LONGITUDINAL IMPEDANCE TUNER
USING HIGH PERMEABILITY MATERIAL

K.Koba, D.Arakawa, M.Fujieda, K.Ikegami, C.Kubota, S.Machida, Y.Mori, C.Ohmori, K.Shinto,
S.Shibuya, A.Takagi, T.Toyama, T.Uesugi, T.Watanabe, M.Yamamoto,M.Yoshii
KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

Space charge effects cause the emittance growth and the beam instability, when the short bunched beams are accelerated in a high intensity proton synchrotron. The impedance tuner using high permeability materials has been developed to cancel the longitudinal space charge effects.

We installed the impedance tuner in the main ring of KEK proton synchrotron (PS) and observed the canceling effect.

1 INTRODUCTION

In a high intensity proton synchrotron, the emittance growth and the beam instability are caused by space charge effects. In the longitudinal phase space, the space charge forces weaken the RF focusing force below the transition energy. When a short bunch is required, for example in a proton driver of a muon collider, the effects are further enhanced and they limit bunch length.

It is clear that an inductive device in a ring can cancel the space charge force since the space charge impedance is capacitive. The electric field created by the inductance has the opposite sign to the field of the space charge.

Recently a very high permeability material, FINEMET, becomes available. It turns out that the material has enough permeability at the beam frequency region and possibly cancels the space charge impedance. We designed a device, called "impedance tuner", consisting of FINEMET cores and installed it in the KEK PS main ring.

We will describe the characteristics of FINEMET and a setup of impedance tuner in the KEK PS main ring. At the end, experimental results up to date will be presented.

2 CHARACTERISTIC OF 'FINEMET'

The FINEMET is a toroidal core with the outer diameters of 340 mm, the inner diameter of 140 mm, and the thickness of 25 mm. The inductance as a function of frequency is measured in the condition of bias current from 0 to 48A*turn and shown in Fig.1. The measurement was carried out for a single core using a test cavity[1].

At the KEK main ring at the injection the space charge impedance is about 300 ohm. From this plot, the inductive impedance(|Z/n|) is about 5 ohm. It need about 60 pieces of 'FINEMET' to cancel the space charge impedance completely.

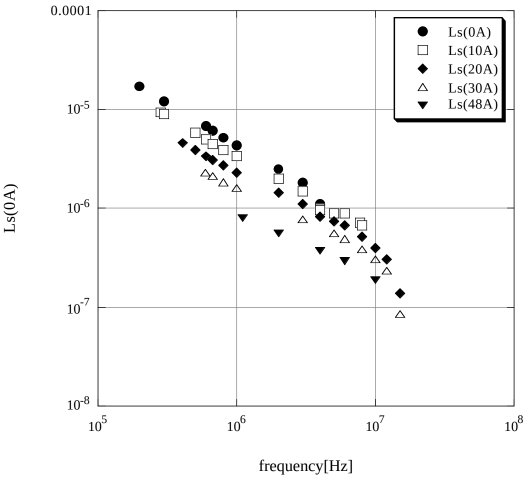

Fig1. The inductance as a function of frequency is measured with a bias current from 0 to 48A/turn.

3 EXPERIMENTAL SET UP

We have developed three different types of the impedance tuner so far.

The first impedance tuner consisted of eight cores of FINEMET and 6 turn bias coil were wound around the cores to control the inductance. All of the cores were installed in a single cylindrical vacuum chamber. The bias current was varied from 0 to 30 A (0 to 180 A*Turn). The problem of this type was that the large capacitance caused by a bias coil coupled with the inductance of the FINEMET cores and made a resonant circuit whose resonance frequency were about 2MHz. This resonant frequency was relatively low compared with a foundamental frequency of the beam spectrum about 6MHz. To avoid the low frequency resonance the second type of impedance tuner was developed.

The second type of the impedance tuner consisted of identical three units and each unit had 4 pieces of FINEMET, ceramic gap and cupper shield. All of the FINEMET cores were placed outside of the ceramic gap. There are short bars as shown in Fig.2. The space charge canceling effect would be obtained by observing the difference between with and without the short bars. The total length was 1.2m. With this type of the impedance tuner, the resonant frequency was raised to about 8 MHz.

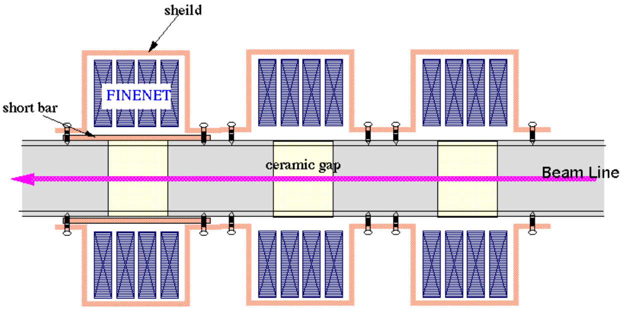

Fig.2 The setup of the second type of the impedance tuner.

The third type of the impedance tuner consisted of 8 units and each unit has 1 piece of FINEMET. With the type of the impedance tuner, the resonant frequency was raised to above 30MHz.

Reactance as a function of frequency was measured for each type of impedance tuner by network analyzer and the results were shown in Fig.3.

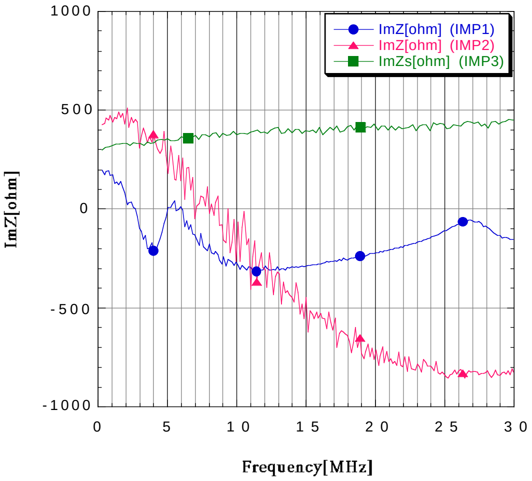

Fig.3 Reactance was measured as a function of frequency.
IMP1: first type, IMP2: second type, IMP3: third type

4 MEASUREMENT

Synchrotron oscillation frequency is perturbed by the potential of the space charge and the inductive wall impedance. The perturbed frequency is written by[2],

$$f^2 = f_0^2\left[1-\frac{3ef_0N}{\pi^2 hV\cos\phi_s}\left(\frac{2\pi R}{l}\right)^3\left[\frac{g_0Z_0}{2\beta\gamma^2}-\left|\frac{Z}{n}\right|\right]\right]. \qquad (1)$$

Although the incoherent frequency shift is not observed by the dipole oscillations, it can be inferred from the quadrupole oscillation frequency. There is the following relation between two oscillation frequencies[3]

$$\frac{\Delta f_{2s}}{f_{2s}} = \frac{1}{4}\frac{\Delta f_s}{f_s}. \qquad (2)$$

Measurement of the quadrupole oscillation is to look at the bunch envelope oscillation. The quadrupole oscillations were caused by a mismatch in the longitudinal phase space at the injection to the KEK PS main ring. The bunch shape were observed from the signal of wall current monitor. The envelope of the bunch height oscillations (Fig.4) was fitted with a function of

$$y = p1 + p2 * \cos(2\pi * p3 * t + p4) * \exp(p5 * t). \qquad (3)$$

The fitted value of "p3" is the frequency of quadrupole oscillations.

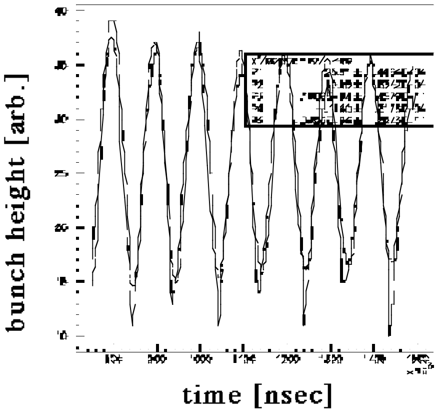

Fig.4. The envelope of the bunch amplitude oscillations.

5 RESULTS

The frequency of the quadrupole oscillation were measured as a function of intensity using the second type of the impedance tuner and plotted in Fig.5. The dashed line is a fitted line of the data on the condition when one ceramic gap was shorted and the rest of the gaps were opened. The long-dashed line is a fitted line of a data on the condition when all of the ceramic gap were shorted. The solid line shows the frequency when all of the gaps were opened. When the impedance tuner is active, the slope of the frequency shift becomes lower, which implies that space charge effects are compensated.

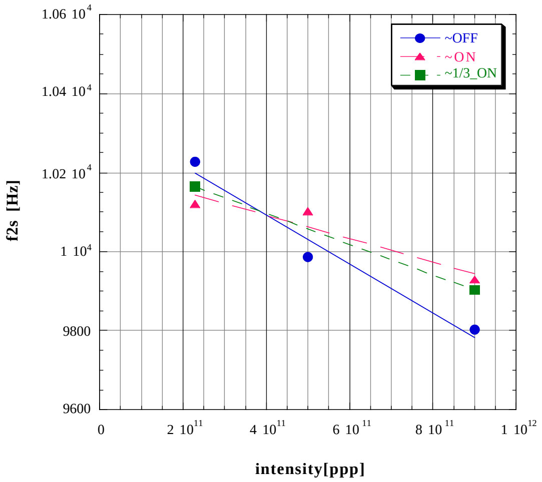

Fig.5 The frequency of quadrupole oscillation as a function of intensity were measured.
OFF: all of the gaps were shorted,
ON: all of the ceramic gap were opened,
1/3ON: the one ceramic gap was opened and the rest of the gaps were shorted.

In order to simulate that observation, we have done a particle tracking calculation. The quadrupole oscillation frequency which obtained by the calculation as a function of the beam intensity are shown in Fig.6.

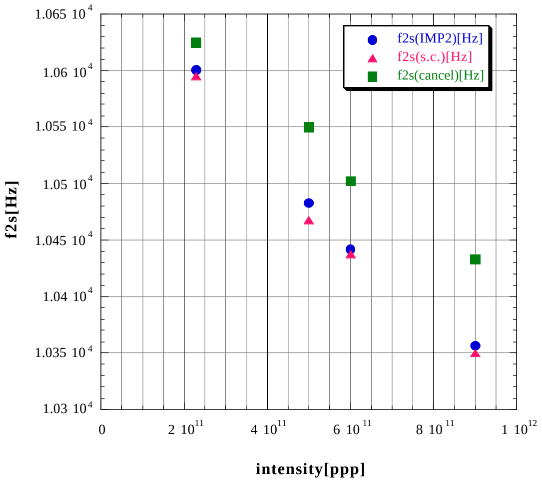

Fig.6 The quadrupole oscillation frequency which obtained from the calculation. (sc): calculation with space charge impedance only. (IMP2): calculation with space charge impedance, partially compensated by the second type of impedance tuner. (cancel): the case assuming the space charge impedance is fully compensated with impedance tuner.

Even though we assume the space charge impedance is fully compensated (the case “cancel”), the intensity dependence dose not become flat. The gradient of each line is not able to be solely explained by the space charge and the inductive impedance when non-liner effect in an RF bucket is not negligible. To make that clear, the simulation has been done under the condition that the space charge effect kept constant although the bunch length was changing(n/l**3=const). The result is shown in Fig.7.

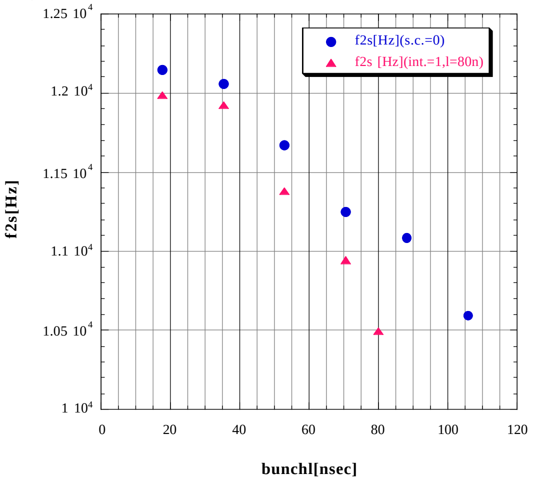

Fig.7 RF bucket non-linear effect.
(sc=0): calculation without impedance.
(int.=1,l+80nsec): calculation with space charge impedance. (intensity=1e12ppp,bunch length= 80 nsec)

It is manifest that, the quadrupole oscillation frequency is lowered when bunch length increases. In fact, the bunch length in the measurement varied as a function of beam intensity as shown in Fig.8.

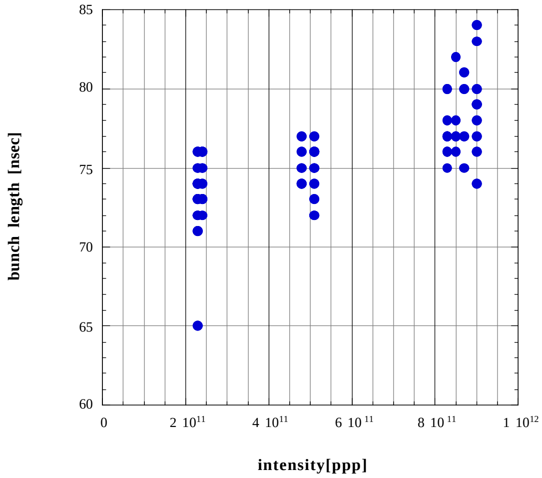

Fig.8 The bunch length in the measurement varied as a function of the beam intensity.

The bunch length changed from 73nsec to 78nsec and the frequency shift caused by non-liner effect was about 120~400Hz. It also explains the large quadrupole frequency shift at the higher beam intensity in Fig.5. In order to clearly identify the impedance canceling effects, we need to do more experimental and theoretical works in detail.

6 SUMMARY

We have installed three types of the impedance tuner in KEK main ring to compensate the space charge impedance. The effect are measured by the shift of the envelope oscillation frequency. Since the nonlinear effects in an RF bucket is not negligible and they introduce another source of tune shift, an interpretation of the result is not straightforward. Nevertheless, the difference of frequency shift with and without the tuner indicates that the compensation is realized.

We have already started a new measurement which is based upon the beam transfer function in observing the quadrupole oscillation. We will install more pieces of FINEMET cores near future.

REFERENCES

[1] T.Uesugi et al., JHF internal report, JHP-31, 1997

[2] S.Hansen, IEEE vol.NS-22, NO.3, 1975

[3] F.Sacherer, CERN/SI-BR/72-5, 1972