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Requirements to the CESR-c RF system.

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Abstract

CESR RF system consists of four superconducting cavity cryomodules [1]. Conversion of CESR to low energy CESR-c will require modification of the RF system hardware and operation. This paper discusses requirements to the CESR-c RF system.

1. RF system upgrade for CESR-c

CESR-c design calls for a short bunch length of 1 cm and requires an RF voltage increase (see Table 1). Raising operating gradient on some of the existing cavities and replacing others with new/refurbished cryomodules will attain the RF voltage increase. Two of the cavities, BB1-4 (E1) and BB1-1 (W1), can operate at the accelerating gradient of 9 MV/m producing 2.7 MV per cavity. BB1-2 (E2) cavity can safely operate at 8 MV/m though this cavity has losses at least two times higher than BB1-4 and BB1-1 at high RF fields. Two others, BB1-5 (spare, former E1) and BB1-3 (W2), are gradient limited by surface defects to 6.5 – 7 MV/m [2]. We are confident that BB1-5 cavity can be repaired and its performance improved. Repair of BB1-3 cavity is more problematic due to the nature of the defects. Tests of this cavity indicate that it has multiple defects embedded into the material during manufacturing process of the niobium sheets, which will be very difficult, if possible at all, to remove. BB1-3 will have to be replaced with a healthier cavity. As part of a previously planned upgrade for 5.3 GeV operations, two additional cryomodules were ordered. New cavities have improved Q factors by means of vacuum bake at 140°C. Thus after repairing the BB1-5 cavity we will have 6 healthy cryomodules to choose from. We anticipate having at least four cavities capable to operate at 9 MV/m. This will provide CESR with maximum RF voltage of 10.8 MV, which is still 1.2 MV short of the required 12 MV at 2.5 GeV, but should be sufficient, as it will not degrade CESR performance too much.

Table 1: Selected parameters of CESR

Parameter	**Present**	**CESR-c upgrade**		
Energy [GeV]	5.3	1.55	1.88	2.5
No. of cavities	4	4	4	4
Gradient [MV/m]	6.2	6.25	8.33	10
Voltage [MV]	7.4	7.5	10	12
Beam power [MW]	1.2	0.04	0.09	0.16
Beam current [A]	0.75	0.26	0.36	0.46
Synchrotron frequency [kHz]	21	41	43	41
Bunch length [mm]	18	9.9	10.2	10.2

The high power circuits of the RF transmitters will not require significant modifications. Two transmitters will be configured to two cavities per klystron (Figure 1). Depending on the energy of experiments we will choose the number of cavities operating in active and passive modes for most efficient operation of the RF system. Three-stub waveguide transformers [3] are installed to adjust individually each cavity coupling to its optimal value. New sets of low-level RF controls and cryomodule electronics will be built with an extensive use of digital signal processing. RF tuners will be modified by adding piezo-electric elements and special feedback will be developed to suppress microphonic noise. Micro-stepping option will provide smoother operation of stepping motors. Tuner controls will be modified to be compatible with operation in passive mode.

2. Present RF control system

The present RF system control design is based on “classic” amplitude and phase analog feedback loops. The RF system can be configured to run with two cavities per klystron or with individual klystrons for each cavity. At present two East cavities have individual klystrons and the two West ones are connected to one klystron. The West transmitter has amplitude and phase control loops that allow regulation on a combination of two cavity amplitudes or phases with a possibility to choose any ratio of two signals. The amplitude loop is set to a so-called “master-slave” configuration, when a cavity field signal from only one cavity (“master”) is used in the feedback loop. The other cavity (“slave”) passively follows by virtue of the cavities’ similarity. Of course, any difference in cavity couplings, positions, RF phase, non-equal power split by a magic T, etc. causes the field of the “slave” cavity to deviate form the set point. That is why the “master” is always the weaker cavity, i.e. the cavity with lower accelerating field limit. The RF phase loop is configured to regulate the average of two RF phases (50%:50% ratio).

The open loop transfer function is the product of the cavity transfer function and the loop amplifier transfer function. Original design of the CESR RF feedback loops used an integrator. When the cavity is tuned to the RF frequency, its amplitude transfer function is a first order low-pass filter. For increasing cavity detuning (as it is done automatically in storage rings to compensate reactive beam loading) this transfer function becomes more resonant and the stability of the loop becomes more marginal (see, for example, [4]). This did not present a problem for the old normal-conducting cavities, as their bandwidth was much higher than that of the control loop. It is not true anymore for superconducting cavities as their bandwidth is comparable with the feedback loop bandwidth. Therefore the simple integrator was replaced by a proportional-integrating circuit, which (if properly tuned) compensates pole of the cavity transfer function and improves stability. This was done for both amplitude and phase loops. The resulting closed loop transfer function has the characteristics of the low-pass filter (which is distorted more and more as cavity is being detuned) with the roll-off frequency of 2 kHz [5].

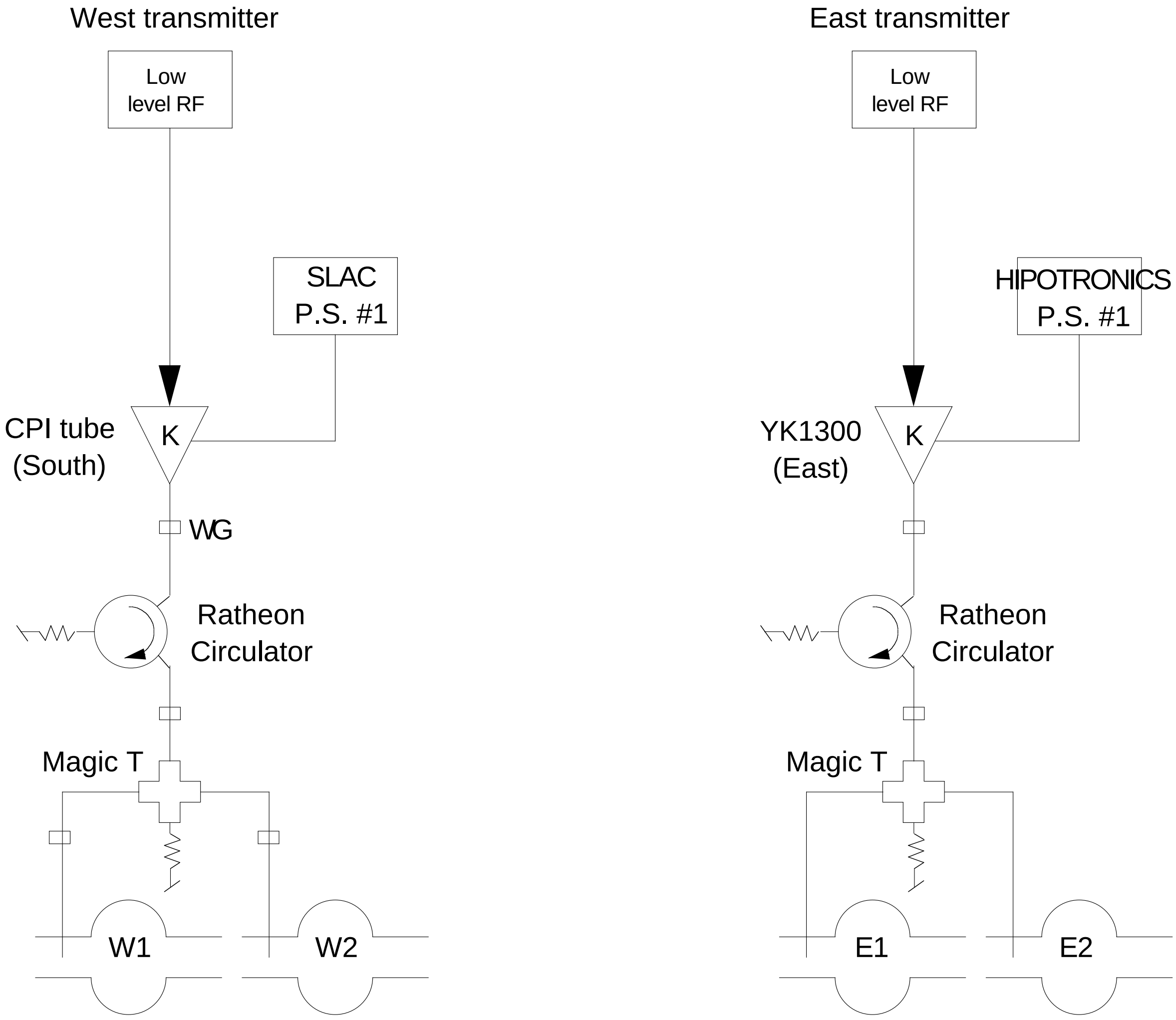

Figure 1: CESR-c RF system configuration.

3. General requirements to amplitude and phase stability

RF phase and amplitude errors do not cause IP position errors; they cause only timing error, but as far as errors are small, they do not present a problem for detectors. Parasitic beam motion due to RF phase and amplitude modulation should be much smaller than the bunch length. Let us set those modulations to be ten times smaller than the rms bunch length (10 mm). Then the permitted phase modulation is 1.2° (correlated) and the amplitude modulation is 16% (correlated) for 2 active cavities. In general, as we can already see, requirements to the amplitude stability are more relaxed than requirements to the phase stability. A possible source of parasitic excitation of synchrotron oscillations (observed at ALS [6]) is the phase noise of the master oscillator. This effect was negligibly small at CESR so far and we expect it to be of no concern in CESR-c as the synchrotron frequency is two times higher than at present and the phase noise falls exponentially with frequency. RF cavity position error causes change in the IP position and should be kept smaller than bunch length to avoid hourglass effect. The requirement here would be 1 mm for correlated errors and 2.8 mm for uncorrelated errors.

4. Beam loading and tolerances

The beam loading of accelerating cavities in high intensity storage rings ("factories") is heavy. The ratio of the beam-induced voltage (V_{br}) on resonance to the cavity voltage (V_{c}), $Y = V_{\mathrm{br}}/V_{\mathrm{c}}$, is frequently used as a measure of the beam loading. Factories typically operate in the beam loading parameter range of $Y = 2\ldots5$ [7] with very small steady-state (Robinson) stability margin. CESR operated at even higher value of $Y \approx 9$ and at the beam synchronous phase $\varphi_{\mathrm{s}} \cong 80°$ [8]. Such a heavy beam loading causes very high sensitivity of RF system to small amplitude and phase errors. In this section we consider the beam loading issues of the CESR-c RF cavities.

While RF voltage required by CESR-c is high, the beam power demand is very moderate in comparison to high energy operation (Table 1). Even one transmitter is more than adequate to supply necessary power. On the other hand, such a low power demand at very high voltage will present a challenge for RF regulation loops and for RF power splitting. The beam loading parameter and synchronous phase at this conditions will be 34.5 and 88.3° at 2.5 GeV, 40 and 88.6° at 1.88 GeV, and 48.7 and 88.8° at 1.55 GeV, meaning that Robinson stability margin will become extremely small and bunches will pass the cavity gap very close to the null of RF wave. Even the slightest RF phase error will cause a large cavity mismatch and unacceptable change of the cavity voltage and power delivered to beam and very small disturbance can lead to Robinson instability. For example, an RF phase error of ±0.1° between two cavities in a pair (caused by a small difference in waveguide lengths) will cause cavity voltage error of ±15%. Also, to obtain matching conditions at maximum beam current, the external quality factor will have to be increased to 2.5×10^6 (2.5 GeV), 3.1×10^6 (1.88 GeV), and 4.0×10^6 (1.55 GeV), which is beyond the practical capability of three-stub waveguide transformers.

Table 2: Some RF parameters

Parameter	**Present**	**CESR-c upgrade**		
Energy [GeV]	5.3	1.55	1.88	2.5
No. of active + passive cavities	4+0	2+2	2+2	2+2
Beam loading parameter Y	7.2	8.2	7.8	7.6
Synchronous phase φ_{s}	80°	83.0	82.6	82.5
Q_{ext} active	2×10^5	6.6×10^5	6.1×10^5	5.6×10^5
Q_{ext} passive	–	1×10^6	1×10^6	1×10^6
$P_{\mathrm{pass\ max}}$ [kW]	–	40	70	101
P_{RF} [kW]	964	120	230	362
Bunch length [mm]	18	9.9	10.2	10.2

To ease this problem we proposed [9] to operate some of the cavities in a passive mode. Here we consider operating two out of four cavities in the active mode from a single klystron and the other two in the passive mode. The function of the passive cavities is to provide missing voltage for bunch shortening. This voltage is induced by the beam and therefore its phase follows the beam automatically. The beam loading parameter and synchronous phase for two active cavities become now comparable to high energy operation and hence should be manageable as well as values of the Q_{ext} of both active and passive cavities. Additional RF power will be required to compensate beam losses due to the finite Q_{ext} of passive cavities. Some RF parameters for different operating energies are listed in Table 2.

Let us now evaluate the sensitivity of the RF to the change in different parameters. CESR-c requires operating of cavities at a higher voltage hence they will be more prone for quenches in case of voltage increase. We set maximum voltage difference between two cavities in a pair to ±10% and then calculated tolerances to different errors. The major source of the RF phase error for active cavities is difference in the waveguide lengths after an RF power split. The relative cavity position error causes RF phase error between electron and positron beam currents and as a result different beam loading for cavities in question. The major source of the RF amplitude error is the RF power split. Another source of the amplitude error is difference in values of the cavity external coupling. The calculated tolerance numbers are presented in Table 3. All tolerances are very similar to the present high- energy operation except the coupling error tolerance. It is more relaxed for CESR-c because of lower beam currents. Also, we estimated an additional RF power demand at maximum beam current in the case when all errors are one half of calculated for ±10% voltage difference (including microphonic noise), but they add unfavorably. This produces RF voltage difference bigger than 10%. A –10° tuning offset is added for Robinson stability [8].

Table 3: Tolerances for ±10% voltage difference.

Parameter	**Present**	**CESR-c upgrade**		
Energy [GeV]	5.3	1.55	1.88	2.5
Phase error	1.5°	1.4°	1.5°	1.6°
Waveguide length error [mm]	3.4	3.2	3.4	3.5
Position error [mm]	2.5	2.4	2.5	2.6
RF power split error [dB]	0.37	0.46	0.46	0.46
Coupling error $k=Q_1/Q_{ext}=Q_{ext}/Q_2$	1.24	1.9	1.7	1.6
Peak microphonics [Hz]	250	77	85	90
Additional RF power [kW] required if all errors are one half of listed above, but add unfavorably plus –10° tuning offset for Robinson stability	-3 (±13%)	9 (±20%)	14 (±17%)	18 (±14%)

Recent observations in CESR [10] indicate that parasitic modulation of the cavity resonant frequency may be as high as 100 Hz peak. This modulation will cause cavity mismatch and will result in amplitude and phase errors. Part of this modulation is due to the microphonic noise and part due to the cavity response to steps of a stepping motor. The latter part will be dealt with by using microstepping [11]. A major benefit of microstepping is that it reduces the amplitude of the resonance that occurs when the motor is operated at its natural frequency or at sub-harmonic of that frequency. We expect that use of microstepping will reduce the peak modulation to < 50 Hz. At present microphonics is an inconvenience, which causes occasional RF trips (2 to 3 per a weekend HEP run) and reduces efficiency of the RF system (extra RF power is required for regulation). As higher external *Q* factor is required for CESR-c, the RF system becomes less tolerant to microphonics (see Table 3). Also, as we mentioned above, one can allow smaller fluctuation of cavity field in CESR-c conditions. So from a mere nuisance microphonics might become a problem if it is not properly addressed. This dictates necessity of developing special feedback to suppress the amplitude of microphonic noise.

Amplitude and phase modulation of a passive cavity voltage by microphonics was analyzed in [9] and does not appear to be a problem.

5. Injection/beam transients

The RF system must be robust to transients during normal operation of the accelerator. Such transients are the bunched beam structure, the beam injection, and the fast partial beam losses. CESR beam comprises of 9 bunch trains of up to 5 bunches each with 14 ns spacing between bunches. Due to high external *Q* factors of superconducting cavities this bunch pattern does not produce any significant modulation of cavity voltage. The other two transients should be addressed in simulations. The best injection rate achieved so far in CESR is 160 mA/min for the electron beam.

Another task the RF control system has to deal with in CESR-c configuration is "turning on" passive cavities. One scenario [9] is to keep the cavity at a "home" position until the cavity voltage reaches nominal value, then to turn on tuner feedback loop configured to keep cavity voltage constant by detuning the cavity according to raising beam current. The "home" position determines the beam current at which cavity voltage reaches its operating level. This scenario may not be very convenient in operation because some beam parameters (synchrotron frequency, bunch length) will change dramatically with the beam current. The other option would be to keep the cavity detuned far from resonance during injection so that the beam induced voltage is negligibly small. When injection is complete, one would slowly bring the cavity to its operating voltage and close the tuner feedback loop. This will probably simplify the injection process by "decoupling" injection and cavity tuning though it will take longer time.

6. Summary

We considered different factors setting requirements to CESR-c RF system. It was shown that operating all four cavities in the active mode would set very tight requirements to RF controls. The proposed operation with two passive cavities and two active cavities eased tolerances to the same level as those at present. We think that the phase should be controlled to better than 0.5° and the amplitude to better than 1%. Though this level of control is reachable with the present system, the new electronics based on digital signal processing will offer more flexibility and better diagnostics. Developing new tuner controls easily switchable from active to passive mode of operation, with microstepping and with active feedback to suppress microphonics is necessary.

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