Bergoz Instrumentation
Espace Allondon Ouest
01630 Saint Genis Pouilly, France
Tel.: +33-450.426.642
Fax: +33-450.426.643

bergoz
Instrumentation

Visit our web site at
http://www.bergoz.com

Parametric Current Transformer User's Manual

Rev. 3.2

Japan:

REPIC Corporation
28-3, Kita Otsuka 1-Chome
Toshima-ku, Tokyo 170-0004
Tel.: 03 - 3918 - 5326
Fax: 03 - 3918 - 5712
sales@repic.co.jp

U.S.A.:

GMW Associates
955 Industrial Road
San Carlos, CA 94070
Tel.: (650) 802-8292
Fax: (650) 802-8298
sales@gmw.com

WARNING ! DO NOT HEAT TOROID SENSOR BEYOND 80°C / 176°F

SUMMARY

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Annex I: The Parametric Current Transformer, a beam current monitor... for LEP, K.B.Unser

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

This instrument is operated from the mains power supply. For safe operation, it must be grounded by way of the grounding conductor in the power cord. Use only the fuse specified. Do not remove cover panels while the instrument is powered. Do not operate the instrument without the cover panels properly installed.

The Toroid sensor contains materials such as cobalt and iron. Those materials may become radioactive when exposed to high energy particle beams. Follow applicable radiation-protection procedures when the Toroid sensor must be moved out of controlled areas.

GENERAL DESCRIPTION

The parametric current transformer is designed to measure the DC intensity of a charged particle beam. It was invented in 1969 at CERN by Klaus B. Unser. It consists of two transformers cascaded in a common feedback loop: a Hereward-type active current transformer and a magnetic parametric amplifier using the second-harmonic detection technique, also called flux gate. It features exceptionally large dynamic range (up to 2×10^7), high resolution (down to less than 1 μA rms at dc), excellent linearity and long term stability.

The magnetic parametric amplifier uses a magnetic modulator of novel design. A digital excitation generator drives its modulator in an avalanche mode with high peak currents. This reduces the effect of Barkhausen noise and improves dc zero stability in a very important way. The demodulator uses a parametric amplifying mechanism with a very good signal to noise ratio. It virtually eliminates the contribution of noise from active amplifier circuits. The Toroid cores of the parametric transformer are made out of high permeability amorphous alloy thin ribbons. We developed a special manufacturing process to improve the magnetic characteristic stability of the parametric current transformer cores. In addition, these cores require a very careful packaging and a sophisticated annealing treatment, both thermal and magnetic, using a longitudinal field and a transverse field. A multilayer magnetic shield using amorphous alloys provides a good shielding factor from external magnetic fields. This is important if low values of current have to be monitored.

Annex I. The Parametric Current Transformer.... by Klaus B. Unser gives a detailed description of the instrument.

LEGAL RIGHTS

The Parametric Current Transformer was developed by Dipl. Ing. Klaus B. Unser of the LEP Division at CERN in the framework of the Collaboration Agreement N° K017/LEP between CERN and BERGOZ. This agreement grants Bergoz Instrumentation the right to commercialize the resulting technology.

ACKNOWLEDGEMENTS

This instrument was designed by Dipl. Ing. Klaus B. Unser of CERN's LEP instrumentation group.

YOU JUST RECEIVED YOUR PCT....

Check the line voltage marked at the rear of the output chassis. Make sure it conforms to your mains voltage. If it does not conform, do not connect the PCT to the mains power supply and ask for advice from Bergoz Instrumentation or its distributor.

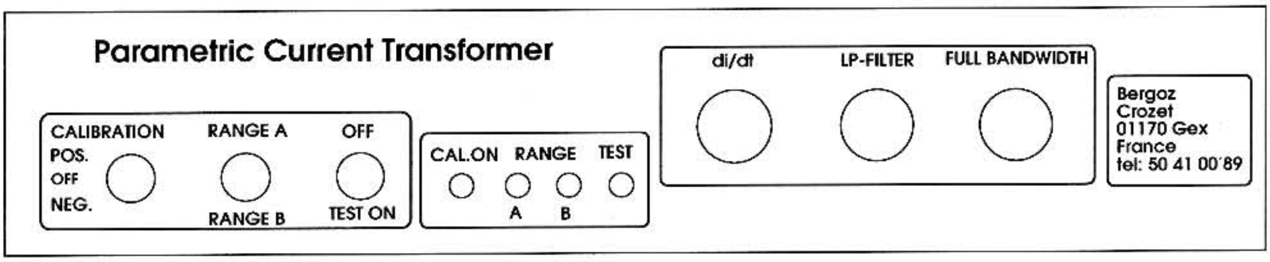
QUICK CHECK

The following steps are intended to make you familiar with the PCT operation and behavior before you install it in its final place. You only need your PCT and a voltmeter or oscilloscope (any oscilloscope). Additionally, you may want to put a signal into the PCT. Then you need a function generator or DC power supply and an burden resistor ≥ 100Ω.

The PCT consists of:

- Toroid sensor
- Front-end electronics box
- Output chassis
- Two multicore cables connect the Toroid sensor to the Front-end electronics box
- Another multicore cable connects the front-end electronics box to the output chassis
- An optional long cable set comprising two cable extensions and a front-end filter.

Output chassis front panel



CALIBRATION switch positions:
OFF: normal operating position
POS.: sends a positive calibration current equal to 80% of full scale range A
NEG.: sends a negative calibration current equal to 80% of full scale range A

RANGE switch positions:
Range A
Range B

TEST switch positions:
OFF: normal operating position
TEST ON: performs an overall loop gain test. *Replaced by "CAL.B ON" on some units*

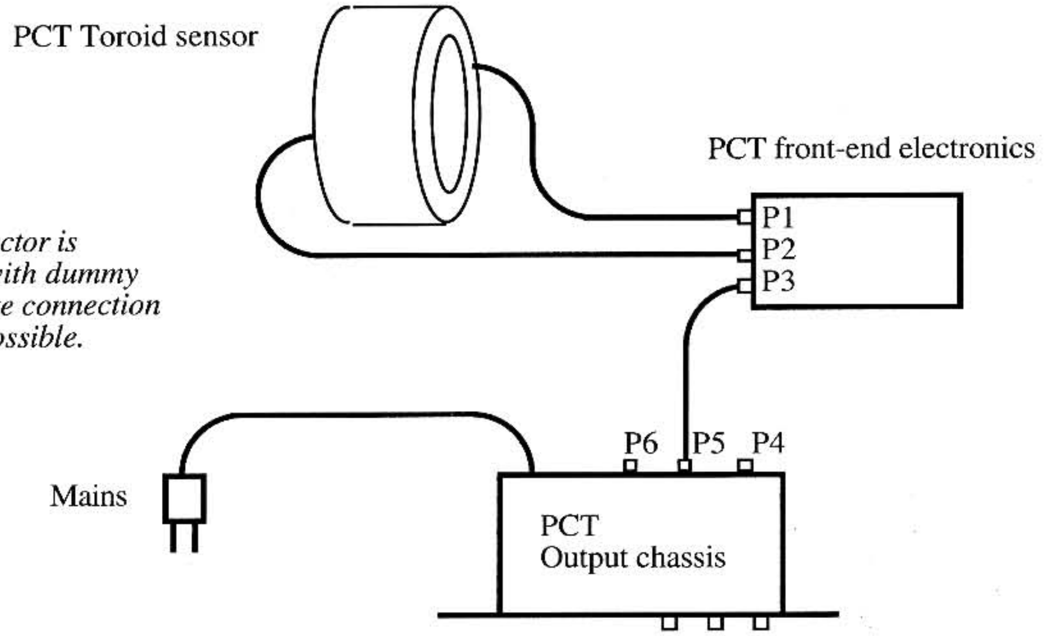
Note: Remote control TTL signals applied to the rear connector P6 override the front panel switches.

"CAL.ON" LED: when lit, means calibration positive or negative is applied
"RANGE A" LED": when lit, means the instrument is in range A
"RANGE B" LED: when lit, means the instrument is in range B.
"TEST" LED: when lit, means self test is going on. *Replaced by "CAL.B" on some units.*

QUICK CHECK (Cont'd)

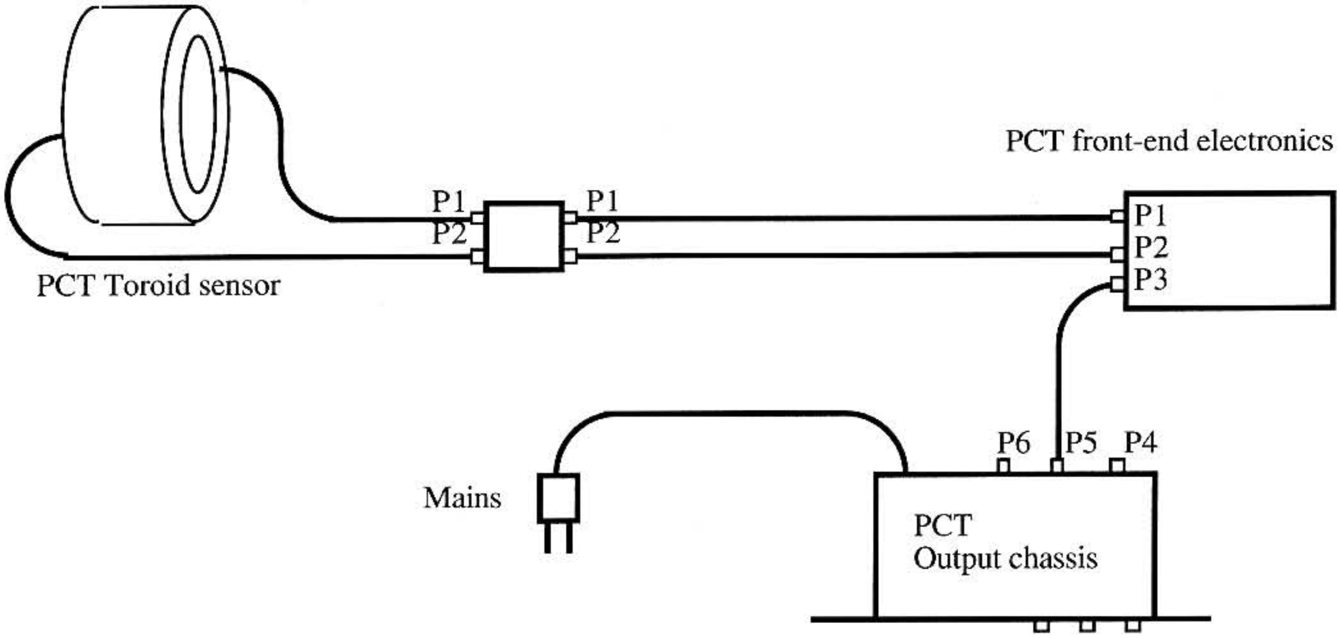
Setup

Before connecting to the mains, connect the system's components together:



Each connector is equipped with dummy pins to make connection errors impossible.

PCT with Opt.-LIC Long sensor to front-end cable set (includes a front-end filter box and two multicore cables)



QUICK CHECK (Cont'd)

Connect an oscilloscope or voltmeter to the output chassis front panel BNC labelled 'LP-Filter'. Set the voltmeter or oscilloscope on ±10 Volts full scale. Set the output chassis front panel switches as follows:

• Calibration:	'OFF'
• Range:	'A'
• Test:	'OFF'

Note: The PCT system is not equipped with a mains power switch because it is intended to remain powered permanently: the system consumes less than 10VA.

Connect the output chassis to the mains. This starts a low frequency high current demagnetizing sequence which may last up to 60 seconds depending on sensor size. It is important for the performance of the instrument that this sequence is not interrupted. If the power is interrupted during this sequence, the demagnetisation process is incomplete and must be repeated. To repeat the demagnetization sequence, remove the power plug from the chassis socket, wait at least 15 minutes and reapply the mains power again.

After the demagnetizing sequence is completed, the PCT output voltage is likely not to be zero. It corresponds to the magnetic field received by the Toroid sensor, ie. earth magnetic field and other fields. Rotate and displace the sensor: The output voltage changes, reflecting the change of the magnetic fields the sensor is exposed to.

Functional tests

Observe that the LED 'Range A' is lit. Make a note of the output voltage.

Set the calibration switch to 'Calibration Pos.'
Observe the LEDs 'CAL.ON' and 'Range A' are lit.
Observe that the output voltage increases by + 8 Volts.

Return the switch to 'Calibration OFF'. Observe the LED 'CAL.ON' goes off.

Set the Calibration switch to 'Calibration Neg.':
Observe that the LEDs 'CAL.ON' and 'Range A' are lit.
Observe that the output voltage changes by - 8 Volts.

Note: If the output voltage exceeds either +10.5 or -10.5 Volts, the output circuit may be in saturation, This does not harm the PCT.

Return to Calibration OFF. Make sure the range is still set to 'Range A'.

Set the Test switch to 'Test ON':
Observe that two LEDs: 'Test' and 'Range B' are lit.
Observe that the 'zero' reading does not change more than ± 0.5 Volt.

Note: Some PCT units are modified at the user's request: "Test ON" is replaced by "Calibration B". To use the range B calibration feature, set the Range switch to "B" and set the "Calibration B" switch ON: The output reading changes by 8 Volts. The calibration polarity can be inverted by setting a jumper on the front-end electronics board.

QUICK CHECK (Cont'd)

Zero adjustment

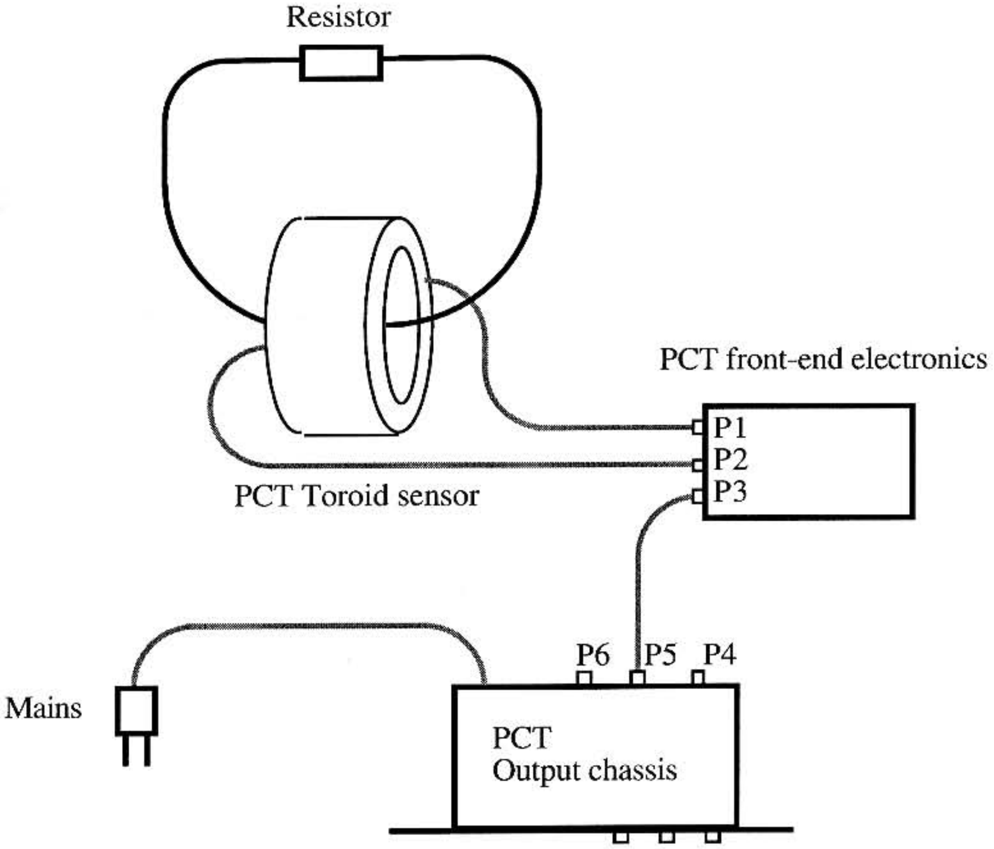
The zero output can be adjusted for a given position of the Toroid sensor in respect to its magnetic environment:

- Set the range switch on 'Range A'
- Set the Calibration switch on 'Calibration OFF'
- Set the Test switch 'OFF'
- Remove the M3 screw located on the side of the front-end electronics box
- Insert a screwdriver in the screw hole and rotate the 20-turn potentiometer to adjust the output voltage to zero.

Note: The zero adjustment displaces the working point of the PCT. A temporary output voltage drift may occur. Allow the instrument to stabilize up to a few hours depending on the amplitude of the adjustment.

Observe the effect of a resistive load on the Toroid sensor

Load the Toroid sensor with a resistive loop, and observe the PCT output signal with the oscilloscope. For resistor values below 100Ω, the 7-kHz output ripple increases.

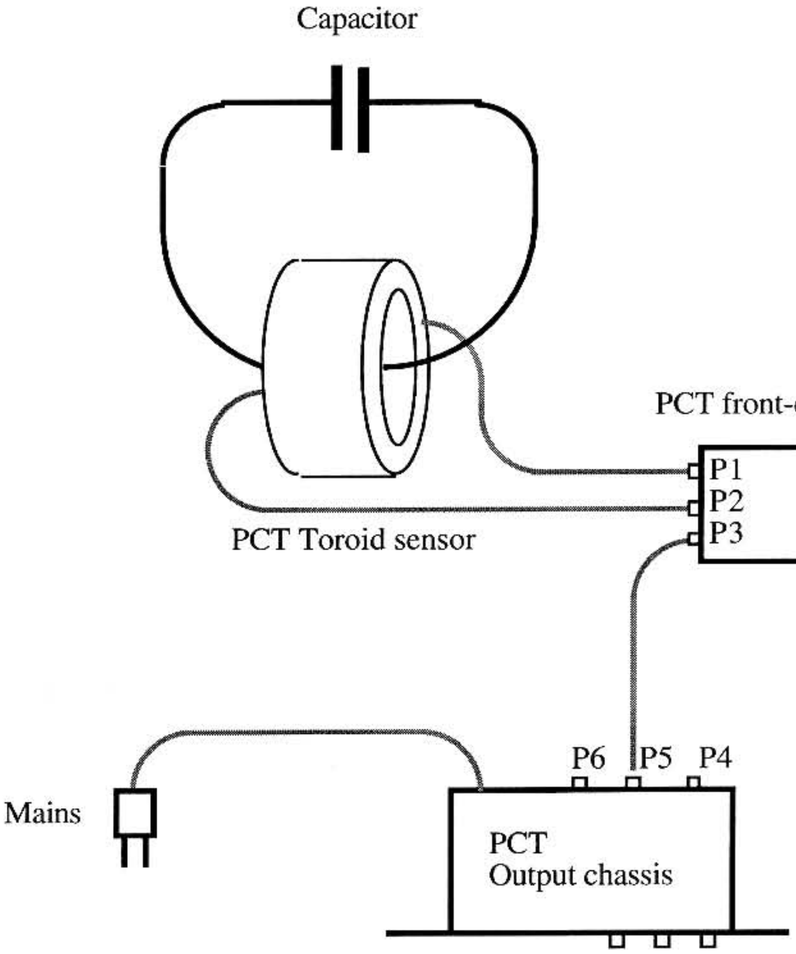


When the resistor value becomes too low, the PCT stops working: The PCT modulator is shorted. This does not damage the PCT.

QUICK CHECK (Cont'd)

Observe the effect of a capacitive load on the Toroid sensor

Load the Toroid sensor with a capacitive loop, and observe the PCT output ripple on the oscilloscope. For values of capacitors above 200 nF, the 7-kHz ripple increases.

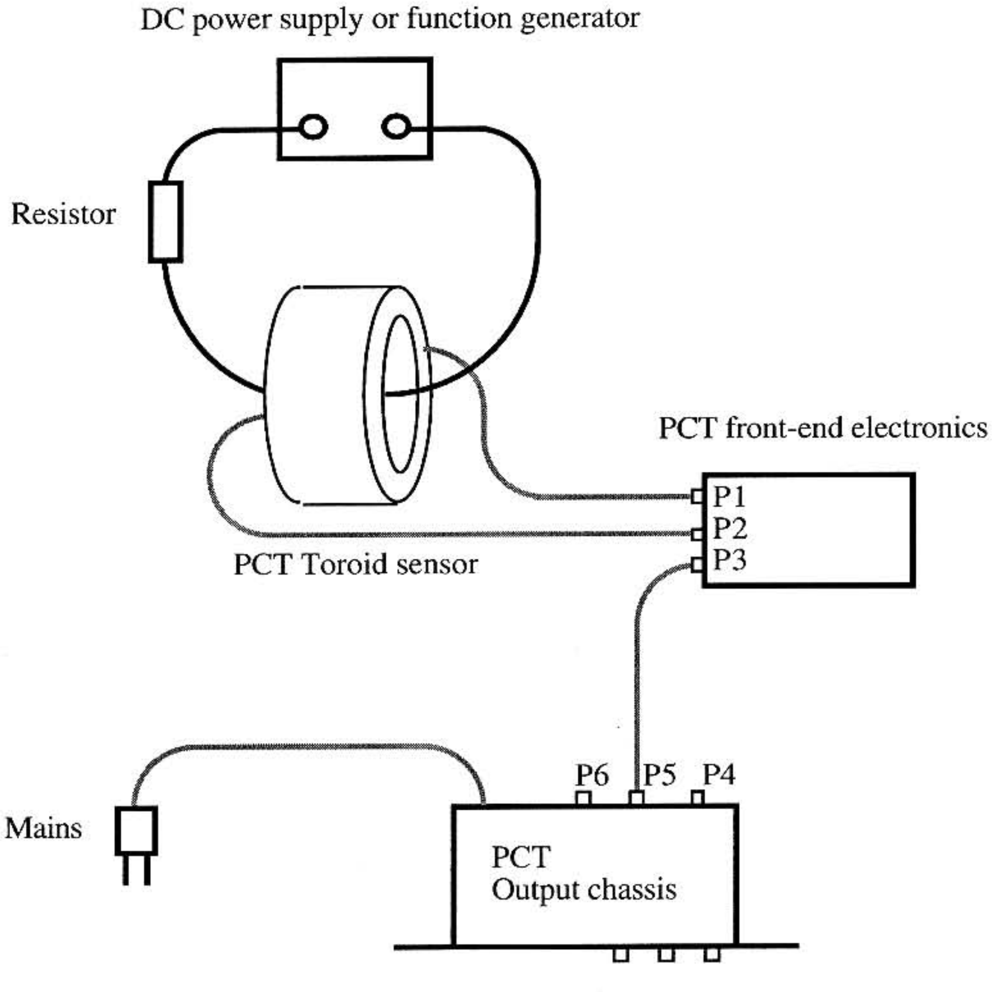


At higher capacitor values, the PCT stops working: The PCT modulator is shorted. This does not damage the PCT.

QUICK CHECK (Cont'd)

Simulate a beam current

Pass a current through the sensor and observe the output voltage:



Note: Do not use load resistor lower than 100Ω: It loads the PCT modulator too much, and the PCT 7-kHZ output ripple increases; but it does not damage the PCT.

When this sequence of functional tests is working as described, the PCT basic functions are OK.

SPECIFICATIONS

Standard features

Full-scale range, first range	Any value from 10mA to 10A (down to 1mA on second range)
Second range, full scale	= 1/10 of first range
Resolution in 1s integration	< 5µA rms (down to 0.5µA on Opt. -VHR)
Linearity error	< ±0.01 % ± zero error
Zero drift (1 hour)	< 1µA, 1 hour after power up
Zero drift (1 year)	< 5µA , at constant temperature
Bandwidth	DC to 20kHz, (up to 100 kHz on Opt.-XBW)
Output, direct	–10V to +10V, true bipolar
Direct output slew rate	> 0.1 V/µs (> 1 V/µs on Opt.-XBW)
Lowpass output	–10V to +10V, 4.2 kHz (-3 dB)
Output di/dt	–5V to +5V
di/dt output sensitivity	–10 V/Vs^{-1}
Built-in calibration source	± 80 % of full-scale range A
Absolute accuracy	> ±0.1 %
Beam position dependence	< 0.1 µA over 50% of inner Ø
Sensor sensitivity to external magnetic fields	1µA/Gauss (axial) typ., 100µA/Gauss (radial) typ.
Sensor saturation flux density of sensor	100 Gauss (axial) typ., 20 Gauss (axial) typ.
Temperature coefficient	Electronics: < 0.1µA / K, Sensor head: 5µA / K typ.
Power requirements	100, 115 or 230 Vac, 50/60 Hz, 15 VA
Mains fuse	230V units: 1.6 A slow-blowing fuses 5x20mm 100/115V units: 2.5 A slow-blowing fuses 5x20mm

Extended bandwidth option (Opt. -XBW)

The upper cutoff in range A is increased up to 100 kHz (-3 dB). Range B upper cutoff is marginally increased too.

High resolution option (Opt. -HR)

Through a severe selection of magnetic modulator core pairs, higher resolution is offered with this option: Noise in 1 s integration windows is < 1 µA.

Very high resolution option (Opt. -VHR)

Through this option, we offer the very best PCT we can possibly build, in terms of noise and stability. Noise in 1 s integration windows is < 0.5 µA.

Long Front-end electronics to Output chassis cable option (Opt. LIC-XXXm)

Offers a long interconnect cable, up to 300 meters, from the Front-end electronics to Output chassis.

Toroid Sensor to Front-end electronics Extension cable set option (Opt. LSC-XXXm)

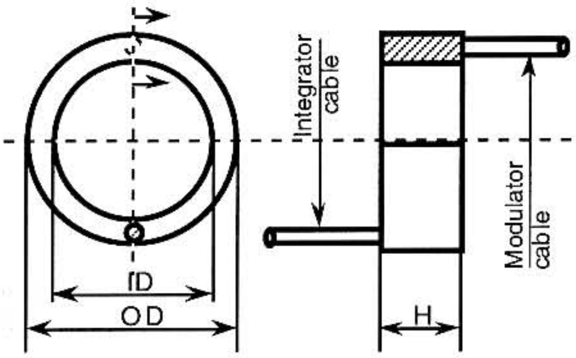
Cable extensions and a Front-end filter are included in this option. Cables can be up to 75 meters. This option increases the residual modulator ripple (6927 Hz) significantly. Recommended only when the Front-end electronics must be removed form the accelerator tunnel. Special rad-hard cables are not available with this option. This option requires the Front-End Filter **PCT-FEF.**

Rad-hard sensor (Opt. -H)

With this option, a special Toroid sensor with improved radiation resistance is offered. See Radiation Resistance chapter hereafter for details of materials used.

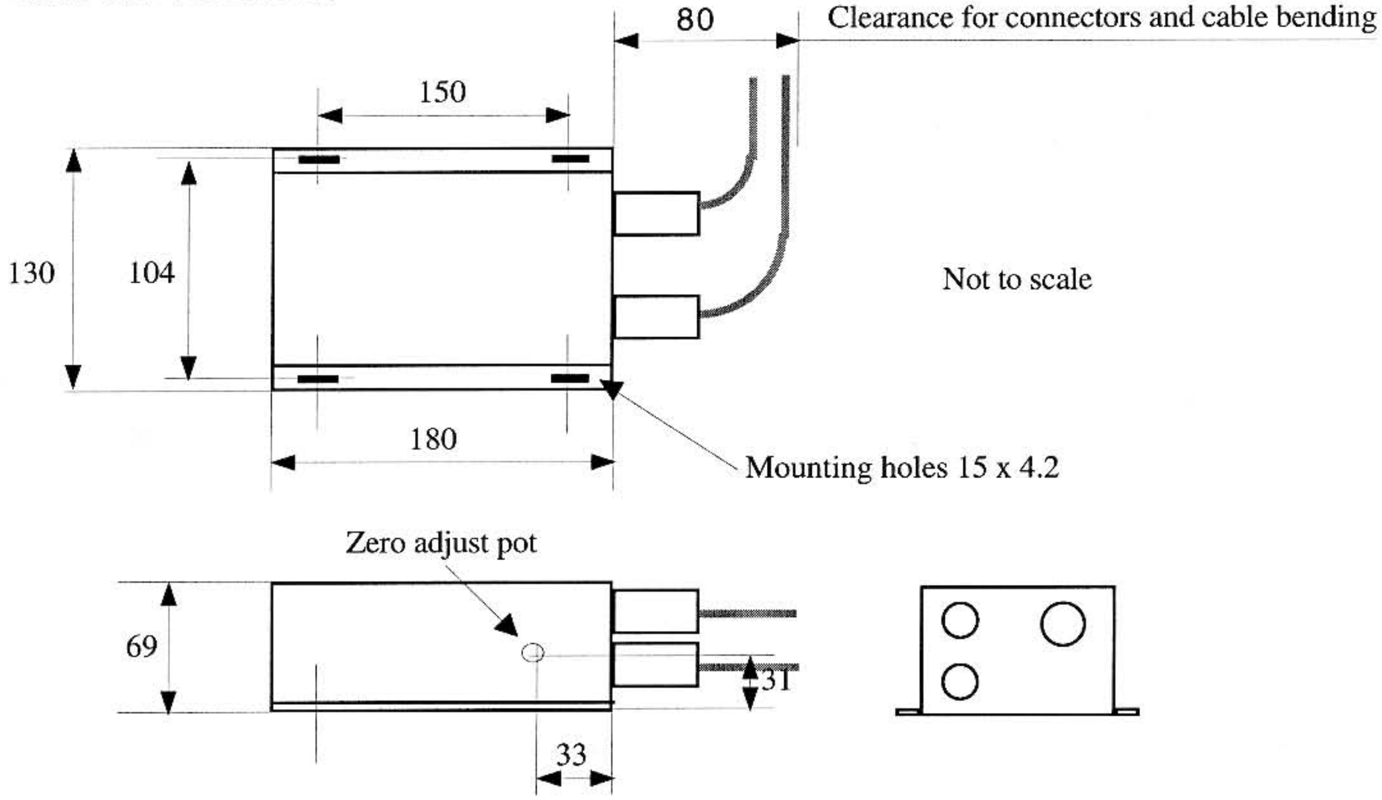
DIMENSIONS

Toroid sensor



Sensor model	ID (min.) [mm]	OD (Max.) [mm]	H (max.) [mm]	Mass [kg]
PCT-052	52	102	107	0.9
PCT-073	73	123	107	1.2
PCT-113	113	163	107	1.7
PCT-175	175	225	107	2.4
PCT-190	190	240	107	2.6
PCT-245	245	295	107	3.3
Cable sheath outer diameter				< 7 mm
Cable bending radius				20 mm min.

Front-end Electronics



Output chassis

Each PCT Output Chassis consists of one half-width 19" chassis.
All PCTs are systematically delivered with two Output chassis, one being a spare. The two chassis are loosely attached together. One or the other can easily be removed to return it to Bergoz Instrumentation for calibration or repair.

When attached together, the two output chassis can be rack-mounted in a standard 19" bay.
Their height is 1U. The chassis depth is 230 mm, but a minimum of 310 mm depth must be available for rear connectors and cables.

SWITCH SETTINGS AND EXTERNAL COMMANDS

The instrument can be controlled either from the front panel switches or by TTL levels fed to the instrument's logic via the Output chassis rear connector P3.

In all cases, an external command overrides a switch setting.

The front panel LEDs always display the actual mode of operation of the front-end electronics.
The LEDs remain off when the front-end electronics box is not connected to the output chassis.

The valid commands are:

- Range A (P6 pin H low), or
- Range B (P6 pin H high).

When Range A set:

- "Calibration Pos." can be set (P6 pin C high and pin E low), or
- "Calibration Neg." can be set (P6 pin C high and pin E high).

When Range B set:

- "Test ON" can be set (P6 pin L high).

Note: Some PCT units are modified: "Test ON" is replaced by "Calibration B".

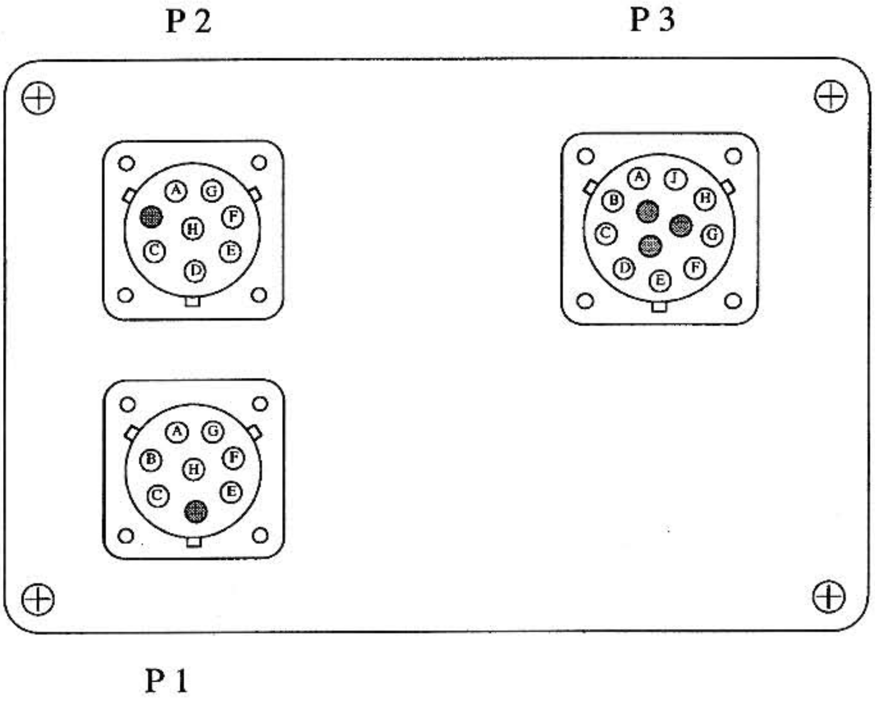
Some command combinations are incompatible and would disturb the instrument
(ie. sending a full scale calibration current when the instrument is set on range B, etc.).
To protect the PCT against damaging commands, the following combinations are forced, respectively inhibited:

When 'Test ON':	Range B is forced to allow maximum sensitivity. Calibration is inhibited.
When "Calibration B" (modified units only)	Range B is forced, calibration B is set Calibration Pos. and Calibration Neg. are inhibited
When 'Calibration Neg.' or "Calibration Pos."	Range A is forced.

This protection logic makes it impossible to issue a command combination which would damage the PCT.

CONNECTORS AND CABLES

Connectors P1, P2 and P3 are located on the front-end electronics box cover



P1 Connector - MODULATOR CABLE

Sensor side Function	Cable Belden 8777 3 shielded twisted pairs		Cable connector Burndy Metalok Bantam 8-pin male UTG 612-8PN			Electronics box side Burndy Metalok Bantam 8-pin female UTG 012-8S		
	Pair	Wire	Std pin #		CERN pin #	Std pin #		CERN pin #
Static screen	cable shield		A	or	8	A	or	8
Outer screen	blue	black	B	or	2	B	or	2
Free			C	or	3	C	or	3
N/C	dummy		D	or	4	D	or	4
Sense •	red	red	E	or	5	E	or	5
Sense	red	black	F	or	6	F	or	6
Excitation 1	green	white	G	or	7	G	or	7
Excitation 2	green	black	H	or	1	H	or	1

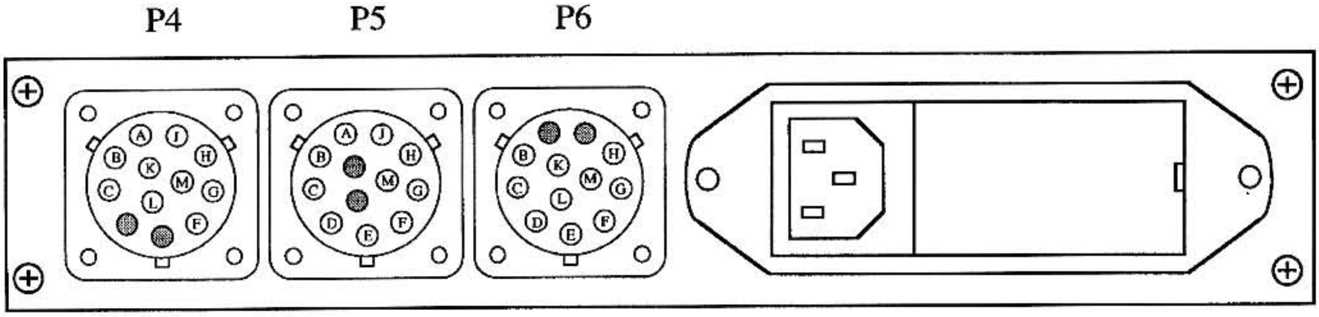
P2 Connector - INTEGRATOR CABLE

Sensor side Function	Cable Belden 8777 3 shielded twisted pairs		Cable connector Burndy Metalok Bantam 8-pin male UTG 612-8PN			Electronics box side Burndy Metalok Bantam 8-pin female UTG 012-8S		
	Pair	Wire	Std pin #		CERN pin #	Std pin #		CERN pin #
Static screen	cable shield		A	or	8	A	or	8
N/C	dummy		B	or	2	B	or	2
Sense	green	white	C	or	3	C	or	3
Sense •	green	black	D	or	4	D	or	4
Feedback •	red	black	E	or	5	E	or	5
Feedback	red	red	F	or	6	F	or	6
Calibration	blue	black	G	or	7	G	or	7
Calibration •	blue	green	H	or	1	H	or	1

P3 & P5 Connectors - PCT INTERCONNECT CABLE

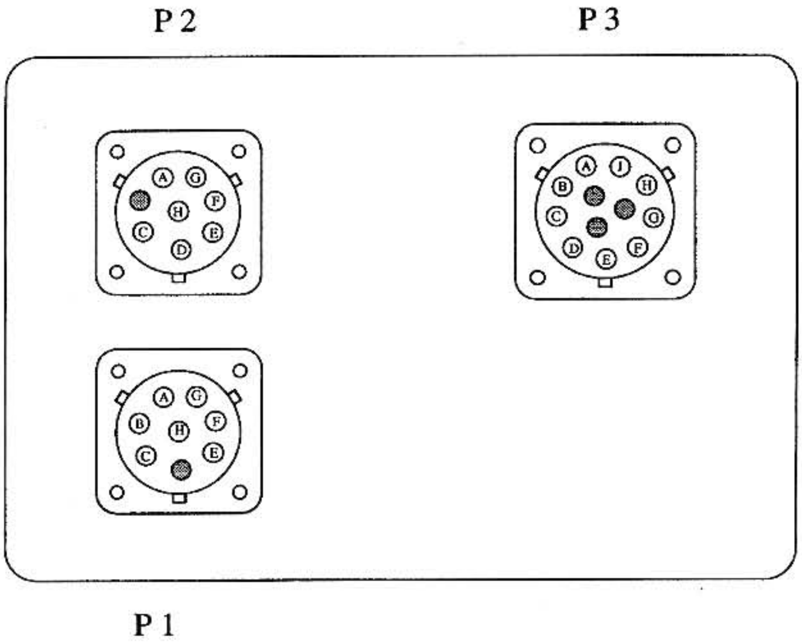
Front-end electronics box side Chassis connector : Burndy Metalok Bantam 12-pin female UTG 014-12 S		Cable Belden 8777 3 shielded twisted pairs		Cable connector (male) Burndy Metalok Bantam 12-pin male UTG 614-PN				Back-end chassis side
Function		Pair	Wire	Std pin #		CERN pin #		Function
Ground		cable screen		G	or	12		Ground
Ground	N/C			H	or	4	N/C	Ground
Vib output +		red	black	J	or	5		Vib output +
Vib output -		red	red	A	or	6		Vib output -
+ 15 V		green	white	B	or	7		+ 15 V
Mux'd control		green	black	C	or	8		Mux'd control
- 15 V		blue	green	D	or	9		- 15 V
Mux'd status		blue	black	E	or	10		Mux'd status
Free	N/C			F	or	11	N/C	Free
	dummy			K	or	1	dummy	
	dummy			L	or	2	dummy	
Free	N/C			M	or	3	N/C	Free

Connectors P4, P5 and P6 are located at the back of the back-end chassis :



CONNECTORS AND CABLES

Connectors P1, P2 and P3 are located on the front-end electronics box cover



P1 Connector - **MODULATOR CABLE**

RAD-HARD VERSION ONLY (with PEEK cables)

Sensor side Function	Cable PEEK 3 shielded twisted pairs		Cable connector Burndy Metalok Bantam 8-pin male UTG 612-8PN			Electronics box side Burndy Metalok Bantam 8-pin female UTG 012-8S		
	Pair	Wire	Std pin #		CERN pin #	Std pin #		CERN pin #
Static screen	cable shield		A	or	8	A	or	8
Outer screen	white	white	B	or	2	B	or	2
Free			C	or	3	C	or	3
N/C	dummy		D	or	4	D	or	4
Sense •	white	white	E	or	5	E	or	5
Sense	white	white	F	or	6	F	or	6
Excitation 1	white	white	G	or	7	G	or	7
Excitation 2	white	white	H	or	1	H	or	1

RAD-HARD VERSION ONLY (with PEEK cables)

P2 Connector - INTEGRATOR CABLE RAD-HARD VERSION ONLY (with PEEK cables)

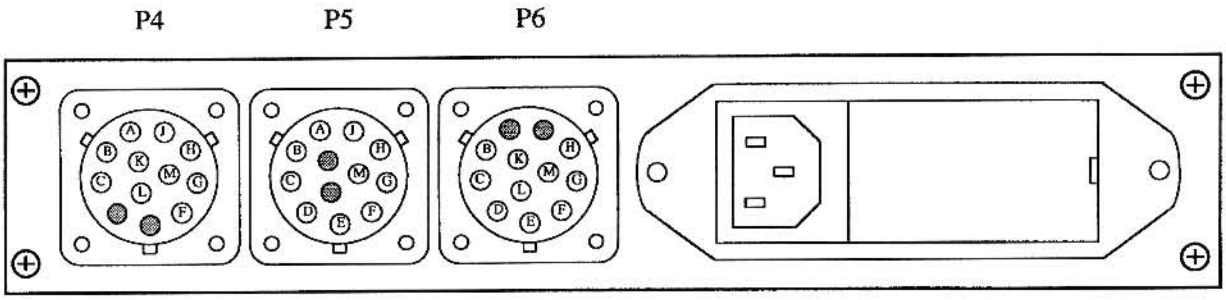
Sensor side Function	Cable PEEK 3 shielded twisted pairs: Pair	Wire	Cable connector Burndy Metalok Bantam 8-pin male UTG 612-8PN: Std pin #		CERN pin #	Electronics box side Burndy Metalok Bantam 8-pin female UTG 012-8S: Std pin #		CERN pin #
Static screen	cable shield		A	or	8	A	or	8
N/C	dummy		B	or	2	B	or	2
Sense	white	white	C	or	3	C	or	3
Sense •	white	white	D	or	4	D	or	4
Feedback •	white	white	E	or	5	E	or	5
Feedback	white	white	F	or	6	F	or	6
Calibration •	white	white	G	or	7	G	or	7
Calibration	white	white	H	or	1	H	or	1

RAD-HARD VERSION ONLY (with PEEK cables)

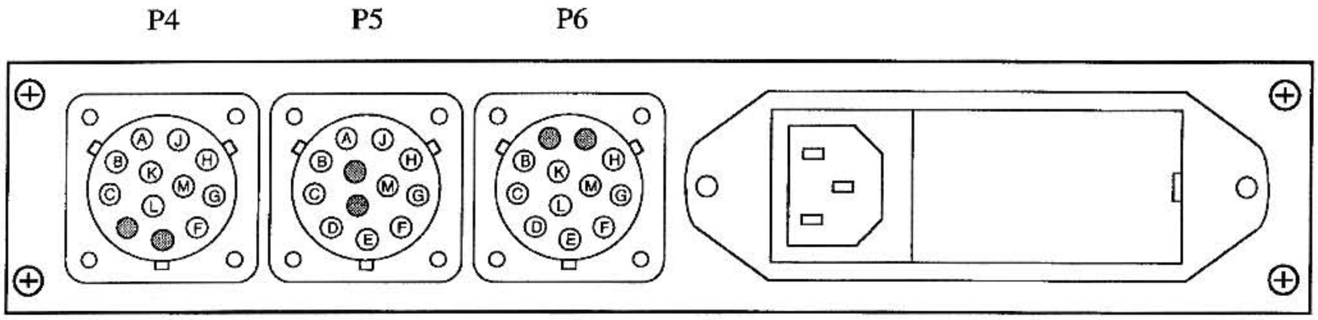
P3 & P5 Connectors - PCT INTERCONNECT CABLE

Front-end electronics box side Chassis connector : Burndy Metalok Bantam 12-pin female UTG 014-12 S: Function		Cable PEEK 3 shielded twisted pairs: Pair	Wire	Cable connector (male) Burndy Metalok Bantam 12-pin male UTG 614-PN: Std pin #		CERN pin #		Back-end chassis side: Function
Ground		cable screen		G	or	12		Ground
Ground	N/C			H	or	4	N/C	Ground
Vib output +		red	black	J	or	5		Vib output +
Vib output -		red	red	A	or	6		Vib output -
+ 15 V		green	white	B	or	7		+ 15 V
Mux'd control		green	black	C	or	8		Mux'd control
- 15 V		blue	green	D	or	9		- 15 V
Mux'd status		blue	black	E	or	10		Mux'd status
Free	N/C			F	or	11	N/C	Free
	dummy			K	or	1	dummy	
	dummy			L	or	2	dummy	
Free	N/C			M	or	3	N/C	Free

Connectors P4, P5 and P6 are located at the back of the back-end chassis :



Connectors P4, P5 and P6 are located on the front-end electronics box cover



P4 Connector - ANALOG OUTPUT CONNECTOR

Function

Cable connector
Burndy Metalok Bantam
12-pin female UTG 014-12 S

Mating connector is :
Burndy Metalok Bantam
12-pin male UTG 614-12 PN

Function	Std pin #		CERN pin #	
Vib + differential output	K	or	1	
Vib - differential output	L	or	2	
di/dt signal	M	or	3	
di/dt signal ground	H	or	4	
LP-filtered signal	J	or	5	
LP-filtered signal ground	A	or	6	
Full bandwidth signal	B	or	7	
Full bandwidth signal ground	C	or	8	
N/C	D	or	9	insert dummy to prevent cable mix-up
N/C	E	or	10	insert dummy to prevent cable mix-up
Ground	F	or	11	
Cable screen	G	or	12	

IMPORTANT : Use only shielded twisted pairs

P6 Connector - EXTERNAL CONTROL AND MONITORING CONNECTOR

Function

Burndy Metalok Bantam
12-pin female UTG 014-12 S

Mating connector is :
Burndy Metalok Bantam
12-pin male UTG 614-12 PN

Function		Std pin #		CERN pin #	
Status :	Calibration	K	or	1	When signal out is TTL high : Calibration is ON
Control :	Test	L	or	2	When signal in is TTL high : PCT sets to Test
Status :	Test	M	or	3	When signal out is TTL high : Test is ON
Control :	Range B	H	or	4	When signal in is TTL high : PCT sets to Range B
		J	or	5	Insert dummy pin to prevent cables mix-up
		A	or	6	Insert dummy pin to prevent cables mix-up
Status :	Range B ok	B	or	7	When signal out is TTL high : Range B active
Control :	Calibration	C	or	8	When signal in is TTL high : PCT sets to Calibration
Status :	Range A ok	D	or	9	When signal out is TTL high : Range A active
Control :	Calibr. polarity	E	or	10	When signal in is TTL high : PCT sets to Calibr. negative
Ground		F	or	11	
Ground		G	or	12	Cable screen

Note: Some PCT units are modified: "Test" is replaced by "Calibration B"

MAKING PRECISE MEASUREMENTS WITH THE PCT

The Challenge

The PCT features excellent resolution (down to < 1µA in 1s integration time), outstanding linearity (< 0.01% error) over a large dynamic range (up to 2 x 10^7).

To get the full benefit of these excellent performance, the user must pay special attention to the sensor temperature and its magnetic environment, because:

- The Toroid sensor has a temperature drift of (typically) 5 µA / K
- The Toroid sensor has a sensitivity to external magnetic fields of (typically) 100 µA / Gauss.

Note: The PCT electronics are fully compensated for temperature drift.

In spite of the many challenges posed by its installation, many PCT users obtain in their accelerator, performances very close to the maximum attainable in a noiseless, temperature-stable environment.

To make precise measurements, much attention must be paid to:

- Proper installation of the Toroid sensor over the vacuum chamber.
  A whole chapter is hereafter dedicated to this alone
- Appropriate grounding scheme
- Good RF rejection
- Careful output readout

RF Rejection

The PCT system is well protected against RF interference at every stage of the circuit. However, high-energy accelerators can have RFI power so high that it cannot be handled by the PCT protections alone. When the PCT protections are overwhelmed by RF, the PCT output usually goes to saturation level:
+ or −11.5 V.

To further protect the PCT against RFI, ferrite cores can be installed on the cables between the Toroid sensor and Front-end electronics: Two ferrite cores are needed, one for each cable. It can be installed at any convenient distance from the sensor. Ferrite cores of large diameter are needed, to allow the body of the Burndy connector to be passed through the core hole. Ideally, the cable will make up to 7 turns around the ferrite core. This requires a core with ID ≥ 37 mm. To be effective, the core magnetic material must present high insertion loss over the frequency spectrum of the RF interference.

When RF interference couples into the PCT system via the Front-end electronics to Output chassis cable, another ferrite core can be placed on this cable, at any point along its length.

Occasionally, EMI, electromagnetic interference has been observed. It could be partially eliminated by wrapping the Toroid sensor to Front-end electronics cable with aluminium foil.

MAKING PRECISE MEASUREMENTS WITH THE PCT (Cont'd)

Grounding scheme

The PCT system has only one ground reference point. That is the Output chassis itself.
All other internal grounds of the PCT are locally floating and referred to the Output chassis ground.

The Output chassis itself is connected to the mains ground by way of the power cord ground lead.
The power cord ground lead MUST be connected to ground for safety reasons.

Note: Around accelerators, significant voltage noise can be observed between the various ground points: the metal frame of the bay, the power cord ground lead, the coaxial cable shields, etc. Several 100's of mV wideband noise can be observed between these "grounds". The amplitude and frequency of this noise will determine the precautions to be taken.

The body of the Output chassis front-panel BNCs are connected to the Output chassis ground.
The ground pins of the Output chassis rear Burndy connectors are connected to the Output chassis ground.

The Front-end electronics metal enclosure and the metal body of the Burndy connectors are not connected to the PCT system ground. They can be connected to the local ground, or left floating.

The metal shielding box of the optional Front-end Filter (p/n PCT-FEF) IS connected to the PCT system ground. It is IMPERATIVE to let it float: It must NOT be grounded.

The Toroid sensor magnetic shield is conductive. It is connected to the PCT system ground via a 4-5 cm long yellow/green (beige on rad-hard versions) wire on the side of the Toroid sensor.

If the Toroid sensor magnetic shield gets electrically connected to the vacuum chamber, at ground loop is formed, which will cause noise in the PCT output. To prevent this ground loop from occurring, there are two possibilities:
a) Isolate the Toroid sensor magnetic shield from the vacuum chamber. This is the preferred solution.
b) Cut the yellow/green wire (beige on rad-hard versions). It disconnects the Toroid sensor magnetic shield from the PCT system ground.

The user's readout devices: ADC, voltmeter, oscilloscope, must be connected to the same ground as the Output chassis. When this is not possible, common-mode rejection filters must be installed on the cables carrying the PCT output signal.

Note: Simple common-mode filters can be made by passing the signal cable (twisted pair or coaxial) through a ferrite core. Passing the signal cable several times through the ferrite core increases the magnetic coupling -hence the common-mode noise rejection- by the square of the number of turns... until the capacitive coupling defeats the rejection. In practice, about 7 turns are optimum.
The magnetic characteristics of the ferrite cores must correspond to the frequency spectrum of the noise to be rejected.

MAKING PRECISE MEASUREMENTS WITH THE PCT (Cont'd)

Output readout

The user's supplied instrument measuring the PCT output is called here the "Readout device".

Depending on the user's needs, the Readout device may be a simple oscilloscope, quite useful in the case of a cycling machine: PS, booster, etc.

More often, the Readout device will be a high-resolution ADC or voltmeter matching or exceeding the dynamic range of the PCT.

Example: A PCT with high-resolution option has less than 1 µA noise in 1 s integration time.
If its full scale range is 100 mA, The output signal dynamic range exceeds 10^5, plus sign. The Readout device must cover/exceed this dynamic range: 17 bits + sign bit.

The PCT output voltage range exceeds -10V to +10V. The Readout device input must preferably be bipolar. Even though the beam current is unipolar in most machines, the PCT output can be of opposite sign because of the zero offset.

50/60 Hz noise being always present, PCT output measurement should eliminate it by averaging the readouts over multiples of the mains period.

So-called "system" voltmeters have been used very successfully. They offer adequate triggering/ averaging functions. Their output can be read through GPIB / IEEE-488. Many manufacturers offer system voltmeter, for instance: Hewlett-Packard, Keithley, Enertec-Solartron, Prema Instruments, etc.

Suitable VXI voltmeters are also available, notably from Hewlett-Packard. Models HP-E1312A/1412A in B-format (6U x 160 mm) are VME compatible (A32. D32).

Note: The PCT output presents an offset of its "zero" value. That is, even in the absence of beam current, the PCT output will never be zero exactly. This offset can be positive or negative. It will change with temperature and external magnetic fields.

The PCT zero offset can be nulled (for a given temperature and magnetic environment) with the 20-turn "Zero Adjust" potentiometer located on the side of the Front-end electronics box.

The readout software must assume the PCT output voltage to be bipolar. The software could measure the zero offset when there is no beam and deduct it from actual beam intensity readings.
When beam intensity measurement accuracy is impaired by insufficient magnetic shielding of the Toroid sensor, the software could read the offset caused to the PCT by nearby magnets and bars, in the absence of beam. The magnets and bars currents could be read and stored, and the corresponding PCT offset could be deducted from further readings with same current in magnets and bars.

MAKING PRECISE MEASUREMENTS WITH THE PCT (Cont'd)

Readout device installation and connection

The readout device must preferably be grounded at the same point as the PCT Output chassis.
A readout device with differential input –i.e. with floating inputs– is advisable when the grounds of PCT and Readout device are not the same, or in very noisy environments.

The Readout device input must be of high impedance.

Note: All PCT signal outputs –whether on the front-panel BNCs or at the rear Burndy connectors– have a series 100Ω protection resistance. Take it into consideration if you use a Readout device with low input impedance.

Common-mode rejection filters must be installed on the signal cable from Output chassis to Readout device, at any place along its length.

Note: Simple common-mode filters can be made by passing the signal cable (twisted pair or coaxial) through a ferrite core. Passing the signal cable several times through the ferrite core increases the magnetic coupling -hence the common-mode noise rejection- by the square of the number of turns... until the capacitive coupling defeats the rejection. In practice, about 7 turns are optimum.
The magnetic characteristics of the ferrite cores must correspond to the frequency spectrum of the noise to be rejected.

To reject differential mode noise, install a 100nF ceramic capacitor between signal wire and ground AT THE INPUT of the Readout device.

Tip: Observe -easily- the noise going into your Readout device.

1. *Disconnect the Output chassis to Readout device cable from the Output chassis.*
2. *On this disconnected connector, connect the signal pin to the ground pin (or body).*
   The noise seen by the Readout device is now only the noise picked up by the cable.
3. *While the signal pin is still connected to ground pin, connect this ground pin to the Output chassis ground. Now, the Readout device sees all sources of noise which do not come from the PCT.*

INSTALLATION ON THE VACUUM CHAMBER

The installation of a Current Transformer 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 Toroid sensor, otherwise any current circulating in the vacuum chamber will be "seen" by the PCT. This includes –of course– the wall current induced by the beam, but also all other parasitic currents.

b) The wall current must be diverted around the Toroid sensor via a low impedance path.

c) A fully-enclosing shield must be installed over the Toroid sensor 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 Toroid sensor must be protected from being heated beyond 80°C during vacuum chamber bake-out.

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

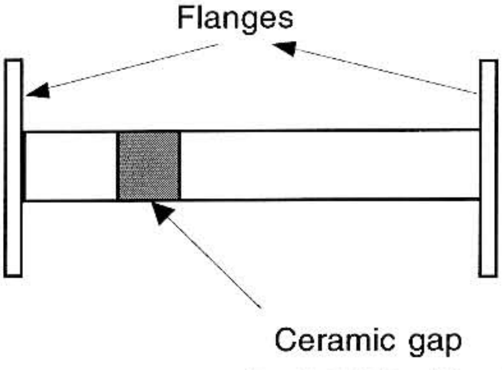
Note: PCT and MPCT-S sensors are sensitive to external magnetic fields, typically 100µA/Gauss. For precision measurements, these sensors must be shielded.
FCT and ICT sensors do not need to be protected from external magnetic fields. When they are exposed to external magnetic fields they may saturate; this causes the droop to increase up to a factor of 2. It has no effect on the sensor linearity at the frequency of the beam.

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:

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

PCT and MPCT-S current sensors are adversely affected by an ohmic value $R < 100\Omega$ because it shorts the transformer. The commonly used solution is to etch a narrow groove in the metal deposit to prevent DC conductivity of the gap metallization.

Magnetic shield

This is required only for PCT and MPCT-S sensors. It is typically not required for FCT and ICT.

The magnetic alloy most commonly used for this application is mu-metal because it presents a high permeability when it has been annealed. Mu-metal is Ni/Fe alloy in 80/20 proportions. Magnetic soft annealing is performed at 1050°C in a hydrogen atmosphere oven. After annealing the permeability may reach 120’000 in the best case, more typically 80’000.

Any shock, stress or deformation applied to a mu-metal annealed shield make it loose its permeability. Manipulation of the shield must be done with utmost precautions. A mu-metal shield can be re-annealed as often as desired. It regains high permeability after annealing.

For a cylindrical shield, the most effective use of the alloy is obtained with a cylinder of proportions:

$$L = 3\,D$$

Closing the ends of a cylindrical shield with shielding disks, or flanges, adds very little to the shielding factor.

For mu-metal alloy, the “ideal” thickness is around 1 mm. This thickness combines ease of manufacturing, good mechanical stability during annealing, and good shielding.
Increasing shield thickness does not increase the shielding factor significantly.

To increase the shielding factor, multiple cylinders must be used. The inner cylinders should ideally be shorter than the outer cylinders. They must be separated by an air gap. 1-mm gap is a typical value.

The shield will saturate when exposed to a strong magnetic field. A mu-metal cylindrical shield will typically saturate with the following external fields:
- 20 Gauss radial (transverse) field
- 100-200 Gauss axial (longitudinal) field.

When the shield is saturated it becomes “transparent” to strong magnetic fields: The PCT or MPCT–S sensors do not function anymore.

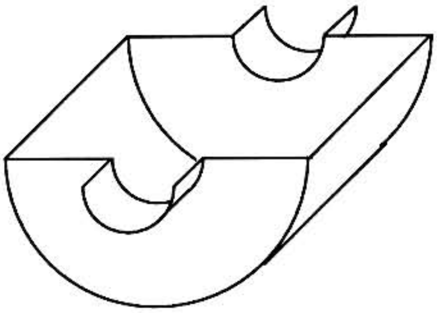
To protect the sensor against stronger fields, an outer shield with high saturation value must be installed. Typical materials are soft iron, low-carbon steel. 1-2 cm is typical thickness.
This shield must preferably be longer than the mu-metal shields.

INSTALLATION ON THE VACUUM CHAMBER (Cont'd)

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 sensor

The sensor 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 sensor.
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 sensor aperture. It must enter and go out on the same side of the sensor, otherwise it makes a current loop around the sensor toroid.

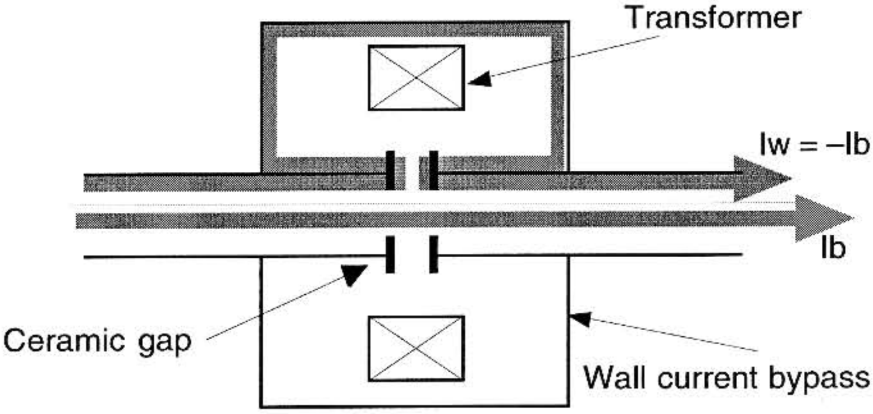
MAXIMUM STORAGE AND OPERATING TEMPERATURE 80°C (176°F) AT ANY TIME. The alloy looses its characteristics when heated beyond this temperature.

INSTALLATION ON THE VACUUM CHAMBER (Cont'd)

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 harmonics above the frequency range of the PCT from entering the cavity:

The beam current passes through the vacuum chamber.
The wall current follows the conductive vacuum chamber walls.



The wall current splits in two: The high frequencies pass through the capacitance of the ceramic gap, and the low frequencies follow the wall current bypass, therefore do not pass through the sensor hole. The sensor –which "sees" the sum of all currents passing through its hole– "sees" only the low frequencies of I_b, because the high frequencies of I_b are cancelled by high frequencies of I_w.

Note that the full charge of the beam pulse passes thru the sensor hole, 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.

For FCT, the gap capacitance should be $100\text{ pF} \le C \le 1\text{ nF}$
For ICT with 70 ns output, the gap capacitance should be $1\text{ nF} \le C \le 1\text{ μF}$
For PCT and MPCT-S, the gap capacitance should be $10\text{ nF} \le C \le 220\text{ nF}$

The gap impedance is determined by its capacitance:

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

INSTALLATION ON THE VACUUM CHAMBER (Cont'd)

Designing a gap with high capacitance

Different laboratories use different techniques to obtain the required low-inductance 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]

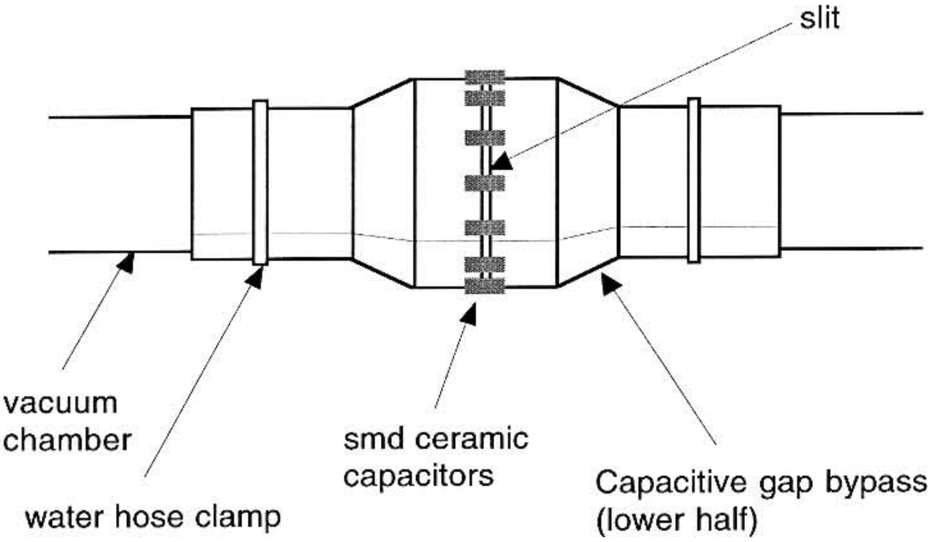
d is the dielectric thickness [m]

ε_r is the relative dielectric constant, 3.5 for Kapton polyimid

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

Example, for C = 2.54 nF and d = 100µm and $\varepsilon_r = 3.5$, 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:



In lepton accelerator with short bunch length, the frequency spectrum extends into the 10's of GHz. SMD capacitors of the microwave type will be preferred; their inductance being lower.

WHAT COULD (AND WOULD) GO WRONG....

Saturating the Toroid sensor

You may accidentally saturate the magnetic material of the Toroid sensor and its ultra high permeability inner shield. When the cores and inner shield have been saturated, the PCT becomes extremely sensitive to external magnetic fields: its output may remain permanently at saturation levels: beyond +11.5V or –11.5V. The cores and shield do not desaturate spontaneously.

Note: Accidental deep saturation of a Toroid sensor can happen (and has happened) when welding was performed on the vacuum chamber. The current return path happened to pass through the Toroid sensor hole...

Low level saturation is usually "erased" by the action of the PCT modulator. In this case, the PCT output has a temporary offset up to 100 mV which drifts back to zero after a few hours. Example of low-level saturation:

- Exposing the sensor to an external magnetic fields in excess of 20 Gauss.
- Passing a beam current in the sensor while the PCT is not powered.
- Passing a current exceeding the set range by more than 20%.

When the sensor has been saturated, the instrument will drift for several hours towards equilibrium unless you demagnetize it.

Demagnetizing the Toroid sensor

Demagnetizing occurs automatically each time you apply the mains to the instrument. To demagnetize the sensor:
- Pull the mains plug off the output chassis.
- Reapply the mains power.

If you want to observe the demagnetizing process:
- Connect an oscilloscope to the middle BNC labelled 'LP-Filter'. Set it on 1V/div., 20ms/div.
- Observe the demagnetisation process on the oscilloscope.
  It will last ca. 30 seconds depending on sensor's size.

If for whatever reason the power is interrupted during this sequence, the mains power should be reapplied again only after 15 minutes. The zero may need to be readjusted.

Shorting the Toroid sensor

The Toroid sensor must not be shorted. Any conducting loop passing thru the center of the Toroid sensor and closing outside of the toroid is a short. It may be resistive, inductive or capacitive.

Shorting can happen in unexpected ways, thru additional shields, mechanical holders or braces, thermal shields, water cooling pipes, etc.

A short with an impedance <100 Ω at 7 kHz will cause an increase of the output signal 7 kHz ripple. This impedance corresponds –for instance– to ≥220 nF capacitance.

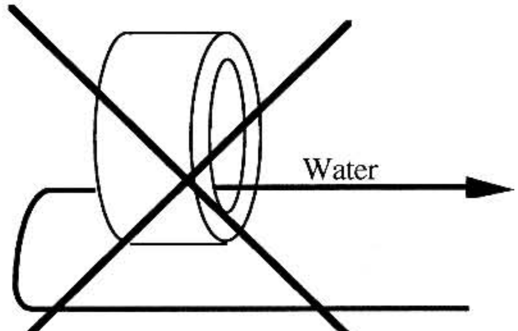
WHAT CAN (AND MIGHT) GO WRONG.... (Cont'd)

Unwanted currents

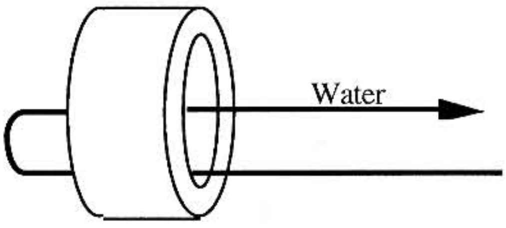
The PCT reads the sum of all currents passing thru the Toroid sensor.

Any current flowing thru the vacuum chamber, bake-out sleeve or thermal shield will be 'seen' by the PCT. Make sure the vacuum chamber has an isolating gap to avoid unwanted currents.

All currents entering the Toroid sensor must return to the same side of the Toroid sensor:
- Assure that all currents injected into a bake-out sleeve are returned to the same side of the Toroid sensor.
- Water cooling pipes passing thru the Toroid sensor hole must return and exit on the same side as they enter. Even a rubber pipe –passing through the Toroid sensor– with demineralized water, may carry more than 100 μA of ion current.



Not allowed



Allowed

External magnetic fields

The PCT cores are sensitive to magnetic fields. They are protected by several layers of magnetic shield made out of ultra-high permeability material. The remaining sensitivity to magnetic fields is typically 100 μA per Gauss.

When the PCT is installed in a place where external magnetic fields cause unacceptable reading errors, the external magnetic fields seen by the PCT sensor must be reduced by user-supplied magnetic shields.

Ionizing radiations

The Front-end electronics box and the Output chassis must be protected against exposure to ionizing radiations. Doses as small as 10^2 Gy can damage the Mos components used. When the Front-end electronics box has to be installed in a place where significant levels of radiation are present, it is advisable to hide the electronics box in a pigeon hole either in a wall or in the floor.

The Toroid sensor contains materials which can be activated by high energy particles, particularly, the sensor contains large quantity of cobalt and iron.

Other materials used in the construction of the Toroid sensor can be damaged at high doses and release halogens which turn into acids.

RADIATION RESISTANCE

Radiation sensitive materials used in the "Standard" Toroid sensor

The "Standard" sensor is the default sensor unless the "Rad Hard Sensor" option was ordered (see front page of this manual for eventual "Rad Hard Sensor" option)

			Radiation resistance[1]
Wiring insulation		Polyvinylchloride	2 x 10^5 Gy
		Fiber glass	> 10^8 Gy
		with rubber adhesive	> 10^6 Gy
Stress absorbent		Silicon rubber tape	5 x 10^5 Gy
		Silicon rubber	2 x 10^5 Gy
Cables	Insulation	Polyvinylchloride	2 x 10^5 Gy
	Shield	Aluminium Polyester	> 10^5 Gy
	Sleeve	Polyvinylchloride	2 x 10^5 Gy
Connector	Insulation	Polyphenylene sulphide Ryton-R-4	> 5 x 10^7 Gy

Radiation sensitive materials used in the "Rad Hard" Toroid sensor

The "Rad Hard" sensor is only used when this option is ordered (see front page of this manual for eventual "Rad Hard Sensor" option)

Wiring insulation		Polyether-ether-ketone PEEK	6 x 10^7 Gy
		Fiber glass	> 10^8 Gy
		with rubber adhesive	> 10^6 Gy
Stress absorbent		Polyurethane foam	5 x 10^6 Gy
		Polyurethane rubber	5 x 10^6 Gy
Cables	Insulation	Polyether-ether-ketone PEEK	6 x 10^7 Gy
	Static shield	Copper	no limit
	Sheath	Polyurethane rubber	6 x 10^6 Gy
Connector	Insulation	Polyphenylene sulphide Ryton-R-4	> 5 x 10^7 Gy

The above radiation resistance values are only indicative. 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.

Last revised: February 1998

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

The Parametric Current Transformer, a beam current monitor developed for LEP

K. B. Unser, CERN, CH-1211 Geneva 23 (Switzerland)

Abstract: Toroidal transformers are used to measure the beam current in beam lines and accelerators. Placing such a transformer in the feedback loop of an operational amplifier will increase the useful frequency range (active current transformer). A magnetic modulator can be added to extend the response to DC current, maintaining with a control loop the transformer core at a zero flux state. The magnetic modulator in the parametric current transformer gives not only the DC response but provides parametric signal amplification up to a transition frequency of about 500 Hz. The low frequency channel (magnetic modulator) and the high frequency channel (active current transformer) are linked together in a common feedback loop. A large dynamic range together with good linearity and low distortion is obtained. This arrangement protects the magnetic modulator from dynamic errors in case of a sudden beam loss, which could impair its zero stability. Dynamic overload protection is an important condition to obtain high resolution and good zero stability, even in applications which require in principle only a very limited frequency response.

Introduction

Beam current transformers are among the oldest examples of beam instrumentation. Their development has followed the evolution of particle accelerators. Two important milestones of this development should be mentioned here:

The current transformer was placed in the feedback loop of an operational amplifier (H. Hereward and J. Sharp[1]). This extended the low frequency range by a factor approximately equal to the gain of this amplifier. The differentiation time constant L/R of the "Active Current Transformer" could exceed 1000 seconds, making it possible to measure the circulating beam in the proton synchrotron during several seconds with a negligible shift of the baseline.

A magnetic modulator[2] and a control loop was added to prevent any magnetic flux change in the core of the active beam current transformer. This "zero flux DC current transformer" was originally developed for beam current measurements in the ISR[1], a storage ring, where the proton beams would circulate for days and weeks. It is an example of a technology developed for particle accelerators which has found many industrial applications[3] for precision DC and AC current measurements.

A new generation of beam current monitors.[5] was developed for the LEP project. This gave the opportunity to introduce a number of new ideas to improve the performance and to reduce the influence of environmental factors like stray magnetic fields, electromagnetic interference and mechanical vibrations (microphony). The new instrument is called the Parametric Current Transformer (PCT), because the magnetic modulator provides parametric amplification in the low frequency channel, up to a transition frequency of about 500 Hz.

The development work was done in collaboration[7] with an industrial company in France (technology transfer) who intended to produce this instrument commercially. This meant that a number of economical factors had to be considered which were of lower importance in earlier projects. The priorities for a commercial product are cost, reliability and performance - in that order! The new design goal was to reconcile these requirements without sacrificing the performance. This was achieved by reducing the number of components and their cost (cables, connectors, electronic components and circuit boards) and by cutting down on the volume, the *weight and the power consumption.*

This paper gives a summary of the new techniques which are now available for DC beam current measurements. It does not necessarily imply that all of them are required in every practical application.

System description

The simplified block diagram (Fig. 1) of the PCT system shows 3 distinct transformers and their associated circuits:

- the zero flux transformer (T_5) together with the L/R integrator circuit.
- the magnetic modulator (T_1, T_2, T_3) with excitation generator and demodulator.
- the ripple feedback transformer (T_4) for the ripple compensation circuits.

The transformers are surrounded by electrostatic screens and some of the windings are screened from each other to eliminate unwanted coupling. Current feedback and calibration windings are common to *all* transformers. Inductive coupling with the beam *is symbolically* indicated with a one turn beam coupling winding.

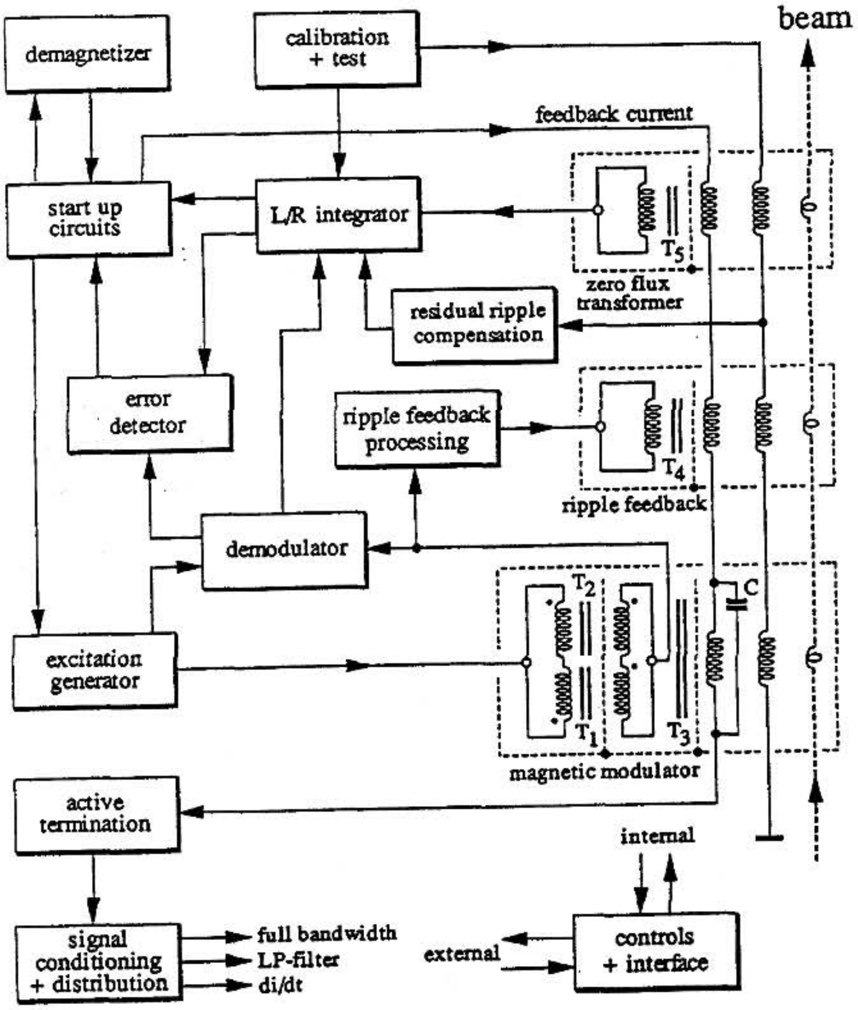

Fig. 1. Simplified block diagram of the PCT

The magnetic cores are demagnetized (depolarized) automatically each time the mains power is applied. The demagnetizer generates a sinusoidal 50 Hz current (>12 A_{pp}) in the feedback windings and this current decays exponentially with a time constant of a few seconds. Demagnetization of the modulator cores is enhanced by programming the excitation generator simultaneously to the highest amplitude before bringing it progressively down to the normal excitation level.

Demagnetizing is important for the zero flux transformer to define the working point close to the center of the B/H loop. This helps to reduce microphony effects, where mechanical vibrations produce a modulation of the residual (remanent) flux and generate parasitic signals. The microphony effects, without this precaution, are very disturbing and could limit the resolution of the monitor in a practical application (vicinity of vacuum pumps etc.).

The magnetic modulator has a memory of previous exposure to a large current. This is probably due to a residual remanence effect. Zero readings may change by more than 1 mA after measuring a current of 1 A, which was, for some reason, not compensated by feedback. This is not only a static offset error, but it is followed by a tendency to drift back during days in the direction of the original zero state. Demagnetization at low frequency permits erasure of this memory effect with an residual error of less than ± 2 μA.

The zero remanence state of the magnetic cores has to be maintained under all operating conditions. This is the task of the start-up circuits, which apply the feedback current after the demagnetizing cycle is completed, on condition that there is no error signal from the circuits in the feedback loop. Error signals are generated if an excessive external current is applied. This is also transmitted as an error message to the control interface. The error detector has the additional function to supervise the positive and the negative power supplies. A drop in power causes an immediate controlled shut-down followed by a demagnetizing cycle when the power is restored again.

The calibration circuit applies a precision current source to the calibration windings. This is useful as a system test and permits the calibration of the entire data acquisition chain (for both polarities) in a typical application. There is also another function of this circuit: in the control state "test", a known current is added to the current in the feedback windings. The feedback current will try to compensate the error caused by this current source. The change in the zero reading of the PCT can be used to calculate the internal d.c. loop gain of the PCT.

Fast current changes (beam or feedback current) are shorted out with capacitor C, which is decoupled[4] from the modulator with the help of an additional transformer core T3. This capacitor both protects the magnetic modulator from fast transients and attenuates at the same time high frequency components in the modulator output signal, which are coupled into the feedback current loop. This coupling, an undesirable effect, is the origin of modulator ripple in the PCT output signal. A processed modulator output signal is returned back via the ripple feedback transformer to compensate this unwanted signal at the source (reduction up to 98%).

Earlier instruments[4] of this type required a complete 19"- crate with 8 plug-in modules to house the electronics. The new design, in spite of many additional circuit functions, requires only 2 Eurocards (100 × 160 mm) with 4 micro modules in surface mount technology. The total power consumption was reduced by 94% and is now only 3 watts (at zero input current). The electronics is placed in a sealed box without ventilation holes (185 × 130 × 70 mm).

The interconnection between the front-end electronic box and the back-end chassis is a single cable with 3 shielded wire pairs. The first carries the analog signals, the second the power supply and the third the multiplexed bidirectional controls and the power for the demagnetizer. The back-end chassis contains only the analog signal conditioning and distribution circuits, the control interface and the power supply.

The Magnetic Beam Sensor

The magnetic beam sensor consists of 5 separate magnetic cores, packed together in the toroid assembly (Fig. 2). The cores are strip wound toroids having a useful cross-section between 5 and 25 mm^2 depending on the application. Small cross-sections of the cores were possible thanks to the choice of a high modulation and transition frequency of the system. The soft magnetic material is a thin ribbon (5 mm wide, 23 µm thick) of Vitrovac® 6025*, an amorphous magnetic alloy with the composition $(CoFe)_{70}(MoSiB)_{30}$. This material features higher values of permeability and can be used at higher frequencies than conventional (crystalline) nickel/iron alloys.

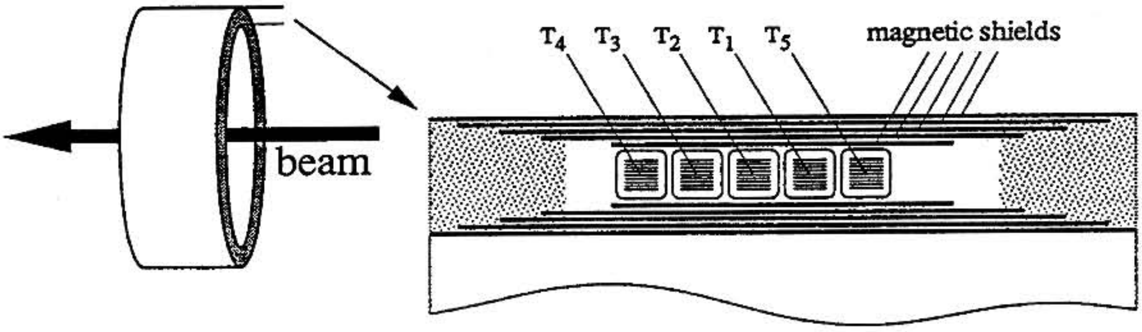

Fig. 2. Toroid assembly, simplified cross-sectional view (windings not shown)

The cores for the 2nd-harmonic magnetic modulator (T_1 and T_2) are the most critical components of the system and the magnetic properties of these cores determine the resolution and the zero stability of the instrument. Vitrovac® 6025 is now produced in quantity, but the normal commercial grade has a very large spread of magnetic characteristics. A special quality is selected by the manufacturer using a detailed set of specifications containing among others the following selection criteria:

- low value of magnetostriction ($\lambda s < 0.2 \times 10^{-6}$)
- low value of saturation flux density ($Bs < 0.5$ Tesla)
- good surface quality
- no brittleness

The selected material is submitted to a series of tests to determine the specific annealing conditions[5] for each production batch and the important parameters for the modulator application, i. e. the modulator gain and the magnetic modulator noise. The magnetic noise (Barkhausen noise) depends essentially on the number and the structure of the magnetic domains in the material, which can change with the composition and the annealing treatment of the material. Less than 5% of the material received will pass these tests, but the rest can be used for all other applications, where these specific characteristics are not relevant.

Certain aspects of the fabrication of the cores have been treated in an earlier publication[5] and will not be repeated here. The winding of the modulator cores is a very critical operation. The ribbon has to be continuously controlled with the microscope for mechanical defects (micro fractures and surface defects). The correct winding tension has to be carefully maintained. The insulation between the layers, a mylar foil of 2 µm thickness, is very delicate and difficult to handle. It has to be placed with great care to maintain a minimum and equal spacing between

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* Vitrovac® 6025 is a trade name of Vacuumschmelze GMBH, D-6450 Hanau, Germany

the layers. It is not only necessary to wind all cores with exactly the same number of layers, but also to position the start and the finish of the ribbon in a well defined position in respect of each other. The magnetic ribbon is not simply cut at 90° to the longitudinal axis of the tape but at a very narrow angle in order to distribute the discontinuity in the cross-section over a larger circumference. The finished cores are vacuum impregnated and cross field annealed. The toroidal excitation winding is applied and all magnetic parameters are measured and recorded. Core pairs are selected by matching the dynamic hysteresis loop to better than 1% (defined by the factor of attenuation of the modulation frequency in the common output winding).

The magnetic modulator, in the center of the assembly, is a very sensitive magnetometer to external magnetic fields. This is an undesirable feature which can only be attenuated by extensive magnetic shielding. The magnetic shield of the PCT consists of a number of concentric magnetic cylinders of different length, inside and outside the magnetic cores (Fig. 2). The shields which are closest to the cores consist of several layers of Vitrovac 6025 and provide the best shielding factor, but this material is only available with a maximum width of 50 mm. All other shields are Mumetal. Seen in this context, the small cross section of the magnetic cores is also an important advantage for efficient magnetic shielding. It helps to bring the inner and the outer shields closer together and reduces the volume of the magnetic beam sensor.

This shielding attenuates the external field by a factor between 50 to 500, depending on the number of shields in use. This is not enough in many applications. One has also to consider that high permeability shields are easily saturated by a strong external magnetic field.

The Excitation Generator

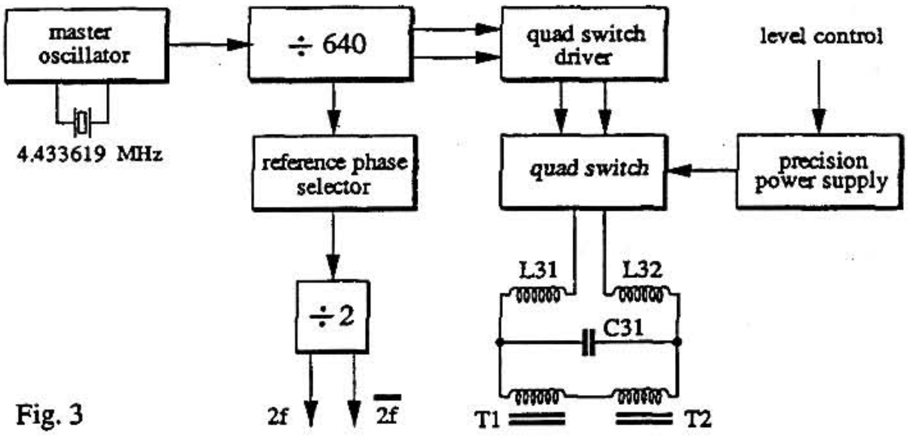

Fig. 3

Basic design consideration: The resolution and zero drift of the PCT should only be limited by the magnetic noise of the magnetic modulator. The contribution of noise from the electronic circuits should ideally be considerably lower. As a design limit, the tolerance for these contributions have been arbitrarily set to ≤ 10 nA rms of equivalent beam current.

This translates into the following specifications for the excitation generator (assuming matching errors ≤ 1% for the modulator core pair):

- variation of 2nd harmonic distortion: ≤ 5 ppm
- variation of frequency: ≤ 10 ppm
- variation of amplitude: ≤ 50 ppm (parts per million)

The excitation frequency of the magnetic modulator should be as high as possible, but eddy currents in the core material impose an upper limit which is in our case around 7 kHz.

A crystal controlled master oscillator (Fig 3) with a stability ≤ 3 ppm and a synchronous divider generate the excitation frequency ($f = 6927.3$ Hz). The tolerance is less than 1 ns for the differential timing error (difference in duration of the positive and the negative half period) and less than 100 µV for the differential amplitude error. The difference of rise and fall times and the corresponding transmission delays of the digital control signals have to be taken into account. A perfect symmetry of all pulse forming elements is required and symmetric transmission lines for the timing signals are used. The circuit board lay-out is critical. A quad DMOS transistor array (on a single chip) in a symmetrical H-bridge configuration[5] is used to switch the output of a precision regulated power supply. A passive low pass filter (L31; L32 and C31) eliminates the higher frequency components. The capacitor C31 supplies high current peaks (Fig. 4) in an avalanche discharge to drive the cores hard into saturation and recuperates a large part of the stored energy on the return swing. The optimum value of this capacitor and the optimum value of peak excitation current as a function of resolution are individually determined for each magnetic sensor in a semi-automatic test set up.

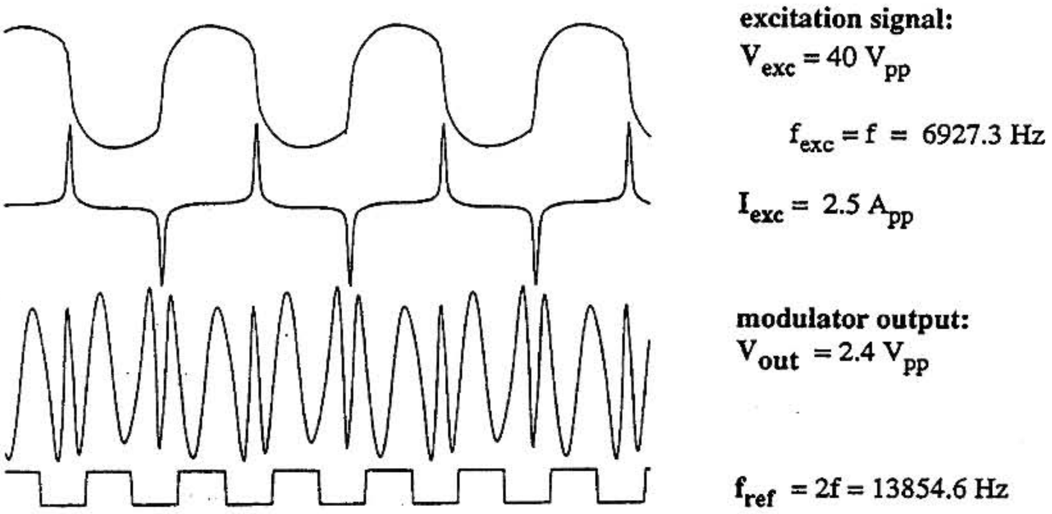

Fig. 4. Typical signal waveforms observed on a magnetic modulator (plot of display, averaged signals, on LeCroy 9410 oscilloscope). The core matching in this example is better than 0.5%. The exact waveform of the output signal is an individual "signature" for every magnetic modulator.

The Demodulator

The demodulator has to detect and to amplify the 2nd harmonic component in the output signal of the modulator. It has to satisfy the following specifications, taking into account the parametric amplification[5] in the magnetic modulator:

Resolution:	0.1 µV rms (for a bandwidth of 1 Hz)
	10 µV rms (for a bandwidth of 500 Hz)

This 2nd-harmonic signal is completely masked by a parasitic output (see Fig. 4) of the magnetic modulator, resulting from the core matching error of the magnetic modulator. This parasitic signal is composed of the modulation frequency f and a spectrum of odd harmonics (3f; 5f; 7f; 9f; 11f etc.). It has an amplitude of several volts, more than 150 dB higher than the required resolution for the 2nd harmonic signal.

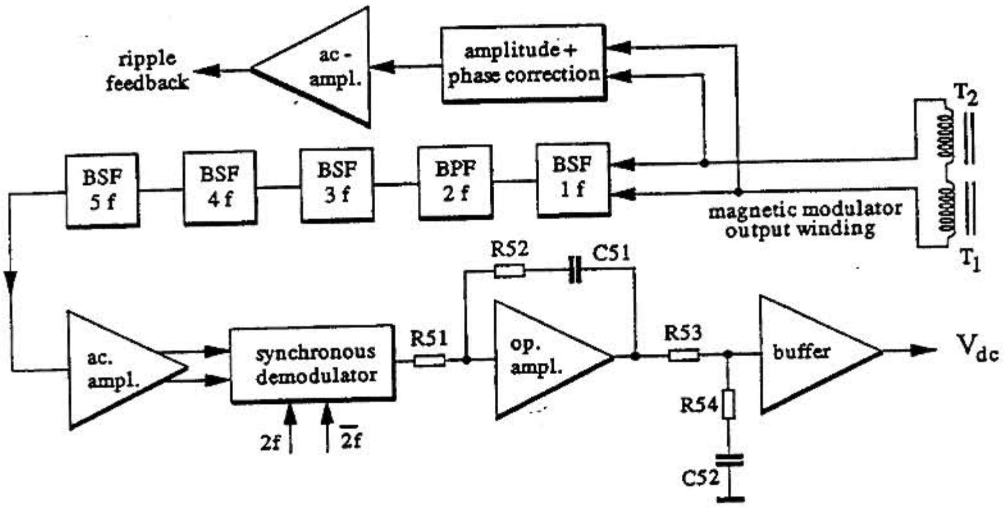

Fig. 5. Simplified block diagram of demodulator

To obtain the specified resolution, it is necessary to attenuate, with a filter, the parasitic signals by more than 50 dB and to amplify the 2nd harmonic component at least 30 dB before demodulation. The bandwidth of the filter should be 2.5 kHz above and below 2f in order to accommodate the upper and lower sidebands of the modulated signal with an acceptable phase error. This is one of the conditions which has to be satisfied to make the overall feed-back loop stable, considering a transition frequency of 500 Hz for the low frequency channel.

The filter is a passive LC-network and consist of 1 band pass (BPF) and 4 band stop (BSF) sections. The signal, after demodulation in a synchronous detector, is integrated with the time constant R51 × C51 for a 6 dB/octave (frequency) roll-off. This determines the transition (cross-over) frequency between the modulator channel and the active current transformer channel.

The Active Current Transformer

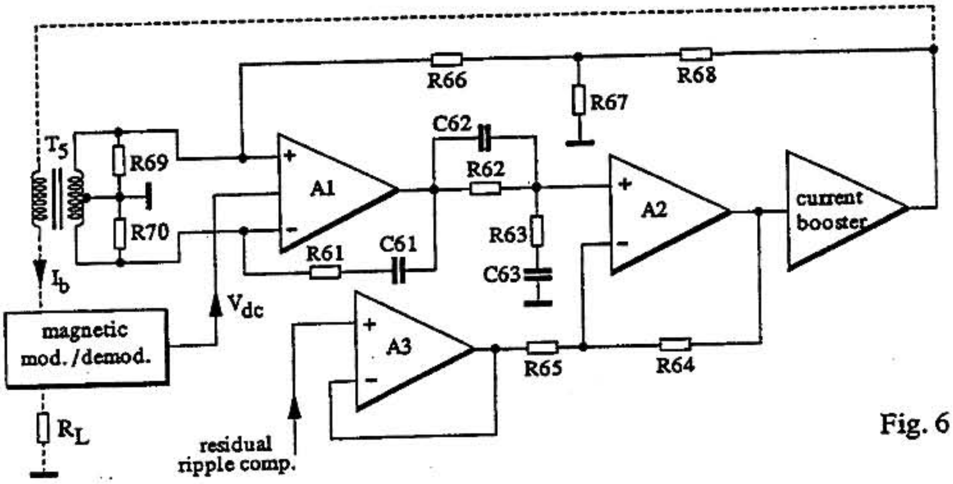

Fig. 6

The active current transformer with the zero flux transformer (T_5) and the overall feedback loop of the PCT is shown in Fig. 6. The signal gain for medium and high frequencies (up to 1 MHz) is provided by a composite amplifier (the L/R integrator), consisting of A1; A2 and a current booster for max. 100 mA. The DC and low frequency gain comes from the magnetic modulator/demodulator in cascade with a part of the high frequency channel. The 2 channels have therefore 2 independent inputs, but one common output and one common feedback loop, which defines the (closed loop) signal gain of the system. The signal path is always via the channel with the highest open loop gain at any particular input frequency.

Considerations of loop stability impose an upper frequency limit (< 1/10 f) for the transition from the low to the high frequency channel. A high transition frequency has many advantages. It reduces the required core cross-section for the zero flux transformer T_5, limits the noise contribution of amplifier (A1) and reduces the microphony effect of core T_5. All these effects increase rapidly at lower frequencies.

The open loop gain of both cascaded channels is very high (> 150 dB at DC). This is how good linearity, low distortion and the large dynamic range of the PCT is obtained. It requires a carefully tailored roll off (gain and phase) in the direction of the unity gain cross over frequency (1 MHz) of the system. Phase correction elements in the active current transformer (R61, C61 - R62, C62 - R63, C63) and in the demodulator (R52, C51 - R53, R54, C52) have to be set for optimum loop stability and a clean step response. Range switching does not influence the dynamics of the feedback loop, because the (virtual) load impedance R_L is constant and small.

Damping resistors (R69 and R70) eliminate undesirable high frequency resonances of the zero flux transformer T5. They cause a small gain error (2 to 3 %) in this channel, which is compensated by a corresponding amount of positive feedback (via R66, R67 and R68).

The parasitic output signal of the magnetic modulator, coupled into feedback loop, causes an unwanted error current (modulator ripple) in this loop. This effect is unfortunately enhanced by the low output impedance of the current buffer and the low value of (virtual) load impedance (R_L= 50 ohms). The ripple feedback via T_4, mentioned earlier, reduces this effect already by a large factor. The remaining ripple signal is measured at the calibration winding and added via A3 and A2 to the signal of the current booster (compensation by "bootstrapping").

The Active Termination

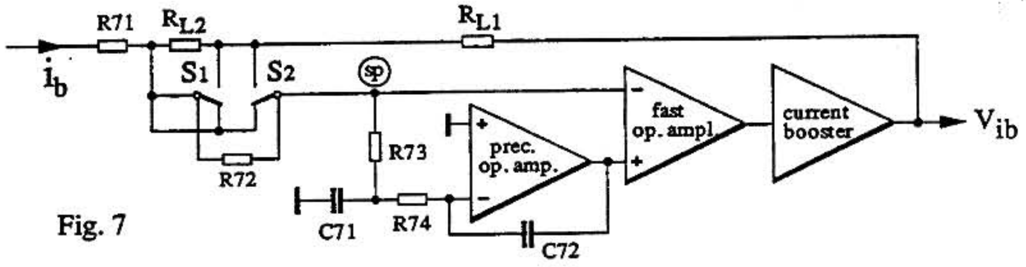

Fig. 7

The active termination converts the feedback current i_b into an output voltage V_{ib}. Two precision load resistors (R_{L1} and R_{L2}) in the feedback loop of an operational amplifier provide a virtual ground reference at the summing point (sp). The operational amplifier is in reality a composite amplifier with a separate high and low frequency channel and a current booster (100 mA max.). This arrangements permits an accurate measurement of the average beam current, even if the input signal consists of very short pulses, separated by a long time interval.

The switches S1 and S2 select the current ranges A and B without interrupting the feedback path and without adding the contact resistance to the load resistor values. The load resistors R_{L1} and R_{L2} are composed of several precision resistors in parallel in order to keep the power dissipation in each of them at a low level. Resistor R71 (50 Ω) defines the actual impedance of this active termination in the main feedback loop and keeps it at a constant and low value to reduce the effects of parasitic capacitance of the different elements in this loop, a condition for loop stability, independent of the selected current range

Signal conditioning and distribution

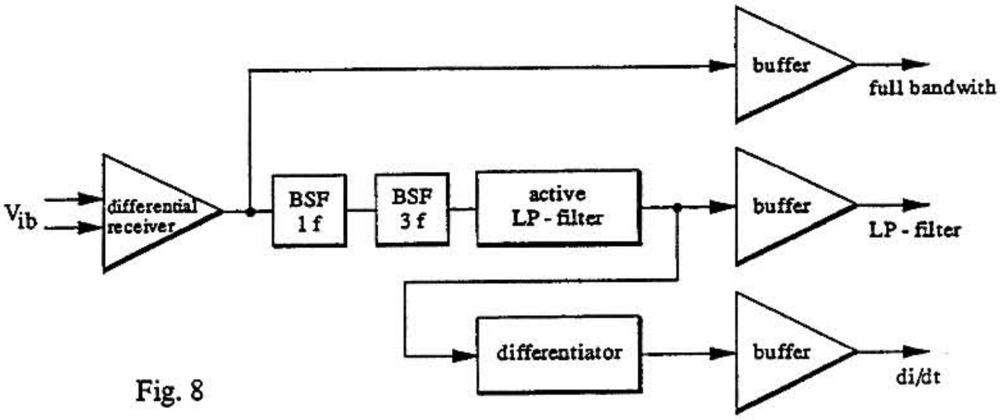

Fig. 8

The analog signal V_{ib} from the front end is transmitted over a symmetrical transmission line, up to a distance of several hundred meters. A differential line receiver rejects all common mode noise which may be present on the line. The signal path is either direct or via a low pass filter and optional band stop filters[6] (BSF) for f and 3f to reject spurious modulator noise. A differentiated signal, proportional to beam loss, is also provided. There is a buffer amplifier for every signal output.

Results

The following specifications can be obtained with a selected sensor:

Sensor dimension	225 mm o.d. 175 mm i.d. 100 mm length
Range A, full scale	any range from 10 mA to 100 A (both polarities)
Range (B)	1 to 20 % of range A
Linearity error *	± 0.001 % ± zero error
Resolution *	± 0.3 ppm of range (A) ± 0.4 µA rms (± 1 µA rms typical)
Zero drift *	± 1 µA/°C (± 5 µA/°C typical)
Zero drift (24 h) *	± 2 µA rms (at constant temperature)
Bandwidth	DC to 100 kHz
Accuracy (calibration source)	± 0.05 %

*) measurements with a 1 sec. integration window

Resolution and zero drift are not at all limited by the electronics, but depend only on the quality of the magnetic sensor. The quality of the Vitrovac 6025 material is in this respect of crucial importance. Material purchased 5 years ago gave in general better results than that currently produced at present. One observes very different zero drift behavior among sensors which are built with exactly the same batch of material. This is an indication, that all the factors which influence these characteristics are not as yet clearly identified.

The temperature drift is not so much caused by the temperature coefficient of the material itself than by the uneven mechanical constraints in the two modulator cores. The temperature dependent zero drift is generally reduced after a period of artificial ageing (temperature cycling between 20°C and 80°C) and the temperature coefficient of the sensor becomes in any case more reproducible. It is a good idea to incorporate a temperature gauge in the beam sensor, if the temperature drift is critical in a particular application.

During long term zero drift test one can sometimes observe in intervals of several hours or days a fairly sudden change of up to 2 µA. The cause of these phenomena are not known.

Acknowledgments

Many people have made their contributions: C. Bovet and R. Jung gave their support to the project and many useful discussions are gratefully acknowledged. The computer controlled test bench for dynamic testing of core samples was designed and built by P. Buksh. The mechanical design of the core winding machine and the different tooling required in the project was first the responsibility of A. Maurer and at a later date of G. Burtin.

J. Bergoz, A. Charvet, R. Lubès and P. Pruvost (BERGOZ, F-01170 Crozet. France) designed circuit lay-outs and built the different prototypes. They made experiments with the different construction methods for the magnetic cores and the toroid assembly and performed an incredibly large number of tests to find the optimum annealing procedures. Their practical experience in building a large number of PCT's is a valuable help for any future improvements.

G.Herzer, R. Hilzinger, W. Kunz and R. Wengerter (Vacuumschmelze GMBH, D-6450 Hanau, Germany) contributed with their knowledge of amorphous magnetic alloys and helped with the selection of a suitable quality of Vitrovac material.

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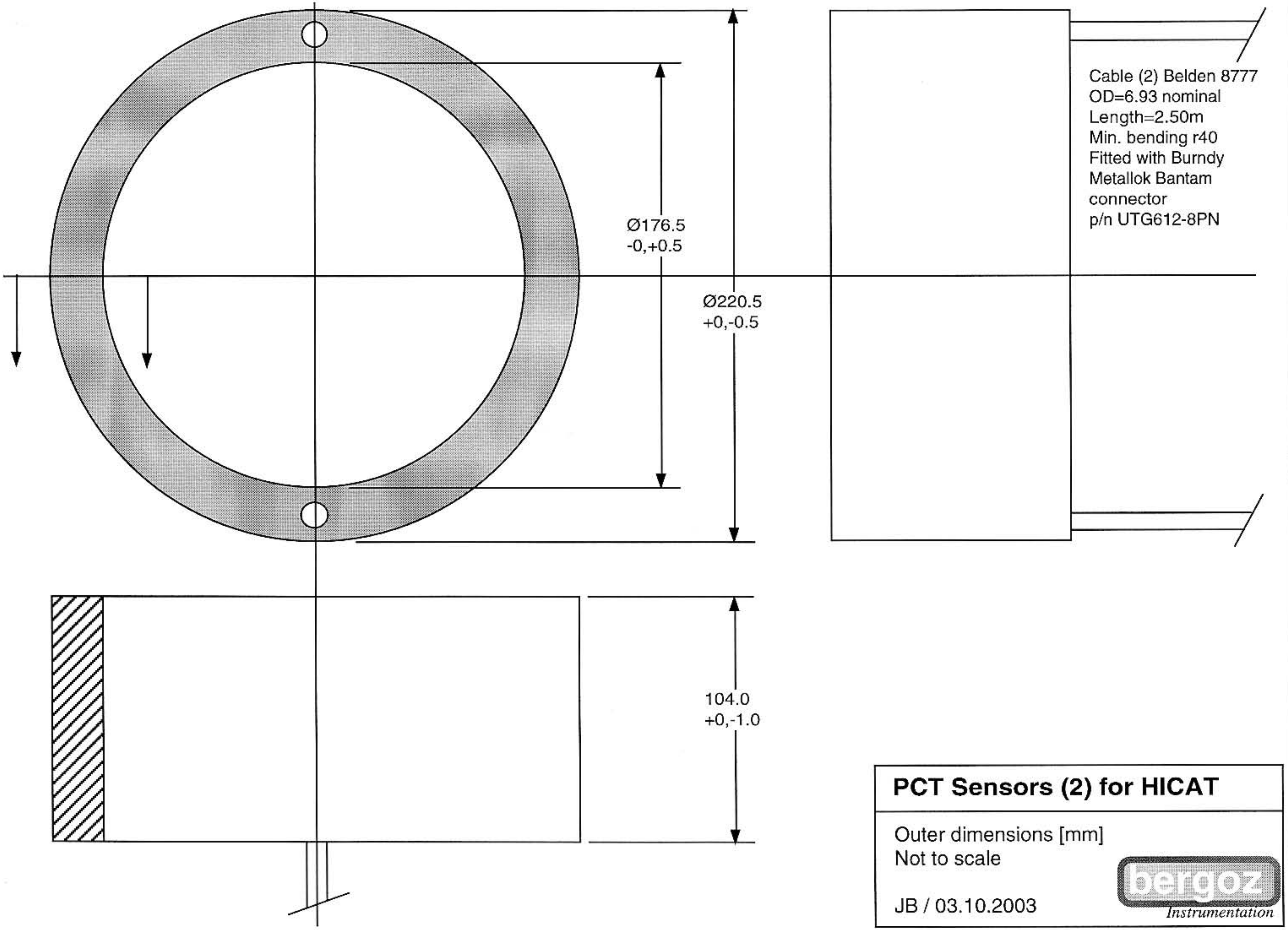

Cable (2) Belden 8777
OD=6.93 nominal
Length=2.50m
Min. bending r40
Fitted with Burndy
Metallok Bantam
connector
p/n UTG612-8PN

PCT Sensors (2) for HICAT

Outer dimensions [mm]
Not to scale

JB / 03.10.2003

bergoz
Instrumentation