UPC 064

TEVATRON RF REPORT

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I. Introduction

The basic requirement for the rf system is that it be capable of accelerating a beam of up to 2.5×10^{13} protons at a rate of 50 GeV/s. Measurements made at 400 GeV and 2×10^{13} protons in the Main Ring indicate a longitudinal emittance of ~0.3 ev-s, about four times larger than the value measured at 8 GeV; for design purposes we make the conservative assumption that the 100 GeV Main Ring beam to be injected into the Tevatron will have the larger value. An rf frequency of 53 MHz is chosen for the following reasons: (a) to permit a high-efficiency transfer of the beam from Main Ring to Tevatron by means of a synchronous bunch-to-bucket scheme; (b) to minimize the rf voltage required for the Tevatron; (c) to take advantage of the availability of an existing 160 kW power amplifier at this frequency; and (d) to maintain the possibility of colliding the Main Ring and Tevatron beams in the simplest way.

Table I gives the Tevatron rf power and voltage requirements for two possible beam intensities and two ramp slopes, viz. 2.5×10^{13} ppp and 1×10^{14} ppp with ramp slopes of 50 and 100 GeV/sec in each case; in all cases we have provided a minimum bucket-area of 0.6 ev-s. The values per cavity shown in Table I are based on the assumption of four cavities for 50 GeV/sec and 8 cavities for 100 GeV/sec ramp slopes.

TABLE I

Tevatron RF Requirements

	I	II	III	IV
Ramp Slope	50 GeV/s	50 GeV/s	100 GeV/s	100 GeV/s
Synchronous Voltage	1.05 MV/Turn	1.05 MV/Turn	2.10 MV/Turn	2.10 MV/Turn
Number of Cavities	4	4	8	8
Beam Intensity	2.5×10^{13} ppp	1.0×10^{14} ppp	2.5×10^{13} ppp	1.0×10^{14} ppp
DC Beam I	0.191 Amperes	0.765 Amperes	0.191 Amperes	0.765 Amperes
Beam Power	200 kW	803 kW	400 kW	1607 kW
Bucket Area (100 GeV)	0.6 eV/sec	0.6 eV/sec	0.6 eV/sec	0.6 eV/sec
Synchronous Ø	47 degrees	47 degrees	52 degrees	52 degrees
RF Ring Voltage	1.44 MV/Turn	1.44 MV/Turn	2.66 MV/Turn	2.66 MV/Turn
Cavity Peak RF	360 kV	360 kV	333 kV	333 kV
Cavity RF Power	64 kW	64 kW	55 kW	55 kW
Total RF Power/Station	126 kW	295 kW	117 kW	285 kW
Beam Power/System Power	0.4	0.68	0.43	0.7

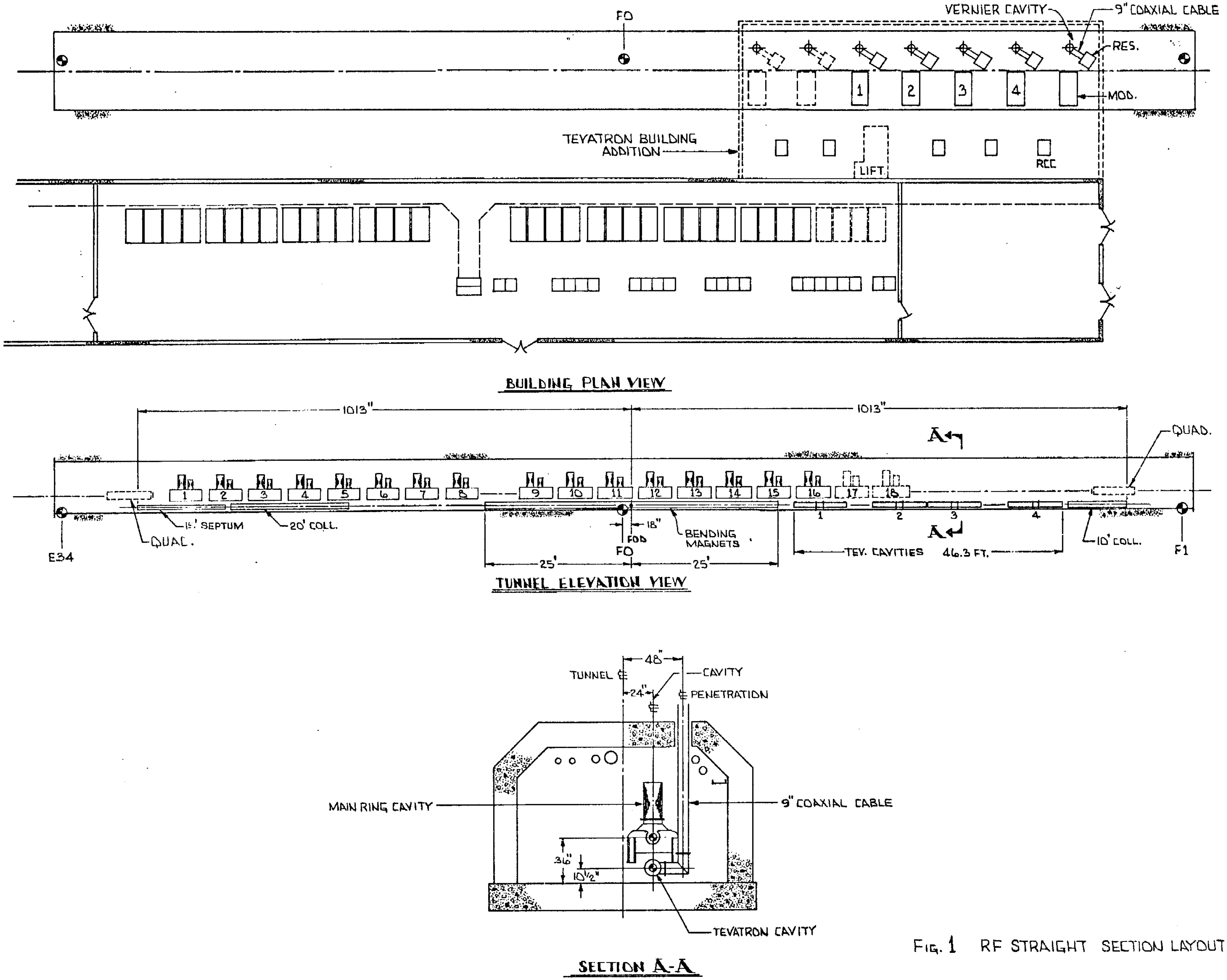


Fig. 1 RF STRAIGHT SECTION LAYOUT

II. Cavity Location and Layout

In order to take advantage of the existing rf facilities and to minimize the additional long-straight section space used for rf hardware, the location of the cavities in the F0 straight-section is desirable. A possible layout of the rf systems at the F0 straight-section is depicted in Fig. 1. This shows 4 cavities which satisfy the requirements for 50 GeV/sec as listed in columns I and II of Table I. Cavity locations shown occupy the minimum length of the straight section for allowing acceptable $\bar{p}$-p acceleration in the Tevatron. If capability to 100 GeV/sec is required, additional cavities will be required (Table I, columns III and IV). These cannot be installed at F0 with the present extraction plans. Further, difficulty in placing doubler cavities under MRRF cavities may make it desirable to seek other straight sections for higher acceleration rates.

The four cavity solution allows the following boundary conditions to be met.

1. Maintain the present performance capability (5×10^{13} ppp with 160 GeV/s acceleration) of the MRRF system up until the time the Tevatron is operational.
2. Minimize modifications to the existing MRRF system.
3. Allow reasonable access to both Main Ring and Tevatron cavities for maintenance and repair.
4. Maintain the options of colliding beams; $\bar{p}$p in either Main Ring or Tevatron, and pp between the two.

The tunnel geometry sketched in Fig. 1 places four accelerating Tevatron cavities at the downstream end of F0. They are spaced as shown in Fig. 2. If 8 cavities are used, the total straight section required is 92.6 ft.

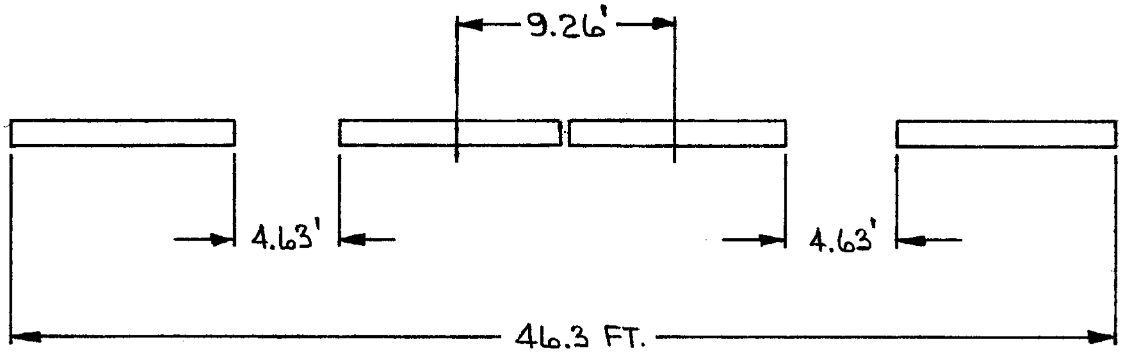


Fig. 2

Two Main Ring cavities, stations No. 17 and No. 18, have been removed to provide sufficient space for nearly complete longitudinal separation of Main Ring and Tevatron cavities; this makes an enormous saving in the cost and complexity of design, installation, and maintenance. The removal of two Main Ring cavities without degradation of Main Ring performance is made possible by recent development work in upgrading the voltage and power levels of a Main Ring station (see Section III).

The rf power amplifiers (PA's) will be remotely located in a new ground-level equipment building (65' x 28') located directly above the F0 straight section. RF power will be delivered to the Tevatron cavities by a $3\lambda/2$ long 9-inch coaxial transmission line connecting between the equipment room and the tunnel. Locating the power amplifier upstairs has several advantages: less space is required in the tunnel, all of the active electronics (the least reliable subsystem) are directly accessible for fast repair, and radiation exposure to personnel is reduced.

In addition to the normal acceleration of protons in the Tevatron for fixed-target physics, the plan of Fig. 1 can accommodate the following $\bar{p}p$ colliding beam capabilities:

1. Simultaneous acceleration of p's and $\bar{p}$'s in the Main Ring 8 cavities for each beam) at a rate of 60 GeV/s with control of the interaction point location through relative phasing of the two groups of 8 cavities.[2]
2. Similar acceleration of p's and $\bar{p}$'s in the Tevatron with a ramp of 25 GeV/s.

III. Upgraded Main Ring RF Station

In order to preserve the Main Ring performance level when the number of cavities is reduced to sixteen it is necessary to provide a peak cavity voltage of 270 kV and rf power of 160 kW. Presently, Main Ring cavity voltage averages 240 kV with some cavities as low as 180 kV and some as high as 270 kV. RF power from the PA averages 100 kW. A program is underway to increase the rf power amplifier capability to 160 kW and to increase the Main Ring cavity peak accelerating voltage to 280 kV.

1. 160 kW RF Power Amplifiers. We have increased present rf PA power capability to 160 kW by increasing available rf current and plate voltage.[1] Eight amplifiers have been modified and we can produce 160 kW at 28 kV anode voltage. We are presently testing these modified PA's (in MR and Booster systems as well as on test stands) to see if there is significant degradation of reliability at the higher operating levels. So far no significant degradation has been observed. Additional current limiting and crowbar protection is being implemented to upgrade reliability of the higher power PA's.

2. Super MR Cavity. The higher voltage cavity for the Main Ring is referred to as a "super" MR cavity. Prototype efforts have started with promising results. A 240 kV cavity was cleaned, reworked mechanically and it has been run at approximately 280 kV. We use a spark detector of the type built for the Booster system. A detected spark is arrested by gating off rf drive to the cavity. Air, blown through the cavity, aids in drifting ionized air from regions that spark. The air flow also provides cooling to ceramics and the coupling loop area which, previously, trapped pockets of warm air and led to sparking. A dust collector has been installed in the F0 section to clean the air so that sparking in the cavities due to dust particles is reduced.

Raising the rf voltage along with high duty factor (8-second machine cycle) results in marginal tuning capability due to rf heating in the cavity. Additional cooling is being added to the cavity shell, but most of the remaining tune shift is due to heating of the drift tubes. Major rework would be required to water cool the drift tubes for their full length. Other solutions to the tuning difficulty are under consideration, for example, temperature control of the cavity cooling water, heating a "cold" cavity with rf during beam-off time, and increasing the Booster extraction energy to 10 GeV which reduces the Main Ring 292 kHz tuning range by 33%.

IV. Description of Tevatron RF Station

An overall cross section of a Tevatron station is shown in Fig. 3. The components are described in the following text.

1. Power Amplifier. The power amplifiers will be located upstairs for two reasons. First, with no redundancy,the rf system power

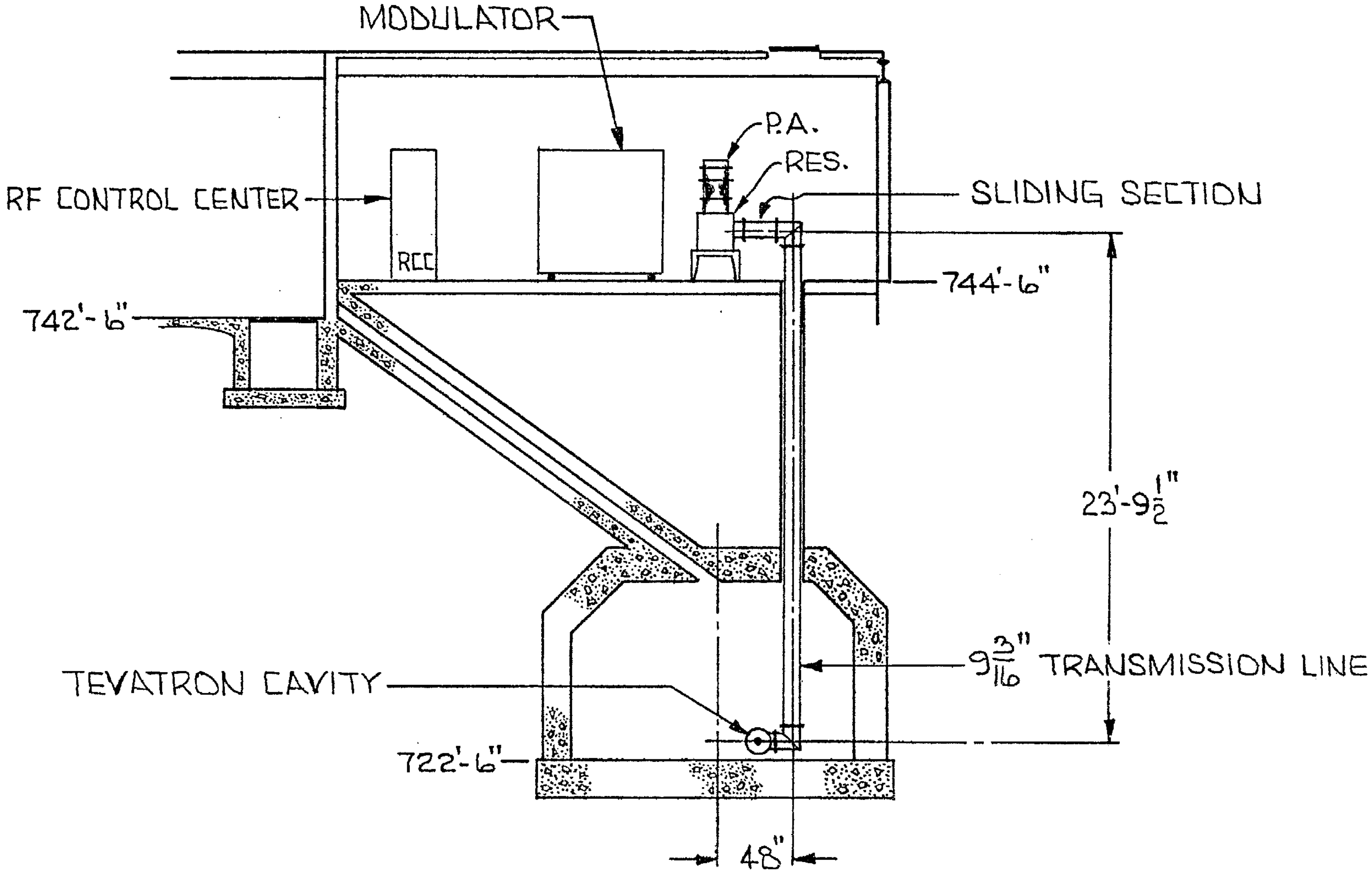


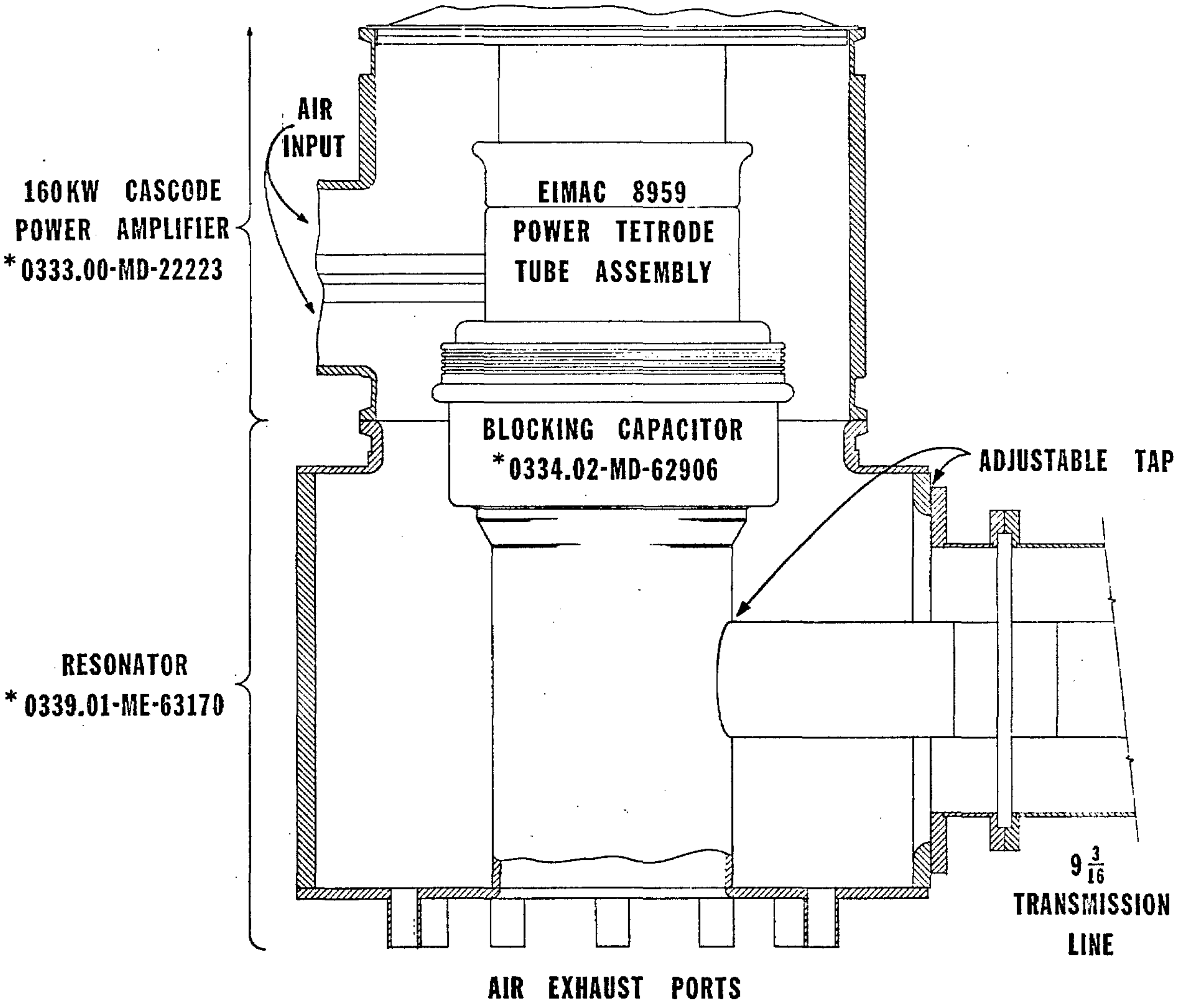
Fig 3. TEVATRON ACCELERATING STATION

amplifier maintenance must be fast and direct. With the PA's upstairs we have the option of continuing "beam-on" operation of the MR while an amplifier is being changed. Secondly, Tevatron cavities placed in restricted areas should be as free as possible of additional equipment because tunnel space is at a premium.

The 160 kW power amplifier (Section III) is capable of operating an rf station at power levels appropriate for 2.5 x 10^{13} ppp intensities (Table I, column I and III) with sufficient current drive to compensate satisfactorily for beam loading. Above intensities of 2.5 x 10^{13} ppp it will be necessary to consider additional rf power for both real and reactive beam loading, for example, two PA's per system or a single higher power PA. By the time beam intensity dictates increased requirements, a new power amplifier design could be available. The parameters in column II and IV can be met with the higher power amplifiers plus fast beam loading feedback.

2. Resonator. A tunable resonator is used to match the power amplifier output impedance into a 50Ω transmission line. A newly designed blocking capacitor of the type used in the Fermilab Booster will be used to couple the power amplifier into the resonator. Figure 4 shows a cross-sectional view of the PA, resonator, and impedance-matching tap arrangement.

A prototype resonator has been constructed for testing of the 160 kW power amplifier. A means of automatic tuning of the resonator over a Δf, of a few kHz, will be worked out to adapt the test resonator to the Tevatron system. Power is coupled out of the resonator by means of a 3/2 wavelength 9-3/16" transmission line.



* REFERS TO FINAL DRAWING NUMBER

FIG - 4

RF STATION
IMPEDANCE MATCHING RESONATOR

3. 9-3/16" Coaxial Transmission Line. The coaxial line will be 9-3/16" rigid 50Ω line with "Rexolite" insulators. The average power rating of 9-3/16" rigid line at 53 MHz is 600 kW. This average rating is based on an allowable temperature rise above 40°C ambient of 23°C for the outer conductor and 62°C for the inner conductor. The maximum peak power for the 9-3/16" line is 5.8 megawatts which corresponds to a 24 kV peak.

The transmission line will be fixed at the cavity end and have a sliding section at the resonator end. The sliding section will act as an adjustment for line length.

4. Modulators. Statements about the modulator suitability require some knowledge of the exact rf program intended for the Tevatron cycle. The Main Ring modulators are presently being modified to operate at 30 kV output for Main Ring operation with super MR cavities. They are capable of a regulated output current of 10 amperes as presently designed.

At 2.5×10^{13} intensity the required PA power is 126 kW, with 57% efficiency. Therefore, the power required from the modulator at (28 kV dc) is 221 kW. The modulator current is 7.75 A which, with a 5 kV series tube drop, results in a modulator series tube power dissipation of 38.8 kW. When power is being delivered to the beam, the rf voltage will remain high so we will keep the series tube voltage drop near 5 kV. Present modulators are a good match to the 160 kW PA at 2.5×10^{13} ppp. At flattop there is no real beam power but there is reactive beam load and cavity power to be considered. Maximum dissipation, occurs when the modulator output is approximately 33/2 kV. By careful programming of the voltage drop across the series tube we can use the 15 A capability of the series tube.

We propose that Main Ring rf modulators be used initially as designed and later with modifications to deliver 15 A as beam intensity increases. To achieve 1 x 10^{14} ppp a new modulator design will be required. One modulator will then be used to supply plate voltage to a higher power rf amplifier.

5. Anode Power Supplies. Presently two anode power supplies across from the F0 RF Building supply dc voltage for modulators. They are each rated for 33 kV at 48 A average dc load. A series 20Ω resistor is installed in the dc output of the supply to prevent overstressing the power transformer during crowbar operation.

Anode supply requirements depend on the machine operating cycle that is selected. If we run Tevatron stations with two modulators on each anode supply the resulting 30 ampere load current is well below the average rating of the supply. This occurs for machine cycles where we accelerate in the Main Ring only during the fall of the Tevatron field. If, however, a machine cycle requiring acceleration in the MR during Tevatron acceleration or during Tevatron flattop (Fig. 5) is contemplated, additional anode power supply capability will be necessary for intensities greater than 2.5 x 10^{13}.

V. Tevatron Cavity Design and Operation

1. Electrical Design Parameters. The cavity, Fig. 6, is a coaxial resonator, 12" in diameter x 108-1/4" long, formed of copper 102 with ceramic rf windows. The characteristic impedance Z_o is approximately 70 ohms over most of its length, purposely lowered in the center section, and modified at each end by corona rings. Because the required frequency range Δf, is a maximum of 2.271 kilohertz, the cavity is designed as a fixed-tuned, 2-gap

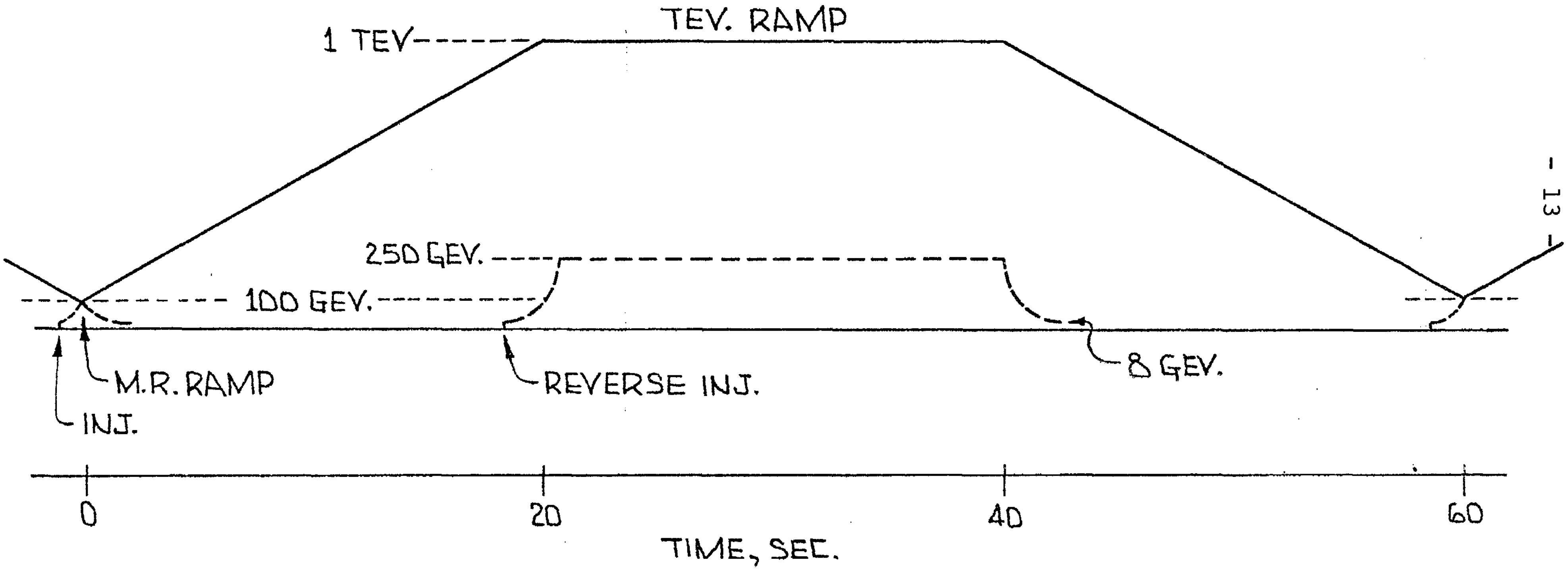
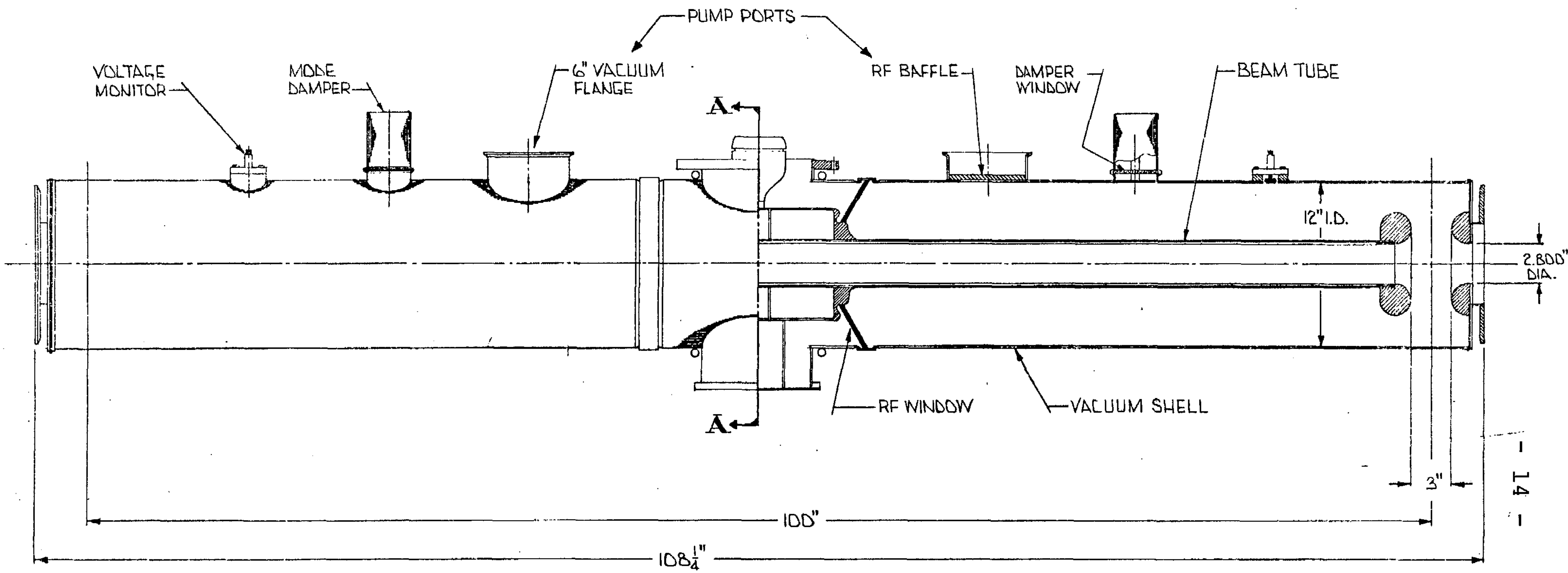
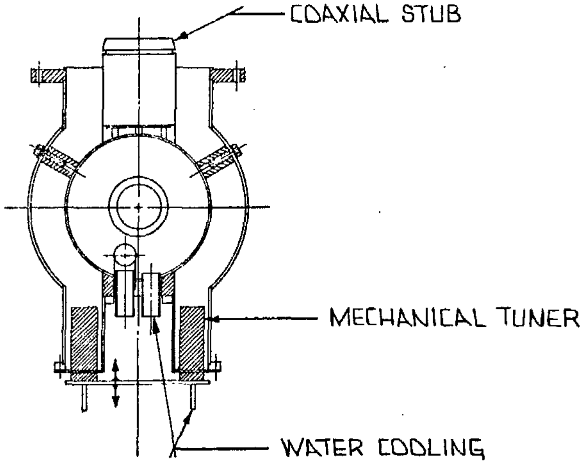


FIG. 5 MR AND TEVATRON COLLIDING MODE

TOP VIEW





SECTION A-A

FOR FURTHER DETAIL SEE FNAL DRAWINGS

BEAM TUBE ASSEMBLY --------- 1734.02-ME-63224

VACUUM SHELL ASSEMBLY---- 1734.02-ME-63225

CENTER SECTION------------- 1734.02-ME-63252

Fig. 6 TEVATRON ACCELERATING CAVITY

structure of length $\ell \simeq \beta\frac{\lambda}{2}$. Actually, the drift tube is electrically 160° long rather than 180°, so that $V_{effective} = V_{gap} \sin\frac{\phi}{2}$ is slightly less than the maximum achievable, but the $\sin\frac{\phi}{2}$ term is $\simeq$.98, and the cavities resultant mechanical length permits mounting them end-to-end at electrically 180° spacing if desireable.

The 160° drift tube is supported by ceramic rf windows and is capped by corona rings dimensioned to minimize the corona ring gradient. At 200 kV peak gap voltage, the gradient ~ 70 kV/cm. The corona ring capacitance somewhat increases the skin loss. The design results in the parameters in Table II.

TABLE II

Tevatron Cavity Parameters

Parameter	Unloaded Cavity	Cavity w/Beam Load (2.5 x 10^{13} ppp)
Peak Voltage	360 kV	360 kV
Frequency	53 mHz	53 mHz
Z_o	70Ω	70Ω
Q	6,500	3,650
Shunt Impedance	1 MΩ	560 K
Time Constant	39 μsec	22 μsec
RF Power Required	64 kW	114 kW
.707 Bandwidth	8 kHz	14 kHz
Stored Energy	1.2 Joules	1.2 Joules

RF power is applied near the center of the cavity at a point tapped down on the drift tube where the 50 ohm coax drive line is impedance-matched at full load. At less than full load the

$3\lambda/2$ line will operate at the same rf voltage at the voltage maxima as in the full-load use, but rather than be a flat line, will develop voltage minima. This scheme was chosen to minimize the possibility of coax line sparking. There will be spark protection circuitry that interrupts rf drive and anode supply voltage for either cavity, coax line or PA sparking.

2. Mechanical Design. The mechanical design is shown on Fig. 6. The drift tube is cooled by internally circulating water necessary to minimize thermal detuning. The outer copper tank is also water-cooled.

The rf windows are 99% Al_2O_3 ceramic cones, metallized and brazed to OFHC copper rings that in turn are heliarc welded to the copper inner and outer coaxial conductors. Thus, the entire cavity structure is vacuum tight with no organic vacuum seals, and is completely bakeable to 250°C if needed to lower initial outgassing rates.

3. It is expected that the cooling and spark protection will allow operation at 360 kV peak accelerating voltage per cavity (180 kV peak per gap).

4. Damping of obnoxious modes will be accomplished by resistors, coupled through the side walls of the resonator, comparable to what was successfully done on the present Main Ring cavities.[3] At $N = 1 \times 10^{14}$ ppp, the average circulating beam current is 0.765 amperes. We anticipate loading of this magnitude will be handled by the same techniques (mode dampers and screen feedback to lower dynamic PA anode impedance) as used successfully in the Main Ring RF system, plus the idea of the "stuntbox", which involves sending an "anti-pulse" through the PA to arrive at the

cavity synchronously with the beam loading perturbation.[4] This feed-forward technique is available to us in principle at any time, but we will have to construct additional low-level hardware for its implementation.

VI. Utilities

1. AC Power. At the present time feeder 45B is rated at 4 MVA. Off this feeder are two 13.8 kV-to-480 V step-down transformers rated at 1.5 MVA each. One transformer is dedicated to operation of the 1st 16 MRRF ferrite bias supplies. The other transformer supplies the rest of the conventional power to the building and power to station 17 and 18 ferrite bias supplies. The two anode power supplies are on a separate feeder, feeder 48.

For the Tevatron operation MRRF stations 17 and 18 will be removed. This will allow us to transfer 2 modulators to the Tevatron (modulator power ~15 kW). Since two ferrite bias supplies (75 kW each) will no longer be used, their power will be available for 3 additional modulators and other equipment such as a second available LCW pump and auxilliary equipment. Hence, no additional installed ac power is required to implement the requirements in Table I, column I.

2. LCW System. At the present time we have two major low conductivity water systems at MRRF. The first is a 65°F system with a temperature control range from 55°F to 120°F, which operates through a heat exchanger whose primary cooling water comes from the Central Utilities Building. The second is the 95°F system which is similar to the 65°F except the primary water for the heat exchanger is the pond water. Since the pond water temperature varies from season to season, a lower temperature limit is reached on hot summer days.

In the Tevatron we have an additional problem in that we need to regulate the temperature of the water that is supplied to the cavities to ±1°F. We want this system to be continuously variable over the range from 70°F to 120°F. This will require an additional heat exchanger and pump capable of delivering the following:

Supply Pressure:	120 psi
Return Pressure:	20 psi
Δp:	100 psi
Full Flow:	500 gpm
Heat exchanger Capacity:	600 kW

The existing 95°F system is adequate for the Tevatron modulators and power amplifiers. We will make use of the existing penetrations in the pump room for getting the Tevatron cavity cooling water into the tunnel.

VII. Present Status and Plans

1. Prototype Tevatron Cavity. The basic mechanical and electrical designs of the cavity have been completed. All of the major metal and ceramic parts have been machined. The drift tube has been assembled; a thermal test of the drift tube, simulating rf heating with heater tapes, is underway in order to extrapolate to dimensional changes under full power conditions. Following this test, the full cavity will be assembled and its basic electrical parameters measured at low rf power levels. If needed, minor dimensional changes will be made to obtain the correct cavity frequency and driving point impedance. A 160 kW PA will then be coupled to the cavity to conduct high power testing at the 360 kV level. Once the 360 kV rf voltage is achieved on the test stand,

it would be prudent to install the prototype cavity in the Main Ring in order to demonstrate that the 360 kV level can be maintained in the presence of the proton beam and ba-kground radiation from an extraction septum to be installed just upstream of the Tevatron cavities; the possibility of beam induced sparking at these high voltage levels must be investigated.

2. Resonator. A new resonator designed to be used in the high-power check-out of rebuilt PA's, has just been fabricated. A slightly modified version of this resonator will be built for coupling the 160 kW PA to the 9" coax transmission line.

3. Main Ring Station Upgrade. The specification of cavity modifications to allow operation at the 280 kV level and to accommodate the Tevatron beam pipe has been completed. One cavity has been completely modified and is ready for high-power check-out. Eight PA's have been modified to permit operation at the 160 kW level and are currently in use in both Main Ring and Booster for evaluation purposes. Finally an air filtering system employing an electrostatic precipitator has been installed in the Main Ring tunnel just upstream of F0.

4. RF Monitor and Beam Abort Trigger. A suitable monitoring system of the Tevatron rf will be designed such as to protect the Tevatron against beam loss due to rf malfunctions. It should inhibit injection of beam into the ring unless the voltage and frequency are within prescribed limits; in the event the rf

system malfunctions with the beam in the ring (sparking or station trip) it will generate a beam abort trigger well in advance of significant beam motion.

VIII. Summary

The Tevatron rf system described here consists of four or eight accelerating stations. The system with four cavities is located in the downstream end of the F0 straight section, longitudinally separated from the 16 Main Ring cavities. The tevatron cavity is a coaxial resonator of new design, capable of producing a peak rf voltage of 360 kV. The cavities are fed through coax lines from remote power amplifiers located ~28' ($3\lambda/2$) away in a new ground-level building addition (68' x 28') directly above the Main Ring tunnel. The basic 4 cavity plan has the following virtues: (a) minimizes the disturbance to the existing Main Ring RF system while maintaining its performance level and accessibility for maintenance; (b) minimizes the Tevatron RF hardware to be installed in any already-crowded tunnel while providing reasonable access to the cavities and optimum access to the power amplifiers, and (c) the cavity geometry can accommodate simultaneous $\bar{p}p$ acceleration in either the Main Ring or the Tevatron.

The basic system to power the cavities utilizes existing Fermilab modulators and power amplifiers (one per station); a capability of accelerating 2.5×10^{13} ppp at a rate of 50 GeV/s is achieved. The existing HV anode power supplies and installed ac utility power are adequate to support both Main Ring and Tevatron systems over a broad range of operating modes; a modest addition to the LCW system is needed for cooling the cavities.

To reach beam intensities greater than 2.5×10^{13} to 1×10^{14} ppp, will require development of a higher power rf drive system. Additional rf cavities will be required to increase the ramp slope beyond 50 GeV/second.

References

1. H. W. Miller and J. Reid; Internal Note to F. Turkot; "Immediate Steps to Increase RF Power Amplifier Output." August 17, 1978.
2. This method for simultaneous acceleration in Main Ring using two orthogonal groups of eight cavities each, without change of physical spacing of the cavities, was suggested by F. Mills.
3. Q. A. Kerns and H. W. Miller; "Fermilab 500-GeV Main Accelerator RF Cavity 128 MHz Mode Damper;" IEEE Trans. on Nucl. Sci., Vol. NS-24, No. 3, 1977.
4. Section VI, Q. A. Kerns; "Proton-Proton Colliding-Beam Storage Rings for the National Accelerator Laboratory," Design Study, 1978.