



FERRITE DAMPING FOR THE MAIN ACCELERATOR CAVITIES - I

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INTRODUCTION

Accelerators¹ and storage rings² share the problem of unwanted interactions between rf cavities and the particle beam. Various types of instability may arise, especially at appreciable beam current³. Unless care is taken to decouple or damp unwanted resonances or place them in "safe" frequency zones, instabilities may arise either at the fundamental or at frequencies above the fundamental. Efforts to synthesize special rf cavities (which may be regarded as two part or 3 port networks from the point of view of network theory) to give a prescribed gap impedance spectrum over a wide frequency range have not yet had unqualified success - it remains easier to analyze a given resonator for its modes, poles and zeros than to synthesize a resonator to order^{4, 5}.

The question of limits on cavity impedance spectra (in magnitude, frequency and phase angle) tolerated by the 400 ma Main Accelerator proton beam of the NAL machine is being actively pursued by J.E. Griffin at the present time. It is assumed for this report that resonances between 53 Mhz (the fundamental), and 212 Mhz (the fourth harmonic) can be displaced into safe zones; for higher frequencies, appreciable damping will be required.

PRIMARY GOALS

This report describes the use of two ferrite rings added to the Main Accelerator cavity of ref. 1 to damp resonances above 53 Mhz.

The primary goals of the ferrite absorber to be described are:

1. Added power loss at the fundamental shall not exceed 2-3 KW (which is 2 - 3% of the design power level of 100 KW).
2. The absorber shall be a water-cooled, permanent part of the cavity.

3. Tuning and tolerances shall be as broad as possible in the absorption range, which extends from above 53 Mhz continuously to 1000 MHz or higher.
4. The absorber shall at the upper frequencies approximate a black-body absorber (i.e. = an open window to empty space). This requires that the absorber material present a wave impedance in the neighborhood of 377 ohms/square.
5. The external tuning means used to swigg the cavity fundamental resonance by the required 0.55% shall not destroy the effectiveness of the absorber.
6. Accelerating gap shunt impedance shall be of the order of a megohm at the fundamental, and 1000 ohms or less from 265 Mhz onward.

The two ferrite rings can be regarded as lossy microwave windows, absorbing most of the short-wave energy incident on them but transmitting with little loss at the longer wavelength of 53 Mhz. They transmit 53 Mhz energy to a mirror whence it is reflected back into the cavity.

FERRITE PROPERTIES OF SPECIAL INTEREST

Ferrites, ceramic ferrimagnetic materials with the spinel crystal structure,^{6, 7} have complex (possessing real and imaginary parts) permeability and permittivity spectra. Two ferrite features of special interest for the present absorber application are:

1. The imaginary part μ'' of the complex permeability varies by orders of magnitude over a frequency range determined by the type of ferrite selected, and 2. The wave impedance $Z \equiv \sqrt{\frac{\mu \mu_0}{\epsilon \epsilon_0}} (1 + j \frac{\tan \delta}{2})$

comes reasonably close to 377 ohms, $\sqrt{\frac{\mu_0}{\epsilon_0}}$,

in certain useful frequency regions, again determined by the types of ferrite selected.

The two types of ferrites discussed in this report are Indiana General Q-2, and Stackpole 12 (see references 8 and 9)

CIRCUIT REPRESENTATION

The absorber is an addition to the basic accelerating cavity. See Figure 7-2, Main-Synchrotron Accelerating Cavity, of Reference 1.

Although the absorber is in fact a distributed microwave transmission system, we for simplicity first describe it as if it were constructed of lumped circuit elements. (In the Recommendations section, Recommendation #1 points out that an adequate description in wave terms is a next step to be undertaken).

First, imagine the cavity "unfolded", Figure 1.

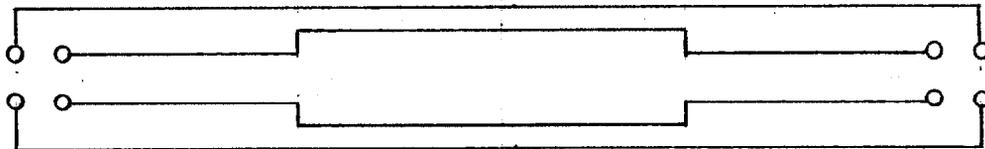


FIG. 1 - A view of the Main Accelerating Cavity, unfolded.

Second, picture the connection of a series RC combination across each gap, spanning the gap voltage V_{pk} . See Fig. 2

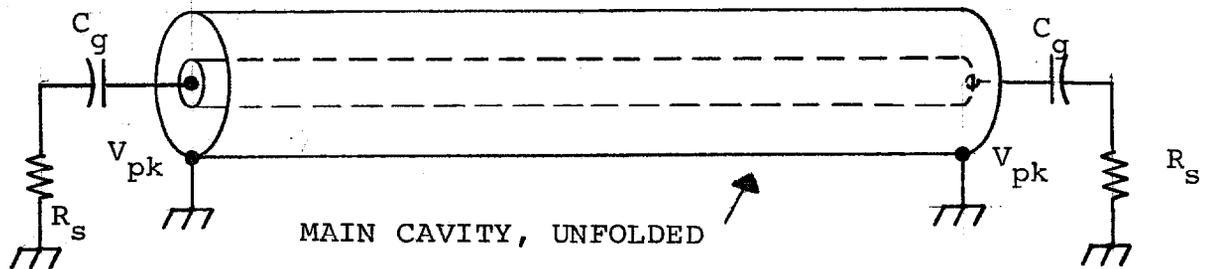


FIG. 2 - Circuit Representation of Absorbers

Two remarks can be made: 1. TEM waves, (and some others) in the main cavity will see some damping, probably increasing as the frequency rises, and 2. there will always be some power loss at the fundamental.

It is proposed to use the existing cavity gap to provide C_g (about 4 pf), and to use the μ''_s of ferrite rings to supply R_s (which is frequency-dependent, rising from .1 Ω at the fundamental to tens of ohms at higher frequencies).

Let us discuss the power loss at the fundamental. We agree to dissipate one to one and a half kilowatts in each resistor R_s . We shall take $V_{pk} = 120$ KV. There is a certain rms current I flowing in the RC circuit at the fundamental. Table I lists a few possibilities for the current and power loss.

TABLE I - CURRENT AND POWER LOSS

FREQUENCY	I	C_g	R_s	$P = I^2 R_s$
53 Mhz	100 amps	3.7 pf	.1 Ω	1 KW
53 Mhz	100 amps	3.7 pf	.15 "	1.5 KW
53 Mhz	113 amps	4 pf	.0785 "	1 KW
53 Mhz	113 amps	4 pf	.1175 "	1.5 KW
53 Mhz	200 amps	7.5 pf	.025 "	1 KW
53 Mhz	200 amps	7.5 pf	.0375 "	1.5 KW

On the basis of $C = \frac{K_0 A}{d}$ for gap capacitance, taking the gap to be approximated by a pair of discs 3-3/4 inches in radius spaced 3 inches apart, I find $C \approx 3.7$ pf. A more elegant calculation of gap capacitance is in order, but on the basis of the present calculation I take 4 pf as a design value (the gap can in fact be adjusted to exactly 4 pf if we desire).

Thus the current I at the 53 Mhz fundamental is 113 amps, and we wish R_s to be about 0.1Ω at the fundamental. We summarize the values obtained so far:

$$f = \text{fundamental resonant frequency} = 53 \times 10^6 \text{ Hz}$$

$$R_s = \text{equivalent series resistance} \approx 0.1 \Omega \text{ at } 53 \text{ Mhz}$$

$$C_g = \text{equivalent gap capacitance} = 4 \times 10^{-12} \text{ f}$$

$$X_c = \text{reactance of gap} = 750 \text{ ohms @ } 53 \text{ Mhz}$$

$$I = \text{RMS current through } R_s = 113 \text{ amps @ } 53 \text{ Mhz}$$

$$V_{pk} = \text{peak rf voltage at one gap} = 120 \times 10^3 \text{ volts at } 53 \text{ Mhz}$$

$$\omega = 2\pi f$$

$$I = \frac{\sqrt{2}}{2} \omega C_g V_{pk}$$

Now visualize a ferrite toroid threaded on a current-carrying conductor, Figure 3:

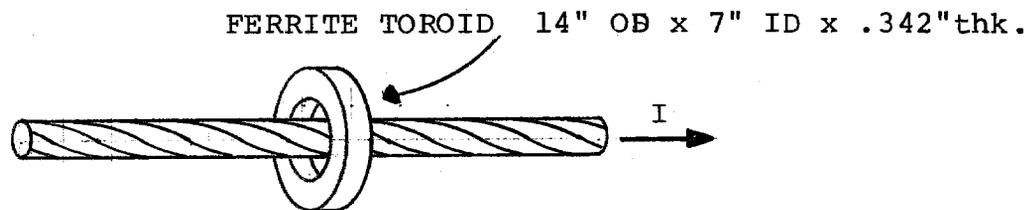


FIG. 3 - Ferrite toroid on current-carrying conductor.

The conductor carries 113 amps at 53 Mhz.

The impedance of the inductor so formed may be written as

$$Z = j \omega L_0 \mu'_s + \omega L_0 m''_s \quad (1)$$

$$= j \omega L_s + R_s \quad (2)$$

L_s is the inductance added to the circuit by the presence of the ferrite and R_s is the series resistance added to the circuit by the presence of the ferrite.

L_0 is the "air-core" equivalent inductance due to flux in the core (i.e. flux in a space = core geometry). Let the cores' outer diameter = D , the inner diameter = d , and the thickness = ℓ .

(This calculation fits TEM mode geometry)

Then

$$L_0 = \frac{\mu_0 \ell}{2\pi} \ln \frac{D}{d} \quad (3)$$

where $\mu_0 = 4\pi \times 10^{-7}$ Hy/meter (permeability of free space)

$$\vec{\mu} = \mu'_s - j\mu''_s \quad (4)$$

The permeability of the ferrite is complex; the real part of the series complex permeability μ'_s establishes the inductance L_s whereas the imaginary portion of the complex permeability μ''_s determines the loss resistance R_s .

The concept of series complex permeability is normally implied in magnetic material manufacturers' handbook specifications. That is, the value of permeability usually published is the real part μ'_s of the series complex permeability. Most unfortunately, it is often designated as μ_0 , ergo when it appears in manufacturers literature, care should be taken * not to confuse it with μ_0 , the permeability of free space.

Not all manufacturers quote μ''_s for their material, but may quote the magnetic Q or the loss tangent. The imaginary part, μ''_s , is contained in the loss tangent:

$$\text{Tan } \delta = \frac{\mu''_s}{\mu'_s} = \frac{R_s}{\omega L_s} = \frac{1}{Q} \quad (5)$$

where $\text{Tan } \delta$ = tangent of the magnetic loss angle, and Q is the magnetic Q .

It clearly follows that the dielectric constant (permittivity) is also complex in ferrite, and has to be taken into account:

$$\epsilon = \epsilon' - j\epsilon'' \quad (6)$$

A set of relations analogous to (5) holds for the dielectric loss tangent and dielectric Q .

STUDY OF SELECTED LITERATURE

Refer to the published data for Q-2 ferrite (Indiana General, Keasby, N. J.). Reference 8.

For an introduction, observe that at 53 Mhz,

$$\mu' = \text{real part of series complex permeability} = 42$$

$$\epsilon' = \text{real part of complex dielectric constant} = 10$$

$$\text{Tan } \delta_d = \text{dielectric loss tangent} = .006$$

$$\text{Tan } \delta_m = \text{magnetic loss tangent} = .006$$

Note that ϵ' is practically constant from 50 Mhz to 2 Ghz. Note that Indiana General used μ_0 to denote μ' .

We can calculate values of μ''_s from the I.G. curves:

TABLE II VALUES OF μ'' FOR Q-2

f, Mhz	μ'_s	Tan δ_m	$\mu''_s = \mu'_s$ Tan δ_m
10	40	.004	.16
40	41	.005	20
53	42	.006	.25
100	58	.2	12
200	20	1.0	20
400	10	1.6	16
1000	7	1.4	10
2000	.8	8	6.4

The dramatic rise of μ''_s with frequency is a basic property we wish to use effectively as possible. It depends on domain wall resonance (the first loss peak) and gyromagnetic precession (the second loss peak).

Now refer to the published data for ST-12 (Stackpole Carbon Co., St Marys, Pa.), Fig. 2 on page 3, Stackpole Bulletin 50B, Ref. 9. We can construct the following table, this time starting with $\mu_0 Q$ as the input:

TABLE III VALUES OF μ'' FOR ST-12

f Mhz	$\mu_0 Q$	$\mu''_s = \frac{(\mu')^2}{\mu_0 Q}$
10	10,000	
20	8,500	
30	7,100	
40	6,200	
50	5,300	.231
60	4,500	
70	3,800	
80	3,100	
90	2,400	
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Although the $\mu_0 Q$ is not published for higher frequencies, we can conclude that ST-12 is a material worth investigating.

Cross licensing agreements have been in effect between Indiana General and Stackpole on these materials.

DETERMINATION OF WINDOW DIMENSIONS

The size of the window will now be discussed. Figure 4 shows the configuration of the ferrite absorber windows. They are placed on each side of the gap splitter plane in the center of the cavity and appear as the cross-hatched regions in the figure. The method of attachment is to metallize the ferrite and braze it to the OFHC copper heat sink. After brazing to the heat sink, the ferrite could be ground flat.

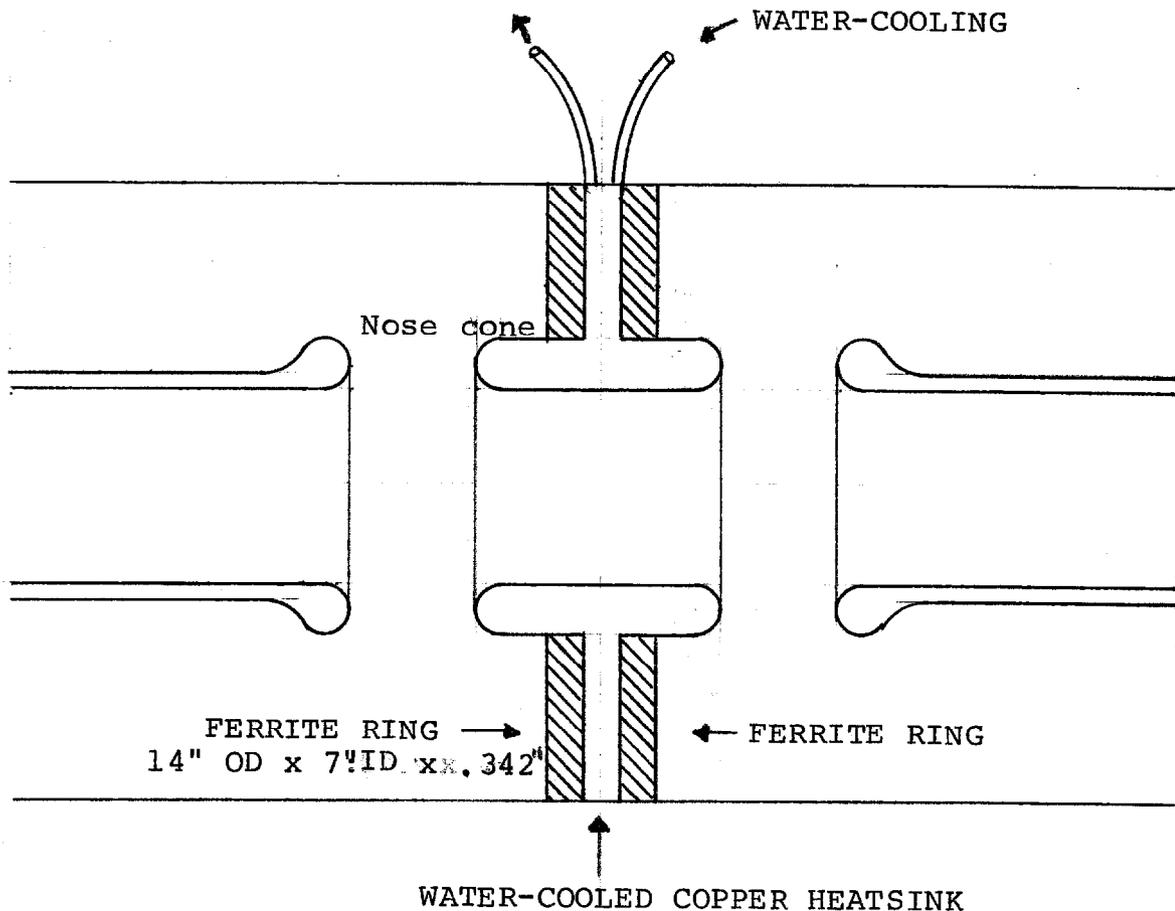


FIG. 4 - Configuration of ferrite absorber windows

Since we desire the window to present the maximum possible area to waves approaching from the left and right, we choose the window outside diameter $D=14$ inches, the window inside diameter $d = 7$ inches, and are left to calculate L_0 and the thickness ℓ , which we can do immediately.

From equations (1) and (2),

$$R_s = \omega L_0 \mu''_s, \quad \text{or}$$

$$L_0 = \frac{R_s}{\omega \mu''_s} \quad (7)$$

Given $R_s = 0.1$ ohm (power loss - 1280 watts)

$$\omega = 2\pi 53 \times 10^6 \text{ Hz}$$

$$\mu''_s = 0.25,$$

$$L_0 = \frac{0.1}{2\pi 53 \times 10^6 \times 0.25} = 1.2 \times 10^{-9} \text{ Hy.}$$

From equation (3), the window thickness

$$\ell = \frac{2\pi L_0}{\mu_0 \ln \frac{D}{d}} = \frac{2\pi \times 1.2 \times 10^{-9}}{4\pi \times 10^{-7} \times 0.69315} = .867 \text{ cm} = .342 \text{ inches}$$

In summary, the window dimensions are:

$$\text{od} = 14 \text{ inches} = 35.5 \text{ cm}$$

$$\text{id} = 7 \text{ inches} = 17.75 \text{ cm}$$

$$\text{thickness} = 0.342 \text{ inches} = 0.867 \text{ cm}$$

$$\text{volume} = 645 \text{ cm}^3$$

$$\text{weight} = 7 \text{ lb.}$$

$$\text{area of one face} = 115 \text{ inches}^2$$

$$\text{power/unit area} = 1.7 \text{ watts/cm}^2$$

$$\text{window } L_0 = 1.2 \times 10^{-9} \text{ Hy @ 53 Mhz}$$

$$\text{window } R_s = 0.1 \text{ ohm @ 53 Mhz}$$

$$\text{Cost} = \$280 \text{ @ } \$20/\text{lb.}, \text{ for two windows}$$

$$\text{Power loss for two windows} \sim 2.6 \text{ KW}$$

PHYSICAL PROPERTIES

Thermal conductivity $\approx 1.5 \times 10^{-2}$ cal/sec/cm/°C

Young's modulus $\approx 1.5 \times 10^{12}$ dynes/cm²

Coeff. of Thermal Expansion $\approx 8 \times 10^{-6}$ /°C

Density ≈ 4.5 gm/cm³

The ferrites need not be one-piece rings; they may be ring segments bonded to the heat sink.

ESTIMATE OF DAMPING

The following rough formula for damping is based on Fig. 2, where Z_0 is the characteristic impedance ($\approx 60 \Omega$) of the main cavity and X_C is the reactance of C_g . The Q of any high impedance resonance (pole) is

$$Q \approx \frac{\pi X_C^2}{4 R_S Z_0}$$

We can construct a table of values of for X_C and R_S as a function of frequency: recall that

$$R_S = \omega L_0 \mu''_s, \text{ and see Table II.}$$

TABLE IV - VALUES OF X_C , R_S AND Q

<u>RESONANCE-</u>	<u>f Mhz</u>	<u>X_C ohms</u>	<u>R_S ohms</u>	<u>Q</u>
fundamental	53	750	0.1	75,000
2nd	106	375	9.6	
3rd	159	250	19	
4th	212	188	32	15
5th	265	150	36	8
6th	318	125	41	5
10th	530	75	56	~ 2
20th	1060	37.5	79	~ 1

CAUTIONS

A list of caveats is appropriate here. For one thing, calculations based on a lumped circuit and published values should not be pushed to the limit and indeed Table IV is intended foremost as an illustration of the powerful absorption trend.

Second, the ferrite is operating warm and at a flux level of 80 gauss ($H = 2$ oe), and hence its properties will be somewhat different from the handbook values.

Third, Q-2 is a Perminvar ferrite; its properties are altered if it is strongly gaussed (as is ST-12).

Fourth, there will be various modes possible in the ferrite window itself, the wavelength being contracted by the factor $\sqrt{\mu\epsilon}$. This point, however, can be an advantage; at these dimensional-resonant frequencies, the absorption will generally increase (the right direction). Therefore, the ghost modes could be set to specifically kill certain main cavity resonances.

RECOMMENDATIONS FOR FURTHER WORK

1. Make an engineering study of the absorber geometry, treating it as a lossy microwave window at the end of a short-circuited coax line. Window thickness, length of nose cones, and gap spacing should be studied. (For a given power loss, $C_g^2 \ell \mu''_s = \text{constant}$).
2. Assemble additional ferrite permeability and permittivity spectra for likely materials. (MIT Laboratory for Insulation Research is a suggested source).
3. Construct a reduced-diameter, full axial length prototype test cavity with absorber windows, designing the windows (and cavity) to utilize a stock size Q-2 core. Note that TEM modes will remain at 1:1 in frequency, but TE and TM modes will be displaced to higher

frequency, with respect to the full-size prototype. Perform cold tests over the range 53 to 1000 Mhz.

4. Explore the use of Q-3 material for TE and TM mode damping.

5. Construct a full-size prototype, using segments of ferrite to approximate a ring, and cold-test.

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