

# PERFORMANCE OF THE CESR SUPERCONDUCTING RF SYSTEM AND FUTURE PLANS\*

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## 1 INTRODUCTION

As we have reported at the last SRF Workshop two years ago, staged transition of the Cornell Electron Storage Ring (CESR) RF System from normal conducting to superconducting was completed in September 1999 with installation of the fourth superconducting B-cell cavity [1]. Since that time the last cavity has been commissioned and RF system has operated stably providing CESR beams with up to 1.13 MW of RF power to support total beam current up to 800 mA.

CESR is a symmetric energy  $e^+e^-$  collider operating in a bunch train mode with CLEO detector studying B meson decays at the center of mass energy near the  $\Upsilon(4S)$  resonance ( $\approx 5.3$  GeV) [2]. At the same time CESR provides beams for experiments with synchrotron radiation (SR) at the Cornell High-Energy Synchrotron Source (CHESS). CHESS facility operates in a parasitic mode simultaneously with high-energy physics experiments at CLEO. The latest running period lasted nine months ending in June 2001. The emphasis was put on a steady running of the machine aiming to reach integrated luminosity of at least  $10 \text{ fb}^{-1}$ . This goal was achieved by delivering of just over  $11 \text{ fb}^{-1}$ . The typical total beam current at the start of the fill was 750 mA and typical RF power delivered to beam by one cavity was 280 kW.

Beginning in the fall 2001 CESR will run at  $Y$  resonances below  $\Upsilon(4S)$ , and during machine studies periods at  $J/\Psi$  resonances [3]. Eventually, after some hardware modification and upgrade, CESR will be able to operate over the energy range of 1.5 to 5.6 GeV with expected luminosity of  $3 \times 10^{32} \text{ cm}^2 \text{ s}^{-1}$  at 1.9 GeV. CLEO and CHESS will then operate in a time-sharing mode of operation. The CESR upgrade includes modification of the RF. Two more superconducting cavities will be added to provide higher total RF voltage for bunch shortening.

## 2 SUPERCONDUCTING RF SYSTEM PERFORMANCE

### 2.1 System Description and Configuration

CESR RF system [5] consists of four single-cell superconducting cavity cryomodules. The cryomodules are installed in pairs in the East (E1 and E2 locations) and in the West (W1 and W2) RF straight sections in the CESR tunnel. Cryogenic liquids are supplied to cryostats

via satellite distribution boxes located next to the cavities.

Four transmitters are available to provide RF power to the cavities in CESR and to the RF processing area for various high power tests. Over the few latest running periods each transmitter was equipped with a 600 kW CW YK1300 klystron. The system can be configured to provide RF power from one klystron to one or two cavities depending on RF power demand. Due to both RF power demand and desire to have more flexibility to adjust RF parameters of individual cavities, the RF system configuration was one cavity per klystron.

### 2.2 Performance and Operating Experience

Superconducting cavity cryomodules operated at the average gradient of 6.2 MV/m, providing the total voltage of 7.4 MV and supplying RF power to high current beams. Figure 1 presents recent history of RF power delivered to beams by four SRF cavities. The maximum power delivered so far is 294 kW.

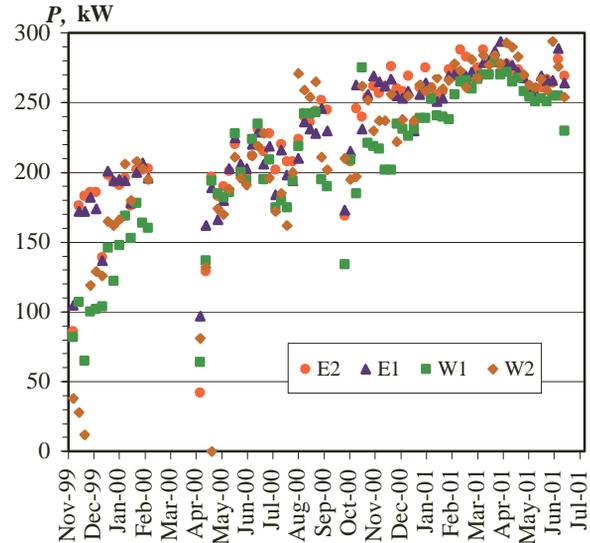


Figure 1: Recent history of RF power delivered to CESR beams by SRF cavities.

Under heavy beam loading conditions RF phase errors lead to uneven power demand between RF stations. For example,  $1^\circ$  phase error on one of the CESR cavities produces 21 kW change in power delivered to the beam by that cavity. Even though RF phase loop can regulate phase with error much smaller than one degree, slow thermal drifts in the reference line, in the cable between a cavity field probe and phase detector or in electronics can

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exceed one degree. Indeed, we measured RF phase drift up to  $\pm 2^\circ$  over the course of several days [6]. This effect pronounces itself as a data point scatter in the Figure 1. One can notice that the scatter became significantly smaller starting early 2001. This improvement was due to implementation of an RF phase control computer program. The program measures RF power for each cavity once per HEP run and adjusts RF phase set points to keep beam power loading of cavities equal. During the last two weeks of CESR running the program was disabled and one can see again much larger scatter during that time.

The latest running period was the longest period of B-cell cavities being kept cold, namely 271 days. During that period we had to occasionally pulse process cavities (E1 and E2) and/or RF couplers (W1 for the most part) to cure frequent quench detector trips due to field emission or multipacting. The main cause of a cavity performance degradation is condensation/adsorption of residual gases on the cold surfaces of the superconducting cavity [8]. The total amount of gases condensed during the latest running period and then released in a warm-up to room temperature was 11.8 (E1), 10.6 (E2), 8.6 (W1), and 6.5 (W2) equivalent monolayers of hydrogen. The typical vacuum in the CESR vacuum pipes surrounding SRF cavities is 2 to 3 nTorr with full beam load and less than 1 nTorr without beam. The East cavities though were exposed to a much worse vacuum. It was occasionally higher than 10 nTorr because of the beam-induced heating of an O-ring seal in the E1 round beam tube (RBT) gate valve (manufactured by MDC). Those gate valves suffer from bad RF contacts. This is the reason why the total amount of condensed gases is higher in the East. Both West cryomodules had all-metal-seal RBT gate valves (manufactured by VAT) and the MDC valve on the E2 cavity was replaced last year with VAT gate valve.

Although introducing all-metal-seal gate valves will help to improve vacuum environment, it is not enough. RGA data indicate that one of the dominant gas species is hydrogen [8]. The problem with this gas is that it is very poorly evacuated by ion pumps and it has a vapor pressure higher than  $10^{-6}$  Torr even at 4.2 K. During the summer 2001 shutdown we installed NEG pumps on the beam pipes adjacent to all four cryomodules. NEG pumps have high pumping speed for hydrogen (measured at >230 liter/sec [11]) and will help us to reduce the gas load on cold surfaces. We hope to operate eventually with a vacuum below 1 nTorr even with full beam load.

As we have already reported elsewhere [5], W2 cryomodule suffered from a vacuum leak on a wire seal. A vacuum dam installed around the leaky seal proved to be a successful cure: this cavity has the least amount of condensed gases.

So far the most troublesome cavity in terms of delivering power to the beam is W1. Unlike in other cavities, multipacting zones in W1 do not remember processing well and therefore RF power coupler requires periodic pulse power processing. We typically have to process W1 coupler every two to three weeks for 2 hours by applying to the cavity 1 msec long RF pulses with

forward power in excess of 400 kW. Most likely reason for this behavior is poor copper plating of the waveguide, which left spots of bare stainless steel and “spongy” surface. All other cavities need only mild amount of pulse processing after initial cool-down or after reaching power level of the new multipacting barrier.

Because multipacting in a rectangular waveguide continues to be an actual problem in CESR cavities, we do not cease efforts searching for a better understanding of this phenomenon and for a most effective cure [9, 10]. A recently developed analytic model [9] allows us to generate a multipacting map for the B-cell reduced height rectangular waveguide. This map is plotted in gray in the Figure 2 as a reflection coefficient versus forward power. Each multipacting zone is shown with two lines to indicate its width and consists of two “branches”. The first branch corresponds to an over-coupled cavity and the second one corresponds to an under-coupled cavity. The two branches are connected at zero reflection point, where the cavity presents matching load to the waveguide.

One can easily show that those lines are described by the same formula as the cavity loading curves if the cavity-beam system is kept on resonance and at constant cavity voltage. We superimposed the multipacting map with the loading curves of the CESR cavities in the Figure 2. These curves correspond to the beam current change from 0 to 800 mA. In real operation we keep cavities slightly off resonance to provide Robinson stability. That is why loading curves deviate off the ideal case and do not reach zero reflection. Each cavity has individual settings for the cavity field and tuning offset. Loaded  $Q$  factor values differ from cavity to cavity as well as synchronous phases. Also, loading curve of W1 does not follow exactly other curves because strong beam-induced signal on the cavity field probe confuses amplitude and phase controls and the cavity voltage and phase change with beam current. Points where a loading curve crosses multipacting zone lines correspond to multipacting barriers seen during operation.

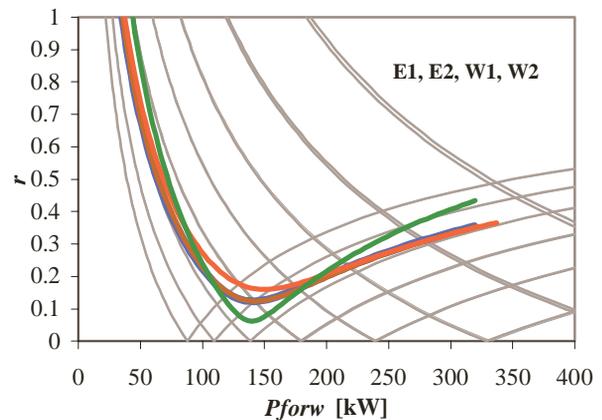


Figure2: Multipacting zones for the B-cell reduced height rectangular waveguide superimposed with loading curves of the CESR SRF cavities for the total beam current from 0 to 800 mA.

### 2.3 Spare Cryomodule

The fifth, spare cryomodule is built around BB1-4 cavity and accommodates several design changes we wanted to try. We describe here only those design changes, for detailed description of the cryostat design see [1]. First of all, the cavity itself was baked at 140°C for 48 hours and reached accelerating field of 14 MV/m with  $Q_0=10^9$  at 4.2K in a vertical test [5]. The cryostat has an extra layer of external magnetic shielding. The double-bend elbow of the waveguide is made of solid copper as opposed to copper plated stainless steel in other cryostats and has smooth, not grooved, internal surface. We hope that the new elbow will provide better, cleaner surface to reduce multipacting. Solenoid coils have been added to the waveguide for experiments with DC magnetic bias [10] to counter multipacting. The helium vessel contains a ballast to reduce amount of liquid He. Some of the changes, such as a helium vessel ballast that slows down significantly both cool-down and warm-up, are already proved to be troublesome and will not be carried out to retrofit other cryostats. The others are still in process of evaluation.

Two tests have been performed with the spare cryomodule: a cold test to check integrity of the cryostat and a high power RF test. The cavity reached 8.5 MV/m in CW mode and 14.5 MV/m in pulsed mode. It has the best  $Q$  vs.  $E$  curve of all cavities in CESR. The static heat leak of this cryostat is 45 W, which is 15 W higher than other cryostats. We could not find an explanation of this so far. The other unexplained result is the low loaded  $Q$  factor of  $1.2 \times 10^5$ , twice as small as it should be. To accommodate this change one needs to introduce a large discontinuity and significant change in the waveguide length between the RF window and the coupler hole. We could not account for either of those. In spite of lack of satisfactory explanations for these results, they do not present major operating concerns and the commissioning of the cryomodule in CESR will begin in September '01.

### 2.4 Reconfiguring RF System

We have reported in [1] that 800 kW CPI klystron was used in one of our transmitters to feed two West cavities with RF power. The tube, however, developed a vacuum leak and was sent back to the factory for a warranty repair. It has been rebuilt and tested to full power at CPI and was just installed in the West transmitter again. From now on we plan to operate in a mixed configuration. That is, two East cavities will be fed individually from YK1300 klystrons and two West cavities will be connected to CPI klystron via magic T.

Having completed testing spare cryomodule (equipped with the BB1-4 cavity), we used it to replace the BB1-5 cavity cryomodule in the E1 position. This will allow us to operate E1 cavity at higher accelerating gradient and provide an opportunity to repair BB1-5.

A three-stub waveguide transformer, similar to [12], has been designed, fabricated and tested up to 200 kW average power, 400 kW pulsed. The temperature rise of

3°C (traveling wave) and 6°C (standing wave) was registered by an infra-red camera. Four more such transformers have been manufactured and installed in the waveguide for each cavity. We are going to use these devices to do fine adjustment of the loaded  $Q$  factor and RF phase.

## 3 UPGRADE

### 3.1 CESR Upgrade

The primary modification to CESR in preparation for low energy running includes: i) installation of superconducting IR (interaction region) quads to expand operating energy range and lower  $\beta^*$  at the interaction point (in progress, will be finished in September 2001); ii) upgrade RF system (in 2002) to shorten the bunch length compatible with lower  $\beta^*$ ; iii) install ~18 m of 2.1 T wigglers to enhance synchrotron radiation effects. The first two items will improve CESR performance at all energies whereas the wiggler magnets are the only major upgrade specifically for low energy operation.

The modified machine, called CESR-c, requires a short bunch length of 1 cm. This translates into a total RF voltage of 12 MV at 2.5 GeV. Two new superconducting cavity cryomodules have been ordered from ACCEL and will be installed in CESR in addition to the existing four [4]. Six cavities will deliver 12 MV with confidence, operating comfortably at the average accelerating gradient of 6.7 MV/m. Further increase of RF voltage to 19 MV is envisaged by lowering operating temperature to ~3 K.

### 3.2 New Configuration of Superconducting RF

CESR-c design calls for a significant RF voltage increase (see Table). Some additional voltage is available in present configuration of RF by raising operating gradients. Three of the cavities, BB1-2 (currently in the E2 position), BB1-1 (W1) and BB1-4 (just installed in the E1 position to replace BB1-5), can operate at the accelerating gradient of 8 MV/m producing 2.4 MV per cavity. Two others, BB1-5 (was in the E1 position until July 2001) and BB1-3 (W2), are gradient limited by surface defects to 6.5 – 7 MV/m [5]. We are confident that BB1-5 cavity can be repaired and its performance improved to the level of other cavities. 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. Thus, after repairing the BB1-5 cavity and installing it in the W2 position we could have four cavities capable to operate at 8 MV/m. This will provide CESR with maximum RF voltage of 9.6 MV, which is 2.4 MV short of the required 12 MV. Therefore two new cryomodules have been ordered to provide additional RF voltage. Maximum average accelerating gradient with six cavities in the ring will be 6.7 MV/m. In

the case if the CESR-c lattice change will call for even higher RF voltage, it is possible to increase it by raising accelerating gradient to 8 MV/m at 4.5 K reaching 14.4 MV. Further increase would require improving  $Q$  factors of all cavities by means of vacuum bake at 140°C as it has been already done for BB1-4 [5] and lowering operating temperature of the two new cavities to 3 K. Then we should be able to operate four old cavities at 3 MV per cavity (accelerating gradient of 10 MV/m at 4.5 K) and two new ones at 3.5 MV per cavity (at 3 K), providing total RF voltage of 19 MV.

Table: Selected parameters of CESR

Parameter	Present	CESR-c upgrade		
Energy [GeV]	5.3	1.55	1.89	2.5
No. of cavities	4	6	6	6
Gradient [MV/m]	6.2	4.2	5.6	6.7
Voltage [MV]	7.4	7.5	10	12
Beam power [MW]	1.1	0.04	0.09	0.16
Beam current [A]	0.75	0.26	0.36	0.46
Bunch length [mm]	18	9.9	10.2	10.2

New cryomodules (Figure 3) will be located in the CESR interaction region (IR) on both sides of the detector CLEO. The cryomodules will have some minor design changes. Because of higher magnetic field in the IR region new cryostats have better magnetic shielding. Smaller footprint available for cavity installation prompted us to shorten the RF window length and redesign some beam line components. The side benefit of this is that with the short version of the window its ceramic is now placed at the standing wave minimum as oppose to standing wave maximum for the old design. IR cavities will have tapers on both ends of the cryomodule. The RBT taper is made of stainless steel and has two 110 l/s ion pumps and copper SR masks. The fluted beam tube (FBT) taper is made out of copper to accommodate a rather wide angle SR coming from the interaction region. Gate valves on both tapers have horizontal orientation. Two satellite cold valve boxes will be installed in the IR region to provide cryogenic coolants to new cavities. Their design will be similar to the design of valve boxes used for the existing cryomodules but each will feed only one cavity instead of two.

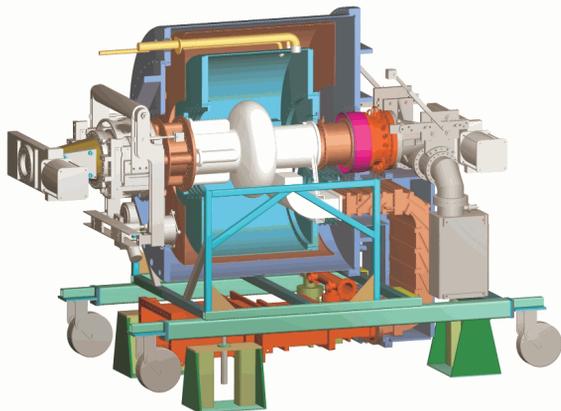


Figure 3: New IR cryomodule.

High power part of RF transmitters will not require significant modifications. New waveguides will be connected to IR cavities for high power processing and supplying RF power in active mode of operation. Three-stub waveguide transformers will be installed to individually adjust cavity couplings to their optimal values. Three transmitters will be configured to two cavities per klystron (Figure 4). The fourth klystron will be available for processing area tests. New RF and cryogenic controls, data acquisition electronics, and interlocks will be designed and built for IR cavities. This will provide a basis for possible future upgrade of electronics for other cavities.

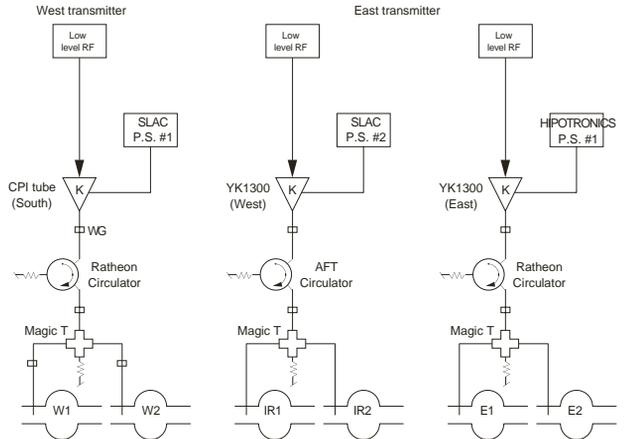


Figure 4: RF system configuration for CESR-c.

### 3.3 Passive Cavity Mode of Operation

While RF voltage required by CESR-c is high, RF power demand is very moderate (see Table). These power levels hardly present a problem for RF power couplers of CESR superconducting cavities. 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 problem for RF regulation loops [6]. To ease this problem we proposed to operate two out of six cavities in active mode and the other four in passive mode. The function of the four passive cavities will be to provide missing voltage to shorten bunches. This voltage is induced by the beam and therefore its phase follows the beam automatically. Detailed analysis of this mode of operation was presented elsewhere [7].

To check feasibility of the passive mode of operation we performed a machine studies experiment. A tuner control loop of one of the four SRF cavities installed in CESR was reconfigured for the passive regime. The passive cavity home position was set so that it would reach the voltage set point at a beam current of 100 mA. We monitored the beam induced voltage and the synchrotron tune. The beam induced voltage reached predicted value of 0.9 MV at 100 mA and stayed constant afterwards. Figure 5 presents measured synchrotron frequency in comparison with calculations. The agreement is quite good. Our experiment confirmed feasibility of the passive mode operation of superconducting cavities in CESR.

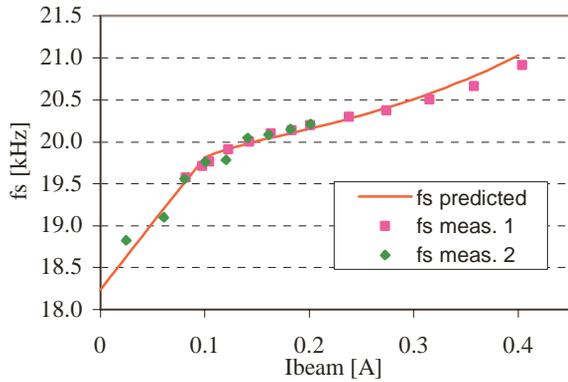


Figure 5: Comparison of measured synchrotron frequency with predictions.

#### 4 CONCLUSIONS

RF system based on four single-cell superconducting cavities has been commissioned in its final configuration in 1999 and since then providing RF power up to 1.13 MW to CESR beams. Stable operation of the system allowed CESR to reach its integrated luminosity goal during last running period.

The work is in progress to upgrade the RF system for short bunch operation of CESR. Addition of two more cryomodules will lead to increase of accelerating voltage to 12 MV to shorten bunch length to 1 cm. Further increase of RF voltage up to 19 MV is possible. Low power demand and tight requirements to RF regulation loops at low energy operation of CESR prompted us to propose running four out of six cavities in the passive mode.

#### 5 REFERENCES

[1] S. Belomestnykh, et al., "Operating Experience with Superconducting RF at CESR and Overview of Other

SRF Related Activities at Cornell University," *Proc. of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999, Vol. 1, pp. 24-30.

[2] D. L. Rubin, et al., "CESR Status and Performance," PAC'01, Chicago, IL, June 2001.

[3] D. Rice, et al., "Parameters for Low Energy Operation of CESR," PAC'01, Chicago, IL, June 2001.

[4] S. Bauer, et al., "Industrial Production of Turn Key Superconducting Accelerator Modules for High Current Storage Rings," PAC'01, Chicago, IL, June 2001.

[5] S. Belomestnykh, et al., "Running CESR at High Luminosity and Beam Current with Superconducting RF System," *Proc. of the 7th EPAC*, Vienna, Austria, June 2000, Vol. 3, pp. 2025-2027.

[6] S. Belomestnykh, et al., "Superconducting RF Control Issues at CESR," PAC'01, Chicago, IL, June 2001.

[7] S. Belomestnykh, et al., "Superconducting RF System Upgrade for Short Bunch Operation of CESR," PAC'01, Chicago, IL, June 2001.

[8] R. L. Geng and H. Padamsee, "Absorption and Evacuation of Residual Gases in the SRF System for the CESR Luminosity Upgrade," *Proc. of the 1999 Part. Accel. Conf.*, Vol. 2, pp.983-985.

[9] V.D. Shemelin, "Multipactor Discharge in a Rectangular Waveguide with Regard to Normal and Tangential Velocity Components of Secondary Electrons," Cornell LNS Report SRF010322-03 (2001).

[10] R. L. Geng, H. Padamsee, V. Shemelin, "Multipacting in a Rectangular Waveguide," PAC'01, Chicago, IL, June 2001.

[11] Y. Li, in Cornell LNS Report SRFM032101 (2001).

[12] B. Dwersteg, "SC-Cavity Operation via WG-Transformer." *Proceedings of the 4th SRF Workshop*, KEK Report 89-21, Vol. 2, pp. 593-604.