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Integrating Current Transformer User's Manual

Rev. 3.0

Includes: Active Integrating Current Transformer models

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GMW Associates
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Tel.: (650) 802-8292
Fax: (650) 802-8298
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WARNING ! ICT maximum temperature AT ANY TIME: 80°C / 176°F

SUMMARY Page

INITIAL INSPECTION

It is recommended that the shipment be inspected immediately upon delivery. If it is damaged in any way, contact Bergoz Instrumentation or your local distributor. The content of the shipment should be compared to the items listed on the invoice. Any discrepancy should be notified to Bergoz Instrumentation or its local distributor immediately. Unless promptly notified, Bergoz Instrumentation will not be responsible for such discrepancies.

WARRANTY

Bergoz Instrumentation warrants its beam current monitors to operate within specifications under normal use for a period of 12 months from the date of shipment. Spares, repairs and replacement parts are warranted for 90 days. Products not manufactured by Bergoz Instrumentation are covered solely by the warranty of the original manufacturer. In exercising this warranty, Bergoz Instrumentation will repair, or at its option, replace any product returned to Bergoz Instrumentation or its local distributor within the warranty period, provided that the warrantor's examination discloses that the product is defective due to workmanship or materials and that the defect has not been caused by misuse, neglect, accident or abnormal conditions or operations. Damages caused by ionizing radiations are specifically excluded from the warranty. Bergoz Instrumentation and its local distributors shall not be responsible for any consequential, incidental or special damages.

ASSISTANCE

Assistance in installation, use or calibration of Bergoz Instrumentation beam current monitors is available from Bergoz Instrumentation, 01630 Saint Genis Pouilly, France. It is recommended to send a detailed description of the problem by fax.

SERVICE PROCEDURE

Products requiring maintenance should be returned to Bergoz Instrumentation or its local distributor. Bergoz Instrumentation will repair or replace any product under warranty at no charge. The purchaser is only responsible for transportation charges.

For products in need of repair after the warranty period, the customer must provide a purchase order before repairs can be initiated. Bergoz Instrumentation can issue fixed price quotations for most repairs. However, depending on the damage, it may be necessary to return the equipment to Bergoz Instrumentation to assess the cost of repair.

RETURN PROCEDURE

All products returned for repair should include a detailed description of the defect or failure, name and fax number of the user. Contact Bergoz Instrumentation or your local distributor to determine where to return the product. Returns must be notified by fax prior to shipment.

Return should be made prepaid. Bergoz Instrumentation will not accept freight-collect shipment. Shipment should be made via Federal Express or United Parcel Service. Within Europe, the transportation service offered by the Post Offices "EMS" (Chronopost, Datapost, etc.) can be used. The delivery charges or customs clearance charges arising from the use of other carriers will be charged to the customer.

SAFETY INSTRUCTIONS

The instrument designated as "Integrating Current Transformer" may become RADIOACTIVE when exposed to ionizing radiations.

It contains :
- Cobalt…………………………………………………Up to 0.8 Kg
- Iron……………………………………………………Up to 0.8 Kg

ORDERING CODES

ICT–ppp – ppp – pp:1–xpp –p –p

Inner diameter [mm]:
Standard IDs =
–016
–028
–055
–082
–122
–178
Optional: other ID

Output pulse duration (6σ) [ns]:
Standard: 070
Optional: from 003 to 500

Turns ratio:
–05:1
–10:1
–20:1
–50:1
–100:1

Gain:
Nothing: Passive ICT
–x20 Active ICT

Connector type:
No suffix SMA
–B BNC
–L Lemo
–N N

-H Rad-hard

GENERAL DESCRIPTION

The Integrating Current Transformer (ICT) is a transformer designed to measure the charge in a very short pulse with high accuracy. Passive models do not contain any electronics. Active models incorporate electronics, including radiation-sensitive semiconductors.

The ICT is capable of integrating a very fast pulse with rise time in the order of picoseconds with no significant loss. This kind of performance is needed, for instance, to measure very short particle bunches.

The ICT magnetic core and associated windings are essentially noisefree. The measurement noise –and consequently the measurement resolution– is determined by the signal processing. Active ICT models have been demonstrated to measure pulsed particle beams with less than 1 nA rms noise.

The Integrating Current Transformer is a capacitively shorted transformer and a fast read out transformer in a common magnetic circuit.

The magnetic cores are made from thin ribbons of Cobalt / Molybdenum amorphous alloy interleaved with Nickel / Iron crystalline alloy.

The ICT integrates the signal with a time constant of 1 to 20 nanoseconds, depending on the model. As a result, rise and fall are both slowed down, the eddy current losses become negligible and the instrument is a very linear integrator for the very high frequency spectrum typical of a bunched beam

GENERAL DESCRIPTION (Cont'd)

signal. The ICT output frequency spectrum is decreased by orders of magnitude in comparison to the beam frequencies.

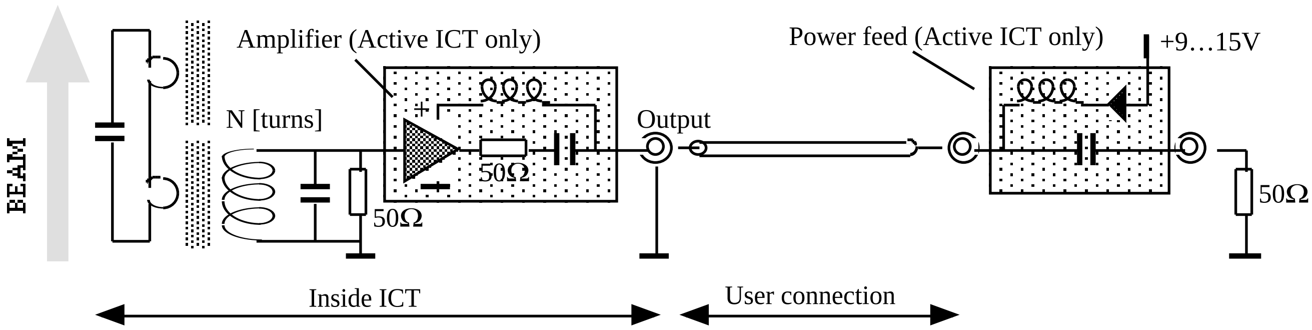
Very precise calibration is possible. The ICT's only drawback is that the original shape of the signal is lost. The ICT delivers its output in a 50 Ω load.

Linearity and beam position sensitivity were tested first in 1987 on the electron/positron collider CESR at Cornell University[1]. A measure of linearity showed an error < 3 x10^{-4} for a bunch length variation of 20% (56ps to 70 ps). A measure of beam position dependency showed an error <10^{-4} for ±10 mm of beam axis change (off-center).

The temperature dependence is negligible.

OPERATING PRINCIPLE

The Integrating Current Transformer (ICT) is a transformer designed to measure the charge in a very fast pulse with high accuracy. It is capable of integrating a pulse with rise time in the order of picoseconds with no significant loss.



The ICT is a capacitively shorted transformer coupled to a fast readout transformer in a common magnetic circuit[2]. It delivers a pulse with ca. 20 ns rise time irrespective of the beam pulse rise time. The ICT output pulse charge is in exact proportion to the beam pulse charge.

1 Design and preliminary tests of a beam monitor for LEP , K.B. Unser, CERN, proceedings of the 1989 IEEE Particle Accelerator Conference, Vol. 1 page 71.

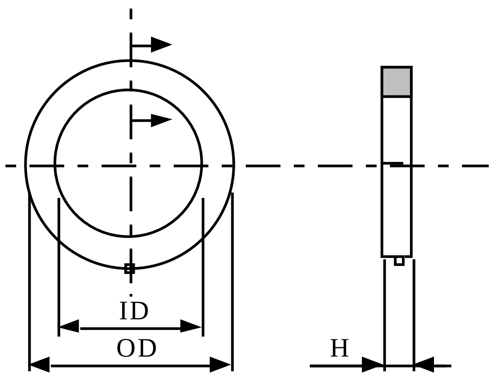
2 Measuring Bunch Intensity, Beam Loss and Bunch Lifetime in LEP, K.B.Unser, Proceedings of the 2nd European Particle Accelerator Conference, 1990, Vol.1, p.786

SENSITIVITY

The sensitivity of the Integrating Current Transformer is also called the transfer impedance. It depends on the ICT model. It is expressed in terms of the integral of the output pulse voltage as a function of the input pulse charge, therefore in V.s/C, or Ω.

	Sensitivity in a 50Ω termination	Beam charge to output charge ratio in 50Ω load	Beam charge to output charge ratio in a virtual 0Ω load
Passive models			
ICT-XXX-XXX-50:1	0.50 V.s/C	100:1	≈ 50:1
ICT-XXX-XXX-20:1	1.25 V.s/C	40:1	≈ 20:1
ICT-XXX-XXX-10:1	2.50 V.s/C	20:1	≈ 10:1
ICT-XXX-XXX-05:1	5.00 V.s/C	10:1	≈ 5:1
Active model			
ICT-XXX-XXX-10:1-x20	50 V.s/C	1:1	N/A

MECHANICAL DIMENSIONS



Ordering code	ID (min.)	OD (max.)	H (max.)	Mass (g)
ICT-016-070-20:1	16	42	32	110
ICT-028-070-20:1	28	64	32	180
ICT-055-070-20:1	55	91	32	300
ICT-082-070-20:1	82	118	32	400
ICT-122-070-20:1	122	156	32	520
ICT-178-070-20:1	178	226	32	980
All dimensions in mm				
ICT-XXX-070-10:1 are sometimes larger than -20:1 models ICT-XXX-070-05:1 are always larger than -20:1 models Active ICTs can be larger than passive models				

ELECTRICAL CONNECTIONS

ICT model	*Ordering code………………………………………… Connector type*
Standard	No suffix………………………………………………SMA 50Ω female
BNC	-B suffix………………………………………………BNC 50Ω female
Lemo	-L suffix……………………………………………Lemo 00 50Ω female
N-type	-N suffix…………………………………………………… N 50Ω female
Active	-x20…………………………………… Solder pin on Power Feed box

The body of the connector is connected to the shield.

OUTPUT SIGNAL POLARITY

The Integrating Current Transformer is bipolar.
Arrows are printed on the outer surface of the toroid.
Charges (positive) crossing the aperture in the direction of the arrow give positive outputs.
The Active ICT has better linearity for positive pulses than for negative pulses.

POWER SUPPLY (active ICT only)

Power supply ………………………………… +9V…15V, 25 mA (0.225 W) @ 9V

CABLE CONNECTION

Most 50Ω coaxial cable types are appropriate to connect the ICT to its measuring instrument.
When short primary pulses are measured (fwhm ≤ ICT output pulse duration / 3), the signal to be carried by the cable always has the same frequency spectrum, irrespective of the primary pulse rise/fall time and charge. The fundamental frequency "seen" by the cable is very low:

$$f = \frac{1}{\text{ICT output pulse duration } (6\sigma)}$$

I.e ≈14 MHz for standard models ICT-XXX-070...

SPECIFICATIONS

Pulse charge to output ratio	50:1	20:1	10:1	05:1	
Input current rise time	< 1	< 1	< 1	< 1	ps
Pulse length (max)	2*	2*	2*	2*	µs
Linearity error	< 0.1	< 6	< 10	< 20	%
Droop in 50Ω load	< 2	< 6	< 10	< 20	%/µs
Droop in virtual 0Ω load	<< 1	< 1	< 1	< 2	%/µs
Eddy current loss	< 1	< 1	< 1	< 1	%
Position sensitivity (on axis)	< 0.01	< 0.01	< 0.01	< 0.01	%/mm
Output risetime	≈ 30	≈ 30	≈ 30	≈ 30	ns
Output pulse duration (99% = 6 sigma)	70**	70**	70**	70**	ns
* Longer pulses or macropulses with low-droop special models					
** From 3ns to 500ns output pulse length on request					

INSTALLATION ON THE VACUUM CHAMBER

The installation of an Integrating Current Transformer (ICT) on the outside of a vacuum chamber requires some precautions.

a) The electrical conductivity of the vacuum chamber must be interrupted in the vicinity of the ICT, otherwise the wall current will flow thru the ICT aperture and cancel the beam current.

b) The wall current must be diverted around the ICT thru a low impedance path.

c) A fully-enclosing shield must be installed over the ICT and vacuum chamber electrical break to avoid RF interference emission.

d) The enclosing shield forms a cavity. Cavity ringing at any of the beam harmonics must be avoided.

e) The ICT must be protected from heat during vacuum chamber bake-out. Its temperature should never, at any time, exceed 80°C (176°F).

f) The higher harmonics of the beam should be prevented from escaping the vacuum chamber, because (1) they are not "seen" by the ICT therefore unnecessary, (2) they heat the ICT and any other conductive material inside the cavity, (3) they cause quarter-wave mode ringing in the cavity.

g) Electrostatic (capacitive) coupling between the ICT body and the vacuum chamber must be avoided. This is especially true for Active ICTs.

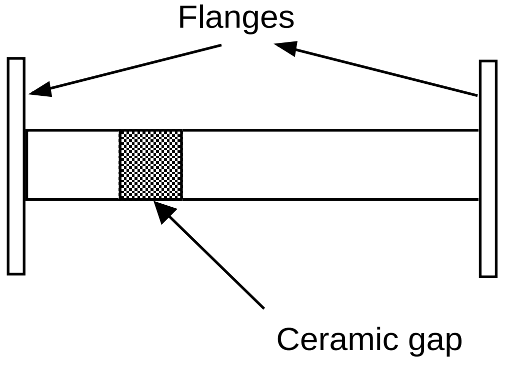
Note: The ICT does not need to be protected from external magnetic fields. When it is exposed to external magnetic fields it may saturate; this causes the droop to increase up to a factor of 2. It has no effect on the ICT linearity.

Break in the vacuum chamber electrical conductivity

If the vacuum chamber does not require bake-out and the vacuum requirements are moderate, a polymer gasket in-between two flanges is adequate to assure the desired galvanic isolation.

If the vacuum chamber needs bake-out, the most commonly use solution is to braze a section of ceramic on the vacuum chamber tube. This is called a "ceramic gap".

The ceramic gap may be installed on centre or off-centre of a short pipe section:



INSTALLATION ON THE VACUUM CHAMBER (Cont'd)

Vacuum chamber impedance

The ceramic gap causes a disruption of the impedance seen by the beam. This is particularly undesirable for leptons accelerators. The most usual corrective measure consists of metallizing the inside of the ceramic gap. Metallization has been used successfully on many electrons / positrons accelerators. Depending on the type of current transformer being installed (AC or DC), the resistance of the desirable metallization varies:

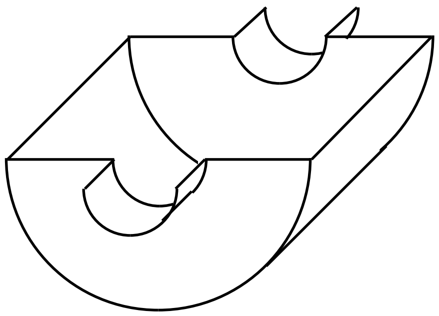
ICT current sensors tolerate a metallization with ca. 1Ω without problem, provided the wall current bypass is of very low impedance.

If a DC current transformer PCT or MPCT-S is installed over the same ceramic gap, these latter instruments are adversely affected by an ohmic value $R < 100\Omega$ because it shorts the PCT or MPCT sensor. The commonly used solution is to etch a narrow groove in the metal deposit to prevent DC conductivity of the gap metallization.

Wall current bypass and RF shield

The two functions of wall current by-pass and RF shield can be performed by a solid metal shield attached to the vacuum chamber on either side of the electrical break.

The easiest is to make a cylindrical enclosure which splits into two half shells:



The shells can be firmly attached to the vacuum chamber with water hose clamps.
Material can be aluminium, stainless steel or copper. Copper oxidation does not seem to be a problem.

Thermal protection of the ICT

The ICT must not be heated beyond 80°C. If the vacuum chamber requires bake-out, a thermal shield must be installed between the vacuum chamber (or the heating sleeves) and the ICT.
The thermal shield can be a simple copper cylinder cooled by water circulating in a copper tube brazed onto the cylinder.
The water circuit must not pass thru the ICT aperture. It must enter and go out on the same side of the ICT, otherwise it makes a shorting loop around the ICT toroid.

MAXIMUM STORAGE AND OPERATING TEMPERATURE 80°C (176°F) AT ANY TIME. The alloy looses its characteristics when heated beyond this temperature.

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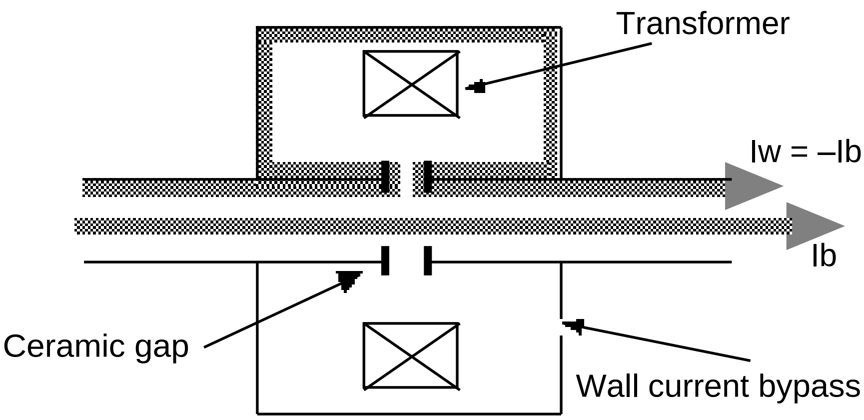
Keeping high harmonics of the beam out of the cavity

The transformer, the gap capacitance and the wall current bypass form together a cavity.
It is important to prevent unnecessary harmonics from entering the cavity:

The beam current flows thru the vacuum chamber.
The wall current follows the conductive vacuum chamber walls.

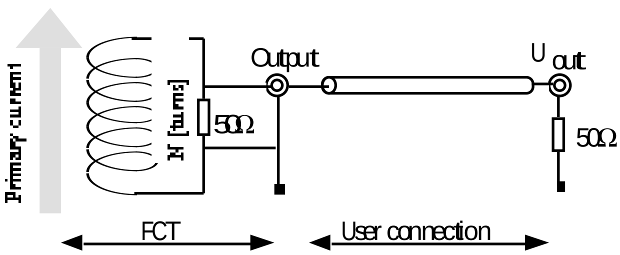


The transformer "sees" the wall current Iw. The higher frequencies of the wall current frequency spectrum will pass thru the capacitance of the ceramic gap, while the lower frequencies will enter the cavity and induce a flux in the transformer core.

Note that the full charge of the wall current pulse passes thru the cavity, irrespective of the value of the gap capacitance.

The value C of the gap capacitance determines the higher cutoff frequency of the wall current entering in the cavity. The -3dB point is obtained when the impedance of the cavity Z_{cavity} is equal to the impedance of the gap Z_{gap}.

The impedance of the wall current bypass itself can be ignored because it is much lower than the transformer's reflected impedance, therefore:



$Z_{cavity} = R / N^2$, where:

R is the load impedance of the transformer = 25Ω (50Ω termination || 50Ω internal load)
N is the transformer's turns ratio
Example, an ICT with 20:1 turns ratio (i.e. ICT-XXX-20:1), $Z_{cavity} = 0.0625\ \Omega$.

Keeping high harmonics of the beam out of the cavity (Cont'd)

The gap impedance is determined by its capacitance:

$$Z_{gap} = 1 / \omega C, \text{ and } \omega = 2\pi f$$

For $Z_{cavity} = Z_{gap}$: $C = N^2 / 2\pi f R$

Example: ICT with 20:1 turns ratio, f_{-3dB} = 1GHz, R = 25Ω : C = 2.54 nF

Different accelerator laboratories use different techniques to obtain the required gap capacitance. A simple method consists in building a capacitor over the ceramic gap with layers of copper foil separated by layers of 100µm-thick kapton foil.   To obtain the desired capacitance value, the overlapping area is obtained by:

$$S = C\, d / \varepsilon_r\, \varepsilon_o$$

Where:

C is the capacitance [F]

S is the area [m^2]

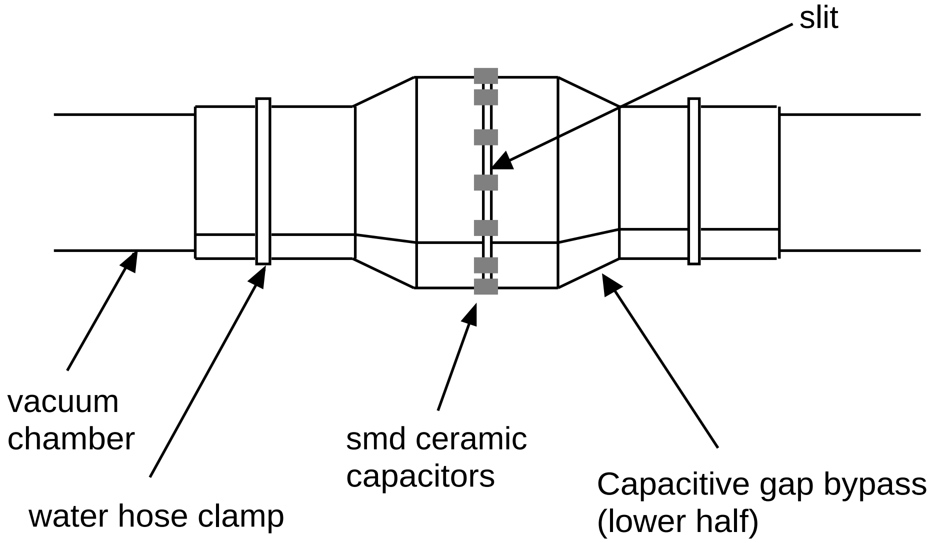
d is the dielectric thickness [m]

ε_r is the relative dielectric constant, 3.5 for Kapton polyimid

ε_o is the dielectric constant 8.86 x 10^{-12}

Example, for C = 2.54 nF and d = 100µm and ε_r = 3.5, S = 82 cm^2.

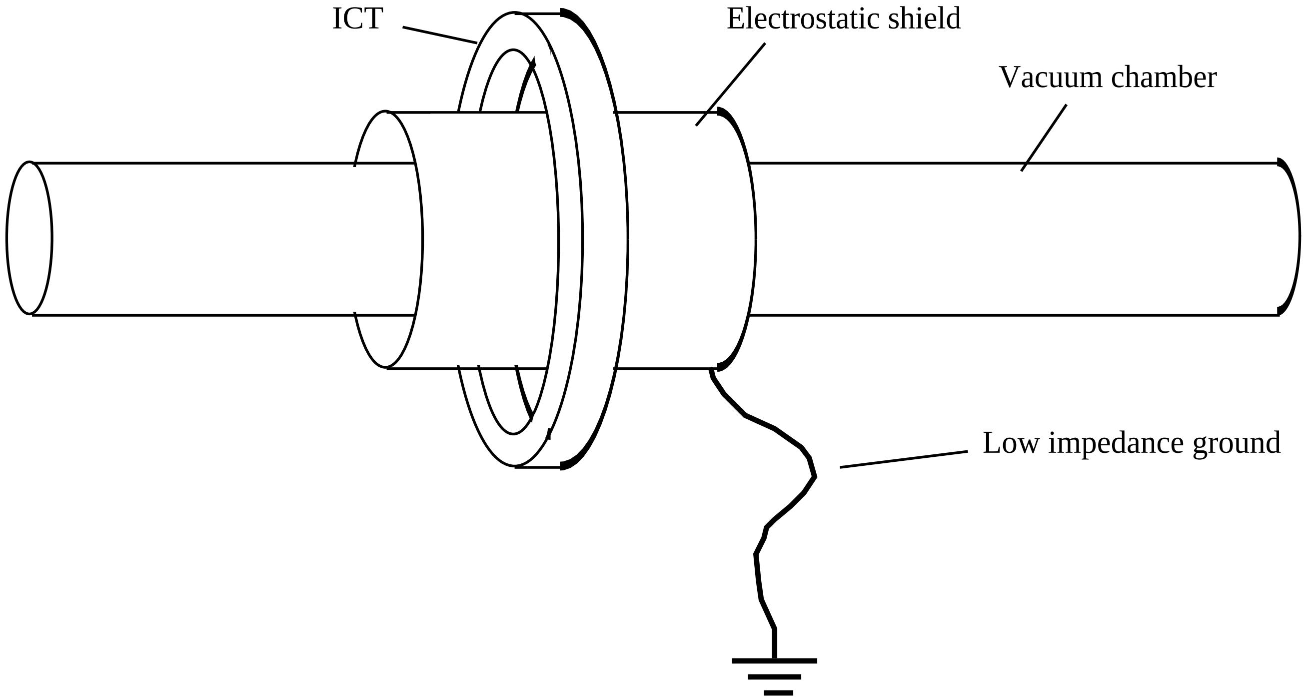
Other laboratories install a capacitive gap bypass with surface-mount capacitors distributed over the slit. The capacitive bypass is made in two halves for ease of mount:



Electrostatic shield

To measure beams with low charge per pulse, electrostatic (capacitive) coupling between the ICT body and the vacuum chamber must be avoided. This is especially true when an Active ICT is used.

An electrostatic shield may be installed:



The shield must be grounded on one side only (!)

Depending on the cables layout, grounding on one side will <u>increase</u> the noise pick-up, while grounding on the other side will <u>decrease</u> it. There is no easy way to predict on which side the electrostatic shield should be grounded: Different grounding conditions must be tried until the noise pickup is at its minimum. The quality of the grounding –thus the efficiency of the shield– is determined by the impedance of the grounding scheme. In practice, its inductance is the parameter to minimize.

Note: the noise picked up by capacitive coupling with the vacuum chamber is wideband noise. It is best observed with a wideband oscilloscope, while the accelerator is running.

The electrostatic shield can be made in any conductive metal, provided the grounding cable connects properly with the shield. It may have the dual purpose of thermal shield and electrostatic shield. In this case, one should take care that the cooling water pipes do not bring noise to the shield.

To hold the shield and the ICT sensor in place, while providing good isolation, the space between vacuum chamber, shield and ICT sensor can be filled with polyurethane foam. If the vacuum chamber requires high temperature bake-out, fiber glass wool will be preferred.

Note: The ICT accuracy is not affected by its radial, angular or axial position in respect of the beam axis.

Ferrite cores, tubes and beads installed on the coaxial cable contribute significantly to eliminate the noise picked up by the ICT body via capacitive coupling. Avoid the split cores when possible.

ICT RADIATION RESISTANCE

ICTs contain materials which may be damaged by ionizing radiations. They are listed hereafter:

Organic and radiation-sensitive materials used in the "Standard" sensor:

The "Standard" sensor is supplied when the "Rad-Hard" option is not ordered.

Component	*Material*	*Radiation resistance*[3]
Wiring insulation	Polyvinylchloride PVC	2 x 10^5 Gy
	Fiber glass	> 10^8 Gy
	with rubber adhesive	> 10^6 Gy
Stress absorbent	Silicon rubber tape SIR	5 x 10^5 Gy
	Silicon rubber SIR	2 x 10^5 Gy
Connector isolation	PTFE "Teflon"	< 10^3 Gy

Organic and radiation-sensitive materials used in the "Rad-Hard" sensor:

The "Rad-Hard" sensor is supplied when the "Rad-Hard" option is ordered. The ordering code and model number are then terminated by -H.

Component	*Material*	*Radiation resistance*
Wiring isolation	Polyether-ether-ketone PEEK	6 x 10^7 Gy
	Fiber glass	> 10^8 Gy
	with rubber adhesive	> 10^6 Gy
Stress absorbent	Polyurethane foam PU	5 x 10^6 Gy
	Polyurethane rubber PUR	5 x 10^6 Gy
Connector isolation	Polyimid "Kapton"	6 x 10^7 Gy

Semiconductors used in the "Active" sensor:

The Active ICT is a sensor which part number contains a multiplying factor.
*Example: ICT-122-070-10:1-**x20**.*

The lifetime of an "Active" sensor is essentially limited by the radiation resistance of the embedded bipolar technology amplifier. There is no data available on its radiation resistance.

The above radiation resistance values are indicative only. They do not imply any guarantee of whatever nature from the manufacturer.
The manufacturer specifically declines any responsibility for any damage, direct or consequential, caused by ionizing radiations.

[3] Compilation of Radiation Damage Test Data, H.Schönbacher et al., CERN 79-04, 79-08, 82-10 and 89-12.

DESIGN AND PRELIMINARY TESTS OF A BEAM INTENSITY MONITOR FOR LEP

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Abstract: The beam intensity monitor for the circulating beams in LEP uses toroidal cores of an amorphous magnetic alloy as sensors. It consists of two independent systems:

- A current transformer employing a parametric amplifying principle to measure the sum of the currents of both beams (dc component). This system has a resolution better than 0.2 μA and gives the absolute calibration of the monitor.

- A passive integrating current transformer to measure the relative charge of each individual bunch. Synchronous analog signal processing correct for baseline offsets and track a selected bunch over many revolutions. This permits to measure the number of circulating particles with great precision and for each bunch separately.

1. Introduction

The Large Electron-Positron collider (LEP) in CERN has a circumference of 26.7 km. The particles in each of the two colliding beams are concentrated in 4 regularly spaced circulating bunches, having a minimum rms length of 45 picoseconds and a nominal intensity of about 4×10^{11} e^+ or e^- per bunch. The peak value of beam current of these short bunches may be high (> 1 kA), but the mean value of beam current in LEP is rather low (≈ 0.75 mA per bunch).

A parametric dc current transformer is used to measure the total number of circulating particles in LEP. This intensity monitor does not require any timing information for proper operation and it provides a precise, absolute calibration without any ambiguity. The limitation of this system is its inability to distinguish between individual bunches. It measures simply the sum of the currents of both beams, even so they circulate in opposite directions.

A fast, integrating current transformer measures the charge of each individual bunch in LEP. The signal from this single transformer is used as an input for 8 parallel analog signal processing channels. Each of these channels is timed to track one particular bunch on every revolution and generates an output signal proportional to the number of particles in this bunch.

The limited space of this paper does not allow to treat both systems of the LEP beam intensity monitor completely. The following chapters will therefore concentrate on a selected number of novel features.

2. Magnetic cores made from amorphous alloys

High permeability alloys with amorphous structure have become commercially available in recent years. They exhibit exceptional magnetic properties, which makes them very attractive for beam current transformers. Their practical use in this context presents a number of technological problems. Different types of alloys are available and a preliminary investigation [12] selected Vitrovac 6025, with the composition $(CoFe)_{70}(MoSiB)_{30}$, made by Vacuumschmelze A.G. (Hanau, Fed. Rep. Germany). It is supplied in the form of a continuous ribbon of about 25 μm thickness, which is used to wind a toroidal core of any dimension. Compared with polycrystaline nickel/iron alloys, it has a higher permeability and lower eddy current losses (resistivity 2...3 times higher). One of the disadvantages of this material is a high level of magnetic noise (Barkhausen noise), a critical parameter for the application as magnetic modulators.

The amorphous structure is originally acquired by rapid quenching (cooling) at a rate of ≈ 10^6 K/s. The desired magnetic properties are obtained later by a thermal/magnetic annealing and relaxation process, below 500°C (recrystallization temperature). This has to be done with the material in its final core shape.

The magnetic cores for the beam current monitor have such specific requirements, that we had no choice but to learn to manufacture them ourselves. For a magnetic modulator with high resolution, we require an identical core pair with magnetic characteristics of exceptional stability, high permeability and a minimum of Barkhausen noise. A long series of systematic experiments permitted to set the following rules for the construction:

- a specially selected quality of Vitrovac 6025
- magnetic toroid free of internal constraints and freely "floating" inside a rigid support structure
- insulation between layers [11] without any defect, obtained with a Mylar foil of 1...2 μm thickness
- choice of geometry to avoid major magneto-mechanical resonances within modulator frequency range
- vacuum impregnation with a viscous damping fluid to reduce secondary resonances
- annealing for maximum permeability, minimum Barkhausen noise, best frequency response.

3. Magnetic field annealing

This chapter is a very simplified description of a rather complex subject. The annealing of the finished core consists of a controlled high temperature cycle in the presence of a magnetic field, which magnetizes the sample to the saturation level.

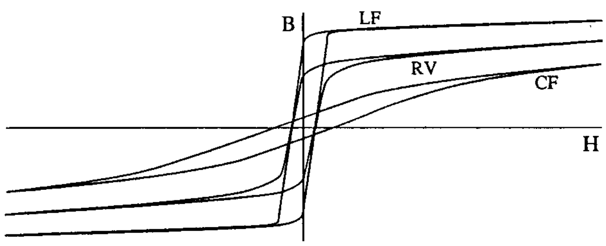

Fig. 1 Effect of annealing Vitrovac 6025.
Dynamic BH-curves at 100Hz

The field is most commonly applied in the longitudinal direction of the ribbon (LF). This produces a rectangular hysteresis loop (Fig. 1) with the highest value of max. permeability (≈ 500 000). The uniaxial anisotropy is at its maximum, leading to very large domain structures associated with a high level of Barkhausen noise and a relatively poor frequency response [9].

Cross-field annealing (CF) with the field perpendicular to the axis of the ribbon, yields a very flat BH curve with a much lower value of max. permeability (≈ 70 000), with improved frequency response. There are smaller magnetic domains and less Barkhausen noise than in the previous case.

It would be ideal in our application, to suppress the field induced anisotropy [10] and its associated macroscopic structures. Annealing without any field unfortunately does not work, because the magnetic domains tend to line up spontaneously in the axis of the ribbon, producing a situation analog to LF but with much lower permeability. There are methods reported [7], like heating above Curie temperature, followed by fast cooling (in water), or rotation of small samples in a stationary field. This is not a solution in our case, because the first method produces unstable magnetic characteristics and the second requires a very big magnet.

Our specially designed annealing plant permits simultaneous application of LF and CF. By suitable controls of the respective amplitudes, we are able to rotate the magnetic vector in a stationary sample. This type of processing is not easy to apply and at present certainly not yet optimized. It yields a hysteresis loop (RV) with the best dynamic properties.

4. The zero flux current transformer (ZFCT)

The basic operating principles of the zero flux current transformer has been described in two earlier papers [1; 6]. It consists basically of a toroidal current transformer and an operational amplifier, connected together in a closed feedback loop. The current to be measured (for example a particle beam) passes through the center of the toroid and is the single turn primary winding. The operational amplifier maintains the dynamic balance between primary and secondary current over a wide frequency range and particularly far down into the mHz region.

An auxiliary circuit with a magnetic modulator/demodulator, using a pair of toroidal modulator cores, senses the dc error between primary current and feedback current and corrects this error in the feedback loop. This maintains the main toroid (dynamic and static) at zero flux level and extends the frequency range to dc. The feedback current is measured with a precision resistor.

The ZFCT was originally developed as a beam current monitor for the ISR [2]. It is a good example of a specific accelerator technology [3], which has found a wide range of industrial applications [4]. It was this type of applications which did bring it back to the accelerators again [5; 13]. The trend is well illustrated in the LEP project, where more than 500 ZFCT's will be used for precision power control in conventional and cryogenic magnet systems and for monitoring the electrode and anode currents of the high power klystrons (security interlocks).

5. The parametric current transformer (PCT)

The parametric current transformer is a new step in the development of the ZFCT and has the same basic operating principle. It differs from the ZFCT in the electronic circuit concept. Important details concerning the excitation and demodulation circuits have changed and a parametric amplification scheme reduces the effect of amplifier noise.

The practical differences are a much higher modulation frequency and the use of magnetic cores with very small cross sections (in LEP: 5 mm^2; I.D. 210 mm). Circuits and interconnections have been simplified, without sacrificing performance. The PCT covers a frequency range from dc to 100 kHz and a dynamic range of 2×10^7 without range switching. The absolute resolution of the PCT depends only on the quality of the magnetic cores. Best performance so far obtained (with RV annealing) is < 0.2 µA rms (1 s integration window).

5.1. The modulator driver

The modulator excitation drive signal should be of very stable amplitude and frequency, completely free of even harmonic distortion. A square wave of perfect symmetry (≈ 7 kHz), is generated in a symmetrical D-MOS transistor bridge (Fig. 2). The amplitude is controlled by a precision dc regulator. The control signals to the switching transistors are derived by synchronous frequency dividers from a quartz controlled master clock.

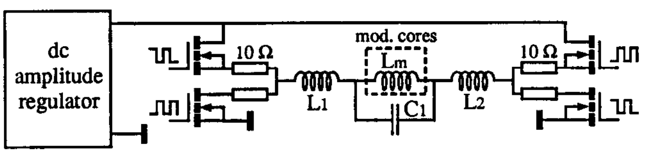

Fig. 2 schematic of modulator driver

The square wave driver supplies the excitation windings of the modulator cores via a symmetrical, passive low pass filter (L_1+L_2 and C_1). The value of capacitor C_1 is critical, because it is not only part of the LP-filter, but also the source of an avalanche current discharge into the excitation winding L_m, when the modulator cores approach saturation. This current can easily reach a peak of 4 A . Most of the energy initially stored in this capacitor may be recuperated. This requires an optimum choice of the resonance frequency, determined by the (changing) inductance of the modulator excitation winding L_m and the avalanche capacitor C_1.

The modulator driver of the PCT for LEP has a high efficiency. The absorbed dc power is less than 1 W for an excitation amplitude of 50 V and a peak current of 2 A into the modulator core windings. It has the simplicity of a square wave driver and provides the spectral purity and the high modulator sensitivity which is typical for sine wave excitation. The high value of peak saturation current is equivalent to an applied magnetic field of H ≈ 6 A/cm in the modulator cores (500 times more than the minimum to reach saturation). This reduces Barkhausen noise and residual magnetic remanence (memory effect) and improves resolution and zero stability of the PCT in an important way.

5.2. Parametric amplification

Any magnetic modulator satisfies the definition of a parametric amplifier. The PCT uses a circuit arrangement to increase the sensor signal amplitude before it is applied to the transistor amplifier, thereby improving the signal to noise ratio.

Parametric amplification is commonly obtained in flux gate magnetometers, by loading the sense coil with a capacitor and tuning it to the second harmonic frequency [12]. The periodic permeability change of the flux gate cores provides the pumping action for parametric amplification. This principle cannot be applied directly to the PTC for two reasons:

- The sense coils are wound on a ring core (closed magnetic circuit) and have a low Q value
- Due to the very tight coupling between excitation and sense windings and any inevitable unbalance between the 2 cores of a modulator pair, the direct capacitive loading interferes with the avalanche circuit and may cause parasitic oscillations.

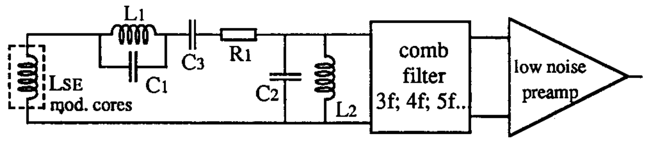

Fig. 3 Sensor signal conditioning circuits for the PCT.

Parametric gain is possible with the circuit in Fig. 3. A series and a parallel resonance circuit are connected to the sense windings L_{SE} of the magnetic modulator. L_1, C_1 is a band stop filter, tuned to the excitation frequency f. It attenuates the unwanted fundamental frequency components and eliminates interactions with the excitation circuit. L_{SE} is the source and the reactive load of the parallel resonance circuit (L_2, C_2) tuned to 2f. The parametric gain of this arrangement is adjusted with series capacitor C_3 and resistor R_1, which control respectively coupling and damping of the 2f resonance circuit.

6. The integrating current transformer (ICT)

Measuring the intensity of very short beam pulses (< 1 ns) with conventional beam current transformer is problematic. Core losses increase very rapidely with frequency and eddy currents limit the penetration of the magnetic field to a very thin surface layer of the magnetic material. One can use very thin magnetic ribbons (10 µm) and increase the core cross-section to compensate partially these effects, but the method is expensive and the calibration of such a current transformer is bunch-shape and beam position dependent.

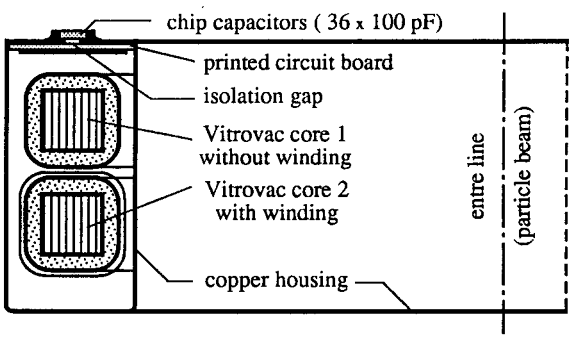

Fig 4. The integrating current transformer (cross-section)

A simple solution for this problem is the integrating current transformer (ICT) of the LEP bunch intensity monitor (Fig. 4). It contains two cores of Vitrovac 6025 (cross section 5 × 5 mm, I.D. 210 mm, magnetic ribbon of 25 µm thickness, RV-annealing). The two cores are completely surrounded by a toroidal copper housing. This housing is closed on one side with a ring shaped printed circuit board. The conductive pattern on this board form a coaxial capacitor of approximately 200 pF. Chip capacitors (36 × 100 pF) are soldered at regular intervals across a circular insulating gap and increase the total capacity to about 3800 pF. The toroidal enclosure with the coaxial capacitor form the single turn secondary winding of the current transformer. The beam passing through the centre of the toroid should be considered as the primary turn.

The charge induced by each short beam pulse I_B is temporarily stored in the coaxial capacitor C_1 (Fig. 5). This capacitor can only discharge through the single turn winding in the direction of the output load R_L. The rise and fall time of this discharge current is essentially controlled by the inductance L_1 and the core losses R_1, associated with core 1, and the equivalent load capacitance $n^2 C_L$. The load capacitance C_L (chip capacitors: 660 pF) is integrated directly into the winding of core 2.

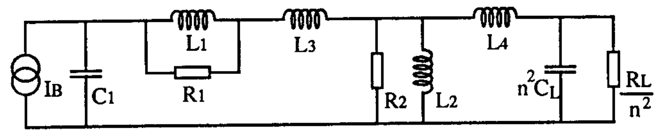

Fig. 5 Simplified equivalent circuit diagram of ICT

I_B	:	beam current (current source)
C_1	:	storage capacitor of secondary loop
C_L	:	storage capacitor of tertiary loop
L_1	:	inductance associated with core 1
L_2	:	inductance associated with core 2
L_3	:	leakage inductance in secondary loop
L_4	:	leakage inductance in tertiary loop
R_1	:	core losses of core 1
R_2	:	core losses of core 2
R_L	:	load resistor (coaxial cable, 50 ohms)
n	:	number of turns, winding of core 2 (10 ... 20)

The transfer function corresponds to a band pass filter, stretching the beam pulse signal by a factor of approximately 1000 (from 50 ps to 50 ns). This effectively lowers the frequency spectrum seen by the magnetic cores by a similar factor. The core losses under these conditions are small and the collected charge in the load resistor R_L is close to 100 % of the original charge of the beam pulse, divided by the turns ratio n. Cores with very small cross-sections can be used. The output signal is free from overshoot and ringing. It has always the same shape (the same frequency spectrum), independent of signal amplitude and bunch duration, providing that a certain design limit (1 ns) of bunch duration is not exceeded. The charge transfer ratio to R_L (calibration constant) is independent of bunch duration and beam position.

7. Fast analog signal processing

The bunch signal, after preconditioning in the ICT, is applied to 8 parallel analog signal processing channels. Each channel begins with a buffer amplifier, providing a low impedance source for 2 identical, fast analog gates (2 ns opening and closing time). These analog gates apply the same signal to either the positive or the negative input of a differential ac integrator. Each gate is only conductive during a short time interval t, for example 200 ns in LEP (60 ns for CESR). The gate to the negative input provides the sampling window t for one selected bunch in synchronism with the revolution frequency of LEP and the gate to the positive input samples the baseline immediately afterwards with a window t' of exactly identical duration. This symmetrical circuit arrangement restores the dc reference of the baseline, which has been lost by differentiation in the ICT. It provides not only the cancellation of the various known defects of fast analog gates, but is also a powerful method to reduce the influence of random input and amplifier noise.

The output signal of the integrator is proportional to the charge (number of particles) of the selected LEP bunch and averaged for a given number of revolutions.

8. First tests with beam

We had in autumn 1987 the opportunity, to install and test an early prototype of the LEP beam intensity monitor in CESR, thanks to an offer of collaboration from the Wilson Laboratory of Cornell University (Ithaca, N.Y., USA). The circumference of the e^+e^- collider ring CESR is about 35 times smaller than LEP, which scales up revolution frequency and beam currents in the same proportions. Minimum separation between bunches at the monitor location was 157 ns. This required modifications of the full scale range of the PTC, a shorter ICT time constant and an analog signal processor with a sampling time window of 60 ns.

8.1. Summery of test results:

PCT:

dynamic range:	+250 mA .... 0 .... -250mA	(single range)
tested with beam:	up to 130 mA	
resolution:	0.6 µA rms	(for 1 s integration time)

ICT+bunch signal prossesor
(for 60 ms integration time):

full scale (range A):	1.5×10^{11}	e
resolution (range A)	4.3×10^{5} rms	e
full scale (range B), estimated:	1.5×10^{12}	e
resolution (range B)	4.3×10^{6} rms	e
verified linear dynamic range (max. intensity during tests):	2.5×10^{11}	e

error for change of:

beam position (±10 mm):	$< 1 \times 10^{-4}$
bunch length (1.7 to 2.1 cm):	$< 3 \times 10^{-4}$

attenuation of bunch signals outsite sampling window: -66 dB

9. Acknowledgements

Many people in the LEP-BI group, have made valuable contributions to the beam monitor project. P. Buksh designed the computer controled instrumentation for the dynamic testing of the core samples and did much of the measurements in the early phase of the project. A. Maurer and G. Burtin were of greatest help, whenever a professional mechanical engineer was required.

J. Bergoz and P. Pruvost (BERGOZ, Crozet, France) build the electronic units of the PCT (circuit diagrams furnished by CERN), constructed the annealing plant and manufactured a very large number of sample cores and transformer assemblies for the different tests. This work was done during 2 years in the framework of the collaboration contract K 017/LEP, free of charge to CERN in exchange for the transfer of technology and resulting commercial rights.

The tests at CESR would not have been possible without the active collaboration of M. Billing, R. Littauer, D. Rice and R.H. Sieman of Cornell University.

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