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Instrumentation

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New Parametric Current Transformer User's Manual

Rev. 0.4

**Includes special cabling
for Keep-alive circuit**

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WARNING ! DO NOT HEAT TOROID SENSOR BEYOND 120°C / 250°F

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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 email to info@bergoz.com or by fax at +33-450.426.643.

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 $1 \mu\text{A rms at dc}$), 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.

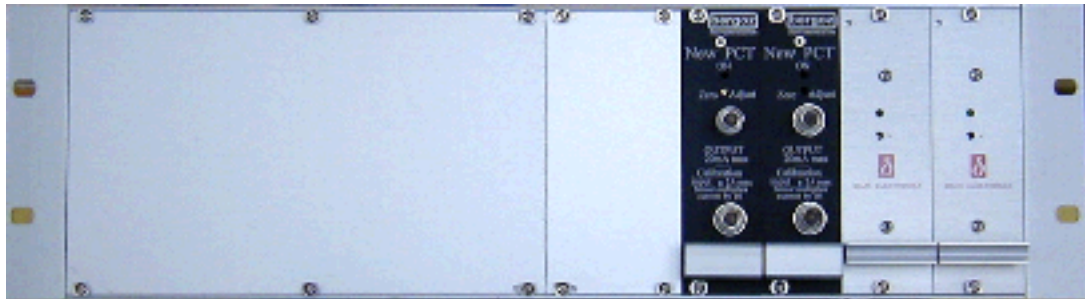
ACKNOWLEDGEMENTS

The New Parametric Current Transformer was designed by Klaus B. Unser, a partner of Bergoz Instrumentation since 1999.

Prototypes of New Parametric Current Transformers were built by Michel Duraffourg from 2000 to 2004.

YOU JUST RECEIVED YOUR New-PCT...

Front view



Rear view



Check the line voltage range marked at the rear of the output chassis. Make sure your mains voltage falls within the range. If it does not, do not connect the New-PCT to the mains power supply, but ask for advice from Bergoz Instrumentation or its distributor. New-PCT consists of:

Order code

NPCT-XXX- consists of:

- New-PCT sensor head with XXX mm inner diameter
e.g. NPCT-175- includes 175-mm ID sensor
- New-PCT interconnection cable
- New-PCT 3U-high chassis

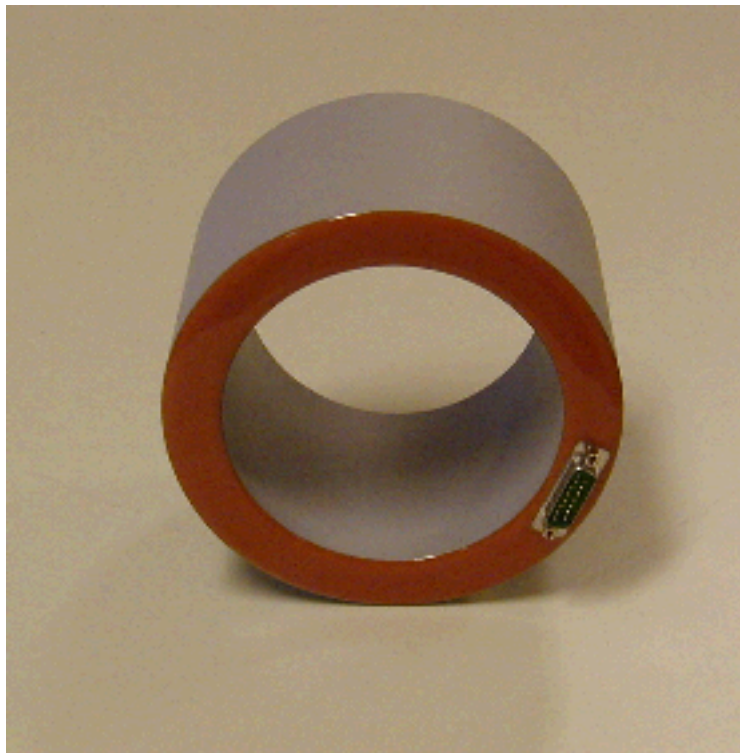
Within the chassis, there are:

- Two plug-in power supply modules, one as spare
 - Two New-PCT electronics cassette, one as spare.
- CXXX- specifies:
- Interconnect Cable length XXX meters
e.g. -C050- means interconnect cable is 50-meter long
- HR- specifies:
- "High Resolution" sensor has been ordered
Note: -HR consist in selecting a higher quality sensor
-HR is not a unit by itself
- H specifies:
- "Rad-hard" i.e. improved radiation resistance
Note: -H is a selection of materials and processes
-H is not a unit by itself.

Note: The two New-PCT electronics cassettes are matched to their associated sensor head and cable's length. When used with another sensor head, their output will most likely be unstable and noisy. It may even not work at all. Connecting another sensor head does not damage the electronics.

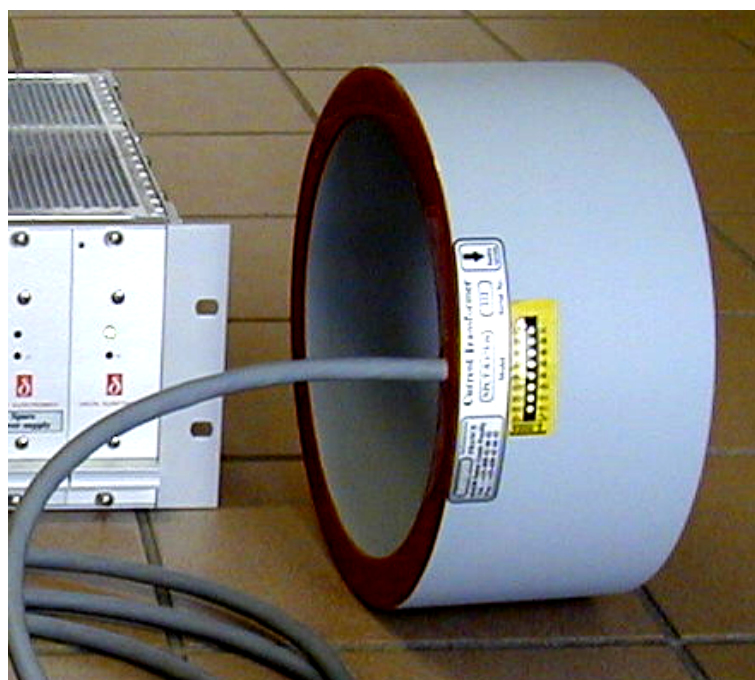
YOU JUST RECEIVED YOUR New-PCT...

Standard sensor head



115-mm ID standard sensor head

Rad-hard sensor head

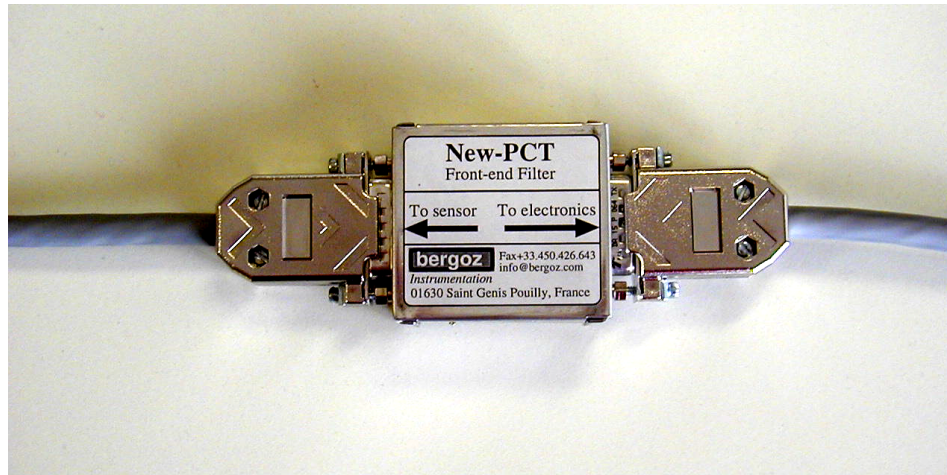


175-mm rad-hard sensor head

Note 3-meter interconnect cable straight out of sensor head

YOU JUST RECEIVED YOUR New-PCT...

Front-end filter (with Rad-hard sensor head only)

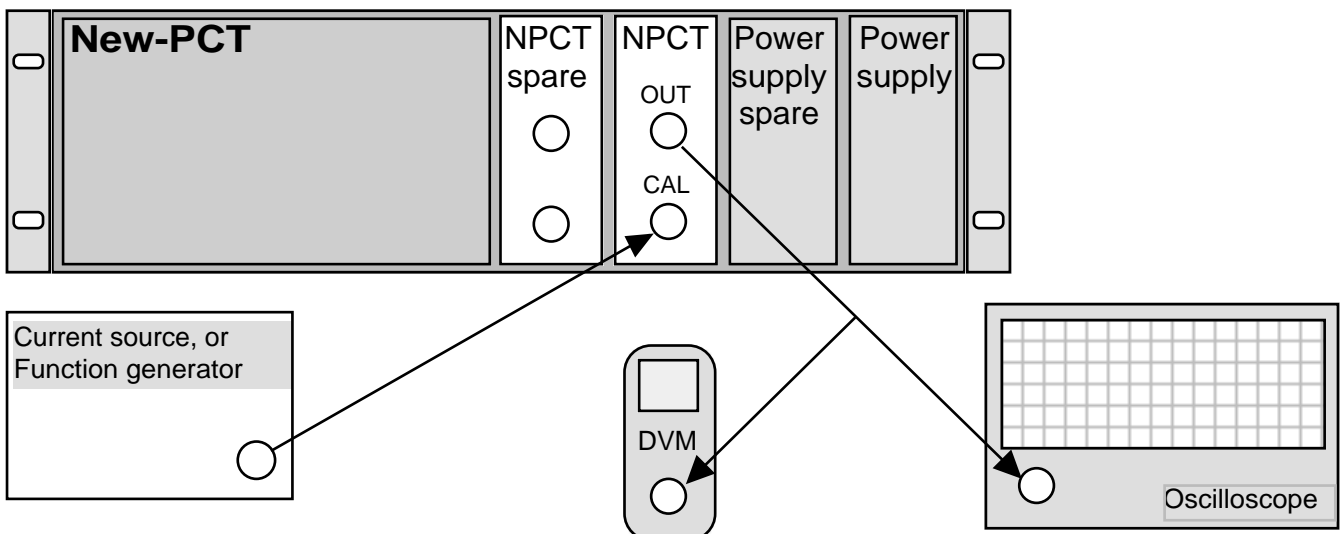


Note: Front-end filter box should not be grounded

QUICK CHECK

Checking New-PCT operation

The following steps are intended to make you familiar with the New-PCT operation and behavior before you install it in its final place. You only need a DC current source or function generator, and a voltmeter or oscilloscope:

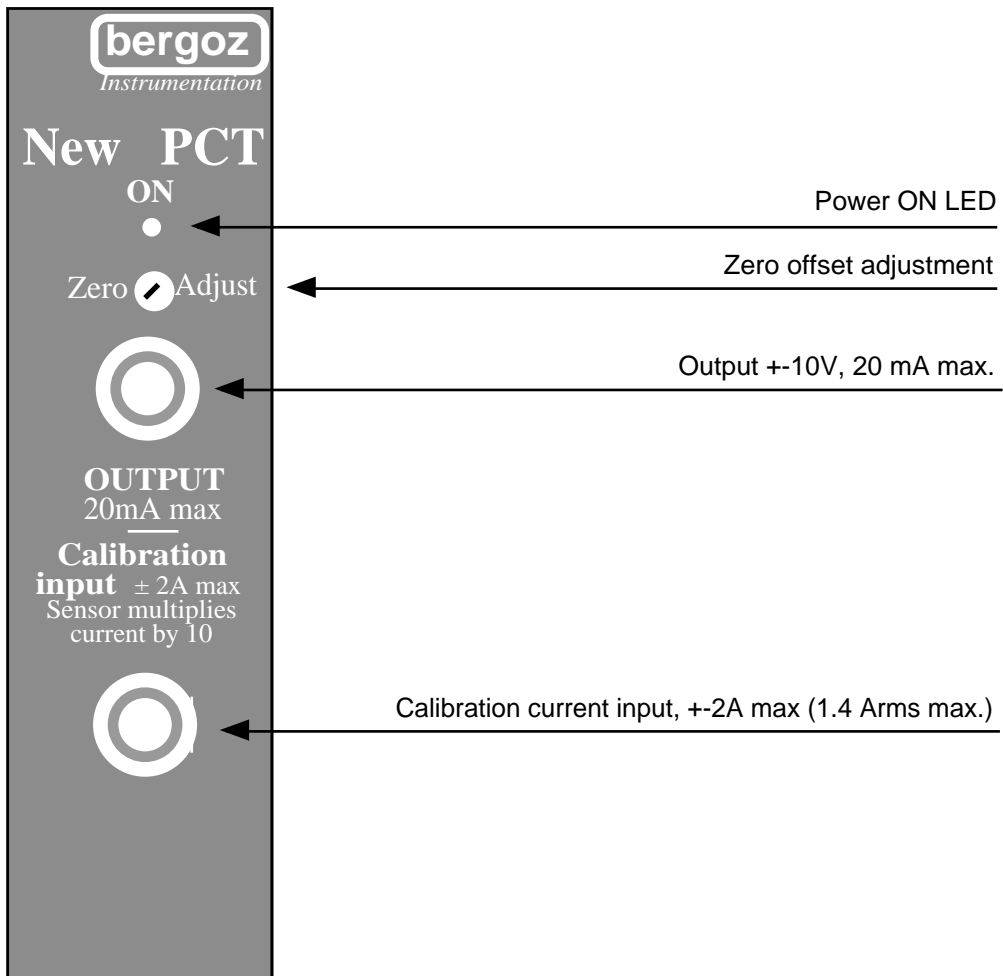


Note: Current entered into the calibration input is multiplied by 10 by the 10-turn calibration winding

Connect New-PCT sensor head to electronics before you connect to the mains

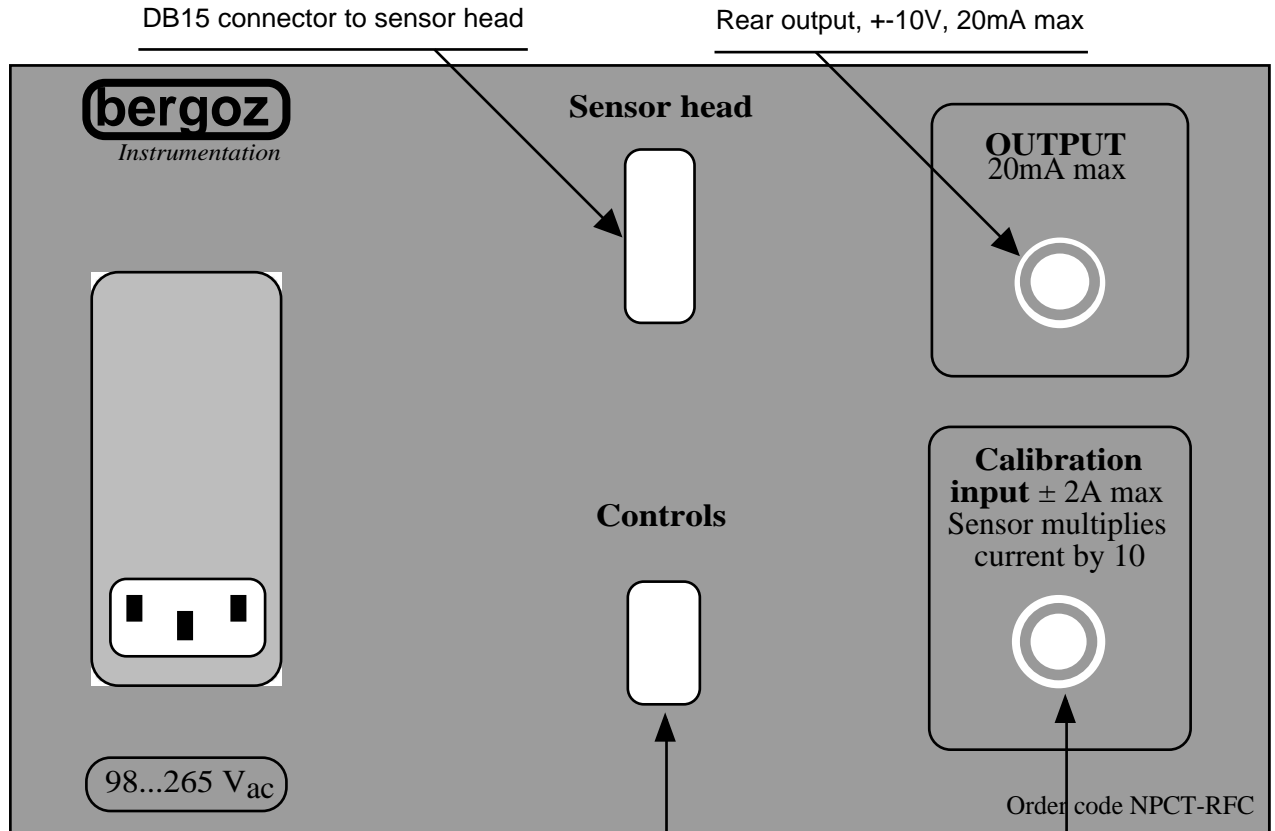
QUICK CHECK (Cont'd)

New-PCT cassette front panel



Note: New-PCT is in +-20A range (default range) unless another range is set.
Ranges can be set through a rear panel DB9 "Controls" connector. See next page.

QUICK CHECK (Cont'd): New-PCT Rear panel and Controls



DB9 Controls connector

Rear panel shown truncated. Real width is 42F

Logic is controlled by TTL levels

Control pins and mnemonics

DB9 pin 2:	TEST
DB9 pin 6	RANGE/10
DB9 pin 7	RANGE/100
DB9 pin 5	GND (ground)

Control inputs are pulled up (default state = High)

Pull down to ground (Low) to set a state

FULL SCALE RANGES:

Range	Pin 6	Pin 7
+20A (default range)	High	High
+2A	Low	High
+200mA	High	Low
+20mA	Low	Low

TEST

TEST mode when active injects +100mA in the sensor

State Pin 2

TEST inactive (default state) High

TEST active Low

Note: Ground (GND) is on pin 5

Rear calibration current input
 +-2A max, i.e. 1.4 Arms max.

QUICK CHECK (Cont'd)

When New-PCT sensor head is connected to the electronics, connect the chassis to the mains. Connect a voltmeter, oscilloscope or low-frequency spectrum analyser to "Output", on the front panel or rear panel.

Then, with a current source or a function generator, enter a signal into the front panel or rear panel "Calibration input".

The current entered into the Calibration input is multiplied by 10, by the 10-turn calibration winding. Observe the Output signal.

All ranges check

Increase the New-PCT sensitivity. To change the full scale range, connect to ground rear panel DB9 Control pins 6 and /or 7.

Note that pins 6 and 7 default state is "High".

<i>Range</i>	<i>Pin 6</i>	<i>Pin 7</i>
+20A (default range)	High (default state)	High (default state)
+2A	Low	High
+200mA	High	Low
+20mA	Low	Low

Note: Ground (GND) is on pin 5.

Preferably, avoid that calibration current exceeds the full scale range. It may saturate the sensor magnetic cores.

Note: The sensor cannot be damaged by an excessive dc current. Its cores saturate. When the sensor cores are saturated, they will normally desaturate by themselves when the excess current is removed, and New-PCT is powered ON. The desaturation process may take many hours, depending on the cores saturation depth. While the cores desaturate, the New-PCT output slowly drifts back to its pre-saturation zero voltage.

Zero offset check

Turn up and own the front panel Zero Offset multiturn potentiometer, and observe the output on a voltmeter. Set the potentiometer so that Output is close to zero.

Notes:

Setting the range to +20mA permits a more precise zero setting.

The zero value will change with:

- Temperature of the sensor
- External magnetic field value
- Direction of the magnetic field

Therefore, when the sensor is moved or rotated on its axis, the zero value does change.

Functional test

New-PCT elementary functions can be tested. To test them, a +100mA test signal can be fed into the sensor head.

The test signal is normally inactive (default state). It can be activated by grounding pin 2 of the DB9 rear panel Controls connector:

<i>TEST</i>	<i>Pin 2</i>
Inactive	High (default state)
Active	Low

Notes: Pin 2 default state is "High". Ground (GND) is on pin 5.

CONTROLS

New-PCT is controlled by TTL levels. There are no manual controls (switches).

VIAQS Versatile Instrumentation Acquisition Server has the capability to process New-PCT output for lifetime measurements, top-up master control. It controls New-PCT by Ethernet as:

- An EPICS IOC
- A LabVIEW socket server
- An http web server

New-PCT can be controlled by any other "I/O" register.

Controls are entered thru Rear panel Controls DB9 connector.

Two functions can be controlled:

- Ranges: +-20A, +-2A, +-200mA and +-20mA.
Default range is +-20A
- Test: Inactive and Active.
Active consists of pushing +100mA current thru the sensor head
Inactive is the default state.

Ranges

RANGE/10	DB9 Controls pin 6 Default state = High (+5V 4K7 pull-up) Divides full scale range by 10
RANGE/100	DB9 Controls pin 7 Default state = High (+5V 4K7 pull-up) Divides full scale range by 100
GND	DB9 Controls pin 5 (ground)

Test

TEST	DB9 Controls pin 2 Default state = High (+5V 4K7 pull-up) Activates test, injects +100mA into sensor head
GND	DB9 Controls pin 5 (ground).

INTERCONNECT CABLE AND PAIRS ALLOCATION

New-PCT interconnect cable are assembled using Belden 9508NH multicore cable:



Product datasheet

page 1 of 1

date 13/04/04

9508NH

24 AWG (7*32) Tinned copper, Pe insulated 8 twisted pairs, overall Beldfoil-Polyester shield with a shorting fold, 24 AWG stranded tinned copper drain wire, LSNH jacket.

Nom. insulation Thickness	0.25	mm
Nom. diameter over insulation	1.12	mm
Nom. Jacket thickness	0.89	mm
Nom. outer diameter	8.39	mm
Max. operating voltage	300	V Rms
Max. Continuous current per conductor @ 25 deg. C	2.2	A
Nom. Capacitance between conductors of a pair @ 1kHz	98	nF/km
Nom. capacitance conductor to shield @ 1 kHz	164	nF/km
Nom. Conductor DC resistance @ 20 Deg. C	82.0	Ohm/km
Nom. Shield DC resistance @ 20 Deg. C	54.1	Ohm/km
Velocity of propagation	60	%
Temperature rating	-15 to +80	Deg. C
Insulation material	PE	
Jacket material (color)	LSNH (Chrome RAL 7037)	
Type shield and % coverage	Aluminium-Polyester 100%	
Max. pulling tension	400	N
Min. bend radius	83	mm
Applicable specifications	BS 7655 Section 6.1 Table 1 LTS 3	
Flame resistance	IEC 332-3-C	

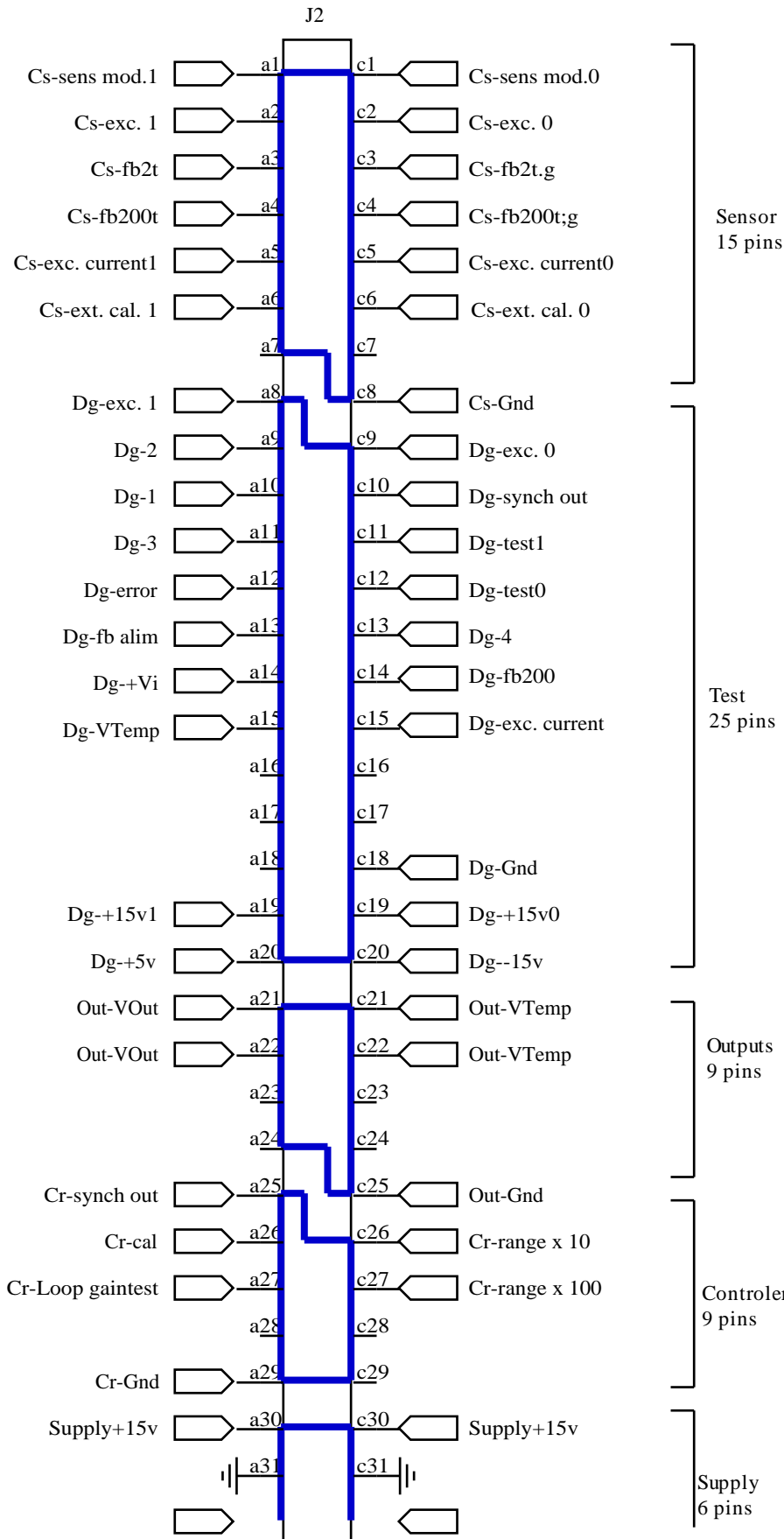
Black&Red / Black&White / Black&Green / Black&Blue / Black&Yellow / Black&Brown / Black&Orange / Red&white
Instrumentation cables for EIA RS-232 Data transmission Applications (Label contains Ce marking)

© Belden Wire & Cable B.V.

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INTERCONNECT CABLE AND PAIRS ALLOCATION



New-PCT cassette connects to rear panel connectors DB15, DB9 and floating BNCs via a 64-way flat cable:

INTERCONNECT CABLE AND PAIRS ALLOCATION

DB15-DB15 interconnect cable pins allocation

Standard version

Signals	DIN41612D	DB15	Pair	Belden 9508NH
Modulator sense	c1	8	P1	White P1
Modulator sense•	a1	15	P1	Red P1
Excitation•	c2	7	P2	Black P2
Excitation•	a2	14	P2	White P2
Feedback2	c3	6	P3	Black P3
Feedback2•	a3	13	P3	Blue P3
Feedback200	c4	5	P4	Black P4
Feedback200•	a4	12	P4	Green P4
Monitoring	c5	4	P5	Black P5
Monitoring	a5	11	P5	Yellow P5
Calibration•	c6	3	P6	Black P6
Calibration	a6	10	P6	Orange P6
Feedback20/2	c7	2	P7	Black P7
Feedback200/2•	a7	9	P7	Red P7
Ground	c8	1	P8	Black P8
Unused	N/C	N/C	P8	Brown P8

Dots indicate winding polarity.
 Excitation wires from winding pairs in phase opposition, thus same polarity.

Special version with Keep-alive circuit

Signals	DIN41612D	DB15	Pair	Belden 9508NH
Modulator sense	c1	1	P1	Red
Modulator sense•	a1	9	P1	Black
Excitation•	c2	2	P2	Green
Excitation•	a2	10	P2	Black
Feedback2	c3	3	P3	White
Feedback2•	a3	11	P3	Black
Feedback200	c4	4	P4	Brown
Feedback200•	a4	12	P4	Black
Monitoring	c5	5	P5	Orange
Monitoring	a5	13	P5	Black
Calibration•	c6	6	P6	Yellow
Calibration	a6	14	P6	Black
Jumper	c7	7	P7	Blue
N/C	a7	15	P7	Black
Jumper	c8	8	P8	Red
Unused	N/C	N/C	P8	White

SPECIFICATIONS

Full scale ranges	-20 mA...+20 mA -200 mA...+200 mA -2 A...+2 A -20 A...+20 A
Range control	2 TTL lines on rear panel "controls" DB9
Output nominal	-10 V...+10 V, proportional to current
Output over range	up to +12V
Output bandwidth	+20mA range: dc to 2 kHz Other ranges: dc to 10 kHz
Output noise/resolution (typical)	0.3 uArms/ $\sqrt{\text{Hz}}$
Output accuracy	+/-0.5% +/-zero-offset (can be zeroed) +/-magnetic field drift +/-temperature drift
Output impedance	100-ohm for high-impedance readout,
Output current	20mA max, source or sink
Output connectors	Isolated BNC on rear panel, for readout Isolated BNC on front panel, for monitoring
Readout	High impedance, unipolar or differential
Test function	Injects +100mA in sensor
Test control	TTL line on rear panel "controls" DB9
Calibration function	Under user control
Calibration winding	10-turn floating calibration winding on sensor
Calibration current	from external source (2A max, $Z > 100$ ohm)
Calibration connectors	Isolated BNC on rear panel, and Isolated BNC on front panel
Sensor	See dimensions and weight table
Sensor saturation	External magnetic field: 20 Gauss max.
Radiation resistance	Standard sensor contains PVC Optional radiation resistant sensor made from halogen-free high radiation resistance materials (PE, PEEK; Radox..)
Sensor connector	On standard sensor: DB15 male on sensor On radiation-resistant sensor: 3-meter sensor cable, DB15 male terminated, attached to sensor
Sensor cable	On chassis back panel: DB15 female 8-pair multicore DB15/DB15 cable, 8.39-mm outer diameter, 83-mm minimum bending radius, radiation-resistant, flame retardant, low-smoke, halogen-free.
Sensor cable length	130 meters max.
Front-end filter	On standard model: Not required Required on optional radiation-resistant model
Destructive level	DC current: Unlimited Pulse charge: Unknown, but > 100 mC
Magnetic field sensitivity	100 $\mu\text{A}/\text{Gauss}$ (1mA/mT), typ.
Saturating field (axial)	100 Gauss (10mT) typ.
Temperature coefficient	Electronics: < 0.1 uA/K Sensor: 5 $\mu\text{A}/\text{K}$ typ.
Power supply autorange	98-132 & 185-264 Vac, 50/60 Hz, 1.5 Amax
Mains power connector	IEC; mains power cord not supplied
Operating temperature	-40...+80°C
Humidity maximum	Non-condensing
Sensor baking	$> 150^\circ\text{C}$, unknown max. temperature

DIMENSIONS

Toroid sensor

NPCT-xxx order codes	ID (min)	OD (max)	H (max)	Weight (Kg)
NPCT-055-	55	98	102	0.9
NPCT-075-	75	118	102	1.2
NPCT-115-	115	158	102	1.7
NPCT-130-	130	175	102	2.0
NPCT-175-	175	222	102	2.4
NPCT-195-	197	250	102	2.6
NPCT-202-	202	248	102	2.7
NPCT-245-	245	298	102	3.3
Dimensions en mm				

Electronics chassis

Height: 3U (DIN norms)
 Width: 19"
 Depth: 300mm + protruding connectors

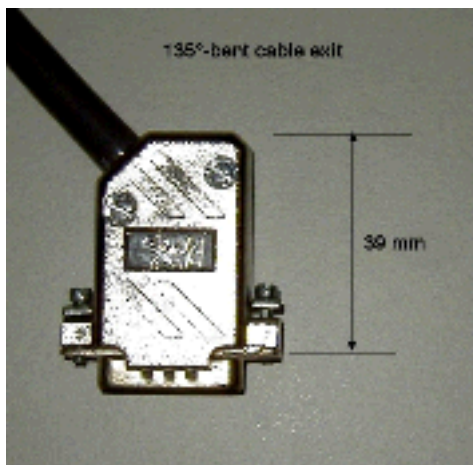
Sensor connector

DB15 sensor connector dimensions to be taken into consideration when designing the sensor installation and shield:

"Rad-hard" sensors, which order code includes "-H" suffix, are equipped with a 3-meter multicore cable going radially out of the toroid sensor head, terminated by a DB15 male connector (unless otherwise specially ordered).

Note: Belden specifies 83 mm as minimum bending radius.

"Standard" sensors which order code does not include "-H" suffix, are equipped with a male DB15 connector on the outer side of the sensor head. The connector point axially, its base flush with the sensor outer surface.



Interconnect cable connector mating the sensor head connector is female DB15 with metallized shell type 3M 3357-6515.

MAKING PRECISE MEASUREMENTS WITH New-PCT

The Challenge

New-PCT features excellent resolution ($<0.3 \mu\text{A}/\sqrt{\text{Hz}}$), outstanding linearity ($<0.01\%$ error), over 7 decades. To get the full benefit of these excellent performance, the user must pay special attention to the sensor temperature and its magnetic environment, because:

- Sensor head temperature drift is $5 \mu\text{A} / \text{K}$ typ.
- Sensor head external magnetic field sensitivity is $1\text{mA}/\text{mT}$ typ. ($=100 \mu\text{A}/\text{Gauss}$).

Note: New-PCT electronics are fully compensated for temperature drift.

Many PCT users obtained –on their accelerators– performances very close to the maximum attainable in a noiseless, temperature-stable lab environment. This should be possible too with the New-PCT.

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

- Proper installation of the sensor head 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 New-PCT system is well protected against RF interference at every stage of the circuit. To further protect the New-PCT against RFI, ferrite cores can be installed on all cables connecting to the New-PCT:

- a) the interconnect cable. They can be installed at any convenient distance from the sensor.
- b) the mains power cord
- c) the readout cable
- d) any calibration cable, permanently or occasionally connected to New-PCT.

Grounding scheme

The New-PCT system has two ground reference points:

- 1) The electronics chassis
- 2) The optional grounding 5-mm wide lug on the sensor head.

The electronics chassis is grounded thru many points, any of which may cause interference:

- a) the 19" cabinet ground
- b) the mains power ground
- c) the readout cable shield
- d) the calibration current shield, even though the calibration winding is floating

All New-PCT internal grounds are locally floating and referred to the chassis ground.

Note: The power cord ground lead MUST be connected to ground for safety reasons.

The New-PCT sensor head has an optional grounding 5-mm wide grounding lug. It may be beneficial to connect this grounding lug to the vacuum chamber ground. Whether this is beneficial or not can only be established by experience.

Rad-hard sensor heads, i.e. whose order code contains the suffix "-H", has a 3-meter cable which connects to a front-end filter in a metal shielded box. This box must NOT be grounded.

MAKING PRECISE MEASUREMENTS WITH THE New-PCT (Cont'd)

Output readout

New-PCT output signal must be read by a "Readout instrument".

The type of Readout instrument to be used depends on the user's requirements:

- Oscilloscope
- Voltmeter, 4-1/2 to 7-1/2 digits depending on range and requirements
- Integrating voltmeter
- High-resolution ADC
- High sampling rate ADC, averaged for higher resolution.

In all cases, an anti aliasing filter with a corner frequency equal to or lower than half of the sampling rate is highly recommended.

Voltmeter, ADC input range

The New-PCT output voltage range exceeds -10V...+10V. The Readout instrument input must preferably be bipolar. Even though the beam current is unipolar in most accelerators, the New-PCT output may occasionally be of opposite sign due to the zero offset.

Mains frequency

Whenever the current measurement bandwidth is below 50/60 Hz, every attempt should be made to eliminate the 50/60Hz EMI present everywhere. For instance, the readout could be averaged over 20ms resp. 16.66ms for 50 Hz and 60 Hz installations.

Nulling the zero offset

The zero offset can be nulled with the multi turn front panel potentiometer. This is not convenient during normal operations. For optimum precision, the New-PCT zero offset should be read in the absence of beam current, and deducted from further reading.

Readout software

The readout software can filter the New-PCT output to the desired bandwidth. More than one filter scheme can be implemented depending on the users' individual needs. The software can 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 sensor head, the software can read –when there is no beam– the offset caused by nearby magnets and bars, and deduct it from further readings.

Note: The software must assume the New-PCT output voltage to be bipolar.

Readout instrument installation and connection

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

New-PCT output must be read in a high impedance input.

Note: New-PCT signal outputs on the front-panel BNC and chassis rear BNC are referenced to the New-PCT cassette ground. They are isolated from the chassis.

MAKING PRECISE MEASUREMENTS WITH THE New-PCT (Cont'd)

Readout circuit noise rejection

The readout instrument input should be high-impedance. Therefore, noise can be collected thru EMI and RFI can be demodulated by the readout instrument. These interference's can be significantly reduces or eliminated by the use of common-mode filters. 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.

Ferrite cores can be replaced advantageously by cores of amorphous cobalt alloy or nanocrystalline iron alloy.

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

Check noise going into the Readout instrument.

1. Disconnect output cable from New-PCT chassis.
2. Short disconnected BNC connector. Use a BNC 50-ohm termination if no short is available. The noise measured by the Readout instrument is now the noise picked up by the cable.
3. While the BNC is shorted, let the body of the BNC make contact with the New-PCT chassis. Now, the Readout instrument measured all sources of noise.

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 New-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 quarter-wave mode ringing in the cavity.

Note: New-PCT and MPCT-S sensors are sensitive to external magnetic fields, typically 100µA/Gauss.

For precision measurements, these sensors must be shielded.

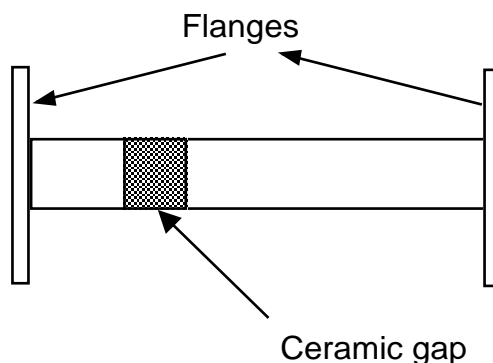
FCT and ICT sensors do not need to be protected from external magnetic fields. When they are exposed to external magnetic fields they may saturate; this causes the droop to increase up to a factor of 2. It has no effect on the sensor linearity at the frequency of the beam.

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.

New-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 New-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 New-PCT or MPCT-S sensors do not function anymore.

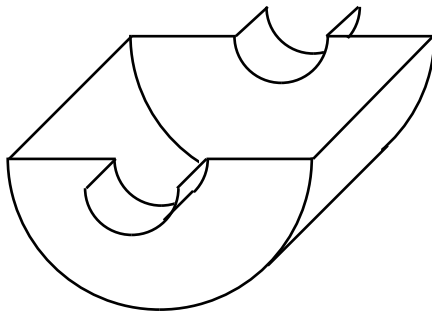
To protect the sensor against stronger fields, an outer shield with high saturation value must be installed. Typical materials are soft iron, low-carbon steel. 1-2 cm is typical thickness. This shield must preferably be longer than the mu-metal shields.

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.

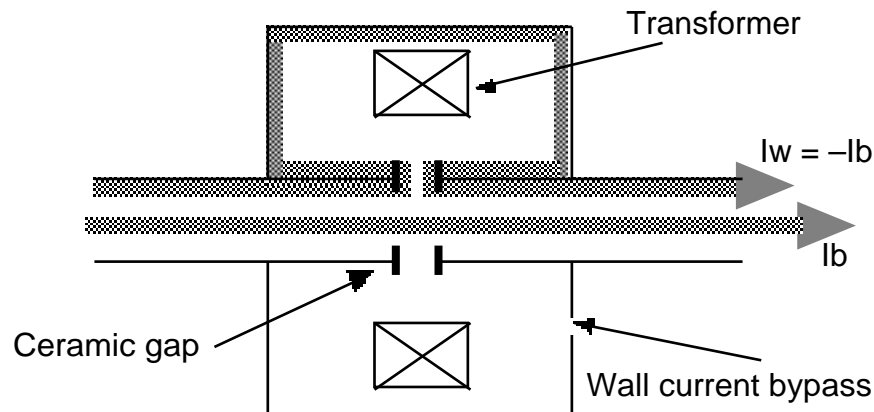
**MAXIMUM STORAGE AND OPERATING TEMPERATURE 120°C (250°F)
AT ANY TIME.** The alloy loses its characteristics when heated beyond this temperature.

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 New-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 $100 \text{ pF} \leq C \leq 1 \text{ nF}$

For ICT with 70 ns output, the gap capacitance should be $1 \text{ nF} \leq C \leq 1 \text{ }\mu\text{F}$

For New-PCT and MPCT-S, the gap capacitance should be $10 \text{ nF} \leq C \leq 220 \text{ nF}$

The gap impedance is determined by its capacitance:

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

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 100 μ m-thick kapton foil. To obtain the desired capacitance value, the overlapping area is obtained by:

$$S = C d / \epsilon_r \epsilon_0$$

Where:

C is the capacitance [F]

S is the area [m²]

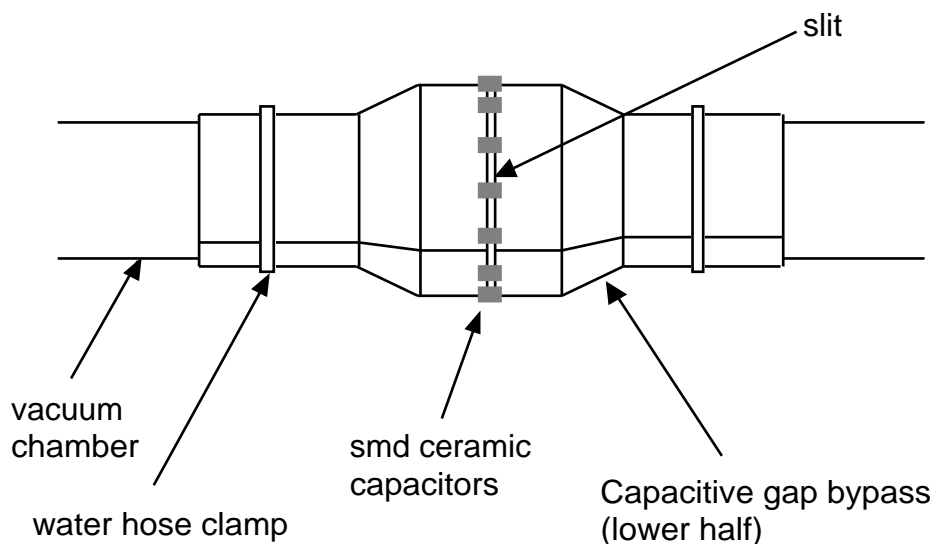
d is the dielectric thickness [m]

ϵ_r is the relative dielectric constant, 3.5 for Kapton polyimid

ϵ_0 is the dielectric constant 8.86×10^{-12}

Example, for C = 2.54 nF and d = 100 μ m and $\epsilon_r = 3.5$, S = 82 cm².

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 New-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 sensor head hole...

Low level saturation is usually "erased" by the action of the New-PCT modulator. In this case, the New-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 New-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:

- Switch off the mains power, or pull out the chassis mains plug.
- Reapply the mains power.

If for whatever reason the power is interrupted, the sensor head is demagnetized.

After demagnetization, the zero offset 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 $<10 \Omega$ at 30 kHz will cause an increase of the output noise.

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

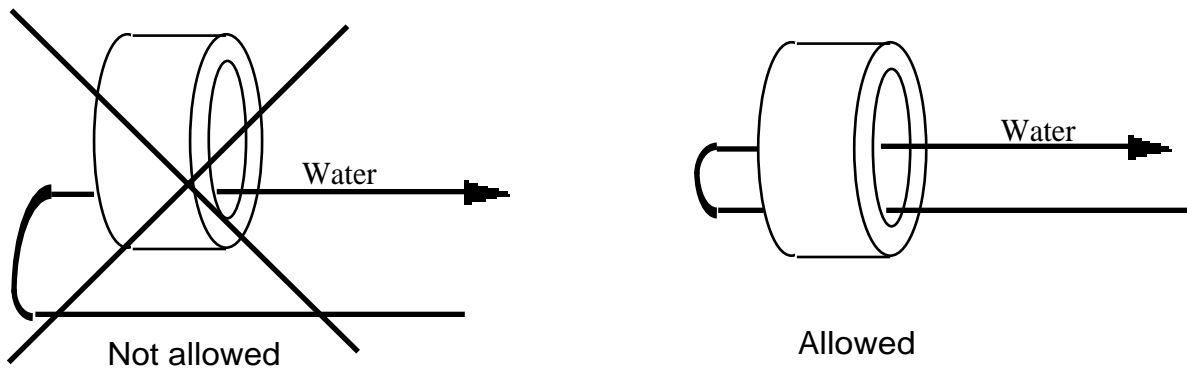
Unwanted currents

The New-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 New-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.



External magnetic fields

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

Ionizing radiations

The New-PCT chassis must be protected against exposure to ionizing radiations. Doses as small as 10² Gy can damage the Mos components used.

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

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

RADIATION RESISTANCE

Radiation sensitive materials used in the "Standard" sensor head

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

			Radiation resistance ¹
Wiring insulation		Polyvinyl chloride	2×10^5 Gy
		Fiber glass	$> 10^8$ Gy
		with rubber adhesive	$> 10^6$ Gy
Stress absorbent		Silicon rubber tape	5×10^5 Gy
		Silicon rubber	2×10^5 Gy
Cables	Insulation	Polyvinyl chloride	2×10^5 Gy
	Shield	Aluminium Polyester	$> 10^5$ Gy
	Sleeve	Polyvinyl chloride	2×10^5 Gy
Connector	Insulation	Polyphenylene sulphide Ryton-R-4	$> 5 \times 10^7$ Gy

Radiation sensitive materials used in the "Radiation Resistant" sensor head

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

Wiring insulation		Polyether-ether-ketone PEEK	6×10^7 Gy
		Fiber glass	$> 10^8$ Gy
		with rubber adhesive	$> 10^6$ Gy
Stress absorbent		Polyurethane foam	5×10^6 Gy
		Polyurethane rubber	5×10^6 Gy
Cables	Insulation	Crosslink Polyolefin	10^6 Gy
	Static shield	Metallized polyester	$> 10^5$ Gy
	Sheath	Polyethylene low-smoke, no-halogen	10^6 Gy
Connector		Connector is on cable: no connector on sensor	

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: December 2004

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

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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. Sharp¹). 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 modulator² 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 ISR¹, 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 applications³ for precision DC and AC current measurements.

A new generation of beam current monitors⁵ 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 collaboration⁷ 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.

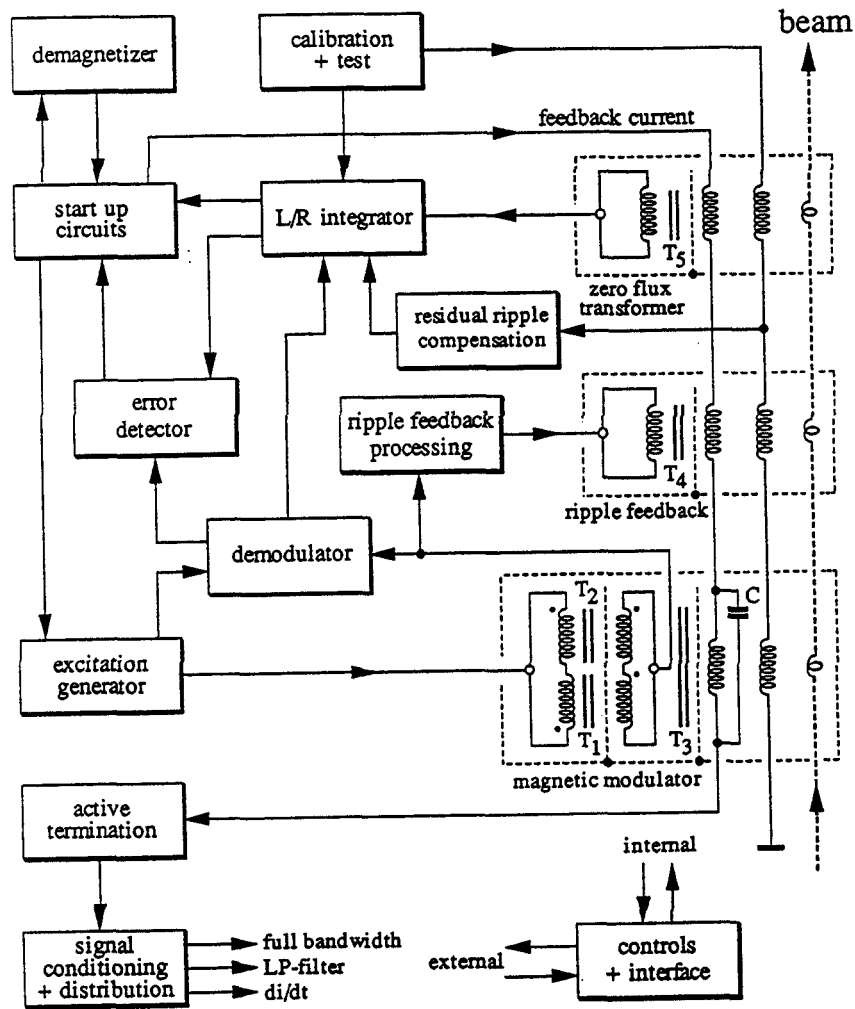


Fig. 1. Simplified block diagram of the PCT

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 $\pm 2 \mu A$.

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 decoupled⁴ 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 instruments⁴ 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 mm² 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.

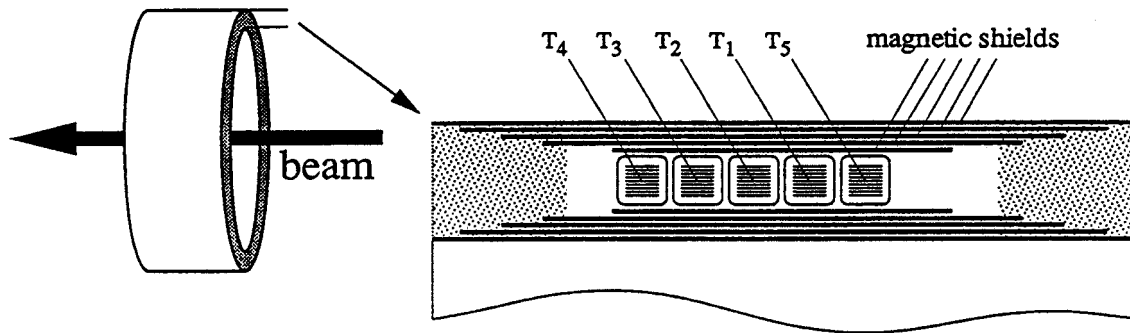


Fig. 2. Toroid assembly, simplified cross-sectional view (windings not shown)

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 ($B_s < 0.5$ Tesla)
- good surface quality
- no brittleness

The selected material is submitted to a series of tests to determine the specific annealing conditions⁵ 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 publication⁵ 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

* 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

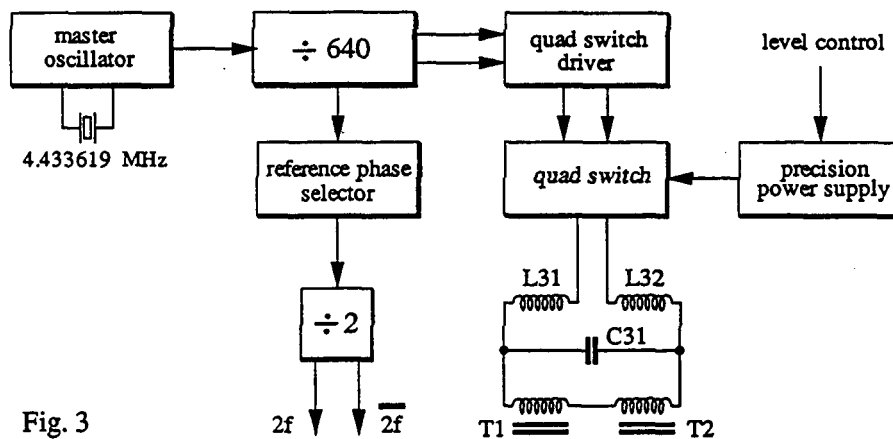


Fig. 3

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 $\leq 1\%$ 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 configuration⁵ 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.

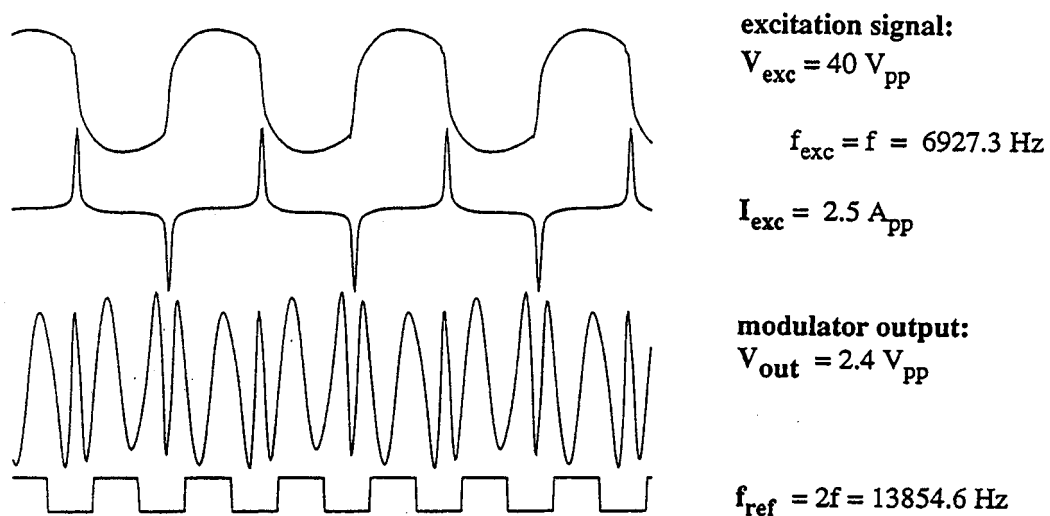


Fig. 4. Typical signal waveforms observed on a magnetic modulator (plot of display, averaged signals, on LeCroy 9410 oscilloscope). The core matching in this example is better than 0.5%. The exact waveform of the output signal is an individual “signature” for every magnetic modulator.

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 amplification⁵ 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.

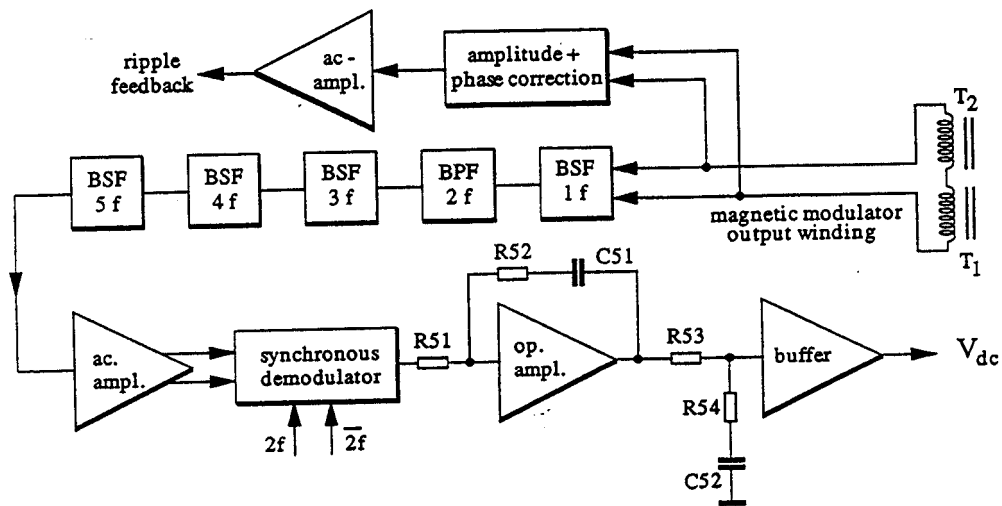


Fig. 5. Simplified block diagram of demodulator

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 $R51 \times C51$ 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

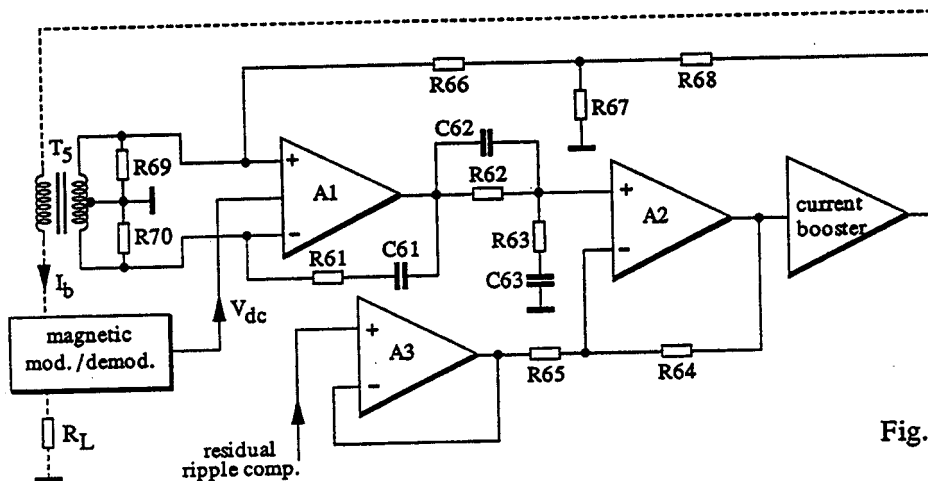


Fig. 6

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 T_5 . 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

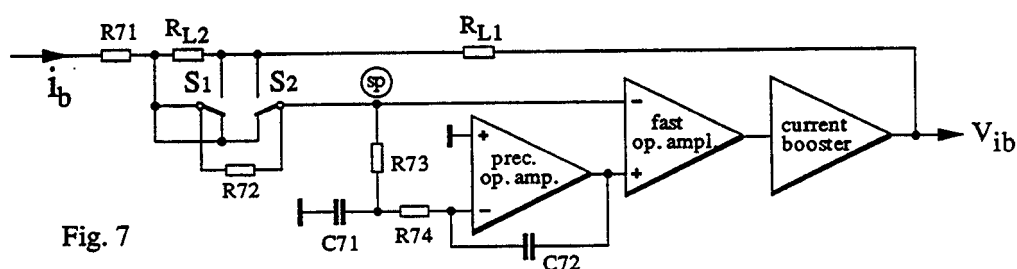


Fig. 7

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 (50Ω) 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

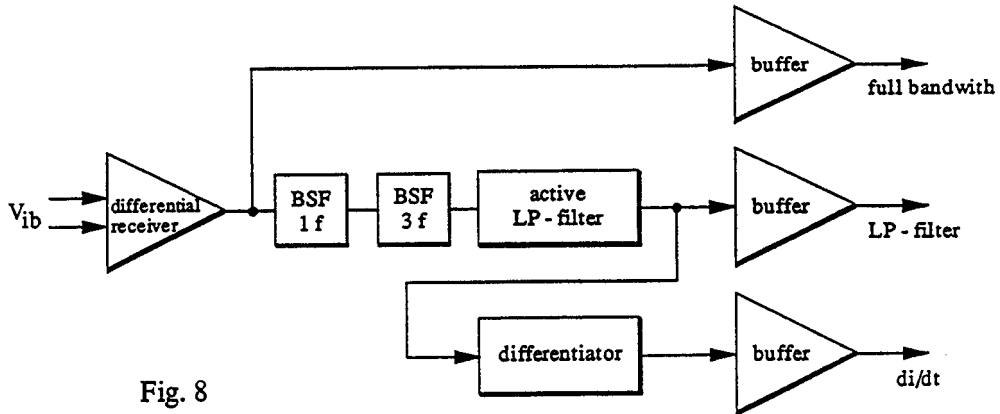


Fig. 8

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 filters⁶ (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 *	$\pm 0.001 \% \pm$ zero error
Resolution *	± 0.3 ppm of range (A) $\pm 0.4 \mu A$ rms ($\pm 1 \mu A$ rms typical)
Zero drift *	$\pm 1 \mu A/^{\circ}C$ ($\pm 5 \mu A/^{\circ}C$ typical)
Zero drift (24 h) *	$\pm 2 \mu A$ rms (at constant temperature)
Bandwidth	DC to 100 kHz
Accuracy (calibration source)	$\pm 0.05 \%$

*) 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 μ A. The cause of these phenomena are not known.

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