J Fusion Energ
DOI 10.1007/s10894-011-9456-6

ORIGINAL RESEARCH

Measurement and Processing of Fast Pulsed Discharge Current in Plasma Focus Machines

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Abstract The fast pulsed electric discharge current drives all physical processes in the plasma focus device; in turn all physical processes in the focus affect the current waveform. Thus the discharge current waveform is the most important indicator of plasma focus performance. This underlies the importance of properly measuring, processing and interpreting the discharge current waveform. This paper reports the measurement of fast pulsed discharge current by the Rogowski coil, in two different modes: the current transformer, "I" mode, and current derivative, "Idot" mode. The processing and interpretation of recorded current waveform to obtain useful information about the physical processes in the plasma focus device are discussed. The current transformer with a large number of turns and a sub-1 Ohm terminator has good high frequency response, necessary for the sharp current dip region when *dI/dt* exceeds 2×10^{11} A/s. However the signal is "noisy" in the current dip region. Several methods to extract the current dip from the noise are discussed and examples of how low pass filters affect the signals are shown. The *dI/dt* coil, the Rogowski coil in "Idot" mode, with a few turns terminated by 50-Ohm is also described. Integrating the 1 GSa/s digital waveform does remove the high frequency noise components, yet the extracted waveform shows sharp angular features indicative of the retention of short-time features. This makes the *dI/dt* coil superior to the current transformer. A 7-turn coil is tested against the Lee Model code and found to be suitable to measure the plasma focus discharge current.

Keywords Pulsed current measurements · Plasma focus · Rogowski coil · Lee Model code

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Introduction

The research efforts on plasma focus devices have recently been intensified with the emergence of many new research groups across the globe [1–4] and also due to construction of many new plasma focus facilities, particularly at lower energies, by established research groups [2, 5–7]. The increasing popularity of plasma focus devices is attributed to the fact that it is relatively simple and economical to construct, is an excellent platform for studying complex high energy density dense magnetized plasmas and also

Published online: 28 July 2011

provides a multiple radiation source with diverse applications. The plasma focus uses one of the oldest methods of high-current pulsed discharges between metal electrodes for the generation of high temperature dense magnetized plasmas. In this device, a large fast pulsed discharge current flows through a gas in a sheath of current accelerating down a coaxial tube at highly supersonic speeds. The current sheath is compressed radially, by self-generated magnetic field of high-current discharge, into a hot dense plasma 'pinch' with temperatures exceeding a million °C (1–2 keV). The electric current is supplied by switching a large, high voltage fast discharging capacitor or capacitor bank across the coaxial electrode assembly of the plasma focus device.

One of the basic strategies used during the construction and designing stages of any new plasma focus is to measure the short-circuit discharge current for the estimation of system inductance L_0, system impedance Z_0, peak discharge current I_0 and the quarter time of period $T/4$ of the discharge current. According to Lee and Serban [8] most of the neutron optimized plasma focus devices have the typical speed factor, $I_0/a\sqrt{P}$, of about 90 kA cm^{-1} Torr$^{-1/2}$ where a and P denote the anode radius and deuterium filling gas pressure in Torr, respectivley. Using the short-circuit peak discharge current measured by current probe and approximate deuterium operating pressure of say 5 Torr, one can estimate the approximate anode radius that one should be using in this plasma focus device. Based on the quarter time period of the discharge current, which represents the time for the discharge current to reach the maximum value, one can estimate the approximate anode length (z_a) using the relation $Z_a = v_a[T/4 - a/v_r]$ where v_a and v_r represent the typical axial and radial speeds of current sheath in axial and radial phases having typical values of about 10 and 25 cm/μs, respectively. This highlights the importance of accurate current measurement even at the designing and construction stages of plasma focus device for the estimation of approximate dimensions of electrode assembly.

The initial electrode dimensions, estimated using short-circuit discharge current characteristics, however may not result in optimized plasma focus operation as with the plasma focus load additional dynamic impedance comes into play which changes the discharge current characteristics. Further experimental iterations in electrode dimensions and operating gas pressure are required for the optimization of plasma focus performance in terms of its radiation yields. The experimental iterations, however, are time and resource consuming exercises and faster convergence to optimal plasma focus operation can be achieved by using Lee Model Code [9–15] in conjunction with experimental current traces obtained for initial electrode design. The Lee Model Code once fitted well to the accurately and correctly measured discharge current trace can help to estimate various difficult to measure physical parameters of interest such as dynamic impedance, mass shedding and current coupling in axial and radial phases and the pinch current, etc. These parameters, in turn, can be used to simulate more accurate electrode dimensions and other operating parameters for optimized plasma focus performance; highlighting the importance of precise and accurate measurement and processing of the discharge current.

Recently, a 30 μF, 15 kV, 3 kJ UNU-ICTP type plasma focus [1, 16–21] has been institutionalized at INTI International University and is designated as INTI PF. In the INTI PF the total current typically rises to 150 kA in 3 μs, with a peak current rise rate exceeding 5×10^{10} A/s. During the compression or the pinch phase, the energy is extracted from the capacitor bank to pulse heat the pinched plasma in a time scale of 0.1 μs. The loss of energy from the electrical circuit results in a current drop (called 'dip') typically of 30 kA in 0.2 μs resulting in an even greater current change peaking above 2×10^{11} A/s. The electro-mechanical arrangement is as shown in Fig. 1 along with representative current sheet positions in the axial phase and the radial phase.

The current traces are used not only during the construction and optimization stages but also during the routine operation of the device as they are one of the key performance indicators of the plasma focus device. The axial and radial phase dynamics and the crucial energy transfer into the focus pinch are among the important information that is quickly apparent from the current trace recorded by Rogowski coil which is placed around any of the current return paths, as shown in Fig. 1. The exact time profile of the total current trace is governed by the capacitor bank parameters, the focus tube geometry and the operational parameters like charging voltage and operating gas pressure. It also depends on the fraction of mass swept-up and the fraction of sheath current through the axial and radial phases [22–25]. These parameters determine the axial and radial dynamics of the current sheath in the plasma focus, specifically the axial and radial speeds which

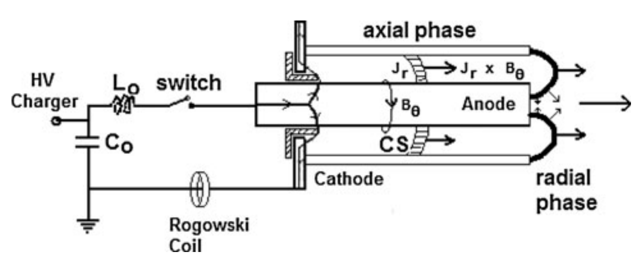

Fig. 1 Electro-mechanical setup of plasma focus device with current sheath in axial and radial phase

in turn affect the profile and magnitude of the discharge current. The detailed profile of the discharge current during the pinch phase also reflects the Joule heating and radiative yields. At the end of the pinch phase the total current profile also reflects the sudden transition of the current flow from a constricted pinch to a large column flow. The discharge current thus powers all dynamic, electrodynamic, thermodynamic and radiation processes in the various phases of the plasma focus. Conversely, all the dynamic, electrodynamic, thermodynamic and radiation processes in the various phases of the plasma focus affect the discharge current. It is then no exaggeration to say that the discharge current waveform contains information on all the dynamic, electrodynamic, thermodynamic and radiation processes that occur in the various phases of the plasma focus [26–30]. This explains and further underlines the importance of accurately measuring, processing and interpreting the current waveform which can then be matched to the computed current trace in order to connect any modeling to the actual physical situation. This paper reports the measurement of fast pulsed discharge current by the Rogowski coil, in two different modes viz "I" mode and "Idot" mode, and the processing and interpretation of recorded current waveform so that the useful information about the physical processes in the plasma focus device can be obtained.

Measurement of Large Pulsed Discharge Current in the Plasma Focus

Pulsed power systems are integral part of any pulsed plasma radiation device such as plasma focus and hence the associated electrical diagnostics plays vital role in investigating the overall device performance and its characteristics. As discussed before one of the prime parameters of interest for plasma focus is the measurement of high impulse current, which has both high frequency and a low frequency components. A common and effective way to measure pulsed discharge current is by the use of a coil in toroidal geometry. Such a system is generally called a Rogowski coil [31–34]. The Rogowski coil operates on simple laws of electromagnetism and the conceptual understanding is clear; however the bandwidth response of such diagnostics is often limited by various parasitic effects that impairs the factual measurement of parameters. It is therefore important to carefully design the coil and process the captured current signal.

Figure 2a shows a schematic of the coil with its terminating resistance. Figure 2b shows the circuit diagram of the current coil with its inductance represented by L_c, the coil resistance represented by r_c and the terminating resistance represented by r_t. The coil current I_c, driven by the induced voltage V generates a voltage V_m measured across the terminating resistance r_t where $V_m = I_c \times r_t$. The voltage V is induced by the pulsed current I and $V = k dI/dt$ where k is a constant dependant on the geometry of the coil and the coupling of the coil to the current I.

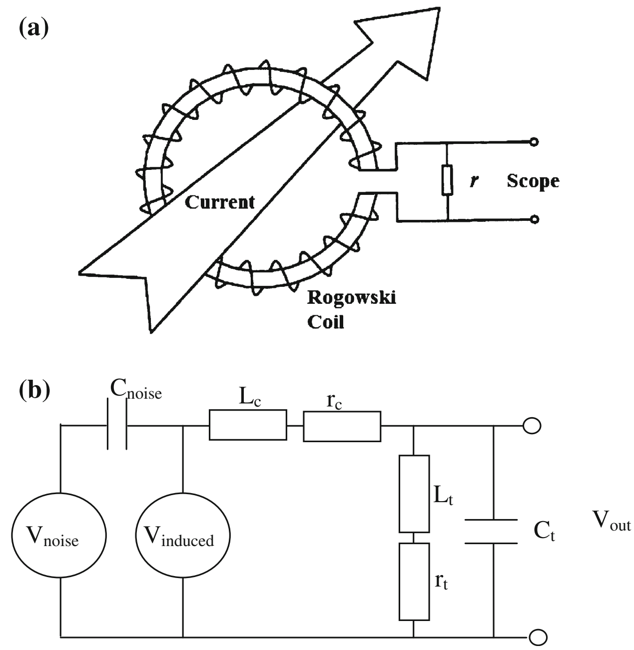

Fig. 2 **a** The Rogowski coil with a small terminating resistance to give an output proportional to current I threading through the coil. **b** Equivalent circuit of a Rogowski coil

Neglecting the parasitic capacitances, the circuit equation of the current measuring systems of Fig. 2 is:

$$(L_c + L_t)\frac{dI_c}{dt} + (r_c + r_t)I_c = V_{\text{induced}} = k\frac{dI}{dt} \tag{1}$$

With the output voltage

$$V_{\text{out}} = L_t\frac{dI_c}{dt} + r_t I_c$$

The current coil is typically operated in one of the following two modes; in one mode the circuit parameters are adjusted so that the LHS of (1) is solely dependent on dI/dt (referred as "Idot" mode) while in the other mode it is solely dependent on I ("I" mode).

Two Modes of Operations of the Rogowski Coil

Current Transformer "I" Mode

Assuming that the terminating inductance is much lower than the coil inductance, the condition for this mode is:

$$L_c\frac{dI_c}{dt} \gg (r_c + r_t)I_c \tag{2}$$

To express this condition into operational terms we assume alternating current at a particular angular frequency, ω, i.e. $I_c = I_{c0}e^{i\omega t}$.

Then the condition to operate the Rogowski coil in this current transformer mode is represented by a low frequency cutoff.

$$\omega \gg \frac{r_t + r_c}{L_c} \text{ or } \tau \ll L_c/(r_t + r_c) \quad (3)$$

And in this mode, condition (2) applied to (1) gives,

$$L_c \frac{dI_c}{dt} = k \frac{dI}{dt}$$

So that

$$I_c \propto I \quad (4)$$

At frequencies much lower than this cutoff, the coil operates in "Idot" mode as described below. It should be noted that at the cutoff frequency the coil operates as a "combination" "I" and "Idot" modes. This mode of operation is undesirable as it is difficult to analyze.

Further assuming that $L_t \frac{dI_c}{dt} \ll r_t I_c$, the measured voltage $V_{\text{out}} = I_c r_t$ is directly proportional to I, the large plasma focus current being measured.

If $L_t \frac{dI_c}{dt} = r_t I_c$, we define a condition that the coil must obey to show only I

$$\omega \ll \frac{r_t}{L_t}$$

Idot (*dI/dt*) Mode

The condition for this mode is:

$$L_c(dI_c/dt) \ll I_c(r_t + r_c) \quad (5)$$

$$dI_c/dt \ll I_c(r_t + r_c)/L_c$$

Thus the condition to operate in this "Idot" becomes:

$$\omega \ll L_c/(r_t + r_c) \quad (6)$$

And in this mode, condition (5) applied to (1) gives

$$I_c(r_t + r_c) = kdI/dt \quad (7)$$

So that

$$I_c \sim dI/dt \quad (8)$$

Further assuming that $L_t \frac{dI_c}{dt} \ll r_t I_c$, the measured voltage $V_{\text{out}} = I_c\ r_t$ is directly proportional to *dI/dt*, the rate of change of the large plasma focus current I which is being measured.

The INTI PF Current Measurement Systems

The INTI PF uses two current measurement systems.

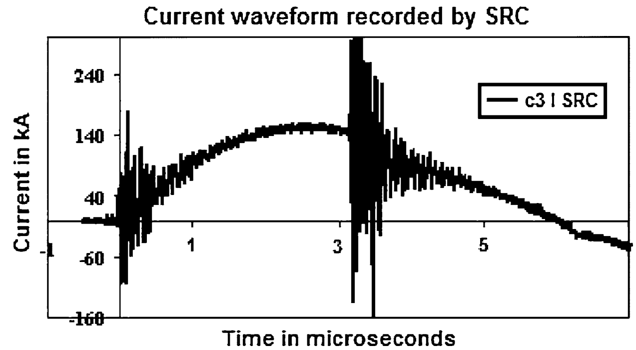

Fig. 3 Typical INTI PF current waveform measured by SRC coil measurement system

The first is a current transformer SRC
with the following parameters

$N = 1{,}000$, $r = 5 \times 10^{-3}$ m, $D = 0.25$ m; hence $L_c = 120\ \mu$H;
$r_t = 0.2\ \Omega$; and
r_c is estimated to be 0.2 Ω and L_t is estimated to be 2 nH.

Thus the low frequency cutoff for this coil is 530 Hz. The high frequency cutoff for this coil is estimated to be 100 MHz. This implies that this current coil system is good for high frequency measurements and suitable to investigate the INTI PF discharge which has a period of 12 µs.

Figure 3 shows a current waveform taken with the INTI PF current transformer SRC. The peak current of the plasma focus discharge for the conditions of this particular shot is known to be 150 kA occurring at about the time 3 µs. The burst of oscillatory waveform at time zero lasting for half a microsecond and the other burst starting just after time 3 µs indicates (1) a resonant condition of the coil system or (2) a resonant condition of the plasma focus cables (round trip time ~10 ns), collector plates etc. which shows up as Idot and (3) capacitive coupling from large *dV/dt* in proximity to the coil. It is suspected that the second burst of electrical 'noise' may hide a substantial dip which unfortunately cannot be clearly seen due to the large accompanying noise.

To extract the current dip from the noisy signal, several methods had been tried including manual averaging, sequential differentiation and integration and reversed sequence, bandwidth limitation and Fast Fourier Transform (FFT) filtering using software such as Origin 8.0® Software package. From these attempts it became clear that there is a distinct current dip, a distortion of the current trace away from the otherwise near damped sinusoidal behaviour of the current waveform, corresponding to the pinch phase of plasma focus.

Figure 4 shows the effect of FFT filtering. There are 3 traces. The first is filtered with a low pass frequency of

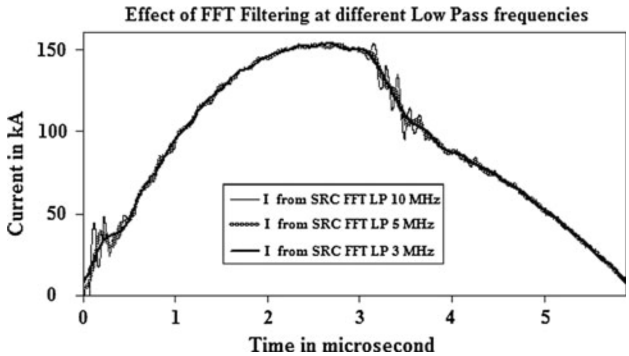

Fig. 4 Effect of FFT filtering at different low pass (LP) frequencies on the current waveform

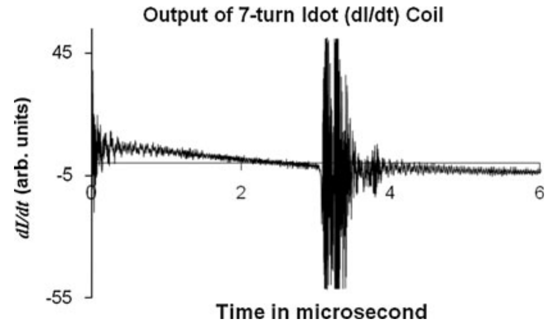

Fig. 5 A typical output from the INTI PF 7-turn "Idot" coil. Vertical scale is *dI/dt* in arbitrary units

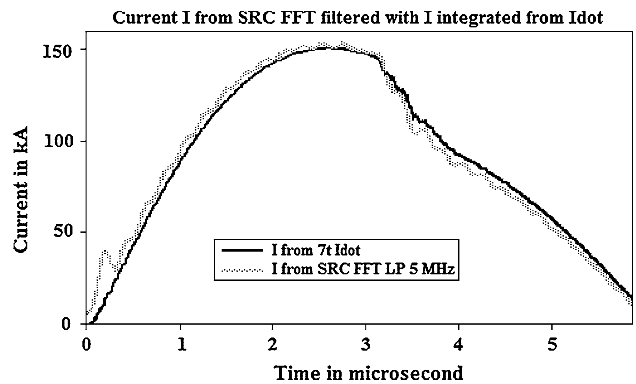

Fig. 6 Comparing the current waveform integrated from the 7-turn "Idot" coil with the current waveform taken from the SRC and FTT filtered at low pass of 5 MHz

10 MHz which outputs a signal still with a large 'noise' component (see thin dark trace of Fig. 4). The second trace, broad hatched trace, shows the result of FFT filtering at a low pass frequency of 5 MHz. This filtering is already sufficient to reduce all the noise oscillations. It is thus not necessary or advantageous to go lower in lowpass frequency. Thus the FFT filtering at 5 MHz lowpass is sufficient to suppress the noise. However from the smoothness of the current dip it is clear that the filtering has also degraded the signal content by removing the fast risetime components of the signal. If the source of noise is due to the actual resonant condition of the plasma focus, and if the frequency response of the coil can be obtained, the appropriate FFT filter can be designed to compensate the coil response. However it would not be possible to improve the situation if it is due to coil resonance or capacitive pickup of *dV/dt*.

The second current measurement system is an "Idot" coil of the following parameters

$N = 7$, $r = 3.5 \times 10^{-3}$ m, $D = 0.06$ m; hence $L_c = 10$ nH

$r_t = 50\ \Omega$; and we assume r_c is negligible, and L_t is estimated to be 2 nH.

Thus the high frequency cutoff for this coil is 800 MHz and it should have no problems with 10 ns time scales expected from the INTI PF.

The "Idot" signal is typically collected by a digital storage oscilloscope (DSO) in a digital file at a sample rate of 1 GSa/s. This data is then numerically integrated using a scheme such as:

$$I_{n+1} = I_n + (\delta I/\delta t)(t_{n+1} - t_n)$$

Alternatively the "Idot" signal could be integrated electronically using a RC integrator circuit. However the RC integrator would introduce additional distortion into the final signal. Figure 5 shows an "Idot" (*dI/dt*) waveform taken with the INTI PF 7-turn "Idot" coil. Figure 6 shows the current waveform numerically integrated from the "Idot" waveform (see the darker line). For comparison the FTT filtered (5 MHz low bandpass) current waveform duplicated from Fig. 4 is also shown in the Fig. 6 (the broader hatched trace). There is good agreement in the waveform of the current measured by the current transformer SRC system and the "Idot" system. The more angular (less smooth) appearance of the current measured from "Idot" indicates the better frequency response of the measurement using this system.

The Lee Model Code as the Ultimate test for Current Measurement Systems

A final test of the performance of the current measurement systems used in the INTI Plasma Focus is to test it against the Lee Model code [9–15] which incorporates within it the circuit equations coupled to the dynamic equations. Hence the model is charge, energy and mass consistent. This model has been tested against all the well-published plasma focus machines for which current waveforms are available [11, 27, 29, 35, 36]. The experience gained with the application of this model code to the various machines is that the computed current waveforms fit the correctly measured current waveforms very well.

For the current measurement system perform well, it must be able to respond correctly to

(1) low frequencies (i.e. time scale of the decay of the damped sinusoid of a typical short circuit discharge which is necessary for an in situ calibration of the coil ~30 μS for INTI pF),
(2) mid frequencies (i.e. time scale of the period of the damped ~12 μS for INTI PF),
(3) high frequencies (i.e. time scale of the "focus" ~100 nS for INTI PF), and
(4) ultra high frequencies (i.e. time scale of the "instabilities" ~1nS for INTI PF)

The low frequency response can be benchmarked by comparing the magnitude of the measured current with that from the Lee model code.

The mid frequency response can be benchmarked by comparing the rising part of the current with the code.

The high frequency response can be benchmarked by comparing the slope of the current dip with the code.

The code's current behavior is modified by two mass shedding parameters. A good current measurement system should be able to reproduce magnitude, rise and dip accurately and in fact should closely match the actual shape of the computed current.

For example, a current waveform was taken with an "Idot" coil system connected to a DSO under poor grounding or shielding conditions. The DSO output shows a large time-varying baseline shift which distorts the output waveform significantly so that no fit to the Lee Mode code could be made. This is shown in Fig. 7 (see the thin black line). In this respect further work shows that if the base line shift exceeds 5 kA over a period of 1 μs (this is easily measured by looking at the baseline displacement before the start of the plasma focus discharge) then the measured current is not reliable. In the same figure is shown the current waveform from an "Idot" coil of 100 turns (which has a poor response time). Neither current waveform can be fitted by the computed current waveform (dark line) no matter how the model parameters are adjusted.

Testing the 7-Turn INTI PF "Idot" Coil Against the Lee Model Code

The 7-turn coil is tested against the Lee Model code by comparing its integrated current waveform against the computed current waveform. The result is shown in Fig. 8. For this particular fitting we use the latest version of the Lee Model code which includes a phase between the pinch phase and the large column phase. This is the pinch breakup phase and in the latest version of the Lee Model code this phase is simulated using anomalous resistance (R_{an}) terms [37].

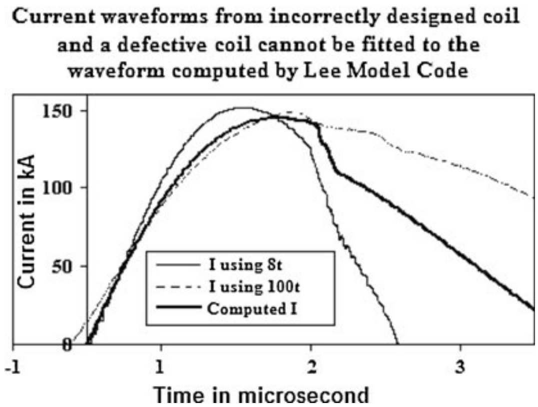

Fig. 7 Current waveform from an incorrectly designed "Idot" coil (100 turns) represented by a dashed line, and current waveform from a defective coil (*thin line*) compared to current waveform computed from the Lee Model code. The waveform computed from the code could not be made to fit either incorrect current waveform

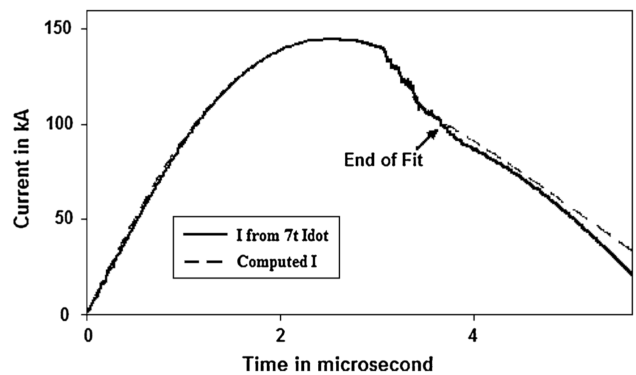

Fig. 8 Fitting the measured current waveform by the Lee Model code using realistic physical INTI PF system and operating parameters and Lee code model parameters

The Fig. 8 shows the fitting of the measured current waveform by the Lee Model code using (i) realistic physical parameters of INTI PF system of system inductance $L_0 = 110$ nH, system capacitance $C_0 = 30$ μF, system impedance $r_0 = 13$ mΩ, cathode radius $b = 3.2$ cm, anode radius $a = 0.95$ cm, and anode length $z_0 = 16$ cm; (ii) Lee model code parameters of mass and current coupling in axial and radial phases as $f_m = 0.029, f_c = 0.7, f_{mr} = 0.29$ and $f_{ca} = 0.7$; and (iii) system operating parameters of 12 kV charging voltage at 1.75 Torr neon. From Fig. 8 it is seen that the computed current waveform (dashed line) fits the measured waveform (from the 7-turn "Idot" coil) very well up to the end of fit, which covers all regions of interest of the plasma focus. This shows that the 7-turn "Idot" current coil used in the INTI PF has an output with sufficiently good response to correctly measure the plasma focus current waveform.

Conclusion

The importance of accurate measurement and processing of discharge current in the plasma focus using a Rogowski coil in two different modes is discussed. The current transformer shunted Rogowski coil with its output filtered using different lowpass FFT filtering is compared to a 7-turn "Idot" (*dI/dt*) coil. The latter is found to be superior in terms of frequency response and is generally agreed to be used in collaborative research projects among several research laboratories. In work related to the above it was found that the Lee Model code could be used as the ultimate test of the suitability of the current measurement systems used in plasma focus machines. Moreover a properly measured plasma focus current waveform when used in conjunction with the Lee Model code enables the realistic estimation of the dynamics and many important properties of the plasma focus including neutron and soft x-ray yield [1, 11–14, 18–21, 25–30, 35–37]. This further underlines the importance of properly measuring the plasma focus current.

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