A PULSE SELECTION AND SHORTENING SYSTEM FOR CYCLOTRONS

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Abstract

The design and performance of a system for selecting and shortening beam pulses near the cyclotron center is reported. The pulse selector gates from one in two to one in 79 pulses in the cyclotron beam. The pulses selected for acceleration are shortened by a unique axial RF deflection system which allows the central portion of the pulse to pass unattenuated. The external cyclotron beam has been measured to be 0.3 x 10^{-12} coulomb per pulse with 0.8 ns width at 10% above the baseline. The rejection of unwanted pulses is typically over 400 to 1 for long term measurements.

Introduction

The Model CV-28 cyclotron manufactured by The Cyclotron Corporation accelerates $^{1}H^{+}$ over the range of 2-24 MeV, $^{2}H^{+}$ over the range of 4-14 MeV, $^{3}He^{++}$ over the range of 6-36 MeV and $^{4}He^{++}$ over the range of 6-36 MeV. All acceleration is in the fundamental mode. Pulse selection or phase limiting devices are normally not employed.

The basic CV-28 design was modified by The Cyclotron Corporation to meet the requirements of a particular user (1) for intense, short beam pulses with a repetition rate adjustable to submultiples of the orbit frequency. A further requirement for low radiation background from the cyclotron demanded that pulse selection and shortening be done near the cyclotron center.

The system which was developed comprised four subsystems: (1) pulse selector, (2) pulse shortener, (3) satellite trimmer, (4) non-intercepting beam monitor. Figure 1 shows schematically the arrangement of these devices. Design considerations and overall results are summarized below. The development and testing were completed in June of 1976.

Pulse Selection

The cyclotron beam is effectively blocked by an axial electric field which covers about 90 degrees of the first turn. This field induces an axial oscillation which causes the ions to strike a horizontal collimator located in the dee electrode. The electric field required to completely eliminate the beam depends directly on the beam height, the collimator aperture, the square of the orbit frequency, and the vertical focusing frequency. The required field also depends inversely on the length of the deflecting electrode (in radians). If the beam height is 6mm, the collimater 6mm, the orbit frequency 22 MHz, the vertical focusing frequency 1/6, and the azimuthal extent of the deflecting field is 1.5 radians, then about 1.3 x 10^{5} volts per meter are required to cleanly eliminate the beam. When it is desired to "gate" a beam pulse for further acceleration the axial deflection field is removed by an electronic pulser.

Pulse Shortening

Once a pulse has been selected for acceleration it must be shortened if it is to be extracted on a single turn. Vertical slit and post systems commonly used for pulse shortening collimate too many ions within the allowed pulse width. To overcome this difficulty the beam pulses are shortened by causing several turns to pass through a time varying axial electric field whose frequency is an integral multiple of the orbit frequency. The phase of the axial field is adjusted so that the portion of the pulse to be saved for further acceleration passes the center of the axial field at the time when the field is zero. Ions arriving earlier are deflected upward (or downward) and collimated while ions arriving later are deflected downward (or upward) and collimated. Ions which pass the center of the deflection region when the field is zero are not deflected and, since the collimator spacing exceeds the axial beam height, are not collimated. If the axial shortening field has sufficient radial extent to include one complete axial betatron oscillation the ions at the leading and lagging ends of the shortened pulse will be recentered about the cyclotron median plane. This process is illustrated in figure 2.

The electric field required to produce a given pulse length depends on the azimuthal extent of the field, the vertical focusing frequency, the collimator spacing, the orbit frequency, and the number of turns passing through the field. Typically a peak electric field of 3 x 10^{6} volts per meter at three times the orbit frequency will produce a one nanosecond full-width at tenth maximum pulse if the vertical focusing frequency is 1/6 of the orbit frequency (at 22 mHz), the collimator gap is 6mm and the azimuthal extent of the field is 0.25 radians. The phase jitter of the shortening field with respect to the orbit frequency must be an order of magnitude less than the phase width of the shortened pulse.

The use of a time-varying field for pulse shortening does increase the energy spread in the pulse. Acceleration in the shortening field depends on the axial position of the ions. Since the leading and lagging portions of the pulse occupy, on the average, different axial positions, differential acceleration is unavoidable. This effect is minimized by using a small axial collimator spacing and delivering a beam of small vertical height to the shortener. In practice the energy spread introduced by the pulse shortener is much less than the energy gain per turn and does not disturb single turn extraction.

Satellite Pulse Trimmer

Between 5 and 10 KV of RF synchronized to a submultiple of the cyclotron orbit frequency is applied to the cyclotron electrostatic deflector so that it operates as a post acceleration beam chopper as well as an extractor. This has two advantages. It

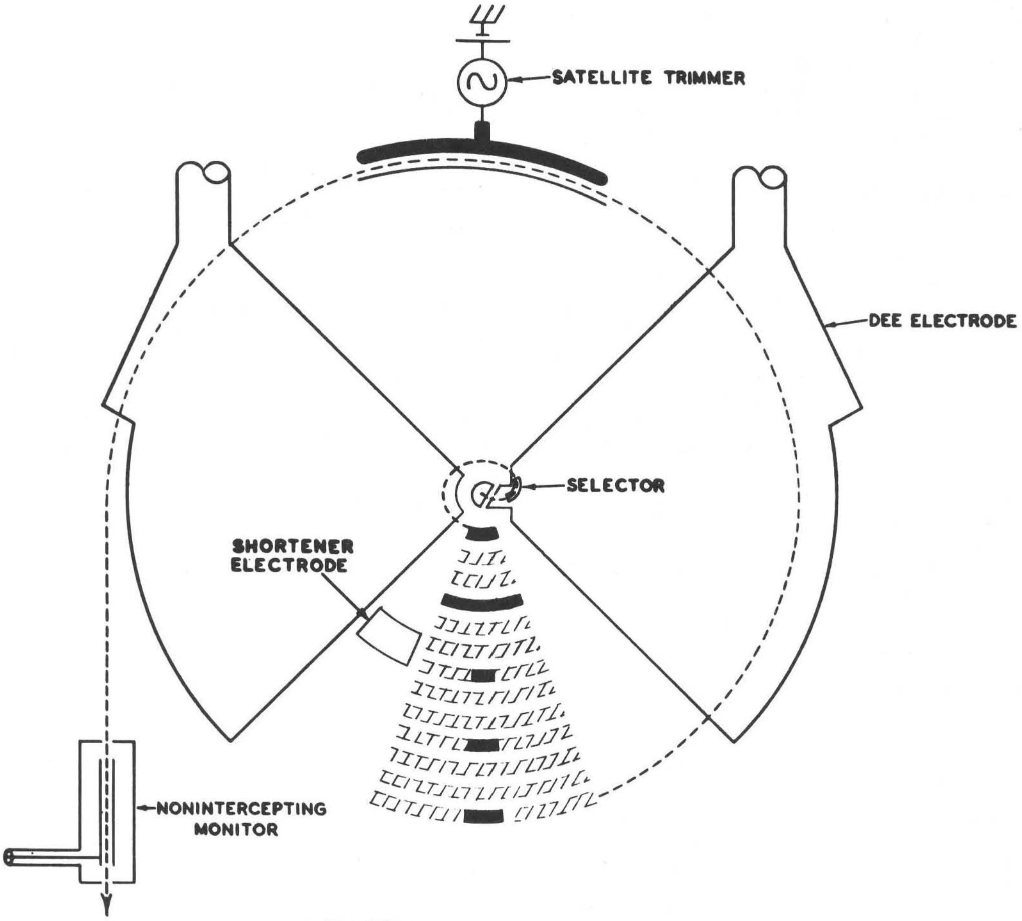

FIGURE 1
BEAM DEVICES ADDED TO CV-28 CYCLOTRON FOR PULSE OPERATION

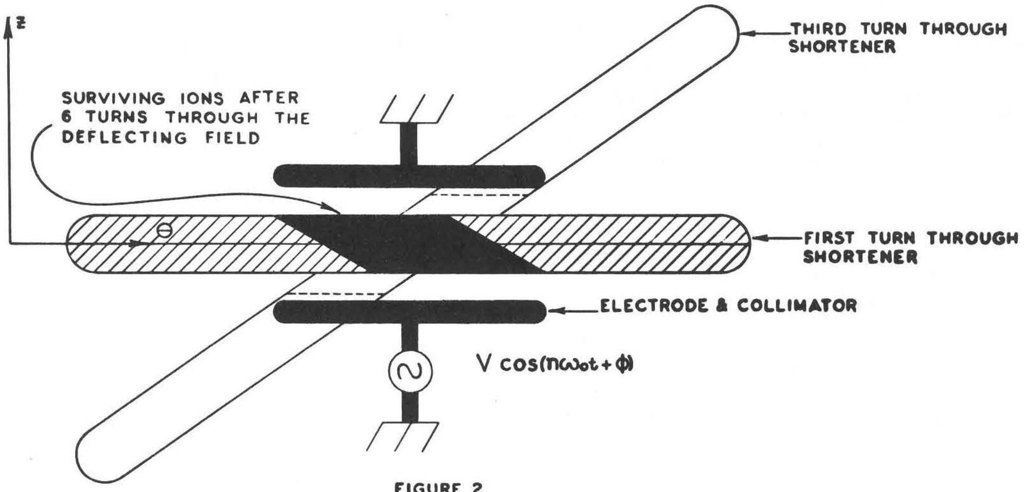

FIGURE 2
BEAM ENVELOPE IN θ & z FOR TURNS 1, 3, AND 6 IN SHORTENER

allows elimination of satellite pulses even if one desires a pulse length longer than that required for single turn extraction. Further, it reduces the degree of positional stability that would be required of the beam if satellite elimination were accomplished entirely by single turn extraction. From a practical point of view this facilitates satellite pulse elimination over long term measurement periods. Since only relatively small amounts of beam are interrupted at high energy, the radiation background is not substantially increased.

Non Intercepting Beam Monitor and Tuning

In order to obtain and maintain a beam of short intense pulses without interference from satellite pulses, it is necessary to see the time structure of the external beam. The nonintercepting beam monitor is a tube through which the external beam must pass and which forms the inner conductor of a 50 ohm transmission line. The downstream end of the tube is connected to a high quality, 50 ohm transmission line which connects to a fast real-time oscilloscope. When the beam enters the tube it induces a wave on the transmission line which has the time structure of the beam pulse. When the pulse exits from the tube a pair of reflected pulses are generated; these may be clearly distinguished from the entering pulse if the tube is longer than the beam pulse. The first step in obtaining a pulsed beam is to select one pulse out of N (N between 2 and 79 inclusive) RF cycles for acceleration. This pulse is then extracted and its time strucuture observed. Typical displays and the radius-phase envelopes which produce them are shown in figures 3.a and 3.b. The beam condition illustrated in figure 3.a is usually what is achieved without fine tuning. In this case the central intense core of the beam pulse has not been centered on the R.F. accelerating potential and has consequently been spread out radially and diffused. By tuning the cyclotron profile coils and main magnetic field the condition illustrated in figure 3.b is achieved. This condition is clearly indicated by an intense leading pulse followed by paired trailing pulses. If the ion source slit is too wide or the inner harmonic coils are mistuned, a small prepulse is observed along with a non-zero valley in the center of the first lagging pulse. Experience indicated that a real-time nonintercepting beam monitor is a very powerful tool for rapidly diagnosing beam quality and tuning the pulsed beam.

Equipment-Description-Pulse Selector

The pulse selector deflection field is formed by a small plate located behind the puller aperture which is held at a potential of +2000 VDC with respect to the dee. The deflecting plate is connected to a high-power distributed amplifier through a low-loss 125 ohm coaxial transmission line which is brought out along the dee stem and down the resonator strap.

The dee structure normally operates at a negative DC potential with respect to ground to prevent multipactoring. Provision is made for connecting the necessary bias potentials while preventing RF leakage which would disturb overall system operation.

The center conductor of the pulse-selector line carries the positive deflection bias. The outer conductor is at the same potential as the dee and carries the negative dee bias. The whole line is decoupled for RF by means of a "stub" which acts as a high impedance over the range of operating frequencies of the cyclotron.

The pulse-selector distributed amplifier comprises five sections, each of two 4CW800B beam tetrodes in parallel.

The plate networks provide the lumped equivalent of a 125 ohm transmission line. The near end of the line is terminated by a 125 ohm, 10 KW water-cooled resistor.

A negative 2000 volt pulse is required to remove the deflection bias. A -1000 volt pulse is sent down the line which doubles at the far end due to constructive interference with the reflected pulse. The peak current supplied by the pulse amplifier is 1000/(Zo/2) = 16 amperes, including the component which is absorbed in the terminator at the near end. The duty factor is adjustable from one pulse per 2 RF cycles to one pulse every 79 RF cycles.

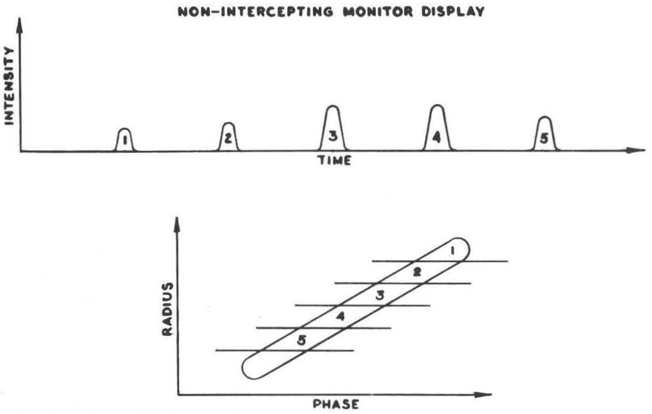

FIGURE 3.A A NON-SYMMETRICAL RADIUS-PHASE ENVELOPE WITH REDUCTION IN PEAK PULSE CURRENT DUE TO ENERGY SPREAD IN THE CENTRAL CORE OF THE BEAM

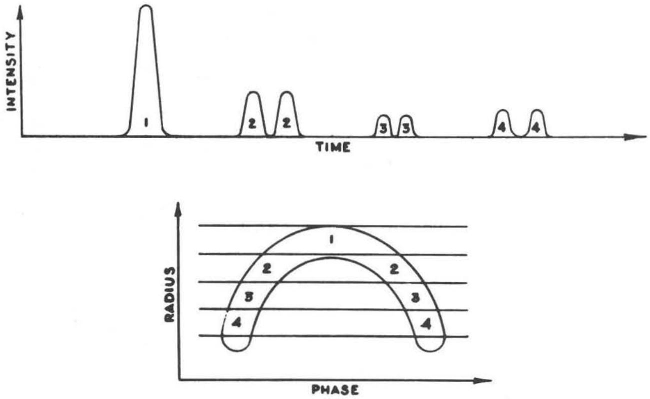

FIGURE 3.B A PROPERLY TUNED RADIUS-PHASE ENVELOPE & ITS RESULTING DISPLAY

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Pulse Shortener

The high-frequency sinusoidal field for pulse-shortening is provided by a high-powered phase-locked oscillator shown in simplified schematic in figure 4. The heavy horizontal line represents the stem supporting the deflecting electrode. This structure constitutes a foreshortened half-wave line. The dotted line denotes an RF standing wave. Coupling the anode and grid of a triode tube to the line as illustrated, provides the conditions for sustained oscillation.

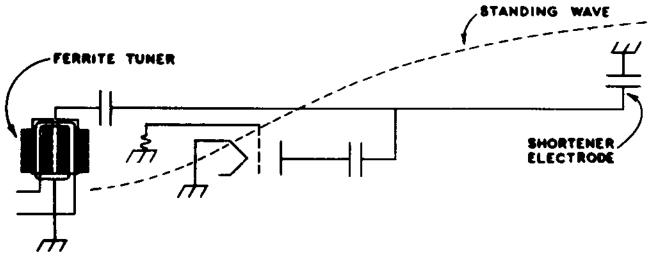

FIGURE 4
SIMPLIFIED PULSE SHORTENER OSCILLATOR CIRCUIT

The frequency of oscillation may be coarsely varied by changing the length of the resonant line. This is accomplished by means of a sliding trombone section in the anode portion of the line. The grid end of the resonant line is foreshortened by an air dielectric capacitor. The precise frequency and phase of the oscillator are controlled by changing the amount of energy stored per cycle in the magnetic field in the ferrite tuner shown in figure 4. The energy stored is a function of the permeability of the ferrite material which, in turn, can be varied by applying a DC bias field through a control winding. Normal operating bias is approximately 2000 ampere-turns per meter. The ferrite must operate well into saturation so as to minimize RF losses.

The pulse-shortener oscillator operates at a harmonic relative to the main cyclotron oscillator. The particular harmonic depends on the frequency of the main oscillator and may be varied between N=6 (cyclotron frequency = 7 mHz) and N=2 (cyclotron frequency = 22 mHz). The pulse-shortener oscillator is most efficient in the range of frequencies between 38 and 45 mHz. In general the effectiveness of the pulse shortener depends on the rate of change of voltage at the deflecting electrode so that higher harmonics are more effective for a given field amplitude. However, too high a harmonic may actually permit the "tails" of the ion bunch to be accelerated.

The pulse-shortener must be precisely synchronized with the cyclotron oscillator so as not to degrade the quality of the beam pulse. Phase coherence between the two oscillators is maintained within one degree at the cyclotron frequency through the use of phase-lock control of the ferrite tuner.

The phase lock control system includes a dynamically variable loop-gain adjustment capability so that under sparking conditions the loop can quickly recover and acquire lock, while maintaining tight tracking under normal operating conditions.

Satellite Trimmer

The satellite trimmer is a class C grounded grid amplifier capacitively coupled to the cyclotron extraction system which, in turn, forms part of the amplifiers' resonant anode structure. Fine tuning of this resonant structure is accomplished by means of a motor-driven variable capacitor.

This amplifier is cathode-driven by a broadband distributed amplifier, which is driven, in turn, by a pulse train synthesized in frequency and adjustable in phase such that:

$$F_{\text{trimmer}} = \frac{\text{INT}\quad(N/2)}{N} \times F_{\text{orbit}}$$

where 1/N = pulse selector duty cycle, and INT ( ) means integer part of ( ).

Results

A summary of test results are given in table 1. The system does indeed provide single turn extraction of narrow, high-amplitude pulses. Tuning of the system is straightforward using the non-intercepting beam pickup.

Acknowledgements

The authors would like to acknowledge several fruitful discussions with Dr. R. Jahr which contributed to the development and testing of this system. The measurements reported in Table 1 were carried out by the staff of the PTB Braunschweig, West Germany.

MEASURED

ION	Energy MeV	N	Freq. MHz	Pulse Width 10% Base	External μa Beam	Pulse Charge μa-ns	Charge Satellites / Charge	Test Time
PROTONS	18	3	23.14	1.00	1.88	.244	400/1	6 Hr
	18	10	23.14	.8	.59	.255	100/1	2 Hr
	14	3	21.01	1.15	1.9	.271	300/1	6 Hr
	14	10	21.01	1.15	.76	.363	50/1	2 Hr
	10	3	17.6	1.32	1.5	.251	400/1	6 Hr
	10	10	17.6	1.34	.3	.175	600/1	2 Hr
	6	3	13.3	1.7	1.36	.307	1200/1	6 Hr
	6	10	13.3	1.7	.7	.528	450/1	2 Hr
$^2D^+$	14	10	14	.95	.548	.391	180/1	2 Hr
	10	10	11.8	1.0	.421	.355	50/1	2 Hr
	5	10	8.4	1.29	.158	.188	300/1	2 Hr
$^3He^+$	36	10	18.2	1.0	.332	.182	200/1	1 Hr
	18	10	13.2	1.4	.190	.119	60/1	1 Hr
	5	10	7.0	1.9	.027	.04	100/1	1 Hr

TABLE # 1