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Design of the RF Cavity and Power Amplifier for the Fermilab Antiproton Source

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Summary

In the Fermilab program for production of an intense antiproton beam,[1] trains of 82 short antiproton bunches (1 nsec) separated by 18.8 nsec are produced with a large momentum spread about a mean energy of 8.9 GeV. The bunch trains are delivered to a Debuncher ring where a 3% momentum bite is reduced to about 0.2% by exchanging momentum spread for time spread.[2] This exchange is a two step process involving synchrotron rotation of the bunches in mismatched buckets followed by adiabatic debunching. During the bunch rotation the rf system is required to provide a stable rf voltage of 5 MV at 53.1035 MHz for 60 μsec, or about 35 turns. Then the voltage must be lowered to 98 kV within about 56 μsec to match the rotated distribution. The voltage is then reduced to 5 kV in about 12 msec for final adiabatic debunching of the antiprotons. The process is repeated at a 2 second repetition rate.

The rf voltage is to be generated by eight rf cavities in a long straight section. Each cavity, when excited with 112 KW of rf power, will generate a peak voltage of 625 kV. Each cavity is excited by a self contained power amplifier mounted directly on top of the cavity to minimize rf interference with nearby high sensitivity stochastic cooling systems. The cavity, 90.9 cm dia. and 182.6 cm long, is made of aluminum and completely evacuated. The rf power is fed into the cavity through ceramic vacuum feedthrus through a top plate. Details of the cavity and amplifier design as well as prototype cavity measurement are presented.

Cavity Design

The criteria for cavity design are moderate excitation power, Q consistent with rapid de-excitation, freedom from harmonic or spurious resonances, physical length, vacuum integrity and structural simplicity. Because of the very low duty factor the average power will be quite low, nevertheless the relatively large voltages could require very large peak power unless the cavity Q is maintained at a reasonable level. A very high Q, on the other hand, would make it difficult to drive the cavity to low voltage quickly, as is required. A cylindrical quarter-wavelength structure would be excessively long and it would pose a threat of badly located harmonic resonances.

The structure selected as best meeting the criteria was a folded re-entrant coaxial resonator with an intermediate cylinder and centrally located accelerating gap, Figure 1. Detailed dimensions and internal fields were developed using the computer program SUPERFISH. A SUPERFISH field plot (representing E field scaled by radius) in a one-quarter sector of the structure at the fundamental frequency is shown in Figure 2. The maximum surface electric field gradient is 6.84 MV/m at a total gap voltage of 650 kV. This field appears on the accelerating gap corona roll.

*Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

The rf voltage waveform required for bunch rotation and debunching is sinusoidal with minimum harmonic content. Since the cavity excitation current will have appreciable odd harmonic content it is important that the cavity is free of resonances near integral harmonics of the fundamental frequency f_0. SUPERFISH was used to locate and evaluate the Q of as many higher order resonances as possible. The results of this search are shown in Table I. The resonance closest to an integral harmonic is the seventh harmonic, which differs fromfrom $7f_0$ by 1.84 MHz. The Q of that resonance is 33500 giving it a linewidth of 11 kHz so it is adequately displaced from $7f_0$. Field plots of the resonance contain information which indicate the optimum adjustment of cavity geometry for moving the offending resonance if that is deemed necessary.

PRE-PROTOTYPE CAVITY			SUPERFISH CALC.		
Harmonic	Measured Resonance MHz	Δ nf_0-f MHz	Δ MHz	Resonaut Freq. MHz	Calculated Q
f_0	52.960			53.0521	12500
3	117.324	41.56	40.93	118.228	15800
5	218.950	-45.85	46.53	218.729	26000
7	372.000	- 1.28	- 2.08	373.442	33500
9	516.460	-39.82	-38.5	515.967	36100
11	558.205	24.36	23.58	559.991	35500
13			13.38	676.289	42400

Table I. Pre-prototype cavity harmonic resonances compared with those calculated by SUPERFISH.

The cavity is a welded aluminum structure with sufficient outer shell thickness (1.3 cm) to provide mechanical rigidity and stability when exacuated. The entire volume of the cavity is to be evacuated to 10^{-9} Torr. RF power is delivered to a coupling loop through ceramic vacuum seals mounted on a flat plate at the top of the cavity. DC anode power is delivered to the two push-pull tubes by applying it to the center of the coupling loop through an additional ceramic feed-through. The amplifier bed-plate, containing the vacuum seals and the coupling loop, is welded as a unit to a rectangular opening in the top of the cavity. The plate is designed so that it can be removed and replaced in case of failure by grinding off the original welds and rewelding. The intermediate cylinder is held in place by a welded support at the bottom. In normal operation no rf current should pass through this support between the cavity outer shell and the intermediate cylinder.

Initial cavity tuning is done by adjusting the accelerating gap spacing before welding the central beam tubes in place. In operation the cavity will be fine-tuned by electrically varying the temperature of the inner conductor. Water cooling is provided on the end plates to keep the remainder of the cavity at constant temperature.

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The design Q of the cavity is 12500 and the total gap shunt impedance is 1.89 MΩ. The total stored energy at 650 kV is 2.6 J and the cavity requires 112 kW to develop the design gap voltage.

Beam Loading

Each bunch train entering the system will contain 2×10^7 antiprotons corresponding to an rf current of about 3.4 μA. In addition, the beam will contain a flux of π^-, K^-, and μ^- mesons and electrons, all generated at the target. The total charge in elements of the spurious beams which are accepted by the ring will be between 10 and 100 times the total antiproton charge, so an initial beam loading current as large as 3×10^{-4} A may be present. All of the spurious particles will be lost either by synchrotron radiation (electrons) or decay (mesons) within tens of microseconds, a time short with respect to the cavity time constant (√ 76 μsec) so anamalous gap voltage developed by bunched charge current in the cavity shunt impedance is expected to be negligible.

Amplifier Deisgn

Figure 3 is a tenative circuit diagram for the final rf power amplifier. The amplifier is a push-pull grounded grid, cathode driven system using 3CX10000U7 triodes operating class B. The cathode driven configuration minimizes or eliminates neutralization and, because of its intrinsic low input impedance, makes possible the band-broadening required for tube-driven cavity de-excitation.

The selected tubes, operating with very short pulses (100 μsec) and low duty factor (2 sec rep. rate) are capable of delivering more than 60 kW each when operated at 8 kV anode voltage and 30 amp peak current. Each cathode must be driven with 3200 W at 380 peak rf volts.

The voltage step-up ratio from a single tube anode to the half gap voltage is 1:43, so the 0.95 MΩ half-gap shunt impedance is transformed to a real load resistnace of 511 Ohms per tube at resonance. The cavity drive loop has a leakage inductive reactance near the operating frequency of j 20 Ohms, small with respect to the tube output capactive reactance (at resonance) of -j 132 Ohms so the lowest resonance of the drive loop system is well above the operating frequency. The plate resistance of each tube is nominally 1 kΩ, sufficiently larger than the driving point impedance so that the tubes operate nearly like current sources.

Cavity De-Excitation

Following the initial quarter-turn of synchrotron bunch rotation the total rf voltge must be reduced from 5 MV to 98 kV in 56 μsec., a time short compared to the natural cavity decay time. Six of the eight cavities will be reduced to zero voltage and turned off during this period with the remaining two providing the subsequent voltage reduction. This will be done by quickly reversing the phase of the drive signal at the cathode of each tube while maintaining the drive amplitude constant. In this condition the tubes are being driven to conduction when the anode voltage is at its maximum point, 15.5 kV. The peak current available in this condition is very large since the tubes are triodes with oxide cathodes. As the cavity rf voltage decreases the tube current also decreases, so the de-excitation process has to be analyzed in several steps. The inital peak current will be about 80 A. which will generate a fundamental Fourier current of 34 A. Translated to the half-gap shunt impedance this is 0.79 A which would create a half-gap voltage of 750 kV, or 2.3 times the initial voltage if left on for many cavity time constants.

The cavity voltage is the sum of the naturally decaying voltage and the opposite phase voltage build up to the reversed excitation. Normalized to unity, this is

$$v(t) = e^{-\alpha t} - 2.3\,(1-e^{-\alpha t}).$$

where $\alpha = 1.32 \times 10^4\ \mathrm{sec}^{-1}$, the cavity decay constant.

If the counter-excitation remains constant the above expression reaches zero in 27 μsec. so with decreasing counter-excitation the cavity voltage can be driven to a low value, or zero, as required, within the required time.

Prototype Cavity

A pre-prototype cavity has been built to verify the location of calculated higher order resonances, to check for spurious resonances, and to obtain design data for the coupling loop. The outer tank is aluminum and the inner structures are copper cylinders of appropriate dimensions. A half-coupling loop linking the area indicated by SUPERFISH field calculations was inserted with one end grounded. Impedance measurements were made on the loop using a network analyzer. Table I shows the results of these measurements together with the calculated results. The calculated result also includes the calculated Q for each resonance. The rf joints of the pre-prototype cavity are not sufficiently good so that Q measurements are meaningful, although they are quite reasonable. The resonance locations, however, are well matched to the calculated frequencies. The location of the $7f_o$ resonance will be observed carefully under various tuning conditions, and if necessary it will be moved slightly by appropriate geometry changes.

References

1. J. Peoples, The Fermilab Antiproton Source, Paper 131, this conference.
2. J. Griffin, et al, Time and Momentum Exchange for Production and Collection of Intense Antiproton Beams at Fermilab, Paper S-21, this conference.

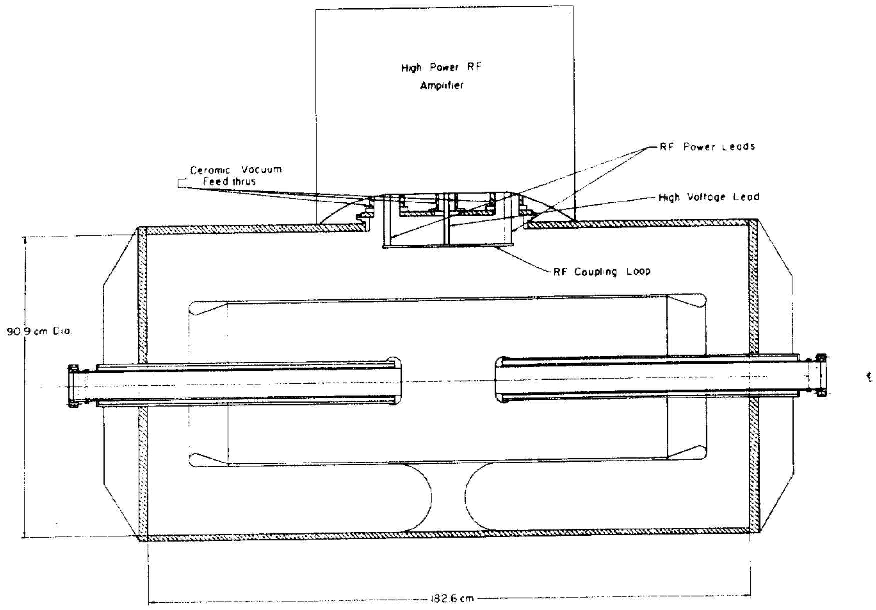

Figure 1. Debuncher Ring RF Cavity. 650 kV at 53.1035 MHz.

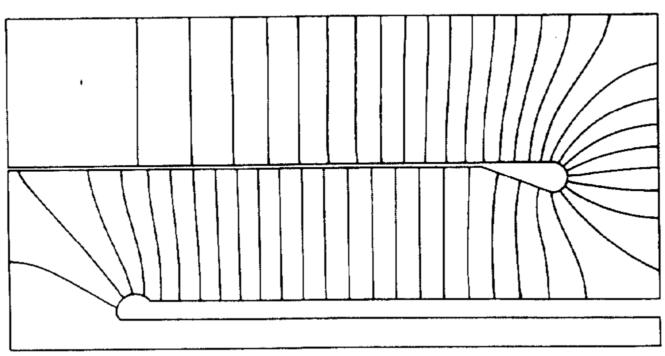

Figure 2. SUPERFISH field plot for one-quarter sector of the Debuncher rf cavity. The maximum electric field intensity occurs near the top of the beam-gap corona roll.

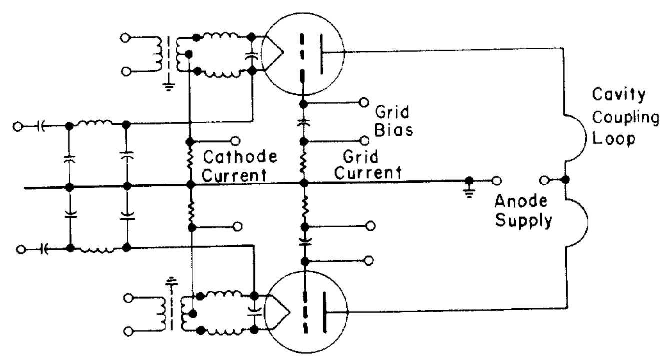

Figure 3. Circuit diagram of the cathode-driven push-pull final rf amplifier.