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# ENERGY SAVER PROTOTYPE ACCELERATING RESONATOR

Q. Kerns, M. May, H.W. Miller, J. Reid, F. Turkot
R. Webber and D. Wildman

Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, ILL 60510

## Summary

A fixed frequency RF accelerating resonator has been built and tested for the Fermilab Energy Saver.[1] Table I shows the design parameters and prototype resonator test results. The resonator features a high permeability nickel alloy resistor which damps unwanted modes and corona rolls designed with the aid of the computer code SUPERFISH.[2] In bench measurements, the prototype resonator has achieved peak accelerating voltages of 500 kV for a 1% duty cycle and CW operation at 360 kV. The prototype has also been successfully operated with beam in the FNAL Main Ring.

## Resonator Design

The accelerating structure is designed for a high $\beta$ beam. The resonator is excited with a standing wave and has two accelerating gaps separated by a drift space and phased $\pi$ radians apart. Because there is only a small frequency range required around the center frequency, it is a fixed-tuned structure.

Two major design constraints were imposed on the design of the Energy Saver accelerating resonator. First, it should operate at a frequency of 53.104 MHz and second, be located directly under the existing Main Ring components. A frequency of 53.104 MHz was chosen to give high efficiency transfer of beam from the Main Ring by means of a synchronous bucket to bucket scheme. This necessitated building a long thin structure that could be installed under a vertical clearance of only 15 3/16 inches. The prototype resonator shown in Figure 1 is made of OFHC copper and consists of a 12" ID outer shell 108" in length with a coaxial inner drift tube ($Z_0 \approx 70\Omega$). Because of the required placement of the resonator in the tunnel ($180^o$ electrical spacing) the drift tube is actually $170^o$ long electrically rather than $180^o$. Therefore, $V_{eff} = V_{gap}\sin(170^o/2) = .996\ V_{gap}$, which allows installing resonators end to end.

The drift tube is supported by two 3" diameter stems which carry 1800 A RMS RF current and also act as water manifolds providing water to the entire length of the drift tube. The drift tube consists of two concentric tubes welded at each end and separated by an arrangement of water channels. Every other channel has a "soda-straw" arrangement of 5 turns of .0015" stainless rolled in a manner so they may be slid into the cooling channels. This minimizes the counter-flow heat exchange. The ends of the drift tube are capped by two electropolished corona rolls which provide the accelerating gaps. The shape of the corona rolls was designed with the aid of the computer code SUPERFISH.[2] RF power is applied near the center of the resonator at a point which is electrically tapped down on the drift tube at 1/8 of the gap voltage, a convenient level for the 9 3/16" diameter coax line. A ceramic RF window of 94% $Al_2O_3$ is the vacuum seal between the resonator and the transmission line.

The required frequency range of the acceleration system is narrow. The 7.5 kHz natural bandwidth of the resonator allows for the 19 ppm change in $\beta$ from 150 GeV.

Table I

| | DESIGN PARAMETERS | PROTOTYPE RESONATOR |
|---|---|---|
| Peak Voltage | $V_o$ = 360 kV | $V_o$>360 kV |
| Frequency | $f_o$ = 53.104 MHz | $f_o$ =53.104 MHz |
| Unloaded Q | Q = 6500 | Q =7050 |
| Shunt Impedance | $Z_s$ = 1M$\Omega$ | $Z_s$ =1.2 M$\Omega$ |
| Resonator Dissipation | P = 65 kW | P =52 kW |
| Stored Energy | W = 1.09 J* | W =1.1 J |
| RF Time Constant | $\tau$ = 39 $\mu$s | $\tau$ =42 $\mu$s |
| .707 Bandwidth | $\Delta$f = 8.2 kHz | $\Delta$f =7.5 kHz |

*Calculated for a uniform 70$\Omega$ line.

injection and also permits radial displacements of up to $\pm$2 cm. Gross frequency adjustments during initial assembly were made by mechanically positioning the corona rolls and end plates. Final fine tuning to the desired center frequency is accomplished by thermally adjusting the length of the drift tube and outer shell. This is done by a temperature controlled water system that circulates 30 GPM of water through the drift tube and cooling coils on the outer shell. The water system is intended to hold the resonator frequency constant independent of RF power levels.

The TEM modes that exist in the resonator can be grouped into two sets. One set corresponds to the two gap voltages oscillating in phase. Excitation of the fundamental mode results in the desired acceleration of the beam bunch at both gaps. Higher order in-phase modes couple to the transmission line and may be externally damped. The second set of modes correspond to the two gap voltages oscillating $180^o$ out-of-phase. For the principal mode a beam bunch accelerated by the upstream gap will be decelerated at the downstream gap. In order to suppress these unwanted out-of-phase modes, which are not easily coupled out of the resonator, a resistor element has been added to the center section of the drift tube. For these out-of-phase modes which all have current maxima at the center of the drift tube, the resistor element lowers the resonator Q.

The resistor had to meet two important criteria. It had to be capable of dissipating 500 watts and operating in a vacuum with pressures below $10^{-9}$ torr. This required using materials with low outgassing rates at elevated temperatures. This led to a novel resistor design using the high permeability magnetic alloy Hipernom.[3] The resistor consists of a stack of 80, .027" thick annular disks with a 5" ID and 8" OD fastened around the center section of the drift tube. The disks are separated from each other with a series of ring-shaped copper spacers. The long RF current path length along the surface of the Hipernom disks and the decreased skin depth combine to provide an effective resistance

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


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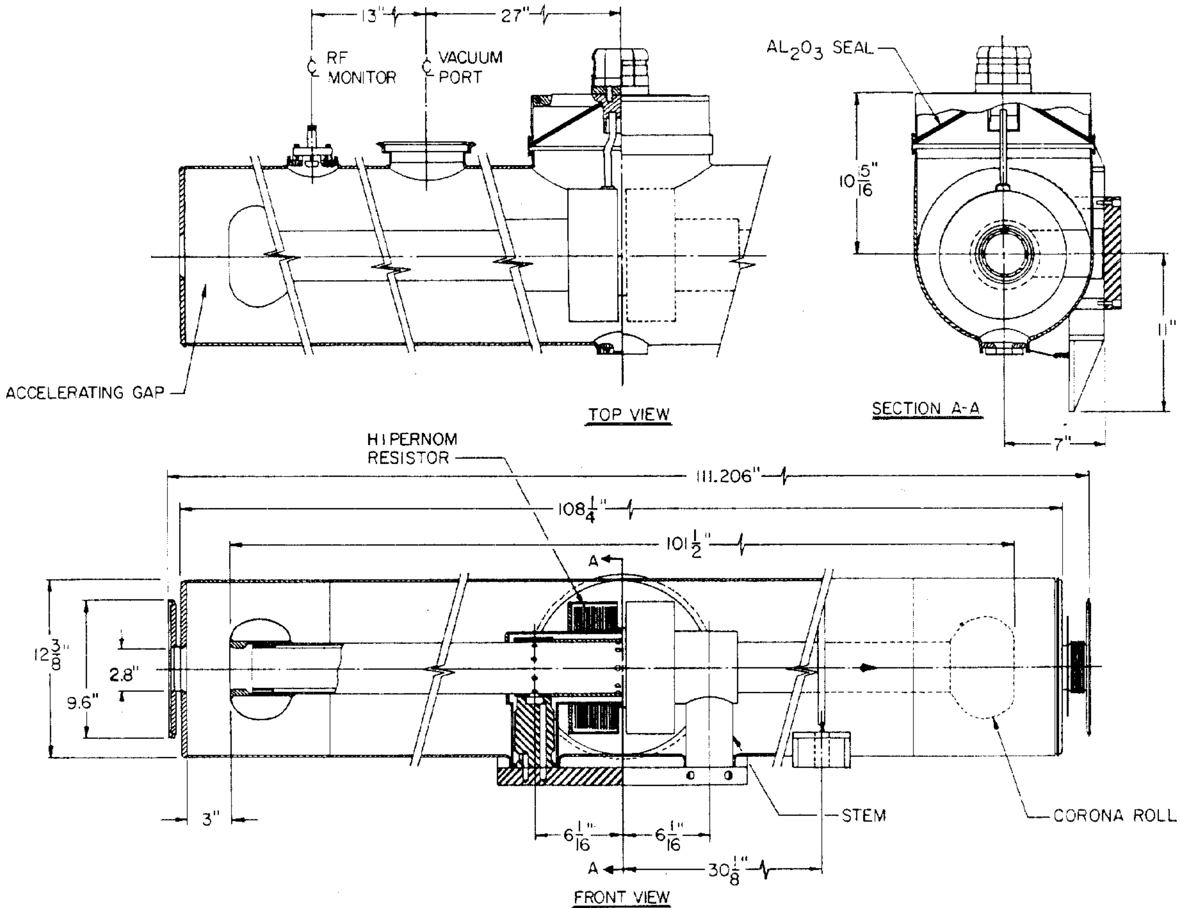


Fig. 1 Energy Saver prototype resonator

of 5Ω at 53 MHz. To illustrate its effectiveness in damping, the fundamental out-of-phase mode (f=54.512 MHz) has a Q = 240 with the Hipernom resistor.

## Corona Roll Design

The Energy Saver resonator is required to generate accelerating voltages in excess of the FNAL Main Ring cavities and must do so in spite of severe physical constraints. This presents a problem of excessive electric fields and sparking near the gaps and corona rolls. Sparking is objectionable because it can cause surface damage inside the resonator further impairing voltage standoff capability and because excessive sparking could result in the loss of a stored particle beam which may have taken hours to accumulate.

With a goal of minimizing electric gradients for a specified gap voltage within the given physical constraints, calculations were performed to determine the optimum geometry for the corona rolls and end plates of the resonator. The computer code SUPERFISH[2] was utilized to perform the necessary field calculations. Though not intended particularly for this purpose, SUPERFISH was selected because of its availability and its convenient way of manipulating the geometry.

A "best guess" corona roll geometry was used as a starting point. SUPERFISH outputs, including the maximum electric field on the surface, electric fields along given line segments, and graphic plots of field trajectories, were used to evaluate the geometry. Shape changes were then made attempting to reduce high field concentrations and the new geometry was run and evaluated. Iteration in this manner was continued until we were convinced that we had converged on a nearly optimum design. The drift tube corona roll cross section arrived at is somewhat like a flattened semicircle consisting of four arc segments of three different curvatures. A corona roll was not found to be useful on the resonator end plates, contrary to our first intuition. The geometry is shown in Figure 2.

The calculated maximum field strength for the final geometry is 5 MV/m at 360 kV. This is a 22% improvement over the 6.3 MV/m for the initial geometry. The SUPERFISH calculation was also applied to the present Main Ring cavity and gave an answer of 3.5 MV/m for the maximum electric field on the corona rolls at 270 kV.

Limitations of SUPERFISH for this application included the fact that the minimum usable calculation mesh size approached the size of some parts of our geometry. This is the result of our focusing attention on a small area of a large resonator. There was no way to decrease mesh size in the area of interest without doing so throughout the resonator requiring too large a computer memory area. Also there was no provision for directly plotting electric field intensity lines which would have been useful for suggesting geometry changes.

SUPERFISH also provided useful approximations for resonator power loss and stored energy. An idealized quarter wave resonator was used as the model. This predicted a power loss of 41 kW and 1.05 J stored energy

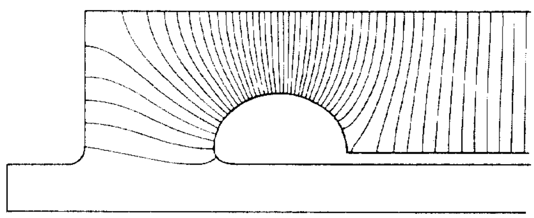

Fig. 2 SUPERFISH plot of lines of constant $rH_\phi$

with the resonator at 360 kV. These numbers compare with measured values of 52 kW and 1.1 J. Unfortunately, the stems which carry high current and have high power losses could not be precisely simulated.

## Test Results

The Energy Saver prototype resonator has undergone a series of four tests: low level RF measurements, simulated beam loading bench tests, high power RF tests without beam, and operation as an accelerating cavity in the FNAL Main Ring. The low level RF measurements were made to set the center frequency (53.104 MHz), minimize the fundamental power loss in the 5Ω resistor, locate the higher order modes, calibrate the gap voltage monitors ($10^4$:1), and measure the resonant frequency as a function of the circulated water temperature (1.02 kHz/°C).

A bench test was performed to determine the beam-induced excitation of the resonator modes. The quantity most often used in measuring the energy losses is known as the loss parameter, k, defined as the amount of energy lost per charge for a 1 Coulomb bunch transversing the resonator. The loss factor k contains both the energy lost to the fundamental mode as well as losses to higher order modes. Using the bench measurement technique of Sands and Rees,[4] a .044" diameter wire was inserted along the axis of the resonator. A reference tube was made by placing a wire of the same length in a copper tube with the same inner diameter as the drift tube. The transmission of two identical pulses through the resonator and reference was then sampled using a Tektronix type S-4 sampling head (rise time <25 ps) and the outputs were then compared to give the total energy lost into all modes of the resonator. This value was obtained by simply subtracting the energy of the pulse passing through the resonator from the pulse energy transversing the reference tube.

Two different pulses were used to investigate the dependence of the energy loss parameter k on pulse shape. A Gaussian shaped pulse with a full 1/e width of 130 ps was formed using the output of a Tektronix S-52 pulse generator head (rise time <25 ps) into a section of shorted 50Ω line. To simulate an energy saver beam bunch a 3 ns wide flat-topped pulse with rise and fall times of 500 ps was used. As expected the energy loss parameter for the 130 ps pulse was substantially larger (k = .53 V/pC) than that measured for the 3 ns pulse (k = .035 V/pC). This is due to the higher frequency components of the short pulse exciting the higher order resonator modes.

Before high power testing, the resonator was vacuum baked at 120°C for several days and a pressure of 5 x $10^{-9}$ torr was achieved. At the start of testing a multipactoring regime was quickly discovered extending from 1.3 kV to 70 kV peak accelerating voltage. However, multipactor free operation was observed below 1.3 kV and between 70 kV and 500 kV (500 kV being the highest voltage tested). The resonator was successfully operated at 500 kV peak accelerating voltage with a duty cycle of 1% and CW operation was maintained for several hours at 360 kV. The prototype has also been operated CW at 440 kV for several minutes until the outer resonator shell began to overheat. The resonator has been refitted with more cooling coils on the outer shell which should maintain the temperature of the shell at its design value of 40°C.

After the high power bench measurements were performed, the resonator was installed in the FNAL Main Ring. Since it was designed as a fixed frequency device, it was not capable of tracking the full operating range of the Main Ring RF system. The prototype was excited after the beam energy reached 150 GeV in the Main Ring. The resonator stably contributed 230 kV of ring voltage to the system while accelerating beam intensities of 0.5 x $10^{13}$ protons to 400 GeV, which was the highest intensity available at the study time. Further experiments are planned to test the resonator to its full design voltage and higher intensity as machine study time becomes available in the Main Ring.

## References


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3. Registered trademark of the Westinghouse Corporation.

4. M. Sands and J. Rees, PEP-95, August 1974 (unpublished).