DESIGN STUDY OF 1MHZ INDUCTION CAVITY FOR INDUCTION SYNCHROTRON

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Abstract

An induction cavity was designed for the POP experiment of induction synchrotron using the KEK 12GeV PS. It must be operated at a repetition rate of 667-882 kHz for acceleration from the injection energy to the flat-top energy. Design issues include handling of heat deposit, minimization of voltage droop and coupling impedance, and tolerable jitter. Its Q-value on the cavity assembled following the design was obtained from the longitudinal coupling impedance measurement. Effects of the droop in the acceleration voltage on the synchrotron motion, which has been estimated from the circuit parameter measurement on R, C, and L, was analysed from a longitudinal beam dynamics point of view. The effect of the droop is given by the square of phase delay.

INTRODUCTION

A novel idea of the induction synchrotron, which was proposed by Ken Takayama and Junichi Kishiro [1], enables us to have an extremely long bunch, called a super-bunch [2]. Employing this novel technique, it seems to be possible to multiply the beam intensity without increasing the line density. A POP experiment of the induction synchrotron is scheduled in 2003 [3]. For super-bunch production a long and flat accelerating voltage and a short-pulse barrier bucket are crucial instruments. Important issues to realize the induction cavity are among (1) heat deposit and cooling, (2) high voltage shielding in the cavity, (3) ceramic accelerating gap, (4) longitudinal and transverse coupling impedances, (5) droop. It depends on a chosen magnetic material and a repetition rate how serious the first issue is. Since the issue (1) and (2) have been discussed in another place [4], they are not mentioned much here.

INDUCTION ACCELERATING SYSTEM

The Induction accelerating system including a diver is represented as an equivalent parallel LCR circuit within a certain range of frequency. Such an equivalent circuit model is schematically shown in Fig.1. In this model, L stands for the inductance of the magnetic core, C for the stray capacitance of the cavity, R for the effective loss of the core, respectively. Responses of the cavity to a rectangular-shape input-pulse are characterized by a delay in the rise time and a voltage droop, as shown in Fig. 1. A rise time of the voltage is proportional to a factor 1 / CR, and the voltage droop is determined by L / R. The cavity is connected with a pulse modulator [5] through a coaxial cable so as to keep its semiconductors away from the radiation in the accelerator ring. Therefore, the pulse operation requires wideband matching to suppress the reflection from the cavity.

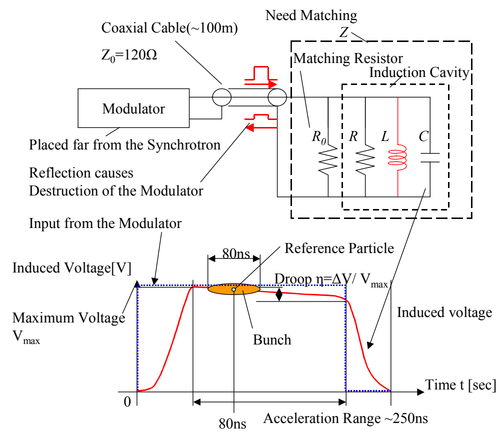

Figure 1: Induction Acceleration Setup

LONGITUDINAL IMPEDANCE MEASUREMENT

A measurement of longitudinal impedance of the cavity was made within the frequency range of 300 kHz - 1 GHz by employing the S-matrix technique [6]. The assembled cavity and longitudinal impedance measurement setup are shown in Fig. 2, and the measurement composition is shown in Fig. 3. The results are given in Table 2. Resonant structures at 289MHz and 578MHz were found to be a quality factor of 66 and 68. These resonances are understood to result from the length of the primary current loop (0.5m). Each of other resonances has a much lower Q-value.

Figure 2: Induction Cavity with Transmission Lines

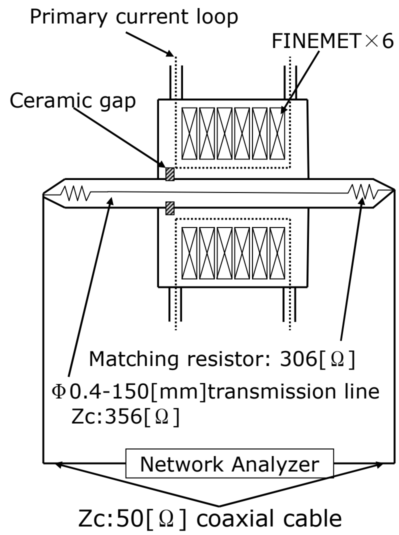

Figure 3: Measurement Composition

Table 1: Longitudinal Impedance of the Induction Cavity

Freq.[MHz]	Long. Imp. [Ω]	Freq. Width[MHz]	Q-value
203	24	46	4
289	4	4	66
299	18	6	50
386	25	14	27
431	24	23	19
578	37	9	68
830	21	61	14

L, C, R OF INDUCTION CAVITY

An impedance of the cavity Z_{cavity} is measured as an equivalent circuit expression of RLC-series,

$$Z_{cavity} = R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right) = R_s + jX_s$$

where R_s and L_s is expressed by the complex permeability of the donut-shaped core $\mu = \mu' + j\mu''$,

$$R_s = \frac{\mu'}{2\pi} D \ln\frac{b}{a}, L_s = \frac{\mu''}{2\pi} D \ln\frac{b}{a}$$

where D, a and b represent the thickness, the inner diameter and outer diameter of the core, respectively. In general, each of μ', μ'' has frequency dependence, not a constant. The step voltage input consists of many higher-order frequencies. Therefore, the measurement of $\mu'(\omega), \mu''(\omega)$ is required.

Consequently, a transformation of equivalent parallel RLC circuit is performed by

$$R_p = \frac{{Z_{cavity}}^2}{R_s}, L_p = \frac{{Z_{cavity}}^2}{\omega^2 L_s}, \frac{1}{C_p} = \omega^2 C_s {Z_{cavity}}^2 .$$

For consideration of the impedance matching, a reflection ρ is related as the function of impedance between the cavity Z_{cavity} and the transmission line Z_{line},

$$\rho = \frac{Z_{line} - Z_{cavity}}{Z_{line} + Z_{cavity}} .$$

The real part and the imaginary part of impedance are measured for certain frequency range by network analyzer. In this measurement, the inductance and the capacitance are determined by employing Q-value at a resonance frequency.The frequency dependence of the L and R of the cavity can be obtained by changing the resonant frequency by adding a capacitor of known value to the measurement setup. The frequency dependence of the inductance and the resistance is measured to compare the equivalent L, R of the naked core with that of the assembled cavity. The results are shown in Fig.4.

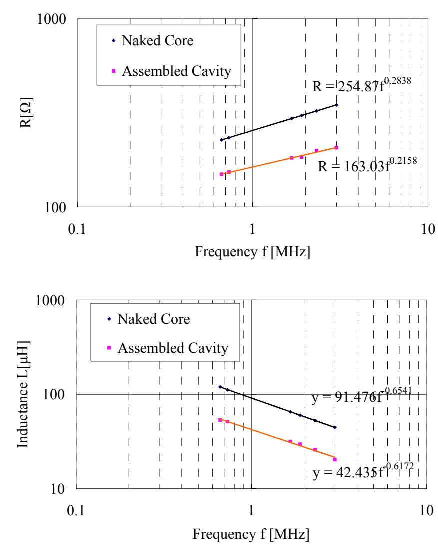

Figure 4: Comparison of Naked Core and Cavity

Design parameters of the required induction cavity are listed in Table 2. The frequency dependence of the inductance and resistance has considerable effect on impedance matching between the induction cavity and the power modulator. Consequently, the repetition rate change of synchrotron operations induces an acceleration voltage error and an additional feedback system will be needed to satisfy the stability criteria.

Table 2: First Plan of the Design Parameters for an Induction Synchrotron POP Experiment at KEK-PS

Induction Voltage	2500V
Repetition Rate (injection)	667kHz
Resistive Component of a core	46Ω
Inductive Component of a core	20μH
Capacitance of the Cavity	300pF
Core Stacks	6
Impedance of the Cavity	267Ω
Matching Resistor	215Ω
Impedance of Coaxial Cable	120Ω
Loss of the Cavity (50% Duty)	11.4kW
Loss of Matching Resistor (50% Duty)	14.5kW
Required Total Power (50% Duty)	25.9kW

VOLTAGE DROOP 'S EFFECTS ON RF BUNCH CONFINEMENT

The induced voltage, shown in Fig.1, is expressed as a function of the synchrotron phase ϕ, maximum induced voltage V_0 and voltage droop V_{drp},

$$V_{ind}(\phi) = V_0 - V_{drp}\frac{\phi}{2\pi}.$$

In the POP experiment step-I, an RF confined bunch is accelerated with induction voltage. Therefore, the applied total voltage is given by

$$V_{total}(\phi) = V_{RF}\sin\phi + V_0 - V_{drp}\frac{\phi}{2\pi}$$

Consequently, the potential well $U(\phi)$ is written in the form of

$$U(\phi) = \frac{heV_{RF}}{2\pi}(-\cos\phi - A\phi^2),\ A \equiv \frac{V_{drp}}{4\pi V_{RF}}.$$

The voltage droop changes the RF potential and modifies the RF buckets as shown in Fig.5. In the droop effect, a ratio of $\frac{V_{drp}}{4\pi V_{RF}}$ becomes an important parameter representing the RF bucket distortion.

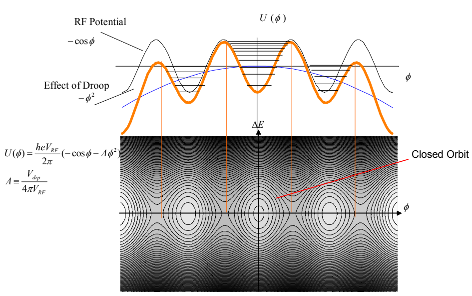

Figure 5: Effect of Voltage Droop in Potential Well

Changes in the phase-space as a function of structure the ratio A are shown in Fig.6. In the POP experiment, V_{RF} = 92kV, and V_{drp} ≈400V. The parameter A is an order of 10^{-4}. A modification in the phase space should be negligibly small; RF bunch confinement can be performed well.

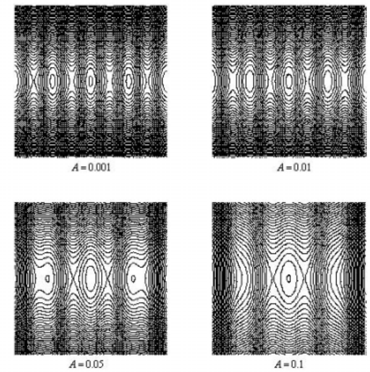

Figure 6: Effect of Voltage Droop in Phase Space

CONCLUSIONS

From the comparison of the naked core and the whole cavity, the cage reduces effective permeability to 1/2. Therefore, an induction cavity for the POP experiment is designed with that effect. As for an induced electric field, a sufficient gap distance and a narrowed primary loop are effective to reduce the structural capacitance. 4-68 Q-values were obtained from a longitudinal coupling measurement. Mode specifications of the resonances are now being made. From the acceleration voltage analysis, voltage droop distort the potential well and decreases the stable area as a function of ϕ^2 and $\frac{V_{drp}}{4\pi V_{RF}}$.

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