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 IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

RF SYSTEM FOR A 1 GEV PULSE STRETCHER RING

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Summary

A design study has been completed for the RF system of a pulse stretcher ring to be operated in conjunction with the Bates Linear Accelerator. The 390m circumference ring is to operate from 300 MeV to 1 GeV, with 80 mA injected current and 1 msec extraction time. The stretcher ring is for nuclear physics research and has radiation damping time and quantum lifetime long compared to the extraction time. The special requirements of the RF system have been considered. Dynamic behavior at the fundamental frequency has been investigated by computer simulation. Higher-order mode impedance limitation has been specified by an investigation of transverse multi-bunch multi-turn instabilities.

Specification

The RF frequency is to be 2856 MHz, the operating frequency of the linac, in order to maximize the effective duty factor of the beam. The beam aperture of the cavity must be at least 4 cm. All of the injected beam is contained within 4 parts in 10^4 in energy and 84 degrees in phase, and an important system requirement is to maintain this energy definition during extraction, minimizing the effects of synchrotron oscillations excited during the fast (two-turn) injection process, as well as compensating radiative and parasitic losses. Table I presents synchrotron radiation loss per turn (V_s) and total loss per turn (V_o) for various beam energies. The subscript f refers to a value at the end of extraction, and the subscript i to the end of injection (beginning of extraction). Cavity voltage (V_c) and synchronous phase (ϕ_s) required to both compensate these losses and to match the input phase-energy distribution are also presented in Table I. An initial stored current of 80 mA is used to estimate parasitic losses. The ring is characterized by momentum compaction parameter α = .014 and harmonic number k = 3710. A final specification concerns the synchrotron period. An investigation of extraction techniques indicates that for high duty cycle output over total extraction times as short as one millisecond, the synchrotron period should not be less than 50 orbital periods [1].

Table I

Beam Energy (MeV)	$V_s = V_{of}$ (KeV)	V_{oi} (KeV)	$V_{ci} \approx V_{cf}$ (KeV)	ϕ_{si} ($^\circ_\phi$)	ϕ_{sf} ($^\circ_\phi$)
300	0.1	0.8	5.0	9.2	1.1
500	0.6	1.3	8.1	9.2	4.2
800	4.0	4.7	17.2	15.9	13.4
1000	9.8	10.5	27.6	22.4	20.8

Prediction of System Performance

The required cavity voltage (Table I) can be easily obtained from a single-celled S-band cavity. We estimate the effective shunt impedance of such a cavity with 4 cm beam aperture to be Z = 2 MΩ, with unloaded $Q_o \approx 16000$ [2]. It remains to determine an appropriate loaded Q, Q_L, which governs the transient behavior of the system during the two-turn injection process and the $\approx$ 1000 turn extraction process. Q_L is controlled by the coupling parameter, β, which determines the external interaction of the cavity with a load at a circulator located between power source and cavity. Q_L is related to Q_o by $Q_L = Q_o/(1 + \beta)$. The system must be overcoupled. With the system critically coupled (β = 1, with half the source power dissipated in the circulator load and half dissipated in the cavity in absence of beam) the cavity voltage induced by the beam (V_b) is much larger than the required cavity voltage even at 1 GeV. Matched operation under such conditions is only possible with large positive values of the tangent of the cavity tuning angle ψ ($\tan\psi = 2Q_L\Delta f/f$, with Δf the difference between cavity resonance frequency and operating frequency). Under these conditions synchrotron oscillations excited during injection will be large and unstable (Robinson instability) and the control of source power and phase very critical. In addition to determining the choice of $\beta(Q_L)$ and whether it must be varied over the beam energy range, the study of system transient behavior determines source power, control and stability specifications for source power and phase, and the required range of tuning angle.

The phase vector diagram for the RF cavity is shown in Fig. 1. With the expected bunch lengths, $V_g = 2(PZ\beta)^{1/2}\cos\psi/(1+\beta)$ and $V_b = iZ\cos\psi/(1+\beta)$. P is the source power, i the beam current. The phase θ of the source power can be controlled, as can ψ and P. An important question concerns the desirability of

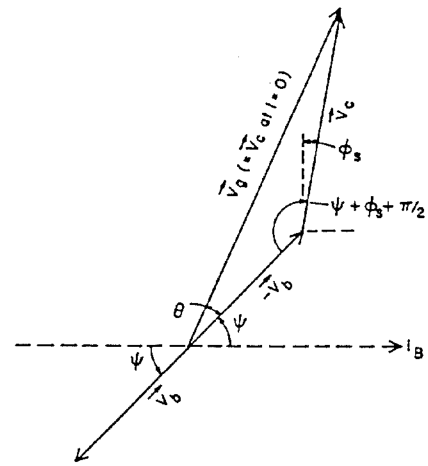

Fig. 1 Phase Vector Diagram

varying source power and/or phase during injection or extraction. The prediction of system performance (beam energy and energy spread as a function of time during extraction given source power and phase and cavity tuning angle) was done by computer integration of the Robinson equations [3]. These are given below with a choice of variables appropriate to Fig. 1.

$$\frac{1}{\omega}\frac{dV_c}{dt} = (2Q_L)^{-1}\left(-V_c + V_{go}\sin(\theta+\phi_s) - V_{bo}\sin\phi_s\right)$$

$$\frac{1}{\omega}\frac{d\theta}{dt} = \alpha E^{-1}\,\Delta E$$

$$\frac{1}{\omega}\frac{d\phi_s}{dt} = -\alpha E^{-1}\,\Delta E + (2Q_L)^{-1}\cdot\left(-\tan\psi + V_{go}\cos(\theta+\phi_s)/V_c - V_{bo}\cos\phi_s/V_c\right)$$

$$\frac{1}{\omega}\frac{d\Delta E}{dt} = (2\pi k)^{-1}\left(V_c\sin\phi_s - V_o\right)$$

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ω is the RF angular frequency and ΔE the difference between the beam energy E and the synchronous energy E_o. $V_{go} = V_g/\cos\psi$ and $V_{bo} = V_b/\cos\psi$.

Note the appearance of $(2Q_L)^{-1}\tan\psi = \Delta f/f$ in the expression for $d\phi_s/dt$. This term represents the cavity driving the system at its resonant frequency. For positive α (systems, such as this one, operating above transition energy) Robinson showed that a negative ψ is sufficient to produce system stability for small changes in equilibrium conditions [3]. ψ here carries the sign of cavity reactance rather than that of cavity admittance, with voltage leading current for positive ψ. In practice instability growth times are long relative to extraction times.

The above equations have been computer integrated for a variety of system parameters. The calculations were made using a "pyramidal" distribution in phase-energy within the bunch, with injected density decreasing linearly with radius in E - ϕ space to extreme values of ±42° in phase and ± 2 x $10^{-4}E_o$ in beam energy. All injected bunches were identical in charge and phase-energy distribution. Source power and phasing conditions remained constant during the injection-extraction process. V_{bo} and V_o are appropriate linear functions of time as the injection-extraction process proceeds.

The result of the system simulation study is that adequate system operation can be obtained over the 300 MeV to 1 GeV range in E_o by choosing $\beta \approx 15$ ($Q_L \approx 1000$). There is little to be gained by varying source power or phase during injection or extraction. Tuning angle and source power and phase are not critical. An illustration is shown in Fig. 2. This figure

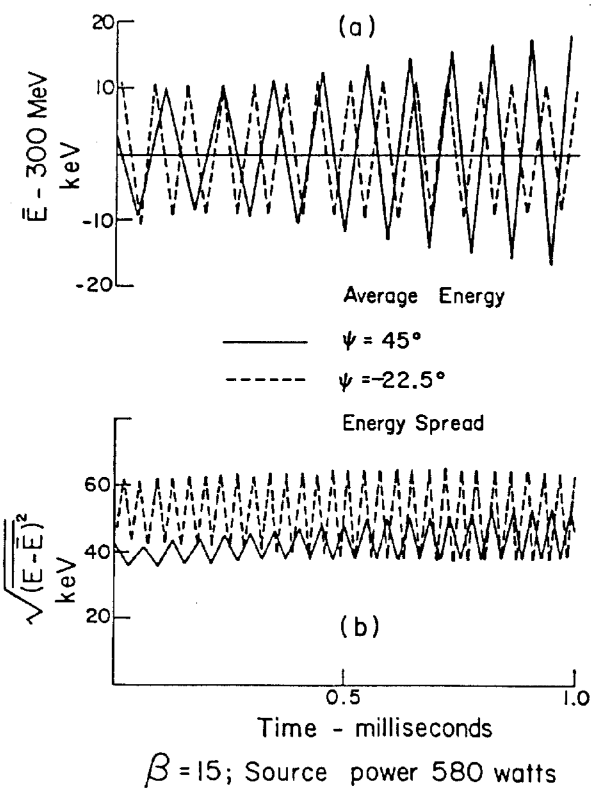

Fig. 2 System Performance Example

shows the results for bunch-by-bunch integration of the Robinson equations for 80mA two-turn injection and one millisecond extraction for 580 Watt source power for tuning angles + 45° and -22.5°. Source power is phased 5° from the optimum, where optimum is defined by minimum synchrotron oscillations excited during injection. Beam energy E_o is 300 MeV. Fig. 2a shows beam energy as a function of time, averaged over each charge bunch and then all 3710 bunches in the ring. The solid curve represents the unstable ψ = 45°, the dashed curve the stable ψ = -22.5°. For clarity the variations are shown in sawtooth form, although actually they are approximately sinusoidal in shape. Fig. 2b shows the rms energy spread relative to the energy of Fig. 2a.

Given a suitable choice for β, it is useful to display the system operation conditions by solving the vector diagram Fig. 1 for the magnitude of the cavity voltage V_c:

$$V_c/\cos\psi = V_{go}(1-V_b^2/V_g^2)^{\frac{1}{2}}\,[1+V_b^2\sin^2(\psi+\phi_s)/V_g^2(1-V_b^2/V_g^2)]^{\frac{1}{2}} - V_{bo}\sin(\psi+\phi_s)$$

Fig. 3 shows the above relation for chosen values (β = 15, Z = 2 MΩ) as a function of P for i = 0 (solid curve) and (dashed curves) for i = 80mA with $\psi+\phi_s$ as parameter. One can, for example, look up in Table I the required V_c and ϕ_s for some beam energy at, say, the beginning of extraction, and then, for an arbitrary

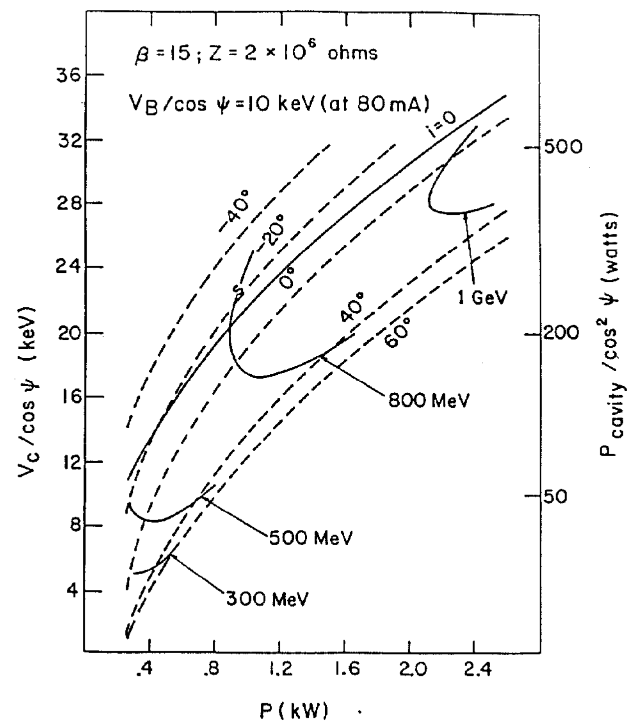

Fig. 3 System Operating Conditions

choice of ψ, plot a corresponding point on Fig. 3, giving the source power requirement. The locus of such points are shown in Fig. 3 for 300, 500, 800, and 1000 MeV. The corresponding ranges of ψ for the segments shown are 0° to +50° for 300 MeV, -30° to +40° for 500 MeV, -45° to +25° for 800 MeV, and -30° to +10° for 1 GeV. Note that the ψ = 45° case shown in Fig. 2 is a matched condition at the beginning of extraction lying on the appropriate curve of Fig. 3. The ψ = -22.5° case is operating far from the locus of matched points, yet the price paid in increased energy spread is modest.

Higher-order Mode Requirements

The excitation of higher order modes (narrow band impedances) of the RF accelerating cavity will produce long-range, low frequency forces which couple the motion of a large number of charge bunches to generate multi-bunch instabilities and which allow the beam to interact with its own field after one or more turns to produce multi-turn instabilities. In the dimension transverse to the beam the nature of this problem is very similar to that of beam breakup in a recirculating linear accelerator. In this case the higher modes of interest are those with significant 'deflecting mode' (TM_{1jk}) contribution which, in the absence of transverse damping, will produce exponential growth in emittance of stored beams. These modes have transverse magnetic fields on axis, and, in quadrature, radial gradients of longitudinal electric fields by means of which an off-axis charge couples energy to the mode.

The computer code used to simulate the excitation of such multi-turn, multi-bunch instabilities is an adaptation of a code developed by R. Helm to study beam breakup in linear accelerators. A beam of energy E and current i is carried by k point-like bunches equally spaced in time by $1/f_o$. The bunches, each characterized by its transverse position and momentum, pass in succession through a cavity (or series of cavities) characterized by f, Q, and (R/Q). f represents the frequency of a deflecting mode and Q its quality factor. (R/Q), the associated 'normalized shunt impedance', or 'geometric quality factor', is defined such that i (R/Q) is the energy transferred to the mode by an off-axis beam current i per two radians of phase and per radian of spatial phase off-axis. The field integral in the cavity is represented by a complex number argument the frequency f and with amplitude exponentially damping according to f and Q. Each bunch passage augments the real part of the field, and the imaginary part augments the transverse momentum of the bunch. Between successive passages of a particular bunch through the cavity the transverse coordinate-momentum of the bunch is transformed by the betatron matrix characterized by μ (betatron phase shift per turn) and β (machine function at the cavity). The instability is excited by offsetting the cavity a small distance from the beam axis.

Fig. 4 represents the results of a series of simulation calculations. The time required for the transverse rms bunch position spread to grow to 1 mm is

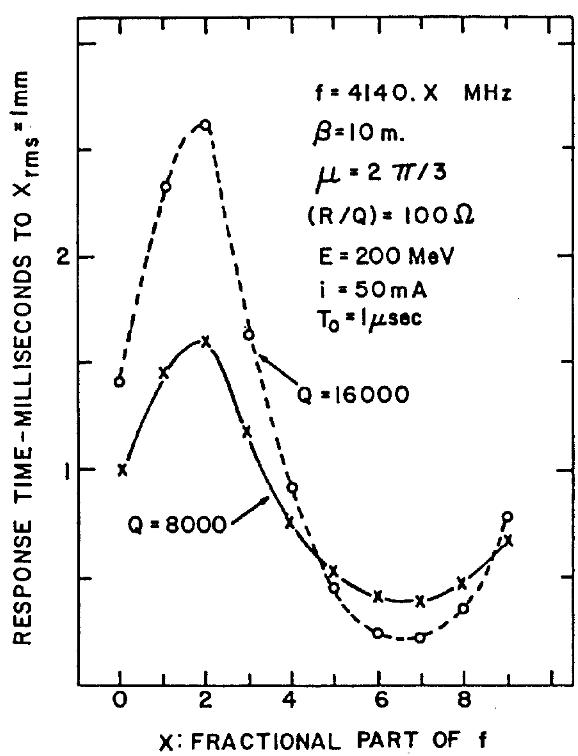

Fig. 4 Transverse Instability Example

plotted versus the fractional part of f. Note that the orbital revolution period $T_o = k/f_o = 1/f_{rev}$ is, in this example, 1 microsecond. This response time to 1 mm is about $6\tau_{10}$, where τ_{10} is the 10-fold growth time of rms bunch position spread. On resonance ($f = n\, f_{rev} - f_\beta$) the growth rate is inversely proportional to beam energy E and directly proportional to i, β, Q, (R/Q), and to f. At lower values of Q than shown on Fig. 4, when the width of the resonance (f/Q) becomes greater than f_{rev}, the resonance behavior disappears and f is always "on resonance". Growth and response times are approximately independent of ring circumference. The on-resonance 10-fold growth time is, typically:

$$\tau_{10}\ (\mu\text{sec}) = 320 \cdot \frac{2856}{f(\text{MHz})} \cdot \frac{1000}{Q} \cdot \frac{100}{(R/Q)(\text{ohms})} \cdot \frac{10}{\beta(\text{meters})} \cdot \frac{100}{i(\text{mA})} \cdot \frac{E(\text{MeV})}{200}$$

The bunch mode is fully developed long before the rms position spread reaches physically significant (mm) dimensions. In the example of Fig. 4 the bunch mode has only two significant Fourier components. The most prominent is the second subharmonic of the 2856 MHz bunch frequency f_o (bunch transverse displacements from the central axis alternate in sign). It would be the only component if f were exactly $3/2\ f_o$. The second prominent component is the difference between f and $3/2\ f_o$. In general there are no significant low frequency components (comparable to f_{rev}) unless either a) f is very near nf_o, or b) the cavity memory time $Q/\pi f$ is much smaller than T_o so that multi-turn effects are not important.

We expect the single-celled 2856 MHz structure to have only one predominantly TM deflecting mode below cutoff (at about 4700 MHz, with $R/Q \approx 10$ ohms), and one other mode at a somewhat lower frequency, predominantly TE, with an order of magnitude lower impedance [4]. In order that rms transverse position spread remain below 0.1 mm for 1 msec, for the proposed Bates ring with $\beta \approx 8$m, E = 300 MeV, and i = 80 mA, the Q of the prominent mode must be below about 25000. Since the loaded Q of the fundamental will only be about 1000, there should be no difficulty in exceeding the above higher-order mode specification by at least two orders of magnitude.

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