# LUMINOSITY IMPROVEMENT AT PEP-II BASED ON OPTICS MODEL AND BEAM-BEAM SIMULATION*

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*Abstract*

Since the beginning of this year, we have made significant improvements in the machine optics at PEP-II. As a result, the specific luminosity increased nearly 20%. The largest luminosity gain actually came from minimizing nonlinear chromatic effects and running both rings much closer to the half integer resonance in the horizontal plane.

## INTRODUCTION

The model independent analysis (MIA) [1, 2] was successfully used in the past to understand machine optics and improve the luminosity at PEP-II. However, the rate of success was rather limited because the improvement of optics does not necessarily lead to increase of luminosity. To improve the situation, we introduced a new strategy, as illustrated in Fig. 1, for tuning the collider. First, we extended MIA to include the longitudinal excitation. Now, the MIA model matches the measured dispersion as well. Second,

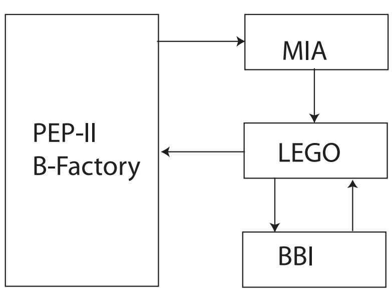


Figure 1: A tuning strategy using modelling and simulation codes for PEP-II.

we were able to reconstruct MIA model in a full optics code LEGO [3] and used it to calculate complete lattice and beam parameters. Finally, these parameters were fed to the beam-beam code BBI [4, 5] to understand the luminosity histories at PEP-II over the past year. More importantly, we made quantitative predictions of luminosity gain by vary the beam parameters in the simulation. These results were used to guide the choice of machine developments (MD). As shown in Fig. 2, a tune scan was simulated with the parameters listed in Table 1. The machines were operated with 1722 colliding bunches. Since the bunch separation is only 4.2 ns, the two adjacent parasitic collisions were included in the simulation. The simulation showed a possible 15% gain in luminosity if the tunes in both horizontal and vertical planes were moved closer to half integer.

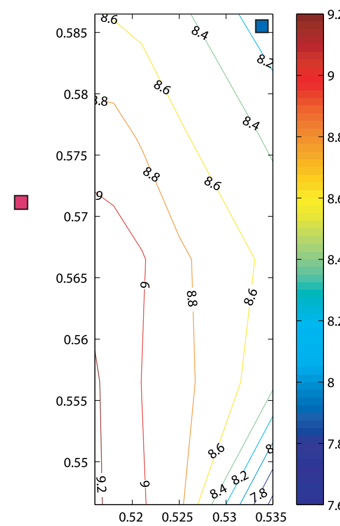

Figure 2: A contour plot of luminosity in unit of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the LER tune plane based on the three-dimensional beam-beam simulation. The blue and red squares indicate respectively the tunes before and after the recent tune change in the LER.

Table 1: PEP-II Operating Parameters, April 12, 2006

| Parameter | LER (e+) | HER (e-) |
|---|---|---|
| beam energy $E$ (Gev) | 3.1 | 9.0 |
| bunch population $N$ | $6.39 \times 10^{10}$ | $4.39 \times 10^{10}$ |
| x beta at the IP $\beta_x$ (cm) | 37.0 | 42.0 |
| y beta at the IP $\beta_y$ (cm) | 0.97 | 1.08 |
| x emittance $\epsilon_x$ (nm-rad) | 27.0 | 49.0 |
| y emittance $\epsilon_y$ (nm-rad) | 2.07 | 1.25 |
| x tune $\nu_x$ | 38.5350 | 24.5143 |
| y tune $\nu_y$ | 36.5965 | 23.6208 |
| synchrotron tune $\nu_s$ | 0.0314 | 0.0438 |
| bunch length $\sigma_z$ (cm) | 1.25 | 1.15 |
| energy spread $\sigma_\delta$ | $6.5 \times 10^{-4}$ | $6.1 \times 10^{-4}$ |
| x,y damping $\tau_t$ (turns) | 9800 | 5030 |
| z damping $\tau_z$ (turns) | 4800 | 2573 |

* Work supported by DOE Contract DE-AC02-76SF00515
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## NONLINEAR MODEL

In the MD that implemented the suggested tune change, we found the beam-beam lifetime of the several bunches in the head of the bunch train was extremely low. The poor lifetime indicated that the tune space near the half integer was rather small and not enough to accommodate the tune spread along the train. As a result, the tune change in the machine was backed out.

To understand the poor lifetime problem near the half integer, we used the beam-based MIA/LEGO model outlined in the previous section and actual setting of the sextupoles to calculate the tune shifts as a function of $\Delta p/p$ as shown in Fig. 3. The calculated values were in a good agreement with the measurements. One can see from the figure that there was a large quadratic term in the vertical plane and a cubic term in the horizontal plane. We set the negative chromaticity (between -1 to -2) in the horizontal plane in the LER to compensate the cubic term, and in the vertical plane we raised the strength of the four local sextupoles 7% to reduce the quadratic term. Both changes nearly doubled the beam-beam lifetime (30 minutes) when they were implemented during the delivery of luminosity. Since the gain in the lifetime is not required because of the trickle charge injection, it was quickly traded to a gain in luminosity by lowering the tunes respectively as shown in Fig. 2.

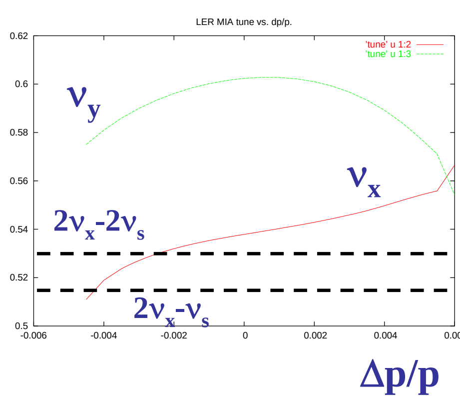


Figure 3: Tunes as a function of $\Delta p/p$ in the LER.

Dynamic aperture was also scanned in the tune plane as shown in Fig. 4. To determine a dynamic aperture, the particles were tracked using LEGO up to 1024 turns with $5\sigma_p$ synchrotron oscillation. It is worth noting that the best tune in the scan coincides with the working point used over a year in the LER before the recent tune change. It also predicted that the off-energy particles will become unstable when $\nu_x < 0.516$. That was the reason why the beam-beam tune scan shown in Fig. 2 was limited to $\nu_x > 0.516$.

The final jump of the tune toward $\nu_x = 0.508$ was achieved during the delivery of luminosity by operators after the RF voltage was lowered from 4.5 MV to 4.0 MV to lengthen the bunches and reduce the heating in the ring. It is not yet clear to us if the change of the synchrotron tune was the sole reason that allowed the machine to operate so

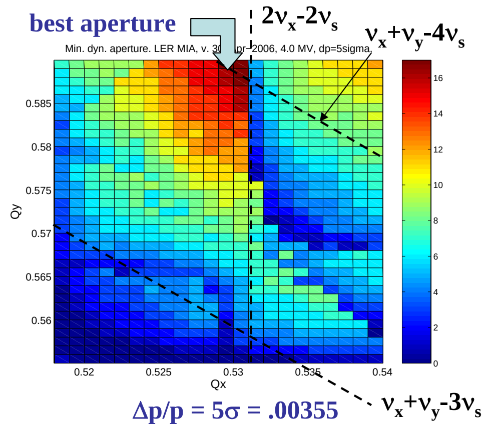


Figure 4: Scan of dynamic aperture in the tune plane using a beam-based model of the LER.

close to the half integer.

Since our model predicted an unstable machine at $\nu_x = 0.508$, ironically, one may note that we have made so much progress in the modelling of the accelerators that we succeeded in pushing the accelerators beyond the expectation of the models. This indicates that machine near the half integer is much more sensitive and a better model is required to make any meaningful prediction.

## LUMINOSITY

More than 10% specific luminosity was gained after the tune change in the LER. Since then, additional 6% gain was coming from the minimization of the W-functions (the energy dependence of the beta-functions) in the horizontal plane in both rings by tweaking the sextupoles near the interaction point during the collision.

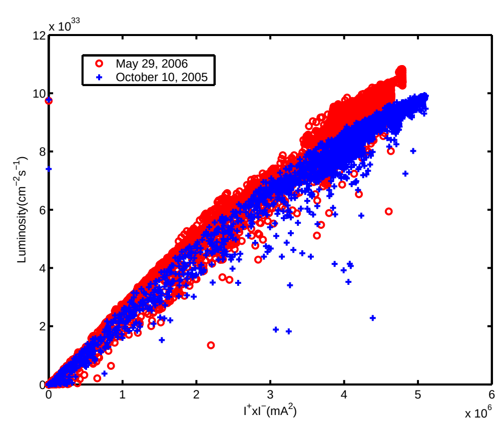


Figure 5: Measured luminosity as a function of product of beam currents for PEP-II. The blue pluses represent the best results achieved in October 2005 and the red circles are data in May 2006.

To show the recent increase of the luminosity, we plotted two sets of data in Fig. 5, each covered twenty consecutive days and included the peak luminosity in that run respectively. Compared to the last run, we were able to reach higher luminosity with less beam currents because of the reduction of beam sizes at the collision. The peak luminosity $1.0877 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved in May 25, 2006, with 1722 bunches at the beam currents, 1775mA in the HER and 2700mA in the LER.

## OTHER IMPROVEMENTS

In this paper, we made emphasis on the most recent events largely because they have made direct impacts on achieving the peak luminosity. Actually, many small but steady advances made on machine optics paved the way to the final success. Here is a list of major improvements since the beginning of this year:

- Reduced the beta beating in the HER from 250% to 10% and allowed its horizontal tune operated extremely close to the half integer.
- Speeded up the MIA fitting process and made it available online in the control system to improve the orbit steering and bump making.
- Minimized the orbit excursion and corrected the beta beating and coupling in the LER to reduce the over heating in the beam position monitors.
- Introduced many new correction schemes in LEGO to reduce the beta beating, coupling, and dispersion using orbit bumps at paired sextupole positions.
- Made the emittance knobs to better match the beams during the collision.

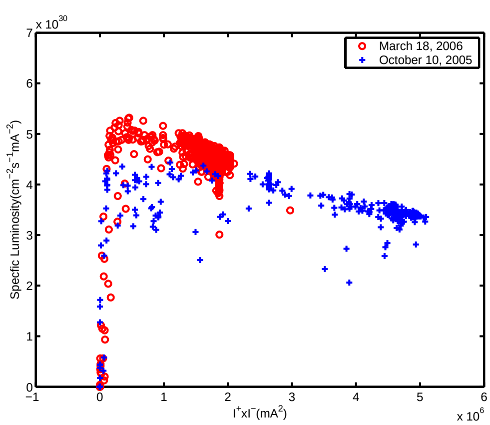


Figure 6: Specific luminosity as a function of product of beam currents for PEP-II. The blue pluses represent the best results achieved in October 10, 2005 and the red circles are the data in March 18, 2006.

As this progress was made, we saw a steady improvement in the specific luminosity, for example as shown in Fig. 6, at the low beam currents, which were limited by the vacuum problems at the time.

## CONCLUSION

The modern accelerators are controlled and continually improved using linear optics model. In this paper, we provided examples of how to use nonlinear models including the beam-beam interaction to improve the machine performance. These models were not only used to select a better set of machine parameters but also used to validate suggested optical improvements. As a result of using these nonlinear models, we have significantly increased in the rate of success for the MD at PEP-II and therefore saved valuable machine time for the delivery of luminosity.

As one could see in this paper, sometimes a prediction based on the model could be wrong. There are several common reasons that cause a model makes a wrong prediction: first, due to the inaccuracy of the data used to build model; second, missing nonlinear elements in the model; third, physics that is neglected in the codes; finally, human errors during the implementation of the prediction. All these uncertainties make the accurate and reliable prediction very difficult. Sometime making a prediction seems more like an art than science. Finally, we would like to point out that despite so many improvements we have made in the modelling efforts, the empirical tweak of skew quadrupoles and sexupole bumps by operators and accelerator physicists are still necessary and vital to achieve the peak luminosity at PEP-II.

It takes many years to develop codes for these sophisticated simulations. More importantly, dedicated experiments are required to validate the simulation codes before they could be used to make any reliable prediction. Here, we would like to stress the importance of supporting the long-term research activities for accelerator physics.

As the machines operated near the half integer, we found out recently that the beta beating in both rings became quite large again. A new round of improvement in optics is necessary to gain more luminosity. A challenge and quest for accurate modelling remain as we approach ever closer to the half integer.

## REFERENCES

[1] J. Irwin, *et al*, “Model-independent beam dynamics analysis,” Phys. Rev. Lett. **82** 1684-1687, 1999.

[2] Y.T. Yan and Y. Cai, “Precision PEP-II optics measurement with an SVD-enhanced least-square fitting,” Nucl. Instrum. Meth. A558:336-339, 2006.

[3] Y. Cai, M. Donald, J. Irwin, and Y. Yan, “LEGO: a modular accelerator design code,” SLAC-PUB-7642, August 1997.

[4] Y. Cai, A.W. Chao, S.I. Tzenov, and T. Tajima, “Simulation of the beam-beam effects in e+e- storage rings with a method of reducing the region of mesh,” Phys. Rev. ST Accel. Beams. **4**, 011001 (2001).

[5] Y. Cai, “Symplectic treatment of a finite crossing angle in the beam-beam collision,” SLAC-PUB-10674, August 2004, ICFA Beam Dyn. Newsletter, **34** 11-19, 2004.