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FABRICATION AND OPERATION OF THE 4 MV 53 MHZ RF SYSTEM FOR THE FERMILAB ANTIPROTON SOURCE DEBUNCHER RING

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Summary

Design of a 53 MHz 4 MV short duty cycle rf system for bunch rotation in the Fermilab antiproton source has been described previously.[1,2] Fabrication and installation of the system has been completed. The rf cavities in the system are comletely evacuated welded aluminum structures, each capable of generating 700 kV with a very low duty factor. This report will describe fabrication procedures, multipactor inhibiting techniques, and initial operating experience with the system. Of particular interest is the capability for reduction of the rf voltage to a very small value witin 40 microseconds (25 turns) at the end of the momentum reduction, thus inhibiting further bunch rotation.

Introduction

The rf cavities are substantially like that shown in Fig. 1 of ref 1. A slight, though significant, modification is that the intermediate cylinder is supported within the outer cylinder by a welded circular cylindrical post 14 cm O.D. This creates an easy access port to the intermediate cylinder for cooling water (if required) and it also provides close access to the high gradient accelerating gap region for gap voltage sensors or possibly spurious mode damping pick-ups. In Fig. 1 the internal structure of a cavity is shown with one endplate and beam pipe removed. The intermediate cylinder with its support post are visible as is the beam tube and corona roll extending from the far end. The input power coupling loop (not shown) is suspended by ceramic feed-through seals to a rectangular plate which is to be welded to the matching opening visible at the top of the structure.

Two small holes slightly above the median plane close to the near end of the outer cylinder are visible. During assembly these holes and their counterparts at the opposite end are used as access ports through which titanium flashing equipment (Varian Corp. "Ti-ball" sublimation pump elements) are inserted. During normal operation these holes contain vacuum feed-through rf pick-ups for cavity monitoring. The cavity body has no vacuum pumping port other than the beam pipes, although the intermediate cylinder support post could be adapted to this purpose if necessary.

The cavity is supported on large rollers which are used to rotate the entire cavity body during end-plate welding. Frequency measurement equipment required to monitor the cavity frequency during assembly can be seen in the background.

Fabrication and Assembly

All cavity components were manufactured from 6061-T6 almuninum by a commercial shop. Completed vacuum tested sub-assemblies consisting of end plates with carefully fitted but not welded beam tubes and the central cavity body were delivered to the laboratory. The central cavity body assembly

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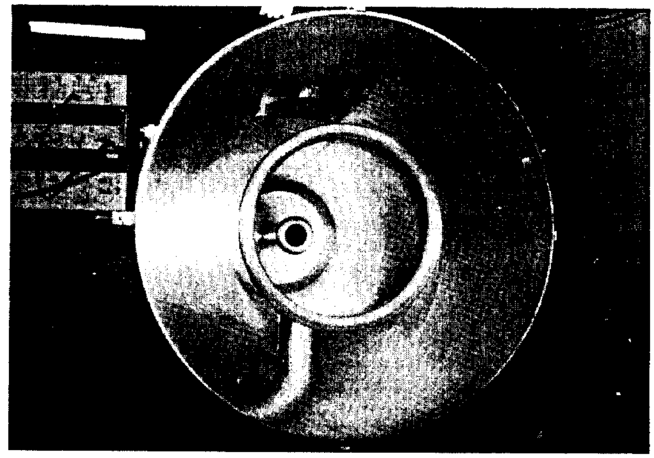

Figure 1. End view of cavity with near endplate and beam pipe removed.

consisted of the outer cylinder with rectangular coupling loop opening and intermediate cylinder with its support. All aluminum surfaces were chemically cleaned before delivery and protected during shipping and handling by thin polyethelyne sheet. After arrival in the laboratory all surfaces were again chemically cleaned in preparation for final assembly. Cleaning consisted of Oakite No. 202 steam cleaning followed by treatment with Easy Etch,[3] distilled water rinse, and final drying with methyl alcohol blown with dry nitrogen.

After cleaning, the cavities are mounted in a welding jig which holds the endplates in correct position against the cavity body while the beam pipes are centered on a mandrel. After centering, the mandrel is removed and the beam pipes adjusted longitudinally so that the accelerating gap is centered. With a standard input coupling loop clamped in place the cavity frequency is adjusted to a value 30 kHz below the final target value of 53.145 MHz by adjusting the beam pipe gap spacing. With the beam pipe clamped in position one endplate is removed and an internal weld is made between the beam pipe and the endplate. This weld must be done in a way which does not change significantly the alignment of the beam pipe with respect to the endplate. The weld is dressed and vacuum checked externally before the endplate is again clamped to the cavity. With the alignment mandrel in place the endplate is reclamped to the cavity. After removing the mandrel the frequency is again measured. The weld will typically pull the beam pipe into the endplate such that the frequency is raised by 15 kHz. The endplate is then welded to the cavity body by rotating the cavity body in place. This is a fillet weld delivered to a vee groove established by a slight taper at the end of the cavity body. It is not, however, a full penetration weld. The intention is to allow a small region of the cavity body to bear directly on the end wall so that no appreciable frequency or alignment change results from this weld.

At this time any unexpected frequency change resulting from the first endplate weld can be compensated for by adjustment of the remaining beam tube position. After a vacuum check of the completed end, the process is repeated on the other end. The final frequency will be the result of another 15 kHz increase upon welding the second beam pipe in place.

Finally a preassembled coupling loop is fitted to the cavity. After the step-up ratio and assembled frequency have been checked for correctness the coupling loop plate is welded in place.

All welds are done by dc MIG (metal inert gas) procedure using 4043 aluminum filler wire and helium-argon mixture appropriate to the weld temperature required.

Evacuation of the cavity results in an increase in frequency of 15 kHz, exactly consistent with the change expected from the removal of the air dielectric. The endplates are sufficiently rigid so that the frequency change resulting from cavity distortion due to evacuation is negligible.

The 15 kHz frequency increase upon evacuation is almost exactly compensated for by a decrease in frequency which occurs when the power amplifier tubes are coupled to the input power coupling loop.

Vacuum and Multipactoring

After assembly and vacuum checking each cavity is baked at 150°C for twenty-four hours. Attempts to operate the cavity at high rf gradient after baking resulted in prolonged erratic operation due to multipactoring. Consequently the regions between the end of the intermediate cylinder and the endplate and the accelerating gap area of each cavity were flashed with titanium. Access to the gap area was through the beam pipe and access to the end areas was through monitor ports mentioned above. The end areas were flashed from eight separate Ti-Ball positions working from each side and at each end simultaneously. The gap area was flashed at the same time. Each flashing was applied for three minutes at a pressure of 10^{-5} Torr. Following the titanium evaporation the cavities were back-filled with dry nitrogen. A titanium nitride deposition of about 100 Angstroms is estimated. The procedure has completely eliminated multipactoring during normal cavity operation although if rf power is removed and the voltage allowed to decay naturally a multipactor snap-off is sometimes observed at about the 40 kV level.

During normal operation the cavities are pumped by 400 l. ion pumps connected to the short section of beam pipe joining the cavities. Vacuum pressures of 10^{-8} Torr at the vacuum pump and 10^{-7} Torr in the cavity beam pipe are observed after a few weeks of operation. (Proton beam lifetime of greater than 83 minutes at 8 GeV has recently been observed in the Debuncher Ring.)

Cavity Operational Tuning

The beam tubes of the cavities are double walled with the space between the walls accessible from each end. Eight hundred watt heating buttons are inserted about three quarters of the way into each beam tube so that the beam tubes can be heated on command. The cavities are known to tune 15.75 kHz per mm change in accelerting gap length so a 2.67 mm increase in beam pipe length is required to decrease the cavity operating frequency from 53.145 MHz to 53.103 MHz, the required operating frequency. The beam pipes are each 0.76 m long so a $\Delta\ell/\ell$ of 3.5×10^{-3} is required. This change in length can be accomplished by heating each beam tube 153°C above the body temperture of the cavity. Because of the very low duty cycle of the cavities in normal operation, little or no water cooling is required. However a very small flow of constant temperature water is provided on the body of each cavity to provide a normalizing temperture against which the beam tubes are heated.

The amount of beam tube heating is controlled by delivery of constant amounts of ac power to the heaters for varying lengths of time. The heating cycle is determined by a simple calculation performed in a microprocessor assigned to each cavity. The computation is based upon a phase comparison of the anode voltage phase (or cavity standing wave phase) and the power amplifier cathode drive current phase. The phase difference is measured once during each cavity operation and the result is digitized and held until the next cavity operation. The cavities re required to operate for a burst of about 300 μseconds every 2-3 seconds.

The digital feedback tuning system requires about one hour to come to equilibrium and during normal operation the cavity phsae is held constant with respect to the drive phase to approximately ±1 degree.

Cavity Performance

After assembly and evacuation to 10^{-8} Torr the cavity can be operated at high gradient immediately. The cavities typically generate full voltge as quickly as it is possible to tune the rf source to resonance with no period of conditioning.

The calculated Q of the cavity is 12500 with R/Q 152 ohms. The measured unloaded Q is 11000 implying a total gap shunt impedance of 1.7 M ohm. The cavity is driven by two air cooled 10 kW grounded grid troides each capable of delivery peak power of about 75 kW during the short excitation period, so gap voltages of 750 kV can be developed. Six cavities are installed generating a total ring voltage of 4.5 MV.

The cavity time constant during excitation is about 52 microseconds implying a Q at normal excitation of about 8600. The cavities are gated on about 200 microseconds before the arrival of antiproton bunches and they must remain on for another 65 microseconds (one quarter phase oscillation period).

In Fig. 2a the rf envelope of one cavity is shown. The cavity is gated on for 250 microseconds and allowed to decay naturally. In actual operation the rf voltge must be removed quickly at the end of one-quarter phase oscillation. This is done by reversing the phase of the power amplifier drive and driving the cavity down, essentially absorbing the cavity stored energy in the tube anodes. Triodes are well suited to this purpose because the tube peak current becomes very large when the phase of the excitation is reversed so that the cavity energy can be removed much more quickly than it was originally supplied. This is shown in Fig. 2b where the cavity voltage is driven down at the end of the operation period. The de-excitation time is about 40 microseconds. The total stored energy in the cavity is about 4.5 J. Removal of this energy in 40 microseconds means that each tube must dissipate a peak power of about 60 kW during this period. The tubes are easily able to do this. The average power dissipation is only a few hundred watts.

After the cavity voltge is driven down to a very low value the beam momentum spread can be reduced even further by a period of adiabatic debunching. This requires a ring voltage of a few hundred kV to be established and reduced slowly over a long period. We expect to accomplish this by turning all but two cavities off and reducing the amplitude of the remaining two cavities slowly by both drive reduction and counterphasing. This requires that the excitation phase of the two selected cavities be reestablisned to the correct value at some point during the drive-down period and reduced slowly thereafter. Fig. 2c shows the envelope of a cavity on which this re-reversal of phase and subsequent reduction is being applied. Fig. 2d shows the required voltage contour as specified in the Antiproton Source Design Report.[2] Here the voltge is plotted as a function of number of turns (1.6 microseconds per turn) following the injection of antiprotons.

During the initial phase of commissioning of the Debuncher Ring studies were done using 8 GeV protons of an intensity easily observable on beam pick-ups. By injecting a small burst (say, 10 bunches) of protons which are not matched in phase to the rf buckets the net cavity gradient has been evaluated by direct measurement of the coherent phase oscillation period. This has been done with two cavities operating and it has been verified that each of the cavities produces an accelerating gradient slightly larger than 700 kV.

Acknowledgements

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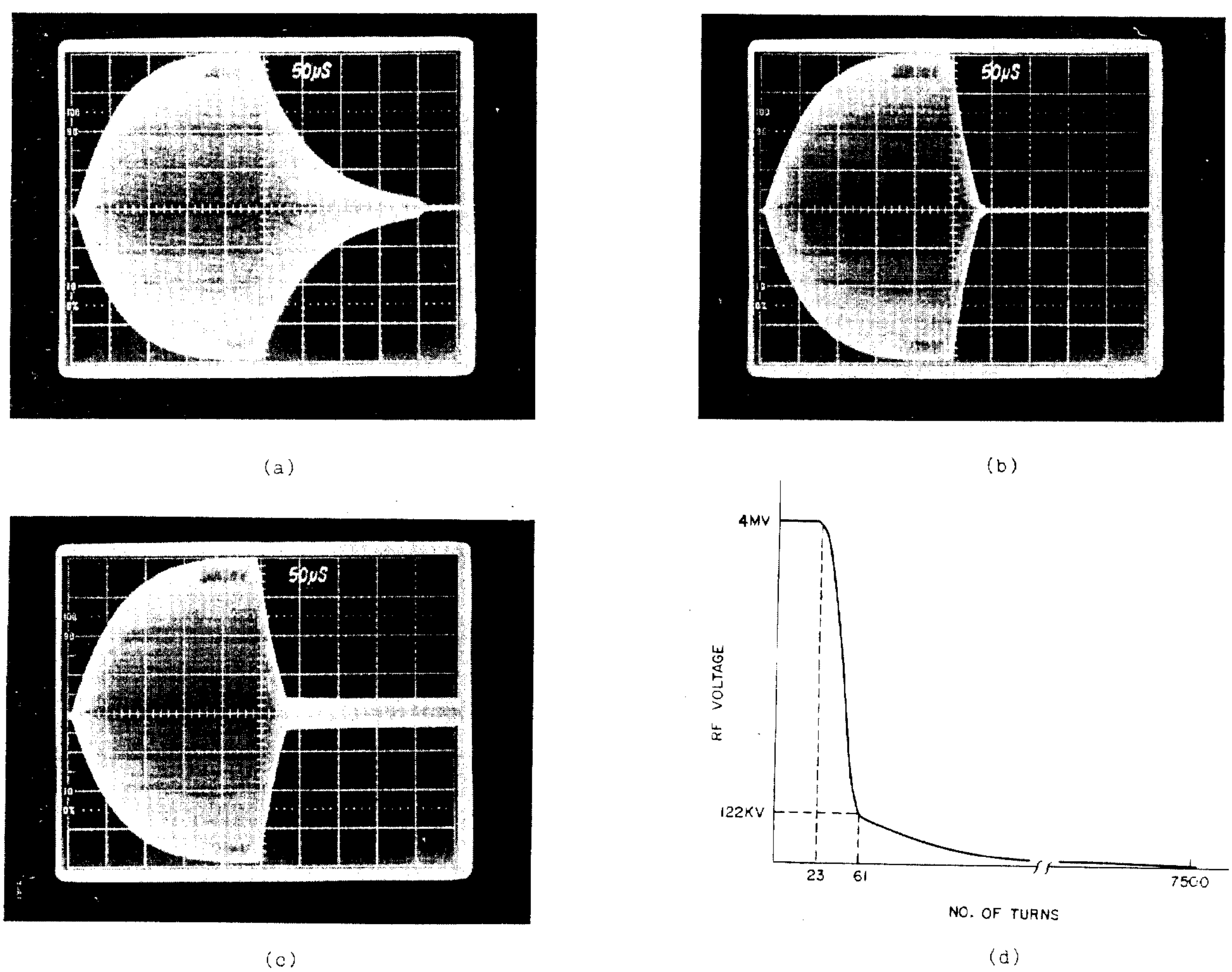

Figure 2. a) Single cavity rf envelope with normal decay.
b) RF envelope with turn-off driven down by drive reversal.
c) RF envelope with re-reversal for adiabatic debunching.
d) Design Report specified rf amplitude per turn following injection.