Beam-Beam Limit at LEP1 and LEP2

– Impact from Number of IP's –

Ralph W. Aßmann
Leading Scientist
DESY Accelerator Division

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References

Proceedings of EPAC 2000, Vienna, Austria

THE BEAM-BEAM INTERACTION IN THE PRESENCE OF STRONG RADIATION DAMPING

R. Assmann and K. Cornelis, CERN, Geneva, Switzerland

Nucl.Phys.Proc.Suppl. 109B (2002) 17-31.

A Brief History of the LEP Collider

Ralph Assmann, Mike Lamont, Steve Myers for the LEP team

Vertical beam-beam parameter

The vertical beam-beam parameter ξ_y is calculated from the measured luminosity L, the beta function β_y^* at the IP, the beam energy E, and the bunch current i:

$$\xi_y = \frac{2 r_e e m_e c^2 \cdot \beta_y^*}{n_b \cdot i \cdot E} \cdot L \qquad (1)$$

The term n_b denotes the number of bunches, r_e, e and m_e are the classical radius, charge and mass of the electron, and c is the light velocity. The ξ_y is related to the vertical beam-beam tune shift ΔQ_y [6,7]. With a typical value for the vertical tune in LEP ($Q_y \sim 0.18$) the tune shift is up to 10% smaller than the measured ξ_y.

Geometric Parameters LEP

Table 1
Geometric parameters of LEP.

Parameter	Symbol	Value
Effective bending radius	ρ	3026.42 m
Revolution frequency	f_{rev}	11245.5 Hz
Length of circumference, $L = c/f_{\mathrm{rev}}$	L	26658.9 m
Geometric radius $(L/2\pi)$	R	4242.9 m
Radio frequency harmonic number	h	31320
Radio frequency of the RF-system, $f_{\mathrm{RF}} = h\, f_{\mathrm{rev}}$	f_{RF}	352 209 188 Hz

LEP Performance

Table 2
Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_b I_b$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

LEP: Design and Reality

Table 3
LEP: design and reality.

Parameter	Design (55/95 GeV)	Achieved (46/98 GeV)
Bunch Current	0.75 mA	1.00 mA
Total Beam Current	6.0 mA	8.4 mA/6.2 mA
Vertical Beam-beam parameter	0.03	0.045/0.083
Emittance ratio	4.0%	0.4%
Maximum Luminosity	$16/27\ 10^{30} cm^{-2} s^{-1}$	$34/100\ 10^{30} cm^{-2} s^{-1}$
Horizontal beta function at IP	1.75 m.	1.25 m.
Vertical beta function at IP	7.0 cm.	4.0 cm.

- Factor 2.8 higher in vertical beam-beam parameter than in design
  - Factor 10 better in emittance ratio: much smaller vertical emittance than assumed could be achieved
  - The higher the beam energy the smaller vertical emittance could be obtained in LEP

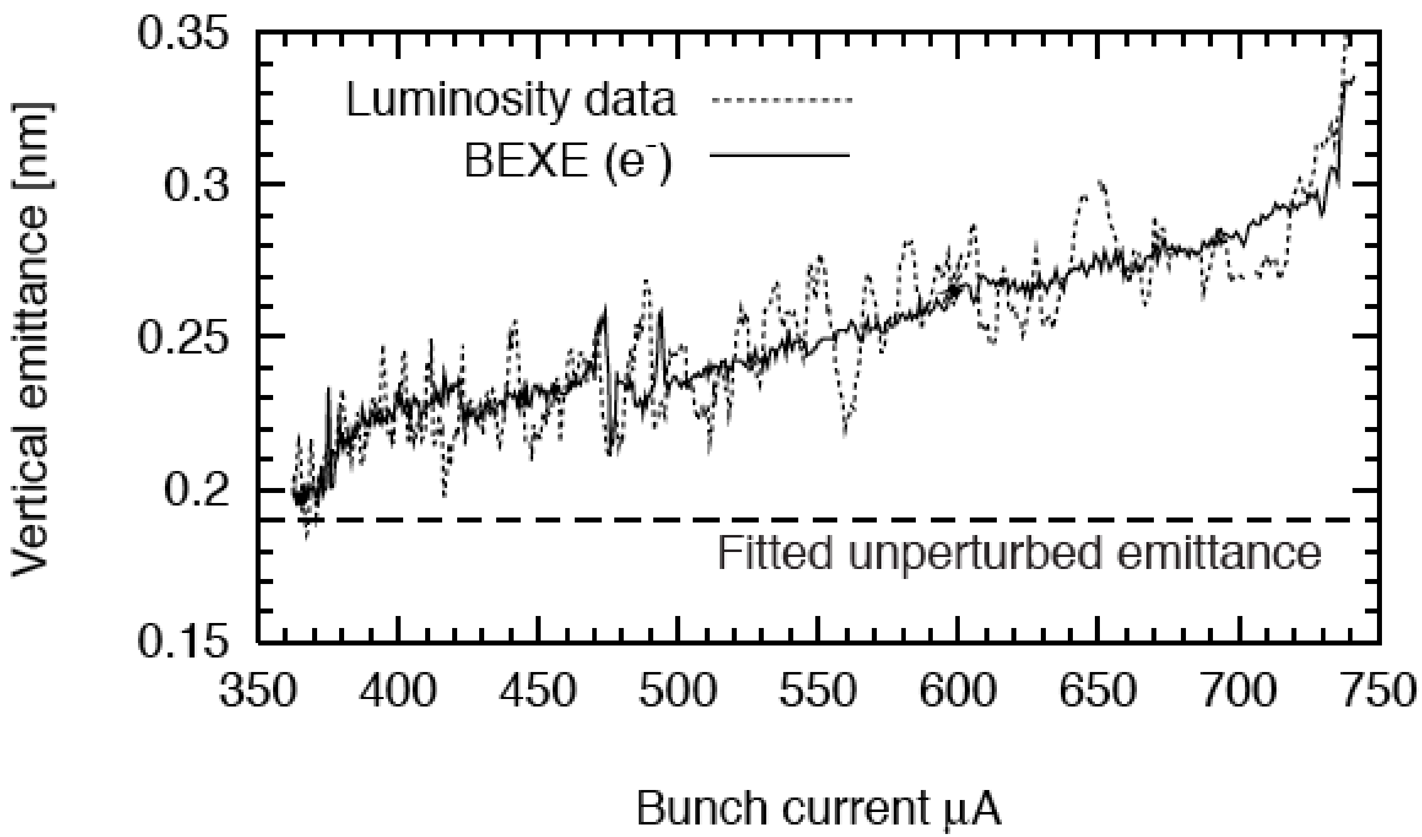
Beam-beam Achievements

Table 5
Maximum vertical beam-beam parameter ξ_y, IP beta functions β_x^*/β_y^*, bunch current i_b, horizontal damping partition number J_x, and transverse damping time τ_{transv} (in number of turns) for different beam energies.

Energy [GeV]	ξ_y per IP	β_x^*/β_y^* [m]	i_b [μA]	J_x	τ_{transv} [T_0]
45.6	0.045	2.00/0.05	320	1.0	721
65.0	0.050	2.00/0.05	400	1.0	249
91.5	0.055	1.50/0.05	650	1.6	89
94.5	0.075	1.25/0.05	750	1.8	81
98.0	0.083	1.50/0.05	800	1.6	73
101.0	0.073	1.50/0.05	700	1.3	66
102.7	0.055	1.50/0.05	650	1.1	63

- Note that the vertical beam-beam parameter is calculated from the luminosity per IP.
- Therefore the achieved beam-beam parameter in LEP is per IP!
- LEP took data with simultaneous interactions in 4 IP's!

Emittance Blow-Up in LEP2 During a Fill



- Clear current dependent emittance blow-up in LEP
- Both calculated from luminosity and measured (BEXE)
- From beam-beam…

Functional Dependence of Beam-Beam Parameter on i_b

$$\xi_y = \sqrt{\frac{1}{A + (B \cdot i_b)^2}} \cdot i_b \, . \tag{4}$$

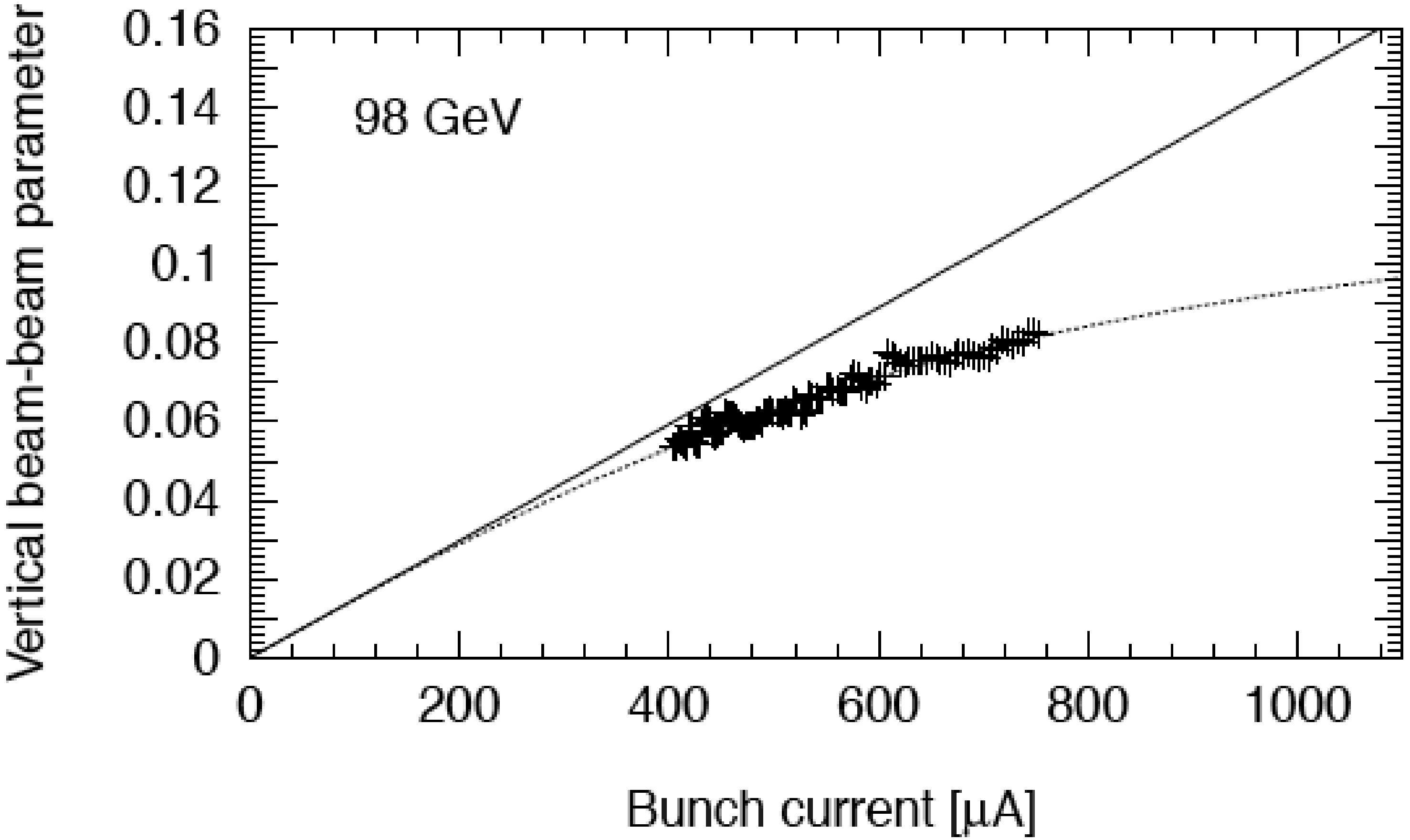
Here, i_b denotes the bunch current. The parameter A is given by the known machine parameters and the zero current emittances ϵ_x^0 and ϵ_y^0:

$$A = \left(\frac{2\pi e f_{rev} \gamma}{r_e} \right)^2 \cdot \frac{\beta_x^*}{\beta_y^*} \cdot \epsilon_x^0 \cdot \epsilon_y^0 \, . \tag{5}$$

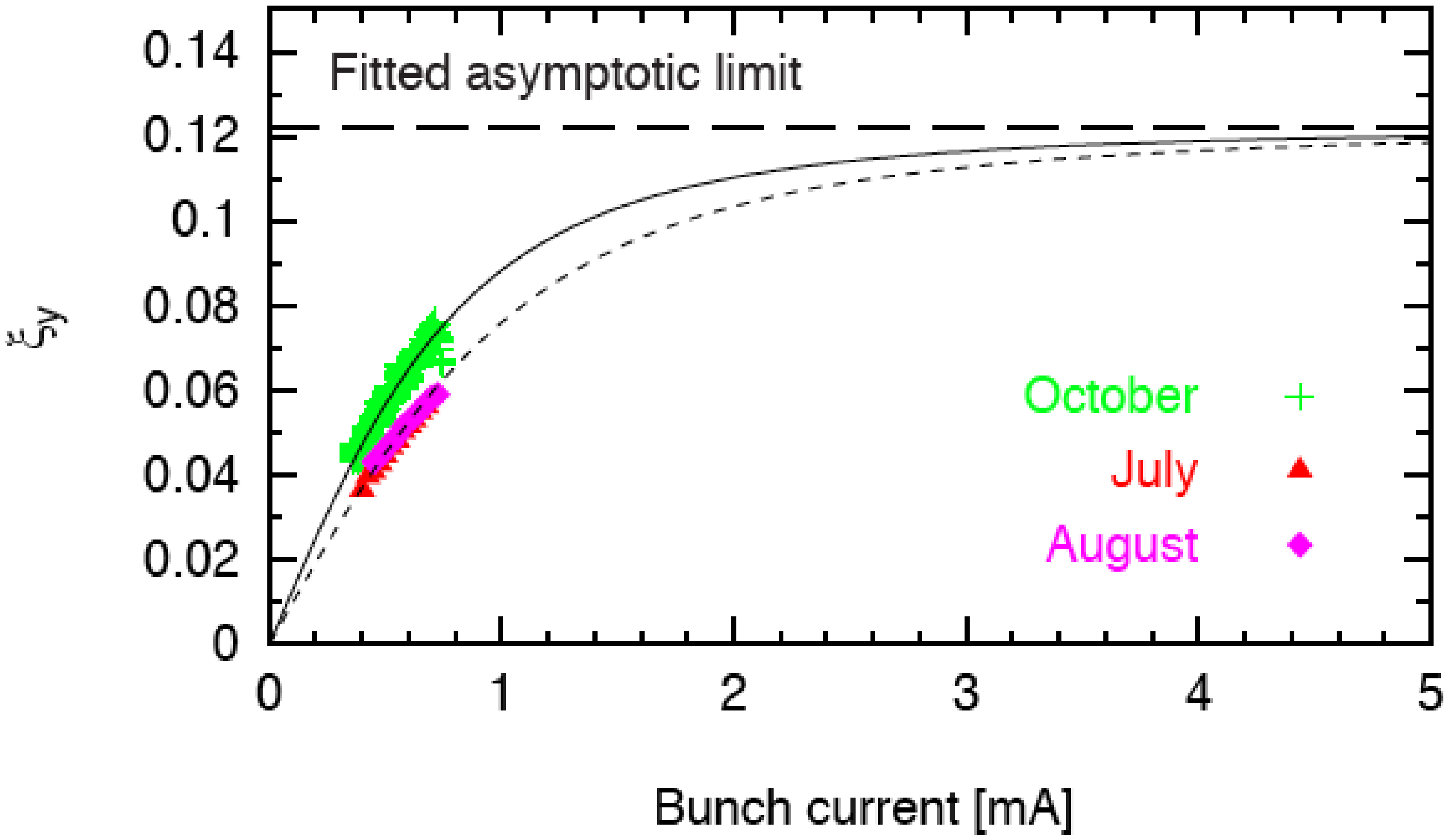
The parameter B is a measure of the asymptotic beam-beam limit ξ_y^∞:

$$B = \frac{1}{\xi_y^\infty} \, . \tag{6}$$

98 GeV – One Fill



94.5 GeV – Three different periods



Beam-beam Limit for LEP Luminosity

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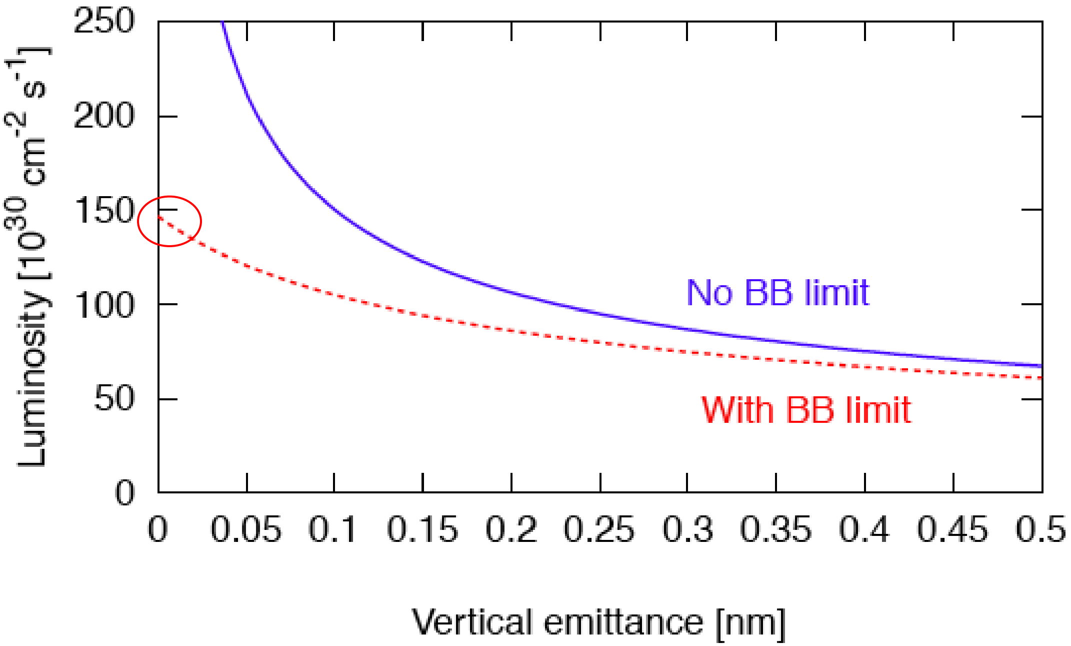

Figure 5: Predicted luminosity versus unperturbed vertical emittance (emittance at zero beam intensity). The calculation assumes a beam energy of 98 GeV and a bunch current of 750 μA. It is based on the fitted beam-beam limit of 0.115 for 98 GeV (Figure 4, top).

Beam-beam Limit Scaling Law from LEP Data

- Damping decrement:

$$\lambda_d = 1/(f_{rev} \cdot \tau \cdot n_{ip})$$

- Suggested by Peggs:

$$\xi_y^\infty \propto \lambda_d^{0.3}$$

- Found in LEP

$$\xi_y^\infty \propto (\lambda_d)^{0.4}$$

Impact from Number of IP's

- As published:

$$\xi_y^\infty \propto (\lambda_d)^{0.4}$$

Note that the LEP data was obtained with four interaction points ($n_{ip} = 4$), covering a wide range of different transverse damping times τ (63 to 721 turns).

Extrapolating with Number of IP`s

- For LEP damping times we would fitted the following asymptotic vertical beam-beam parameter per IP: **0.12**
- This was determined with 4 simultaneous IP's.
- The asymptotic vertical beam-beam parameter scales (due to our scaling law) as follows:

$$\propto 1/(f_{rev} \ \tau \ n_{IP})^{0.4}$$

- With 1 IP instead of 4 IP's: Gain factor 1.75 ➔ **0.21**
- Note: Asymptotic beam-beam limit only achievable with infinite bunch current...
  Not achievable: At LEP we reached about 70% of the asymptotic value!
  At some point other limits might be reached with beam-beam tune shift and strong resonances for example!

Conclusions

- The vertical LEP beam-beam parameter achieved high values much above design (up to 0.083) and was calculated (as published) per IP.
- A beam-beam induced emittance growth was observed: vertical emittance was limited by beam-beam blow-up.
- An asymptotic value of 0.12 was fitted at LEP2 beam energies (around 100 GeV) for infinite bunch current.
- A scaling of the asymptotic beam-beam parameter with the damping decrement was confirmed, with an exponent close to the prediction by S. Peggs.
- The fitted scaling law can be used to scale the LEP result to different energies and different numbers of IP's. For example, same energy but only one IP instead of four, as in LEP:

  Asymptotic vertical beam-beam parameter: **0.12 → 0.21**

- Please take into account notes on previous slide!