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DESIGN OF AN ELECTRON BEAM SPECTRAL MODIFICATION SYSTEM*

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ABSTRACT

We report the design of a spectral modification system (SMS) for use with the proposed NEAL linac-pulse stretcher ring, cw electron beam facility. The SMS allows tailoring of the energy distribution of electrons in beams produced by a pulsed linac operating in the transient beam loading (TBL) regime. Modification of the energy distribution of electrons injected into the pulse stretcher ring will increase the duty factor of current extracted from the ring and improve the efficiency of the extraction process. Physically, the SMS consists of an anisochronous, achromatic magnetic lattice followed by a pair of traveling-wave accelerating sections. For beams in the energy range of 500 MeV to 4 GeV, TBL ripple on the energy envelope of microsecond long beam spills is expected to be reduced from 1% peak-peak to less than 0.01% while the desired width of the energy profile due to the phase extent of the microbunches in the beam spill is preserved.

INTRODUCTION

The recently proposed NEAL accelerator is composed of a pulsed linac and a pulse stretcher storage ring (PSSR).[1] Attainment of a high duty factor and a large efficiency in the pulse stretching operation rely on a good match between the temporal and spectral characteristics of the linac beam and the admittance of the PSSR. For monochromatic extraction of current from the PSSR in the energy range of 500 MeV to 2.0 GeV, it is required that the linac generate 1.2 μs beam spills with a spectral width which is variable between about 0.2% at the low energies to about 2.0% at the higher energies. Achromatic extraction from the ring has been proposed for beam energies greater than 2 GeV, dictating a linac beam spectrum whose width of less than 0.1%.

This paper reports the design of a spectral modification system (SMS) to be used for tailoring of the spectra of the linac beam spills beyond the control which can be expected with the use of delayed klystron triggering and through the variation of the phase extent of the microbunches.[2] The SMS can be used as a Ripple Suppressor to remove ripple on the beam energy envelope caused by transient beam loading in the linac due to peak beam currents > 200 mA. It can also be used as an Energy Compressor when narrow spectra are required.

Figure 1 illustrates the components necessary for the SMS. A triplet of magnetic dipoles

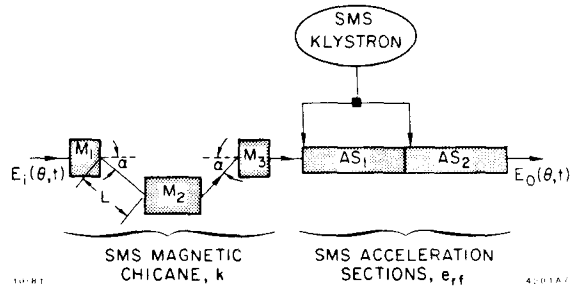

Fig. 1. Schematic of the SMS.

(M_1, M_2, M_3) followed by a pair of accelerating sections (AS_1, AS_2) are placed at the end of the linac. The magnets form an achromatic, anisochronous, horizontal bump in the beam trajectory to disperse the beam longitudinally according to energy. A pair of accelerating sections is used to differentially accelerate the dispersed beam, thereby achieving either ripple suppression or energy compression. The hardware of the SMS is quite similar to that of existing energy compression systems.[3]

ANALYSIS

Linac beam spills comprise a pulse train of N electron microbunches, each microbunch having the same amount of charge in the identical distribution and each microbunch riding along the crest of the RF acceleration wave in the linac at the same position as any other microbunch. It is assumed that changes in the energies of electrons in the microbunches due to TBL is constant across a single bunch but may vary from bunch to bunch.

The energies of electrons in the linac beam spill are given as $E_i(\theta,t)$:

$$E_i(\theta,t) = \sum_{n=1}^{N} E_n(\theta,t) \qquad (1)$$

where $E_n(\theta,t)$ = the energies as a function of rf phase, θ, and time, t, of electrons of the nth microbunch in the beam spill. $E_n(\theta,t)$ is defined as

$$E_n(\theta,t) = E_1\cos(\theta)\delta(t-t_n) + E_{b1}(t)\delta(t-t_n) \qquad (2)$$

where E_1 = the maximum energy available for electron acceleration in the linac; θ = the phase position of electrons within the nth microbunch, $\theta_2 < \theta < \theta_1$ with θ_2 the phase of the tail of the bunch and θ_1 the phase of the head of the bunch; $E_{b1}(t)$ = the change in the energy of microbunches due to TBL; and $\delta(t')$ = the Dirac delta function with t_n = the temporal location of the nth microbunch within the beam spill.

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When the beam described by Eqs. (1) and (2) is transported through the SMS, the energies of electrons leaving the SMS are given by $E_o(\theta,t)$

$$E_o(\theta,t) = \sum_{n=1}^{N} E_n(\theta,t) \qquad (3)$$

$$- e_{RF} \sin\left[\frac{k(E_n(\theta,t)-E_{sms})}{E_{sms}} + \theta_{sms} + \theta \right]$$

where e_{RF} = the energy gain available in the SMS; k = the SMS dispersion constant; E_{sms} = the centroid energy of the magnet chicane; and θ_{sms} = the phase of the SMS RF with respect to the linac RF phase. Specification of the SMS parameters (e_{RF}, k, E_{sms}, and θ_{sms}) determine the operating behavior of the system.

As a Ripple Suppressor, the SMS is required to preserve the desired energy width of the beam spill, determined by the phase extent of the microbunches, while reducing the ripple on the energy envelope caused by transient beam loading. In the case of energy compression, the SMS should reduce the full width of the beam energy spectra to be less than some tolerable energy spread, Δ. With these constraints in mind, the values of the SMS parameters have been determined and are listed in Table I.

COMPUTER MODELING AND SIMULATIONS

In order to evaluate the foregoing analysis, the linac beam spill is assumed to be 1.2 μs long and the transient RF filling time of the linac is 0.87 μs. $E_{bl}(t)$ has been modeled as a sinusoid during the transient period:

$$E_{bl}(t) = \left(-0.5\times10^{-3} E_1 \sin[\omega t]\right)\left(U[t]-U[t-0.87\ \mu s]\right) \qquad (4)$$

with $\omega = 2\pi/0.87$ μs, t = time measured from the beginning of the beam spill, and U(t') = a unit step function.

Figure 2(a) is a plot of the linac beam spill for $E_1 = 1.00$, $\theta_2 = 0.0^\circ$, and $\theta_1 = 6.0^\circ$. The different energy contours across the plot represent equally spaced values of θ between between θ_2 and θ_1. The variation in contour density with respect to energy is expected because of the COSINE dependence of beam energy on phase. Figure 2(b) depicts the linac beam spill after transmission through the SMS, when operated as a Ripple Suppressor.

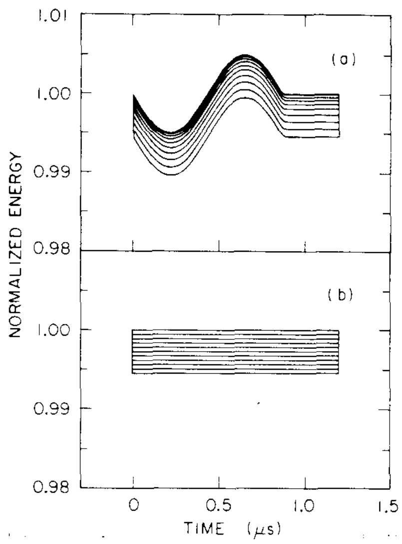

Fig. 2. Ripple suppression: (a) the input beam and (b) the output beam. For (b), k = 19.06 and $e_{RF} = 5.24\times10^{-2}$.

TABLE I. SMS Parameters

Parameter	Description	Ripple Suppression	Energy Compression
e_{RF}	Available energy gain in SMS acceleration sections	$\frac{\Delta_{tbl}}{\sin[\Delta_{tbl}(\theta_1-\theta_2)/E_1(\cos(\theta_2)-\cos(\theta_1))]}$	$\frac{\Delta}{(\theta_1 - \theta_2)}$
k	Dispersion constant of the SMS magnetic chicane	$\frac{[\theta_1-\theta_2][\cos(\theta_2)+\cos(\theta_1)]}{2[\cos(\theta_2)-\cos(\theta_1)]}$	$\frac{E_1[\theta_1-\theta_2][\cos(\theta_2)+\cos(\theta_1)]}{2\Delta}$
E_{sms}	Centroid energy of the magnetic chicane	$\frac{E_1[\cos(\theta_2)+\cos(\theta_1)]}{2.0}$	$\frac{E_1[\cos(\theta_2)+\cos(\theta_1)]}{2.0}$
θ_{sms}	Phase of the SMS RF WRT linac RF phase	$\pi - \left(\frac{\theta_1+\theta_2}{2}\right)$	$\pi - \frac{(\theta_1-\theta_2)}{2}$
θ	RF phase of beam	$0^\circ < \theta_2 < \theta_1$	$\theta_2 < \theta_1 < 0^\circ$

Δ_{tbl} ≡ maximum magnitude of TBL energy ripple.

Δ ≡ maximum tolerable final energy spread after energy compression.

In order to examine the effect of the SMS on the energy distribution of the beam spill, an initial electron phase distribution of $p_o(\theta)$ has been assumed:

$$p_o(\theta) = A|\theta-\theta_3| \exp[(\theta-\theta_3)^2/2\sigma^2] \quad (5)$$

where A = a normalization constant, $\theta_3 = 6.0^o$, and $\sigma_o = 1.85^o$. $p_o(\theta)$ is plotted in Figure 3 for $0^o < \theta < 6^o$. Figure 4(a) illustrates the energy distribution of the linac beam shown in Figure 2(a) having the phase distribution of Figure 3. Figure 4(b) illustrates the energy distribution of the same beam spill after the SMS. In Figure 4(b), the full width of the distribution, has been reduced to that expected for a 6^o bunch, $\Delta E = 5.5\times10^{-3}$, and the shape of the energy distribution is identical to that of the initial phase distribution.

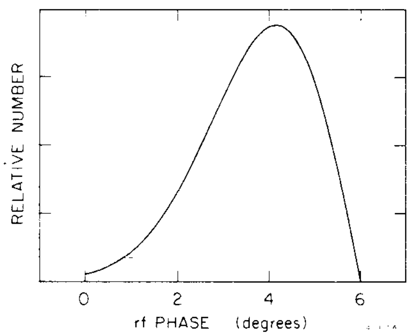

Fig. 3. The initial phase distribution particles within the microbunches comprising the input beam spill.

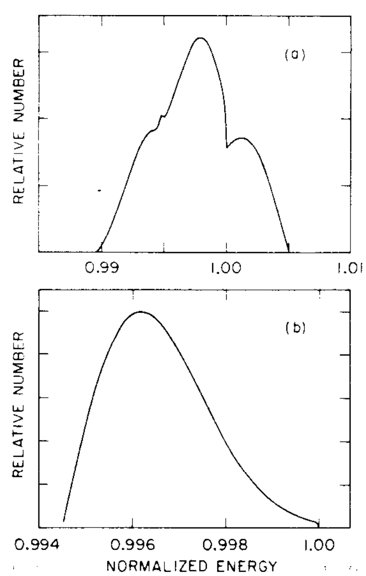

Fig. 4. The energy spectra of the beams (a) before and (b) after Ripple Suppression.

Figure 5 illustrates the behavior of the SMS when used as an Energy Compressor. Figure 5(a) is a plot of an input beam spill for the case of $E_1 = 1.0$, $\theta_1 = 0.0^o$, and $\theta_2 = -2.5^o$; Figure 5(b) depicts the same beam after compression in the SMS. As seen from Figure 5, the SMS effectively removes the TBL ripple and compresses the total spectrum.

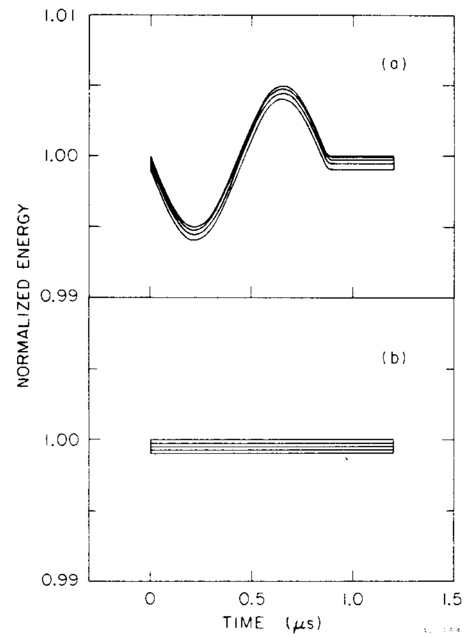

Fig. 5. Energy compression: (a) the input beam and (b) the output beam. For (b), k = 52.34 and $e_{RF} = 1.91\times10^{-2}$ for $\Delta = 1\times10^{-3}$.

SMS HARDWARE

The SMS consists of an achromatic, anisochronous magnetic chicane and a pair of linac accelerating sections. Chicane achromaticity is ensured by requiring all magnetic pole faces to be normal to the undeflected trajectory; the accelerating sections are assumed to be identical to those used in the linac proper. Figure 6 illustrates the dependence of the required energy gain in the SMS, e_{RF}, and the desired dispersion constant, k, on the length of the microbunches for the cases of ripple suppression and energy compression.

The magnitude of e_{RF} is determined by the amount of RF power fed into the accelerating sections, the shunt impedance and attenuation parameter of the sections, and the beam current, should beam loading in these sections become appreciable. As shown in Figure 6(a), the required value of e_{RF} can become quite large for the case of ripple suppression at the longer microbunch lengths. It can be shown by expanding the SIN term in Eq. (4) to first order, however, that for a fixed value of e_{RF} and k, the width of the SMS output beam spectrum is given as ΔE_o,

$$\Delta E_o = E_o(\theta_2,t) - E_o(\theta_1,t) = e_{RF}(\theta_1 - \theta_2) \quad (6)$$

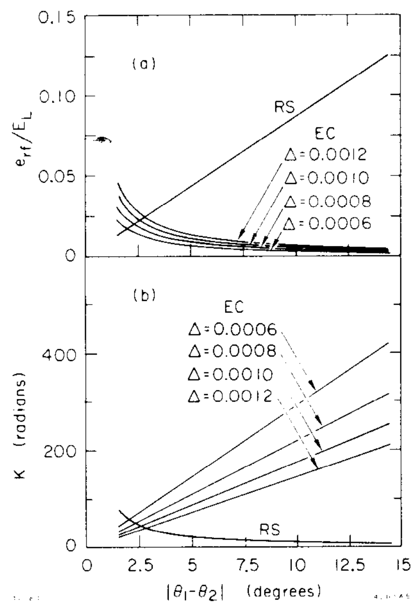

Fig. 6. Dependence of e_{RF} and k, (a) and (b) respectively, on the length of the microbunches, $|\theta_1 - \theta_2|$, for the cases of ripple suppression (RS) and energy compression (EC).

where $(\theta_1 - \theta_2)$ = the length of the microbunches. Equation (6) indicates that for a fixed value of e_{RF}/E_o, any value of ΔE_o may be achieved through suitable variation of $(\theta_1 - \theta_2)$, thus alleviating the need for arbitrarily large values of e_{RF}.

The dispersion constant, k, is the R_{56} element of the TRANSPORT [R][4] matrix of the magnetic chicane. For an α-2α-α bend angle geometry, k is given as

$$k = [4\pi/\lambda][L(\tan^2(\alpha) + (\rho_1+\rho_2)(\tan[\alpha]-\alpha)] \quad (7)$$

where λ = the wavelength of the SMS RF, L = the separation between pole faces of the α-2α magnets as measured along the beam trajectory, α = the bump angle, and ρ_1 and ρ_2 are the bend radii of the α and 2α bends, respectively.

CONCLUSIONS

By effectively smoothing and narrowing the spectra of beams generated by a pulsed linac for injection into a PSSR, the duty factor of current extracted from the ring and the efficiency of the extraction procedure are both increased. Standard magnets and beam acceleration components as well as modest levels of RF power required in the design of the SMS attest to the feasibility and economy of the system. With regard to the NEAL project, accurate estimates of the capabilities of the SMS will allow specification of constraints on: the electron bunch structure generated in the linac injector; the phase stability of the linac RF; and the energy admittance of the PSSR; needed for the detailed design of a Linac-Pulse Stretcher Storage Ring accelerator system.

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