CONF-8705288--1
BNL-41284

III Eloisatron Workshop New Techniques for Future Accelerators, Erice Sicily, May 1987.

RADIO FREQUENCY SYSTEMS FOR PRESENT * AND FUTURE ACCELERATORS

Eugene C. Raka

Brookhaven National Laboratory
Upton
Long Island, NY 11973, USA

BNL--41284
DE88 010666

INTRODUCTION

In order to bunch, accelerate and store charged particle beams it is necessary to install one or more "accelerating" gaps on the circumference of the machine. These gaps are usually part of a resonant structure driven by a source of radio frequency power. The frequency, phase and amplitude of the voltage appearing at the gap(s) is controlled by servo loops that use programmed inputs as well as error signals derived from the particle beam itself in many instances.

The design specifications for any rf system would include the initial (injection) and final (at maximum beam energy) frequencies and thus the harmonic number $h=f_{rf}/f_o$ where f_o is the particle rotation frequency; the peak gap voltage and the number of gaps; the acceleration rate in keV or MeV per turn and hence the maximum power to be delivered to the beam; the amount of power needed to make up for the losses in the resonant structure and the impedance presented to the beam image current by the structure at the principal resonant frequency and at the resonant frequencies of any higher order modes that produce significant longitudinal or transverse field at the gap. There are also other parameters of interest to the designer and many of these will be referred to in our discussion of present and future rf systems.

FNAL MAIN RING

Some of the parameters for this rf system are listed in Table 1, and a sketch of the resonator is shown in Figure 1. It consists of a pair of $\lambda/4$ standing wave resonators folded back on themselves to conserve linear space. The outside diameter is 0.68 m and the length 1.78 m.[1] Tuning is accomplished by varying the bias field (in the same direction as the coupled rf magnetic field) in stacks of ferrite rings loop coupled to the cavity. A pair of loops are installed on each cavity as can be seen in Figure 2. Each loop can change the stored energy in the cavity by 0.7% thus giving a tuning range of about 400 kc (at 53 MHz).

*Work performed under the auspices of the U.S. Dept. of Energy.

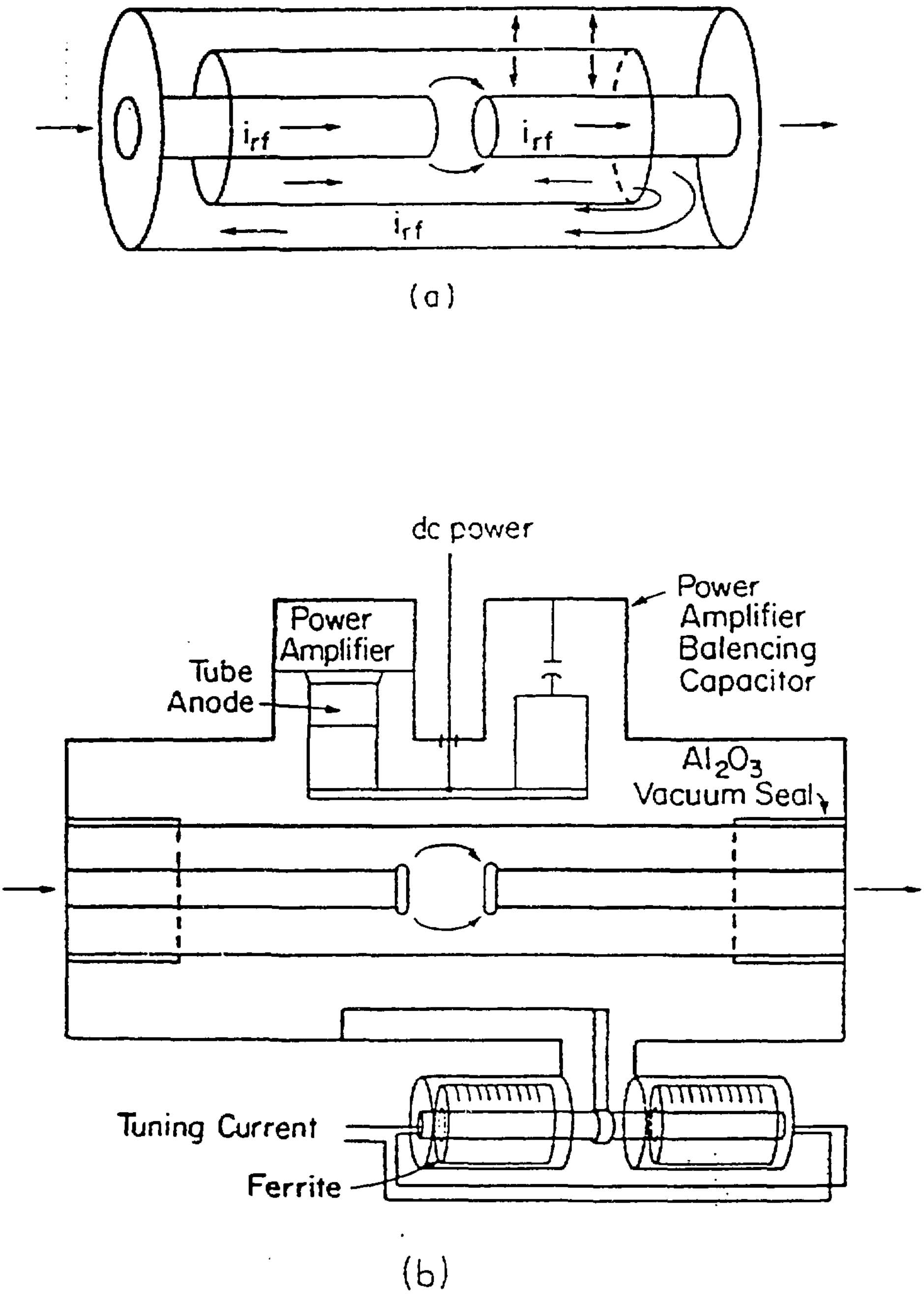


Fig. 1. Sketch of FNAL main ring rf cavity.
(a) Folded (14) TEM resonators.
(b) Method of coupling rf power and tuning.

Table 1. FNAL Main Ring rf System Parameters	
Injection Energy	8 GeV
Final Energy (pre tevatron)	400 GeV
f_∞ (f_o at $\beta = 1$)	47.7 kc
f_{rf}	52.81-53.104 MHz
h (harmonic number)	1113
Acceleration Rate (Φ_s 45° & 135°)	2.6 MeV/turn
Peak rf voltage (18 cavities)	3.67 MV
Peak rf voltage per cavity	>200 kV
Beam current at 3.25×10^{13} protons	≈250 mA
Cavity R_s/Q	104
Q_ℓ	5800
R_s (including PA)	600 KΩ
Excitation power @ 204 kV/gap (total)	624 kW
Maximum power to beam @ 3.25×10^{13}	650 kW

Now in addition to tracking the change in the rf frequency during acceleration, the tuning loop must also correct for changes in beam loading. Usually the phase of the total voltage appearing across the gap is compared to the phase of the drive current applied to the final stage of the power amplifier. Zero error signal corresponds to a real load impedance (shunt impedance of the resonator plus beam impedance). In general the resonator will be detuned by an amount $\Delta\omega = (\omega_{rf}-\omega_r) \approx -\omega_r \tilde{I}_b R_o \cos\Phi_s/2V_c$ where $\tilde{I}_b$ is the component of the beam image current at ω_{rf}, $R_o = R_s/Q$ and ω_r is the nominal resonant frequency of the cavity. In the FNAL main ring the transition energy occurs at ≈17.6 GeV so the fractional detuning due to beam loading changes sign. Hence a change of $2|\Delta\omega|$ must take place. Since normally the tuning loop response is quite slow compared to the time it takes the cavities to respond to a phase jump of $2(\pi/2-\Phi_s)$ the power amplifier will not see a real load for a brief period and hence must supply some reactive current. We note that for 3.5×10^{13} in the main ring $\Delta\omega/\omega_r \cong 0.9 \times 10^{-4}$ or $\Delta f \approx 4.7$ kc.

Fig. 2. FNAL main ring cavities (July 1976)

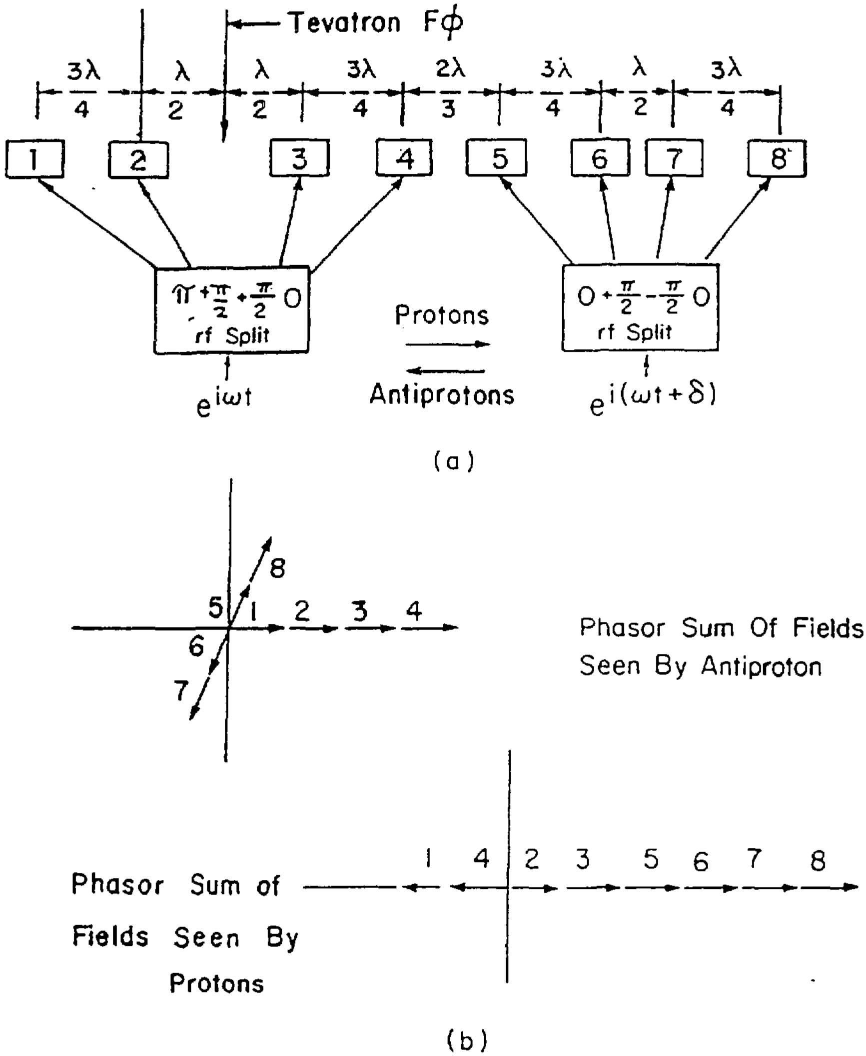


Fig. 3. Tevatron rf power distribution system.

In order to damp higher order resonant modes in the structure, nickle zinc ferrite was installed in enclosures located at the end walls of the cavity which are iris-coupled to the resonator.[1] It was later found necessary to install a ferrite loaded waveguide at the central low impedance point of the cavity in order to couple to some modes which have a large magnetic field there but not at the end walls.[2] This addition eliminated the coupled bunch longitudinal instabilities observed at 8 x 10^{12} protons/pulse and no further longitudinal instabilities were observed up to a peak intensity of 3.25 x 10^{13}.

FNAL TEVATRON RING

The FNAL Tevatron ring is a superconducting accelerator and storage ring. In the fixed target mode it accelerates protons to 900 GeV and in the colliding beam mode it accelerates three protron and three antiproton bunches to 900 GeV and then stores them at this energy for several hours. Eight resonators are installed on the ring in two groups of four, each spaced in such a manner that by proper phasing, protons and antiprotons can be accelerated simultaneously (see Figure 3). In Table 2 we summarize the parameters of this system. Typical acceleration time for $p,\bar{p}$ is ≈25 seconds with 1.4 MV available for each group of bunches. The acceleration rate for the fixed target mode is not much greater since the limiting factor is the ramp rate of superconducting magnets. At 2 x 10^{13} protons/pulse the maximum power delivered to the beam is ≈20 kW per station while the resonator excitation power alone is 54 kW. Thus static beam loading will never be severe in this machine (this can occur when the power delivered to the beam is equal to the cavity excitation power plus the rf power dissipated in the internal impedance of the power amplifier).

TABLE 2. FNAL Tevatron rf System Parameters

Injection Energy	150 GeV
Final Energy	0.8-0.9 TeV
f_∞	47.7 kc
f_{rf}	53.104 MHz
h	1113
Accelerator Rate (6 stations @ 1.8 MV peak)	785 keV/turn
Peak voltage (8 cavities)	$\geq$2.4 MV
Peak voltage/cavity (two gaps)	360 kV
Cavity power at peak voltage	54 kW
R_s (two gaps)	1.2 M
Φ_o	7100
τ_c (unloaded cavity time constant)	42 μ/sec
τ_c (loaded)	12 μ/sec

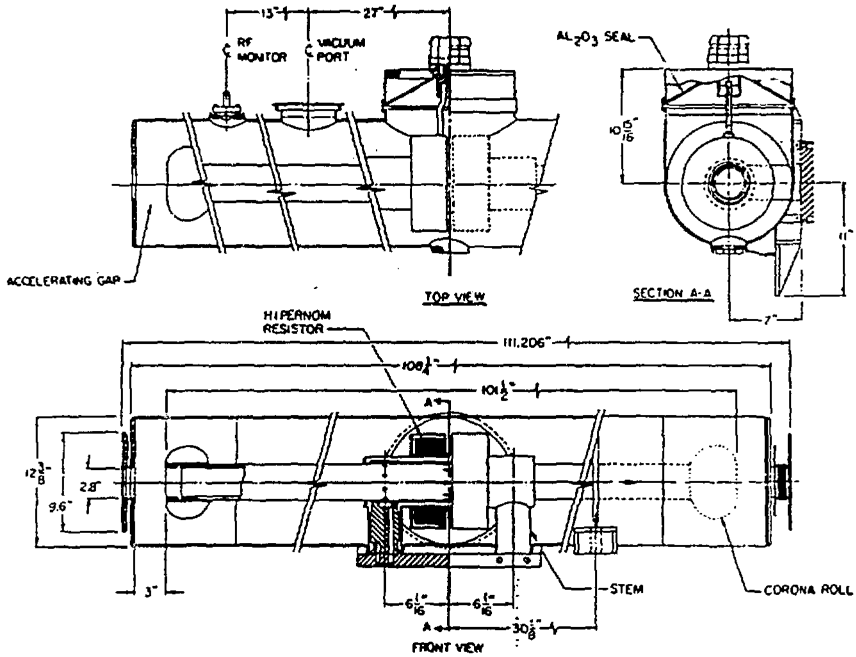


Fig. 4. Prototype tevatron resonator.

In Figure 4 we show a drawing of the resonator[3] and in Figure 5 a cross section of the accelerator tunnel where the power amplifiers and resonators are located. The power tube is an Eimac Y576B (special 4CW 200,00E) whose output capacitance along with its enclosure is part of a quarter wave resonator tuned independently to 53.104 MHz. A 9-3/16 inch 50Ω transmission line is connected to the anode end of the resonator and it feeds the tube output to the cavity resonator on the ring. The length of this line is adjusted to be 2 wave lengths at 53.104 MHz so that the real and reactive component of the load (beam and cavity) are transmitted to one to the tube circuit.[4]

The two halves of the resonator are driven in parallel while the electrical length of the resonator at 53.104 MHz is 170° so that V_{eff} sin (170°/2) = 0.995 V_{gap}. There are two sets of modes that can be excited in the resonator; one set is characterized by both gaps oscillating in phase and these modes couple to the transmission line and hence are controlled by the source impedance; the other set is characterized by the gaps oscillating 180° out of phase and these result in a current maxima at the center of the resonator. The Hipernom resistor located at the center of the drift tube serves to damp these resonances.

Tuning is accomplished by controlling the cooling water applied to the drift tube and coils on the outer walls. There is no beam controlled turning loop since at 180 kV/gap and 2 x 10^{13} protons, the required detuning is ≈3.75 kc or only one half of the natural bandwidth of the resonator.

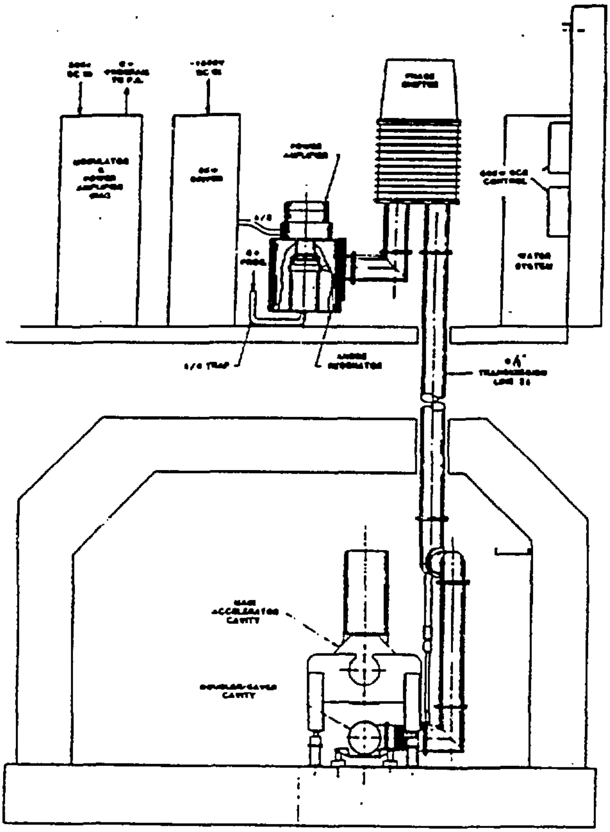


Fig. 5. Tevatron rf station installation

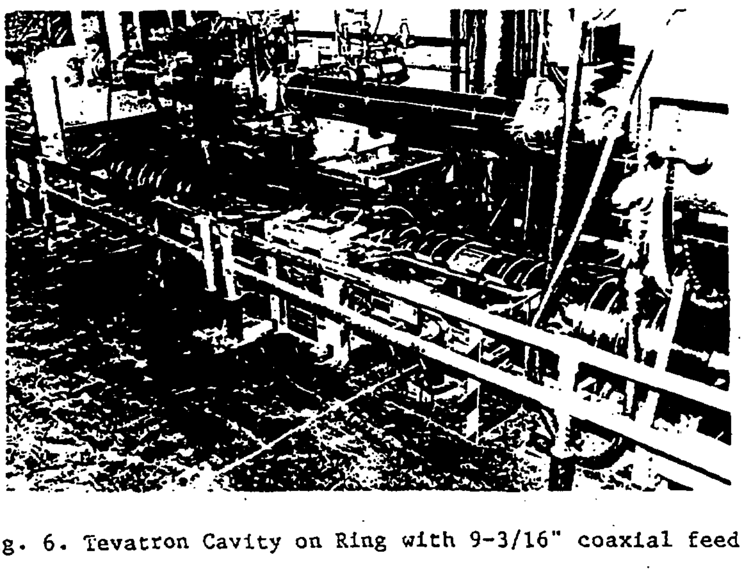


Fig. 6. Tevatron Cavity on Ring with 9-3/16" coaxial feed

Now Figure 3(a) shows the relative location of the eight resonators and Figure 3(b) demonstrates how they act on the proton and antiproton bunches in the collision mode for an arbitrary phase angle δ. The angle δ can be used to move the collision point of the bunches but the normal value for the spacing shown is $\pi/6$. In Figure 6 we see a cavity installed on the ring along with the 9-3/16" coaxial feed from the power amplifier.

CERN SPS

Originally the CERN Super Proton Synchroton was designed only to accelerate protons. In the early 1980's it was adapted to accelerate and store simultaneously protons and antiprotons. Before 1990 it will function as an injector for the CERN LEP accelerator by providing both electrons and positrons at 20 GeV. In order to perform these functions, it has been necessary to augment the initial 200 MHz travelling wave system for $p\bar{p}$ physics and it will be necessary to add 32.200 MHz standing wave cavities for lepton acceleration.

Travelling Wave System

In designing the SPS rf system, it was decided to employ travelling wave structures.[5] This permitted the location of the power source at ground level while the accelerator tunnel was located 60 m underground. The structures always present a matched load to the source independent of the frequency and beam loading. Since the required frequency swing (see Table 3) was less than 5×10^{-3} it was possible to design a structure with the desired bandwidth, thus removing the need to tune a resonator.

The rf system specifications are shown in Table 3. One parameter not listed is $\tau = (\omega-\omega_o)\ 1/V_g$ the total phase slip between the travelling wave of group velocity V_g and the proton bunches along the structure length 1. Here ω_o is the rf frequency at which there is perfect synchronism between the particles and the wave. In order to be able to jump the stable phase angle at transition without changing the amplitude of the incident, wave ω_o is chosen to be equal to ω_{rf} at the transition energy.[5]

The accelerating structure which consists of identically spaced drift tubes supported by horizontal bars is shown in Figure 7. Since the passband of the bar structure is of the backward wave type, the power is fed into the downstream end of the cavity. It operates in the $\pi/2$ mode at ω_o i.e. the phase shift from bar to bar is 90°. A cavity consists of five sections of 11 cells, each of which is 3.74 mm long, including two half cells for input and output coupling. Fine tuning of the overall structire to ω_o is achieved by controlling the cooling water temperature.

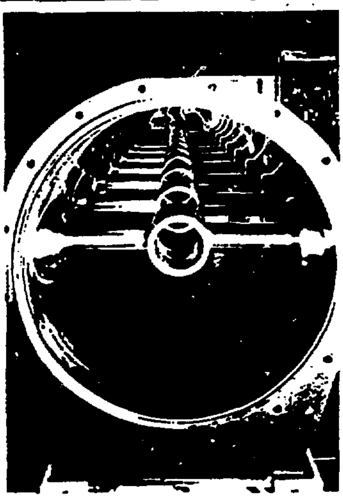
There are many higher order modes of the structure that are synchronous with the beam. Since these couple poorly to the input and output loops two addditional loops are installed on the ends of the cavity to damp these modes without extracting significant power from the main resonant mode. Transverse deflecting modes have also been identified in the structure and additional loops were installed to damp them.[6] Because of the wide bandwidth of the cavities, there is significant impedance at frequencies $\pm nf_o$ from the driving frequency hf_o where $n = 1,2....20$. Longitudinal coupled bunch instablities driven by this impedance with mode numbers of 1 to 17 have been observed and damped with feedback.[6]

Table 3. SPS $p\bar{p}$ Acceleration System Parameters	
Injection energy p's	10 GeV (f_{rf} = 199.526 MHz)
Injection energy $p\bar{p}$	26 GeV
Final energy p's	400 GeV (f_{rf} = 200.396 MHz)
Final energy $p\bar{p}$	270 GeV
Transition energy	24 GeV (f_{rf} = 200.222 MHz)
Peak acceleration voltage	4 x 2 MV
f_{∞}	43.2 kc
h	4631
Beam current at 3 x 10^{13} p's	210 mA
Acceleration rate (nominal)	≈2.5 MeV/turn
Beam power at 3 x 10^{13}	525 kV
Incident power required (4 cavities at 0.9 mV peaks Φ_s = 45°, 135°)	678 kW
Power dissipation in 4 cavities @ 0.9 mV	13 kW
R_s/cavity (6 MΩ/m)	121 MΩ
Beam cavity coupling impedance r_c	1.4 MΩ
τc (cavity filling time)	0.7 μ/sec
Φ	19,650
V_g (group velocity)/c	0.0946 (backward wave)
Interaction length (54 cells)	20.196 m

Now the beam induced voltage is zero at the drive end of the cavity, so the power source does not see the beam. The beam power is subtracted from the power incident on the terminating load at the upstream end and it is only necessary to supply additional power as a function of beam current to maintain the same total cavity voltage. This required power can be written as (τ = 0):

$$P_{max} = 1/8 \left[\frac{|V|^2}{r_c} + r_c I_b^{\,2} + 2|V| I_b \cos\Phi_s\right]$$

where I_b is the component of beam current at ω_{rf}, V is the total cavity voltage and Φ_s is measured from the peak of the rf wave.



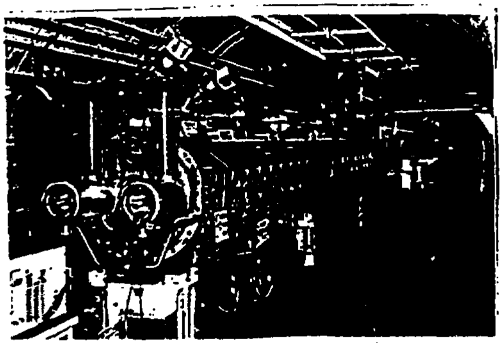


Fig. 8. Cavity Installation in SPS tunnel.

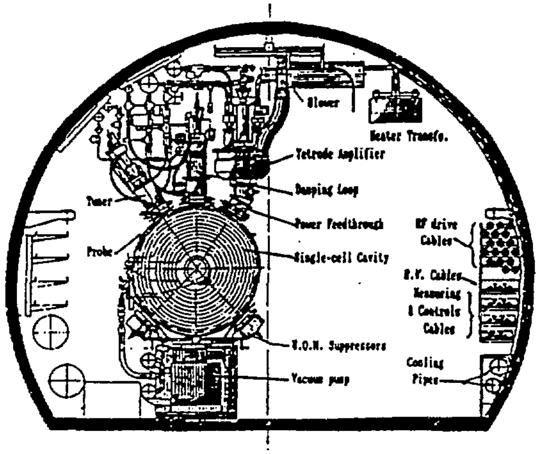
Fig. 7. Drift tube and bar assembly inside of the cavity.

There are now four travelling wave cavities installed on the accelerator, each with its own 500 kW power amplifier. A second set of power amplifiers of 2 MW capability has also been installed in order to insure that power is always available. In the $p\bar{p}$ mode one changes the direction of power input of two of the cavities so that the $\bar{p}$'s are accelerated by one pair of cavities and the p's by the other set. Since one is dealing with only six bunches in this mode the effect of the beam induced signal in either set of structures can be ignored. Since the cavity filling time including power amplifier is ≈1μsec, while the spacing for three $\bar{p}$ or 3p bunches is 7 μsec, individual phase and amplitude control is possible for each one.

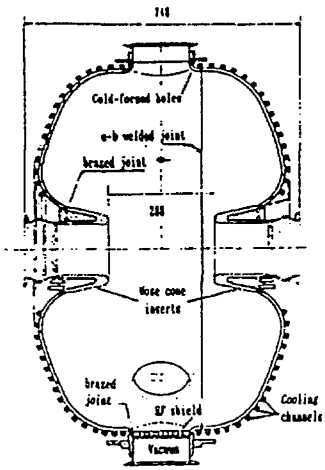
It should be noted that three cavities now have four sections each so that the four cavities total 17 sections[6] versus 15 for the original three.[5] Figure 8 shows one of the cavities in the SPS tunnel.

200 MHz Standing Wave System

In order to accelerate electrons and positrons to the 20 GeV energy necessary for injection into LEP about 30 MV of rf at 200 MHz is required. This will be provided by 32 single cell copper cavities each fed by a power amplifier capable of 60 kW CW and 110 kW peak power for a 1 second period and 20% duty factor.[7] At the design value of |MV| gap (288 mm long) 60 kW is required to excite the cavity which has an R_s of ≈8.5 MΩ and a Q_o ≈49,000. The peak surface electric field is ≈12 MV/m at this voltage. A piston tuner which is servo controlled, compensates for thermal effects, mechanical variations and beam loading conditions. The total range is 400 kc which is also sufficient to cover the variations during $p\bar{p}$ acceleration, since in the latter case the injection energy is 26 GeV. The power tube is a Siemen's RS 2058 CJ tetrode operated class AB with a grounded screen and 10 kV anode voltage at an efficiency of 64%.



Cross-section of the SPS tunnel with a new acceleration module



Cross-section of a single-cell cavity

Fig. 9. SPS 200 MHz standing wave cavity and ring installation.

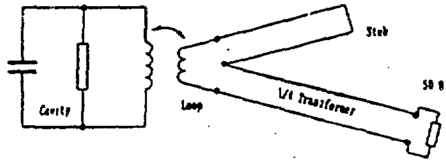


Fig. 10. SPS 200 MHz cavity damping loop schematic.

In addition to the power tube and tuning piston, both of which are mounted on the cavity, Figure 9, there are also higher order mode suppressors[7] and a fundamental mode damper. The former are two resonant loops that are water cooled, mounted so as to couple to two field polarizations. When the SPS is operating in the fixed target mode with 3 x 10^{13} protons the standing wave cavities must not perturb the 4000 bunches due to beam induced voltages. Hence the 200 MHz mode must be strongly damped. This is accomplished by a magnetic coupling loop connected to a shorting stub and a $\lambda/4$ transformer terminated in a 50Ω load as shown in Figure 10. The stub compensates for the circuit reactance so that the resulting real impedance is transformed to the load which is water cooled.[7] The loop which is rectangular is plunged into the cavity during proton acceleration producing a damping factor of 500 and is retracted for lepton acceleration so that both types of machine cycles can be interleaved.

<u>100 MHz Standing Wave System</u>

In addition to the two 200 MHz systems mentioned above, a third set of six cavities operating at 100 MHz are also being installed on the SPS ring. These will be used to capture the larger $\bar{p}$ bunches expected from the new antiproton collector ring ACOL. During acceleration, both the 100 MHz and the 200 MHz systems (travelling wave) will be used. In the storage mode the 100 MHz system can also be used depending upon bunch length requirements.

Six cavities each giving 400 kV with 16 kW excitation are required. A mechanical tuner provides the necessary 70 kc frequency swing for $\bar{p}$ acceleration. The cavities are also equipped with higher order mode suppressors and a tuned loop that is plunged in to reduce the cavity Q by 200 during fixed target proton running and lepton acceleration.

CERN LEP rf SYSTEM

In phase I of LEP the large electron positron collider the maximum energy will be 55 GeV. The necessary rf voltage is to be supplied by 128 accelerating structures driven by 16 Klystrons, each capable of furnishing 1 MW of rf power at ≈350 MHz.[8] Figure 11 shows the power distribution system for one of the eight units, while in Figure 12 is shown their location on the LEP ring. Thirty-two units are placed on each side of two of the eight intersecting regions determined by the four e^+ and four e^- bunches circulating in the machine. Now the spacing between adjacent cavities is $\lambda/2$ while the spacing between cavities 1,16 or 2,15 etc. is an odd number of half wavelengths. Thus the rf must be 180° out of phase between each pair so that with an e^- bunch entering from the left will always see the same accelerating voltage while an e^+ bunch coming from the opposite direction will also always see the same accelerating voltage.

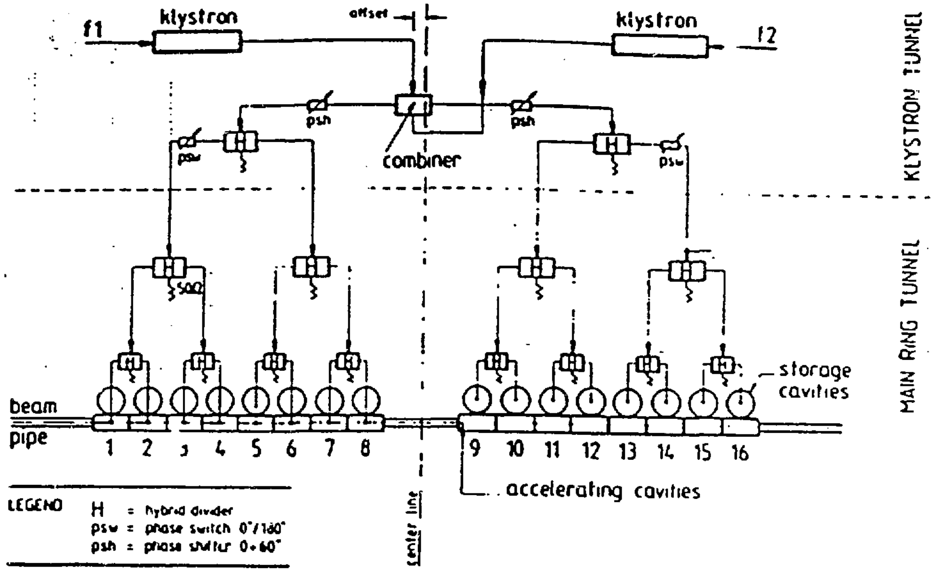


Fig. 11. rf power distribution for one LEP unit

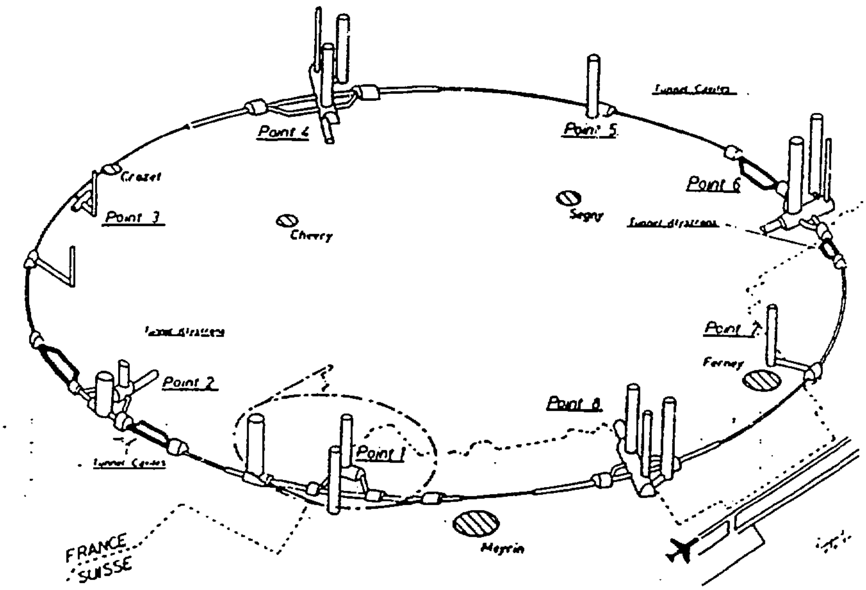


Fig. 12. LEP tunnel showing regions equipped with rf power in Phase I

TABLE 4. LEP rf SYSTEM PARAMETERS[8]

Frequency (ω /2π)	352.209 MHz
Δf	
h	31320
f_{∞}	11.2425 kc
Effective shunt impedance of accelerating cavities (5 cells)	27.66 MΩ
Effective shunt impedance with storage cavity	42.56 MΩ
Maximum voltage gap	625 kV
Average excitation power/cavity	114.7 kW
Accelerating cavity Q	≈40,000
Storage cavity Q	≈160,000
τ_c for coupled system	56.5 μsec
Cavity input coupling factor	1.21
Cavity active length (5 x λ/2)	2.1279 m

The accelerating structures are five cell π mode slot coupled cavities side coupled to a spherical storage cavity operated in the H_{011} mode. The combined structure has two resonant frequencies separated by $\Delta\omega = 2\pi \times 8f_o$ or

$$\omega_1 = \omega_{rf} = \Delta\omega/2 \qquad \omega_2 = \omega_{rf} - \Delta\omega/2$$

and if one excites them with the sum of two voltages:

$$V_i = V_o \cos\omega_1 t + V_o \cos\omega_2 t$$

the two cavity voltages will be given by[9]

$$V_1 = 2V_o \cos\omega_{rf} \cos \Delta\omega/2 \qquad V_2 = -2V_o \sin \omega_{rf} \sin \Delta\omega/2$$

Thus the amplitude of the accelerating cavity voltage will be modulated at $4f_o$ the e^- or e^+ bunch repetition frequency. Energy will be transferred between the cavities at the frequency Δf and the power dissipation is reduced by the factor q where

$$q = 1/2 \frac{(Q_1 + Q_2)}{Q_2} \text{ and } P = 1/2 \left[\frac{V^2}{2R_1} + \frac{V^2}{2R_2}\right] = \frac{V^2 q}{2R_1}$$

Now $Q_1 = 40{,}000$ for the accelerating cavity and $Q_2 = 160{,}000$ for the storage cavity so that one has $q = 0.625$. Figure 13 is a drawing of the combined structure showing the storage cavity which is ≈1.23 m in diameter. In Table 4 we list the rf system parameters.

In phase I the reflected power due to beam loading can produce a missmatch that will result in a VSWR 1.3 at design intensity. It is expected that this can be tolerated by the klystrons and hence initially no isolators were to be installed though space was reserved for them. However during preliminary system testing, one of the klystrons suffered damage and it was decided to purchase and install isolators for all units prior to start up.

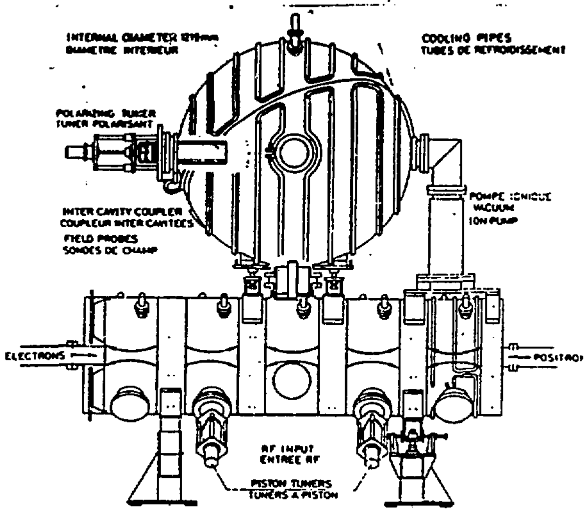


Fig. 13. LEP storage cavity and accelerating cavity assembly.

HERA PROTON ACCELERATION SYSTEM

The HERA[10] project located at the DESY laboratory in Hamburg will collide 30 GeV electrons on 820 GeV protons. The latter particles will be accelerated from 40 GeV injection energy in a ring containing superconducting magnets. The injector will be the PETRA ring which has been adapted to accelerate protons as well as electrons (the latter are accelerated to 14 GeV before being injected into the HERA electron ring). We will only describe the proton rf systems in PETRA and HERA here but note that for electron acceleration the 500 MHz cavities used in PETRA will be employed in both rings. Superconducting 500 MHz cavities will be added to the storage ring in order to obtain the design energy of 30 GeV.

In Table 5 we list some of the parameters for proton acceleration. The 2.4 MV at 208 MHz in the HERA ring will be provided by four single cell copper cavities of the same design as the CERN SPS 200 MHz standing wave cavities. The nose cones will be slightly longer to increase the resonant frequency and they will be operated at 600 kV/gap. Since the shunt impedance will be essentially the same only 21.5 kW excitation power per cavity will be needed. The acceleration rate will be even slower than in the FNAL Tevatron ring so that the beam power at the design current will be only a fraction of the excitation power.

The tuning range required for acceleration is ≈50 kc which is well within the range of the system developed for the CERN design. We note that in the storage mode and during acceleration as well, since the stable phase angle is very small, the cavities will be detuned by ≈4 kc, or about twice the half bandwidth, due to reactive beam loading. It may become necessary in the future to introduce feedback around the cavity and driver to lower the voltage induced by the component of the beam current at 208 MHz.

At injection this component of beam current is not expected to be appreciable since the bunches will be too large to fit into 208 MHz buckets. First the 52.033 MHz rf system must capture three groups of 70 bunches from PETRA (leaving a 10 bunch gap) into every fifth bucket.

Table 5. HERA Proton rf System Parameters	
PETRA II injection energy (p)	7 GeV
PETRA II final energy (p)	40 GeV
HERA final energy (p)	820 GeV
rf frequency PETRA II (h = 400)	52 MHz
rf voltage PETRA II	≈200 kV
HERA rf frequency at injection (h = 1100)	52.033 MHz
Peak 52 MHz voltage	310 kV
Number of bunches	210
rf frequency for acceleration (h = 4400)	208.13 MHz
Peak voltage	2.4 MV
Average beam current	130 mA
γ_{tr} HERA	27.6
η at 40 GeV	7.63×10^{-4}
η in PETRA at 40 GeV	0.0249
f_{∞} HERA	47.3 kc

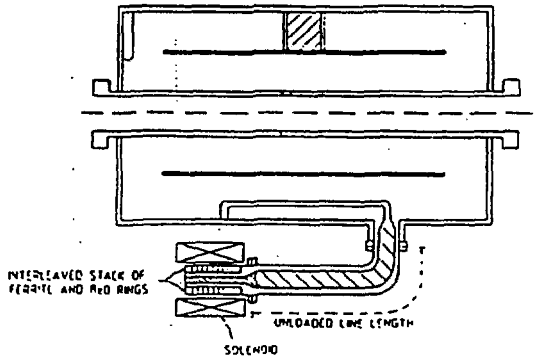
We can write for matched transfer of the bunches from buckets at the same rf frequency in both machines

$$V_H = \frac{R_H}{R_p}\frac{\eta_H}{\eta_p} V_p$$

where H and p refer to the separate rings. Now the factor $\eta = (1/\gamma_{tr}^2) - (1/\gamma^2)$ at 40 GeV is positive in both machines as this is above the transition energy in each one (since $\gamma_{tr} = 6.265$ in PETRA and the proton injection is at 7.5 GeV transition is not crossed in either machine). However as shown in Table 5 there is a large difference between them and this results in $V_H = 0.084\ V_p$ so that at 200 kV in PETRA one needs only 16.8 kV in HERA to match the phase space trajectories in both machines.

Now the second function of the 52 MHz system is to compress the bunches so that they will fit into the high frequency rf buckets. Since the bunch length for fixed bunch longitudinal phase space area is proportional to $V^{1/4}$ this process requires much less voltage in the HERA ring. The peak voltage will be raised to 310 kV giving a bunch width reduction of greater than 50%. During this process it will be necessary to insure that the induced voltage at 208 MHz is minimized so that each of the 210 bunches is captured in only one of the high frequency buckets.

The 52 MHz rf systems are being developed at the Chalk River Laboratory in Canada.[11,12] A sketch of the PETRA II cavity is shown in Figure 14. It is based on the FNAL design described in Figure 1(a). Here the intermediate cylinder is supported by a single post at the center and the cavity is in air with a ceramic seal at the gap. The power amplifier is coupled to the cavity as shown in Figure 1(b) and higher order modes are damped with a system described in reference (12). In Figure 14 we have shown only the external resonant tuning cavity. This is a $\lambda/2$ resonator which uses the coupling loop as part of the half wavelength line. It is loaded with perpendicular biased microwave ferrite at one end.[11] At high bias current the resonant frequency is far above that of the main cavity and there is little interaction between



Schematic layout of the PETRA II 50 MHz cavity with the loop coupled, external perpendicular biased ferrite loaded frequency tuner.

Fig. 14. Proposed PETRA II cavity

them. At low bias current the external resonant frequency is lowered which then also lowers the accelerating mode frequency. A tuning range of 500 kc is required and by using the perpendicular biased ferrite it is possible to obtain this with a single tuner and in a more efficient manner than in the original FNAL tuning system (400 kc tuning range).

The 52 MHz HERA cavities will be of a similar design but the entire cavity will be evacuated. There will be no ceramic seals and no tuning loop. The intermediate cylinder will again be supported on a post. Since a tuning range of at least 25 kc will be needed to compensate for beam loading some form of electrical tuning is necessary. Higher mode dampers will also be required. Because the peak voltage per gap will be about 160 kV the rf power required is about three times greater than for the PETRA cavities.

CERN PS e^+e^- ACCELERATION SYSTEM

As mentioned earlier the CERN SPS will accelerate e^+ and e^- beams for injection into LEP. However prior to this, these beams will also be accelerated in the Proton Synchrotron. The rf system will be required to accelerate these particles from 600 MeV to 3.5 GeV. Two high Q resonators operating at 114.511 MHz with a gap voltage of 500 kV have been constructed and tested.[13] Figure 15 shows the cavities and auxiliary equipment while the system parameters are listed in Table 6. They are driven by power amplifiers rated at 50 kW cw and 200 kW pulsed, through 40 m of coaxial cable.

Slow tuning is accomplished with the piston tuner. Fast tuning which is required to position the bunches prior to extraction is accomplished with two coaxial lines partially loaded with perpendicularly biased microwave ferrite and loop coupled to the cavity Figure 16(a). The rf power loss in each tuner is below 1 kW at 500 kV gap voltage which is estimated to be 1/10 the loss of ordinary ferrite with parallel bias. Four higher order mode dampers (O in Figure 15) are employed to suppress resonances above the accelerating frequency. This triaxial structure is shown in Figure 16(b). The 50Ω load is coupled to the resonator through a notch filter tuned to 114 MHz, that consists of the

Table 6. CERN PS e^+e^- Acceleration System Parameters	
Injection Energy	600 MeV
Final Energy	3.5 GeV
rf frequency (h = 240)	114.511 MHz
Peak rf voltage	1 MV
Q_ℓ	56,000
R_s/Q_ℓ	180 Ω
Cavity excitation power	12.5 kW
Tuning range (slow)	260 kc
Tuning range (fast)	20 kc

outermost enclosure and the outer conductor of the coaxial line that connects the loop to the load. In Figure 17(a) is shown the resulting parasitic mode attenuation.

It was not possible to reduce the very high shunt impedance of these cavities at 114 MHz to the few kΩ required for proton acceleration, using coupling loops and external loads as was done with the 100 MHz and 200 MHz cavities installed on the CERN SPS. Thus two shorting bars that can be inserted across the gap were designed and installed (S in Figure 14). This moves the lowest resonant mode to 180 MHz where the mode dampers produce additional attenuation [Figure 17(b)]. Under normal operation the shorting arms absorb 3% of the total cavity dissipation. At full cw power it will be necessary to provide water cooling for the shorting bars.

CERN EPA MONOCHROMATIC CAVITY

Another link in the series of injectors for the CERN LEP project is the Electron Positron Accumulator ring. It takes particles from a fast cycling (100 Hz) linac at 600 MeV and accumulates them for injection into the PS. The rf system[14] operates at 19.08 MHz (h = 8) and must provide a peak voltage of 50 kV. A sketch of the model cavity used to test novel methods of damping higher order modes is shown in Figure 18. The cavity is a single capacity loaded λ/4 coaxial resonator. The outer cylinder is 2 m long by 1 m in diameter. A ceramic gap bridges the vacuum chamber which passes through the stem of the resonator.

In order to damp higher order modes provision is made to place ferrite rings at either end of the gap; to place ferrite in "disc" at the end of the stem and also inside the stem; and to put water in a box located at the far end of the cavity. Radial slits in the "disc" and longitudinal slits in the stem expose the ferrite to higher order "dipole" modes. Tests showed that with just one ring near the gap plus the stem and disc ferrite reduced the Q value of the measured modes by 10-80%. The final cavity incorporated two ferrite rings and the water box which together produced further attenuation and essentially eliminated some of the modes completely. It was decided to use tap water rather than demineralized water since the former resulted in greater damping. The additional 3 kW loss was easily made up by the 50 kW power amplifier.

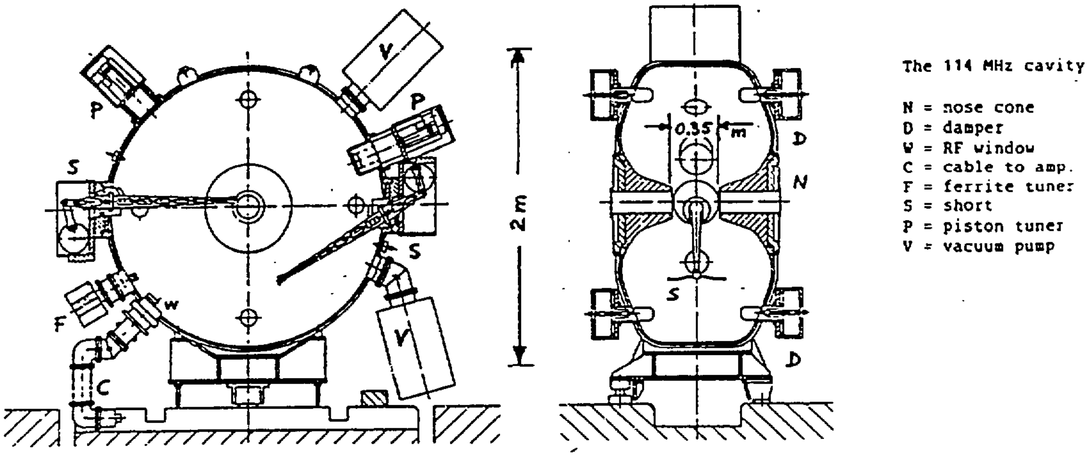
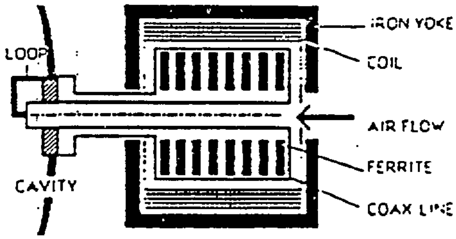
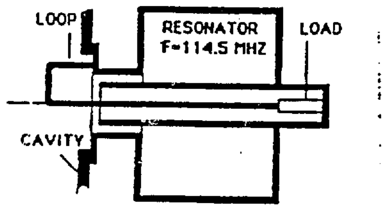


Fig. 15. CERN e^+e^- cavity for PS accelerator



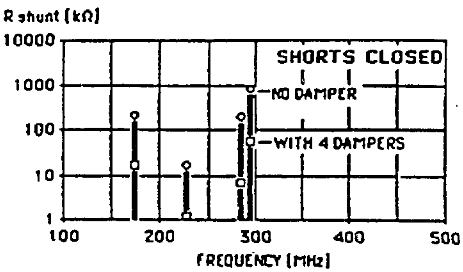
The ferrite tuner

Fig. 16(a). 114 MHz cavity fast tuner.



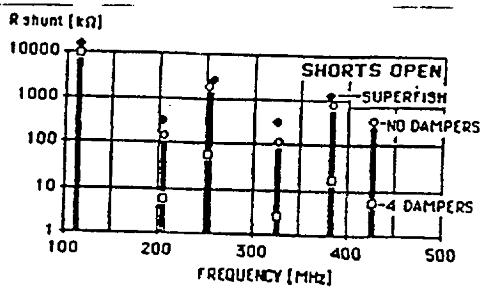
The higher mode damper

Fig. 16(b). 114 MHz cavity mode damper.



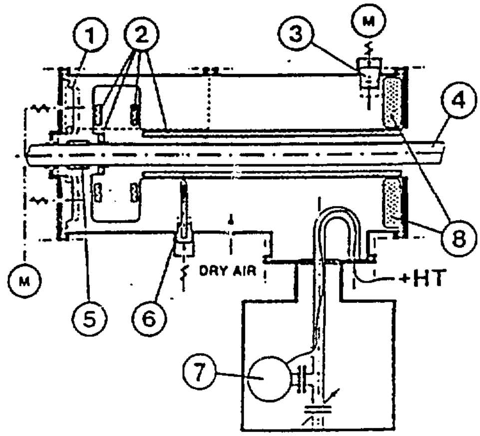
R shunt with and without damper (for protons)

Fig. 17(a). Parasitic mode attenuation without gap shorts.



R shunt with and without damper (for electrons and positrons)

Fig. 17(b) Parasitic mode attentuation with gap shorts



Cavity Layout; (1) Coarse tuner
(2) Ferrite absorbers (3) Fine tuner
(4) Vacuum chamber (5) Ceramic cylinder
(6) Ceramic Support (7) Power Tube (8) Water Box

Fig. 18. CERN Monochromatic test cavity.

Mechanical tuning is employed and no provision is made for beam loading compensation. The fully loaded Q is ≈ 3400 and the R_s/Q is 35–40Ω. Operation at the design intensity of 2.2×10^{10} particles/bunch and 500 MeV has already been achieved.

LOW IMPEDANCE RF SYSTEMS

Very low impedance rf systems are required in machines where one has both dc beams and bunched beams. This was the case in the CERN Intersecting Storage Rings, and would have been the case in the Brookhaven CBA had it been completed. It is also the situation in the CERN Antiproton Accumulator ring. The impedance requirements depend upon the intensity and the square of the momentum spread in the dc beams. If this limit is exceeded then the beam would tend to self-bunch at some harmonic of the revolution frequency in an uncontrolled manner.

CERN ISR System

In the CERN ISR low impedance (< 50Ω at ≈ 10 MHz) per cavity (six cavities) was achieved by a feedback loop between the cavity and the power amplifier including the driver.[15] The resonant impedance of each cavity was 3 kΩ, so an overall reduction of greater than 60 was obtained with the feedback. Higher order modes were damped with ferrite rings that were an integral part of the distributed 100 pF fixed tuning capacitor placed across the accelerating gap.[15]

Operationally twenty bunches from the PS were injected into the ISR which was 3/2 larger so that at h = 30 it had the same rf frequency as the PS. The bunches were accelerated slowly and deposited into a stack of dc beam. During this process the voltage per cavity could vary from 3 kV to less than 15 volts. Hence a low impedance presented to the beam was also necessary to reduce the signal induced at the rf frequency and

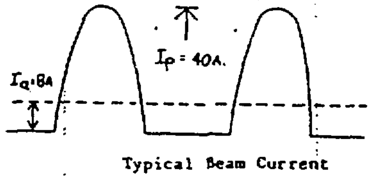


Fig. 19. Beam current pulses in proposed CBA.

its harmonics. In addition a complementary or feed forward compensation system was employed to further reduce the beam voltage appearing at the gap. A beam derived signal from a wideband pick-up electrode was fed into the driver stage with the correct phase (or time delay) and amplitude to produce an output current in opposition to the bunch beam current appearing at the gap. This open loop correction further reduced the dynamic impedance at f_{rf} to < 5Ω/gap.

It should be noted however that the feedback loop and/or a wideband feed forward system can put severe peak current limitations on the power tube driving the cavity. A tightly bunched beam can have peak currents of several amperes and this must be supplied by the tube if the overall system is to function in a linear manner. In the case of the ISR the original system had to be augmented with a separate power amplifier per cavity as the injected currents from the PS were increased.[16]

Proposed CBA System

For the Brookhaven Colliding Beam Accelerator it was proposed to inject bunched beams and stack them as was done in the CERN ISR. However after accumulating up to 8 amperes this beam was to be rebunched and accelerated from 30 GeV to 200 GeV. Thus in addition to a stacking rf system that would have been similar to the ISR, an acceleration system operating at h = 3 (≈ 240 kc) and capable of providing 36 kV (12 kV/gap) was required. In addition the impedance per gap had to be 15Ω or less so that in the presence of the 8 A beam the beam would not rebunch of its own accord.

A solution to the design problem was obtained by developing a cathode follower power amplifier.[17,18] The inherent feedback present in this configuration guarantees a low output impedance if stable operation of a large high power tube can be achieved. In addition the peak current requirement mentioned above is easily satisfied if the tube is large enough. This can be understood by referring to Figure 19 which is a typical plot of beam current pulses. Once the beam is bunched the tube quiescent current must always be greater than the average or dc component of the circulating current in order to avoid cutoff (i.e. for any very low impedance system the power tube must always operate class A). With the cathode connected to an accelerating gap which is upstream of the ground plane, the peak beam image current will always tend to increase the tube current and hence preserve class A operation. If one attempted to excite the cavity in push pull then one tube at least (whether cathode follower or plate coupled) would always have to operate with a quiescent current $\left(I_{peak} - I_{average}\right)$.[18]

SSC RF SYSTEM

The Superconducting Super Collider is a two ring proton-proton accelerator, colliding beam machine that has been proposed for

Table 7. SSC rf System	
Injection	1 TeV
Final energy	20 TeV
f_∞	3.614 kc
rf frequency	374.74 MHz
h	103,680
Bunch frequency	62.4 MHz
Acceleration rate	5.26 MV/turn
Peak rf voltage	20 MV
Acceleration time	≈1000 sec
Beam current	73 mA
Peak beam current	2 A
Maximum power to beam	384 kW
Cavity Excitation power (total)	1 MV

construction in the United States in the early 1990's. In Table 7 we list the rf system parameters for the present design.[19] The choice of frequency was primarily determined by the well developed technology for efficiently producing large power and obtaining high gap voltages around 350 MHz. Examples being the PEP electron storage ring at SLAC[20] and the CERN LEP project mentioned above. The peak voltage requirement (20 MV) was based on the need to provide bunches with sufficient momentum spread in the storage or colliding mode to ensure a minimum growth rate due to intra-beam scattering. Again the acceleration time is long as in the Tevatron or the HERA proton ring but the energy gain per turn is necessarily larger because of the machine size and required energy increase.

It is assumed that eight full cell π mode cavities similar to the PEP cavities (and to the LEP accelerating cavity shown in Figure 12) but made from copper will be employed. The unloaded Q will be ≈40,000 with an R_s = 5 MΩ/cell and 40 cells at 500 kV/gap will provide the necessary voltage. At present it is proposed not to detune the cavities to compensate for beam loading. This is because the maximum detuning which would be $\Delta f \cong 6.8$ kc (occurring during storage) or almost twice the rotation frequency of 3.614 kc could result in the cavities driving coupled bunch instabilities.[19]

Since the cavities will be resonant with the drive frequency there will always be reflected power whether one is accelerating or storing the beam. The coupling coefficient β, which is defined as the ratio of the power radiated out of the coupling loop to the power dissipated in the cavity walls if excited by the beam, can be chosen to minimize the reflected power using the following expression.[21]

$$P_i = \frac{{V_c}^2}{8\beta R_s}\left[\left\{(\beta+1) + \frac{I_b R_s}{V_c}\sin\Phi_s\right\}^2 + \left\{\frac{I_b R_s \cos\Phi_s}{V_c} + \tan\psi\right\}^2\right]$$

Now $\tan\psi = (\beta+1)\tan\Theta$ where Θ is the detuning angle of the cavity given by

$$\tan\Theta = \frac{-I_b R_s}{(\beta+1)}\cos\Phi_s$$

I_b is the rf component of the beam current and Φ_s the stable phase angle. Here we have assumed that $\Phi_b = \Phi_s$ where Φ_b is the phase of the rf component beam current relative to the rf frequency (this is true if the bunch is short compared to the rf wavelength). Thus for the SSC one assumes $\Theta = 0$ and taking $\Phi_s = 164.75$ the minimum value for β is found to be 1.92. The required incident power P_i would be 1. 65 MW for the eight cavities. If the coupling is increased to $\beta = 3$ then the required power is 1.79 MV during acceleration and 1.51 MW during storage while the impedance seen by the beam at f_{rf} is reduced to 5 MΩ ÷ (β+1) or 1.25 MΩ/gap.[19]

Since it takes only 1 MW to excite the cavities there is considerable reflected power (≈250 kW/klystron) which must be absorbed before reaching the klystrons. Now transient beam loading is present due to a 2.7 μsec gap required in the chain of bunches for extraction (as well as during injection when only fractions of a turn are stacked sequentially). In order to compensate for this it is necessary to feed the cavities in such a manner that precludes the power distribution system originally proposed for SSC.[19] Thus in order to absorb the reflected power circulators similar to those employed at LEP will be required at every cavity.[22]

REFERENCES

1. J.E. Griffin, Q.A. Kerns, NAL main-ring cavity test results, IEEE Trans. Nucl. Sci. NS-18, No. 3, 241-243 (1971).
2. R.F. Stiening, J.E. Griffen, Longitudinal instabilities in the Fermilab 400 GeV main accelerator, IEEE Trans. Nucl. Sci. NS-22, No. 3, 1859-1861 (1975).
3. Q. Kerns, M. May, H.W. Miller, J. Reid, F. Turkot, R. Webber, D. Wildman, Energy saver prototype accelerating resonator, IEEE Trans. Nucl. Sci. NS-28, No. 3, 2782-2784 (1981).
4. Q. Kerns, C. Kerns, H. Miller, S. Tawzer, J. Reid, R. Webber, D. Wildman, IEEE Trans. Nucl. Sci. NS-32, No. 5, 2809-2811 (1985).
5. G. Dome, The SPS acceleration system, Proc. 1976 Proton Linac Conf. Chalk River, Canada, 138-147 (1976).
6. D. Boussard, G. Dome, T.P.R. Linnecar, Acceleration in the CERN SPS. Present status and future developments, IEEE Trans. Nucl. Sci. NS-26, No. 3, 3231-3233 (1979).
7. P.E. Faugeras, H. Beger, J.P. Kindermann, V. Rodel, G. Rogner, A. Warman, The new rf system for lepton acceleration in the CERN SPS, Proc. 1987 IEEE Particle Accel. Conf. Vol. 3, 1719-1721 (1988).
8. H. Frischolz, Generation and distribution of radio-frequency power in LEP, IEEE Trans. Nucl. Sci. NS-32, No. 5, 2791-2793 (1985).
9. P. Brown, H. Frischholz, G. Geschonke, H. Henke, I. Wilson, Development and first results with a storage resonator, IEEE Trans. Nucl. Sci. NS-28, No. 3, 2707-2710 (1981).
10. B.H. Wiik, Progress with HERA, IEEE Trans. Nucl. Sci. NS-32, No. 5, 1587-1591 (1985).
11. R.M. Hutcheon, A perpendicular-biased ferrite tuner for the 52 MHz PETRA II cavities, Proc. 1987 IEEE Particle Accel. Conf. Vol. 3, 1543-1545 (1988).
12. R.M. Hutcheon, J C. Brown, R.J. Burton, R.A. Vokec, A simple higher order mode damping system for the PETRA II cavities, Proc. 1987 IEEE Particle Accel. Conf. Vol. 3, 1546-1548 (1988).
13. B.J. Evans, R. Garoby, R. Hohbach, G. Nassibian, P. Marchand, S. Talas, The 1 MV 114 MHz electron accelerating system for the CERN PS, Proc. 1987 IEEE Particle Accel. Conf. Vol. 3, 1901-1903 (1988).

14. S. Bartalucci, M. Bell, F. Caspers, K. Hubner, P. Marchand, A. Susini, R. Power, A monochromatic rf cavity, Proc. 1987 IEEE Particle Accel. Conf. Vol. 3, 1791-1793 (1988).
15. F.A. Ferger, W. Schnell, The high power part of the rf system for the CERN ISR, CERN-ISR-RF/70-34 (1970).
16. H. Frischholz, W. Schnell, Compensation of beam loading in the ISR rf cavities, IEEE Trans. Nucl. Sci. NS-24, No. 3, 1683-1685 (1977).
17 T.W. Hardek, W.E. Chyna, Common-anode amplifier development, IEEE Trans. Nucl. Sci. NS-26, No. 3, 3959-3961 (1979).
18. S. Giordano, M. Puglisi, A cathode follower power amplifier, IEEE Trans. Nucl. Sci. NS-30, 3408-3410 (1983).
19. SSC Central Design Group. Conceptual design of the SSC, SSC-SR-2020, (March 1986).
20. M. Allen, I. Korvonen, J.L. Pellegrin, P.B. Wilson, rf system for the PEP storage ring, IEEE Trans. Nucl. Sci. NS-24, No. 3, 1780-1782 (1977).
21. P.B. Wilson, High energy electron linacs, AIP Conf. Proc. No. 87, Physics of high energy particle accelerators, 474 (1982).
22. E. Raka, Transient beam loading and rf power distribution in the SSC, Proc. 1986 Summer Study on the Physics of the SSC, 542-544 (1987).