# INDUCTION SYNCHROTRON (6): BEAM LOADING

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*Abstract*

When a steep beam bunch comes into the induction unit, it conceivably cause voltage modification and/or beam instability in the induction synchrotron[1]. The effect may depend not only on the impedance of driving circuit but also the non-linearity of the magnetization characteristics of the core material. Using induction modules with FET(Field Effect Transistor) switches, the effect of beam loading on the acceleration voltage was experimentally estimated. The tested cores were nano-crystalline alloy (Finemet) and Co-amorphous alloy. The beam was simulated by a resistive secondary source and the loading effect was measured as functions of $\Delta B$ and current rise of secondary loop(dI/dt), up-to 100A/µsec. Experimentally observed values of the voltage modification did not depend on the $\Delta B$(as far as being used at not-saturation region of the core) and were almost proportional to di/dt. However, they depended on the bias voltage for Co-amorphous. These results indicate that the response of the core material depend on the magnetic-domain shape. Based on those results, voltage modification caused by the effect of beam on the module in the induction synchrotron at KEK-PS was evaluated.

## 1 INTRODUCTION

The beam current and the acceleration voltage can be schematically expressed as figure 1. When an induction module accelerates a high intensity beam with steep bunch, the acceleration voltage was modified by dI/dt of the beam current. That is to say, when the wall return current flows in the induction module, not only impedance of the module but also non-linearity of the core material would change the acceleration voltage.

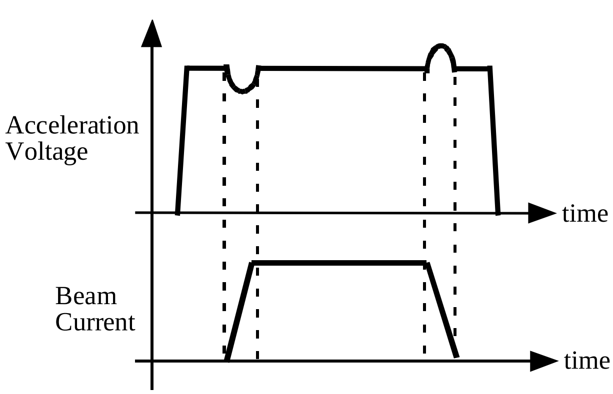


Figure 1: Schematic illustration of beam loading

As the induction accelerator module is equivalent to a transformer with the beam acting as a single-turn secondary, an equivalent circuit of the induction module can be expressed by figure 2. Although induction accelerators have quite lower impedance than RF accelerators, the beam circulate about $10^4$times in acceleration ring for the induction synchrotron of KEK-PS, so the beam loading effect can not be ignored to keep the beam waveform and the modified value in acceleration voltage must be compensated by another(burrier-bucket) induction module which excites short pulse voltage to decelerate the head and to accelerate the tail of the beam bunch[2]. So the effect of beam loading on the acceleration voltage was experimentally estimated.

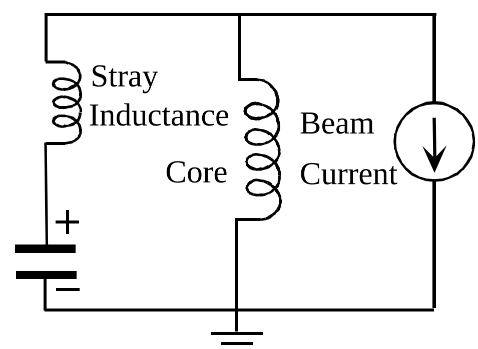


Figure 2: Equivalent circuit of induction module with beam loading

## 2 EXPERIMENTAL SET UP

A schematic diagram of experimental arrangement is shown in figure 3. Acceleration voltage was excited by a primary voltage source using 3 paralleled FET switches [3].

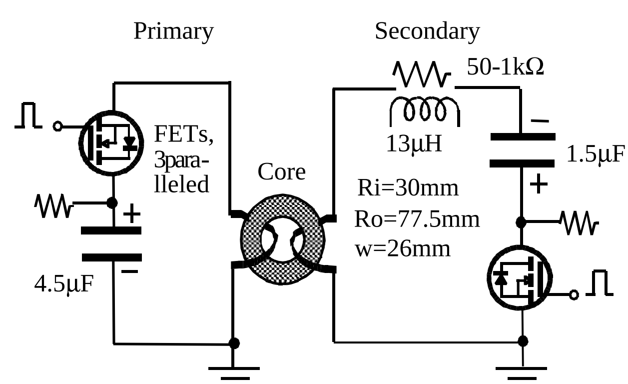


Figure 3: Equivalent circuit of experimental set up

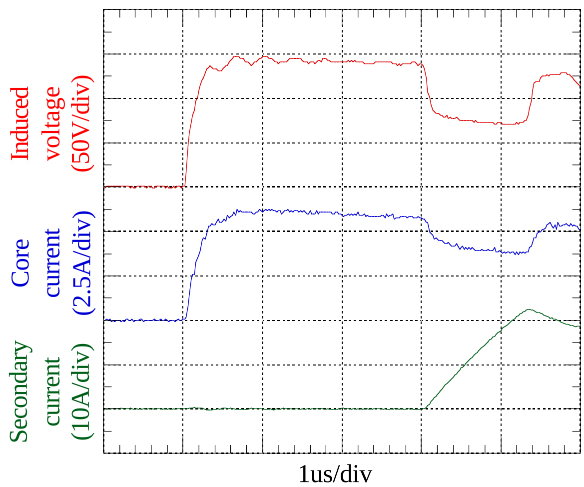


Figure 4: Typical waveform for long pulse loading

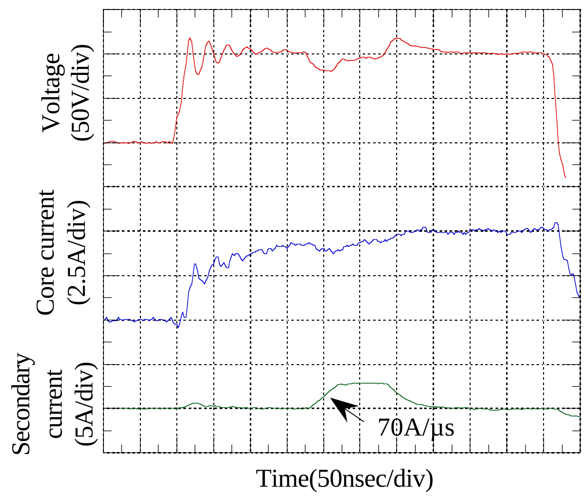


Figure 5: Voltage modulation for short pulse loading

As shown in the figure, the beam current was simulated by a secondary voltage source. The secondary current was adjusted by resisters(50-1kΩ) to make short rise time(~50ns), or an inductor(13µH) to make long rise time(~1µs). The toroidal magnetic cores measured are nano-crystalline alloy, Finemet(FT-1H), and cobalt-based amorphous alloy(ACO-5H), made by Hitachi Metals Ltd[4]. The core was placed in a coaxial enclosing structure. The core has inner radius of 30mm, outer radius of 77.5mm and width of 26mm. Resistivity of the material is 1.1µΩm for Finemet and 1.3µΩm for Co-amorphous respectively. The film thickness is 20µm, the insulation material is $SiO_2$ and the packing factor is 0.7. The cores are demagnetized before the measurement.

## 3 RESULTS

The change of voltage may depend on the current rise(dI/dt) and rise time of the beam and also ΔB and dB/dt because of the non-linearity of the magnetization characteristics of the core material. So first of all, effect of rise time of beam current was investigated. For long rise time of the beam, core current and secondary current for Finemet, is shown in figure 4. A 3µH solenoid inductor is connected in series with the core to enlarge the change of the voltage in this experiment. A 13µH solenoid inductor is connected in series with the core to make long rise time of the beam. The core is operated at non-saturating region. The induced voltage, the core current and the secondary current signals were detected by a resistive voltage monitor(Tektronix, 6139A), a Rogowski coil(Pearson, Model 110) and a Rogowski coil(Pearson, Model 2100), respectively. As shown in figure 4, modulated voltage has a plateau against the secondary dI/dt. This result means that the core response went to steady state region. As the core current is almost constant, the dI/dt is flowing primary 3µH(see equivalent circuit in figure 2), therefore change of the voltage is estimated to be about 60V ($V=L_1 dI_2/dt=$ 20A/µs×3µH).

The induction synchrotron at KEK-PS is expected to operate with current load of 1A and the duration of 50ns(20A/µs). So resisters(50-1kΩ) were connected in series with the core to make short rise time of the beam instead of 13µH. The induced voltage is 100V, dB/dt is 0.12T/µs, which corresponds to bar-domain mode[4]. An example of experimental results; induced voltage, core current and secondary current waveform, is shown in figure 5. The B-H curve for the short pulse loading is shown in figure 6. To draw the B-H curves, change of magnetic flux density ΔB and magnetic field H were calculated by

$$\Delta B=\int V dt/S=\Sigma V(\Delta t)/S, \qquad (1)$$

$$H=\{\ln(Ro/Ri)\}I/\{2\pi(Ro-Ri)\}, \qquad (2)$$

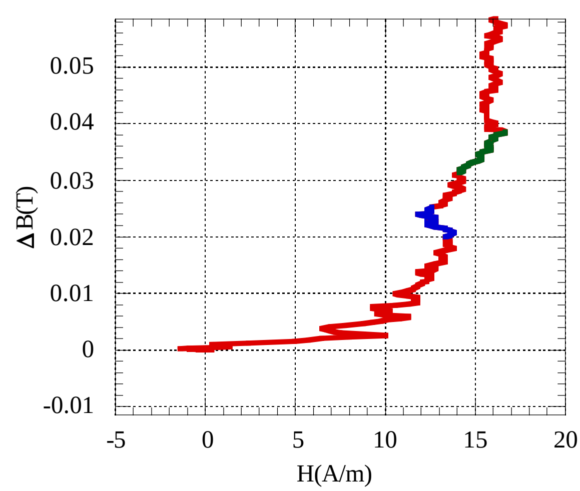


Figure 6: Typical B-H curve for short pulse loading

where Δt is the time interval and S is the effective cross sectional area of the magnetic core. As shown in figure 6, the B-H curve is modified at the moment when the secondary current is turning on(colored by blue) and off(colored by green). Change of the voltage against biased level; ΔB, is shown in figure 7. The changed values are almost same if the core has not been saturated (saturation induction is 1.35T for Finemet and 0.62T for Co-amorphous). In the induction synchrotron, the core is designed to operate along B-H minor loop(ΔB is approximately 0.2T) to suppress the core-loss for highly repetitive module[6]. So the change of voltage is expected to have no dependence on the magnetization level.

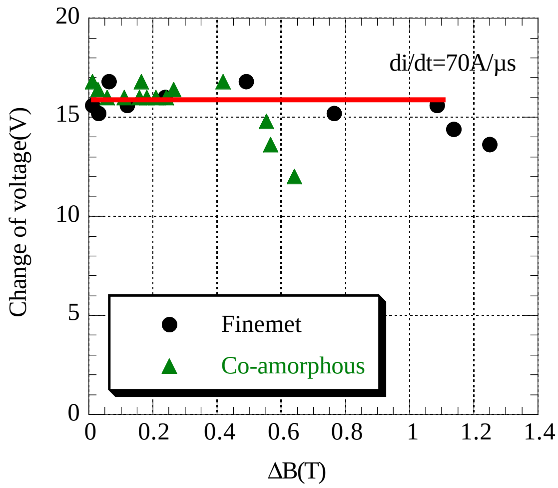


Figure 7: Voltage change versus magnetization

Changes of the voltage against dI/dt are summarized in figure 8. As shown in the figure, the change of voltage of both cores was almost proportional to dI/dt. However, for Co-amorphous core, response from off-set magnetization level was different from the zero off-set response. This result seems to indicate that the magnetic domain shape is different both condition. The core response, which is equivalent to relative permeability from the beam di/dt point of view, was evaluated for Finemet using the equivalent circuit (see figure 2). The equivalent value of relative permeability was 270. This value is almost same as the initial permeability.

## 4 ESTIMATION OF VOLTAGE MODULATION IN KEK-PS

The modulation level of acceleration voltage against dI/dt of the beam in the operational range of induction module design is estimated. The core in our design has inner radius of 7cm, outer radius of 15cm and width of 20cm. Acceleration voltage is 2kV and stray inductance of the module is supposed to be 0.5µH. The current of the proton beam is 1A and the duration of 50ns(20A/µs). Using PSpice, the evaluated change of the voltage was 9.5V. This value is less than 0.5% of the acceleration voltage.

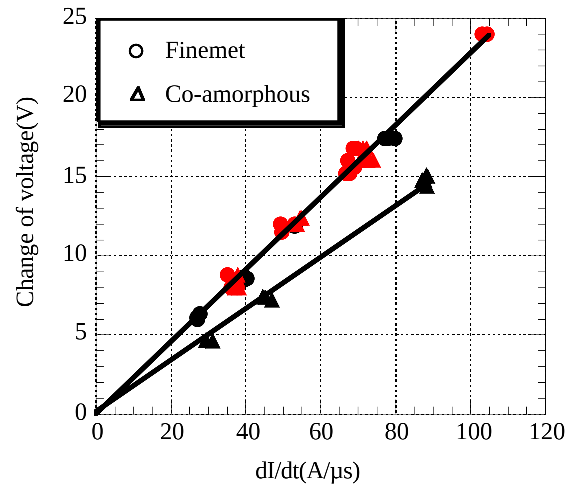


Figure 8: Voltage change dependence on dI/dt
Black: 0-off set, Red: 100V-biased

## 5 CONCLUSIONS

Effects of the beam loading were experimentally estimated. In transitional mode region of the core response, the change of voltage seems to depend on magnetic domain shape. Changed values of the voltage are proportional to secondary dI/dt for identical ΔB level, even in the transitional region of the core response. The change of acceleration voltage for designed induction module was evaluated to be less than 0.5% of the acceleration voltage.

## 6 REFERENCES


[1] K. Takayama and J. Kishiro, “Induction Synchrotron”, Nucl. Instr. and Meth. A451/1, 304(2000).

[2] K. Takayama and Intensity Working Group, “KEK-PS Upgarde Scenario 500Mev Accumulator and Super-bunch Acceleratiion”, Proc. of EPAC, 382(2000).

[3] J. Kisiro, K. Takayama, E. Nakamura, K. Horioka, M. Watanabe, A. Tokuchi and S. Naitoh, “Rapidly Switched Accelerating Devices for Induction Synchrotrons”, Proc. of EPAC, 1966(2000).

[4] S. Nakajima, S. Arakawa, Y. Yamashita and M. Shiho, Nucl. Instr. and Meth. A331, 318(1993).

[5] C. H. Smith, “Applications of Amorphous Magnetic Materials at Very-high Magnetization Rates”, J. Appl. Phys. 67, 9, 5556(1990).

[6] M. Watanabe, M. Nakajima, M. Honda, J, Kisiro, K. Takayama, K. Horioka, “Voltage Moduration and Repetitive Operation of Induction Accelerator Unit”, Proc. Int. Sym. Pulsed Power and Plasma Applications, 31(2000).