EXAMINATION OF THE LONGITUDINAL STABILITY OF THE HERA PROTON RING

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Abstract

Since the luminosity upgrade of the electron proton collider HERA, the proton bunch length is relevant for the achievable luminosity. Coherent oscillations of the proton beam during acceleration lead to an increase of the bunch length and a decrease in luminosity. A fast longitudinal diagnostic system was developed to investigate these oscillations. Applying a modal analysis one can check whether coupled bunch oscillations are correlated with the increase in the longitudinal emittance. Measurements of decoherence times supply information about available Landau damping. The results obtained, provide the necessary information for the design of feedback systems.

1 INTRODUCTION

At HERA, new, strong focussing, superconducting magnets inside the detectors H1 and ZEUS lead to smaller beam cross sections at the interaction regions and hence, to higher luminosity. Due to the strong focussing, the beta function and the bunch length are comparable in magnitude. This enhances the effective cross section, 'hour-glass-effect' [1]. A reduction of the bunch length would result in smaller effective cross sections and so further increase the luminosity.

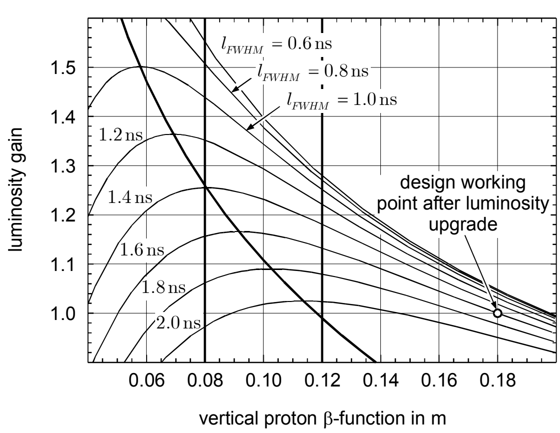

Figure 1: Dependence of the luminosity gain on the vertical proton β-function and the bunch length. ($\mathcal{L}_{design} \approx 7 \cdot 10^{31} \frac{1}{\mathrm{cm}^2\,\mathrm{s}}$)

Figure 1 shows the luminosity gain, scaled from the design value as a function of the vertical proton β-function and the bunch length[1].

Typical FWHM bunch lengths after injection (40 GeV) into 52 MHz buckets are 2.4 ns, during ramping (to 920 GeV) these reduce to 1.6 ns due to the compression of an additional 208 MHz RF system. Theoretically one would expect a bunch length of $l_{920\,\mathrm{GeV}} \approx 0.27\, l_{40\,\mathrm{GeV}}$ i.e. ≈ 0.6 ns. This means that there are processes during the ramp which increase the longitudinal emittance. In order to take measures against this emittance dilution it was first necessary to develop new diagnostic tools, which measure the longitudinal positions and the lengths of all 180 proton bunches in HERA simultaneously.

2 FAST LONGITUDINAL DIAGNOSTICS

A bunch passing a resistive gap monitor produces a broadband RF pulse, whose shape is identical with the longitudinal bunch shape. This signal is analyzed by analog signal processing [2]:

The bunch signal excites an oscillation in a 52 MHz band pass filter, whose properties are chosen so that the oscillation stops when the signal from the next bunch arrives after 96 ns. This oscillation is down-converted by an I/Q demodulator to the real and imaginary part from the accompanying phasor. By sampling these parts at the maximum value of the phasor length one obtains, via the arctangent, the bunch phase and, via the absolute value, the 52 MHz Fourier coefficient.

Assuming a specific bunch shape, one can calculate the bunch length from two Fourier coefficients at two different frequencies of the longitudinal bunch shape. By using a 208 MHz band pass filter and a RF diode a second Fourier coefficient is determined.

For the detection of multi-bunch oscillations, the clock (10.4 MHz) and trigger signals must be provided to the ADCs in a special way:

The ADC boards used, are able to start several times a measurement cycle with an eligible number of samples, before reading out. Sampling all 220 bunch positions, separated by 96 ns, only every 104th revolution has turned out to be a good compromise between time and frequency resolution. In this way, the phase and amplitude of an individual bunch are sampled with a frequency of 455 Hz (47.310 kHz / 104), fast enough for the observation of bunch phase oscillations (about 40 Hz) and length oscillations (about 80 Hz).

[1] Here we quote bunch length in the time domain.

3 MULTI-BUNCH OSCILLATIONS AND EMITTANCE DILUTION

With the new diagnostic system one is able to determine whether the emittance dilution is correlated to multi-bunch oscillations [2].

The time-evolution of the emittance [3, 4] is plotted in the upper graph of figure 2. One observes a strong increase

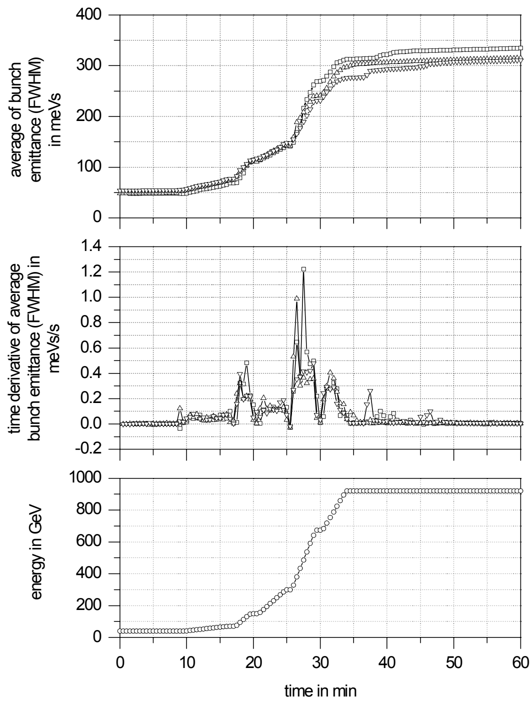

Figure 2: Evolution of the longitudinal emittance (FWHM) during the energy ramp from 40 GeV to 920 GeV.

in the emittance from 40 GeV to 920 GeV. To provide more insight, the time derivative of the emittance is also plotted. It exhibits strong maxima associated with multi-bunch oscillations of large amplitude.

4 MODAL ANALYSIS

Bunches, passing an impedance in a storage ring, excite electromagnetic fields. These fields influence subsequent bunches. This mechanism can lead to a coupling of bunch oscillations. This is only expected for particular resonant frequencies of the impedance and when the synchrotron frequencies of the individual bunches have similar values [5].

If the multi-bunch oscillation pattern is composed by only a few modes, coupling is present. According to the properties of the coupling impedance, some modes are unstable. A growing oscillation amplitude, together with emittance blow-up, is evidence of a coupled bunch instability. In the case of non-coupled bunches, the multi-bunch oscillation is made up of a random distribution of all modes.

Figure 3 shows a multi-bunch phase oscillation during ramping of the 180 proton bunches in HERA. One can im-

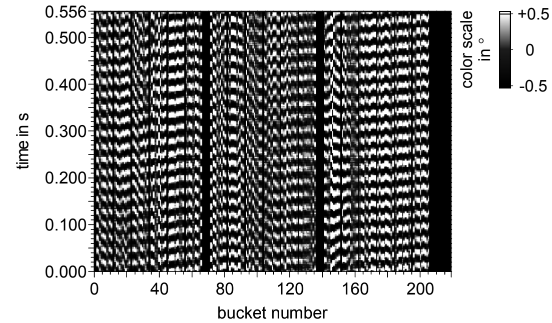

Figure 3: Multi bunch phase oscillation during ramping, showing particular modes. (Beam current: 110 mA)

mediately recognize regular patterns. One is a phase shift of $2\,\pi$, accumulated over the whole bunch train, e.g. from bunch position 0 to 219. A second phase shift leads to 'lines' from top left to bottom right.

By applying the modal analysis described in [2] we obtain the modal spectrum shown in figure 4.

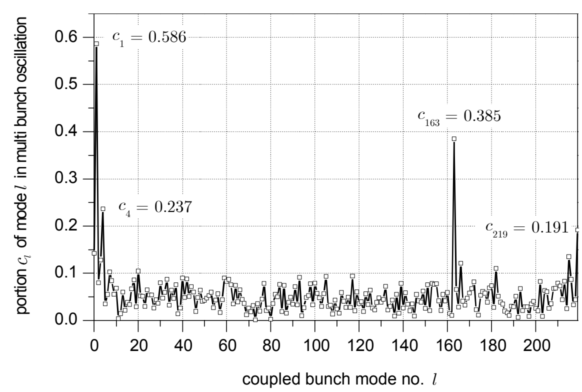

Figure 4: Modal spectrum of multi bunch oscillation.

The multi-bunch oscillation in figure 3 consists mostly of mode $l = 1$ which shows the above mentioned phase shift of $2\,\pi$ from bunch position 0 to 219. The second strong mode is $l = 163$ which is near $l = \frac{3\,M}{4} = 165$. It is one of the unstable modes, most likely to occur [2, 5].

Half a minute later, multi-bunch oscillations are still present but they are composed uniformly of all modes, i.e. they are de-coupled.

All the ramps, which were observed, behaved similarly, i.e. coupling is visible several times but disappears again after a short time, as the bunch to bunch frequency spread and the emittance increase. The values observed fit with the rule-of-thumb for coupling and de-coupling of bunch oscillations [5].

From the available recorded data of multi-bunch oscillation patterns, one can determine, by making particular assumptions, an instability growth rate of $\frac{1}{\tau} = 1\,\frac{1}{\mathrm{s}}$ [2].

5 WHICH IS THE DRIVING IMPEDANCE?

The first step to preserve emittance, is to try to find the source of the unstable beam behavior.

A method to identify possible sources for beam instabilities is, to estimate the so called effective impedance of every individual device [6]. The total impedance is a measure of the overall stability. Using the relations from [6] we can calculate the strength of the total impedance, driving the observed bunch oscillations. The result is $|Z_{eff}| \approx 0.5\,\Omega$. By the calculation of the effective impedances we determine a sum value in the same order of magnitude [2]. This value is state-of-the-art for proton accelerators and indicates that the coupled bunch oscillations are not driven by a single strong impedance.

6 SUFFICIENT LANDAU DAMPING?

A rule-of-thumb, for suppression of an instability by Landau damping, is that the intra-bunch frequency spread should be four times greater than the instability growth rate [5, 7].

Measurements of the decoherence time τ_d provide information on the intra-bunch frequency spread s_ω and, consequently, the Landau damping. The bunch center oscillation, after a small RF phase kick, decays for a Gaussian bunch with a time constant of $\tau_d = \frac{\sqrt{e-1}}{2\,|s_\omega|} \approx \frac{0.655}{|s_\omega|}$ [2, 8].

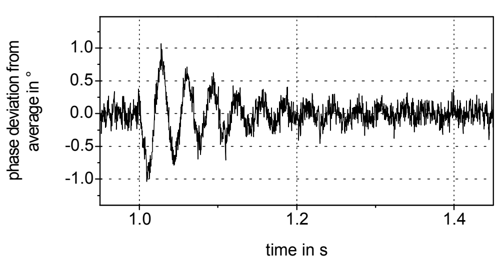

Figure 5: Typical single bunch kick response (at 920 GeV).

Figure 5 shows a typical measured bunch response. The value for the frequency spread at 40 GeV is $s_\omega \approx 28\,\frac{1}{\mathrm{s}}$, and at 920 GeV we have $s_\omega \approx 8\,\frac{1}{\mathrm{s}}$. Hence, an instability with a growth rate smaller than $7\,\frac{1}{\mathrm{s}}$ is Landau damped at 40 GeV and at 920 GeV if the growth rate is smaller than $2\,\frac{1}{\mathrm{s}}$. The spread obtained at 920 GeV fit with the expectation $|s_\omega| \approx \frac{4.10}{\mathrm{s}}\,(l_{FWHM}\,/\,\mathrm{ns})^2$ [2] for a bunch length of 1.4 ns. But, the theoretically accessible bunch length (0.6 ns) shows a spread of $1.5\,\frac{1}{\mathrm{s}}$. For such short bunches only instabilities with growths rates smaller than $0.4\,\frac{1}{\mathrm{s}}$ are suppressed. The instabilities observed are stronger.

7 CONCLUSION

In this paper, the occurrence of coupled bunch instabilities during proton acceleration in HERA and the longitudinal stability have been discussed. Coupled bunch oscillations appear not to be driven by a single strong impedance. At 40 GeV the instability threshold is not exceeded. During acceleration Landau damping seems to be reduced by the shortening bunches. Coupled bunch oscillations lead to a bunch lengthening, to larger frequency spread and more Landau damping, until the beam is stabilized.

To improve the longitudinal stability, one should consider a further reduction of over all machine impedance - not easily obtainable. Whether a Landau damping cavity, or a coupled bunch feedback would lead to shorter bunches at high energy, requires some consideration.

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