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FINEMET VERSUS FERRITE — PROS AND CONS

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Abstract

There is a new magnetic alloy called Finemet which has very constant $\mu_p' Qf$ up to ~2 kG and is very stable at high magnet flux density and temperature. It may be a good candidate for high-gradient rf cavities.However, it has a rather low quality factor and is therefore very lossy. We compare the pros and cons of Finemet versus the common ferrite, when used in low-energy accelerating cavities, insertion for space-charge compensation, and barrier cavities.

1 INTRODUCTION

Ferrite has been used extensively in rf cavities for particle accelerators that require tuning. Some ferrite used can operate up to more than 100 MHz but the saturation magnetic flux intensity is often limited to $100{\sim}200$ G. Recently, there is a met-glass-like material called Finemet developed in Japan [1] that can hold up to 2 kG of magnetic flux intensity (Fig. 1). Ferrite is ceramic in nature and is manufactured by baking in an oven. Therefore, large ferrite cores are difficult to produce. On the other hand, Finemet is in the form of a tape which can be wound into a core over 1 m in diameter, making very high magnetic flux possible. For this reason, Finemet may open up a new way to the construction of high gradient acceleration cavities. However, there are also shortcomings. Its relative permeability μ_p' starts to drop at a much lower frequency, ~2 MHz, and the quality factor is low, $Q\sim1$, although they can be boosted to ~8 MHz and $Q\sim12$ by cutting the cores and leaving an air gap between the two semicircular halves. This implies that Finemet is more lossy with larger power consumption. Fortunately, Finemet has a Curie temperature $\sim600^\circ$C while that for ferrite is only 100 to 200°C, meaning that heat dissipation will be more efficient. The manageable power dissipation [1] is believed to be around 10 W/cm^3. Thus, the limitations Finemet are power dissipation and high frequency, while that of ferrite is high magnetic flux density, In this note, we compare the use of Finemet and ferrite in three respects: accelerating cavities, space-charge compensating insertions, and rf barriers for multiple-turn injection. The proposed future Fermilab low-energy booster and the Brookhaven AGS will be used in the application.

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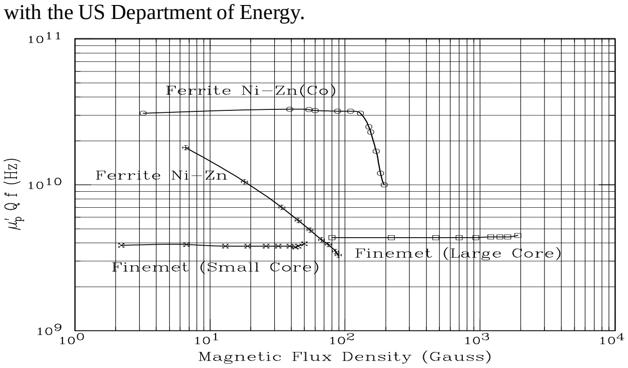

Figure 1: Plots showing the $\mu_p' Qf$ properties of ferrite and Finemet as a function of magnetic flux density.

2 ACCELERATING CAVITIES

The future Fermilab booster consists of two rings [2]. The low-energy ring has a circumference of 158.0676 m (1/3 of present booster), cycles at 15 Hz, and accelerates 4 proton bunches, $N_b = 2.5\times10^{13}$ protons each, from kinetic energy 1 GeV to 3 GeV. The 10 accelerating cavities have a rf frequency span of 6.638 to 7.368 MHz, and require a total peak voltage of ~190 kV, or ~20 kV each. For such a small ring, small cavities are preferred, making high-field Finemet very appealing. The FT3M Finemet cores considered here have inner and outer radii 10 and 50 cm, respectively, while the Philips 4M2 ferrite cores have inner and outer radii 10 and 25 cm. Both cores have a thickness of 2.54 cm. The Finemet cores are cut with an air separation of 4.6 cm so that the quality factor can be boosted to $Q=11.4$ [1]. The details are listed in Table 1. If there were only one core, the flux density would be $B_{\rm rf}=V_{\rm rf}/(\omega_{\rm rf}A_f)$. To limit dissipation to below the manageable 10 W/cm^3, at least 2 Finemet cores are required per cavity. Allowing ~2.54 cm separation between cores for air cooling, the length of a cavity can be made as short as ~13 cm. However, the power loss is 324 kW per cavity. On the other hand, if ferrite is used, to satisfy its flux density limitation, we need 11 cores with a total cavity length ~28 cm. Here core spacing is not required because the total power loss for the whole cavity is only 10.2kW. Although longitudinal space is saved in the Finemet cavities, power loss will be 31.8 times larger, totaling 3.24 MW for 10 cavities. Assuming the acceleration of 1×10^{14} particles takes place in 1/30 of a second, the average

Table 1: Properties of a Finemet and a ferrite cavity.

	Finemet	Ferrite
Inner radius r_i	10.00	10.00 cm
Outer radius r_o	50.00	25.00 cm
Core width t	2.54	2.54 cm
Flux area $A_f=(r_o-r_i)t$	101.60	38.1 cm^2
Core volume $V_c=\pi(r_o^2-r_i^2)t$	19155	4189 cm^3
Rf frequency $f_{\rm rf}$	7.37	7.37 MHz
Quality factor Q	11.4	45
$\mu_p' Qf$ at $f_{\rm rf}$	6.00	61.0 GHz
Permeability ($\mathcal{R}e$) μ_p'	71.43	184.0
Permeability ($\mathcal{I}m$) $\mu_p''=Q\mu_p'$	814.33	8279
Inductance L	0.5840	0.8654 μH
Resistance $R=Q\omega_{\rm rf}L$	308.2	1784 Ω
Capacitance $C=1/(\omega_{\rm rf}^2 L)$	798.9	544.9 pF
Accelerating voltage $V_{\rm rf}$	20	20 kV
Total flux density if one core $B_{\rm rf}$	425.2	1134 G
Suitable flux density per core	250	100 G
Number of cores required N	2	11
Power per core P_1	162.2	0.926 kW
Power for N cores $P=NP_1$	324.4	10.19 kW
Power per volume P_1/V_c	8.47	0.221 W/cm^3

power delivered to the particles is only 0.96 MW. Of course, more Finemet cores can be used to reduce the power dissipation, but its advantage of accommodating high flux density will be lost. However, Finemet cavities do have other merits. Because of the low quality factor, no tuning may be necessary during the whole acceleration cycle, and the cavity may be able to encompass several higher harmonics. In fact, a multiple-harmonic cavity had been built using similar material but in amorphous form called Vitrovac [4].

Each bunch carries a charge of $q = 4.0\,\mu$C. On passage of a cavity, some amount of negative charge will be deposited at the upstream end of the gap. An equal amount of positive charge will accumulate at the downstream end. For a Gaussian bunch, the transient beam-loading gap voltage at a time t after the bunch center passes the cavity gap is

$$V_t = \frac{q\omega_r R}{2Q\cos\phi}\mathcal{R}e\, e^{j\phi - t^2/(2\sigma_\tau^2)} w\left[\frac{\sigma_\tau\omega_r e^{j\phi}}{\sqrt{2}} - \frac{jt}{\sqrt{2}\sigma_\tau}\right], \quad (1)$$

where w is the complex error function, $\sin\phi = 1/(2Q)$, R the *total* resistance of all the cores in series. When the rms bunch length $\sigma_\tau \to 0$, this becomes q/C, C being the *total* capacitance of all the cores in series. With $\sigma_\tau = 12.63$ ns, V_t reaches the maxima of 5.30 and 44.6 kV, respectively, for the Finemet and ferrite cavities when $t \approx 0.85\sigma_\tau$. This is understandable because there are many more ferrite cores than Finemet cores in a cavity. Since V_t are not negligible with respect to the designed gap voltage, compensations must be made at the gap through feed-forward [3]. If the Finemet cores do not have the 4.6 cm gap, one will have $\mu_p' Qf = 3.7$ GHz and $Q = 1$ instead. Now 3 cores have to be used. The power dissipation increases to only 351 kW, but the maximum beam-loading voltage to 34.8 kV.

The inductance of Finemet is very sensitive to the longitudinal bias field, as is illustrated in Fig. 2. This is a merit in the sense that the inductance can be changed easily. However, this can also be a disadvantage that the precision of inductance control will be much worse than ferrite.

3 SPACE-CHARGE COMPENSATION

A high-intensity and low-energy bunch experiences a large longitudinal space-charge force. A particle at time advance τ from the bunch center sees, for each turn, a space-charge voltage $V_{\rm spch} = -\omega_0^{-1}(d\rho/d\tau)|Z_\parallel/n|_{\rm spch}$, where $\rho(\tau)$ is the linear density of the bunch and ω_0 the angular frequency of the ring. The space-charge impedance per harmonic is $Z_\parallel/n = -jZ_0[1+2\ln(b/a)]/(2\beta\gamma^2)$, where β and γ are the Lorentz factors, $Z_0 \approx 377\ \Omega$, a and b the radii of the beam and the beam pipe. In order to keep the beam particles bunched, extra rf voltage will be required. One way to cancel this space-charge impedance is to add an inductive insertion in the vacuum chamber [5]. Such an attempt [6] had been performed at the Los Alamos PSR, where 60 Toshiba M_4C_{21A} ferrite cores were inserted intending to cancel about 2/3 of the space-charge force. Wire windings on the outside were used to provide perpendicular biasing so that the relative permeability of the ferrite could be controlled. With the ferrite insertion, it was found that only about 2/3 of the usual rf voltage would be required to keep the bunch stable. When the solenoidal current was turned on, the bunch was found lengthened. Thus the ferrite insertion did actually cancel part of the space-charge force. Another similar experiment had been performed at the KEK Proton Synchrotron with 8 Finemet cores [7]. The incoherent quadrupole synchrotron frequency was measured as a function of beam intensity. The slope of the frequency was reduced by half. The result is consistent with a partial cancellation of the space-charge impedance.

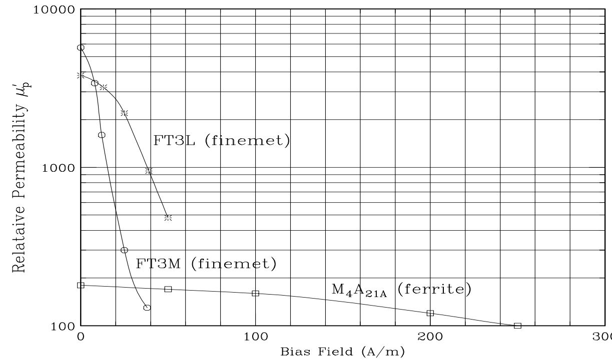

Figure 2: Sensitivity to bias field for Finemet and ferrite.

Here, we would like to apply the inductor insertion to the Fermilab low-energy booster ring, with bunches having half widths $\hat\tau = \sqrt{5}\sigma_\tau = 28.25$ ns. The space-charge impedance per harmonic is about $-j89.5\ \Omega$. Unlike the accelerating cavities, the bunch current will dump energy into the insertion at all frequencies. To estimate this energy, assume a simple model consisting of an *ideal* inductance L and an *ideal* resistor R in parallel, which gives

$$Z(\omega) = j\omega L\frac{1 - j\omega/\omega_r}{1 + \omega^2/\omega_r^2} \propto j\omega(\mu_s' - j\mu_s'')\ , \quad \omega_r = \frac{R}{L}\ , \quad (2)$$

so that the series μ_s' is relatively constant at low frequencies and rolls off near ω_r, while μ_s'' increases as ω at low frequencies and resonates at ω_r. The corresponding longitudinal wake potential is $W(t) = R\left[\,\delta(t) - \omega_r e^{-\omega_r t}\,\right]$, and the energy the particle lost to the inductor in one passage is

$$\mathcal{E} = \frac{3e^2N_b}{2}\left[\frac{\tau}{\omega\hat\tau^3} + \frac{1}{\omega_r\omega_0}\right]\left|\frac{Z_\parallel}{n}\right|_{\rm ind}\ , \quad (3)$$

where a parabolic bunch distribution has been assumed. The first term is the linear force from the inductive impedance $Z_\parallel/n|_{\rm ind} = j\omega_0 L$, which is supposed to cancel the space-charge force, leaving behind the second term, which is the actual energy lost to the insertion. Thus for $n_b = 4$ bunches the total power lost to the insertion becomes

$$P = \frac{3en_bN_b^2}{4\pi\omega_r\hat\tau^3}\left|\frac{Z_\parallel}{n}\right|_{\rm ind}\ . \quad (4)$$

If ferrite having a resonant frequency $\omega_r/(2\pi) = 60$ MHz is used, the power lost to the insertion amounts to 0.16 MW. Assuming the ferrite cores in Table I, ~ 34 cores will be required for space-charge cancellation. On the other hand, if Finemet having a resonant frequency 6 MHz is used, the loss becomes 1.6 MW. According to Table 1, 15 Finemet cores are required. The heat dissipation will be 5.6 W/cm^3. However, not much longitudinal space is gained by using Finemet but much more energy has to be injected to counteract the power loss. If uncut Finemet core with $Q = 1$

is used, the resonant frequency is ~ 1 MHz and the power loss will be increased 6-fold. Here, the merits of high μ'_p for Finemet can hardly be utilized, because that will lead to a lower Q and lower ω_r, thus increasing the power loss.

Using the same calculation, the power loss to the ferrite cores in the Los Alamos experiment is only 0.82 kW even when the resonant frequency is only 30 MHz. This is because the power loss is inversely proportional to the cubic power of the bunch length. At the Los Alamos PSR, the half bunch length was $\hat{\tau} \sim 133.6$ ns, which is 4.73 times longer. Also, there were only 2.5×10^{13} particles in the PSR.

4 RF BARRIERS

Rf barriers are designed in the Fermilab Recycler ring to confine the antiproton beam bunch and shape the bunch distribution waiting for the next collider refill. Rf barriers are also planned to be used in the Brookhaven AGS and the Japan Hadron Project for multiple injections. For the latter, tens of kV are required and a barrier cavity is necessary. We model the cavity by a parallel RLC circuit. When the switch is closed, the current generator delivers a current $I(t) = I_0\theta(t)$. The cavity gap will respond with a voltage

$$V(t) = \theta(t)\,\frac{I_0 R}{Q}\,e^{-\alpha t}\sin\bar{\omega}t\ , \tag{5}$$

where $\omega_r = (LC)^{-1/2}$ is the angular resonant frequency, $\alpha = \omega_r/(2Q)$, $\bar{\omega} = \sqrt{\omega_r^2 - \alpha^2}$, and $Q = R/(\omega_r L)$ the quality factor. If the current is turned off at $t = 2\pi/\bar{\omega}$, or another current pulse of opposite sign is turned on at that time, the cavity gap voltage will vanish due to cancellation, providing that the degradation $\exp(-2\pi/\sqrt{4Q^2-1})$ is not too excessive. A cycle of sinusoidal gap voltage is generated with peak voltage $V_0 \approx I_0R/Q$. Thus, a large Q will require a large current pulse. But a small Q will lead to incomplete cancellation of the sinusoidal rf wave after the current pulse.

Consider a rf barrier at barrier frequency $f_b = \omega_b/(2\pi) = 2$ MHz and barrier voltage $V_b = 40$ kV in the AGS. This implies a barrier length of $0.5\ \mu$s, while the AGS circumference at 1.5 GeV injection kinetic energy is $2.917\ \mu$s. Again we use the large FT3M Finemet cores with a cut of 4.6 cm and the 4M2 ferrite listed in Table 1. The properties of such a Finemet or ferrite barrier cavity are listed in Table 2. In order to keep the power loss of Finemet below 10 W/cm^3, we have to use at least 6 cores with an average flux density of 522 G. If ferrite is used, the average flux density has to be limited to 100 G, requiring 84 cores. The Finemet cavity will take up only ~ 33 cm while the ferrite cavity ~ 214 cm. However, the power dissipation in the Finemet is 95.6 times larger than the ferrite. Since the barrier wave is only present for 0.5 μs, the average power dissipation $P_{\rm av}$ is about 148 kW for the Finemet and 1.55 kW for the ferrite, much less than those computed in the rf cavities in Section 1. Finemet may therefore be a good choice in building a barrier cavity if space limitation is a serious problem.

For an AGS bunch with 6.0×10^{12} protons and $\sigma_\tau = 60$ ns, the transient beam-loading voltages computed using Eq. (1) have maxima 0.20 and 4.5 kV, respectively, for the Finemet and ferrite barrier cavities. If required, they should be compensated by feed-forward. If uncut Finemet cores are used, $\mu'_p Q f = 2$ GHz and $Q = 1$. One requires 7 cores so that the loss is still below 10 W/cm^3. The total average power dissipation increases to only 191 kW, but the maximum transient beam-loading voltage jumps to 2.2 kV.

Table 2: Properties of a Finemet and a ferrite barrier cavity.

	Finemet	Ferrite	
Barrier frequency f_b	2.00	2.00	MHz
Quality factor Q	24	110	
$\mu'_p Q f$ at $f_b = 2$ MHZ	3.00	36.0	GHz
Permeability ($\mathcal{R}e$) μ'_p	62.5	163	
Permeability ($\mathcal{I}m$) $\mu''_p = Q\mu'_p$	1500	18000	
Inductance L	0.511	0.762	μH
Resistance $R = Q\omega_b L$	154	1053	Ω
Capacitance $C = 1/(\omega_b^2 L)$	12400	8314	pF
Barrier voltage V_b	40	40	kV
Total flux density if one core $B_{\rm rf}$	3133	8355	G
Suitable flux density per core	522	100	G
Number of cores required N	6	84	
Peak power per core P_1	144.2	0.1077	kW
Pk power for N cores $P = NP_1$	865.2	9.046	kW
Average power for N cores $P_{\rm av}$	148.3	1.55	kW
Av power per volume $P_{\rm av}/(NV_c)$	7.53	0.026	W/cm^3

5 CONCLUSION

It is clear that longitudinal space will be saved and transient beam loading will be smaller when Finemet is used instead of ferrite, especially in acceleration and barrier cavities. However, this gain arrives at the expense of much larger power dissipations. The obvious reason comes from the fact the Finemet has much lower resonant frequencies and lower Q's than ferrite. Therefore when longitudinal space is limited, especially for very small low-energy rings, Finemet cavities may be a solution. It is possible that Finemet will become very valuable in other applications at sub-MHz frequencies when high magnetic flux densities are required.

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