ENERGY MODULATED BEAM INJECTION AT THE ARGONNE ZERO GRADIENT SYNCHROTRON*

W. Myers
Argonne National Laboratory
Argonne, Illinois

Introduction

A discussion of energy-modulated beam injection and a description of the equipment employed at Argonne National Laboratory (ANL) have been presented earlier.[1] This paper will describe the methods used and the results obtained from Zero Gradient Synchrotron (ZGS) machine studies in which the energy modulation technique was applied to both fast and slow ring rf turnon-programs.

The ZGS capture efficiency is a maximum for particles having radial betatron oscillation amplitudes ranging from about 4" to about 9", and survival occurs out to a maximum of 13". Hence, following normal proton synchrotron theory, useful beam can be injected only over the time interval required to reach 13" of amplitude, or approximately one-half of the chamber width. Furthermore, the maximum capture cutoff occurs at about 9" so capture occurs at peak efficiency only over the time required to fill 1/4 of the chamber. In addition, another sizeable portion is injected at reduced efficiency due to the low average capture for particles with amplitudes from 4" to 0". If one were able to inject continuously at an amplitude which would insure maximum capture efficiency, the capture would be increased by about 50%. Since the normal capture of the ZGS is about 22% with fast rf turnon, one could expect it to be increased to about 33%. If the beam pulse were nearly doubled, which would be possible because of the elimination of all of the radial betatron oscillations larger than about 4", the relative charge efficiency then approaches 70%. This should lead ultimately to accelerated beam intensities of over 3 x 10^{12} protons per pulse.

System Operation

The fast variation of particle mean energy during injection is accomplished by phase modulation of the debuncher cavity rf voltage. The phase modulation program is arranged so as to decelerate those particles at the beginning of injection and accelerate those at the end, thus maintaining a stationary equilibrium orbit and a small but constant radial betatron oscillation amplitude. The phase program shown in Fig. 1 has a sawtooth waveform, which is symmetric about 0^o phase. 0^o phase is here taken to be the phase at which normal debunching occurs, without any change in mean energy of the linac beam. Approximately $\pm 25^o$ maximum phase range is required to provide the $\pm$360 keV mean energy range to fill the ring rf bucket. Approximately fifteen to twenty-five kW of rf power is required from the debuncher rf amplifier. Since the beam contributes energy during the first half of the program and receives energy during the second half, an automatic level control (ALC) regulating loop is used to regulate against these rf level variations. In addition amplitude variations that are introduced when the phase program is initiated are also regulated by the ALC system. Amplitude variations of 10% caused by both of these programs are reduced to 0.5% by the ALC system.

The 3 dB bandwidth of the rf amplifier is of the order of 2.4 MHz. This is sufficient to insure that none of the important sidebands resulting from the phase modulation are affected.

Although provision has been made for a feedback loop in the phase program, this refinement has not been found essential to obtaining most of the benefits of this injection mode.

Procedure

The ring guide field was used as a momentum analyzer. The first turn of 25 μsec of coasting beam was observed in the ring at the azimuthas position at which maximum radial distribution with momentum occurred. The beam pattern without the debuncher on was observed as to width and center position. Power was applied to the debuncher cavity, and the amplitude and phase of the rf adjusted to minimize the beam pattern width, while the center of the beam was maintained at the initial location so as not to introduce a shift in the synchronous energy. Optimum debunching was then achieved. For a 100 μsec injection pulse 90% of the beam was initially within a total energy range of 495 keV. With the debuncher the spread was reduced to 83 keV. The value of rf phase for best debunching is the reference ϕ_o for the phase program. A separate phase adjustment in the phase bridge was provided to make the oscilloscope readout correspond to the theoretical

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phase program.

The initial value of the phase at the onset of injection was chosen as -25° relative to the reference phase ϕ_0. This position, identified as ϕ_2 on Fig. 1, is adjusted by the trombone in series with the rf drive to the first stage of the rf amplifier. The video drive pulse to the phase modulator is symmetrical about ϕ_0. The $\dot{\phi}$ was varied until a 100 μsec injection pulse occupied the same radial width as a 25 μsec pulse. When the $\dot{\phi}$ of the debuncher rf was correctly matched to the $\dot{B}$ of the guide field, the beam at each time slot in the pulse occupied the same position on the L_3 TV monitoring screen. The TV monitor showed the center of a 100 μsec coasting beam to be 7" radially outward from the center of the chamber, with a full width of 4.5".

In order to exploit the full advantages of this method of injection the minimum radial betatron oscillation amplitude, for which maximum beam capture occurs, must be used. This amplitude was determined by progressively moving the linac turnon time earlier until a loss in coasting beam collected in a cup was observed. The minimum amplitude at which full coasting efficiency was realized was approximately 6". In principle, 4" should be obtainable and would increase captured beam by about 10%.

A 50 μsec beam pulse was then accelerated, and the linac timing, ring rf program, magnets, and debuncher rf gradient, and ϕ program adjusted to give the best accelerated beam. The pulse length was increased in step-wise fashion to 195 μsec, optimizing all parameters at each point.

The study was begun with a ring rf slow turnon program which had been used successfully for high intensities with normal injection. The debuncher rf amplitude and phase program were adjusted for maximum accelerated beam at 195 μsec. The normal slow turnon length is approximately 150 μsec.

Data Analysis

Summaries of the experimental data are presented in Table I, which compares the four types of machine injection: fast turnon, constant energy; fast turnon, variable energy; slow turnon, constant energy; and slow turnon, variable energy.

The first two columns compare two optimized cases which show that the energy modulation increased the accelerated beam in fast turnon by 53%, although the increase in pulse length was only 14.8%. Furthermore, the constant energy case did not provide more beam for pulses longer than 170 μsec, whereas the variable energy case was limited by phase ramp loading and linac transmitter pulse length. At equal pulse lengths of 150 μsec, the energy modulation accelerated 37% more beam.

The increase in captured Q for energy modulation was 16.2%, which compares well with the 14.8% increase in injection pulse length.

In actual operation to date the anticipated increase in capture has not been realized when using variable energy, and nearly the same capture efficiency has been obtained. However, in terms of accelerated beam the variable energy makes much better use of captured charge, since 57% is accelerated as opposed to 43%.

The changeover from an optimized fast turnon with variable energy to unoptimized slow turnon with variable energy, did not change the accelerated beam intensity but held steady at 2.83×10^{12}. A somewhat greater df/dt than for constant energy was found to be better.

A good comparison between constant and variable energy injection for slow turnon is somewhat difficult because the constant energy data were taken two days after the other three sets. However, it represents typical ZGS operation on current high energy physics runs. In spite of the previously noted problems, the energy modulation was able to closely approach the ZGS record of 2.969×10^{12}. The variable energy capture efficiency is considerably lower, but as with fast turnon, better use is made of what charge is captured.

An indication of what is possible is shown by intensities of 3.3×10^{12} which were observed accelerated out to about 160 msec. It is believed that careful refinement in early tuning will allow this beam to be carried to full energy. A peak beam of 3.082×10^{12} was observed with the slow Q reading at 4130 gauss and 4.4×10^{12} captured. Accelerated to captured Q ratios of 0.75 appear to be a possibility.

The accelerated beam was approximately 6" wide as viewed on the ion collector display; the normal width is about 3", this enlargement made beam steering difficult to avoid large beam losses later in the acceleration cycle.

The starting point on the debuncher rf phase program was -28°, and the final phase was +58°. The unusually high value of final phase was a compromise which was necessary because of the phase ramp distortion.

Conclusion

Several interesting sidelights were observed. One was the relative insensitivity of the accelerated beam intensity to linac rf gradient when operating slow turnon, variable energy. Changes in linac rf level which caused losses in constant energy were found to leave a much smaller effect when using energy modulation.

A second effect was observation of the negative mass instability. This was observed on MUTS (multiple trace system) initially at 50 μsec pulse length. No significant change in the magnitude of the effect occurred at pulse lengths out to 195 μsec. The MUTS display also showed the ring rf buckets to be well filled during variable energy operation.

The pulse-to-pulse stability of the ZGS when operating at intensities of 2.8×10^{12} and above was good. Typical variations observed were $\pm 0.04 \times 10^{12}$.

During constant energy operation a ramp is put on the linac rf, but this was removed during energy modulated injection to avoid problems with beam debunching. The ramp was later tried with slow turnon, variable energy after all parameters were optimized, but did not increase the accelerated beam.

Although the first efforts with the energy modulation system were rewarding, more time will be required to find better combinations and realize the maximum benefits to be gained. The phase ramp problem has been corrected and should boost the intensity by about 15%. The cause of the low capture is not known, but it is expected that further operation will bring this quantity closer to the theoretical value.

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Reference

1. W. Myers and J. A. Abraham, Use of a Debuncher to Obtain Variable Energy From a Linear Accelerator Beam, IEEE Transactions on Nuclear Science, June 1967, Volume NS-14, Number 3, pp. 666-669.

TABLE I

SUMMARY OF FOUR INJECTION METHODS

Quantity	Fast Turnon Constant Energy	Fast Turnon Variable Energy	Slow Turnon Constant Energy	Slow Turnon Variable Energy
Optimized Injection Pulse Length	170 μsec	195 μsec	145 μsec	195 μsec
Injected Current	18.5 mA	18.5 mA	19.0 mA	18.5 mA
Injected Q	19.67×10^{12}	22.55×10^{12}	17.20×10^{12}	22.55×10^{12}
Captured Q	4.3×10^{12}	5.0×10^{12}	5×10^{12}	4.4×10^{12}
Capture Efficiency	21.9%	22.2%	29.0%	19.5%
Accelerated Q	1.855×10^{12} (1.761×10^{12} at 150 μsec.)	2.841×10^{12} (2.413×10^{12} at 150 μsec.)	2.288×10^{12}	2.957×10^{12}
Ratio of Accelerated Q to Captured Q	43.1%	56.9%	46.8%	67.2%
Remarks	Ramp on Linac rf	No Ramp on linac rf	Ramp on linac rf	Ramp on linac rf tried, but not useful.
Notes			2.969×10^{12} peak has been obtained at full energy.	3.3×10^{12} accelerated to 160 mS.