HEAD-TAIL INSTABILITY AT TEVATRON*

P. M. Ivanov#, J. Annala, A. Burov, V. Lebedev, E. Lorman, V. Ranjbar, V. Scarpine, V. Shiltsev
FNAL, Batavia, IL 60510, USA

Abstract

Tevatron performance suffers from a coherent transverse instability. Experimental and theoretical studies allow identifying the instability as a weak head-tail, driven by the short-range wake fields in presence of the space charge. Growth rates and coherent tune shifts are measured at injection of single high-intensity proton bunch using a fast strip-line pickup. Landau damping through the octupole-generated betatron tune spread for all unstable head-tail modes has been demonstrated.

INTRODUCTION

In order to prevent developing a transverse coherent instability for high intensity proton beam, the Tevatron lattice chromaticities should be set above $\xi_{x,y} \cong 8$ at the injection (150 GeV) and above $\xi_{x,y} \cong 26$ at the collision energy (980 GeV). Although it suppresses the instability, it results in a degradation of the machine performance due to reduction of beam lifetime. Observation of the particle loss in vicinity of the CDF-detector clearly demonstrates that the minimum loss is achieved at $\xi_{x,y} = 0$ [1], and the loss increases with growth of absolute value of the chromaticity. That stimulated us to investigate a driving mechanism for this instability, as well as to search for possible solutions to operate at zero chromaticities. The measurements performed in November 2002 exhibited that the transverse impedance significantly exceeds the Run II transverse impedance budget [2]. The source of the excessive impedance was tracked to two laminated Lambertson magnets. The removal one of them in January 2003 shutdown significantly reduced the chromaticities required for the beam stabilization. This summer we plan to insert a shielding liner into the remaining injection Lambertson magnet.

INSTABILITY OBSERVATION

A fast digital oscilloscope, connected to the horizontal and vertical 1-meter long strip-line pickups, records turn-by-turn data for 2000 turns. Each turn data are sampled during 80 ns with 0.4 ns rate so that the transverse head-tail dynamics of single bunch could be observed. After the measurement, the signal is deconvoluted and transverse positions along the bunch are computed. The measurements are synchronized with the beam injection. Chromaticities are set below zero so that the mode l=0 would be unstable.

At N_{ppb}=2.6·10^{11} and chromaticity values of $\xi_{x,y} \approx -2$, we identified that the coherent mode with l = 0 was developed with the coherent tune shift $\Delta\nu$=0.0011±0.0001 and the growth rate $1/\tau_0$=120±5 s^{-1}. The coherent tune shift for the strongest mode is smaller than the synchrotron tune, $\Delta\nu \approx 0.7\nu_s$. That classifies the instability as a weak head-tail.

To crosscheck the measurements we also measured the chromaticity by pinging the beam and measuring the phase shift between head and tail. The chromaticity was calculated from this phase difference according to [3]:

$$\xi_{x,y} = -\eta \frac{\Delta\Psi_{x,y}}{\omega_0 \Delta\tau \left(\cos(2\pi n \nu_s) - 1\right)} \qquad (1)$$

Here $\Delta\Psi$ is the head-tail phase difference, η is the slippage factor, ω_o is the revolution frequency, and $\Delta\tau$ is the time length of the bunch. Comparison of the head-tail chromaticity measurement with the traditional RF technique is presented in Figure 1.

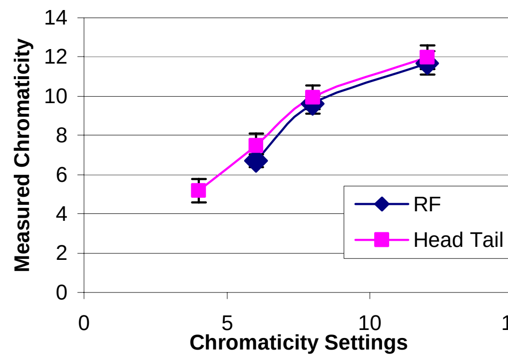

Figure 1. Comparison of the Head-Tail chromaticity measurement with the traditional RF technique.

To compute the transverse impedance with good accuracy we build a computer model of the instability. An ensemble of macro-particles with the Gaussian longitudinal distribution has been tracked many turns for particles interacting through the resistive wake field. The Landau damping was not taken into account in the model, and therefore matching the measurements and simulations yields the low boundary for the transverse impedance. The measurements were performed at the injection orbit where the growth rate is 120 s^{-1}. That results in $Z_{\perp min} \approx$ 4-5 MΩ/m.

Tevatron stainless steel vacuum chamber has a square cross section with 2h=6 cm, the transverse impedance of which amounts to ~0.9 MΩ/m at 100 MHz [2]. That is about 5 times smaller than the measured value. After careful examination it was suggested that a major source of impedance is the Lambertson injection magnet. Its value can be estimated by integrating the resistance over

* Work supported by the Universities Research Assos., Inc., under contract DE-AC02-76CH03000 with the U.S. Dept. of Energy.
# pmivanov@fnal.gov

the low frequency current pass through the laminas [4]:

$$Z_{\perp} \approx \frac{2Z_o}{\pi\, b^2} \cdot \frac{\mu}{\kappa} \cdot F \cdot \frac{L}{d} \qquad (2)$$

where $\kappa^2 = -4\pi i \sigma\mu\omega / c^2$, $Z_o \approx 377\Omega$, $\mu \cong 100$, $F = 0.5 - 1.0$ is a geometry form-factor, $L = 11.2\ m$ is a total length of the magnet, $d \approx 1\ mm$ is the lamination thickness, and b is the distance from the beam to the wall.

To prove that the injection Lambertson magnet makes dominant contribution into the transverse impedance the stability bounds in chromaticity space have been measured for the three local beam orbit offsets (see Fig.2). The results are presented in Figure 3. As one can see the beam displacement in the magnet strongly affects the stability bounds. Using Eq. (2) one can find the following values for the Lambertson transverse impedance at different locations inside the magnet: (1) injection local orbit bump, b_1≈6 mm, $Z_{\perp}$≈5 MΩ/m; (2) central regular orbit, b_2≈9 mm, $Z_{\perp}$≈1.8 MΩ/m; (3) local orbit bump with respect to the central orbit, ΔY=-3 mm, ΔX=-10 mm, b_3≈18 mm, $Z_{\perp}$≈0.6 MΩ/m.

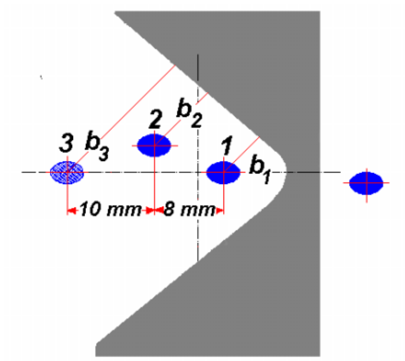

Figure.2. Layout of the local orbit bumps.

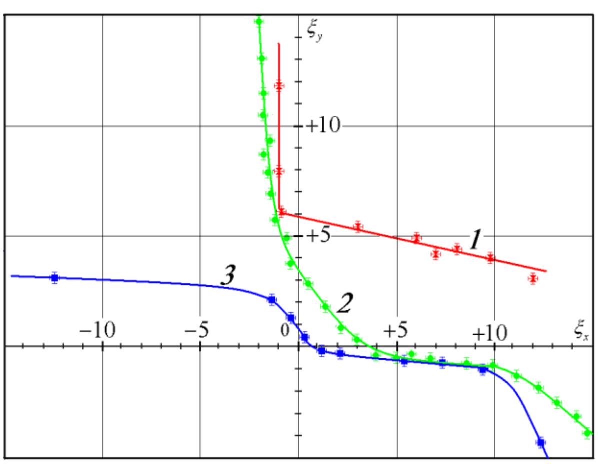

Figure 3. The stability regions for the head-tail modes in the chromaticity space. All measurements are performed with single proton bunch (N_{ppb}=2.65·10^{11}). The thresholds of the excitation correspond to an increase in the coherent component of the Schottky spectrum as the chromaticities were smoothly decreased.

On the injection orbit, the head-tail instability is polarized in the vertical plane at positive chromaticities. Stability is limited by excitation of the quadrupole mode with longitudinal number ***l=2*** (see Fig. 4). The coherent mode with the monopole longitudinal configuration ***l=0*** limits stability in horizontal plane when $\xi_x \approx -1$.

Horizontal and vertical impedances of Eq. 2 are approximately equivalent, but the stability bounds for the vertical and horizontal modes are different (Fig.3). A possible reason could be related to the space charge tune shifts, which are different for the two planes because of dispersion. The vertical incoherent shift is two times larger than the horizontal shift. Calculated coherent tune shifts for the first two horizontal modes are found to be comparable with the incoherent space-charge tune shift that promotes Landau damping due to a synchrotron tune spread. The vertical modes are in worse conditions because the space-charge shift is higher. At Tevatron injection energy the synchrotron tune and rms-tune spread are: $\nu_{s0} = 1.8\cdot 10^{-3}, \delta\nu_s \approx 2.2\cdot 10^{-4}$.

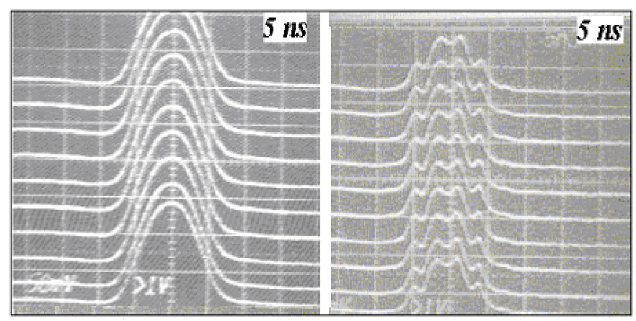

Figure 4. Longitudinal density profiles of the initial (N_{ppb}=2.65·10^{11}) and remaining (N_{ppb}=1.03·10^{11}) proton bunches before and after self-stabilization of the vertical instability due to the particle losses. The particles were lost in accordance with the longitudinal configuration of the coherent vertical oscillations that points qualitatively at excitation of the head-tail mode with ***l=2.***

The Tevatron tunes ν_x=20.585 and ν_y=20.575 are located in vicinity of the coupling resonance ν_x - ν_y=0. At crossing the resonance both the vertical and horizontal coherent modes become unstable that can be caused by a repartition of the direct space-charge tune shift between two normal betatron modes with the coupling increased.

On central orbit (curve 2 in Figure 3), a single coherent vertical mode with dipole longitudinal configuration is observed at the chromaticity threshold $\xi_y \le 3$. The horizontal higher order head-tail modes are stable out of the resonance ν_x - ν_y=0.

At the orbit bump (ΔY=-3 mm, ΔX=-10 mm) with negative chromaticities (curve 3), the unstable mode ***l=0*** can be easily stabilized by means of octupoles. Similar stability conditions are expected after installation of planned shielding of the magnet bare lamination.

These experimental studies clearly identified the transverse coherent instability as a single bunch head-tail effect, driven by resistive wall impedance [5].

SPACE CHARGE EFFECT

The space charge effect results in a non-linear incoherent detuning and plays important role in coherent head-tail dynamics. Laslett tune shifts due to electric- and magnetic-image fields are not included in our consideration because for the Tevatron performance parameters, the image terms are negligibly small as compared with a contribution of the electromagnetic self-fields. For the 3D-Gaussian charge distribution the direct space-charge linear tune shifts are given by:

$$\Delta\nu^{sc}_{x,y} = -\frac{N_{ppb}\, r_0\, R_0}{\sqrt{2\pi}\beta^2\gamma^3\sigma_z}\left\langle \frac{\beta_{x,y}}{\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}\right\rangle \quad (3)$$

where $\sigma_{x,y}(s)=\sqrt{\varepsilon_{x,y}\beta_{x,y}(s)+D^2_{x,y}(s)\sigma^2_{\Delta p/p}}$ are the transverse beam sizes, the $\langle\cdots\rangle$ -denotes averaging over the machine. For N_{ppb}=2.6·10^{11} and $\sigma_S = 90cm$, it comes out as:

$$\Delta\nu^{sc}_x \approx -0.36\cdot10^{-3},\ \Delta\nu^{sc}_y \approx -0.7\cdot10^{-3}$$

DAMPING OF THE HEAD-TAIL MODES

Presently, in order to work at low chromaticities ($\xi_x\approx6$, $\xi_y\approx4$), the transverse dampers are used to prevent an excitation of the transverse instability at the multi-bunch mode of operation [7].

An universal method for damping the instability is to introduce a betatron frequency spread that is larger than the growth rates. Landau damping is effective when the following approximate condition is satisfied:

$$\sqrt{\left(\delta\nu^{oct}_{x,y}\right)^2+\left(\delta\nu^{sc}_{x,y}\right)^2+\left(|l|\cdot\delta\nu_s\right)^2} \ge \left|\Delta\nu^{sc}_{x,y}-\Delta\nu^{coh}_{x,y}(l)\right| \quad (4)$$

The two Tevatron regular octupole families are used to provide Landau damping for the head-tail modes:

$$OZD\left(n=12,\ \beta_x>\beta_y\right),\ OZD\left(m=24,\ \beta_y>\beta_x\right).$$

There are two sources of the octupole-driven tune spread: first due to the betatron amplitude spread, and second due to the dispersion in the octupole locations.

$$\delta\nu^{\beta}_{x,y}=\frac{1}{16\pi B\rho}\left[J_{x,y}\sum_1^{n,m}\left(\bar{K}_3\beta^2_{x,y}\right)_{n,m}-2J_{y,x}\sum_1^{n,m}\left(\bar{K}_3\beta_x\beta_y\right)_{n,m}\right] \quad (5)$$

$$\delta\nu^{D}_{x,y}=\frac{\sigma^2_{\Delta p/p}}{16\pi B\rho}\sum_1^{n,m}\left(\bar{K}_3\,\beta_{x,y}\,D^2_x\right)_{n,m} \quad (6)$$

where $J_{x,y}=a^2_{x,y}/\beta_{x,y}$ are single particle Courant-Snyder invariants and

$$\bar{K}_3(n,m)=I_{n,m}(Amps)\int_0^L\frac{\partial^3 B_y}{\partial x^3}ds\,/\,1\,Amp$$

$$\bar{K}_3(n,m)=616\cdot I_{n,m}(Amps)\quad [T/m^2]$$

are the normalized octupole strengths with I_n and I_m as the OZF- and OZD-family octupole currents. On the central orbit, damping the vertical mode ***l=1*** required currents $I_{OZD}\approx4.2$ A and $I_{OZF}=0$ with the estimated tune spreads as:

$$\left\langle\delta\nu^{Oct}_y\right\rangle\approx0.28\cdot10^{-3},\ \left\langle\delta\nu^{Oct}_x\right\rangle\approx1\cdot10^{-4}.$$

At the chromaticity of $\xi_{x,y}\approx-2$ the coherent mode ***l=0*** has been stabilized at $I_{OZD}\approx5.0$ A and $I_{OZF}=2.0$ with $\left\langle\delta\nu^{Oct}_y\right\rangle\approx0.52\cdot10^{-3}$, $\left\langle\delta\nu^{Oct}_x\right\rangle\approx0.38\cdot10^{-3}$.

In both cases the widths of betatron spectra measured by Schottky monitor are in a reasonable agreement with this calculation taking into account the contributions from the synchrotron and direct space-charge tune spreads. The octupole cubic non-linearity has the positive sign that is better from dynamic aperture point of view since the vertical tune is slightly above the resonance ν_y= 4/7. Besides, it has the “right” sign to minimize the octupole strengths of the *OZD*-family in consequence of:

$$\left(\Delta\nu^{sc}_y-\Delta\nu^{coh}_y(l=0)\right)>0$$

In the horizontal plane the incoherent and coherent tune shifts are comparable but the space-charge tune spread does not promote Landau damping without octupoles.

CONCLUSION

The observed single-bunch head-tail instability has been found to be driven by the resistive impedance of laminated Lambertson magnets. To reduce the impedance, the insertion of a thin shielding liner inside the magnet is planned. It is expected that it will stabilize the higher order head-tail modes at positive chromaticities and significantly reduce the growth time at negative chromaticities.

Landau damping through the octupole-generated betatron tune spread for all of the unstable head-tail modes at positive and negative chromaticities has been seen. After performing additional experimental studies, this method is planned to be involved in the routine machine operations. That will result in an enhancement of the peak and integrated luminosity.

ACKNOWLEDGMENTS

We would like to thank V. Danilov (ORNL) for useful discussions of the instability problems and Dean Still (FNAL) for helping in machine studies.

REFERENCES

[1] X. Zhang, *et al.*, Experimental Studies of Beam-Beam Effects in Tevatron, Proc. of this conference.

[2] Tevatron Run-II Handbook, FNAL 1998.

[3] D. Cocq et. al., The measurement of chromaticity via a head-tail phase shift, BIW98, Stanford CA, 1998.

[4] A. Burov, V. Danilov, unpublished note, 2003.

[5] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, John Wiley&Sons, New York, 1993

[6] D.Mohl, Part.Acc.,v.50, p.177, 1995.

[7] C.Y. Tan, J. Steimel, The Tevatron Transverse Damers, Proc. of this conference, RPPB025, 2003.