# A PROTOTYPE 7.5 MHZ FINEMET® LOADED RF CAVITY AND 200KW AMPLIFIER FOR THE FERMILAB PROTON DRIVER

J. Dey, I Kourbanis, Z. Qian, and D.Wildman, FNAL*, Batavia, IL 60510, USA

*Abstract*

A 7.5 MHz RF cavity and power amplifier have been built and tested at Fermilab as part of the proton Driver Design Study. The project goal was to achieve the highest possible 7.5 MHz accelerating gradient at 15 Hz with a 50 % duty cycle. To reduce beam loading effects, a low shunt impedance (500Ω) design was chosen. The 46cm long single gap cavity uses 5 inductive cores, consisting of the nanocrystalline soft magnetic alloy Finemet, to achieve a peak accelerating voltage of 15 kV. The 95cm OD tape wound cores have been cut in half to increase the cavity Q and are cooled from both sides using large water-cooled copper heat sinks. The prototype cavity has a shunt impedance of 550Ω, Q=11, and is powered by a 200kW cw cathode driven tetrode amplifier. Both cavity and amplifier designs will be described. Results from recent cavity tests coalescing beam in the Fermilab Main Injector will also be presented.

## 1 INTRODUCTION

The RF group of the Fermilab Proton Driver Design Study has spent the past two years studying the RF requirements for new, fast cycling, high intensity proton synchrotrons in the 8–16 GeV energy range [1]. Initially, the group focused on a 3-16 GeV synchrotron design operating below transition at 15 Hz with an RF harmonic number h=12. A total beam current of 1E14 would be distributed in four equally spaced bunches. Early in the design study it was decided to construct a prototype RF cavity and power amplifier using these machine parameters. For the 3-16 GeV machine the RF cavity would operate between 7.17 and 7.586 MHz. The highest frequency, 7.586 MHz, although slightly above the 16GeV frequency was chosen to allow the prototype cavity to be tested as an h=84 system in the Fermilab Main Injector. To avoid any Robinson type instabilities [2] resulting from the heavy beam loading, the cavity would be tuned to the highest frequency 7.586 MHz and have a shunt impedance, Rs < 1 KΩ. A Q=10 is necessary to span the operating frequency range.

The original design called for the cavity to be driven by two separate power amplifiers, one to provide the sinusoidal excitation of the cavity at the fundamental frequency and the second to provide short, high intensity current pulses to cancel the transient beam loading. Due to budgetary constraints, it was decided to only build the one amplifier needed to excite the cavity at the fundamental frequency and postpone the development of the second amplifier.

## 2 FINEMET®

To achieve the highest possible accelerating gradient, the cavity is loaded with the new nanocrystalline soft magnetic material Finemet [3,4] instead of conventional nickel-zinc ferrites. Finemet has a Curie temperature of 570°C, a permeability of about 300 at 7.5 MHz and is available in several different alloys and heat treatments in the form of 20 µm thick tape wound cores. The Finemet type FT-3M cores used in this cavity were manufactured by Hitachi and supplied to us by KEK as part of the US/Japan Collaboration on High Energy Physics. The core dimensions are 950 mm OD x 260 mm ID x 25.4mm thick.

Finemet cores have the property that they can be operated at RF fluxes ten times higher than the Ni-Zn ferrites [5]. However; at 7.5 MHz, the Finemet cores are very lossy with a Q <1. This low Q makes it difficult to take full advantage of its high rf flux handling capabilities since very large power sources are needed to achieve the high RF fluxes and cooling the cores becomes a major problem. To reduce our driver amplifier power requirements and achieve a Q=10, we chose to use Finemet cores that had been cut in half using a water jet. By varying the air gap spacing between the core halves in the cavity, the cavity Q became an adjustable parameter

## 3 RF CAVITY

The Finemet cavity, shown in Fig. 1 is a λ/4 single gap structure 46 cm in length. It has two octagonal shaped, 1″ thick, aluminum end plates. The end plates are connected at the top and bottom by aluminum support plates. A 17″ ID quick disconnect type flange is machined directly into the 4” thick top plate for mounting the power amplifier. Six 1″ x 4″ aluminum rectangles are used to provide additional support along the other sides. The remaining open area is covered with a 1/16″ thick aluminum sheet metal skin. Only the 6″ ID stainless steel beam pipe and gap ceramic are under vacuum, the remaining cavity being operated in air. The beam pipe/ceramic assembly is electrically connected to the cavity by two rings of Be-Cu finger stock.

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

0-7803-7191-7/01/$10.00 ©2001 IEEE. 

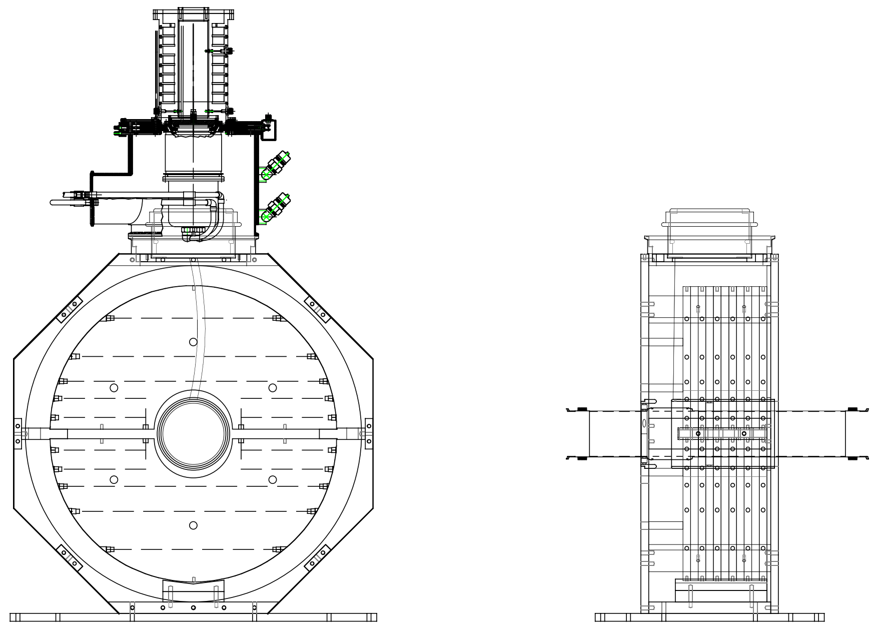

Figure 1: Assembly drawing of the 7.5MHz Finemet Cavity

The cavity contains five Finemet cores which have been cut in half. The cut core halves are encased in a fiberglass reinforced epoxy coating about .025″ thick. The epoxy does not penetrate between the Finemet windings. The cores halves are vertically separated by 34 mm to give a Q=11. During operation, 10 kW of RF power is dissipated in each half core. Although the Finemet may be operated at temperatures over 500°C, the epoxy coating has a relatively poor thermal conductivity and softens at 150°C. Two methods of core cooling were considered. Direct water cooling of the split cores was considered, but concerns over material erosion and LCW contamination led us to choose indirect cooling with 1″ thick water-cooled copper plates. They are the same shape but slightly larger than the cut cores and have been deep drilled with a pattern of 0.5″ ID cooling channels. Each cooling plate is electrically isolated from its neighboring Finemet cores by two sheets of Kapton® film. It was originally thought that the epoxy coating might provide sufficient isolation. However; early test revealed sparking between the edges of the cores and the adjacent cooling plates. This sparking problem was cured by inserting .005″ thick sheets of Kapton 500HN film between the cores and cooling plates. Later these Kapton 500HN sheets were replaced with .003″ thick sheets of the higher thermal conductivity, corona resistant, Kapton 300CR.

To maintain a good thermal contact between the Finemet/Kapton/copper interfaces, each surface was coated prior to assembly with a layer of zinc-oxide and silicone resin thermal compound (Wakefield 120). The two stacks of six cooling plates and five Finemet cores were then compressed in the cavity by two 10 ton hydraulic jacks and then held in place by six, 1″-8 fiberglass threaded rods in the accelerating gap region. The entire core and cooling plate assembly was supported and electrically isolated from the aluminum cavity by a V-block and 0.5″ thick spacer made from UHMW polyethylene. Each cooling plate section is individually cooled with 5 GPM of LCW flowing through Parker Parflex® insulating hoses.

The shunt impedance of the cavity Rs = 550Ω. The accelerating gap voltage is measured by two capacitively coupled calibrated (4500/1) gap monitors.

## 4 POWER AMPLIFIER

The power amplifier used to drive the Finemet cavity is a version of the Fermilab Main Injector 200kW amplifier [6] modified to operate at 7.5MHz instead of 53MHz. The cathode driven, grid biased tetrode is the CPI/EIMAC Y567B which is similar to the EIMAC 4CW150000E. The tetrode has a 150kW anode dissipation rating. The dc anode voltage can be varied from 3 to 24kV using one of the spare Main Injector RF series tube modulators modified for higher current operation. The tetrode anode is connected to one side of the accelerating gap through a 1100pF air-cooled ceramic blocking capacitor. An RF choke, made from 5 turns of AWG14 silicone HV wire (rated at 60 kV) wrapped around the inside of the cavity was used to prevent 7.5 MHz signals from feeding back into the modulator. The Y567B tetrode is operated with a screen voltage of 1 kV and a dc grid bias of -300 V.

The cathode-grid resonant circuit is a foreshortened quarter wave coaxial line tuned to resonance by the

Y567B's input capacitance. The coaxial line is filled with six Ceramic Magnetics C2050 and one Toshiba M4C21A 8″ OD x 5″ ID x 1″ thick ferrite rings. The Q of the cathode resonator was lowered to 5 by placing an air-cooled 50Ω termination along the line. The cathode circuit is driven by the combined outputs of two Amplifier Research 3500A100 broadband solid-state amplifiers. Each amplifier is capable of delivering a minimum of 3500W over the frequency range of 10kHz to 100MHz. The 50Ω output impedance of the combiner is matched to the 12.5Ω input impedance of the cathode circuit by a quarter wave matching section consisting of two 50Ω (Heliax® LDF4-50A) cables in parallel.

## 5 TEST RESULTS

The cavity and amplifier were bench tested in three different modes; short pulse, cw, and 15 Hz with a 55% duty cycle. In the short pulse mode, the cavity achieved a gap voltage of 17.6kV in a 40µs pulse that was limited by the 273kW available from the power amplifier. The cavity was run at 10kV cw for more than one hour. In the 15Hz mode, the cavity ran continuously with a gap voltage of 14.6kV at a 55% duty factor. The gap voltage in both the cw and 15Hz cases was limited by excessive heating at the inner corners of the cores near the air gap. At this location, the fringe fields from the gap are no longer parallel to the core laminations and additional eddy current heating occurs. Two core corners in the middle of the core stack were badly burned during the testing while the remaining cores appeared unaffected.

Following the advice of Fred Mills, one core was modified with water jet cut profiles on the inner and outer corners of the cores. The correct profiles [7] were approximated by a simple 35mm radius on the inner corner and an elliptical shape (51mm x 38mm radii) on the outer corner. No signs of excessive heating were observed on this core. We believe that by shaping all of the core corners in this manner, higher average power can be achieved.

As a final test, the Finemet cavity and amplifier were inserted into the MI-60 straight section of the Main Injector. Figure 2 shows a "mountain range" or "waterfall" display of proton bunches being coalesced at 150 GeV in the Main Injector by the 7.5 MHz Finemet system. Time proceeds from bottom to top with 7.75ms between traces. Measurements of the synchrotron frequency yield a peak accelerating voltage of 10.5kV which is in agreement with the gap monitor signals.

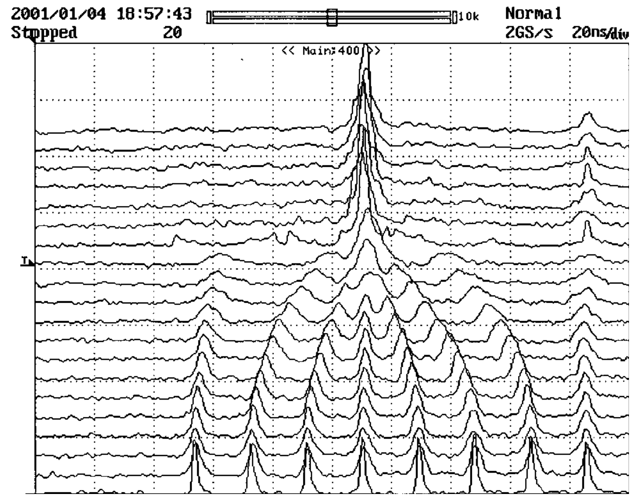


Figure 2: Mountain range plot showing coalescing of proton bunches in the Main Injector using the 7.5MHz Finemet RF system.

## 6 REFERENCES

[1] W. Chou, C. Ankenbrandt, E. Malamud, "The Proton Driver Design Study," Fermilab-TM-2136, Dec. 2000.
[2] K. W. Robinson, "Stability of beam in radiofrequency system," CEAL-1010, Cambridge, Feb. 1964.
[3] Y. Yoshizawa, S. Oguma, K. Yamauchi, "New Fe-based soft magnetic alloys composed of ultrafine grain structure," J. Appl. Phys. 64(10), p.6044, Nov. 1988.
[4] Y. Yoshizawa K. Yamauchi, "Effects of magnetic field annealing on magnetic properties in ultrafine crystalline Fe-Cu-Nb-Si-B alloys," IEEE Trans. Mag., No.5, p.3324, Sept. 1989.
[5] M. Fujieda, et.al., "Studies of magnetic cores for the JHF Synchrotrons," PAC 1997, p.2992, Vancouver, May 1997.
[6] J. Reid and H. Miller, "A 200 kW power amplifier and solid state driver for the Fermilab Main Injector," PAC 1995, p.1544, Dallas, May 1995.
[7] F. E. Mills, "Iron Dominated Resistive Magnets," unpublished note, June, 1997.