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Tune Feed-Forward for PEP-II *

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The PEP-II B-Factory achieved design performances in 2000. The tune shifts of the rings are already about twice the design numbers of 0.03. This requires constant adjustments from the operators during fills and top-offs. A tune feedback was envisioned first, but the wide, multi-peaked tune signals make it tricky even for a human to adjust the tunes correctly. Since tunes are strongly correlated with the currents in the high and low energy rings (HER and LER), a tune feed-forward system was implemented. Each ring uses the measured dependences on its own current of about + or -0.018 per Ampere for the *x*- or *y*-tune. There is also a provision to adapt to the other beam's current. This parameter is usually a factor of ten lower. How these parameters change for different scenarios like optimizing the visual tune profile, the luminosity, or the measured single beam tune peak is discussed.

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1 FEED-FORWARD VERSUS FEEDBACK

Measuring the beam tunes and building a feedback to keep them constant was the initial goal to reduce the frequent adjustments by the operators. By looking at the LER tune spectrum (Fig. 1) it gets clear that this is not an easy task. The diamond-shaped markers near the vertical cursors show a frequency of 87.86 kHz in *x* and 75.88 kHz in *y* for the tune peaks. This divided by the revolution frequency of 136.311 kHz gives a tune of 0.645 and 0.557 respectively for *x* and *y*. The frequency spread due to collision-broadening is about 3 kHz or 0.022 in tune while the sensitivity to tune tweaks might be as low as 0.001.

Additionally, we also see the LER *y*-tune and the HER *x*-tune, around 79 kHz, on the upper plot. Another complication is that the LER *x*-tune sometimes splits into two or three peaks, making it really hard to figure out what the tune really is. These peaks represent most probably tune line of higher order [2], which excite the beam and cause some lifetime decrease.

It is possible to measure the tune of a non-colliding beam very precisely, because the peak is much narrower. This route is followed by the KEK B-factory, where the signal of a non-colliding pilot bunch is gated and its tune is measured and controlled. Since we don't yet have good single-bunch signals under these conditions, we went the other way to find the main cause of the tune shift and correct for it with a tune feed-forward.

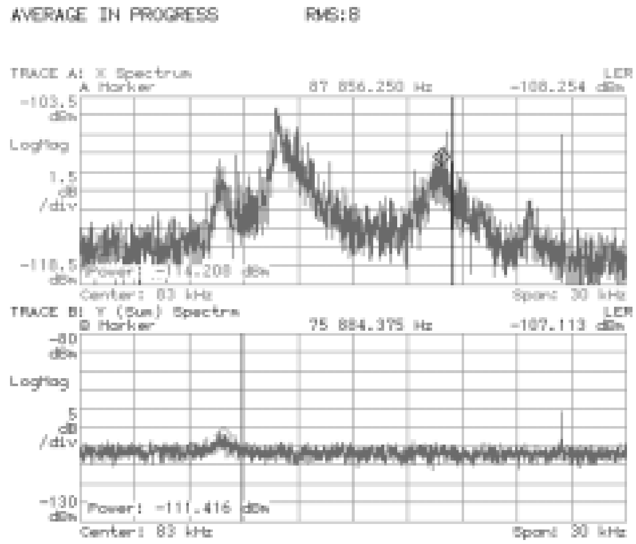

Fig. 1: LER tune spectrum with colliding beams: 1550 mA (LER) on 850 mA (HER). The spectrum shows a lot of structure, which make it hard to use it as a feedback.

2 DEPENDENCES OF THE TUNES

The beam tunes and especially the tune shifts depend on various parameters: the current in the ring, the bunch separation, and the shift due to beam-beam forces of the other beam.

2.1 Current Dependence

Due to the elliptical or hexagonal shape of the beam chamber (not symmetrically round), the tune shifts in *x* and *y* of a long bunch train have a current dependence with different signs due to the strong quadrupolar wake-field [1]. Otherwise, for a single bunch with mainly the dipole wakefield, it would be large and only negative, as measured in HER with -0.4/A and –1.1/A for an *x* and *y* tune change respectively [1]. For a by-4 bunch pattern with about 700 bunches this current dependence was measured (Fig. 2) and gave the following results:

Tunes	LER *x*	LER *y*	HER *x*	HER *y*
Tune slope [1/A]	0.0175	-0.0170	0.0145	-0.0195

Table 1: Tune shifts per current for LER and HER.

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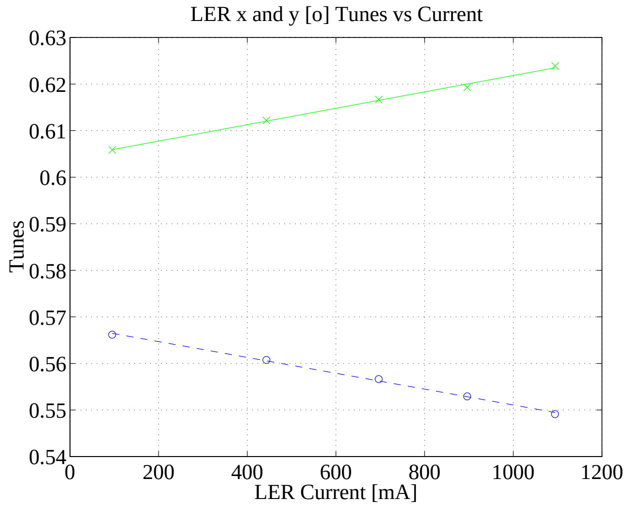

Fig. 2: LER tune variation versus current with 700 bunches in a by-4 pattern. The desired tune adjustments have nearly the same values with opposite signs.

2.2 Beam-Beam Tune Shift

The tune shift due to the beam-beam interaction depends on the beam sizes and the beta functions at the interaction point and of the current of the opposing beam. When the beam emittances and beta functions do not change, the tunes of one beam should be only dependant on its own current and of the current of the opposing beam. This assumption was used for the feed-forward system that will be described in the next paragraph. Even the case is covered for effects, where the resulting tune shift is linear with the currents. For instance, when the beam emittance and beta (dynamic beta) change, due to the beam-beam-force at the interaction point, induce a linear tune shift.

3 TUNE FEED-FORWARD SYSTEM

The basics of the tune feed-forward system are pretty simple. You measure the current of both beams I^+ and I^- with the DCCT (DC Current Transformer), multiply each of them with the negative slope factor (*a*, *b*) to find the desired change, e.g.: $\Delta\nu_x = a \cdot I^+ + b \cdot I^-$. This is done for LER and HER in *x* and *y*, and the corrections are applied with 'knobs', which adjust the tune quadrupoles. The coefficients (*a*, *b*) have to be determined experimentally and there lies a little problem. What are the right coefficients for colliding beams, for the coast down, for the fill from scratch; how does it change with time; should the coefficients be determined for the highest luminosity or the longest lifetime? All these questions are the source of many discussions among operators.

2.1 Initial Setup

The initial setup was used for the coast down after the rings were filled. The current variation is less than filling from zero, typically now from 1500 to 1000 mA in LER and from 850 to 800 mA in HER. This is a 40% variation in LER and only a 6% variation in HER, therefore the first parameters were setup for the LER ring.

It should be mentioned that a precursor of the feed-forward existed in the form of a 'correlation plot', where the tune quadrupoles were adjusted according to the time of a coast down. When the ring got filled this procedure had to be stopped and the tunes were abruptly restored in the middle of the top off, which gave of course some tune jump. The feed-forward was supposed to smoothen this and hopefully reduce also the necessary tweaks when filling from scratch. The initial coefficients for LER were between –15 and –20E–6/mA for ν_x and between 20 and 25E–6/mA for ν_y. These values have the opposite sign than in Tab 1, since they are the correction terms, otherwise they are very close to the single beam tune shift, which obviously dominates.

2.2 Optimizing the Tune Spectrum

As seen from Fig. 1 it seems difficult to optimize a certain tune spectrum. Due to the outstanding pattern recognition capabilities of a human being and especially of an operator, it was possible to try to duplicate a spectrum for different beam currents. This has the advantage of also giving the cross terms of the other beam (Tab. 2).

Tune	LER *x*	LER *y*	HER *x*	HER *y*
Coefficient of I^+ [E-6/mA]	–17.0	+20.0	+2.0	–2.5
Coefficient of I^- [E-6/mA]	–	–	–13.0	+27.0

Table 2: Correcting coefficients for a tune shifts per current for LER and HER.

Since the current in LER changes about ten times more than in HER (500 to 50 mA) during a coast, the overall HER correction nearly cancels: $\Delta\nu_x$ = (+2*500–13*50)E-6 = +0.00035 or $\Delta\nu_y$ = (–2.5*500+27*50)E-6 = +0.00010. This is the reason why it seems unnecessary to have the HER part of the feed-forward on, although it will help to fill from scratch (see below). The coefficients for the LER tunes from the HER current I^- has not any big significance since the HER current doesn't change much during the coast down and during the fill from scratch the HER ring usually gets filled first.

2.3 Luminosity and Lifetime

Since in the end the luminosity, or better the integrated luminosity, counts, we tried to arrive at coefficients to optimize these. The difference to Tab. 2 is small, but there is a compromise possible, which gives you more luminosity (around +5%) for less lifetime (–10%). This is done moving mainly ν_y and ν_x down, (ν_x is 40% less effective).

4 RUNNING EXPERIENCE

Running the PEP-II accelerator with the tune feed-forward has shown that the operators get time to concentrate on other things instead of constantly watching the tunes.

4.1 Top offs and Fills from Scratch

Figure 3 shows a typical 160 min period with four top-offs and one fill from scratch. The LER was under feed-forward control, while the HER was not. During top-offs the HER needs a manual change of -0.012 for ν_y, while it sometimes even need a small adjustment of +0.010 for ν_x (not seen here). The y tune change is mainly to get a clean injection with no backgrounds in the detector since the beam gets injected in y and has therefore an orbit with big oscillations.

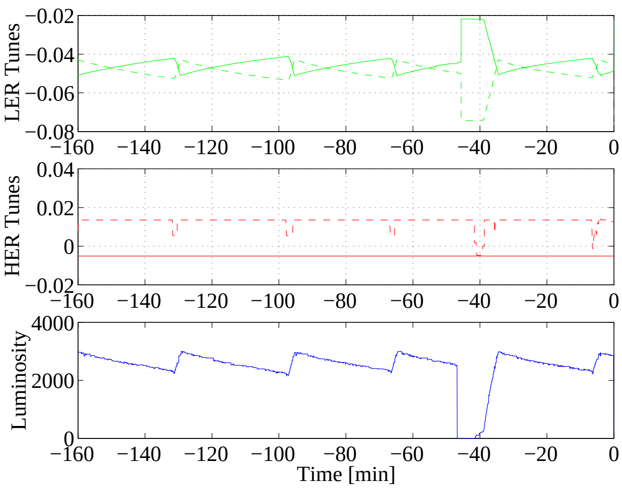

Fig. 3: LER and HER tunes as a function of time. The x (solid) and y (dashed) tunes are calculated backwards from the tune quad setting, including the part from the feed-forward and the operator tweaks.

4.2 Long Term Changes

The coefficients of the feed-forward can be adjusted, so that there is no additional intervention necessary by the operators. This is done by optimizing the tunes at the top of a fill, watching luminosity and lifetime. Then again at the end of a coast down we check whether any additional adjustments are necessary. The resulting tune change has to be divided by the variation in current, to get the amount by which to change the feed-forward coefficients (after which the system has to get restarted!). As seen in Fig. 4, these coefficients are not often changed: the LER ν_x coefficient varied in a range of –8 to –20E-6, while LER ν_y got changed between 10 and 26E-6.

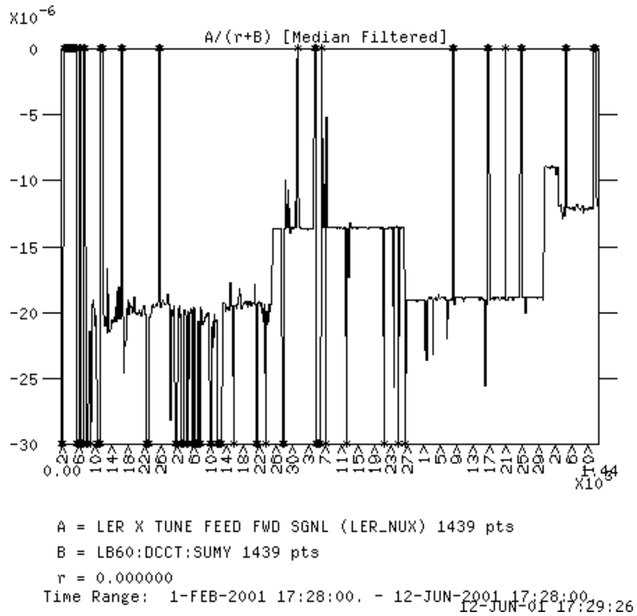

Fig. 4: History of the LER ν_x feed-forward coefficient, which was calculated by dividing the feed-forward signal by the LER DCCT current. Till March it was off, then it got turned on cautiously (-14E-6), at the end of April the old value of –20E-6 got restored, while recently other values were tested.

4.3 Slope Changes

Most probably due to the beam blow-up from beam-beam interaction or from the electron cloud in the LER, there seem to be hints that the straight linear approach is not enough and there should be a non-linear term or a kink in the variation of the tune versus current during a longer coast down.

5 SUMMARY

The tune feed-forward system takes care of the major tune changes, which are related to current changes. When the number of bunches changes, or the spot sizes at the interaction point the feed-forward coefficients might need some minor adjustments.

6 ACKNOWLEDGEMENTS

The operation crews had a very important role for figuring out the precise features of a tune feed-forward system and the calibrations of the coefficients. Special thanks go to Z. Van Hoover, J. Bringetto and H. Smith.

7 REFERENCES

[1] A. Chao, S. Heiferts, B. Zotter, “Tune Shifts of Bunch Trains due to Resistive Vacuum Chambers without Rotational Symmetry”, to be published.
[2] M. Minty, private communication.