# RESONANT STRIP LINE BPM FOR ULTRA LOW CURRENT MEASUREMENTS

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*Abstract*

Proton beams used in proton therapy facilities like PROSCAN have extremely small currents of an order of nanoamperes, which create a challenge for a precise beam position measurements due to their extremely low signal level and subsequent bad signal per noise ratios. For suitable power levels with these currents, pickups need to have a high shunt impedance, something, which is difficult to design for wide band devices. So for a new strip line BPM design, the coupling of the signal outputs to the electrode was deliberately mismatched to create a resonance at the second harmonic of the RF frequency at 145 MHz. The optimum Q-factor to use is given by the coupling between the BPM electrodes leading to to a Q of 50, an overall shunt impedance of 2.9 kOhms and power output levels of an order of -120 dBm at the design current of 1 nA. A prototype of the device has been manufactured, first measurement results will be presented.

## INTRODUCTION

The PROSCAN project at PSI aims at the development and construction of a dedicated facility for proton therapy. It consists of a supra conducting 250 MeV cyclotron built by ACCEL Instruments GmbH and will allow the treatment of interior tumors with protons [1].

Due to the extremely small beam currents, the conventional measurement of position and beam profile using ionization chambers must be performed outside vacuum, which limits its application [2]. Furthermore the measurement always introduces some degradation of the beam due to its intrusive character. To overcome these restrictions, it was decided to adapt the design of the strip lines in the SLS transfer lines, which have increased signal levels due to a non conventional resonant layout and so are more suitable for low current measurements. Adding a low noise RF front end and a sophisticated digital receiver should allow a performance suitable for PROSCAN.

With bunch trains in the order of seconds, the signal to be measured is essentially mono frequent and the bandwidth of the system can be chosen at convenience. The design current is 1 nA, for minimum interference and crosstalk a center frequency twice of the RF frequency of 72.7 MHz was defined. A further requirement was to have 100 mm clear space for the beam.

## BASIC DESIGN CONSIDERATION

The central figure of merit in a beam position device is the obtainable signal to noise ration. With the position dependent difference part of the signal $\Delta$ and the independent sum part $\Sigma$, the beam offset computed from these signals can be written as

$$x = C\frac{\Delta}{\Sigma}, \tag{1}$$

where $C$ is the inverse device sensitivity. Linearizing the equation with respect to the sum gives

$$x \approx C\Big(\frac{\Delta}{\Sigma_0} - \frac{\Delta}{\Sigma_0^2}\delta\Sigma\Big),$$

so that one can get the statistical variance of the position reading as

$$\sigma_x^2 = C^2\frac{\sigma_\Delta^2}{\Sigma_0^2}\Big(1+\frac{\sigma_\Sigma^2}{\Sigma_0^2}\Big) \tag{2}$$

With the sum signal noise $\frac{\sigma_\Sigma}{\Sigma_0}$ typically being small, the optimum device has a high sensitivity (low factor $C$), low noise in the difference signal (mostly determined by thermal noise) and high signal levels $\Sigma_0$.

One option for the BPM would be to use a pair of cavities as a BPM, one using a dipole resonance to procure the position dependent signal and monopole resonant cavity for the sum signal. The Q factors and so the bandwidth could be optimally adapted to the beam spectrum. The problem with this would have been the relatively high temperature variations in the measurement location, which would have led to frequency drifts and subsequent accuracy problems. So it was decided to go for a strip line design, which has been designed in a similar way already used for the transfer lines of the swiss light source (SLS).

A conventional strip line design, as shown in the upper part of figure 1, consisting of strip line shorted on one side and perfectly matched to the output coupler, has a FIR pulse response consisting of two peaks giving a transfer impedance of

$$Z_T = \frac{U_{out}}{I_{beam}} = jZ_l e^{-j\omega\tau}\sin\omega\tau$$

with $\tau = l/c$ as the electrical strip line length and $Z_l$ the characteristic impedance of strip line and coupling. The first idea of changing the characteristics consists in introducing a deliberate mismatch by lowering the strip line impedance $Z_s$ with respect of that of the coupler. The transfer impedance becomes

$$Z_T = Z_l\frac{1+e^{-2j\omega\tau}}{1+Z_l/Z_s+e^{-2j\omega\tau}(1-Z_l/Z_s)}.$$

The method has two drawbacks, the first having to realize mechanically very low characteristic strip line impedances

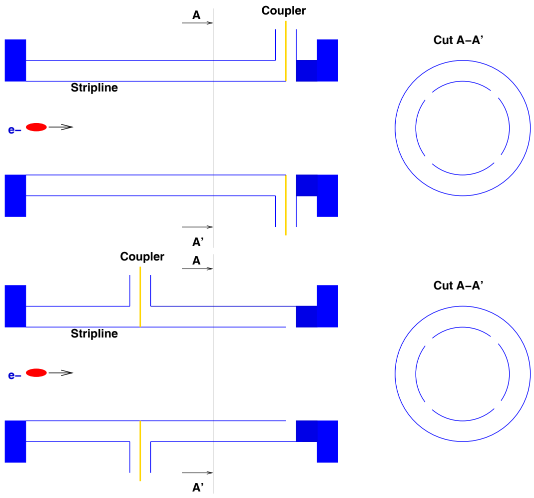


Figure 1: Strip line designs with conventional coupling at strip line end (upper figure) and changed coupling

in order to reach small bandwidths and the second, more important, the impedance maximum is given by impedance of the coupler (i.e. that of the connecting coaxial cable) and does not change at all with bandwidth

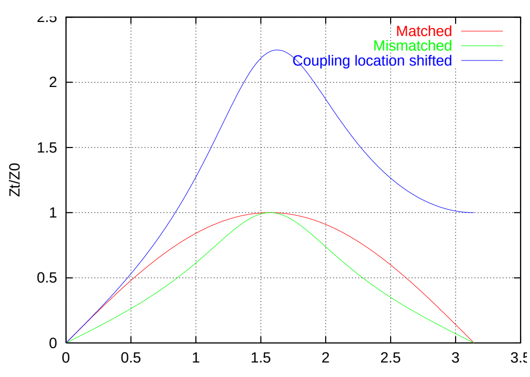


Figure 2: Transfer impedances $Z_T = U_{out}/I_{beam}$ for conventional matched strip line design, effect of introducing mismatch (strip line impedance is half the coupler impedance and shifting the coupler location into middle of strip line.

Only the second method, that of changing the location of the coupler itself has a simultaneous effect on bandwidth and impedance maximum as the impedance of coupler and shorted strip line is transformed to higher values seen at the gap. As can be seen in figure 2, shifting the location from the end of the strip line to its middle increases the peak impedance by a factor 2.2, shifting the coupler further to the shorted end leads to further improvements.

Given the non negligible coupling between the strip lines, there are three different resonant frequencies inside the structure, the the monopole/sum resonance, the difference/dipole resonances and a quadrupole resonance. The central frequency of the measurement should lie in between the monopole and the dipole resonances and, interestingly,

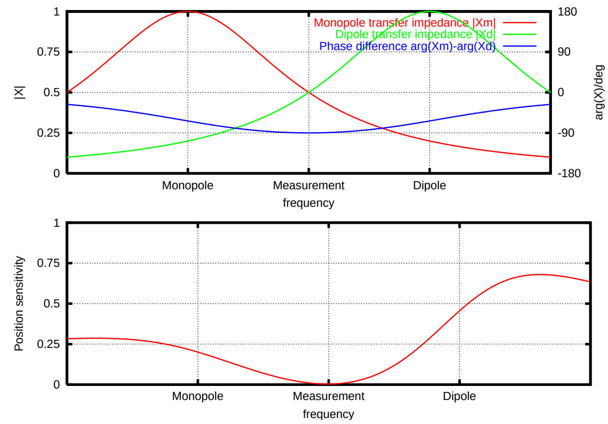


Figure 3: Example of dysfunctional choice of resonant frequencies and Q factors: At measurement frequency, resonances combine with a 90 degree phase difference, so that position sensitivity of output signal goes to zero.

it is not the extreme Q factors, which gives the best results, but the one, where monopole and dipole resonance overlap with the measurement frequency, as can be seen in the upper plot of figure 3.

A second condition on the choice of the Q factor comes from the way of the post processing. The individual electrode signal contains a mix of monopole and dipole components:

$$V_e = V_m + \Delta x V_d = \frac{C_m}{j\omega - j\omega_m + \alpha} + \Delta x \frac{C_d}{j\omega - j\omega_d + \alpha}$$

In our case, each electrode signal passes the RF front end, mixer and demodulator channel and only at the end, the absolute values of the electrode signal are used to determine sums and differences. Now the electrode signal is a sum of two complex phasors, so phase differences have an important influence on the variation of the absolute signal levels. Figure 3 shows a pathological case in that respect. The bandwidth of the monopole and dipole resonance are chosen so, that we obtain a 3 dB drop in the middle between both frequencies, which at first glance seems to be the best setting. But the problem lies in the phases of monopole and dipole parts, which are at 90 degree offset versus each other. Adding a small dipole amplitude at 90 degrees phase offset to the big monopole one will create negligible changes in the overall electrode signal, so that in this case, the sensitivity of the BPM would be zero! As a conclusion, an even lower Q and larger bandwidth is required.

## LAYOUT AND MEASUREMENTS

Figure 4 gives a view of the inner layout of the BPM. In order to have a minimum distance between monopole and dipole frequency, the coupling between the electrodes is minimized via metallic shielding plate, located between the strip line blades. The theoretical characteristic impedance of the blades is 66 Ohms, when driven in the monopole

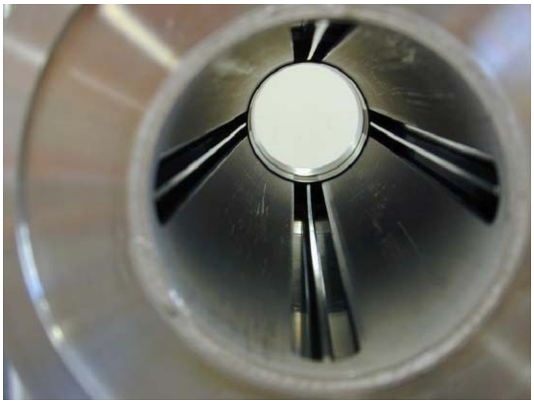

Figure 4: View into BPM showing strip line with shielding fins

mode (all blades being in phase) and 57 Ohms in the dipole mode. Going higher in impedance would have resulted in mechanical problems like impractical dimensions and e.g. the shielding plates having to stick into the beam cross section. The big part of the resonant enhancement comes from the location of the coupler. With a complete length of the strip line blades of 500 mm, output coupling takes place at 35 mm from the shorted and, giving a theoretical loaded Q of 53 for the monopole and 57 for the dipole mode. The overall shunt impedance of the monopole resonance comes out to as 2.9 $k\Omega$ corresponding to an output power level of about -120 dBm at 1 nA beam current.

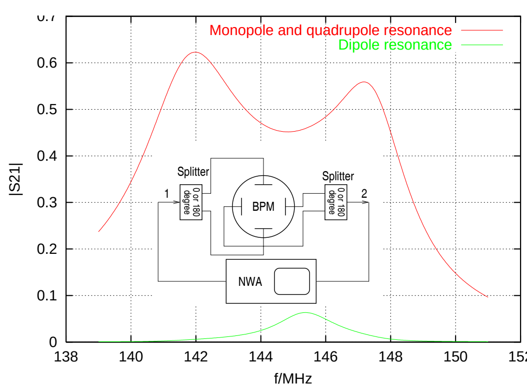


Figure 5: Transmission between pairs of strip line blades revealing monopole, dipole and quadrupole spectra

A prototype of the structure has been manufactured and measured in the laboratory in order to check the electrical properties and to prepare the structure for tests with the beam. A first set of measurements concentrated on identifying the modal spectrum inside the BPM. As shown in figure 5, either one pair of opposite electrode were connected to zero degree power splitters and the transmission from one splitter to the next was measured using a network analyzer. With opposite electrodes driven at even phase, this will excite only the monopole and quadrupole modes, which can be seen clearly in the plot at approximately 142 and 147 MHz.

In a second step, the zero degree splitters are replaced by 180 degree splitters, so that (assuming ideal splitters) only dipole modes are excited. Since the two dipole modes (horizontal and vertical) are decoupled, one would expect no transmission in theory. In reality however, there are slight asymmetries leading to some signal showing the dipole at 145.5 MHz.

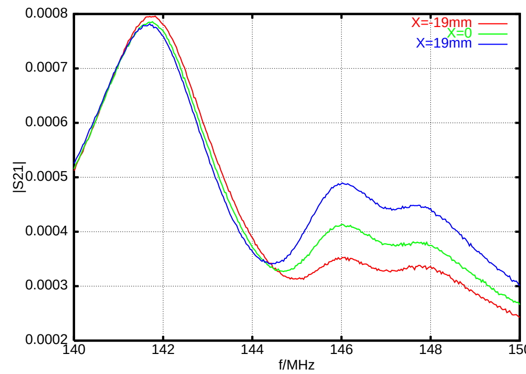


Figure 6: Transmission from on axis antenna inside BPM to BPM output coupler as a function of frequency and antenna offset

In figure 6, a small antenna was inserted on the axis of the BPM and the transmission to the electrodes were measured with the network analyzer for different offsets. As has been shown in the preceding paragraph, the sensitivity does not simply follow the curve of the dipole resonance, since also complex phase changes play a role. The overall sensitivity parameter comes out to be approximately 75 mm.

## CONCLUSION

A new strip line beam position monitor has been developed for ultra low current operation. The structure employs a resonant design to maximize shunt impedance and so also the transfer impedance. The obtainable maximum is given by the modal spectrum within the structure, in turn determined by the mutual coupling between the strip line blades. A prototype has been built and characterized in laboratory measurements. Further tests with the proton beam will follow in summer during the commissioning of the PROSCAN facility.

## REFERENCES

[1] J.M. Schippers, J. Duppich, M. Jermann, H. Reist, et al, “The SC cyclotron and beamlines of the PROSCAN project at PSI accepted for publication in Proc. of 17th International Conference on cyclotrons and their applications”, Tokyo, October 2004

[2] R. Dölling, “Profile, Current and Halo Monitors of the PROSCAN Beam Lines”, 11th Beam Instrumentation Workshop (BIW04), Knoxville, Tennessee, USA, May 3-6, 2004, to be published in AIP Conf. Proc. 732, p. 244-252