AN IMPROVED 1.26 MHZ SYSTEM FOR THE FERMILAB ANTIPROTON ACCUMULATOR

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Abstract

A new 1.26 MHz RF system has been installed in the Fermilab Antiproton Accumulator. The high power and wide dynamic range of the system allow it to be used for a variety of beam acceleration and capture tasks. A description of the mechanical, cooling, and electrical considerations for the high power ferrite loaded cavity as well as the design of the low level electronics will be presented. Operational experience including double bunch unstacking performance will be discussed.

Introduction

The Fermilab Antiproton Accumulator has a beam revolution frequency of 628 kHz when operating at 8 GeV[1]. Three RF systems are used for particle injection and extraction. One of these systems , ARF1, operates at the 84th harmonic (53 MHz) and the other two, ARF2 and ARF3, operate at the second harmonic (1.26 MHz). The installation of the E760 medium energy experiment[2] in the accumulator ring required modification of the existing RF systems for deceleration of the beam over a wide range. An improvement of the cavity tuning range and increased voltage capability of the ARF3 1.26 MHz system allows H=2 deceleration of the beam below transition with sufficient bucket area. Table 1 shows the system requirements. A system block diagram is shown in figure 1.

Table 1.
System Requirements

Frequency	1.257 MHz
Deceleration Frequency Range	-2.5%
Harmonic Number	2
Maximum Gap Voltage	4000 Volts (0-P)
Maximum Shunt Impedance	1500 Ohms at H=2

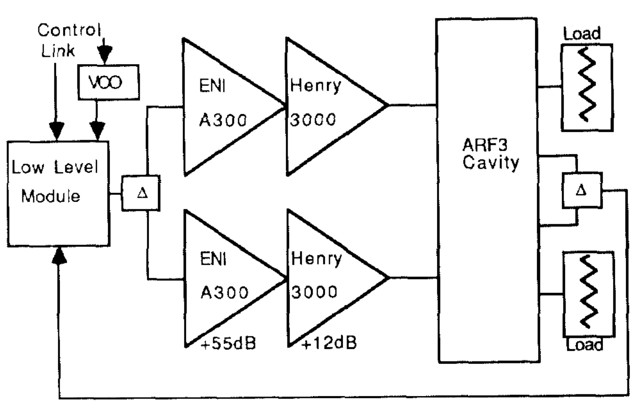

Figure 1.
Block Diagram of ARF3 System

*Operated by the Universities Research Association under contract with the United States Department of Energy.

Mechanical Design

Main Housing

The main housing shown in figure 2 is fabricated from 1.27 cm (1/2") thick aluminum sheet rolled into a closed cylinder 71 cm (28") in diameter and 1.7 m (66") long. It is split lengthwise and flanged to allow access to the two assemblies of 15 ferrites each and the electrical connections. The stand is fabricated from steel channel and I-beams, with screw adjustments in both the x and y planes to allow for alignment of the cavity.

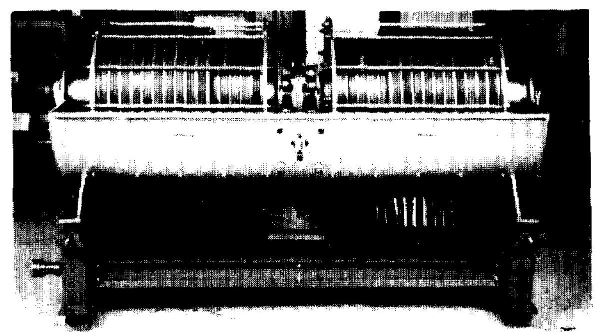

Figure 2. Photograph of cavity before installation. Top cover has been removed showing ferrites. The gap is in the center. Water cooling hoses are seen underneath cavity.

Vacuum Chamber

The vacuum chamber shown in figure 3 is a 10 cm (4") diameter stainless steel tube with a 10 cm (4") diameter by 5 cm (2") long ceramic gap in the center of the chamber. The stainless steel chamber is wrapped with heat tape and insulated to allow for in situ bake-out of the vacuum chamber. Silver plated clamp rings are fitted at each end for electrical conductivity and component installation.

Cooling System

A water cooling system was designed to remove the heat from the ferrite rings, anticipated to be as high as 300 watts per ferrite. The copper cooling discs are 1.27 cm (1/2") thick with a rectangular copper water tube brazed to the outer circumference. This gives a maximum temperature differential of 3° C across the face of the copper disc with nominal water flow. The copper cooling discs are stacked alternately between ferrite discs and the entire assembly is compressed using a system of G-10 epoxy resin laminated clamping rods (Fig. 3) and end flanges. To assure good thermal contact between ferrites and cooling discs a total clamping force of 30 kN (6800 lbs.) is used. The cooling discs are connected in parallel through insulated hose to the water supply and return manifolds located below the cavity (Fig. 2).

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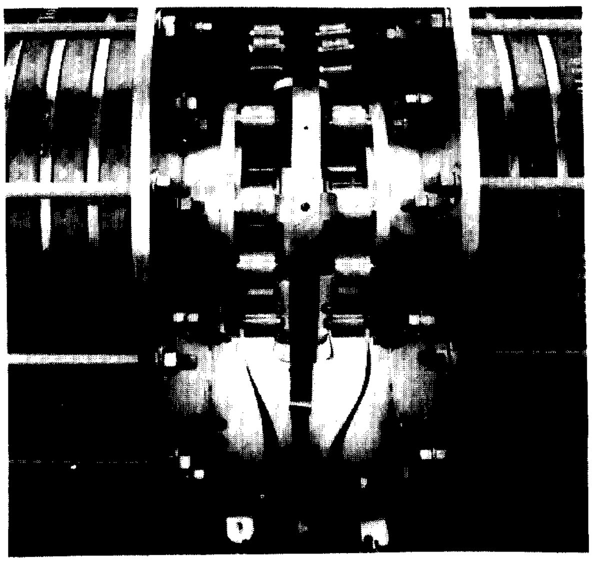

Figure 3. Photograph of gap detail. Grounding strap is in center. Input coupling caps are in background and monitor and tuning caps are in lower foreground. Left and right sides show ferrites with cooling rings and tension rods.

Electrical Considerations

Gap Impedance

The RF cavity provides a transformation from the drive impedance of the amplifiers (50 Ohms) to the gap impedance of the cavity. Maximum cavity voltage can be realized by maximizing the gap impedance but there is the additional restriction that the shunt impedance (R_s) not exceed 1500 Ohms (this is from the Z/n stability requirement of 750 Ohms or less). Tests of the ferrites indicated that the cavity requires about 2200 pF of additional capacitance to resonate at 1.26 MHz ($\omega/2\pi$). The desired quality factor (Q) of the cavity is given by

$$Q = R_s \omega C \tag{1}$$

Using the values given above this yields a Q of about 26. The measured Q of the ferrites used is about 80 and so additional 50 Ohm deQing loads are coupled the cavity. The advantages of using 50 Ohm loads are their low cost, reliability and wide bandwidth. An alternative method would be to use active feedback from the amplifier but this would require the amplifier to be functional at all times and would also require a wide bandwidth to suppress higher order modes in the cavity.

Each half of the cavity uses input coupling capacitors of 500 pF, gap shunt fixed capacitors of 1400 pF plus a 250 pF variable, load coupling capacitors of 400 pF and a monitor coupling capacitor of 10 pF (Fig. 4).

The shunt capacitors for each half of the cavity are connected to the central ground strap (Fig. 3) and when the cavity is drive is balanced this strap carries no current to ground. If the drive to two halves is unequal then the ground strap provides better than 22 dB of isolation between the drive ports thus protecting the power amplifiers from each other.

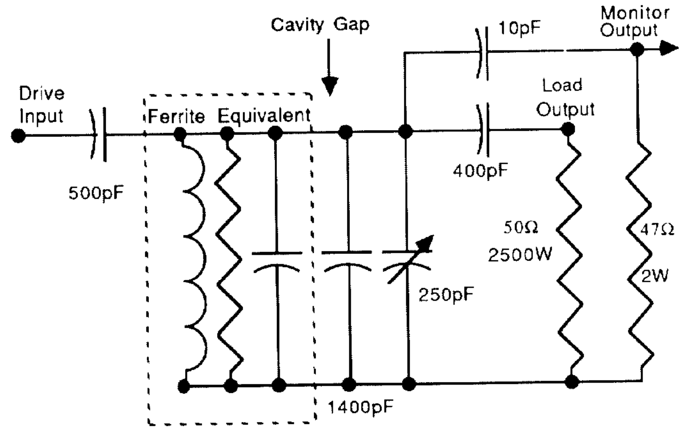

Figure 4. Cavity Equivalent Circuit.

Ferrite Behavior

The ferrite Q and permeability (μ_r) are a function of flux density and therefore dependent on drive level. Bias coils for ferrite tuning[4] were considered but not implemented. Figure 5 shows the cavity resonant frequency as a function of gap voltage. The cavity is tuned for best match to the amplifiers at maximum power required for the intended type of operation. Antiproton extraction requires at most 2000 volts peak at the gap. Figure 5 shows that the cavity is currently tuned for achieving this voltage at about 1.26 MHz.

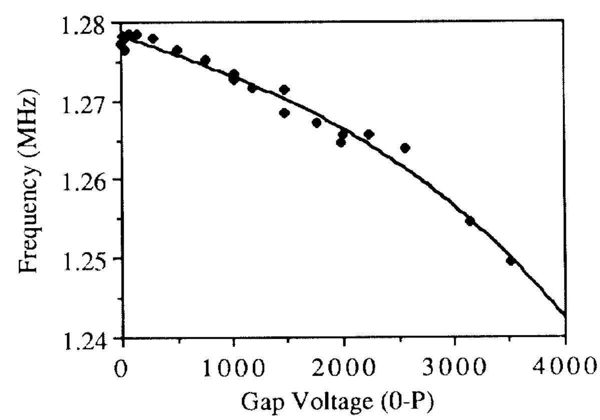

Figure 5. Cavity Frequency vs. Gap Voltage

High Level Amplifiers

Each half of the cavity is driven by a commercially available tube amplifier[5] with characteristics shown in table 2.

Table 2.
Power Amplifier Requirements

Frequency of operation	1.2 to 1.3 MHz
RF output power	3000 watts rms
Linear	(Class A operation)
Impedance	50 Ohms (VSWR 2:1 max)
Minimum gain	12 dB
Unconditionally stable	
Continuous duty up to 50° C ambient	

Low Level RF Amplitude and Phase Control Module

Purpose: This module provides a means of control and regulation of the ARF3 accelerating cavity voltage and phase over a >70 dB amplitude range.

Phase Loop: The Phase Loop regulates phase between the 1.26 Mhz reference oscillator and the cavity rf monitor signal to compensate for power level and temperature dependent phase variations in the PA and cavity system. The loop consists of a commercial phase shifter and a 360° range phase detector incorporating a Fermilab designed limiter circuit with <1° insertion phase variation over an 80 dB input signal range. The phase loop range is intentionally limited to 90° to prevent problems such as trying to operate on the wrong slope of the phase detector. The closed loop bandwidth is about 3 kHz, limited by the control bandwidth of the commercial phase shifter, and the loop gain at dc is 2000.

Amplitude Loop: The Amplitude Loop regulates the cavity rf voltage to a level determined by a 0-10 volt analog input program supplied by the accelerator control system. The amplitude control circuitry includes a feedforward section as well as a feedback regulation loop consisting of a logarithmic detector, loop amplifier, antilog conversion stage, and a linear attenuator.

The feedforward section directly controls the attenuator, operating on the output rf, to dead reckon the correct output level for a given amplitude program. The feedforward relieves some burden from the feedback loop and provides a safe and approximately correct control function in the event the feedback input is disconnected.

To achieve the >70 dB amplitude regulation range, a logarithmic detection of the cavity voltage signal is performed, utilizing the signal strength indicator section of a Signetics NE604 FM IF system integrated circuit[6]. This inexpensive chip provides stable log detection accurate to better than 1 dB over a 75 dB range. The error between the detected signal level and the amplitude program is amplified, filtered, added to the feedforward voltage, anti-logged, and used to control the attenuator thus regulating the detected cavity voltage. The attenuator, consisting of two series double balanced mixers driven by current sources, has a >80 dB linear range. The amplitude regulation loop has 3 kHz bandwidth, limited by the antilog IC function.

The amplitude program control point and the loop amplifier, located where they are, operate on the logarithms of the controlled variable resulting in an interesting control system analysis problem beyond the scope of this paper. For instance, the error in the loop is proportional to the ratio between the desired and the actual cavity voltage, not to the difference between them as would be the case in a linear loop.

The output of the log detector is also monitored by a comparator circuit able to turn off both the amplitude and phase feedback loops, defaulting the phase shifter to a preset phase and defaulting the amplitude section to open loop feedforward control only. The trip point is set a few dB below the minimum operating level. This feature prevents the feedback from trying to operate with insufficient input signal and prevents the output rf amplitude from going to maximum should the feedback input be inadvertently disconnected.

Operational Experience

The new ARF3 system has provided higher RF voltages and wide dynamic range for extraction of antiprotons during colliding beam runs. Double bunch extraction has been done with some success although the evaluation of the performance is complicated by the effect of the accumulator stochastic cooling system operating with bunched beam on the extraction orbit.

The phase and amplitude feedback features of the low level module allow for a wide dynamic range and tolerance of amplifier variations. At present only one high level amplifier is needed to provide enough voltage for antiproton extraction.

Further studies are scheduled in the next few months, including investigation of the system performance during deceleration for the medium energy experiment. This deceleration will require the system to run at maximum output for long periods.

Acknowledgements

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