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CESR RF SYSTEM*

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INTRODUCTION

Operation of CESR 14-cell 500 MHz parallel coupled cavities at a CW voltage of 6.8 MV (1.6 MV/m) is described. Intrinsic thermal stability is observed, and a single mechanical tuner and single power window are used. A novel cooling method permits the power window to operate at a power level equivalent to 1 MW of CW transmitted power. Good correspondence is found between the threshold observed for coherent instabilities during 61 bunch operation and the threshold predicted from the higher mode damping provided on the cavity. Advantages and disadvantages of the economical "sheet metal" fabrication technique used are discussed. Salient features of the transmitter and controls are described.

General requirements on the CESR RF system are that it provide a peak CW voltage of 12 MV and couple 1.4 MW into the beam at 8 GeV, and that it present a sufficiently low higher mode impedance to the beam so that the instability threshold during 61 bunch operation (positron stacking) is as high as possible.

The RF system, as presently configured, consists of two 14-cell cavities, each powered by one 600 kW klystron and isolated from the cavity by a circulator. This configuration is suitable for present operation, at energies up to 6 GeV per beam. Provision has been made for adding a second klystron if high current operation at 8 GeV becomes desirable (the present configuration is expected to support up to 30 mA per beam at 8 GeV, but this has not been tested). Provision is also being made to operate both cavities from one klystron for reasons of economy, since most operation takes place in the upsilon region.

CAVITY

The general philosophy adopted for the CESR cavity was that it should contain as many cells as practical in order to minimize cost and maximize system reliability through minimization of the number of power windows, the number of mechanical tuners, the number of interlocks and RF controls, and the number of waveguide splits. Other objectives include maximization of the fundamental mode shunt impedance and consequent minimization of higher mode shunt impedance divided by Q_0, provision of adequate higher mode damping, cost minimization through use of sheet metal techniques and welding, and provision of high field gradients to minimize the higher mode impedance in the ring.

The 14-cell parallel-coupled cavity developed to achieve the above objectives has been described previously.[1] A number of changes have been made since that time. Most important of these was the discovery that the higher mode cell frequency spread was not sufficiently large to prevent formation of passbands in which appreciable amounts of energy occurred in more than one cell simultaneously, contrary to our previous information. Although no such instances were discovered in the first prototype, the passband formation could prevent adequate coupling of higher mode power into the single load on the coupling line, and can also increase the higher mode shunt impedance at a particular frequency. As a result, the coupling line load was abandoned, and damping probes were developed for use on each cell.

The damping probes consist of a loop connected to a coaxial line. A two-stage notch filter provides 56 dB rejection of the fundamental, with no further notches at frequencies up to four times the fundamental. The probe assembly is terminated in a ceramic window, which is followed by a 45° 1-5/8" coax elbow leading into a 10 kW coaxial load. A polarizing stub at another location in each cell is used to help control the polarizations of the higher modes so that the coupling probe couples effectively to each of them. The probe acts as a combination electric and magnetic probe, and its geometry, orientation, and position on the cell surface were chosen by a combination of Superfish (to study TM_0 mode field patterns and shunt impedances), probe and bead measurements (to study TM_1 mode field patterns and shunt impedances), calculations of beam instability thresholds for each of the modes[2], and empirical methods (to determine the coupling of a particular probe geometry to a given combination of magnetic and electric fields and to determine deflecting mode polarizations). In addition to providing adequate coupling to each important higher mode, coupling to the fundamental mode was reduced through destructive interference of electric and magnetic coupling so that dissipation in the notch filter and the coaxial line between the notch filter and loop is minimized. The location of the notch filter was chosen to minimize fundamental mode standing waves between the loop and the notch filter. Separate water cooling is provided to the coupling loops, the polarization stubs, and the loads. The remainder of the coupling system is cooled by immersion in the cavity main water tank. Required and achieved higher mode loaded Q's are listed in Table I. A sectional drawing of the probe assembly is shown in Fig. 1, and a photograph of the assembly in Fig. 2. The probes have been tested at 10 kW CW at 714 MHz. The probes have been placed on the cavity in such a location that they, with their loads attached, fit into the cavity water tank with the cavity under vacuum. The net effect of removing the protuberances on the original design and adding the coupling probes was to raise the fundamental mode shunt impedance at 20°C slightly to 28.0 MΩ per meter. The cavities are normally operated at a copper temperature of 65°C in order to make the cooling towers more efficient, resulting in a 9% reduction in shunt impedance. The fundamental mode field flatness in the absence of the protuberances was measured and found to be adequate.

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TABLE I: Max. Tolerable Q_L at 2x94 mA, 8 GeV, σ=4.5 cm.

Mode	Freq., MHz	Q_0	Q_L, meas	Max. Q_L	ZT^2/Q, Ω/m	$Z''T^2/Q$, Ω/m³
TM_{010}	499.76	32535	8134		860.6	.
TM_{011}	771.36	35473	101	1009	182.0	
TM_{020}	1126.27	40688	1349	39890	4.23	
TM_{022}	1353.50	62219	3515	14571	27.4	
TM_{021}	1398.57	36222	1319	7438	84.31	
$TM_{0??}$	1762.97	40926	-	$>Q_0$	38.92	
$TM_{0??}$	1800.36	57402	-	$>Q_0$	29.27	
TM_{110}^{P1}	871.10	42107	1361	2286		38046
TM_{110}^{P2}	882.28	43815	167	2304		38046
TM_{111}^{P1}	1139.00	27877	1415	1679		108431
TM_{111}^{P2}	1140.95	26279	1531	1679		108431
TM_{120}	1624.83	58884	-	$>Q_0$		225.1

The power window has been equipped with a trickle cooler using 1,1,2 trichloro, 1,2,2 trifluoroethane (B. P. 47°C) as a coolant. The coolant is recirculated using a small pump, heat exchanger, and microfilter, at a rate of 10 liters/minute. Using this scheme, the window temperature rises 6°C at a power level

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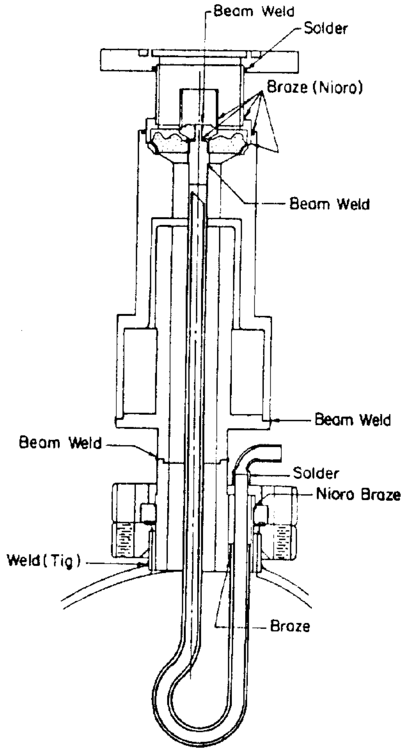

Fig. 1. Sectional view of higher mode probe.

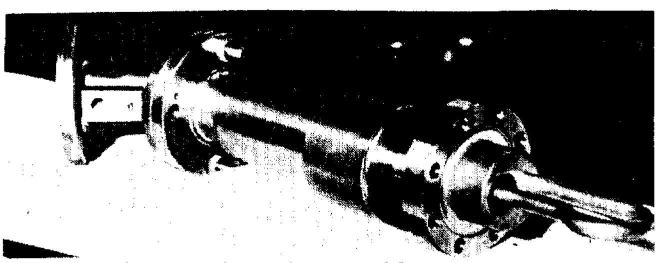

Fig. 2. Higher mode probe assembly.

equivalent to a 1 MW travelling wave passing through the window. The match of the cavity has been adjusted so that 21% of the incident power is reflected without beam, and the reflected power is minimized for 8 GeV at 94 mA per beam.

The original notch-filter tuner has been replaced by a stub tuner which tunes the cavity by varying its gap from the center conductor of the coupling line. This tuner provides a range of ±100 kHz. It is cooled by a separate water system with a circulating pump and heat exchanger, the flow rate being 35 liters/minute.

The cavities are baked at 200°C for at least 24 hours to outgas them. Pressures of 10^{-8} torr with beam and RF are typical. The coax coupling line acts as a pumping manifold, leading to two 400 l/s pumps at the tuner end.

A complete cavity, with water tank, is shown in Fig. 3, and a cavity without water tank is shown in Fig. 4.

CAVITY INTERLOCKS

Three temperature interlocks and 19 differential temperature interlocks are used on each cavity. Of these, 20 are associated with the protection of ceramic windows and two with the monitoring of tuner temperatures. All liquid pumps are interlocked for AC power, pressure, and liquid level. Two arc detectors monitor the power window, and a VSWR detector monitors the

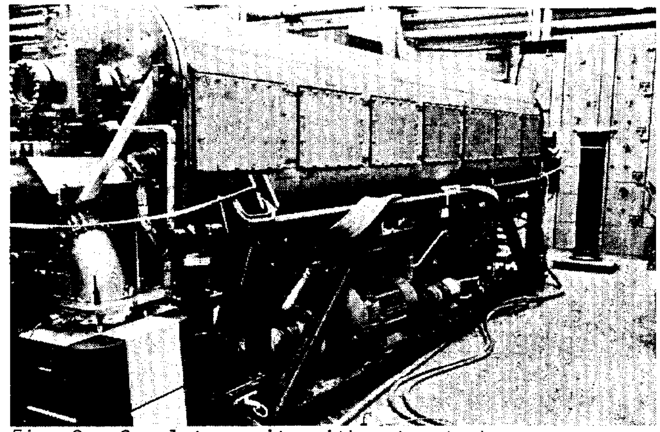

Fig. 3. Complete cavity with water tank.

Fig. 4. Cavity without water tank.

fraction of incident power reflected from the cavity. Four ion pump pressures (one pump being on the beam line at each end) are limited to 10^{-7} torr, and an ion gauge monitoring the power window is limited to 5×10^{-7} torr. These pressure limits are chosen to prevent RF sputtering of copper onto the ceramics. Most of these interlocks interrupt the drive through electronic switches and RF relays. A tripped ion pump supply closes the gate valves adjacent to the cavity. When a beam is stored, time delays and coincidence requirements are imposed on several of the interlocks to reduce unnecessary trips.

TRANSMITTER

Each of the two transmitters employs a YK1300 klystron, with provision for addition of a second one. The modulator consists of a floating deck, a Y546 tetrode, and a 200 kΩ oil-cooled load. A fiber-optic link using a V to f and f to V converter controls the tetrode grid. Each transmitter is isolated by a Raytheon circulator, and is connected to the cavity by 1800 aluminum waveguide. Each transmitter receives its high voltage from a Hipotronics 60 kV, 32 A supply with a variable autotransformer on the 13.2 kV primary. Two modified Nike-Zeus power supplies capable of 18 A at 60 kV serve as backup supplies. An oil insulated high voltage interconnect box permits any power supply to be connected to either transmitter. Each transmitter is also equipped with an ignitron crowbar and a capacitor bank.

RF CONTROLS

The RF controls provide four modes of operation. In the "run" mode, the field in the cavity is regulated by varying the drive power. A sample-and-hold circuit samples the field just before a bunch arrives. This type of control was chosen over mod anode control because it provides a greater gain-bandwidth product. The phase in the cavity is regulated relative to the drive line using a varactor phase shifter. This phase is also sampled at the bunch revolution frequency. The phase of the power reflected from the cavity is regulated to a pre-set (but electronically adjustable) value, and is also sampled. Regulation is accomplished by the mechanical tuner, which moves in 500 Hz increments under stepping motor control, and by variation of the water temperature set point in accordance with the prescribed field level. The water system, which is open to the atmosphere, circulates water at 3500 liters/minute, and exchanges water directly with the CESR water system. Temperature regulation is accomplished using a pneumatically controlled cold water inlet valve. This valve is controlled by an AIM65 computer programmed to use, in parallel, integral gain, variable DC gain (depending on the power level), and feed-forward. This system keeps the water within 1°C during 400 kW transients, and within .05°C in equilibrium. The computer uses EPROM to resume operation automatically following a power interruption. The thermal resistance between the copper and the water is 0.008°C per kW/m dissipated in the cavity. The klystron current is programmed, based on the RF output of the klystron, so that the drive remains slightly below saturation. A drive limit, also based on the RF output power level, prevents accidentally crossing the saturation peak and causing positive feedback. During initial turn-on, the mechanical tuner is held at a predetermined position, and the drive is provided by a local oscillator which is phase locked to the cavity resonance. After 30 seconds (to allow the copper to reach equilibrium temperature relative to the cooling water), the power is ramped down in 100 μsec, oscillators are switched from the local to the master in 1 msec, and the power is ramped back up in 100 μsec. Phase regulation of the cavity is disabled while on the local oscillator. There is also an operator-controlled phase shifter between the master oscillator and the RF controls.

In the "process" mode, the power incident upon the cavity is regulated by varying the drive. The phase in the cavity is not regulated, and the local oscillator is phase locked to the cavity resonance. At powers below 30 kW, the starting frequency for the local oscillator is established by the water temperature and the weighted power history of the cavity. The klystron current is programmed as in the "run" mode, and the mechanical tuner is held at a predetermined position.

The "hyperprocess" mode is similar to the "process" mode except that the duty cycle is reduced. The klystron current is pulsed to a current based on the RF power set point, and the RF drive is then turned on. The local oscillator control voltage is sampled and held between pulses.

In the "inhibit" mode, the drive is inhibited, and the klystron current is reduced to the lowest safe non-zero value, which is approximately 4 A.

SYSTEM PERFORMANCE

One cavity has been processed to a CW power level of 500 kW, which corresponds (at 20°C) to a voltage of 6.8 MV (1.6 MV/m). The required voltage for two-cavity operation is 6.0 MV per cavity. No thermal instability has been observed, and the power window and tuner, the two weakest elements in the system, demonstrated adequate safety margins. The other two cavities have been processed to 430 kW, but klystron heating problems prevented processing to higher power.

Single beam 61 bunch instability thresholds at 5.5 GeV, with one 14-cell cavity installed, have been calculated using the Sacherer[2] theory to be 15.5 mA for transverse oscillations, and 43 mA for longitudinal oscillations, using the assumption that a single resonance of the passband having the highest effective shunt impedance falls directly on an unstable sideband of the revolution frequency. These numbers are based on the measured higher mode impedances with the damping provided by the higher mode coupling loops. Without the external loops, the computed thresholds are 0.9 mA for transverse instabilities and 0.6 mA for longitudinal instabilities. These numbers do not take account of other vacuum chamber elements, whose higher mode losses are 75% of these of the cavity. With the natural octupole moment of the machine cancelled, a transverse instability is encountered at 5.3 mA. In view of the other impedances in the machine, this threshold is considered to be in acceptable agreement with predictions based on the cavity impedances alone. No longitudinal instability was observed up to the same current, and appreciably higher currents could not be reached in the 61 bunch mode because attempts to suppress this instability by feedback have not been successful. However, the threshold has been raised substantially through the use of octupoles[3].

CESR operated for 22 months with only one cavity installed. A number of asymmetries between electrons and positrons were observed, including a two-beam flip-flop effect which depends on the RF field level. Although there are no immediate plans to operate above the upsilon region, a second cavity has recently been installed. However, its effectiveness in removing these asymmetries has not yet been evaluated.

The cost of CESR cavities, measured in 1978 dollars, is as follows: accelerating structures: $9451/m; cooling equipment: $6583/m; interlocks and RF controls: $23108/m. These costs include all development expenses, but exclude all in-house labor. If the equivalent system were employed on a larger scale, instrumentation cost reduction could be achieved by developing stripline networks for RF signal processing.

The reliability of the CESR cavities has been as follows: except for specific design defects, which have been corrected, the principal problem has been with weld leaks. Numerous weld leaks were encountered in initial welding and during bakeout, and a few occurred during initial processing. Only one weld leak has occurred in a cavity in the ring, and that was rewelded in situ. It has been discovered that the cavities are extremely intolerant to air leaks; a leak which causes a pressure rise of less than 10^{-9} torr causes RF-induced pressure bursts at frequent intervals. However, a water leak can cause a pressure as high as 10^{-7} torr with no malfunction of the RF. Trips of the RF system, using a cavity which has been processed well above its operating point, are very infrequent, and are usually caused by lost beam spraying radiation in the region of the arc detectors, causing a false source of light.

CONCLUSION

Except for the need to develop more reliable technology for vacuum-tight welding of copper, the CESR RF system has proven to be a satisfactory solution to all of our original design objectives.

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