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A SCHEME FOR ASYNCHRONOUS OPERATION OF THE APS-U BOOSTER SYNCHROTRON*

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Abstract

The APS-U MBA lattice has a shorter circumference by about 40 cm compared to the present-day APS storage ring. As a result, the rf frequency increases by about 125 kHz relative to the Booster synchrotron. We describe a timing system that allows asynchronous operation of the Booster relative to the storage ring. The ability to change the Booster central momentum during acceleration, facilitates injection on momentum but extraction at a negative momentum offset, thereby reducing the horizontal emittance.

INTRODUCTION

The APS upgrade [1] will replace the present APS storage ring with a new, low-emittance MBA storage ring operating at twice the beam current and with a transverse emittance reduced to 42 pm. To avoid moving the photon beam lines the position of the insertion-device (ID-) beam lines is maintained. This defines the overall geometry of the lattice reducing the length from a present nominal 1104.000 m to 1103.608 m. The machine has a harmonic of 1296 and the rf frequency changes from 351.93 MHz to 352.06 MHz, a change of +125 kHz.

If not realigned to change its circumference, the Booster will continue operating at 351.93 MHz. Bunch-to-bucket beam transfer can be facilitated if the Booster beam can be transferred into the storage ring without relocking the rf systems. The ability to inject on momentum and extract at a negative momentum offset by varying the rf frequency along the energy ramp would significantly aid injection into the Booster and into the storage ring. Random access to the storage-ring buckets has to be supported to preserve swap-out injection. This is possible by carefully calculating the frequency ramp in the Booster thus varying the time the beam spends in the Booster depending on the target bucket in the storage ring.

PRINCIPLE OF BOOSTER-MBA SYNCHRONIZATION

Each ring has a turn clock lined up with bunch 0 passing by the extraction kicker (Booster) or the injection kicker (MBA). The difference between these turn clocks is compared to a pre-calculated function that establishes the program. Once the Booster has reached its top energy within a prescribed tolerance, beam transfer is initiated. The frequency program for the Booster is designed to achieve three objectives:

- Set momentum offset at injection (nominally 0);
- Set momentum offset at extraction (nominally < 0);
- Ensure the total time (on the pico-second level) taken for the Booster bunch being accelerated matches the time to inject into the chosen rf bucket in the MBA.

The rf program is calculated for the beam momentum offset at injection, the momentum-offset at extraction and the target bucket in the storage ring. Starting form $t = 0$, the Booster momentum offset $\delta p(t)/p_0$ follows a sinusoidal ramp from *i*nitial to *f*inal energy according to:

$$\frac{\delta p(t)}{p} = \left.\frac{\delta p}{p}\right|_i + \frac{1}{2}\left(\left.\frac{\delta p}{p}\right|_f - \left.\frac{\delta p}{p}\right|_i\right)\begin{cases}0 & t<0\\ 1-\cos\left(\frac{t\pi}{t_l}\right) & 0\le t\le t_l\\ 2 & t_l<t\end{cases}$$

where t_1 denotes the end of the momentum ramp (which may be shorter than the B-field ramp by a few damping times). We convert this to a time difference using

$$\frac{\delta t}{t} = \alpha_p \frac{\delta p}{p}$$

(α_p is the momentum compaction) and integrate across the Booster cycle, from $t = 0$ to $t = t_c$ (t_c being the time of the Booster acceleration cycle), to get the total time difference of a bunch compared to the on-momentum bunch ($\delta p/p|_i = 0, \delta p/p|_f = 0$):

$$\delta t_r = \frac{\alpha_p}{2}\left((2t_c - t_1)\frac{\delta p}{p}\Big|_f + t_1\frac{\delta p}{p}\Big|_i\right)$$

Here t_1 is the time for the momentum ramp, at most equal to t_c. For $\delta p/p|_i = 0$ and $t_1 = t_c$ this collapses to

$$\delta t_r = \frac{1}{2}\alpha_p \left.\frac{\delta p}{p}\right|_f t_c.$$

so the change in path length is just proportional to the average $\delta p/p$ from $t = 0$ to $t = t_1$ as one would expect. Note that in our case $\delta t_r < 0$ since $\delta p/p|_f \le 0$. The path-length correction ramp is expressed as follows:

$$\frac{\delta p_c(t)}{p} = F_c\begin{cases}0 & t<0\\ 1/2 - 1/2\cos\left(2\frac{t\pi}{t_l}\right) & 0\le t \text{ and } t\le t_l\\ 0 & t_l<t\end{cases}$$

where F_c is the maximum momentum deviation contributed by the path-length correction bump. Integrating this from $t \le 0$ to $t \ge t_1$ and converting to a time difference yields:

$$\delta t_c = \alpha_p \frac{t_1 F_c}{2}$$

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for the change in pathlength due to this correction. The total path length difference to the on-momentum beam is then

$$\delta t = \delta t_r + \delta t_c$$

It turns out that δt is always negative to avoid overshoot due to the path-length correction ramp. Numerically, for a Booster momentum ramp from 0 to -0.006 in 0.225 s with $t_1 = 0.20$ s this results in $-8.73\times10^{-6} < \delta t < -5.82\times10^{-6}$ (in seconds). F_c is given by

$$F_c = \frac{\left(\left(\left.\frac{\delta p}{p}\right|_i - \left.\frac{\delta p}{p}\right|_f\right) t_1 + 2\,t_c \left.\frac{\delta p}{p}\right|_f\right)\alpha_p + 2\,\delta t}{\alpha_p\, t_1}$$

Referring to Fig. 1 we consider the timings of both the MBA and the Booster together. We define Booster injection to happen at $t = 0$ and can write for the Booster extraction time

$$t_{e,B} = t_C + \delta t = t_{r,B} n_B + \delta t = t_{i,M} - t_{BTS}$$

where t_C is the nominal Booster acceleration cycle time, $t_{r,B}$ is the Booster revolution time for on-momentum beam and n_B, the number of turns of the Booster for the whole cycle from injection to extraction. t_{BTS} is the delay time due to the length of the BTS. The third equality defines the MBA injection time $t_{i,M}$ against the same reference in time. For the MBA, we can write down the injection time

$$t_{i,M} = t_{0,M} + n_{b,M}\delta t_{b,M} + t_{r,M} n_M$$

again using the moment of Booster injection as reference. Here $t_{0,M}$ is the (arbitrary) time of the passing of bunch 0 by the injection kicker, $n_{b,M}$ is the MBA bucket to be injected into and $\delta t_{b,M}$ is the time difference between two neighboring bunches (2.8405 ns). $t_{r,M}$ is the revolution time of the MBA and n_M is the turn to be injected into.

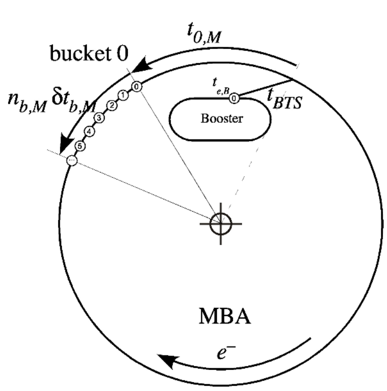

Figure 1: The APS-U Booster and PAR rings.

With a bit more arithmetic we can find the number of turns in the Booster (Fig. 2) and the delay time (Fig. 3), both as a function of the target bucket in the storage ring. The frequency ramp is shown in Fig. 4 for the extreme cases and the average delay. After the frequency ramp a period of constant frequency is provided to damp any transients.

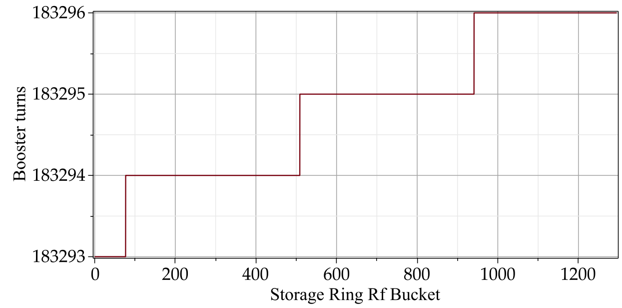

Figure 2: Number of Booster turns *vs* the storage-ring bucket to be injected into.

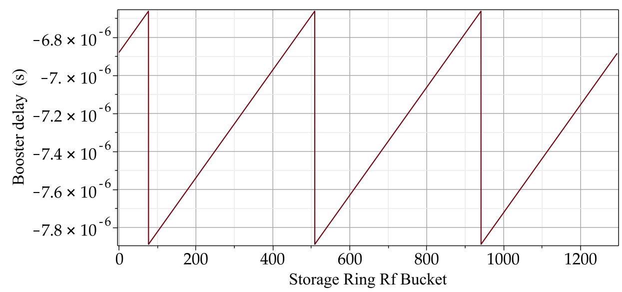

Figure 3: Booster path-length correction time δt *vs* the MBA bunch number injected into.

IMPLEMENTATION

Timing The proposed scheme must integrate with the existing timing system. A key feature to be preserved is the synchronization of the injector cycle with the 60-Hz line frequency, necessary to ensure reproducible operation of the injectors. This is achieved by initiating the whole cycle using the existing "Start Ramp" fiducial. A timing diagram is shown in Fig. 5. The existing modules generating the trigger signals for the kickers (EIT100) were found to have intrinsic jitter of about 10 ps, compared to about 100 ps rms tolerable injection timing jitter for APS-U (but that includes other sources as well). [2] A new module, here called "Booster Timing Controller" (BTC) is needed to determine the frequency ramp parameters and calculate the ramp ta-

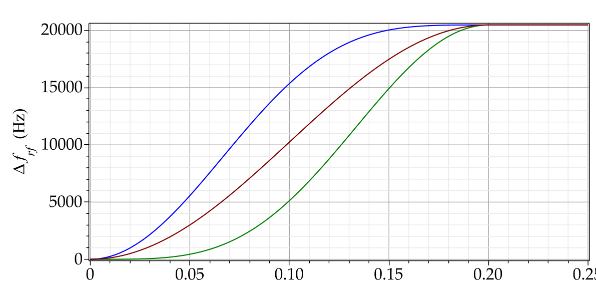

Figure 4: Rf frequency program for the Booster, injection on-momentum and extraction at $\delta p/p = -0.006$. The maroon curve has no path-length correction, the green curve has the most negative correction and the blue curve the most positive correction.

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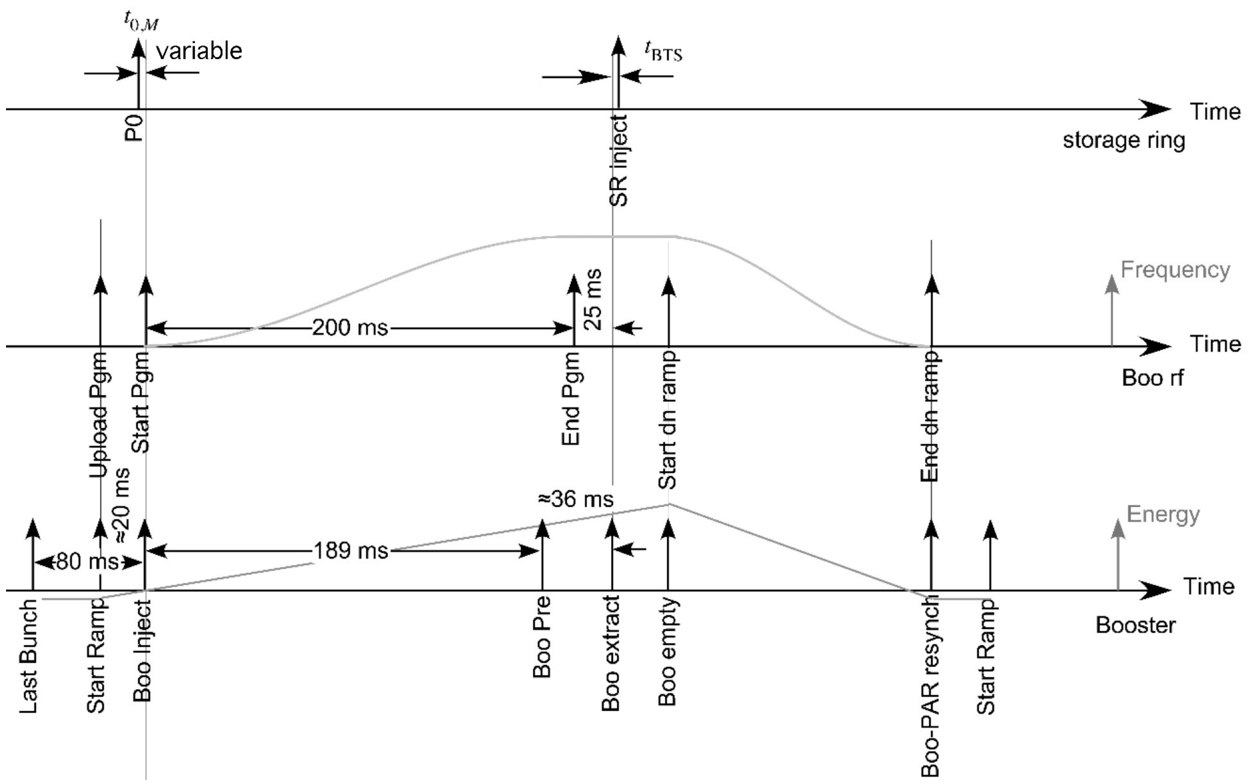

Figure 5: Timing fiducials. Start Ramp initiates the Booster B-field ramp; Upload Pgm indicates calculation of the frequency ramp and upload to the DDS controller; Start Pgm indicates the start of the frequency ramp play-out. Injection and extraction happen during the B-field ramp.

ble, which will have 1024 entries. The frequency ramp will be played into out using a DDS. Using simulation tools it was determined that the whole table can be calculated in an FPGA in less than 50μs, to be compared to a 20 ms window within which the table has to be calculated and be ready to start playing back through the DDS.

Rf Changing the rf frequency by as much as 30 kHz involves dynamically tuning the rf cavities. A conceptual design for a suitable ferrite tuner is presented in [3], it is modeled after the FNAL Recycler Ring tuner [4]. First modelling results indicate that up to 60 kHz range can be obtained with reasonable tuner parameters and with a predicted average power density of about 0.06 W/ccm for the APS-U Booster acceleration cycle. To maintain overall coherency of the rf waveforms, all rf synthesis—one DDS per machine—is derived from a common master clock. Storage ring and PAR operate at fixed rf frequency, while the Booster frequency is swept. This allows to ensure the PAR rf phase is correct during injection into the Booster and also opens up the possibility of diagnostic variation of the rf frequencies independently, e.g. for chromaticity measurement.

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