THP10

Calibration of beam current monitors at J-PARC accelerator facility

Kenichirou Satou※, Takeshi Toyama, and Aine Kobayashi, J-PARC/KEK

Abstruct

Accelerators at J-PARC, a high-intensity proton accelerator facility, consists of a 400 MeV linac, 3 GeV RCS, and 30 GeV MR. The RCS is aiming for steady operation with output beam power of 1 MW, while the MR has achieved its initial target of 750 kW by shortening its operating cycle, and further beam tunings and developments are underway to achieve the next target of 1.3 MW. At J-PARC, it is necessary to suppress beam losses to an extremely low level to suppress the activation of the accelerator devices, and thus it is essential to improve the measurement accuracy of beam loss and beam current monitors (BCMs). Particularly in MR, with the significant improvement in beam power, there is a need to improve the measurement accuracy of the beam current monitors from 1% at the present. Accordingly, the current monitors have been calibrated regularly but have not been carried out in a unified manner throughout the accelerators. In this presentation, we will report on the calibration methods of 3-50BT BCM and its accuracy.

1, Motivations and targets of this study

Background

1, Investigating the measurement accuracy and consistency of beam current (intensity) in Li, RCS, and MR facilities
- ・The Beam Current Monitor (BCM) at each facility is operated independently.
- ・Each BCM guarantees an accuracy of 1%, but the calibration method, calibration accuracy, and consistency between facilities have not been investigated.
- ・With the power upgrade at J-PARC, high-precision evaluation of output power and loss power is required. ➡ **Requirements for precise beam tuning and radiation management.**

2, High-precision measurement of beam charge injected to MR
- ・Measured charge per beam bunch by 3-50BT BCM: 1% accuracy guaranteed
- ・Measured accumulated charge in MR by DCCT: 1% accuracy guaranteed
- ※Injection beam loss occurred immediately cannot be measured with DCCT due to limited cutoff frequency.

Table of BCMs for J-PARC (reprinted table from [6])

Facility	BCT name	Type	Number	Turn N	Magnetic core	Core size (Inner ϕ, Outer ϕ, width)	L(H)	BW	Remark
Li	FCT	Passive	14	1	FT-3M [2]	90, 114, 5	3n		
	SCT	Active [3]	7	50	FT-3M	90, 114, 10	15m	10Hz~	
	FCT/SCT		13		FT-3M				Mounted in a same case
RCS	FCT	Passive	4	20	FT-3M	390, 470		>100MHz	
	MCT	Passive	1	1000	FT-3M	390, 470			
	SCT	Feedback	1	-	FT-3M	390, 470		~10kHz	
	DCCT	DCCT	1	-	Manufactured by Berboz inc.	-		DC~10kHz	
	WCM	WCM	3	-	FT-3M	390, 470		200Hz~>10MHz	
3-50BT	FCT	Passive [1]	5	25	FT-3M	272, 335, 35	18m	~20MHz	
MR	DCCT	DCCT	2		FT-3M	[4]	[4]	DC~20kHz	Parallel feedback
	FCT	Passive	3	25	FT-3M			16Hz~180MHz	
	WCM	WCM	6		FT-3M			>100MHz	

The importance of measuring beam charge with extremely high accuracy at BCT of 3-50BT

Good accuracy of << 1.5%
Less than 1/5 of collimator power limit ➡ less than 0.3%

MR upgrade campaign (on going)
- ・3-50BT 130kW
- ・MR 1.3MW (at present 800 kW)

※By increasing the bunch charge and by shortening the repetition down to 1.16 s

Accuracy of ~ 0.08%

New requirements based on beam collimator's power limit
- ・3-50BT collimator unit, **2kW max**
- ・MR collimator unit, **2kW max**

※Both are equivalent to 1.5% of injection beam power

New Requirements from the viewpoint of beam loss evaluation during high power daily beam operation
- ・Required to evaluate the incident beam loss power with an error of about 100W (~ 0.08%) for radiation management

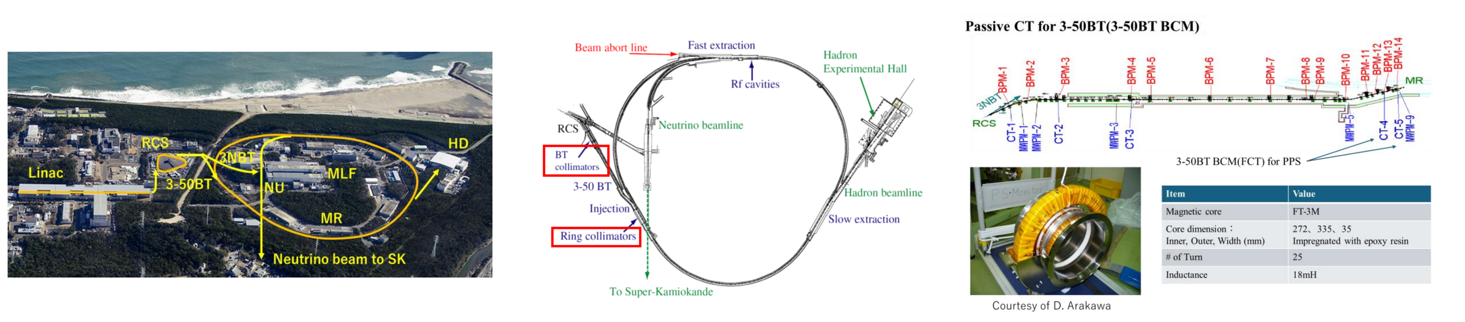
※Beam loss monitors measure its distribution along the MR, but it is difficult to accurately evaluate the total loss power.

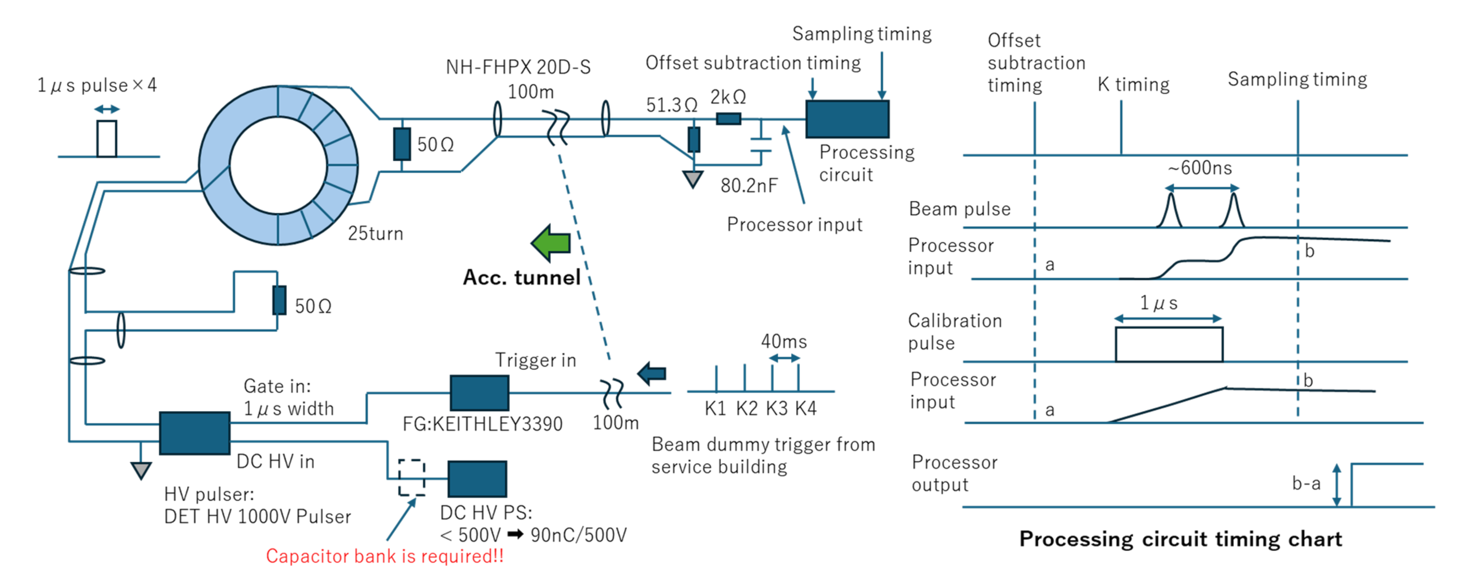
0.1% calibration accuracy is needed for 3-50BT BCM

Investigate the limits of calibration accuracy : Present method
- **・How much accuracy can be improved "in principle"?**
- **・How to improve it?**

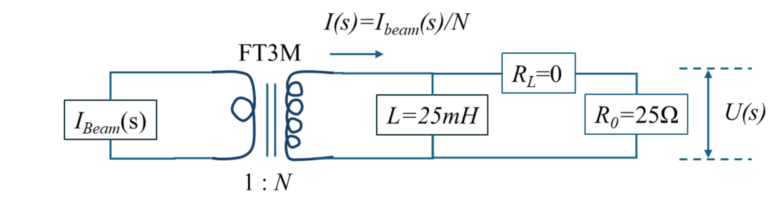
※The accuracy of the signal source and the voltmeter will be evaluated independently.

2, Present calibration setup of 3-50BT BCM





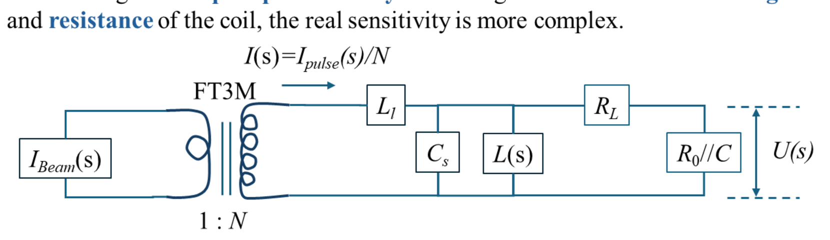
In an ideal case, the beam current $I_{beam}(s)$ at the center of BCM induces the output voltage of



$$U(s)=\frac{I_{beam}(s)}{N}R_0\frac{1}{1+R_0/sL}=I_{beam}(s)\frac{1}{1+231/f}=I_{beam}(s)S_0(s)$$ ← **Ideal Sensitivity of 3-50BT BCM**

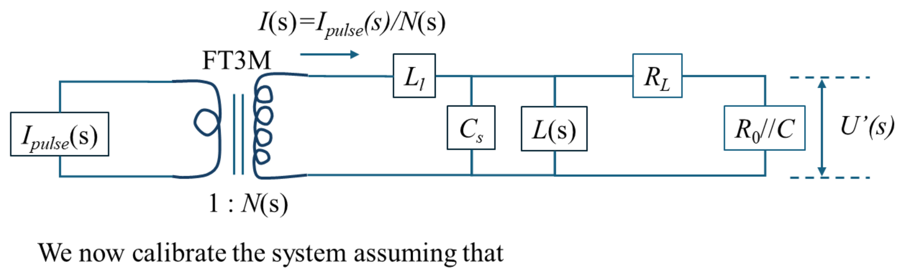
where the load impedance is R_0=25 Ω, # of turn of the FT3M toroidal coil is N=25, and inductance is L=18 mH (measured).

Considering the **complex permeability** of the magnetic core as well as **leakage inductance**, **stray capacitance** and **resistance** of the coil, the real sensitivity is more complex.



$$U(s)=I_{beam}(s)\,S(s)$$

In case of the signal calibration using 1 turn coil and single rectangle pulse signal, output voltage can be expressed as,



$$U'(s)=\chi(s)I_{pulse}(s)\,S(s)$$

Current transmission efficiency to secondary coil

$$\chi(s)=\frac{N(s)}{N}$$

We now calibrate the system assuming that

$$\frac{\int_o^{\Delta T}u'(t)dt\ \left(=\int\chi(f)I_{pulse}(f)S(f)df\right)}{\int i_{pulse}(t)dt}=\frac{\int_0^{\Delta T}u(t)dt\ \left(=\int I_{Beam}(f)S(f)df\right)}{\int i_{beam}(t)dt\ \ (=Q_{Beam})}$$

Output of signal integrator of BCM

$$Q_{Beam}=\frac{\int_o^{\Delta T}u(t)dt}{\int_0^{\Delta T}u'(t)dt}\int i_{pulse}(t)dt$$ ➡ Calibration factor

These are measured by the oscilloscope

The method is true only in case,,,,,
1, $I_{Beam}(s)=I_{pulse}(s)$ ➡ frequency response is similar
2, Transmission efficiency is unity ➡ $\chi(s)=1$

It's not exact, but 1% accuracy is fine !

3, Effect of eddy current loss in a core

Relative permeability is defined as,

$$\mu=\mu'-j\mu''\quad \text{where}\quad B=\mu H$$

Magnetic reluctance $\mathcal{R}$ is defied as,

$$\Phi=NI\cdot\frac{\mu A}{l}=\frac{\mathcal{F}}{\mathcal{R}}$$

Where, Φ(=BA) is magnetic flux and $\mathcal{F}$(=NI) is magnetomotive force.

$$\mathcal{R}=\frac{l}{\mu A}=\frac{l/A}{\mu'-j\mu''}=\mathcal{R}'+j\mathcal{R}''\qquad \mathcal{R}'=\frac{\mu'}{\mu'^2+\mu''^2}\frac{l}{A},\quad \mathcal{R}''=\frac{\mu''}{\mu'^2+\mu''^2}\frac{l}{A}$$

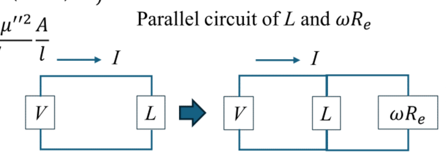
Using the real and imaginary parts of the magnetic reluctance, $\mathcal{R}'$ and $\mathcal{R}''$, The voltage and current induced in the coil wound around the magnetic toroidal core (N turn) are as follows:

$$V=N\frac{d\phi}{dt}=j\omega N\phi=\frac{j\omega N^2 I}{\mathcal{R}'+\mathcal{R}''}=I\left\{\left(j\omega\frac{N^2}{\mathcal{R}'}\right)^{-1}+\left(\omega\frac{N^2}{\mathcal{R}''}\right)^{-1}\right\}^{-1}=I\{(j\omega L)^{-1}+(\omega R_e)^{-1}\}^{-1}$$

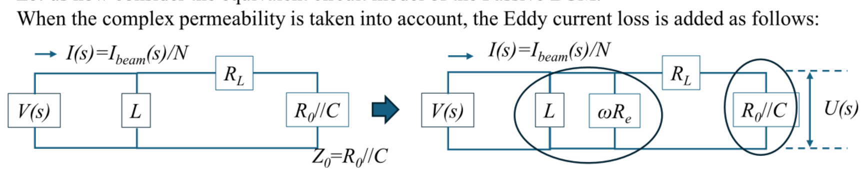
Parallel circuit of L and ωR_e

$$L=\frac{N^2}{\mathcal{R}'}=N^2\frac{\mu'^2+\mu''^2}{\mu'}\frac{A}{l},\quad R_e=\frac{N^2}{\mathcal{R}''}=N^2\frac{\mu'^2+\mu''^2}{\mu''}\frac{A}{l}$$

$$\therefore\ \frac{R_e}{L}=\frac{\mu'}{\mu''}$$



Let us now consider the equivalent circuit model of the Passive BCM.
When the complex permeability is taken into account, the Eddy current loss is added as follows:



$$U(s)=\frac{Z_0}{Z_L+Z_0}V(s)=\frac{I_{beam}(s)}{N}\frac{Z_0}{R_L+Z_0}\left(\frac{1}{Z_L}+\frac{1}{R_L+Z_0}\right)^{-1}=\frac{I_{beam}(s)}{N}Z_o\frac{Z_L}{Z_L+R_L+Z_0}$$
$$=\frac{I_{beam}(s)}{N}sLZ_0\frac{1}{sL\left(1+\frac{R_L+Z_0}{\omega R_e}\right)+R_L+Z_0}$$

1) If $sL\left(1+\frac{R_L+Z_0}{\omega R_e}\right)\ll R_L+Z_0$ and $s\ll\frac{1}{R_0C}$ → $Z_0=R_0$

$$s\ll\frac{R_L+R_0}{L\left(1+\frac{R_L+R_0}{\omega R_e}\right)}\approx\frac{R_L+R_0}{L}\left(1-\frac{R_L+R_o}{\omega R_e}\right)=\tau_0^{-1}-\tau_e^{-1}=\tau^{-1}$$

Time constant is reduced by the eddy current loss

$$U(s)=\frac{I_{beam}(s)}{N}sL\frac{R_0}{R_L+R_0}$$ Monotonically increasing with increasing frequency

2) If $sL\left(1+\frac{R_L+Z_0}{\omega R_e}\right)\gg R_L+Z_0$ and $s\ll\frac{1}{R_0C}$ → $Z_0=R_0$

$$s\gg\frac{R_L+R_0}{L\left(1+\frac{R_L+R_0}{\omega R_e}\right)}$$

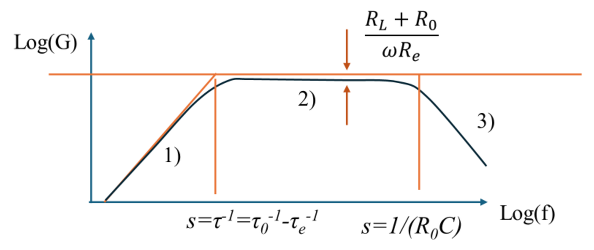
$$U(s)=\frac{I_{beam}(s)}{N}\frac{R_0}{1+\frac{R_L+R_0}{\omega R_e}}\approx\frac{I_{beam}(s)}{N}R_0\left(1-\frac{R_L+R_0}{\omega R_e}\right)$$

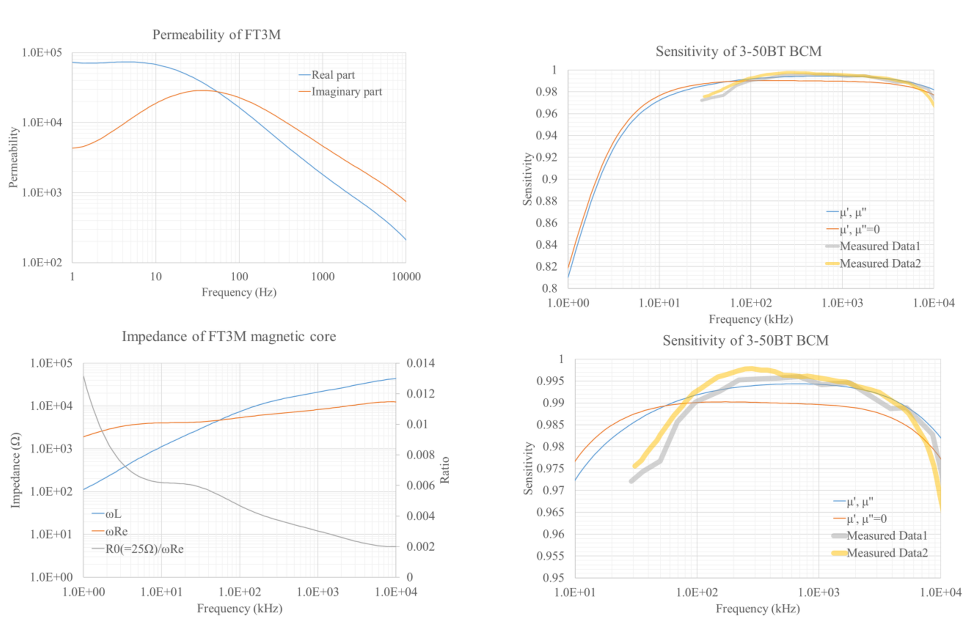
Flat response but slightly modulated by the eddy current loss

In a real case, a situation is more complex as an inductance L is not constant but has frequency dependence.

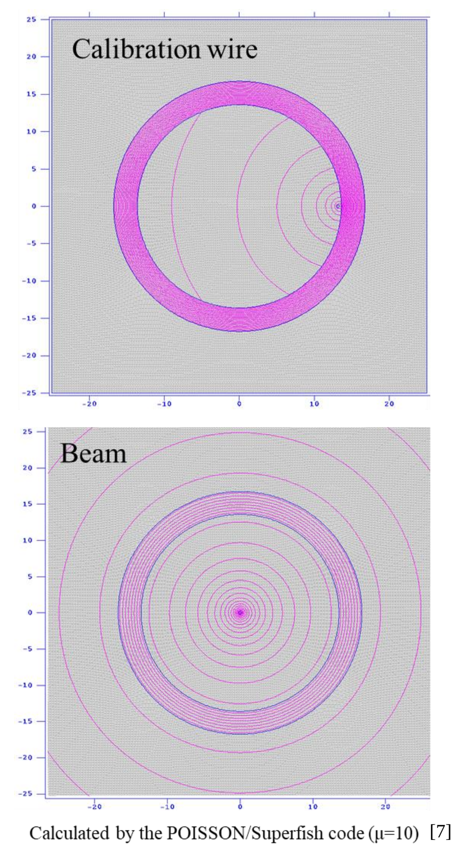
3) If $s\gg\frac{1}{R_0C}$ → $Z_0=\frac{1}{sC}$

$$U(s)=\frac{I_{beam}(s)}{N}(sC)^{-1}\left(1-\frac{R_L+(sC)^{-1}}{\omega R_e}\right)=\frac{I_{beam}(s)}{N}\left\{\frac{1}{sC}\left(1-\frac{R_L}{\omega R_e}\right)-\frac{1}{\omega R_e}\frac{1}{s^2C^2}\right\}$$



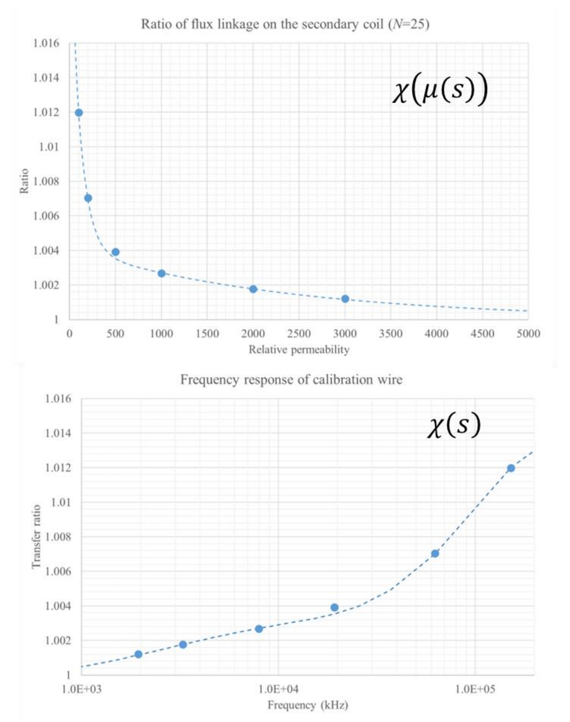


3, Current transmission efficiency

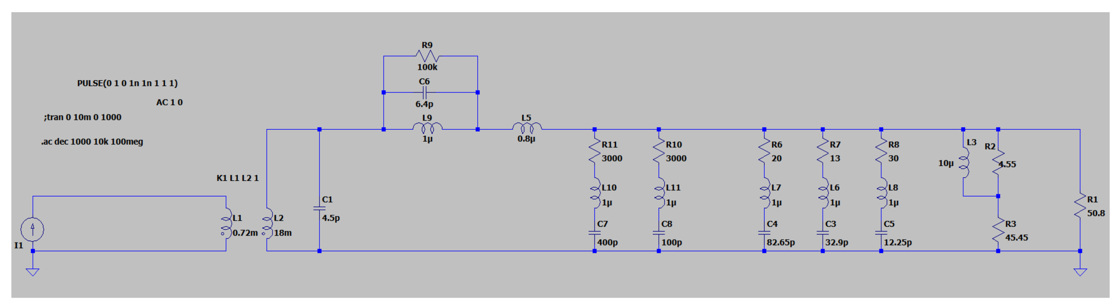


Calculated by the POISSON/Superfish code (μ=10) [7]

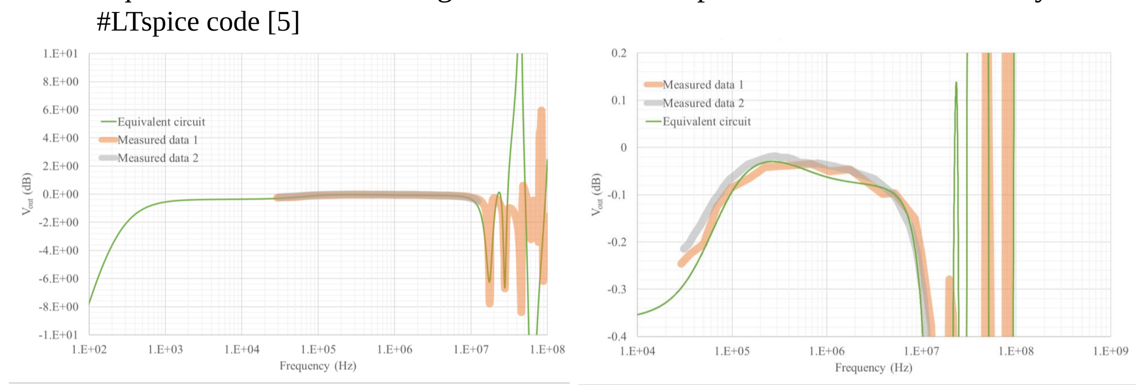
$$\chi(s)\approx\frac{\iint\phi_{wire}(\theta,r)dr\,d\theta|_{inside\ core}}{\iint\phi_{beam}(\theta,r)dr\,d\theta|_{inside\ core}}$$



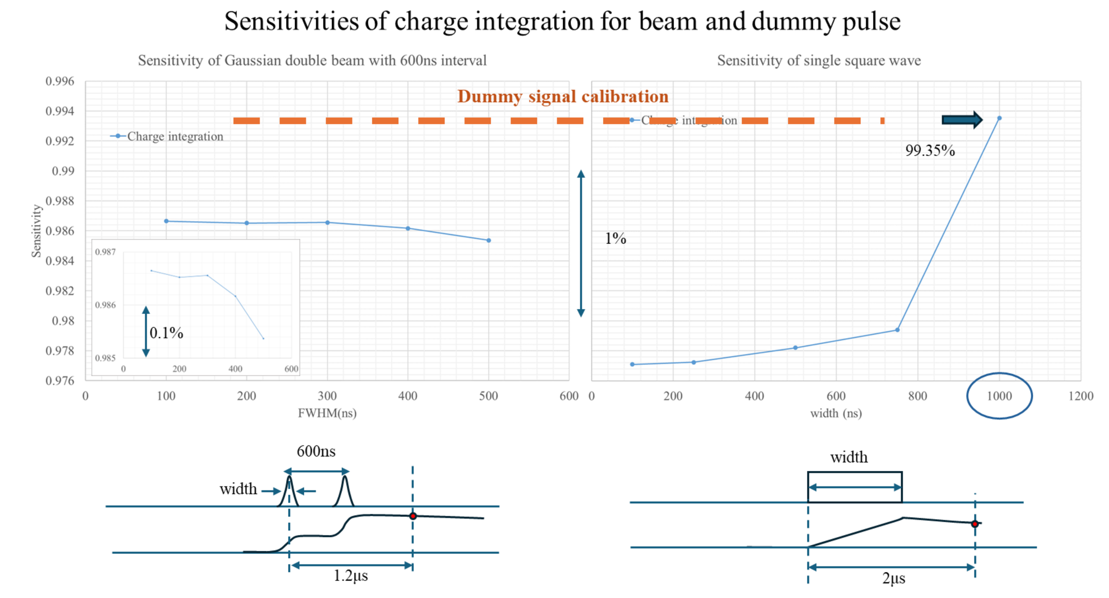
4, 3-50BT BCM sensitivity: charge integration



Equivalent circuit was designed to estimate the present calibration accuracy
#LTspice code [5]



Sensitivities of charge integration for beam and dummy pulse



Summary

1, A detailed analysis was performed for the 3-50BT BCM to evaluate the sensitivity and its calibration methods at present.
- ・Complex permeability ➡ Eddy current loss in a FT3M magnetic core
- ・Equivalent circuit ➡ Sensitivity function ➡ Charge integration : beam current vs. dummy current
- ・Current transmission efficiency : 2 D analysis using POISSON/Superfish code

2, Calibration method at present
- ・Calibration using 1μs width dummy pulse: Time domain analysis
- ・The current transmission coefficient is not taken into account, but the effect is at most 0.2% in the region of interest (f<10MHz)
- ・Errors occur due to differences in frequency distribution between the dummy pulse and the beam pulse
  - ➡ It is an overestimation of about 0.5%, but the initial calibration target of 1% accuracy has been achieved

3, Future calibration method (under consideration)
- ・Evaluation of the transmission coefficient and eddy current loss is essential
- ・Frequency domain analysis of sensitivity is effective
- ・Aging of magnetic core (permeability) needs to be considered ➡ Future issues

References

[1] D. Arakawa, "Beam Intensity Monitor for 500 MeV Beam Transport Line at KEK Proton Synchrotron", KEK Internal 93-9, Nov. 1993 (in Japanese).
[2] https://www.proterial.com/products/soft_magnetism/.
[3] S. Hiramatsu *et al.*, "Beam Intensity Monitor for KEK Proton Synchrotron", KEK-77-21, Feb. 1978 (in Japanese).
[4] K. Satou *et al.*, "PRESENT PERFORMANCE OF A DCCT FOR J-PARC MR", Proceedings of the 13th Annual Meeting of Particle Accelerator Society of Japan, Chiba, Japan, Aug. 8-10, 2016, pp. 1076-1080 (in Japanese).
[5] https://www.analog.com/jp/resources/design-tools-and-calculators/ltspice-simulator.html
[6] K. Satou *et al.*, "Calibration of beam current monitors at J-PARC accelerator facility", Proceedings of the 21th Annual Meeting of Particle Accelerator Society of Japan, Yamagata, Japan, Jul. 31-Aug. 3, 2024 (in Japanese).
[7] Reference Manual for the Poisson/Superfish Group of Code", Los Alamos Accelerator Code Group, LA-UR-87-126.

※E-mail: Kenichirou.satou@j-parc.jp