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The Sensitivity of a Meander Coupler to Particle Displacement

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Abstract: The sensitivity of a 80 cm long meander pickup to particle displacement has been theoretically obtained. The pickup is a travelling wave coupler, and its phase velocity is designed to synchronize a 60 MeV/c beam, aiming at betatron cooling at LEAR. Based on the calculated pickup sensitivity, cooling time is estimated with an acceptable result.

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1. Meander pickup under examination

The coupling impedance of the meander coupler discussed here is derived from theory [1]. In the calculation, the geometrical structure of the coupler, other than the length, is set same as that of the test piece installed in LEAR in September 1986 (see Fig. 1). The length of the test piece is 20 cm; in this note, we will discuss also for other lengths.

In the actual set up of a pickup for betatron cooling, two identical couplers sandwiches the beam as in Fig. 2(a) and are used in difference mode. In the calculation, however, the characteristics of the coupler (phase velocity, characteristic impedance, and coupling impedance) are obtained for the structure as in Fig. 2(b), where a ground plate is set on the equilibrium orbit. This model is equivalent to the actual setup in difference mode. The differential coupling impedance obtained from the half geometry is transformed to that of the actual full geometry by dividing by a factor of two. The explanation is as follows. Applying the Lorentz reciprocity thorem to the diagrams in Figs. 3(a) and (b), we can calculate voltage induced by the beam.

$$V_\ell = -\sqrt{\frac{Z_c}{8P_s}} \int_{vol} \vec{E}_s \cdot \vec{J}_\ell \, dV \,, \qquad (1.1)$$

where P_s and E_s are power flow and electric field generated by an external power source, respectively, and J_b density of the beam current [2,3,4]. For the half geometry (Fig. 3(a)), where a ground plate is set on the median plane, the voltage is given by

$$V_\ell^H = -\sqrt{\frac{Z_L}{8P_s^H}} \int_{vol} \vec{E}_s \cdot \vec{J}_\ell \, dV \,, \qquad (1.2)$$

where Z_L is the characteristic impedance of the pickup. For the full geometry (Fig. 3(b)), the voltage is

$$V_\ell^F = -\sqrt{\frac{Z_L/2}{8P_s^F}} \int_{vol} \vec{E}_s \cdot \vec{J}_\ell \, dV \,. \qquad (1.3)$$

Putting $P_s^H = P_s^F/2$, we have

$$\frac{Z_p^F}{Z_p^H} = \frac{V_\ell^F}{V_\ell^H} = \frac{1}{2} \,. \qquad (1.4)$$

The phase velocity β_w of the coupler is about 0.06, and the characteristic impedance is about 50 Ω both in theory and experiment. The overall length of the pickup discussed here is 80 cm; we examine the three configurations as shown in Fig. 4: a) four pairs of couplers of 20 cm long each, b) two pairs of couplers of 40 cm long each, and c) one pair of couplers of 80 cm long each. The reason for the examination of such configurations is that a long coupler gives a high coupling impedance for a beam with a velocity close to the phase velocity of the coupler, whereas a shorter coupler has more "broad-band" and hence more efficient for beam velocities different from the phase velocity [5].

2. Total differential coupling impedance of pairs of couplers

Coupling impedance of one pickup, consisting of a pair of couplers, is a function of the beam position x_b, which is measured from the equilibrium orbit, 30 mm far from the meander line in our case. In this note, we define the coupling impedance of one pickup $Z_p(x_b)$ by the ratio of the voltage at the output of a differential power combiner to the beam current. Figure 5 shows dZ_p/dx_b of a pickup consisting of a pair of 80 cm long single couplers for a 60 MeV/c beam. At an ideal pickup dZ_p/dx_b is constant, or Z_p is proportional to x_b, but at our pickup dZ_p/dx_b has a large value at large $|x_b|$, especially at high frequencies. In the calculation of cooling time to be discussed later, the coupling impedance is approximated by

$$Z_p = Z_p' \cdot x_b \quad , \tag{2.1}$$

where

$$Z_p' = \left. \frac{dZ_p}{dx_b} \right|_{x_b = 0} \quad . \tag{2.2}$$

We consider a pickup system consisting of n_{pu} pairs of couplers as shown in Fig. 6. The output signals from n_{pu} differential power combiners are fed into a sum power combiners. For this system, the total differential coupling impedance Z'_{pt} is given by

$$Z'_{pt} = \sqrt{n_{pu}}\ Z'_p \tag{2.3}$$

Figure 7 shows Z'_{pt} for the three coupler configurations and for beam momenta of 60 MeV/c (β_b = 0.06382) and 100 MeV/c (β_b = 0.1060). For the 60 MeV/c beam (the top figure), of which the velocity is close to the coupler's phase velocity, the single pair of 80 cm long couplers has the highest peak value at 90 MHz, but is bandwidth is narrow (up to 150 MHz). In contranst, the four pairs of 20 cm long couplers have the broadest band, but its peak value is low. At present we cannot conclude which coupler configuration is best, because we have not determined the system bandwidth, which is to be determined not only by the coupling impedance but also by the mixing between the pickup and the kicker, to be discussed in Sect. 3.2. For the 100 MeV/c beam (the bottom of Fig. 7), the four pairs of 20 cm couplers have the highest peak value and the broadest band; therefore, this configuration will be best.

3. Cooling time

3.1 Differential equation for the cooling process

We will estimate the cooling time using the following equation [6]:

$$\frac{1}{\tau} = -\frac{1}{\epsilon}\frac{d\epsilon}{dt} \tag{3.1}$$

$$= \sum_n \frac{1}{\tau_n} ,$$

$$\frac{1}{\tau_n} = \frac{f_0}{N}\left[2 g_n |\sin\mu| \cos n\omega_0 \delta T_{PK} - g_n^2 (M_n + U_n)\right] , \tag{3.2}$$

where f_0 is the revolution frequency, N the number of particles, μ the phase advance of betatron oscillation between the pickup and the kicker, M_n the mixing factor between the kicker and the pickup, U_n the noise to signal ratio, and δT_{PK} time−of−flight (T.O.F.) error of a particle caused by its momentum error. The cosine term in Eq.(3.2) can be replaced with an value averaged over the momentum distribution. Assuming a flat momentum distribution, we have

$$\langle \cos n\omega_0 \delta T_{PK} \rangle = \mathrm{sinc}\,\frac{n\omega_0 \Delta T_{PK}}{2} , \tag{3.3}$$

$$\operatorname{sinc} x \equiv \frac{\sin x}{x} \quad . \tag{3.4}$$

Here ΔT_{PK} is the full width of T.O.F. error and is related with the full momentum spread $\Delta p_0/p_0$ of the beam:

$$\frac{\Delta T_{PK}}{T_{PK}} = \left| \frac{\Delta L_{PK}}{L_{PK}} - \frac{1}{\gamma^2} \frac{\Delta p_0}{p_0} \right| , \tag{3.5}$$

where L_{PK} is the orbit length from the pickup to the kicker. At LEAR we can approximate

$$\frac{\Delta T_{PK}}{T_{PK}} = \frac{1}{\gamma^2} \frac{\Delta p_0}{p_0} \quad . \tag{3.6}$$

Putting this into Eq.(3.3), we have

$$\langle \cos n\omega_0 \delta T_{PK} \rangle = \operatorname{sinc} n\alpha , \tag{3.7}$$

$$\alpha = \frac{\pi}{\gamma^2} \frac{T_{PK}}{T_0} \frac{\Delta p_0}{p_0} \quad . \tag{3.8}$$

The condition that the coherent correction term in Eq.(3.2) is positive for any δT_{PK} and at any harmonic leads to

$$n\omega_0 \frac{\Delta T_{PK}}{2} < \frac{\pi}{2} , \tag{3.9}$$

or

$$n < n_c = \left(\frac{2}{\gamma^2} \frac{T_{PK}}{T_0} \frac{\Delta p_0}{p_0} \right)^{-1} \tag{3.10}$$

At this harmonic number, sinc $n\alpha$ in Eq.(3.7) is

$$\operatorname{sinc} n_c \alpha = \frac{2}{\pi} \quad . \tag{3.11}$$

In Eq.(3.2) U_n is inversely proportional to beam emittance, as will be shown later. Let $U_n(0)$ be the initial value of U_n, then

$$U_n(t) = \frac{U_n(0)}{\sigma(t)} , \tag{3.12}$$

where σ is beam emittance normalized by its initial value:

$$\sigma(t) \equiv \frac{\epsilon(t)}{\epsilon(0)} \quad . \tag{3.13}$$

Using Eqs.(3.7) and (3.12), we have

$$\frac{1}{\tau_n} = \frac{f_0}{N} \left[2 g_n |\sin\mu| \operatorname{sinc} n\alpha - g_n^2 \left(M_n + \frac{U_n(0)}{\sigma} \right) \right] . \tag{3.14}$$

At $t = 0$, τ_n takes a minimum value τ_{0n}

$$\frac{1}{\tau_{on}} = \frac{f_0}{N} \frac{(\sin\mu \ \mathrm{sinc}\ m\alpha)^2}{M_n + U_n(0)} \ , \tag{3.15}$$

with

$$g_n = g_{on}$$
$$\equiv \frac{|\sin\mu| \ \mathrm{sinc}\ m\alpha}{M_n + U_n(0)} \ . \tag{3.16}$$

For another gain, we write as

$$g_n = G \, g_{on} \ ; \tag{3.17}$$

then,

$$\frac{1}{\tau_n} = \frac{G}{\tau_{on}} \left[\frac{(2-G) M_n + 2U_n(0)}{M_n + U_n(0)} - \frac{G U_n(0)}{M_n + U_n(0)} \frac{1}{\sigma} \right] . \tag{3.18}$$

Defining the following parameters

$$\frac{1}{\tau_0} = \sum \frac{1}{\tau_{on}} \ ,$$
$$A = \sum \frac{1}{\tau_{on}} \frac{U_n(0)}{M_n + U_n(0)} \ , \tag{3.19}$$
$$B = \sum \frac{1}{\tau_{on}} \frac{M_n}{M_n + U_n(0)} \ ,$$

we have

$$\frac{d\sigma}{dt} = -G\left(\frac{2}{\tau_0} - GB\right)\sigma + G^2 A \ . \tag{3.20}$$

This yiels a solution

$$\sigma = (1 - \sigma_\infty) e^{-t/\tau'} + \sigma_\infty \ , \tag{3.21}$$

$$\frac{1}{\tau'} = G\left(\frac{2}{\tau_0} - GB\right) , \tag{3.22}$$

$$\sigma_\infty = G^2 A \tau' . \tag{3.23}$$

The cooling time τ_g to attain a goaled emittance σ_g ($> \sigma_\infty$) is

$$\tau_g = \tau' \ln \frac{1 - \sigma_\infty}{\sigma_g - \sigma_\infty} \ . \tag{3.24}$$

3.2 Parameter setting

In order to solve the differential equation, the needed parameters are evaluated here for beams of 60 MeV/c (β_b = 0.06382, f_0 = 244 kHz) and 100 MeV/c (β_b = 0.1060, f_0 = 405 kHz) circulating in LEAR, of which the circumference is 78.5 m. The number of particles N is set at 1×10^9, and the initial beam radius $\sqrt{(\beta\varepsilon)}$ at 3 cm. For the location of the pickup and the kicker, we examine two cases as shown in Fig. 8. The PU−K distances and the phase advances are as follows.

$$L_{PK} = \begin{cases} 11.3 \text{ m} & (\text{Location I}) \\ 25.6 \text{ m} & (\text{Location II}) \end{cases},$$

$$\mu = \begin{cases} 97.2^\circ & (\sin\mu = 0.992) & (\text{Location I}) \\ 292^\circ & (\sin\mu = -0.927) & (\text{Location II}) \end{cases}$$

The system bandwidth is determined to meet the following two conditions. First, the pickup has high coupling impedance in the frequency range. The result in Chapt. 2 (see Fig. 7) gives the answer. Second, the coherent correction term must be positive, as mentioned above. The critical harmonic number defined by Eq.(3.10) depend strongly on the PU−K distance. For a momentum spread of $\Delta p_0/p_0$ = 6 ‰ in full width,

$$m_c = \begin{cases} 579 & (\text{Location I}) \\ 256 & (\text{Location II}) \end{cases}$$

The resulting upper limit of the frequency is

$$f_c = \begin{cases} 141 \text{ MHz} & (\text{Location I}) \\ .62 \text{ MHz} & (\text{Location II}) \end{cases}$$

for the 60 MeV/c beam, and

$$f_c = \begin{cases} 234 \text{ MHz} & (\text{Location I}) \\ 103 \text{ MHz} & (\text{Location II}) \end{cases}$$

for the 100 MeV/c beam. These frequency limit infers that the Location II with the long PU−K distance is appreciably disadvantageous.

The mixing factor M_n is approximated by

$$M_n = \begin{cases} \dfrac{n_s}{2n} & (n \le n_s/2) \\ 1 & (n > n_s/2) \end{cases} , \qquad (3.25)$$

where n_s is defined by

$$n_s = \frac{f_0}{\Delta f_0} = \frac{1}{\eta_f} \frac{p_0}{\Delta p_0} , \qquad (3.26)$$

$$(\eta_f \simeq 1/\gamma^2 \text{ at LEAR}) .$$

Noise to signal ratio U_n at the input of the kicker is given by

$$U_n = \frac{k T_{amp} f_0}{\frac{1}{50} \left(e f_0 Z'_{pt}(nf_0) \right)^2 N \langle A^2 \rangle} , \qquad (3.27)$$

where $< A^2 >$ is the rms value of amplitude of betatron oscillation. If we assume the phase space density is uniform in the ellipse

$$\gamma x_\ell^2 + 2\alpha x_\ell x'_\ell + \beta x_\ell'^2 = \epsilon , \qquad (3.28)$$

$< A^2 >$ is given by

$$\langle A^2 \rangle = \frac{1}{2} \beta \epsilon . \qquad (3.29)$$

Therefore, U_n is inversely proportional to emittance, as assumed above (Eq.(3.12)).

3.3 Resulting cooling time

We have obtained the parameters necessary to calculate the cooling time. The result of the calculation is summarized in Table I. Comparing the PU − K locations of L_{PK} = 11.3 m and 25.6 m, the cooling time is appreciably long at the 25.6 m distance because of the limited bandwidth. Therefore, this location should be excluded. In the case of L_{PK} = 11.3 m, p_0 = 60 MeV/c, $\Delta p_0/p_0$ = ±3 ‰ and T_{amp} = 400 K (a conventional amplifier), the coupler configuration of 1 × 80 cm is best: the goaled emittance σ_g = 0.33 is attained in 1 min. The conventional amplifier is good enough, though the cooling time is reduced to 35 s with a cryogenic amplifier of T_{amp} = 100 K. The cryogenic amplifier is usefull for a pessimistic momentum spread of ±6 ‰. For a 100 MeV/c beam, the coupler configuration of 4 × 20 cm is best. With the cryogenic amplifier, the cooling time is around 1 min for the both momentum spreads of ±3 and ±6 ‰.

The decrease of beam emittance with time is graphically shown in Figs. 9(a) and (b) for the 60 MeV/c beam (PU : 1 × 80 cm) and the 100 MeV/c one (PU : 4 × 20 cm). Figure 10(a) shows τ_n, $U_n(0)$, g_n as a function of frequency (harmonic number) for the 60 MeV/c beam (T_{amp} = 400 K, $\Delta p_0/p_0$ = ±3 ‰). Cooling time τ_n is large at the edge regions of the bandwidth [0 MHz, 142 MHz] because of small pickup coupling impedance. Therefore, a narrower bandwidth, say [15 MHz, 140 MHz], does not lengthen the cooling time τ_g. A similar result is obtained for the 100 MeV/c beam (T_{amp} = 400 K, $\Delta p_0/p_0$ = ±3 ‰) as shown in Fig. 10(b). A bandwidth of [15 MHz, 150 MHz] is acceptable instead of [0 MHz, 168 MHz].

4. Discussion

The total length of the pickup system discussed here is 80 cm, and the phase velocity is designed to synchronize a 60 MeV/c beam. In order to gain a capability to a 100 MeV/c beam, the pickup should be divided into four couplers, 20 cm long each, as shown in Fig. 4(a). When the divided pickup is used to a 60 MeV/c beam, for which a pair of 80 cm long single couplers is better, the couplers can be connected in series, i.e., the output siganl from a downstream coupler is injected to the upstream one.

This configuration is in principle equivalent to the 80 cm long single coupler. But there is a problem in dividing a pickup into short couplers. That is an edge field effect. In the theory for the calculation of the coupler's characteristics, the structure is assumed to be infinitely long, and the fields at the input and the output end are not considered. In an actual pickup, some edge fields may appear and kill the travelling wave signal. The coupling impedance of the 20 cm long test piece installed in LEAR was measured with a 100 MeV/c and a 200 MeV/c beam. The measured impedance is a half of a theoretical value at 100 MeV/c, and a fourth at 200 MeV/c. This discrepancy could be attributed to the edge field effect. A new pair 60 cm long single couplers are now prepared and to be installed in LEAR. (Estimation of cooling time with this new pickup is presented in Appendix.) The measurement with this long pickup will be useful to solve this problem; at a long pickup, the edge field effect will be smaller than the travelling wave signal. If it will be evident that the edge field effect spoils a 20 cm long coupler, a pickup of two pairs of 40 cm long couplers would be better.

The gain g_n discussed in this note is a relative value. To know the actual amplifier gain, we must express g_n with the transfer functions of the feedback system, i.e., pickup impedance, amplifier gain, kicker impedance, etc.. It is a subject of another note.

Acknowledgment

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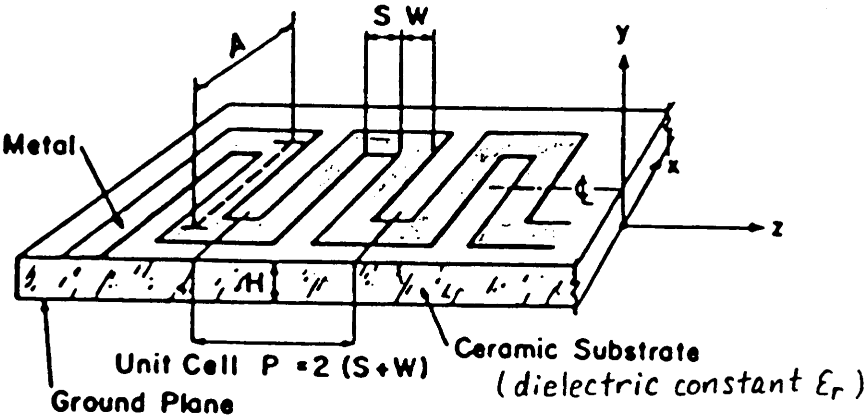
Table I. Summary of cooling time τ_g (σ_g = 1/3) for a beam of $\Delta p_0/p_0$ = ±3 or ±6 ‰, N = 1 × 10^9, $\sqrt{(\beta\varepsilon)}$ = 3cm, and T_{amp} = 100 or 400 K. The values of bandwidth with "PK" are limited by the mixing between the pickup and the kicker, and those with "P" are limited by the pickup coupling impedance.

L_{PK}	Momentum (MeV/c)	Coupler configuration	$\Delta p_0/p_0$ (%)	W (MHz)	T_{amp}=400K τ_g (s) (G)	T_{amp}=100K τ_g (s) (G)
11.3 m	60	4 × 20 cm	±3	142 (PK)	112 (0.90)	50 (0.70)
μ = 97.2 deg		2 × 40 cm	±3	142 (PK)	73 (0.80)	39 (0.64)
sinμ = 0.992		1 × 80 cm	±3	142 (PK)	61 (0.78)	35 (0.62)
			±6	70 (PK)	199 (0.83)	95 (0.70)
	100	4 × 20 cm	±3	168 (P)	106 (0.91)	42 (0.75)
			±6	118 (PK)	163 (0.90)	65 (0.75)
		2 × 40 cm	±3	97 (P)	241 (0.93)	86 (0.80)
		1 × 80 cm	±3	52 (P)	789 (0.95)	313 (0.84)
25.6 m	60	4 × 20 cm	±3	62 (PK)	933 (0.95)	302 (0.85)
μ = 292 deg		2 × 40 cm	±3	62 (PK)	500 (0.91)	190 (0.77)
sinμ = -0.927		1 × 80 cm	±3	62 (PK)	302 (0.90)	136 (0.70)
			±6	31 (PK)	1752 (0.95)	576 (0.84)
	100	4 × 20 cm	±3	104 (PK)	228 (0.91)	90 (0.75)
			±6	52 (PK)	1047 (0.95)	341 (0.85)
		2 × 40 cm	±3	97 (P)	326 (0.93)	117 (0.80)
		1 × 80 cm	±3	52 (P)	946 (0.95)	313 (0.84)



Meander width	A = 87 mm
Tape width	W = 3 mm
Tape spacing	S = 4 mm
Cell length	p = 14 mm
Substrate thickness	H = 10 mm
Dielectric constant	ε_r = 9.5

Fig. 1. Geometry of the meander coupler.

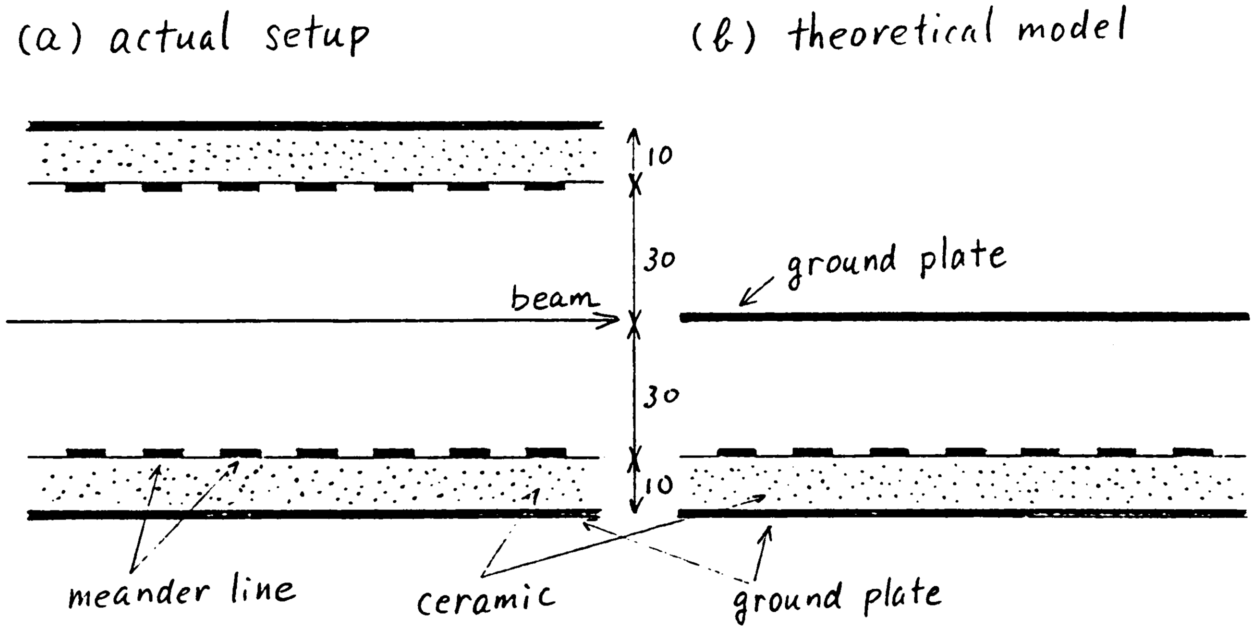


Fig. 2. (a) Actual setup of a meander pickup made up by two identical couplers sandwiching the beam, and (b) its theoretical model with a ground plate on the equilibrium orbit.

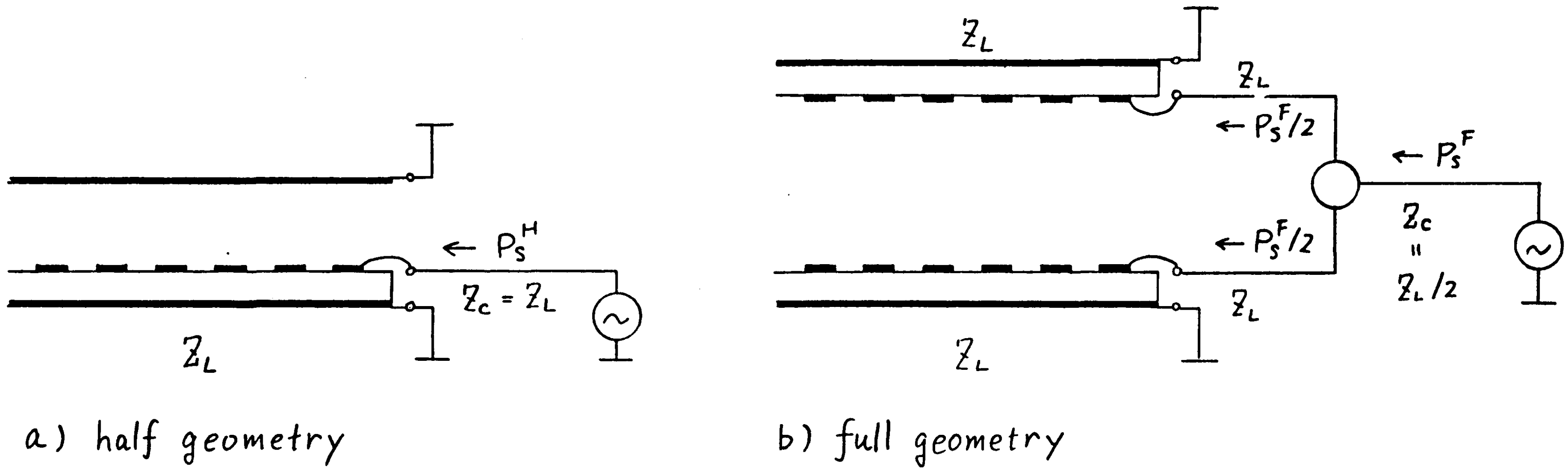


Fig. 3. Schematic diagrams for the application of the Lorentz reciprocity theorem. The coupling impedance is calculated for the half geometry and transformed to that for the full geometry.

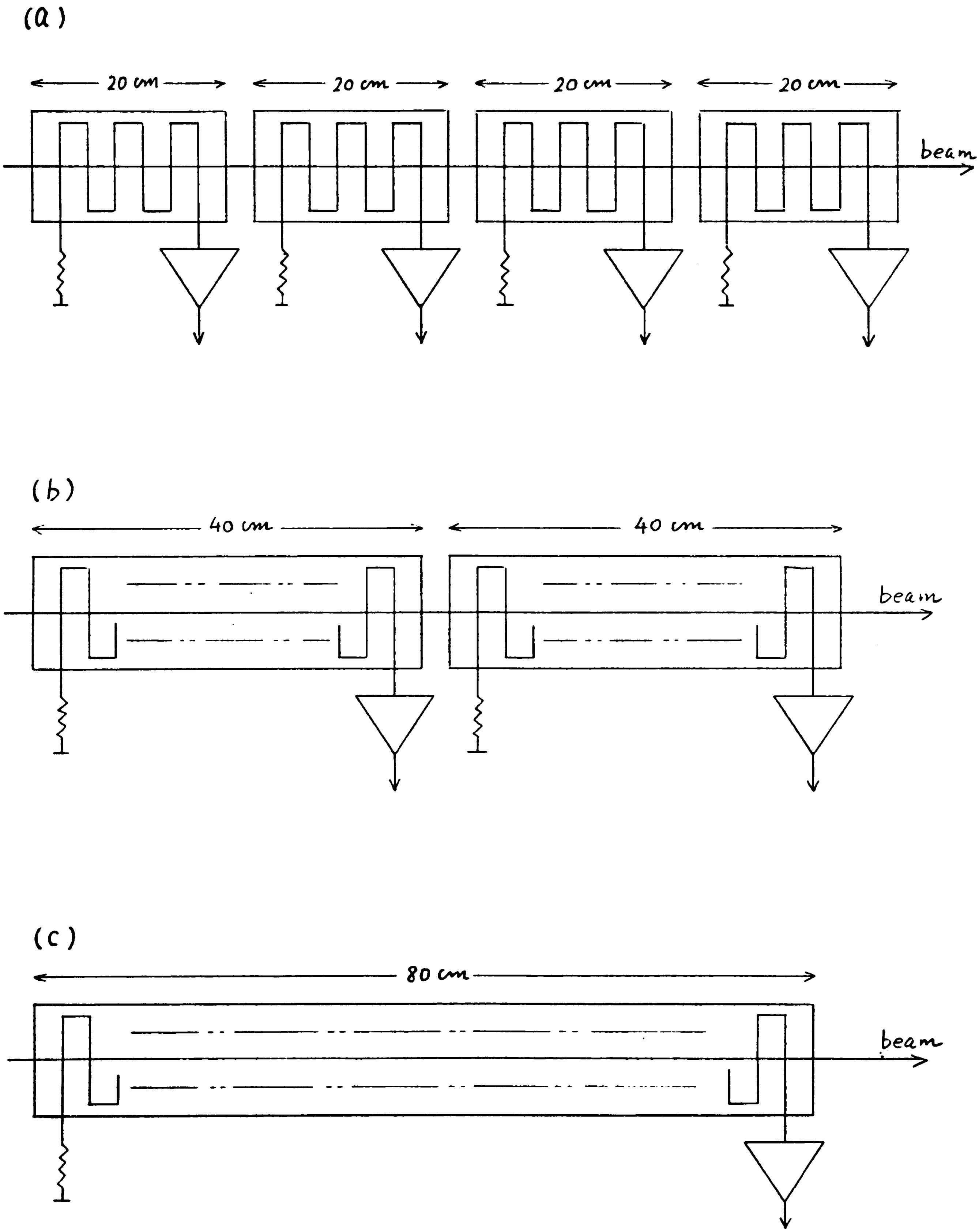


Fig. 4. Configurations of couplers.

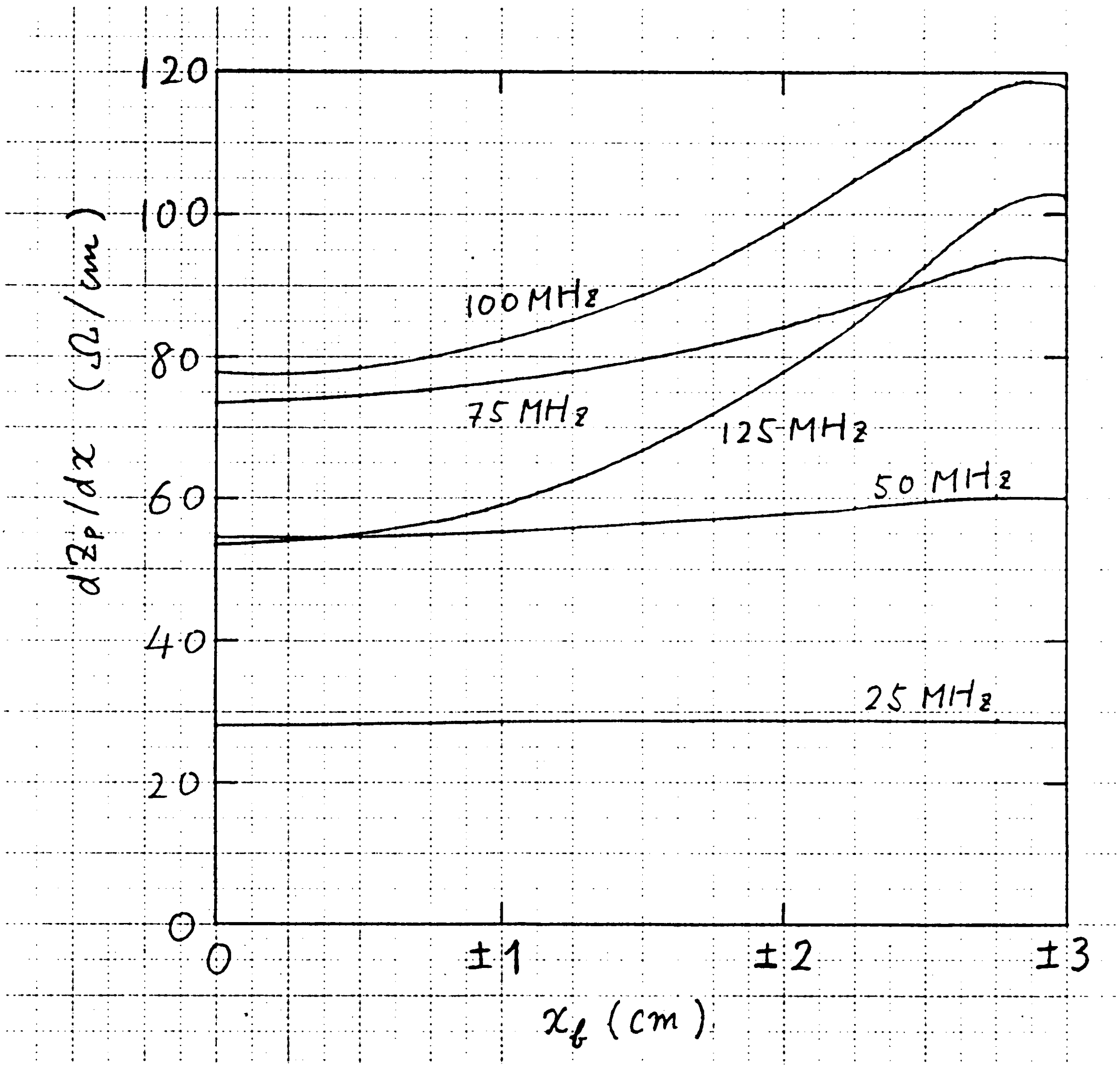


Fig. 5. Differential coupling impedance dZ_p/dx_b of a pickup consisting of a pair of 80 cm−long single couplers for a 60 MeV/c beam.

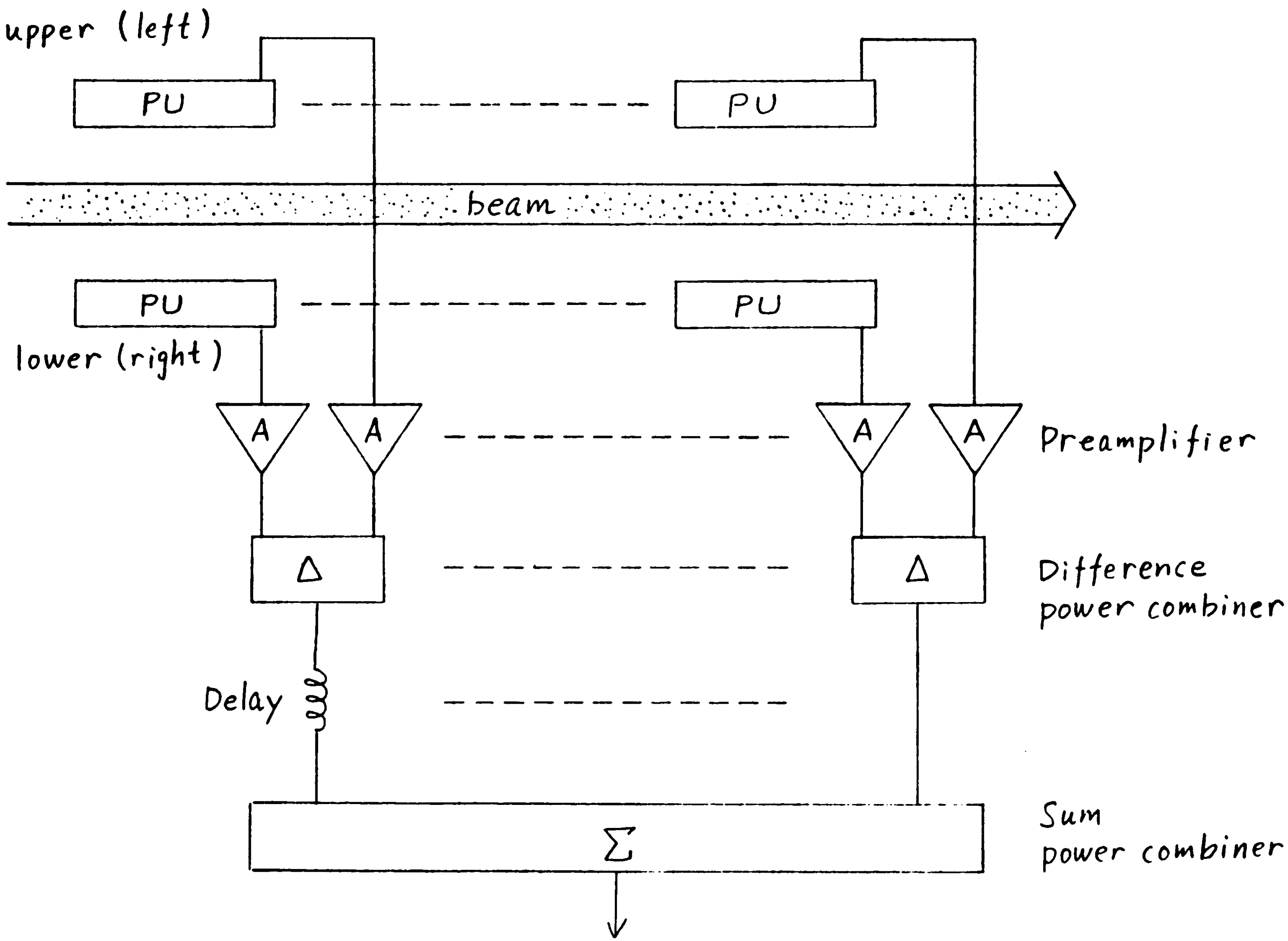


Fig. 6. Pickup system consisting of plural pairs of meander couplers, difference power combiners, delay lines, and a sum power combiner.

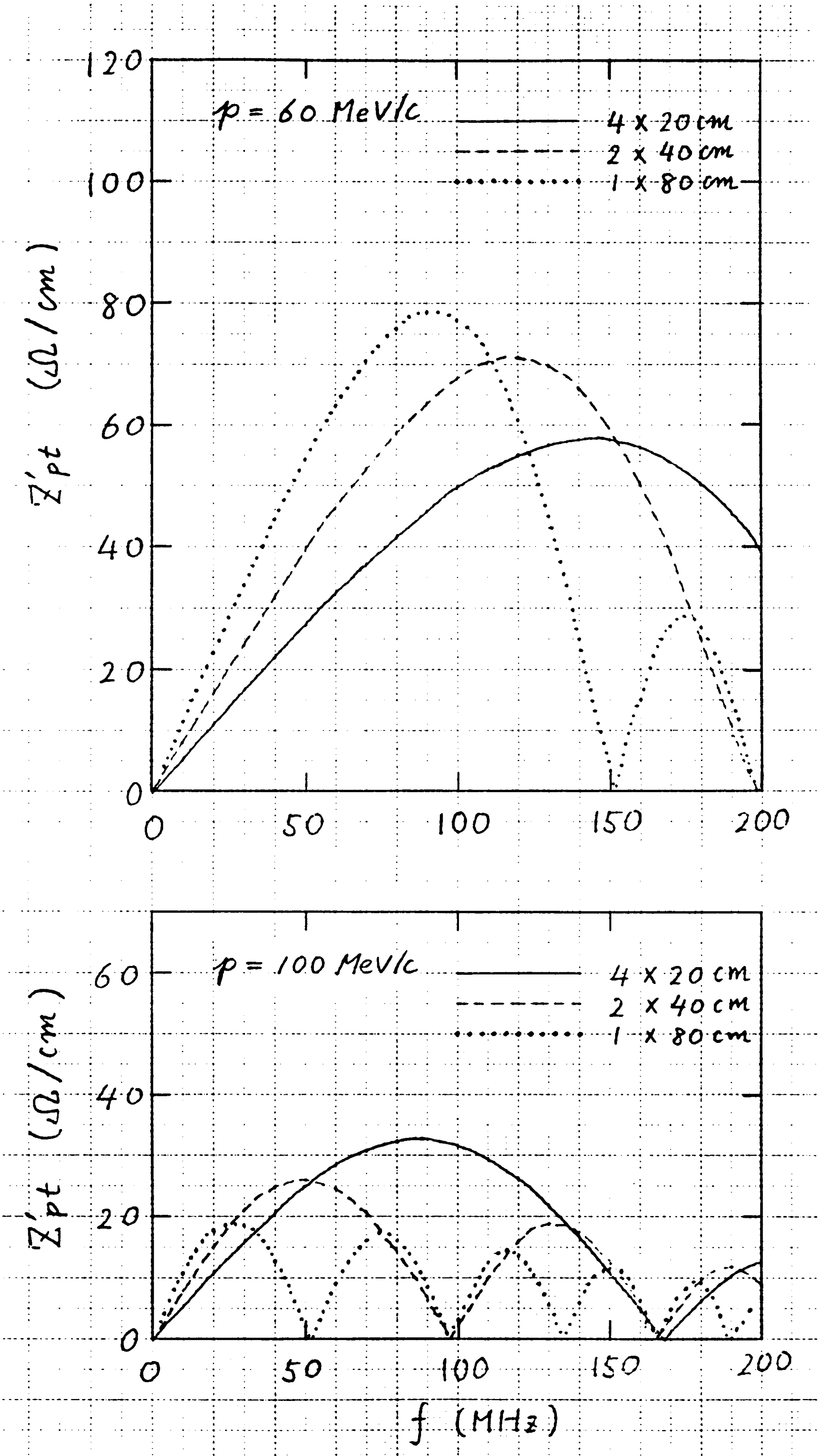


Fig. 7. Differential coupling impedance Z'_{pt} of the whole pickup system for a 60 MeV/c beam (top) and a 100 MeV/c one (bottom).

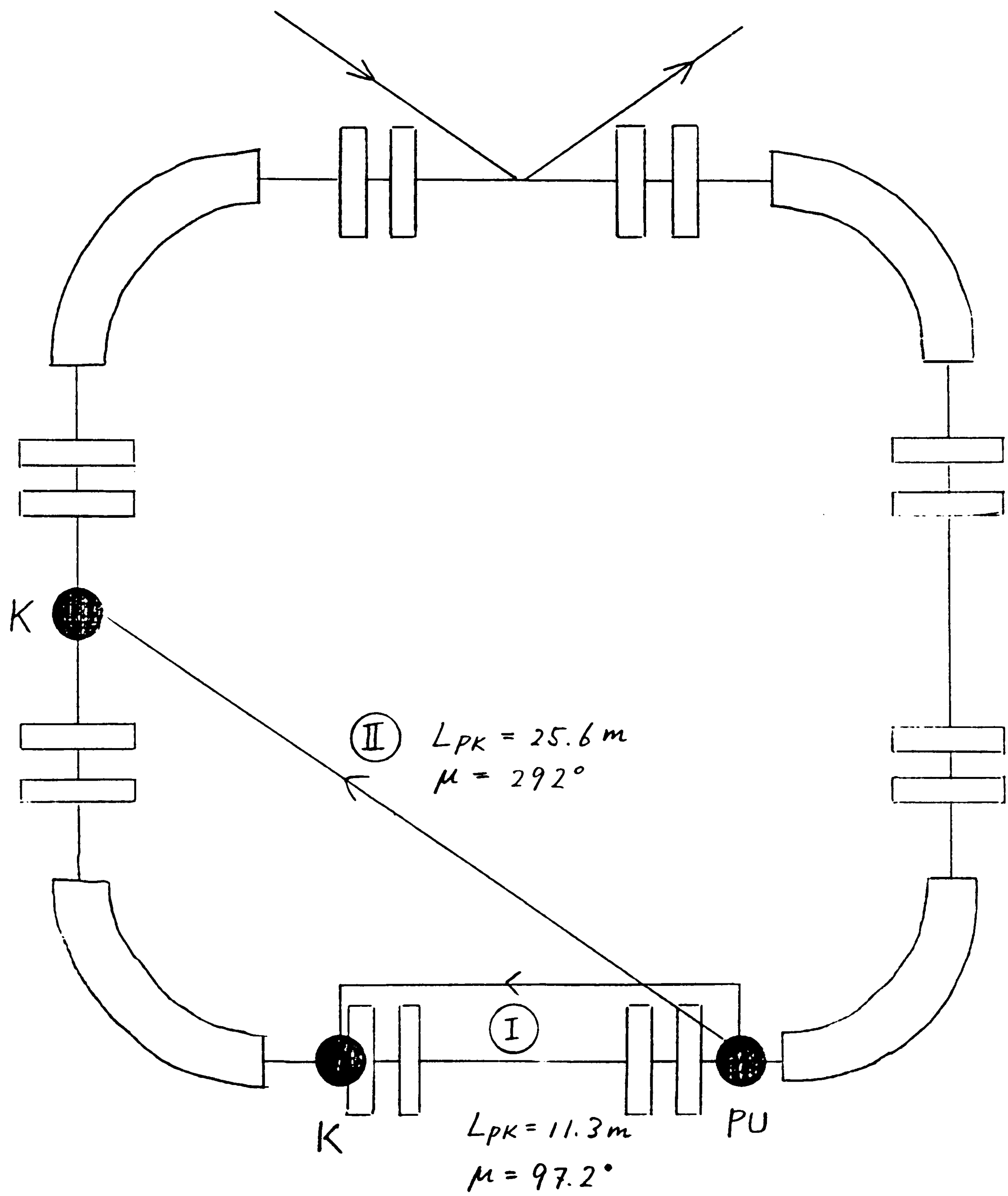


Fig. 8. Locations of the pickups and the kickers in LEAR. At the location I, the orbit length L_{PK} from the pickup to the kicker is 11.3 m, and phase advance μ of betatron oscillation is 97.2° ($\sin\mu$ = 0.992); at the location II, L_{PK} = 25.6 m, and μ = 292° ($\sin\mu$ = -0.927).

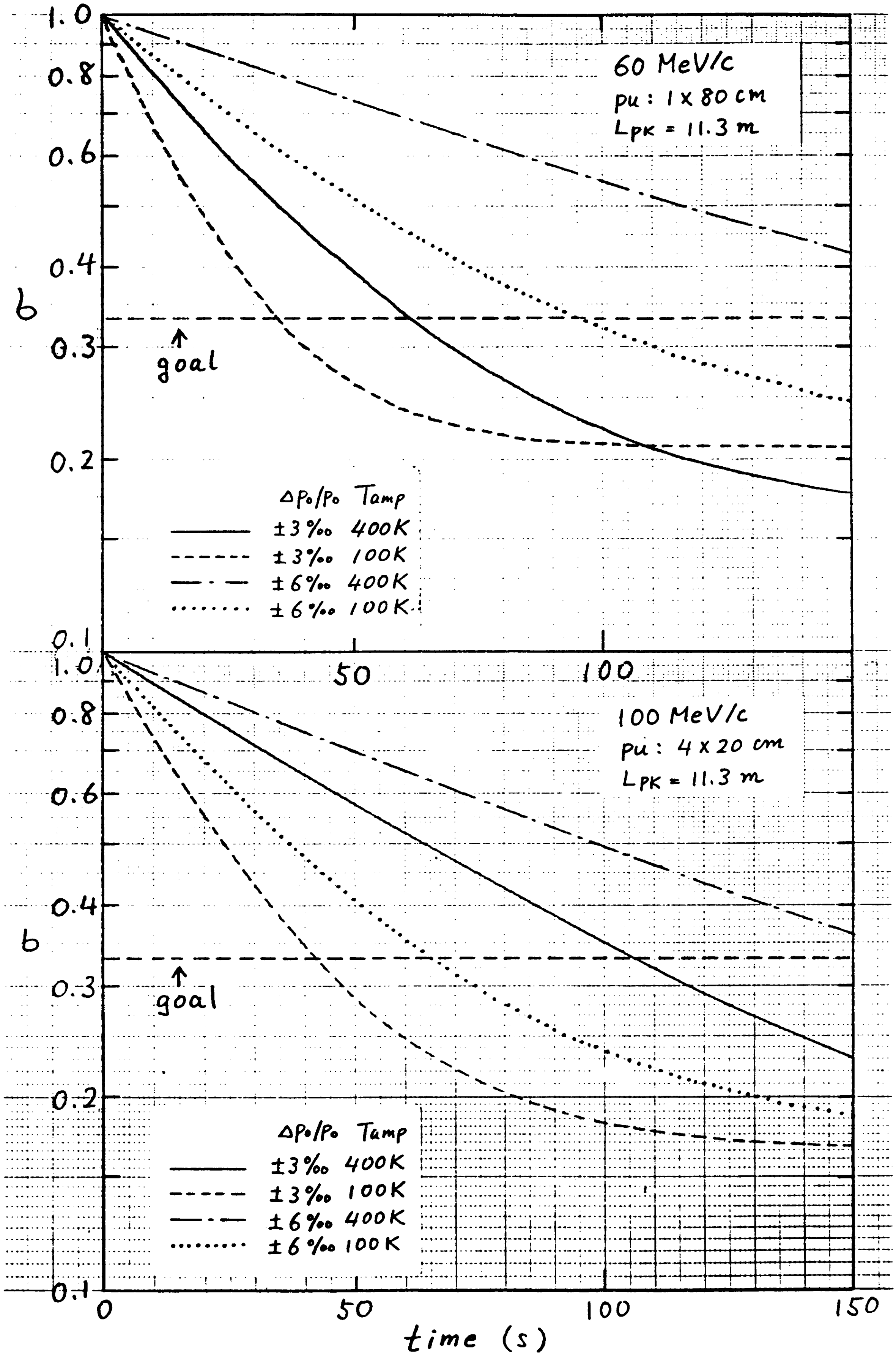


Fig. 9. Emittance decrease with time for a 60 MeV/c beam (top) and a 100 MeV/c one (bottome) under the condition of N = 1 × 10^9, $\sqrt{(\beta\varepsilon)}$ = 3 cm, $\Delta p_0/p_0$ = ±3 ‰. The gain G is optimized to minimize the cooling time to attain the goaled emittance (σ_g = 0.33).

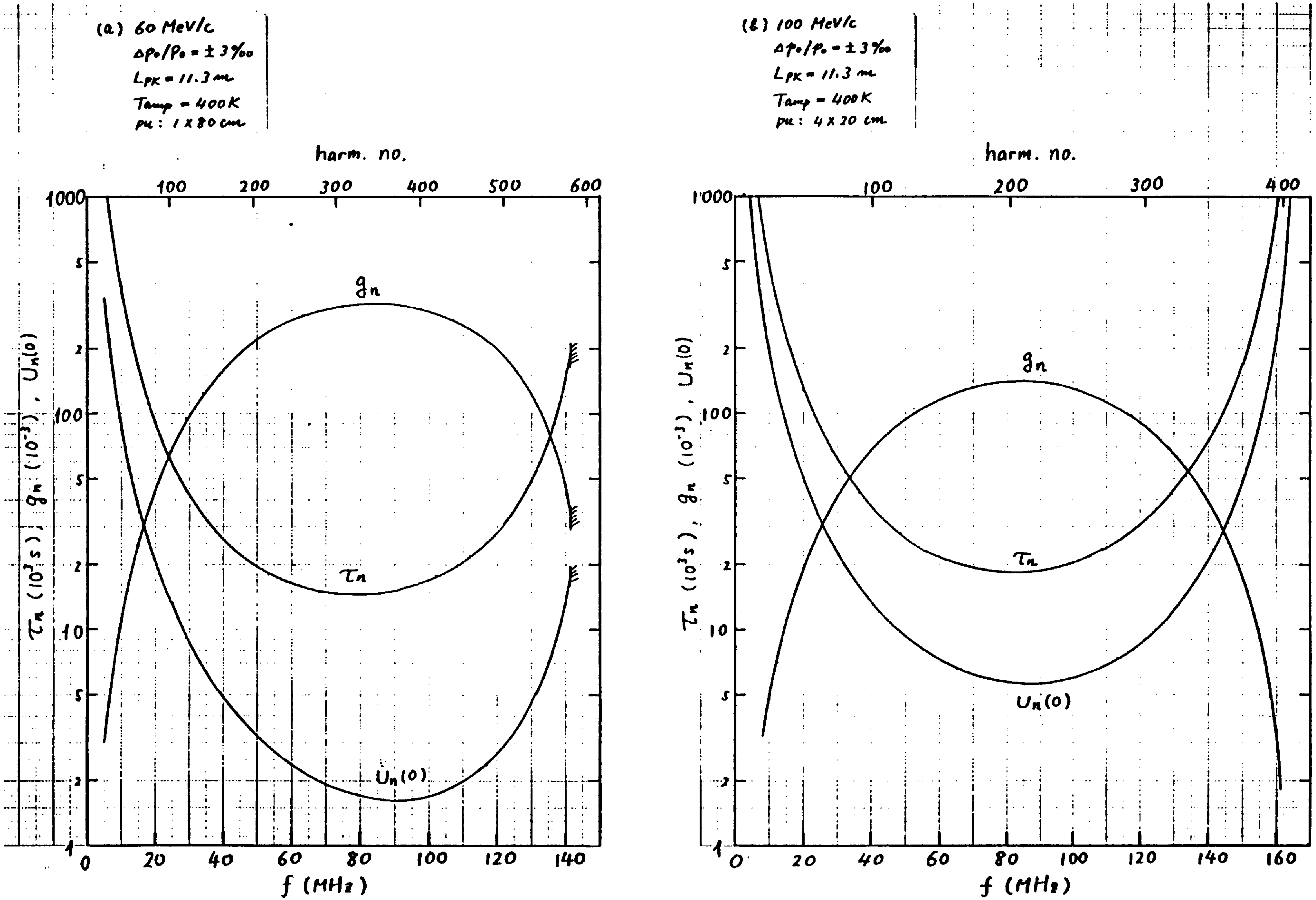


Fig. 10. τ_n, g_n and $U_n(0)$ for the 60 MeV/c beam (a) and the 100 MeV/c one (b).

APPENDIX

COOLING TIME WITH A PAIR OF 60 CM LONG SINGLE COUPLERS

A pair of 60 cm long single couplers are installed in LEAR in July of 1987. The geometry, except the length, of the meander coupler is same as that in the text. The cooling time is estimated, and the result is summarized in Table AI and Figs. A1 and A2.

Table AI. Summary of cooling time τ_g (σ_g = 1/3) for a pair of 60 cm long single couplers. (cf. Table I in the text.)

L_{PK}	Momentum (MeV/c)	$\Delta p_0/p_0$ (‰)	W (MHz)	T_{amp}=400K τ_g (G) (s)	T_{amp}=100K τ_g (G) (s)
11.3 m	60	±3	142 (PK)	77 (0.82)	39 (0.65)
μ = 97.2 deg		±6	71 (PK)	305 (0.90)	125 (0.74)
sinμ = 0.992					
	100	±3	69 (P)	593 (0.96)	188 (0.90)
		±6	69 (P)	622 (0.96)	192 (0.90)
25.6 m	60	±3	62 (PK)	474 (0.91)	183 (0.76)
μ = 292 deg		±6	31 (PK)	2643 (0.97)	783 (0.90)
sinμ = -0.927					
	100	±3	69 (P)	738 (0.96)	235 (0.90)
		±6	52 (PK)	1028 (0.96)	319 (0.90)

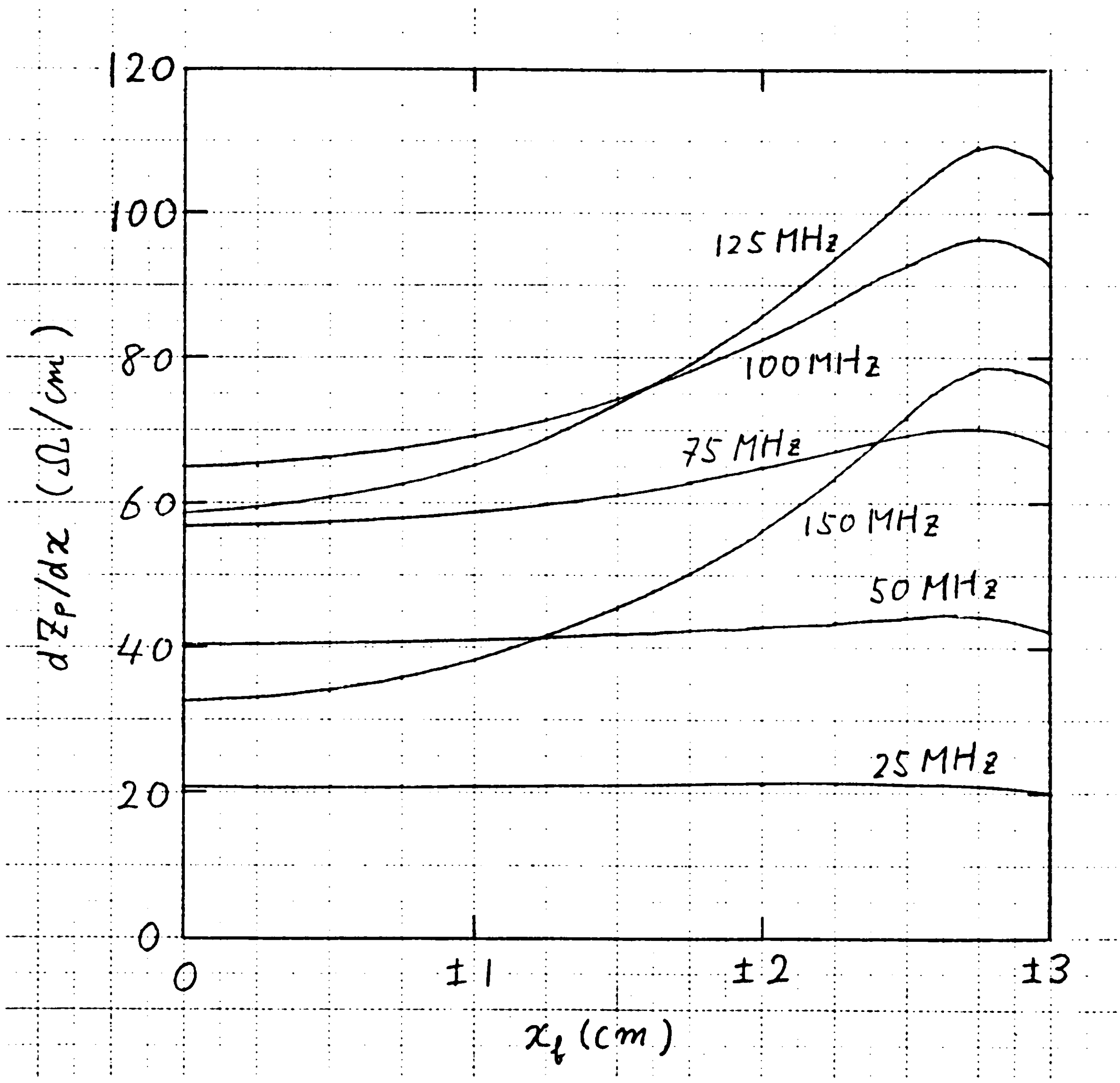


Fig. A1. Differential coupling impedance dZ_p/dx_b of a pair of 60 cm−long single couplers for a 60 MeV/c beam (cf. Fig. 5).

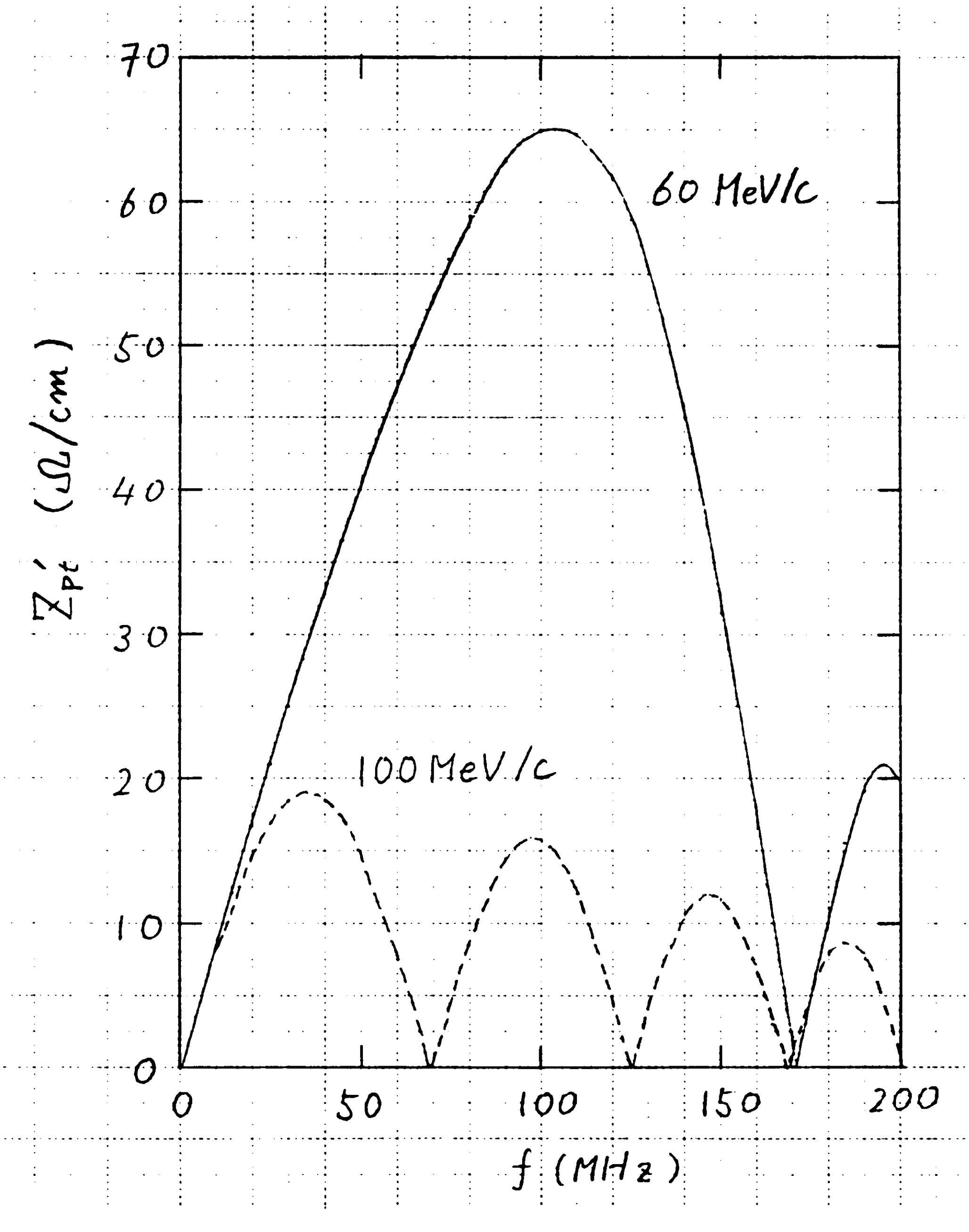


Fig. A2. Differential coupling impedance Z'_{pt} of a pair of 60 cm long single couplers (cf. Fig. 7).