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Note on the strip line BPM sensitivity to the signal induced by the electrons in PSR vacuum chamber.

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1.Introduction.

Experimental observations from proton storage rings show that considerable amount of electrons can be created by the circulated proton beam. In the case of bunched beam these electrons being released from the potential well during the beam gap and strike the vacuum chamber walls. It was suggested that signal induced by the electrons on electrodes of BPM can affect beam position measurements. In this paper we analyze this effect using real digitized signals from PSR strip line BPM.

2.Analitical estimation of electron's contribution to BPM signal.

We can represent the signal induced on BPM strip line as sum of three terms:

$$U_t = U_{pi} + U_{ei} + U_{ed} ,$$

where U_{pi} is voltage induced by protons moving near the electrode, U_{ei} is voltage induced by electrons moving near the electrode, U_{ed} is voltage induced by electrons hitting the electrode and absorbed to it. Movement of the protons is well defined, it's longitudinal current near the center of the vacuum chamber so we can use well known expression for induced voltage:

$$U_p(t) = (I_p(t) - I_p(t-t)) \cdot Z_0 \cdot \frac{j}{4p} .$$

where $I_p(t)$ is proton current, Z_0 is impedance of the strip line, τ_0 is strip line delay time and φ is strip line subtended angle. (We neglect here non-relativistic term and position dependence). Dynamics of the electrons is not well understood up to now. Obviously there is a transverse component in the electron movement but also can be a longitudinal motion, both of this components are coupled to strip line electrode and coupling coefficient are different. We can write in general form:

$$U_{ei} \approx a \cdot \dot{I}_e \cdot \frac{j}{2p} ,$$

where a is some unknown constant and I_e is electron current. Proportionality of the induced voltage to derivative of the current reflects the fact that only the changes in the current induce voltage on a separated electrode. It is not a true for electrons hitting the electrode. If the strip line is matched on both ends then electrons collected by the BPM electrode produce voltage pulse of the following amplitude:

$$U_{ed}(t) = I_{ed}(t) \cdot \frac{Z_0}{2} \cdot \frac{j}{2p} \quad ,$$

where $I_{ed}(t)$ is electron current to walls at the strip line location. We assume here that electron distribution is azimuthally symmetric. 2 divide strip line impedance because electrons current flows through both terminations.

Beam position measurement system works in narrow band usually so we calculate Fourier transformation of above equations:

$$U_p(w) = I_p(w) \cdot Z_0 \cdot \sin(w t_0) \cdot \frac{j}{4p} ,$$

$$U_{ei}(w) \approx a \cdot w \cdot I_{ei}(w) \cdot \frac{j}{2p} ,$$

$$U_{ed}(w) = I_{ed}(w) \cdot \frac{Z_0}{2} \cdot \frac{j}{2p}$$

Beam position measurement system is supposed to measure proton current induced signal only so we can treat electron contribution as ‘error’. The relative error due to the electron signal is:

$$dU = \frac{(U_p + U_{ei} + U_{ed}) - U_p}{U_p} = \frac{U_{ed} + U_{ei}}{U_p} = \frac{I_{ed}(w) + \frac{2a}{Z_0} I_{ei}(w)}{I_p(w) \sin(w t_0)} .$$

If beam position measurement system operates on revolution frequency ω_0, then

$$dU = \frac{I_{ed}(w_0)}{I_p(w_0)\sin(w_0 t_0)} + \frac{\frac{2a}{Z_0} I_{ei}(w_0)}{I_p(w_0)\sin(w_0 t_0)} = \left(\frac{I_{ed}(w_0)}{I_p(w_0)} + \frac{2a}{Z_0}\frac{I_{ei}(w_0)}{I_p(w_0)}\right) \cdot \frac{1}{\sin(2p \frac{l}{\Lambda})} \approx$$

$$\approx \frac{1}{2p} \cdot \frac{\langle I_{ed} \rangle + \frac{2a}{Z_0} \langle I_{ei} \rangle}{\langle I_p \rangle} \cdot \frac{\Lambda}{l} = \frac{1}{2p} \cdot m \cdot \frac{\Lambda}{l}$$

,

where < > means averaging, μ is relative neutralization of the proton beam at the BPM location, l is strip line length and Λ >> l is circumference of the ring. Electrons oscillate inside the proton bunch with high frequency therefore we can assume $\langle I_{ei} \rangle \approx 0$. One can see that contribution from the electron signal is proportional to average beam neutralization and enhanced by ratio of the ring circumference to the strip line length that is quite a big factor. For PSR parameters $\delta U \approx 60 \cdot \mu$, so if μ is about 1%, electron signal can give 60% shift to amplitude of the signal read from one BPM lobe. If electrons contribute equally to all four lobes it will not affect beam position measurement accuracy. Therefore the dependence of the azimuthal distribution of the electrons on the wall upon beam centroid position is important.

3.Analysis of measured signal from PSR BPM.

The signals from PSR strip line BPM wm41 in section N4 were digitized with 1ns sampling time. Unfiltered signal from one turn is shown in figure 1. As was stated above, the total voltage U_t on the electrode is sum of motion-induced signals Up, Uei and direct electron current signal U_{ed}. If we integrate U_t over one complete turn motion induced contribution become zero because DC component of beam current is not coupled to strip line electrode:

$$U_{av} \cdot T = \int_0^T U_t dt = \int_0^T U_p dt + \int_0^T U_{ei} dt + \int_0^T U_{ed} dt = 0 + \int_0^T U_{ed} dt = \int_0^T I_{ed}(t) \cdot \frac{Z_0}{2} \cdot \frac{j}{2p} \cdot dt = \frac{Z_0}{2} \cdot q_e \quad ,$$

from this we have:

$$U_{av} = \frac{Z_0}{2} \cdot \frac{q_e}{T}, \quad or \quad \langle I_{ed} \rangle = \frac{q_e}{T} = \frac{2 \cdot U_{av}}{Z_0} \quad ,$$

where q_e is electron charge collected on BPM plate during one turn. So we can calculate electron contribution by averaging BPM signal over each turn. The dependence of average voltage on turn number is shown in figure 2. The integrated signal contains low frequency noise and electron contribution. We can estimate electron contribution as

$$\langle I_e \rangle_{rms} \le \frac{2 \cdot (U_{av})_{rms}}{Z_0} = \frac{2 \cdot 2.7mV}{50\Omega} = 108mA.$$

For comparison the signal from electron detector is shown in fig. 2. There is no any correlation between collected electron charge and calculated electron contribution so we can conclude that noise gives the main contribution to U_{av} and our estimation is well above of the real electron contribution.

The next step is to measure the contribution from motion induced signal U_{ei}. We can do it by comparison of longitudinal proton beam profile derived from BPM measurements with the same profile measured by wall current monitor. Wall current monitor is only sensitive to longitudinal proton current while BPM measured profile contains electron signal as well. The both profiles are shown in figure 3 and the dependence of its difference upon turns is shown in figure 4. As in the previous case there is no correlation between collected electron charge or proton current and difference signal. So we can refer observed difference signal to the noise. Note that BPM strip line signal and WCM signal were filtered by low pass filter with 50MHz bandwidth. This filter doesn't affect operation of beam position measurement system if it operates in narrow band around revolution frequency.

4.The dependence of azimuthal electron distribution upon beam position.

As we mentioned above the effect of electron signal on beam position measurement accuracy depends on the azimuthal distribution of the electrons on the wall. If this distribution is symmetric and doesn't depend on beam centroid position the accuracy of beam position measurements is not affected even if electron induced signal on each lobe of BPM is large. The experimental observation of the signal from PSR electron detector demonstrates that electron distribution does depend on the proton beam transverse position. As one can see in figure 5 the current in the electron detector has strong oscillating component when beam becomes transversely unstable. The Fourier spectrum of these oscillations is shown in figure 6. The oscillation frequency is equal to fractional tune of transverse betatron oscillations of the proton beam. It proves that number of electrons hitting the wall at the electron detector location depends on proton beam transverse position.

5.Conclusion.

Our simple analysis shows that electrons generated inside the vacuum chamber of a proton storage ring can affect the performance of beam position measurement system working at revolution frequency if neutralization degree of the proton beam at BPM location is high enough (about 10^{-3} for typical ring parameters). But observation of the real signals from PSR strip line BPM shows that it is not the case even for the ransversely unstable beam when electron charge registered by electron detector is much larger than during normal operation. This conclusion is based on the analysis of the signal from one particular PSR BPM wm41 installed in section N4 where number of electrons collected by electron detector is higher then in other PSR locations. Distribution of electrons around whole PSR ring is unknown but described above technique of BPM signal analysis can be used to investigate electron distribution. Note that our analysis uses integration over revolution period so it can not be applied to a wide band or high frequency (substantially higher than revolution frequency) beam position measurement system. High frequency case will be analyzed in a separate note.

6. Acknowledgements.

I wish to thank Bob Macek who provided experimental data from PSR storage ring and Peter Cameron who initiated this work.

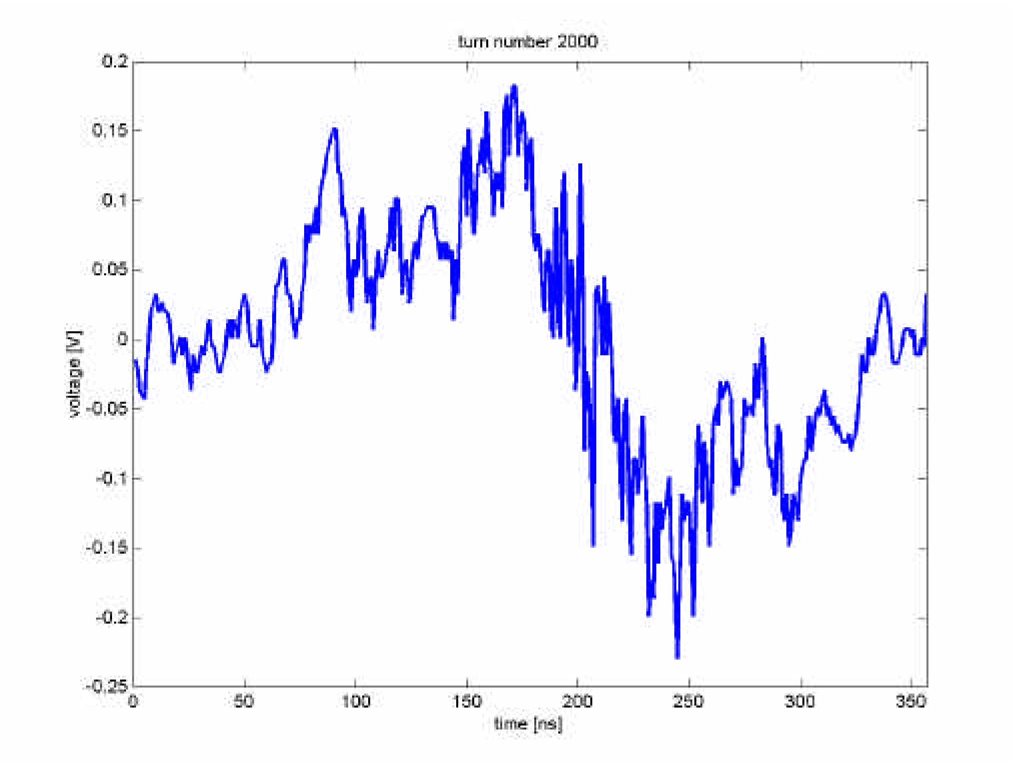

Figure 1. Raw data from PSR stip line BPM wm41 (one turn is shown).

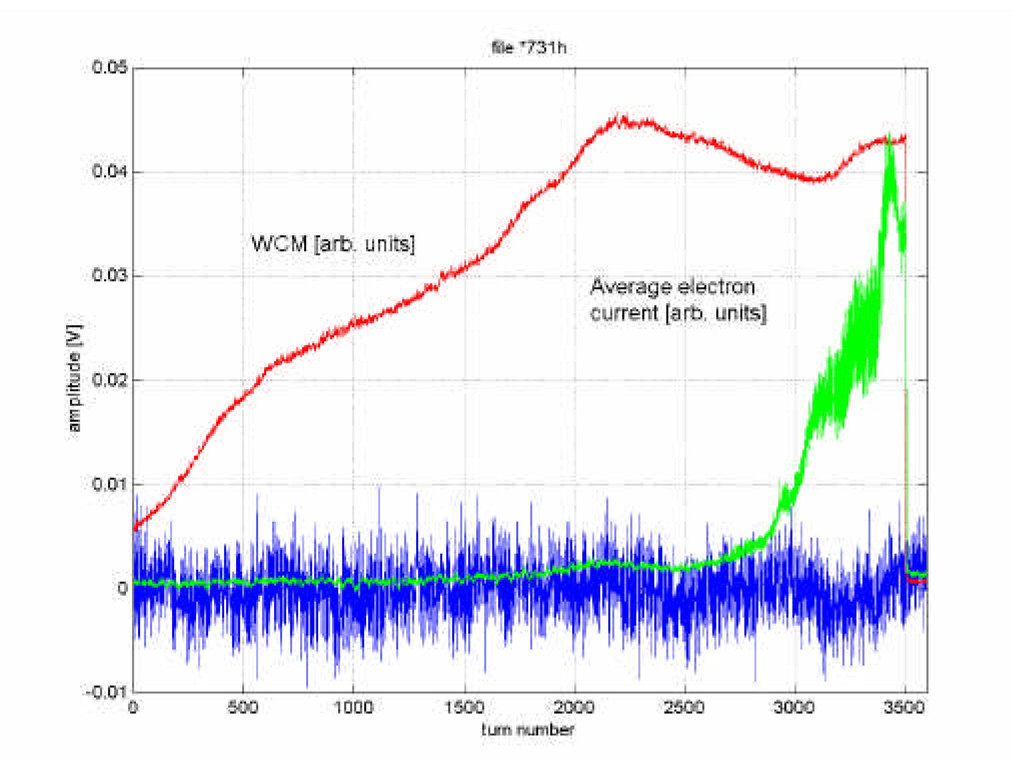

Figure 2. BPM voltage averaged for each turn (blue line), proton current

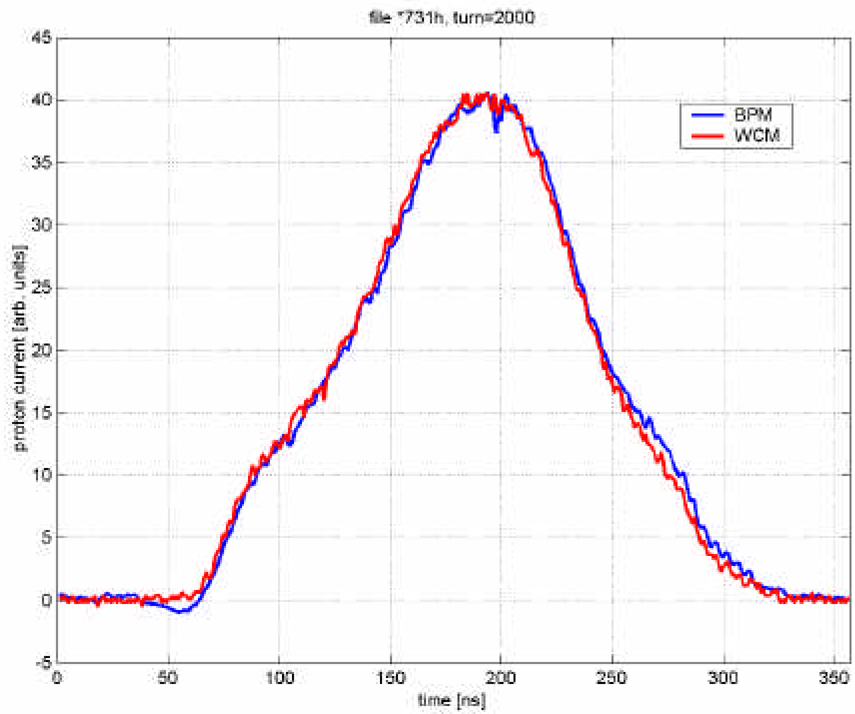

Figure 3. Proton beam longitudinal profile measured by WCM (red curve) and restored from BPM signal (blue curve) .

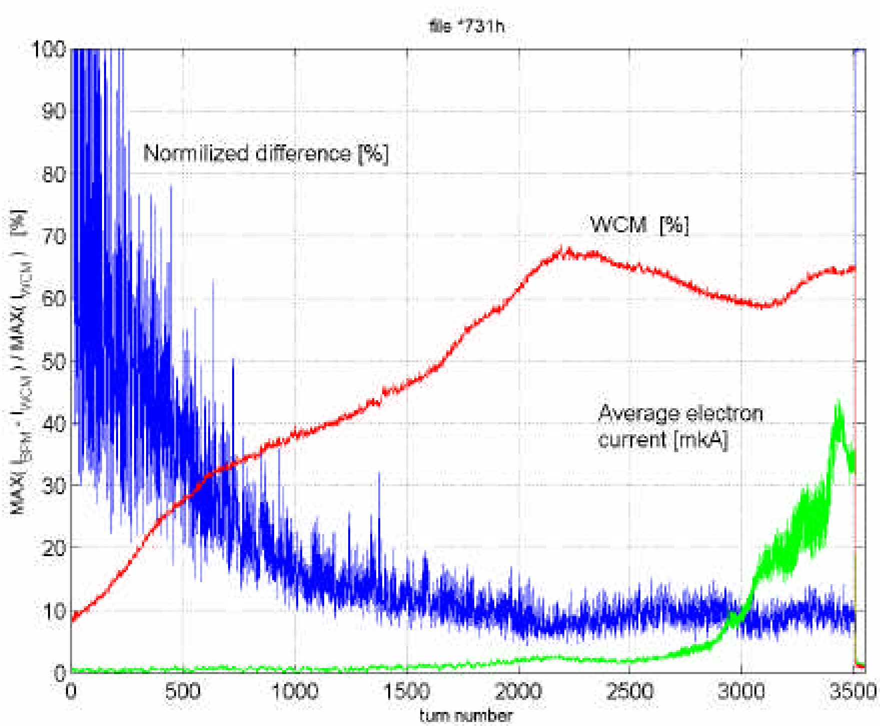

Figure 4. Normalized difference between WCM and BPM profiles (blue line), proton current (red line) and signal from electron detector (green).

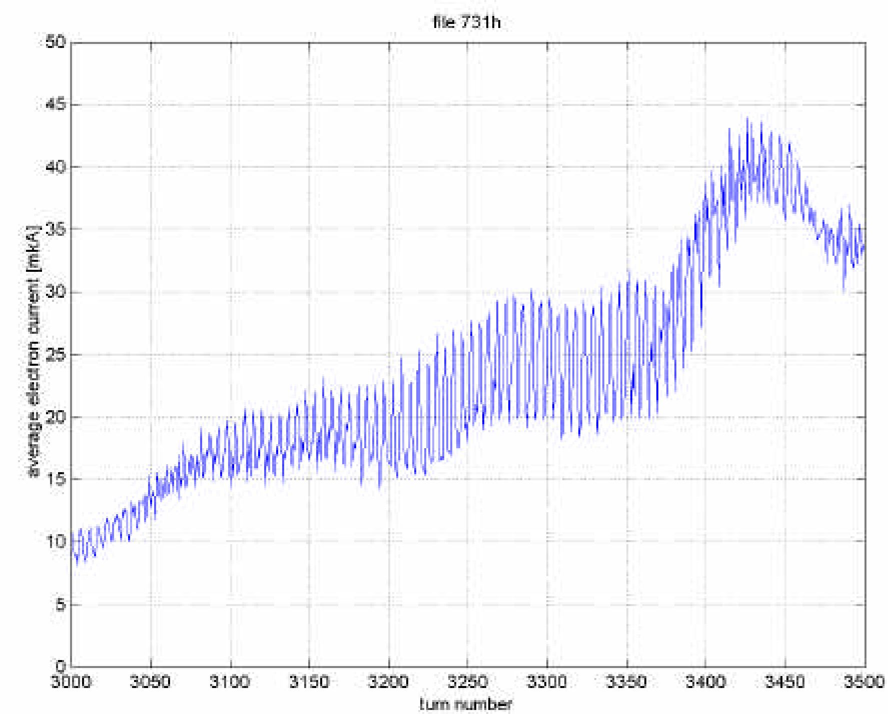

Figure 5. Current in the electron detector.

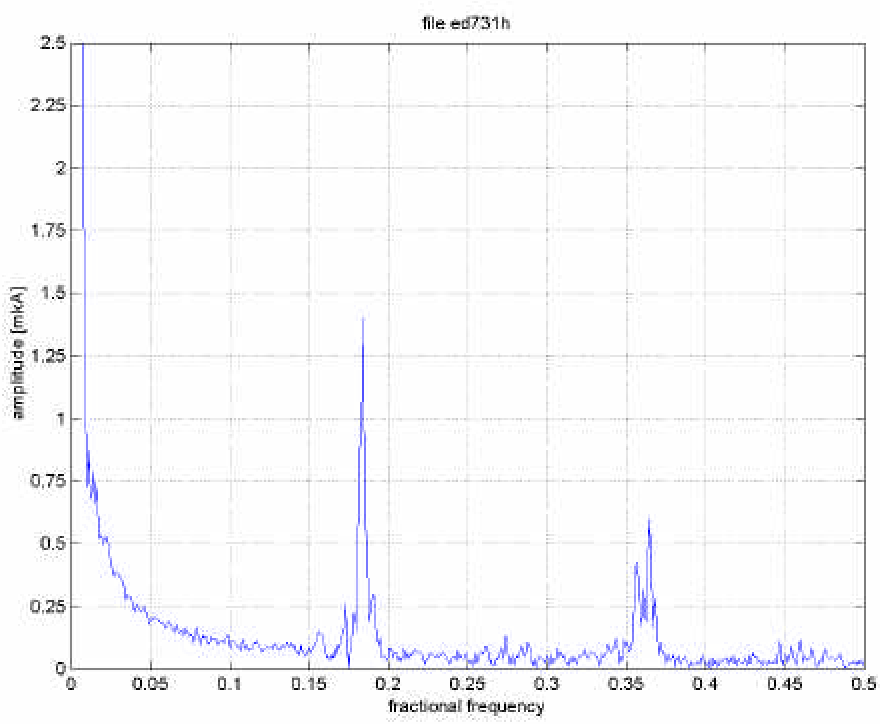

Figure 6. Fourier spectrum of the electron current.