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A Proposal for an Inductive Pick-Up for Measuring the Position and Current of Proton Beams in the Transfer Lines between the Linac 2 and the PSB

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Abstract

Positions of proton beams on the transfer lines between the Linac 2 and the PS Booster are currently measured by 20 magnetic pick-ups (MPUs). These devices were installed almost 30 years ago and now they show signs of fatigue. The pick-ups are radioactive, which complicates maintenance and some of the spare parts are not easily available any more. The pick-ups have two control/acquisition systems based on the obsolete BODY protocol. The software runs on two DSCs and, since the MPUs do not provide intensity signals, the position signals are normalized using beam transformer readings. This paper describes a proposal for replacing the old system by an adapted version of a position and current measurement system recently developed for CTF3, based on an inductive pick-up (IPU). The replacement would only require a modest development effort consisting of scaling up the CTF3 IPU for dimensions of the transfer line vacuum chamber and building a transresistance amplifier to lower the low cut-off frequency of the system for the much longer (as compared to CTF3) Linac 2 pulses. The paper contains a more detailed description of these two crucial parts. The rest of the system, namely the active hybrid circuit, the calibration current generator, the acquisition system based on fast digitizers and its software could be copied from the CTF3 system with only minor modifications. The new system would provide intensity signals, conserve the low cut-off frequency of the present system and increase the high cut-off by a decade. It is expected to be less sensitive to electromagnetic interference and have better noise performance. The whole system could be run on a single DSC and would have a much simplified timing system. In addition it could provide an accurate absolute current measurement of proton beams by calibration with a precise current source.

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1. Introduction

Positions of proton beams on the transfer lines between the Linac 2 and the PS Booster [(1)] are currently measured by 20 magnetic pick-ups (MPUs) [(2)] **[1, 2, 3]**. These devices were installed almost 30 years ago and now they show signs of fatigue. The pick-ups are radioactive, which complicates maintenance and some of the spare parts are not easily available any more. The pick-ups have two control/acquisition systems based on the obsolete BODY protocol. The software runs on two DSCs and, since the MPUs do not provide intensity (Σ) signals, the position (Δ) signals are normalized using beam transformer readings.

This paper describes a proposal for replacing the old system by an adapted version of a position and current measurement system recently developed for CTF3 **[4]**, based on an inductive pick-up (IPU) **[5]**. The replacement would only require a modest development effort consisting of scaling up the CTF3 IPU for dimensions of the transfer line vacuum chamber and building a transresistance amplifier to lower the low cut-off frequency of the system for the much longer (as compared to CTF3) Linac 2 pulses. The paper contains a more detailed description of these two crucial parts. The rest of the system, namely the active hybrid circuit, the calibration current generator, the acquisition system based on fast digitizers **[4]** and its software could be copied from the CTF3 system with only minor modifications. The new system would provide intensity signals, conserve the low cut-off frequency of the present system and increase the high cut-off by a decade. It is expected to be less sensitive to electromagnetic interference and have better noise performance. The whole system could be run on a single DSC and would have a much simplified timing system. In addition it could provide an accurate absolute current measurement of proton beams by calibration with a precise current source.

2. The present system

The MPUs of the Linac 2 to PS Booster transfer lines (LBTL) were constructed in the 70s. In total there are 20 pick-ups listed in **Table 1**, 12 of which are like shown in the photograph of **Fig. 1a**. The remaining 8 pick-ups are stacked by fours forming two stations for the PSB injection. Such a station can be seen in the photograph of **Fig. 1b**.

Despite the fact that all the sensors are of the same type, they are distributed over two control/acquisition systems, as indicated in **Table 1**. The LTU system runs in the DSC `dlintraf` and BIU in the DSC `dpsbbdi`.

The MPUs have two acquisition systems, one located close to the Linac 2 and the second close to the PSB injection, to limit the necessary cable length and, in consequence, the cable cost which is an important part of the system total price.

(1) The PSB proton injection lines are considered in the paper also as a part of the transfer lines.

(2) In CERN jargon the pick-ups are called also UMAs.

Table 1. General information about the magnetic pick-ups currently installed. SW – software controlling the pick-up, BT – the corresponding beam transformer used for the position signal normalization. The beam transformer station BI.TRA20 contains four sensors stacked up.

#	Pick-Up	SW	BT	Remarks
1	**LT.U10**	LTU	LT.TRA10	single
2	**LT.U20**	LTU	LT.TRA20	single
3	**LT.U30**	LTU	LT.TRA20	single
4	**LT.U40**	LTU	LT.TRA30	single
5	**LT.U50**	LTU	LT.TRA40	single
6	**LTB.U10**	LTU	LT.TRA50	single
7	**LTB.U20**	LTU	LT.TRA50	single
8	**LTB.U30**	LTU	LT.TRA60	single
9	**BI.U00**	BIU	BI.TRA10	single
10	**BI.U10**	BIU	BI.TRA10	single
11	**BI.U20**	BIU	BI.TRA10	single
12	**BI.U30**	BIU	BI.TRA10	single
13	**BI1.U40**	BIU	BI1.TRA20	PSB ring #1
14	**BI2.U40**	BIU	BI2.TRA20	PSB ring #2
15	**BI3.U40**	BIU	BI3.TRA20	PSB ring #3
16	**BI4.U40**	BIU	BI4.TRA20	PSB ring #4
17	**BI1.U50**	BIU	BI1.TRA20	PSB ring #1
18	**BI2.U50**	BIU	BI2.TRA20	PSB ring #2
19	**BI3.U50**	BIU	BI3.TRA20	PSB ring #3
20	**BI4.U50**	BIU	BI4.TRA20	PSB ring #4

The MPUs only provide Δ signals, which are intensity dependent. To normalize the Δ signals and therefore remove this dependency, the intensity signal from a beam transformer located nearby is used. The beam transformers are also treated by software tasks running in the same abovementioned DSCs, such that each MPU system can get the necessary intensity information locally. The beam transformers used for the normalization are listed in **Table 1**.

The Δ signals of the LTU and BIU systems are digitized at a rate of 10 MHz by STR755 type ADC modules (8-bit, 40 MHz flash ADCs, obsolete). Since the Linac 2 beam is chopped to feed the four PSB rings, the samples corresponding to each part, injected later into the individual rings, are treated separately. On the operator display one can see four trajectories already starting in the Linac 2, each for one PSB ring.

The MPU construction is shown in the photographs of **Fig. 1**. Each MPU consists of two sub-pick-ups for measuring the beam position in the horizontal and vertical planes; the sub-pick-ups are identical but they are turned by 90 degrees as shown in **Fig. 1c**. The ceramic insertion with bellows and conical flanges on both sides is also visible.

The heart of each sub-pick-up, the sensing loop, is shown in the photograph of **Fig. 1d**. It makes one turn coupling to the beam electromagnetic field and the current induced depends on the beam position. The current in the loop is sensed by a current transformer shown also in the photograph. The transformer installation is shown in **Fig. 1c**. The sensing loops are surrounded by ferrite tiles.

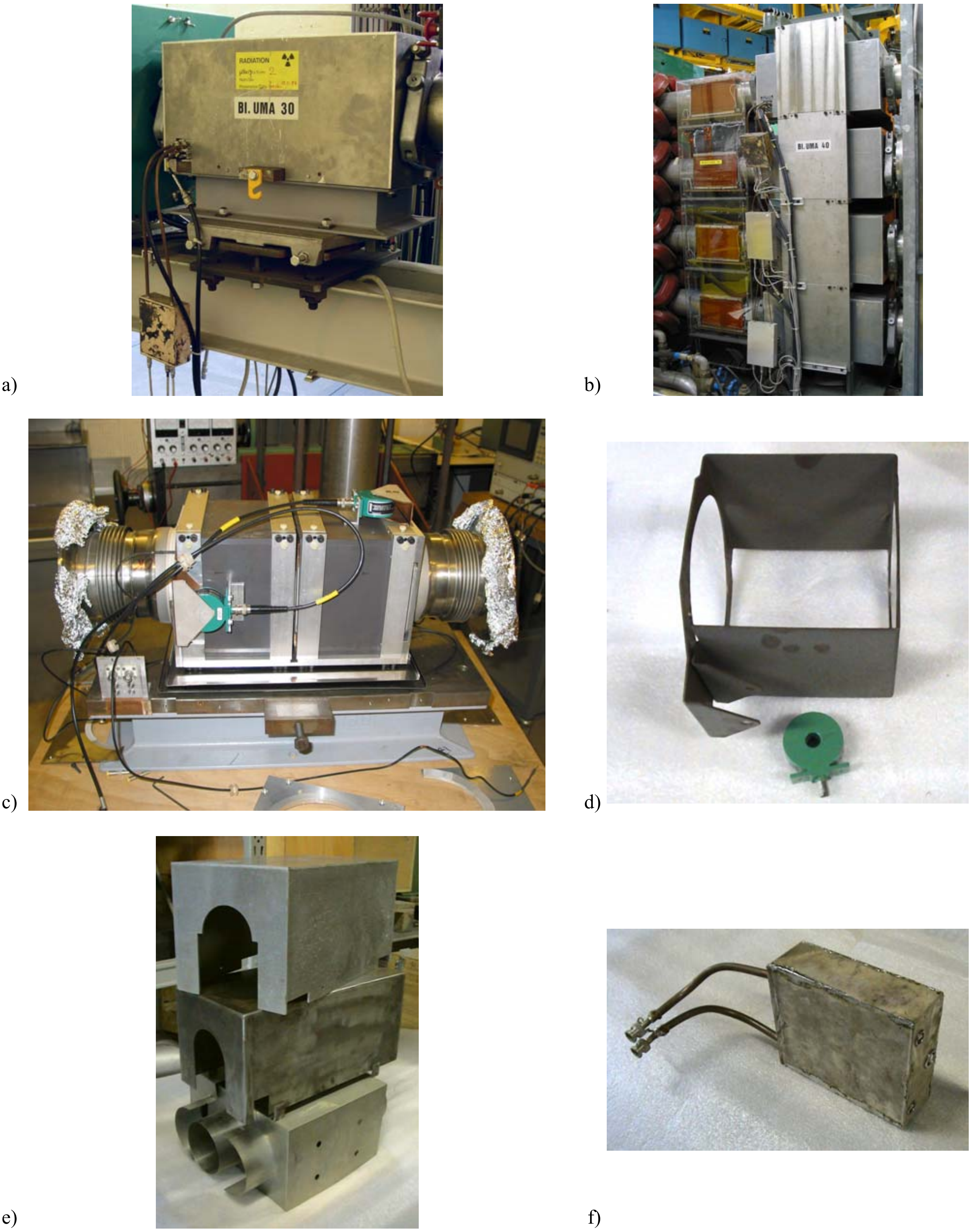
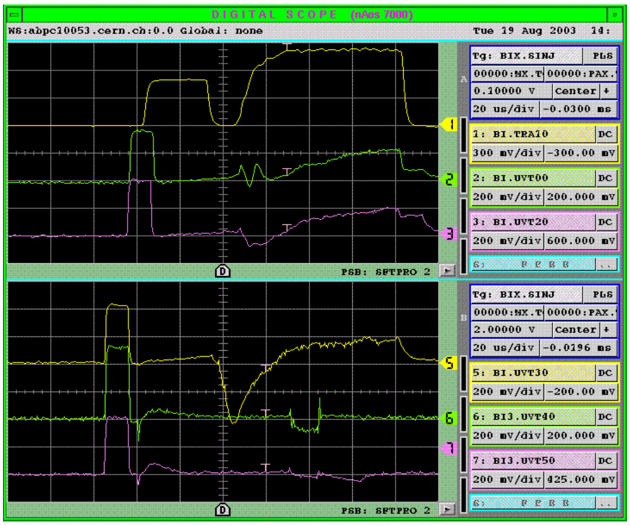
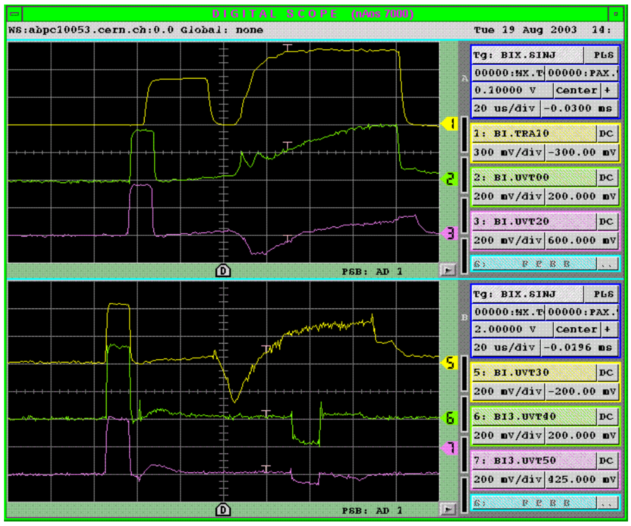


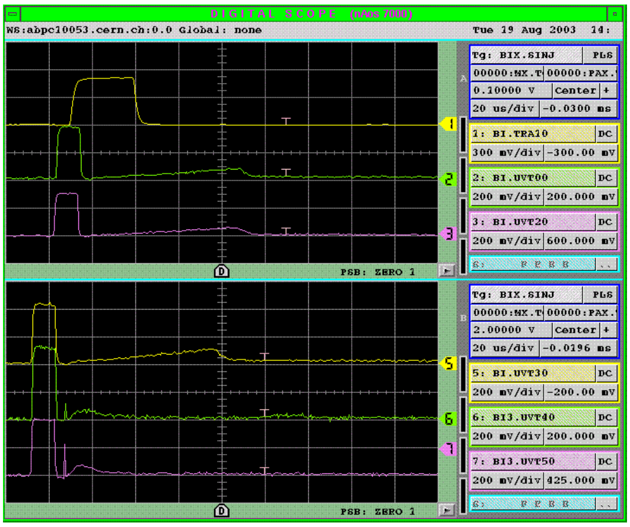
Fig. 1. Magnetic pick-ups of the present design and their amplifiers. **a)** A pick-up (LTB.U30 alias BI.UMA30) installed on a single transfer line. **b)** Four pick-ups (BI.U40 alias BI.UMA40) stacked for the PSB injection lines. **c)** LT.U20 in a lab with shielding shells removed for reparation during the shutdown 2002/2003 (courtesy of L. Søby). The left and right halves measure the horizontal and vertical positions respectively. The shielding shells do not have any connection to the vacuum chamber and there is no other electrical connection between the ceramic insertion extremities. **d)** The sensing loop. Each pick-up has two of them and each has its current transformer delivering the position signal. **e)** The four shielding boxes. The pick-up shown in Fig. c is put inside the innermost shell. All of them are insulated from each other and from the vacuum chamber. There is neither a DC nor a good AC path for the beam image current. **f)** The pick-up preamplifier. The box, containing horizontal and vertical channels, is soldered shut. There exist some newer amplifiers which can be opened. In Fig. b there are seen new and old amplifier types.



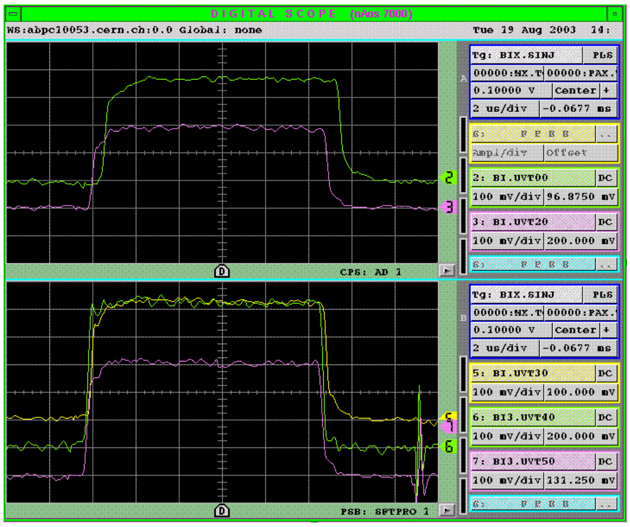
a) Cycle SFTPRO, 20 µs/div.



b) Cycle AD, 20 µs/div.



c) Cycle ZERO, 20 µs/div, no beam, only calibration seen.



d) Cycle SFTPRO, 2 µs/div, only calibration signals magnified.

Fig. 2. Intensity signal from the beam transformer BI.TRA10 (channel 1, yellow) and vertical Δ signals from the following magnetic pick-ups: BI.U 00 (channel 2, green), BI.U 20 (channel 3, magenta), BI.U 30 (channel 5, yellow), BI3.U 40 (for ring 3, channel 6, green), BI3.U 50 (for ring 3, channel 7, magenta). The signals were acquired with the nAaos observation system. **a)** All the six signals are shown for cycle SFTPRO. **b)** The signals for cycle AD. **c)** The signals for cycle ZERO. **d)** The signals for cycle SFTPRO, but with the calibration pulses magnified. In all pictures the first pulses on the signals (of the MPUs as well as of the beam transformer) are the sensor responses for calibration signals. The signals after the pulses in Fig. a and b correspond to the passing beam. In Fig. c it is shown a cycle without the beam to reveal the base line drifts. The responses to calibration signals are shown in Fig. d; they are quite noisy and of different amplitude.

The pick-up has as many as four shielding shells, shown in **Fig. 1e**. The pick-up core, shown in **Fig. 1c**, is put inside the smallest shield and then surrounded by the other three put one inside the other. The shells are insulated from one another as well as from the vacuum chamber, thus, to the author's surprise, there is no DC path for the beam image current from one side of the pick-up to the other. Also the capacitive coupling seems to be relatively small. The lack of a good connection between the pick-up extremities together with the number of pick-ups inserted in the transfer lines might result in an excessive longitudinal impedance, which, in consequence, could be a potential source of quality deterioration of the lines.

The pick-up has a calibration wire simulating the beam (seen in **Fig. 1c** as a wire sticking out on the left of the left pick-up box).

The pick-ups provide horizontal and vertical Δ signals with amplitudes as small as 160 µV/mm with beam currents of 200 mA **[1, 2, 3]**. The signals are amplified by a two channel amplifier with differential outputs and a gain of about 500. The output signals are transmitted to the equipment room by twisted pair cables and there connected to base line restitution circuits. These are needed to suppress strong interference superimposed on the useful signals. They clamp the base line at zero level before and after each beam passage and they let the signals change only during the time of expected beam. The circuits require triggers derived from timing signals.

The base line restitution modules have also an additional low frequency gain to improve the MPUs low cut-off. Probably it would have been much better if this had been done in the amplifier installed close to the pick-ups to avoid amplifying interference likely gathered along the twisted pair cables.

The vertical Δ signals from 5 MPUs are shown in **Fig. 2** together with the intensity signal from the beam transformer BI.TRA10 (channel 1, in yellow). They were captured using the nAos observation system. The signals shown are from the following MPUs:

- BI.U00, channel 2, in green,
- BI.U20, channel 3, in magenta,
- BI.U30, channel 5, in yellow,
- BI3.U40, channel 6, in green, MPU of the ring #3,
- BI3.U50, channel 7, in magenta, MPU of the ring #3.

In **Fig. 2a** all six signals are shown for cycle SFTPRO, in **Fig. 2b** for cycle AD, in **Fig. 2c** for cycle ZERO and in **Fig. 2d** also for cycle SFTPRO, but with the calibration pulses magnified.

In all pictures the first pulses on the signals (of the MPUs as well as of the beam transformer) are the sensor responses for calibration signals. In **Fig. 2a** and **2b** the signals after the pulses correspond to the passing beam. In **Fig. 2c** a cycle with no beam is shown to reveal the base line drifts, which for some pick-ups are not small at all. Before and after the expected beam transition the base line is flat since the signals are tied to ground by the base line restitution circuits. The signals are subject to change only during the period of possible beam transitions and only then the base line can drift. And it does. The worst captured case is the BI.U30 (channel 5, in yellow) having the drift at the expected beam pulse end as high as some 20 % of the calibration pulse amplitude.

The responses to calibration signals are shown in **Fig. 2d**; they are quite noisy and of different amplitudes. From their rise time of about 0.2 μs (3) the high cut-off frequency of the system can be assessed as some 2 MHz. No important signal droop can be seen. Assuming that the droop of some 3 % over the 10 μs pulse length could have been noticed one can estimate the low cut-off frequency to be not smaller than some 200 Hz. The time constant of the MPU signal decay is specified in **[3]** as 600 μs, corresponding to the cut-off frequency of 260 Hz. The observed value is obtained by a frequency characteristic correction in the base line restitution modules.

3. The new system

The new system would be based on the IPU system **[4]** developed for CTF3. Both systems would be very similar except for two parts: the pick-up itself, which would have to be scaled up to fit to the vacuum chamber of the LBTL, and a transresistance amplifier (4). Four identical channels of the amplifier would provide a very low impedance load for the pick-up outputs to obtain an appropriate low cut-off frequency of the system. The amplifier would be connected to the active hybrid circuit developed for CTF3. The rest of the new system could be very similar to that of CTF3.

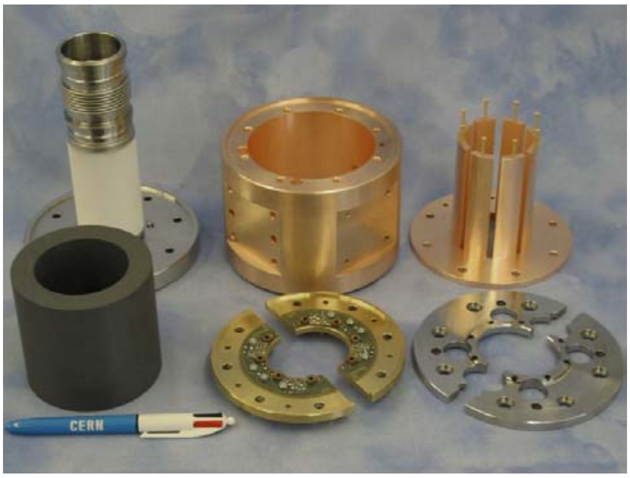


Fig. 3. Parts of the IPU of CTF3

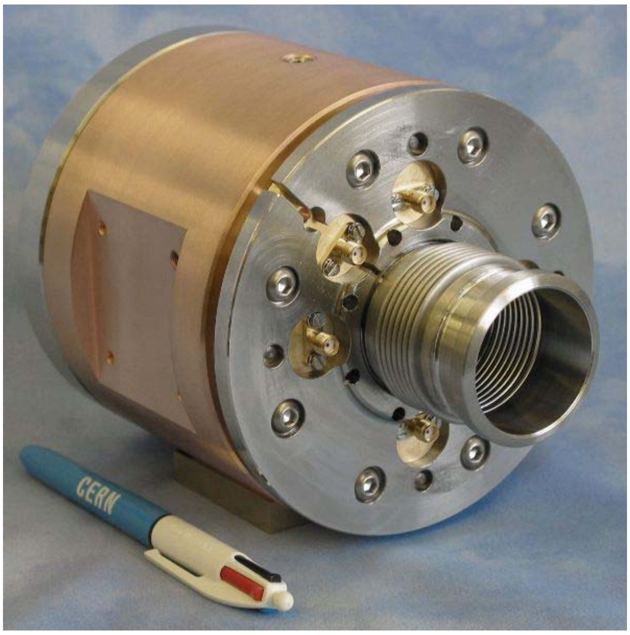


Fig. 4. The IPU of CTF3 assembled.

The parts of the IPU of CTF3 are shown in **Fig. 3** and the assembled pick-up in **Fig. 4**. The simplified cross-sections of the IPU for the LBTL and of the CTF3 IPU are shown in **Fig. 5** (scale about 1:4).

The IPU senses the azimuthal distribution of the beam image current. Its construction is similar to a wall current monitor, but the pick-up inner wall is divided into 8 electrodes, each of which forms the primary winding of a toroidal transformer. The beam image current component flowing along each electrode is transformed to a secondary winding. Adjacent electrodes are combined in pairs by connecting the secondary windings in series and each pair has one corresponding output. In the CTF3 system four pick-up output signals drive an active hybrid circuit producing the usual Δ and Σ signals. Some further details concerning the IPU of CTF3 can be found in **[5]**.

For the LBTL the pick-up would be scaled up from the 40 mm aperture to 120 mm to fit the larger vacuum chamber and to be mechanically compatible with the present MPUs. The principal features of the IPU, namely

(3) The amplifiers have bandwidth of 16 Hz – 3 MHz and a rise time of about 0.14 μs [3].

(4) In the paper the circuit is referred to as a transresistance amplifier since its input signal is a current and the output signal – a voltage. It can be also understood as a current to voltage converter.

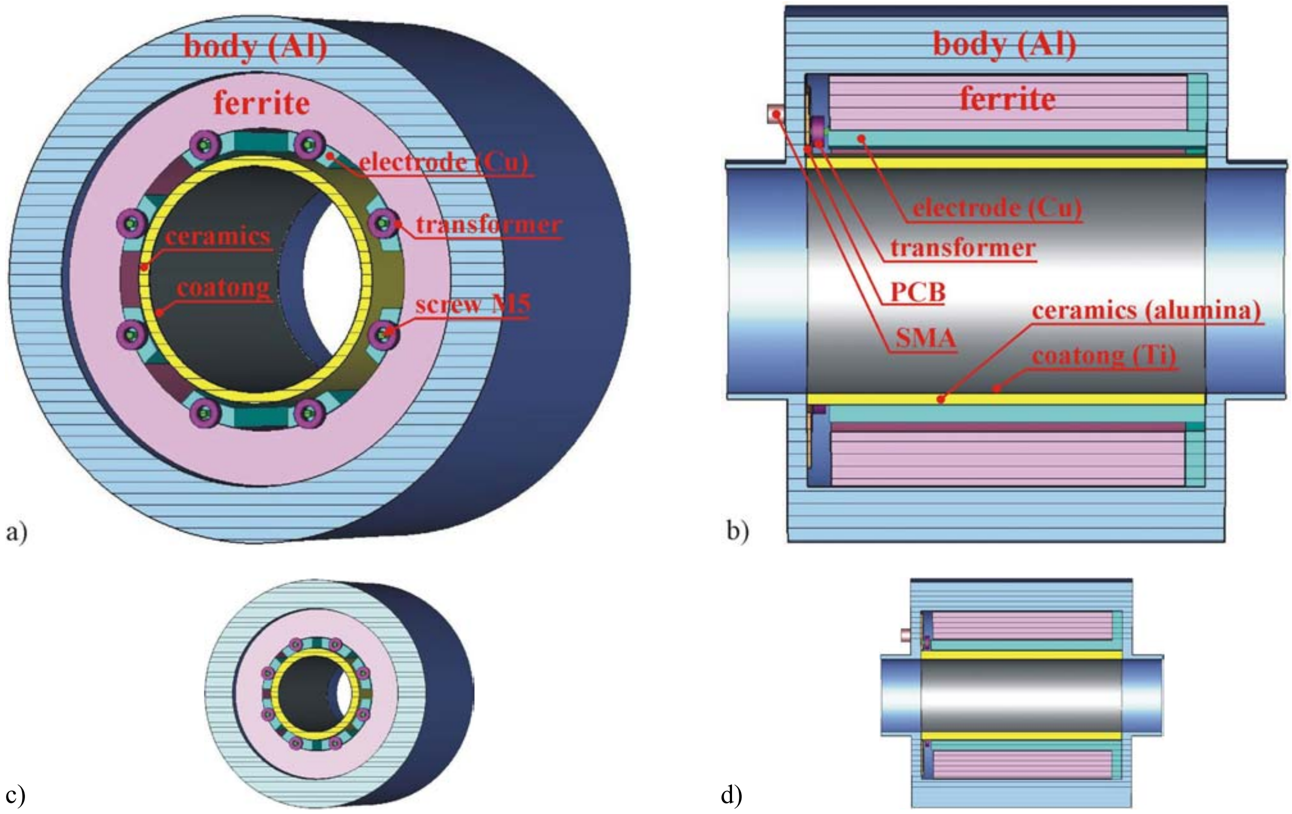


Fig. 5. Simplified cross-sections of the IPU being proposed (Fig. a and b) and the IPU of CTF3 (Fig. c and d). Scale about 1:4.

assembly scheme, eight electrodes, transformer arrangement and calibration methods would be conserved. Some minor changes would be necessary, for example, the pick-up body would be made of an aluminium alloy instead of copper to limit cost of the material and reduce the pick-up weight. Probably the electrodes and the supporting plate would be made as separate parts to limit the amount of copper needed. That would be possible, since requirements for high cut-off frequency and mechanical precision are less demanding than those of the CTF3 system.

The other modifications would lower the Δ signal low cut-off frequency of the system from 1 kHz as achieved for CTF3, to some 200 Hz to limit the droop of the 110 μs long Linac 2 pulse **[6]** and improve system performance for smaller beam currents. The modifications would be the following:

- Since each existing MPU occupies about 60 cm of the transfer line, the new IPU can be made much longer than that of CTF3 to improve its low frequency response. On the other hand, the electrodes have to be rigid so they cannot be too long. It seems to be reasonable to have the electrodes some 200 mm long. The IPU would not have any bellows, but they would be part of an adaptation vacuum assembly making it mechanically compatible with the existing MPUs.
- To get sufficient low cut-off frequency, the parasitic resistances in the electrode paths have to be kept below 0.1 mΩ. For this, the cross-section of the electrodes would be increased. That would allow also using much bigger transformer screws made from copper. In the CTF3 design CuBe M2 screws were used, which introduced most of the parasitic resistance observed.
- The electrode transformers would have much fewer turns wound with a thicker wire. They would be much simpler to make. No PCB would likely be needed.

In the existing MPU the current transformer has some 500 turns, making it very big and slow. That was needed to provide the large transformation ratio of its 50 Ω load to the sensing loop. The new design would have much smaller transformers with only some 10 turns, but it would be loaded with a very small impedance produced actively by a transresistance amplifier. Fewer turns would give more current in the secondary winding, improving noise performance of the system. Four transresistance amplifiers would be connected to each pick-up output and drive the standard CTF3 active hybrid circuit producing Δ and Σ signals. The insulation between Δ and Σ channels would not be as good as in the CTF3 system, but, since the new system would be meant to work up to some 10 MHz, some 50 dB insulation should still be possible. For frequencies below 1 kHz the common mode rejection might be smaller due to asymmetry arising in the transformer circuits.

The new pick-up would introduce a very small resistance in the beam path, since it has a fraction of a mΩ galvanic connection between its extremities. It was also optimized to have a low longitudinal impedance up to the GHz range.

The IPU being proposed is expected to be better coupled to the beam than the existing MPU, meaning a better noise performance, since for the IPU the whole image current would have to pass through the transformers.

It is observed that the existing MPUs are very sensitive to external magnetic fields, which can be quite strong as

Table 2. Mechanical parameters of the IPU of LBTL being proposed and the IPU of CTF3.

Part	Dimensions for the transfer line IPU	Dimensions for the CTF3 IPU
Beam pipe diameter	120 mm	40 mm
Total length, external diameter	≈ 300 mm, no bellows, ≈ 300 mm	168 mm with bellows, 130 mm
Electrode length	≈ 200 mm	85 mm
Electrode internal ∅, electrode thickness	≈ 140 mm, ≈ 10 mm	49 mm, 5 mm
Electrode width, gap between electrodes	≈ 20 mm, ≈ 35 mm	14.2 mm, 5 mm
Δ electrode inductance / its parasitic resistance	≈ 250 nH, < 0.1 mΩ	70 nH, 0.5 mΩ
Ferrite internal ∅, thickness, length	≈ 170 mm, ≈ 30 mm, ≈ 200 mm	60 mm, 15 mm, 85 mm
Ferrite material, relative permeability	Ceramic Magnetics C2050, 100	Ceramic Magnetics C2050, 100
Ceramics internal ∅, thickness, length	120 mm, ≈ 8 mm, ≈ 200 mm	40 mm, 4 mm, 85 mm
Ceramics coating end-to-end and sheet resistance	≈ 5 Ω, 10 Ω/☐	10 Ω, 15 Ω/☐
Transformer internal ∅, external ∅, thickness	14.5 mm, 8.5 mm, 5.3 mm (standard)	7 mm, 3.2 mm, 2.3mm (special)
Transformer turn number, wire ∅, screw	≈ 10, ≈ 0.5 mm, M5 Cu	30, 0.15 mm, M2 CuBe

Table 3. Expected electrical parameters of the transfer line IPU system being proposed and the actual parameters of the CTF3 system in High Gain.

Parameter	Value for the transfer line IPU	Value for the CTF3 IPU system in High Gain
Maximum / minimum beam current	300 mA / 30 mA	1 A / some mA
Maximum / minimum pulse length	110 μs / 0.16 μs	1.5 μs / 5 ps (one bunch operation)
Measured displacement	± 40 mm (67 % of the aperture)	± 20 mm (50 % of the aperture)
Absolute accuracy	± 0.25 mm	± 0.1 mm
Σ, Δ low cut-off frequency of the system	< 100 Hz, ≈ 200 Hz	300 Hz, 1 kHz
Σ, Δ high cut-off frequency of the system	10 MHz	250 MHz, 150 MHz
Σ, Δ signal droop @ maximum beam pulse length	< 7 %, ≈ 13 %	0.3 %, 1 %
Σ, Δ rise time	40 ns, 40 ns	2 ns, 2.5 ns
Displacement for Δ = Σ	40 mm	10 mm
Calibration pulse	200 mA ± 0.1 %, 1 μs or 100 μs	300 mA ± 0.1 %, 1.5 μs or 150 μs
Σ channel noise	< 0.5 mA_{RMS}	< 5 mA_{RMS}
Δ channel noise @ maximum beam current	< 0.1 mm_{RMS}	< 0.1 mm_{RMS}

they are induced by nearby pulsing magnets. Even if an aggressor is located not very close, its far field is seen by the sensing loops of rather big surface and induces a signal in very much the same way as the useful magnetic field induced by the beam. The MPU Δ signals are very weak, so even relatively small fields can falsify pick-up readings by some millimeters, as seen in **Fig. 2c**, where signal drifts with no beam are quite important as compared to the calibration pulses.

Magnetic interference problems are recognized as the most challenging also for the new design. The new IPU is supposed to be relatively less sensitive for magnetic interference as it is better coupled to the beam and therefore bigger useful signals are expected. Also the electrodes would be surrounded by a thick ferrite cylinder, bypassing the interfering external magnetic fields. These are the two features of the new design on which one may count. To what extend this helps can be verified only by measurements.

Mechanical parameters of the IPU of LBTL are listed in **Table 2**, together with corresponding parameters of the IPU of CTF3. The expected electrical parameters of the new system are given in **Table 3** with corresponding parameters achieved in the CTF3 system. The expected parameters are calculated according to model simulations using PSPICE and Microwave Studio (pictures in **Fig. 5** are embellished input structures for Microwave Studio simulations). They seem to be compatible with operator specifications **[6]**.

The low frequency behaviour of two opposite pairs of electrodes, forming one IPU plane, together with two channels of the transresistance amplifier, can be modelled by the circuit shown in **Fig. 6**. Its parts are the following:

- Four branches with inductances L_Δ represent two opposite pairs of electrodes with one 1:n current transformer on each and resistors R_C stand for parasitic resistances of electrodes, screws and contacts. R_P represents the secondary winding load transformed to the primary.
- The current source ΔI_B represents a position signal induced by a beam displacement.
- L_Σ represents the inductance of loops built from electrodes and the pick-up body walls; the inductance is increased by the ferrite filling the loops. L_Σ shunts the beam image current I_B seen by the pick-up.
- The transmission lines represent cables connecting the pick-up with its transresistance amplifier; the cables would be some 0.5 m long.
- R_S represents parasitic resistances of the transformer windings (in total some 20 mΩ), resistance of about 0.5 m of coaxial cable (some 15 mΩ) and resistance of two SMA connectors (some 10 mΩ for both). The R_S value is estimated as 50 mΩ.
- R_I provides the line termination for high frequencies while for low frequencies it is shunted by L_I of only 500 nH or so. This is a small value, so L_I could be built

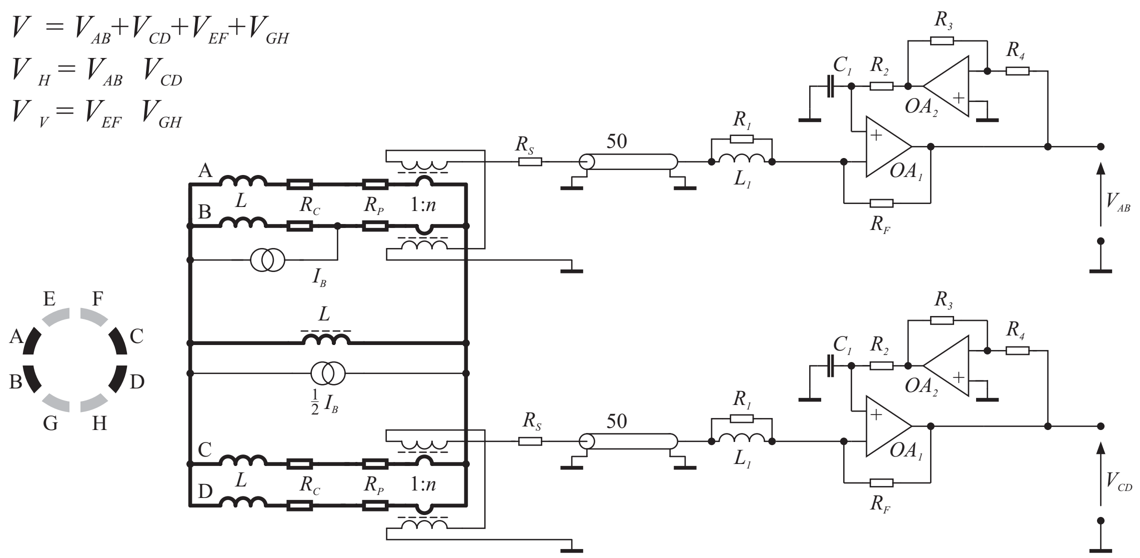


Fig. 6. An inductive pick-up model for one plane together with two channels of the transresistance amplifier.

as a ferrite bead on the cable central conductor and as such would introduce no important parasitic resistance.

- The operational amplifier OA_1 converts the secondary winding current into a voltage; the value of R_F is the conversion factor (for simulations 75 Ω was used).
- Since OA_1 has large DC gain ($R_F/R_S \approx 1500$), an auxiliary op-amp OA_2 provides a very low frequency feedback to compensate for the offset voltage of OA_1. Due to the very small impedance of the OA_1 inverting input, capacitive coupling cannot be used.

Components of the beam image current I_B flow through four $1{:}\,n$ electrode transformers, which are combined in pairs. Each transformer sees half of the secondary winding load R_S. The op-amp OA_1 creates a virtual ground at the inverting input, so the output Σ signal voltage (the sum of four electrode pairs) is

$$V_\Sigma = \frac{R_F}{2n} I_B \qquad (1)$$

and decays with the time constant set by $R_P = R_S/2n^2$ (representing R_S transformed to the primary winding), and inductance L_Σ. Taking into account parasitic resistances R_C of the primary loops this yields the Σ signal low cut-off frequency

$$f_{L\Sigma} = \frac{1}{2\pi\, L_\Sigma}\left(\frac{R_S}{2n^2} + R_C\right) \qquad (2)$$

provided that the transformer low cut-off is still smaller.

Similarly, the current ΔI_B resulting from the beam displacement decays with the time constant set by the sum $R_P + R_C$ and electrode inductance L_Δ. The corresponding low cut-off frequency is

$$f_{L\Delta} = \frac{1}{2\pi\, L_\Delta}\left(\frac{R_S}{2n^2} + R_C\right) \qquad (3)$$

Since $L_\Delta << L_\Sigma$, the more challenging demand is obtaining the Δ signal low cut-off frequency $f_{L\Delta}$. From Microwave Studio simulations L_Δ was evaluated as some 250 nH, so to have $f_{L\Delta}$ not smaller than 200 Hz, the term $R_S/2n^2 + R_C$ should be smaller than 0.32 mΩ. With $n = 10$ and $R_S = 50$ mΩ, the term $R_S/2n^2$ amounts to 0.25 mΩ, so for parasitic resistances in the primary circuit 70 μΩ remains. The resistance of the electrode and an M5 screw, both made from Cu, could be as small as some 30 μΩ, so there is another 40 μΩ to spare for contact resistances. If this was not enough, the turn number n could be easily doubled and the amplifier feedback could be modified to have an extra gain for low frequencies to correct the low cut-off frequency over an octave or two.

The system low cut-off frequency for the Σ signal would not be limited by the pick-up itself, but rather by the largest affordable value of series capacitors along the signal chain. It should be possible to get the frequency below 100 Hz.

The noise performance of the new system is expected to be better than that of the existing one. PSPICE noise analysis showed signal to noise ratio of some 70 dB in both Δ and Σ channels for a beam current of 300 mA and with an op-amp OPA642 (noise spectral density of $2.7\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, an op-amp with still better noise performance might be used). For noise parameters included in **Table 3** a smaller signal to noise ratio of 60 dB was used.

A big advantage of the new system would be the fact that the transresistance amplifiers would have a similar gain to the amplifiers of the existing system only for very low frequencies. The Δ signal gain G_Δ would decay 20 dB per frequency decade, limiting the total noise at the amplifier output. G_Δ is set by the ratio of R_F and the impedance seen from the *OA1* inverting input

$$G_\Delta = \frac{R_F}{2n^2(R_C + R_P + 2\pi \mathrm{j}\, L_\Delta f)} \cong \frac{R_F}{R_S + 4\pi \mathrm{j}\, n^2 L_\Delta f} \qquad (4)$$

reaching unity already at some 300 kHz. The gain for Σ signals is as (4) but with L_Δ replaced by an L_Σ bigger value, resulting in a still smaller gain.

Four transresistance amplifiers would be connected to a standard CTF3 active hybrid circuit. Further details concerning the acquisition system can be found in **[4]**.

The new IPUs system would conserve the CTF3 calibration scheme with a precise current source. For this purpose each electrode transformer would have an additional one turn winding (not shown on the schematic of **Fig. 6**), used to inject a current pulse of an amplitude known to 0.1 %, which, in addition, is independent of parasitic resistances of cables, connectors and the like. Similar pulses would be used to test the Δ and Σ channels, calibrate their gains and check the common mode rejection ratio of the system by applying identical signals to the transformers of opposite electrode pairs.

Unlike the existing system, there would be only one calibration generator and its signal would be multiplexed to calibrate one pick-up at a time. That would guarantee the same calibration pulse amplitude and very good relative calibration of IPU Σ channels to measure precisely the beam current along the line to reveal beam losses. A loss resolution better than 1 % can be expected. That would simplify the beam current measurement in the line, which now is done by beam transformers. They are calibrated by applying a known voltage and to evaluate the calibration current it is necessary to measure the cable impedances. This is why some better resolution and precision of proton beam current measurement is expected from the new system. The new system would also increase the high cut-off frequency of the beam current measurement from some 100 kHz as given by existing beam transformer systems, to some 10 MHz.

The displacement characteristics of the present MPUs are very linear: to 1 % even for large beam displacements **[1]**. This is also due to the fact that there are two sub-pick-ups, one for each plane, so there is no or very little coupling between the planes. On the other hand, the Δ signals are normalized using beam transformer readings and this process may be quite far from being perfect and, in addition, it cannot be directly verified.

The linearity of the new design might be slightly worse and there might be some coupling between the planes. If needed, this could be removed by appropriate calibrations and signal treatment. The Δ and Σ signals would be derived from the same pick-up signals, so the normalization of the position signals would be straightforward.

4. A possible scenario

It seems to be possible to install one IPU prototype instead of an existing MPU during the shutdown 2003/2004. For that it would be necessary to perform the following steps:

- As soon as possible mechanical studies of the new design would have to be started to yield dimensions of the hardest pieces to manufacture, namely the ceramic insertion with flanges and the ferrite cylinder. These parts would have to be done outside CERN, which most likely would take some months.
- The pick-up prototype would be constructed, to gain time preferably with parts made by the CERN workshop.
- The transresistance amplifier would be built in parallel with the previous steps.
- One MPU should be selected to be replaced by the IPU of the new design. The MPU should be in a representative place for the whole system in terms of interference and radiation levels. LT.U20 seems to be a good choice, because other diagnostic means could substitute it (to some extent) in case of trouble. Another possibility would be installing the prototype in a completely new place on a free section of the transfer line. This would require installing also a new support with an alignment table, which would not be necessary in the previous option.
- Four coaxial cables (Σ, ΔH, ΔV, Cal) should be pulled to connect the new IPU to one of the existing system patches. In addition one multiwire cable would be needed to send the power supply voltages (+6V, -6V) and control (Cal+, Cal-) to the active hybrid module.
- For operation during the year 2004 the new IPU could be used in parallel with the other pick-ups of the system. If needed, it could be connected to one of the existing acquisition systems at the expense of some software modifications.
- One active hybrid circuit would be necessary.

The next steps would be performed according to results obtained.

The new design might encounter a few problems. The first would be interference from nearby power equipment.

The IPU would be designed without any dedicated shields, since, as it was described, the design is supposed to be less sensitive for parasitic magnetic fields than the existing MPUs. Nevertheless, the possibility to install an additional steel cover would be foreseen, shielding the plates with the transformers. Such a shield would be the first attempt to remedy interference problems. Next, studies and trials would have to be performed to improve the grounding and cabling scheme.

Another difficulty could be a radiation sensitivity of the transresistance amplifiers. These would include the only active components located close to the beam. The active hybrid circuits can be located several meters away, since they have matched 50 Ω inputs, which would be connected to the 50 Ω outputs of the transresistance amplifiers. The amplifiers would include 8 op-amps, four of which should be low noise ones (the power supply would be taken from the active hybrid circuits). There are several types of op-amps that could be used, so there would be some freedom to choose one standing radiation. Also the transresistance amplifiers could be put further away from the IPUs at the expense of longer cables and possible deterioration of the high cut-off frequency foreseen. If this was not enough, an ultimate solution would be to put the op-amps in sockets and change them each shutdown as is the case for some other systems. The task could be easily done in place within 5 minutes per transresistance amplifier module.

5. Conclusions

Currently, 20 magnetic pick-ups, built some 30 years ago, are installed on transfer lines between the Linac 2 and the PSB to measure positions of proton beams. Their signals are treated by two control/acquisition systems running on two DSCs. The pick-ups do not provide intensity signals, so the position signals are normalized using readings from beam transformers, operated by another two systems running on the same two DSCs. The pick-up signals are affected by noise and suffer from interference.

In the long term, the two pick-up systems and two beam transformer systems could be replaced by a new system measuring both, the position and current of proton beams, and one system including beam transformers dealing with ions. Another option to be considered for economical reasons would be to divide the new pick-up and ion transformer systems to be run on two DSCs as it is now to keep shorter cables from the pick-ups to the equipment room.

The new pick-up system could be introduced with relatively small development effort, since most of its parts could be almost directly copied from a similar system developed recently for CTF3. The two crucial parts that would need development are the sensor itself – the inductive pick-up, and a new module – the transresistance amplifier. The two have been described in the paper together with an estimate of the new system performance based on calculations and model simulations.

The new system is expected to conserve low cut-off frequency of the present system, increase by a decade the high cut-off, be less sensitive to interference, represent far smaller longitudinal impedance, have better noise performance and deliver absolute measurement of proton beam currents with resolution and accuracy better than the existing systems based on beam transformers, and high cut-off frequency improved by some two decades. Displacement characteristics of the new pick-ups might be less linear but the position signals normalization would be straightforward.

As a first step, the inductive pick-up and its transresistance amplifier prototypes could be built, tested in the lab and installed on the transfer line during the shutdown 2003/2004.

If the pick-up and transresistance amplifier performance were up to expectations, the whole new system could be built.

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7. References

[1] K. Schindl, T.R. Sherwood, *Magnetic Position Monitors for the New Linac and the PSB Injection Line*, MPS/BR/LIN/Note 75-12, CERN, April 1975.

[2] M. Bourgeois, *Detecteurs de Position du Faisceau, Circuits Electroniques Assoies*, PS/LIN/Note 76-16, CERN, June 1976.

[3] M. Le Gras, *Electronique des Détecteurs Magnétiques de Position de la Ligne d'Injection Booster*, PS/BR/Note 77-53, CERN, 1977.

[4] M. Gasior, *Hardware of the CTF3 Beam Position Measurement System*, CTF3 Note 053, CERN, February 2003.

[5] M. Gasior, *An Inductive Pick-Up for Beam Position and Current Measurements*, CERN-AB-2003-053-BDI, DIPAC 2003 - 6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, Mainz, Germany, 5 - 7 May 2003.

[6] R. Scrivens, *Trajectory System Specification for Linac 2.* Draft Version of 8 May 2003.