The 52 MHz RF System for PETRA II

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Abstract

The PETRA II proton rf system is a contribution from Canada to HERA construction. With the 52 MHz rf system for the main HERA ring [1], it was built by CRNL under contract to the Institute of Particle Physics, with funding by the Natural Sciences and Engineering Research Council. Cavities and amplifiers, modelled on FNAL AA ring components, have been delivered to DESY and are being installed in the PETRA tunnel. We review major features of the system and discuss commissioning experience.

Introduction

The conversion of PETRA from an electron-positron collider to a synchrotron capable of accelerating electrons, positrons or protons is part of the plan for the construction of the HERA e-p collider at DESY [2,3]. The specification for the PETRA proton rf system calls for a circumferential voltage of 100 kV during capture and acceleration of the beam from DESY III (now reduced to 45 kV after more detailed beam dynamics studies), and up to 190 kV for adiabatic shortening of the bunch prior to transfer to the superconducting HERA ring. The system must be tunable from 51.64 MHz to 52.04 MHz, to match the particle momentum variation during acceleration from 7.5 GeV/c to 40 GeV/c. Maximum average design beam currents are 0.17 A, so that the rf system must cope with large reactive beam-loading effects. An rf feedback system with an open-loop gain of 50 was specified, as was significant reduction of higher-order cavity mode impedances. The sensitivity of the superconducting magnets in HERA to heating by lost beam led to a requirement for continuous operation in beam compression mode, to allow single bunch extraction for tuning of the PETRA-HERA beam transfer-line and HERA optics. The total system was designed to be operable from the DESY central control computer, but at the same time is capable of operation in a stand-alone mode for commissioning and testing at CRNL.

Cavity Design

The Fermilab Antiproton Accumulator rf system [4] was chosen as the starting point for cavity design (Figure 1), as its operating characteristics closely match the specification above. Fabrication from aluminum was chosen for reasons of cost and ease of manufacture. Further simplification of fabrication was achieved by spanning the acceleration gap with a ceramic cylinder, restricting the evacuated region to the beam-pipe. The balance of the cavity is air-filled, eliminating concerns about multipactor, and simplifying cavity access for installation of tuners, dampers and probes. The inner conductor, intermediate cylinder, portions of the cavity outer wall, tuner and higher-order mode dampers are water cooled. Two cavities are sufficient to meet the requirements of PETRA, and provide flexibility for future changes in operating procedures.

The cavity is tuned by varying the resonant frequency of a partially external half-wave coaxial resonator, loop-coupled into the main cavity [5] (Figure 2). The coax line is loaded at its shorted end with orthogonally biased ferrite, sandwiched with beryllia disks for cooling. The ferrite is immersed in a solenoidal magnetic field. Low-loss orthogonal bias ferrite allows higher power densities and reduced ferrite

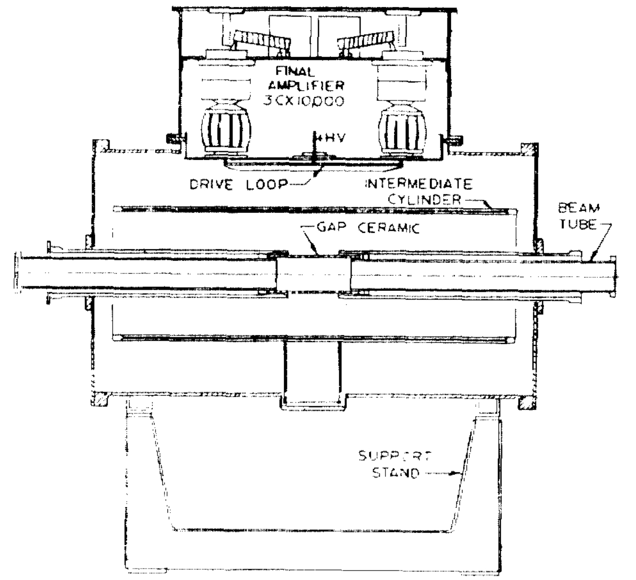

Figure 1. PETRA 52 MHz cavity cross-section.

volume. The winding geometry is also simpler, and leads to a more conventional power supply requirement.

The higher-order mode damper is also a half-wave coax line resonator (Q~200), loop coupled into the main cavity [6] (Figure 3). A 10 Ω power resistor is placed across the coaxial line, one-half wavelength (52 MHz) from the shorted end. At integral multiples of 52 MHz, the resistor is shorted out by the coaxial line. All other frequencies are damped. For this cavity geometry, modes with significant impedance at the gap are not, in general, integrally related to the fundamental. The most dangerous modes are those with the lowest frequencies, with the largest Fourier components in the beam, and the largest transit time factors. To selectively damp such modes, the coupling-loop/resistor line length has been tuned to give near-optimal coupling to the lowest HOM around 125 MHz. This sacrifices some damping at the higher modes, but is thought to be adequate. Further determination on this point can only be made when the system is exposed to beams of protons and electrons.

The loaded cavity Q, without feedback, is 4500 at 52.04 MHz, and 4200 at 51.64 MHz. The calculated (SUPERFISH) R/Q is 149 Ω, giving shunt impedances of 625 kΩ and 670 kΩ.

Rf Amplifier Design

The amplifiers are also closely modelled on the FNAL AA design. The 13 dB final amplifiers each consist of two air-cooled Eimac 3CX10000A7 triodes in a push-pull circuit, operating grounded-grid, class AB, in a chassis mounted atop the cavity, and directly coupled into it with a drive loop which gives a 30:1 step-up ratio between plate and gap voltage swings. The 6 kV plate supply is directly attached at the rf null at the mid-point of the loop. If required, higher-order mode dampers may be attached at this point. Cavity shunt impedance is approximately 500 kΩ, and the 20 kW dissipation of the final amplifier is required for

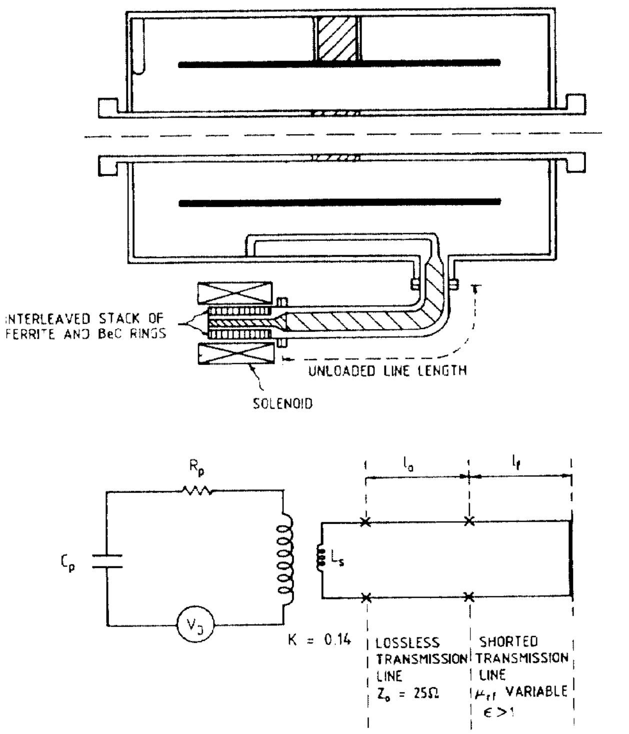

Figure 2. Cross-section and schematic of the orthogonally biased ferrite loaded, near-resonant tuner, attached to the cavity.

absorbing the reactive power associated with beam loading, rather than generating the gap voltage. The cathode load resistance is approximately 50 Ω, allowing the large input capacity to be resonated out with a simple coaxial transformation network.

Each driver is also push-pull, but with independent 3-section π-L networks adjusted to give the wide bandwidth (>2.5 MHz) required by the fast feedback regulation system. A pair of zero-bias, air-cooled Eimac 3CX1200A7 triodes are operated grounded-grid in class AB. The input transformers are designed to match the outputs of the 3 dB equal-phase power splitter to the 100 Ω cathode load resistance and to provide the necessary phase reversal. Gains of 10-11 dB have been achieved. The 55 dB, 150 MHz bandwidth, solid-state exciter is an ENI 3100LA.

At each stage, propagation delay and line length have been minimized, to achieve the demanding 34 dB open-loop power gain specified by DESY. This included minimizing the physical separation of the cavities and low-level electronics and choosing high bandwidth components and high group velocity cable.

Analog Controls

Resonance Control

The feedback resonance controller mixes cavity field and drive signals to measure tuning error. Integrated phase error drives the tuner power supplies and corrects the cavity resonant frequency. In steady state, the system is driven to the frequency at which the cavity appears to be resistive. During beam loading, this method automatically detunes the cavity to produce a total voltage that is in phase with the drive.

Automatic gain control maintains an input of +7 dBm to the local oscillator (LO) input of the mixer, and decouples the cavity field level from the resonance control loop gain. The drive signal is attenuated in

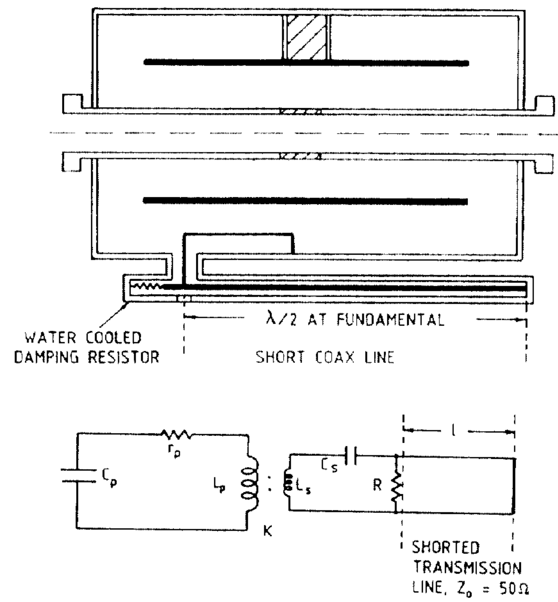

Figure 3. Cross-section and schematic of the resonant, loop-coupled higher-order mode damper, attached to the cavity.

proportion to LO input attenuation, and applied to the rf mixer input at ~+3 dBm. Because this input is within its linear characteristic, and inversely proportional to cavity field, the rf input and resonance control loop gain are increased during tuning errors with the "fast loop" closed and in range.

Although the PETRA II resonance controller lock-in over a 400 kHz range, its 9 s response time to a 100 kHz step change is slower than expected.

"Fast Loop" and Feedforward Compensation

Separate amplitude and phase control loops were rejected due to strong, beam-load dependent, coupling. A simple feedback loop on cavity field controls both amplitude and phase and is insensitive to coupling.

System layout requires 60 ns of cabling within the "fast loop", with significant linear phase rotation within the controller bandwidth; necessitating wideband coupling networks in the drive chain and reductions in sensitivity to undesired resonances.

While feedback control of the rf field reduces the cavity impedance as seen by the beam, it makes a larger portion of this impedance appear resistive. The achieved open-loop gain of 50 reduces cavity impedance sufficiently that the resistive component is also reduced at the revolution sidebands.

Feedforward compensation is also available to counteract beam-induced transients. It further reduces the cavity impedance as seen by the beam, on the fundamental and all sidebands. Achievement of the field stability targets of ±2%, ±5°, for the worst beam-loading, requires at least 70% beam compensation by feedforward and a feedback open-loop gain of 50.

Digital Controls

One 80186-based computer controls each rf system. This includes monitoring analog and digital signals, detecting fault conditions and taking remedial actions, automatic start-up and shut-down, displaying system status locally, and reporting to the main DESY control computers. All rf system interlocks, other than those involving personnel safety or those requiring very fast response, e.g. crowbars, are in computer software rather than hardwired.

Each computer consists of a 4-slot MULTIBUS I chassis, with a 8 MHz 80186-based single board computer, a 72-channel digital I/O board, a 64-channel differential input ADC board, an 8-channel DAC board and a custom 8-bit parallel I/O board to interface to DESY's computer network. All software is stored in 128 kBytes of EPROM, and 128 kBytes of Static RAM is used. One RS-232 serial port communicates with an ANSI standard terminal that serves as local control console. A second RS-232 serial port is available for logging system parameters during testing and commissioning.

The operating system is a specially configured version of INTEL's iRMX-86 operating system. Only portions of the operating system required for real-time multi-tasking and simple non-file oriented I/O have been used. The PL/M-86 programming language was used for all application programming. All digital and analog inputs are read and checked every 20 ms and 100 ms respectively. Inputs are checked for fault conditions after every read operation. Outputs are updated on the same schedule. During normal operation, the system is controlled by the main DESY computers and the local console only indicates the system status. During maintenance and testing, however, the local console can operate the entire system.

Commissioning Status and Operational Experience

The system has been extensively tested at CRNL (Figure 4). Some problems encountered were: excessively lossy gap ceramics, insufficient gain and phase margin at the tube/drive loop and tuner frequencies for stable operation, harmonics in the low-level rf circuits, sparking in the tuner and on the vacuum side of the ceramic and inadequate tuner current regulation at low frequency settings. These have now all been resolved, and acceptable performance obtained in tests at CRNL.

The system is presently being installed in the PETRA ring, and acceptance testing by DESY is underway.

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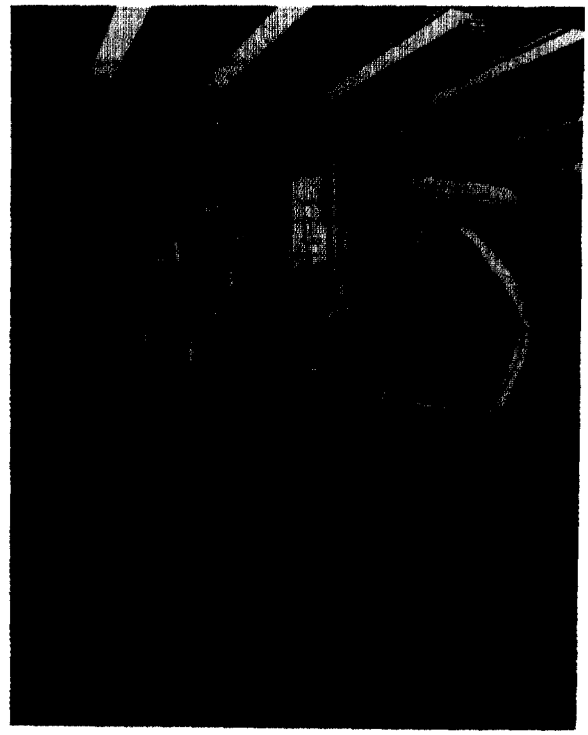

Figure 4. Cavity assemblies just before shipment to DESY

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