TRANSVERSE INSTABILITIES IN RHIC*

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Abstract

The beam quality in RHIC can be significantly impacted by a transverse instability which can occur just after transition[1]. Data characterizing the instability are presented and analyzed. Techniques for ameliorating the situation are considered.

DATA

During the run of 2003 a button beam position monitor was used to measure instabilities in the deuteron beam. During the injection process the most intense bunch was determined. Beginning at transition, triggers were generated every 100 turns (1.28 ms) for this bunch. A total of 4000 triggers were generated each acceleration cycle and sent to a digital oscilliscope (Lecroy waverunner) in segmented memory mode. Each trigger generated 200 ns of data sampled at 2 GHz. Instabilites were observed in the vertical plane. Horizontal signals were much smaller.

Figure 1 shows a mountain range plot of sum (blue) and difference (red) signals from the buttons. The spacing between the buttons is 7 cm. The RC time constant of the button is 0.5 ns and has been ignored in the analysis. Trigger jitter was removed by integrating the sum signal, fitting a parabolic cap to the peak, and shifting the data using linear interpolation. Next, closed orbit effects were removed by subtracting the same fixed multiple of the sum signal from all the difference signals. Finally, each difference trace was viewed as a vector and a principle component analysis was done. This technique is refered to as canonical variables in the statistical literature [2]. In brief, one starts with a set of vectors $v_m(n)$, where $m = 1, 2, \ldots M$ is the index within a vector, and $n = 1, 2, \ldots N$ denotes the vector in the set. In Fig 1, each red trace corresponds to a different n, and m varies from 1 to $M = 30$ within a trace. The question is whether it takes all 30 indicies to characterize the data. Toward this end assume the existence of a vector x_m and consider the Lagrangian

$$L = \sum_{n=1}^{N} \left(\sum_{m=1}^{M} v_m(n) x_m \right)^2 - \lambda \sum_{m=1}^{M} x_m^2,$$

where λ will be an eigenvalue. Demanding that $\partial L/\partial x_k = 0$ for $k = 1, 2, \ldots M$ leads to the equations of principle component analysis. A principle component analysis corresponds to changing the set of basis vectors, and this new set of basis vectors concentrates the signal power in a natural way. A similar technique has been used to great benefit in various steering algorithms at the SLC [3]. Fig. 2 shows the 3 strongest principle components for the data in Fig. 1.

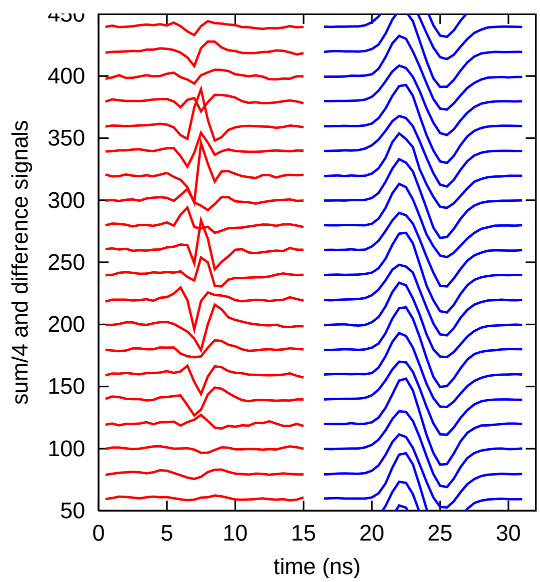

Figure 1: Difference (red,left) and sum (blue,right) data from a pair of vertical buttons. The sum data have been divided by 4.

Using the raw button signals leads to the least noise in the principle component analysis but the eigenvectors are not intuitive. Integrating the eigenvectors with respect to time yields a basis that is proportional to the product of the offset and the instantaneous current. Fig. 3 shows the integrals of the principle components as well as the reconstructed beam current pulse from the average of the sum signal. The three strongest principle components are concentrated near the middle of the beam pulse. This is not a rigid or head-tail mode. The time series of the principle components are shown in Fig. 4. The envelope over-plotted on component 1 has an e-folding time of $\tau = 15.4$ ms. During the exponential phase, the amplitude of vertical oscillations evolves as $\hat{y} \propto \exp(t/\tau)$. The synchrotron frequency was $f_s = 14$ Hz, and the e-folding time of the transverse mode coupling instability should satisfy $\tau_{TMC} \gtrsim 1/\pi f_s = 23$ ms. After the instability saturates, the signal for component 1 beats with a ~ 30 ms period. This

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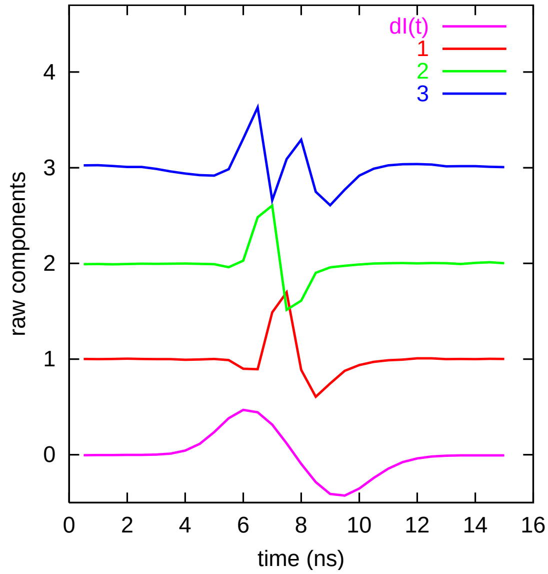

Figure 2: Average of sum signal and 3 strongest principle components for data in Fig 1. Component 1 accounted for most of the variation, then 2, then 3. The traces are offset vertically to improve clarity.

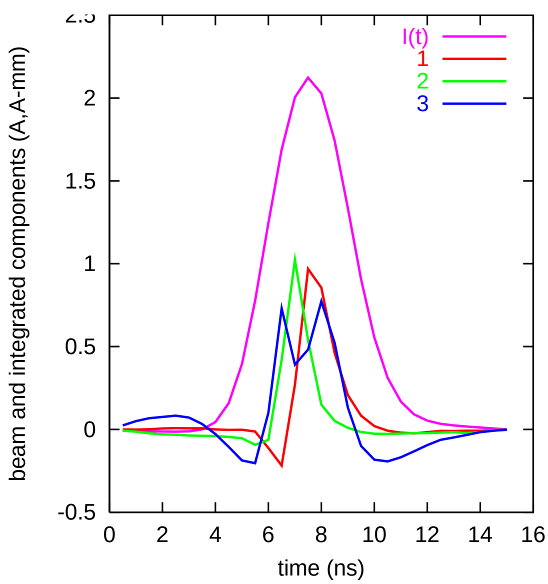

Figure 3: Integrals of the average sum signal and the 3 strongest principle components for data in Fig 1.

is about $1/2$ of the synchrotron period. One would expect a beating period $\gtrsim 1/f_s$ for two, recently decoupled, head-tail modes. Analyzing the sum data provides no evidence of longitudinal dipole or quadrupole oscillations.

Slower growing instabilities were also seen. Fig.5 shows the integrated eigenmodes and the reconstructed beam current pulse when such an instability was present. While the integrated mode 1 is narrower than the average profile, the effect is small compared to that shown in Fig. 3. Also, a strong, longitudinal, quadrupole oscillation was present when this instability occured. The time series of the two

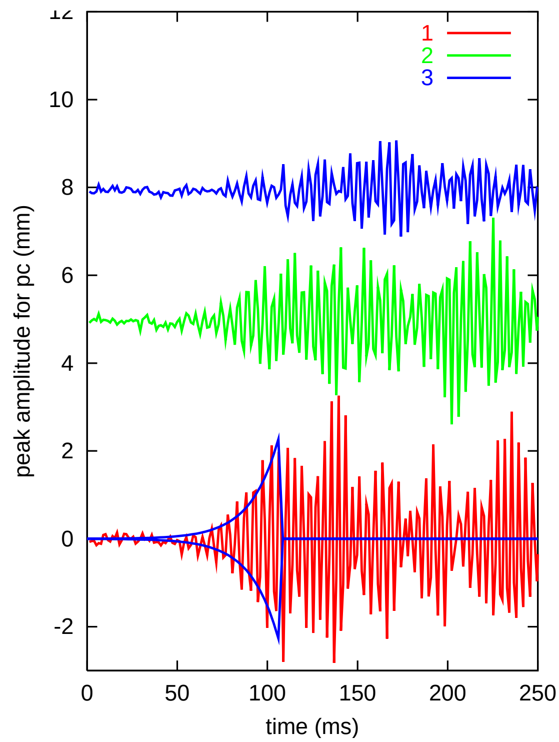

Figure 4: Time series of the 3 strongest principle components for the data in Fig 1. The traces are offset vertically to improve clarity.

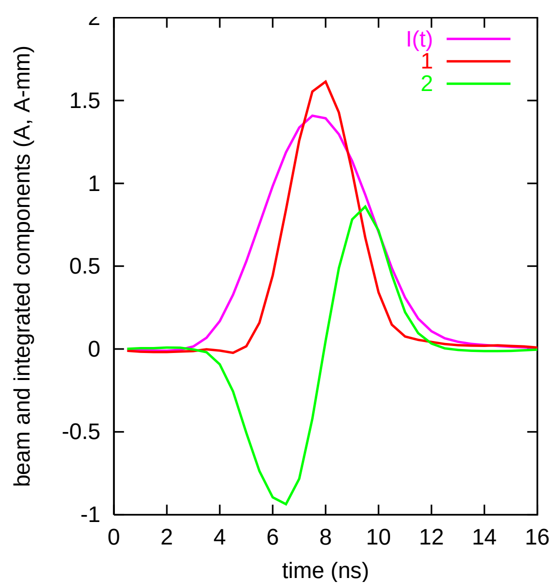

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Figure 5: Integrals of the average sum signal and the strongest principle components for a slower instability.

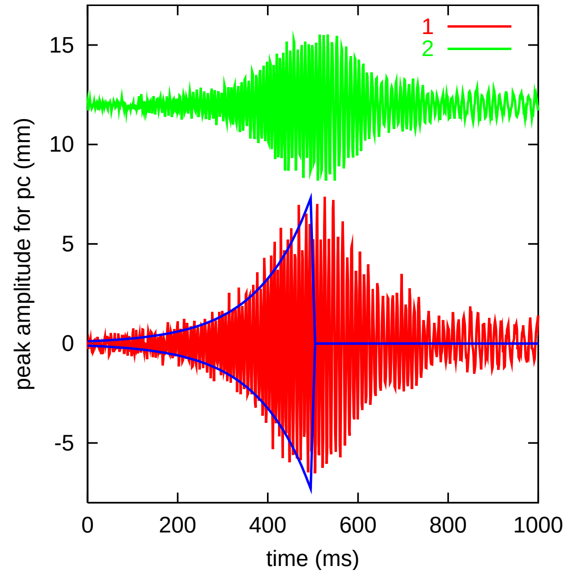

Figure 6: Time series of the 2 strongest principle components for a slower instability. The traces are offset vertically to improve clarity.

strongest principle components are shown in Fig 6. The envelope over-plotted on the time series for component 1 has an e-folding time of $\tau = 118$ ms.

While instabilities are fascinating from an intellectual point of view, they are a menace in the control room. The technique described above is not useful as a tool for tuning the machine so a new technique was developed. The coherence monitor takes data gated around the most intense bunch in the ring. The sum and difference voltages $V_s(t)$ and $V_d(t)$ are from a stripline BPM. On each turn n, a single number is generated,

$$S_n \approx C \int_{bunch} V_s(t) V_d(t) dt.$$

In actuality the product signal is low passed and then sampled, but parameters are such that the result is effectively identical. Next this discrete time series is put through a chip that calculates rms averages, and the control system samples the output at 720 Hz. This 720 Hz signal can be viewed through any operations console. Figure 7 displays the output during a vertical instability. Once the coherence monitor was commissioned, instabilities were readily identified and addressed. In fact, single bunch currents that are twice those shown in Figures 3 and 5 are now routine.

A few words on the tuning required to cure these instabilities is in order. First, since RHIC goes through transition, the chromaticity $\xi = \Delta Q/(\Delta p/p)$ must pass from negative to positive in the vicinity of transition. The initial configuration had ξ passing through zero a second or two after transition and the rate of $\dot{\xi} \approx 3\mathrm{s}^{-1}$ was as fast as the magnets allowed. However, it was found that ξ passing though zero before transition worked better. In fact, because of the transition jump and other considerations, the chromaticities

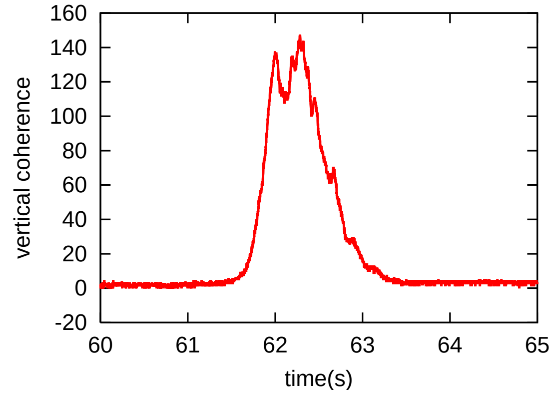

Figure 7: Vertical coherence signal used in the control room.

are not smooth, monotonic functions but exhibit excursions of order $\Delta\xi \sim 1$. By passing through ξ before transition the possibility of nearing $\xi = 0$ again, after transiton, was reduced. However, why is having ξ pass through zero well before transition better than well after?

Along with tuning the chromaticity, octupoles were used to increase the tune spread. To leading order the tune shifts with betatron action are $\Delta Q_x = a_{xx}J_x + a_{xy}J_y$ and $\Delta Q_y = a_{xy}J_x + a_{yy}J_y$. For RHIC parameters

$$\begin{aligned}\delta Q_N &\equiv < a_{xx}J_x > \approx < a_{yy}J_y > \approx 5.6\times 10^{-4},\\ \delta Q_S &\equiv < a_{xy}J_x > \approx < a_{xy}J_y > \approx -8.8\times 10^{-4},\end{aligned}$$

where $<>$ denotes averaging over the beam.

Since $\delta Q_S > \delta Q_N$, any theoretical treatment of octupole detuning should include both transverse dimensions. So far, only one transverse dimension has been modeled, but a few points are of interest. Firstly, even though $\gamma_t = 23.8$, the space charge tune shift, ΔQ_{sc} is many times larger than the synchrotron tune, Q_s. Neglecting space charge in our simulations, yields stable beams. However, when space charge is included, the unstable modes don't look like the figures, and the calculated growth time is $\tau \sim 100$ ms. Measurements of the transverse impedance [4] suggest that the actual transverse impedance is about 3 times larger than the our impedance model. It is possible that using the correct impedance in the simulations will yield agreement with the data, in Fig. 1 but impedance measurements of higher resolution are required.

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