T.1: Development of Nondestructive type Fast Current Transformers (FCTs) and Monitors for Accelerators at RRCAT

R.S.Shinde, (Email: shinde@rrcat.gov.in)
P.Pareek, R.R Yadav and Karan Singh
Ferrite and Pulsed magnet Technology, Accelerator Magnet Technology Division

1. Introduction

Beams of charged elementary particles, such as electrons or protons, are produced in particle accelerators and are used as a research tool in high- energy physics. The characteristics of the beams to be monitored are important for accelerators [1].

A synchrotron light source requires a diagnostic system to carry out its commissioning and maintain its design performance during normal conditions of operation. Diagnostic devices must measure both machine and beam parameters under all modes of standard operations. The goal is that a stable photon beam within the nominal specifications is guaranteed to be delivered to the users of. To this end various devices will be distributed around the accelerator. These devices, together with their signal processing electronics make up the diagnostic system. The diagnostic system is needed to store the beam, to reach the desired performance and to keep the storage ring running efficiently. Standard devices used for diagnostics at synchrotron sources and their functions are listed in Table T.1.1

Table T.1.1: Diagnostic devices and their use in Synchrotron

Diagnostic device	Functions
Faraday cup	Beam charge and time structure in transfer lines
Fluorescent screen	Transverse profile and position
DC Current Transformer(DCCT)	Average beam intensity and beam lifetime
Fast Current Transformer (FCT)	Observing short beam pulses in transfer lines
Integrating Current Transformer(ICT)	Charge in a pulse in transfer lines.
Beam Position Monitor (BPM)	Transverse Position, closed orbit and tune measurement
Stripline	Position, beam spectra and tune measurement
Scraper Beam loss monitor	Dynamic aperture and beam profile To minimize radiation level
Photon monitors, CCD camera	Transverse distributions, position and emittance.
Streak camera	Bunch shape and beam instabilities

The recording of the beam position and current is a typical function of the diagnostic system. The knowledge of these parameters is essential in the injection and storage of the electron beam.

Several types of devices should be installed around the accelerator complex for the monitoring and recording of electron beam currents. A Faraday Cup is used to measure the total charge from the pre-injector. With this destructive device the beam charge is collected by an electrode. This type of system is relatively simple and sensitive but it can operate only at low energies and currents. The DC component of the stored beam will be measured with a high precision DC current transformer. DCCTs detect the magnetic field induced by the moving charges onto its core, and provide an absolute measurement of the average beam current.

Instruments for monitoring the beam intensity in a circular accelerator must not impose any form of physical obstruction on the beam trajectory and should be independent of beam position. Beam current transformer have a high resolution and provide an output directly proportional to the beam current ,covering the entire frequency range as determined by the time structure of the beam. These are integrated to measure non-destructively the charges of circulating electrons in the transfer lines and the booster. They have to be installed in straight sections; preferably well away from magnet end-fields, where a ceramic break in the vacuum chamber must be installed, and a carefully-designed magnetic and RF shield must be provided. Monitoring beam currents at appropriate positions in the accelerators complex provides measurement of the injection efficiency.

1.1 The Basic Beam current transformer

Time distribution of particles in a beam is important for assessing the performance of an accelerator and for monitoring its operation. A beam current transformer is ideal device for this purpose.

Fig. T.1.1 shows operating principle of beam current transformer. The particle beam passes through the centre hole of a toroidal core made of high permeability Ni-Zn-Co ferrite material.The beam can therefore be considered as the single turn primary winding of this toroidal transformer. The core carries a secondary winding, distributed evenly around the circumference, which is terminated in the remote load resistance [2].

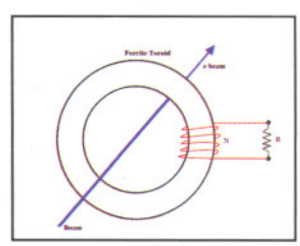


Fig. T.1.1: Operating principle of a ferrite monitor

The magnetic field component, concentric to the beam, couples via the toroidal core and induces a signal in the secondary winding, which has N turns & inductance L.

In an accelerator, the current is formed by N particles of charge state q per unit of time t or unit of length l and velocity $\beta = v/c$. The electrical current is $I_{beam} = qeN/t = qeN/l.\beta c$

The magnetic field B of a current can be calculated according to the Biot-Savart law

$dB = \mu_0 \, I_{beam} \, . \, dl \times r / 4\pi r^3$

Where $\mu_0 = 4\pi \times 10^{-7}$ Vs/Am = Permeability of free space (or vacuum), dl = the length in direction of the beam and r = the distance between the centre of the beam and the point the field is measured.

For cylindrical symmetry only the azimuthally component of magnetic field has to be considered along the unitary vector as shown in Fig. T.1.2.

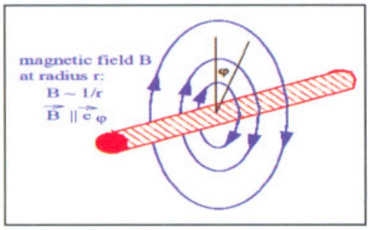


Fig. T.1.2: The magnetic field of a current

Magnetic field of a beam is given by

$B = \mu_0 (I_{beam} / 2\pi r) \times e_\varphi$

The beam current can be determined by monitoring the accompanied magnetic field with a current transformer.

The beam passes through centre of toroid of high permeability and acts as primary. An insulated wire, wound around the torus with N turns, serves as the 'secondary winding' of the transformer with the inductance L. Toroidal magnetic core is closed magnetic circuit to efficiently guide the field-lines. Then only the azimuthal component of magnetic field is measured and the signal strength is nearly independent of the beam position inside the vacuum pipe. Fig.T.1.3 shows the magnetic core guides the field lines for electron beam in circular accelerator [3].

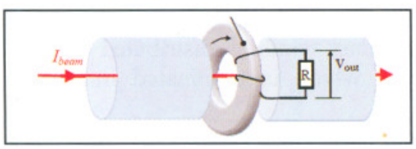


Fig. T.1.3: Magnetic core guide the field lines for e beam

Generally for an ideal current transformer loaded with a low value of ohmic resistance R the ratio between the primary current Iprim and secondary current Isec is given by

$I_{sec} = I_{beam}/N$

A voltage is measured: $U = R \cdot I_{sec} = R/N \cdot I_{beam}$

$\equiv S \cdot I_{beam}$

Where S= Sensitivity (V/A) which is equivalent to transfer function or transfer impedance Z

The equivalent circuit of beam current transformer is depicted in Fig. T.1.4.

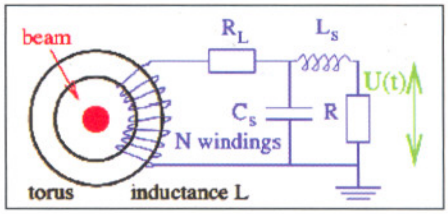


Fig. T.1.4: Practical equivalent circuit of FCT

Frequency domain response of FCT

In practice, we have to consider stray capacitances Cs into account, which are caused by the capacitance between the windings, the windings and the torus and along the shielded cable to the resistor R. The voltage U (t) and the impedance of the three elements are dependent on excitation frequency.

Thus for parallel shunt, dependence of the excitation frequency is

$1/Z = 1/j\omega L + 1/R + j\omega C_s$. This is equivalent to

$Z = (j\omega L)/(1 + j\omega L/R - \omega^2 L C_s)$

This equation can be analyzed for three different frequency ranges of FCT operations.

A) Low frequency range assuming $\omega << R/L$:

$Z \rightarrow j\omega L$. This means that the usable signal at the resistor R decreases proportional to the excitation frequency because the inductance acts as a short circuit for the considered low frequencies. At $\omega = 0$, no signal is recordable. Thus, no dc-transformation.

B) High frequency range assuming $\omega >> 1/RC_s$

Thus, $Z \rightarrow 1/j\omega C_s$

The fact that for high frequencies the current is mainly flowing through the capacitor and therefore the voltage drop at the resistor R is low.

c) Working region

$R/L << \omega << 1/RC_s : Z \sim R$

This is the usable working region, where the voltage drop at the resistor is significant. The working region is very broad due to the values of the electronic elements. In particular, the low value of the resistor R = 50 to ground annihilates the flowing current, resulting in an over-damping of possible oscillations.

Lower cut-off frequency, $\omega_{low} = R/L$

Upper cut-off frequency $\omega_{high} = 1/RC_s$

Frequency response of FCT is illustrated in Fig. T.1.5. It is clearly seen that stray capacitance impairs the high frequency response whereas inductance of core plays a vital role in low frequency mode.

The above mentioned frequencies restrict the working region with a true response of the measured signal with respect to the beam current [4].

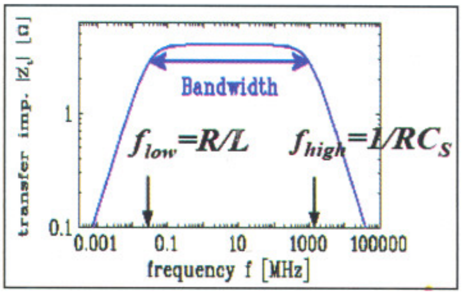


Fig. T.1. 5: Frequency domain response

Time domain response

The time response of FCT to a realistic beam pulse is described in terms of rise and droop time constant is presented in Fig. T.1.6.

For step excitation function, we can analyze rise and droop time constant expressed as

$\tau_{rise} = 1/\omega_{high} = 1/2\pi f_{high} = RCs$

$\tau_{droop} = 1/\omega_{low} = 1/2\pi f_{low} = L/R$

Further, rise and droop time can be simplified to

Rise time: $t_{rise} = 1/3 f_{high} = \sqrt{LsCs}$ (with cables)

$= 1/RCs$ (ideal without cables)

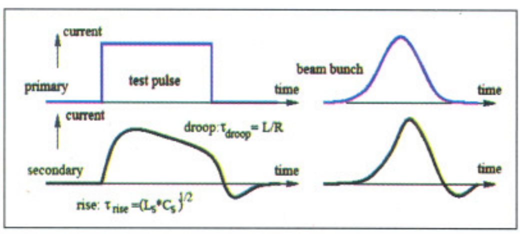


Fig. T.1.6: Time response of FCT to a realistic beam pulse (Rectangular Pulse)

Droop time: tdroop= $1/3 f_{low} = L/R$

For the working region, the output voltage is

$U(t) = (R/N).(e^{-t/\tau_{droop}}).Ibeam$

$U(t) = (Ibeam.R/N).e^{-(R/L)t} = U(0).e^{-(R/L)t}$

Output voltage of monitor decays with time is described in Fig. T.1.7. At low frequency; it shows a roll-off typical of an LR circuit. The rise time are determined by the ferrite core's frequency dispersion and the transformer's shunt capacitance.

signal, U (0) = (IbeamR/N) decays away with τ_r, which is lower cutoff frequency of FCT.

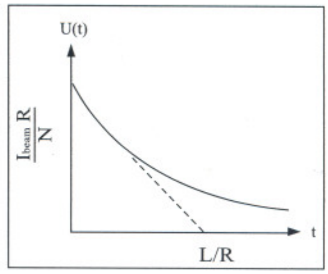


Fig. T.1.7: Exponential decay of FCT

For slowly varying beam currents to be measured, τ must be large as possible. This can be accomplished by making large value of inductance[5].

For the high frequency response it is essential to consider the frequency dependence of the magnetic core. This is represented by complex permeability of magnetic core. The permeability decreases above 100 kHz with a scaling $\mu r \propto 1/f$ and therefore also the inductance of the torus decreases. For frequencies above 100 MHz, the stray inductance is the dominant contribution. With these two modifications the rise and droop times are modified to yield

$\tau_{rise} = \sqrt{Ls\,Cs}$ and $\tau_{droop} = L/R + RL$.

Fast Current transformers are mainly used when short beam pulses are to be observed. In particular the observation of the bunch structure during acceleration inside a synchrotron or the fast extraction from a synchrotron. The beam pulse length is typically between 1 ns and 10 µs.

The Transformer Core

The transformer core requires a magnetic material with high permeability and minimum losses at working frequency or under pulse conditions. This can either be toroid made of soft ferrite, or a tape wound core using Ni-Fe alloy or ultra perm amorphous metallic ribbons (Fe-Co alloy). For slowly varying beam currents, the tape wound cores are the best because of high permeability at few KHz. Soft ferrites are preferred for fast rise FCTs. For the diagnostics of few nanosecond beams, a broad RF spectrum is involved. It is important to understand complex permeability of ferrite toroids. The ferrite's relative permeability is represented as a frequency-dependent complex parameter, $\mu^*(f) = \mu'(f) - j\mu''(f)$. The real part represents the permeability (reactive portion); the imaginary part represents the permeability losses. We have conducted an extensive study and developed large ferrite toroids at Ferrite Lab[6].

Requirement of Ferrite Cores:

Among soft ferrite family, Mn-Zn ferrite core with relative permeability (~5000) well suited for frequency up to 2 MHz corresponding pulse lengths of few µs. Whereas Ni-

Zn-Co ferrites with optimum permeability are suitable for operation in excess of GHz frequency range. This can handle fast pulses in the order of 100- 500 ps. Minimizing the noise while maximizing the signal-to-noise ratio (SNR) is the prime consideration in the development of Precision, current monitoring system. This is accomplished by

i) Complex permeability of ferrite must not change with frequency drastically but nearly constant over harmonic content of beam pulse.

ii) Large pulse permeability provides low reluctance path for magnetic flux completion at the joint between two halves of ferrite segments.

iii) Highest ferromagnetic resonance must be at least five times apart from beam pulse frequency for precision, accurate and stable pulse response.

iv) Narrow hystersis loop with low remeance and low corecivity so that no resetting required during pulse injection.

v) Shielding the toroid from electromagnetic fields with a Mu-metal can and a steel outer chassis.

Moreover, with the passive transformer, the bunch structure in time can be observed and a bandwidth up to 500 MHz (corresponding to a rise time of $\tau rise \leq 1$ ns) can be achieved. For easy access and fast response, the passive transformer has to be installed on ceramic in the beam pipe outside the synchrotron. The image current of the walls have to be bypassed by a gap and a metal housing. This housing uses μ-metal and acts as a shield of external B-fields as shown in Fig. T.1.8

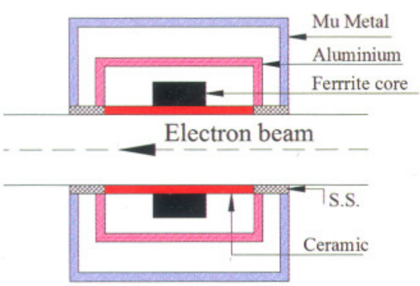


Fig T.1.8: Shielding of FCT installed over ceramic

The electrical conductivity of the beam pipe has been interrupted using ceramic duct so as to prevent a flow of image current inside the torus.This image current has the opposite sign and without the gap, the fields of the image current and beam current add up to zero. The image current has to be bypassed outside of the transformer torus by some metallic housing. It is surrounded of high permeability μ-metal, also used for the shielding of the transformer against external magnetic fields. Shielding housing for precision current monitor is shown in Fig. T.1.9.

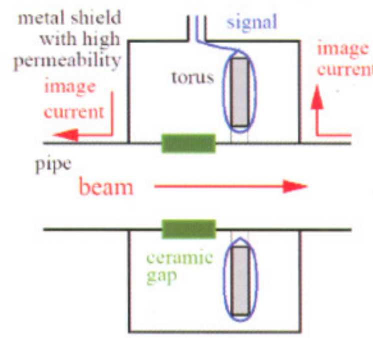


Fig. T.1. 9: FCT with ceramic duct in ring

2. Need of Fast Current Transformers (FCTs) for Indus Accelerator

For the fine operation of Indus Accelerators it is important to measure beam current and pulse shape. A wide band FCT is required to measure electron beam turn to turn current and stored current accumulation during 1μs pulse injection into booster synchrotron. The parameters required for FCT are 1) fast rise time 2) large L/R ratio 3) high signal to noise ratio 4) good linearity. It is difficult to achieve above characteristics using single large ferrite toroid. To achieve this goal, we have developed three types of FCTs with varying rise time & decay constants.

In this article, we provide brief overview of development of various FCTs using in-house fabricated large size ferrite toroids at Ferrite Lab and technological challenges to achieve desired goal [7].

We have developed large size toroids (150 mm OD X 100 mm ID X 15 mm thick) at Ferrite Lab. They have narrow B(H) with high pulse permeability & wide frequency response (> 200 MHz) .Two types of ferrite composition systems were developed & large ferrite toroids fabricated for FCTs is shown in Fig. T.1.10.

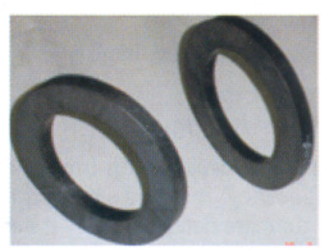


Fig. T.1.10 :Ni-Zn-Co ferrite toroid developed at Ferrite Lab

Complex permeability of ferrite toroids have been measured using RF network analyzer (100 KHz to 3GHz). A co-axial fixtures have been designed and developed for pulsed magnetization and HF characteristics. Pulsed B(H) curve at high magnetization rates(~ 2 T/μs) were also studied. Snokes limit for ferromagnetic resonance have been evaluated from complex permeability spectrum. A close agreement with predicted values has been observed. These parameters have been used in design of Fast current transformer systems [8].

Measured complex permeability spectrum of ferrite toroids have been presented in Fig. T.1.11 and Fig. T.1.12.

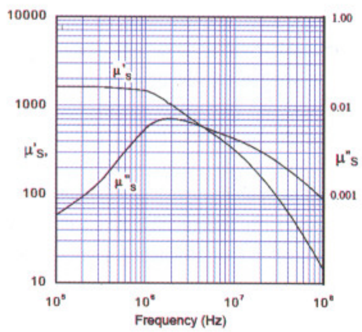


Fig. T.1. 11: Complex permeability of CAT - 3/2 ferrite (FCT M1 & M2 -Transfer line -1)

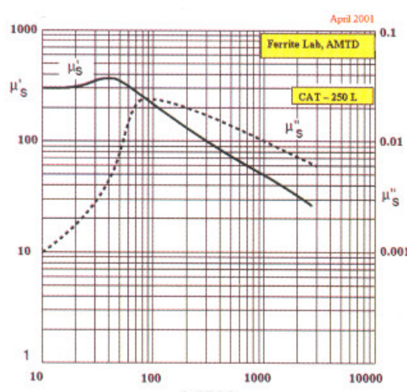


Fig. T.1. 12: Complex permeability of CAT -250 L (Fast rise time FCT - Wide band (10 ns - 50-μs & Bunch monitor (Tr ~ 500 ps)

2.1 Dual Mode Wide Band FCT for Booster Synchrotron

The FCT picks up the magnetic field generated by electron beam. A simplified equivalent electrical circuit diagram is shown in Fig. T.1.13.

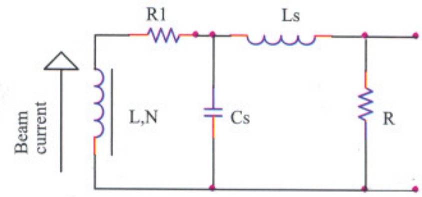


Fig. T.1.13: Equivalent electrical circuit model

Where

- L, the pickup coil or secondary inductance
- N, the number secondary turns
- R, the load resistance
- R1, the resistance of cable of secondary circuit
- C_s, Stray capacitance between components
- L_s, stray inductance between the components

The stray inductance and capacitance influences the rise time, combination of L_s & C_s results in overshoot and damped oscillation of the output signal.[9].

Fast FCT

The pickup coil (20 turns) wound on small region of the core, so the leakage inductance cannot be neglected. The current transferred to secondary will be equal $M*I_{beam} / L_{pickup}$ instead of I_{beam} / N. M is the mutual inductance between pickup coil and I_{beam} acting as primary. The measured M and coupling coefficient K are 15 μH and 0.6 respectively. The signal across load resistance is amplified by differential video amplifier MC1733. A cable driver LH0033 was used to transmit the signal through a 50 Ω coaxial cable to control room. The electronic block diagram is shown in Fig.T.1.14.

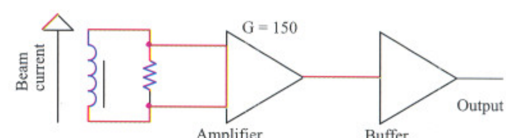


Fig. T.1.14: Electronic circuit block diagram - fast mode

Slow FCT

In this case pickup coil (350 turns) wound on entire region of the core. The measured M and coupling coefficient K are 307 μH and 0.72 respectively. High gain is achieved in three stages using video amplifier and operational amplifier. A cable driver LH0033 was used to transmit the signal through a 50Ω to control room. The electronic block diagrams for slow response are shown in Fig. T.1.15.

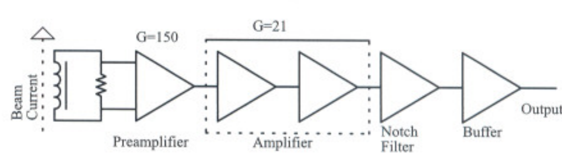


Fig T.1.15: Electronic circuit block diagram- slow mode

Designed parameters are described in table T.1. 2.

Table T.1.2: Parameters of FCTs

FCT	Number of Turns	Inductance	Load Resistance	Time constant
Fast	20	417μH	4.75Ω	87μs
Slow	350	124mH	3.2Ω	38ms

The current monitor composed of two ferrite toroids of dimension 120 mm (OD) x 100 mm (ID) x 15 mm thick. These toroids were cut using diamond wafer blade of 0.4 mm thick into two pieces. They were annealed then placed into aluminum casing with spacing 10 mm between them to minimize mutual coupling between them. The complete FCT system is enclosed in Mu-metal enclosure to reduce magneto static as well as electromagnetic interference shown in Fig. T.1.16.

Fig T.1.16: Photograph of Wide band FCT

Calibration

The output voltage of the FCT is given by,
$V = G*R*M*I_{beam} / L_{pickup}$.

Pulse current through single wire was measured by fast current probe (Tektronix TCP202) and output of FCT was measured by DSO (Tektronix TDS 540C, 500 MHz. Fig. T.1.17 and Fig. T.18 shows the pulse response of the FCTs.

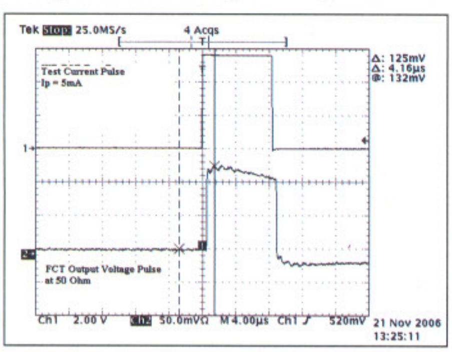


Fig. T.1. 17: Pulse response of fast FCT

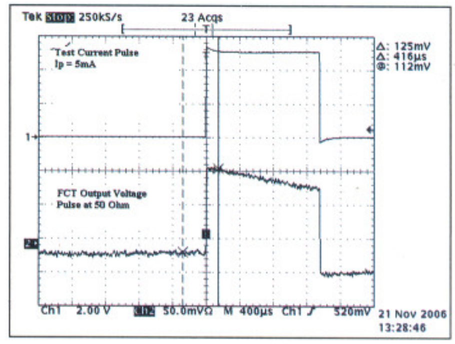


Fig. T.1.18: Pulse response of slow FCT

2.2 Modified Single Mode Wide Band FCT

Wide band FCT system developed in the year 2007 has two independent modes for slow and fast operation. Further it has been upgraded for single mode operation with fastest rise time of about 30 ns and 40 ms decay constant. To meet this requirement, a new wide band FCT has been developed for measurement of fast electron beam intensity; turn-to-turn observation and stored current accumulation during 1 μs pulse injection into Booster Synchrotron. We have investigated new technique for achieving low frequency response without affecting fast response. This approach uses active feedback to compensate droop by sensing the dB /dt in the ferrite core and restoring it through an additional winding with pick up coil. This effectively increases the secondary inductance resulting large decay constant (L/R) [10].

The low frequency response is limited by the permeability of the core and secondary inductance, Whereas high frequency response is limited by leakage inductance, self winding capacitance and amplifier's bandwidth. Improving the low frequency response by increasing the secondary turns, increases the self capacitance and leakage inductance so detoriating the high frequency response. We have optimized the no of turns (20) on half periphery of the ferrite core and placed damping resistors symmetrically about the secondary windings and tying them to common but independent ring adjacent to the winding. This has improved the high frequency response. Low frequency response has been improved using active feedback to compensate for droop. This effectively increases the secondary inductance resulting in a large decay constant (L/R)[11].

A simplified equivalent electrical circuit diagram is shown in Fig.T.1.19. The signal induced at output results in overshoot and damped oscillations due to leakage inductance and stray capacitance. Damping resistors have been employed with secondary winding for shifting the ringing and coil resonance above the frequencies of our interest. The damping resistances are connected to secondary at equal intervals and tied at common low inductance circular loop as shown in Fig. T.1.20.

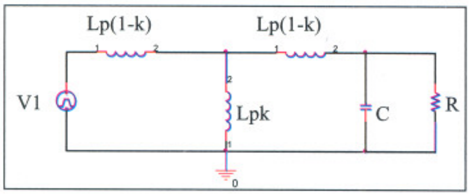


Fig. T.1.19: Equivalent primary side reflected electrical circuit diagram

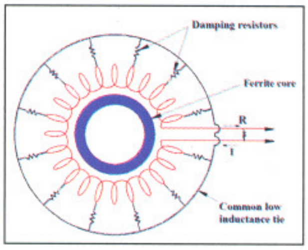
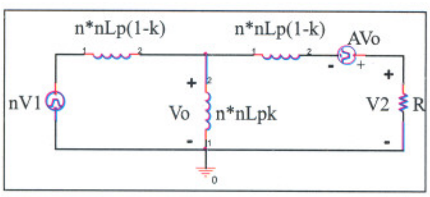
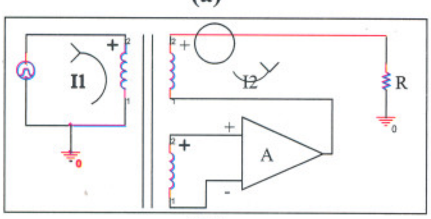


Fig. T.1.20: Construction of damping resistors

We have optimized 800 Ω resistors at interval of 4 turns. The low frequency response is improved by using negative feedback. The equivalent circuit is shown in fig. T.1.21.



(a)



(b)

Fig. T.1.21: (a) Secondary side reflected equivalent circuit after negative feedback
(b) Schematic diagram for negative feedback

Where Lp = primary inductance, k = mutual coupling coefficient, $n^2 = Ls/Lp$ & A = gain of amplifier

The residual flux in the core induces the voltage across detector winding which is amplified by an amplifier. The output of amplifier is fed to the secondary. Therefore the primary excitation is balanced by secondary($I_1N_1 = I_2N_2$)and inductance of secondary is increased effectively by gain of the amplifier. Thus the decay time constant has been increased by gain. The signal across the load resistance is amplified before transmitting it to the control room. Differential video amplifier MC1733 as a preamplifier and driver LH0033 was used to transmit the signal over 50Ω cable to the control room. The output of the FCT is given by $V = G*I_1*R/N_2$. The FCT is calibrated using coaxial bench shown in Fig. T.1. 22.

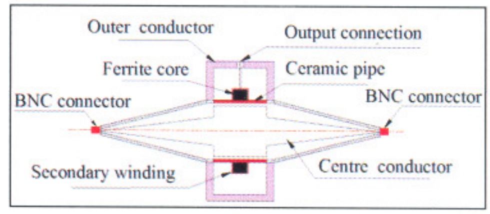
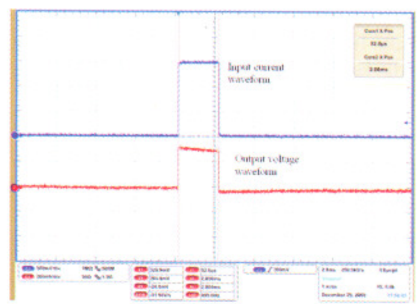
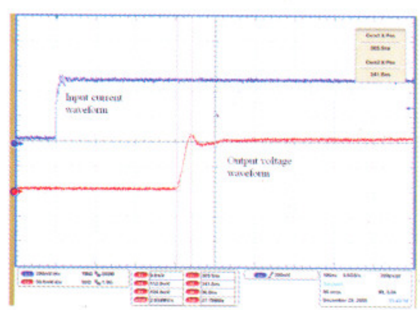


Fig. T.1. 22: Tapered co-axial bench

The centre conductor of the bench acts as primary. Ceramic pipe is used as current break for image current and bypass current path has given which passes through outer conductor of the FCT, which avoids secondary short circuit and enables to induce the voltage in secondary winding. The observed output waveforms of FCT system is shown in Fig. T.1.23.



(a)



(b)

Fig. T.1.23:(a)Waveforms for the droop measurement
(b) Waveforms for the rise time measurement

The sensitivity & droop of the WBFCT observed 10mV/mA and 2.5 %/ms respectively.

3. Prototype Bunch current monitor

Fast rise time FCT system is developed for observation of the extracted electron bunches from Booster Synchrotron.

Design scenario

Minimization of leakage Inductance and stray capacitance is the prime consideration. To minimize the leakage flux through air, the secondary is wound by coaxial cable. Its centre and outer conductors are connected in such a way that current in both the conductor flows in opposite direction as shown in Fig. T.1.24.Therefore the flux outside the cable is negligible Basically this configuration acts as inverting 1:1 Transmission line transformer. The starting end of outer conductor is connected to the output end of centre conductor thus raising the line negative voltage to output voltage i.e. at zero voltage. This is called bootstrap effect; this effect transmits to the output end after time delay td due to transmission line effect. Since the disturbance created at input side by bootstrapping travels down the output side, sees the resistive impedance (ideally) that is the characteristic impedance of the line. In this way the leakage inductance and stray capacitance are minimized. Its low frequency response is determined by the reactance of winding. In practice this reactance should be 10 times greater than the characteristic impedance of the line.[12].

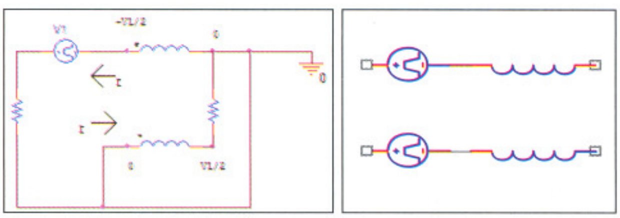


Fig. T.1.24: Equivalent circuit diagram for secondary wound coaxial cable

Prototype FCT system has been built using this configuration. Tapered coaxial bench was built for development and calibration of fast rise current monitor. The sensitivity & pulse response was tested using a tapered co-axial test stand and Tektronix probe. The monitors showed the fast rise (< 600 ps), fall time (< 900 ps), and the sensitivity (2 mV/mA) .Measured pulse response is shown in Fig. T.1. 25.

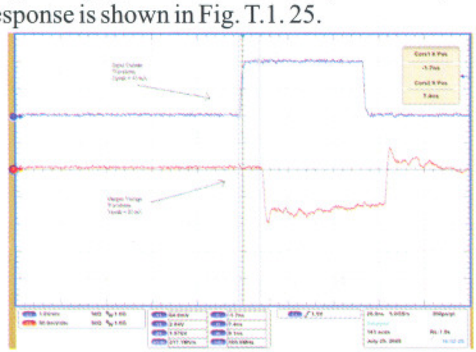


Fig. T.1. 25: Measured response of Bunch Monitor

Prototype Bunch monitor system is now under reliability tests at Lab.

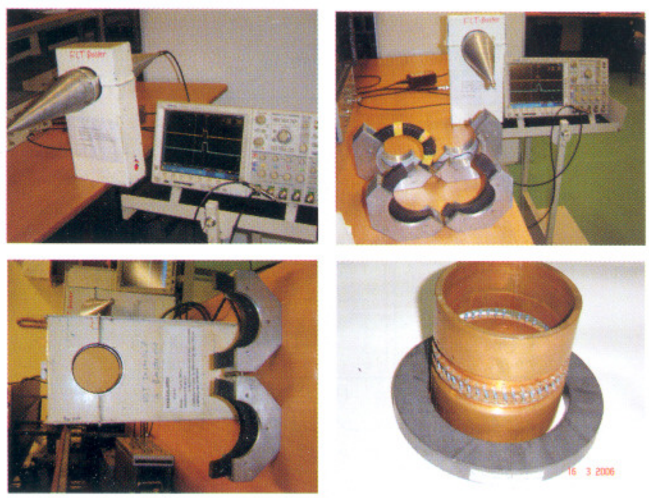
4. FCTs Development for Accelerators

During Initial commissioning of Booster Synchrotron (1992-96), we developed about five FCTs which were installed in Tl-1 and Booster ring. After successful commissioning of Indus-1 FCTM1 with two coaxial output installed in Tl-1 at exit of Microtron and FCTM2 installed in Tl-1 at Booster injection. For further diagnostics Wideband FCT installed adjacent to DCCT in Booster ring. These FCTs are working satisfactorily and they require no operating adjustments and has proved stability, accuracy and reliability during Indus operation.

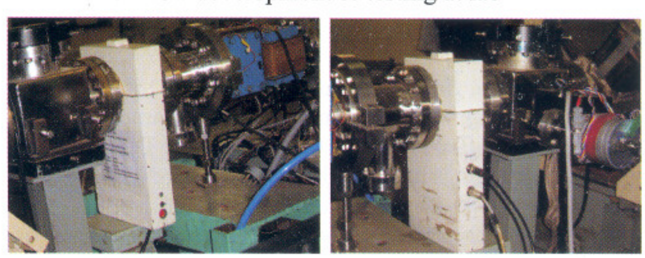
Besides above mentioned FCTs, we have also designed, developed FCTs for Accelerator facilities in India as per given below.

1. Mangalore University, June 1995: 2 Nos.
2. FEL, RRCAT: 5 Nos.
3. IMA,RRCAT for Radiotherapy machine: 2 Nos.

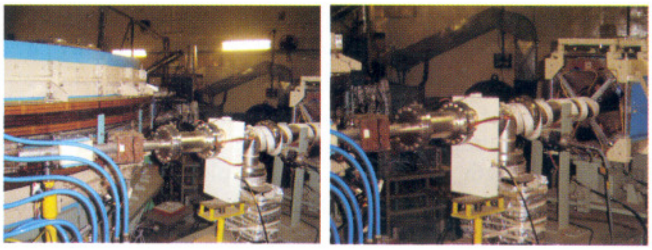
Photographs of FCTs and Test facilities



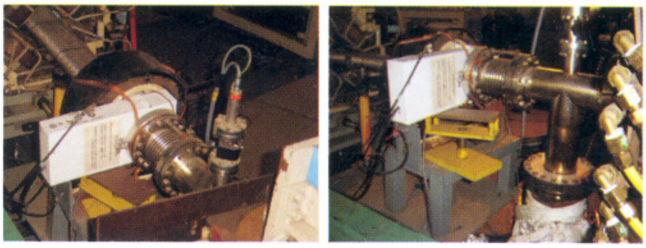
FCT development & testing at lab



FCTM1 installed at Exit of Microtron in TL-1



FCT M2 installed at Booster Injection in TL-1



Wide Band FCT installed in Booster Ring

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