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Evaluation of the Diamagnetic Energy in the JFT-2M Tokamak
Compensation of the Poloidal Field Effects on the Diamagnetic Loop –

Jae Sung Yoon, Seung Ho Jeong, Bong Kuen Hong

Korea Atomic Energy Research Institute
P.O.Box 105, Yusong, Taejon, 305-600, Korea

ABSTRACT

Owing to the perpendicular motion of electrons and ions the plasma excludes a small amount df of the toroidal flux f. Measuring df allows determination of the diamagnetic beta poloidal $b_{p\perp}$, defines as the ratio of transverse plasma pressure to magnetic field pressure at the plasma surface. $b_{p\perp}$ is measured by a loop mounted inside of the vacuum vessel. As in tokamaks one has $df/f \approx 10^{-4}$, even very slight magnetic stray fields, coil displacements and eddy currents in the structure during the discharge pulse can influence the diamagnetic signal. We show the separate interference of poloidal field coils on the diamagnetic loop in the JFT-2M tokamak and describe the method for compensating these effects.

1. INTRODUCTION

The measurement of the diamagnetic poloidal beta of a tokamak plasma has several attractive features. It provides a continuous measure of the total transverse plasma energy, time-dependent throughout a single discharge, without requiring a knowledge of the radial profiles of T_e, T_i, n_e and n_i [1, 2, 3]. But as the excluded toroidal flux(df) is extremely small (df/f ~ 10^{-4}) , this diagnostic technique has been hampered by its low accuracy in conjunction with the low plasma energy content of the small tokamak machines of the past. But it must still be able to detect a signal change of the order of 0.1mT in the presence of a toroidal magnetic field of 2 to 3T in the hostile environment of a tokamak discharge. In this paper the technical realization for diamagnetic measurements in the JFT-2M tokamak are described. JFT-2M is a middle size Tokamak with major radius R_o ~ 1.31 m and minor radius a ~ 0.3 m.

2. THEORY AND DESCRIPTION OF JFT-2M DIAMAGNETIC LOOP SYSTEM

In a tokamak configuration the plasma is kept in equilibrium by poloidal magnetic fields. When the kinetic plasma pressure remains smaller than the poloidal magnetic pressure at the plasma boundary(r = a), $b_{p\perp}$ is smaller than one and the difference is compensated by a decrease of the toroidal magnetic field within the plasma. Beta poloidal $\beta_{p\perp}$ is defined as the ratio of the kinetic plasma pressure $<p>$ (acting perpendicularly to B_θ towards the plasma center) to the poloidal magnetic pressure $B_{\theta a}^2/2\mu_0$ at the plasma boundary (ρ = r/a = 1)

$$\beta_{p\perp} \equiv \frac{2\mu_0 <p>}{B_{\theta a}^2} = 1 + \frac{B_{\phi a}^2 - <B_\phi^2>}{B_{\theta a}^2}$$

Where < > indicates average over the plasma cross section, the subscript a means quantities evaluated at $r = a$, and we have assumed $p_a = 0$. This is an expression for the ratio of kinetic pressure to (poloidal) magnetic field pressure, the plasma beta $\beta_{p\perp}$. In its present form the equation is not very useful because it is not clear how to measure $<B_\phi^2>$, but if B_ϕ varies only weakly across the plasma, which will be the case if $B_\phi \equiv 2\mu_0 <p>/B_\phi^2 << 1$ and $B_\theta << B_\phi$ (as occurs in tokamaks), then

$$B_{\phi a}^2 - <B_\phi^2> \approx 2B_{\phi a}(B_{\phi a} - <B_\phi>)$$

and so

$$\beta_{p\perp} \approx 1 + \frac{2B_{\phi a}(B_{\phi a} - <B_\phi>)}{B_{\theta a}^2}$$

and

$$\delta\phi = \pi a^2 (<B_\phi> - B_{\phi a})$$

$\delta\phi$ is the diamagnetic flux of the longitudinal magnetic field in the plasma column, then we obtain

$$\beta_{p\perp} = 1 - \frac{2B_{\phi a}}{B_{\theta a}{}^2} \bullet \frac{\delta\phi}{\pi a^2}$$

The poloidal field $B_{\theta a}$ can be measured with a Rogowski coil wound around the vacuum vessel. The induced voltage in the Rogowski coil is integrated by integrator. $B_{\phi a}$ can be measured with the DC current transformer(DCCT) located at toroidal field(TF) windings. The measured voltage of the DCCT have a proportional value to the toroidal magnetic field. To measure the diamagnetic flux change $\delta\phi$, diamagnetic coil and DCCT are used. The diamagnetic coil encircles the whole plasma area and measures the total toroidal flux $\phi = \delta\phi + \phi_{TF}$ created by the diamagnetic current of the plasma and the toroidal field coils. The DCCT at toroidal field measures the toroidal flux ϕ_{TF} created by the toroidal field coils alone. The flux differences are given by

$$\delta\phi = \phi - \phi_{TF}$$

The main problem in the measurement of plasma diamagnetism is that the plasma toroidal flux is of the order of 10^{-4} of the total toroidal flux. The instruments used on JFT-2M are a flux loop(diamagnetic loop) and Rogowski coils. Ideally, the flux loop should be perfectly parallel to f = constant plane and mechanically stable to avoid coupling to the poloidal field and to avoid time-dependent error fluxes. The flux loop and Rogowski coil signals are combined in the analog circuit of Fig.1. On the JFT-2M experiment we use a compensated diamagnetic loop consisting of a main loop, one turn for measuring the total toroidal flux f, and a DCCT for measuring only the toroidal flux of the toroidal field coils f_{TF} . Diamagnetic loop is mounted in the vacuum vessel and DCCT are used to measure poloidal field coil currents. Rogowski coils, which measure a plasma current, was constructed to have a $1.95x10^{-7}(NSm_0)$ sensitivity and $1.43x10^{-7}(NSm_0)$ at the outside and inside vacuum vessel respectively, where N is the number of turns and S is the area of the one turn.

3. COMPUTATIONAL COMPENSATION OF THE DIAMAGNETIC LOOP

3.1 Reduce TF Effect

We have poloidal coil sets of Q-coil, S-coil, V_{UP}-coil and V_{LOW}-coil to control plasma in the JFT-2M tokamak. Table 1 shows three different poloidal field connection, named A2, USNL and LSNL. In the case of USNL or LSNL, we can make a null point inside of the vacuum vessel. The positions and characters of poloidal coils are shown in JAERI-M Report [4].

	A2 connection	**USNL connection**	**LSNL connection**
S-coil	S1U = 14 turns	S1U = 14 turns	S1U = 14 turns
	S2U = 28 turns	S2U = 28 turns	S2U = 28 turns
	S3U = 24 turns	S3U = 24 turns	S3U = 24 turns
	S1L = 14 turns	S1L = 14 turns	S1L = 14 turns
	S2L = 28 turns	S2L = 28 turns	S2L = 28 turns
	S3L = 24 turns	S3L = 24 turns	S3L = 24 turns
VUP-coil	V1U = 10 turns	V1U = 10 turns	V1U = 10 turns
	V2U = 4 turns	V2U = 4 turns	V2U = 4 turns
	S3/2L = -14turns	S3/2L = -14turns	S3/2L = -14turns
VLOW-coil	V1L = 10 turns	V1L = 10 turns	V1L = 10 turns
	V2L = 4 turns	V2L = 4 turns	V2L = 4 turns
	S3/2U = -14turns	S3/2U = -14turns	S3/2U = -14turns
Q-coil	Q1/1U = 0 turn	Q1/1U = 8 turn	Q1/1U = 0 turn
	Q1/2U = 8 turns	Q1/2U = 8 turns	Q1/2U = 8 turns
	Q2 = -16 turns	Q2 = -16 turns	Q2 = -16 turns
	Q1/1L = 0 turn	Q1/1L = 0 turn	Q1/1L = 8 turn
	Q1/2L = 8 turns	Q1/2L = 8 turns	Q1/2L = 8 turns

Table 1 Connection methods of poloidal coils

The fluxes contributing significantly to the diamagnetic loop signal are

$$f_{DL} = f_{TF} + f_{Q-coil} + f_{S-coil} + f_{V_{UP}-coil} + f_{V_{LOW}-coil} + ----,$$

where

f_{DL} : Total flux through the loop,
f_{TF} : Contribution from the TF coil,
f_{Q_coil} : Coupling with Q-coil current,
f_{S_coil} : Coupling with S-coil current,
$f_{V_{UP}\_coil}$: Coupling with V_{UP} -coil current,
$f_{V_{LOW}\_coil}$: Coupling with V_{LOW} -coil current.

The first step of the compensation is obtained by a direct analog integration, as shown in Fig. 1, of the difference between the diamagnetic loop and DCCT voltage

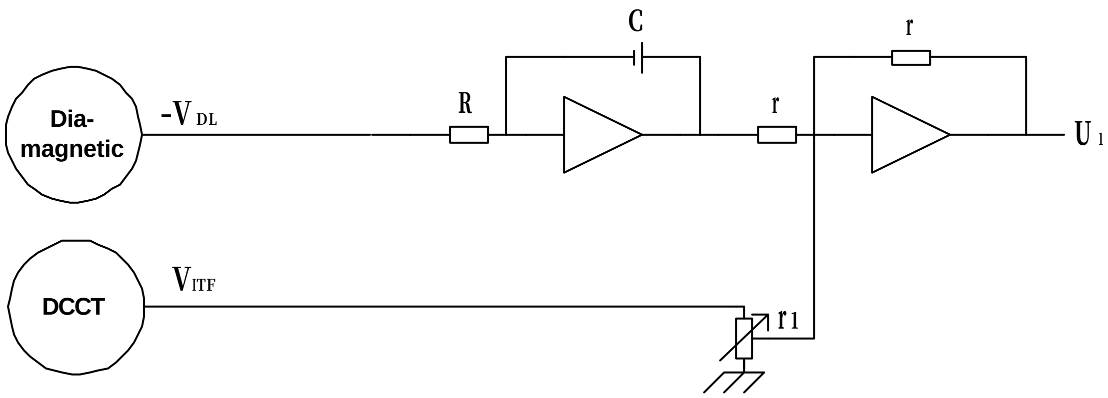


Fig.1 Schematic diagram of the JFT-2M diamagnetic loop compensation circuit

$$U_1 = 1/RC\int(-V_{DL})dt - aV_{I_{TF}}$$

$$f_{DL} - f_{TF} = (RC)U_1$$

$$df = f_{DL} - f_{TF} = \int(-V_{DL})dt - I_{TF}M$$

from $V_{I_{TF}} = R_{TF} I_{TF}$ and $f_{TF} = MI_{TF}$ the balancing coefficient $a(= r/r_1)$ is

$$a = (RC \bullet \frac{R_{TF}}{M})^{-1}$$

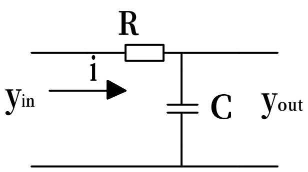
where R_{TF} is the DCCT coefficient and $M(= m_0 NS/2pR)$ is the mutual inductance between I_{TF} and the diamagnetic loop.

3.2 Poloidal Field Effects on the Diamagnetic Loop

To compensate the magnetic coupling of the poloidal fields into the diamagnetic loop during the plasma shots, we measured diamagnetic loop signals and the currents in the poloidal field coil systems with DCCT. For example, measured diamagnetic loop signal and coil current signal of V_{UP} –coil are shown in Fig. 2a. To analyze the signals we eliminate drifts in the integrator for the diamagnetic loop at first, then compared two signals. Fig.2b is signals after get rid of drifts and gain adjustment. For each of these currents a proportional gain and delay time are measured and fed into a computational circuit to add or subtract the compensated diamagnetic signal. To find out parameters for the compensating poloidal field coil effect, we made individual test shot with the Q-coil current, S-coil current, V_{UP}-coil current, V_{LOW}-coil. We don't have an electrical circuit compensating the magnetic coupling of the poloidal fields into the diamagnetic loop system in the JFT-2M Tokamak. So we should compensate magnetic coupling by computational method

3.3 Methods of the Compensation for Poloidal Field Effect

To compensate the magnetic coupling of the poloidal fields into the diamagnetic loop, we should know the relationship between diamagnetic loop and DCCT signals for each coil. To consider the gain between diamagnetic loop and DCCT signal, we compared two signals at the flat top level then got the proportional gains of all coils. To determine the delay time of all coils we considered the simple RC integrator circuit and use "Runge-Kutta method"[5].



Above RC circuit is a first-order delay circuit. By above circuit we can get below equations.

$$y_{in} = iR + \frac{1}{C}\int idt ------------ (eq.1)$$

$$y_{out} = \frac{1}{C}\int idt -------------- (eq.2)$$

From eq.2

$$\frac{dy_{out}}{dt} = \frac{i}{C}, i = C\frac{dy_{out}}{dt}$$

$$y_{in} = RC\frac{dy_{out}}{dt} + y_{out}$$

$$\frac{dy_{out}}{dt} = \frac{1}{RC}(y_{in} - y_{out})$$

If we solve the above equation numerically we can get the y_{out} .
There is a method to solve the differential equation named “Runge-Kutta method”.

$$\frac{dy}{dt} = f(x, y)$$

$$y_{n+1} = y_n + \Delta y_n$$

$$\Delta y_n = \frac{1}{6}(k_0 + 2k_1 + 2k_2 + k_3)$$

Where

$$k_0 = hf(x_n, y_n)$$

$$k_1 = hf(x_n + \frac{h}{2}, y_n + \frac{k_0}{2})$$

$$k_2 = hf(x_n + \frac{h}{2}, y_n + \frac{k_1}{2})$$

$$k_3 = hf(x_n + h, y_n + k_2)$$

Let’ s solve the differential equation to find delay time

$$\frac{dy_{out}}{dt} = \frac{1}{RC}(y_{in} - y_{out})$$

If we set h as a step of the sampling

$$y_{out}^{n+1} = y_{out}^{n} + \frac{1}{6}(k_0^n + 2k_1^n + 2k_2^n + k_3^n)$$

Where

$$k_0^n = \frac{dt}{RC}(y_{in}^n - y_{out}^n)$$

$$k_1^n = \frac{dt}{RC}(y_{in}^n - (y_{out}^n + \frac{k_0^n}{2}))$$

$$k_2^n = \frac{dt}{RC}(y_{in}^n - (y_{out}^n + \frac{k_1^n}{2}))$$

$$k_3^n = \frac{dt}{RC}(y_{in}^n - (y_{out}^n + k_2^n))$$

$$y_{out}^{o} = 0$$

from above equation we can get the output value which have a RC delay time value. To find the delay time of each coil, we select the rising and falling time area of each signals then compare the square value of the difference between diamagnetic signal and time delayed DCCT signal by varying the RC value.

3.4 The Results of the Compensation of Gain and Delay time

Table 2 is the gain values of each coil currents for each connection. For A2 connection the average gain value of S-coil is –4.294, Q-coil is 147.172, V_{UP}-coil is 30.384 and V_{LOW}-coil is 10.017 when we consider the coil current above 1kA. Maximum gain deviations of total average are under 2 % for A2, USNL and LSNL connections in case of coil currents are over 1kA. Gain values are shown Table 2.

	S-coil	Q-coil	V_{UP}-coil	V_{LOW}-coil
A2 connection	-4.294	147.172	30.384	-10.017
USNL connection	-4.293	144.73	30.599	-10.002
LSNL connection	-4.302	106.555	30.412	-10.128
Total average	-4.296		30.465	-10.049

Table 2 average gain values in case of coil currents are over 1kA

Let define the square of the difference, $e = \Sigma\{y^{dia} - G \bullet y_{out}(RC)\}^2$, where y^{dia} is diamagnetic signal, G is the gain shown in Table 2 and $y_{out}(RC)$ is a modified signal with using delay circuit of RC discussed in the section 3.3. Fig.3 shows the dependence of e on the value of RC for the Q, S, V_{UP} and V_{LOW} coil respectively. We can clearly select RC value at the minimum of e. Three values of RC are summarized in the Table 3. In the Table 3, the averaged value of RC for the different coil connection is also shown, the RC value does not show a large difference. Fig. 4 – Fig. 7 shows the temporal behaviors of the poloidal coil effects of Q, S, V_{UP} and V_{LOW} on the diamagnetic loop. In each graph, (a) and (b) show the difference of the poloidal field effects on diamagnetic loop only with the gain, (c) and (d) show the difference after adjusting both gain and delay time. Also shown in (e) is the case of using averaged RC value shown in Table 3. In these graphs, we can clearly show the effect of the delay time and these show no big difference with using an averaged delay time. In the case of small poloidal field coil current, there is a very small current after opening the gate signal for the power supply of the poloidal field coil. This effect enlarges the offset compensation of TF effect and shows a large value of the gain. Therefore we do not use the case of the small poloidal coil current.

	S-coil	Q-coil	V_{UP}-coil	V_{LOW}-coil
A2 connection	16.2ms	8.5ms	21.7ms	11.8ms
USNL connection	15.7ms	7.8ms	21.4ms	11.5ms
LSNL connection	16.2ms	7.7ms	20.6ms	11.1ms
total average	16ms	8ms	21.2ms	11.5ms

Table 3 delay time values in case of coil currents are over 1kA

SUMMARY & FUTURE WORK

The compensated poloidal fields effect in the diamagnetic loop of f_{Q_coil}, f_{S_coil}, $f_{V_{UP}\_coil}$ and $f_{V_{LOW}\_coil}$ are illustrated in Fig.4 - Fig.7. The values of gain and time delay are calculated for all connections and all coils. The gain values of S-coil, V_{UP}-coil and V_{LOW}-coil currents have average gain values of –4.296, 30.465 and –10.049 within 2% error for A2 connection, USNL connection and LSNL connection when the currents are over 1kA. Q-coil has a similar gain value for A2 connection and USNL connection but has a different gain value for LSNL connection. The gains are 147.172, 144.73 and 106.555 for A2-connection, USNL-connection and LSNL-connection when the currents are over 1kA. We got delay time values of all coils for different connections. The average delay time values of S-coil, Q-coil, V_{UP}-coil and V_{LOW}-coil are 16.0ms, 8.0ms, 21.2ms and 11.5ms. In a future, we have to check the effect of plasma current, the plasma minor radius, plasma position etc. to the diamagnetic loop. After that we can evaluate the plasma energy by this method automatically.

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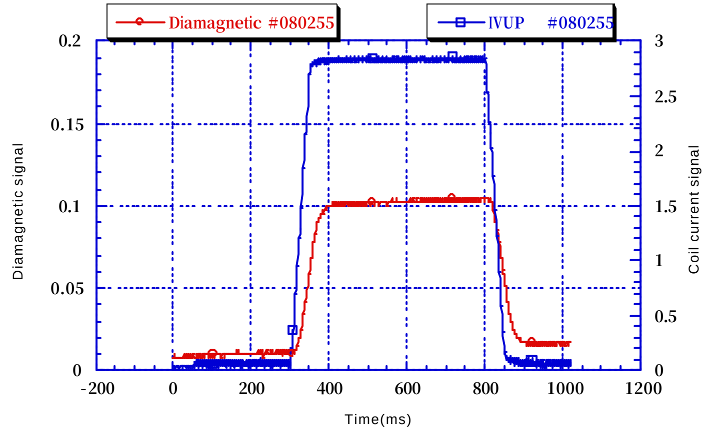


Fig.2a Coil current signal & Diamagnetic signal before gain compensation

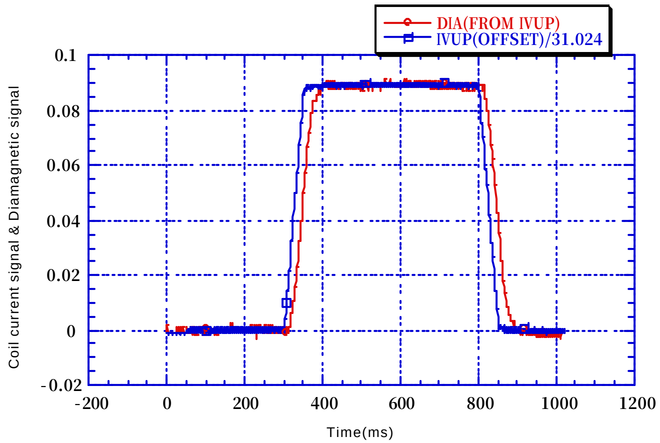


Fig.2b Coil current signal & Diamagnetic signal after gain compensation

Fig.2 Poloidal field effects on the Diamagnetic loop

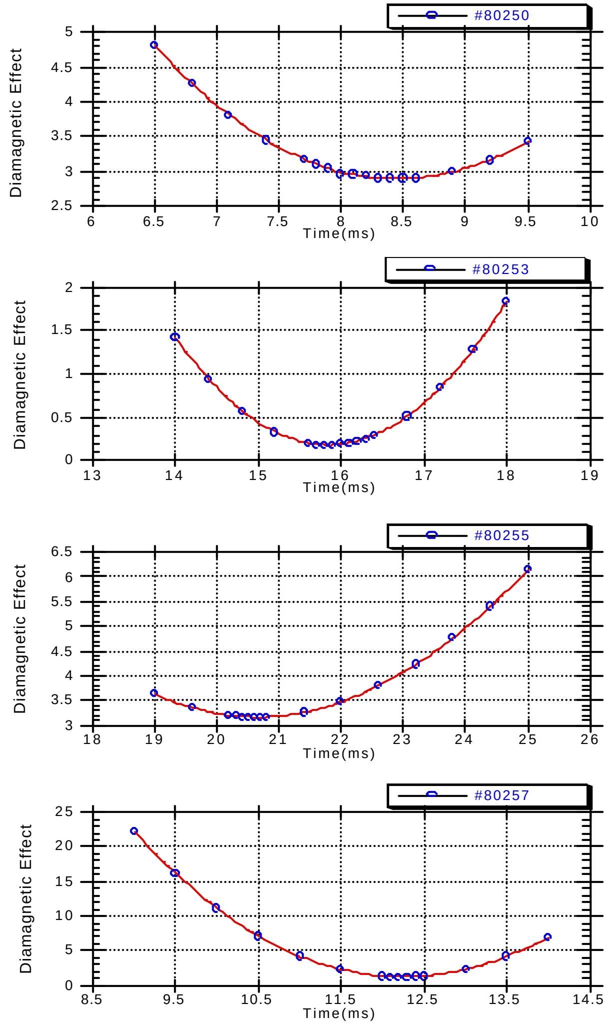


Fig3. Delay time of A2 connection

#80250:Q-coil, 6kA #80253:S-coil, 2kA #80255:VUP-coil, 2.8kA

#80257:VLOW-coil, 2.8kA

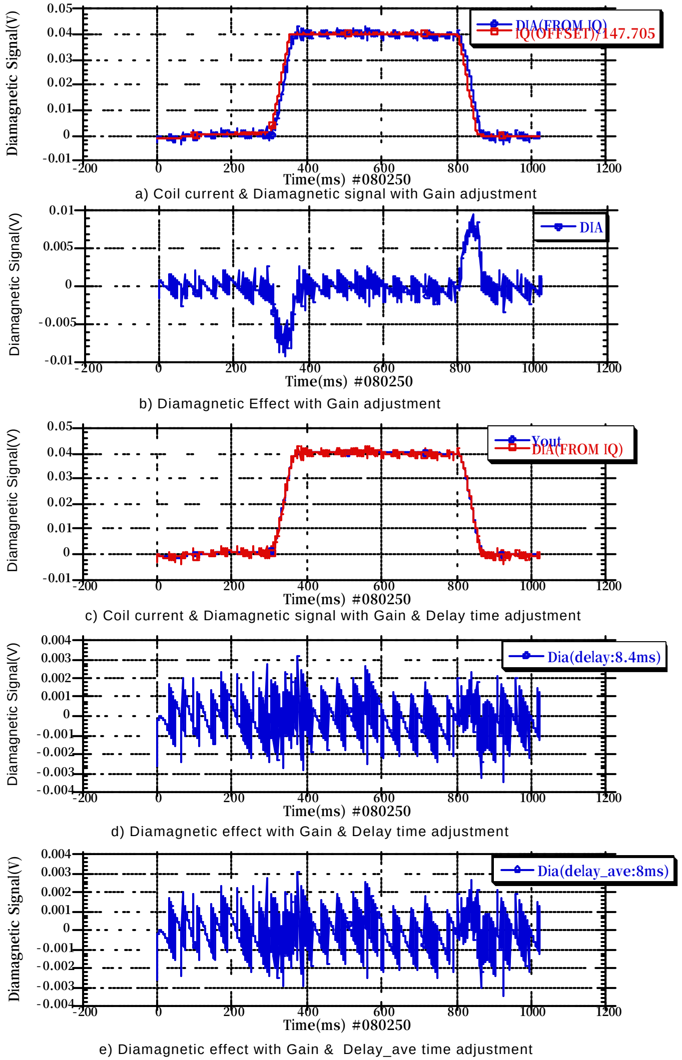


Fig4. Diamagnetic Effect of Gain and Delay time(A2 connection & Q-coil:6kA)

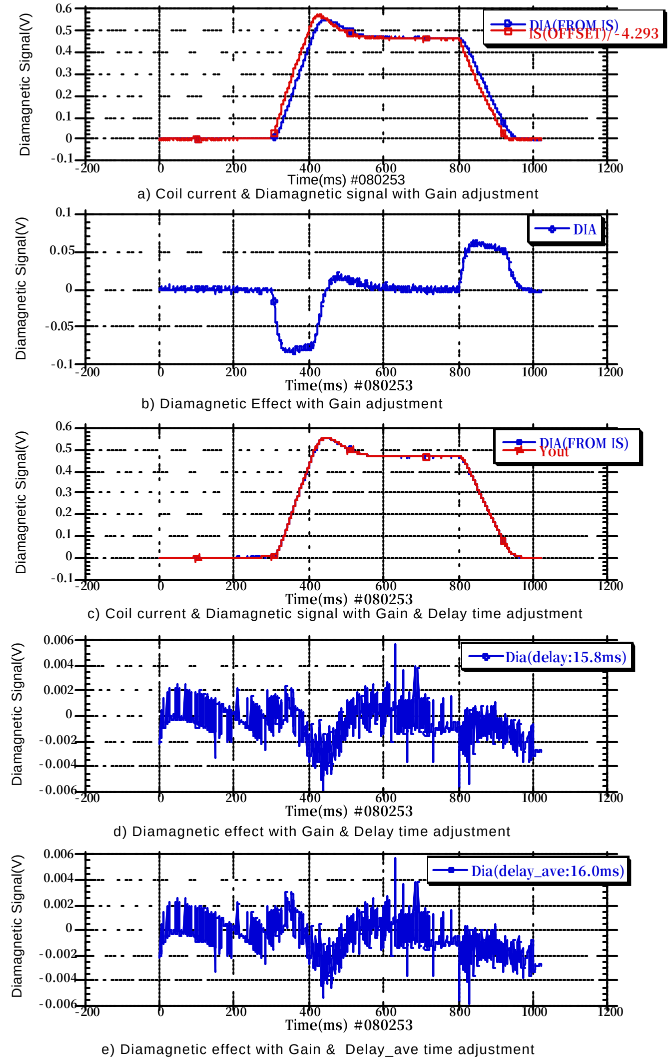
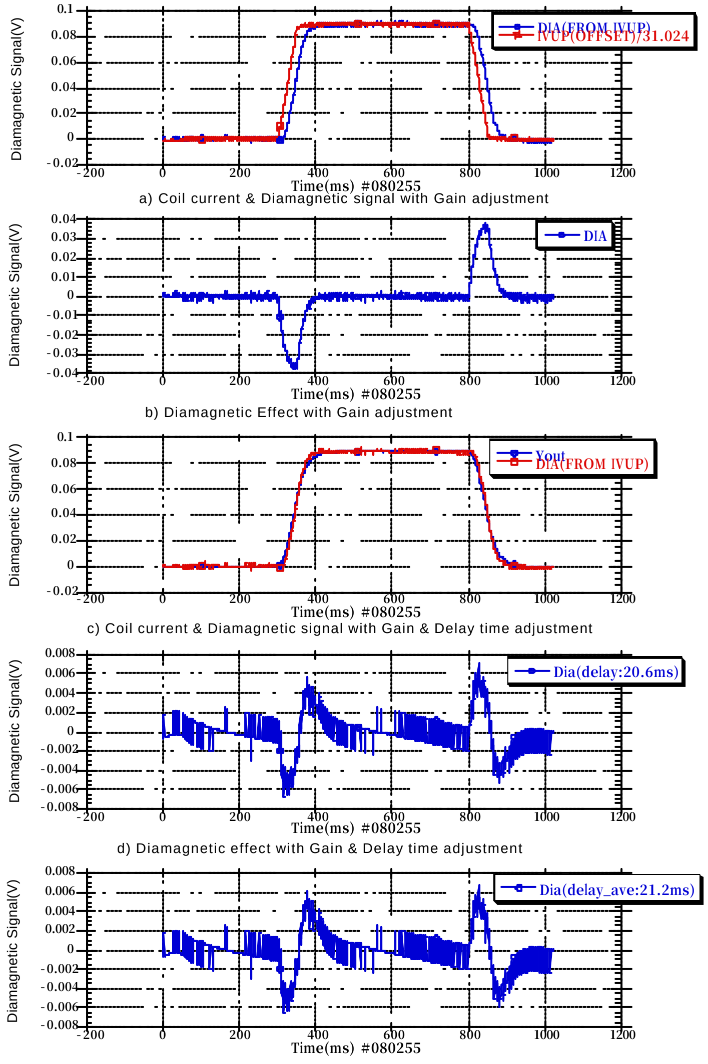


Fig5. Diamagnetic Effect of Gain and Delay time(A2 connection & S-coil:2kA)



a) Coil current & Diamagnetic signal with Gain adjustment

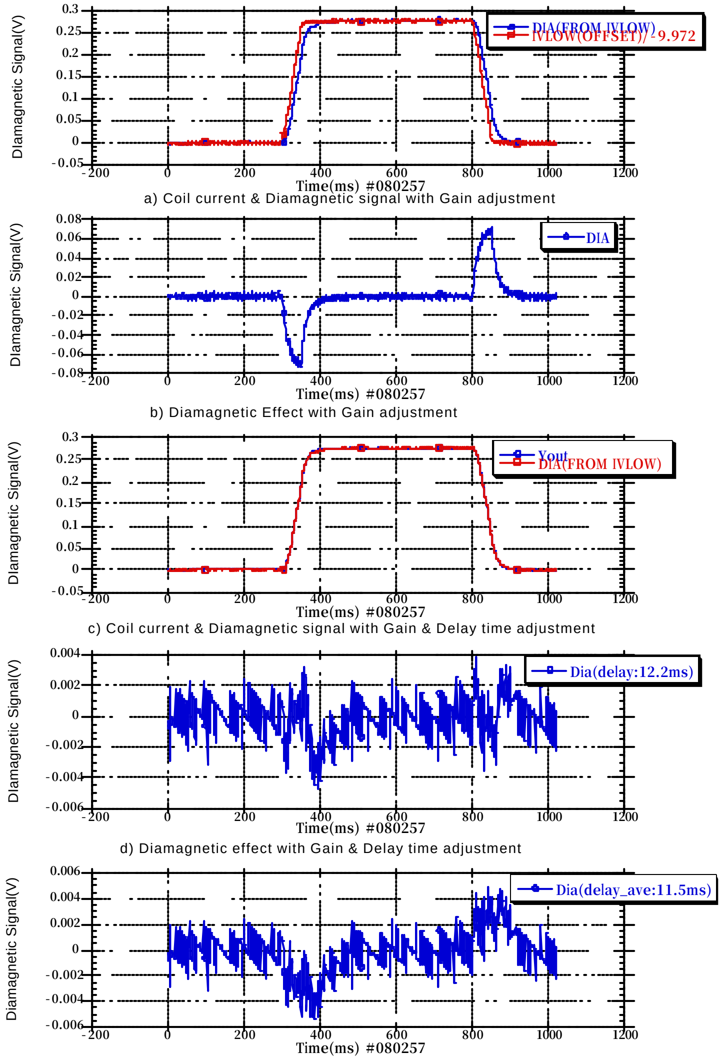
b) Diamagnetic Effect with Gain adjustment

c) Coil current & Diamagnetic signal with Gain & Delay time adjustment

d) Diamagnetic effect with Gain & Delay time adjustment

e) Diamagnetic effect with Gain & Delay_ave time adjustment

Fig6. Diamagnetic Effect of Gain and Delay time(A2 connection & Vup-coil:2.8kA)



a) Coil current & Diamagnetic signal with Gain adjustment

b) Diamagnetic Effect with Gain adjustment

c) Coil current & Diamagnetic signal with Gain & Delay time adjustment

d) Diamagnetic effect with Gain & Delay time adjustment

e) Diamagnetic effect with Gain & Delay_ave time adjustment

Fig7. Diamagnetic Effect of Gain and Delay time(A2 connection & VLow-coil:2.8kA)