FERRITE EVALUATION FOR AHF PROTON SYNCHROTRONS*

J. T. M. Lyles†, L. J. Rybarcyk, LANSCE, J. F. Bridges, TechSource,
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

The Advanced Hydrotest Facility (AHF) proton synchrotrons are likely to use parallel-biased, Nickel-Zinc ferrite cores in accelerating cavities. The Booster frequency is anticipated to be in the range of 0.32 – 1.25 MHz, depending on the choice of final energy and design, while the 50 GeV Main Ring (MR) frequency range is 4 – 5.03 MHz. Experiments were conducted to characterize the response of large rings of Ferroxcube 4M2, 4B3 and 8C12 ferrites over these frequency ranges. Testing of 4M2 for the Booster revealed degraded performance due to the nonlinear response of incremental permeability at elevated flux densities [1]. This constrains the operating voltage to a range well below the thermal power limits of the material. The 4M2 and 4B3 material appears to be satisfactory for the MR. The 8C12 material is satisfactory for the Booster if it is operated below the threshold of a high loss effect. The final cavity designs will be based upon the results of ferrite measurements from the test cavity, for the requirements of the AHF accelerators. Testing methods, analysis and results will be presented.

ADVANCED HYDROTEST FACILITY

The AHF will allow for quantitative proton radiography for hydrodynamic tests and dynamic experiments in support of the stewardship of the nuclear weapons stockpile. The proton accelerators are comprised of an H-injector linac, a Booster synchrotron and a 50 GeV MR. The LANSCE 800 MeV proton linac or a new 157 MeV linac are being considered for the injector. Also under consideration is either 4 or 9 GeV (h = 1 or 2) booster design. A significant portion of AHF consists of beam transport lines with splitters and multiple imaging systems at hydrotest firing sites.

Radio Frequency Systems

The Booster designs under consideration cover a frequency range of 0.32 to 1.25 MHz, with maximum voltages of 39 to 72 kV/turn. The MR frequencies range from 4 to 5.03 MHz, depending on the Booster injection energy. The maximum voltages are from 170-210 kV/turn.

It is expected that the RF cavities will use conventional Ni-Zn ferrite cores in a parallel biased arrangement. The ferrite will be arranged around the beam tube inside the coaxial cavity, in a foreshortened $\lambda/4$ transmission line structure. A capacity-loaded gap completes the LC resonant circuit. This type of cavity is commonly used for proton synchrotrons in this range of frequencies. Co-located drivers will use tetrodes to provide the RF excitation to the cavities.

FERRITE TESTING

We investigated three compositions of ferrite from Ferroxcube. Ferrite types 4M2, 4B3 and 8C12 are all candidates for the two machines, and pairs of large sample cores with 0.5 m outer diameters were obtained. A table-top cavity was constructed to drive several cores of ferrite at realistic magnetic flux densities. This cavity is a coaxial enclosure made from rolled and welded sheet aluminum. It has a short aluminum tube for a center conductor with a thin copper disk at the upper end. This disk connects a ring of radially-oriented ceramic or mica RF capacitors attached to the outer walls of the cavity. RF voltages are developed across these low loss capacitors. Several matching networks were constructed to provide approximately 50Ω impedance to the power amplifier at either 1 or 5 MHz. Power amplifiers of up to 1 kW output power have been used. All testing was done at room temperature without supplemental cooling, by keeping the operating RF pulses under five seconds at a very low duty cycle. Fig. 1 shows a simplified diagram of the test cavity with associated RF instrumentation.

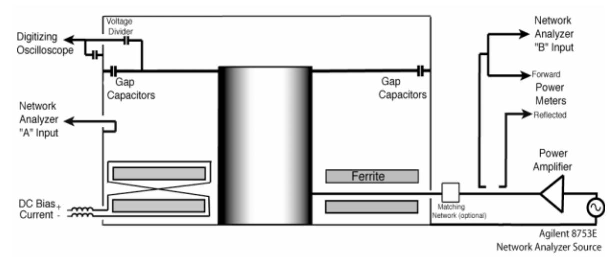

Figure 1: Diagram of Ferrite Test Setup

In the test cavity the RF magnetic flux density (B_{rf}) is in the same direction in both cores by way of RF current in the center post, while the DC bias winding uses a 'figure-of-eight' configuration for opposite sense in each core. The RF current induced in each bias winding is cancelled at the common leads. Residual current due to asymmetry of the layout and lead pickup is blocked with a low-pass filter. Multiple bias windings around the cores provide up to 1110 Amp-turns with a compact lab current source. Susceptibility to stray resonances is a disadvantage of having a multi-turn bias winding. In general these were located above the fundamental resonance and therefore not a problem for our tests.

In figure 2, Agilent network analyzers and the cavity with matching networks are seen left of center; power meters and data acquisition system are on the right. Several high power amplifiers are located on the far right.

* Work supported by the NNSA under US Department of Energy contract number W-7405-ENG-36.
† jtml@lanl.gov

Figure 2: Photograph of Ferrite Test Setup

Determination of u',Q and u'Qf

We developed a data-reduction method to extract the desired ferrite parameters from the RF measurements. The quantities of interest are the relative permeability (μ'_r) of the ferrite, the quality factor (Q) of the ferrite, and μ'Qf. We benchmarked our results against published measurements of 4M2 ferrite at 2 MHz with no bias [2]. The results showed excellent agreement.

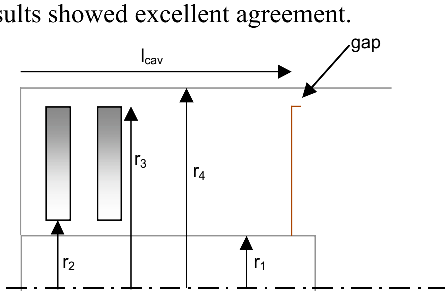

Figure 3: Axially Symmetric Model of Cavity

A physical model of the electrically-short cavity (fig. 3) was used to derive an expression (eq. 1) for μ' for the ferrite cores:

$$\mu'_r = 1 + \frac{l_{cav}}{N \cdot t_{core}} \left(\frac{1}{\frac{\mu_0}{2\pi} \cdot \ln\left(\frac{r_4}{r_1}\right) \cdot l_{cav} \cdot C_{tot} \cdot (2\pi f)^2} - 1 \right) \left(\frac{\ln\left(\frac{r_4}{r_1}\right)}{\ln\left(\frac{r_3}{r_2}\right)} \right) \quad (1)$$

The total capacitance was determined from a fit of the resonance data using several known capacitors across the gap using equation 2.

$$L_{tot} \cdot (C_{ext} + C_{stray}) = \frac{1}{(2\pi f)^2} \quad (2)$$

To determine Q and u'Qf, the equivalent shunt impedance is found by measuring the voltage and power, while ignoring cavity wall losses. The ferrite Q is then deduced from cavity Q and the ratio of inductances (eq. 3):

$$Q_{ferr} \cong \frac{\frac{V^2}{2P}}{2\pi f L_{total}} \cdot \frac{L_{ferr}}{L_{total}} \quad (3)$$

The total (ferrite) inductance is derived from the expression for the magnetic flux in the cavity (cores).

Results with Ferrite 4M2, 4B3 and 8C12

Ferrite types 4M2 and 4B3 were evaluated for both the MR and Booster frequency bands. 8C12 was evaluated only for the Booster frequency band due to its high permeability. A summary of the results are shown in Fig. 4 through 9:

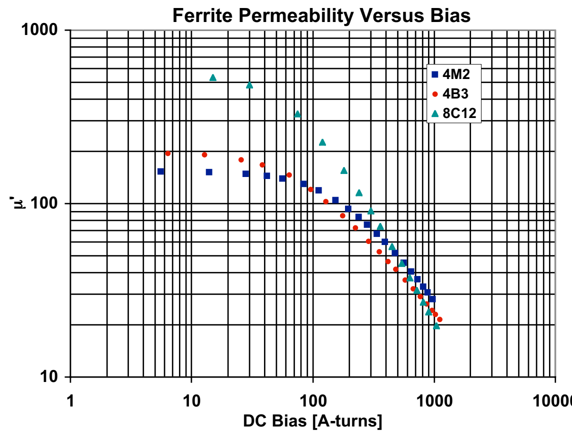

Figure 4: Permeability vs. Bias with ≈ 10 mW RF

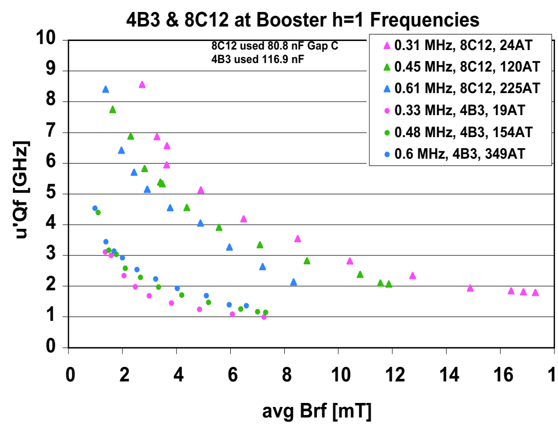

Figure 5: μQf vs. Magnetic Flux Density

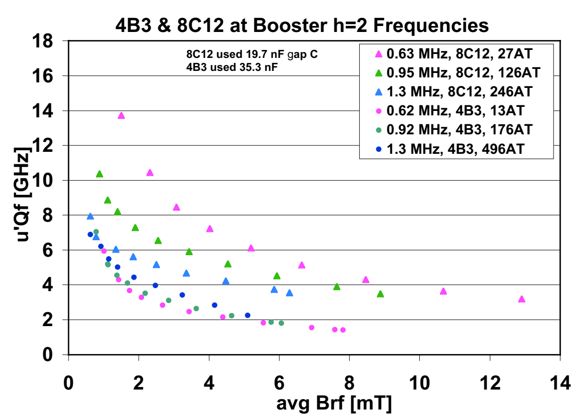

Figure 6: μQf vs. Magnetic Flux Density

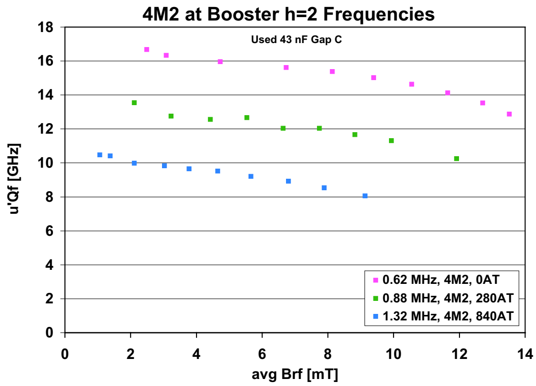

Figure 7: µQf vs. Magnetic Flux Density

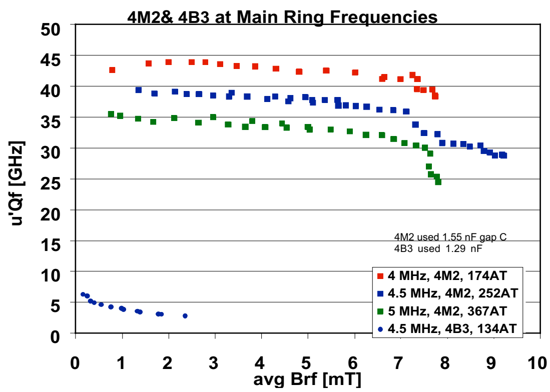

Figure 8: µQf vs. Magnetic Flux Density

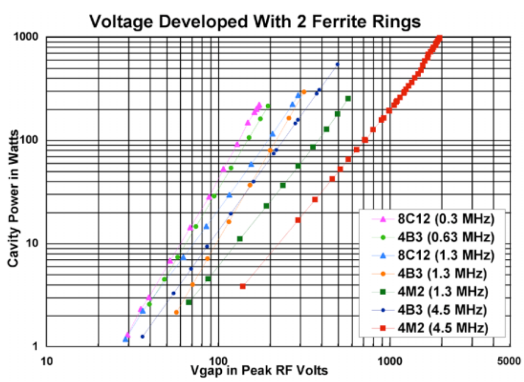

Figure 9: Power vs. Voltage for Various Ferrites

For the 9 GeV h=1 Booster frequencies, the higher B_{rf} drove the 4M2 material into a nonlinear regime in which the observed resonance curve became distorted (left in fig. 10). This effect is caused by the location of the minor BH_{rf} loop inside the major bias *BH* loop [1]. It would be problematic for control loops for the RF system, as gain would rise steeply around resonance in a phase detection process. The same plot shows the response at lower flux density. 4B3 and 8C12 also show evidence of this nonlinearity, but the effect is shunted by the lower ferrite Q. 4M2 is acceptable for the MR, but was eliminated from further consideration for the Booster. 4B3 is acceptable as a lower Q alternative (more power required) for the MR, but µ may be too low for the lower frequency booster design. Material 8C12 is suitable for both Booster designs.

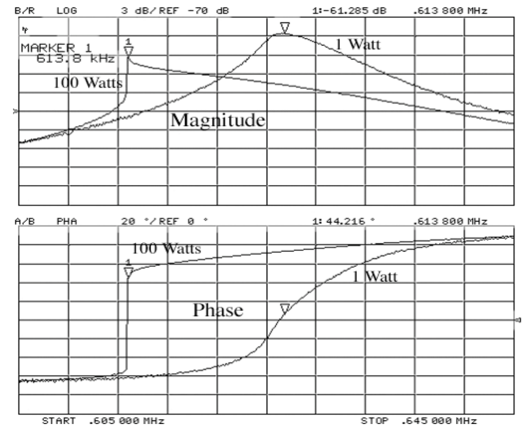

Figure 10: Amplitude/Phase Responses of 4M2 Ferrite at 0.614 MHz, with High and Low B_{rf}

We observed a high loss effect in the 8C12 ferrite, occurring when the flux density was high at certain bias conditions. It is related to stored energy in the ferrite [3] and was manifested as noise on the gap voltage and a significant drop in voltage during long pulses of RF. This can be problematic where the bias is held constant, such as during a plateau of the frequency program. Dynamic losses have not been determined at this time, but will be measured when a suitable bias ramping scheme is incorporated into the setup. All three of these anomalies must be well characterized and mitigated before designing full-sized cavities.

SUMMARY

We have developed an accurate measurement methodology to fully characterize ferrite cores for the design of cavities for the AHF Booster and MR. Three types of ferrite have been tested, and a summary of the results are presented. Material 4M2 or 4B3 appear satisfactory for the MR while 8C12 would be suited for the Booster cavities.

ACKNOWLEDGEMENTS

We would like to thank Dave Wildman of FNAL and Dennis Friesel of IUCF for ferrite cores for this study. We thank Alex Zaltsman for advice and for giving us time to test the prototype SNS buncher cavity at BNL. This full-sized cavity contains 4M2 ferrite.

REFERENCES

[1] G. Rakowsky and A. Tranis, "Nonlinear Effects in Linear Ferrites at High RF Fields", IEEE Trans. Nucl. Sci., NS-16, p. 543-5, June, 1969.
[2] Y. Tanabe, et. al., "Dependence of RF Characteristics on AC Bias Current for Large-Sized Ferrites", Electrical Eng Japan, Vol. 127, No. 4, 1999.
[3] J. Griffin and G. Nicholls, "A Review of Some Dynamic Loss Properties of Ni-Zn Accelerator RF System Ferrite", IEEE Trans. Nucl. Sci., NS-26, p. 3965-7, June, 1979.