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A NEW OPTIMISED QUADRUPOLE PICK-UP DESIGN USING MAGNETIC COUPLING

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Abstract

The idea of quadrupole pick-ups, sensitive to beam size, dates back several decades. Such pick-ups measure the quantity $\sigma_x^2 - \sigma_y^2$, where σ_x and σ_y are the horizontal and vertical r.m.s. beam sizes. Thus, a quadrupole pick-up is a candidate for non-invasive study of processes such as coherent beam width oscillations due to injection mismatch. Up to now, quadrupole pick-ups have been produced essentially by enhancing the electronics of normal position pick-ups to produce the so-called quadrupole signal, with little or no effort being put into the design of the pick-up itself. In developing a quadrupole pick-up for the CERN PS, however, it has been found necessary to optimise the pick-up design. The result is a somewhat unconventional pick-up, where magnetic coupling is employed to suppress the otherwise very strong, and undesired, common mode-signal. In this paper, the basic design idea and the final optimised design are presented, together with simulations, test bench measurements and real beam data.

Key words: quadrupole pick-up, magnetic coupling, beam-size measurement
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1 Introduction

In any accelerator or storage ring, position pick-ups are standard diagnostic devices. A typical pick-up of the electrostatic type is shown in Fig. 1 and consists of four electrodes around the beam. The passing beam induces a signal on each of these electrodes. The individual electrode signals can be combined in four (linearly independent) ways

$$\begin{aligned} \Sigma &= T + R + B + L & (1)\\ \Delta_{\mathrm{H}} &= \phantom{T+{}} R \phantom{{}+B} - L & (2)\\ \Delta_{\mathrm{V}} &= T \phantom{{}+R} - B & (3)\\ \Xi &= T - R + B - L & (4) \end{aligned}$$

where to lowest order

$$\Sigma = Z_{\Sigma}\, I, \quad \Delta_{\mathrm{H}} = Z_{\Delta}\, I\, \bar{x}, \quad \Delta_{\mathrm{V}} = Z_{\Delta}\, I\, \bar{y}, \quad \Xi = Z_{\Xi}\, I\, \kappa. \tag{5}$$

Here, I is the beam current and $(\bar{x}, \bar{y})$ the beam position relative to the pick-up centre in the horizontal and vertical plane, respectively. The Z coefficients are the so-called transfer impedances, and depend on the pick-up geometry. From this, the beam position can be determined as

$$\bar{x} = \frac{Z_{\Sigma}}{Z_{\Delta}} \frac{\Delta_{\mathrm{H}}}{\Sigma}, \quad \bar{y} = \frac{Z_{\Sigma}}{Z_{\Delta}} \frac{\Delta_{\mathrm{V}}}{\Sigma}. \tag{6}$$

The fourth possible signal combination Ξ, called the quadrupole signal, is not used in a position pick-up. However, it can be shown that

$$\kappa = \iint (x^2 - y^2) \rho(x, y)\, dx\, dy = \sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2. \tag{7}$$

The so-called quadrupole moment κ is therefore of interest since it provides information on the beam size. A pick-up which measures κ by extracting the signal Ξ is called a quadrupole pick-up.

Although the idea of a quadrupole pick-up was first introduced by Gol'din[1] as long ago as 1966, very little work has been done since then to optimise the design of such pick-ups. The typical approach has been to use existing beam position pick-ups, and to extract the quadrupole signal using sophisticated electronics. This is in a way a contradiction. Position pick-ups are usually optimised to have a linear response to beam displacement. The quadrupole signal, which originates from the non-linearity (quadratic term) in this response, is therefore extremely small. In particular, a perfectly linear position pick-up is utterly useless as a quadrupole pick-up. Nevertheless, quadrupole pick-ups have been successfully used in different places for various purposes related to measuring the beam width[2–8].

For the future Large Hadron Collider (LHC) and its injectors, not only the beam intensity but also its density (brightness) is important. Thus, there is an increasing need to be able to measure beam-size-related properties accurately, and preferably in a non-destructive way. In the 26 GeV Proton Synchrotron (PS), a quadrupole pick-up would be a useful tool to detect injection mismatch leading to emittance growth. However, for reasons that will become clear, a quadrupole pick-up capable of measuring the very small LHC beam inside the relatively large aperture of the PS, has to be optimised for this purpose.

2 Optimal Quadrupole Pick-Up Design

There are two main problems associated with quadrupole pick-ups. The first is that the measured quantity κ is not only dependent on the beam dimensions, but also on the beam position. This is a fundamental problem which cannot be solved by a clever pick-up design, but only by proper centring of the beam in the pick-up. As long as the beam displacement from the centre is small compared to the beam dimensions, its contribution to the quadrupole signal can be either neglected or corrected for with reasonable accuracy.

The second and more serious problem is the range in signal levels involved. In a typical position pick-up, the Σ signal is much stronger than the Ξ signal, and this difference grows rapidly with the aperture to beam-size ratio. Since in reality only a finite accuracy can be obtained when combining the electrode signals, this sets a limit to the measurement of the quadrupole moment. A good definition of what is meant by an 'optimal' quadrupole pick-up design is therefore one where the quadrupole signal is maximised with respect to the other signals involved.

Gold'in originally proposed an electrostatic pick-up, with parabolic electrodes following the equipotential lines of the quadrupole field component, as the optimum design. His ideas were taken up by Nassibian, who also generalised Gol'din's work to higher-order field components[9], but tests showed that the parabolic electrodes were not practically feasible due to the large inter-electrode capacitance introduced in this geometry.

3 Theoretical Design Considerations

The physical working principle of any pick-up is to measure the relative strength of the different field modes induced by the beam. In a position pick-up for example, the beam position is measured as the ratio between the dipole mode and the monopole mode. A quadrupole pick-up measures the quadrupole moment as the ratio between the quadrupole mode and the monopole mode.

According to Maxwell's equations, higher order modes fall off faster as a function of distance from the source. This is why the Ξ signal is so small with respect to the Σ signal. Because of this, a position pick-up is a very sensitive beam current monitor, a slightly less sensitive position monitor, and not a very sensitive beam size monitor.

It would seem as if the only way to significantly increase the quadrupole signal with respect to the other signals is to reduce the pick-up radius. This is certainly true if the pick-up is electrostatic or measures the distribution of wall currents around the beam pipe. These pick-up types essentially probe the electric potential around the beam, and since the potential is a scalar field, only its magnitude can be measured. The magnetic field however, being a vector field, also has a measurable direction. It will be shown here that this extra degree of freedom can be used to suppress the otherwise dominating sum signal, induced by the monopole field component. In doing so, the pick-up loses its ability to measure the beam current. However, in any given machine there are usually several other monitors dedicated to beam current measurement.

3.1 Magnetic Field Induced by the Beam

Under quasi-static conditions, the magnetic field created by a current distribution $\vec{J}$ is given by the formula[10]

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \iiint \frac{\vec{J}(\vec{r'}) \times (\vec{r} - \vec{r'})}{\left|\vec{r} - \vec{r'}\right|^3} \, dx' \, dy' \, dz', \tag{8}$$

where $\vec{r} = x\,\hat{x} + y\,\hat{y} + z\,\hat{z}$ and $\vec{r'} = x'\,\hat{x} + y'\,\hat{y} + z'\,\hat{z}$ Under the assumption of an infinitely long beam of constant cross section, i.e. $\vec{J} = J(x', y')\hat{z}$, this can be expanded as[11]

$$\vec{B}(x,y) = \frac{\mu_0}{2\pi} \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \underbrace{\iint J(x', y')\, x'^i\, y'^j \, dx' \, dy'}_{\text{source}} \cdot \underbrace{\frac{(-1)^{i+j}}{i!\, j!} \frac{\partial^{i+j}}{\partial x^i \partial y^j} \frac{y\hat{x} - x\hat{y}}{x^2 + y^2}}_{\text{field}} \tag{9}$$

where, in each term, field and source properties have been separated. In the expansion, the source components are simply the different moments of the current distribution J, whereas the field components can be identified as field multipoles. If the field is expressed in cylindrical coordinates

$$\begin{aligned}\vec{B}(\rho,\theta) = -I\,\frac{\mu_0}{2\pi}\Bigg[\frac{1}{\rho}\hat{\theta} + \bar{x}\left(\frac{\cos\theta}{\rho^2}\hat{\theta} - \frac{\sin\theta}{\rho^2}\hat{\rho}\right) + \bar{y}\left(\frac{\sin\theta}{\rho^2}\hat{\theta} + \frac{\cos\theta}{\rho^2}\hat{\rho}\right) + \\ + (\sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2)\left(\frac{\cos 2\theta}{\rho^3}\hat{\theta} - \frac{\sin 2\theta}{\rho^3}\hat{\rho}\right) + \dots\Bigg] \qquad (10)\end{aligned}$$

it can be seen that the first term, corresponding to the monopole mode, has a field component only in the $\hat{\theta}$ direction. Thus, the monopole mode signal can be entirely suppressed by coupling to the $\hat{\rho}$ component of the magnetic field. Such a coupling is achieved by shaping the antenna loops as a cylinder around the beam. To maximise the sensitivity to the quadrupole field mode, the four antenna loops should then be positioned where its radial component is strongest, i.e. at 45° angle to the horizontal plane (see Fig. 2).

3.2 Influence of a Conducting Boundary

If the beam is enclosed in a perfectly conducting cylindrical pipe with inner radius d, image currents will be induced on the inside of the pipe. These currents also induce a field inside the pipe. Since this induced field does not have any sources inside the pipe, it can be expressed in a standard multipole expansion as

$$\begin{aligned}\vec{B}_{\text{wall}}(\rho,\theta) = b_1\left(\cos\theta\,\hat{\theta} + \sin\theta\,\hat{\rho}\right) + b_2\left(\sin\theta\,\hat{\theta} - \cos\theta\,\hat{\rho}\right) + \\ + c_1\left(\rho\,\cos 2\theta\,\hat{\theta} + \rho\,\sin 2\theta\,\hat{\rho}\right) + c_2\left(\rho\,\sin 2\theta\,\hat{\theta} - \rho\,\cos 2\theta\,\hat{\rho}\right) + \dots \qquad (11)\end{aligned}$$

As the field can not penetrate the boundary, the radial component of the total magnetic field has to vanish at d, and the coefficients can therefore be found by term-wise identification. The total field inside the pipe is thus

$$\begin{aligned}\vec{B}_{\text{tot}}(\rho,\theta) = -I\frac{\mu_0}{2\pi}\Bigg[\frac{1}{\rho}\hat{\theta} + \\ + \bar{x}\left(\left(1+\frac{\rho^2}{d^2}\right)\frac{\cos\theta}{\rho^2}\hat{\theta} - \left(1-\frac{\rho^2}{d^2}\right)\frac{\sin\theta}{\rho^2}\hat{\rho}\right) + \\ + \bar{y}\left(\left(1+\frac{\rho^2}{d^2}\right)\frac{\sin\theta}{\rho^2}\hat{\theta} + \left(1-\frac{\rho^2}{d^2}\right)\frac{\cos\theta}{\rho^2}\hat{\rho}\right) + \\ + (\sigma_x^2 - \sigma_y^2 + \bar{x} - \bar{y})\left(\left(1+\frac{\rho^4}{d^4}\right)\frac{\cos 2\theta}{\rho^3}\hat{\theta} - \left(1-\frac{\rho^4}{d^4}\right)\frac{\sin 2\theta}{\rho^3}\hat{\rho}\right) + \dots\Bigg] \qquad (12)\end{aligned}$$

For a magnetic pick-up, the transfer impedance is proportional to the magnetic flux through the antenna loops. Therefore, if the loops measuring the radial field component have an azimuthal opening angle of ϕ, the transfer impedances can be expected to scale as

$$Z_\Delta \propto \left(1 - \frac{a^2}{d^2}\right) \frac{\sin\frac{\phi}{2}}{a^2} \tag{13}$$

and

$$Z_\Xi \propto \left(1 - \frac{a^4}{d^4}\right) \frac{\sin\phi}{a^3}, \tag{14}$$

where a is the pick-up radius. This has been quantitatively confirmed by simulations[12]. There are two important remarks to be made. First, if the conducting boundary is sufficiently far from the loops, it does not affect the transfer impedance. What is sufficiently far depends on the field mode, since the dipole transfer impedance is reduced more than the quadrupole. Secondly, the dipole transfer impedance increases almost linearly with ϕ in the available range $0 - 90^\circ$, whereas the quadrupole transfer impedance levels off. Both these effects can be used to optimise the pick-up.

4 Practical Implementation

Based on the above theoretical arguments, a magnetic quadrupole pick-up has been developed for the PS machine. The final design is presented here.

4.1 Mechanical Design

To maximise the signal, the antenna loops should be placed as close as possible to the beam. Since the pick-up must not reduce the physical machine aperture, the closest possible position is defined by the inner dimensions of the standard vacuum pipe.

However, in the PS pick-up, the antenna loops were placed a little further from the centre than absolutely necessary, so that a ceramic vacuum tube could be placed just inside the loops. By doing this, the entire pick-up structure could be built outside the vacuum and potential problems with vacuum-compatibility of materials and vacuum feed-throughs for the signals were avoided. Avoiding feed-throughs is particularly important since they can introduce a parasitic series impedance in the antenna loops circuit, that would reduce the low-frequency response of the pick-up.

For symmetry reasons, the ceramic was made with a circular cross-section, although the PS vacuum chamber is elliptical. To avoid build-up of static charge, the inside of the ceramic was coated with a thin resistive layer. Moreover, it was possible to optimise the resistivity of this layer to effectively screen all microwave resonances of the cavity, while being transparent to the field at frequencies in the pass-band of the pick-up. In this way, the longitudinal impedance of the pick-up was significantly reduced.

A continuation of the beam pipe had to be made for the image currents. Due to the effect of a conducting boundary, it had to be placed at a certain distance from the antenna loops, in order for them to measure a significant magnetic flux. The by-pass was therefore implemented as a simple pill-box cavity with a radius approximately twice that of the standard vacuum chamber. The cavity between the ceramic and the pipe was divided into four sections by thin metal vanes placed in the electric symmetry planes of the quadrupole field mode. In this way, the longitudinal impedance of the pick-up could be reduced without affecting the quadrupole transfer impedance. At the same time, the dipole transfer impedance was also slightly reduced.

A drawing of the final design of the pick-up is shown in Fig. 3.

4.2 Antenna Loop Design

The four antenna loops were made of parallel, inter-connected rods made of Copper-Beryllium alloy for good conductivity and mechanical rigidity. They were positioned at 45° to the horizontal plane. The azimuthal opening angle ϕ of each loop was set to 45°. This value was chosen as a compromise, to achieve a large quadrupole signal level while keeping the inter-loop coupling small. In order to get a sufficient low-frequency response, the load seen by the loop was reduced by impedance transformation in the readout transformers used to measure the current induced in the loop. Thereby, a $50\,\Omega$ passive hybrid circuit can be used to combine the individual loop signals. This is very desirable in the radiation environment of the PS, where active electronics tend to age quickly.

In order to suppress any capacitive inter-winding coupling in the read-out transformers, the primary winding needed a ground point. However, to avoid common mode rejection problems at high frequencies due to signal path differences, the loop design had to be kept strictly symmetric. Using a single readout transformer, a symmetrically placed ground point would have implied at least two turns on the primary side. Since the rods forming the antenna loop are too thick to be wound on a ferrite core, two separate current transformers were placed on each side of the ground point. These transformers perform the impedance transformation, whereas a third transformer combines the two signals into one $50\,\Omega$ output (see Fig. 4).

At the far end of the loop, seen from the current transformers, a resistive termination to ground was added. Its purpose is to damp high frequency stripline resonances in the loop, which otherwise produces a longitudinal impedance and deteriorate the high frequency common-mode rejection of the pick-up. The value of the resistor was chosen such that it is practically transparent to the loop in the frequency range where measurements are performed.

5 Simulations and bench measurements

Analytic field calculations, such as the case considered in the beginning of this paper, can only be performed in special geometries, and under simplifying assumptions. In order to investigate and optimise the real pick-up, extensive simulations were performed[12]. The simulations were validated, with good agreement, by measurements on a prototype pick-up in the laboratory.

The initial design consisted of only the four loops, the ceramic tube and the surrounding cavity. By adding the metal vanes, the resistive terminations of the loops to ground, and the coating on the ceramic, it was possible to remove all resonances in the longitudinal impedance spectrum (Fig. 5 and 6), and thereby reduce the peak impedance by more than two orders of magnitude according to the simulations. None of these improvements had any negative effect on the quadrupole transfer impedance.

The longitudinal impedance of the optimised pick-up, shown in Fig. 7, is broadband and its value limited by the end-to-end resistance of the coating. It is therefore desirable to choose this value as low as possible. There is, however, a lower limit given by the bandwidth requirement of the pick-up. For the PS, a coating of a few Ω still lets the dipole and quadrupole fields penetrate up to frequencies around 25 MHz. However, at such low resistivity values, mode-conversion, caused by small imperfections in roundness or homogeneity of the layer, was found to spoil the common-mode rejection of the pick-up. The design value of the coating was therefore chosen to be about a hundred Ω.

The transfer impedances of the final design pick-up was both simulated and measured in the laboratory. The measured sum transfer impedance (Fig. 8) is essentially zero, as expected. The dipole (Fig. 9) and quadrupole (Fig. 10) transfer impedances agree very well with simulations. The sextupole transfer impedance (Fig. 11) is small, but important to know since it determines the non-linearity in the position measurement.

6 Beam Measurements

6.1 Proof-of-principle Prototype

At an early stage in the design work, a prototype pick-up was installed in the PS[13]. It was built using a spare ceramic vacuum tube, coated with a thin layer of titanium to removing static charges, and based on the initial design, i.e. it lacked the metal vanes and had a simpler design of the pick-up loops. The loops in the prototype had only one current transformer, and a single ground point placed at the opposite end of the loop with respect to the transformer.

Laboratory measurements of the prototype, before installation, confirmed that the pick-up worked in principle as expected. A very small parasitic common mode signal, increasing approximately linearly with frequency, was however found. This was later traced back to capacitive inter-loop coupling in the current transformer, and triggered the re-design of the current read-out.

6.2 Data Acquisition and Treatment

The four antenna loop signals from the pick-up were combined in a passive hybrid circuit. Due to the pick-up geometry, the signal combination is different from the case of an electrostatic pick-up:

$$\Delta_{\mathrm{H}} = TR - BR - BL + TL \tag{15}$$

$$\Delta_{\mathrm{V}} = TR + BR - BL - TL \tag{16}$$

$$\Xi = TR - BR + BL - TL \tag{17}$$

where TR is the top right loop, BL the bottom left etc. The Σ signal is zero by design, and was not used. Note especially the configuration for the Δ signals where Δ_{H}, for example, is not the difference between the top two loops and the bottom two loops, as might be intuitively expected. This is a consequence of the fact that it is the radial field component that is measured.

After the hybrid circuit, the composite signals were amplified and cabled to a digital sampling oscilloscope in an adjacent building. Since, by design, the pick-up cannot measure the beam current, a separate such measurement device is needed for normalisation. A wall-current monitor signal was used, sampled simultaneously by the scope. Note that, since the synchrotron motion is negligible over one machine turn, the position of this instrument within the ring is not important.

Previously when a quadrupole pick-up was used in circular machines[4–7] the pick-up signal was analysed only in frequency domain. Coherent beam size oscillations give rise to quadrupole signal components at $n\, f_{\mathrm{rev}} \pm 2\, q$, which in this way can be separated from the common-mode components appearing at $n\, f_{\mathrm{rev}}$. Therefore, this analysis reduces the requirements for a good common mode rejection. When doing such a frequency analysis, coherent oscillations of the beam position have to be avoided, since they also give rise to components at $n\, f_{\mathrm{rev}} \pm 2\, q$, due to the quadratic dependence on beam position.

The frequency domain analysis effectively does an average over all the bunches in the machine. However, since in the PS each injected bunch comes from a different Booster ring, there is no *a priori* reason that they should have the same oscillation phase and amplitude. In order to study each bunch individually, the signal was therefore analysed in the time domain.

To minimise the effect of noise and parasitic signals, a Gaussian fit was used to find the peak value of the signals at each bunch passage. When determining the peak value of Δ_{H}, Δ_{V} and Ξ, the bunch length and arrival time were fixed by the value found from the wall current monitor signal. By using this fitting scheme, the influence of the parasitic common-mode signal was significantly reduced. This is because the transfer function for the parasitic signal had a frequency response approximately proportional to ω, giving a signal proportional to the time-derivative of the bunch shape. But the derivative of a symmetric bunch shape is anti-symmetric, and therefore orthogonal to the bunch shape itself. The presence of such a signal does therefore not contribute to the fitted peak height, provided that the bunch shape parameters (position and width of the Gaussian) are known and are not free parameters of the fit.

6.3 Measurement Results

A number of measurements were performed using the 'proof-of-principle' prototype pick-up[14]. Perhaps the most interesting result was the cross-calibration of the measured quadrupole signal with a turn-by-turn SEM grid (see Fig. 12). The oscillation amplitude measured by the two instruments agreed well. From the same series of measurements, it was estimated that the value of κ measured by the pick-up had an offset of about 10 mm^2. In the final version, such offsets will be carefully measured in the laboratory prior to installation in order that its effect can be corrected for.

From the noise floor in the Fourier transform of the measured data after treatment, the r.m.s. error in the measurement of κ was estimated to be 0.5 mm^2 for the prototype pick-up. This is one to two orders of magnitude larger than the theoretical limit given by the amplifier input noise. It is therefore expected that the noise performance can be significantly improved.

7 Adaptation for use in other machines

Although in principle the basic design is applicable for any machine, the pick-up presented here has been optimised for injection studies in the PS machine. There are two properties in the design that are machine specific. These are the aperture and the bandwidth. The aperture can be modified by scaling the drawing and readjusting some related parameters, but the bandwidth is more complicated.

The bunch spectrum at injection into the PS covers the range from 70 kHz to approximately 20 MHz. Many machines, such as the SPS and LHC, have longer revolution times and shorter bunches, leading to much wider bunch spectra.

The low-frequency response of the pick-up can be improved either by increasing the inductance of the antenna loop (i.e. making the pick-up longer) or by reducing its load (i.e. increasing the turns ratio on the current transformers). Reducing the load, however, also means reducing the transfer impedance.

The high frequency response should be dictated by the cut-off of the current transformers. Measurements have however shown that they work to very high frequencies (100 MHz), and that the strong common-mode signal at the first loop resonance is the limiting factor. The loop resonances could be moved towards higher frequencies by shortening the pick-up. However, this means a smaller loop inductance and loss of low-frequency response, which has to be compensated by a smaller load.

In other words, it seems possible to significantly extend the bandwidth at the expense of a lower transfer impedance. For the PS design, the limits have not been fully tested. A dedicated study is therefore needed to optimise the design for a larger bandwidth.

8 Conclusions

A new type of quadrupole pick-up has been designed for the CERN PS. By coupling to the radial component of the magnetic field, total suppression of the common mode signal was demonstrated. As a consequence, the pick-up can be used even when the aperture to beam-size ratio is large, as is the case for the LHC beam in the PS. Using a ceramic vacuum chamber, the whole pick-up structure was built outside the vacuum. By proper choice of the inner coating resistivity, effective screening of the longitudinal impedance was obtained at high frequencies while maintaining the pick-up response in the range of frequencies of interest for measurements. Two pick-ups of this type will be installed in the PS, primarily to study coherent width oscillations due to injection mismatch.

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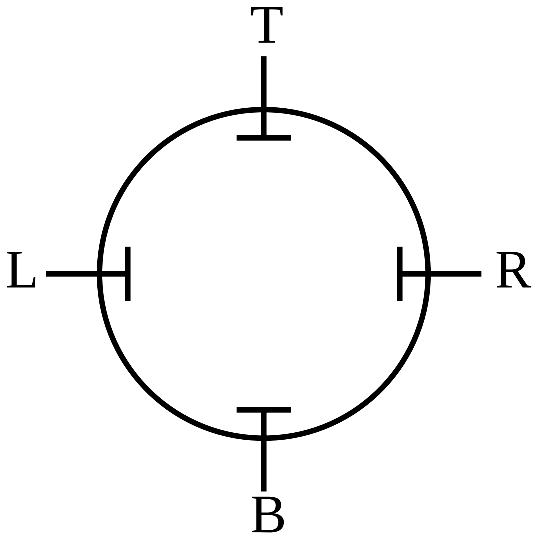

Fig. 1. A typical position pick-up (electrostatic). The beam passes perpendicular to the plane of the drawing.

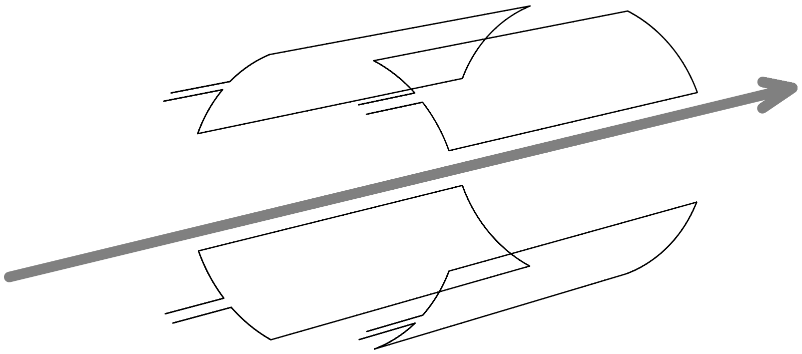

Fig. 2. Arrangement of antenna loops to couple to the radial component of the magnetic field. The arrow symbolises the beam.

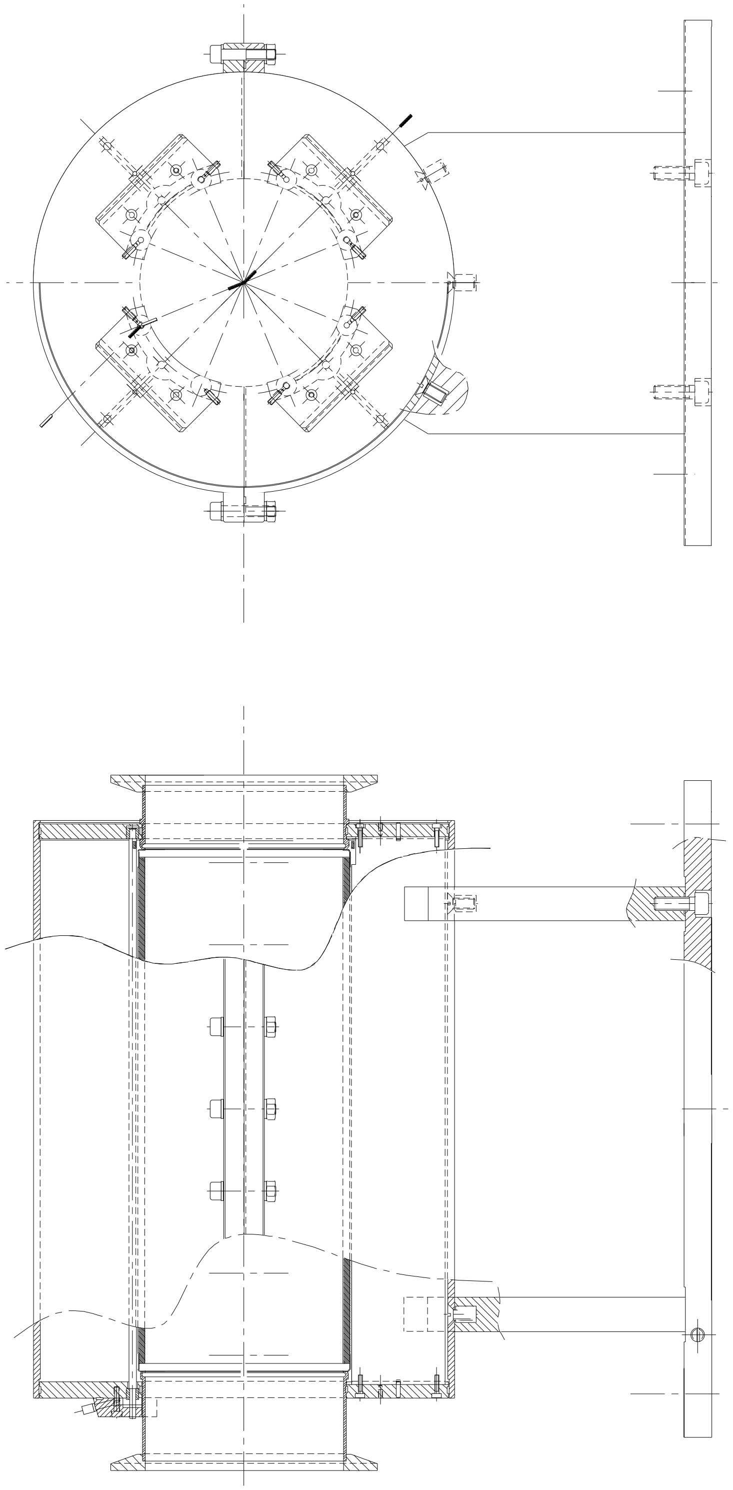

Fig. 3. CAD drawing of the final pick-up design. The total length is 500 mm and the outer radius 300 mm.

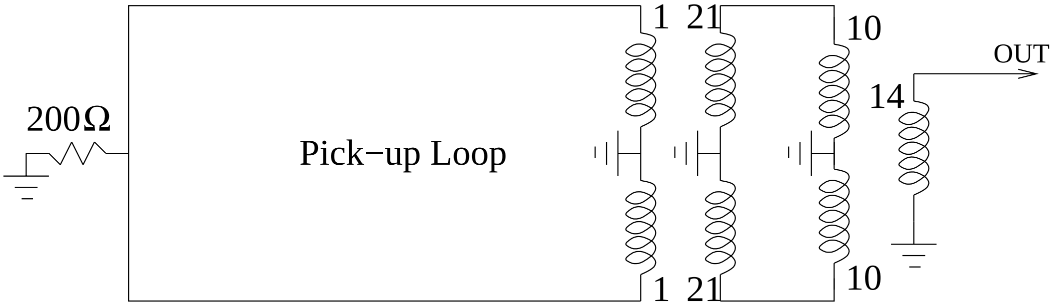

Fig. 4. Schematic layout of one antenna loop, showing the transformer arrangement, the winding ratios and the position and value of the termination resistance.

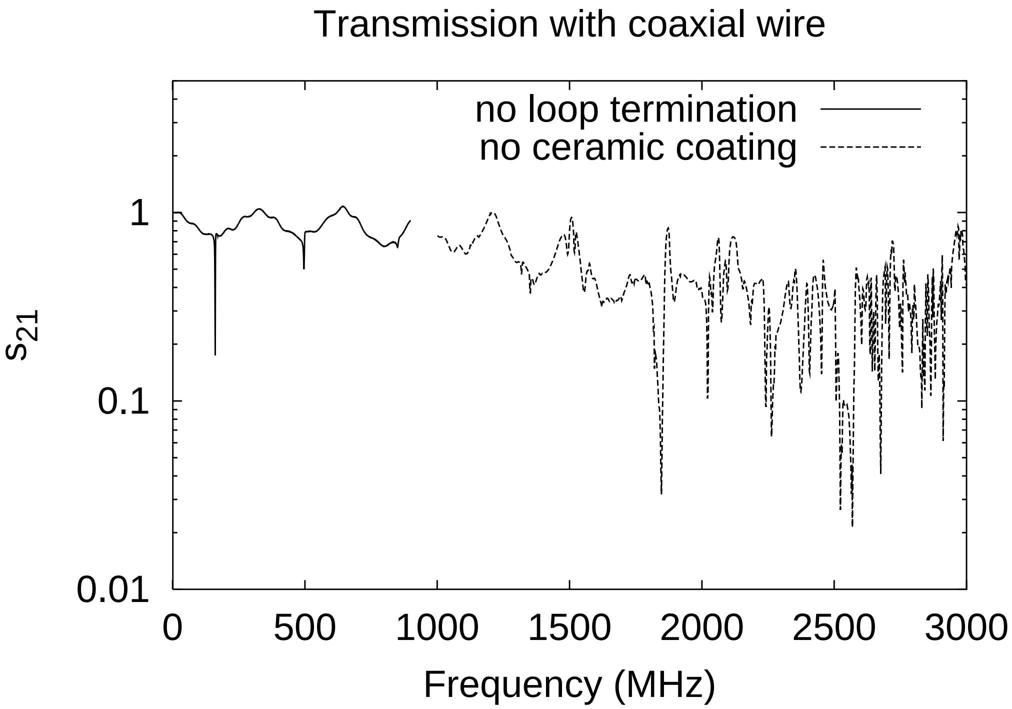

Fig. 5. Measurement of transmission (forward scattering parameter s_{21}) with a coaxial wire in the final pick-up. The two measurements are taken on different pick-up models, and show the effect of strip-line resonances in the antenna loops in the low frequency end, and cavity resonances at the high frequency end.

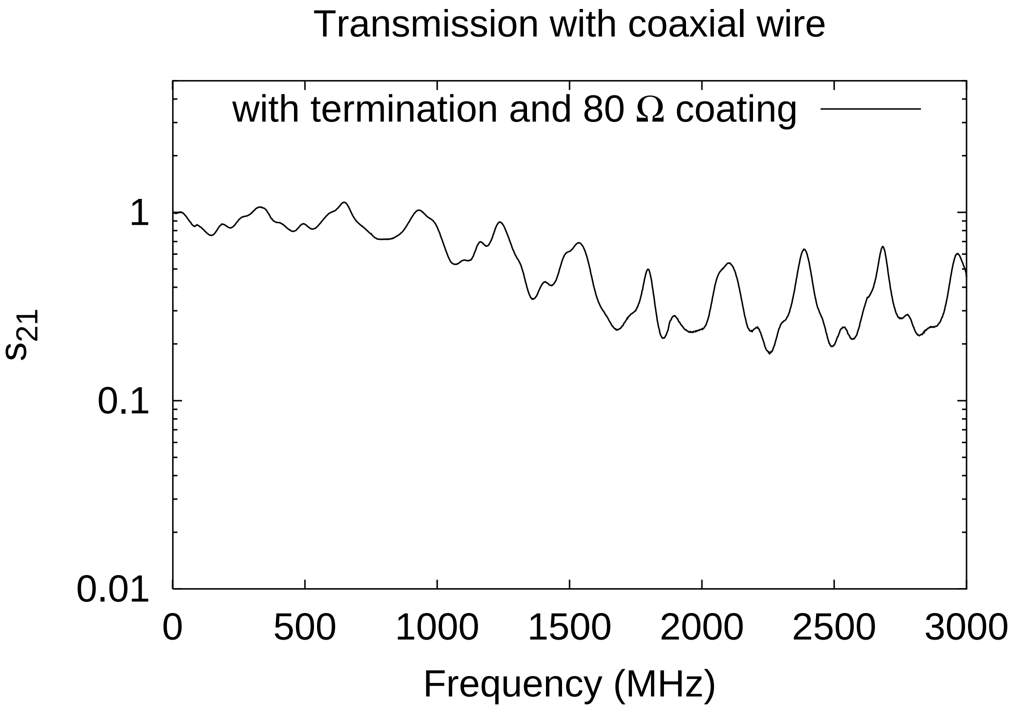

Fig. 6. Measurement of transmission with a coaxial wire in the final pick-up. The resonances present in Fig. 5 have been eliminated with the addition of resistive loop terminations and a 80 Ω coating on the inside of the ceramic. The response is now dominated by the wavy shape due to impedance mismatch at the signal entry and exit, and by losses in the wire at high frequencies

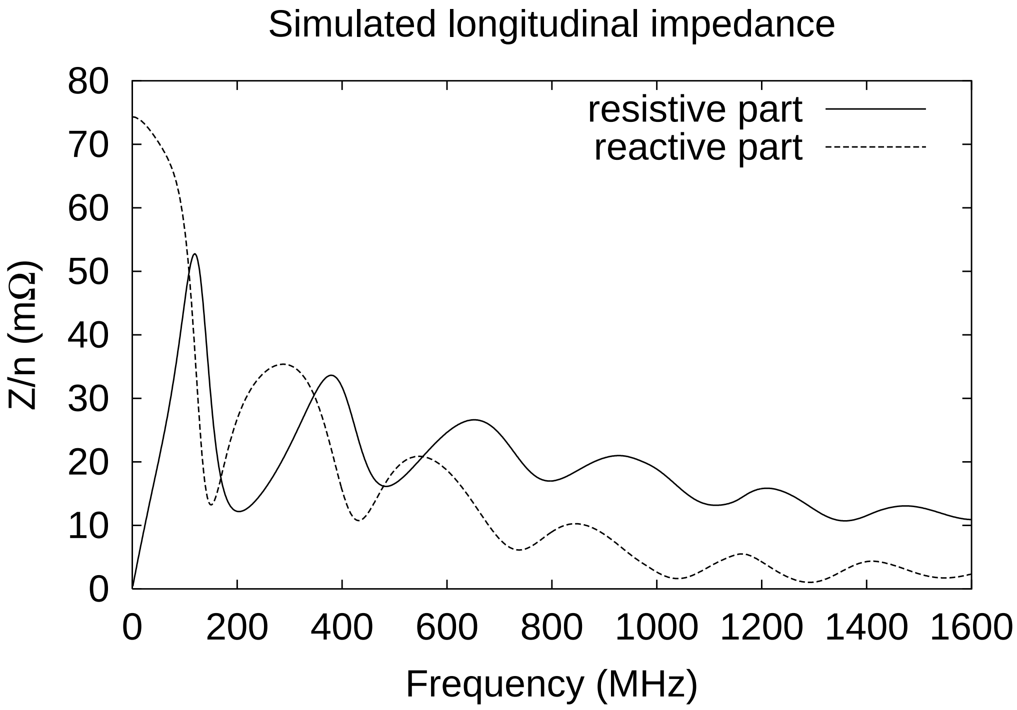

Fig. 7. Simulated longitudinal impedance of the final pick-up.

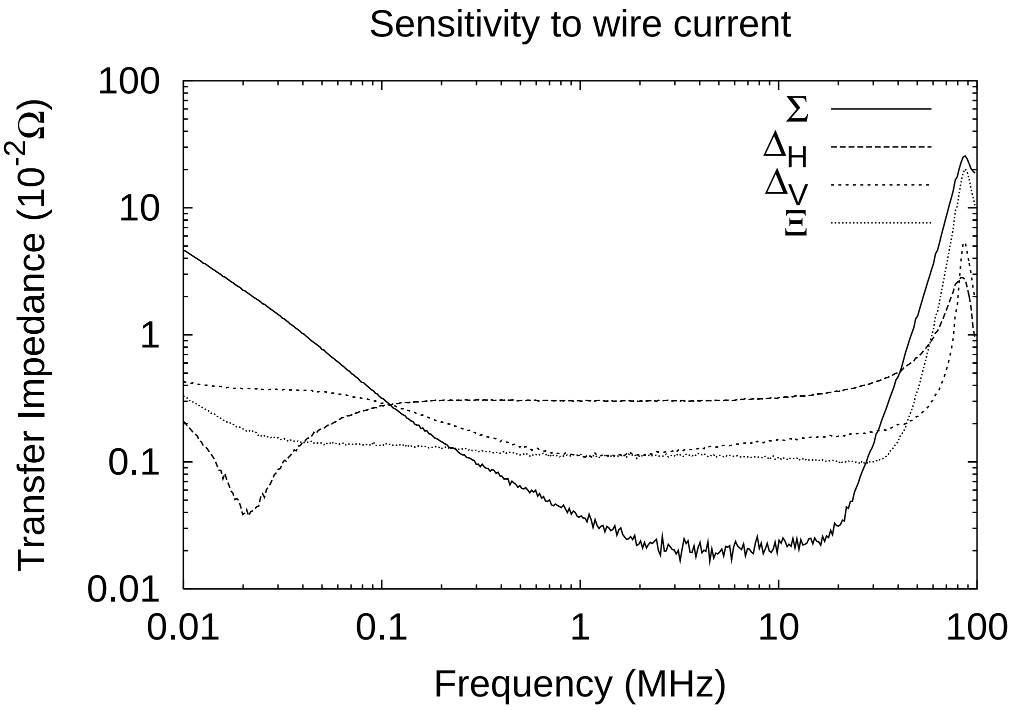

Fig. 8. Measurement of the common-mode coupling (component independent of position) using a wire movable along the x axis. Ideally, all signals should be zero. The common-mode rejection of the Σ signal is very good up to about 20 MHz, where the tail of the loop resonance begins. The other signal levels are affected by a small (less than 0.5 mm) offset between the electrical and geometrical centre (this is within the error of the absolute wire positioning accuracy). The rise of the Σ signal at low frequencies is an effect of the measurement instrument, that also influences the other measurements slightly.

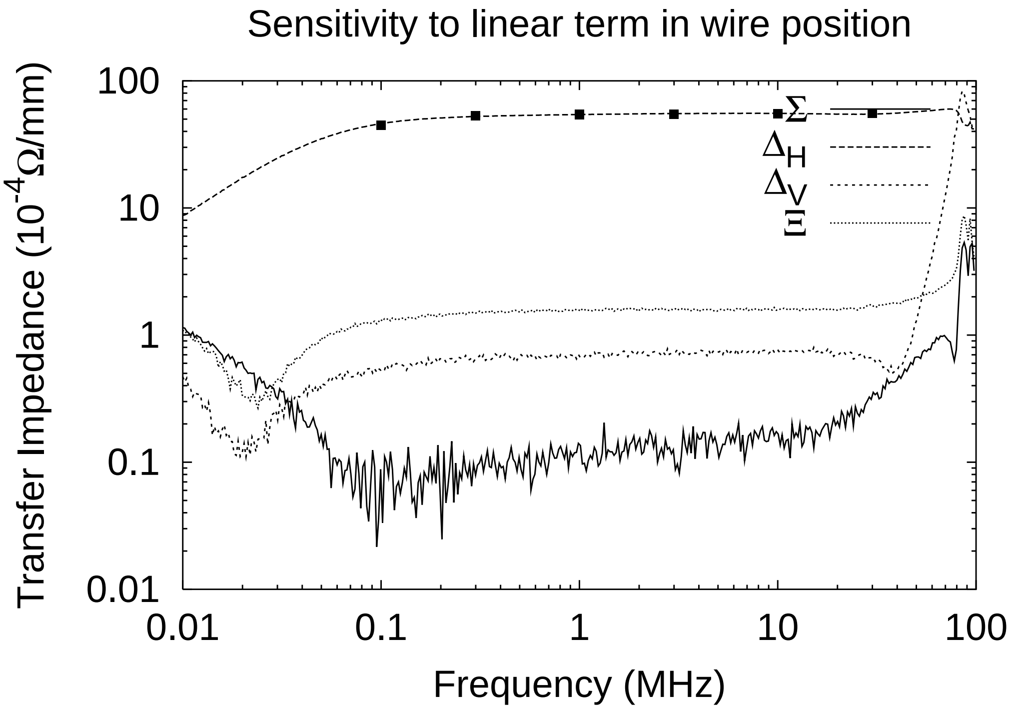

Fig. 9. Measurement of the dipole mode coupling (component with linear dependence on position) using a wire movable along the x axis. Note that the $\Delta_{\rm H}$ response is flat well above 20 MHz. The $\Delta_{\rm V}$ dependence on the horizontal position is due to a tilt of the order of 0.5° (within the alignment error margin). The small linear dependence of Ξ on position is due to the offset between the electrical and geometric centres. The dots are simulated values for $\Delta_{\rm H}$.

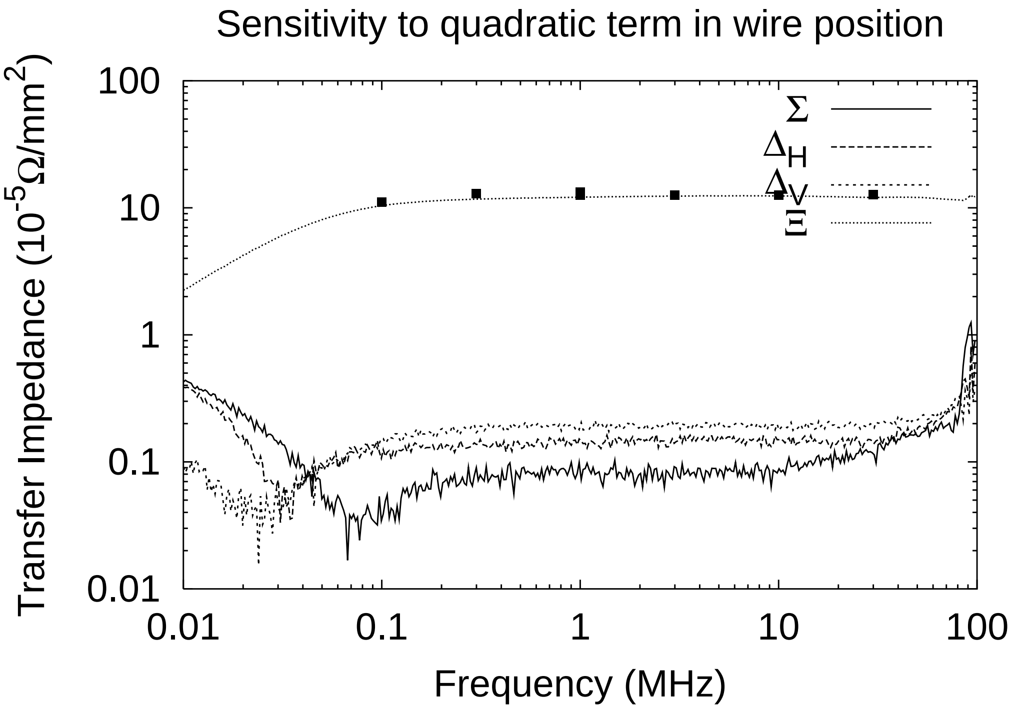

Fig. 10. Measurement of the quadrupole mode coupling (component with quadratic dependence on position) using a wire movable along the x axis. This is the coupling that is used to measure the quadrupole moment κ. Note that the Ξ response is flat well above 20 MHz. The dots are simulated values for Ξ.

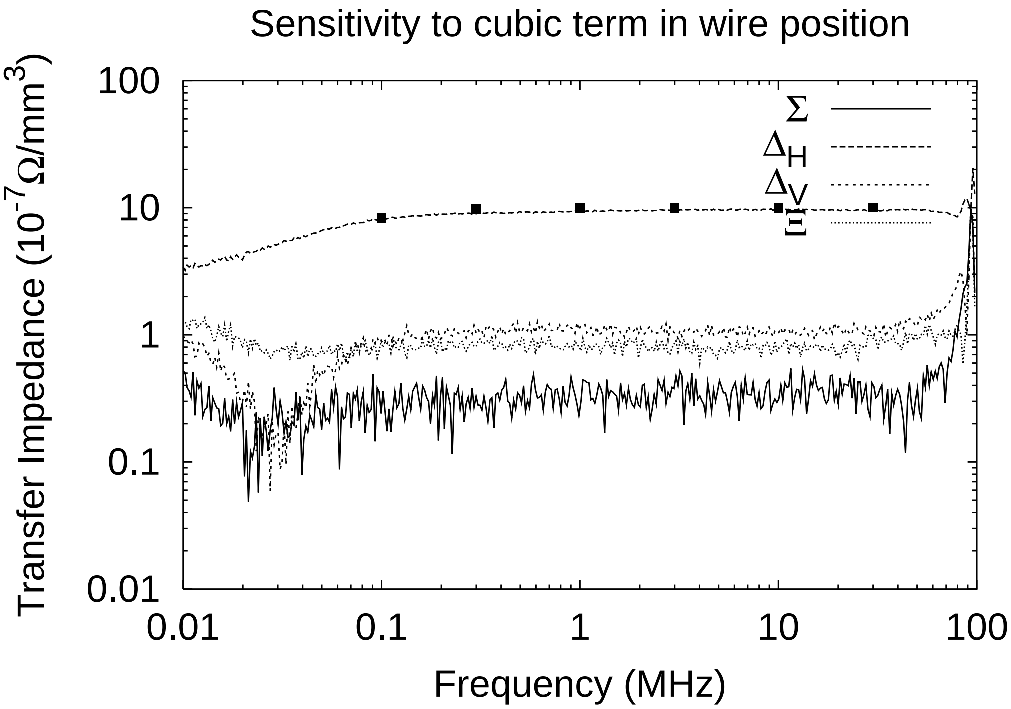

Fig. 11. Measurement of the sextupole mode coupling (component with cubic dependence on position) using a wire movable along the x axis. This coupling produces the lowest order non-linear dependence of Δ on beam position. The dots are simulated values for Δ_{H}.

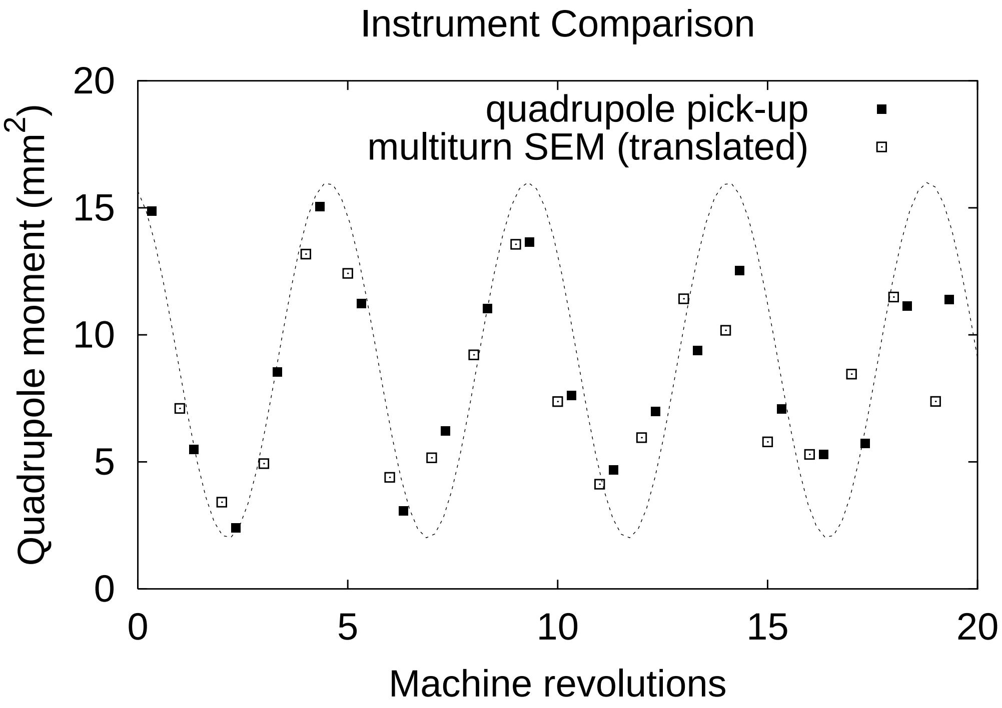

Fig. 12. Measurement of beam width oscillations after injection in the PS (quadrupole moment κ). The beam size oscillations were caused by dispersion mismatch in the horizontal plane, whereas the vertical beam size and the beam position was stable. To enable the comparison, the horizontal beam size measured with the SEM grid was squared and shifted by $-\sigma_y^2 - \bar{x}^2 - \bar{y}^2$ (estimated) to correct for the constant terms in κ. The dotted line is a sine curve fit to the first 6 turns.