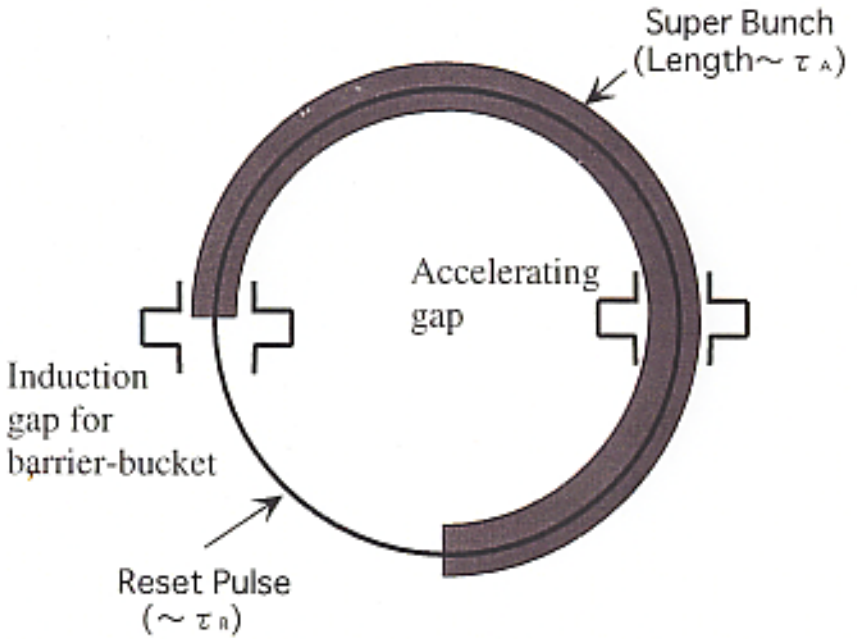
Magnetic Core Studies and Beam Loading Effects for Repetitive Induction Modulator

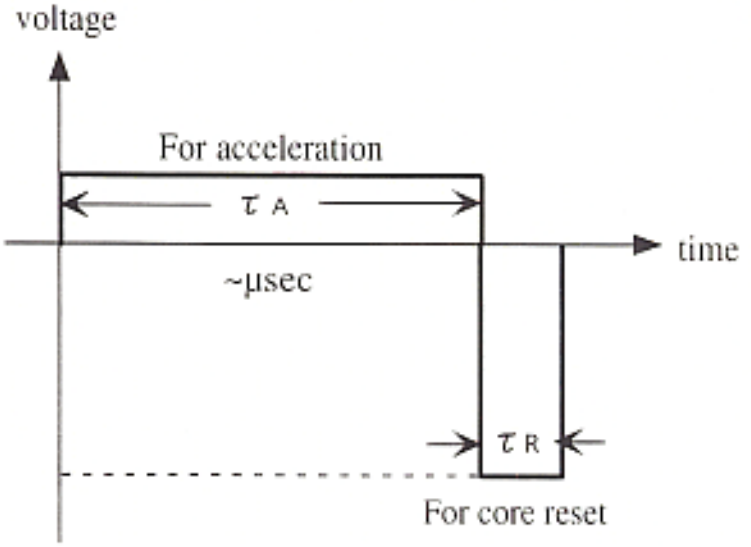
M.Watanabe, T.Ktayama, RIKEN, Saitama, Japan
M.Nakajima, K.Horioka, Tokyo Institute of Technology, Yokohama, Japan
K. Takayama, J. Kishiro, KEK, Ibaraki, Japan

Tokyo Institute of Technology

Schematic illustration of induction synchrotron and acceleration voltage waveform



Induction Synchrotron

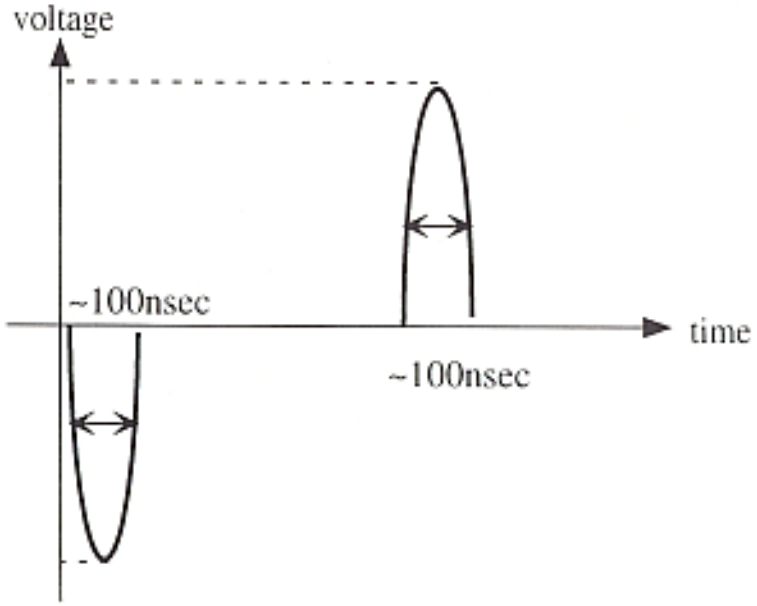


Acceleration voltage waveform

Induction modulator requires highly repetitive operation up-to ~MHz.

↓

Fast switching devices
Core-loss
Beam loading effect



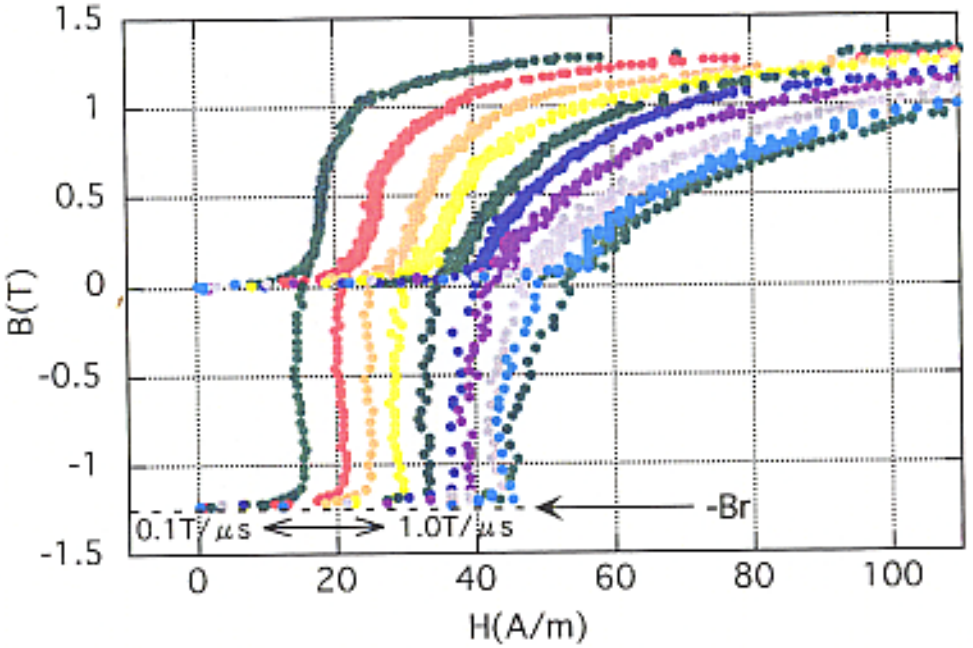
Barrier-bucket waveform

Tokyo Institute of Technology

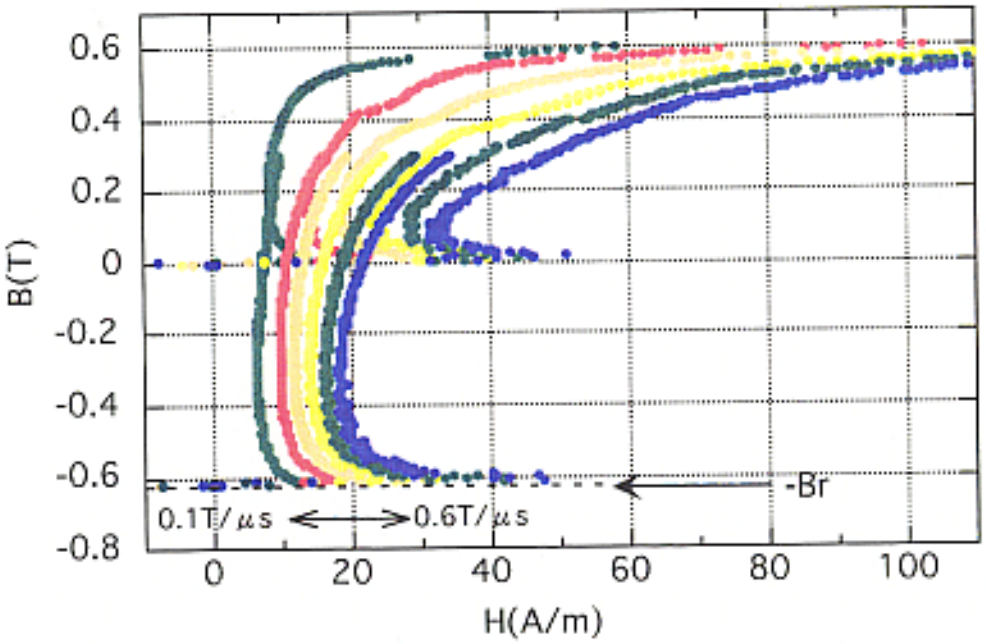
B-H curves from different magnetization state

Magnetization process depends on ΔB and dB/dt.

Finemet(FT-1H)



Co-amorphous (ACO-5H)



Tokyo Institute of Technology

Core-loss depends on Magnetic Domain Motion

Saturation-wave mode

Bar-domain mode

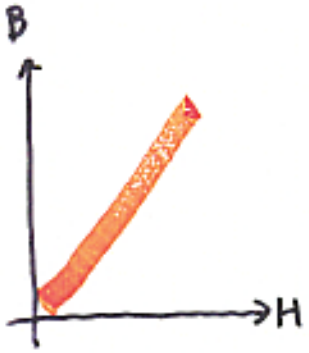
non-saturation region

Magnetic field ⊙

Magnetization

Magnetic field ⊙

saturation region

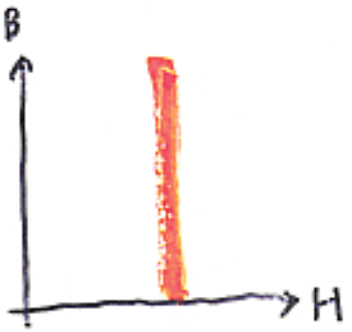


$$H_{SW} \propto \frac{d^2}{\rho}\left(\frac{\Delta B(t)}{2Bs}\right)\left(\frac{dB}{dt}\right)$$

$$H_{BD} \propto \left(\frac{d}{\rho}\right)\sqrt{\left(\frac{dB}{dt}\right)}$$

$$P_{SW}(J/m^3) \propto \left(\frac{d^2}{\rho}\right)\left(\frac{(\Delta B)^2}{2Bs}\right)\left(\frac{dB}{dt}\right)$$

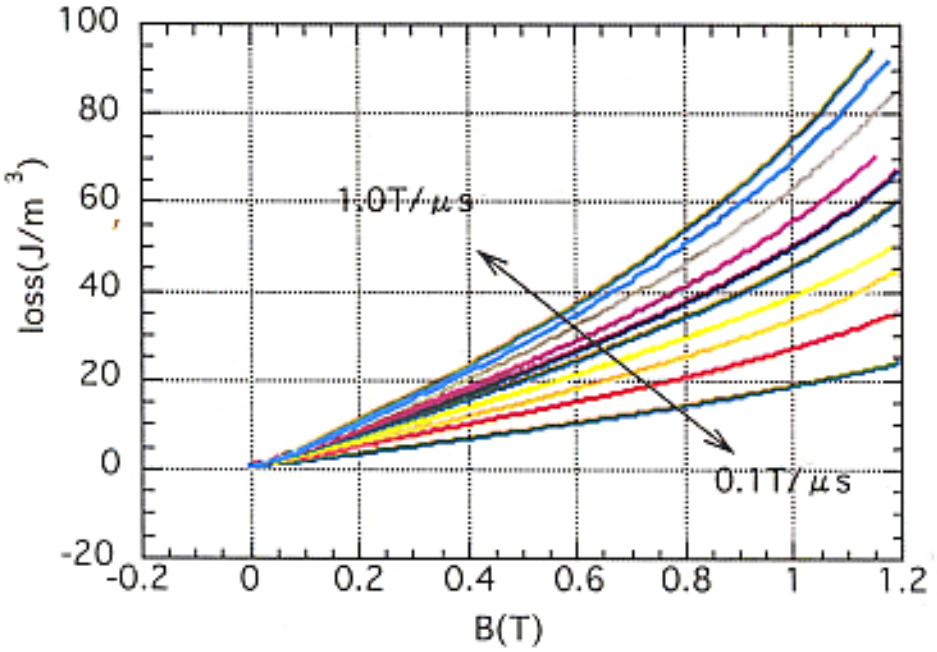
$$P_{BD}(J/m^3) \propto \left(\frac{d(\Delta B)}{\rho}\right)\sqrt{\left(\frac{dB}{dt}\right)}$$



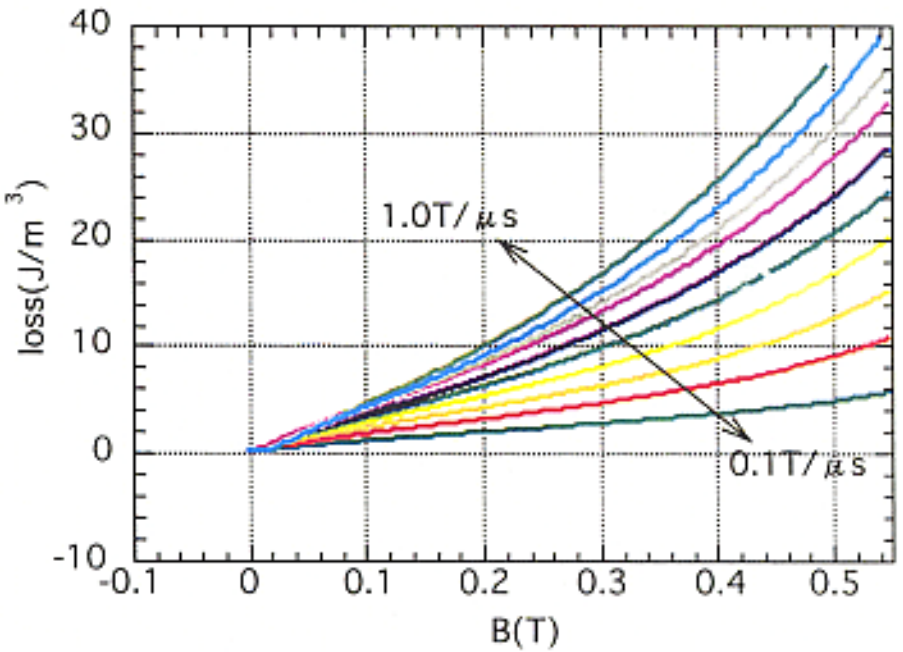
Tokyo Institute of Technology

Core-loss scaling of Finemet(FT-1H) and Cobalt-based Amorphous(ACO-5H) versus flux swing(B)

Finemet(FT-1H)



Co-based amorphous (ACO-5H)



Tokyo Institute of Technology

Core-losses were scaled as functions of $\Delta_0 B$ and dB/dt

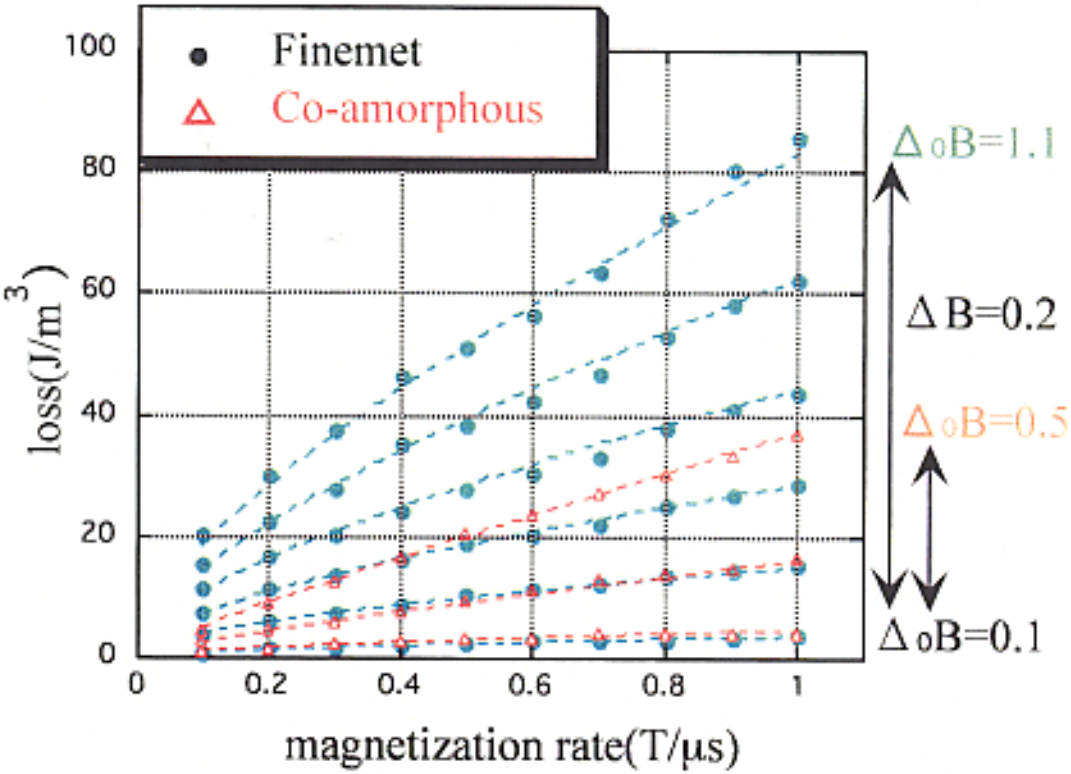
$$P\left(\frac{J}{m^3}\right) = \underbrace{C_1\left(\frac{d}{\rho}\right)\left(\frac{dB}{dt}\right)^{1/2}}_{\text{(Bar-domain mode)}} + \underbrace{C_2\left(\frac{d^2}{\rho Bs}\right)\left(\frac{dB}{dt}\right)}_{\text{(Saturation-wave mode)}}$$

Finmet

$$P(\Delta_0 B, dB/dt) = (-0.44 + 24.7\Delta_0 B)(d/\rho)(dB/dt)^{1/2} + (10.6\Delta_0 B^2)(d^2/\rho/Bs)(dB/dt),$$

Co-amorphous

$$P(\Delta_0 B, dB/dt) = (1.74 + 5.37\Delta_0 B)(d/\rho)(dB/dt)^{1/2} + (24.5\Delta_0 B^2)(d^2/\rho/Bs)(dB/dt),$$

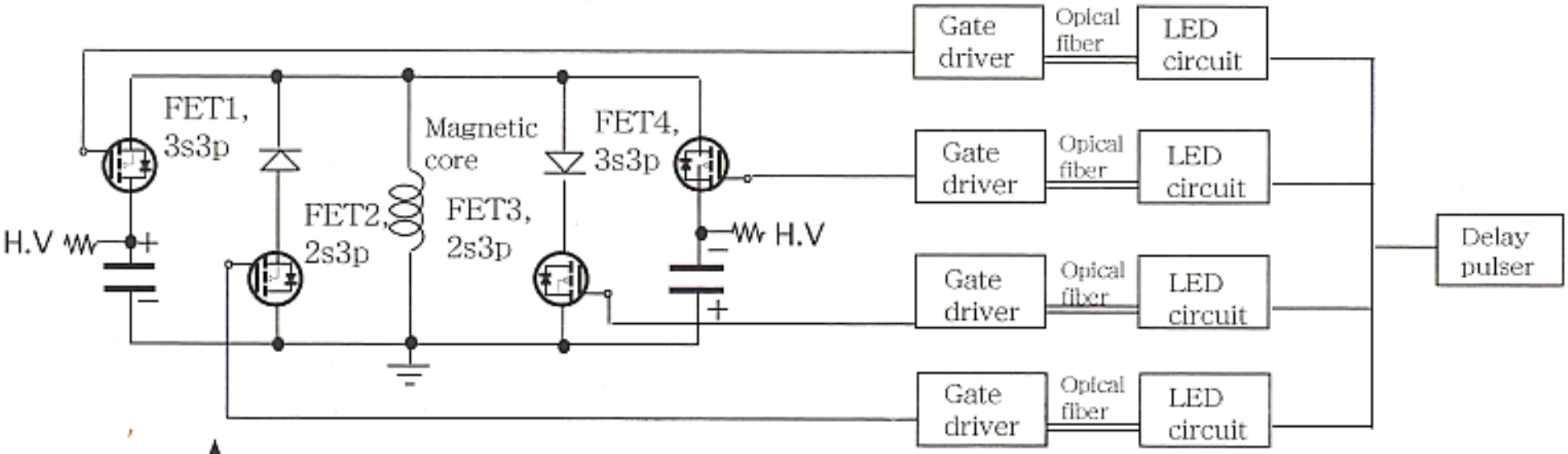


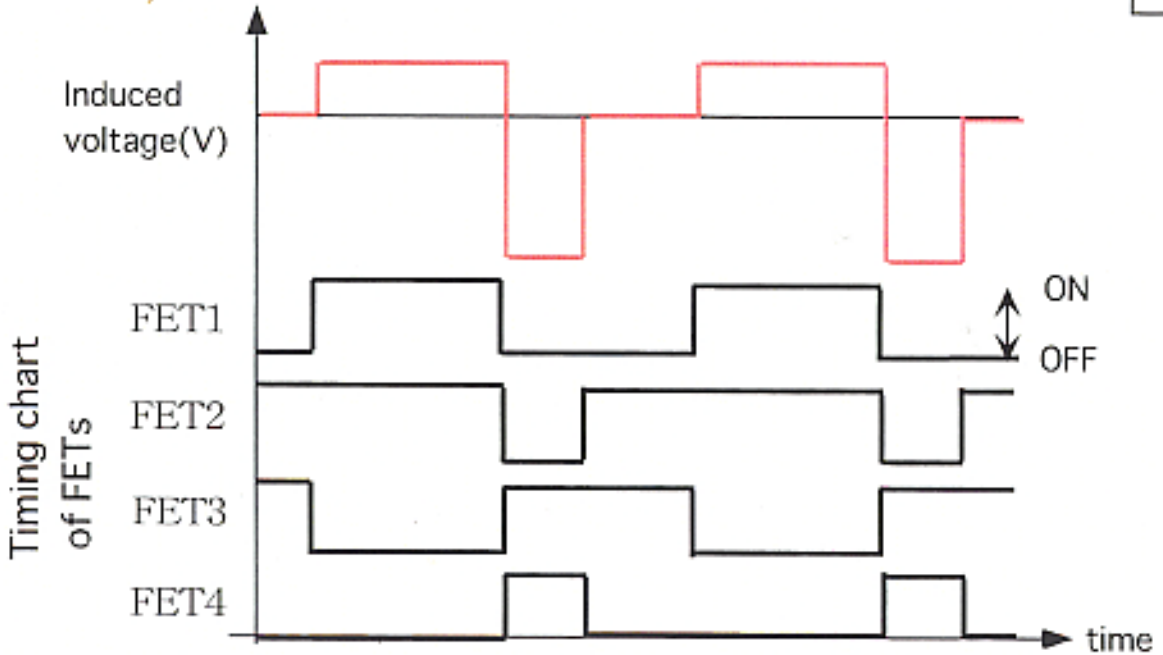
Bs=1.35(T) ρ=1.1(μΩm) d=2(×10μm) (Finemet)

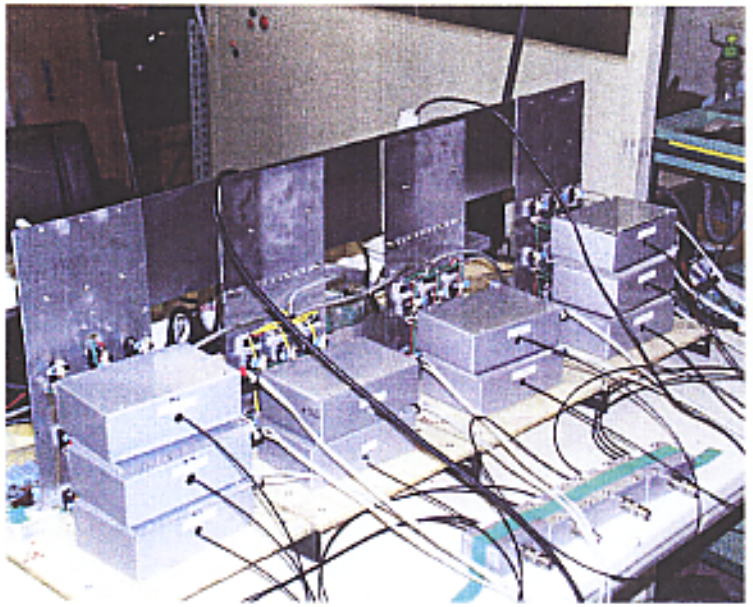
Bs=0.62(T) ρ=1.3(μΩm) d=2(×10μm) (Co-amorphous)

Tokyo Institute of Technology

Schematic diagram of induction module

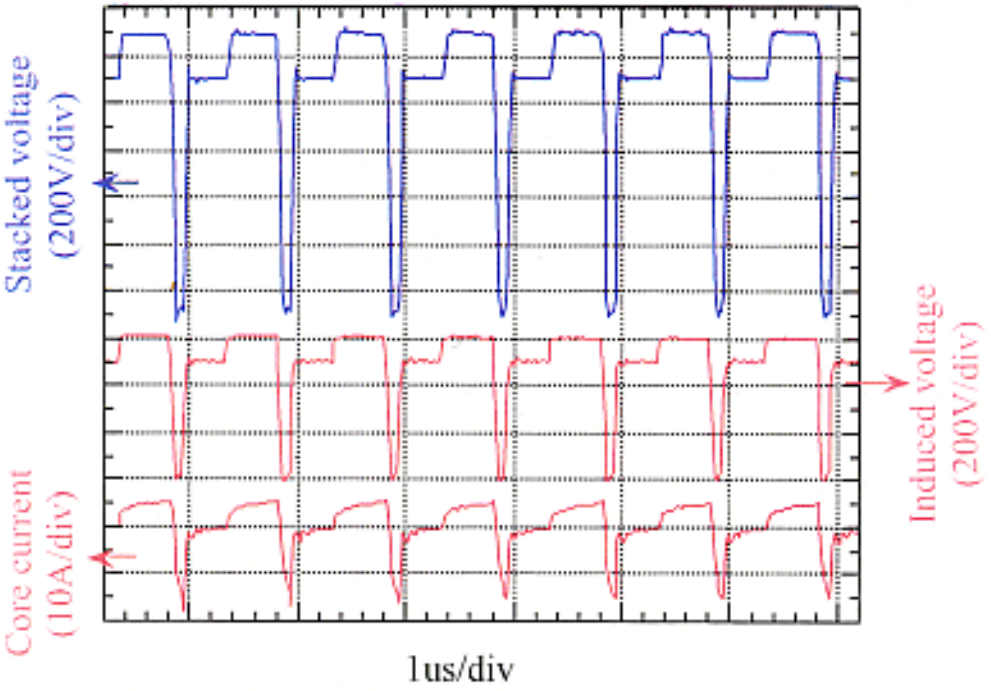






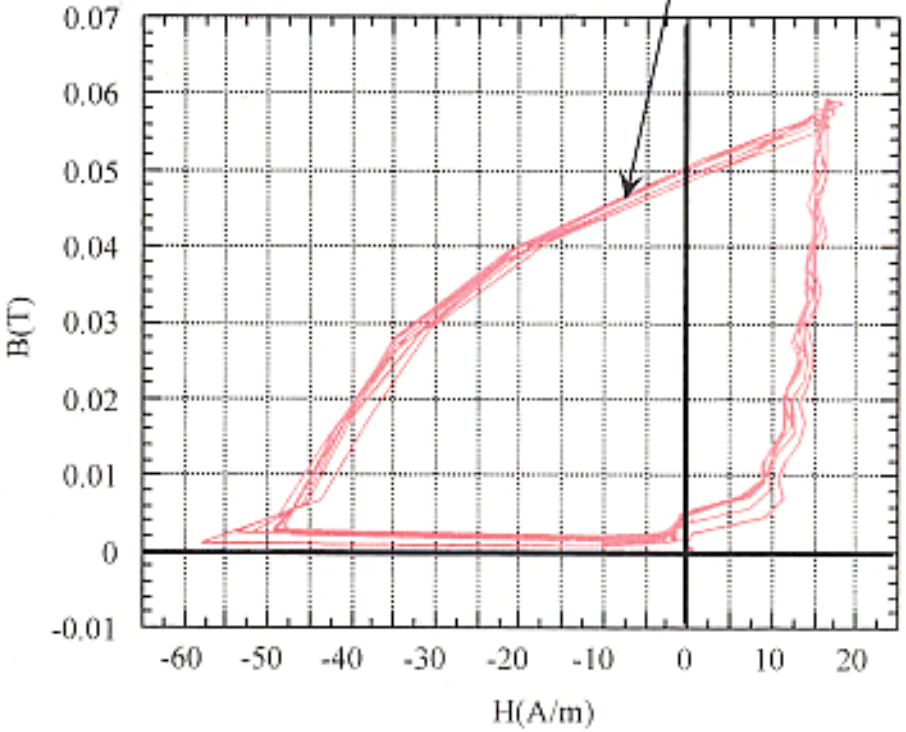
Tokyo Institute of Technology

Voltage, current waveform and B-H minor loop at 1MHz

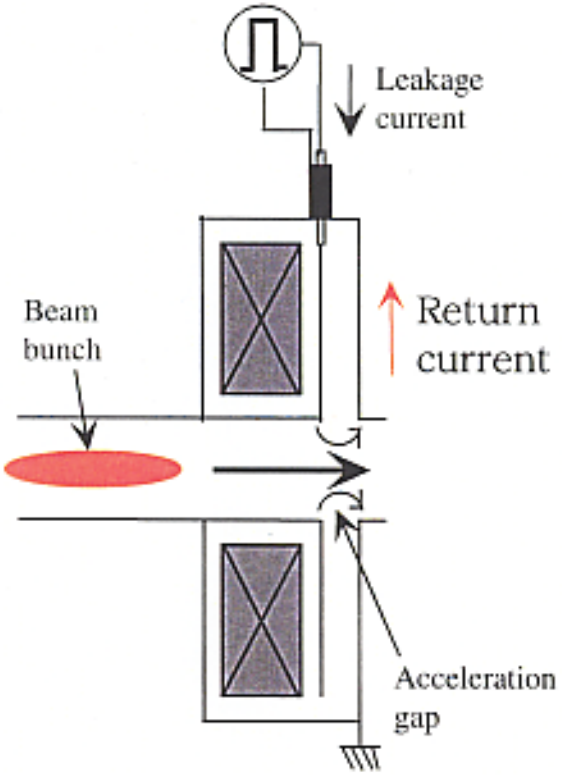


Calculated loss=2.2J/m³

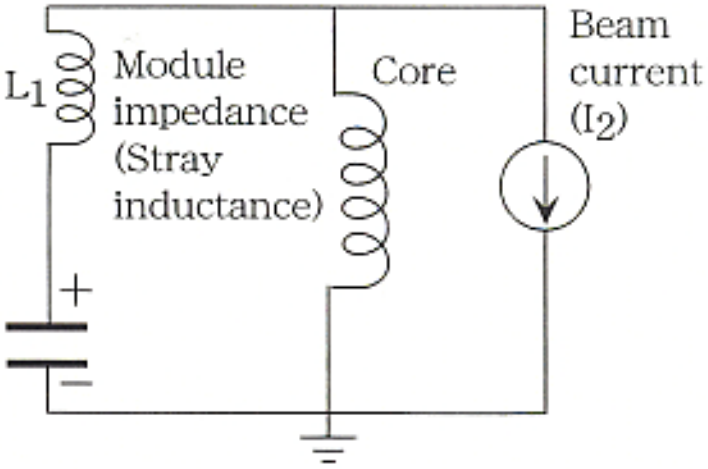
Average loss in one cycle=2.47J/m³



Schematic illustration of beam loading



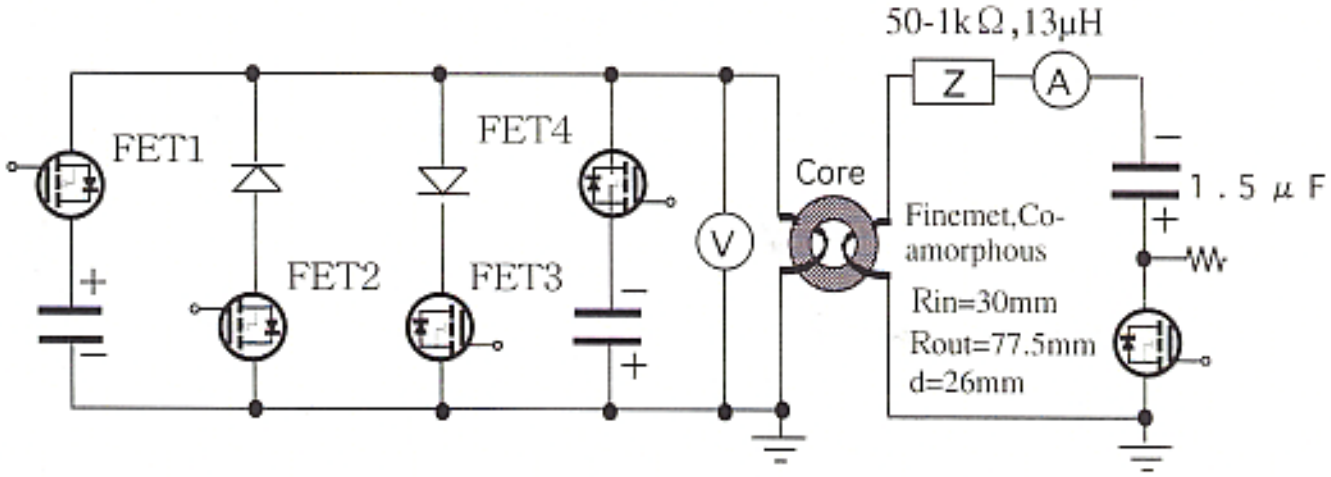
Cross section of
Induction cavity



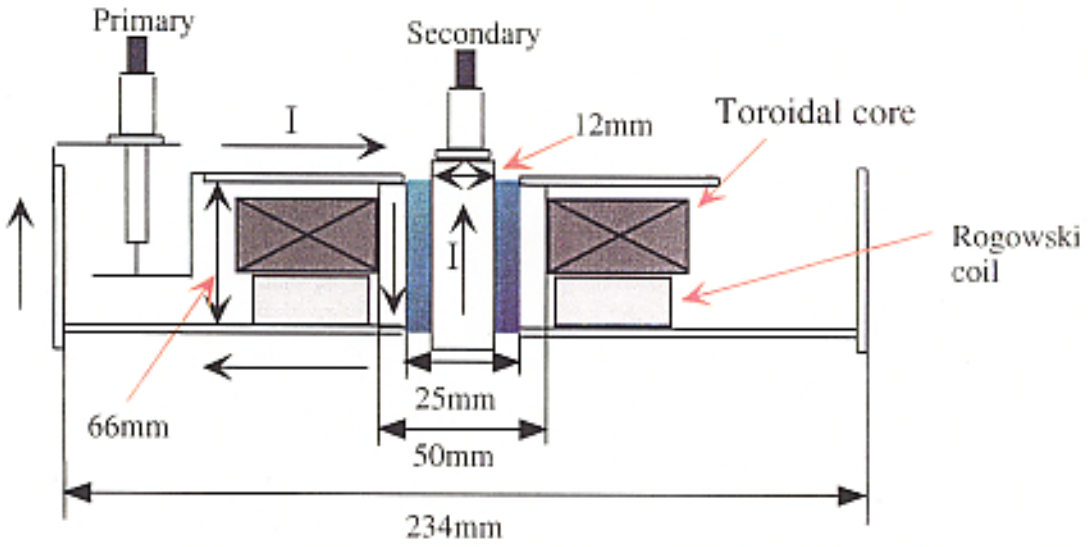
Equivalent circuit of
beam loading effect

Tokyo Institute of Technology

Schematic diagram of experimental arrangement

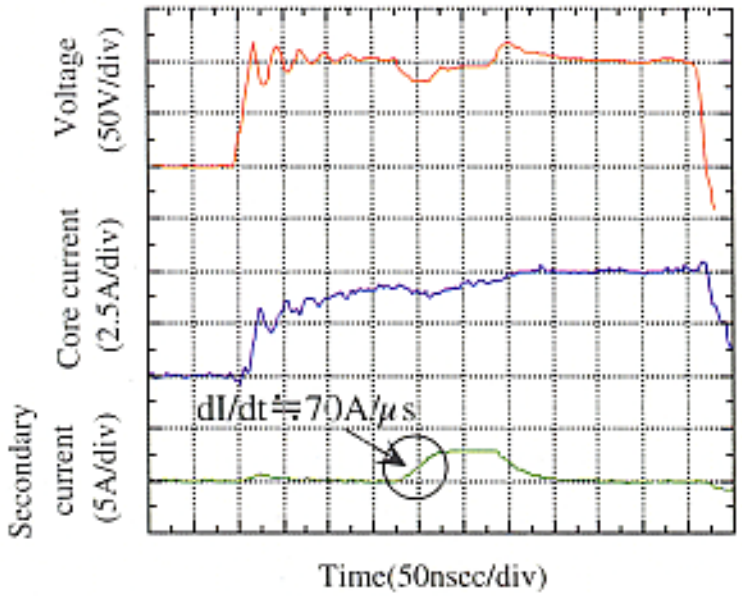


Experimental set up for beam loading experiments

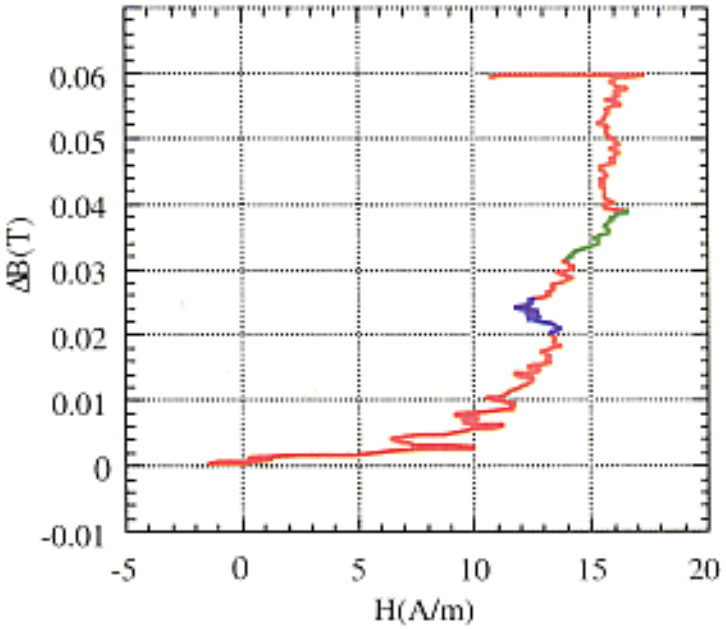


Cross section of induction element

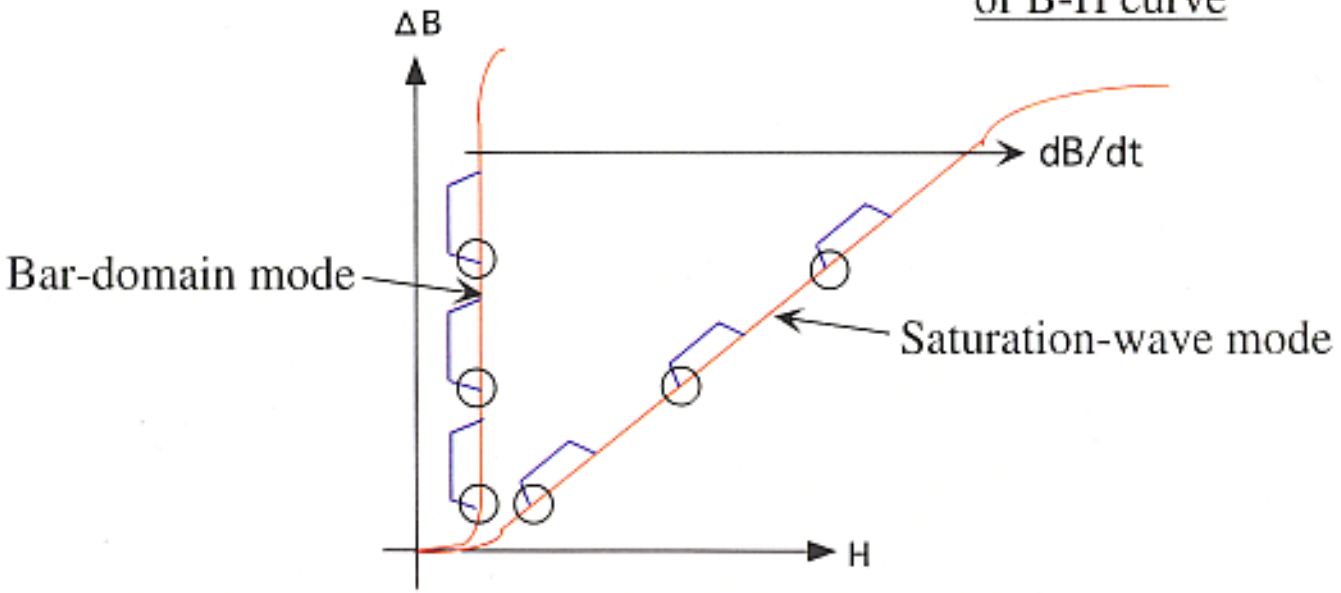
Example of Experimental result of Beam loading



Example of experimental waveform (Finemet)



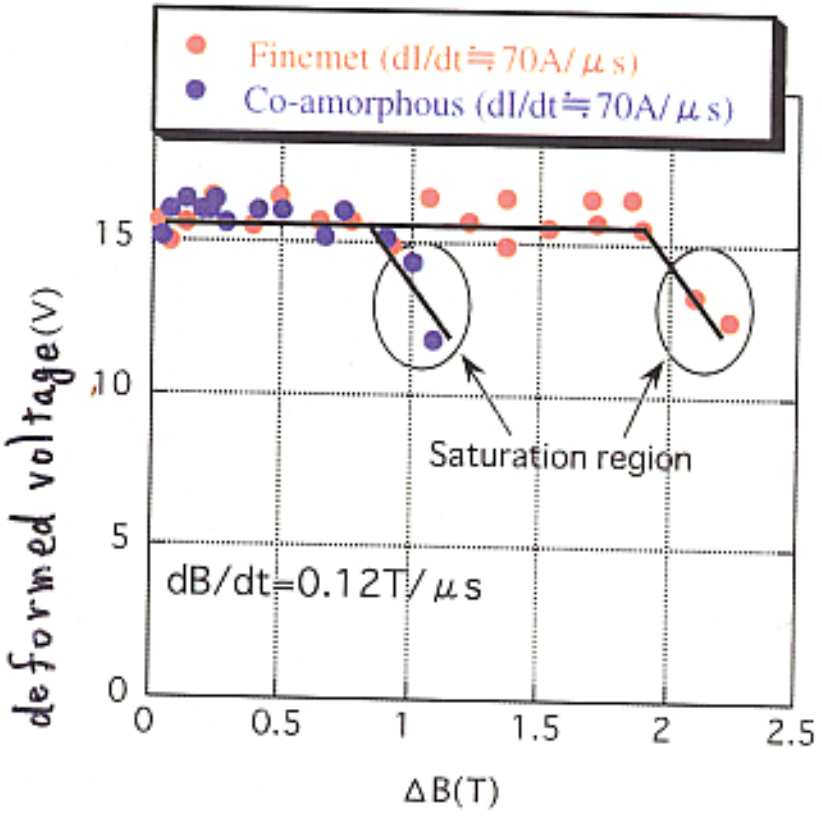
Example of core response of B-H curve



Tokyo Institute of Technology

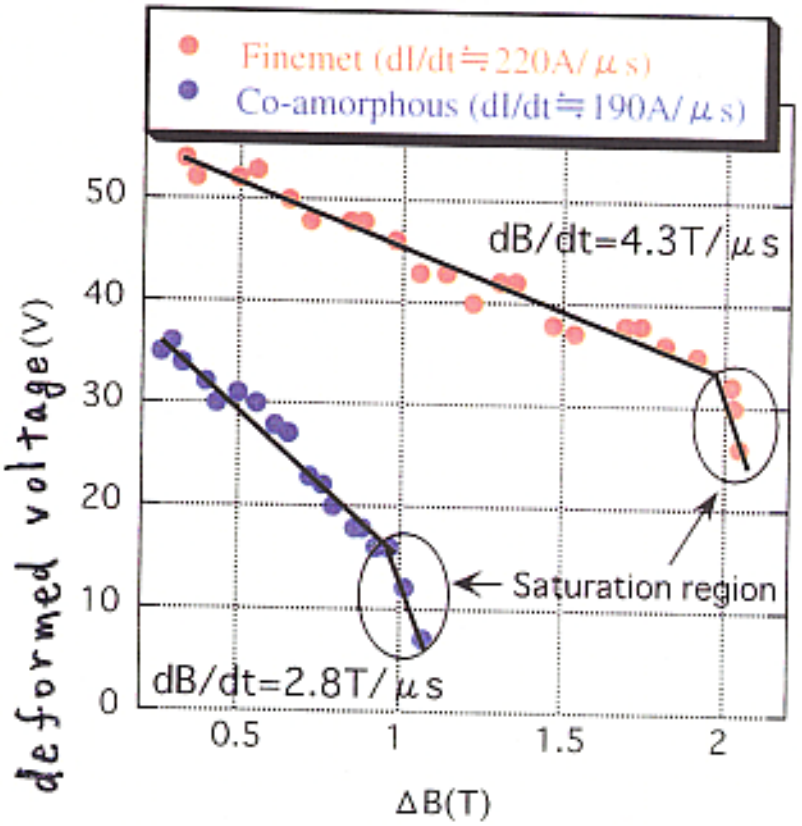
Response versus Progression of Magnetization

Bar-domain mode



Low magnetization rate

Saturation-wave mode



High magnetization rate

Tokyo Institute of Technology

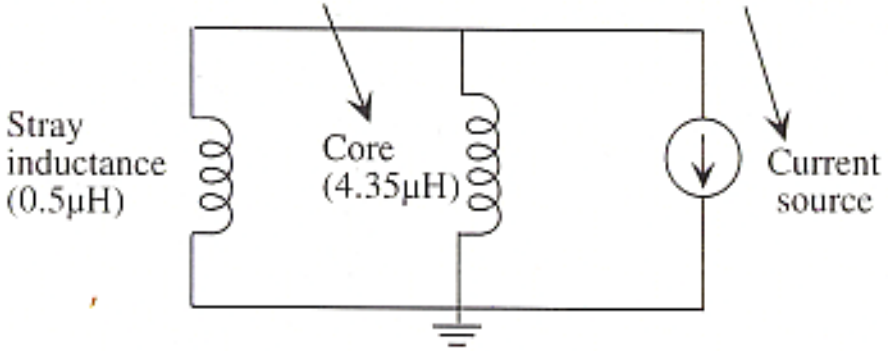
Estimation of change of the votage in designed induction module

core size

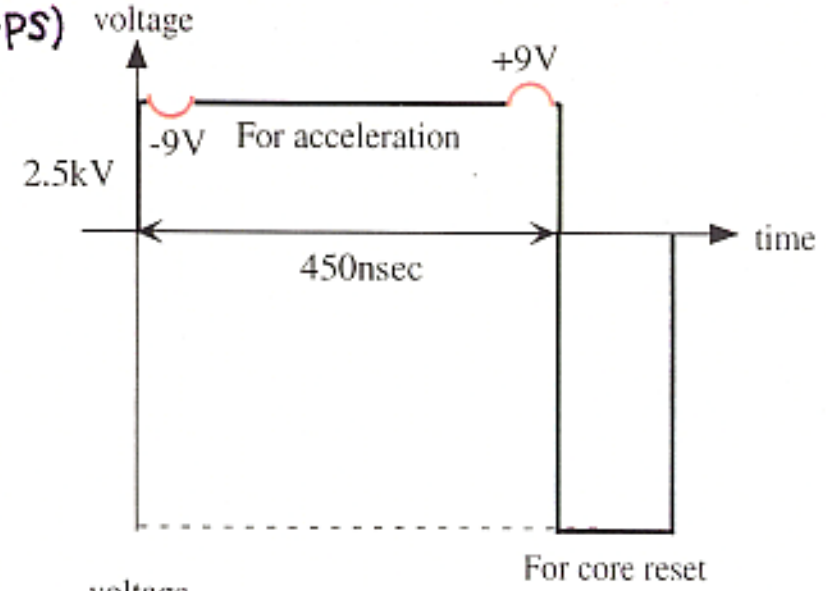
inner diameter	10cm
outer diameter	50cm
width	5cm

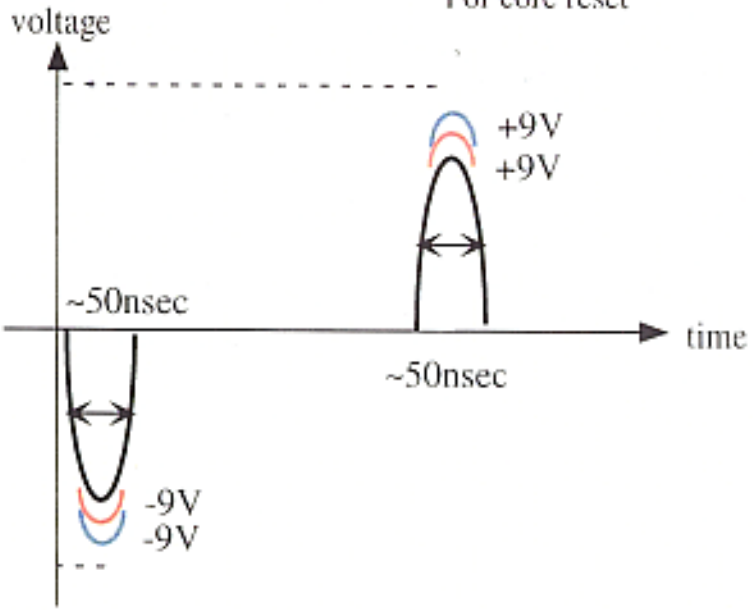
Beam parameter(12GeV-KEK-PS)

current	1A
rise time	50nsec
dI/dt	20A/μs



Equivalent circuit of induction module from the point of view of the secondary when using PSpice





Acceleration voltage is 2.5kV in our design. The estimated change of the voltage was about **9V**. This value is only 0.36% of the acceleration voltage.

Conclusions

- Induction modulators have been operated up-to 1MHz.
- Empirical formulae for core-losses have been obtained, which is useful for a various operating mode.
- Beam loading Effects were experimentally evaluated, which depend on non-linear effects of magnetic cores.