CTFF3 TECHNICAL NOTE

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Note: **CTFF3-008**

Design of a Beam Position Monitor for the CTF3 Combiner Ring

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1. Introduction

In CTF3 a train of short bunches with a distance of 20 cm between bunches is converted into a shorter train of 140 ns, with final bunch spacing of 2 cm.

The LINAC macro bunch compression is obtained in two steps: a factor two in the Delay Loop (DL) and a factor five in the Combiner ring (CR).

Measurement of beam trajectory along the CTF3 compression system will be performed through beam position monitors (BPM) distributed around the ring circumference of the CR and DL.

This note reports on the design and characterization of the prototype of a beam position monitor to be installed in the compression system of CTF3.

Design of the BPM pickup has been based on the time structure of the beam to provide the measurement of the average position of the whole bunch train at each turn in the combiner ring/delay loop.

Beam parameters in different parts of CTF3 compression system are summarised in Table 1 [1].

Table 1: CTF3 beam parameters

Parameter	Name	Delay Loop	Combiner Ring inj.	Combiner Ring ext.	Unit
Pulse Length	T_p	140	140	140	ns
Bunch Charge	Q_b	2.33	2.33	2.33	nC
Num bunch/pulse	N_b	210	420	2100	
Bunch Length	σ_b	0.5 ÷ 2.5	0.5 ÷ 2.5	0.5 ÷ 2.5	mm
Bunch Separation	Δ	20	10	2	cm
	T_b	~666	~333	~66	ps
Max Pulse Current	I_p	3.5	7	35	A

2. General Description of the BPM

Transverse beam position measurements will be performed through comparison of peak voltage signals induced by the beam in pickups located symmetrically around the vacuum chamber.

The pickup to be used should provide voltage signals representing the envelope of the beam pulses with a proper output level. For this reason it must be designed to work in a limited bandwidth [f_{low}, f_{high}] of the low frequency range of the beam spectrum.

More precisely the pulse length of 140ns requires a low frequency cut-off $f_{lo}<<1/(2\pi T_p)\sim1.1$MHz. Simultaneously the high frequency cut-off must be chosen to get a suitable risetime to the voltage signals coming from the pickup: $f_{hi}\approx100$MHz provides a risetime in the order of 3.5 ns.

Pickups resembling the ones formerly installed in the EPA ring ("UMA" beam position monitor) [2][3] have been taken into consideration and re-adapted for the combiner ring needs.

Measurements performed on an existing "UMA" BPM, formerly at CERN, confirmed its capability to integrate the beam pulse signal by responding in the desired frequency range with an high value of transfer impedance, if compared to the DAΦNE button pickup, as reported in Fig. 1.

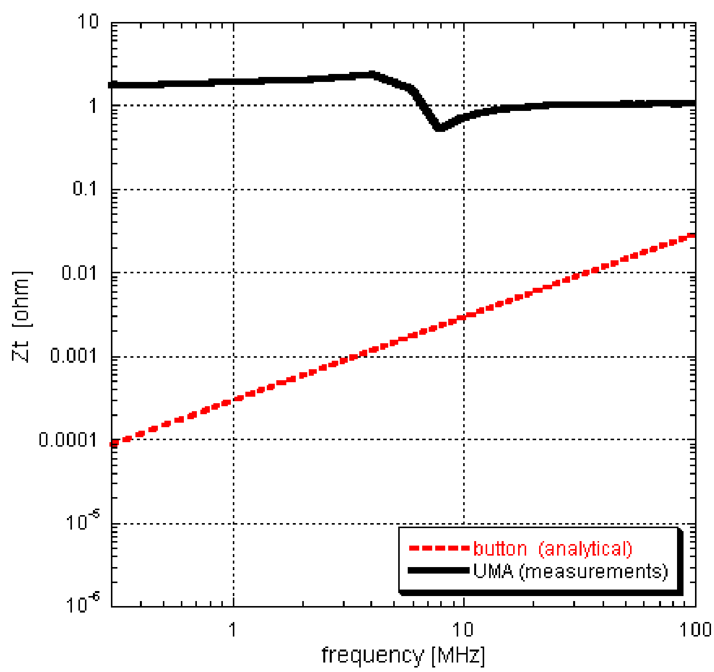
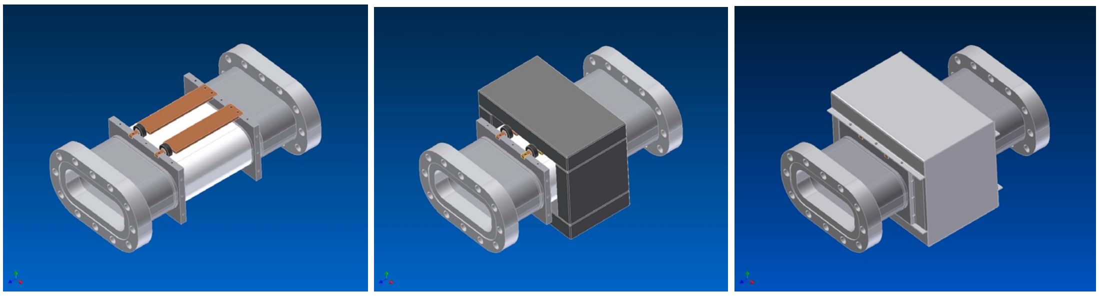


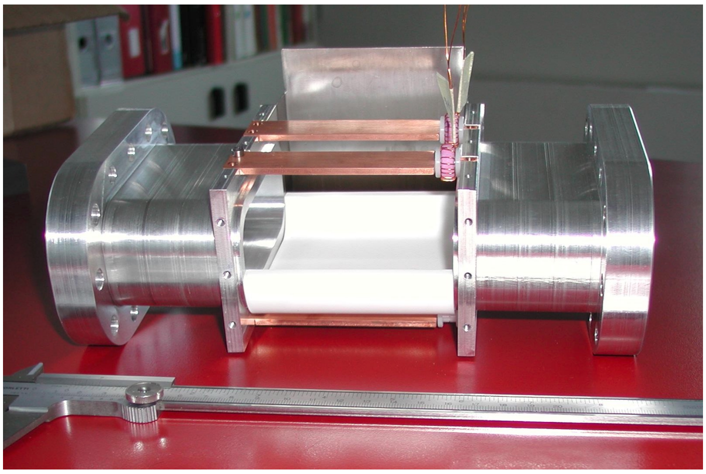
Figure 1: Comparison between transfer impedances of UMAs and button pickups

The layout of the BPM and a picture of the prototype built are shown in Fig. 2 and Fig. 3 respectively.

This BPM works in principle as a transformer excited by the beam, representing a single turn primary loop, whose four secondary windings surround toroidal ferrite cores placed in correspondence of a vacuum chamber ceramic gap. The beam current acts as a winding that drives magnetic flux in the core, inducing a voltage signal in the secondary windings.The beam image current, diverted to the four strip placed outside a ceramic gap and short circuited to the two ends of the metallic vacuum chamber, is picked up through the small ferrite core transformers (FerroxCube 4C65) placed at the end of each strip (Fig. 2a) and providing signals whose amplitude is beam position dependent. The striplines are surrounded (Fig. 2b) by ferrite (Ferroperm Magnetics *PERMAX* n°56) to improve the low frequency response. Such ferrites also become lossy at high frequencies and damp unwanted resonances of the external metallic shield (Fig. 2c).



Figures 2a-b-c: BPM layout



BPM length	24 cm
Electrode Length	8 cm
Num. of secondary windings	20
Vacuum chamber section	90 mm x 39 mm

Figure 3: BPM prototype before assembling

3. Measurements on the prototype BPM

The voltage signal spectrum induced in the *i*-th winding by a centered beam can be written as:

$$V_i(\omega) = Z_t(\omega) \cdot I_b(\omega)$$

where $I_b(\omega)$ is the beam current spectrum and $Z_t(\omega)$ is the pickup transfer impedance.

Measurements based on the coaxial wire method have been performed to estimate the transfer impedance of the device [4].

The beam field is simulated by a copper rod placed along the pickup axis, forming with the outer conductor a coaxial line system having a characteristic impedance of Z_0=160Ω. Resistive networks at the ends of the vacuum chamber section allow impedance matching with 50Ω lines used in our equipment. Scattering parameters related to the two beam tube ports and secondary winding ports have been measured.

The transfer impedance versus frequency can be found directly from the values of the scattering matrix elements and is reported in Fig. 4.

The low frequency value of the transfer impedance approaches the value R_L/4N as expected from a simple equivalent circuit in which the BPM is a current transformer where the beam is the current source on the primary and the output current is picked up through secondary with N=20 windings closed on a R_L=50Ω load impedance, assuming the beam image current equally distributed on each of the four strips.

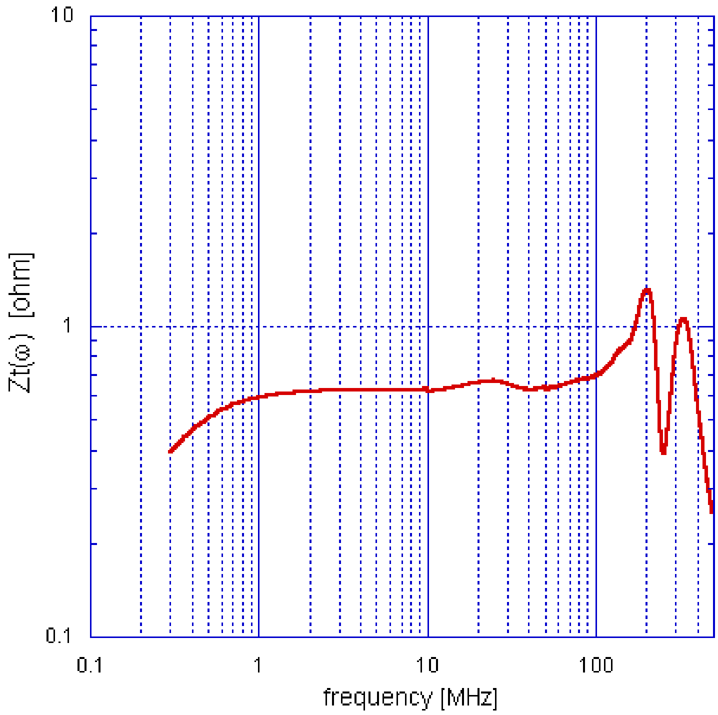


Figure 4: Measured Transfer impedance of the BPM

As expected, the use of ferrite extends the low frequency cut-off of the pickup transfer function as showed in measurements of Fig. 5. The measured f_{low} is now below 400KHz.

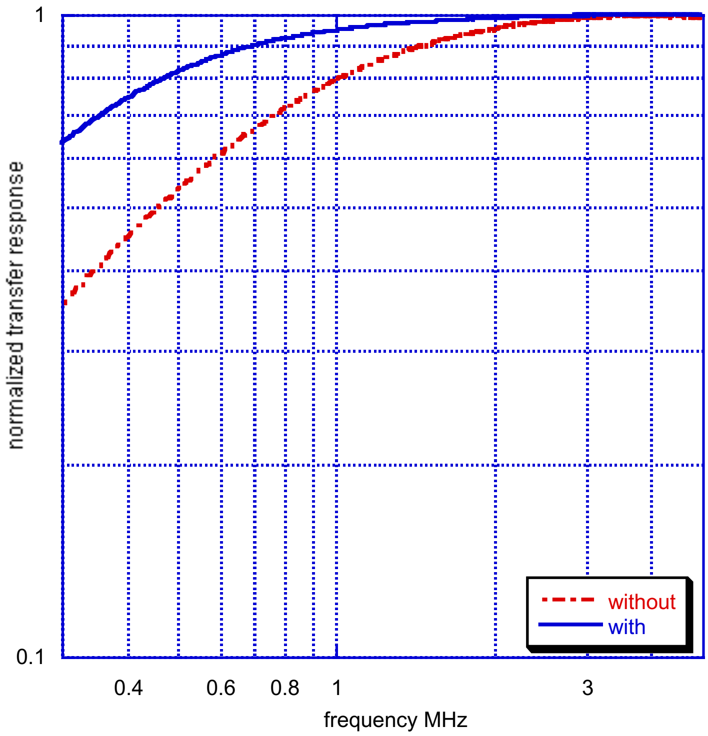


Figure 5: Comparison between low frequency response of the BPM with and without ferrites

To investigate position sensitivities of the device, a series of measurements with a movable wire has been performed. The output at a fixed frequency (100MHz) from each secondary winding has been acquired for several transverse wire positions.

The peak-height ratios *U* and *V* for the horizontal and vertical axis respectively are the dimensionless quantities defined as:

$$U = \frac{v_1 + v_4 - v_2 - v_3}{v_1 + v_2 + v_3 + v_4} \qquad V = \frac{v_1 + v_2 - v_3 - v_4}{v_1 + v_2 + v_3 + v_4}$$

where v_i represents the peak intensity of the i-th button. Fig. 6 reports measured values of *U* and *V* for different wire positions.

Data from these measurements showed as 20dB the maximum amplitude excursion between the four signals v_i for a beam offset by 70% of the vacuum chamber dimensions. Acquisition electronics shall provide at least this value of dynamic range to sample signals from BPM.

Beam position can be accurately derived from the (*U*,*V*) quantities through a non linear fit:

$$x = x_0 + k_x \cdot U + f(U,V) \qquad y = y_0 + k_y \cdot V + g(U,V)$$

where x_0 and y_0 are offsets between electrical and geometrical center of the BPM, k_x and k_y are the inverse sensitivities to beam displacement, and *f*(*U*,*V*) and *g*(*U*,*V*) are polynomial functions, used to correct non linearities of the BPM for large beam offsets, whose coefficients are derived through calibration measurements.

In our case we get from measurements (Figs. 7a-b):

$$k_x = 34.53 \text{ mm} \qquad k_y = 32.13 \text{ mm}$$

Development of the software to process data from (*U*,*V*) measurements is still to be done in order to fit the two dimensional data, to optimize the reconstruction algorithm and finally derive parameters for the fitting functions.

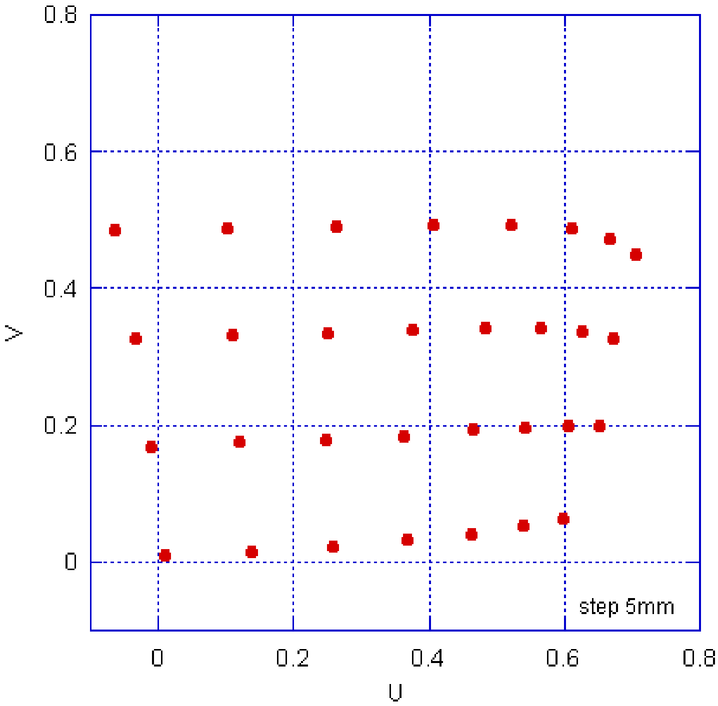
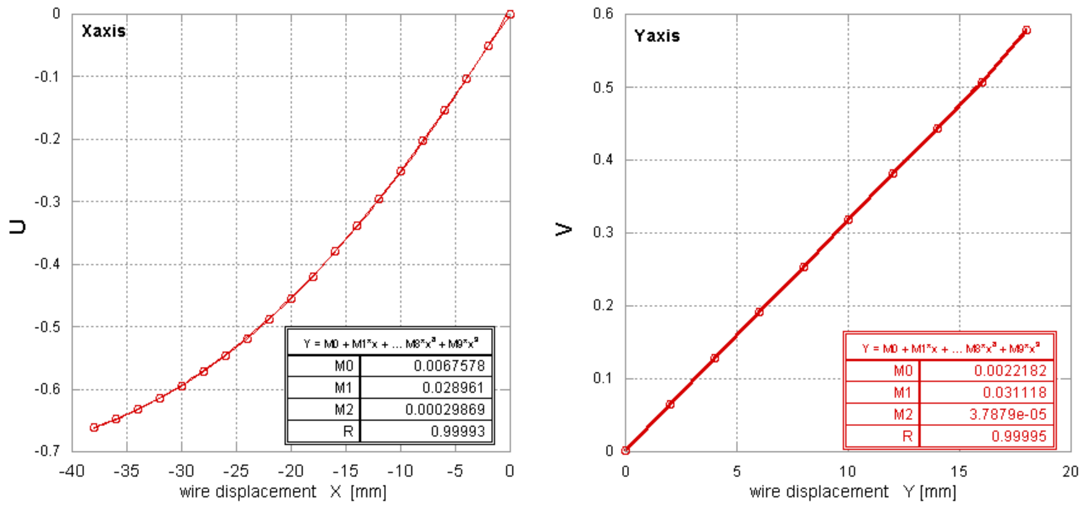


Figure 6: *U* and *V* Measured Values



Figures 7 a-b: Position sensitivities along the horizontal and vertical axis

4. Signal from pickup

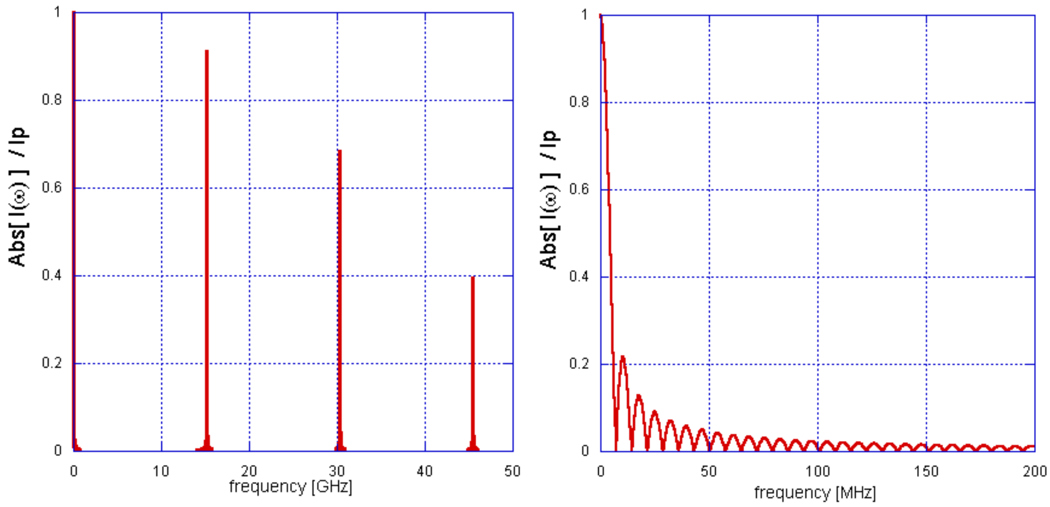
Pickup signals will be transmitted through independent coaxial cables to the acquisition electronics.

In this paragraph the transfer impedance $Z_t(\omega)$ of the BPM, the CR beam spectrum $I_b(\omega)$ and transfer function $H_{coax}(\omega)$ of the coaxial cables are used to reconstruct in the time domain the voltage signal $V_i(t)$ induced by a centered beam up to the acquisition electronics inputs.

Given the beam temporal structure in the CR, $I_b(\omega)$ follows the expression:

$$I_b(\omega) = Q_b \cdot exp\left(-\frac{\omega^2 \cdot \sigma_b^2}{2}\right) \cdot \sum_{k=1}^{N_b} e^{-j\omega k T_b}$$

which describes an amplitude spectrum whose energy is concentrated mainly around the harmonics of the frequency ω_0 corresponding to the temporal distance between the bunches (Fig. 8a). The overall amplitude decreases as $exp(-\omega^2\sigma_b^2/2)$. The amplitude spectrum around DC is reported in Fig. 8b.



Figures 8a-b: Beam amplitude spectrum in the CR

The frequency response of a coaxial cable of length l is function of the transmission line parameters values L, inductance per unit length, and C, capacitance per unit length, and can be approximated by the following expression where K is a constant which takes into account the skin effect [5].

$$H_{coax}(\omega) = \exp\left(-l \cdot \sqrt{(j\omega)^2 \cdot LC + j\omega CK\sqrt{j\omega}}\right)$$

The expected raw signal, limited to the [0,100MHz] bandwidth, coming from the generic winding at the end of a typical 100m coaxial cable has been obtained through the inverse FFT transform:

$$V_i(t) = \mathrm{FFT}^{-1}\left[Z_t(\omega) \cdot I_b(\omega) \cdot H_{coax}(\omega)\right]$$

and is reported in Fig. 9 assuming I_p=3.5A and nominal beam parameters.

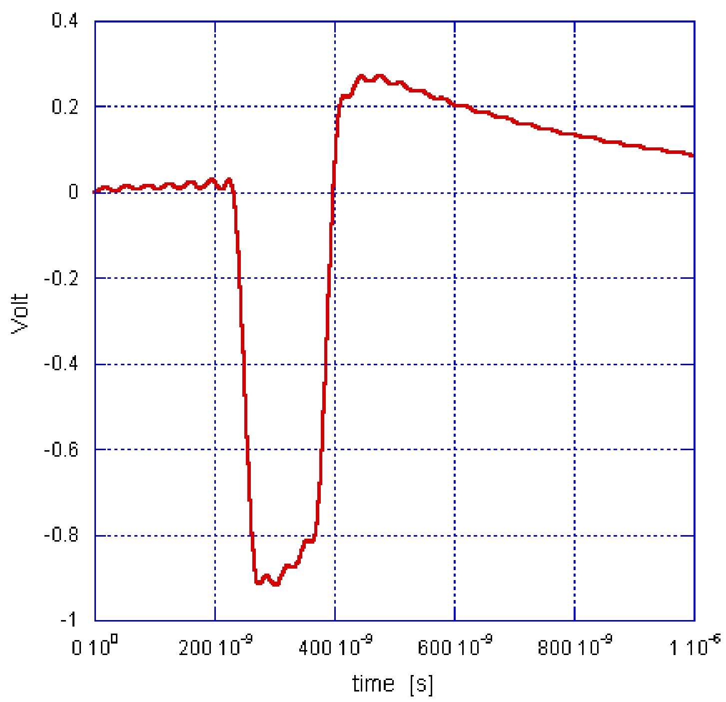


Figure 9: Expected voltage signal from the generic BPM pickup

The waveform reproduces the envelope of the bunch train with a risetime depending on the upper bandwidth limit and a droop rate depending on the low frequency cutoff.

Therefore the level of each voltage signal $v_i(t)$ in a [0,100MHz] bandwidth can be approximated, for a centered beam, with the following expression:

$$v_i(t) \approx Z_p \cdot I_p \cdot e^{-\frac{t}{\tau}}$$

assuming a value Z_p=0.22 Ω, where I_p is the beam pulse current and $\tau = 1/(2\pi f_{lo})$.

5. BPM resolution

Peak signals will be acquired through multichannel 12bit fast digitisers to be software processed to provide (U,V) and hence the beam position.

Resolution of the measurements will be ultimately affected by the thermal noise rms voltage ΔV_{noise} superimposed to the beam induced signals:

$$\Delta V_{noise} = \sqrt{4k_0 \cdot T \cdot R_L \cdot \Delta f} \approx 9\,\mu Volt$$

on a R_L=50Ω load impedance at T=300°K temperature and Δf=100MHz bandwidth.

The following gives an estimate of the rms error on horizontal position caused by the voltage noise (assuming Att_{cable}=6dB cables attenuation):

$$\Delta x_{noise} \cdot I_p \approx k_x \cdot \frac{(v_1 + v_4) - (v_2 + v_3)}{v_1 + v_2 + v_3 + v_4} = k_x \cdot \frac{\sqrt{2} \cdot \Delta V_{noise}}{Z_p \cdot Att_{cable}} \approx 4\,\mu m$$

other source of resolution error is introduced by the 12bit ADC quantization:

$$\Delta x_{adc} \cdot I_p = \frac{1}{\sqrt{2}} k_x \cdot \frac{1}{2^{12}} \approx 6\,\mu m$$

summing the two contributions we get an estimated intrinsec resolution error of:

$$\Delta x_{rms} \cdot I_p = \sqrt{\Delta x_{noise}^2 + \Delta x_{adc}^2} \approx 7\,\mu m$$

which takes into account only thermal noise and ADC quantization error. Similar considerations for the vertical position lead to $\Delta y_{rms} I_p$=6μm.

Noise error of amplifiers, acquisition electronics and any kind of active electronics in the signal chain must be added. From the previous results and assuming a required final resolution of 70μm *rms* at 10% of the nominal beam current, a maximum noise budget of F~70μm/7μm→20dB can be spent in the processing electronics chain.

6. Acknowledgements

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References

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