ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB046

PLAN FOR OPERATING THE APS-UPGRADE BOOSTER WITH A FREQUENCY SWEEP*

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Abstract

The APS-Upgrade presents several challenging demands to the booster synchrotron. Swap-out injection requires the booster to capture a high charge bunch (up to 17 nC), accelerate it to 6 GeV, and maintain a low emittance at extraction for injection into the storage ring. To accommodate these conflicting demands, the RF frequency will be ramped between injection and extraction. However, the RF cavity tuners will remain static, which means the couplers will need to withstand a high reflected power at extraction. This paper presents a plan for a system that will meet the requirements for injection efficiency, extracted emittance, and equivalent power at the coupler. Results from tracking simulations and beam studies with a frequency ramp will also be shown.

INTRODUCTION

The APS-Upgrade[1] storage ring will run at a slightly higher frequency than the present ring. In order to avoid a costly re-alignment of the booster, it was decided to decouple the booster and storage ring RF frequencies. This method also allows us to sweep the booster frequency between injection and extraction, which is helpful for meeting the challenging demands at both ends of the ramp. At injection, the booster must capture high charge bunches (up to 20 nC) with good efficiency (85+%). This requirement favors on-momentum operation. At booster extraction, we will rely on additional transverse damping from off-momentum operation to reduce the beam emittance and improve injection efficiency into the storage ring. In principle, the frequency ramp allows us to do both of these. However, since the booster tuners will remain static, the frequency ramp will place strong power handling demands on the cavity couplers.

In this paper, we discuss each requirement individually, starting backwards from extraction, and list some options for meeting all of them. We then briefly cover tracking simulations of the frequency ramp, our plan for bucket targetting, and preliminary machine studies results.

EXTRACTED BEAM EMITTANCE

The natural emittance of the present booster lattice at 6 GeV is 97 nm. This is too large for injection into the Upgrade storage ring, which requires less than 60 nm horizontal emittance. However, decoupling the booster and storage ring RF frequencies allows us to run off-momentum at extraction, which reduces the natural emittance. Coupling into the vertical plane could also gain us some additional headroom, though we don't presently have a reliable method for doing this. Calculations show that a natural emittance of 60 nm can be achieved with a **-0.8% momentum offset** (Table 1).

Table 1: Emittance vs Momentum Offset for Fixed ϵ_y

Offset	α	ϵ_x (nm)	ϵ_y (nm)
-0.4	71.8	59.8	16.0
-0.6	63.8	53.0	16.0
-0.8	**57.1**	**47.5**	**16.0**
-1.0	**51.8**	**43.1**	**16.0**

FREQUENCY RAMP

Since we have control of the booster RF frequency separately from the storage ring, we can change the frequency (and therefore the momentum offset) along the booster ramp. This process is diagrammed in Fig. 1, which depicts three potential momentum ramps. Each of the ramps has a different inital momentum offset, but a final offset of -0.8%. A "cosine-line" momentum ramp is used between the injection and extraction.

A negative momentum ramp corresponds to a positive RF frequency ramp. Unforunately, since the cavities must be detuned to the negative side for Robinson stability, the frequency ramp leads to a larger detuning at extraction. In other words, the detuning at extraction is the sum of the detuning at injection plus the frequency ramp. One way to think of this is that a limit placed on the equivalent power at extraction gives us a "detuning budget", which can be spent either on detuning at injection, or on the frequency ramp between injection and extraction.

RF POWER REQUIREMENTS

Because the frequency in the booster will be ramped but the tuners are static, the cavities will be significantly detuned at extraction. This creates strong requirements on the cavity couplers. Couplers are typically limited by voltage breakdown, but their performance is specified in terms of power into a matched load. Therefore we give our requirement in terms of an equivalent power P_{eq} (Eq. 1), which corresponds to the maximum voltage in the standing wave that is produced when driving a load with forward power P_{fwd} and incurring a reverse power P_{rev} from the mismatch.

$$P_{eq} = P_{fwd}\left(1 + \sqrt{\frac{P_{rev}}{P_{fwd}}}\right)^2 \tag{1}$$

* Work supported by DOE Contract No. DE-AC02-06CH11357
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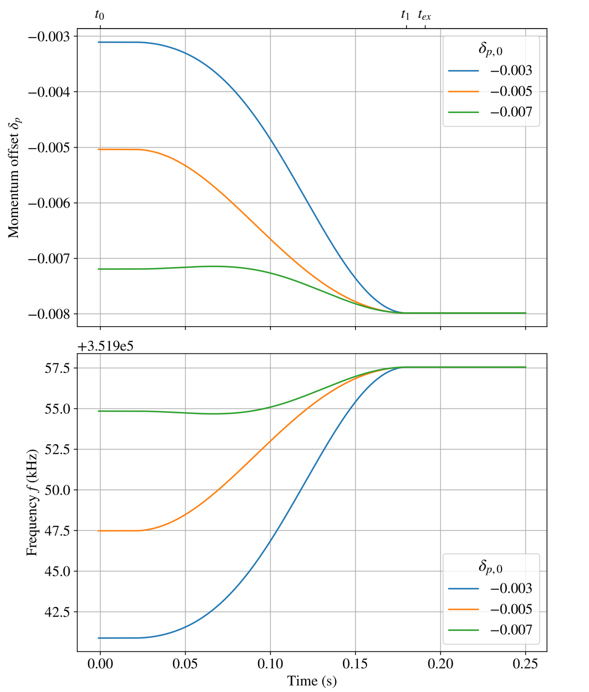

Figure 1: Examples of potential booster frequency/momentum sweeps. The beam is injected at t_0, the frequency ramp ends at t_1, and the beam is extracted at t_{ex}

The present booster cavities have R/Q_a = 1400 Ω, coupling factor $\beta = 1$, and loaded $Q_L \approx 20{,}000$. The required voltage at extraction is 5.2 MV. As shown in Fig. 2, the equivalent power for large detuning is extremely high.

For the upgarde, we plan to over-couple the cavities, increasing the coupling coefficient β from 1 to 3 and therefore reducing Q_L from ~20,000 to ~10,000. While over-coupling increases the power requirements for the matched case, it significantly decreases them in the detuned regime.

The booster cavity couplers need to be replaced for an equivalent power much greater than the 100 kW. A 500 kW coupler prototype has been designed and procured from Canon, and is presently being installed in one of the booster cavities [2]. To be conservative, we plan to limit ourselves to **P$_{eq}$=300 kW**, which allows for about -20 kHz detuning at extraction.

BOOSTER INJECTION EFFICIENCY

The heavy transient beam loading in the booster cavities when beam is injected can be mitigated by detuning the cavities. However, this eats up the detuning budget, thereby reducing the available frequency (i.e., momentum) sweep, which means we have to inject further off momentum to reach -0.8% or -1% at extraction. Finding the best balance between these two effects is a complicated question that requires particle tracking simulations.

The booster injection simulations are described elsewhere in these proceedings [3]. For the results presented here, the incoming bunch charge is 20 nC, and the bunch length is

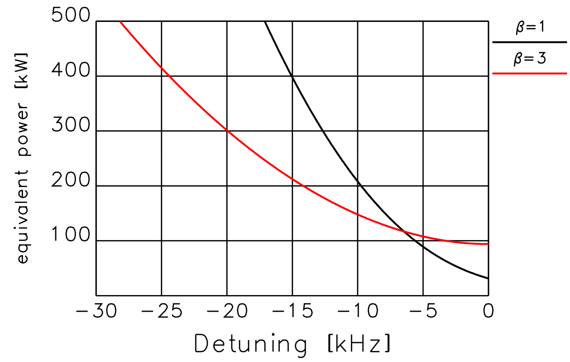

Figure 2: Equivalent power requirements for the booster cavity couplers.

600 ps. In other words, we assume we are able to partially mitigate the PAR bunch length blowup (probably with a high power RF12 amplifier [4]). Our overall goal is 85% injection efficiency into the booster. To give additional headroom, we require **90% simulated efficiency**.

Figure 3 (left) shows the simulated injection efficiency vs booster momentum offset, for different values of cavity detuning, for couplng factor β=1 (Q_L = 20,000). In this case, we would need to significantly detune the cavities at injection to achieve good efficiency. By over-coupling the cavities (Fig. 3, right), we mostly mitigate the beam loading, and can meet the efficiency goal without detuning the cavities at injection. This allows us to spend our detuning budget on the frequency ramp.

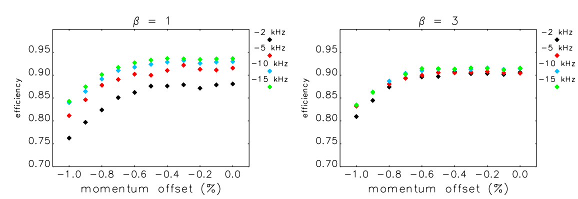

Figure 3: Simulated injection efficiency vs momentum offset for 20 nC injected charge. Left: β = 1. Right: β = 3.

PARAMETER OPTIONS

To sum up the previous sections, our goals are: -0.8% momentum offset at extraction, 300 kW equivalent power, and 90% simulated injection efficiency. The 300 kW limit gives a total detuning budget of -20 kHz, which can be taken up either by detuning at injection, or the frequency sweep between injection and extraction. Table 2 lists some potential parameter sets for -0.8% offset. In fact, this analysis implies that -1.0% extraction offset may also be possible (Table 3).

This scheme has the advantage of being flexible with regards to the exact choice of parameters. For example, if it turns out we need higher detuning at injection, we can maintain the same equivalent power at extraction if we inject farther off momentum.

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Table 2: Options for P_{eq} = 300 kW, Extraction Offset -0.8%

Injection detuning (kHz)	Frequency sweep (kHz)	Injection offset (%)	Injection eff (%)
-2	-18	-0.27	90
-5	-15	-0.36	91
-10	-10	-0.51	91
-15	-5	-0.65	91

Table 3: Options for P_{eq} = 300 kW, Extraction Offset -1.0%

Injection detuning (kHz)	Frequency sweep (kHz)	Injection offset (%)	Injection eff (%)
-2	-18	-0.47	90
-5	-15	-0.56	90
-10	-10	-0.71	90
-15	-5	-0.85	88

FREQUENCY RAMP SIMULATIONS

Particle tracking simulations of beam parameters along the booster energy ramp [3] have been extended to include the frequency sweep. Figure 4 shows the simulated momentum offset for 1 and 18 nC booster charge. While the 18 nC case shows large oscillations at injection (probably due to transient beam loading), these are damped out well before extraction. The simulations predict the frequency sweep should have no impact on any beam parameters (emittance, bunch length, etc.) by extraction time.

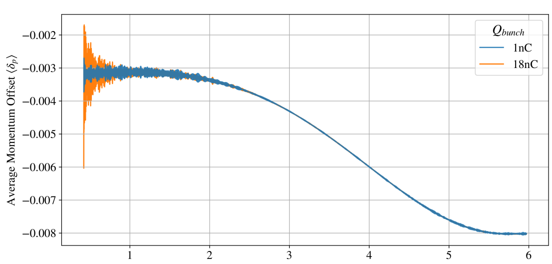

Figure 4: Average momentum offset $\langle\delta_p\rangle$ for an injection charge of 1 nC and 18 nC.

BUCKET TARGETING

Bucket targeting will be accomplished by adding an additional bump to the frequency sweep. This will change the amount of time the beam spends in the booster, so that it lines up with the correct storage ring bucket at extraction. Depending on detuning at injection, this bump could cause the frequency to cross resonance (into the Robinson unstable regime) in the middle of the booster ramp. Figure 5 illustrates a case with no overall frequency sweep, but with a large bump for bucket targetting. The detuning at injection is -2 kHz, and the bump is large enough to briefly cross the cavity resonance. The simulation predicts instability, but no losses, up to 10 nC.

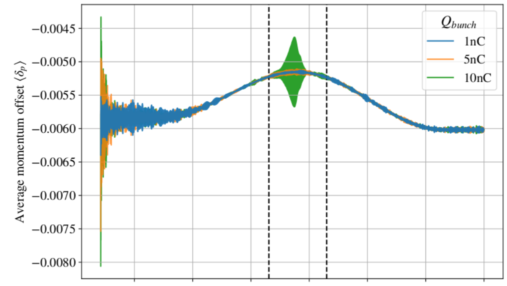

Figure 5: Momentum offset illustrating a frequency bump for bucket targetting. The beam is Robinson unstable between the two dotted lines.

BEAM STUDIES

Preliminary beam studies have been performed with a prototype of the new injector timing system. To date, we have successfully run the booster from a separate RF source, filled specific storage ring buckets using the bucket targeting scheme, and run with a momentum ramp between injection and extraction. Thus the basic capabilities of the frequency sweep scheme have been demonstrated.

Presently, most booster diagnostics are triggered based on the storage ring RF, and don't work well with the frequency ramp. In addition, good efficiency is not maintained through the booster for all cases, and bucket targetting is sometimes off by one bucket. Work is ongoing to understand and remedy these issues.

CONCLUSION

We have developed a plan to operate the booster with a frequency sweep for the APS-Upgrade. In short, the plan is:

- Over-couple the booster cavities to mitigate beam loading and reduce the equivalent power at extraction.
- Inject moderately off-momentum to achieve good injection efficiency up to 20 nC.
- Ramp the frequency between injection and extraction (nominally to -0.8% offset) to reduce the extracted beam emittance below 60 nm.
- Install high power couplers to handle the higher equivalent power at extraction (nominally 300 kW).

Simulations predict that we should be able to maintain the desired beam parameters at extraction, for our planned range of frequency ramp. Beam studies so far have demonstrated the basic functionality of the frequency sweep and bucket targetting scheme, though with some kinks to work out. A high power coupler prototype is presently being installed in the booster.

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