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Introduction

The ferrite assembly in a window frame magnet is usually treated as a simple inductance for the transverse [1] and longitudinal [2] impedance. Under certain conditions with low frequency resonance, such as the cases in [1,3], this model can be used to estimate the kicker impedance. In other cases, the resulted impedance is not always closely agreeable to the measurement.

A better ferrite model includes the losses, which is represented by the imaginary part of the relative permeability. For high permeability ferrite, usually with lower quality factor Q, this loss becomes not negligible.

Perhaps equally important factor is that the beam energy is stored not only in the magnet inductance, but also in the parasitic and/or inherent capacitance in the ferrite assembly.

This indicates that a resonance model for the ferrite assembly, which includes both inductive and capacitive elements, and resistive losses as well, could be used to explain the impedance observed in the measurement.

The window frame magnet is used for the AGS injection kicker, Booster extraction and dump kickers, RHIC abort kicker, and also proposed for the SNS extraction kicker. It is important to have a correct estimate of the associated impedance, both transverse and longitudinal.

In this article, we first review the relevant ferrite model and properties, then a resonance model of the ferrite assembly is proposed. The model is used to explain the transverse and longitudinal impedance observed in the Booster dump kicker impedance measurement. A comparison of this model with the Nassibian-Sacherer formulation will be presented.

In presenting the ferrite properties, we consider first the usual ferrite model with inductance and resistance in series. A parallel model can be derived from the series model. Effective permeability of the ferrite with an air gap is reduced significantly from the one without gap, meanwhile, the quality factor is increased. Therefore, the general situation of the ferrite with air gap will be discussed. The ferrite with air gap is relevant in transverse for the window frame magnet, and also in longitudinal for the magnet with flux break copper sheet. Issues of the dimensional resonance, caused by the high relative permittivity of the ferrite, and the ferrite conductivity, are also discussed.

In presenting the resonance model for the ferrite assembly, each component, i.e. L, R, and C, will be defined for transverse and longitudinal cases, respectively.

For the kickers in application at the BNL, CMD5005 is used, which is a Nickel-Zinc (NiZn) ferrite with the initial permeability of 2,600 at low frequency. To have a better connection with the measurement, actual model of CMD5005 obtained from ferrite measurement will be used. Also other NiZn ferrite with lower initial permeabilities of 650, 300, 100, and 50 will be presented and compared.

In general, the ferrite with high permeability implies lower effective resistance in parallel with the magnet inductance, which can shunt the magnet inductance, and affects the magnet impedance.

Ferrite

Series model

In general, the impedance of a ferrite ring is

$$Z = \frac{j\mu_s\mu_0\omega\ell}{2\pi}\ln\frac{b_2}{b_1}$$

where μ_s is the relative permeability, and $\mu_0 = 4\pi\times10^{-7}$ is the permeability in free space, ℓ is the length of the magnet, and b_1 and b_2 are outer and inner radii. In the case that the resistive loss is not negligible, the permeability μ_s can be written, more completely as,

$$\mu_s = \mu_s' - j\mu_s''$$

where the real part, μ_s', can be used to calculate the inductance the beam sees, i.e.

$$L_s = \frac{\mu_s'\mu_0\ell}{2\pi}\ln\frac{b_2}{b_1}$$

Taking the window frame magnet with $\ell = 0.4$ m, $b_2 = 9.5$ cm, and $b_1 = 7$ cm, with $\mu_s' = 1000$, we get $L_s = 24.4\mu H$.

The imaginary part of the permeability, μ_s'', can be used to calculate the resistance R_s,

$$R_s = \frac{\mu_s''\mu_0\omega\ell}{2\pi}\ln\frac{b_2}{b_1}$$

The quality factor of the ferrite is defined by

$$Q_{ferrite} = \frac{\omega L_s}{R_s} = \frac{\mu_s'}{\mu_s''}$$

Among the losses, hysteresis loss is associated with the field strength, eddy current loss increases with the frequency, and remaining part is the residual loss. Together, these losses cause a phase shift, which is described by,

$$\tan\delta = \frac{1}{Q_{ferrite}}$$

Parallel model

The transformation of the series ferrite model to a parallel one is carried out by,

$$\mu_p' \approx \mu_s'\mu_p' = \mu_s'\left(1+\tan\delta^2\right)$$

and

$$\mu_p'' = \mu_s''\left(1+\frac{1}{\tan\delta^2}\right)$$

One notices that for $Q_{ferrite} >> 1$, $\mu_p' \approx \mu_s'$ and $\mu_p'' >> \mu_s''$. Also for $Q_{ferrite} << 1$, $\mu_p' >> \mu_s'$ and $\mu_p'' \approx \mu_s''$.

Inductance and resistance are then calculated from

$$L_p = \frac{\mu_p'\mu_0\ell}{2\pi}\ln\frac{b_2}{b_1}$$

and

$$R_p = \frac{\mu_p'' \mu_0 \omega \ell}{2\pi} \ln \frac{b_2}{b_1}$$

The quality factor of the ferrite is defined by

$$Q_{ferrite} = \frac{\omega L_s}{R_s} = \frac{\mu_s'}{\mu_s''}$$

It can be shown that the quality factor defined this way is the same as $Q_{ferrite} = \mu_s' / \mu_s''$.

In general, for higher $Q_{ferrite}$, R_s has to be small, and R_p has to be large.

In Fig.1, series permeability parameters are shown for typical NiZn ferrite with the initial permeability μ_i' of 50 to 2600. The one with $\mu_i' = 2600$ is from the measured data of CMD5005 [5] up to 10 MHz [6], beyond that frequency it is projected. Others are from [7,8].

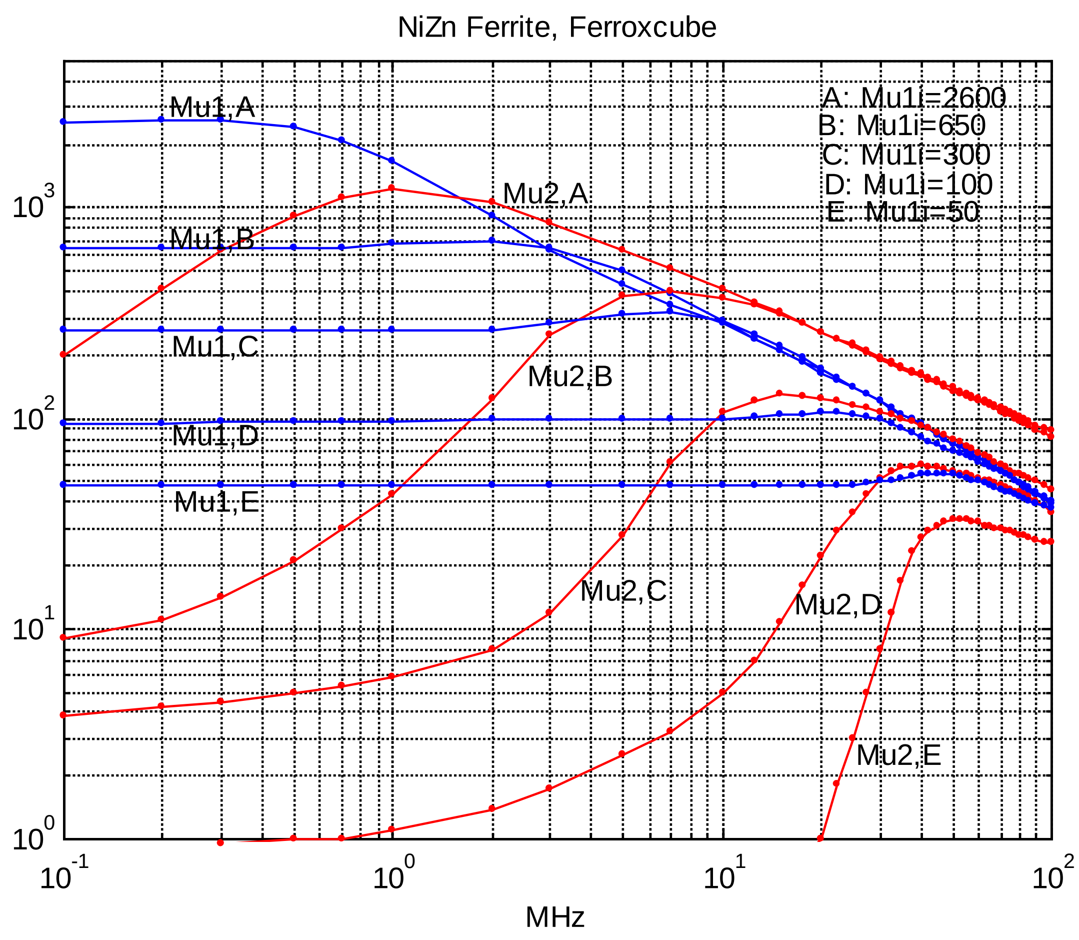

Fig.1

In Fig.2, a comparison of permeability parameters is shown for ferrite with initial permeability of 2600, 300, and 50. The series and parallel parameters are shown on the top and bottom rows, respectively,

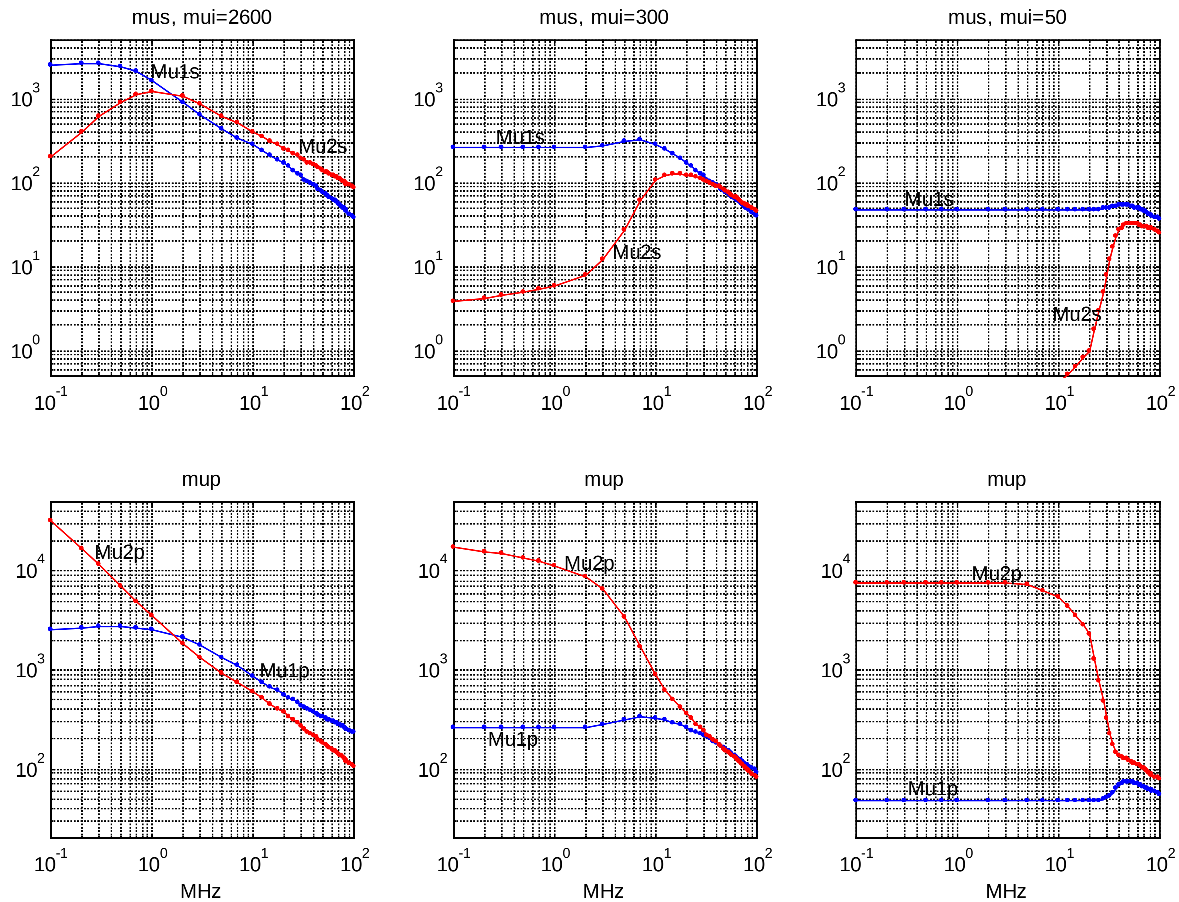

Fig.2

Ferrite with air gap

Assuming that the air gap is small enough that flux does not escape, then the effective permeability, μ'_{se}, is smaller than μ'_s as,

$$\mu'_{se} = \frac{\mu'_s}{1 + g\mu'_s}$$

where g is the ratio of the air gap length over the magnetic flux path. If $g\mu'_s >> 1$, then $\mu'_{se} \approx 1/g$, i.e. the effective permeability is determined by the gap.

To calculate the imaginary part of the permeability, simply write,

$$\mu'_{se} - j\mu''_{se} = \frac{\mu'_s - j\mu''_s}{1 + g(\mu'_s - j\mu''_s)}$$

Equating the imaginary part of the equation, we have

$$\mu''_{se} \approx \frac{\mu''_s}{(1 + g\mu'_s)^2}$$

which shows that with the air gap, the effective ferrite quality factor is increased, i.e.

$$Q_{ferrite,e} = \frac{\mu'_{se}}{\mu''_{se}} \approx \frac{(1+g\mu'_s)\mu'_s}{\mu''_s} > \frac{\mu'_s}{\mu''_s} = Q_{ferrite}$$

The effective parallel parameters can be obtained readily. In Fig.3, the effective parameters with $g = 0.1$ (it is, of course, too large for the ideal condition) are shown for the same ferrites in Fig.2.

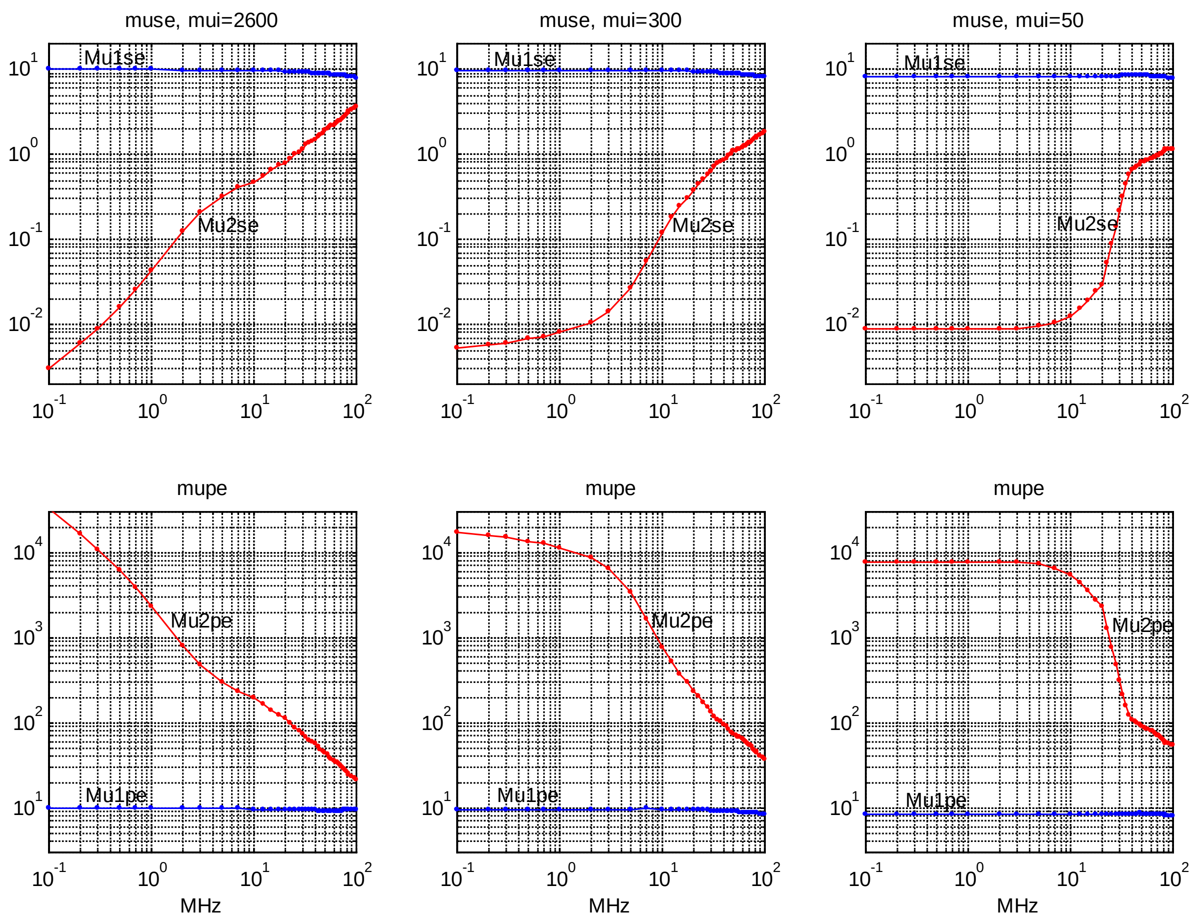

Fig.3

We note that in Fig.3, the formulations developed under the condition of small gap are used for the calculation. The gap ratio of 0.1 is used to get close to the situation of the window frame magnet, but correction is needed in the reading.

Dimensional resonance

In addition to the properties that have been discussed, ferrite usually has high relative permittivity ε_r. At 1 MHz, for Manganese-Zinc (MnZn), typical $\varepsilon_r \approx 10^5$, and for NiZn, $\varepsilon_r \approx 25$. At higher frequency, the permittivity is reduced slightly. For instance, at 100 MHz, $\varepsilon_r \approx 10^4$ for MnZn, and $\varepsilon_r \approx 12$ for NiZn. The consequence following this property is the possible dimensional resonance within the ferrite core. The resonance frequency can be estimated by

$$f_R = \frac{c}{d\sqrt{\mu_i' \varepsilon_r}}$$

where c is the speed of light, and d is the cross section of the ferrite. We consider the NiZn ferrite. For $d = 2.5$ cm, taking $\varepsilon_r \approx 20$, we have $f_R = 53$ MHz and 380 MHz, for the ferrite with $\mu_i' = 2600$ and $\mu_i' = 50$, respectively.

These are marginally relevant to the frequency range of the kicker impedance. However, with air gap, the resonance frequency moves up inversely proportional to the square root of the effective permeability. Therefore, the dimensional resonance of NiZn ferrite is probably not relevant to the kicker impedance. In other words, the intrinsic, or inherent, capacitance of the NiZn ferrite is small, i.e., the dimensional resonance frequency is high, especially with air gap.

Conductivity

The typical conductivity for MnZn is $\sigma = 0.1$ to $10(\Omega m)^{-1}$, and it is much smaller for NiZn, at $\sigma = 10^{-6}$ to $10^{-4}(\Omega m)^{-1}$. For NiZn ferrite, therefore, usually the conductivity is negligible.

Resonance Model

Introducing parasitic capacitance and resistive losses, which are relevant in both transverse and longitudinal impedance, a resonance model for the ferrite assembly is considered. The parallel R, L, and C give rise to

$$Z = \frac{R}{1 + jQ(\omega/\omega_R - \omega_R/\omega)}$$

where

$$\omega_R = \frac{1}{\sqrt{LC}}$$

and

$$Q = R\sqrt{C/L}$$

The key parameters in this model need to be defined as follows.

Inductance

For transverse, the inductance is determined by the large air gap $2a$, which can be estimated by the experimental formulation,

$$L = \frac{\mu_0 b_1 \ell}{a}$$

Taking $\ell = 40$ cm, $a = 5$ cm, and $b_1 = 7$ cm, we get $L = 0.7\mu$H. The measured inductance for a window frame magnet is usually agreeable with this calculation.

We note that if the gap is small, then the inductance can be calculated with the effective permeability. This will be discussed further later.

With the flux break, the longitudinal inductance beam sees is determined by the flux leakage through the copper sheet, which is estimated as [9],

$$L = \frac{\mu_0 \ell}{\pi} \ln \frac{\pi a}{2\delta_{copper}}$$

where δ_{copper} is the thickness of copper sheet, and $2a$ is the inner height of the window frame magnet. Taking $\delta_{copper} = 1$ mm, we get $L = 0.7\mu$H.

We notice that for window frame magnet with copper sheet, the leakage inductance in longitudinal and the field inductance in transverse are quantitatively comparable.

Resistance

The resistance can be estimated using the effective permeability of the ferrite with air gap. As an example, we take the window frame magnet of the AGS Booster dump kicker, with $\ell = 40$ cm, $b_2 \approx 9.5$ cm, and $b_1 \approx 7$ cm, where for simplicity, the window frame structure is approximated by a cylindrical structure. The ferrite is NiZn CMD5005. The parallel resistance and the effective one with air gap of $g = 0.1$, are shown in Fig.4, where the inductance is in a unit of μH, and the resistance is in 100 Ω. The parameters of the ferrite with $\mu_i' = 300$ and $\mu_i' = 50$ are also shown.

We note that for window frame magnet kickers, the air gap is quite large in transverse case, and in the longitudinal case the existence of copper sheet implies more complications. An accurate analytical calculation is not practical. However, a qualitative estimate can be made.

For instance, one may notice from Fig.4 that the effective parallel resistance of the Booster dump kicker magnet with $g = 0.1$ is between 200 Ω to 400 Ω, in the frequency range of 1 to 100 MHz. This is obtained using the formulation for small gap. Meanwhile, the effective inductance is about a half of the experimentally estimated. From Fig.4 we also observe that the effective quality factor is more than 100 times larger than the quality factor without gap. Note that Q is increased by a factor of $1 + g\mu_s'$, the increase of Q is overestimated due to the use of large gap ratio, g.

It is reasonable, therefore, to consider a factor of 5 reduction in this case for the effective parallel resistance, which implies an effective parallel resistance between 40 Ω to 80 Ω, in 1 to 100 MHz, for CMD5005. Also observed is that for a NiZn ferrite with $\mu_i' = 50$, this resistance is around 2,000 Ω at 10 MHz, much larger.

In general, the ferrite with high permeability has smaller parallel resistance. Again, for simplicity, we assume that this applies to transverse and longitudinal case approximately equally.

Capacitance

In the transverse case, differential flux in the core induced by the beam position deviation gives rise to current flow in the winding, which in turn is propagated through the winding to the driver. The relevant capacitance is, therefore, from the conductors along with the driving circuitry. In order to reduce the stray inductance, which affects the kicker rise time, the driving loop has to be small, i.e., two conductors have to be placed very close. For each module this capacitance is in an order of a few tens to even hundred of pf.

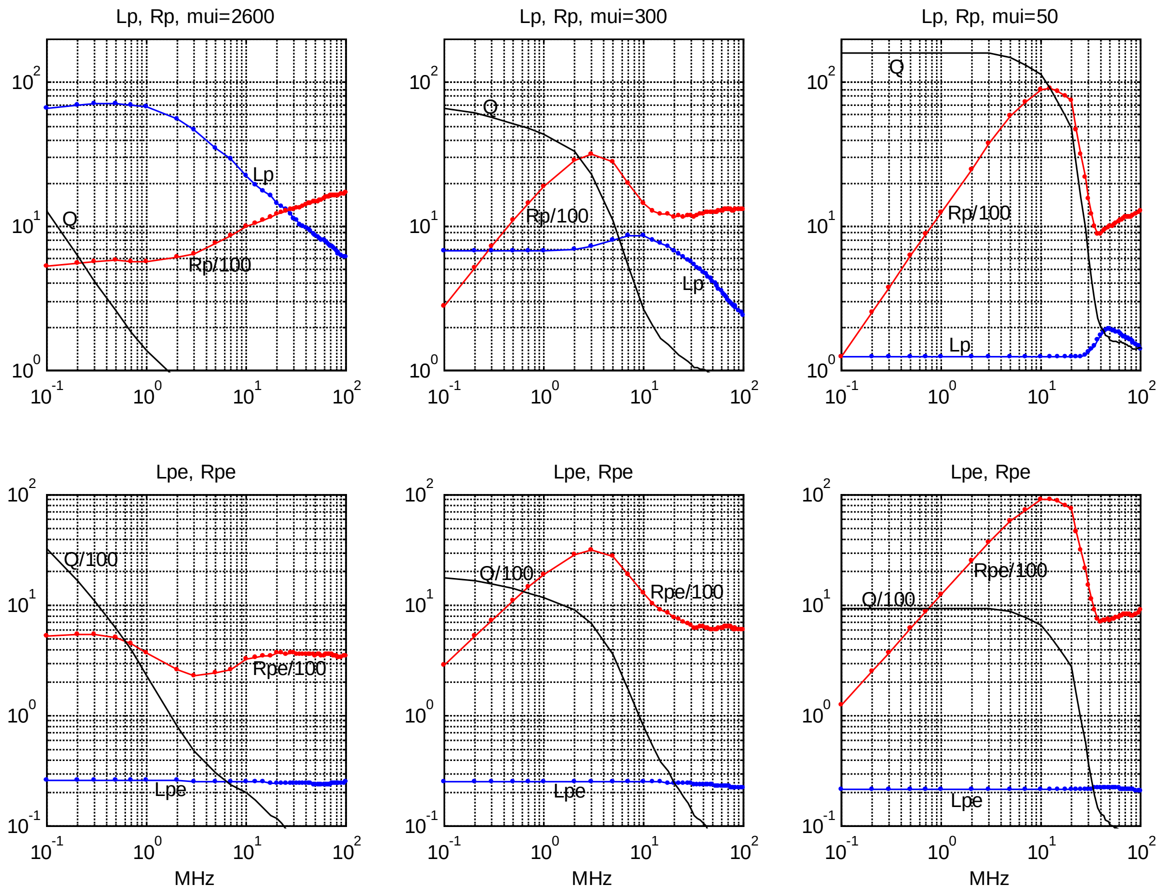

Fig.4

In the longitudinal case, the beam stores energy not only in the magnetic field in the ferrite core, but also in the radial electric field. For the Booster dump kicker, a thin wire placed in the middle of window frame magnet, which is enclosed in a vacuum chamber, implies a 10 pf capacitance. The high relative permittivity ferrite occupies a large volume in the space, and there are also conductors in the assembly, these affect this capacitance. Therefore, for each module this capacitance is in an order of a few tens of pf.

For simplicity, we assume that this capacitance is constant with respect to frequency.

Ferrite Model

In the proposed resonance ferrite assembly model, the experimentally estimated inductance can be used. This inductance is not tightly related with the property of ferrite, provided the ferrite initial permeability is not too low.

Also, the capacitance is mainly from the parasitic factors, and it is also not tightly related with the ferrite.

The parallel resistance is, however, determined by the ferrite. Assuming the same structure, the ferrite with high initial permeability has lower parallel resistance, which shunts the termination and makes the driving circuitry less sensitive.

In comparison with the N-S formulation, if the contribution of the parasitic capacitance and/or the inherent parallel resistance of the ferrite assembly is not negligible, then the resulted impedance will be different.

Transverse Impedance

In a window frame magnet, the transverse impedance is dominated by the differential flux in the core induced by the beam position deviation. Consider the Nassiabian-Sacherer formulation,

$$Z_T = \frac{c\omega\mu_0^2\ell^2}{4a^2 Z_k}$$

where $Z_k = j\omega L + Z_g$, with L the magnet inductance, and Z_g the termination impedance. Here, the ferrite magnet is represented by an inductance.

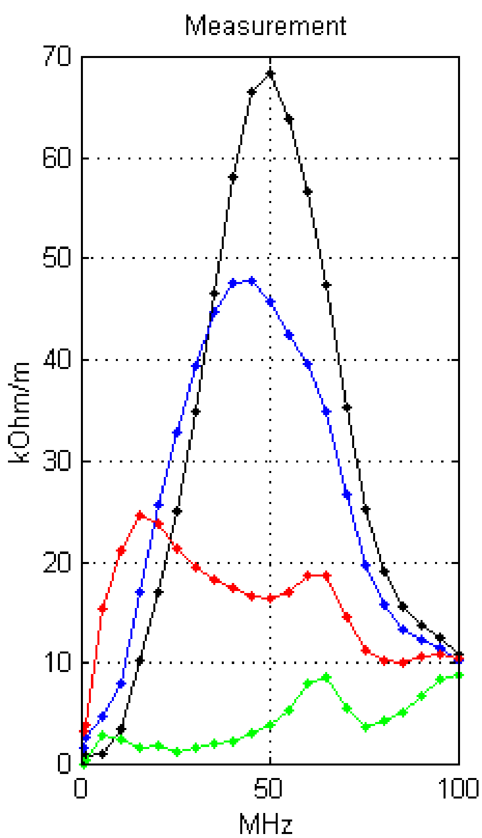

Fig 5a

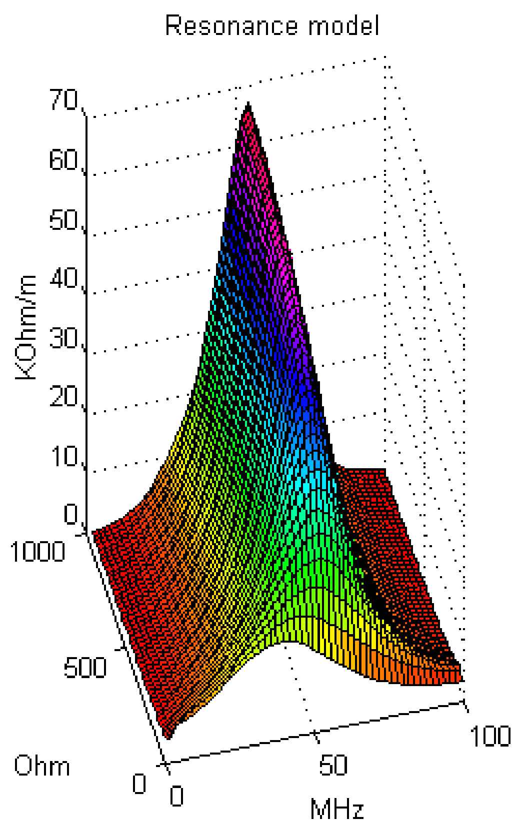

Fig.5b

In the N-S formulation, it can be shown that if the termination impedance is a pure resistance, then the real part of the impedance is not affected by the termination, only the resonance frequency is affected. Smaller the resistance, the lower the resonance frequency.

Introducing parasitic parameters, such as the stray inductance and capacitance, then both the peak of the real part of the impedance and the resonance frequency are affected by the termination resistance. However, the situation is rather sensitive and complicated. Not only large, but also very small termination resistance gives rise to large real part of impedance [10].

Both situations were not closely agreeable with the observation in the measurement [4], where it is clearly shown that the lower the termination resistance, the lower the real part of the impedance, and also lower the resonance frequency. The measurement result is shown in Fig.5a, for the open termination, the termination with the resistance of 360 Ω, 50 Ω, and shorted.

To understand the measurement, a resonance model is used to represent the ferrite, together with the parasitic inductance of 0.3 μH and a 40 pf capacitance in parallel with the termination resistance, the transverse impedance is shown in Fig.5b, which is reasonably agreeable to the measurement shown in Fig.5a.

With smaller termination resistance, the transverse impedance is smaller, and the resonance frequency is lowered. Also, it is shown that for very large termination resistance, the transverse impedance will be saturated.

The higher permeability ferrite implies smaller inherent parallel resistance, and this resistance shunts the ferrite inductance. The effect is not negligible, especially at high frequency. For the Booster dump kicker magnet, the resonance model yields better match with the observed impedance, compared with the N-S formulation.

Longitudinal Impedance

The longitudinal impedance of the Booster dump kicker magnet is also measured. The impedance is not sensitive with respect to the terminations. This is understood with two reasons. The first is that the magnet used in the measurement is driven by a single power supply, and therefore the two conductors are shorted at one end. This eliminates the image current flow in the conductors, and therefore, the coupling to the external termination is not large. The second reason is that again for the high permeability ferrite, the inherent parallel resistance is low, which can shunt the termination. This is agreeable with the measurement performed at LBL [2], where the magnet has two drivers, and the ferrite has the initial permeability slightly larger than 100, but only loose coupling to the terminator had been observed [11].

Applying resonance model of the ferrite to the window frame kicker longitudinal impedance, and the result is shown in Fig.6b. Since the termination is not sensitive, the situation becomes very simple. Only the resonant model itself is involved. In this case, we used a 50 pf capacitance in the parallel model of the ferrite. The result is compared with the measurement, shown in Fig.6a.

The real part of the impedance is peaked at about 30 MHz, and the impedance at the low frequency end is affected by the property of CMD5005, shown in Fig.1. Note that the longitudinal impedance measurement performed at LBL [2] has a similar result.

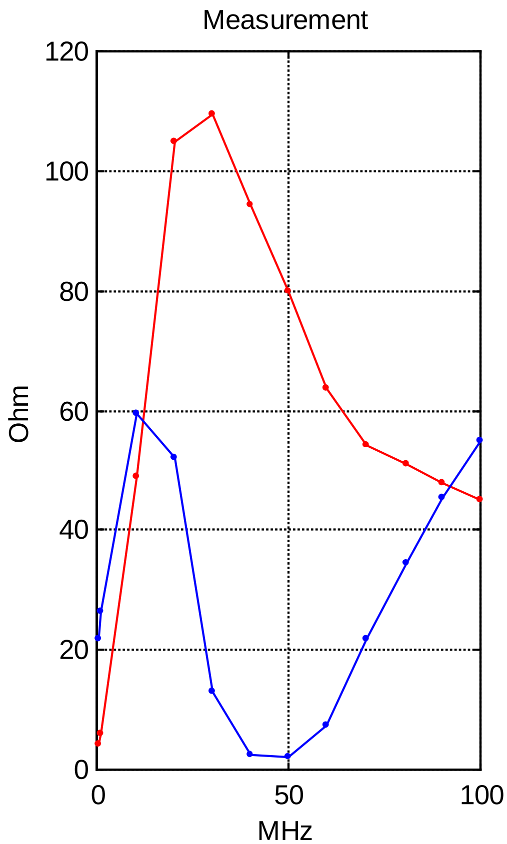

Fig.6a

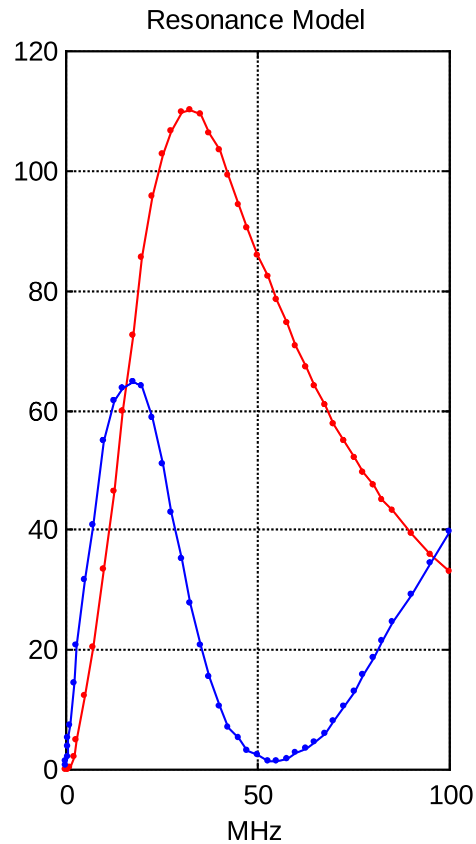

Fig.6b

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