NRDL cyclotron Eq. (17) yields $C < 1/3$ for $(q\epsilon) < 2^{\circ}$ and the value of $\Delta\theta$, definining the original pulse length, is not critical. Furthermore, the total energy spread, from Eq. (12), is seen to be less than 1% for $\Delta\theta = 1/4$ or 15°.

Figure 3 illustrates the linearization of the particle energy gain by the addition of a ninth harmonic.

CYCLOTRON CURRENT OUTPUT

Experience with existing cyclotrons indicates that instantaneous beam pulse currents of 30 mA are readily obtained. As an example, consider the NRDL cyclotron operating in the third harmonic mode of acceleration with an rf ion phase acceptance angle of 25° and a pulse repetition frequency of 0.3 Mc/sec. The average current output will be

$$I = (25^\circ/360^\circ)\ (0.3\text{Mc/sec}/33\text{Mc/sec})\ 30\text{mA} = 0.019\text{mA or } 19\mu\text{A} \qquad (18)$$

which represents about the maximum current that can be accepted on a gas target. However, at higher energies it is to be expected that the lower particle stopping power in the target foil and gas will allow average beam currents approaching 100μA. These larger currents will be obtained by increasing the pulse repetition rate. A comparison of the cyclotron beam pulse length and beam current with that of single stage dc accelerators[5] is quite favorable but of course the ease of energy variation and the beam quality of dc accelerators are superior to that of the cyclotron even though these are not so crucial in the case of neutron time-of-flight experimentation. At higher energies, however, where dc accelerators are forced to use tandem techniques, the cyclotron appears distinctly superior, supplying large beam currents at low pulse repetition frequencies.

REFERENCES

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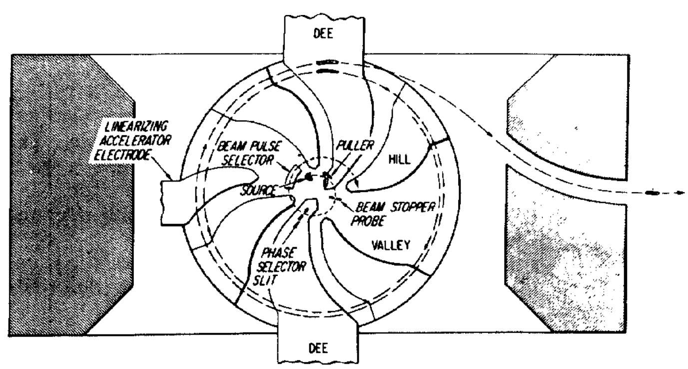

Fig. 1. A schematic view of the NRDL cyclotron showing the special components used for the formation of short beam pulses.

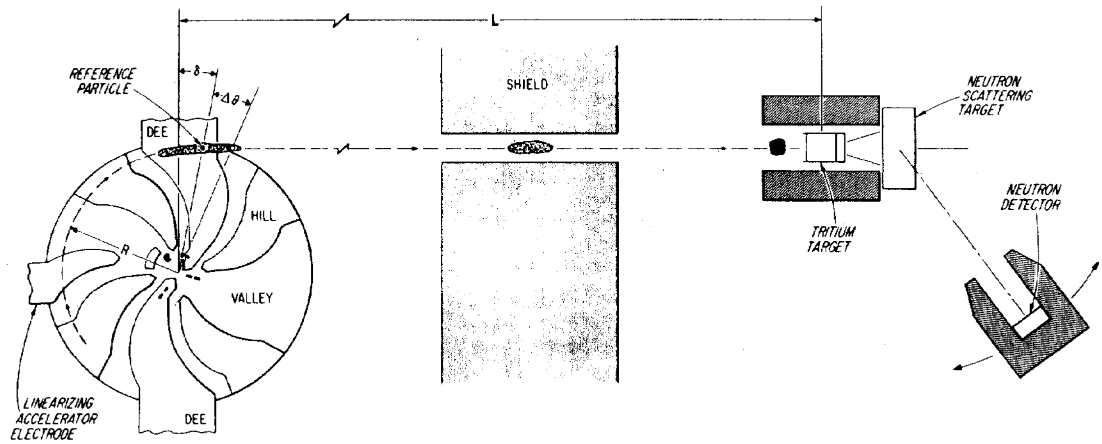

Fig. 2. A schematic view of a neutron time-of-flight scattering experiment.

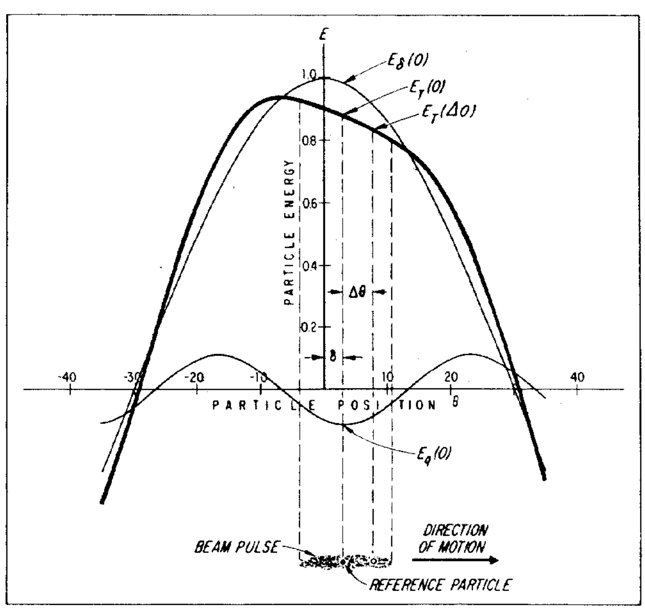

Fig. 3. Linearization of the sinusoidal particle-energy characteristics by the addition of a ninth harmonic.