A CURRENT MODE INDUCTIVE PICK-UP FOR BEAM POSITION AND CURRENT MEASUREMENT

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Abstract

An Inductive Pick-Up (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 electrodes, each of which forms the primary winding of a toroidal transformer. The beam image current component flowing along each electrode is transformed into a secondary winding, connected to a pick-up output. Such sensors are operated in the CERN CTF3 Drive Beam Linac [1]. This paper describes a similar device developed for the CERN Linac 2 to PSB transfer line. To cope with two orders of magnitude longer beam pulses, the new sensor is operated in current mode. The transformers drive transresistance amplifiers (TRA), converting transformer currents into voltages, which in turn are processed by an active hybrid circuit (AHC), producing one sum (Σ) signal, proportional to the beam current, and two difference (Δ) signals proportional also to the horizontal and vertical beam positions. The bandwidth of the Σ and Δ signals spans 6 and 5 decades, respectively. The transformers have an additional one-turn winding to which a pulse from a precise current source can be applied to calibrate the sensor.

INTRODUCTION

The Linac 2 can deliver 50 MeV proton beams of up to some 200 mA in 100 μs pulses to the PSB. The beam position in the transfer line is currently measured with 20 magnetic pick-ups (MPUs) [2] installed 30 years ago, which now show signs of fatigue. Their mechanics is very complex (e.g. 4 layers of magnetic shielding) and in case of a failure, there are no spare parts. To prepare for a future upgrade of the position measurement system, one of the MPUs was replaced by a recently developed IPU [3]. A successful result with this pick-up would allow the new system to be based on this type of sensor, equipped with an acquisition system very similar to that of CTF3 [4]. This solution would require relatively little manpower. In addition, contrary to the old MPUs, the new IPU can measure the beam current, eliminating the need for many of the separate beam transformers.

The IPU cross-section is shown in Fig. 1. Photographs of its components and the installed sensor are shown in Fig. 2 and 3, respectively. The body A, made form alodined aluminium, houses the ferrite cylinder B, surrounding 8 electrodes C. The separate vacuum assembly D with Helicoflex flanges contains a ceramic insert. The insert is titanium coated on the inside with the optimal coating resistance determined by the method described in [5]. The plate E accommodates 8 current transformers F, through which go M5 copper screws, closing the primary transformer circuits. The transformers

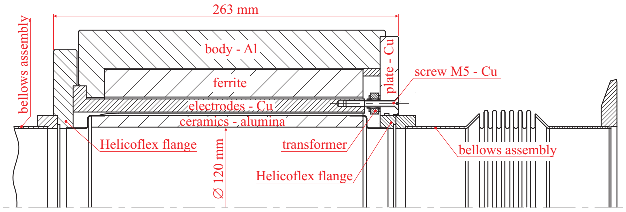

Figure 1: The IPU cross-section.

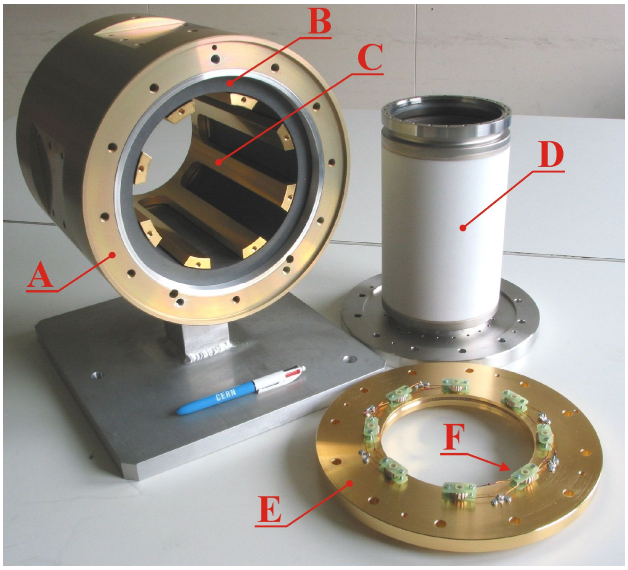

Figure 2: The IPU parts.

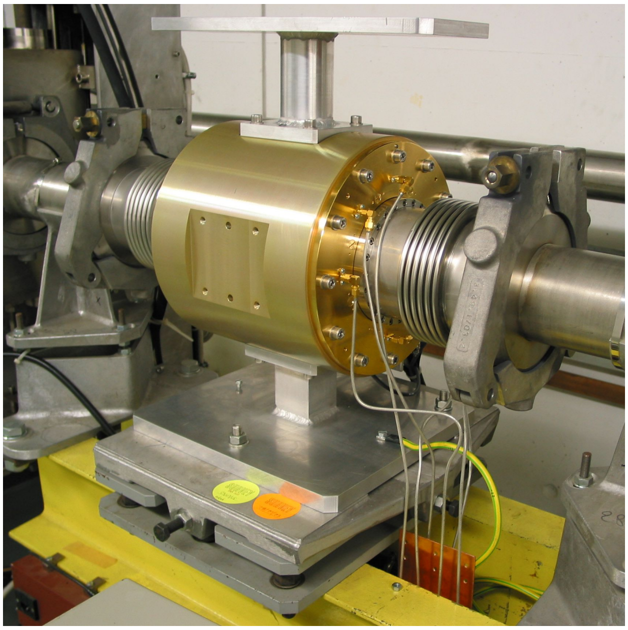

Figure 3: The IPU installed.

are combined in pairs, each of which is connected to a sensor output.

To achieve a good low frequency response, the primary circuit parasitic resistances had to be kept below 0.1 mΩ. Thus the electrodes C and the plate E are made from copper and are gold plated along with the screws. The electrodes and their supporting plate are machined as one piece to minimize primary loop resistances and to achieve good mechanical precision.

Each of the four IPU outputs is connected to one TRA input, representing a low resistance load to the transformers to improve the sensor low cut-off frequency, in order to limit the signal pulse droops. The TRAs convert the transformer currents into voltages, which are then processed by the AHC, producing the Σ and Δ signals.

The whole beam image current must pass through the transformers, so the IPU can be used for absolute beam current measurement. To calibrate the sensor for this purpose, each transformer has a calibration turn, 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 are used to test the Δ and Σ channels, calibrate their gains and check the common mode rejection ratio by applying identical signals to the transformers of opposite electrode pairs.

A MODEL AND RESULTS

The low frequency behaviour of two opposite pairs of electrodes, forming one IPU plane, together with two channels of the TRA, can be modelled by the circuit shown in Fig. 4. Its parts are the following:

- Four branches with inductances L_Δ represent two opposite pairs of electrodes with one 1:n current transformer per pair. Resistors R_C are parasitic resistances of electrodes, screws and contacts, while resistance R_P represents the secondary winding load R_S 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.
- R_S represents parasitic resistances of the transformer windings, cables and connectors.
- R_1 provides the cable termination for high frequencies while for low frequencies it is shunted by L_1 of small value.
- The operational amplifier OA_1 converts the secondary winding current into a voltage, with the value of R_F setting the transresistance.
- Since OA_1 has large DC gain (R_F/R_S is beyond a thousand), an auxiliary op-amp OA_2 is used to provide 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.

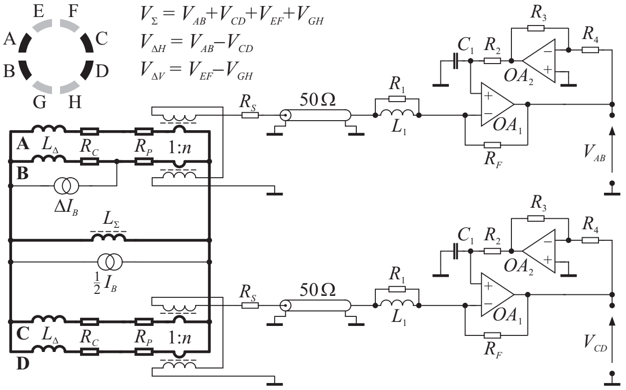

Figure 4: IPU and TRA low frequency model (one plane).

Table 1. Parameters of the IPU and of its electronics.

IPU	Length / body diameter	263 mm / 270 mm
	Overall length with bellows / weight	595 mm / ≈ 50 kg
	Beam pipe / electrode inner diameter	120 mm / 145 mm
	Titanium coating end-to-end resistance	5 Ω (i.e. 9 Ω/□)
	Transformer A_L / turn number n	3 μH / 15
	L_Δ inductance / ferrite μ_r	≈ 250 nH / 100
	Primary parasitic resistance R_C	< 0.1 mΩ
	Secondary winding load R_S	< 50 mΩ
IPU + TRA + AHC	Position sensitivity	30 mm × Δ/Σ
	Electrical center position error	< 0.25 mm
	Linearity error for 20 mm excursions	0.1 % (0.12 mm)
	Min / max measured current	a mA / 300 mA
	Σ low cut-off frequency	50 Hz
	Δ low cut-off frequency	150 Hz
	High cut-off frequency	50 MHz
	TRA transresistance	100 Ω
	AHC Σ channel gain low / high	10 dB / 30 dB
	AHC Δ channel gain low / high	20 dB / 40 dB
	Calibration current pulse	100 mA, 0.1 %

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 is

$$V_\Sigma = \frac{R_F}{2n} I_B \tag{1}$$

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

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

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

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

Since $L_\Delta << L_\Sigma$, the more challenging demand is obtaining the desired Δ signal low cut-off frequency $f_{L\Delta}$.

The TRAs have a high gain only for low frequencies. The Δ signal gain G_Δ decays 6 dB per frequency octave, limiting the total noise at the amplifier output. G_Δ is set by the ratio of R_F and the impedance seen from the OA_1 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 the much larger L_Σ value, resulting in a still smaller gain.

Parameters of the IPU and the channel IPU-TRA-AHC are listed in Table 1. To improve $f_{L\Delta}$, the AHC Δ channels have (6 dB) more gain for low frequencies; the Σ channel has no correction. $f_{L\Sigma}$ was limited by the largest affordable value of series capacitors along the signal chain. The high frequency cut-off is determined by the L R matching circuitry at the TRA inputs.

The IPU linearity error, shown in Fig. 5, was measured by diagonally displacing a 0.2 mm wire across the pick-up aperture. The error is about 0.12 mm (i.e. 0.1 % of the aperture of 120 mm) for excursions up to ±20 mm, which are most important for the transfer line.

An example of a position and current measurement is shown in Fig. 6. No significant signal droops are seen. For this application the 50 MHz high cut-off frequency of the system can be lowered by a decade, as the linac beam does not contain significant components beyond a MHz. This would further lower the system noise.

The pick-up signals contain some components resulting from ground loop currents in the beam pipe, caused by pulsed magnets and power equipment. The components are very slow with respect to the beam signal and only cause a small base line wander. As seen in the measurement, this can easily be removed by a simple base line correction on digital samples and has no significant effect on the measurement quality. Since the pick-up is based on measuring the beam image current, removing the interference could only be achieved at its source, by cleaning up the grounding in the machine.

CONCLUSIONS

An inductive pick-up was commissioned on the CERN Linac 2 to PSB transfer line, replacing an old magnetic pick-up, as a preparation for upgrading the whole transfer line beam position system. The sensor can measure the beam position and absolute current with respectively 5 and 6 decade bandwidths, and can be tested and calibrated in situ with precise current pulses. None of the IPU, TRA and AHC contains adjustable elements. The pick-up has a better performance and a much simpler construction than its old magnetic predecessor, in particular without any magnetic shielding.

Two years of CTF3 experience with some 25 inductive pick-ups have demonstrated that these devices can accurately measure both the beam position and absolute current, and that they are robust and insensitive to beam losses. The new position measurement system for the transfer line can be based on this type of sensor with a relatively small development effort, as many system parts can be copied from the parent CTF3 system. The only different parts are the pick-up itself and the transresistance amplifier. The prototype currently installed can be used for the final system with virtually no modifications.

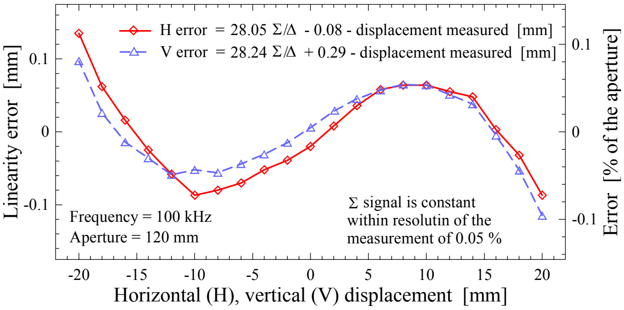

Figure 5: IPU linearity error.

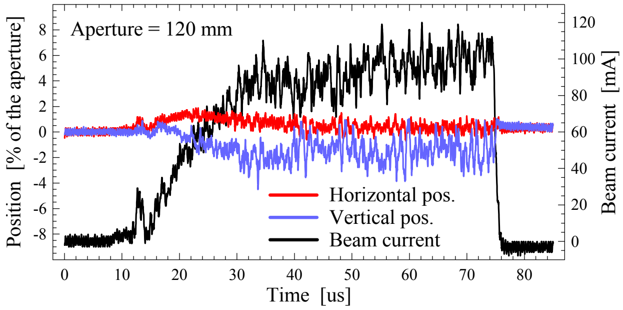

Figure 6: Measured position and current (scope, one shot).

ACKNOWLEDGMENTS

I would like to thank J. Belleman for his help throughout the whole development and U. Raich for supporting the project. I am grateful to Y. Cuvet for the superb mechanical design of the pick-up and to R. Jones for paper corrections.

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