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DAMPING RING RF SYSTEM FOR SLC*

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The linear collider project at SLAC contains two damping rings to reduce the emittance of short electron or positron bunches which contain 5×10^{10} particles per bunch. Two of these bunches are stored at a time and then extracted for acceleration in the collider. The RF system is subject to strong transients in beam loading. A computer model is used to optimize capture while minimizing RF power. The introduction of phase jump in the RF drive at injection time together with offsets in the tuning loops of the RF cavities when no beam is stored allows optimum performance under heavy beam load conditions. The RF system (800 kV at 714 MHZ) for the electron damping ring has been built, tested and installed, and is being tested with beam.

INTRODUCTION

The linear collider project at SLAC (SLC) contains two damping rings to reduce the emittance of the e^+ and e^- bunches. This is necessary to attain high luminosity at collision. The bunches of each charge type are stored in separate damping rings. Each ring is a small high-field storage ring in which radiation damping takes place. The RF system is required to replace the energy lost by synchrotron radiation. The parameters of the RF system are given in Table 1. At the 1.21 GeV energy of the stored beams the radiation per turn is a modest 93 keV. However, each injected bunch contains 5×10^{10} particles and this induces parasitic mode losses and strong transient beam loading. A theoretical treatment of beam loading effects indicates that optimum performance can be obtained by introducing a phase jump at injection together with an offset in the tuning of the cavity under no beam conditions. All particles which arrive with an energy spread of ±1% will be captured with the RF system preset in such a fashion. No rapid tuning is necessary, which greatly simplifies the system, but the offset in the tuning loop has to be applied during the time when no beam is stored to keep the cavities in the proper tune condition.

Table 1. RF System Parameters

RF Frequency	714	MHz
Harmonic Number	84	
Available Klystron Power	50	kW
Total Cavity Shunt Impedance	35	MΩ
Unloaded Q	24000	
Cavity Coupling Coefficient	2.5	
Cavity Tuning Angle	−64°	
Injection Phase Angle	78°	
Phase Jump at Injection	−50°	
Energy of Stored Beam	1.21	GeV
Energy Loss per Turn	93	keV
Parasitic Mode Loss per Turn (full current)	48	keV
Circulating Current per Bunch	70	mA
Storage Time between Pulses	5.56	msec

Two RF cavities with two cells each provide the required gap voltage. Amplitude and phase feedback loops stabilize the RF fields in the cavities and thus give the beams a precise timing when they are ejected into the linear accelerator.

To date the damping ring for e^- particles has been constructed and is being commissioned.

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PARASITIC MODE LOSSES

A bunch of charged particles circulating in a storage ring excites electromagnetic fields in the neighborhood of discontinuities in the vacuum chamber walls. In the damping ring there are discontinuities due to the septum, kickers, beam position monitors, clearing electrodes, and transitions between vacuum chamber components. The bunch can, in addition, excite higher-order modes in the RF cavities. Field and modes excited by the bunch represent an energy loss which is in addition to the synchrotron radiation loss per turn. By adding together losses for all the individual component plus the higher-order mode losses in the RF cavities, an estimate can be made for the total loss voltage, $V_\ell = Z_\ell I_0$, where I_0 is the circulating current per bunch and Z_ℓ is the loss impedance. For the damping ring

$$Z_\ell(M\Omega) \approx 1.9 \exp[-0.17\, \sigma_z(mm)] \quad .$$

Note that the loss impedance depends strongly on the bunch length. At the design current of 70 mA per bunch, the loss voltage is $V_\ell \approx 48$ kV for the damped bunch length of 6 mm. This must be added to the synchrotron radiation loss of 93 kV to obtain the total voltage per turn that must be supplied by the RF system.

TRANSIENT BEAM LOADING

In the damping ring the total stored charge is injected in one or two bunches on a single turn, rather than over many turns lasting many cavity filling times, as is usually the case for a storage ring. Thus transient beam loading effect might affect the RF voltage required to capture the injected bunches. It is not simple to write analytic expressions taking into account transient beam loading effects because of the large injected energy spread (±1%), and the resulting large-amplitude phase oscillations for particles at the extremes of this spread. It is straightforward, however, to write turn-by-turn expressions for the energy and phase deviations from the synchronous energy and phase for a relatively small number of superparticles distributed over the injected phase space. The recurrence relations expressing the energy deviation ε and phase deviation θ of the ith particle on the nth turn in terms of quantities on the previous turn are:

$$\theta_n^{(i)} = \theta_{n-1}^{(i)} + A\epsilon_n^{(i)}$$

$$\epsilon_n^{(i)} = \epsilon_{n-1}^{(i)} + V_{g_{n-1}}^{(i)} - V_{B_{n-1}}^{(i)} - V_S$$

Here $A = 2\pi\alpha h/E_0$ where α is the momentum compaction factors, h is the harmonic number and eE_0 is the beam energy; eV_S is the synchrotron energy loss per turn, V_g is the generator voltage component $V_g = V_{gR} \cos\psi \cos(\theta+\psi)$, where ψ is the tuning angle and V_{gR} is the generator voltage component at resonance; and V_B is the beam loading voltage component given by an appropriate sum over the beam induced voltages of all of the individual super particles. In calculating this sum, the decay of the beam induced voltages between turns due to the finite cavity filling time, and the phase shifts due to phase oscillations, must be taken into account. The program DAMP has been written at SLAC by T. Knight to perform this calculation.[1]

Initial results indicated that a minimum klystron power of 44 kW would be required to capture uniform injected energy distribution with $\Delta\epsilon_{max} = \pm 12$ MeV, $\sigma_\epsilon = \pm 7$ MeV. This minimum power was obtained by adjusting the cavity coupling and tuning, and the injection phase

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and energy deviation of the central superparticle in a distribution which is uniform in energy up to $\delta\epsilon_{max}$ with zero phase width. It was soon realized that the required klystron power could be reduced by making a jump in the generator phase at the moment of injection such that the transient in the generator voltage rougly cancels the transient beam induced voltage. A more precise cancellation of all transient beam loading effects could be obtained by jumping both the phase and amplitude of the generator voltage component, but a phase jump alone gives good results and the hardware and control problems are simpler.

Figures 1 and 2 give a typical example of the oscillations in energy and phase for 500 turns after injection for a phase jump in VC at injection of -40^o.

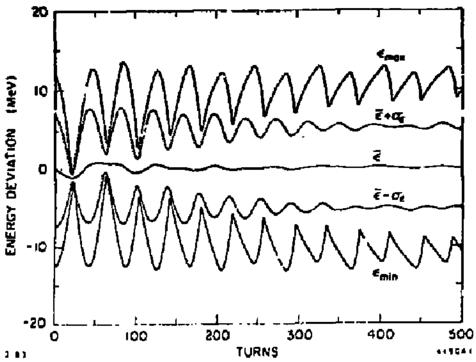

Fig. 1. Variations in the mean phase, the rms phase and the extreme phase excursions for 500 turns.

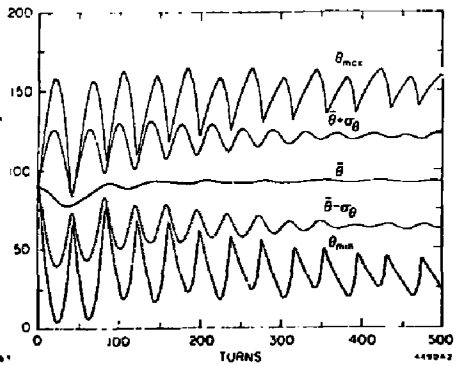

Fig. 2. Variations in the mean energy deviation, the rms energy deviations and the extreme energy deviations for 500 turns.

Details of the other RF and ring parameters are given in Ref. 1. Figure 3 shows the distribution in phase and energy for the injected bunch and for the superparticles after 500 turns (≈60 μs). Also shown is the damped distribution after several damping times (τ_d = 1.5 ms for phase oscillations). Note that the rms energy spread has been reduced by damping by about a factor of six.

By adjusting the magnitude of the phase jump, the cavity coupling coefficient, the cavity tuning angle and the injection phase angle, it is possible to reduce the klystron power required to about 30 kW and still

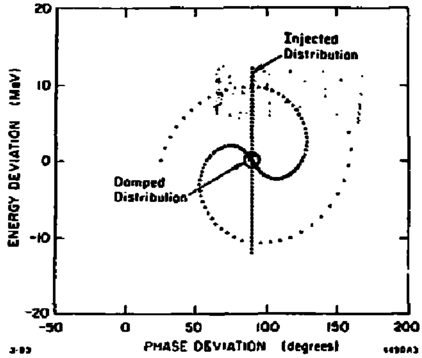

Fig. 3. The injected distribution, the distribution after 500 turns and the damped distribution after 30,000 turns in phase space for 121 superparticles (injected distribution shows for only every third superparticle).

capture the complete injected energy spread. Without a phase jump, the minimum klystron power is 44 kW. The maximum energy excursion is also reduced slightly, from ±15 MeV to ±13 MeV.

RF SYSTEM DESCRIPTION

The block diagram of the RF system is shown in Fig. 4. The design of the RF accelerater structure was optimised to achieve a peak accelerating potential in excess of 1 MV with the available 50 kW of RF power. Calculations with the LALA program yielded a cavity design using four re-entrant copper cells with slot coupling between cells. Due to limited straight section space in the storage ring the four cells were split into two assemblies with two cells each, installed almost opposite each other in the ring. Each structure includes a ceramic window in the input waveguide and a slot coupling from the waveguide into one cell as well as a fixed and a moveable tuner (Fig. 5). Two ports are provided for vacuum pumps. A shunt impedance of $R = V^2/P$ = 17.4 MΩ was measured for each two cell RF structure.

A waveguide magic tee is used to split the power feed to the two RF cavities. Since no counter rotating particles are stored in the damping rings the waveguide lengths and position of the cavities in the ring can be arranged such that reflected power from each cavity is combined in the magic tee's terminated port. Thus the requirement for a costly isolator to protect the klystron is eliminated. The klystron is a commercially available TV tube with 50 kW CW output.

The RF system is stabilized by a total of four feedback loops to assure accurate ejection of the stored and damped beams back into the linear accelerator at the correct phase of the fields in the linear accelerator.

Each cavity is tuned by a feedback loop which compares the RF phase of the field in the cavity to the phase of the driving signal and uses the resulting error to operate the tuner via a stepping motor. Since the intermittantly stored beam is a strong detuning element to the cavity, the tuning loop is adjusted to provide optimum tuning, i.e., minimizing reflected power from the cavity with the beam stored. A pulsed offset is introduced when no beam is in the ring. This offset counteracts the large error which would otherwise be detected when the beam is not present and thus keeps the cavity in a state ready for the next injected beam.

In a similar fashion a pulsed offset is introduced in the main phase feedback loop during the "beam-off" time

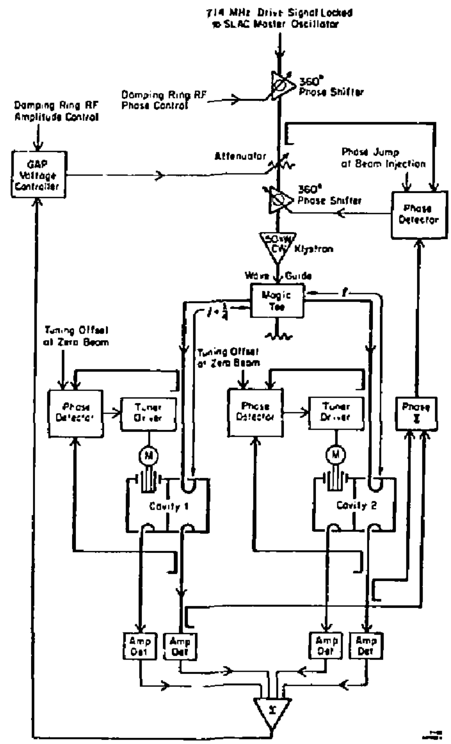

Fig. 4. Block diagram of damping ring RF system.

to rotate the phase of the field in the two cavities to a position where it can best capture the injected beam. The offset is removed at beam injection, and produces the phase jump discussed earlier in this paper. Immediately after injection the rapidly rising beam induced fields rotate the cavity fields to the desired phase. The main function of the phase feedback loop is to lock the vector sum of the field vectors in the two RF cavities to the input signal of the RF system. This signal is derived from the master oscillator of the SLAC linac and this locks the ring RF system to the accelerator RF system. Long cable runs in this loop are temperature stabilized with the coax cable surrounded by a coaxial water jacket operating at +45°C ± 0.1°C. Phase stable coax cables with ±9 ppm/°C temperature coefficient and foam dielectric are used.

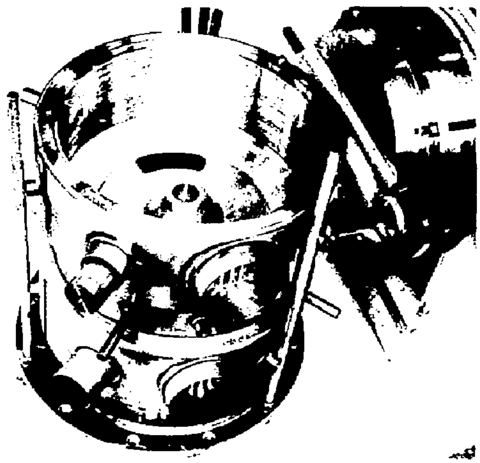

Fig. 5. Two cell RF cavity with one end plate removed (before last braze).

The gap voltage feedback loop sums the field amplitudes detected from samples of each cell and compares it to a fixed reference voltage. The resulting error signal is applied to a variable attenuator in the drive line to the klystron.

The amplitude and phase detectors, electronic attenuators and phase shifters used in the drive and feedback circuits had been developed for the PEP storage ring RF systems and are described in an earlier paper.[2]

PRESENT STATUS

The RF system as described is operational and the damping ring has stored current of ≈1 mA with a lifetime of close to one hour. The synchrotron frequency has been measured as a function of gap voltage and the "cold tested" parameter of the cavities have been verified with the beam. The heavy beam loading tests await the production of intense bunches from the linear accelerator.

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