BEAM PULSE SELECTOR FOR A SECTOR FOCUSED CYCLOTRON

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SUMMARY

For the U. S. Naval Radiological Defense Laboratory's (NRDL) 70-inch sector-focused cyclotron a beam-pulse selector system has been developed by means of which an individual beam pulse or "fish" can be selected near the center of the machine and then accelerated to full energy and extraction. The beam is normally deflected axially into a beam stopper by a negative dc voltage of 10.5 kV applied to the deflector plates via a helically wound coaxial line of 2000 ohms characteristic impedance. An individual fish is transmitted by applying a 5.5 kV positive pulse of less than 40 nsec duration at the input of the coaxial line.

INTRODUCTION

Proposed time-of-flight experiments with the NRDL 70-inch cyclotron require very short external beam bursts separated by relatively long periods of time.[1] This beam timing can be accomplished by means of a beam pulse selector, which is located near the center of the machine and which rejects beam pulses by deflecting them axially into a beam stopper. Placing the beam pulse selector at the center of the cyclotron is desirable to minimize the internal circulating beam and thus reduce radiation background and radioactivity products within the machine. The choice of axial deflection to accomplish beam pulse selection is suitable because of the low magnetic focusing forces and the large orbit separation near the center of the cyclotron.[2] For neutron time-of-flight experiments the beam-pulse selector must be capable of selecting very short individual ion pulses, or "fish", from the normally deflected pulse train, for further acceleration. It will be shown that a high-voltage pulse of less than 40 nanoseconds duration will be required on the deflector. Cooling of the deflector plates is not necessary as the plates will never be hit by the beam. One of the water-cooled, graphite-lined, dummy dees constitutes the beam stopper.

THE BEAM PULSE SELECTOR AND THE COAXIAL LINE

A layout of the geometrical arrangement of the beam pulse selector is shown in Fig. 1. Also pictured are three fish at their respective positions at a given time for the third-harmonic mode of acceleration. The dashed line represents the beam orbit center line. The beam is normally deflected into the beam stopper by a negative dc voltage applied to one of the deflector plates via the helically wound coaxial line. In order to let a single fish pass the deflector for further acceleration to full energy, the negative bias voltage on the deflector plate is cancelled while the fish passes through the deflector. This

is accomplished by feeding the coaxial line with a positive voltage pulse which equals the negative bias voltage. This voltage pulse must be short enough to insure complete deflection of the two fish adjacent to the selected fish. For our deflector design of 45° azimuthal extent and an ion fish of 10° azimuthal length (30° rf phase width in the third-harmonic mode), the maximum length of the positive voltage pulse must be less than 40 nsec when the operating rf is 33 Mc/sec, corresponding to a particle cyclotron frequency of 11 Mc/sec.

For our geometry and azimuthal extents, as labeled in Fig. 1, the electrical field strength K_1, needed to deflect the beam an axial distance, d, in the presence of focusing field components K_2 and K_3 of the acceleration voltage across the succeeding dee gaps, can be found from the following equation (in MKSA units),

$$d = \frac{e}{m} \cdot \frac{1}{\omega_p^2}\left[K_1\alpha(\frac{\alpha}{2}+\beta+\gamma+\delta+\epsilon+\xi)+K_2\gamma(\frac{\gamma}{2}+\delta+\epsilon+\xi) + K_3\epsilon(\frac{\epsilon}{2}+\xi) \right] \qquad (1)$$

where $\frac{e}{m}$ is the charge to mass ratio of the particle and ω_p is the particle angular frequency.

Estimating the focusing field in succeeding gaps to be $K_2=K_3=(-1.6)10^{-5}$ V/m, with $d=(2.5)10^{-2}$ m and the angular extents of α, through ξ as given below, we find for protons that $K_1=(4.20)10^5$ V/m requiring a voltage of $V_1=10.5$ kV across the deflector plates when the plates are separated $(2.5)10^{-2}$ m.

α = 0.785 radians	(deflector)
β = 0.593 radians	
γ = 0.192 radians	(dee gap)
δ = 0.681 radians	
ϵ = 0.200 radians	(dee gap)
ξ = 2.000 radians	

Thus, a 10.5kV bias must be applied to the deflector plates for complete deflection of the beam into the beam stopper. Using the advantage of voltage doubling at the open end of a coaxial line only 5.25kV must be applied to the line if losses are neglected along the line. In order to reduce the current in the coaxial line the inner conductor is helically wound to give a characteristic impedance of 2000 ohms. Formulas for calculating helical lines can be found elsewhere.[3,4] In our case the helix is wound with copper wire of 0.725 mm diameter on a tube of polystyrene of 12.5 mm diameter with 1100 turns/m. The inside diameter of the grounded copper tube is 44.5 mm. The helix is held in place by insulator-spacers made from berylliumoxide, see Fig. 2.

In the model version of the coaxial line of 2.4 m length the rise time of the output pulse was measured to be 15 nsec. Figure 3 shows the output of the coaxial line for a 20-nsec square-wave input. The peak output to input voltage ratio was found to be 0.96, i.e., an attenuation of 0.817 dB/m. The attenuation will probably be somewhat smaller in the final version where we intend to use silver-plated copper wire as well as silver-plated inner surface of the copper tube. The time delay of the pulse through the 2.4 m helical line was 230 nsec.

THE PULSE POWER AMPLIFIER

As the dc bias voltage on the deflector plate has to be negative with respect to ground in order to avoid discharge the voltage pulse fed into the coaxial line for cancellation of the dc potential must be positive. This imposes a problem for electron tubes used in the output stage of the pulse power amplifier as the output tubes must be conducting only during the pulse in order to deliver large currents. Thus one has either to use a transformer for phase inversion or a cathode follower in the final stage. With the requirements as given above a positive voltage pulse of about 5.5 kV is needed. Since the 2000-ohm line is terminated to eliminate reflections at the input end, the resultant input impedance is 1000 ohms. A voltage of 5.5 kV across 1000 ohms requires 5.5A and 30.25 kW peak power. Assuming an effective pulse length of 30 nsec the average power dissipation will be

$$P_a = (30.25)10^3 (30)10^{-9} . f = (90.75)10^{-5} . f \quad W \qquad (2)$$

and the average current from the voltage supply

$$I_a = (5.5)(30)10^{-9} . f = (1.65)10^{-7} . f \quad A \qquad (3)$$

where f is the pulse repetition frequency. A tube which is found adaptable to pulsing in the nano-second region and capable of delivering high currents at the high voltages required is the UHF Planar Triode ML-8533. This tube allows a maximum average plate dissipation of 100 W. Operating at a plate voltage of 7.5 kV the average plate dissipation will be

$$P_p = (7.5-5.5)10^3 (5.5)(30)10^{-9} . f = (33)10^{-5} . f \quad W \qquad (4)$$

Setting the plate dissipation at its maximum value, $P_p = 100$ W, the permissible pulse rate will be $f = 3.10^5$ c/sec. Substituting this value of f in Eqs. (2) and (3) give $P_a = 272$ W and $I_a = 50$ mA.

As the voltage pulse has to be properly synchronized to the rf, a phase-adjusting circuit is incorporated. This is shown in the block diagram of the electronic apparatus in Fig. 4. A pickup coil, located in the rf system near one dee, delivers a signal to a phase-shifting bridge circuit which allows phase changes of nearly 180°. As can be seen from the block diagram the signal from the pickup coil is also fed into a frequency-dividing scaler from which output pulses can be used to trigger a gate circuit, which in turn passes the phase-adjusted pulses to a pulse shaper and preamplifier. The output pulse from the preamplifier is fed to the main power amplifier which drives the coaxial line. The main power amplifier consists of three stages. The first stage uses a UHF Planar Triode ML-2711 and the other two stages use UHF Planar Triodes ML-8533. Phase inversion between the stages is accomplished by transformers with ferroxcube cores. The length of the wire used in a winding of these transformers must be short so that the propagation time of the pulse in the winding is short compared to the pulse length. Otherwise, the reflected pulse in the winding gives rise to a double pulse in the output. Because the relatively high power in the output stage requires a big core for the transformer, the winding is long giving the transformer poor pulse characteristics. Therefore, we have eliminated the transformer and chosen a cathode follower. The rise time of the output pulse is around 10 nsec and the pulses are acceptable for driving the coaxial line.

The pulse power amplifier will be placed directly at the input end of the coaxial line outside the vertical yoke of the magnet where the stray magnetic field is relatively low. However, the amplifier will require additional magnetic shielding.

REFERENCES

1. H. A. Howe, et. al, Paper EE-16, Particle Accelerator Conference, Washington, D. C., March 1965.
2. M. Reiser, et. al, Paper HH-16, Particle Accelerator Conference, Washington, D. C., March 1965.
3. Lewis and Wells, Millimicrosecond Pulse Techniques, pp 42-52.
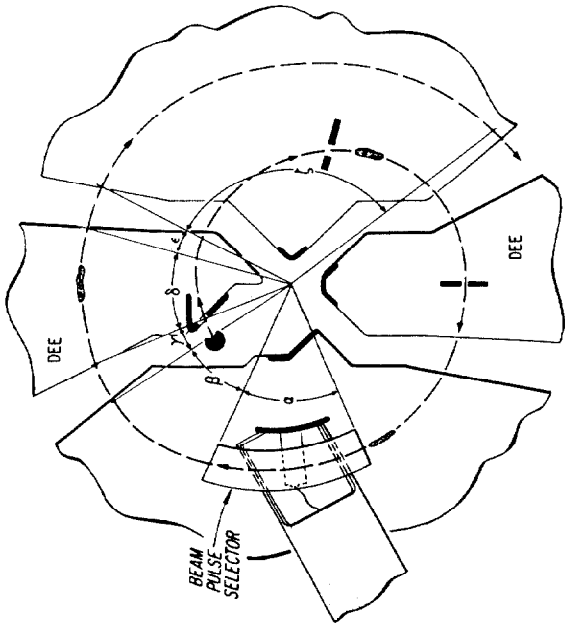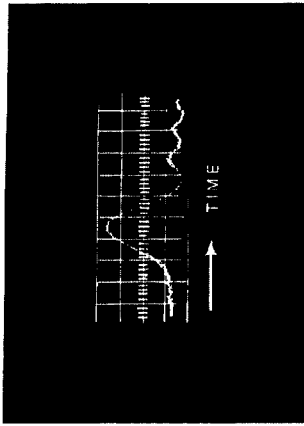4. Terman, Radio Engineers Handbook, p.74; pp. 77-80.

Fig. 3. Picture of voltage pulse at the deflector plates for a 20-nsec, square-wave input pulse. The time scale is 10 nsec/main div.

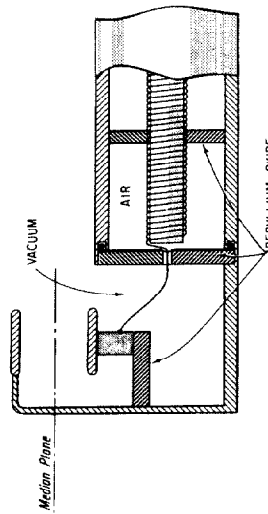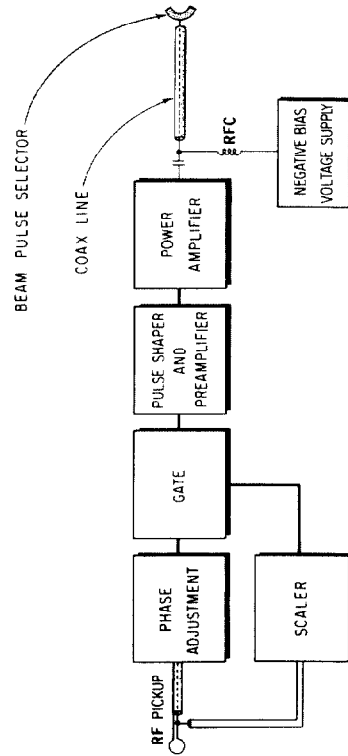Fig. 4. Block diagram of the electronic apparatus for the beam pulse selector.

Fig. 1. Geometrical arrangement of the beam pulse selector.

Fig. 2. Vertical section of coaxial line and deflector plates.