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Дубна

E9-96-4

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COMPENSATION OF SPACE CHARGE EFFECT AT BEAM-BEAM INTERACTIONS IN PROTON-PROTON COLLIDERS

Submitted to «Physics Letters A»

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1996

1. INTRODUCTION

The head-on beam-beam interactions are the major source of nonlinearities in high energy colliders. Such a nonlinearity imposes certain limits on the collider luminosity because of the developed beam instability. The long range beam-beam interactions could be avoided in some crossing schemes, but the head-on beam-beam tune spread and related beam instability remain as the most fundamental luminosity limitations for proton-proton colliders. The strongly nonlinear beam-beam force excites high order betatron resonances, so particles diffuse into the tails of the transverse distributions of the beam and get lost. For the LHC collider the beam-beam interaction luminosity limit is about 2.5×10^{34} cm^{-2}s^{-1}, i.e. still above the design luminosity of 1.0×10^{34} cm^{-2}s^{-1}. However, the tune spread generated by head-on beam-beam interactions causes fast decoherence of the betatron oscillations and, therefore, imposes more stringent requirements on any feedback system. For the LHC collider a solution leading to a reduced beam-beam tune spread would be very important, and the possibility of such solution is considered here.

2. DECOHERENCE OF BEAM OSCILLATIONS DUE TO BEAM-BEAM EFFECT

In the LHC collider, there are many external circumstances in which the centroid of a circulating beam is displaced from the design orbit. If particle motions are linear, the displaced beam will undergo betatron oscillations as a whole (coherently) because all particles in the beam have the same tune, defined by the number of betatron oscillations in one revolution. However, nonlinearities in the machine can cause different particles to have different tunes, i.e. can generate a tune spread in the beam. When this is the case, the betatron motions of particles in a displaced beam will not be coherent, and the so-called phase mixing or decoherence results. Eventually, the phase space distribution of the beam will approach an equilibrium with the beam centroid returning to the design orbit, and the beam size (emittance) enlarged. For the LHC collider, the tune spread is primarily generated by the nonlinear force of space charge experienced by the two counter - rotating beams when they collide at the interaction points, i.e. the so-called head-on beam-beam interaction.

The reasonable approach to the calculation of the head-on beam-beam effect is the so-called weak-strong model. In this model one beam is regarded as "weak" and the counter-rotating beam, unperturbed by the weak beam, is considered as "strong". If the particle distribution of the counter-rotating ("strong") beam is a round Gaussian, the kicks given to the protons of the "weak" beam by the space charge of the "strong" beam are [1]:

$$\begin{bmatrix} \Delta X' \\ \Delta Y' \end{bmatrix} = \frac{2N_b r_p}{\gamma_p} \frac{1}{X^2+Y^2} \left(1 - exp(-\frac{X^2+Y^2}{2\sigma^2})\right) \begin{bmatrix} X \\ Y \end{bmatrix},$$

where N_b is the number of particles in a bunch of the strong beam, r_p the classical proton radius, γ_p the Lorentz relativistic factor of a 7 TeV proton, and σ the rms beam size at the low-β IPs (IP1 and IP5 in Fig.1). We have used $N_b = 10^{11}$ and $\sigma = 15.9$ μm in accordance with the LHC design.

To illustrate the decoherent process due to the beam-beam interactions [2], we show in Fig.2 the phase space distributions of the beam at 200 and 400 turns after its initial displacement of 3σ in a horizontal direction from the design orbit. One can see that the beam distribution in phase space is being homogenized. Fig.3 demonstrates that, as beam decoheres, the position of its centroid oscillates with decreasing amplitude and, eventually, settles around zero (the design orbit) and that the beam emittance increases monotonously and finally approaches a steady-state value. The phase mixing of particles due to the tune spread generated by the beam-beam interactions has lead to a new equilibrium in the beam. One can see also that the decoherence time is rather short. The corresponding tune shift distrubution of the beam particles is shown in Fig.4.

3. SCHEME OF COMPENSATION

An ideal solution for compensation of the beam-beam effect in proton-proton machines is an instantaneous collision of a proton bunch with a counter-rotating beam of negatively charged particles having the same parameters as a counter-rotating proton bunch. We assume that we are still far away from the conditions of one-pass collective instabilities [3]. In this case the angular kick delivered to a primary proton by the space charge of the counter-rotating proton bunch would be exactly canceled by the kick delivered by the negative space charge of the compensating beam. We show that a low energy electron beam could be used as the compensating beam. This idea was initially proposed in [4]. It

is important that the compensating beam be formed with the same transverse distribution as the proton bunch.

The longitudinal profile of the compensating beam is not really important, because the angular kick delivered to the primary proton by the compensating beam could be accumulated along the length of the available collision region (about 2 meters for the LHC case), which is still short in comparison with the wave length of betatron oscillations.

Instead of a compensating collision point placed immediately after the proton-proton collision, one can place the collision point in a more accessible location with a betatron phase advance relative to the proton-proton collision point of $n\pi$, where n is integer, the same in the X-plane and in the Y-plane. Here the image of the proton beam in the X-Y plane is similar to the image in the proton-proton interaction point, being different only in scale. By using a place in the lattice with high beta values one could relax the requirement to form an electron beam of a very small size, as in the low-β IPs. In the LHC case, a beam with $\sigma = 0.2$ mm could be used, close enough to the interaction points. Two separate compensating devices in each ring should be used to compensate full beam-beam interaction in the two low-β IPs.

The current of the electron beam which is necessary for compensation of the beam-beam effect of the counter-rotating beam should be about equal to the current of the proton beam. Electron guns with comparable parameters are available now from the industry. Deviation of the intensity of the individual proton bunches from the average value, if large, could be compensated by strobing the electron beam in time, using available bunch-by-bunch intensity information. See fig.5 where a design of a possible device for beam-beam effect compensation is shown.

Fig.6-7 show the behavior of the beam emittance and tune shift distributions for different displacements of the compensating electron beam from the design orbit. The integral characteristics are summarized in fig.8-9 where the decoherence time (defined as the time at which the relative-to-centroid emittance crosses the midpoint between the initial and final values) and rms of the beam tune shift distribution (tune spread) are plotted versus the electron beam displacement, its relative charge, and transverse size.

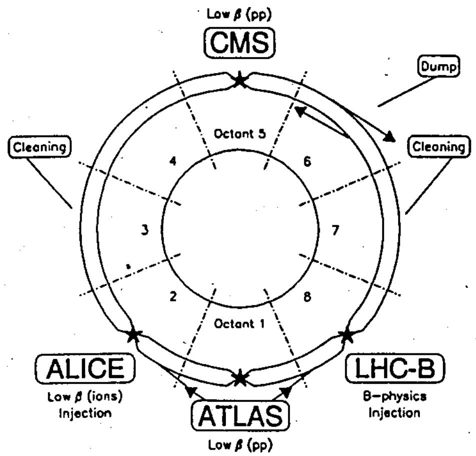

Fig.1. LHC schematic lay-out with four proposed interaction points.

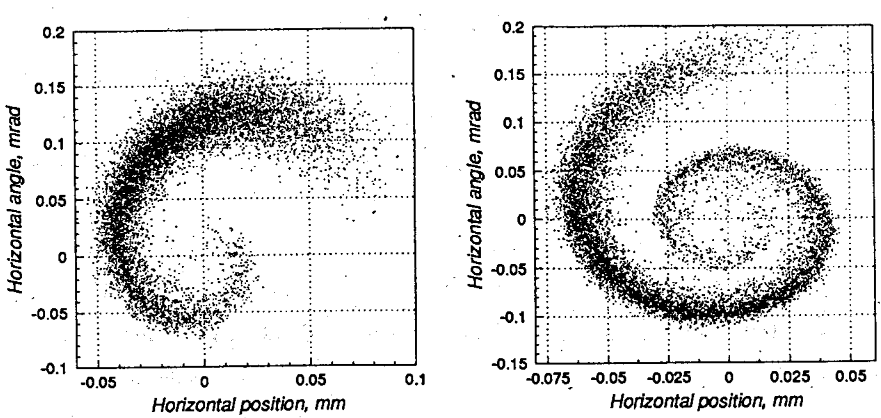

Fig.2. The distributions of the beam in phase space after 200 turns (left), 400 turns (right). Initial horizontal beam displacement is 3 σ, where σ is the rms beam size.

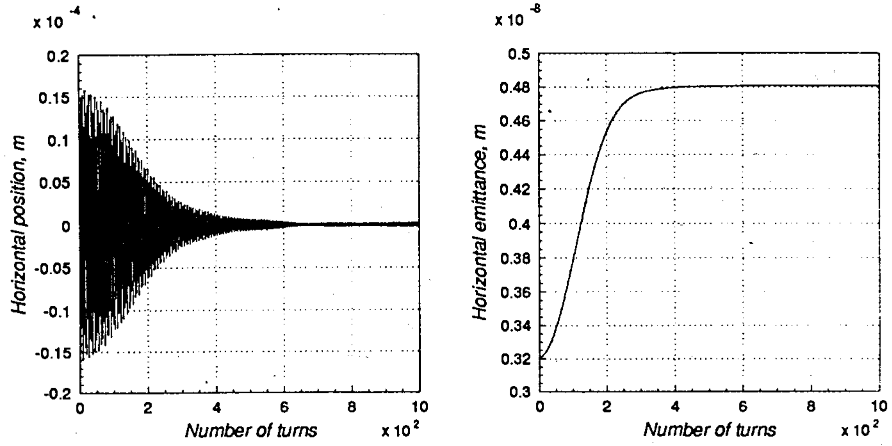

Fig.3. Oscillations of the beam centroid (left) and growth of the relative-to-centroid beam emittance (right) after an initial beam displacement of 1 σ. No compensation.

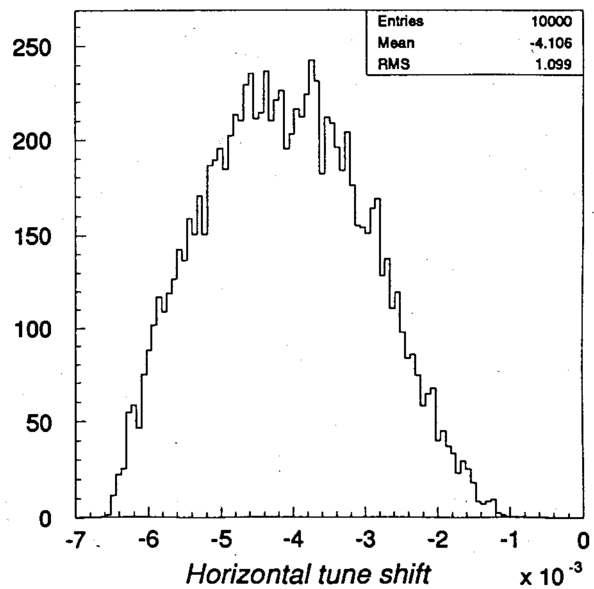

Fig.4. Horizontal tune shift distribution of the beam particles generated by the beam-beam interactions. No compensation.

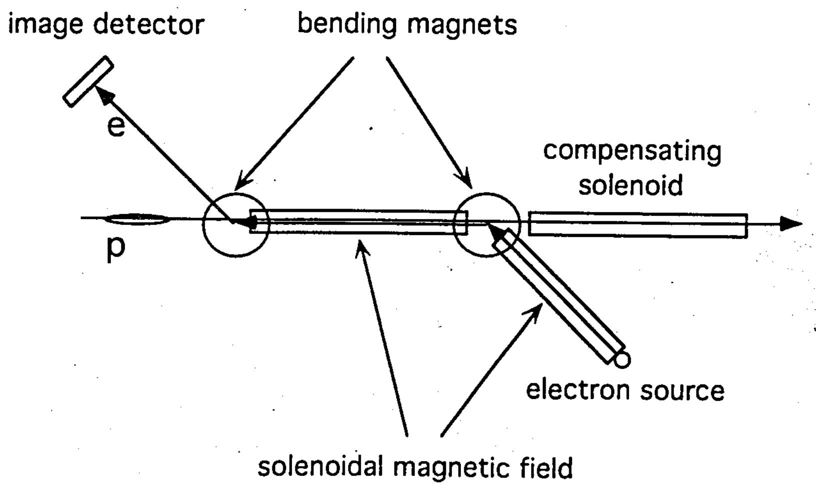

Fig.5. Scheme of the device for the beam-beam effect compensation. A low energy electron beam collides with a bunch of protons. The electron beam distribution is kept stable by a solenoidal magnetic field. After the collision the electron beam is deflected to the image detector which is used for steering the electron beam relative the proton bunch.

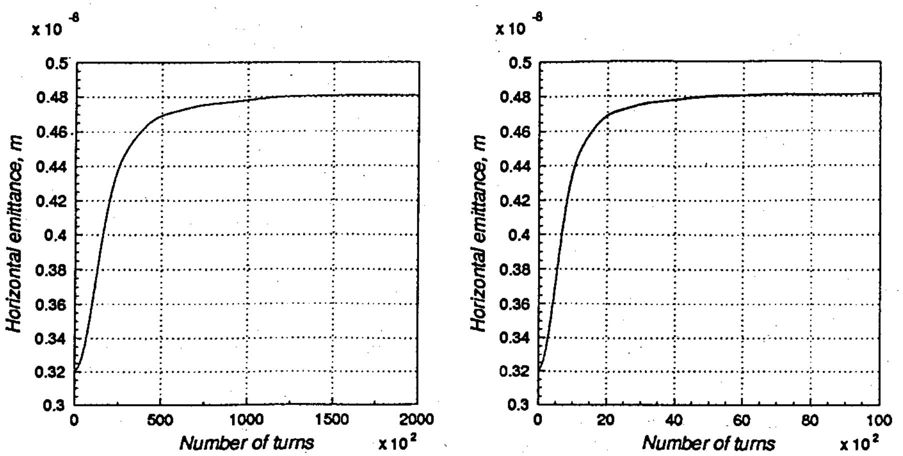

Fig.6. Growth of the relative-to-centroid beam emittance after an initial beam displacement of 1 σ. For the displacement of the compensating electron beam from the design orbit : 0.1 σ (left), 0.5 σ (right).

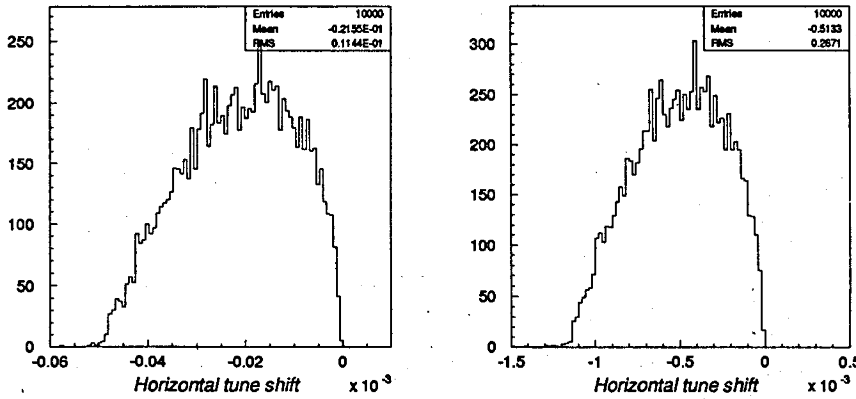

Fig.7. Horizontal tune shift distributions of the beam particles. For the same conditions as fig.6.

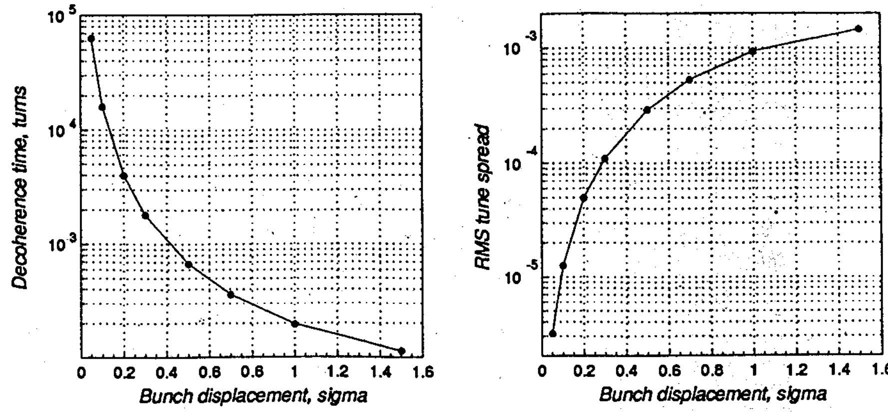

Fig.8. Decoherence time expressed in number of turns (left) and RMS tune spread of the beam particles (right) versus the electron beam displacement. The rightmost point corresponds to the case without compensation. The curve is drawn to guide the eye.

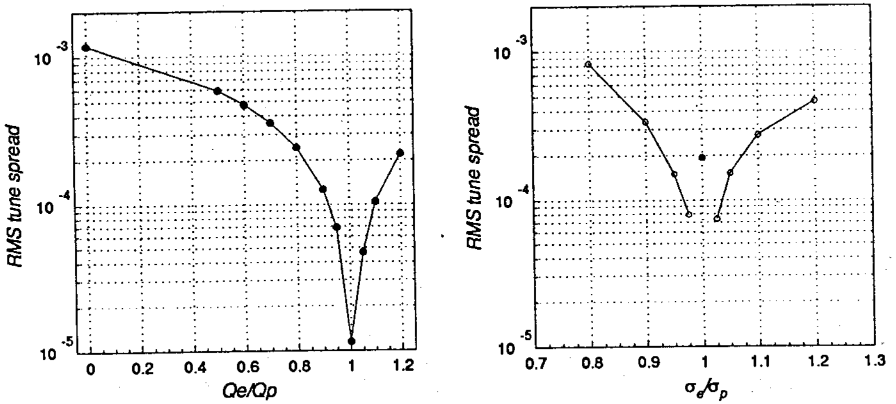

Fig.9. RMS tune spread of the beam particles : (left) versus the ratio of the electron to proton bunch charges. Displacement of the electron bunch is 0.1 σ. The leftmost point corresponds to the case without compensation. (right) versus the ratio of the rms size of the electron to proton bunch (white circles). Black circle presents the result for a cylindrical electron bunch (with radius $r_e = 1.3\sigma_p$ and $Q_e = 0.6Q_p$).

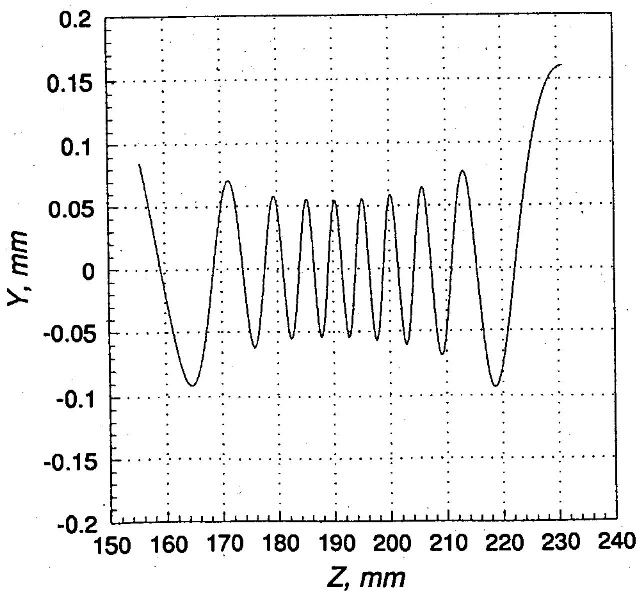

Fig.10. The trajectory of a 10 keV electron with an impact parameter of 160 μm colliding with a proton bunch, Z-Y view. The proton bunch is moving to the right, and the electron is moving to the left. Plus/minus 3σ of the proton bunch charge distribution in Z-direction is treated by the tracing code.

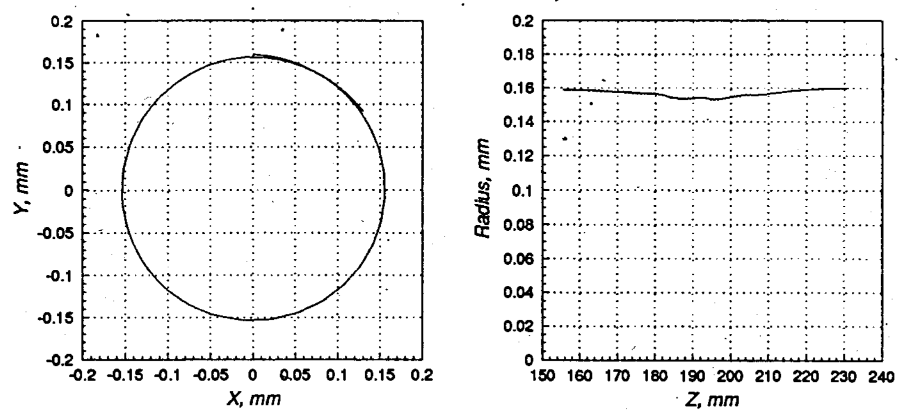

Fig.11. The trajectory of a 10 keV electron with an impact parameter of 160 μm inside a proton bunch when a solenoidal magnetic field of 2 T is applied: (left) X-Y view, (right) Z-R view (R is a distance of an electron from the center of a proton bunch).

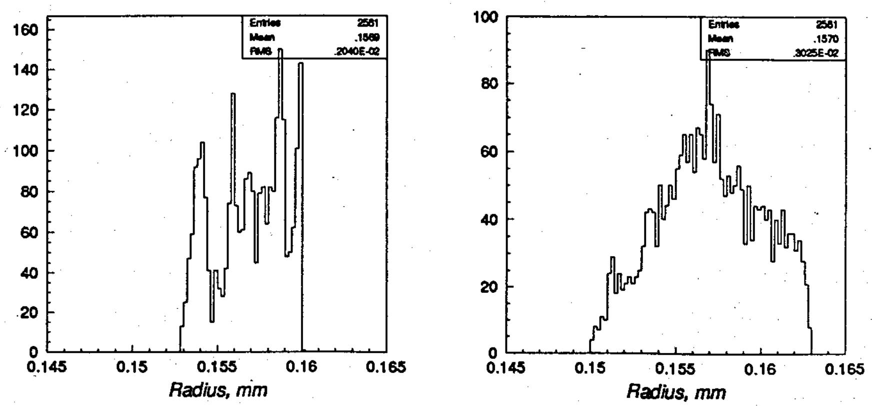

Fig.12. Distributions of the radial positions of the electron with incoming angle of 0° (left) and 1° (right).

4. BEHAVIOR OF LOW ENERGY ELECTRONS INSIDE THE PROTON BUNCH

One of the problems with using a low electron beam for beam-beam effect compensation is electron oscillations during passage through the proton bunch. Even passing once and then being dumped, electrons experience some oscillations inside the proton bunch, which makes it difficult to distribute proper kicks among all the protons in the bunch. Fig.10 presents the calculated trajectory of a 10 keV electron with an impact parameter of 160 μm colliding with a bunch of 10^{11} protons. The space distribution of protons was assumed three dimensional Gaussian with $\sigma_x = \sigma_y = 160$ μm, $\sigma_z = 77$ mm, which represent the typical parameters of the LHC beam. The ZBEAM tracing code used is described elsewhere [5]. To simplify the calculations, only transverse components of the electrical field of the bunch were taken into account. This is a good approximation for a long bunch with small transverse dimensions. Because of the low energy of the electrons we neglect possible radiation effects.

As seen in fig.10, the electron makes several oscillations before it leaves the proton bunch. This immediately imposes difficulties in delivering the proper kick to all the protons in the bunch, because the distribution of electron density in the bunch will vary along the bunch length.

The best way to prevent these radial oscillations of the compensating beam electrons is to use a solenoidal magnetic field directed along the beam in the compensating interaction region, see the device scheme in fig.5. The influence of the solenoidal magnetic field on the proton bunch is then compensated by the same field configuration with the opposite polarity. Fig.11a shows the electron trajectory inside a proton bunch when a solenoidal magnetic field of 2 T is applied. One can see from fig.11-12, that the radial position of the electron with zero incoming angle remains constant with an accuracy of about two micrometers in this case. Even for the electron with non-zero incoming angle the distribution of its radial positions remains practically unchanging, fig.12b.

5. CONCLUSION

The presented results show that for reasonable tolerances of the electron beam parameters it is possible to achieve a good beam-beam effect compensation with the resulting

reduction of the beam tune spread by a factor of up to 100 and improve considerable the high-luminosity performance of future proton-proton colliders.

6. ACKNOWLEDGEMENTS

Two of authors (E.T. and A.Z.) expess their gratitude to the CERN SL/AP Division for the hospitality during these studies. The authors are very grateful also to Prof. A.M. Baldin for his interest and support of this work.

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Received by Publishing Department
on January 10, 1996.

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