Chapter 4

RF Parameters

4.1 Introduction

This chapter discusses the requirements for the KEKB RF system, coupled-bunch instabilities caused by RF cavities and our solutions, and a consistent set of RF design parameters. Detailed descriptions of the cavities and other RF hardware components are given in chapter 8.

Coupled-bunch instabilities arising from the higher-order modes (HOM's) of cavities must be sufficiently suppressed. Since the stored current at KEKB is much higher than that at any existing storage rings, the Q-values of HOM's must be sufficiently lowered, typically much below 100 for dangerous modes, by effectively extracting the field energy out of the cavity. A number of HOM-damped cavity structures have been proposed and studied around the world.

In addition, the accelerating mode itself can give rise to a longitudinal coupled-bunch instability in a large electron/positron storage ring with an extremely high beam current, such as KEKB or other high-luminosity factory machines. If we use conventional normal-conducting damped cavities in KEKB, several modes of coupled-bunch instabilities can be excited. The growth rate will be extremely high due to the high impedance of the accelerating mode.

In order to solve this problem, a new normal-conducting RF structure, referred to as an accelerator resonantly coupled with an energy storage (ARES) [1], was proposed. It employs an energy storage cavity operating in a high-Q mode. Another candidate is a superconducting cavity (SCC), which is fairly immune against this instability. Extensive R&D work is in progress at KEK on both the ARES and the superconducting cavity.

The design parameters of the RF system have been determined by taking the followings into consideration: required accelerating voltage and beam power, growth rates of the coupled-bunch instabilities, RF properties of the proposed cavities, and the power handling capability of high power components.

4.2 Requirements

4.2.1 RF Voltage

The total RF voltage is determined by requirements to provide: (1) a short bunch length ($\sigma_z = 4$ mm) and (2) the desired synchrotron tune. The required RF voltage (V_c) is given by

$$V_c \sin \phi_s = \frac{cC\alpha_p E\sigma_\varepsilon^2}{e\omega_{RF}\sigma_z^2}, \tag{4.1}$$

where c is the velocity of light, C the ring circumference, α_p the momentum compaction factor, E the beam energy, σ_ε the relative energy spread, σ_z the rms bunch length, ω_{RF} the RF angular frequency and ϕ_s the synchronous phase. In general, a short bunch length requires a high accelerating voltage. The synchrotron tune (ν_s) is given by

$$\nu_s = \frac{C\alpha_p\sigma_\varepsilon}{2\pi\sigma_z}. \tag{4.2}$$

It is seen from Equations (4.1) and (4.2) that when σ_ε and σ_z are given, $V_c \sin \phi_s$ and α_p are proportional to ν_s. Since σ_ε is given by the bending radius, V_c and α_p are determined uniquely by giving σ_z and ν_s.

From beam dynamics considerations the synchrotron tune should be variable in order to find the best operation point, while avoiding synchrotron-betatron coupling resonances. It is considered that the synchrotron tune should be variable from 0.01 to 0.02, while keeping the bunch length constant. For this purpose both the momentum compaction factor and the total RF voltage need to be able to be varied in proportion to each other. Thus the RF voltage should be variable over a range of 4.9∼9.4 MV (LER) and 8.7∼16.2 MV (HER), respectively.

4.2.2 Beam Power

The radiation power loss of the beam at bending magnets is 2.1 MW for the LER and 3.8 MW for the HER. An additional beam power loss is caused by wake potentials due to the ring impedance (HOM loss) and by radiation at wiggler magnets. The total ring impedance is estimated to give a loss factor of about 42 V/pC in the LER and 60 V/pC in the HER, which causes a HOM loss of about 0.57 MW and 0.14 MW, respectively. Wiggler magnets may be optionally installed in the LER in the future for reducing the

Table 4.1: RF-related machine parameters.

Ring	LER	HER	
Particle	positron	electron	
Beam energy	3.5	8.0	GeV
Beam current	2.6	1.1	A
Bunch length	0.4		cm
Energy spread	7.4×10^{-4}	6.7×10^{-4}	
Bunch spacing	0.59		m
Synchrotron tune	0.01∼0.02	0.01∼0.02	
Momentum compaction	$0.93 \sim 1.9 \times 10^{-4}$	$1.2 \sim 2.5 \times 10^{-4}$	
Energy loss/turn	$0.81^{\dagger}/1.5^{\dagger\dagger}$	3.5	MeV
RF voltage	4.9∼9.4	8.7∼16.2	MV
RF frequency	508.887		MHz
Harmonic number	5120		
Damping time	$43^{\dagger}/23^{\dagger\dagger}$	23	msec
Radiation Power	$2.1^{\dagger}/4.0^{\dagger\dagger}$	3.8	MW
HOM Power	0.57	0.14	MW
Total Beam power	$2.7^{\dagger}/4.5^{\dagger\dagger}$	4.0	MW

† — without wiggler

†† — with wiggler

damping time from 43 ms to 23 ms, and also to control the emittance. The total beam power loss in the LER is 2.7 MW without the wiggler, and about 4.5 MW with the wiggler. The total beam power loss in the HER is 4.0 MW. These and other RF-related ring parameters are summarized in Table 4.1.

4.3 Cavity-Related Instabilities

The radiation damping time of KEKB is 23 ms (HER) and 43 ms (LER), respectively. (If the wiggler magnets are installed in the LER, the damping time is reduced to 23 ms.) The growth time of any coupled-bunch instabilities must be longer than the radiation damping time, or at least longer than several milliseconds, so that the instability can be suppressed by a bunch-by-bunch feedback system or by an RF feedback system.

4.3.1 Coupled-Bunch Instability due to the Accelerating Mode

In storage rings, the cavity tuning is usually set to minimize the input power to the cavity. The resonant frequency is detuned toward the lower side to compensate for the reactive component of the beam loading. Without this detuning, a large amount of RF power is reflected from the cavity. The amount of detuning frequency for an optimum operation is given by

$$\Delta f = -\frac{I \sin\phi_s}{2V_c} \times \frac{R_s}{Q_0} \times f_{RF} = -\frac{P_b \tan\phi_s}{4\pi U}, \tag{4.3}$$

where I is the beam current, ϕ_s the synchronous phase, V_c the voltage per cavity, R_s the shunt impedance, Q_0 the Q-value, f_{RF} the RF frequency, P_b the beam power and U the stored energy.

If a high beam current is stored in a large storage ring, the detuning frequency can be comparable to, or even exceed the revolution frequency (f_{rev}). The coupling impedance of the accelerating mode at the upper synchrotron sidebands of the revolution harmonic frequencies f becomes significantly high. Here the f is given by $f = f_{rev}(h + m + \nu_s)$, where h is the harmonic number and $m = -1, -2, \ldots$. If we use conventional normal-conducting cavities in KEKB, the detuning frequency would be several times the revolution frequency. It will excite several modes of the coupled-bunch instability with a growth time on the order of 100 μsec, which is much faster than the radiation damping time.

In order to reduce the growth rate of this instability, the detuning frequency should be decreased. As seen in Equation 4.3, a direct solution is to increase the stored energy compared to the beam power. In other words, we need to decrease R/Q, while keeping a high shunt impedance and V_c.

By employing an energy storage cavity operating in a high-Q mode that is coupled to an accelerating cavity,the stored energy is increased and the growth rate is lowered. This was first pointed out by T. Shintake [2]. In order to put this idea into practical use, Y. Yamazaki and T. Kageyama devised the ARES scheme [1]. A schematic view of ARES is shown in Figure 4.1. The accelerating cavity couples with the energy storage cavity through a coupling cavity in between. With the additional coupling cavity, ARES has advantages in the stability of the accelerating mode and in the damping of parasitic modes associated with the accelerating mode. A more detailed description of ARES is given in chapter 8.

The use of a superconducting cavity (SCC) is another possible solution, since its R/Q value is usually lower than that of conventional normal-conducting cavities, and it can be operated at a higher accelerating voltage. The R&D work is in progress at KEK on both the ARES normal-conducting cavity and the superconducting cavity.

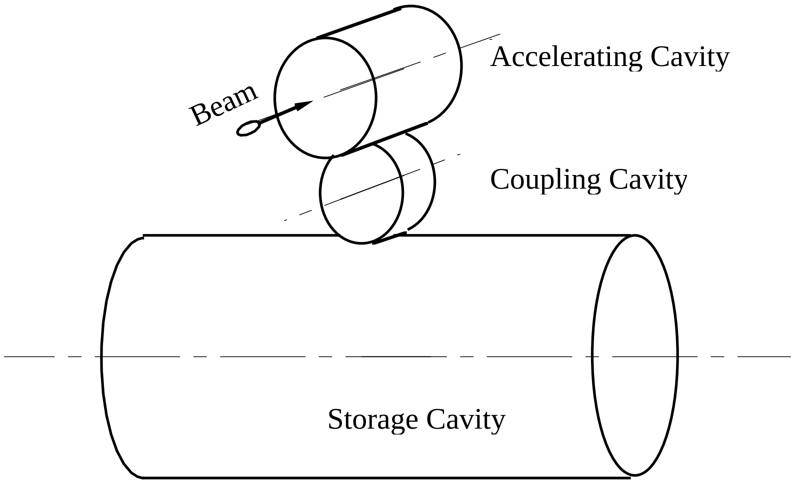

Figure 4.1: Schematic view of the ARES normal-conducting cavity system.

The growth time is quantitatively discussed in the next section in connection with the RF parameters.

Another approach to avoid this instability is to introduce an RF cavity feedback system. This feedback reduces the coupling impedance at the upper synchrotron side-bands of the revolution harmonic frequencies. Along with the development of the cavities, we are developing an RF feedback system with parallel comb filters. It will be applied for providing additional damping, when necessary.

4.3.2 Coupled-Bunch Instability due to HOM's of the RF Cavities

Detailed descriptions on the HOM properties of ARES and SCC are given in chapter 8. This section summarizes the estimated growth time.

Naturally, the accelerating cavity itself that is employed in the ARES scheme must be a HOM-damped structure. The HOM-damping method applied to the accelerating cavity of ARES is to employ a coaxial wave guide which is equipped with a notch filter [3], [4] (see, section 8.1). The R/Q and Q values of the HOM's in the accelerating cavity of ARES was calculated using a computer code MAFIA. The number of cavities is estimated in the next section (20 cavities for the LER and 36 for the HER). The growth time of the fastest growing mode in the LER (HER) is then about 60 msec (150 msec) in the longitudinal case and 30 msec (80 msec) in the transverse case.

In the ARES, since the accelerating cavity is connected to the storage cavity via the coupling cavity, we must be careful concerning the following facts.

- The coupling impedance can be different if the HOM of the accelerating cavity is coupled to other cavities. The impedance of the whole ARES system needs to be accurately estimated.

- Since ARES is a three-cell cavity, the system has 0, $\pi/2$ and π modes which couple to the accelerating mode. The $\pi/2$ mode is the operating mode. The 0 and π modes are parasitic modes; their frequencies are close to the operating RF. The parasitic modes (0 and π) can be damped by a damper attached to the coupling cavity, and the growth time of the coupled bunch instability due to these modes is expected to be longer than 10 msec.

In the case of superconducting cavity, the HOM's are extracted through beam pipes with a large diameter, and are absorbed by ferrite material attached toe the beam pipes. The R/Q values of HOM's have been calculated using a computer code URMEL. The frequency and the Q value of each HOM have been measured with a full-size model cavity made of copper. According to the result shown in section 8.2, when 10 SC cavities are used in the HER, the growth time of the fastest growing mode is about 420 msec for longitudinal and 110 msec for transverse instabilities. They are much slower than the damping time.

4.3.3 Static Robinson Limit

The static Robinson limit gives a maximum stored current of

$$I_{max} = \frac{2V_c \sin\phi_s}{\sin 2(\phi_s - \alpha_L)} \times \frac{1}{\frac{R_s}{Q_0} \times Q_L}, \tag{4.4}$$

where ϕ_s is the synchronous phase, α_L the tuning-offset angle, and Q_L the loaded-Q value. It should be pointed out that if superconducting cavities are operated with the optimum input coupling to the design beam current (I_d) and with the optimum tuning ($\alpha_L = 0$) to compensate for the reactive component of beam loading, the stability condition becomes marginal at the design current. This is because the input coupling is much larger than unity in the case of SCC and the loaded-Q is represented by

$$Q_L = \frac{Q_0}{1+\beta} \approx \frac{Q_0}{\frac{P_b}{P_c}} = \frac{V_c Q_0}{I_d R_s \cos\phi_s}. \tag{4.5}$$

Here, P_b, P_c, β, and Q_0 are the beam power, cavity wall loss, input coupling, and intrinsic Q-value, respectively. It is seen that I_d in Equation (4.5) is equal to I_{max} in Equation (4.4) when $\alpha_L = 0$. In order to avoid an instability, an artificial offset from the optimum tuning should be introduced at the expense of extra RF power. For this purpose, 10$\sim$20 degrees of the tuning offset (α_L) will be sufficient, which requires 3$\sim$13% extra input power. This will be taken into account in the RF parameters discussed in the next section.

4.4 RF Parameters

The RF operation parameters have been optimized by taking the following into account:

- The required RF voltage should be provided. (It should be variable to change ν_s from 0.01 to 0.02)
- The expected beam power should be supplied.
- The growth time of the instability due to the accelerating mode should be longer than the damping time.
- It should also meet the full wiggler option in the LER.
- The high power system should be stably operated.

It should be noted that in KEKB the beam power is rather high, while the required RF voltage is relatively low. In ordinary storage rings where the beam loading is moderate, the number of cavities is determined by the total RF voltage. On the other hand, in a storage ring where the beam power is significantly large, the number of cavities is determined by the cavity input power, which may be limited by the performance of the input couplers, high power source or others. In the latter case, since the cavities are operated with a lower field gradient, and hence with a larger detuning frequency, the growth rate of the coupled-bunch instability due to the accelerating mode is increased. This is in contrast with the growth rate of the coupled-bunch instability due to HOM's, which is simply proportional to the number of cavities. In the following, we quantify the feasibility for both cases of ARES and SCC, operated in the LER and HER, with the full design beam current and the full wiggler option in the LER. The cavity performance, power handling capability, and the growth rate of the instability are taken into account. The RF properties of the accelerating mode of these cavities are listed in Table 4.2.

4.4.1 ARES Normal-conducting Cavity

The maximum cavity voltage is expected to be 0.5$\sim$0.6 MV/cavity, which corresponds to a permissible wall loss of 150 kW. (This wall loss is distributed to the accelerating

Table 4.2: Accelerating mode of the cavities.

	ARES	SCC	
R/Q	12.8	93	Ω/cavity
Q_0	1.33×10^5	$> 1 \times 10^9$	

cavity and the storage cavity of ARES.) The maximum input power to the cavity depends on the technology available for the input coupler. The input couplers for the APS normal-conducting cavities in TRISTAN have been successfully operated up to 200 kW. The R&D work is in progress to develop an input coupler that can handle a much higher power. In addition, since we will feed the power through the storage cavity, two input couplers can be installed for each ARES system. This scheme doubles the power transfer capability.

Figure 4.2 shows the input power, wall loss, and reflection power in each cavity of the HER as a function of the RF voltage. The input coupling was set to give the optimum coupling at 13.2 MV (ν_s=0.016). The maximum required RF voltage of 16.2 MV can be provided by 36 ARES cavities with an input power of 233 kW. The growth time of the coupled-bunch instability due to the accelerating mode is much longer than the damping time. Thus the required range of the RF voltage from 8.7 MV to 16.2 MV can be covered with these cavities without changing the input coupling or the number of cavities. The parameters at 8.7 MV and 16.2 MV are listed in Table 4.3.

In the LER, the input coupling and the number of cavities should be optimized depending on the total RF voltage. As an example, the parameters optimized at 4.9 MV (ν_s=0.01) and 9.4 MV (ν_s=0.02) are listed in Table 4.3. The maximum required RF voltage of 9.4 MV can be provided with 20 ARES cavities, with the input RF power to each ARES being 355 kW. If the operating voltage is 4.9 MV, we need to decrease the number of cavities; otherwise the growth time becomes faster than the damping time. In this low voltage case 10$\sim$12 ARES cavities will be operated, each of which is powered by one klystron. The growth time will be longer than 30 msec in either case. Thus, the required voltage range can be covered by optimizing the input coupling and the number of cavities.

4.4.2 Superconducting Cavity

An accelerating gradient of 10 MV/m can be easily achieved in a bench test with the present technology for 508 MHz superconducting cavities at KEK. The design gap voltage of the KEKB cavity is set to 1.5 MV/cavity, which corresponds to a gradient

Table 4.3: RF Operation Parameters for the ARES Cavity.

		LER		HER	
Beam energy	GeV	3.5		8.0	
Beam current	A	2.6		1.1	
Beam power	MW	4.5		4.0	
RF voltage	MV	4.9	9.4	8.7	16.2
Synchrotron tune		0.01	0.02	0.01	0.02
# of Cavities		10	20	36	
R/Q	Ω/cav.	12.8		12.8	
Q_0		1.33×10^5		1.33×10^5	
Q_L	$\times 10^4$	2.6	3.6	3.9	
Input β		4.19	2.73	2.41	
Voltage	MV/cav.	0.49	0.47	0.24	0.45
Input power	kW/cav.	591	355	157	233
Wall loss	kW/cav.	141	130	34	119
Detuning freq.	kHz	16.2	17.7	13.5	7.8
Growth time†	msec	49	30	100	180
# of Klystrons		10†††	10	18	
Klystron power††	kW	640	760	340	500

Wiggler magnets are included in the LER.

† — Coupled-bunch instability due to the accelerating mode.

†† — 7% loss at the wave guide, circulator, magic tee etc. is taken into account.

††† — In this case one klystron feeds one cavity.

of 6 MV/m. It is expected to have a sufficient margin for stable operation with high beam currents.

The number of SC cavities for KEKB is determined by the capability of power transfer into the cavity, rather than by an available field gradient. This is because the required RF power to the beam is high, while the required RF voltage is low. If sufficient power cannot be transferred to each cavity, a larger number of cavities should be operated at a lower operating gradient than the design value. In this case, the growth rate of the coupled-bunch instability due to the accelerating mode becomes larger, since the detuning frequency increases.

Figure 4.3 shows the input power and reflection power in each cavity in the HER as a function of the RF voltage in the two cases of 10 and 12 cavities. The input coupling was set at 5×10^4, and a tuning offset of -20 degrees was introduced in order to have a sufficient margin for the static Robinson stability criterion. Figure 4.4 shows the growth rate of the coupled-bunch instability due to the accelerating mode. Using ten SC cavities seems to be a good solution; the growth rate is lower than the damping rate, even if the RF voltage is decreased to 8.7 MV. The necessary input power is 450 $\sim$ 550 kW, depending on the RF voltage. Bench tests of the input couplers, which are of the same type as those used in the SC cavities in TRISTAN, have achieved 850 kW CW power transfer. Thus the required range of the RF voltage from 8.7 MV

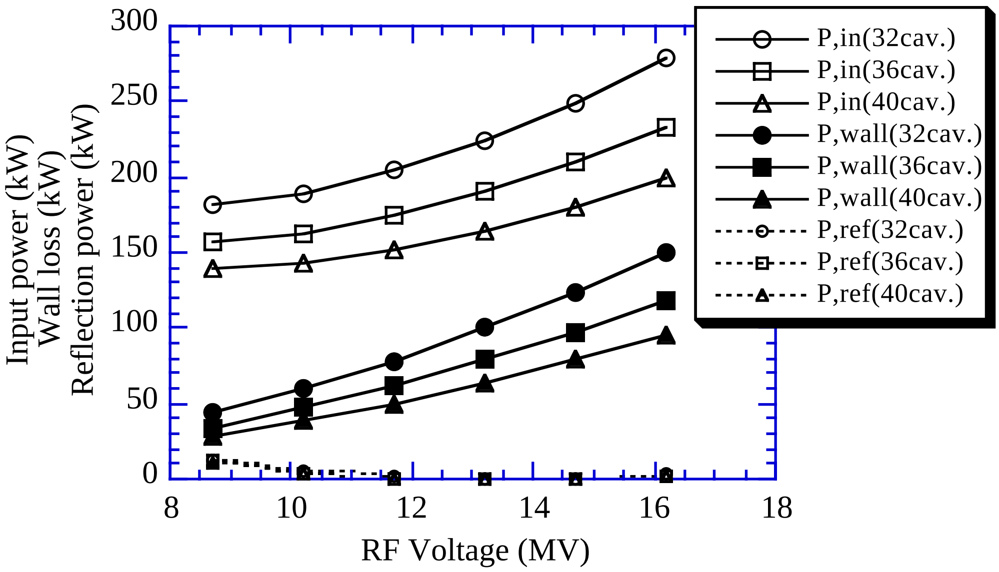

Figure 4.2: ARES in the HER. Input power, cavity wall loss, and reflection power as functions of the RF voltage.

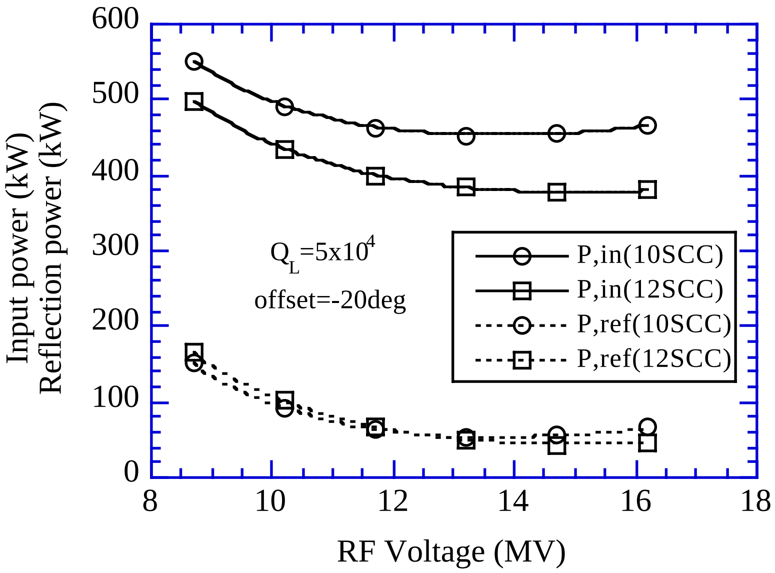

Figure 4.3: SCC in the HER. Input power and reflection power as functions of the RF voltage.

to 16.2 MV can be covered with these cavities.

In the LER, since the beam loading is very heavy and the required RF voltage is low, the detuning frequency is significantly large, even with the SC cavities. An example of the operation parameters is shown in Table 4.4. Even when an input power of 500 kW is fed into the cavity, and even without the wiggler, the growth time is faster than the damping time. If the wiggler magnets are installed, the detuning frequency will exceed the revolution frequency, and the growth time will become on the order of 0.1 msec. If we insist on applying SC cavities in the LER, the impedance seen by the beam must be reduced by 40 dB, for example, by the RF feedback system. This totally defeats the major advantage of SC cavities over the conventional normal-conducting cavities. Thus, the SC cavities are not presently being considered for the LER.

4.4.3 High Power System

As seen from Table 4.3 and Figure 4.3, the klystron output power required in a normal operation is less than 800 kW. However, some margin is needed for the case when one RF unit is down because of a trip or other reason. Thus the maximum power requirement is set to be about 900 kW in the LER with the full wiggler option.

The existing high power systems will be re-used at KEKB, including: the klystrons, power supply systems and cooling systems for the klystrons, and wave guide components, such as the magic tees and circulators. The long-term operation of TRISTAN

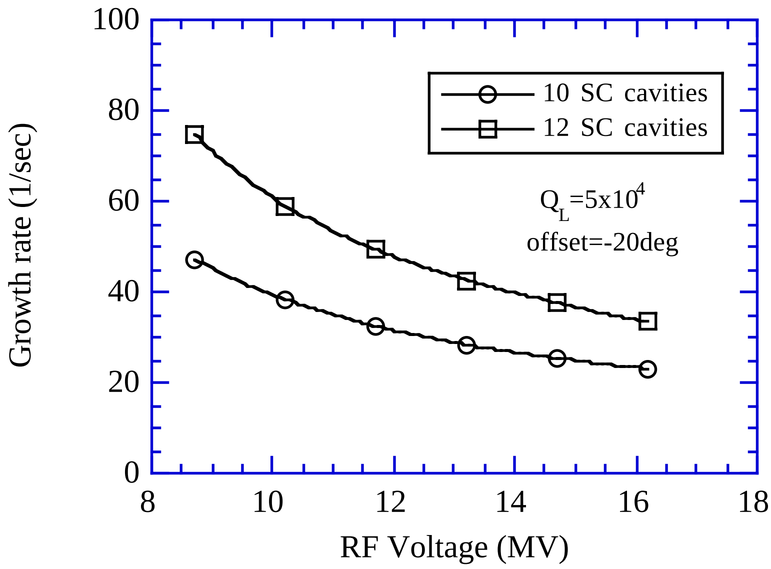

Figure 4.4: SCC in the HER. Growth rate of the instability arising from the accelerating mode.

Table 4.4: RF operation parameters for the superconducting cavity.

	LER		HER	
Beam energy	3.5		8.0	GeV
Beam current	2.6		1.1	A
Synchrotron tune	$0.01 \sim 0.02$		$0.01 \sim 0.02$	MV
Total RF voltage	$4.9 \sim 9.4$		$8.7 \sim 16.2$	MV
	(no wiggler)	(with wigglers)		
Beam power	2.7	4.5	4.0	MW
Number of cavities	6	10	10	
R/Q	93		93	Ω
Unloaded Q	1×10^9		1×10^9	
Gap voltage	$0.8 \sim 1.6$	$0.5 \sim 0.9$	$0.9 \sim 1.6$	MV/cell
Coupler power	450		$500 \sim 400$	kW/coupler
External Q	1.6×10^4 $\sim 6 \times 10^4$	6×10^3 $\sim 2 \times 10^4$	5×10^4	
Growth time	$1.2 \sim 14$	$0.3 \sim 0.5$	$23 \sim 54$	msec

has proven the reliability and stability of our high power system. Furthermore, some R&D efforts will be made to improve the performance.

4.5 Summary

We have studied the RF operating parameters by taking into account the requirements for the RF system, the power handling capability of the cavities and the high power systems, and the growth rate of the coupled-bunch instabilities. A consistent set of RF parameters which satisfies these requirements has been obtained for ARES for both the LER and HER, and for SCC in the HER. Using SCC in the LER will require a very sophisticated RF feedback system.

The growth time of any coupled-bunch instabilities caused by the cavities (arising from the accelerating mode and the higher order modes) is expected to be longer than the radiation damping time, or at least, longer than several milliseconds. Even if the growth time of some modes might be faster than the radiation damping time, it is expected to be cured by a bunch-by-bunch feedback system or the RF cavity feedback system.

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