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Heavy Ion Injection in the Booster: Proposal for Additional Beam Instrumentation

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Technical Note

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1 Motivation

- The principle motivation is to reduce the time required to to set up the injection of heavy ions in the Booster.
- With the present instrumentation it often takes hours (sometimes days) of laborious tuning to achieve the optimum injection efficiency.
- At present, injection efficiencies of some 50 to 60 percent can be achieved. If the time and labor involved can be reduced, improvements in the injection efficiency become more likely.
- Better instrumentation can reduce the time required to recover from various interruptions.
- Better instrumentation will allow for increased understanding of the injection process.

2 Present Instrumentation

- **TTB Profile Monitors 29MW090 and 29MW141**. These are the final two profile monitors in the TTB Line. They are the "eyes" that allow one not only to properly steer the beam into the inflector, but also to set up the optics of the incoming beam. (29MW141 is 0.984 meters upstream of the C3 Inflector. 29MW090 is 15.585 meters upstream of 29MW141. There is one quadrupole doublet between 29MW090 and 29MW141; it is 0.736 meters downstream of 29MW090.)

- **TTB Beam Current Transformer 29XF104.** This is the final current transformer in the TTB Line. It is used to monitor the intensity, timing and shape of the beam pulse near the end of the TTB Line. (It is just downstream of the quadrupole doublet that lies between 29MW090 and 29MW141.)
- **C4 Horizontal PUE.** This is located just downstream of the Inflector and is useful for determining whether or not beam is getting through the inflector.
- **Inflector Current Monitor.** This signal, which is hard-wired to MCR Console 4, is a very sensitive indicator of beam hitting the inflector. One can think of it as a very sensitive loss monitor; it indicates that beam is being lost as it passes through the inflector, or that beam is being lost on the septum on subsequent turns around the machine.
- **Booster C6 Beam Current Transformer.** This is the "eye" used to set up and monitor the beam "stacking" at injection and to monitor the beam current throughout the acceleration cycle. It is located just upstream of the C7 Injection Kicker which is some 3 meters downstream of Quadrupole QHC6. In the high-gain mode, one sees an output of 1 Volt for each 100μA of beam current.
- **Horizontal PUE B6** is very useful for "PIP" measurements (see Refs.[1] and [2]). The sum signal from this PUE is also very useful for observing the RF structure of the beam at injection and throughout the acceleration cycle.
- **Vertical PUE D1** is supposed to be used for "PIP" measurements, but it is only marginally useful because the quality of the difference signal is poor.
- **E3 Wall Current Monitor.** This also allows one to observe the RF structure of the beam at injection and throughout the acceleration cycle. The signal is hardwired to MCR Console 4, but is not always available there; it is sometimes required for dedicated use elsewhere.

- **IPM (Ionization Profile Monitor)**. This device, located in the D3 straight-section, is seldom used. It does give useful information but it requires an "expert" to operate it. When "on" and operational, it reduces the heavy ion beam intensity significantly.

3 Proposed Additional Instrumentation (in order of Priority)

3.1 New Electronics for the Booster PUE's

- The Multiturn Injection process generally fills both the horizontal and vertical apertures. This is because the "bumped" equilibrium orbit in the horizontal plane must be collapsed away from the inflector septum as beam is injected, thereby placing subsequent turns further and further from the orbit. Linear coupling (introduced to enhance the injection efficiency) causes the same thing to happen in the vertical plane. It is therefore critical that the equilibrium orbit be centered in the available aperture at injection.

- The PUE system therefore must be able to give the position of the equilibrium orbit at each PUE shortly after injection (i.e. after the beam has been stacked and bunched). This allows one to center the orbit using the existing array of dipole correctors.

- The current PUE system employs active electronic components located near each PUE in the Booster ring. These components are subject to radiation damage during high-intensity proton runs, and, due to manpower, time, and ALARA constraints, have become increasingly difficult to maintain. The new electronics will be located outside the ring and will be connected to each PUE via coaxial cable. (The cables have been pulled but are not yet connected to the PUE's.)

- At least one Horizontal and one Vertical PUE must be able to provide the kind of turn-by-turn signals discussed in Refs.[1] and [2]. This most likely will require active electronic components in the ring near these PUE's. (An estimate of the voltages on the PUE plates is given in the Appendix.) The SUM signals from these PUE's should also allow one to observe the RF structure of the beam throughout the acceleration cycle.

- The signal from PUE C4 (just downstream of the inflector) should allow one to observe the 100–1000 μs pulse of beam emerging from the infector. This, again, will most likely require active electronic components in the ring near the PUE.

3.2 Dedicated Heavy Ion Injection Current Transformer

- It is desirable to have a current transformer in the ring capable of measuring beam currents at injection in both single-pass and multi-turn modes. In the single pass mode, incoming beam would be stopped (with a dipole magnet or perhaps a vacuum valve) after a single pass through the transformer. With say 20μA of beam coming into the Booster, a sensitivity to some fraction of 1μA would then allow for a good determination of the first-pass injection efficiency. In the multi-turn mode, details of the stacking process would be examined.

- In principle, the C6 current transformer, which produces an output of 1 Volt for each 100μA of beam current in its high-gain mode, would allow for measurements in the single-pass mode; however, at the level of 20μA, the signal-to-noise ratio for this device is poor.

- A current transformer used exclusively for the injection of heavy ions would need to measure currents in the 1μA to 10μA range for the single-pass mode, as well as currents as high as 2000μA for the multi-turn stacking mode. (The first turn of beam entering the Booster can have currents as low as 10μA while 40 turns at 50μA would give an injected "stack" of 2000μA.)

- The current transformers in use in the TTB line have this kind of range. They have two gain settings, denoted by Low and High, in which one sees outputs of 10 mV and 100 mV respectively for each μA of beam current. The maximum output is 10 Volts which corresponds to 1000μA in the low-gain mode and 100μA in the high-gain mode.

- It would be desirable to locate such a transformer in a "quiet" area of Ring, away from injection kickers and other sources of "noise".

However, the only available space in the Booster ring is in the C6 straight-section upstream of the C6 current transformer. (The C7 injection kicker is just downstream of the C6 current transformer.)

- We would need the ability to stop beam after a single pass through the transformer. A correction dipole "three-bump" would probably do the job.

3.3 Multiwire Profile Monitor in the Booster Ring

- It has been several years since we have attempted an emittance measurement in the TTB line, even though we often wonder whether or not the emittance of the beam entering the Booster has changed after a new foil has been inserted in the Tandem terminal or in the TTB line.
- Observing the beam profile on any one of several monitors in the line while sweeping an upstream quadrupole is the technique we have used in the past to obtain the emittance and other beam ellipse parameters. The results generally have not been internally consistent.
- The last two profile monitors in the TTB line together with a third monitor in the Booster ring would allow for an alternative measurement of the emittance and ellipse parameters. In this case a single profile is taken at each monitor (no quadrupoles are swept) and the parameters follow directly from the three profile widths as shown in the Appendix.
- A profile monitor near the exit of the inflector would be particularly useful. Not only could it be used as the third monitor in a three-monitor scheme for measuring the emittance, it would also give the position and shape of the beam at this critical location. However, there is no room here for a profile monitor.
- The only available space is in the C6 straight-section upstream of the C6 current transformer. This is some 10 meters downstream of, and at a betatron phase advance of approximately 90° from, the inflector exit. A profile monitor at this location would be sensitive to the angle of the beam emerging from the inflector. The horizontal correction dipole (DHCC4) just downstream of the inflector exit could be used to center the beam on the profile monitor.

4 Appendix

4.1 PUE Signals

With unbunched ion beam centered in a Booster PUE, the voltage induced on each plate of the PUE is

$$V = \frac{Q}{2C} = \frac{l}{2LC} I\tau = (2.00 \times 10^6) I\tau \tag{1}$$

where $C = 260$ pf is the capacitance of each plate, $Q/2$ is the charge induced on each plate, $l = 0.21$ m is the length of the PUE, $L = 201.775$ m is the Booster circumference, I is the beam current (in Amps), and $\tau = 1/f$ is the revolution period (in seconds). Using the frequencies listed in Table II of Ref.[3] we find $\tau = 9.67$, 9.66, and 15.1 μs respectively for Si^{5+}, Fe^{10+}, and Au^{32+} ions at injection in the Booster. The corresponding values of V for 10 μA of beam current are 0.19, 0.19, and 0.30 mV. These voltages will, of course, increase as the beam is bunched.

4.2 Emittance Measurement with Three Profile Monitors

Consider three profile monitors located at positions s_0, s_1, s_2 along a beamline. Let $\mathbf{M}$ be the transfer matrix from s_0 to s_1, and let $\mathbf{N}$ be the transfer matrix from s_1 to s_2. The transfer matrix from s_0 to s_2 is then

$$\mathbf{T} = \mathbf{NM}. \tag{2}$$

Define

$$a = \epsilon\alpha, \quad b = \epsilon\beta, \quad g = \epsilon\gamma \tag{3}$$

where α, β, γ are the beam ellipse parameters at a point s along the beamline, and ϵ is the beam emittance. Then we have

$$\epsilon^2 = bg - a^2 \tag{4}$$

$$b_1 = M_{11}^2 b_0 - 2M_{11}M_{12}a_0 + M_{12}^2 g_0 \tag{5}$$

and

$$b_2 = T_{11}^2 b_0 - 2T_{11}T_{12}a_0 + T_{12}^2 g_0. \tag{6}$$

(M_{ij}, N_{ij} and T_{ij} are the elements of **M**, **N** and **T**.) The measured widths of the beam at s_0, s_1, s_2 are

$$W_0 = 2\sqrt{b_0}, \quad W_1 = 2\sqrt{b_1}, \quad W_2 = 2\sqrt{b_2}. \tag{7}$$

Rewriting (5) and (6) as

$$M_{12}^2 g_0 - 2M_{11}M_{12}a_0 = b_1 - M_{11}^2 b_0 \tag{8}$$

$$T_{12}^2 g_0 - 2T_{11}T_{12}a_0 = b_2 - T_{11}^2 b_0 \tag{9}$$

and solving for a_0 and g_0 we obtain

$$a_0 = \frac{T_{12}^2(b_1 - M_{11}^2 b_0) - M_{12}^2(b_2 - T_{11}^2 b_0)}{2M_{12}T_{12}(T_{11}M_{12} - T_{12}M_{11})} \tag{10}$$

$$g_0 = \frac{2T_{11}T_{12}(b_1 - M_{11}^2 b_0) - 2M_{11}M_{12}(b_2 - T_{11}^2 b_0)}{2M_{12}T_{12}(T_{11}M_{12} - T_{12}M_{11})}. \tag{11}$$

Thus, using the values of b_0, b_1, b_2 obtained from the three width measurements, we can obtain a_0, g_0 and ϵ.

We also have

$$b_2 = N_{11}^2 b_1 - 2N_{11}N_{12}a_1 + N_{12}^2 g_1 \tag{12}$$

$$b_0 = M_{22}^2 b_1 + 2M_{22}M_{12}a_1 + M_{12}^2 g_1 \tag{13}$$

and therefore

$$-2N_{11}N_{12}a_1 + N_{12}^2 g_1 = b_2 - N_{11}^2 b_1 \tag{14}$$

$$2M_{22}M_{12}a_1 + M_{12}^2 g_1 = b_0 - M_{22}^2 b_1. \tag{15}$$

Solving the last two equations for a_1 and g_1 we obtain

$$a_1 = \frac{N_{12}^2(b_0 - M_{22}^2 b_1) - M_{12}^2(b_2 - N_{11}^2 b_1)}{2M_{12}N_{12}(M_{22}N_{12} + M_{12}N_{11})} \tag{16}$$

$$g_1 = \frac{N_{11}N_{12}(b_0 - M_{22}^2 b_1) + M_{12}M_{22}(b_2 - N_{11}^2 b_1)}{M_{12}N_{12}(M_{22}N_{12} + M_{12}N_{11})}. \tag{17}$$

As before, using the values of b_0, b_1, b_2 obtained from the three width measurements, we obtain a_1, g_1 and ϵ.

For the case in which $\mathbf{M}$ and $\mathbf{N}$ are drifts of length L_1 and L_2 with $L_1 + L_2 = L$ we have

$$a_0 = \frac{L^2(b_1 - b_0) - L_1^2(b_2 - b_0)}{2L_1 L(L_1 - L)} = \frac{L_1(b_2 - b_0)}{2LL_2} - \frac{L(b_1 - b_0)}{2L_1 L_2} \tag{18}$$

$$g_0 = \frac{2L(b_1 - b_0) - 2L_1(b_2 - b_0)}{2L_1 L(L_1 - L)} = \frac{b_2 - b_0}{LL_2} - \frac{b_1 - b_0}{L_1 L_2} \tag{19}$$

and

$$a_1 = \frac{L_2^2(b_0 - b_1) - L_1^2(b_2 - b_1)}{2L_1 L_2(L_2 + L_1)} \tag{20}$$

$$g_1 = \frac{L_2(b_0 - b_1) + L_1(b_2 - b_1)}{L_1 L_2(L_2 + L_1)}. \tag{21}$$

4.3 The Utility of Two Profile Monitors

If we have only two profile monitors, we can still obtain some information about the beam emittance. Using the notation of the previous section we have

$$\beta_1 = M_{11}^2 \beta_0 - 2M_{11}M_{12}\alpha_0 + M_{12}^2 \gamma_0 \tag{22}$$

$$\beta_0\beta_1 = M_{11}^2 \beta_0^2 - 2M_{11}M_{12}\alpha_0\beta_0 + M_{12}^2(1 + \alpha_0^2) \tag{23}$$

$$\beta_0\beta_1 - M_{12}^2 = (M_{11}\beta_0 - M_{12}\alpha_0)^2 \tag{24}$$

Note that we therefore must have

$$\beta_0\beta_1 \geq M_{12}^2. \tag{25}$$

Defining

$$L = M_{12}, \quad M = M_{11} \tag{26}$$

we have

$$b_0 b_1 - L^2\epsilon^2 = (Mb_0 - La_0)^2 \tag{27}$$

$$L^2\epsilon^2 = b_0 b_1 - (M b_0 - L a_0)^2 \tag{28}$$

$$L^2\epsilon^2 = b_0(b_1 - M^2 b_0) + 2LM a_0 b_0 - L^2 a_0^2 \tag{29}$$

$$L^2\epsilon^2\{1 + \alpha_0^2 - 2M\alpha_0\beta_0/L\} = b_0(b_1 - M^2 b_0) \tag{30}$$

Now, if $\alpha_0 = 0$, we have

$$L^2\epsilon^2 = b_0(b_1 - M^2 b_0) \tag{31}$$

while for $\alpha_0 = \pm 1$ we have

$$2L^2\epsilon^2\{1 \mp M\beta_0/L\} = b_0(b_1 - M^2 b_0) \tag{32}$$

Thus, if we know that α_0 is near zero, we can use these equations to estimate the emittance.

5 References

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3. C.J. Gardner, "Heavy Ion Parameters for 1997–98, and Some Preliminary Parameters BAF", AGS/AD/Tech. Note No. 472, November 6, 1997.