Experience with beam-beam effects in LEP

W. Herr, CERN

- **Is LEP experience relevant for LHC beam-beam effects ?**
- **What did we learn from LEP experience for the LHC ?**

LEP versus LHC beam-beam

- One ring for both beams
- Beam-beam parameter 20 times larger: 0.0034 $\rightarrow$ 0.0750
- Strong damping in LEP
- But: LEP had
  - Parasitic encounters
  - Orbit effects
  - Bunch trains
  - PACMAN effects
  - Strong-strong effects
  - Coherent effects
  - Crossing angle
- Good test for the concepts (qualitatively)

LEP parameters at 94.5 GeV

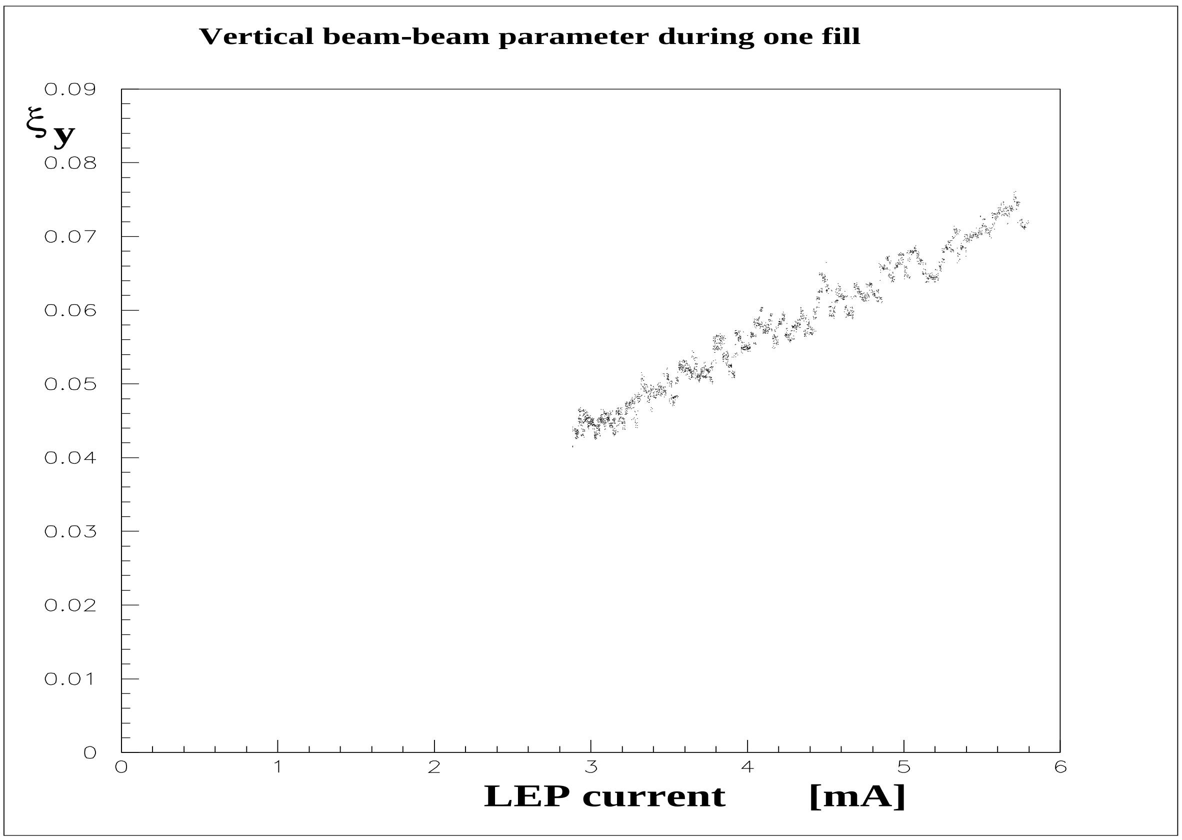
Energy	**94.5 GeV**
ϵ_x $(= \ \sigma^2/\beta)$	$\approx$ **25 nm**
ϵ_y	$\approx$ **0.3 nm**
β^*_x, β^*_y	**1.25 m, 0.04 m**
σ^*_x	$\approx$ **180** μ**m**
σ^*_y	$\approx$ **3.5** μ**m**
Intensity	$\approx$ **4.0**$\cdot 10^{11}$**/bunch**
Damping times	$\approx$ **6.0 ms**
Q_s	$\leq$ **0.15**
ξ_x	$\approx$ **0.05**
ξ_y	$\approx$ **0.07**
ΔQ^{bb}_x	$\approx$ **0.04**
ΔQ^{bb}_y	$\approx$ **0.05**

Consequences

- Resonances are strongly damped
- Synchrobetatron resonances difficult to avoid
- Much larger tune shift:
  - Strong distortion of optics
  - Gap between coherent modes
- Damping much faster at high E:
  - Larger ξ possible for higher energies
  - Beam-beam limited ar 45.6 GeV

"Typical" LEP fill

(94.5 GeV), 4 on 4 bunches



- **No sign of saturation of ξ_y**
- **Not beam-beam limited in classical sense**

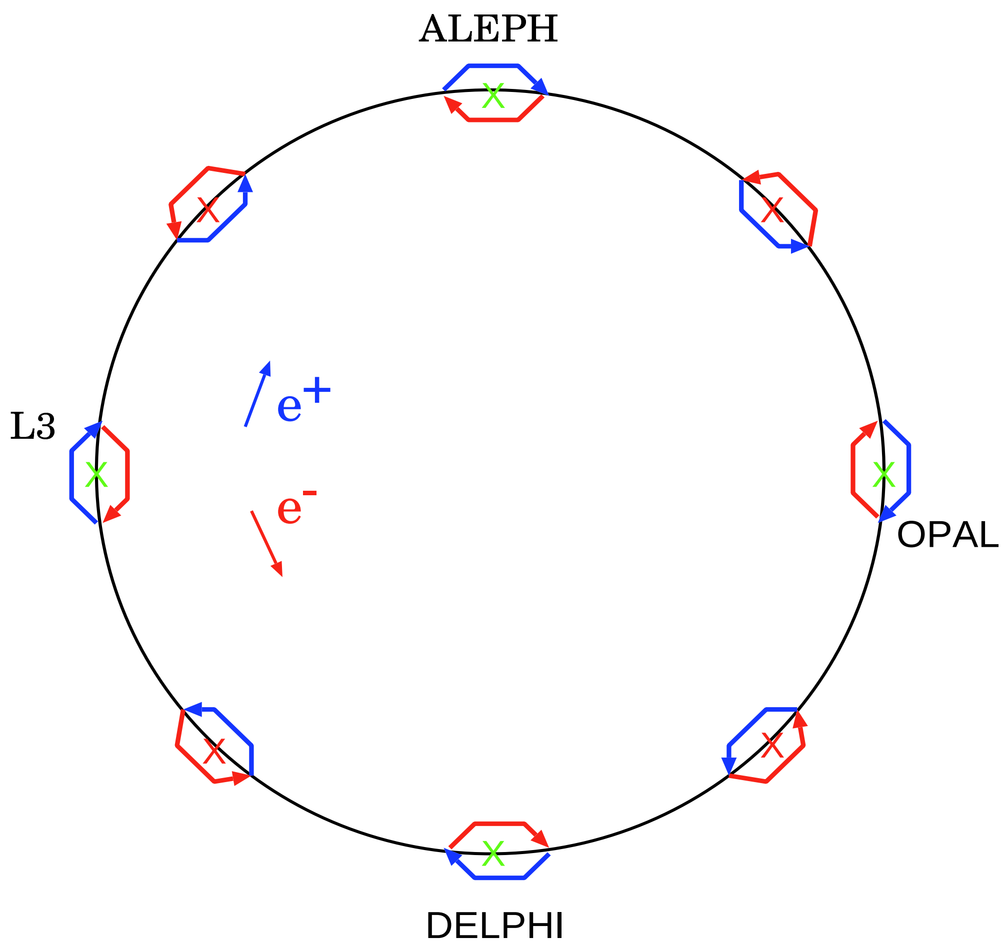
LEP modes of operations

LEP is operated with four experiments, separation needed at injection and unwanted crossings for more than 2 bunches per beam

1989 - 1999:

- **4 bunches with local vertical separation**
- **8 bunches with local vertical separation and horizontal pretzel**
- **4 to 16 bunches with bunch trains and local vertical separation**

"4 bunch" operation



- **Vertical separation in all IPs**
- **Separation remains in odd IPs**

”4 bunch” operation

- **At injection parasitic encounters in all IPs**
- **In collision only in unused (odd) points**
- **Head-on collisions in experimental (even) points**

Typical separation:
max. 2/14 mm in even/odd IPs
(order of $25\sigma_x$, depending on optics)

$$\sum \mid \xi_x \mid \approx 0.0100$$

$$\sum \mid \xi_y \mid \approx 0.0025$$

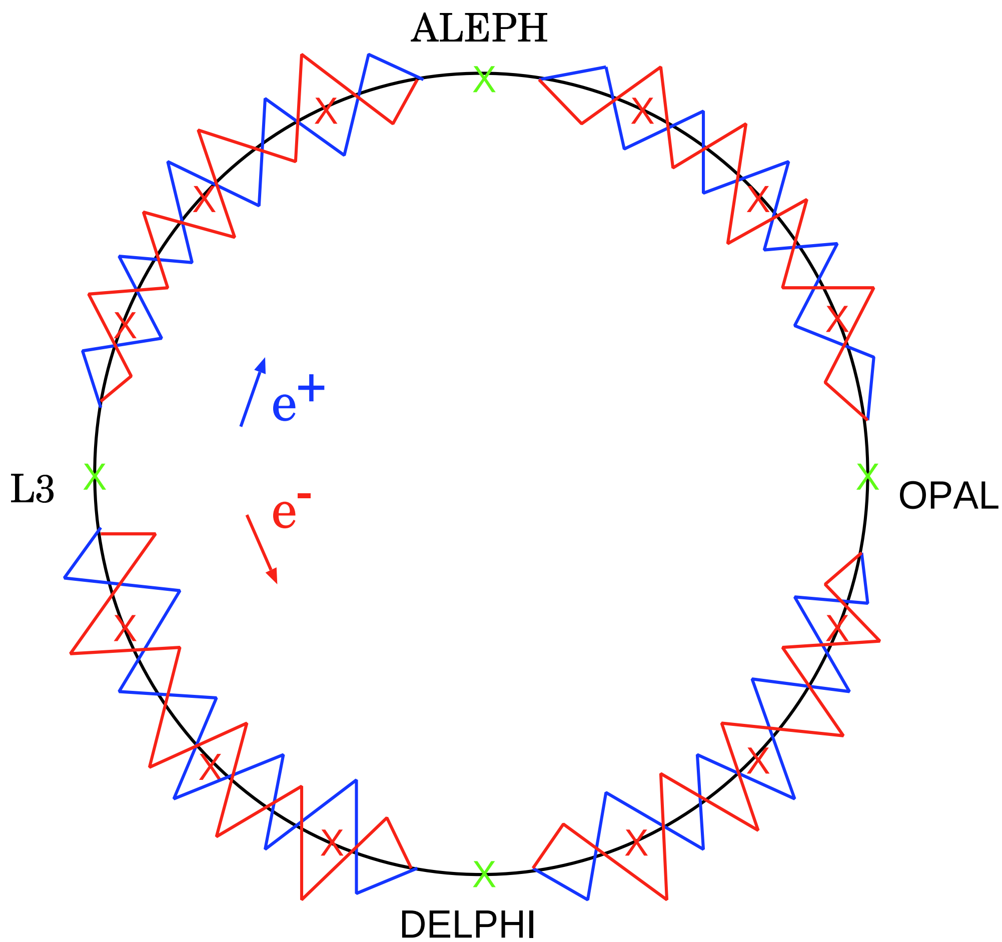
- **Only empirical criteria for necessary separation**

"4 bunch" operation

observations:

- **Maximum $\xi_y \approx$ 0.025 for $\mathbf{I}_b \leq$ 250μA (45.6 GeV)**
- **Maximum $\xi_y \approx$ 0.070 for $\mathbf{I}_b \leq$ 750μA (94.5 GeV)**
- **Orbit effects from parasitic collisions clearly observed**
- **Change of integer part of tune required polarity change of separation**
- **Orbit effects now used to ensure head-on collisions**

"pretzel" operation



- 8 bunches, equally distributed
- Horizontal pretzel in the arcs
- Separation remains in odd IPs

”pretzel” operation

- **At injection vertical parasitic encounters in all IPs and horizontal in the arcs**
- **In collision in odd points and all arcs**

Typical pretzel separation:
max. 20 mm
(order of 12σ_x, depending on conditions)

$$\sum \mid \xi_x \mid \approx 0.0200$$

$$\sum \mid \xi_y \mid \approx 0.0040$$

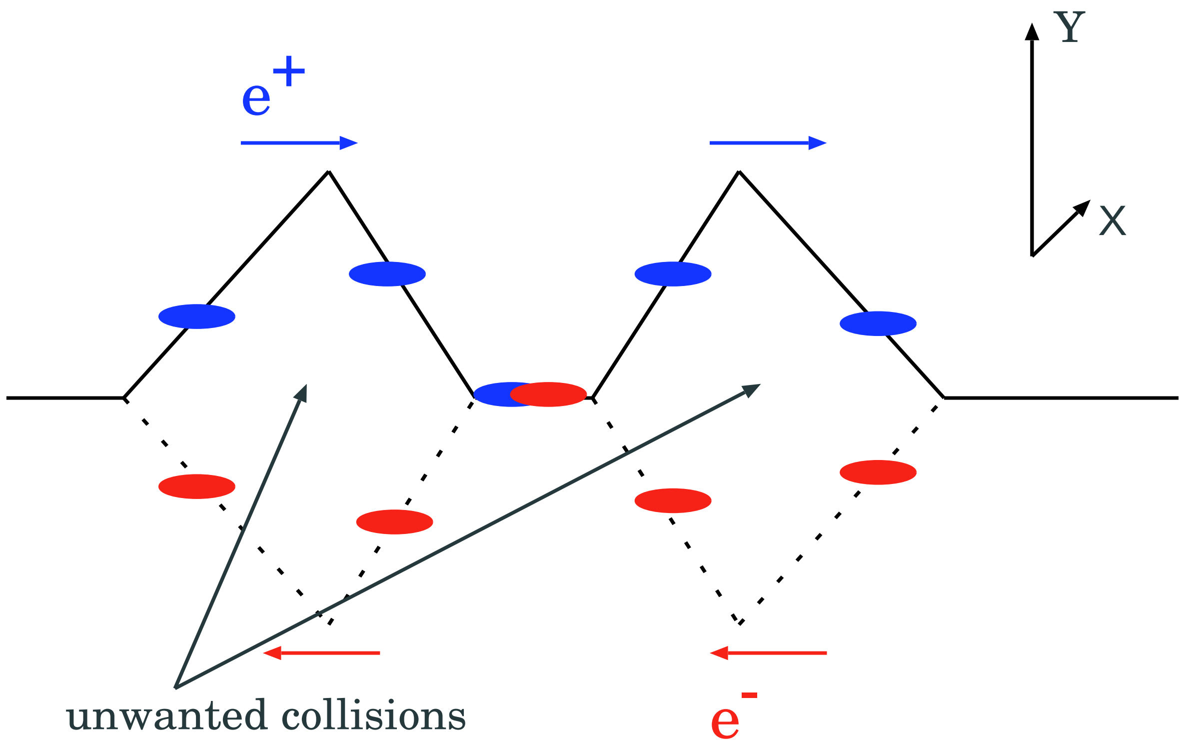
- **Only empirical criteria for necessary separation**

"pretzel" operation

observations:

- Maximum $\xi_y \approx$ 0.040 for $I_b \leq 350\mu A$
- Enhancement of head-tail instability due to beam-beam observed
- Enhancement stronger at mid-arc crossings with finite dispersion
- Parameter splitting between two beams observed (large horizontal orbit difference, partially compensated)

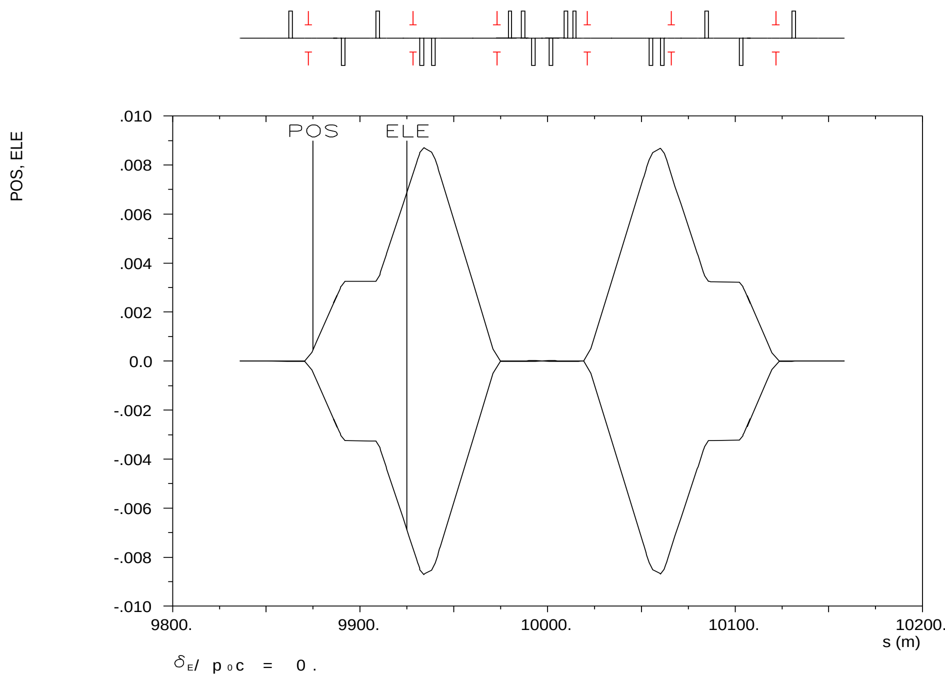
"bunch train" operation



Similar to 4 bunch operation, but:

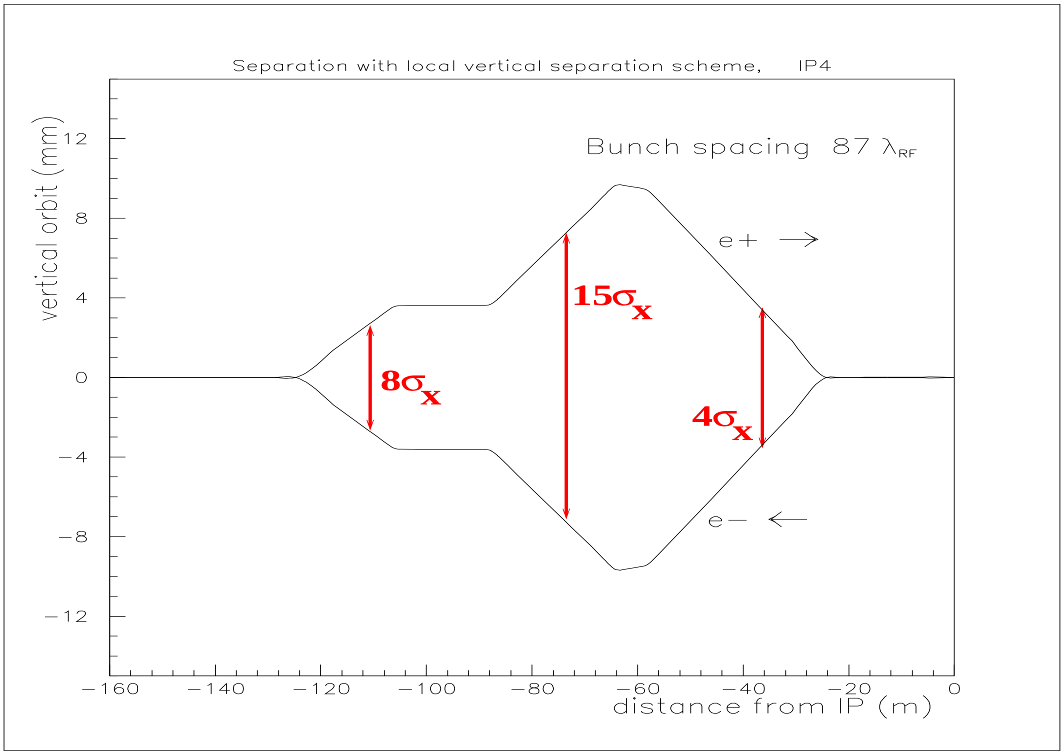
- **Replace single bunch by train**
- **Extended vertical separation**
- **Separation orbits around all IPs**

e+ and e− orbits at IP



- Constraints allow 4 bunches per train, i.e. 16 bunches per beam
- No separation necessary outside interaction area
- "Head-on" collisions
- Alternating sign of separation for compensation

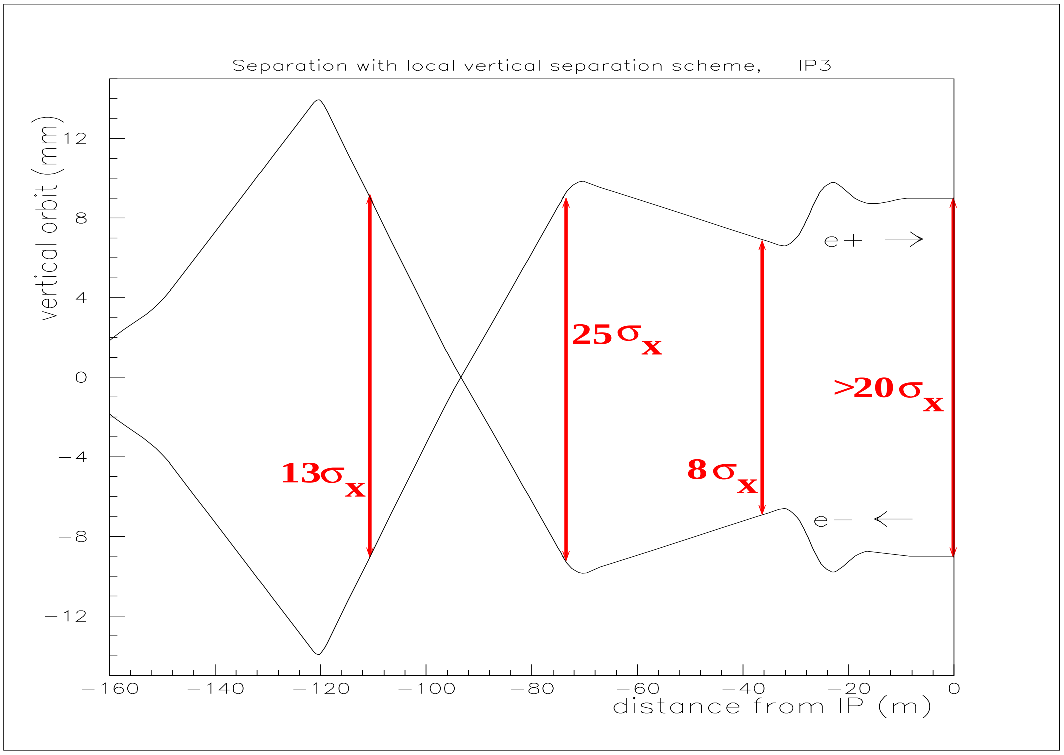
Separation and parasitic tune shifts
(experimental regions)



	3	2	1
$\mathbf{d}/\sigma_x$	$\approx$ **8**	$\approx$ **15**	$\approx$ **4**
ξ_x (10^{-3})	$\approx$ **0.8**	$\approx$ **0.2**	$\approx$ **3.6**
ξ_y (10^{-3})	$\approx$ **-4.8**	$\approx$ **-0.7**	$\approx$ **-0.3**

(ϵ_x = **30 nm**, $\mathbf{I}_b$ = **500** μ**A**)

Separation and parasitic tune shifts
(non experimental regions)



	3	2	1	0
d/σ_x	$\approx$ **13**	$\approx$ **25**	$\approx$ **8**	$\geq$ **20**
ξ_x **(10^{-3})**	$\approx$ **0.3**	$\leq$ **0.1**	$\approx$ **0.7**	$\approx$ **0.1**
ξ_y **(10^{-3})**	$\approx$ **-0.2**	$\approx$ **-0.5**	$\approx$ **-0.2**	$\approx$ **-0.1**

(ϵ_x = 30 nm, I_b = 500 μA)

Interaction schedule

Bunch trains have finite lengths (or huge gaps !)

- **Each bunch in a train has different sequence of encounters**
- **Different beam-beam effects**
- **Different ΔQ, orbit, dispersion, chromaticity, etc.**
- **Some bunches experience very large effects (encounters at small separation)**
- **"PACMAN" like structure - several classes of bunches (at least 4!)**

Parameter calculation

Beam-beam kicks change closed orbit, hence the separation !

- **$\rightarrow$ self-consistent orbits are calculated**
- **Other parameters are calculated when orbits are found**
- **Was done for 4 trains of 4 bunches in each beam**

For LHC: self-consistent treatment of 2835 bunches per beam ?

- **Is it necessary ?**
- **Is it possible ?**

Orbit separation

Individual orbits cause bunch separation at collision point. Also small crossing angles unavoidable.

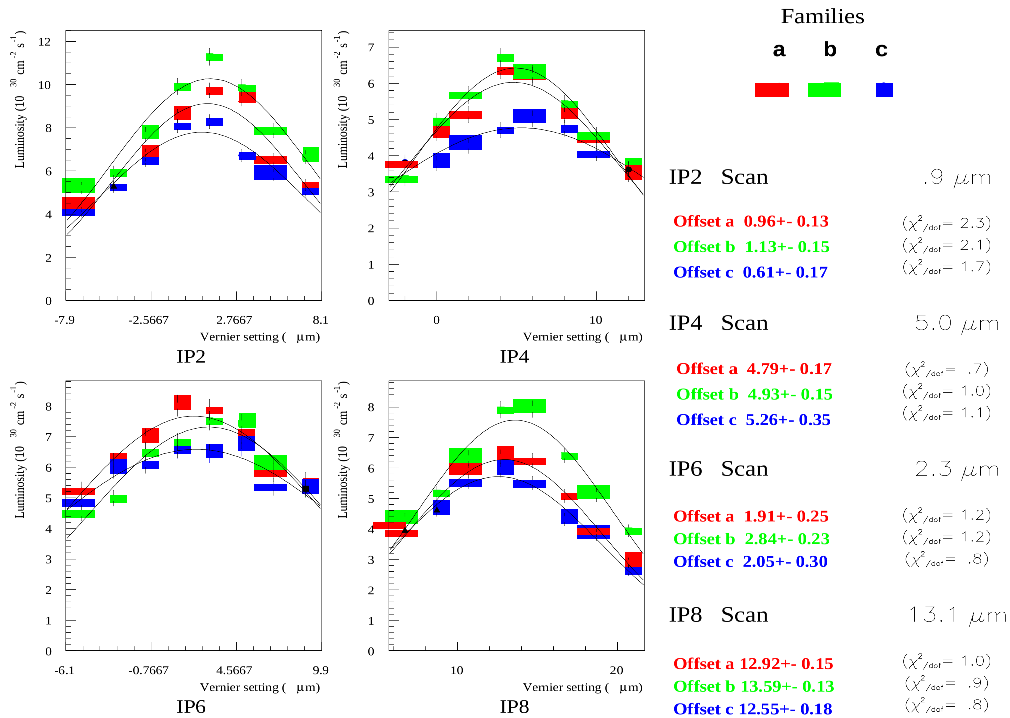
Orbit offsets and separation (at central collision point):

	a	b	c	d
e^+ [μm]	+5.75	+1.10	-1.65	-0.30
e^- [μm]	+0.30	+1.65	-1.10	-5.75
d [μm]	+5.45	-0.55	-0.55	+5.75

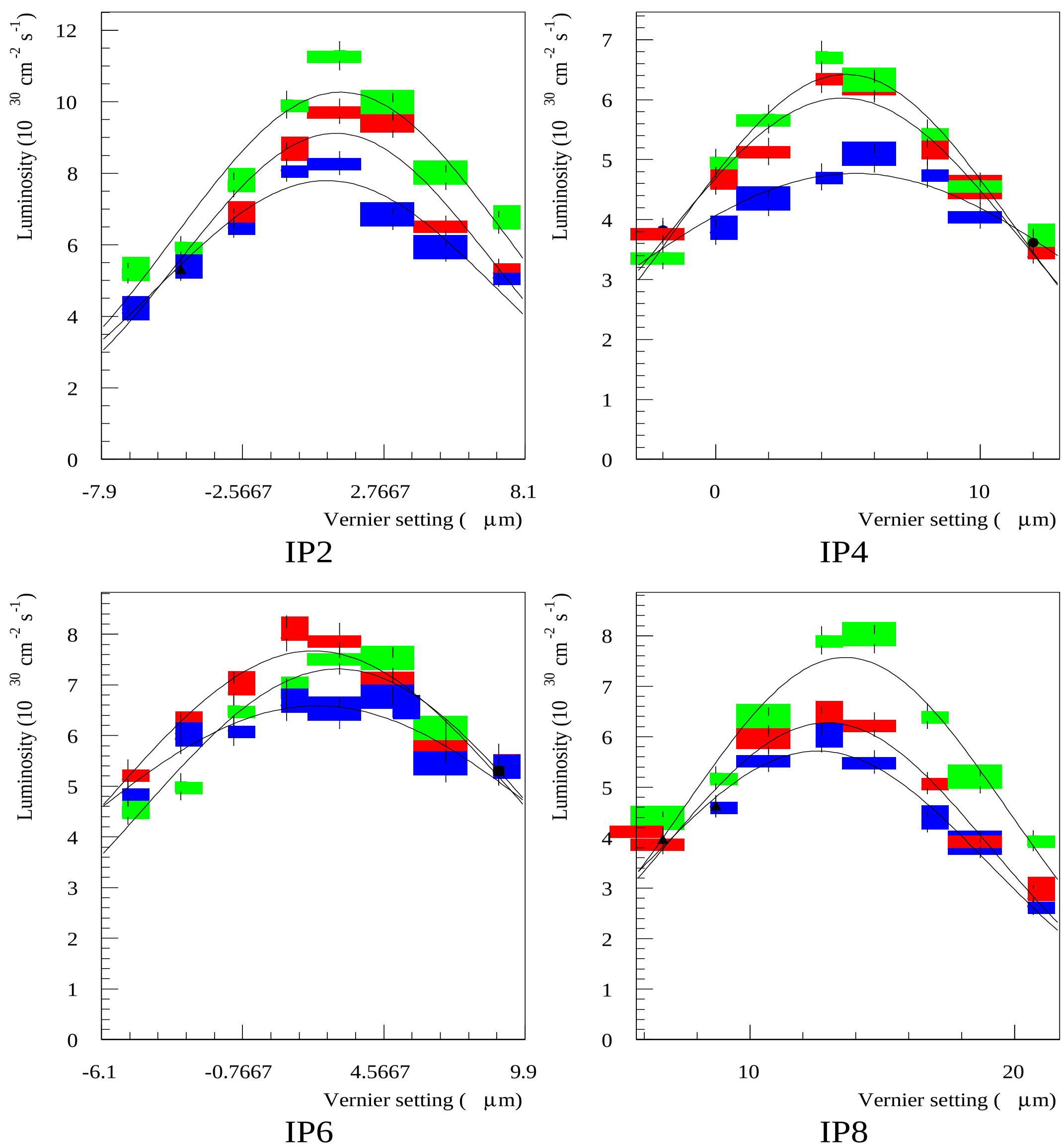
Example at one interaction point for 500 μA per bunch at 45.6 GeV, other interaction points similar.

Difference between highest and lowest bunch more than vertical σ !

Orbit separation



Offsets of individual bunches measured with deflection scan. For 3 bunches per train.



Families

a **b** **c**

IP2 Scan .9 μm

Offset a 0.96+- 0.13 ($\chi^2_{/dof}$= 2.3)
Offset b 1.13+- 0.15 ($\chi^2_{/dof}$= 2.1)
Offset c 0.61+- 0.17 ($\chi^2_{/dof}$= 1.7)

IP4 Scan 5.0 μm

Offset a 4.79+- 0.17 ($\chi^2_{/dof}$= .7)
Offset b 4.93+- 0.15 ($\chi^2_{/dof}$= 1.0)
Offset c 5.26+- 0.35 ($\chi^2_{/dof}$= 1.1)

IP6 Scan 2.3 μm

Offset a 1.91+- 0.25 ($\chi^2_{/dof}$= 1.2)
Offset b 2.84+- 0.23 ($\chi^2_{/dof}$= 1.2)
Offset c 2.05+- 0.30 ($\chi^2_{/dof}$= .8)

IP8 Scan 13.1 μm

Offset a 12.92+- 0.15 ($\chi^2_{/dof}$= 1.0)
Offset b 13.59+- 0.13 ($\chi^2_{/dof}$= .9)
Offset c 12.55+- 0.18 ($\chi^2_{/dof}$= .8)

Tune and chromaticity

Fractional tunes and chromaticities are split inside a train:

	a	b	c	d
q_x	0.3548	0.3612	0.3613	0.3547
q_y	0.2127	0.2235	0.2234	0.2133
Q_x'	0.4526	0.5000	0.5025	0.4848
Q_y'	0.1872	-0.2218	-0.2259	0.0053

Example for 300 μA per bunch at 45.6 GeV. Bunches from other beam antisymmetric.

Maximum tune difference is 0.011 and chromaticity difference 0.41 units in vertical plane.

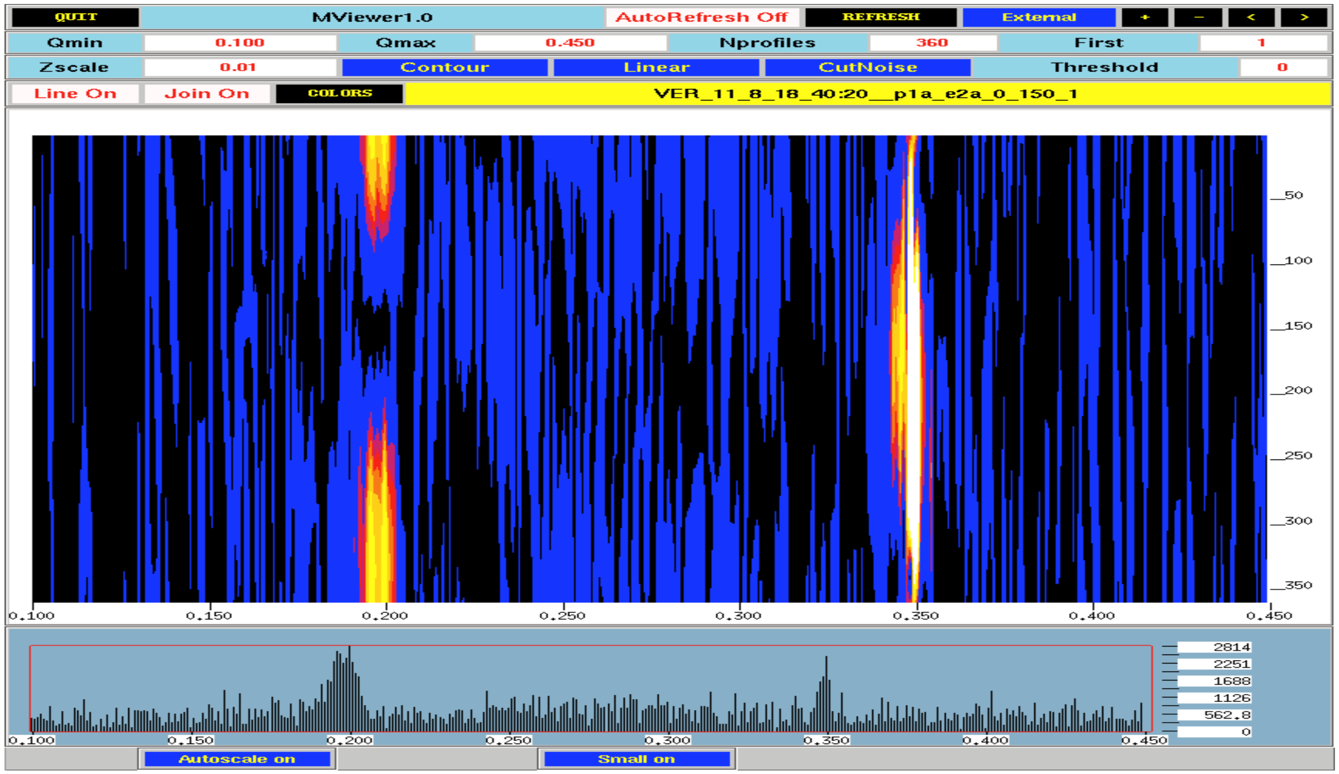
Observations I

- Necessary to optimize bunch overlap
- Overlap however never complete (for more than 2 bunches)
- Difficult to optimize parameters because space largely reduced due to spread
- Always one bunch with bad life time
- Mostly due to outmost parasitic encounter
- Vertical beam-beam parameters ξ_y lower than before
- Running with 3 bunches per train much easier

Observations II

- **Running 2 bunches per train restored previous $\xi_y \rightarrow$ head-on collisions**
- **Problems largely due to offset collision**
- **Self-consistent treatment helped to understand the problems**
- **Compensation effects (separation polarity) essential**
- **Additional effects (non-closure) cause splits between beams**

Coherent modes



(Courtesy G. Morpurgo)

The (vertical) σ and π modes clearly visible

Coherent modes

- **Coherent beam-beam modes observed in both planes**
- **Gap between σ and π mode rather large $\rightarrow$ reduced tune space**
- **Usually suppressed with finite chromaticity**
- **Horizontal π-mode may be responsible for background problems (tune !)**

SUMMARY

- **Orbit effects do cause problems**
- **PACMAN like effects limit the performance**
- **Parameter splits must be kept as small as possible (between beams or inside a beam)**
- **Only empirical rules for necessary separation used**
- **Compensation effects essential**