EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
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CERN - PS DIVISION

PS/ AR/ Note 96-06

A NEW TYPE OF SLOW-WAVE PICK-UP

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A new type of slow-wave PU is proposed using inductive loading by lumped elements. These elements are made of small coils with few turns which interconnect the individual electrodes of the PU structure. The length of each element is chosen such that for the highest operational frequency it is shorter than $\lambda_0/4\beta$ (with λ_0 being the free space wavelength and β=v/c). Thus the electrical circuit can be modeled by means of a quasi-static equivalent circuit of a LC transmission line. The advantage of this lumped-element inductive loading is to minimize the capacitance from PU electrode to ground (i.e. the metallic vacuum chamber wall). If compared to conventional structures used for this purpose, made of short electrodes interconnected by external coaxial delay lines or printed on an alumina substrate, the sensitivity can be improved by a factor up to $1/\beta$.

Geneva, Switzerland
21 March 1996

Introduction

As the field distribution made by a low velocity charged particle is significantly different from the field slice of a relativistic particle with $\beta = 1$, dedicated PU and kicker structures for beam diagnostics and stochastic cooling have been developed. Amongst those, are the helix line PU [1], the printed circuit meander [2] and the strip electrode with coaxial delay lines. We will not discuss here the electrical response from single elements structure like, for example, the button and the shoe-box BPM (Beam Position Monitor) for low-β particles [3]. The above-mentioned group of cascaded elements can be subdivided into structures which act only on momentum (e.g. the helix type) and others which are able to interact with momentum and transverse position (e.g. meander and travelling wave PU's). Note that these travelling wave type PUs mentioned above for low-β applications act as forward couplers: this is in contrast to the classical $\lambda/4$ electrode, which for $\beta = 1$ is a backward coupling PU (the signal appears at the upstream end of the PU). The problem involved in the practical construction is the low phase velocity of the PU to be matched to the low particle velocity of the beam. In other words, one has to slow down the propagation velocity of the PU structure without lowering the characteristic impedance of the line, a problem that is rather easy to solve for the helix line PU's by adjusting the helix pitch. For the other structures the aim is, for a given electrode geometry, to minimize the capacity to ground and obtain the delay required for the phase velocity of the structure and particle velocity matching. Ideally, one would like to use low loss and dispersion free ferrite materials in the gap between the electrodes and the vacuum chamber but these materials do not exist. As the basic idea remains, the desire to substitute the virtual material mentioned above by lumped elements made of tiny coils. This is closely related to the principle of using small coils (Pupin coils) in long transmission lines (transatlantic cables) to increase the characteristic impedance (in this case to reduce attenuation caused by resistive losses).

Mechanical layout of the structure

The geometry of the new structure is sketched in Fig. 1:

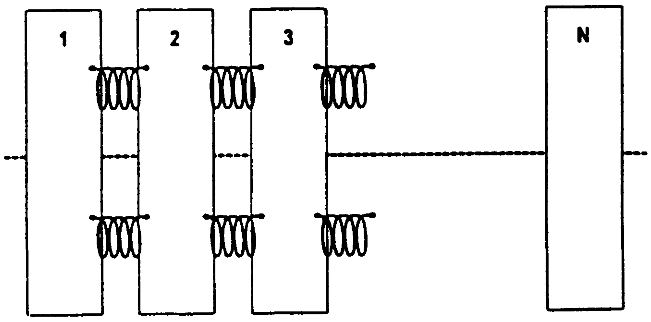

Fig.1. Layout of the slow-wave PU

The structure consists of short rectangular electrodes, the dimension of each electrode along the beam being shorter than $\lambda_0/4\beta$, connected by pairs of small coils as shown in Fig 1. The reason for using two coils is to keep the perturbation of the induced surface current distribution as small as possible (as compared to a single coil in the centre of the electrodes).

For the resulting configuration, a very simple model can be given assuming that both *L'* and *C'* are frequency-independent and using the well-known expressions for the phase velocity and characteristic impedance of a lumped element transmission line.

$$v_{ph} = \frac{1}{\sqrt{L'C'}} \tag{1}$$

and:

$$Z_c = \sqrt{\frac{L'}{C'}} \tag{2}$$

L' and *C'* are the inductance and capacitance per unit length. *C'* is given by the geometry of the electrode. Then setting the phase velocity of this transmission line equal to the given particle velocity ($\beta = v/c$) yields the required inductance *L'*. There is also an interest to maximize the characteristic impedance of the line in order to optimize the coupling impedance, i.e. the sensitivity of the PU. Fortunately, the inductive loading required for matching the low phase velocity of the beam also increases automatically the characteristic impedance of the lumped element transmission line (1), (2). As an example (required reduction in phase velocity by a factor of 3), we would need the inductive loading increased by a factor of 9. Thus the characteristic impedance is increased by a factor of 3 and the coupled power induced by the beam is also raised by a factor of 3.

Numerical simulation

For the numerical simulation of the PU sensitivity a rather simple approach has been chosen (Fig. 2). Each PU plate has a capacity to ground ($C'\Delta L$) and its intrinsic inductance ($L'\Delta L$) with $\Delta L = 2$ cm, determined from (1), (2) by setting $v_{ph} = c$ and $Z_c = 50\Omega$. The width of the strip (for a given distance from the beam pipe surface) has been taken from an earlier 50Ω strip-line design and confirmed by measurements. The transmission characteristics of this lumped element is shown in Fig. 3. The coupling to the beam is represented by properly phased current sources (Fig. 2) feeding a current linearly increasing with frequency into each PU plate.

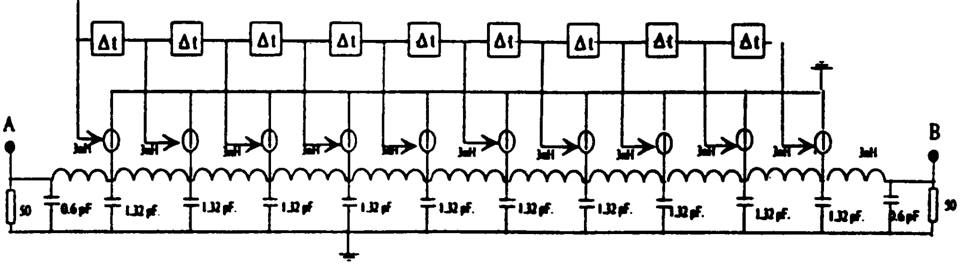

Fig. 2. Electrical circuit used in the numerical simulation

The simulation has been carried out in the frequency domain for the case $\beta_{line} = 0.3$ (and $\beta_{line} = 1$) and a structure of 10 PU plates each 2 cm long. The transmission characteristics for $\beta_{line} = 0.3$ are given in Fig. 3.

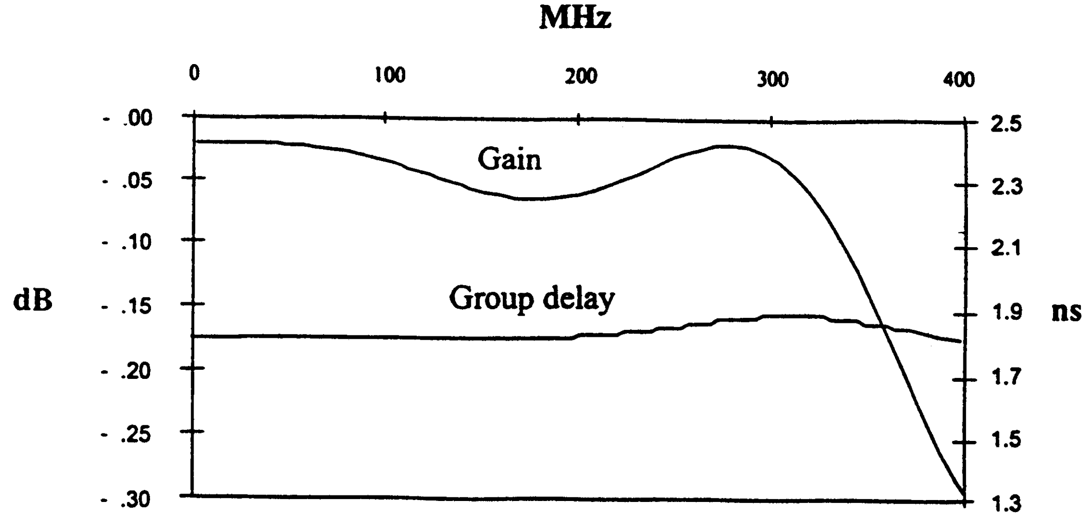

Fig. 3. Results of the numerical simulation: transmission characteristics

For $\beta_{line} = 0.3$ an additional inductive loading $L'' = 30$ nH/cm (thus $L'_{total} = 33$ nH/cm) has been assumed to take into account the effect of the lumped inductance required. For low frequencies (where the whole structure is short compared to a free space wavelength) the response is similar to single plate PU with two connecting wires (upstream and downstream). This means that there is no significant directivity and signal enhancement of the slow wave structure (for a $\beta_{beam} = 0.3$) as compared to $\beta_{line} = 1$ device (normal strip-line). However, for increasing frequencies the evolution of directivity (ratio of forward/backward coupled signal) and signal enhancement of the lumped element structure is clearly visible and merges into the numerically predicted values (Figs. 4a and 4b).

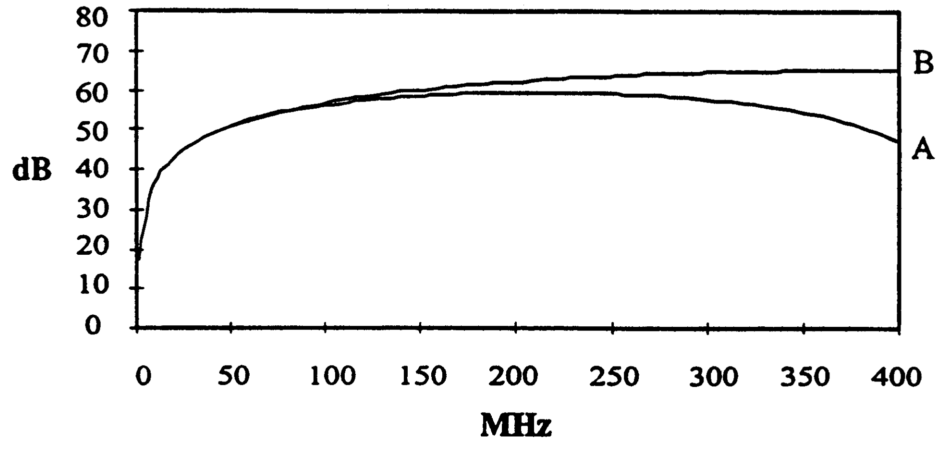

Fig. 4a. Forward and reverse sensitivity calculated without additional inductances (50Ω strip-line); $\beta_{beam} = 0.3$, $\beta_{line} = 1$, vertical scale: relative units.

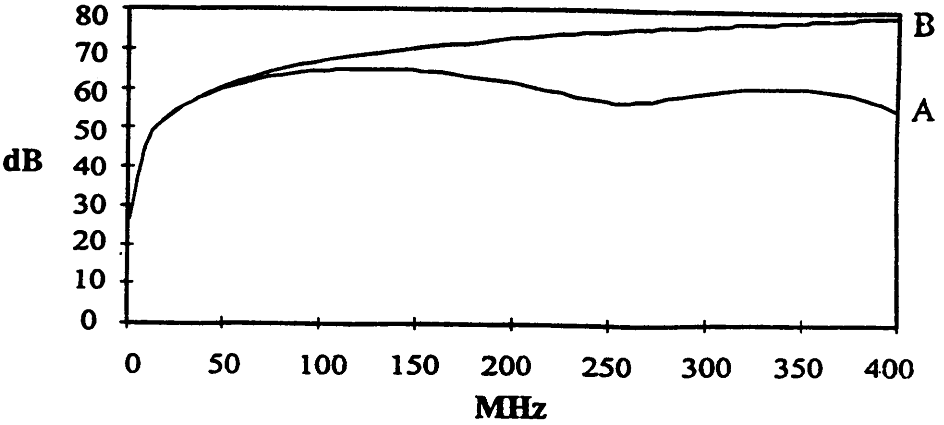

Fig. 4b. Forward and reverse sensitivity calculated with additional inductances (150Ω strip-line); $\beta_{beam} = 0.3$, $\beta_{line} = 0.3$, vertical scale: relative units.

Measurements

These measurements are made in one half of a vacuum chamber, (cf. Fig. 5) taking advantage of the image plane concept, the beam being simulated by an array of small probes [4].

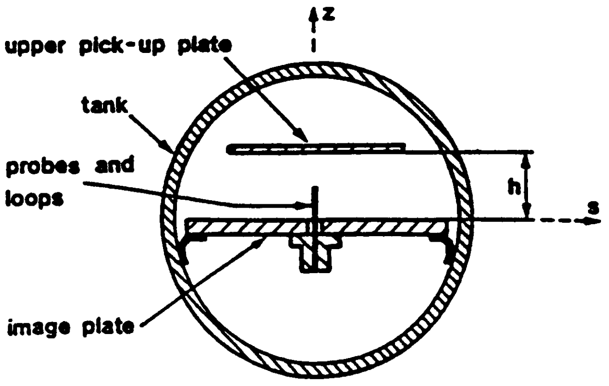

Fig. 5. Bench layout with the upper part of the PU

In general the simulation of a slow beam using this concept requires the presence of both loops and probes in order to simulate the correct ratio of electric and magnetic fields of this slow beam. In the present case, since $\beta = v/c$ was given as 0.3 (i.e. protons of 300 MeV/c), the influence of magnetic fields has been neglected and only electric probes (small vertical pins) were used. Note that the coaxial cables coming from the power splitter (Fig. 6) are "terminated" with 10 dB attenuators within a few mm of the electric probes in order to ensure a reasonably low VSWR(<2) on the cables over a large frequency range (1 MHz to 400 MHz). The characteristic impedances of the PU structure (= lumped element delay line) has been measured by means of a synthetic pulse TDR (Time Domain Reflectometry) technique to be approximately 140 Ω. The phase velocity of this delay line was found to be approximately 0.3 c (as expected) by measuring the transmission delay over a frequency range from 1 MHz to 300 MHz.

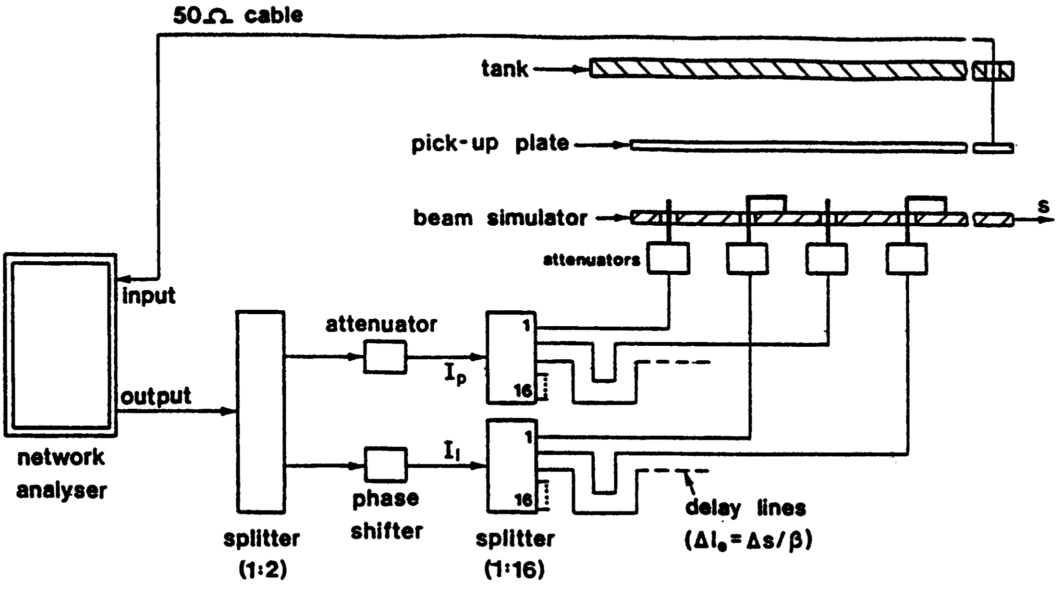

Fig. 6. General layout of the PU simulator

The amplitude and phase transmission characteristics of the PU structure (measured as a transmission line i.e. not the sensitivity characteristic) is shown in Figs. 7a and 7b. One can clearly observe from either plot that dispersion becomes significant beyond 300 MHz. These measurements have been carried out using external matching resistors of 90Ω (in series to the 50Ω generator and load impedances respectively) to provide an impedance matching as seen from the lumped element delay line (characteristic impedance =140Ω). Note that the approximate 10 dB transmission loss at low frequencies is due to the 90Ω matching resistors at either end.

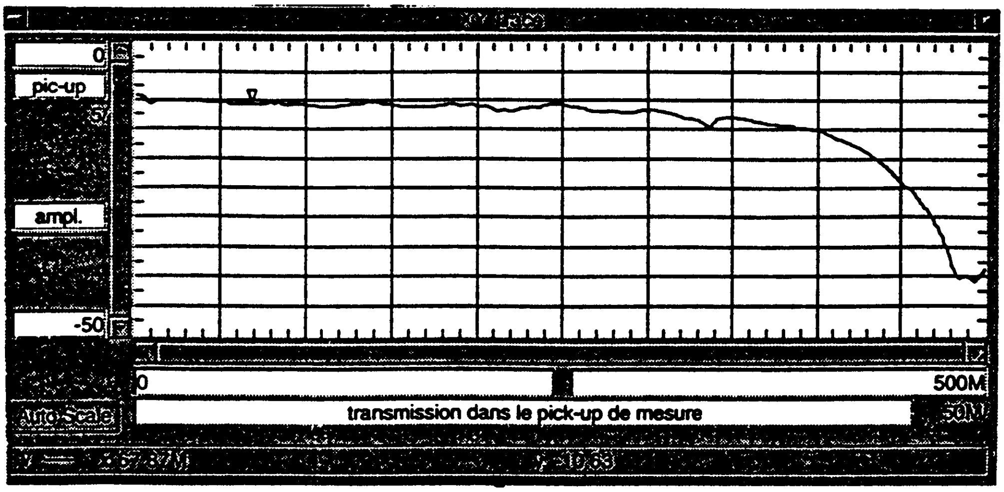

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Fig. 7a. Measured amplitude transmission characteristics of the lumped element delay line ($\beta_{line} = 0.3$), horizontal scale: 50 MHz/div, vertical scale: 5 dB/div (relative units).

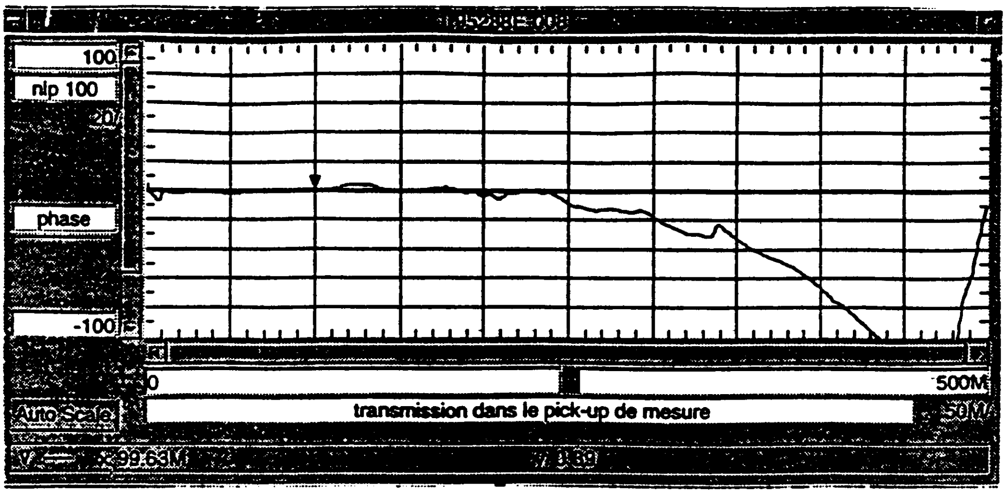

Fig. 7b. Measured phase transmission characteristics of the lumped element delay line for $\beta_{line} = 0.3$, horizontal scale: 50 MHz/div, vertical scale: 20 deg/div .

This configuration assures properly defined measuring conditions. Obviously the lumped element delay line configuration has a low-pass characteristic which is evident from Fig.7a. Sensitivity measurements have been carried out using the beam simulator depicted in Fig.6 without the magnetic field component, and forward and backward coupling has been recorded as a function of frequency in Figs.8a and 8b for the PU terminated by its characteristic impedance (140 = 90+50 Ω). Due to the comparatively short length of the structure (20 cm), the directivity (ratio in forward/backward coupling) starts to become visible from 150 MHz onwards.

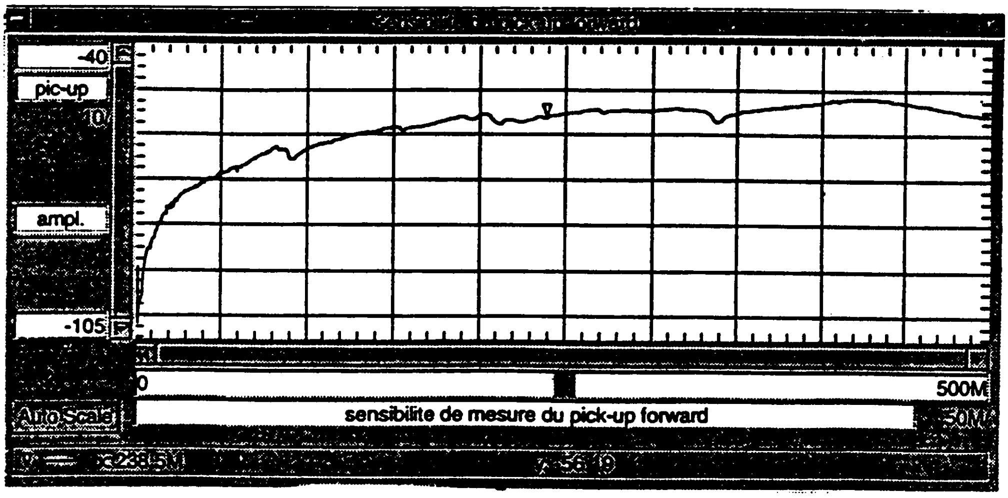

Fig. 8a. Measured forward sensitivity of the PU ($\beta_{beam} = \beta_{lin} = 0.3$), horizontal scale: 50 MHz/div, vertical scale: 10 dB/div (relative units).

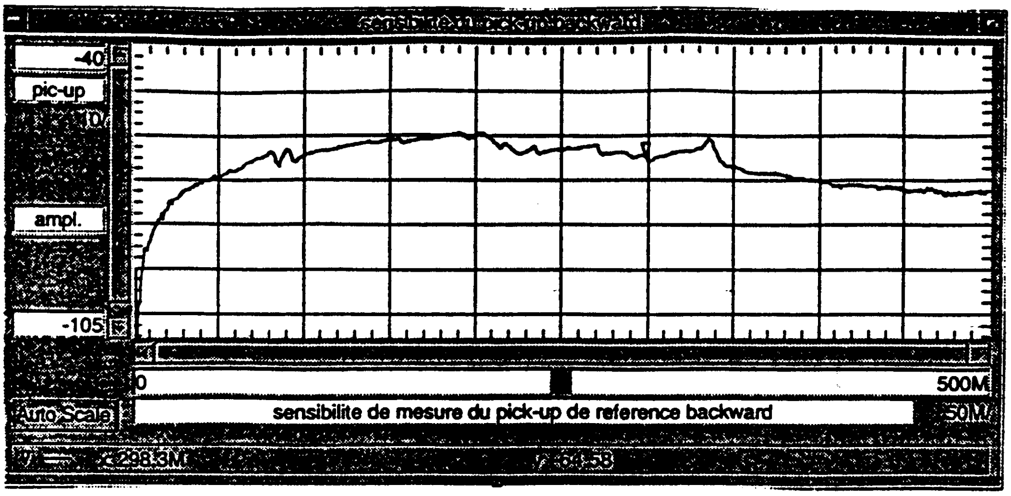

Fig. 8b. Measured reverse sensitivity of the PU ($\beta_{beam} = \beta_{line} = 0.3$), horizontal scale: 50 MHz/div, vertical scale: 10 dB/div (relative units).

Conclusion

Numerical simulations and experimental measurements have shown that it is possible to design a lumped-element delay-line able to meet the requirements of a transverse and longitudinal PU or kicker to be used for the stochastic cooling or the beam monitoring of non-relativistic particle beams. These new structures show a gain in transverse (and also longitudinal) sensitivity by a factor of $1/\beta$ as compared to conventional transverse and longitudinal slow wave PU's. This fact was confirmed by experiments carried out for a β value of 0.3. The improvement is achieved by implementing strong inductive loading using small coils in-between the short plates of the PU structure. A limitation of this technique is imposed by the maximum frequency up to which such small coils are usable before entering their resonance regime.

Acknowledgments

The authors would like to thank D. Möhl and S. Maury for fruitful discussions and for their support.

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