USE OF A DEBUNCHER TO OBTAIN VARIABLE ENERGY FROM A LINEAR ACCELERATOR BEAM*

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Introduction

The amount of charge which can be captured in a proton synchrotron is limited, for the usual case of constant injection energy, by the presence of large radial betatron oscillations. The restriction of beam motion to small oscillation amplitudes, therefore, offers the possibility of a significant increase in beam.[1] A system for realization of such an improvement has been implemented at the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory (ANL).

During injection at constant energy, those particles injected at the beginning of the pulse will have the minimum radial betatron amplitudes; those at the end of the pulse will have the largest possible within the confines of the vacuum chamber. To first order approximation, the amplitude distribution is continuous from r_d (Fig. 1) to the radial half-width of the aperture, A. The quantity of charge captured at RF turn-on can be calculated as a function of the injection phase angle and the result integrated to give the capture ratio. When this is done for the case where $A = \overline{r_s}$, the radial limit of stability of the ring acceptance, the fraction captured is 0.24.

However, when the injection energy is increased during the pulse, the equilibrium orbit can be adjusted to be stationary just outside the inflector at radius r_d. The betatron amplitude will be constant for all particles and can be selected at the particular value which will optimize the coasting beam efficiency. For $A = \overline{r_s}$, the fraction captured is 0.36; in addition, the injection pulse length can be doubled since the turns can now be brought all the way into radius r_i. The relative charge efficiency at this condition is then 3 times that of the constant energy case. The effectiveness of the variable energy decreases, however, as the ratio $A/\overline{r_s}$ changes from the minimum value of 1 to higher values. Figure 2 lists some of the values. The two efficiency curves cross over at about $A/\overline{r_s} = 2$. Therefore to have an advantage $1 \leq A/\overline{r_s} \leq 2$, it should be noted that some improvement in capture by slow RF turn-on will accrue in either case. The variable energy case is much more tolerant of frequency errors at turn-on, since the resulting radial displacement would not cause a loss in beam unless $\Delta r \geq A - \overline{r_s}$.

ZGS Requirements

The radial shrinkage rate in the ZGS is given by:

$$\dot{R} = \frac{-R\dot{B}_0}{B_0 \nu_x^2} = 0.06\text{-in}/\mu s$$

where

$\dot{R}$ = radial shrinkage rate

R = 1020-in, the equilibrium orbit radius

B_0 = 480 G, the injection field

$\dot{B}_0$ = 20,000 G/s, the field rate of rise at injection

ν_x = 0.83, the radial betatron oscillation frequency

The ring RF bucket width is 720 keV, or 12-in in radial extent on the phase acceptance plot. The maximum usable energy variation is, therefore, ± 360 keV. The maximum pulse length for useful beam is:

$$t = \frac{12\text{-in}}{0.06\text{-in}/\mu s} = 200\ \mu s$$

At present a pulse length of 70 to 80 μs is the maximum captured for constant injection energy. The increased pulse length of the variable energy scheme represents a charge efficiency improvement factor of approximately 2.5, neglecting any advantage in reduced sensitivity to radial errors during RF turn-on.

The maximum energy error which can be tolerated during energy modulated injection has been chosen to be ± 30 keV, a value which corresponds to a radial deviation of ± 0.5-in, or a tolerance of ± 8%.

RF System Requirements

The fast variation in particle energy during injection is obtained by electronically shifting the phase of the debuncher RF relative to the linac. The normal debunching operation occurs simultaneously with the energy programming. Experiments with the debuncher and ZGS have shown that under conditions of constant injection energy

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the capture increases as less debunching is applied. The curve falls off as the bunching mode is entered because the increased energy spread spills beam out of the RF bucket.

The peak RF voltage in the cavity is dependent upon the degree of linearity required in that portion of the waveform covered by the phase modulation. Based on the values from the previous section, we now require that even the particles at the extremes of energy spread deviate from the design energy by ± 8% maximum so that for a linac energy spread of ± 370 keV, the total cavity voltage is:

$$V_{peak} = \frac{360 \text{ keV} + 370 \text{ keV}}{\sin (38°)} = 1.18 \text{ MV}.$$

Assuming that the only source of error is in the waveform linearity, the required phase program range for an energy variation of ± 364 keV is:

$$V = \pm\ 364 \text{ kV} = V_{peak} \sin \phi = 925 \text{ kV} \sin \phi$$

and

$$\sin \phi = \frac{+\ 360 \text{ kV}}{1.18 \text{ MV}} = \pm\ 0.305$$

or

$$\phi = \pm\ 17^{\circ}$$

is the necessary phase range.

Experiments performed with the debuncher showed that the phase range required to modulate the linac beam ± 363 keV was $48^{\circ} \pm 5^{\circ}$. These data confirm the calculations.

Power measurements on the debuncher indicate that 62.8 kW accelerates 15 mA of beam to an energy 363 keV greater than the linac mean energy. This measurement was made at a peak cavity voltage of 750 kV. Extrapolation of these data to 1.18 MV yields a power requirement of 214 kW maximum for 25 mA of injected beam.

The contributions of the various components in the phase loop are specified by the energy tolerance of ± 8%, maximum, and must be considerably smaller than that to insure commensurate accuracy at intermediate points. The phase feedback loop has been designed to maintain $\pm\ 0.2^{\circ}$ stability throughout the program.

The simultaneous phase and amplitude modulation of the RF produces a relatively narrow band spectrum primarily because fast waveforms are not required in either loop. Fourier analysis of the phase ramp signal showed that the 30th harmonic was adequate to present a waveform with less than 2% distortion. The bandwidth for distortionless transmission of the phase modulation is 246 kc; the amplitude modulation spectra is of the same order.

System Components

The block diagram, Fig. 3, shows the elements of the system. The RF amplifier designed and built by RCA to ANL specifications, consists of three stages using coaxial cavities. The final amplifier, using a type 4616 tetrode, is operated in grounded cathode configuration. The driver and predriver stages use type 7651 beam power tubes in cathode drive configuration. The power gain is 46 dB; 8 W of drive is required for 350 kW output. The overall amplifier bandwidth is 3.5 MHz centered at 200 MHz. The pulse repetition rate when operated with the ZGS is one pulse in two seconds, but operation at a duty factor of 6% with a 500 μs pulse is possible. The plate efficiency is between 62% and 70%

Approximately 100 feet of Andrew-type H7-50A, 1-5/8-in, 50 Ω, Heliax cable is used for the transmission line between the amplifier and debuncher cavity. The 200 MHz attenuation for this length of line is quite low, being of the order of 0.3 dB. The Heliax is pressurized to about 1 atmosphere of sulphur hexafluoride, and is capable of holding over 500 kW at the operating VSWR.

The debuncher cavity and coupling loop offer a 50 Ω load to the system with a VSWR of 1.07 to 1. The cavity is 37.23-in long and 30.00-in in diameter. The interior structure consists of two cells, formed by one whole and two half-drift tubes. The cavity body was constructed of aluminum with copper end walls. The shunt resistance is approximately 5.5 MΩ.

The 8 W pulsed RF drive is obtained from either a small coupling loop on the linac or from a low level stage in the linac transmitter.

The 4616 plate voltage is applied continuously and the unit is amplitude modulated by pulsing the screen grid. The pulse is generated by transistorized circuitry which is synchronized to provide a pulse slightly shorter than the 500 μs RF drive pulse. The variation in cavity gradient due to the changing beam loading is regulated by the amplitude level feedback loop, consisting of the envelope detector, reference generator, difference amplifier, driver, and modulator. The error signal is derived from a comparison of the integrated cavity RF pulse and an artificially integrated reference pulse. Maximum loop gain with 15 dB amplitude margin is 40 dB. The reference pulse with which the detected cavity pulse is compared for the derived error signal exhibits a short term voltage stability of 1 part in 10^4. A 10 μs delay is incorporated in the reference pulse channel to reduce transients caused by loop time delays.

Electronic fault protection is provided by a type 7390 hydrogen thyratron which discharges the 4616 plate storage capacitor bank through a 20 Ω resistor when an overcurrent is sensed in either the plate or screen circuit. The screen pulse is also blocked simultaneously by removing drive to the 4-1000 A modulator.

The phase feedback loop is of second order and, in addition to the RF amplifier and debuncher, consists of the 200 MHz phase detector, difference amplifier, summing amplifier, ramp generator, and phase modulator. The ramp generator produces a 80 to 240 μs ramp with a linearity of ± 1%. The length of the ramp is adjusted to coincide with the injection pulse. The ramp amplitude controls the energy variation in the beam. An initial phase adjustment is made via a mechanical line stretcher to provide the correct phase for the start of the sweep. The initial bias on the Varactor phase modulator can also be varied for choice of operating points on the Varactor phase versus bias curve. The 200 MHz limiters on the phase bridge inputs allow a greater linear range to be achieved. The linearity is 1% for ± 35°. The loop is capable of correcting a cavity phase deviation of ± 12.5° from the programmed phase. The overall loop gain is approximately 19 dB. The Varactor sensitivity averages 1.5 V/degree over the phase range at normal operating RF power levels.

The system has been installed in the permanent location and all subsystems are operating at the required specifications. Testing of the RF equipment into a resistive load has begun; phase programming checks will then be conducted to insure proper energy modulation of the beam.

Reference

1. G. K. Green, and Ernest D. Courant, The Proton Synchrotron, Encyclopedia of Physics, Vol. 44, (1959).

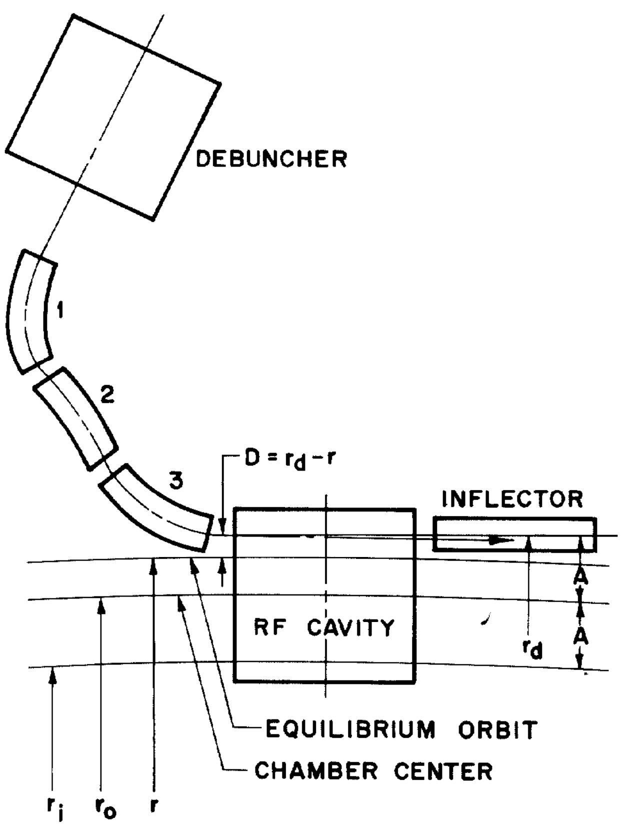

Fig. 1 Injection Area of the ZGS

$\frac{A}{r_s}$	T_i = constant	T_i = variable
1	12%	36%
2	19%	18%
3	22%	12%

Fig. 2 Table of Relative Charge Efficiencies

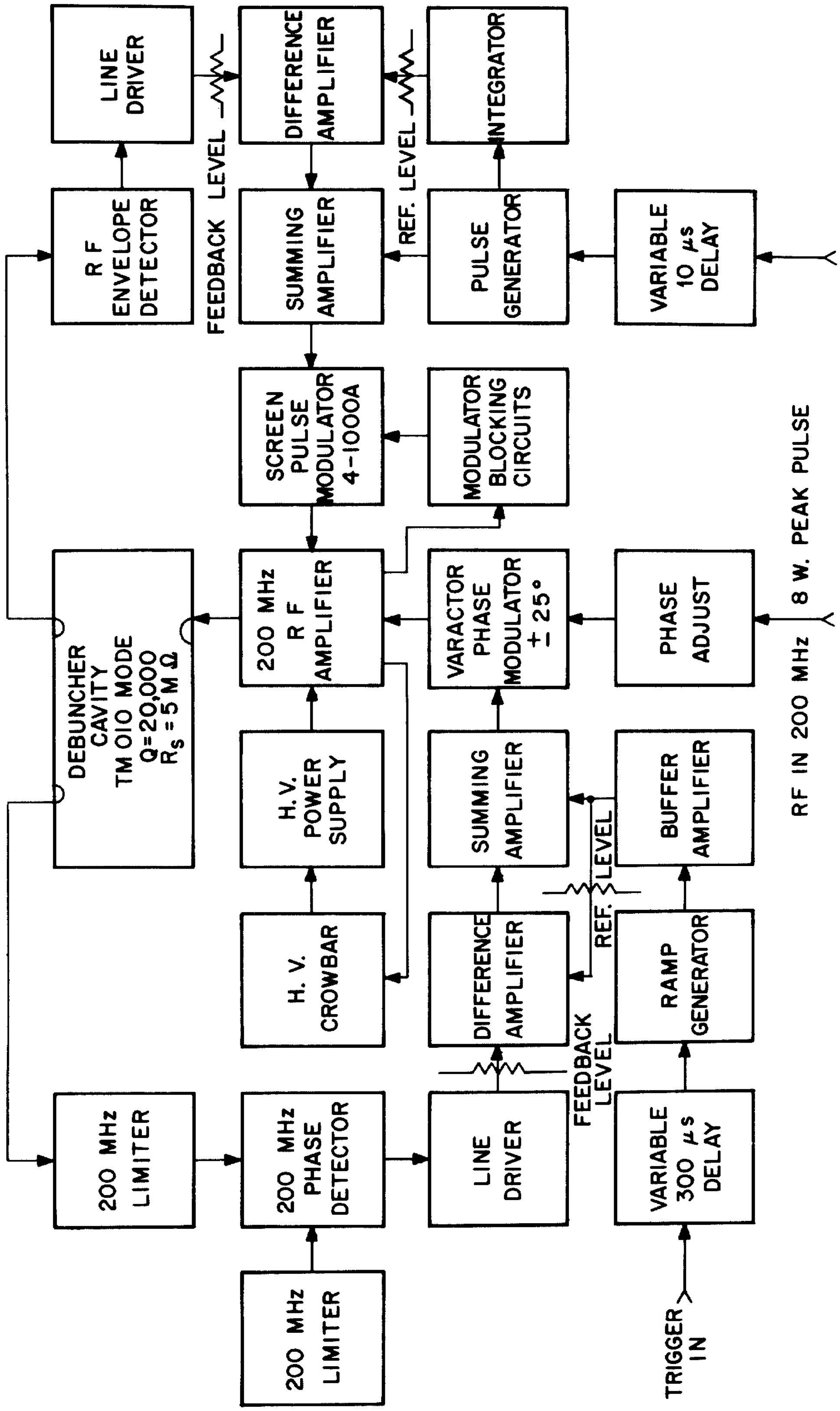

Fig. 3 Block Diagram of Variable Energy Debuncher RF System