LOW-LEVEL RF SYSTEM DESIGN FOR THE ACCELERATOR TEST FACILITY (ATF) DAMPING RING*

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Abstract

The ATF damping ring[1] was built to demonstrate the production of low emittance, high current beams for future linear colliders. To attain high beam currents, multiple high current bunch trains are required. The low-level rf system should be designed to minimize both steady-state and transient beam loading effects in the accelerating cavities. In addition the design should be sufficiently flexible to allow for a variety of beam dynamics tests which require a wide range of beam currents and cavity voltages. The low-level rf system and stability boundaries for reduced power and full power operation are discussed in this paper.

1 INTRODUCTION

Control of the longitudinal beam parameters is just one aspect of many exciting studies to be performed using the ATF damping ring. These include the use of damped cavities[2] for suppression of longitudinal coupled-bunch modes, the use of a sub-rf cavity to compensate for intra-train synchronous phase offsets[3], and beam-loading effect minimization during normal operation using a single-turn beam injection/extraction scheme[1]. Many of the studies planned involve the use of a wide range of beam currents and bunch lengths (i.e., cavity voltages).

2 STABILITY BOUNDARIES

Table 1 shows the operating conditions at the design energy of 1.54 GeV with a full 714 MHz (harmonic number h = 330) rf system (250 kW klystron[1], 4 cavities) for different numbers of bunch trains. The cavity coupling parameter[2] β = 2.4 corresponds to optimum coupling at full current neglecting higher order mode losses. The variables listed are: the dc beam current I_{dc}, the beam energy E_0, the accelerating voltage V_c, the radiation loss per turn per electron U_0, the higher order mode loss per turn[4] U_h, the synchronous phase[1] ϕ_s, the synchrotron frequency f_s, the longitudinal damping time τ_s, the natural energy spread $\frac{\sigma_e}{E}$, the bunch length σ_s, the momentum compaction α, the Robinson damping time τ, the total shunt impedance[2] R, the quality factor Q, the cavity fill time (without direct feedback) T_{fill}, the cavity tuning angle (for minimum reflected power) ϕ_z, the overvoltage[3] q, the rf bucket height $\frac{\Delta E}{E}$, the average klystron power $\langle P_g\rangle$, average dissipated power $\langle P_c\rangle$, the average beam power $\langle P_b\rangle$, and the average reflected power $\langle P_r\rangle$.

Parameter	$N_t = 1$	2	3	4	5
I_{dc} [mA]	120	240	360	480	600
E_0 [GeV]	1.54	1.54	1.54	1.54	1.54
V_c [MV]	1.0	1.0	1.0	1.0	1.0
U_0 [keV]	156	156	156	156	156
U_h [keV]	36	36	36	36	36
ϕ_s [deg]	79	79	79	79	79
f_s [kHz]	17.4	17.4	17.4	17.4	17.4
τ_s [ms]	5.5	5.5	5.5	5.5	5.5
$\frac{\sigma_e}{E}$ [10^{-4}]	6.75	6.75	6.75	6.75	6.75
σ_s [mm]	3.6	3.6	3.6	3.6	3.6
α [10^{-3}]	1.9	1.9	1.9	1.9	1.9
τ [ms]	0.19	0.11	0.13	0.17	0.23
R [MΩ]	7.2	7.2	7.2	7.2	7.2
Q	22100	22100	22100	22100	22100
T_{fill} [μs]	2.90	2.90	2.90	2.90	2.90
ϕ_z [deg]	-26.3	-44.7	-56.0	-63.2	-68.0
q	5.21	5.21	5.21	5.21	5.21
$\frac{\Delta E}{E}$ [%]	1.94	1.94	1.94	1.94	1.94
$\langle P_g\rangle$ [kW]	101	120	140	162	186
$\langle P_c\rangle$ [kW]	70	70	70	70	70
$\langle P_b\rangle$ [kW]	23	46	69	92	115
$\langle P_r\rangle$ [kW]	8	4	1	0	0

Table 1: RF parameters for design operation with 1 to 5, full current bunch trains.

Plots for various operating currents at different number of particles per bunch N_{ppb}, number of bunches per train N_{bpt}, and number of trains N_t are shown in Fig. 1 for the case of a single (top) and five (bottom) bunch trains. The solid curves are contours of constant total dc current. The expected threshold for transient bunch lengthening[1] is shown at $N_{ppb} = 3.5 \times 10^{10}$ assuming a 5 mm bunch length. The vertical lines indicate constraints imposed by the larger of the injection or extraction kicker rise and/or fall times (τ_k):

$$N_{bpt}{}^{max} = [\frac{1}{N_t}(\frac{h}{f_{rf}}) - \tau_k] \times \frac{1}{\tau_{bb}} \qquad (1)$$

where τ_{bb} is the bunch-to-bunch spacing. Assuming τ_k = 60 ns, are shown in Fig. 1(b) a solid vertical line

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[1] $\cos\phi_s = \frac{U_0+U_h}{V_c}$

[2] $R = \frac{1}{2}\frac{V_c{}^2}{P_c}$

[3] $q = \frac{V_c}{U_0+U_h}$

(τ_{bb}=1.4 ns), and a dashed vertical line (τ_{bb}=2.8 ns). The solid vertical line in Fig. 1(a) corresponds to a maximum kicker flattop time of 180 ns with $\tau_{bb} = 2.8$ ns.

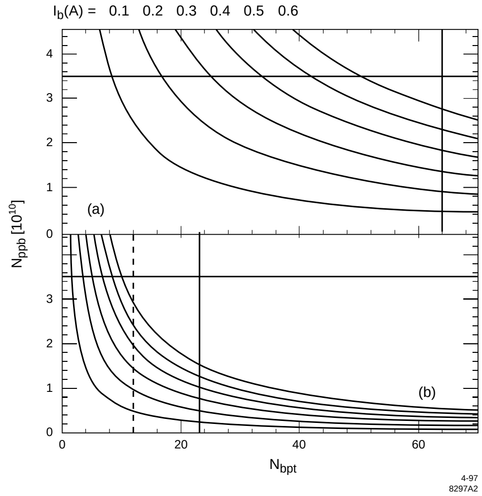

Figure 1: Map of possible fill patterns for the ATF damping ring with a single train (a) and with the design fill of five bunch trains (b).

The parameter space [5] for full current operation at 1.54 GeV is shown in Fig. 2. The horizontal axis is the tuning angle ϕ_z, which is a measure of how far off resonance the cavity is being driven. The open circle designates the design operating point which lies along the line of zero loading angle ($\phi_l = 0$) for minimum reflected power. The shaded region shows a region of instability due to Robinson's high current limit. The region indicated by hatches is accessible as limited by the available klystron output power. In practice, the hatched region may be somewhat reduced, particularly at high currents, if transient loading in the accelerating cavities is not minimized.

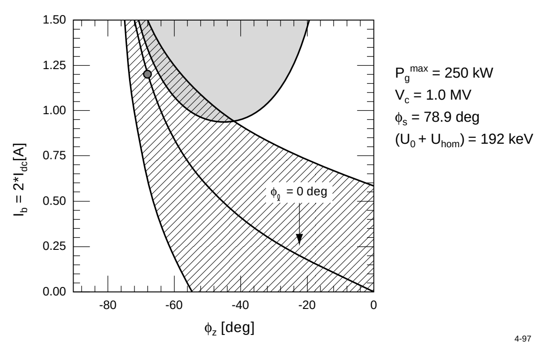

Figure 2: Parameter space for full current operation. Plotted is the beam current ($I_b = 2I_{dc}$) as a function of tuning angle ϕ_z.

Steady-state limitations to the rf beam current (twice the dc beam current) are shown as a function of cavity voltage in Fig. 3. The top two plots are for initial commissioning at reduced power (45 kW) with 2 cavities and a radiative loss per turn of 79 keV at 1.30 GeV and 156 keV at 1.54 GeV. The bottom plot assumes 225 kW available klystron power, 4 accelerating cavities, and a 1.54 GeV beam energy. Shown for zero loading angle are two limits: the maximum klystron output power (circles) and Robinson's high current limit (crosses below the power limit). For experiments requiring both high beam currents and low cavity voltages, direct feedback[6] will be required.

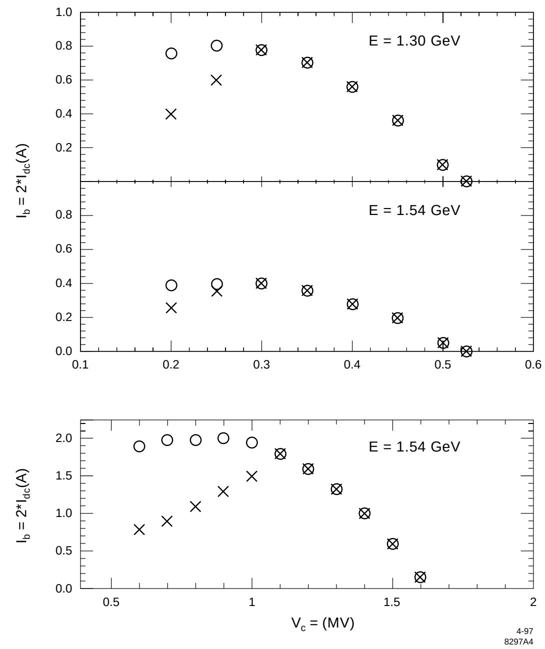

Figure 3: Beam current limits. Plotted is the beam current I_b versus the cavity voltage V_c.

3 LOW-LEVEL RF SYSTEM

The design of the low level rf control system aims towards minimum complexity while satisfying basic requirements. These include compensation for radiation and higher order mode losses, provision of sufficient cavity voltage to ensure an energy acceptance of 1%, regulation of the cavity voltage and beam phase under steady-state operating conditions, and minimization of adverse effects arising from transient beam loading at injection. These requirements should be fulfilled while minimizing the required source power and the power reflected from the cavities.

A block diagram for the low level control system is shown in Fig. 4. In the full rf system, the output of a single 714 MHz klystron is used to power 4 cavities. Conventional isolators are used after the klystron output power has been divided by two. A 1428 MHz master oscillator provides the phase reference for the S-band linac, the damping ring, and the extraction line bunch compressor klystron. The phase of the beam at injection and extraction is varied using phase shifters upstream of the feedback loops. Using the single-turn injection and extraction scheme[1] the injection and extraction phases may not be independently con-

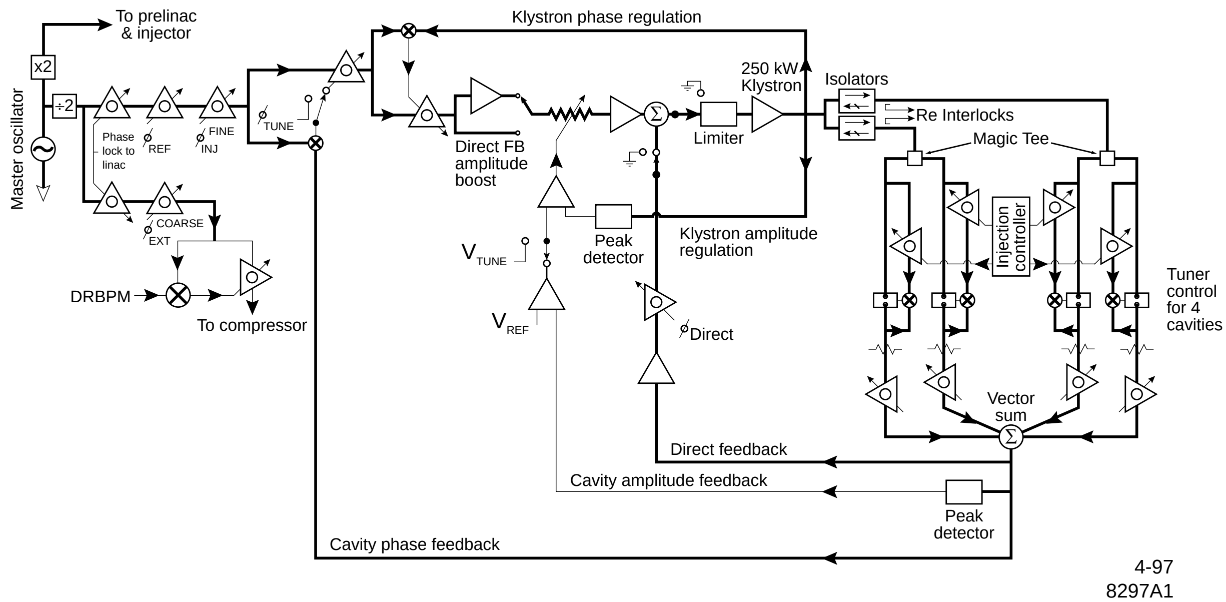

Figure 4: Block diagram of low level rf system.

trolled. In this design, the damping ring rf phase is adjusted for optimum phase at injection; the phase at extraction is therefore fixed. To ensure proper phase in the bunch compressor, the phase of the compressor klystron is adjusted via feedback using a measurement of the beam phase from the damping ring. Conventional feedback loops are used to regulate against changes in the cavity voltage and beam phase. Direct feedback[6] is included to facilitate experiments at low cavity voltage.

4 RAMP TO FULL CURRENT

Due to the proximity of the design operating current to stability boundaries (see Fig. 2), care must be exercised with injection of each bunch train. A suggested injection scheme involves detuning the cavities using the tuner feedback setpoints prior to injection of each train such that after the train has been injected, the average loading angle is zero. The required tuning angle for a train of current ${I_b}^t$ is

$$\phi_z = \tan^{-1}(-\frac{{I_b}^t R_l}{V_c}\sin\phi_s), \tag{2}$$

where $R_l = \frac{R}{1+\beta}$ is the total loaded impedance. But since the tuning feedback loop measures the loading angle (not the tuning angle), the tuner setpoint required at train t is

$$\phi_l = -\tan^{-1}\frac{({I_b}^{t+1} - {I_b}^t)R_l\sin\phi_s}{V_c + {I_b}^t R_l\cos\phi_s}. \tag{3}$$

Note that conventional current ramping with a fixed tuner setpoint would result in beam loss at injection of the final bunch train due to the beam loading limit.

Numerical simulations of the complete rf system have shown that transient loading of the rf system may lead to beam loss at the highest operating currents. This may be avoided using either direct feedback or, for better regulation of the cavity voltage and beam phase, by changing the rf phase (in this case by $\Delta\phi = -\phi_l$ from Eq. (3) at injection of a bunch train. The latter option is particularly useful for maintaining a high duty cycle and is described further in Ref. [7].

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