Energy Compression System Design for the MIT-Bates Accelerator Center

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I. Introduction

The purpose of the Energy Compression System (ECS) is to reduce the energy spread of the beam from the linear accelerator. The benefits of the ECS will be to provide a beam with an energy spread lower than we are capable of producing now; to reduce the energy centroid shifts from operating fluctuations in the accelerator; and to ensure a beam energy spread commensurate with the requirements of the new South Hall Ring (SHR) currently under construction [1]. The last includes minimizing the required RF power for pulse stretcher and storage mode applications. The ECS is to operate with both single pass and recirculated beams [2]. It is desired to produce as low an energy spread as possible over the expected accelerator operating conditions.

Our goal is to achieve a compressed beam full energy spread of less than 0.04%

II. Beam Longitudinal Phase Space

A Phase Length

Design calculations show that the beam phase length can be as small as 1.0°. A measurement of the single pass beam phase length yielded 3.0° (>80% of the beam). Contributions to the additional measured phase length can be due to a number of factors, including imperfect injector adjustment and RF phase ramping in one or more of the transmitters. The ramps within a pulse range from 0.25° when the transmitters are performing well, to values which of late have been found to be as much as 2° over a 20 microsecond pulse.

B Energy Spread

The measured LINAC single pass energy spread when the peak current is below 5ma is about 0.3% (>80% of beam). This is greater than would result from the phase width quoted above, which would add only 10^{-4} to the beam energy spread. Calculations using the rated few tenths percent klystron amplitude fluctuation, statistically distributed over the 12 klystrons, indicate that this should produce beam energy spread of from .2% to .3%, consistent with what is observed. Beam phase spread thus appears not to be contributing significantly to the beam energy spread in normal operation.

With high peak current operation and head-to-tail recirculation some new effects come into play and some existing ones are increased. New effects include transient loading from imperfect first pass to second pass beam transmission, as well as possible gaps or timing mismatches between the tail of the first and head of the second beam passes. Higher peak current produces correspondingly larger beam energy spread: at 40mA operation a 1% current jitter or beam loss within the accelerator will correspond to a ±1 MeV change per pass; i.e. an energy spread increase of .66% at 600 MeV. We have measured the cumulative beam energy spread for all effects during HT recirculation at 40mA. The spread was found to be about 0.6%.

III. South Hall Ring Requirements

The ring will operate with 1812 bunches at 2856 MHz. In order to minimize the possibility of coupled bunch instabilities a single cell RF cavity will be used.

Two modes of ring operation will be employed: pulse stretching to provide high duty ratio beam, and beam storage for internal target experiments.

In storage mode, the RF bucket size must be large enough to produce the quantum lifetimes (minutes) required by the projected Bates experimental program. For this the bucket must be at least 5 times the damped beam energy spread. Time to damp or antidamp, and final beam energy spread at 500 MeV are about 1 second and 0.02%. At 1 GeV these are respectively 100msec and 0.056%. Due to the limitations of gradient available in the one cell cavity it is useful to inject a beam with energy spread as close to the damped spread as possible.

In the pulse stretcher case it is important to keep the energy bucket size as small as possible. An acceptable synchrotron oscillation period, of about 60 ring turns, is achieved with a 0.08% or less bucket size. Most of the energy spread of the beam must be inside the bucket for controlled extraction.

IV. Compression Factors

A Compression Mechanism

The energy compression mechanism is indicated in Figure 1. Beam to the ECS is injected with half phase spread ϕ_o and half energy width γ_o. The original bunch is represented by the vertical contours. The beam phase space is rotated after it passes through the ECS magnetic chicane, emerging with phase extent $\Delta\phi$ which depends on the product $\gamma_o(z/\delta)$ of the initial beam energy spread and the chicane dispersion parameter. The horizontal contours show the bunch after compression by the ECS linac to some minimum energy width.

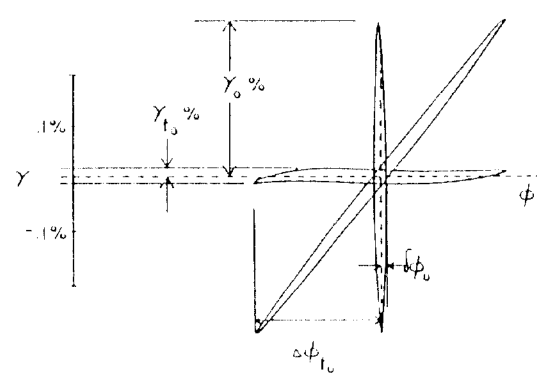

Figure 1. Longitudinal Phase Space Progression during Energy Compression

Figure 1 considers the phase space region being compressed to be bounded by an assumed elliptic constant charge density contour. Our calculations, and the values given for compressed beam spectra in this report have been made using this model, noting that the rectangular phase space shape tends artificially to reduce the magnitude estimated for the effective energy compression factor.

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The effect of either a shift in phase of the entering bunch centroid relative to the ECS linac RF zero crossover point (or a shift in the ECS linac RF phase relative to the bunch centroid), or of beam current loading, is to cause a displacement in the mean energy of the beam bunch relative to its original value. Although the compressed energy spread itself is not greatly affected by moderate beam currents or phase shifts (tens of ma or few degrees), the beam mean energy shift can have significant effect on the beam behaviour in the ring, and must be taken into account by adjusting for appropriate phase offset in the ECS injected beam.

Figure 2 shows plots of the compression factor for a range of incoming beam phase halfwidths ($\delta\phi_0$) as a function of the emergent beam phase halfwidth ($\Delta\phi$). Figure 2 compares compression factors calculated using a rectangular bunch phase space definition with factors calculated assuming the original phase space to be the elliptical form discussed above and shown in figure 1. The curves based on the rectangular formalism are in excellent agreement with curves calculated by others [3],[4].

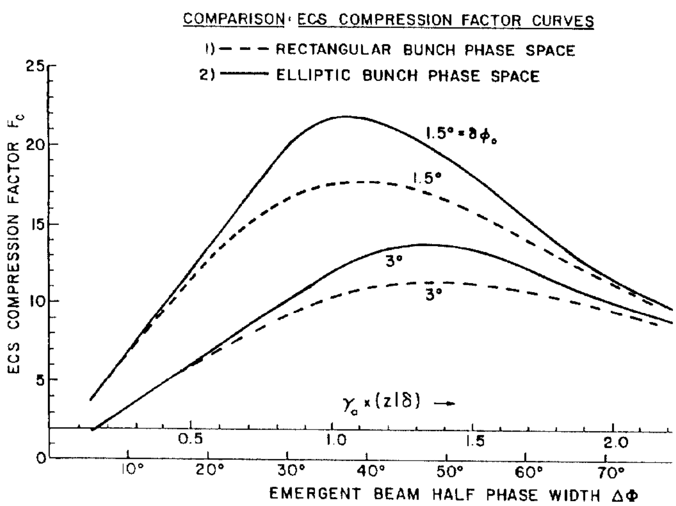

Figure 2. Compression Factors

The crucial parameter is the final ECS compressed beam energy spread. Figure 3 shows a plots for a range of chicane (z/δ) values of the compressed half energy spread γ_f as a function of the input half energy spread γ_0 for an input beam with full phase spread 3°. The ECS RF structure voltage is optimized for these conditions to obtain the best compression factor. For clarity the errors discussed earlier are omitted from the plots in figure 3.

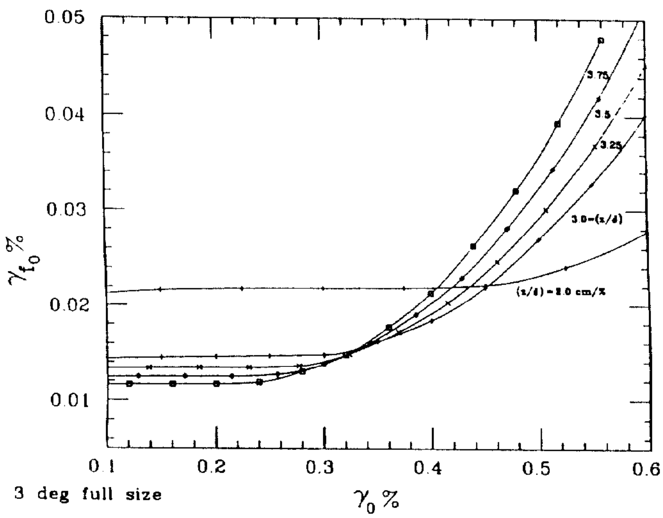

Figure 3. Compression Factors vs (z/δ) and input Energy Spread

B Optimization

The compressing RF field is non-linear with bunch electron phase. The combination of chicane (z/δ) and ECS linac RF power required for best energy compression depends uniquely on the sizes of the incoming beam phase and energy spread.

For beams with a high ratio of energy to phase spread, large RF compression (i.e. voltage) and low phase displacement by the chicane are indicated. For the reverse, higher phase displacement (higher (z/δ)) is favored, provided this does not extend too far into the nonlinear RF region and provided the necessary RF power is available.

In our circumstances we are faced with two important constraints. We desire to accomodate an incoming beam energy spread as high as about one percent, and the RF power we have available for the ECS linac is limited. In particular, we obtain power for the ECS accelerating structure from one of the existing LINAC klystron power sources, with the consequence that 1.5 MW at most is available for the ECS LINAC. Given reasonable ECS linac choices (including the consideration of questions of beam loading and fill time) this imposes a limit of some 5-7 MeV, depending on the linac choice, on the voltage available for energy compression.

We have examined ECS systems using chicanes with magnetic dispersion from 1.6 cm/% to more than 4 cm/%. As shown in figure 3 the effect of the RF non-linearities becomes rapidly greater at γ_0 greater than 0.3%. The higher energy spreads are harder to compress, and increasingly so with chicanes whose (z/δ) is higher. For γ_0 less than about 0.3% the higher (z/δ) chicanes produce a better compression. For a given (z/δ) choice, as γ_0 becomes less than 0.2%, the final compressed energy spread soon becomes limited dominantly by the phase spread of the beam and remains essentially constant. It is apparent that the differences in compressed energy spread as a function of (z/δ) are larger at higher γ_0 than they are at lower γ_0.

Coping with higher incoming beam energy spreads favors lower (z/δ). This needs to be balanced against the potential loss of very highly compressed energy beams in the event that low energy spread input beams become reliably and routinely available in the future. In the light of present and forseeable day to day beam quality, we have chosen a chicane with dispersion of 3.4 cm/%.

V. ECS Components

A . ECS RF System

The ECS RF-System consists of three main components, an accelerating structure, a high power divider and a high power phase shifter, as shown in the schematic drawing of figure 4.

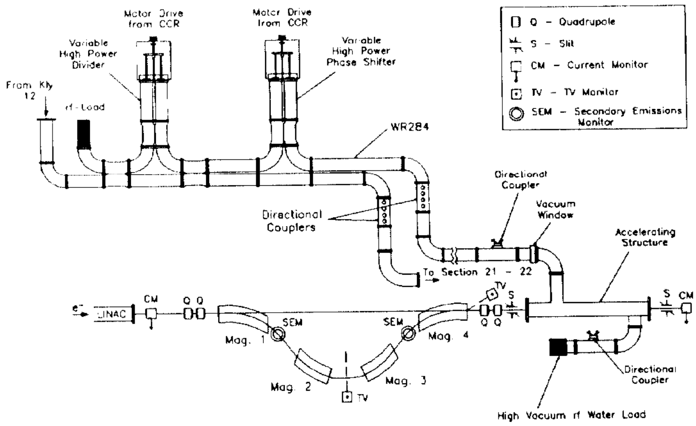

Figure 4. Principle Layout of Energy Compressing System

The ECS Linac will be operated at 2856 MHz in the $2\pi/3$-mode (see Table 1) [5]. A variable power divider, high power phase shifter network (Tables 2 and 3) will be used in order to ensure phase coherency between the bunch sequence and the RF at the accelerating structure. RF power will be provided by the last klystron power source of the existing linac and fed to the ECS RF Linac through the Divider/Phase Shifter network and a 130-foot run of WR 284 rectangular waveguide. To maintain phase shifts within the required tolerance, the waveguide system will be thermally stabilized by a temperature controlled water circuit.

Table 1. Accelerating Structure	
Frequency	2856 MHz
Travelling Wave Mode	TM_0
RF Insertion Loss	1.1 dB
Filling Time	202 ns
Harmonic Mean Group Velocity	0.0336
Zero Load Maximum Energy Gain	5.6 MeV
P_0 at Maximum Energy Gain	1.5 MW
Beam Loading	5.9 keV/mA
Quality Factor	14200
Overall Electrical Length	200 cm

Table 2. Variable High Power Divider	
Frequency	2856±1 MHz
Power	6 MW Peak
Input VSWR	1.1:1 Max
Insertion Loss	0.25 dB Max
Coupling Range	10 dB Below Min Insertion
Isolation	30 dB
Amplitude Balance	±0.3 dB

Table 3. High Power Phase Shifter	
Frequency	2856±1MHz
Power	6MW Peak
Input VSWR	1.1:1 Max
Phase Shift Range	$0\text{-}720^{\circ}$
Phase Stability	$\pm 1^{\circ}$
Insertion Loss	0.15 dB Max

B . ECS Magnetic Chicane

The ECS chicane must have no transverse dispersion and be non-focussing in both the horizontal and vertical planes. Its optics must be correctable to match the existing beam line optics. At the center of the chicane, the horizontal beam size should be dispersion dominated. This will permit the use of slits at that point to remove energy tails from the beam.

The program Transport has been used to investigate chicane designs with dispersion ranging from 3.00 cm/% to 3.75% cm/%, including both four magnet and three magnet versions. A four magnet chicane fitted with quadrupoles, and capable of providing adjustable dispersion, has also been studied.

VI. Summary

The preceding describes an ECS design intended to permit the achievment of 300 MeV to 1 Gev (880 MeV beam loaded) performance goals set for the MIT Bates SHR. In accomplishing this design it has been necessary to meet special conditions (notably RF power limitation and routinely expected quality of the ECS/SHR input beam) which at present apply to the Bates Linac Facility. This has been done by means of a design centered about the use of a short, low-filling time, small beam loading factor TW accelerating cavity and a magnetic chicane system with magnetic dispersion 3.4 cm/%.

VII. References

[1] J.B. Flanz et. al., The MIT-Bates South Hall Ring, Proceedings of the 1989 IEEE Particle Accelerator Conference, March 20-23, 1989 (p.34)

[2] J.B. Flanz and C.P. Sargent, IEEE Trans. Nucl. Sci., NS-32, Oct 1985, (p.3213)

[3] H. Herminghaus and K.H. Kaiser Nucl. Inst. and Meth. 113, 1973 (p. 183-194).

[4] R.E. Laxdal, Thesis, U. Saskatoon 1980

[5] J. Haimson, private communication.