Beam-Beam Simulation for PEP-II

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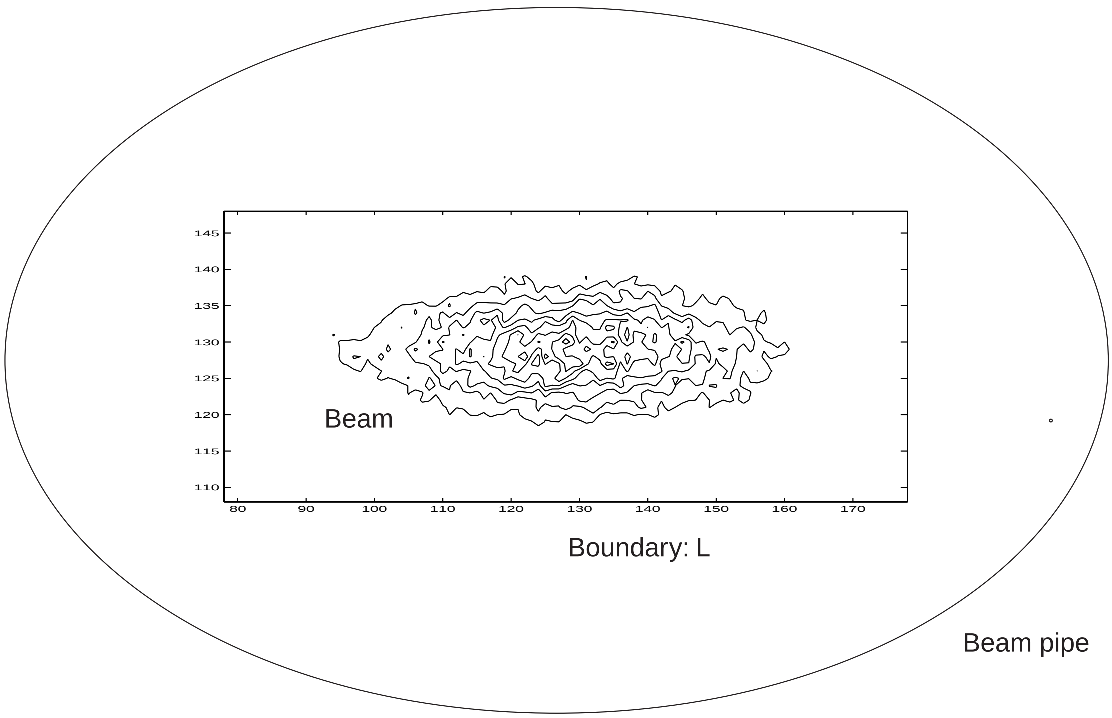
e^+e^- Factories 2003, SLAC

October 14, 2003

Outline

- Method of simulation:
  - Boundary condition
  - Parallel computing
  - Longitudinal slicing
- Present parameters:
  - Dynamical β and emittance
  - Luminosity
  - Spectrum
- Crossing angle.
  - Symplectic treatment
  - Benchmark
- Future prospect
  - Improvements
  - Upgrades
- Conclusion and outlook.

Solving Poisson's Equation with Reduced Region [a]



- Assign potential on the reduced boundary:

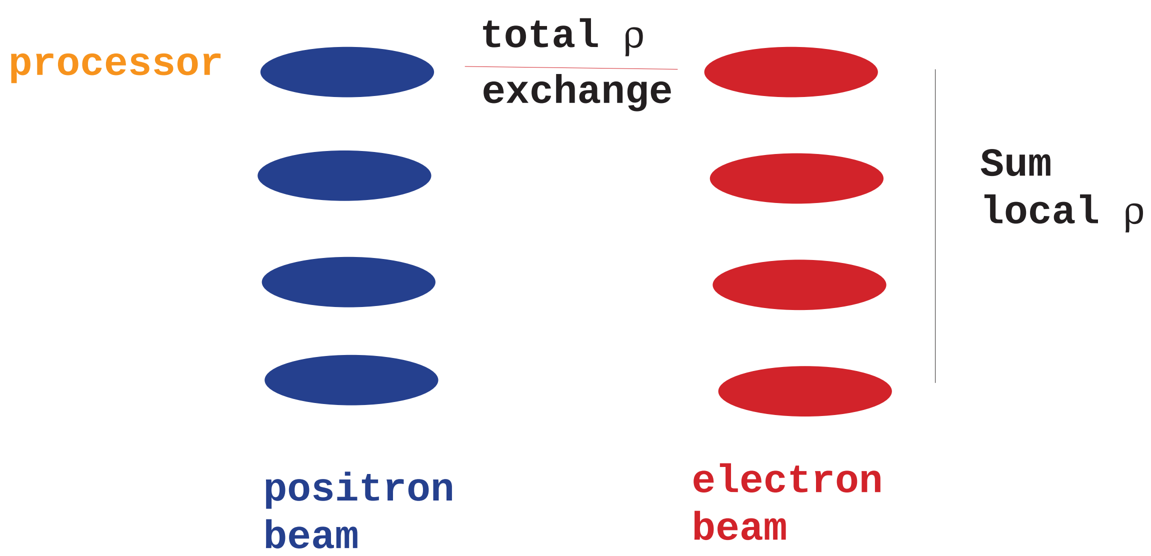
$$\Phi(x, y) = \int dx'dy'G(x - x', y - y')\rho_c(x', y')$$

for $(x, y) \in L$.

- Solve Poisson's equation with inhomogeneous boundary condition.

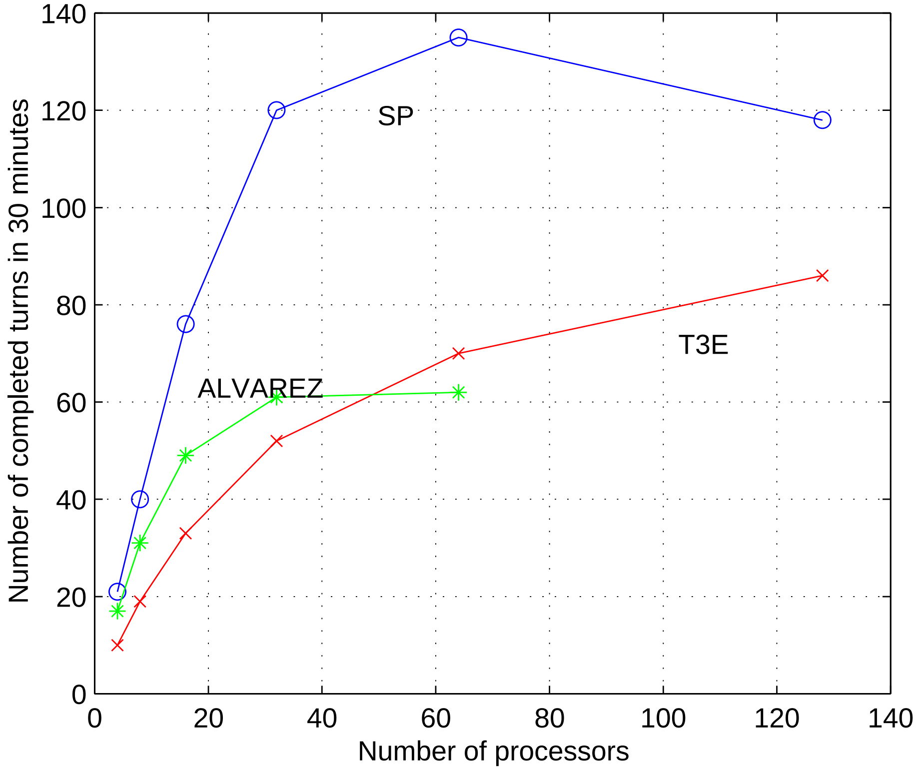
[a] Y. Cai, A. W. Chao, S. I. Tzenov, and T. Tajima, Phys. Rev. ST Accel. Beams **4** 011001 (2001).

Strategy of Parallel Computing



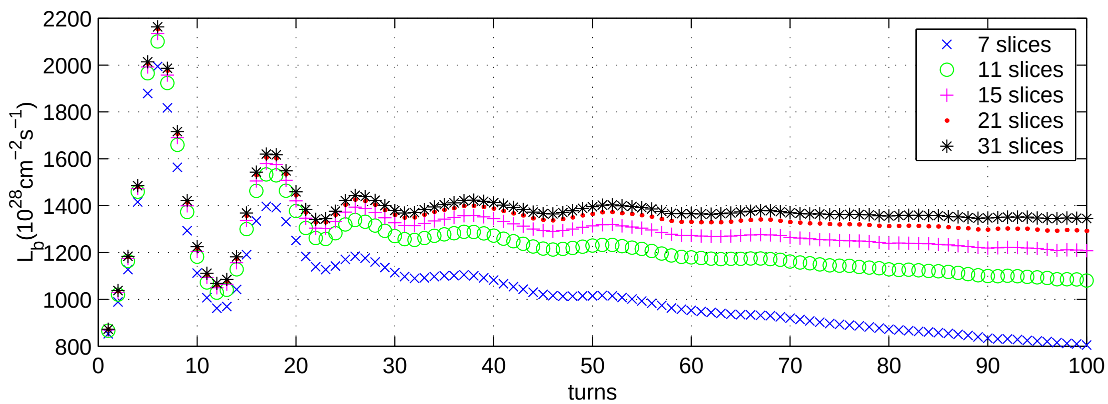
Macro particles are distributed on many processors. The processors are divided into two groups, one for positron beam and the other for electrons. The beam distribution on grid is summed within each group and then exchanged between the groups.

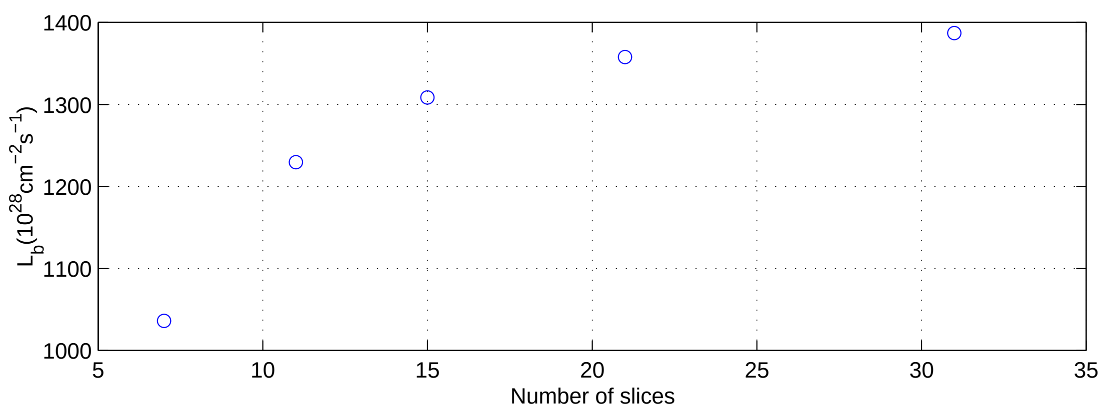
Scaling on Parallel Supercomputers



SP(IBM), T3E(CRAY), ALVAREZ(LINUX PC) are the super computers at NERSC. We gain a factor of 24 in speed with 32 processors on the SP.

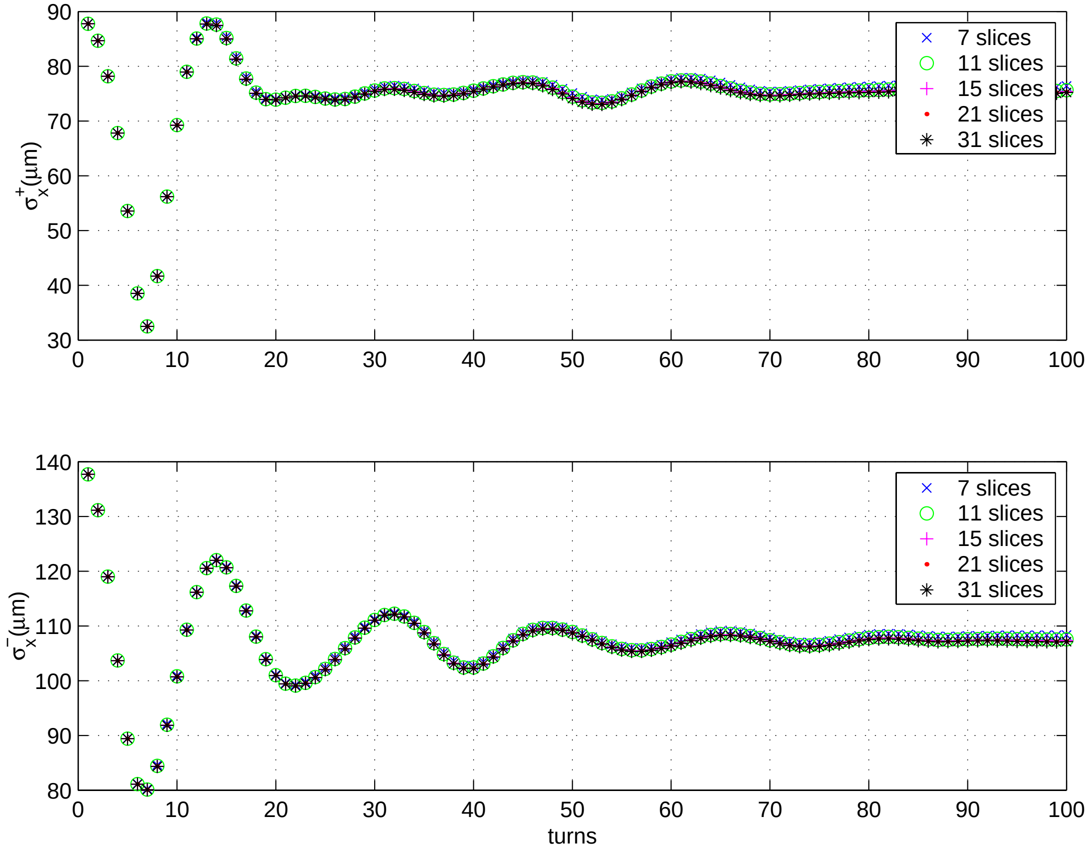
Luminosity Convergence with Equal-Spacing Slices at the Peak Beam Intensities



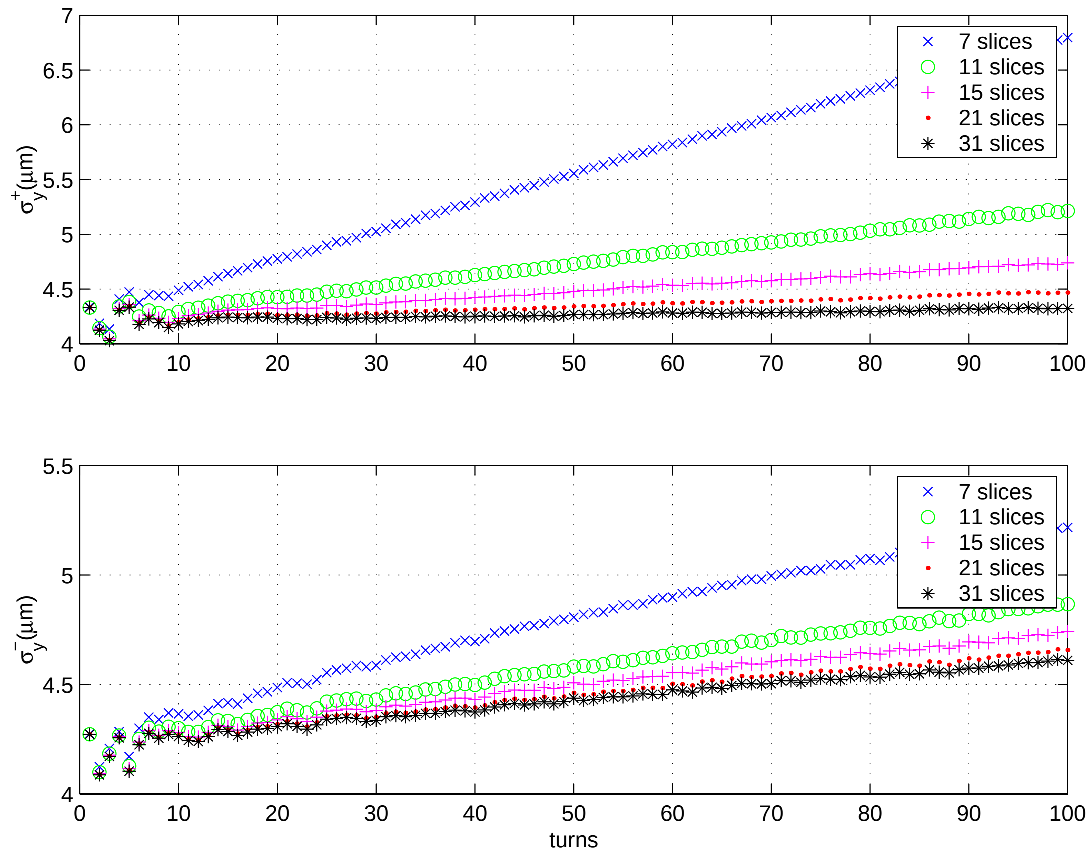


961(31×31) two-dimensional collisions are required for each three-dimensional collision. It takes a week to finish a simulation on 32 processors at NERSC. It is still not very well convergent.

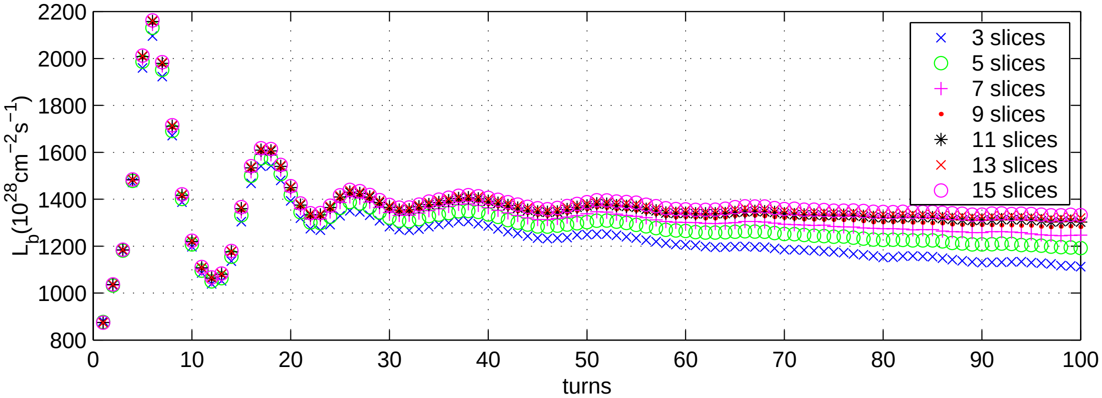
Horizontal Size Convergence with Equal-Spacing Slices

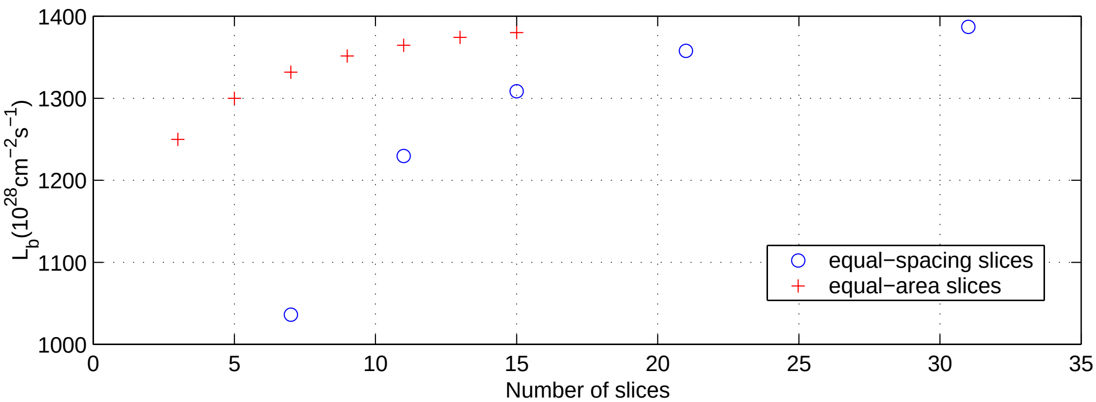


Vertical Size Convergence with Equal-Spacing Slices



Convergence with Equal-Area Slices[b] at the Peak Intensities

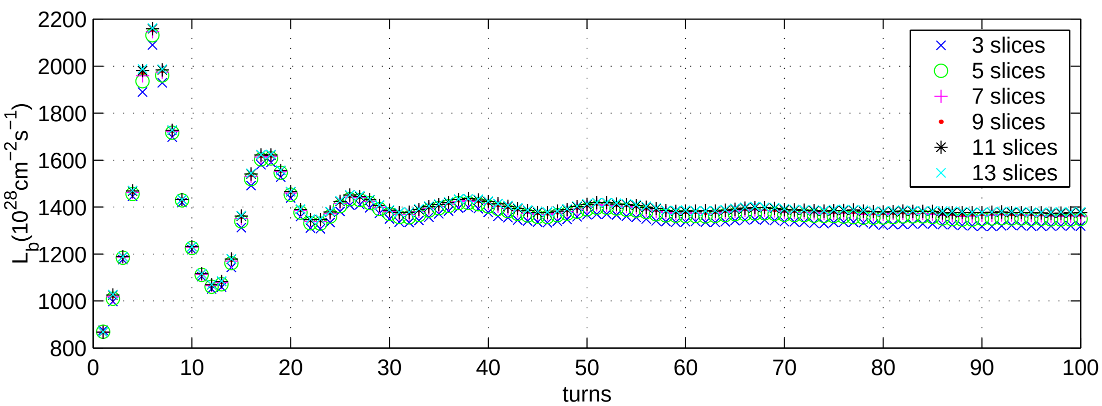


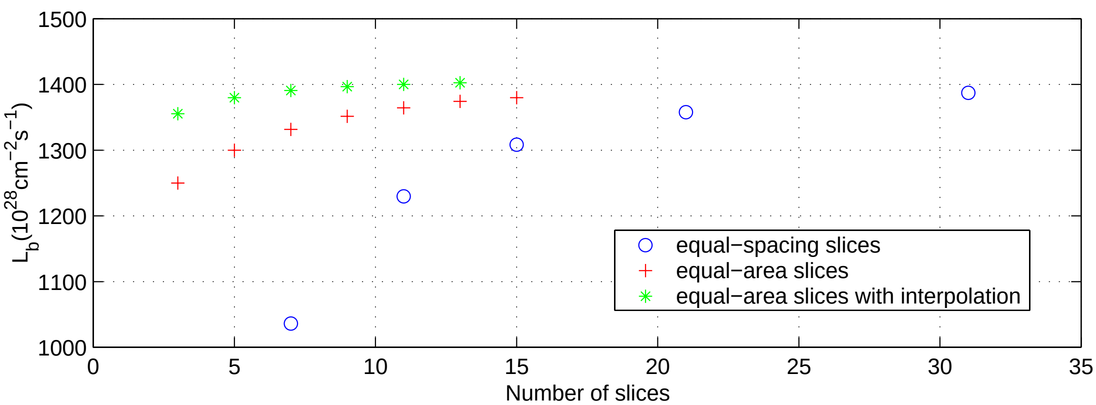


225(15 × 15) two-dimensional collisions are required for each three-dimensional collision. It takes two days to complete a run.

[b] K. Hirata, H. Moshammer, and F. Ruggiero, Particle Accelerator, **40** 205 (1993).

Convergence with Equal-Area Slices and Linear Interpolation between the Slices





25(5×5) two-dimensional collisions are required for each three-dimensional collision. It takes eight hours to complete a job.

Dynamic Beta and Emittance in Horizontal Plane

1. *Beam-beam parameter*

$$\xi_0 = \frac{r_e N \beta_0}{2\pi\gamma\sigma_x(\sigma_x + \sigma_y)}$$

2. *Beam-beam tune shift:*

$$\cos\mu = \cos\mu_0 - 2\pi\xi_0 \sin\mu_0$$

where $\mu = 2\pi\nu$.

3. *Dynamic beta:*

$$\beta = \beta_0 \frac{\sin\mu_0}{\sin\mu}$$

4. *Dynamic emittance:*[c]

$$\epsilon = \epsilon_0 \frac{1 + 2\pi\xi_0 \cot\mu_0}{\sqrt{1 + 4\pi\xi_0 \cot\mu_0 - 4\pi^2\xi_0^2}}$$

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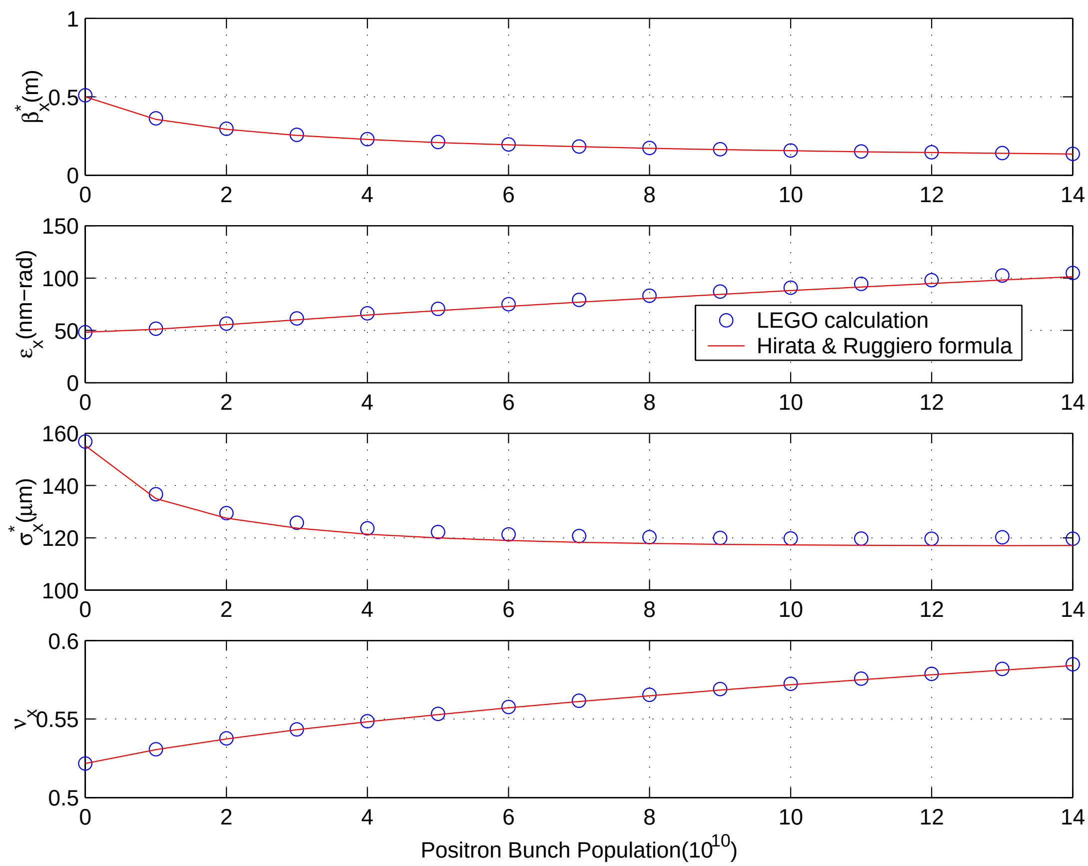
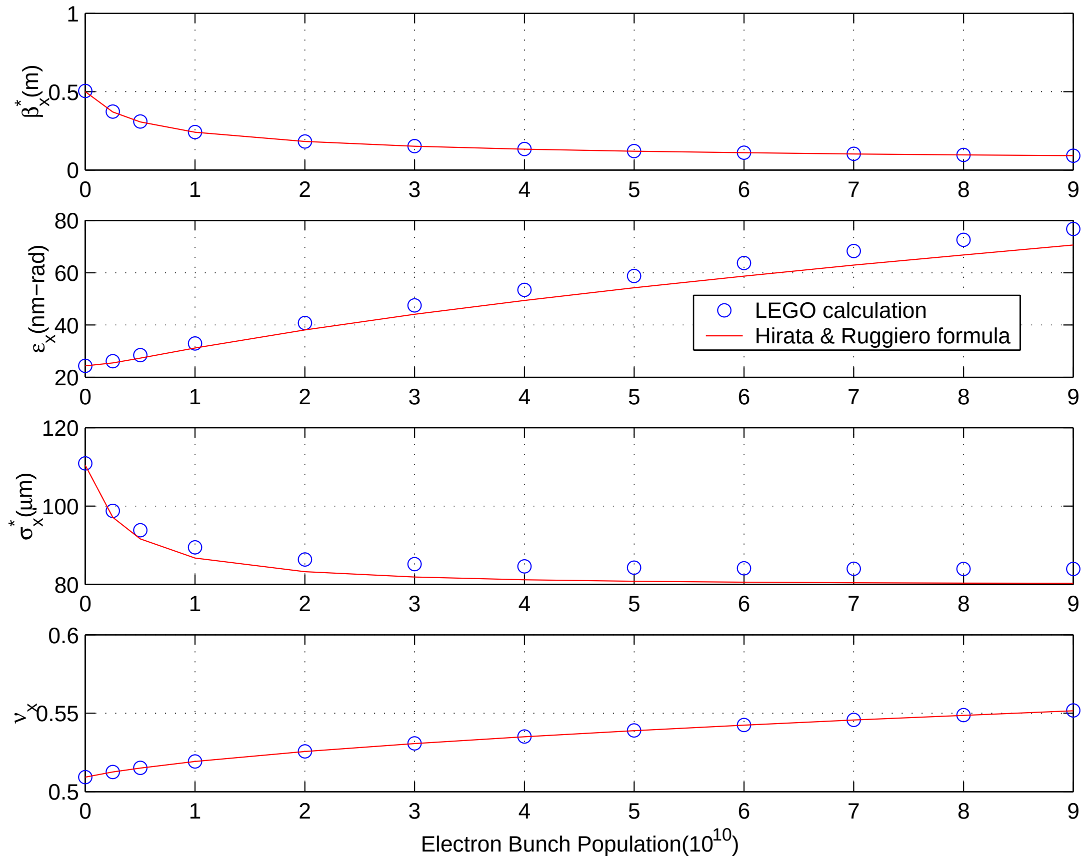
[c]K. Hirata and F. Ruggiero, Particle Accelerator, **28** 137 (1990).

Dynamic Beta and Emittance for the HER



The method introduced by Hirata and Ruggiero is used in our beam-beam simulation.

Dynamic Beta and Emittance for the LER



The method introduced by Hirata and Ruggiero is used in our beam-beam simulation.

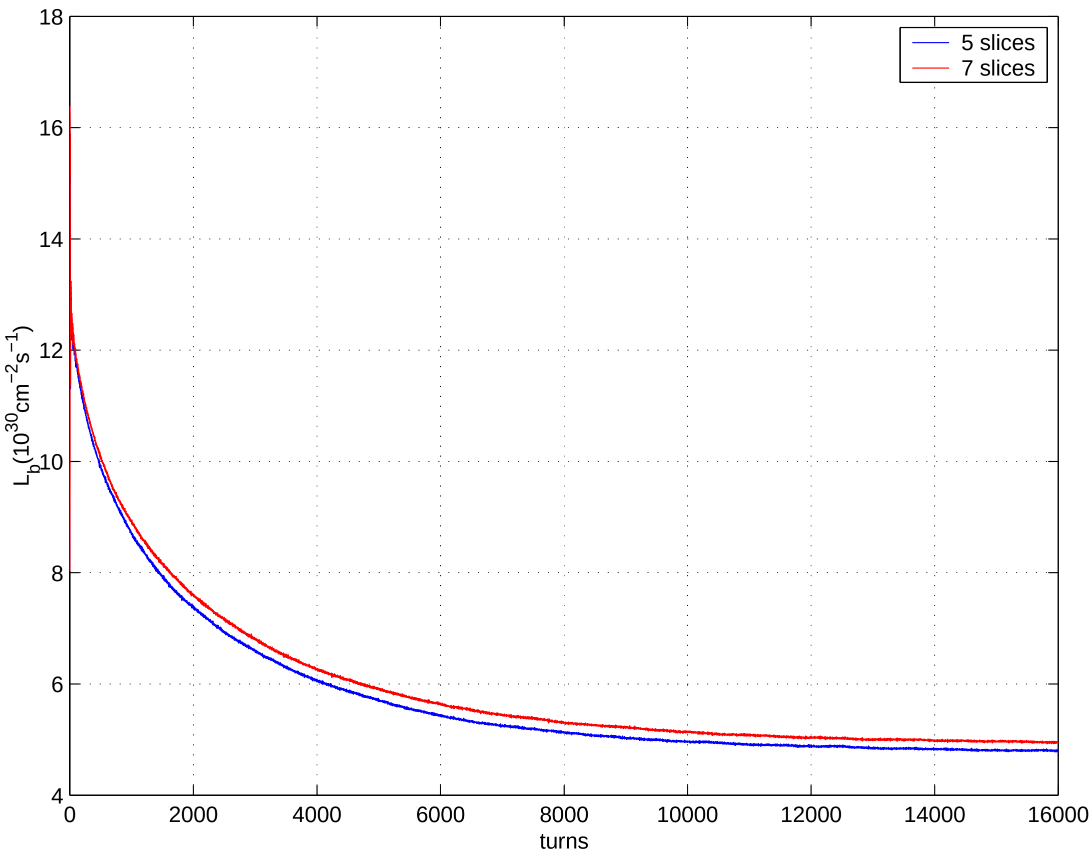
PEP-II Parameters, June 10, 2003

Parameter	LER(e+)	HER(e-)
E (Gev)	3.1	9.0
N	7.34×10^{10}	5.58×10^{10}
β_x^* (cm)	51.0	25.0
β_y^* (cm)	1.21	1.25
ϵ_x (nm-rad)	22.0	49.0
ϵ_y (nm-rad)	1.49	2.33
ν_x	0.5253	0.5203
ν_y	0.5639	0.6223
ν_s	-0.0270	-0.040
σ_z (cm)	1.05	1.25
σ_p	6.50×10^{-4}	6.10×10^{-4}
τ_t (turn)	9800	5030
τ_s (turn)	4800	2573

Simulation Parameters

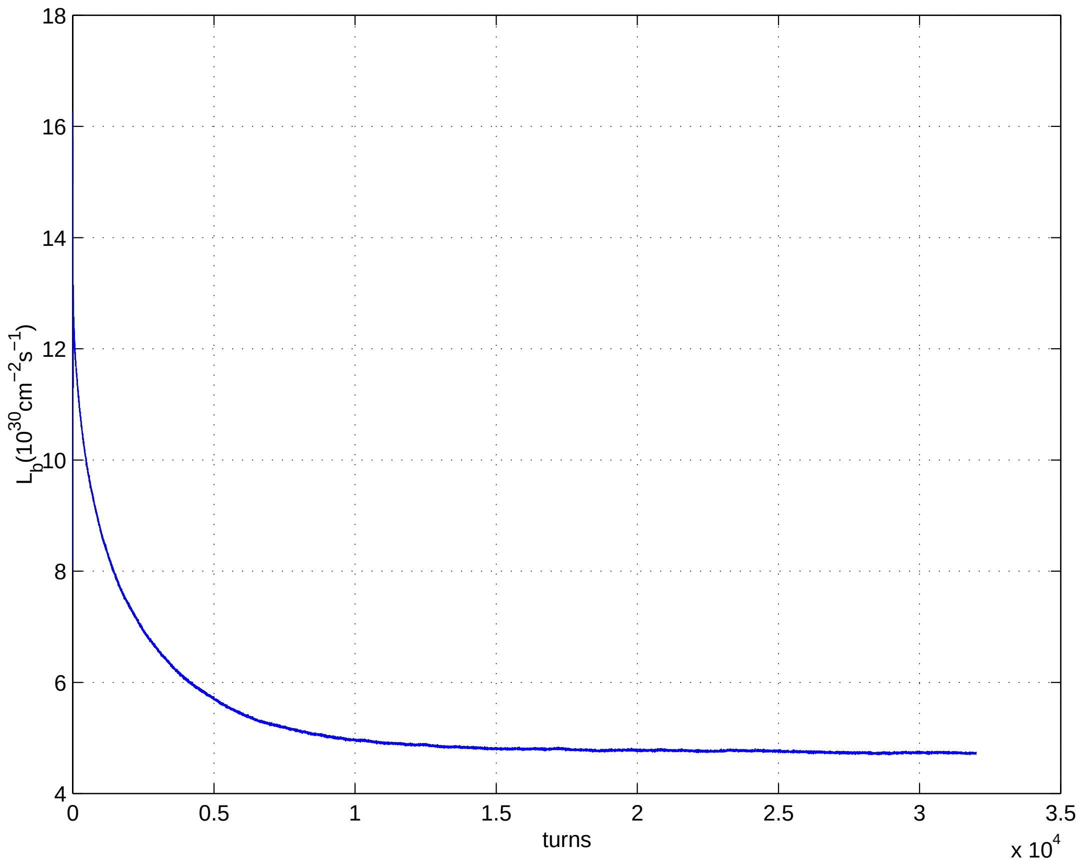
Parameter	Description	Value
N_m	# macro particles/bunch	160000
n (turn)	tracking time	16000
	mesh	128×128
	cell (μm^2)	15×2
n_s	number of slices	5

Long-Term Convergence in Slicing at High Intensities?



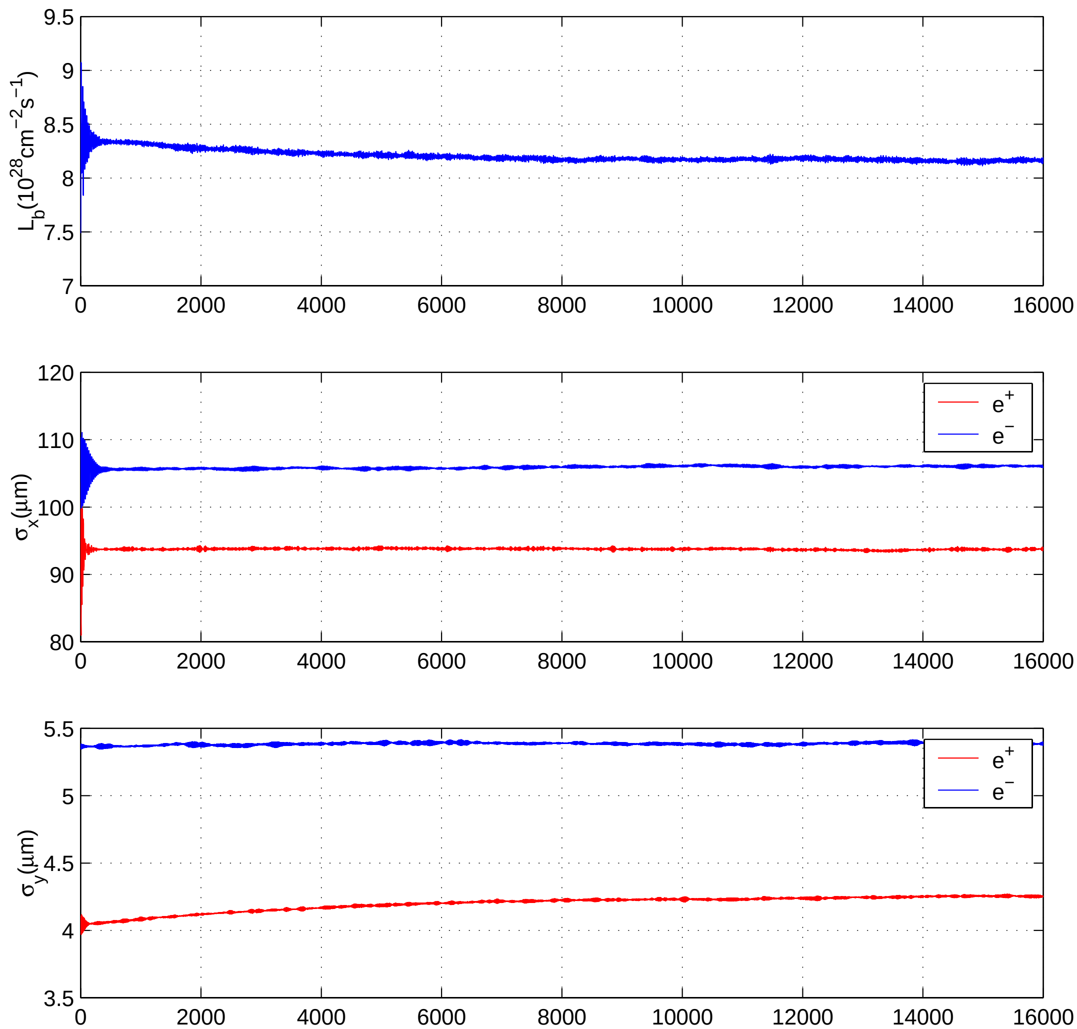
At peak intensities(1.6/1.22mA), simulated luminosity with 5 slices is $4.812 \times 10^{30} cm^{-2} s^{-1}$. With 7 slices, we have $4.954 \times 10^{30} cm^{-2} s^{-1}$. The difference is less than 3%.

Reach Equilibrium at High Intensities?

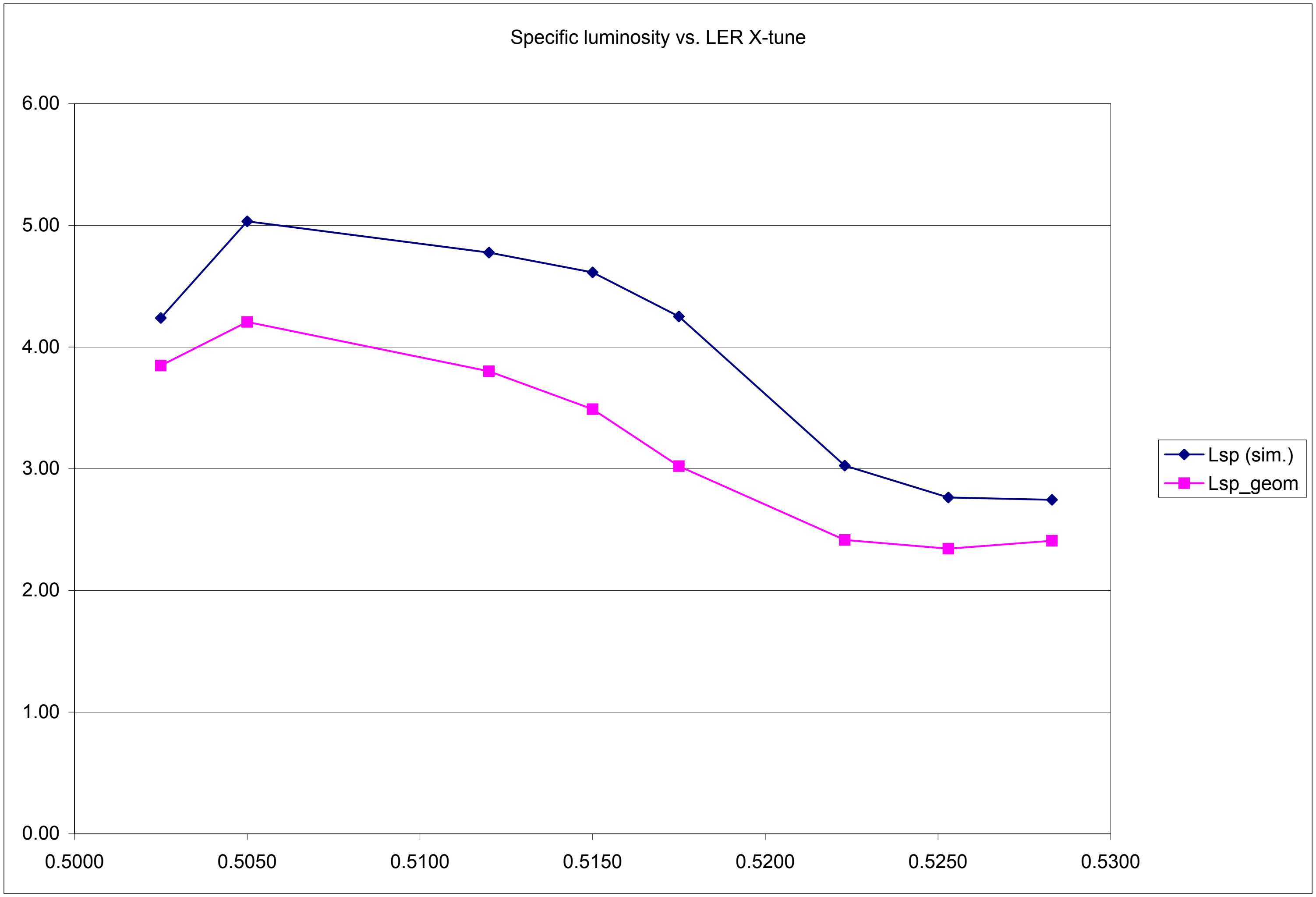


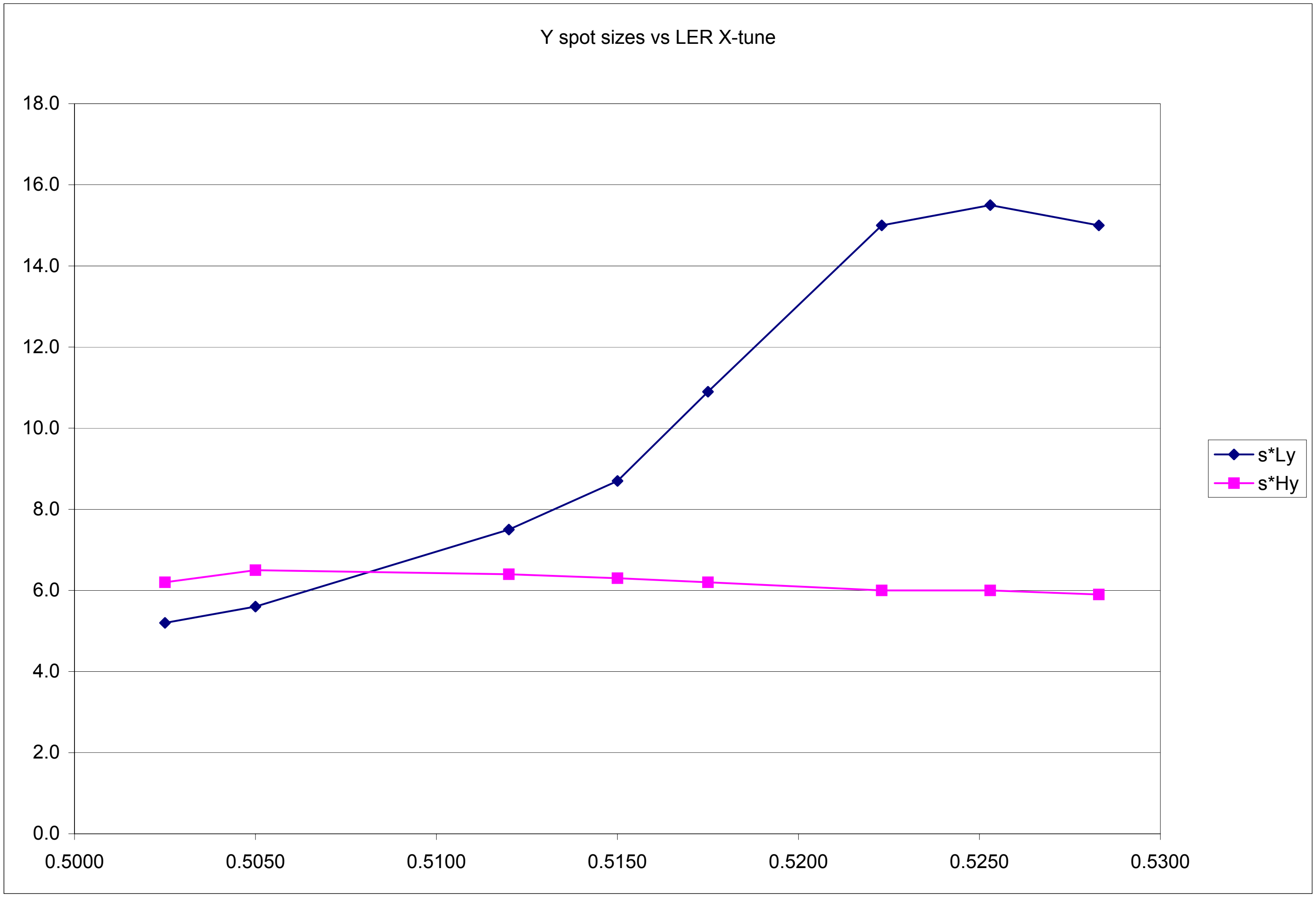
With interpolated slices, beams reach their equilibrium after three damping time.

Simulation at Low Intensities(0.16/0.12mA)

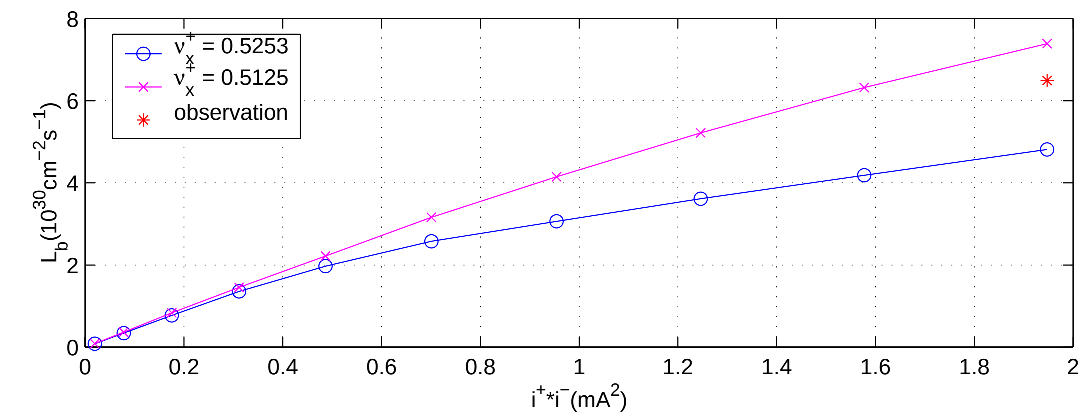


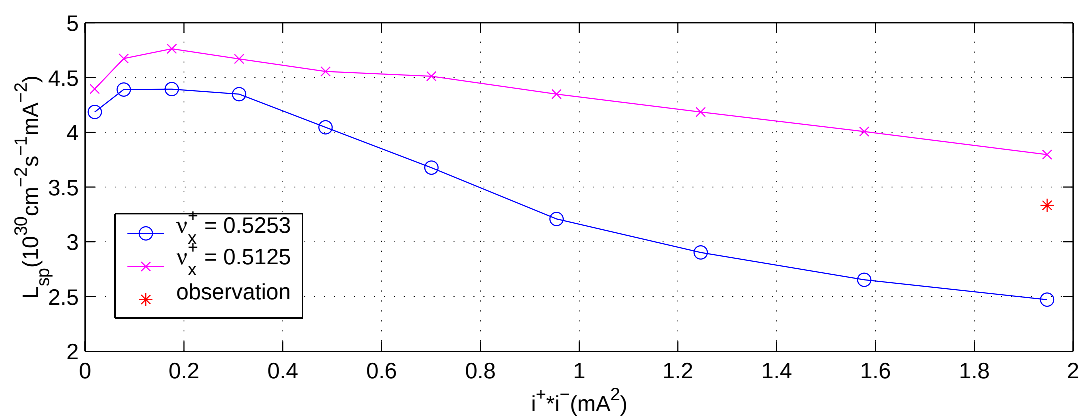
$\Sigma_x = 141\mu$m, $\Sigma_y = 6.9\mu$m, $L_{sp} = 4.21 \times 10^{30} cm^{-2}s^{-1}mA^{-2}$ should be compared to the measured values: $\Sigma_{max} = 160\mu$m, $\Sigma_{min} = 7.01\mu$m, $L_{sp} = 4.2 \times 10^{30} cm^{-2}s^{-1}mA^{-2}$ on June 3, 2003.


Specific luminosity vs. LER X-tune
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.5000
0.5050
0.5100
0.5150
0.5200
0.5250
0.5300
Lsp (sim.)
Lsp_geom


Y spot sizes vs LER X-tune
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.5000
0.5050
0.5100
0.5150
0.5200
0.5250
0.5300
s*Ly
s*Hy

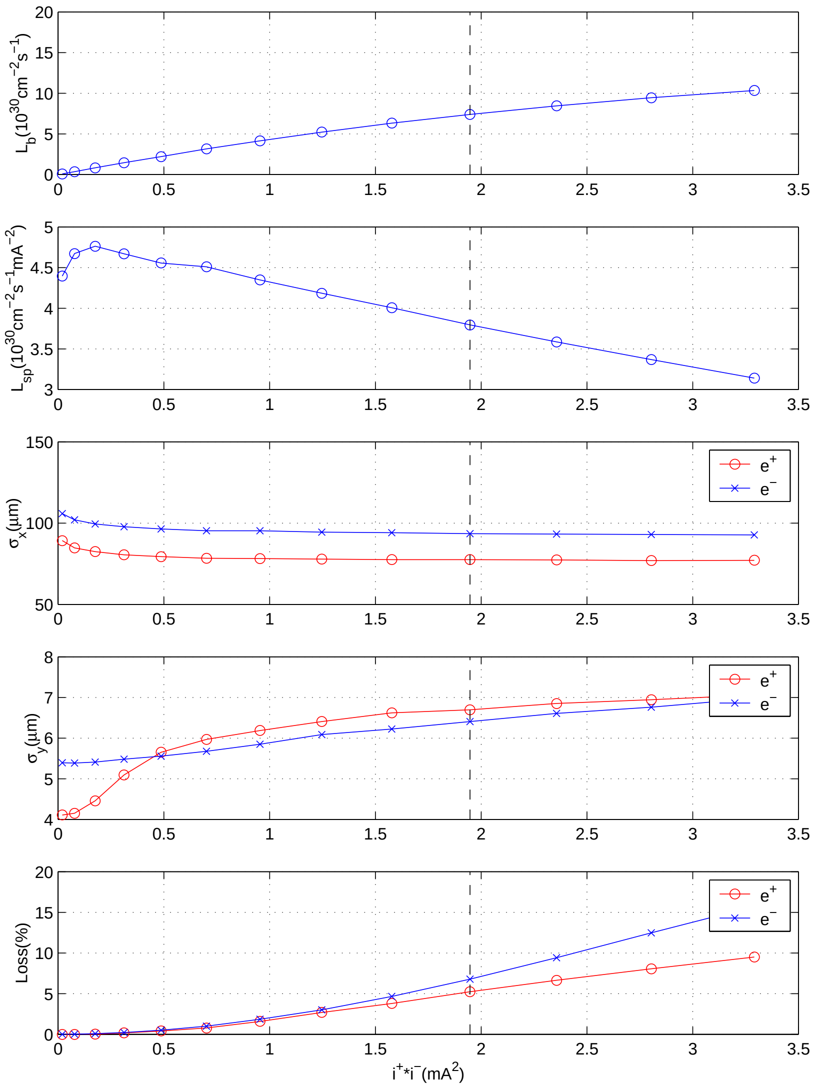
Beam-Beam Effects of PEP-II, June 10, 2003 ($\nu_x^+ = 0.5125$)





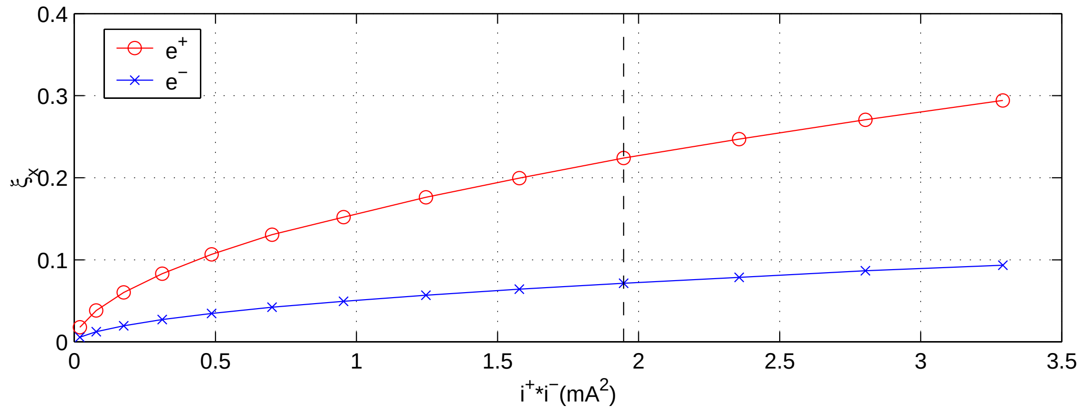
Compared with the observed value $6.49 \times 10^{30} cm^{-2} s^{-1}$ at the peak currents.

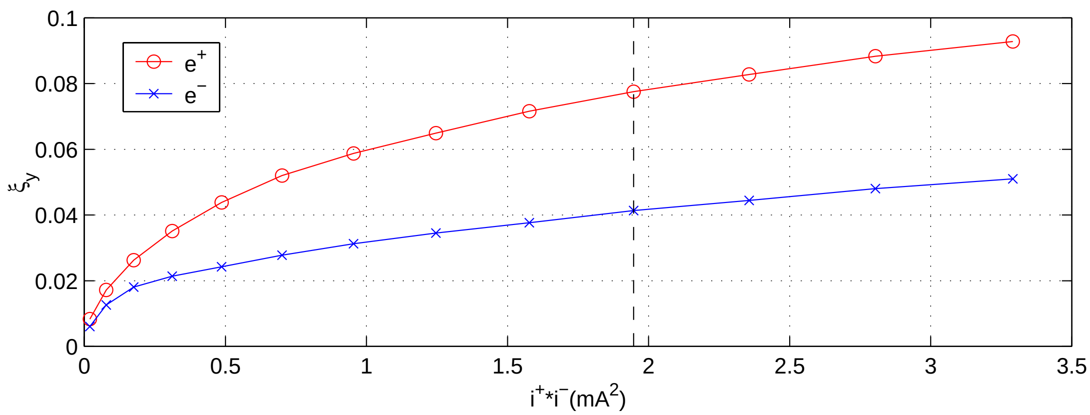
Beam-Beam Effects of PEP-II, June 10, 2003 ($\nu_x^+ = 0.5125$)



There are still room to increase the beam currents. Beams are matched at high currents in the vertical plane. There are more beam loss for electrons than positrons especially at higher currents. That can be a problem if the dynamic aperture is to large enough.

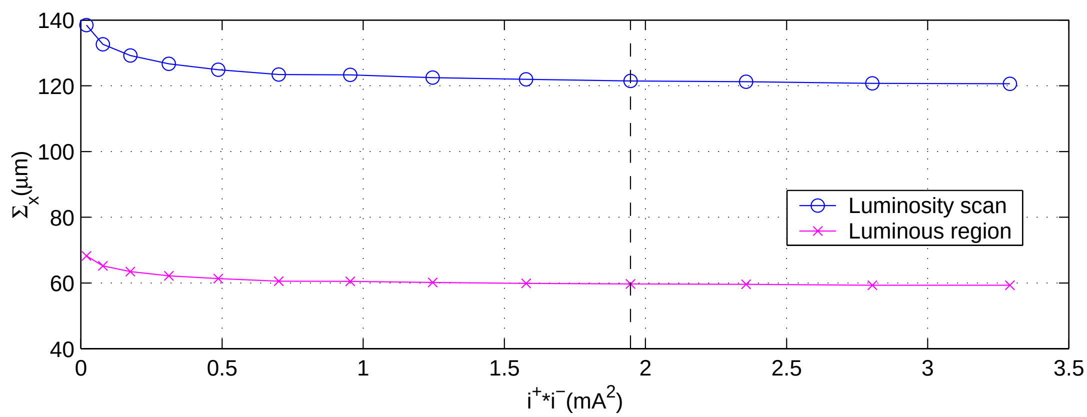
Beam-Beam Effects of PEP-II, June 10, 2003 ($\nu_x^+ = 0.5125$)

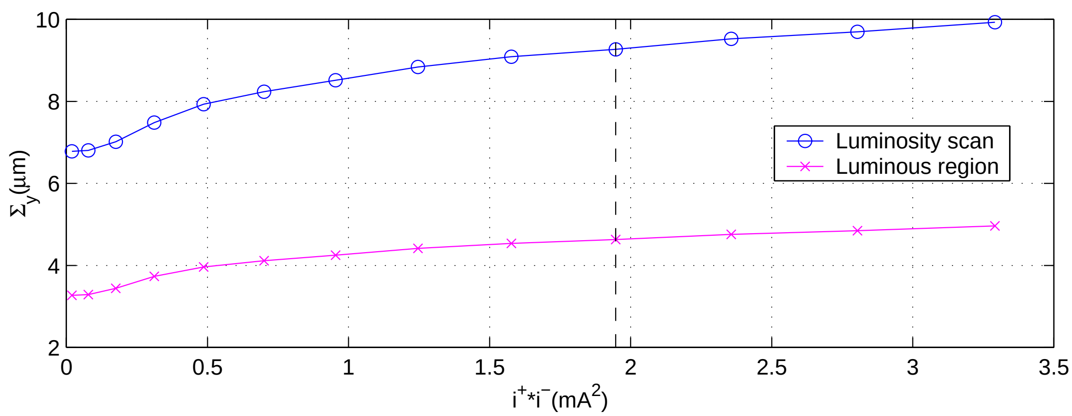




The beam-beam parameters are: $\xi_x^+ = 0.2239$, $\xi_y^+ = 0.0776$, $\xi_x^- = 0.0714$, and $\xi_y^- = 0.0413$.

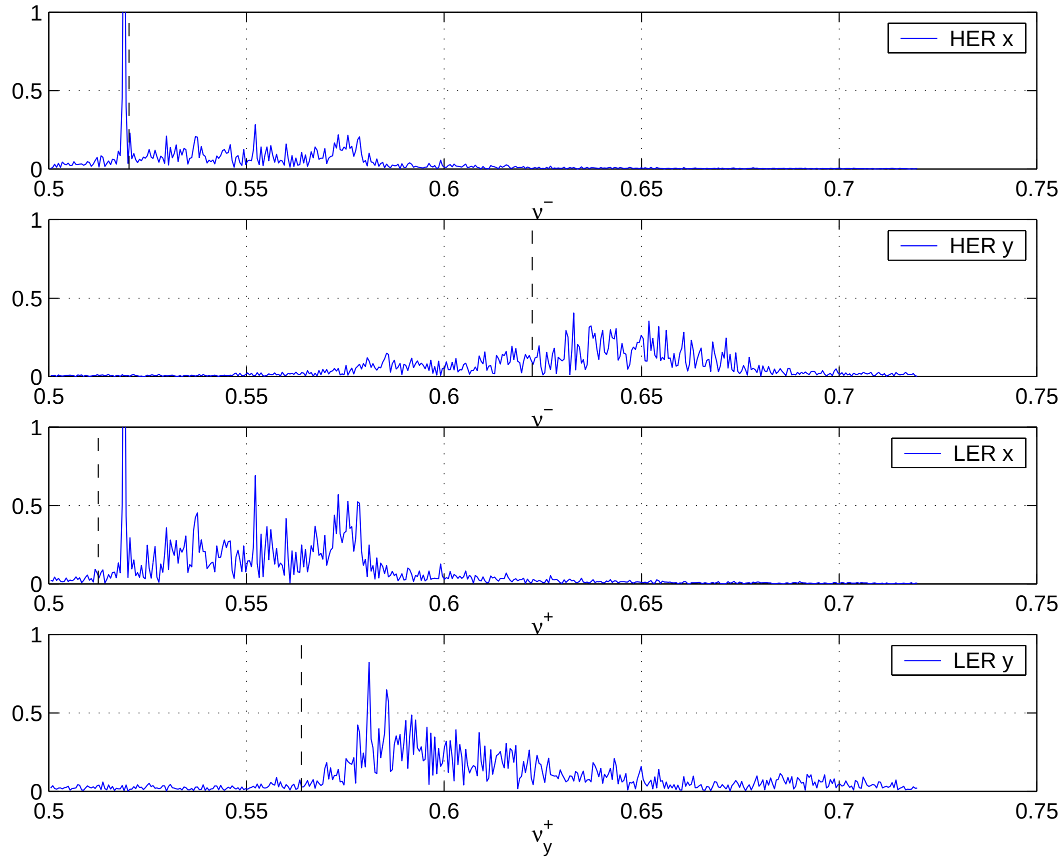
Beam-Beam Effects of PEP-II, June 10, 2003 ($\nu_x^+ = 0.5125$)



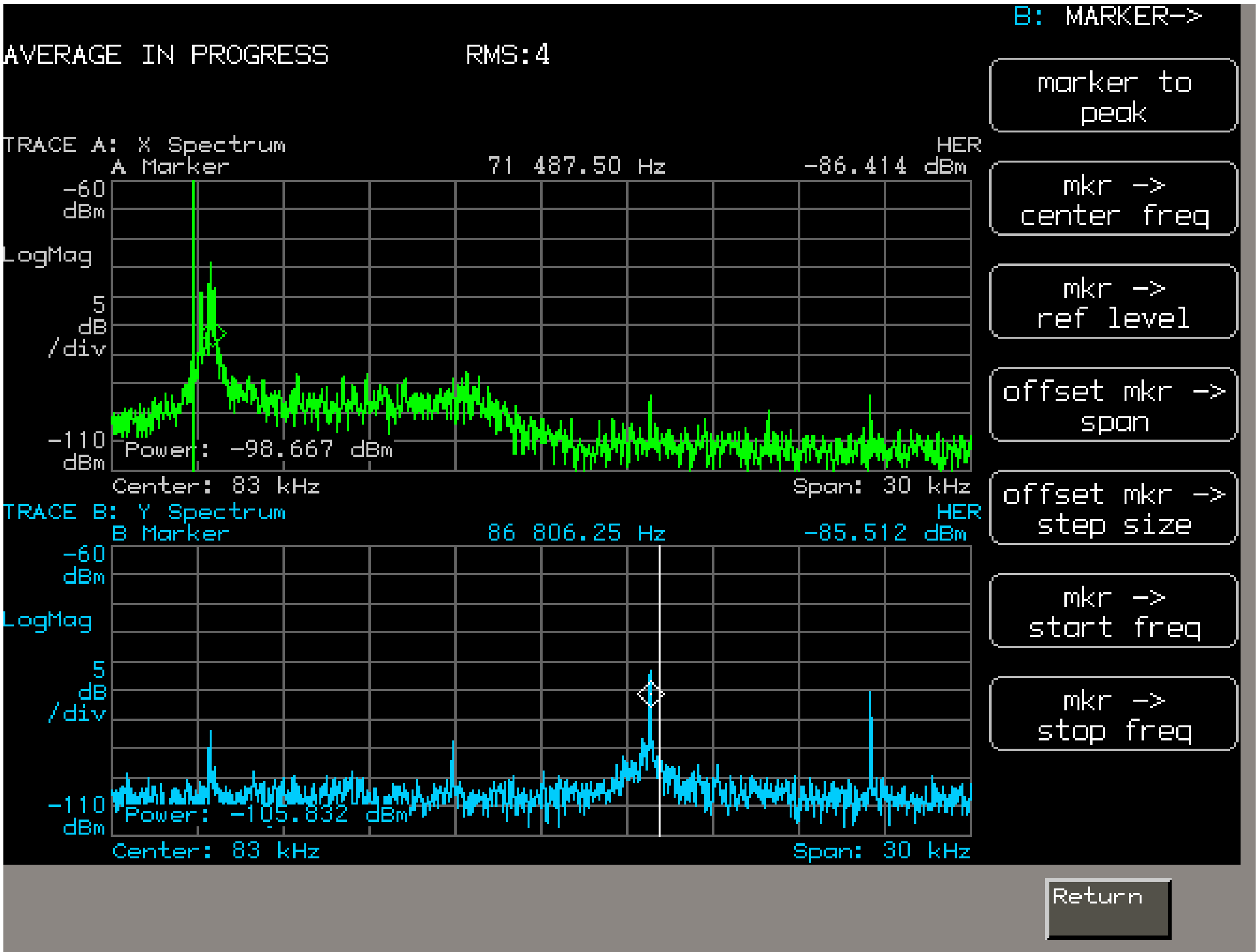


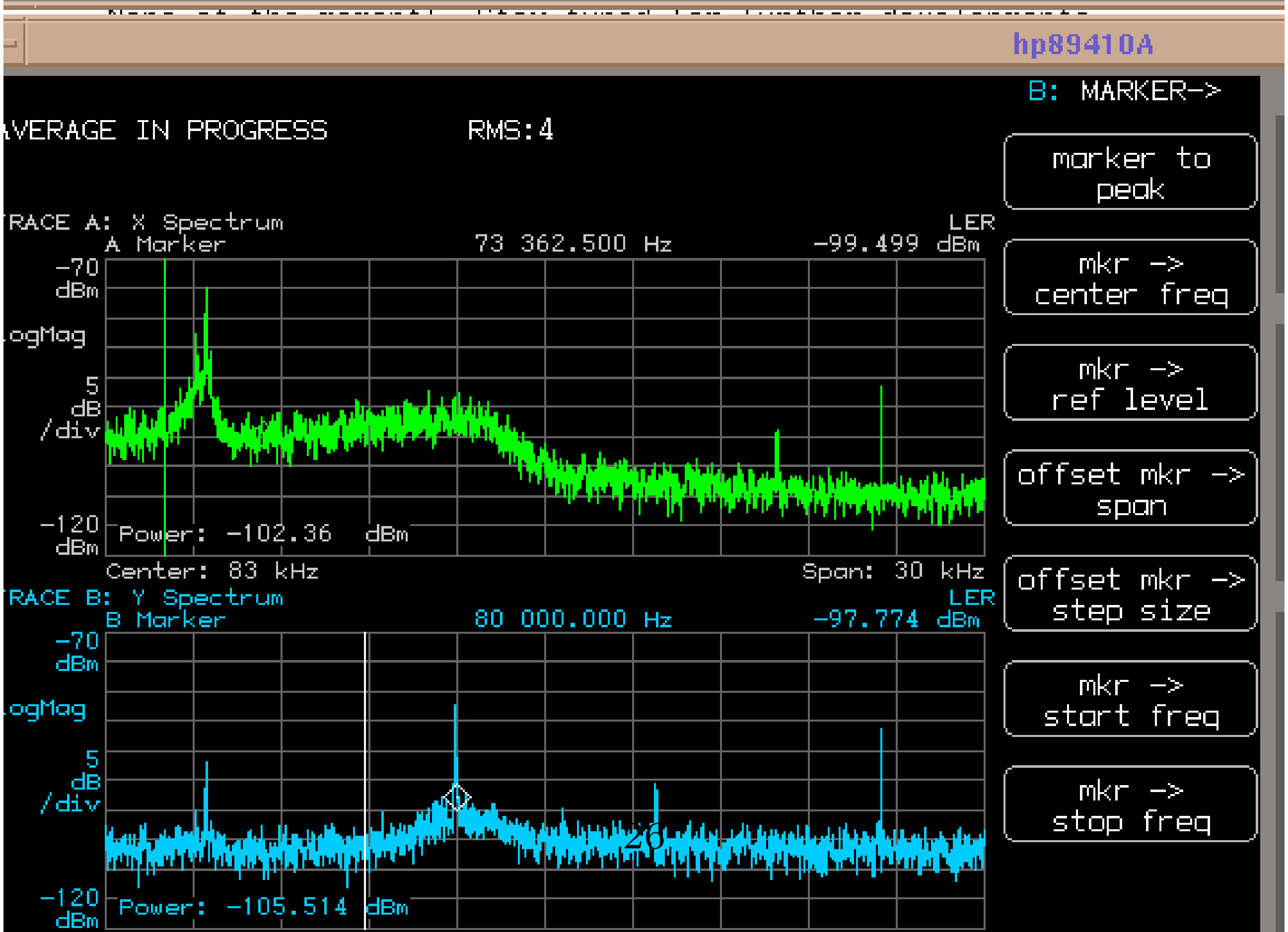
Based on the beam-beam scan at June 3, 2003, we have $\Sigma_{max} = 161\mu m$, $\Sigma_{min} = 7.01\mu m$, and $L_{sp} = 4.2 \times 10^{30} cm^{-2} s^{-1} mA^{-2}$. The luminous region seen by BaBar is $\Sigma_x = 77\mu m$. The larger horizontal beam sizes in the experimental observations may be attributable to the huge beta beating in the High Energy Ring.

Beam-Beam Effects of PEP-II, June 10, 2003 ($\nu_x^+ = 0.5125$)

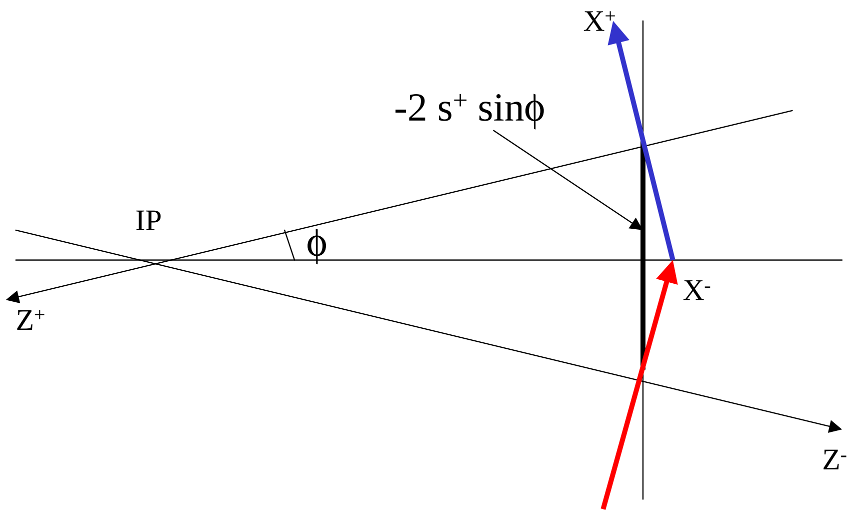


Compared to the measured spectrums of collision at peak currents on June 5, 2003, we have excellent agreements in the horizontal plane. It is not clear why the spectrums differ in the vertical plane.


B: MARKER->
AVERAGE IN PROGRESS
RMS:4
TRACE A: X Spectrum
HER
A Marker
71 487.50 Hz
-86.414 dBm
-60 dBm
LogMag
5 dB /div
-110 dBm
Power: -98.667 dBm
Center: 83 kHz
Span: 30 kHz
TRACE B: Y Spectrum
HER
B Marker
86 806.25 Hz
-85.512 dBm
-60 dBm
LogMag
5 dB /div
-110 dBm
Power: -105.832 dBm
Center: 83 kHz
Span: 30 kHz
marker to peak
mkr -> center freq
mkr -> ref level
offset mkr -> span
offset mkr -> step size
mkr -> start freq
mkr -> stop freq
Return


hp89410A
B: MARKER->
AVERAGE IN PROGRESS
RMS:4
TRACE A: X Spectrum
LER
A Marker
73 362.500 Hz
-99.499 dBm
-70 dBm
LogMag
5 dB /div
-120 dBm
Power: -102.36 dBm
Center: 83 kHz
Span: 30 kHz
TRACE B: Y Spectrum
LER
B Marker
80 000.000 Hz
-97.774 dBm
-70 dBm
LogMag
5 dB /div
-120 dBm
Power: -105.514 dBm
marker to peak
mkr -> center freq
mkr -> ref level
offset mkr -> span
offset mkr -> step size
mkr -> start freq
mkr -> stop freq

Symplectic Treatment of a Finite Crossing Angle



The whole process can be summarized and written as

$$\mathcal{T}^{\pm}(s^{\pm},\phi)\cdot\mathcal{O}^{\mp}_{BB}(x^{\pm},y^{\pm},\phi)\cdot\mathcal{T}^{\pm}(s^{\pm},\phi)^{-1}, \qquad (1)$$

where

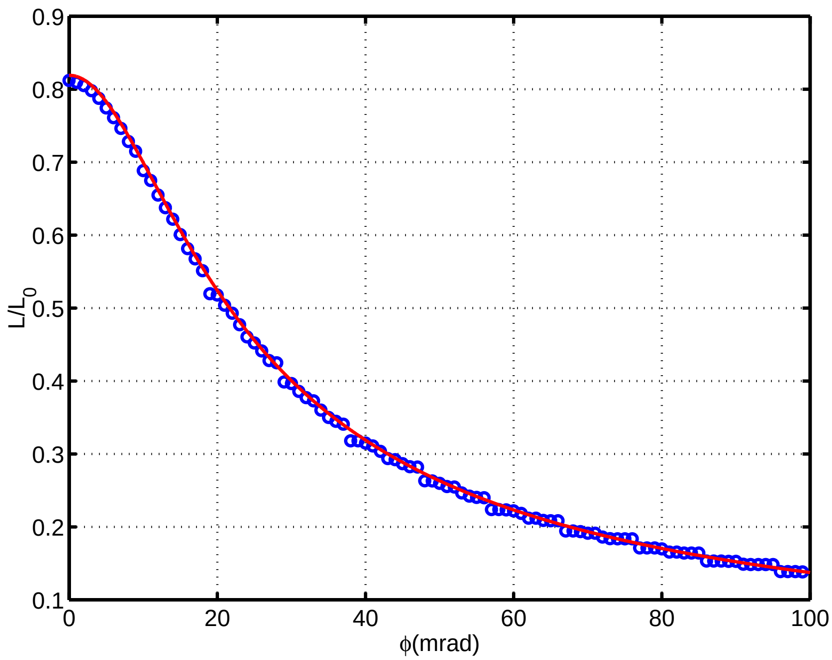
$$\mathcal{T}^{\pm}(s^{\pm},\phi)=\mathcal{D}^{\pm}_{z}(s^{\pm})\cdot\mathcal{R}^{\pm}_{y}(\phi)\cdot\mathcal{D}^{\pm}_{x}(s^{\pm},\phi), \qquad (2)$$

Sympletic Rotation around Y Axis

$$
\begin{aligned}
\tilde{x} &= \frac{x}{\cos\phi(1 - P_x \tan\phi / P_s)}, \\
\tilde{P}_x &= \cos\phi P_x + \sin\phi P_s, \\
\tilde{y} &= y + \frac{P_y x \tan\phi}{(P_s - P_x \tan\phi)}, \\
\tilde{P}_y &= P_y, \\
\tilde{z} &= z - \frac{(1+\delta) x \tan\phi}{(P_s - P_x \tan\phi)}, \\
\tilde{\delta} &= \delta,
\end{aligned}
$$

where $P_s = \sqrt{(1+\delta)^2 - P_x^2 - P_y^2}$. It can be expressed as a Lie operator $\exp(: xP_s : \phi)$. It is also exact for ultra-relativistic particles.

Geometric Effect from a Finite Crossing Angle [d]



$$R_L = \frac{L}{L_0} = \sqrt{\frac{2}{\pi}} a e^b K_0(b),$$

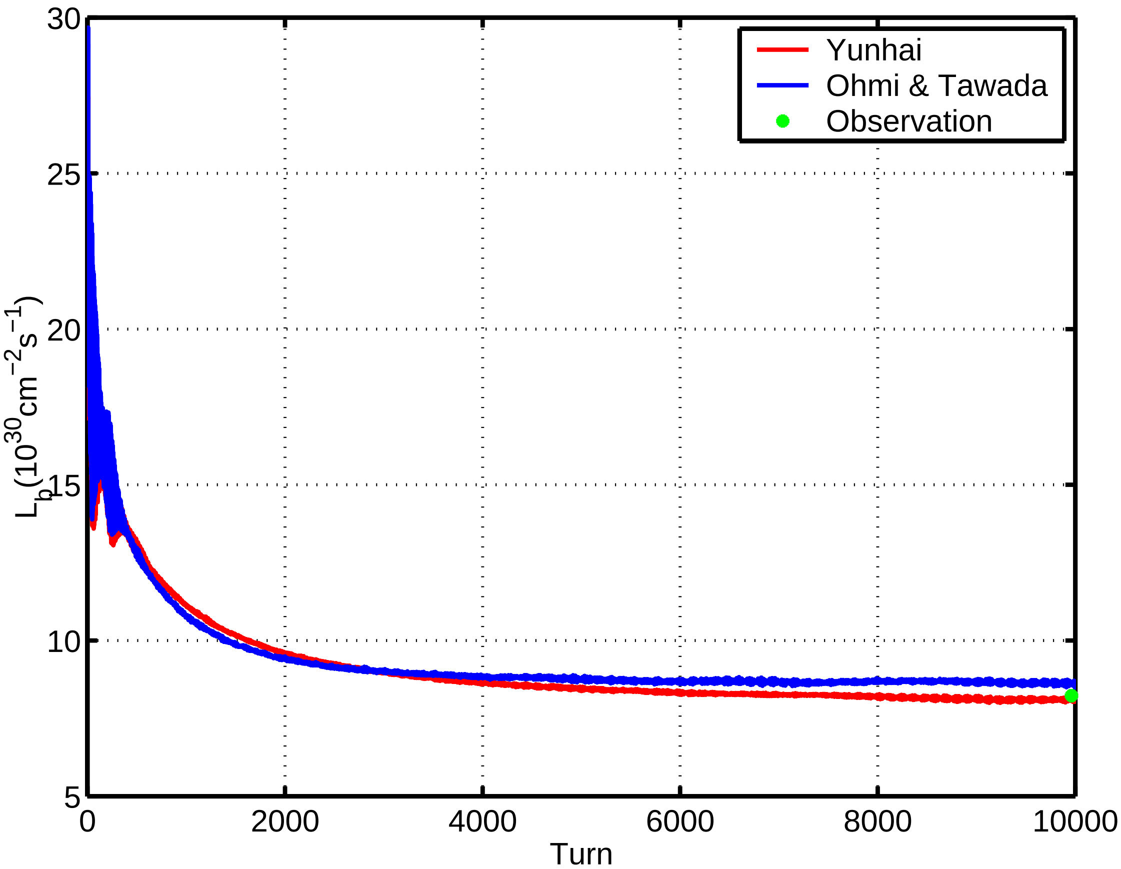
$$a = \frac{\sigma_y^*}{\sqrt{2}\sigma_z^* \sigma_{p_y}^*}, b = a^2[1 + (\frac{\sigma_z^*}{\sigma_x^*} \tan\phi)^2],$$

[d] K. Hirata, Phys. Rev. Lett. **74** 2228 (1995).

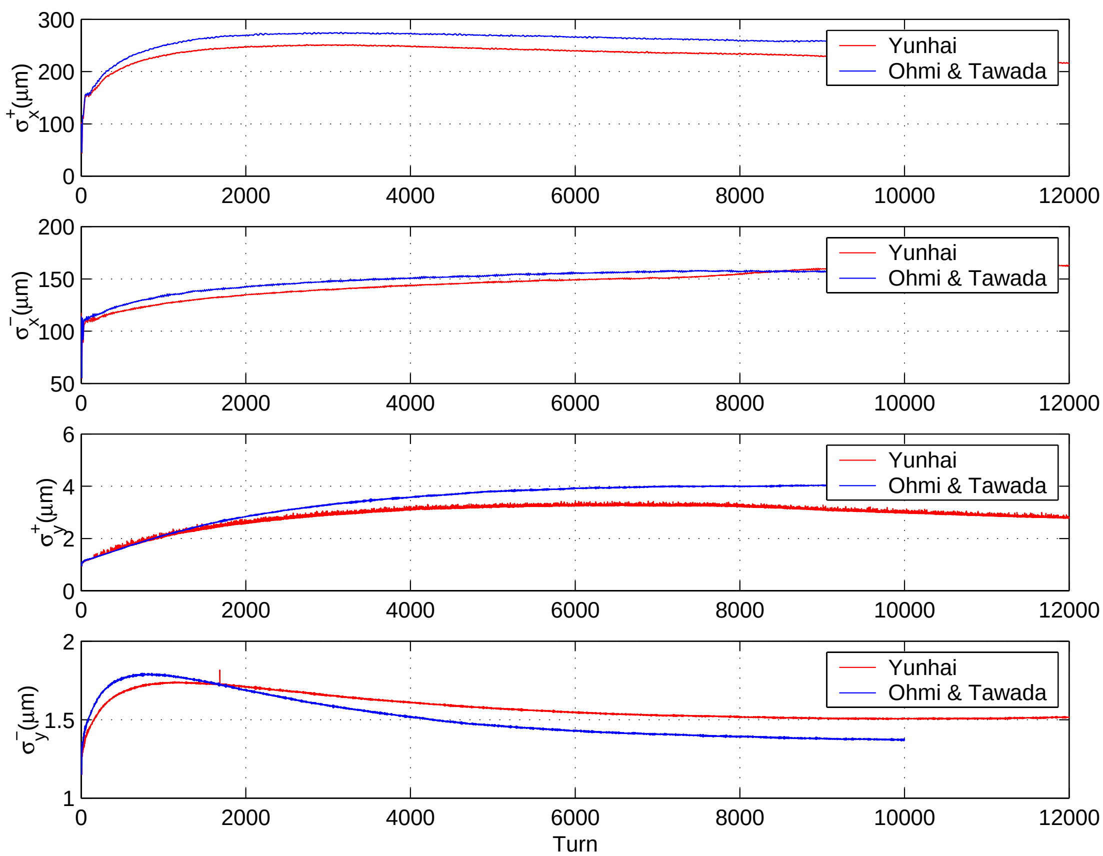
KEKB Parameters, May 13, 2003

Parameter	LER(e+)	HER(e-)
E (Gev)	3.5	8.0
N	7.36×10^{10}	5.28×10^{10}
β_x^* (cm)	59.0	58.0
β_y^* (cm)	0.58	0.70
ϵ_x (nm-rad)	18.0	24.0
ϵ_y (nm-rad)	0.18	0.24
ν_x	0.506	0.513
ν_y	0.545	0.586
ν_s	-0.0249	-0.0207
σ_z (cm)	0.87	0.71
σ_p	7.26×10^{-4}	6.67×10^{-4}
τ_t (turn)	4000	4000
τ_s (turn)	2000	2000

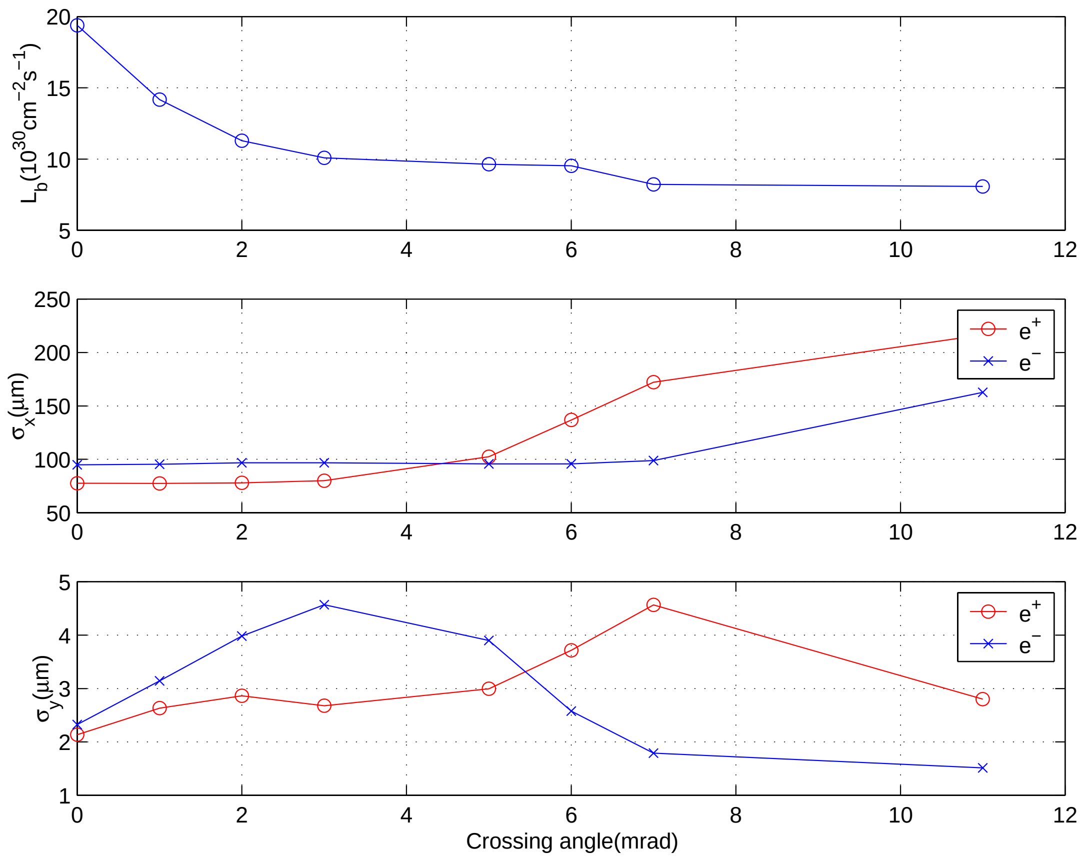
KEKB Parameters($\phi = \pm 11mrad$), 5/13/2003



KEKB Parameters($\phi = \pm 11 mrad$), 5/13/2003



KEKB with a Different Crossing Angle,



Similar results have been obtained by Ohmi and Tawada.

Comparison of KEKB and PEP-II Parameters

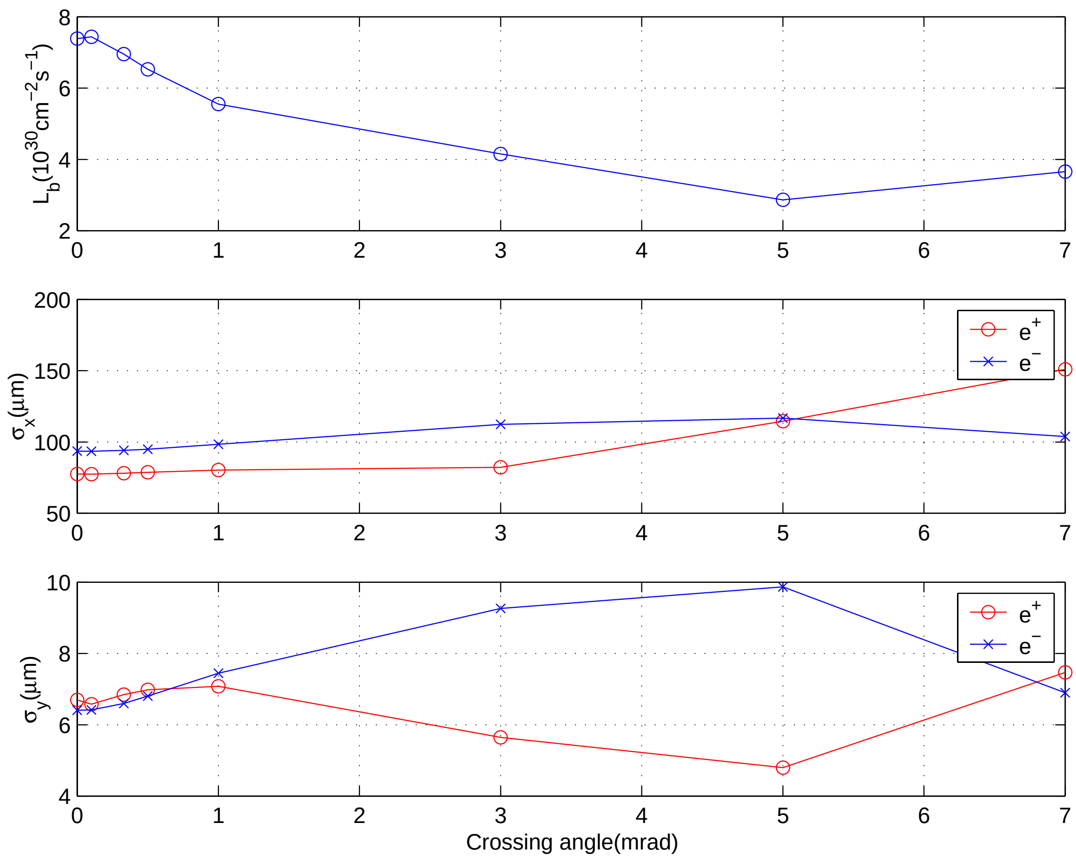
Parameter	KEKB(e+)	PEP-II(e+)
E (Gev)	3.5	3.1
N	7.36×10^{10}	7.34×10^{10}
β_x^* (cm)	59.0	51.0
β_y^* (cm)	0.58	1.21
ϵ_x (nm-rad)	18.0	22.0
ϵ_y (nm-rad)	0.18	1.49
ν_x	0.506	0.5125
ν_y	0.545	0.5639
ν_s	-0.0249	-0.0270
σ_z (cm)	0.87	1.05
σ_p	7.26×10^{-4}	6.50×10^{-4}
τ_t (turn)	4000	9800
τ_s (turn)	2000	4800

Break Down of Luminosity Between KEKB and PEP-II

Description	$\mathcal{L}_b$	$\mathcal{L}_{sp}$	Gain
present PEP-II	7.391	3.795	0%
aspect ratio 30	8.619	4.426	17%
aspect ratio 50	10.226	5.251	38%
aspect ratio 100	12.198	6.264	65%
$\beta_y^*/2$, $\sigma_z/2$	16.573	8.511	124%
$\tau/2$	18.951	9.732	156%
ν_x, ν_y, KEKB($\phi = 0$)	19.393	9.959	162%

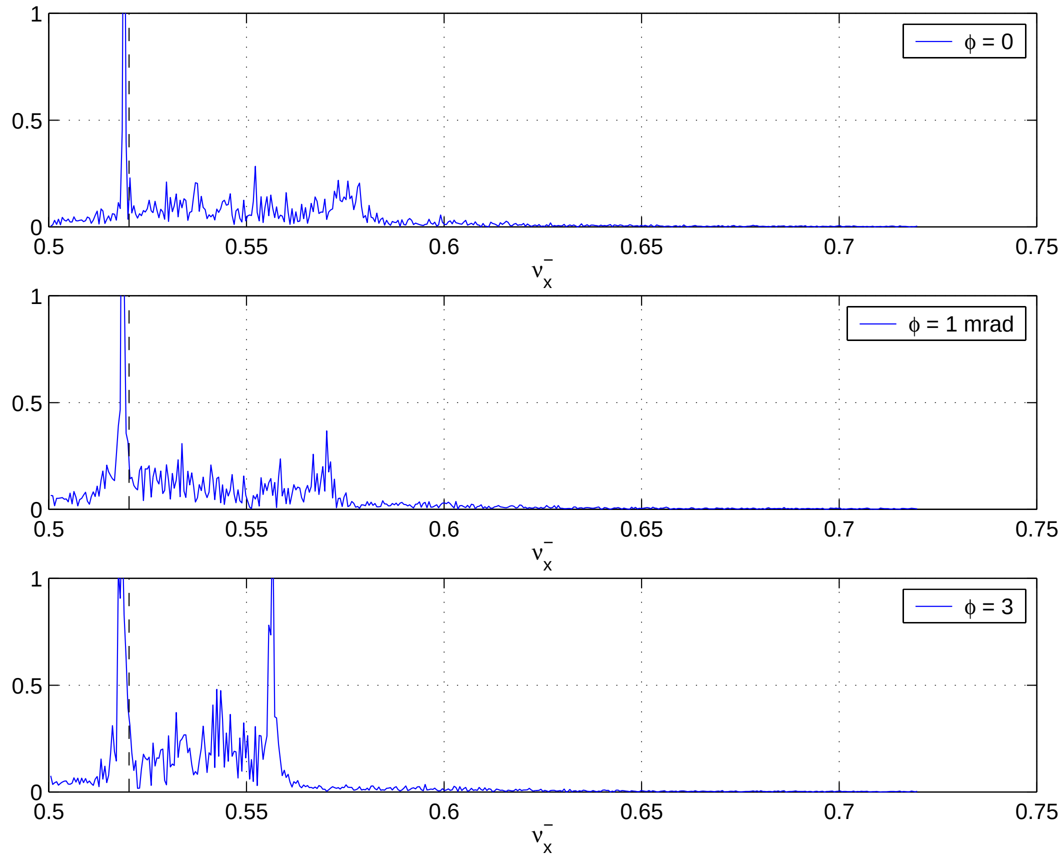
$\mathcal{L}_b$ is the bunch luminosity in unit of $10^{30} cm^{-2} s^{-1}$ and $\mathcal{L}_{sp}$ is the specific luminosity in unit of $10^{30} cm^{-2} s^{-1} mA^{-2}$.

PEP-II with a Crossing Angle



For $\phi = \pm 3mrad$, we see a degradation of luminosity by 43%. Similar results have been obtained by Ohmi and Tawada.

Horizontal Beam Spectrums with a Crossing Angle



Tail-tail motion is seen in the spectrums.

Conclusion

- Over the past few years, we have completed the work of implementing a three-dimensional, fully self-consistent, and parallel PIC code. Now, we can complete a single simulation within 8 hours on parallel supercomputers.
- The code has been benchmarked against a similar code developed by Ohmi at KEK. The simulated luminosity is in a agreement with the experimental observation.
- We have interpolated achievable luminosities based on the simulations and observations at KEKB and PEP-II. It showed that it is very important to reduce the vertical beam size to gain higher luminosity.
- We found a large degradation of luminosity even with a small crossing angle at current working point. This effects should be verified experimentally at PEP-II.

Acknowledgments

Witold Kozanecki (PEP-II & BaBar)

Ilya Narsky (BaBar)

Frank Porter (BaBar)

John Seeman (PEP-II)

Kazuhito Ohmi (KEKB)

Masafumi Tawada (KEKB)