Contents

Chapter 1

RF Systems.

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1.1 Super-B parameters and RF specification

The main task of the Super-B RF system is to provide the power to the beam necessary to compensate the beam energy losses and to control the longitudinal beam stability in the ring. The main parameters of the machine, which will be used in this chapter, are shown in Table 1.1. The majority of the beam energy losses comes from the synchrotron radiation in bending magnets and wigglers. The main part of this radiation is incoherent radiation power, which is proportional to the beam current and the fourth power of the beam energy. There is also a small amount of coherent synchrotron radiation (CSR), which is proportional to the square of the beam current. The beam also loses energy due to wake fields, which are excited in the beam pipe vacuum elements. Wake fields include short-range and long-range fields. Short-range fields are mainly resistive-wall and geometrical wake fields. Long-range fields include higher order modes (HOMs) excited in the RF cavities or kickers and geometrical cavities in the beam pipe, for example between in and out tapers. The power of the wake fields, like the power of CSR, is proportional to the square of the beam current. Total beam losses are:

$$P_{beam} = U_0 \times I + Z_{HOM} \times I^2 \tag{1.1}$$

Table 1.1: Main parameters of the machine.

Parameter	Symbol	Value	Value	Units
		HER	LER	
Beam energy	E	6.7	4.18	GeV
Beam current	I	2.12	2.12	A
RF frequency	f_{RF}	476.0	476.0	MHz
Revolution frequency	f_{rev}	227.97	227.97	kHz
Bunch spacing	τ_b	4.2	4.2	ns
Harmonic number	h	2088	2088	
Number of bunches	n_b	1011	1011	
Energy loss	U_0	2.03	0.83	MeV/turn
Momentum compaction	α	$4.04 \cdot 10^{-4}$	$4.24 \cdot 10^{-4}$	
Relative energy spread	σ_δ	$6.15 \cdot 10^{-4}$	$6.56 \cdot 10^{-4}$	
Longitudinal damping time	τ_s	14.5	14.5 22.0	ms
Total RF voltage	V_{RF}	5.7	4.1	MV

The averaged HOM impedance is proportional to the bunch spacing τ_b and loss factor K of the ring:

$$Z_{HOM} = \tau_b \times K \tag{1.2}$$

The ring loss factor must not include loss factor of the cavity main mode. The loss factor strongly depends upon the bunch length. The natural (zero current) bunch length may be calculated using the formula

$$\sigma_z = \frac{c\sigma_\delta}{f_{RF}} \times \sqrt{\frac{\alpha h}{2\pi} \times \frac{E}{eV_{RF}\cos(90^0 - \phi_s)}} \tag{1.3}$$

where synchronous phase should satisfy the equation:

$$\sin(90^0 - \phi_s) = \frac{U_0}{eV_{RF}} \tag{1.4}$$

Synchrotron oscillation tune and synchrotron frequency are calculated using these formulas:

$$\nu_s = \sqrt{\frac{\alpha h}{2\pi} \times \frac{eV_{RF}\cos(90^0 - \phi_s)}{E}} \tag{1.5}$$

$$f_s = \nu_s f_{rev} = \nu_s \frac{f_{RF}}{h} \tag{1.6}$$

Values for these parameters and synchrotron loss power, calculated from the ring parameters (Table 1.1) are shown in Table 1.2. There must also be

Table 1.2: Other parameters of the machine.

Parameter	Symbol	Value	Value	Units
		HER	LER	
Synchrotron phase	ϕ_s	69.1	78.3	degrees
Synchrotron tune	ν_s	0.01033	0.01163	
Synchrotron frequency	f_s	2.355	2.652	kHz
Bunch length	σ_z	5.0	5.0	mm
S. R. Power	P_{SR}	4.3	1.76	MW

an additional power to compensate the main mode Joule losses in the room-temperature cavities. This power is proportional to the square of the total RF voltage and inversely proportional to the shunt impedance of a cavity and the number of cavities:

$$P_{cav} = \frac{V_{RF}^2}{2Z_{sh}N_c} \tag{1.7}$$

With unmatched conditions when the beam is not perfectly coupled to the cavity, some power will be reflected back from a cavity. We must also include this in the total power consideration. The reflection coefficient can be described by the formula:

$$\Gamma = 1 - \frac{\alpha_{cav}}{1 + \frac{P_{beam}}{(\beta+1)P_{cav}}} \tag{1.8}$$

where α_{cav} and β are geometrical parameters of a cavity. The last one represents the coupling coefficient or coupling factor. The reflected power is proportional to the incident power and reflection coefficient squared:

$$P_{ref} = P_{in} \times \Gamma^2 \tag{1.9}$$

So the total incident power will be the sum of beam power loss, cavity losses and reflected power

$$P_{in} = P_{beam} + P_{cav} + P_{ref} \tag{1.10}$$

1.2 Beam and RF power

Preliminary analysis for possible RF system design can be found in reference [1]. The choice of the RF voltage and number of cavities is based on the bunch length, the maximum operational voltage in a cavity and the maximum transmitted and reflected power through a cavity RF window necessary to separate the cavity vacuum from the waveguide. The existing coupling factor may limit the total beam current because of large reflected power with unmatched conditions. For the Super-B RF system we propose to re-use the main elements of the PEP-II RF system as klystrons, modulators, circulators and cavities with coupling boxes. SLAC PEP-II RF operational experience shows that the power limit for each cavity window is 500 kW [2]. Stable operational voltage in one cavity should be limited by 750-800 kV to avoid cavity arcs. One klystron may supply power for two cavities. Parameters of a PEP-II cavity are shown in the Table 1.3. Detailed information about calculated and measured parameters of the longitudinal and transverse modes of the PEP-II cavity is given in reference [3]. For a given coupling factor we

Table 1.3: PEP-II cavity parameters

Parameter	Value	Units
RF frequency	476	MHz
Shunt impedance Z_{SH}	3.8	MOhm
Unloaded Q_0	32000	
Z_{SH}/Q_0	117	Ohm
Coupling factor β	3.6	
Maximum incident power	500	kW
Maximum cavity voltage	0.75-0.9	MV

may optimize the transmitted power to the beam. The ratio of the incident power to the beam loss, as a function of a ratio of the beam losses to PEP-II cavity losses, is shown in Fig. 1.1

With the PEP-II coupling factor($\beta = 3.6$), the minimum reflected power is achieved when beam losses are 2.2 times larger than the cavity losses. However, the minimum incident power is achieved with a higher ratio of beam to cavity power (4 to 6). Based on this optimization for the SUper-B parameters and taking into account power and voltage limits we can calculate the necessary number of cavities and klystron (stations), and the supply

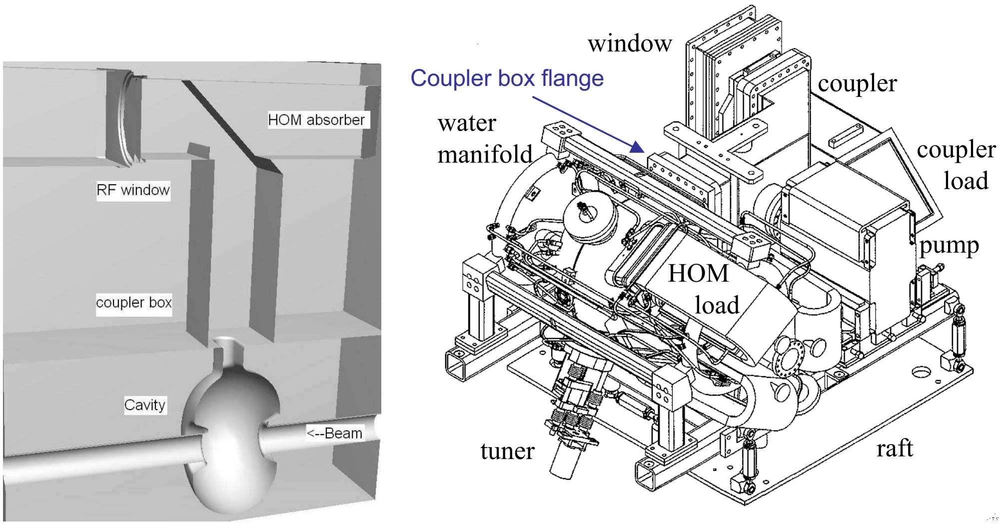

Figure 1.2: PEP-II cavity, coupler box and RF window.

$$Z_{th}(\omega) = \frac{4\pi E\nu_s}{\alpha\tau_s N_c I\omega} \tag{1.12}$$

Figure 1.4 shows impedance of a PEP-II cavity ([3]) and thresholds for 12 and 16 cavities. Left peak is a fundamental mode at 476 MHz. All cavity HOMs are below the threshold, so no feedback to damp HOMs is required.

1.4 RF environment

RF stations are located in the support building (Fig. 1.5). Each station consists of a 2 MW (90 kV, 23 A) high voltage power supply (HVPS); a 1.2 MW klystron amplifier with a high-power circulator for protection of the klystron from reflected power; a power splitter (Magic-tee with a 1.2 MW RF load) followed by waveguide distribution system from a surface level down to the tunnel ending by two cavities. The RF distribution is via WR2100 waveguide, chosen primarily for low group delay. Each cavity has three HOM loads [5]. For safety these loads were specified for up to 10 kW dissipation each.

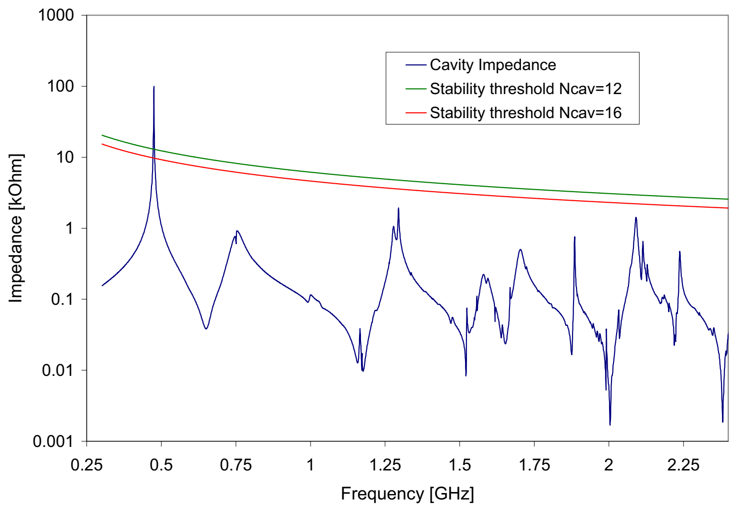

Figure 1.4: Impedance of a PEP-II cavity (blue line) and thresholds for 12 (green line) and 16 cavities (red line).

up-converted to RF and drives the klystron. The direct loop contains a PID controller with an integral compensation for smoothing out the ripple caused by the klystron high voltage power supply and lead compensation that increases the bandwidth and gain of the loop. The direct feedback loop options control the optional functions of the direct loop: frequency offset tracking, integral compensation and lead compensation. The frequency offset tracking loop takes out the phase shift caused by detuning of the cavities during heavy beam loading. It is used as a diagnostic for adjusting the waveguide network. The comb loop provides additional impedance reduction for the cavities at specific synchrotron frequency sidebands around the revolution harmonics of the beam. It operates over a bandwidth of 2 MHz and includes a 1 turn delay. The tuner loop tunes and maintains each cavity at resonance. It corrects for thermal frequency variations and compensates cavity beam loading by keeping the phase relationship between forward power and cavity field, as seen by the cavity probe, constant. The relevant phases are measured by digital IQ detectors and the loop is completed in software controlling the tuner position via a stepping motor. The HVPS loop adjusts the voltage to the klystron to provide sufficient output power to operate the station under whatever gap voltage or beam loading is requested. Functionally the loop keeps the klystron operating at about 10% below saturated output power.

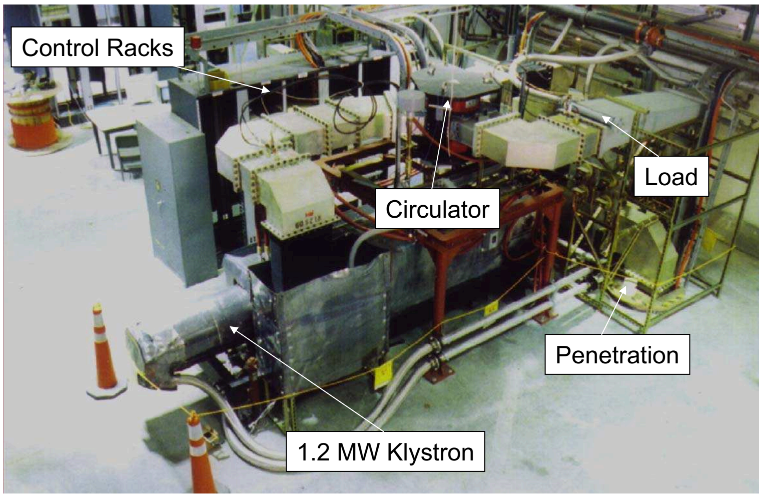

Figure 1.5: PEP-II RF station.

The loop measures the drive power at the input to the klystron and compares it to the ON CW drive power set-point. Based on the error the set-point for the high voltage power supply is adjusted up for excessive drive and down for insufficient drive. This is a slow loop with about a 1 Hz bandwidth. The DAC loop is a slow (0.1 Hz bandwidth) loop in software which functionally keeps the measured gap voltage of the station equal to it's requested "Station Gap Voltage" by adjusting the DAC in the gap voltage feed-forward module. The ripple loop is intended to remove amplitude and phase ripple in the klystron output power but at the time it is only utilized to keep the low bandwidth phase across the klystron and drive amplifier constant as the klystron voltage is varied. The gap feed forward loop is required to tell the direct loop to ignore the effects of the ion-clearing gap in the beam bunch train. Functionally the loop learns about the variation in the klystron drive caused by the beam gap and adds an equal variation in the reference signal so that the error signal driving the klystron stays unchanged. This loop adapts fully in about 1000 beam revolutions. The longitudinal feedback woofer is the third cavity impedance reduction loop along with the direct loop and the comb loop. It derives it's information from the lowest beam oscillation modes detected by the longitudinal multi-bunch feedback system and uses one RF station in each ring as a powerful longitudinal kicker.

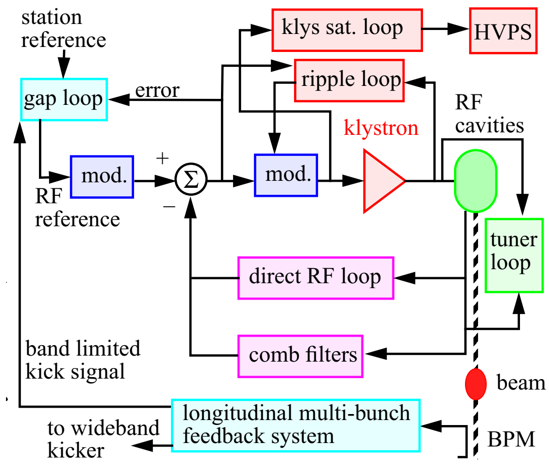

Figure 1.6: Block diagram of RF feedback circuits.

1.6 Synchronization and timing

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