Electron beams for compensation of Beam-Beam Effect in hadron colliders – early works

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LARP Mini-Workshop on Beam-Beam Compensation
Palo Alto, July 4 2007

Outline:

Beam dynamics study for the SSC

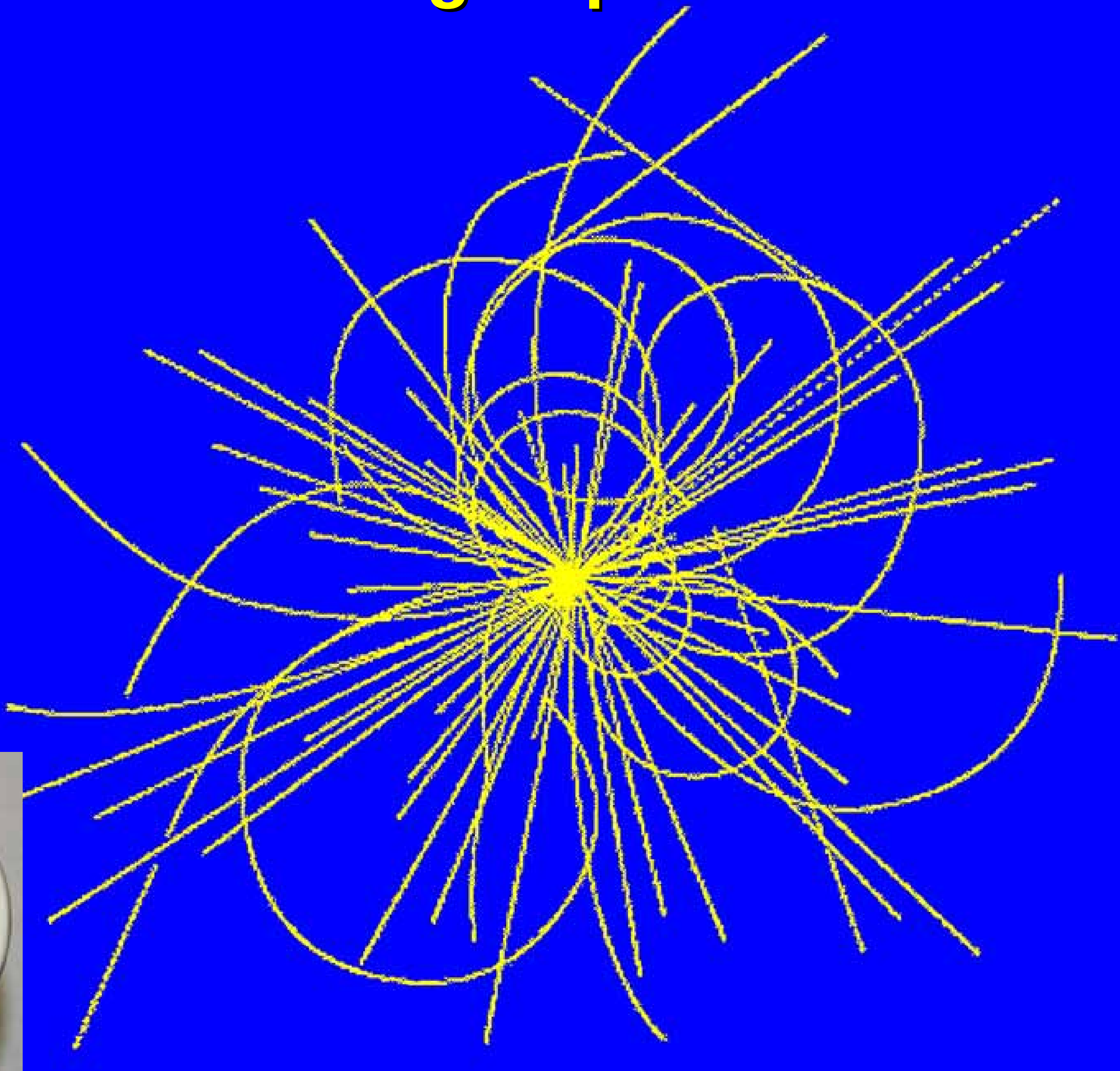
Beam-Beam Effect Compensation at the LHC

The head-on beam-beam effect is the major source of nonlinearities in high-energy colliders.

The head-on beam-beam instability remains the most fundamental luminosity limitation for proton-proton colliders.

The strongly nonlinear beam-beam force excites high-order betatron resonances, particles diffuse into the tails of the transverse distributions and get lost.

Superconducting Super Collider



Dynamic Aperture Studies at the SSC, 1992-1993

Walter Scandale, Frank Zimmermann

Stability of motion in linear systems
Hamiltonian motion
Liouville Theorem
Irrational tunes for X and Y

Phase space with nonlinear elements

KAM (Kolmogorov-Arnold-Moser) Theorem
Poincare-Birkhoff Theorem
Chirikov Criterion
Short term and long term dynamic apertures
Simulations

For the SSC the beam-beam interaction luminosity limit was about 3 x 10^{34} $cm^{-2}s^{-1}$, i.e. well above the design luminosity of 10^{33} $cm^{-2}s^{-1}$.

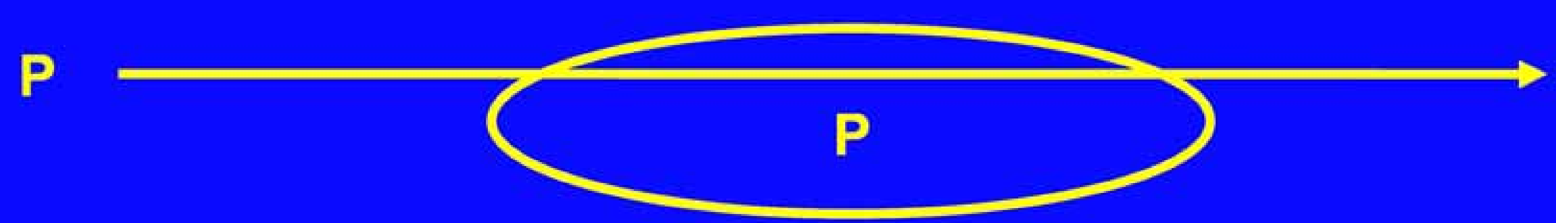
However, the tune spread generated by head-on beam-beam interactions causes fast decoherence of the betatron oscillations and imposes more stringent requirements on a feedback system.

Beam-Beam tune shift and tune spread

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 41, NO. 5, OCTOBER 1994 1791

Decoherence of Beam Oscillations in the SSC due to Beam-Beam Collisions

E. Tsyganov, H.-J. Shih, R. Meinke, W. Nexsen, M. Herath-Banda, and A. Taratin

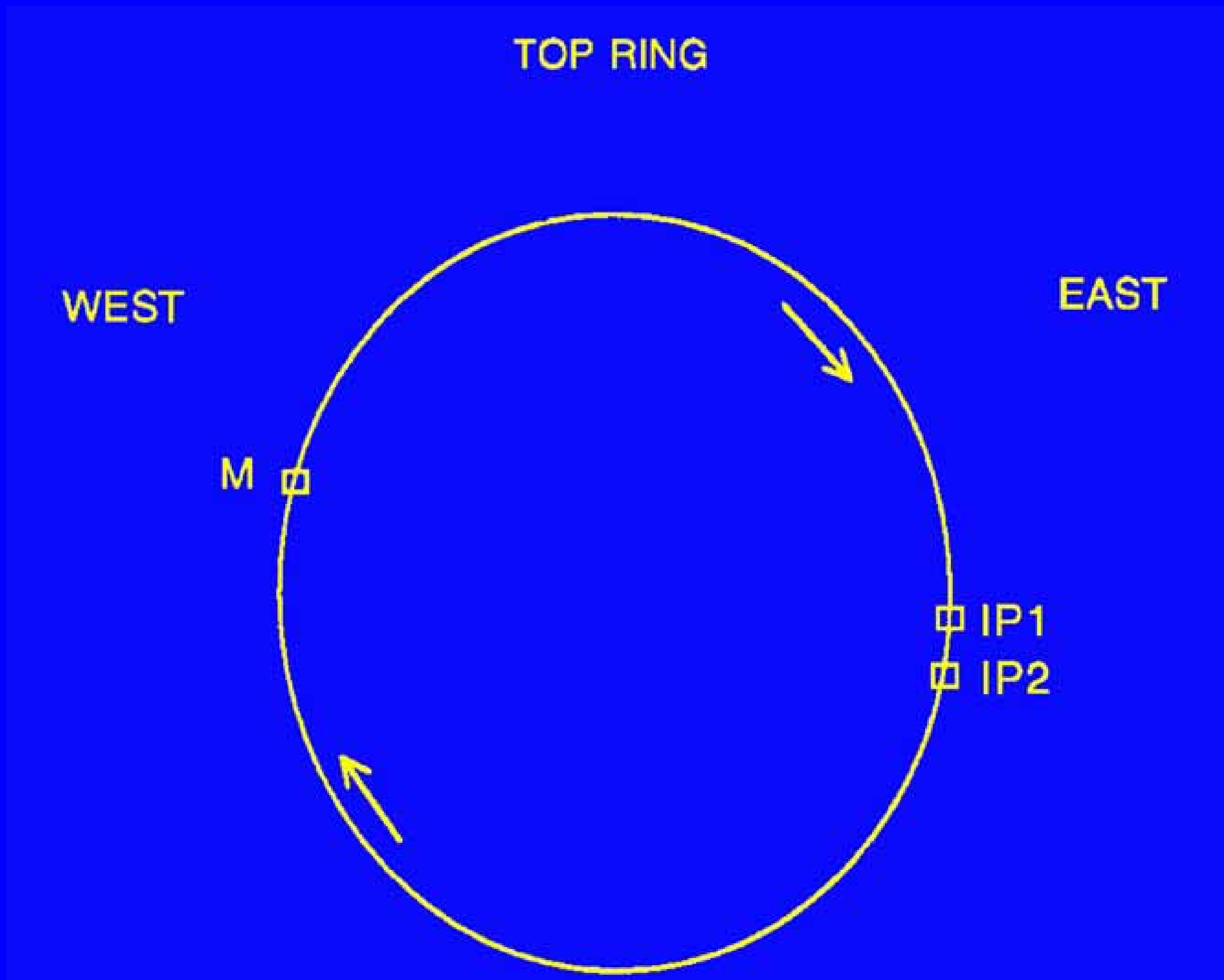


For round beam angular kicks are:

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

Here 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 proton, and σ the r.m.s. beam size at the low-β IPs.

$$r_p = e^2/4\pi\varepsilon_0 mc^2$$

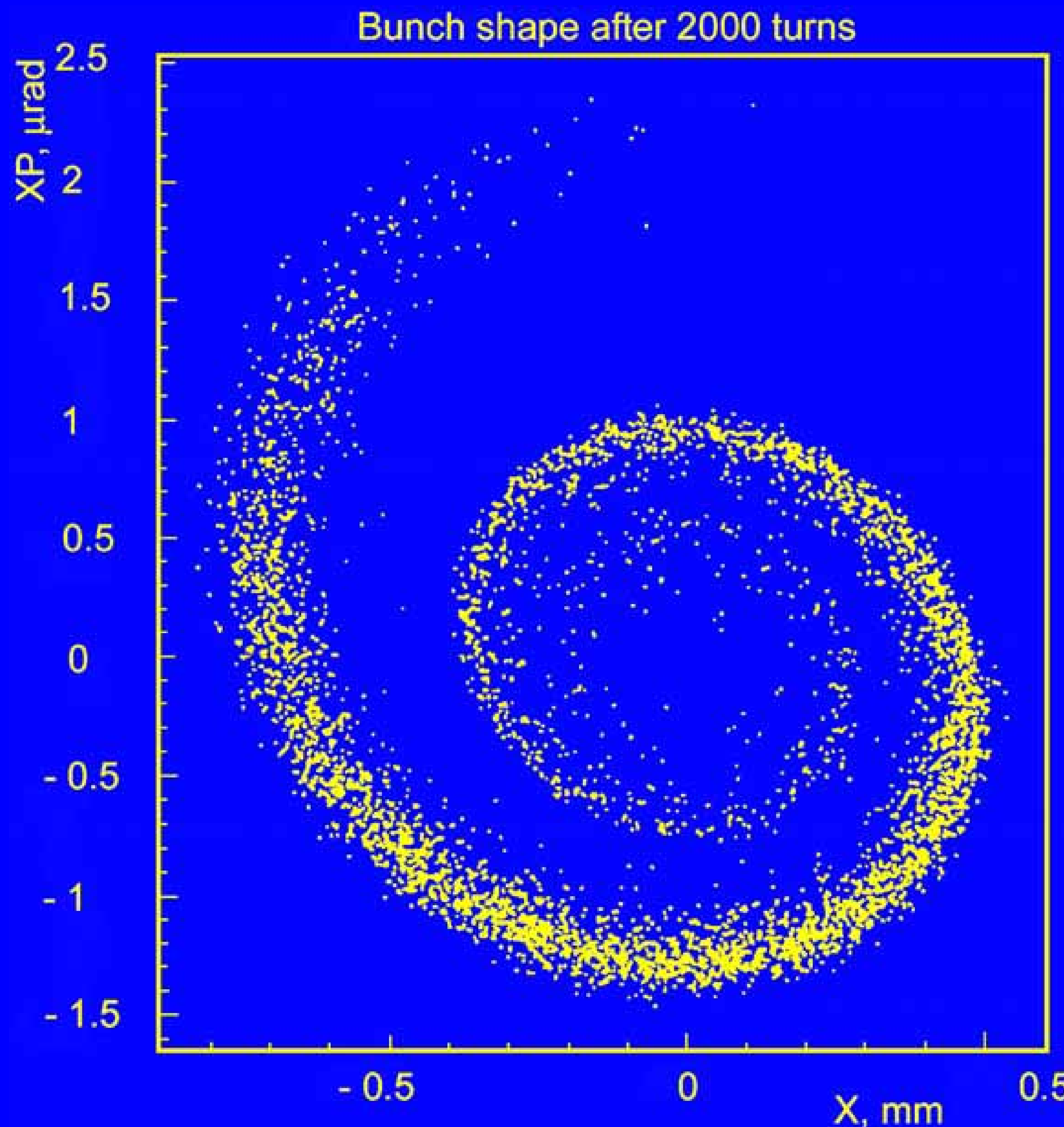


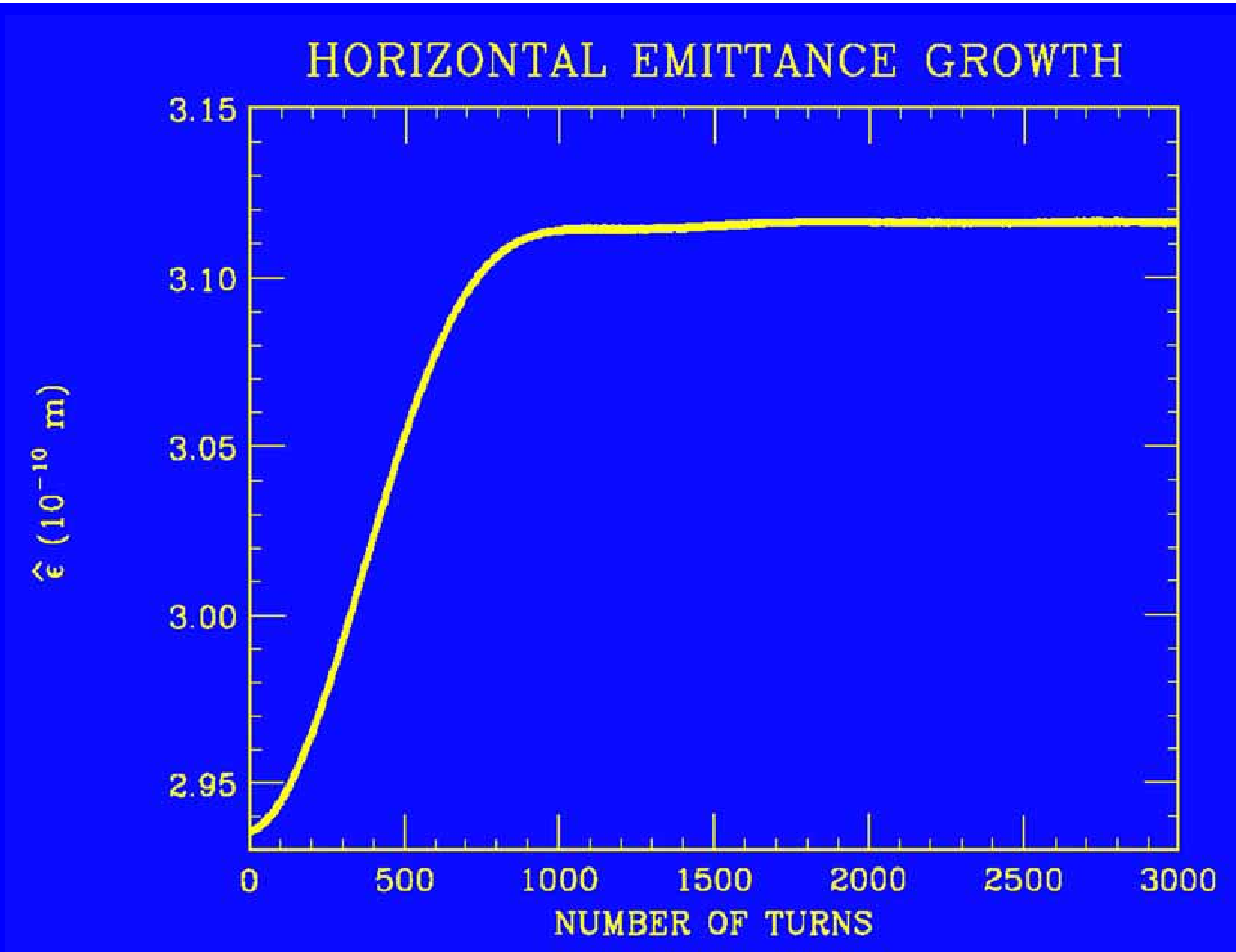
Schematic diagram of the SSC collider ring used in the simulation. IP1 and IP2 - the two low-P interaction points, M-location for beam position measurements.

	IP1	IP2	M
S	36 947.925 m	39 467.925 m	86 525.550 m
α_x	−0.003	−0.015	0.115
β_x	0.501 m	0.502 m	427.477 m
α_y	−0.024	0.001	−0.495
β_y	0.505 m	0.493 m	533.929 m
Q_x	52.022	56.275	122.735
Q_y	51.138	55.385	121.753

Lattice parameters at locations IP1, IP2, and M. S: path length; α, β usual Courant-Snyder parameters; Q_X, Q_Y: tune advances. The total tune advances in one revolution are: $\upsilon_x = 123.285$ and $\upsilon_y = 122.265$

Decoherence of particles after a horizontal displacement of 500 μm





Growth of the relative-to-centroid beam emittance after an initial beam displacement of 50 μm.

We determined the tune for each particle under the interaction. This was done by recording the coordinate *(X* or *Y)* of a particle every turn and applying discrete Fourier transform to the recorded sequence. We have used 8192 turns and the resolution of the procedure was found to be 0.00003. From this distribution we found that

the average tune shift $\Delta\nu_x = 0.00127$

and the r.m.s. tune spread $\delta\nu_x = 0.00033$.

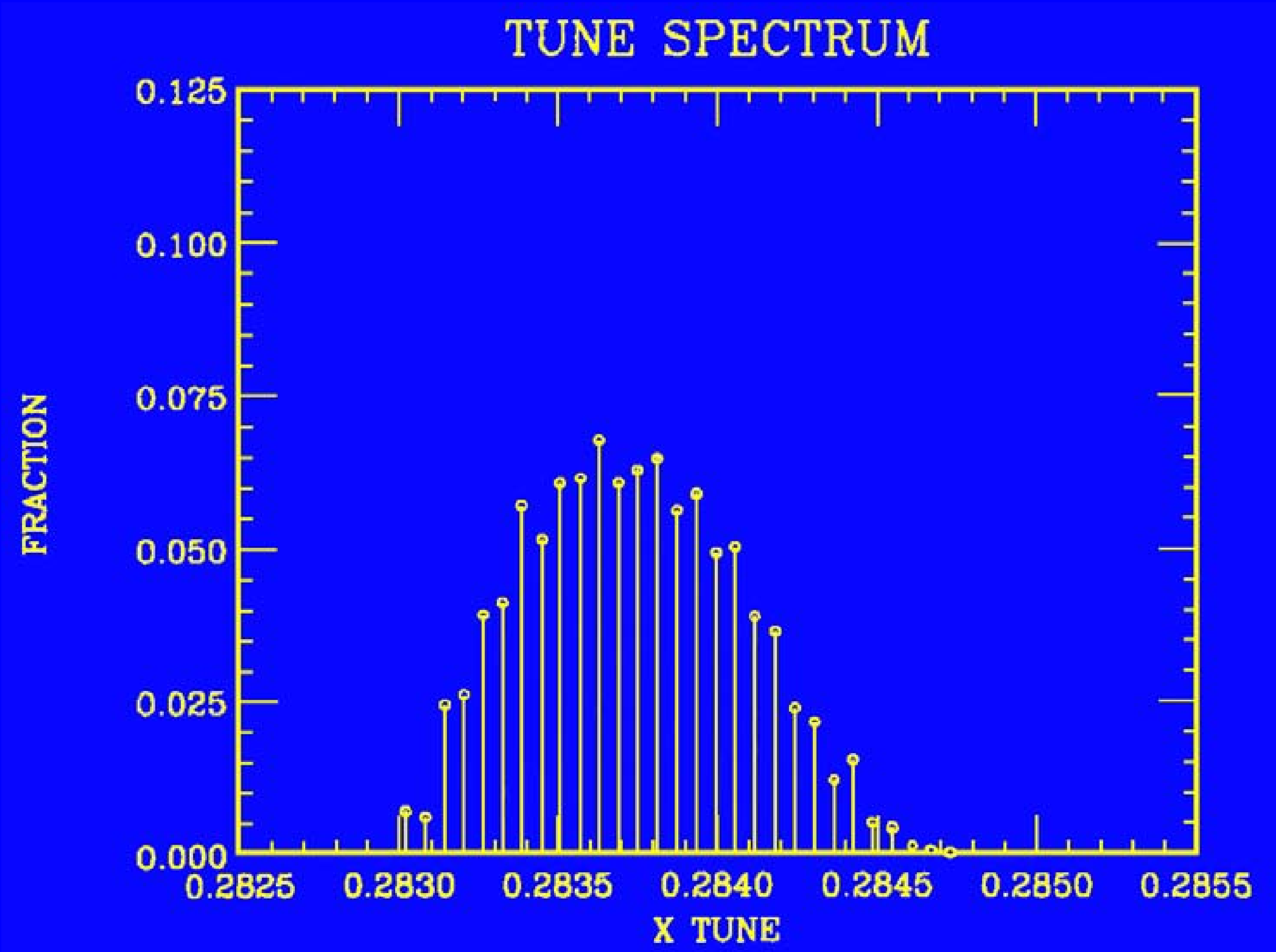
From the theory (Stupakov et al., SSCL Preprint 495, August 1993)

$$\Delta\nu_x = 0.633\xi = - 0.00124$$

$$\Delta\nu x = 0.17\xi = 0.00033$$

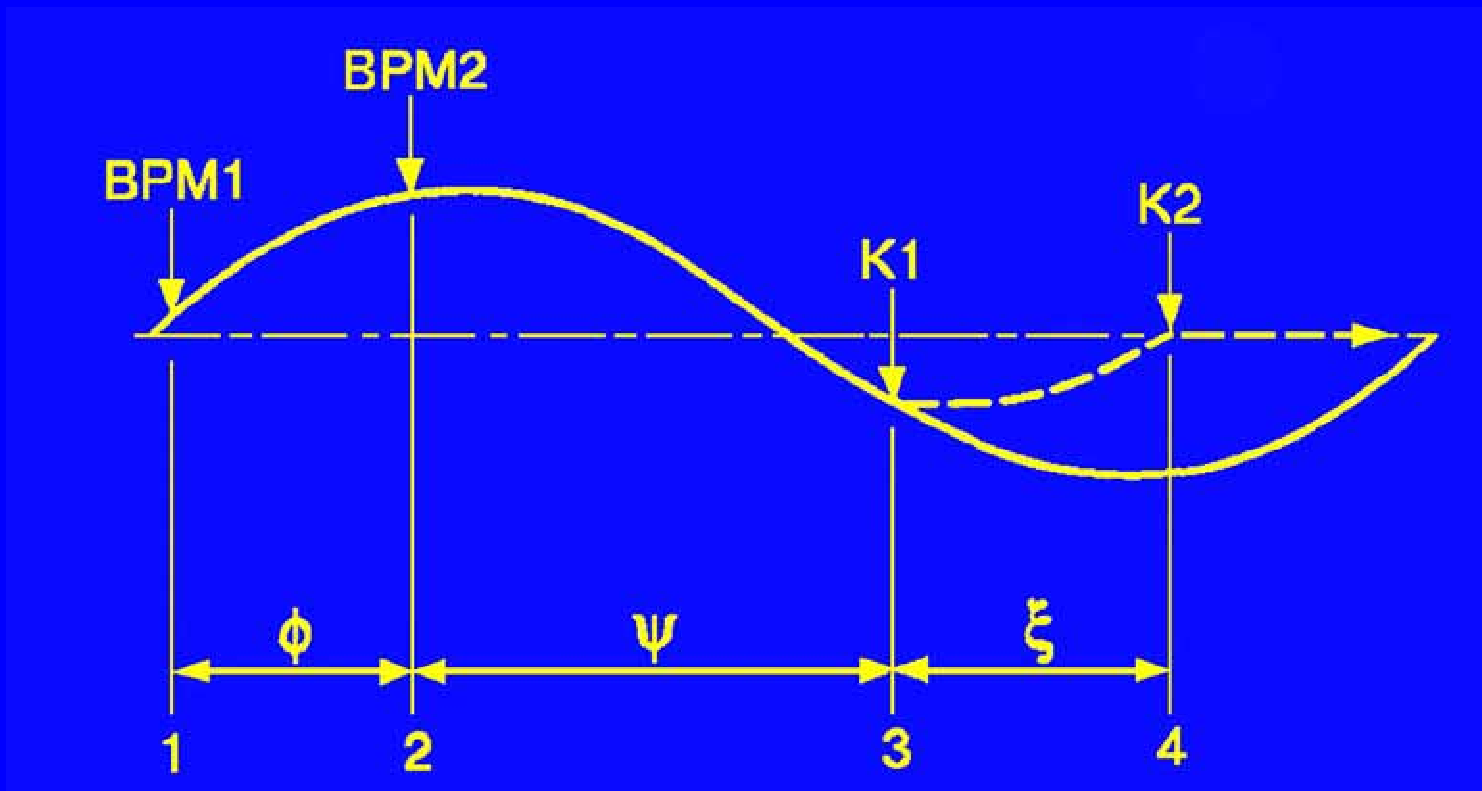
where ξ is the usual tune shift parameter

$$\xi = N_b r_p / 4\pi\varepsilon_N = 0.001954$$



Distribution of the particles in horizontal tune (only the fractional part) under beam-beam interaction. The initial beam is not displaced. The fraction part of the nominal tune is 0.285.

Intelligent damper

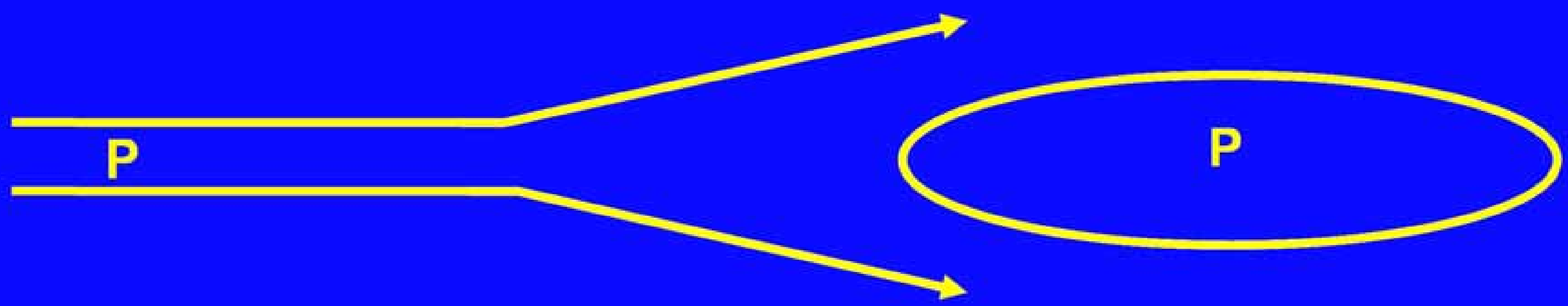


IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 41, NO. 1, FEBRUARY 1994 287

A Proposed SSC Damper System

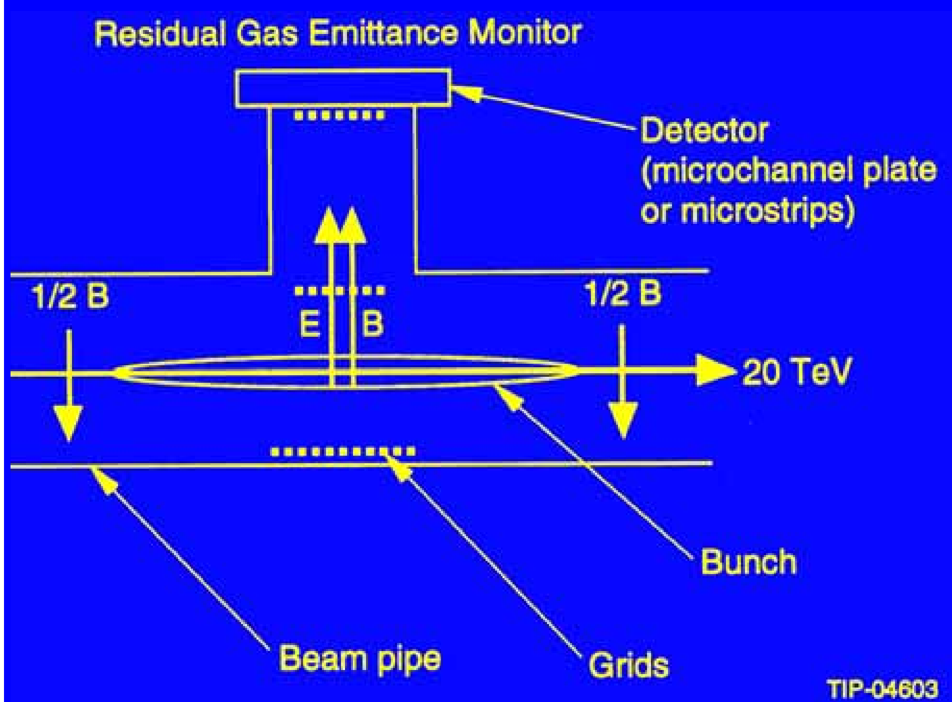
E. Tsyganov, G. Dugan, G. Lopez, R. Meinke, W. Nexson, and R. Talman

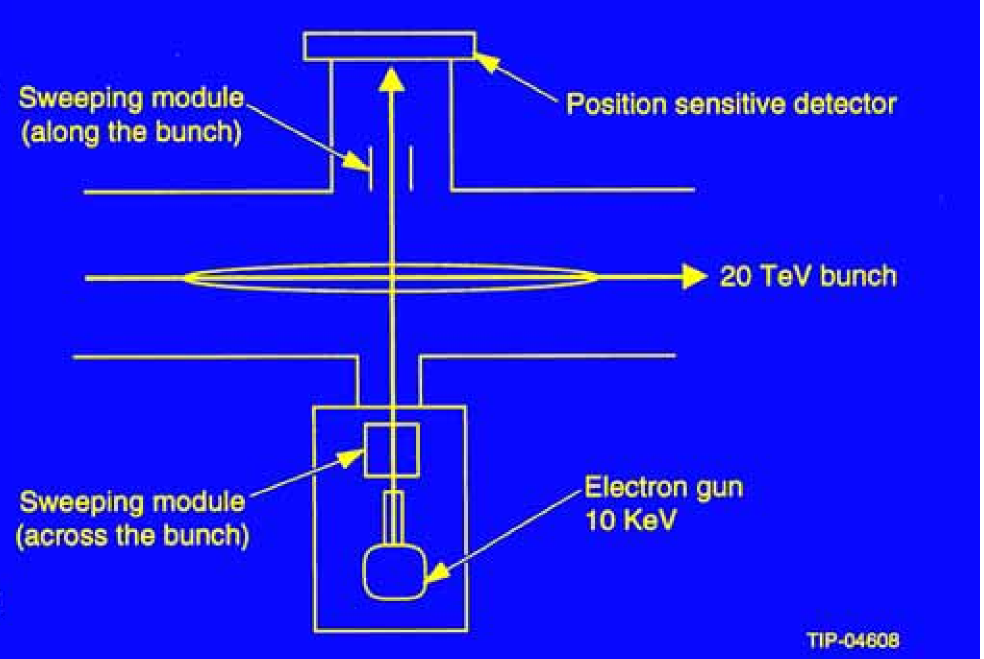
We have a problem in hadron colliders:
Beam-Beam tune spread



For the LHC it limits luminosity by 2.5 x 10^{34} $cm^{-2}s^{-1}$

1993 - we were involved in nondestructive emittance monitoring





SSCL-618

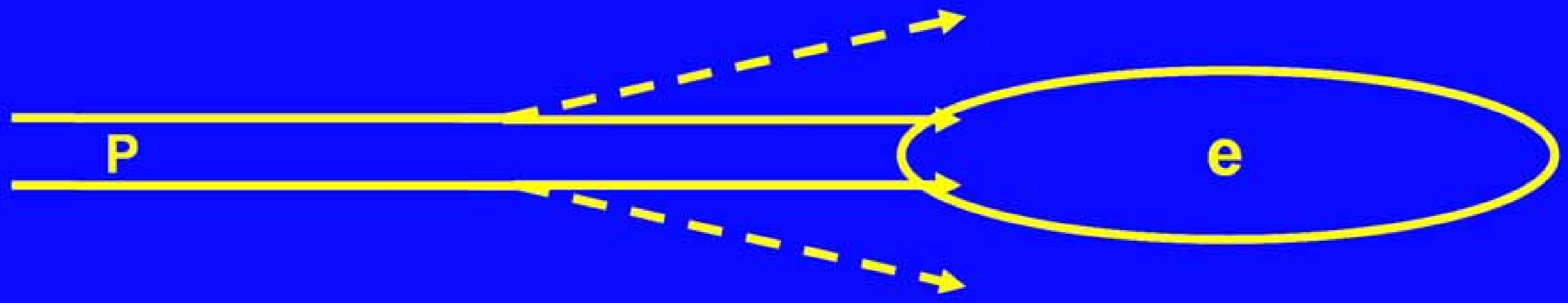
SSCL-618
March 1993
Distribution Category: 414

E. Tsyganov
A. Zinchenko

ZBEAM, Charge Tracing Code for the SSC Environment

$$m\frac{d^2\vec{r}}{dt^2} = q\left(\vec{E} + (\vec{v}_p \times \vec{B}) + \sum_{i=1}^{n}\vec{E}_i + \sum_{i=1}^{n}(\vec{v}_p \times \vec{B}_i)\right)$$

“Obvious solution” of head-on problem:

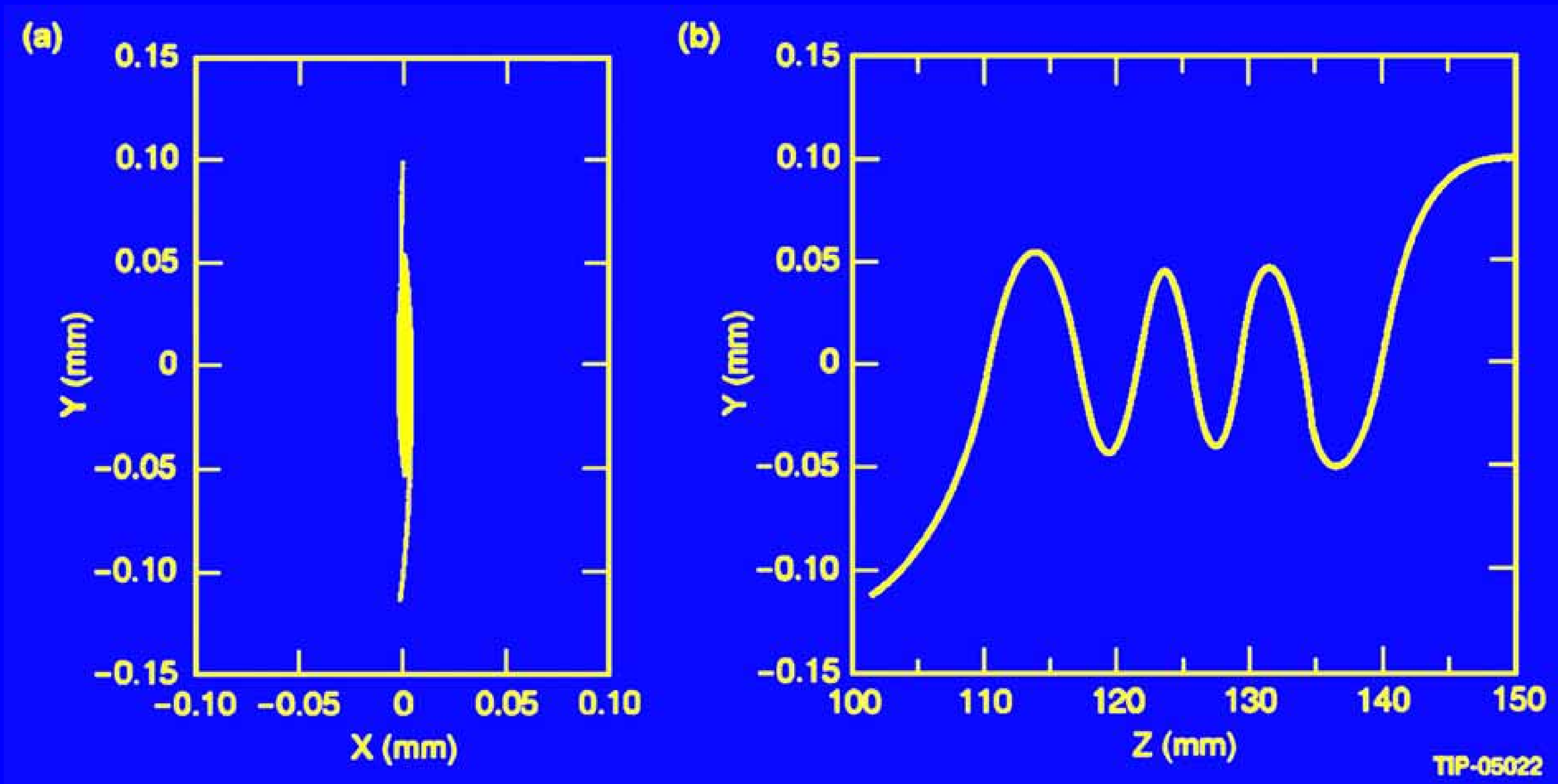


SSCL-Preprint-519

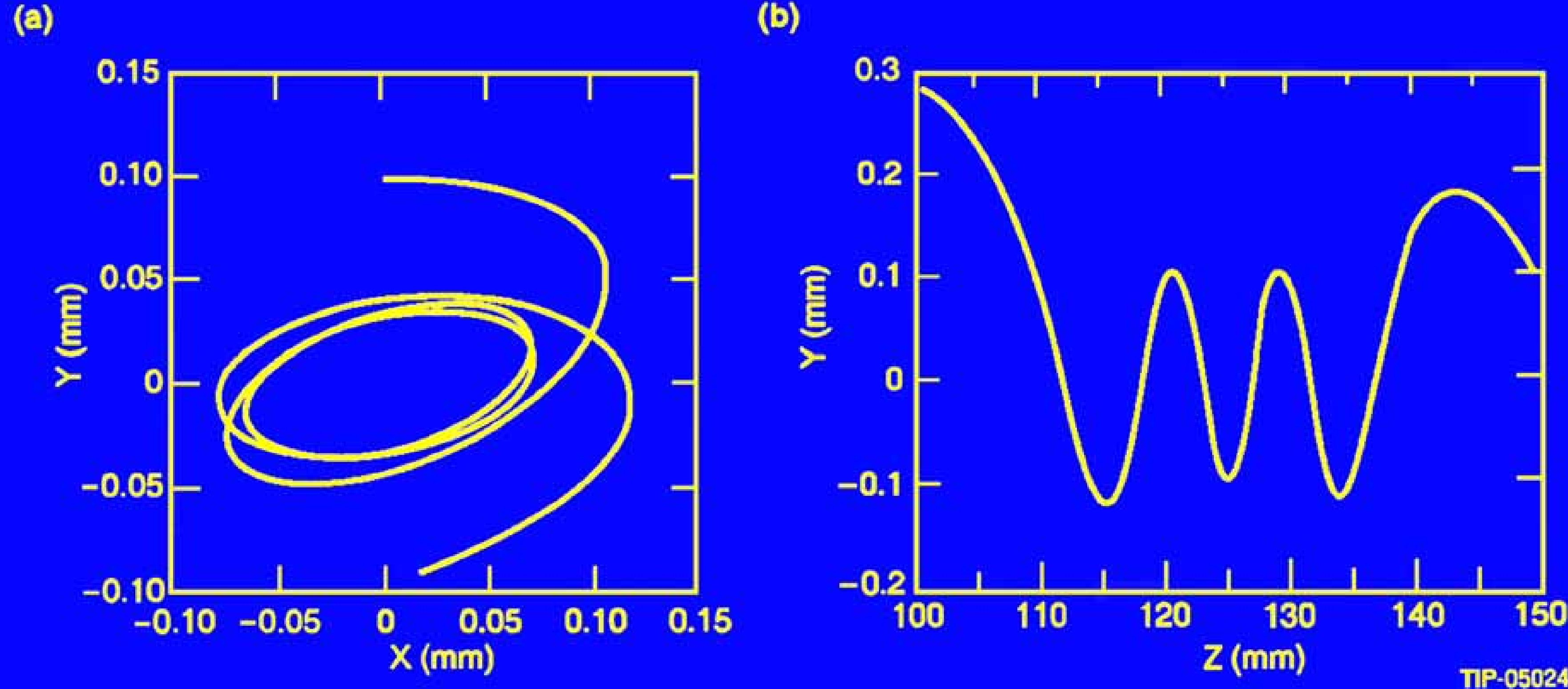
Compensation of the Beam-Beam Effect in Proton-Proton Colliders

SSCL-Preprint-519
October 1993
Distribution Category: 414

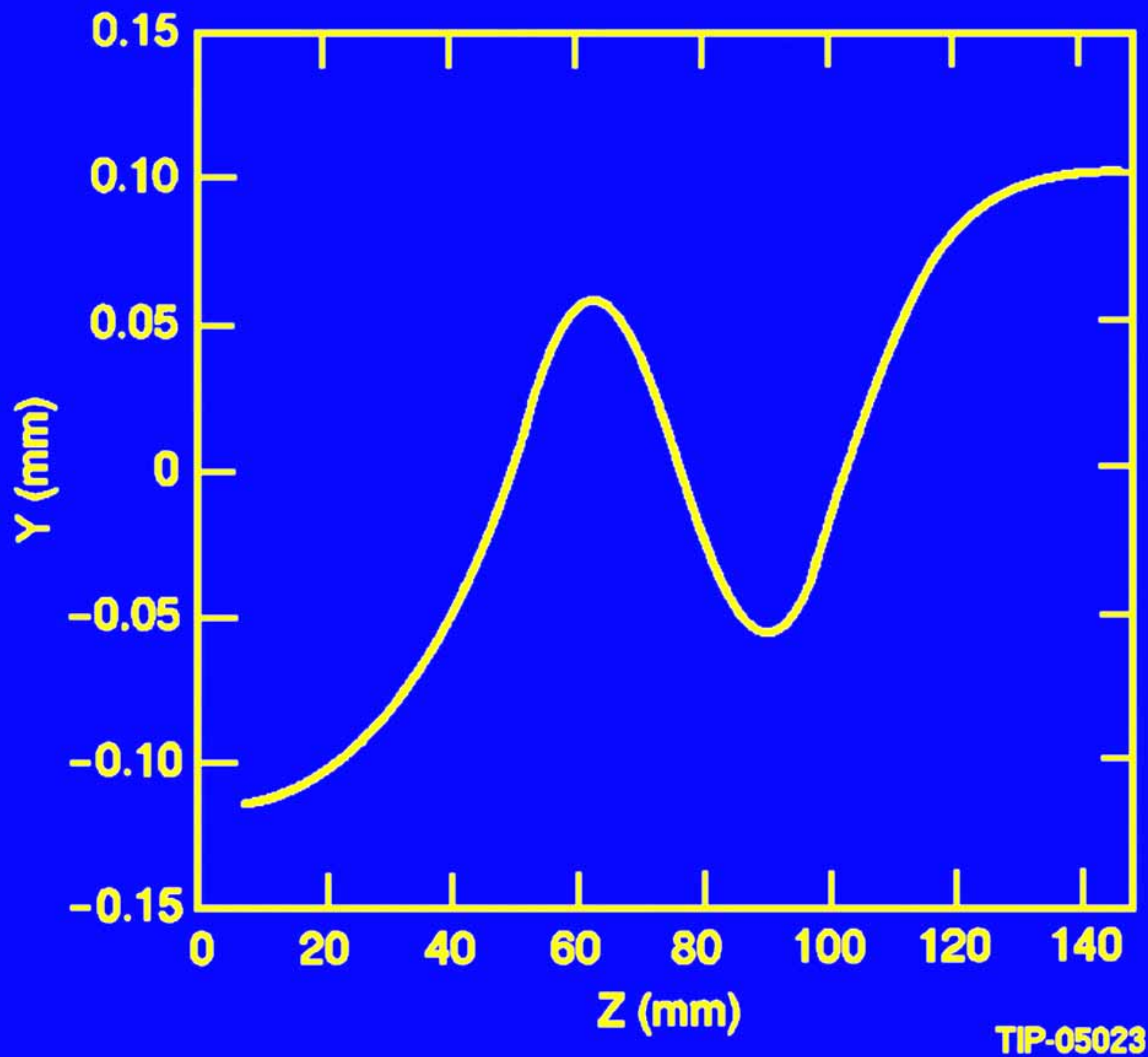
E. Tsyganov
R. Meinke
W. Nexsen
A. Zinchenko



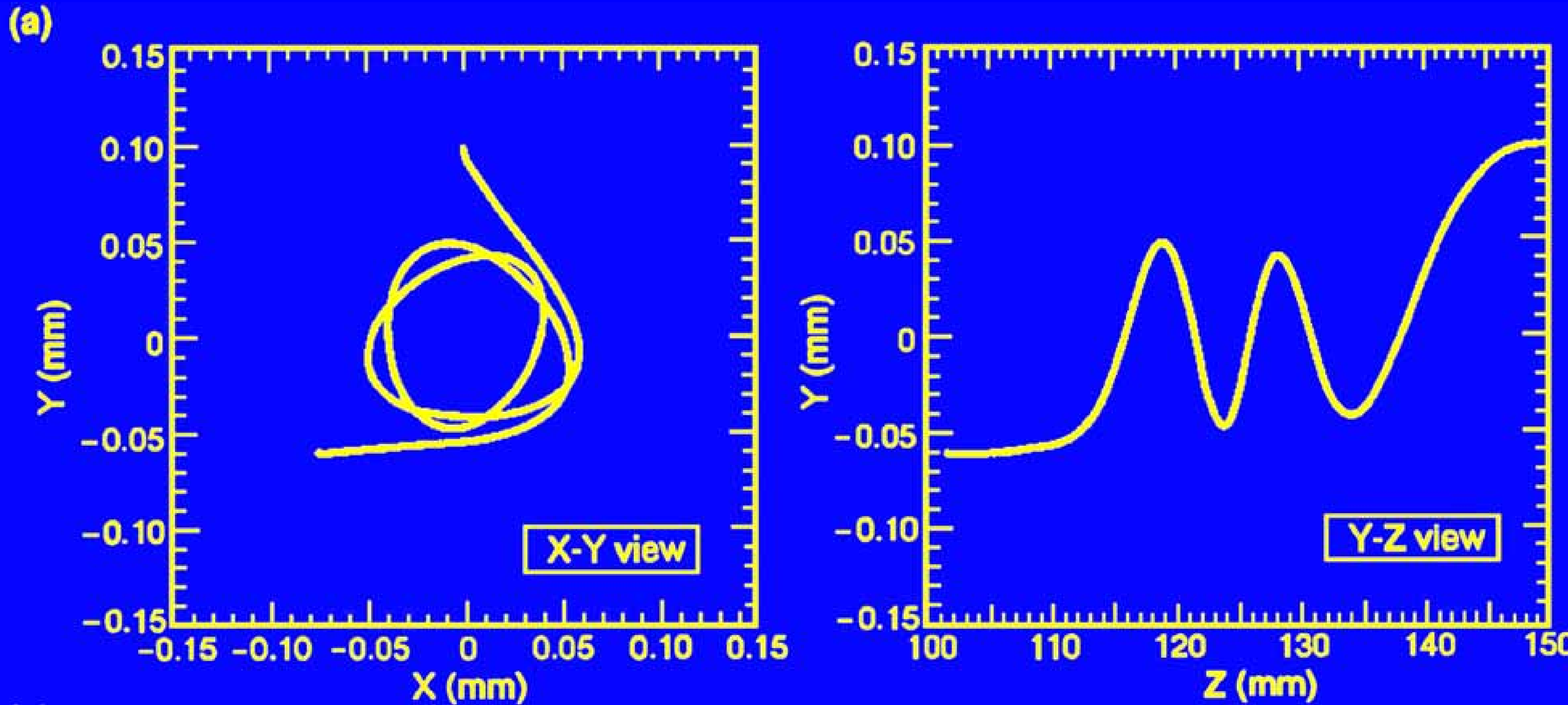
The trajectory of a 10-keV electron with an impact parameter of 100 µm colliding with a bunch of 10^{10} protons, according to the tracing code ZBEAM. The proton bunch is Gaussian in three dimensions with $\sigma_x = \sigma_y = 100$ µm, $\sigma_z = 50$ mm. (a) X–Y view; (b) Y–Z view. The proton bunch (not shown) is moving to the right, and the electron is moving to the left. Plus/minus 3σ of the proton bunch charge distribution in the Z-direction is treated by the tracing code. The time interval used in the calculations is 1 ps.



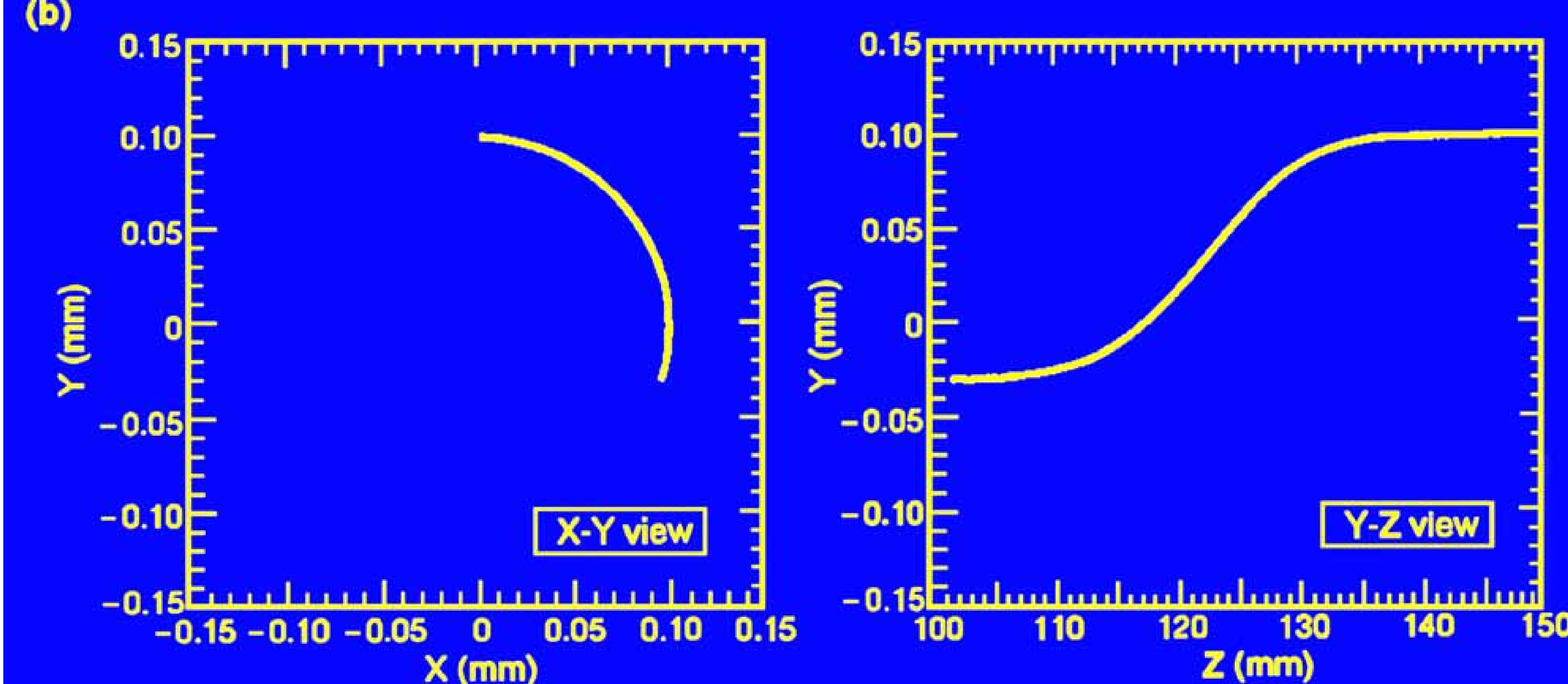
Trajectories of 10-keV electrons with non-zero incoming angles inside the proton bunch. (a) $\phi = 0°$, $\theta = +1°$, X–Y view; (b) $\phi = 90°$, $\theta = +1°$, Y–Z view.



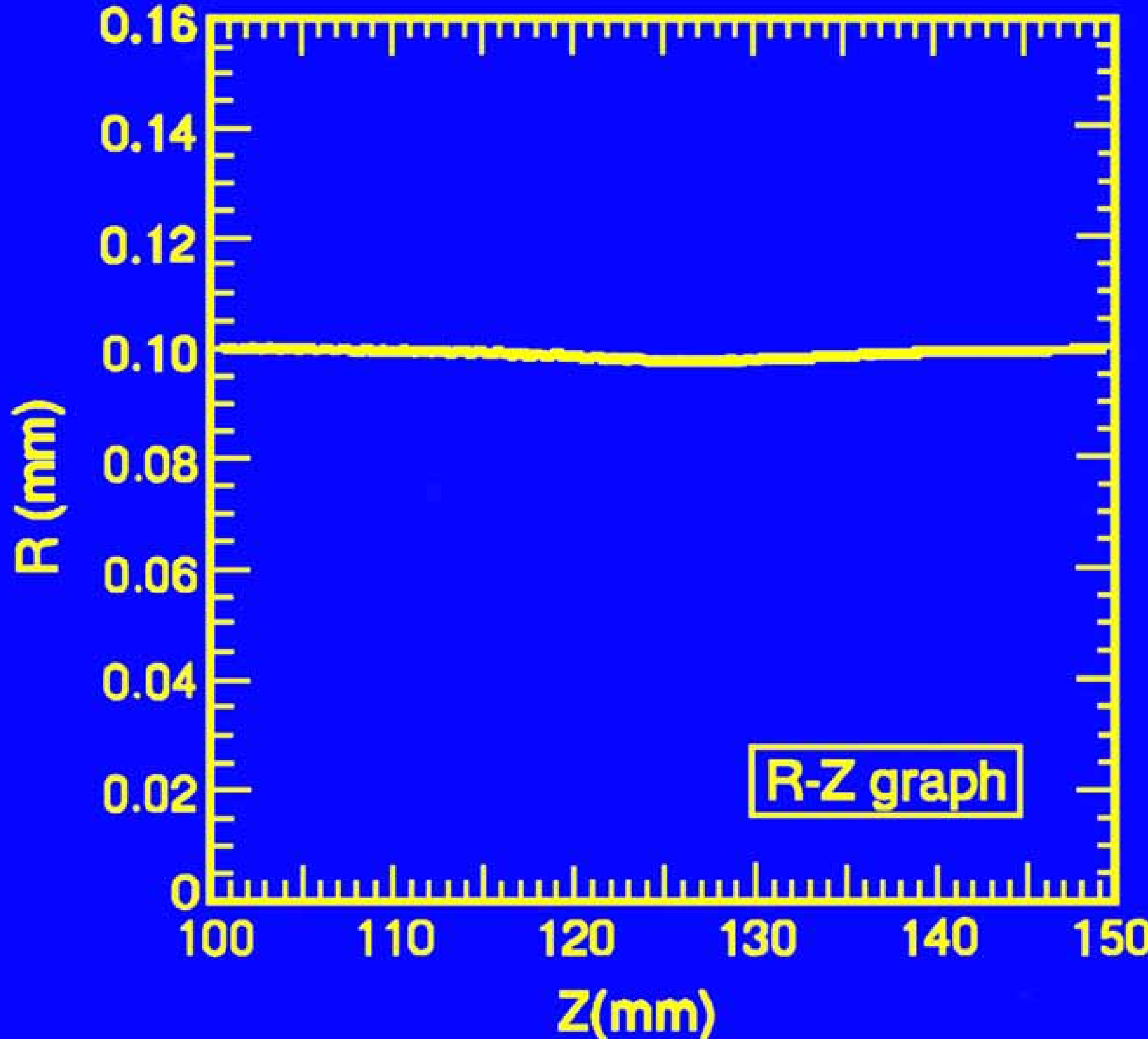
The trajectory of a 1-MeV electron during its interaction with a proton bunch, Y–Z view.



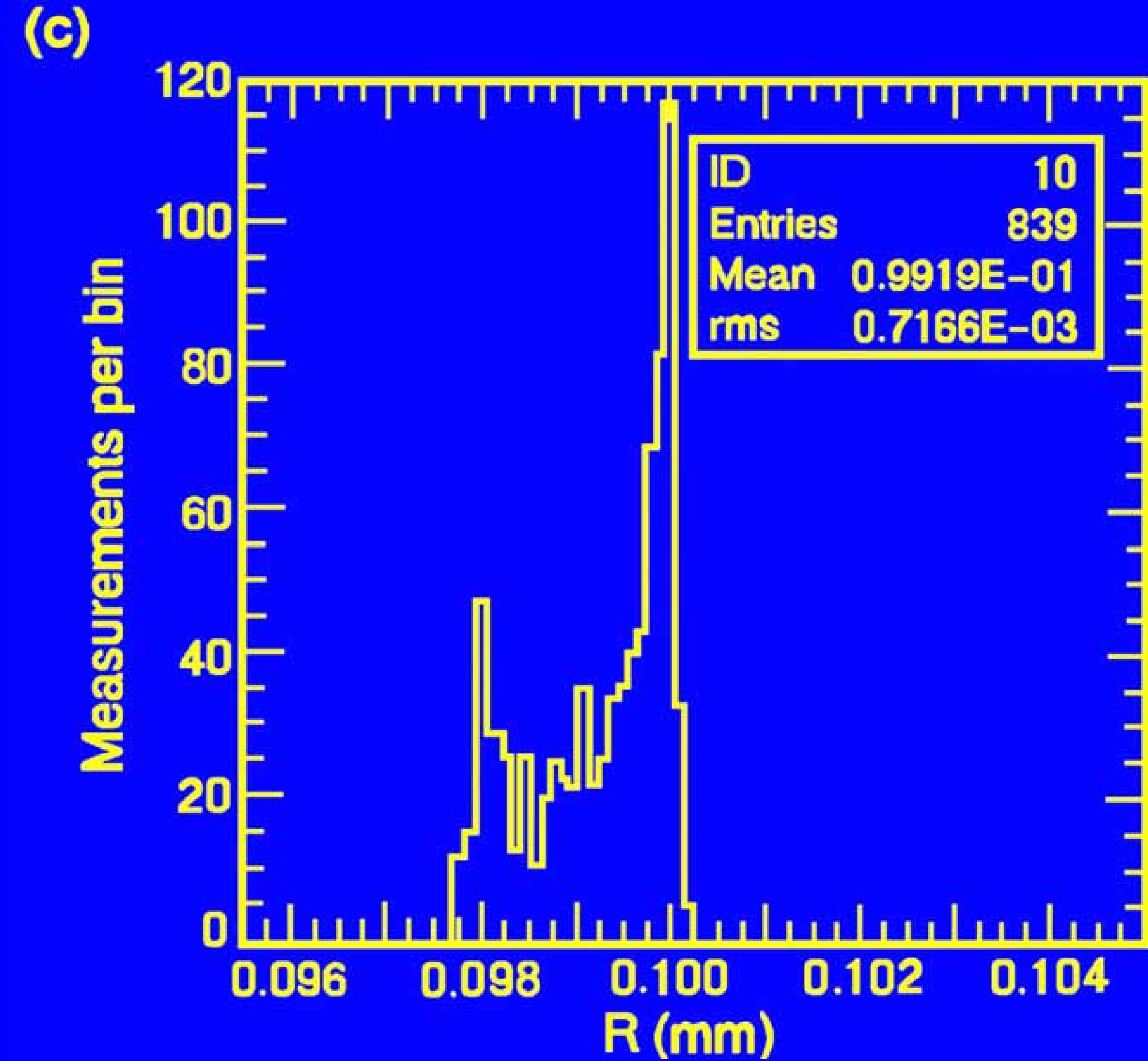
The trajectory of a 10-keV electron with an impact parameter of 100 μm in the proton bunch when a solenoidal magnetic field is applied: (a) solenoidal magnetic field of 0.1 T, projections X–Y and Y–Z



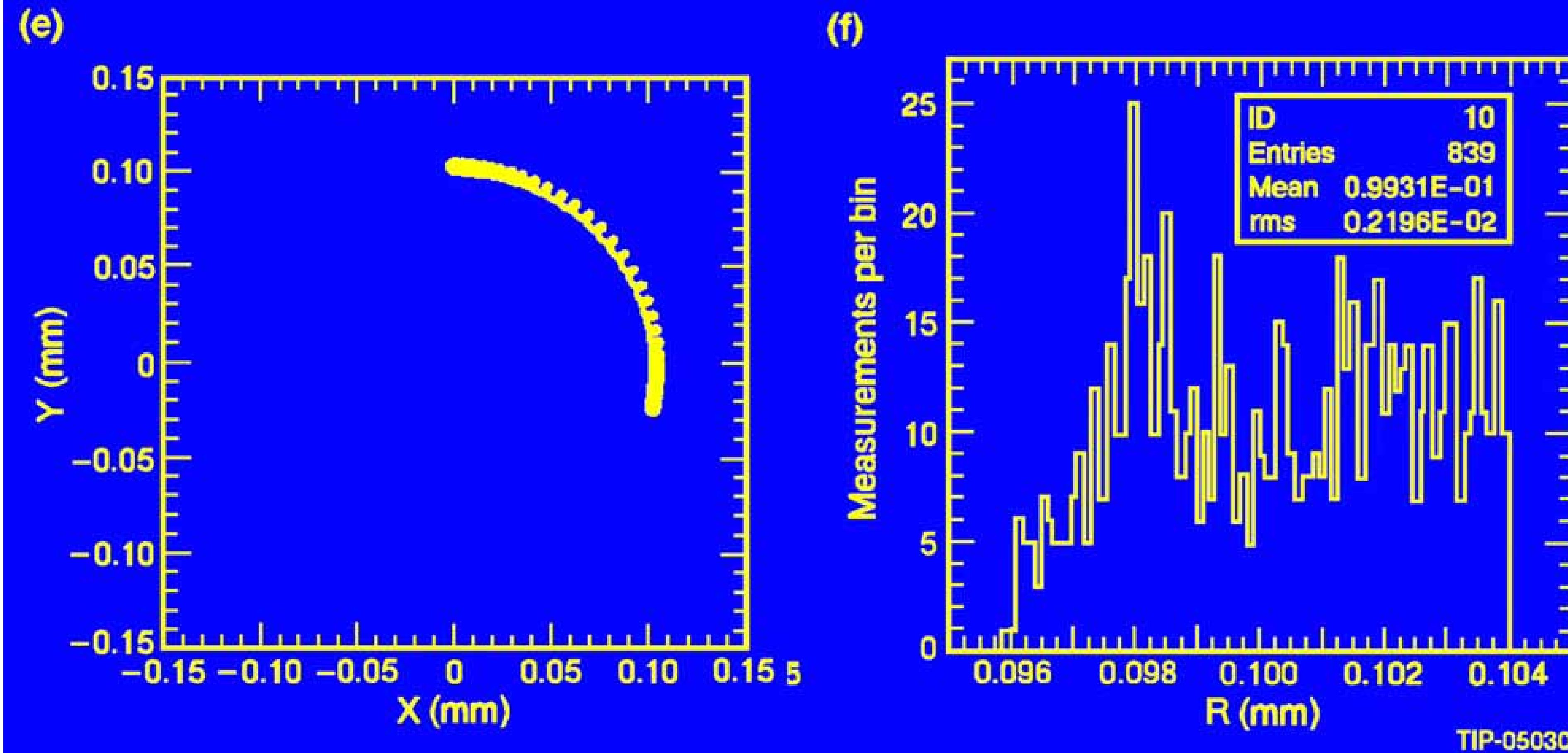
(b) solenoidal magnetic field of 2 T, projections X–Y and Y–Z.



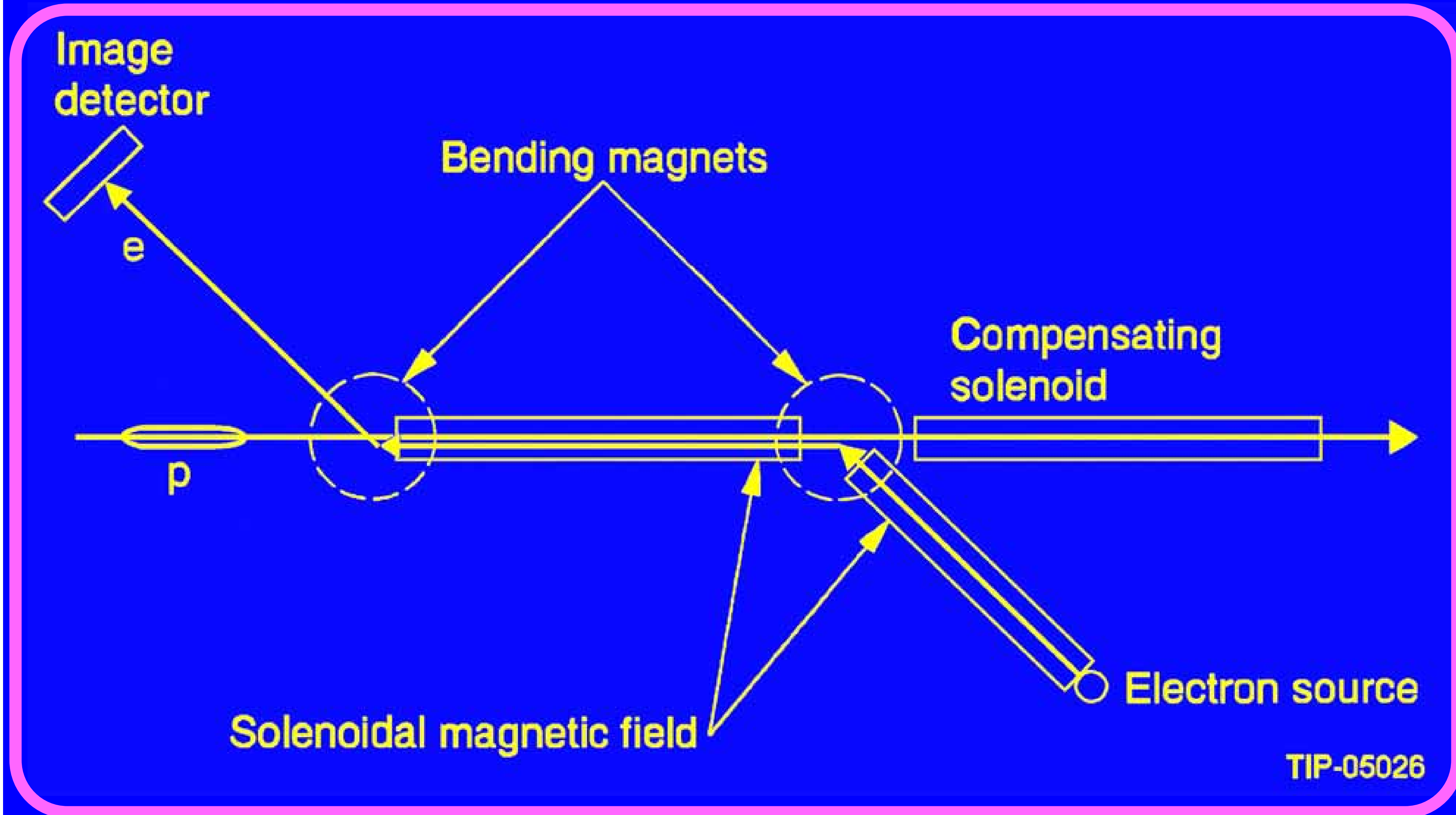
The graph of R–Z, $R = \sqrt{X^2 + Y^2}$



(c) histogram of R-measurements for the case of 2 T. The mean value of R is about 99 µm, the rms value is about 0.7 µm



(e) $\phi = 90°$, $\theta = +1°$, solenoidal magnetic field of 2 T, X–Y view; (f) histogram of R-measurements for case (e). The mean value of R is about 99 μm; the rms value is about 2 μm.



Schematics of Beam-Beam compensating device (1993)

Compensation of the beam-beam effect in high-energy proton-proton colliders using a low-energy electron beam was proposed.

It was concluded that such compensation looks feasible. Requirements for such a device were formulated.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - SL DIVISION

SL-Note 95-116 AP

Beam-Beam Effect Compensation at the LHC

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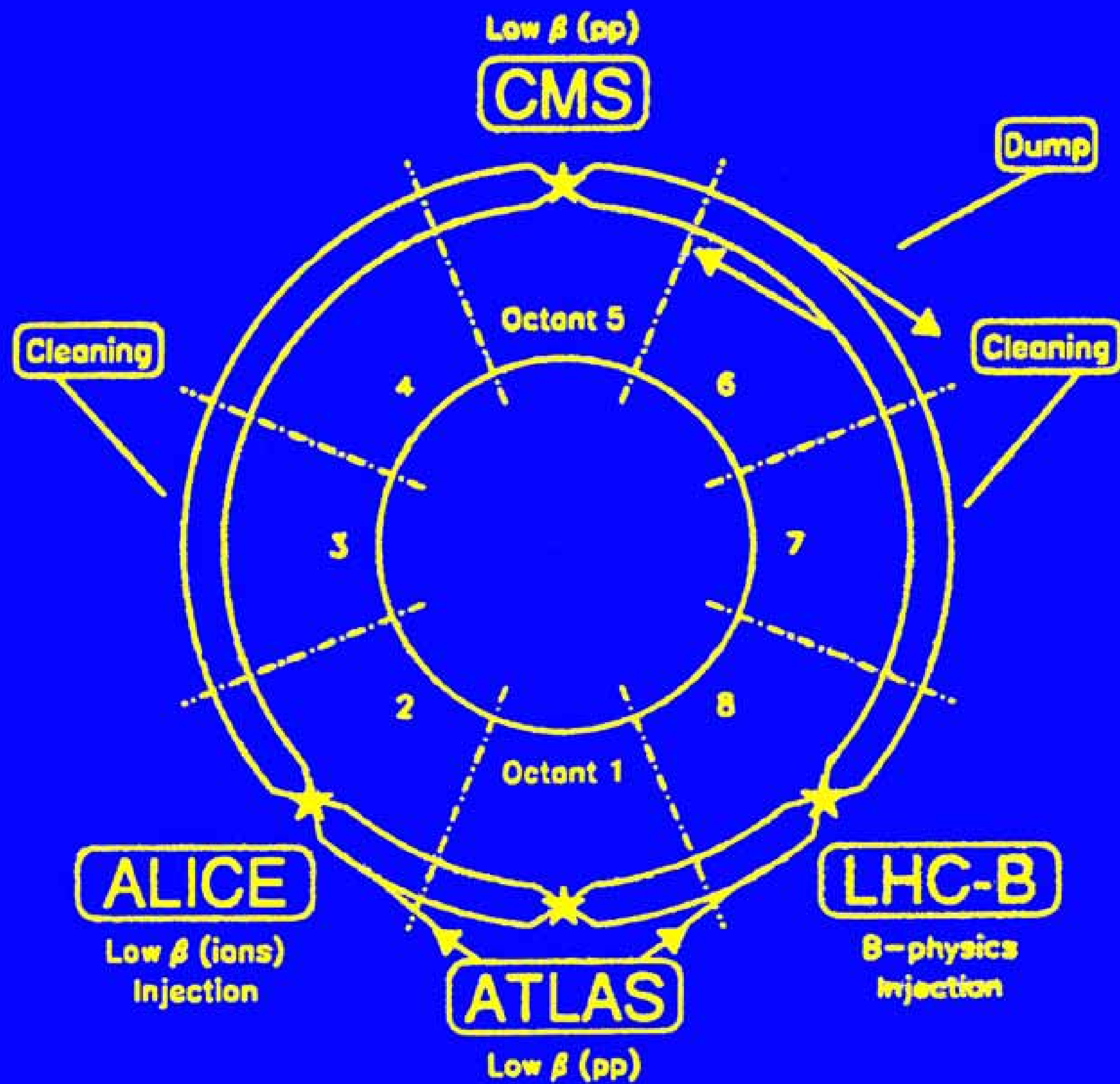


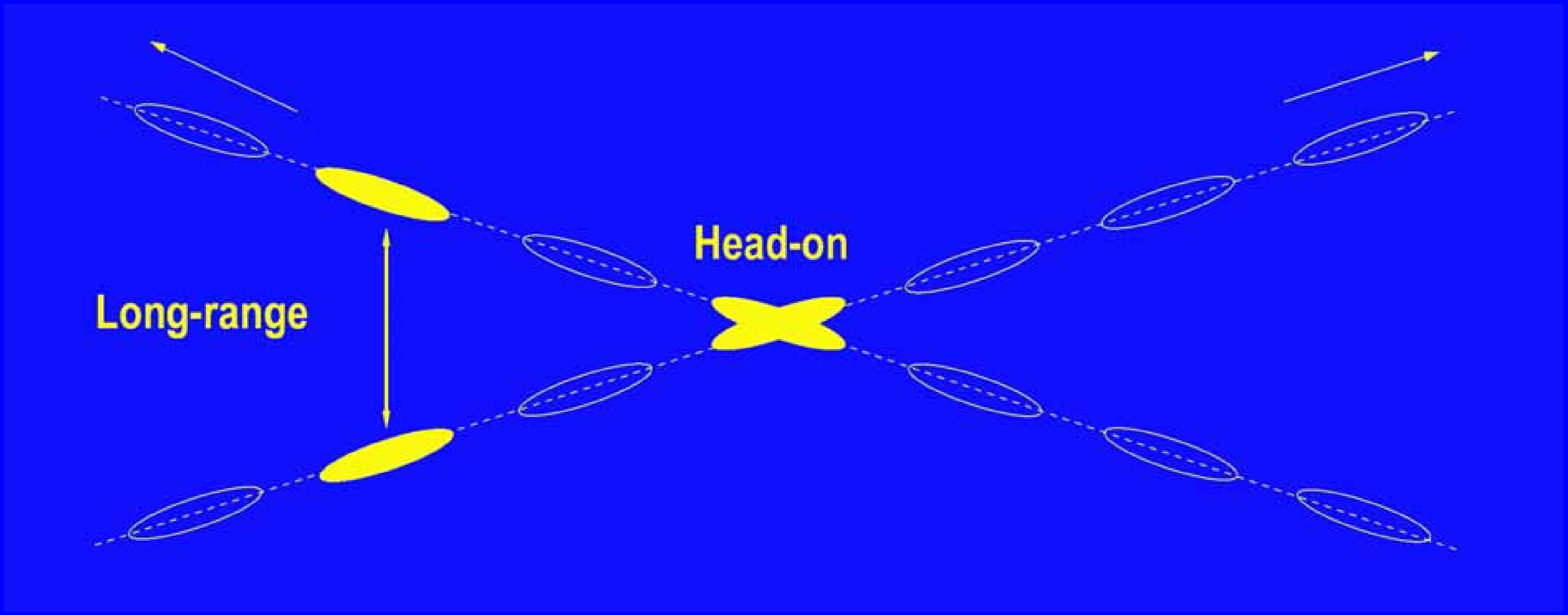
LHC layout with
four crossing points

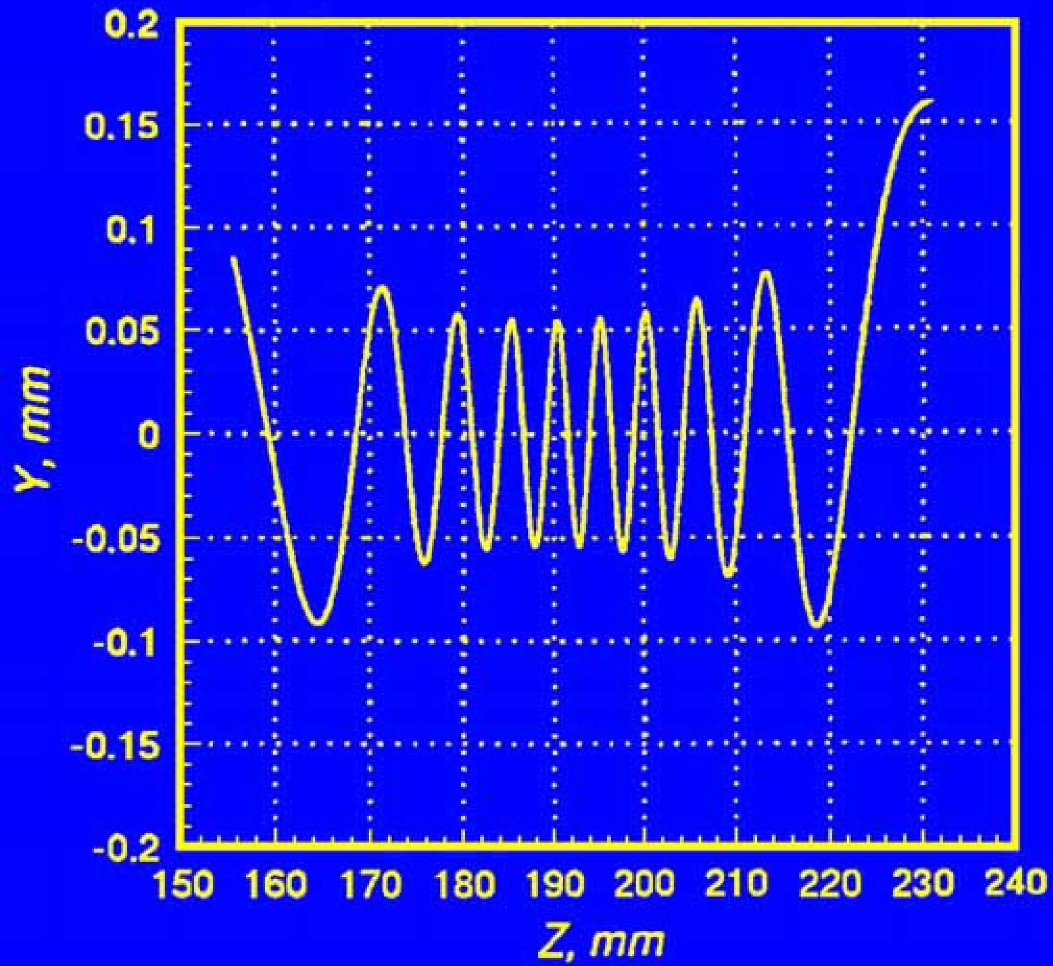
LHC parameters from Werner Herr, Trieste, 2005

	LHC
Beam sizes	$16.6\mu m \cdot 16.6\mu m$
Intensity N	$1.15 \cdot 10^{11}$/bunch
Energy	7000 GeV
$\beta_x^* \cdot \beta_y^*$	0.55 m · 0.55 m
Crossing angle	285 μrad
Beam-beam parameter(ξ)	0.0034

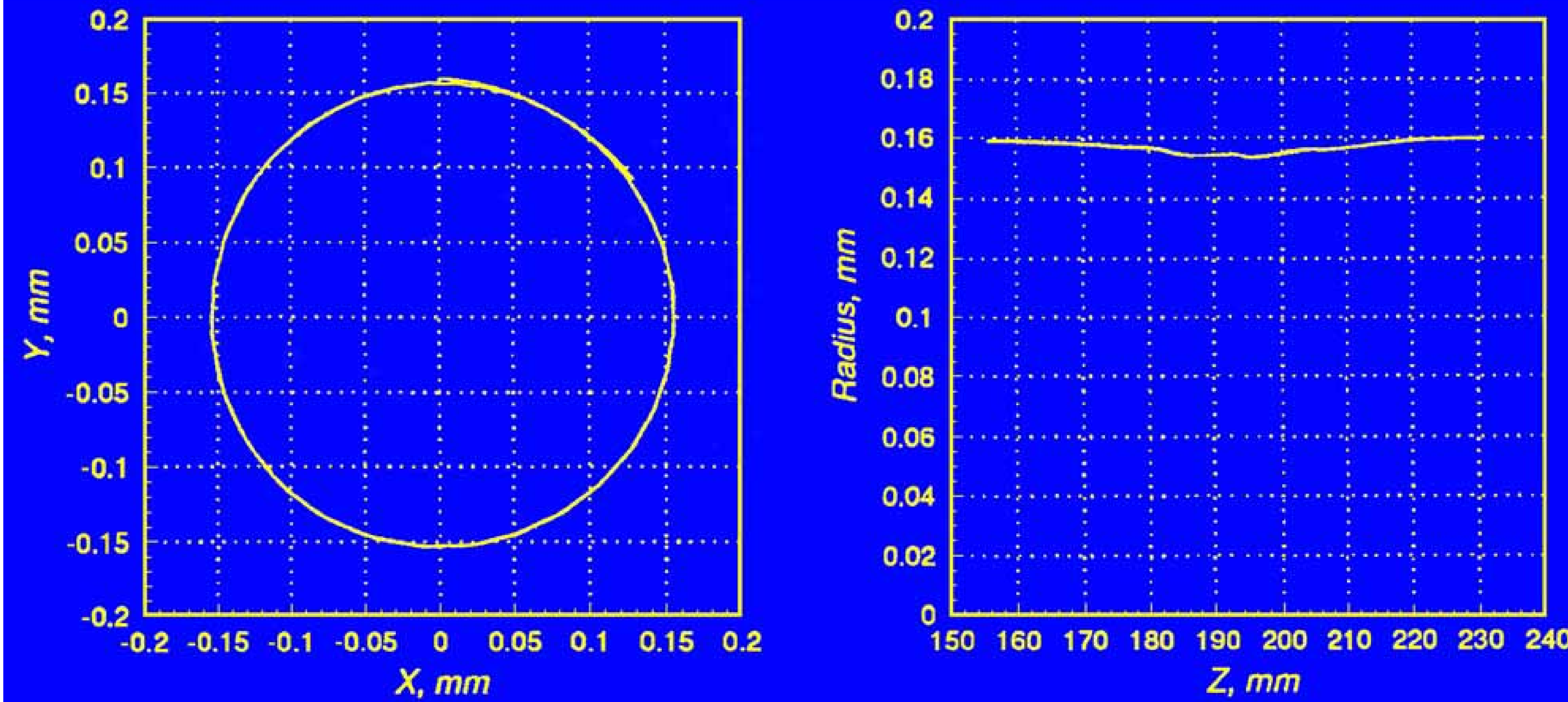
Luminosity: 1.0×10^{34} $cm^{-2}s^{-1}$

Long range and head-on beam-beam interactions
(Werner Herr)

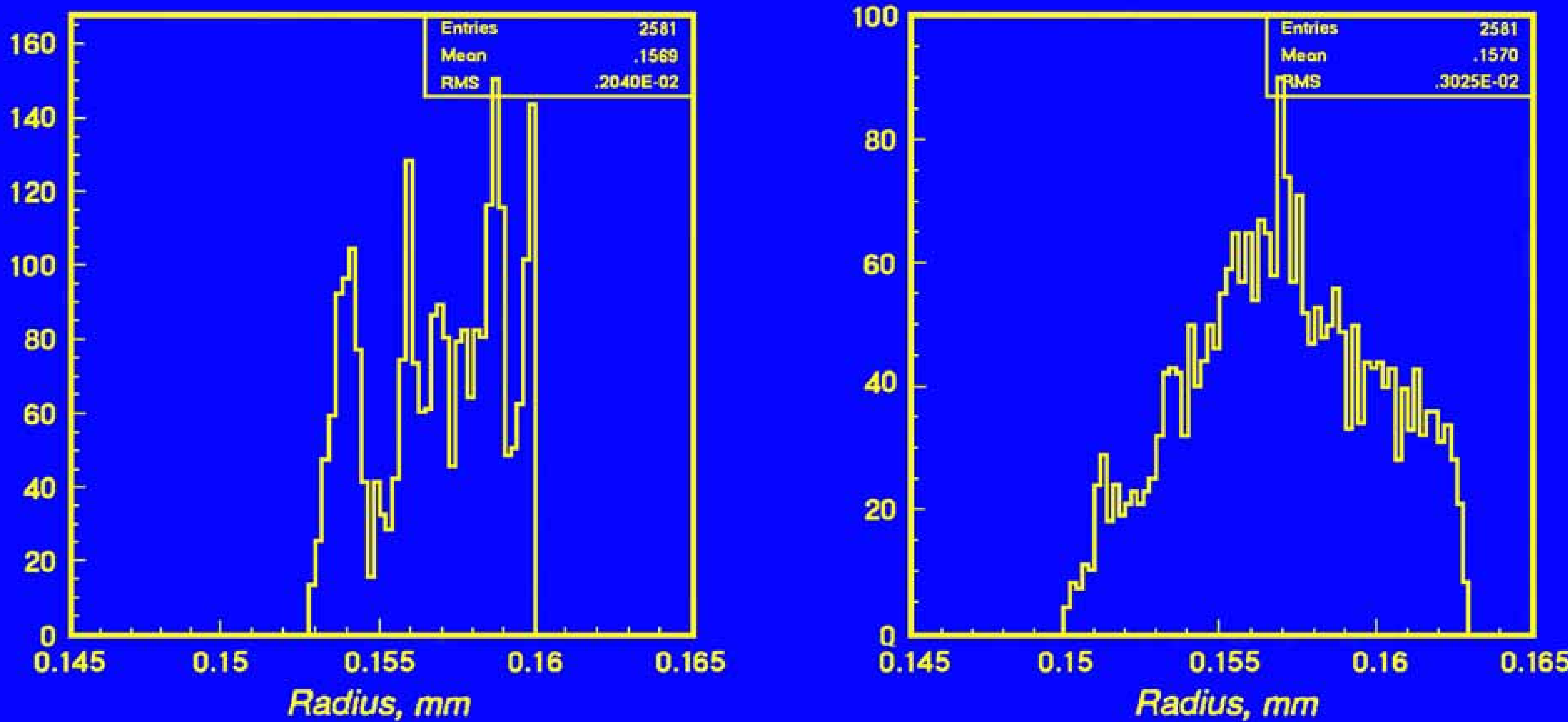




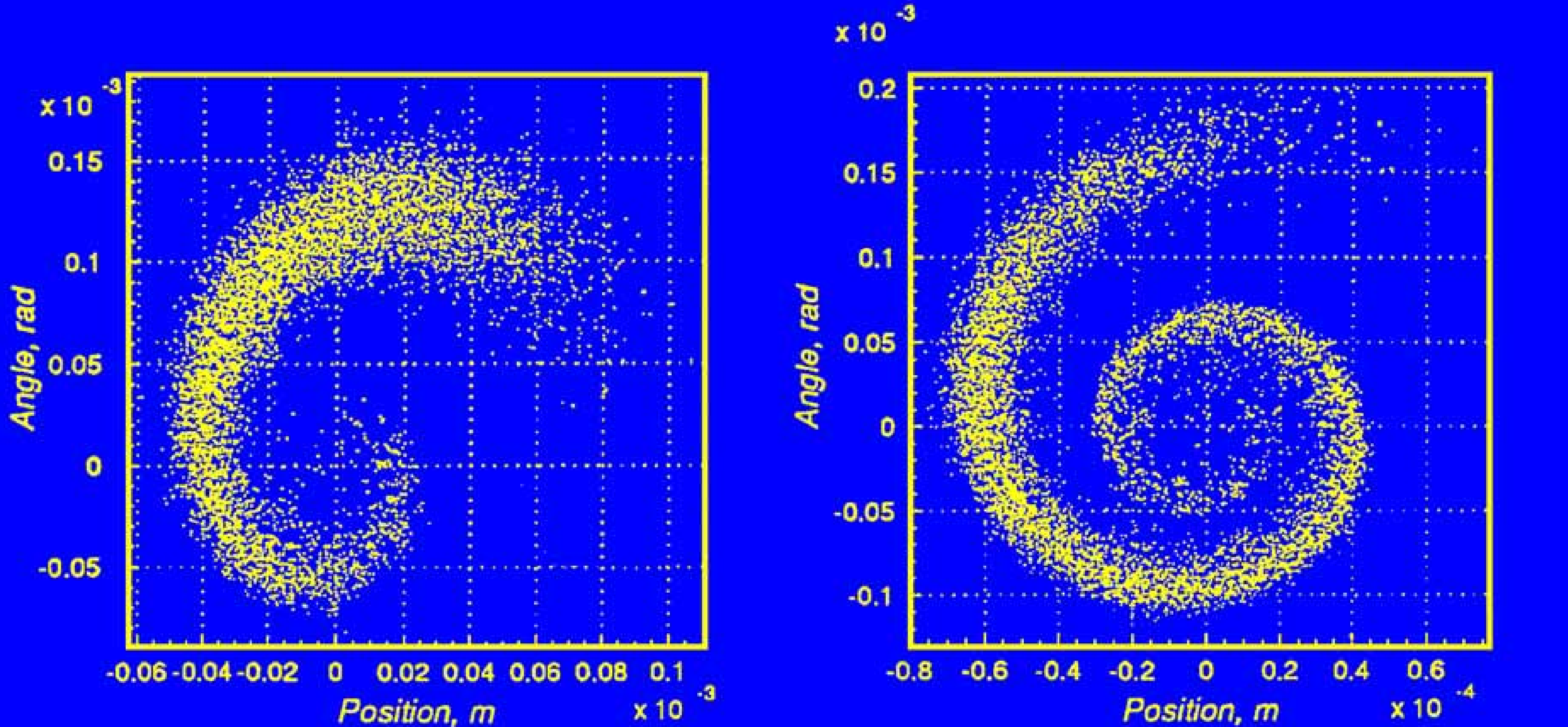
The trajectory of a 10 keV electron with an impact parameter of 160 μm colliding with an LHC proton bunch, Z- Y view. The proton bunch is moving to the right, and the electron is moving to the left. Plus/minus 3σ of the proton bunch charge distribution in Z-direction is treated by the tracing code.



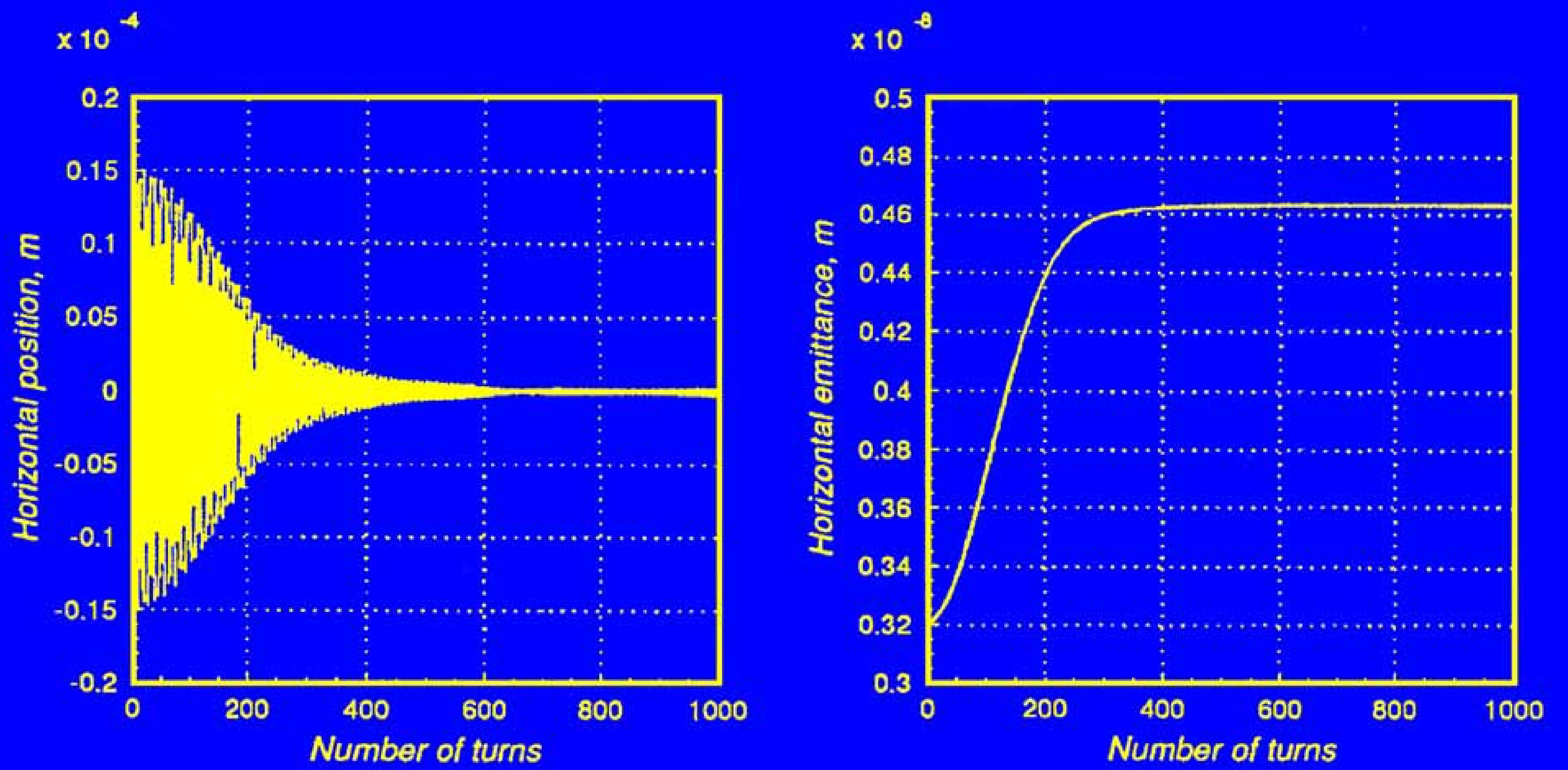
The trajectory of a 10 keV electron with an impact parameter of 160 μm inside a proton bunch when a solenoidal magnetic field of 2 T is applied: left) X- Y view, right) Z-R view (R is a distance of an electron from the center of a proton bunch in X-Y plane).



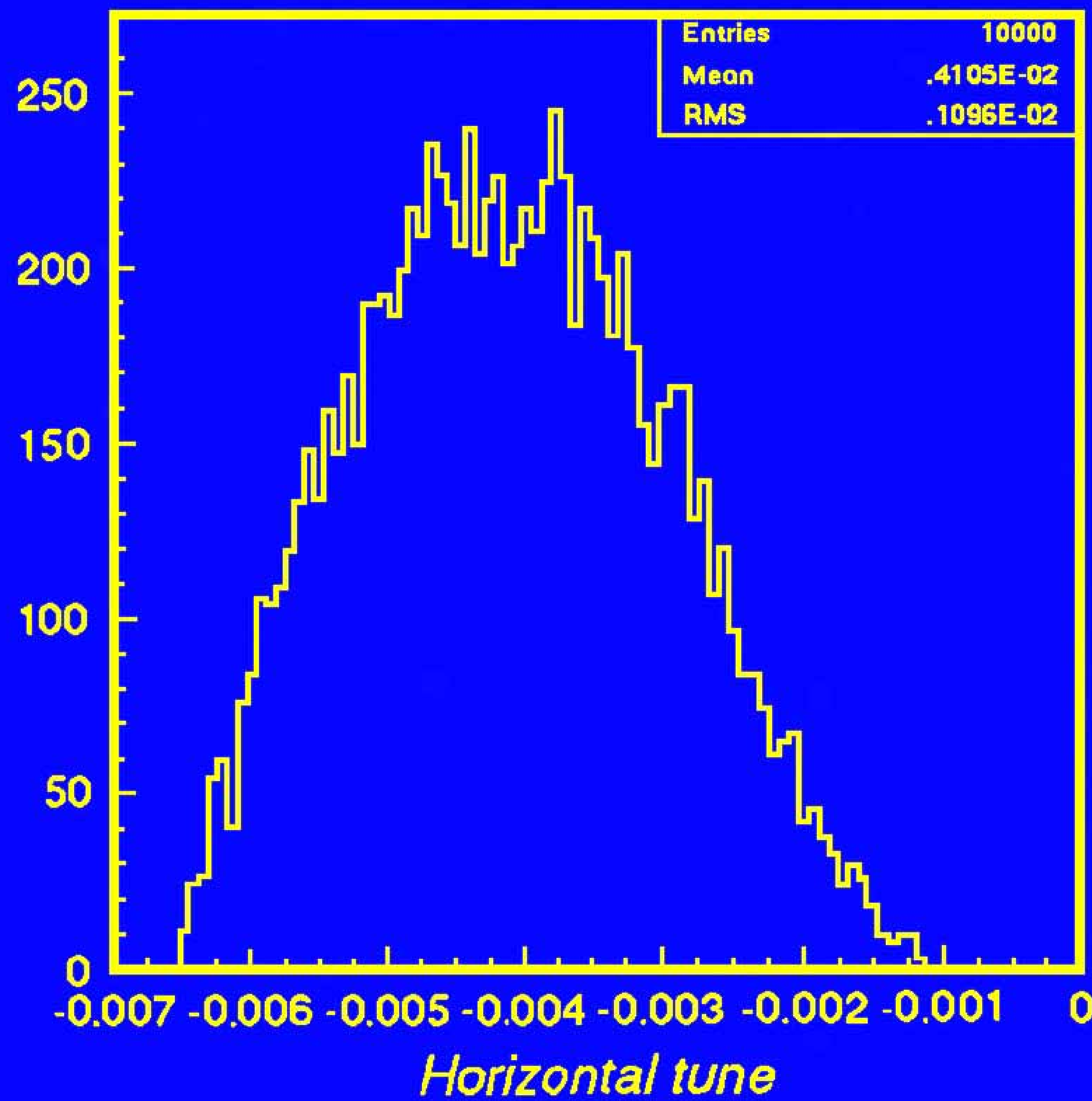
Distribution of R with incoming electron angle of 0^o (left) and 1^o (right).



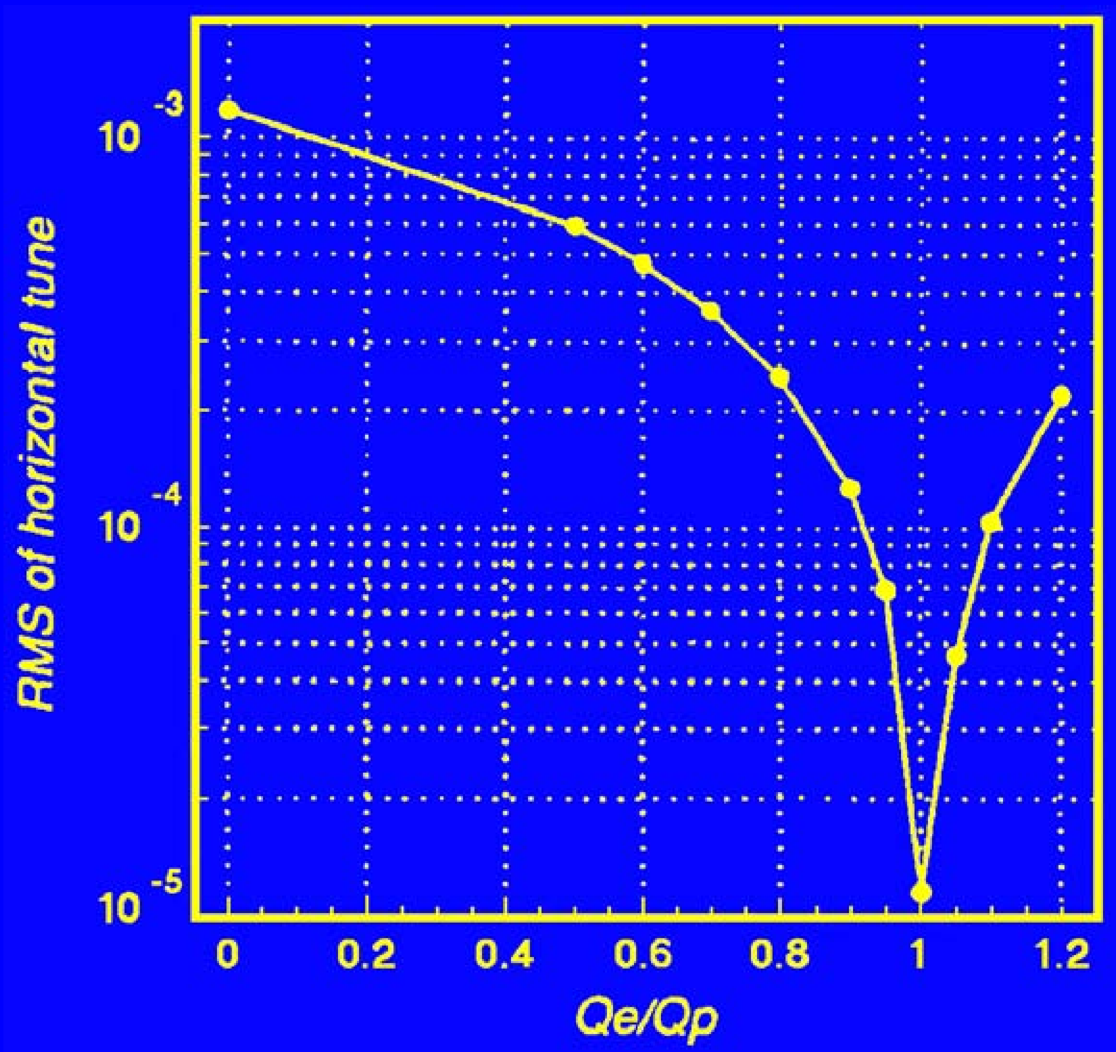
Distributions of the beam in phase space after a horizontal displacement of 3 sigma.
Left) after 200 turns, right) after 400 turns.



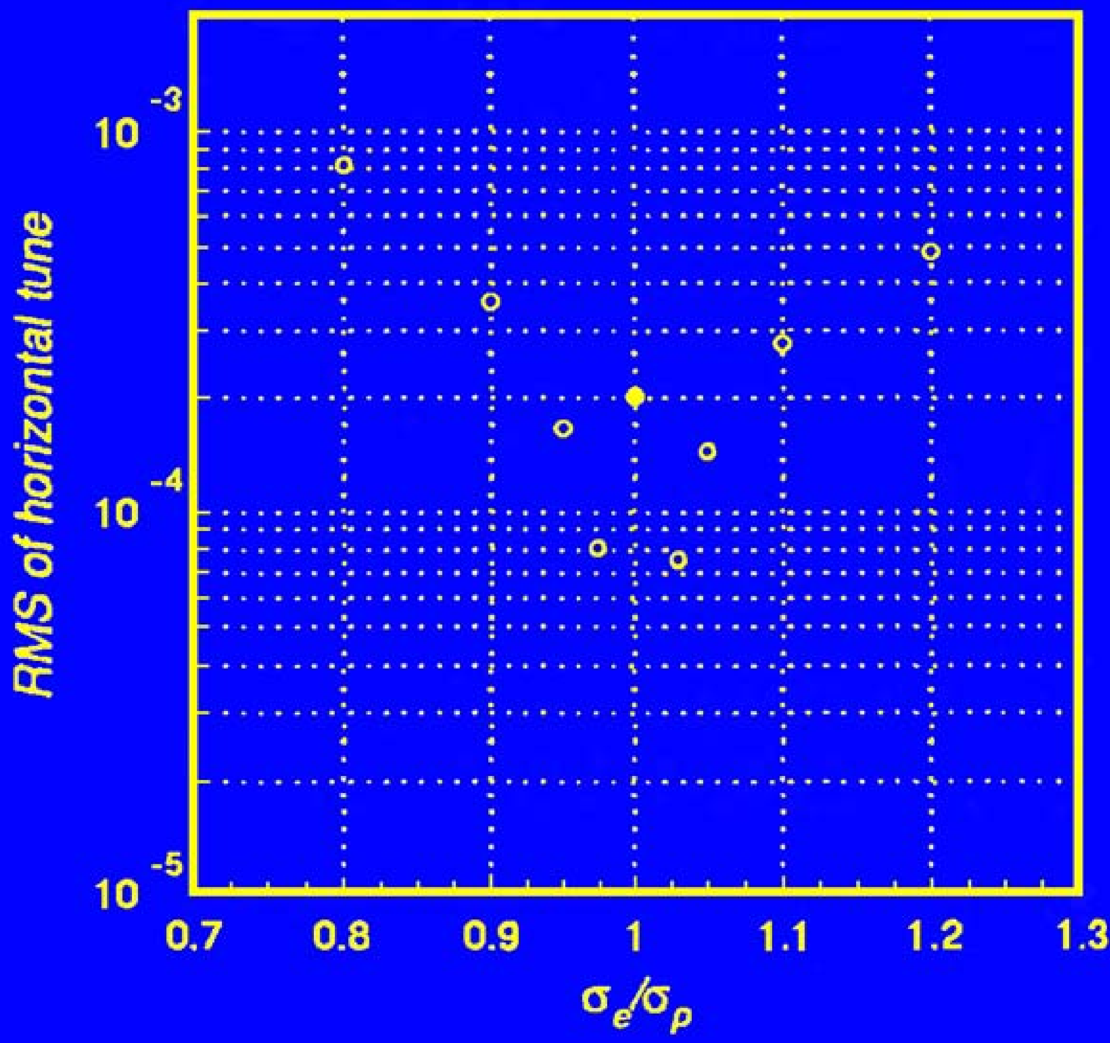
Left) oscillations of the beam centroid after an initial beam displacement of 1 sigma, right) growth of the relative-to-centroid beam emittance. No compensation.



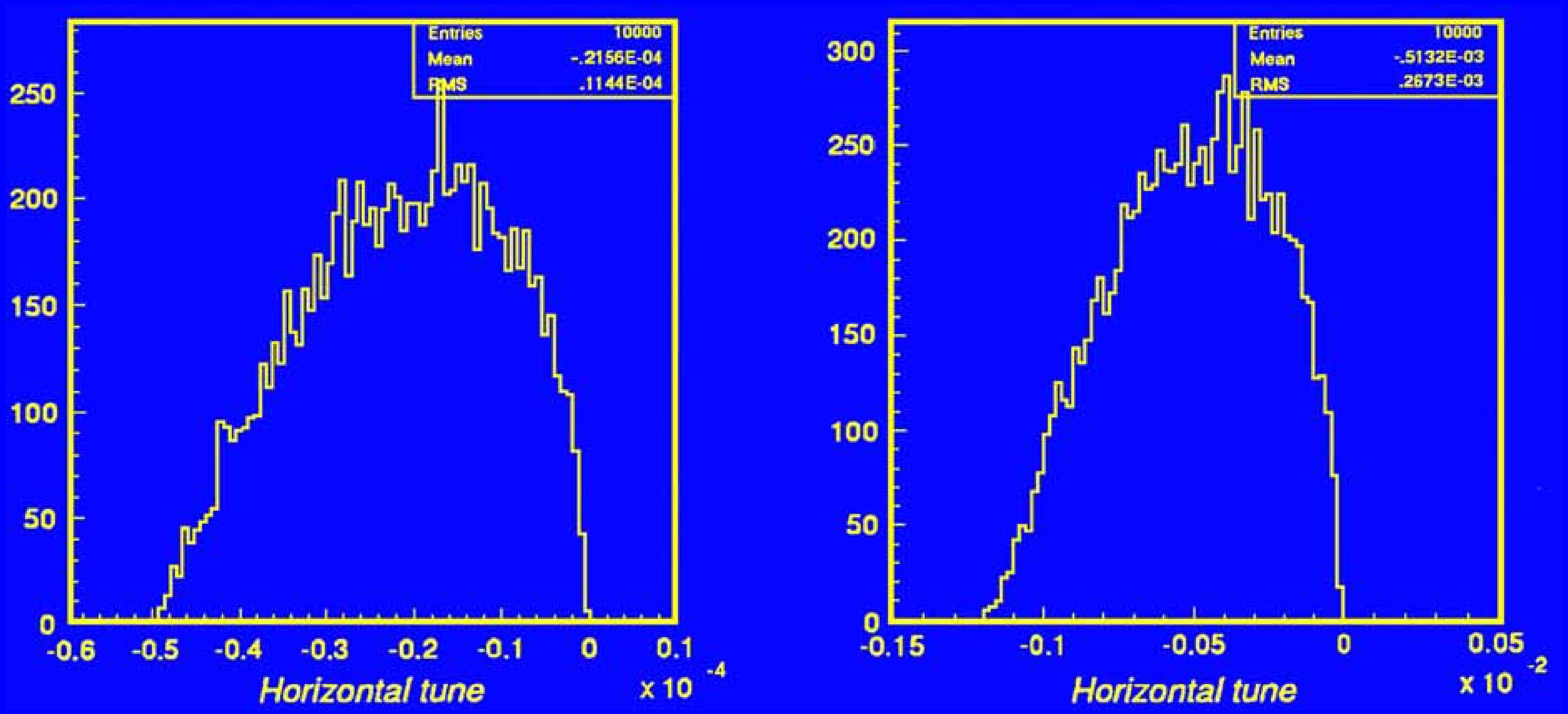
Horizontal tune distribution of beam particles.
No compensation.



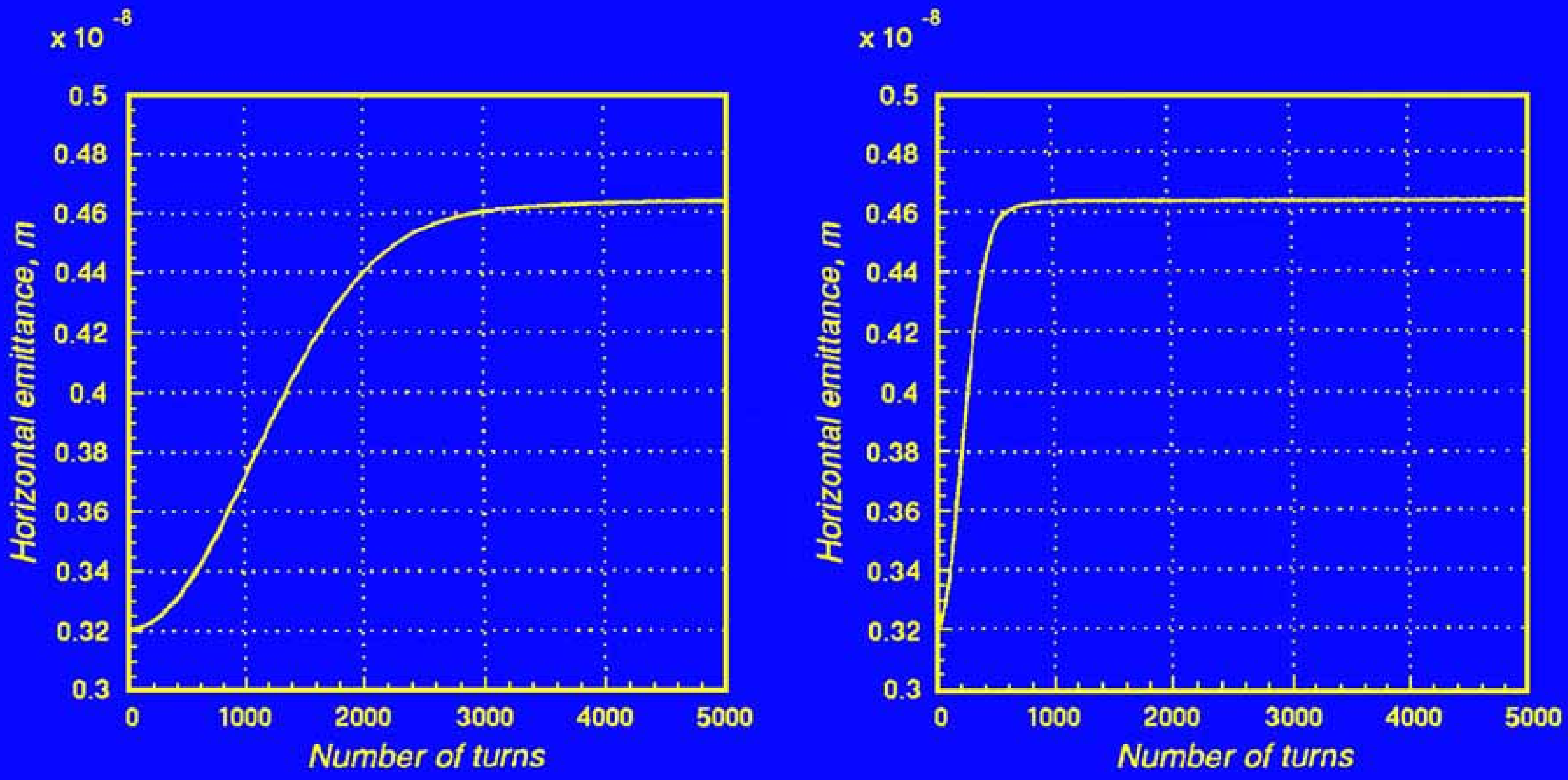
R.M.S. of horizontal tune distribution of the beam particles *vs* the ratio of the electron to proton bunch charges. Displacement of the electron bunch is 0.1 σ. The leftmost point corresponds to the case without compensation.



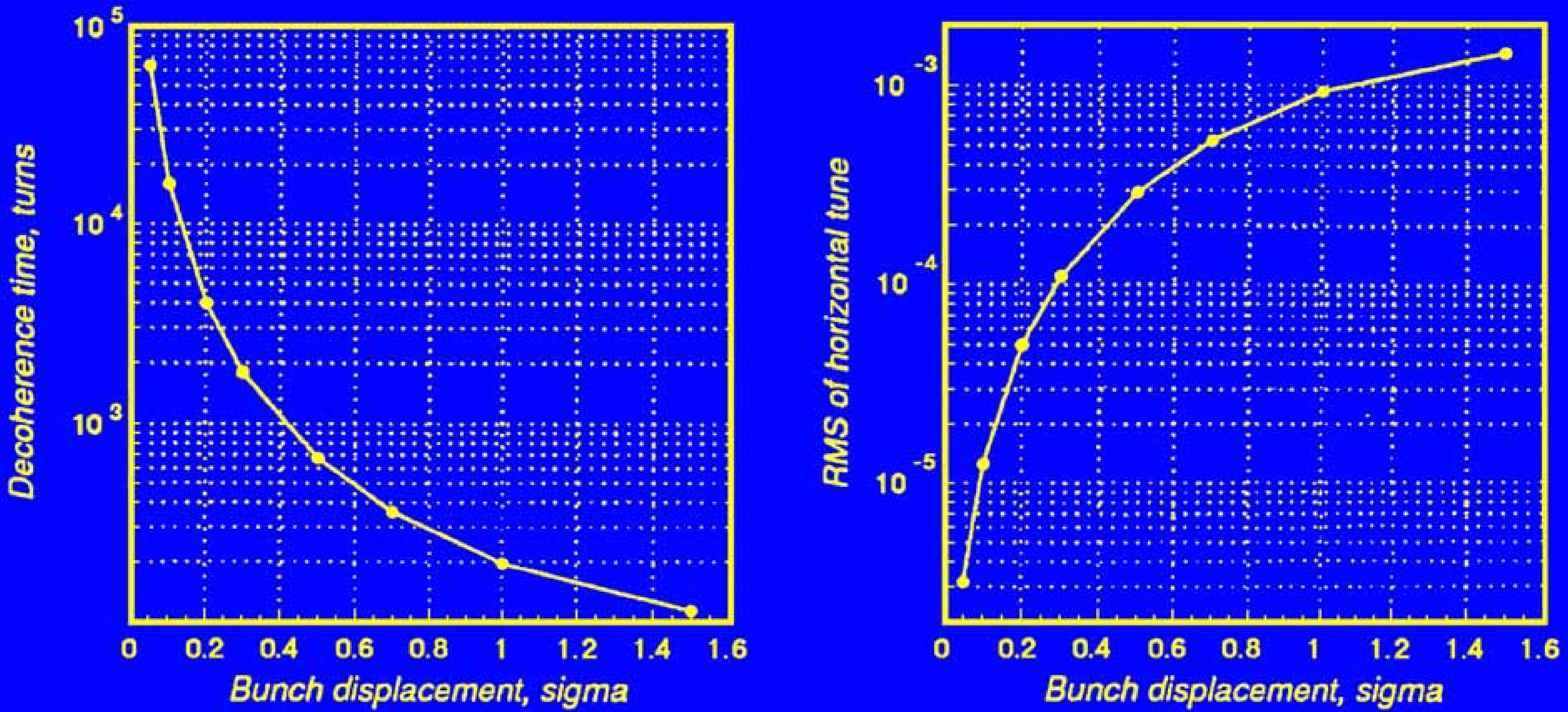
RMS of horizontal tune distribution of the beam particles *vs* the ratio of the electron to proton bunch σ (open circles). White circle presents the best result for a cylindrical electron beam.



Horizontal tune distribution of beam particles. Left) displacement of the compensating electron beam of 0.1 σ, right) displacement of the compensating electron beam of 0.5 σ.



Growth of the relative-to-centroid beam emittance after an initial beam displacement of 1 sigma. Left) cumulative charge of the compensating electron beam is 90% of the proton bunch charge, right) 50% of the proton bunch charge.



Decoherence time expressed in number of turns (left) and R.M.S. of the horizontal tune distribution of the beam particles (right) *vs* electron beam displacement.

ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

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, ТОМ 27, ВЫП.3

Phys. Part. Nuclei 27, 279 (1996)

УДК 539.1.076 + 621.384.6

INNOVATIONS IN ACCELERATOR TECHNOLOGY

E. Tsyganov, A. Taratin, A. Zinchenko*

Conclusions

- Computer simulations were done to study the decoherence of beam oscillations in the SSC and LHC colliders due to the tune spread generated by the head-on beam-beam interactions.

- Beam-beam tune spread might be reduced by collisions of the proton bunch with a space charge of a low energy electron beam. The low energy electron beam could be kept stable during collisions using a solenoidal magnetic field.

- It was shown for the LHC that for reasonable tolerances of the low energy beam parameters quite good head-on beam-beam effect compensation could be obtained and beam-beam tune spread could be reduced by a factor up to about 100.

Werner Herr, Trieste, 2005:

- Head on effects:
  - → Linear "electron lens" to shift tunes
  - → Non-linear "electron lens" to reduce spread
  - → Tests in progress at FNAL

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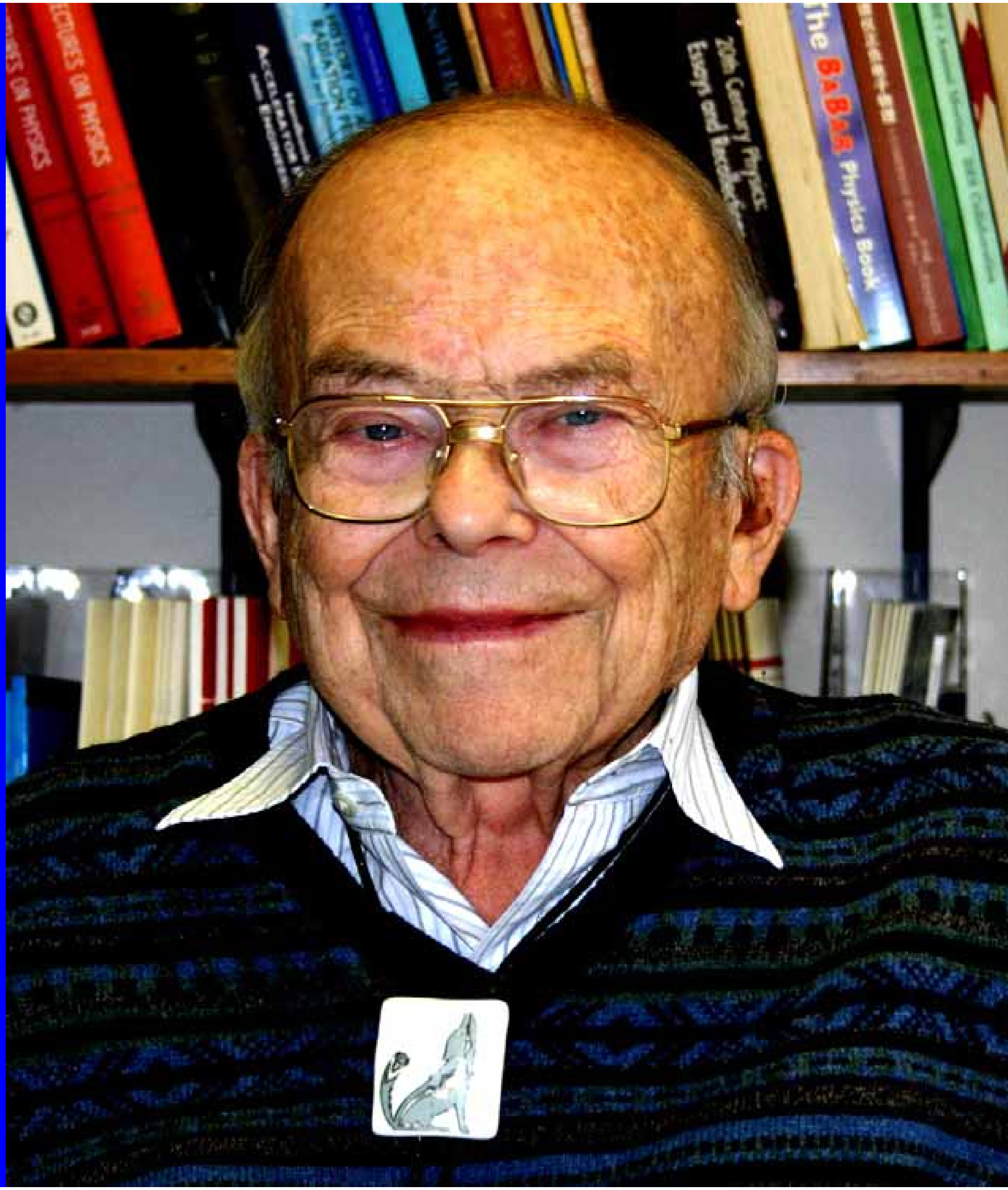
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