# TRANSVERSE BEAM TAIL SHAPING IN HERA-P BY MEANS OF TUNE MODULATION

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## Abstract

The HERA-B experiment utilizes an internal wire target in the halo of the stored proton beam in order to study CP violation. As operational experience shows, interaction rates tend to be extremely sensitive to tiny orbit jitter amplitudes. In order to stabilize these interaction rates, various methods have been studied to increase diffusion in the transverse proton beam tails without affecting the luminosity at the electron-proton collider experiments ZEUS and H1. Tune modulation was found to be a promising method for this task. The present status of these experiments will be reported.

## 1  INTRODUCTION

To study CP violation, the HERA-B detector has been installed in the straight section West of the HERA proton ring. Using an internal wire target in the halo of the stored proton beam, the B-meson decay $B^0 \to J/\psi \, K_s^0$ is being investigated.

To achieve the required interaction rate of $\dot{N}_{\text{interaction}} = 40 \, \text{MHz}$, each bunch crossing has to provide about four interactions. The primary vertices of these interactions must exhibit a sufficient spatial distribution in order to allow a clear reconstruction. Therefore eight target wires of $50 \, \mu\text{m}$ diameter are arranged around the beam. To ensure equal contribution of all four wires to the overall interaction rate, each wire is equipped with a stepping motor that allows accurate target movements in nominal steps of $50 \, \text{nm}$. The interaction rate is kept constant using a $10 \, \text{Hz}$ wire position feedback, thus allowing to counteract slow beam orbit variations by target position adjustment.

As it was observed, this slow wire position feedback is not sufficient to ensure the required interaction rate stability. Especially at high interaction rates above some $20 \, \text{MHz}$ large fluctuations were observed, with relative rms deviations $\sigma_{\text{rel}} = \sqrt{\langle (\dot{N}_{\text{interaction}} - \langle \dot{N}_{\text{interaction}} \rangle)^2 \rangle} / \langle \dot{N}_{\text{interaction}} \rangle$ of more than $50\%$. This can be explained by lack of diffusion into the transverse beam tails, thus requiring the target wires to be positioned extremely close to the beam center, at typically $3 \ldots 4$ transverse rms beam sizes. This tight target aperture in turn leads to sharp "edges" of the initially gaussian distribution, resulting in a high sensitivity of the interaction rate to beam orbit vibrations.

To overcome this effect, a re-population of the transverse beam tails is required. Since HERA is not operated at any

dedicated run mode for HERA-B only, but simultaneously has to provide high luminosity for the colliding-beam experiments ZEUS and H1, this "tail shaping" has to be done in such a way that the detrimental effects at H1 and ZEUS, like luminosity degradation or increased background, are as small as possible. For this reason a simple slow transverse blow-up of the beam is not tolerable, and a more sophisticated method has to be chosen.

It is well known that tune modulation in connection with a strong nonlinearity, in particular the beam-beam interaction, results in an increased diffusion in the transverse beam tails, while the beam core, where the linear part of the beam-beam force dominates, is practically not affected [1, 2, 3]. These are just the properties required for "tail shaping".

In the presence of tune modulation, additional resonance sidebands are created. When the tune coincides with one of these sidebands, this leads to increased diffusion. The corresponding resonance condition can be written as

$$k \cdot Q + l \cdot \frac{f_{\text{mod}}}{f_{\text{rev}}} = m, \qquad k, l, m \text{ integer}, \qquad (1)$$

where $Q$ is the betatron tune and $f_{\text{mod}}$, $f_{\text{rev}}$ are the modulation frequency and the revolution frequency, respectively.

## 2  EXPERIMENTAL SET-UP

In the $920 \, \text{GeV}$ superconducting HERA proton storage ring the main quadrupoles are connected in series with the main dipole magnets. For a fine-adjustment and control of the tunes two families of superconducting quadrupoles are installed in each quadrant of HERA. In the quadrant West the chopper power supplies of these magnets are modified to provide an extra control input to allow for tune modulation with frequencies up to some $1.5 \, \text{kHz}$.

Due to the large inductance of the superconducting quadrupole magnets, high frequency modulation signals are effectively suppressed, while low frequencies of a few Hertz are counteracted by internal feedback loops of the power supplies. Figure 1 shows the measured magnet current (peak value) as a function of the modulation frequency for 1 Volt modulation amplitude of the power supply input signal and DC currents of $30 \, \text{A}$ and $60 \, \text{A}$, respectively. In both planes a magnet current of $1 \, \text{A}$ corresponds to a tune change $\Delta Q$ of about $5 \cdot 10^{-3}$.

The tune modulation input signal is provided by a PC with DATEL PC-420 [5] wave generator board, remotely controllable from the HERA control room. This board is capable of generating an arbitrary, continuous, periodic signal.

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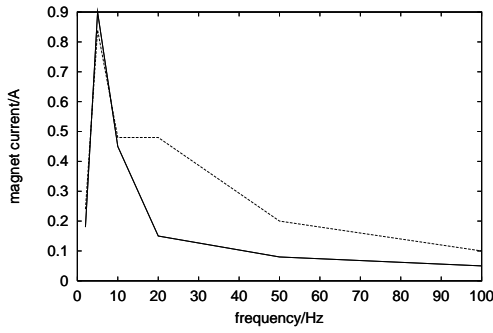[*] christoph.montag@desy.de

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Figure 1: Measured AC magnet current as function of frequency for an input voltage of 1 V and two DC magnet currents of 30 A (lower) and 60 A (upper curve), respectively [4]. The lines have been introduced to guide the eye.

## 3 EXPERIMENTS

During the dedicated tune modulation experiments as well as during regular luminosity operation the tunes were set to $Q_x = .297$ horizontally and $Q_y = .292$ vertically. Therefore the closest resonances of even order are $Q_{x,\mathrm{res}} = 0.3 = 3/10$ and $Q_{y,\mathrm{res}} = 0.286 = 4/14$. Taking into account a total beam-beam tune shift of roughly $\Delta Q_x = 1 \cdot 10^{-3}$, $\Delta Q_y = 2.5 \cdot 10^{-3}$ (the negative sign occurs due to positron-proton operation) and a revolution frequency $f_{\mathrm{rev}} = 47.3\,\mathrm{kHz}$, the resonance condition is therefore fulfilled for a tune modulation frequency of $f_{\mathrm{mod}} \approx 100\,\mathrm{Hz}$ horizontally, and $f_{\mathrm{mod}} \approx 280\,\mathrm{Hz}$ vertically. Here we have taken into account the betatron frequencies of particles in the transverse beam tails rather than the beam core.

The effect of tune modulation on the beam halo was studied in two steps. First a single target wire (Inner I) was moved into the beam halo until an interaction rate of 10 MHz was reached. After retracting the wire by $100\,\mu m$ the target position control was switched off, leaving the wire position constant. After some decay time a lower stable interaction rate of roughly 0.3 MHz was reached.

When the tune modulation was switched on, the new stable interaction rate was recorded. Figure 2 shows the achieved interaction rates for different tune modulation parameters, with

$$U(t) = \sum_i U_i \cdot \sin(2\pi f_i t) \qquad (2)$$

being the power supply AC input voltage that translates into AC magnet current according to Figure 1. For all measurements, the amplitude of all frequency components $U_i$ of the input signal was equal, but due to the frequency dependency of the output current this was not the case in the resulting AC magnet signal.

As Figure 2 shows, the maximum interaction rate was achieved by simultaneous application of two modulation frequencies, namely 190 Hz and 10, 20, or 40 Hz. At an AC magnet current of 1.37 A, an interaction rate of 23

resp. 30 MHz could be achieved. When the 190 Hz tune modulation component was switched off, the interaction rate significantly reduced to 0.35 resp. 0.6 MHz, though the relative reduction in the total AC peak current to 1.25 A was much smaller. When the 190 Hz component was turned on again at a reduced amplitude for both components, the resulting interaction rate of 0.9 MHz was significantly larger than with 10 Hz only even for a lower total AC magnet current of 1.05 A. Furthermore Figure 2 shows that the relation between total tune modulation amplitude and resulting HERA-B interaction rate is even better when the 10 Hz component is replaced by a 20 Hz or 40 Hz signal, while keeping the 190 Hz component. But since these frequencies are already strongly suppressed due to the large magnet inductance the maximum achievable interaction rate is still much smaller than in the case with the 10 Hz component. In a later dedicated HERA run in August
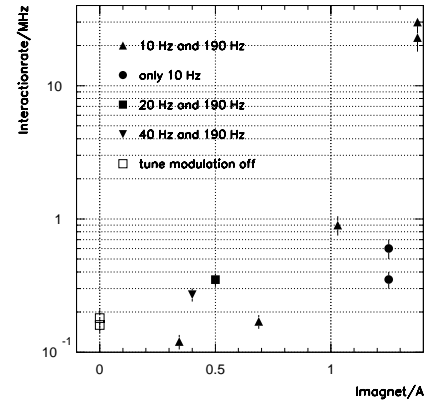


Figure 2: Interaction rates with fixed wire for different tune modulation parameters. For each setting, the input signal voltages for each frequency component are identical, but their sum might be varied. Due to the strong frequency dependency of the magnet power supply output current, the resulting total tune modulation amplitude is different for different frequency parameter sets.

2000 the effect of tune modulation on HERA-B interaction rate stability was studied in detail. For this purpose the wire position feedback was switched on and a single target wire was moved towards the beam until a stable interaction rate of 20 MHz was reached. To avoid artificial effects due to the identical 10 Hz frequencies used for interaction rate data sampling as well as tune modulation, a slightly different tune modulation frequency of 8 Hz resp. 12 Hz was used.

In a first step a tune modulation signal of 12 Hz frequency and 0.5 V resp. 1.0 V amplitude was applied to the beam. A second sine wave of equal voltage amplitude was added, the frequency being varied from 100 Hz to 500 Hz in steps of 100 Hz. Figure 3 depicts the resulting relative rms interaction rate width $\sigma_{\mathrm{rel}}$ as a function of the frequency of this

second input signal for different tune modulation depths.

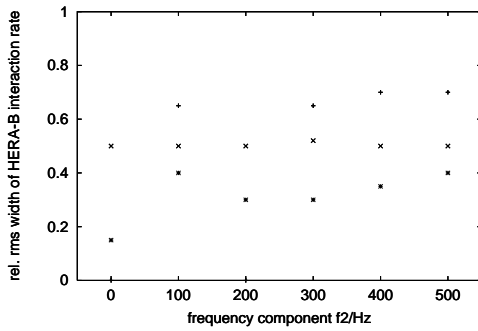In contrast to the measurements with a fixed target wire



Figure 3: Interaction rate stability for different tune modulation frequencies and three different amplitudes ($+$ : $0.5\,\mathrm{V}$, $\times$ : $1.0\,\mathrm{V}$, $*$ : $2.0\,\mathrm{V}$).

position, the interaction rate stability does not exhibit any significant dependency on the second frequency $f_2$. The rate stability depends strongly on the amplitude of the input signal, and thus on the resulting tune modulation depth. This was also observed when the $12\,\mathrm{Hz}$ was replaced by a $8\,\mathrm{Hz}$ signal.

When the tune modulation is switched on, the filling pattern of the electron beam is clearly reflected in the HERA-B interaction rates pe bunch, Figure 4. This is a clear indication
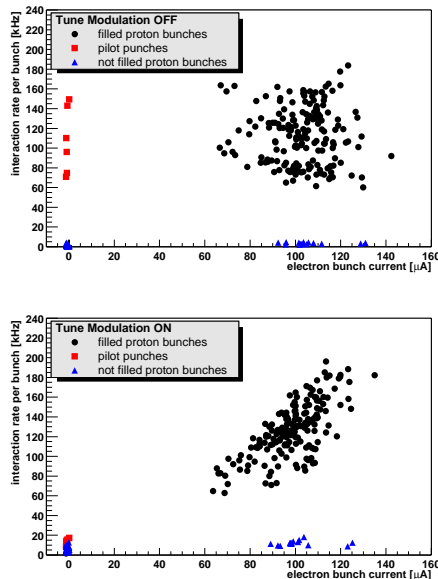


Figure 4: HERA-B interaction rate per bunch vs. bunch current of the corresponding electron bunch. Note that the last two proton bunches ("pilot bunches") in each 60 bunch train have no counterpart in the electron beam.

that the observed effect is indeed dominated by the beam-beam interaction in combination with tune modulation, and not just an orbit effect due to dipole fields caused by orbit

distortions in the modulated quadrupoles.

In parallel to these experiments the specific luminosity at the two colliding beam experiments ZEUS and H1 was recorded. As Figure 5 shows, these tune modulation studies did not result in any decrease of specific luminosity. Furthermore, no significant increase of experimental back-
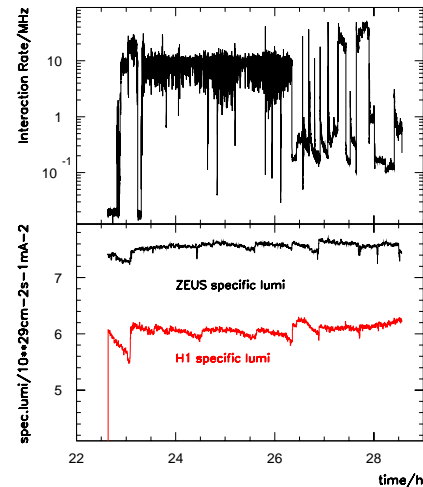


Figure 5: HERA-B interaction rate (top) and specific luminosity during a dedicated run for tune modulation studies (bottom). The luminosity tends to decrease due to slow orbit drifts, but recovers to the initial value after tuning.

ground was observed during several weeks of operation of the tune modulation during regular HERA luminosity runs.

## 4 CONCLUSION

It has been successfully demonstrated that the interaction rate at the internal halo target of the HERA-B experiment can be significantly stabilized by means of tune modulation. Since this method does not result in any detrimental effects such as increased background rates or degradation of specific luminosity at the colliding beam experiments ZEUS and H1, it has become a standard procedure in regular HERA runs.

## 5 REFERENCES

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