# DIAGNOSTIC PULSE FOR SINGLE-PARTICLE-LIKE BEAM POSITION MEASUREMENTS DURING ACCUMULATION/PRODUCTION MODE IN THE LOS ALAMOS PROTON STORAGE RING*

J. Kolski†, S. Baily, E. Bjorklund, G. Bolme, M. Hall, S. Kwon, M. Martinez, M. Prokop,
F. Shelley, and P. Torrez, LANL, Los Alamos, NM, 87545, USA

## *Abstract*

Beam position monitors (BPMs) are the primary diagnostic in the Los Alamos Proton Storage Ring (PSR). When injecting one turn, the transverse motion is approximated as a single particle with initial betatron position and angle ($\vec{x}_0$ and $\vec{x}_0'$). With single-turn injection, we fit the betatron tune, closed orbit (CO), and injection offset ($\vec{x}_0$ and $\vec{x}_0'$ at the injection point) to the turn-by-turn beam position. In production mode, we accumulate multiple turns, the transverse phase space fills after 5 injections (horizontal and vertical fractional betatron tunes $\sim$0.2) resulting in no coherent betatron motion, and only the CO may be measured. The injection offset, which determines the accumulated beam size and is very sensitive to steering upstream of the ring, is not measurable in production mode. We describe our approach and ongoing efforts to measure the injection offset during production mode by injecting a "diagnostic" pulse $\sim$50 $\mu$s after the accumulated beam is extracted. We also study the effects of increasing the linac RF gate length to accommodate the diagnostic pulse on the production beam position, transverse size, and loss.

## MOTIVATION

The PSR BPMs[1] are bi-directional, stripline-type with electrode length $\sim$37 cm (a quarter 201.25 MHz wavelength). The 201.25 MHz longitudinal beam structure, to which the PSR BPMs are sensitive, is imposed during acceleration and decoheres after $\sim$30 turns in the PSR due to momentum spread and synchrotron motion.

We document the PSR in single-turn injection mode. We measure 30 turns of beam position data before the longitudinal beam structure decoheres, which is sufficient to fit the betatron tunes, CO, and injection offset.

Normally, the PSR operates in production mode, where $\sim$1800 turns are accumulated. With the filled phase space, there is no coherent betatron motion in production mode, so the betatron tunes and injection offset can not be measured. The beam position data does yield the CO.

Aside from beam energy, the CO and betatron tunes are independent of machine operation upstream of the ring. The injection offset is very sensitive to steering upstream of the PSR, and we cannot measure this important operational parameter in production mode.

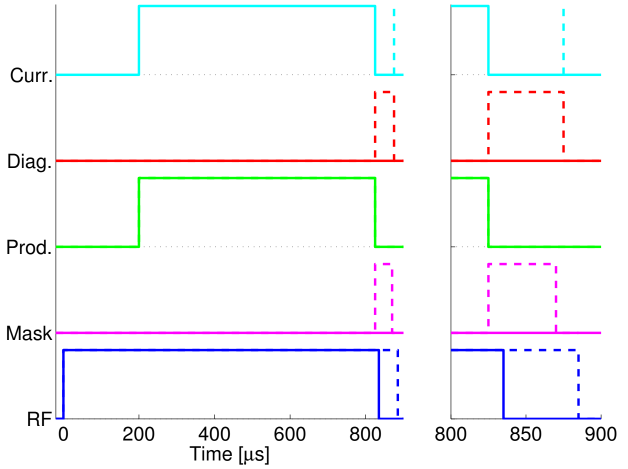

Figure 1: (Color) Timing scheme of one machine cycle for (from bottom to top) the linac RF gate (blue), RF system protect mask (magenta), production beam gate (green), diagnostic beam gate (red), and beam current in transport (cyan) for production mode (solid lines) and production mode with diagnostic pulse (dashed lines). The right plot focuses on the end of the machine cycle.

We develop an operation mode that enables us to document the PSR by measuring the betatron tunes, CO, and injection offset without affecting delivery of production beam. The scheme is to inject a single turn (diagnostic pulse) on the same machine cycle as the production mode $\sim$50 $\mu$s after the accumulated beam is extracted, see Fig. 1. The 50 $\mu$s between production beam and the diagnostic pulse allows the linac RF to recover from the beam-off transient, the injection bump magnets to zero, and for residual field in the PSR buncher to dissipate. The diagnostic pulse coasts in the PSR and is lost.

## EXTENDING THE LINAC RF GATE

The linac RF must be extended for 50 additional $\mu$s to accommodate the acceleration of the diagnostic pulse. The 50 $\mu$s RF gate extension corresponds to a 0.3% increase in duty factor but with almost no additional beam loading. With the RF extended, we are interested in the beam-off transient and the effect on the production beam.

### *Beam-Off Transient*

The linac RF beam-off transient is caused by a sudden change in beam loading after the passage of production

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[†] Electronic address: jkolski@lanl.gov

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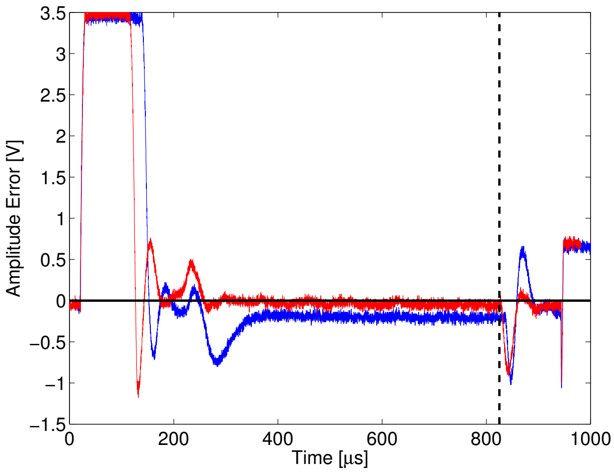

Figure 2: (Color) DTL module amplitude error for a single machine cycle (100 $\mu$s RF gate extension for better RF tuning) before (blue) and after (red) LLRF control tuning. The horizontal solid black line marks zero, while the vertical dashed black line marks the end of production beam and the start of the beam-off transient.

beam. The beam-off transient is observed as error in the RF phase and amplitude. A system protect fault results if the RF error exceeds 1$^\circ$ and 1 V respectively, and beam is turned off for the remainder of the machine cycle.

We observed the beam-off transient in the amplitude and phase error signals of each linac module. The beam-off transient was small for the 805 MHz coupled cavity linac (CCL) modules and was damped in 10 - 30 $\mu$s by the low level RF (LLRF) feed back. Only 2 of the 44 CCL modules occurred a system protect fault due to the beam-off transient. System protect faults due to the beam-off transient do not effect production beam because the fault occurred after its passage. However, a beam-off transient system protect fault would block the diagnostic pulse.

In the 201.25 MHz drift tube linac (DTL) modules, the beam-off transient rang for 50 - 100 $\mu$s before the LLRF feed back damped the error. We found the shape and ring time of the transient could be manipulated by the LLRF feed forward. After tweeking the LLRF, we reduced the beam-off transient ring time in all of the DTL modules to $< 50$ $\mu$s, see Fig. 2.

### *Effects on the Beam*

To ensure a transparent transition from production mode to production mode with a diagnostic pulse, we measure the production beam position, transverse size, and loss along the high energy beam transport (HEBT) from the linac to the PSR before and after the RF gate extension. We found no change in the beam position, see Fig. 3, indicating the beam energy was unchanged because there is a high dispersion region in the HEBT. Likewise, we did not observe a change in the transverse beam size in the high dispersion region of the HEBT. Lastly, the beam loss did not change before and after the RF gate extension. Observing no change before and after the RF gate extension, we conclude that the RF gate extension has no effect on the production beam.

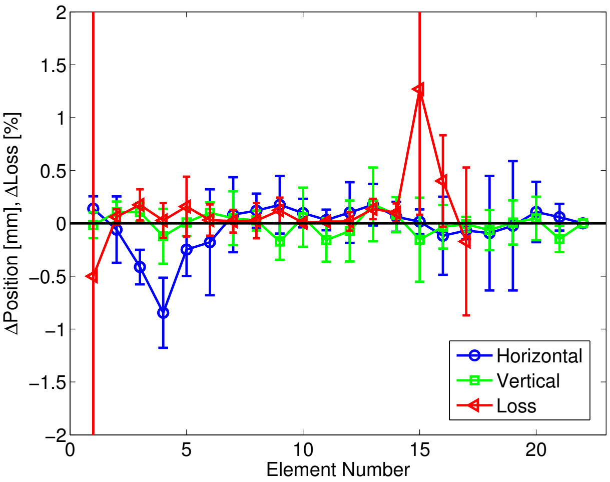

Figure 3: (Color) Change in horizontal (blue) and vertical (green) beam position and loss (red) with 1 rms uncertainty in the HEBT before and after the 50 $\mu$s RF gate extension.

## DIAGNOSTIC PULSE TO THE PSR

We sent the diagnostic pulse to the PSR and encountered several difficulties with system protect faults.

### *RF System Protect Masking*

The first hurdle is the beam-off transient system protect faults. Since we cannot avoid the beam-off transient, we use a timing gate to temporarily "mask" the system protect fault during the time in between the production beam and the diagnostic pulse. The beam-off transient still occurs but does not fault the protective system, while both the production beam and the diagnostic pulse are still protected. The masking was tested and shown to prevent the beam-off transient induced system protect faults.

### *PSR System Protect Faults*

Essentially, we are simultaneously sending two beamtypes to the same location under different run permit (equipment readiness) modes. This is a problem for the protective system because run permit can not switch modes pulse-to-pulse. The production beam runs under the production run permit mode, which requires operational injection bump magnets and PSR buncher. However, the diagnostic pulse operates in a run permit mode, where the injection bump magnets and the PSR buncher are not operational. This is a direct conflict of equipment readiness. In order to accommodate the diagnostic pulse in the production run permit, we modified the protective system for the diagnostic pulse beam gate to not include the injection bump magnets or PSR buncher inputs. The modified protective system was tested and shown to prevent readiness faults from the injection bump magnets and PSR buncher.

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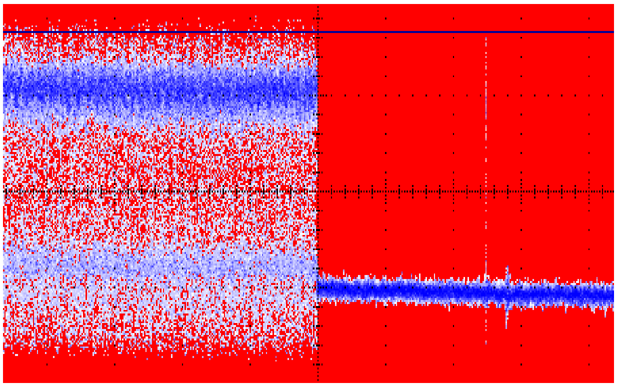

Figure 4: Current monitor signal in the LEBT showing the end of production beam and the diagnostic pulse 50 $\mu$s (time domain 20 $\mu$s/div.) later.

### *Unknown System Protect Fault*

After implementing the PSR protective system modifications for the diagnostic pulse, we uncovered a system protect fault that had previously been hidden. No fault message accompanied this new system protect fault. While this unknown fault did not effect the production beam, it prevented the acceleration and transport of the diagnostic pulse to the PSR. We have not observed the diagnostic pulse in the PSR.

## DIAGNOSTIC PULSE TO 01BL

To avoid complications of down stream system protect faults and to verify the correct chopping pattern of the production beam and diagnostic pulse, we observed the diagnostic pulse in the low energy beam transport (LBET) between the ion source and the linac. The production beam and diagnostic pulse were sent to 01BL, a beam stop immediately upstream of the linac.

### *Diagnostic Pulse Chopping*

The chopper imposes the beam-gap structure for injection into the PSR. The chopper can be programed with different pattern width (PW, length of beam injected each turn) and count down (CD, every 1 of $N$ turns is injected) for the production and diagnostic beam gates. We run the production and diagnostic beam gates with PWs of 290 ns. The production beam gate operates at a CD of 1, while the diagnostic beam gate operates with a CD of 135 so the one unchopped turn is near the end its 50 $\mu$s length.

### *Current Measurement*

We observed the diagnostic pulse with a current monitor in the LEBT. Figure 4 clearly shows the diagnostic pulse 50 $\mu$s after the production beam verifying the CD chopping for the diagnostic beam gate. Zooming in on the diagnostic pulse, Fig. 5, we find its PW to be 200 ns instead of the prescribed 290 ns. The PW error is due to a faulty CAMAC module and will be replaced.

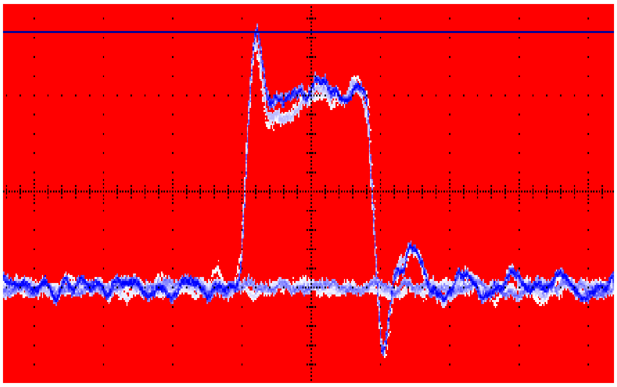

Figure 5: Current monitor signal in the LEBT showing the 200 ns long diagnostic pulse (time domain 100 ns/div.).

## CONTINUING WORK

We are working toward a proof of principle demonstration for the diagnostic pulse in the PSR. The next step in achieving this goal is to identify the source of the unknown system protect fault that blocks the diagnostic pulse. We acquired useful information sending production beam and the diagnostic pulse to 01BL. We believe we can isolate the source of the unknown system protect fault by sending the production beam and the diagnostic pulse to different beam stops along the accelerator because more devices are included in the protective system analysis for beam stops further down stream.

After observing the diagnostic pulse in the PSR, we need to show that it is representative of the production beam, so we need to compare measurements of the betatron tunes, CO, and injection offset in single-turn injection mode and with the diagnostic pulse. We will also measure the increase in beam loss in the PSR due to the dissipation of the diagnostic pulse, which is not extracted.

## CONCLUSIONS

We present our ongoing implementation of an operations mode that will allow for measurement of the betatron tunes, CO, and injection offset without interrupting production beam. A single-turn (diagnostic pulse) will be injected into the PSR 50 $\mu$s after production beam is extracted. We have verified that the RF gate extended for 50 $\mu$s does not effect the production beam position, transverse size, or loss. We have modified the protective system to mask the beam-off transient and to allow for coasting of the diagnostic pulse in production mode. Finally, we have observed the diagnostic pulse in the LEBT. Currently, a system protect fault of unknown origin prevents us from accelerating and transporting the diagnostic pulse to the PSR.

## REFERENCES

[1] J. Kolski, R. Macek, R. McCrady, LA-UR 10-05272, PSR 10-001, AOT-ABS 10-006; J. Kolski, Ph.D. thesis, unpublished (Indiana University 2010).

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