Tuesday, January 26, 2010

RF Systems.

1. Super-B parameters and RF specification

The main task of the Super-B RF system is to provide power to the beam necessary to compensate the beam energy loss 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.

Table 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	476	MHz
Revolution frequency	f_{ref}	227	227	kHz
Bunch spacing	τ_b	4.2	4.2	ns
Harmonic number	h	2100	2100	
Number of bunches	N_b	1018	1018	
S.R. Energy loss per turn	U_{SR}	2.03	0.83	MeV
Momentum compaction	α	4.04 x10^{-4}	2.24 x10^{-4}	
Relative Energy spread	δ_E	6.15x10^{-4}	6.57x10^{-4}	
Longitudinal damping time	τ_b	14.5	22	ms
Total RF Voltage	V_{RF}	5.7	4.1	MV
Longitudinal damping time	τ_s	10.8	10.8	ms

The majority of the beam energy loss comes from the synchrotron radiation in bending magnets. This is mainly 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 synchrotron radiation loss due to coherent synchrotron radiation (CSR).

The beam also loses energy due to wake fields, which are excited in the beam pipe vacuum elements. Wake fields include short-range fields, like resistive wall and geometrical wake fields, and long-range fields like higher order modes (HOMs) excited in the RF cavities and kickers and possible low-Q geometrical cavities in the beam pipe, for example between in and out tapers.

The power of the wake fields, like power of CSR, is proportional to square of the beam current. Total beam losses are:

$$P_{beam} = \underbrace{U_{S.R.} \times I}_{\text{incoherent radiation}} + \underbrace{Z_{HOMs} \times I^2}_{\text{coherent radiation}}$$

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

$$Z_{HOMs} = \tau_b \times K$$

The ring loss factor must not include the 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

$$\sigma_0 = \frac{c}{f_{RF}} \times \delta_E \times \sqrt{\frac{\alpha h}{2\pi} \times \frac{E}{\cos\left(90^\circ - \phi_S\right)}}$$

where the synchronous phase should satisfy the equation:

$$\sin\left(90^\circ - \phi_S\right) = \frac{U_{SR}}{V_{RF}}$$

The synchrotron frequency and synchrotron tune are calculated using these formulas:

$$f_S = f_{RF}\sqrt{\frac{\alpha}{2\pi h} \times \frac{V_{RF}\cos\phi_S}{E}} \qquad \nu_S = h\frac{f_S}{f_{RF}}$$

Values for these parameters and synchrotron loss power, calculated from the ring parameters (Table 1) are shown in Table 2.

Table 2. Other parameters of the machine

Parameter	Symbol	value	value	Units
		HER	LER	
Synchronous phase	ϕ_S	69.1	78.3	degrees
Synchrotron frequency	f_s	2.355	2.652	kHz
Synchrotron tune	ν_S	0.01033	0.001163	
Bunch length	σ_0	5.0	5.0	mm
S.R. Power	$P_{S.R.}$	4.3	1.76	MW

There must also be 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 the cavity and the number of cavities:

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

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

$$\Gamma = 1 - \frac{\alpha_{cav}}{1 + \frac{P_{S.R.} + P_{HOM}}{(\beta+1)P_c}}$$

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

$$P_{ref} = P_{in}|\Gamma|^2$$

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

$$P_{in} = P_{beam} + P_{cav} + P_{ref}$$

2. Beam and RF power

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 [1-8]. SLAC PEP-II RF operational experience shows that the power limit for each cavity window is 500 kW. Stable operational voltage in one cavity should be limited to 750-800 kV to avoid cavity arcs [9-12]. One klystron may supply power for two cavities. Parameters of a PEP-II cavity are shown in Table 3. Detailed information about calculated and measured parameters of the longitudinal and transverse modes of the PEP-II cavity is given in reference[1].

Table 3. PEP-II RF cavity parameters.

Parameter	value	units
RF frequency	476	MHz
Shunt impedance	3.8	MOhm
Unloaded Q	32000	
R/Q	118	Ohm
Coupling factor	3.6	
Maximum incident power	500	kW
Maximum cavity voltage	750-900	kV

For a given coupling factor we 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.

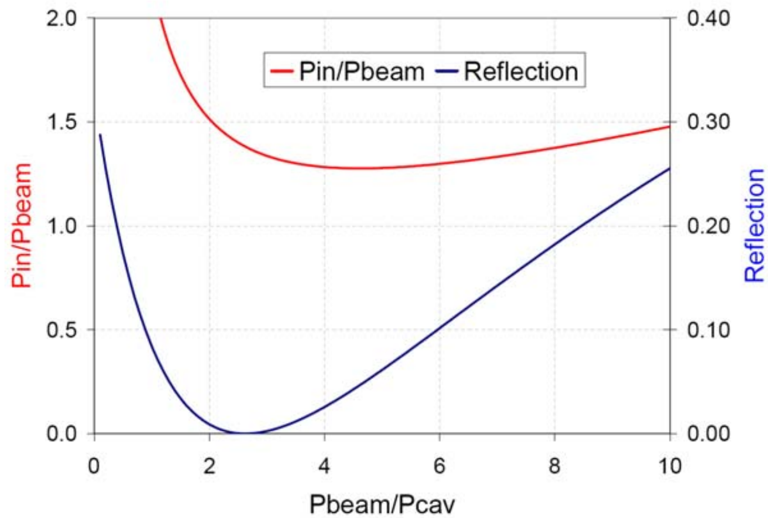

Figure 1: Efficiency of the transmitted power to the beam and reflected coefficient squared as a function of ratio of beam losses to cavity losses. Coupling factor β=3.6.

With the PEP-II coupling factor, 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 power. For HOM power calculation we use the PEP-II LER impedance.

We can change the coupling factor in order to decrease the reflected power and power consumption by modifying only the coupler box of a cavity assembly (Fig 2.)

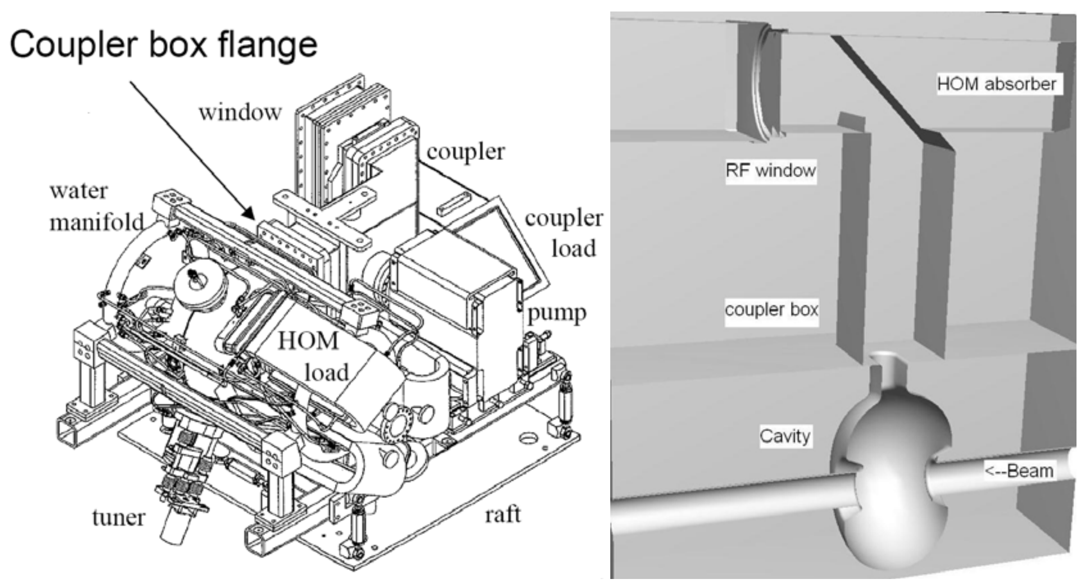

Figure 2: PEP-II cavity assembly (left), a cavity, coupler box and RF window (right).

We will change the small dimension of the waveguide leading to the coupler slot for 1/4 of a wavelength, forming a quarter-wave transformer. The waveguide impedance varies directly with this dimension. A β up to 6 is achievable without changes to the cavity

itself. Since the quality of the match varies only slowly with β, we may optimize for a common coupling factor for all cavities.
RF parameters for the Super-B case are shown in Table 4. We assume that klystrons have 50% efficiency.

Table 4. RF parameters (coupling factor 6.0)

HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER+
Total	Zero I		Max	Number			Total	Total	Total	Power fo	reflected	LER
RF	Bunch	Bunch	voltage	of	S.R.	HOM	cavity	reflectec	forward	to one	from	Total
voltage	length	spacing	per cavit	cavities	power	power	loss	power	power	cavity	one	forward
MV	mm	nsec	MV	klystror	MW	MW	MW	MW	MW	MW	MW	MW
5.78	5.00	4.20	0.51	12.00	4.30	0.45	0.37	1.30	6.41	0.53	0.11	9.03
				6.00								
												HER+
LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER
Total	Zero I		Max	Number			Total	Total	Total	Power fo	reflected	Plug
RF	Bunch	Bunch	voltage	of	S.R.	HOM	cavity	reflectec	forward	to one	from	Power
voltage	length	spacing	per cavit	cavities	power	power	loss	power	power	cavity	one	eff.~50%
MV	mm	nsec	MV	klystror	MW	MW	MW	MW	MW	MW	MW	MW
4.10	5.01	4.20	0.58	8.00	1.76	0.40	0.28	0.17	2.61	0.33	0.02	18.05
				4.00								

We consider using 6 stations for HER and 4 stations for LER. We may install one spare station in each ring, assuming that the impedance of the four detuned cavities will not bring instability problems. The klystrons required, plus several spares, exist at SLAC, although more klystrons may eventually be built to replenish the supply as tubes age.

3. Gap transient and frequency detuning

The existence of an ion-clearing gap in the electron bunch train causes a change in cavity voltage and phase along the bunch train. The cavity voltage change further causes a change in synchronous phase of the electron bunches. The result is a turn-by-turn ``phase transient" or ``gap transient." The phases of the electron bunches will be modulated at the revolution harmonics causing the bunch phases to vary in a quasi-sawtooth fashion along the bunch train.

The β_y* at the SuperB IP is significantly shorter than the bunch length, and the beams cross with a non-zero angle. As a result, the HER and LER bunches must overlap exactly at the IP or the luminosity will suffer. For a 5 mm 1σ bunch length, a 1.0 mm relative shift in z-position (corresponding to about 0.5 degrees of RF phase) between the HER and LER bunches will reduce luminosity by about 1%. The HER and LER phase transients must match to about 0.5 degrees RMS to avoid more than a 1% reduction in luminosity. A large mismatch in phase transients will also cause stability problems due to tune shifts along the bunch train.

The magnitude and shape of the phase transients are functions of cavity beam loading and synchronous phase, which are functions of the number of cavities and the beam currents. With fixed (equal) beam currents in the HER and LER, the number of LER cavities can be adjusted to approximately match the phase transients, yielding the phase transients shown in Fig. 3. The RMS phase error is only 0.2 degrees, resulting in a negligible luminosity reduction.

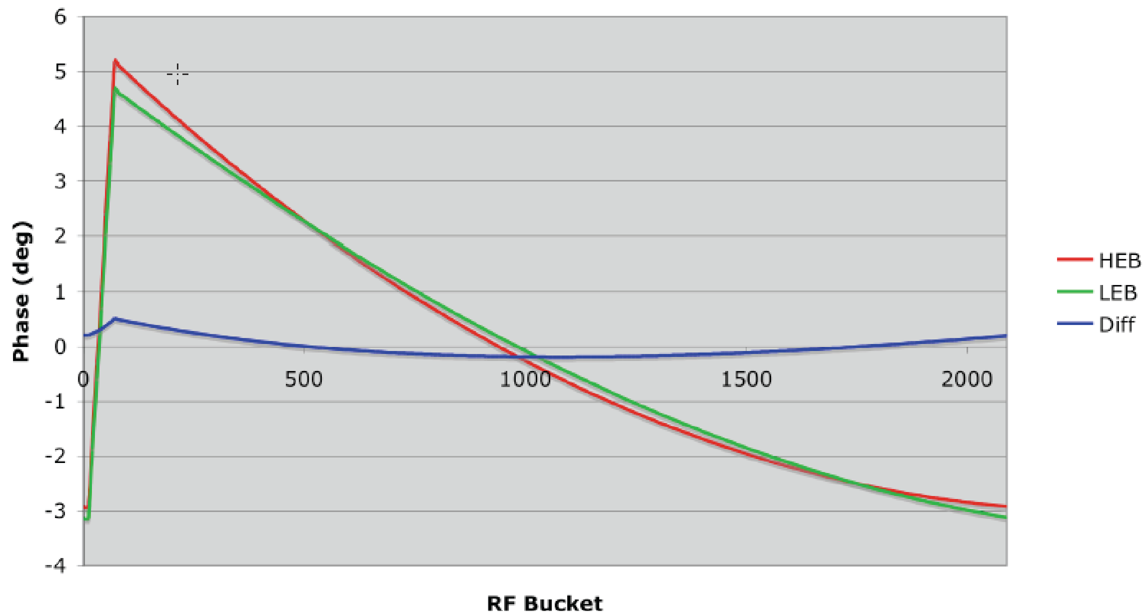

Figure 3: Phase transient in HER and LER and difference. The RMS phase error is 0.2 degree.

To avoid resonant instability at the main frequency (i.e. to compensate for beam loading), the RF cavities must be detuned from resonance according to the following formula

$$\delta f = -f_{RF} \times \frac{Z_{sh}}{Q} \times \frac{I}{V_{RF}} N_C$$

For the Super-B parameters the detuning in HER is 252 kHz and 233 kHz in LER. These numbers are near the revolution frequency (227 kHz). The feedback system must be designed to damp this -1 mode.

We can check beam stability for higher order modes using the same approach as in reference [14]. HOM cavity impedance must be less than the stability threshold defined by the beam and ring parameters including radiation damping time

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

Fig. 4 shows the impedance of a PEP-II cavity [1] and the threshold for super-B LER and HER beams. The left peak is the fundamental mode at 476 MHz. For comparison we present also the thresholds achieved at PEP-II, which are several times lower. If we use

PEP-II type feedback systems we may increase the beam currents at Super-B several times.

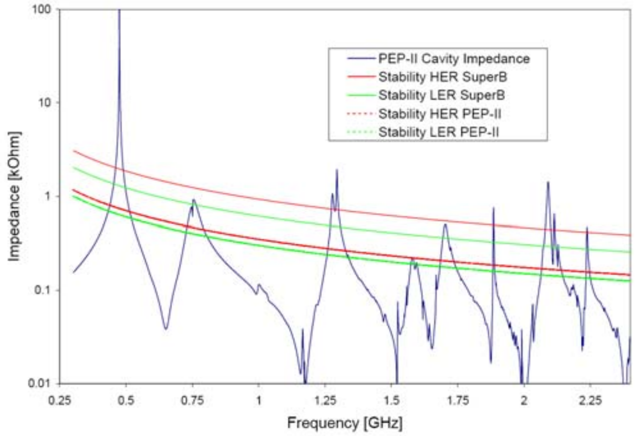

Figure 4: Impedance of a PEP-II cavity (blue line) and thresholds for Super-B HER (red upper line) and LER (green upper line) and for the PEP-II HER and LER rings (down lines).

Increasing the currents we need to increase the number of cavities, increase the coupling factor and total voltage. Plots for number of cavities and voltage as functions of the beam current are shown in fig. 5. We assume that HER and LER have the same currents.

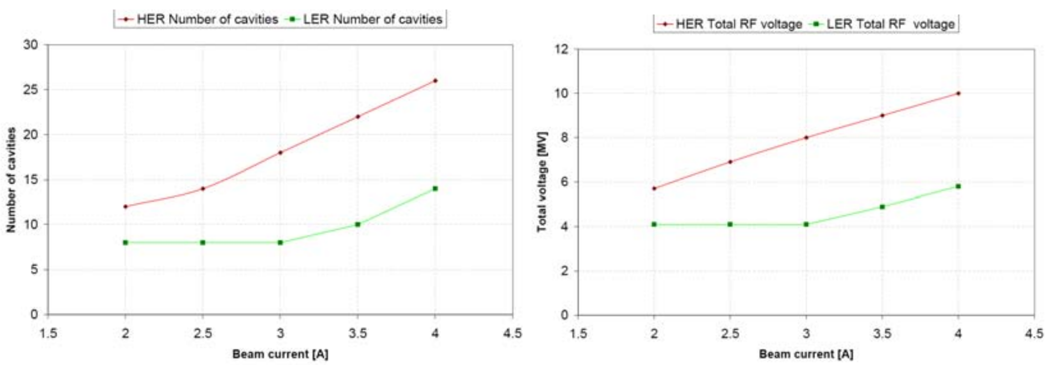

Figure 5: Number of cavities and voltage as functions of the beam current.

The needed wall plug power is shown in Fig. 6.

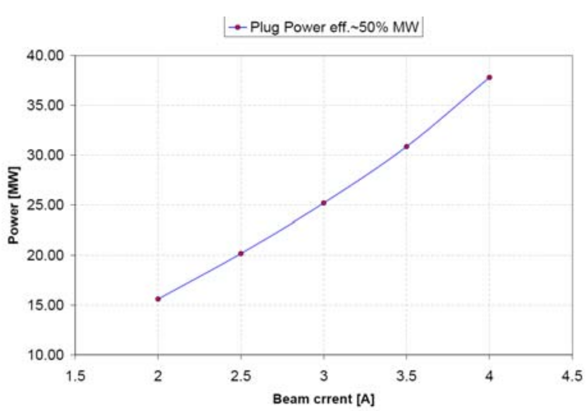

Figure 6: Wall plug power as a function of the beam current.

4. RF environment

The RF stations are located in the support building (Fig. 6). 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 surface level down to the tunnel ending in two cavities. The RF distribution is via WR2100 waveguide, chosen primarily for low group delay. Each cavity has three HOM loads. For safety these loads were specified for up to 10 kW dissipation each [15-16].

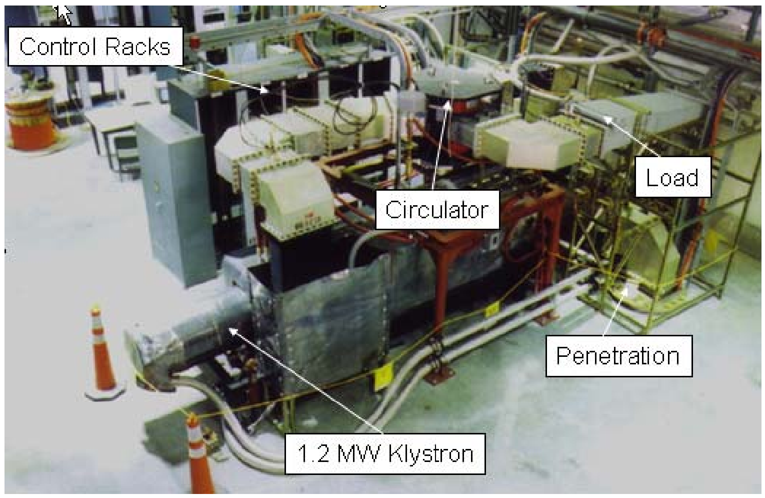

Figure 6: PEP-II HER RF station 12-3

5. Low Level RF System

A low-level RF system provides control and feedback for stable multi-bunch high current operation. There are several feedback loops [17-20].

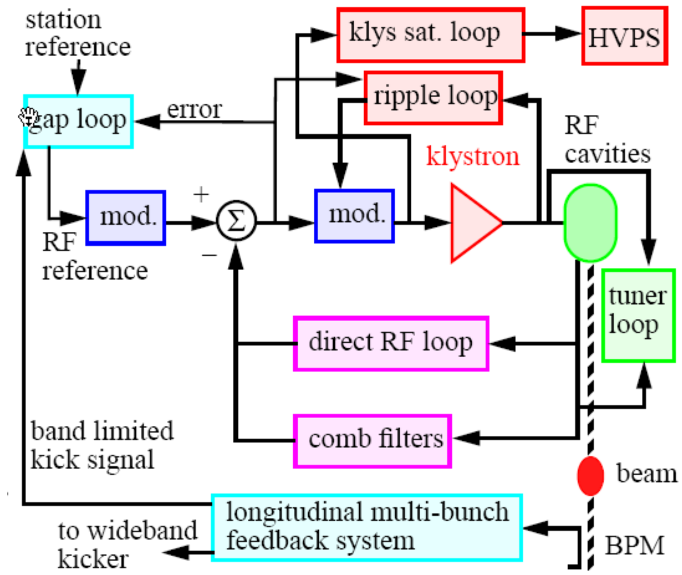

Figure 7: Block diagram of RF feedback circuits

The direct loop is required for lowering the cavity impedance to reduce multi-bunch oscillations of the beam. Functionally the direct loop keeps the gap voltage constant as set by a DAC reference over an 800 kHz bandwidth. The loop compares the combined baseband field signals of a station's cavities to the reference generated by the gap module. The resultant error signal is 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. 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 bunch-by-bunch feedback system and uses one RF station in each ring as a powerful longitudinal kicker.

6. Synchronization and timing

The goal of the synchronization and timing system is to assure that all the RF systems and the other timed devices will be able to work with signal and frequencies locked in phase within the ranges defined by the specifications. A master sinusoidal oscillator at the RF frequency (476 Mhz) including a phase continuity feature must be considered, and it must be able to provide a 10^{-11} short term stability. Small change of frequency in a range <100 KHz (by steps of 1 or 5 kHz) must be accepted without loose of signal phase. The distribution of the RF main signal must be assured with a peak-peak jitter < 0.5 ps. Very low jitter phase shifters must be implemented to synchronize, separately for each ring, beam collisions and bunch injections. The synchronization and timing system must also provide sinusoidal frequencies for the LINAC cavities, typically 6 and/or 12 times the main RF sinusoidal signal. Generation of other (m/n)*RF frequencies, with m and n integer, could be considered if necessary. The utmost peak-peak jitter for these devices can be within 2 ps. The injection triggers have to be locked to the main RF frequency and to the 50 Hz of the main power supplies. Diagnostics and injection triggers must include at least the "Fiducial" (a reference revolution frequency given by main RF frequency divided by the harmonic number) and bunch number triggers, all locked in phase with the RF main frequency within a 2 ps peak-peak jitter.

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