FERMILAB TEVATRON HIGH LEVEL RF ACCELERATING SYSTEMS

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Introduction

Eight tuned rf cavities have been installed and operated in the FØ straight section of the Tevatron. Their mechanical placement along the beam line enables them to be operated for colliding beams as two independent groups of four cavities, group 1-4 accelerating antiprotons and group 5-8 accelerating protons. Their spacing is similar to that described in Ref. 1. The only difference is that the spacing between cavities 4 and 5 was increased to stay clear of the FØ colliding point. The cavities can easily be rephased by switching cables in a low-level distribution system (fan-out) so that the full accelerating capability of all eight cavities can be used during fixed target operations. Likewise, the cables from capacitive probes on each cavity gap can be switched to proper lengths and summed in a fan-back system to give an rf signal representing the amplitude and phase as "seen by the beam," separately for protons and antiprotons. Such signals have been used to phase lock the Tevatron to the Main Ring for synchronous transfer.[2] A cavity consists of two quarter-wave resonators placed back to back with a coaxial drift tube separating the two accelerating gaps by π radians. The cavities are very similar to the prototype which has been previously described[3] and is operating as Station 8 in the Tevatron. Only additional water cooling around the high current region of the drift tube supports and a double loop used to monitor the unbalance current through the Hipernom mode damping resistor have been added. Each cavity has a Q of ~7100, a shunt impedance of 1.2 MΩ, and is capable of running cw with a peak accelerating voltage of 360 kV. For tuning, a temperature controlled water system which circulates tempered water through the drift tube is used to maintain the correct resonator center frequency. A 200 kW amplifier supplies rf power to the cavity via a 9-3/16 inch copper transmission line. The amplifier and associated equipment reside in an equipment gallery above the beam enclosure. A simplified station diagram is shown in Fig. 1.

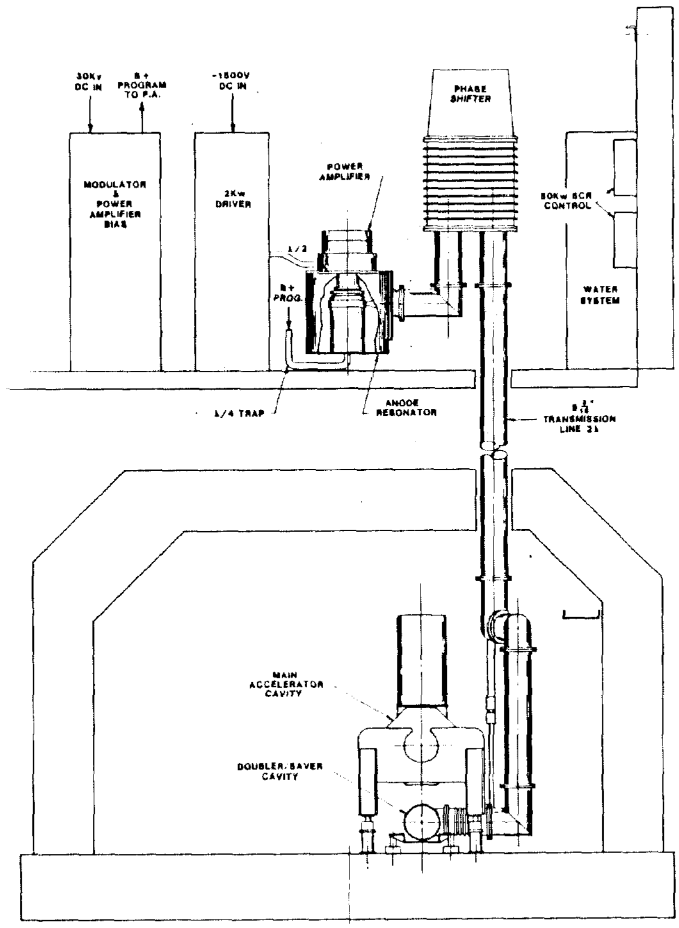

Figure 1. Station Diagram

Power Amplifier-Driver

A cathode driven Eimac Y567B tetrode provides up to 200 kW of rf power to a Tevatron cavity. Fifty kilowatts generate the required 360 kV of peak gap voltage (180 kV per gap) with 150 kVA remaining to supply real beam power and reactively tune the cavity to compensate for beam loading.

Cathode drive is provided by a 14 tetrode (4CW800f) adaptation of the lower half of a Fermilab 100 kW cascode design.[4] The input matching transformer was modified to 50 ohms. The parallel connected anodes are tuned to 53.104 MHz and operate at dc ground. The amplifier provides 2 kW when it is matched into a 50 ohm line and driven with 50 watts. A half-wave 50 ohm line connects between the driver and final amplifier. An additional quarter-wave 25 ohm line is in series to the cathode to provide impedance matching. The cathode capacitance is tuned to 53.104 MHz by an inductor bypassed to ground. Two 50 ohm loads tapped half way up on the inductance broad band the input and swamp impedance changes (1/gm) with cathode current changes in the final amplifier. A common 1000V supply provides the negative voltage for each driver station. Solid state switches in series with each station serve to disconnect the cathodes in 5 microseconds in the event of tube arcing.

A commercial 200W amplifier provides the necessary input power for the driver and its 55 dB of gain allows the station to be driven directly from a one watt low-level signal distributed by the fan-out system of passive splitters. Microsecond fault protection is provided by an rf gate at the input of the 200W amplifier.

The input drive level is constant and cavity voltage is amplitude modulated by programming the high power tetrode anode voltage and current with a series tube modulator and G1 modulation.

The power tube anode, coupled via a 1000 pF ceramic blocking capacitor,[5] forms a quarter-wave resonator tuned to 53.104 MHz. The 9-3/16 inch transmission line connecting the anode circuit to the cavity is tapped on the resonator as close to the anode voltage as possible. Anode voltage from a series tube modulator is introduced across the blocker through the hollow center conductor of the resonator. A quarter-wave trap constructed from a 1-5/8 inch transmission line removes the 2 kV of rf developed across the blocker from the B+ lead.

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Construction Remarks

Disc capacitors made with 0.005 inch Kapton metalized and copper clad on each side are clamped to ground between metal plates to provide rf bypassing of the screen and control grids of the tube.

The one inch thick outer conductor of the resonator is rolled to an i.d. of 26 inches and then welded and machined. Type 1100F aluminum was chosen for its high conductivity. The inner conductor is of copper and is water cooled. Flat end plates were constructed of 6061-T6 aluminum for strength.

The ceramic blocking capacitor, originally designed for pulsed operation in the Fermilab Booster, has performed flawlessly for over a year of operation in six Tevatron systems. Only minor mechanical changes in the copper electrodes were made to adapt to the present use.

The 9-3/16 inch transmission line connects to the cavity through a bellows designed to relieve strain on the cavities vacuum window.

RF Regulation

A screen loop, Fig. 2, regulates cavity rf voltage to better than 2% for beam current fluctuations of 10^{13} ppp.

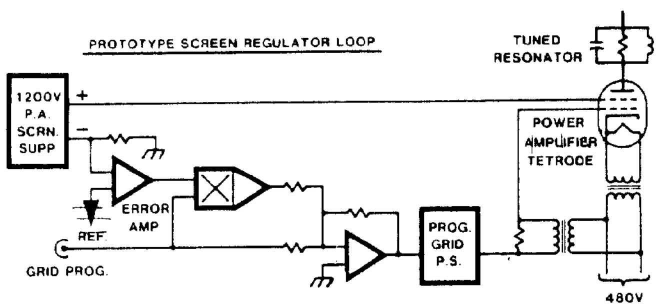

Figure 2. Screen Loop

Peak rf swings approaching the anode to screen voltage produce screen current in pulses at the rf frequency. The current, averaged by a screen bypass capacitor follows rf envelope variations up to 100 kHz. The fluctuations in screen current are compared to a reference and the resulting error signal is summed into the 0-10 volt input of a -500V to 0V, 100 kHz bandwidth grid bias supply. A transformer winding, which taps a fraction of the ac filament voltage, is inserted in series with the grid supply to reduce ripple. The resultant control grid feedback regulates the rf level by modulating the tetrode anode current. The peak rf amplitude essentially tracks the difference between the anode and screen voltage on the tetrode. A 1 kV, 1A unregulated 3-phase power supply provides screen voltage.

Modulator

The series tube floating deck modulator, Fig. 3, is programmable from 0 to 30 kV with a rise time of <10 microseconds. A Y567B tetrode is used as the series pass element in the modulator. Output current of up to 15 amps is monitored with a 0.1 ohm dc shunt, that has a 10 nsec pulse response. Arcs, sensed on the output, block the series tube in a few microseconds. A high voltage divider between the deck and ground is compensated at each end to provide both a ground level monitor and a deck feedback. The monitor is accurate to 0.1% with a risetime of 100 nsec. The amplifier that drives the series tube grid is a grounded grid cathode driven 4CW800F tetrode. A grounded source FET drives its cathode. FET input is from an operational error signal amplifier which compares a reference signal and high voltage divider feedback. The deck reference is transmitted from ground level with 16-bit serial light link. Twelve bits are used for the program, the remaining four are logic functions. Ten volt program level provides 30 kV output from the modulator. Judicious placement of MOVs on the screens of both tetrodes eliminate spark energy at all stages from feeding back into the low level drive circuits.

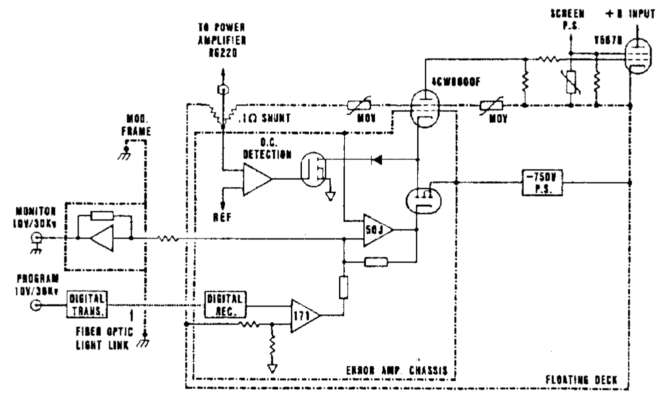

Figure 3. Modulator Deck

All eight stations receive power from a common 30 kV anode supply. If a station or amplifier sparks, detection circuits block the series tube for that station until the fault clears. At the present time we abort the beam if such a fault occurs. In the future, fast acting cavity shorts may eliminate the need for aborts. Aborts are presently needed because the beam induced voltage in an idling cavity drives the gap to a multipactor level. The vacuum becomes undesirably bad when this happens.

Standing Wave on 9-3/16 Inch Transmission Line

To span the distance from the PA in the gallery to the cavity in the tunnel a transmission line is required. We have adjusted the length to exactly two wavelengths to get the one-to-one impedance transforming property of an integer half-wave line. Furthermore the coaxline voltage is set to correspond to a matched power level of about 4 MW. Doing this achieves a stiff coupling from PA to cavity, facilitating voltage control under beam loading.

The reason this is so beneficial to operation is that beam loading, real and reactive, varies over a wide range depending on users' needs for beam. The one-to-one property means that there is a fixed ratio of tube voltage to cavity gap voltage independent of beam loading. What happens then with various beam loadings is that the voltage minima on the transmission line vary drastically, but the voltage maxima are hardly affected. Adjusting the rf current of the tube in direct accordance with beam current is then the proper thing to hold constant gap voltage and is done via the programming and feedback described in the PA section of this paper.

Spark Detection

RF sparking in the cavity, transmission line, and anode resonator is detected by monitoring the rf gap voltage of a cavity. A system similar to the one used in the Fermilab Booster cavities[5] is used. An rf amplitude decrease of >1 dB at a rate >2 dB/microsecond is assumed to be an arc. The 200W ENI drive is gated off for 2 seconds after which time the rf is gated back on. This procedure conditions operating cavities after a few sparks at each level as voltage is increased above 125 kV/gap.

Cavity Tuning

Cavity tuning is controlled by closed loop water systems. The tuning system manipulates cavity temperature to maintain the desired resonant frequency, which depends on the thermal expansion coefficient of the copper. RF operation at pulse lengths and repetition rates comparable to a cavity's seven second thermal time constant demands dynamic temperature modulation as opposed to fixed temperature regulation. Each cavity has individual systems for its upstream and downstream ends. There are pumps, heat exchangers, water heaters and mixing valves. The heaters are mounted directly on the cavity for fast response time, but the rest of the water system is in the equipment gallery. To balance and replace the nominal 50 kW of rf power absorbed by each cavity, 70 kW of cooling and 100 kW of heating are available.

The heat exchangers and proportional control mixing valves are commercial units. The heaters were designed in-house of metal and ceramic materials for small physical size, rapid thermal response, matching to available 480 VAC 60 Hz power, resistance to corrosion and radiation, and general ruggedness. A heater consists of three spool elements of Nichrome V ribbon housed end-to-end in a stainless steel tube. Water flows in direct contact with the windings, 480V SCR-type ac power controllers feed the heaters which at full power deposit 330W per cubic inch to the water and can be controlled uniformly to zero power.

Servo loops with feedforward programs generated by the accelerator drive the heaters. These programs are functions of the rf voltage and are timed relative to each other and the rf voltage program to allow for water flow delays and compensate for thermal lag. In stand-by, the heaters and the cooling are programmed down to a low power level. In preparation for high power operation the cooling and heating are programmed up together while still controlling the proper frequency, then, when rf power is turned on, the heaters are appropriately reduced, trading rf heating for 60 Hz heating. As the rf pulse ends, heater power is once again raised to remain there until rf power is agained turned on, or until it can be lowered in step with system cooling. Phase detectors observe the power amplifier under high power conditions and the keep-alive system when high power is off. The controller switches to the proper error signal and reverts to temperature regulation when both normal error signals are absent beyond a preset period. The controller also detects differences between the rf program and cavity level to allow instant replacement of 60 Hz power for rf power in the event the cavity rf trips off or differs for any reason. This feedforward technique eliminates large glitches in the servo loop.

Keep-Alive System

The keep-alive system, Fig. 4, permits the water loop to keep the resonator in tune at all times, including the time when the high-level rf is off. Typically the high-level rf is off for 20 seconds and on for 40 seconds. During the off time an ∿1 mW signal fed to a loop in the power amplifier excites about 50V in the cavity gap with a phase detector monitoring V&I. The water servo tunes the cavity to run in resonance with the signal generator. This signal generator has a prescribed offset in the frequency from the injection frequency in order to pretune the cavity for the injection beam loading transient.

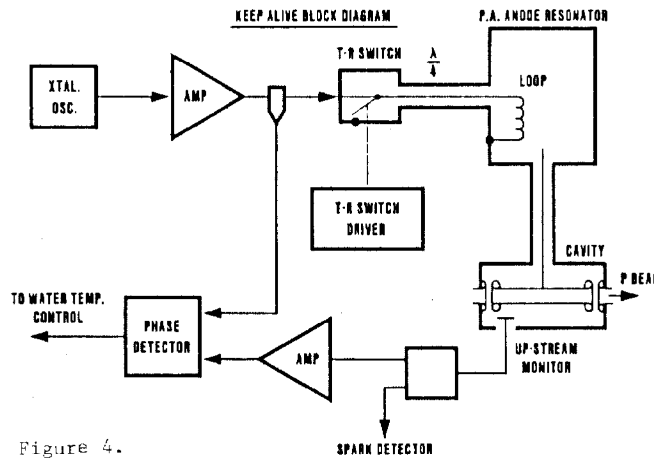

Figure 4.

There is a large range between high-level rf and keep-alive level and there are two devices requiring protection. One is the signal generator and the other is the preamplifier which feeds the phase detector. The signal generator protection problem was solved with a PIN diode T.R. (a' la Radar "Transmit-Receive") switch. The T.R. switch was placed a quarter-wave length away from the previously mentioned loop in the power amplifier, thus providing high impedance coupling protection from the high-level rf with the T.R. switch on. The PIN diodes are switched on by a fast comparator whenever rf exceeds a pre-set threshold. Because the cavity rf level takes 10 microseconds to rise, the PIN switch turning on in one microsecond easily protects the signal generator.

The pre-amp is protected by a specially-designed front end. The pre-amp front end sees a millivolt Pk/Pk during keep-alive time, increasing to about 7V Pk/Pk during high-level on time. RF current steering is used to apply the low-level signal to the input transistors but route the high-level signal to an external terminator with increasing amplitude. We found this approach yields a sufficient dynamic range (∿105 dB) and maintains a reasonably constant input impedance.

Acknowledgements

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