Proceedings of the 2003 Particle Accelerator Conference

ADVANCED PHOTON SOURCE BOOSTER SYNCHROTRON SUBHARMONIC RF CAPTURE DESIGN*

Nicholas S. Sereno, Advanced Photon Source, ANL, Argonne, IL 60439, USA

Abstract

Recent efforts at the APS have focused on improving overall injector system reliability and availability for top-up mode storage ring operation. One proposal being considered is to implement direct injection of the beam from the linac into the booster synchrotron, thereby bypassing the particle accumulator ring (PAR). Efficient capture of the long linac macropulse (>~ 10 ns) can be accomplished by adding an additional rf system in the booster at an appropriate subharmonic of the 352-MHz rf system. The subharmonic system is used during injection up to approximately 3 GeV, then the 352-MHz system is turned on to accelerate the beam to 7 GeV. The particle tracking program elegant is used to simulate rf and magnet ramping, beam loading, and HOM effects at up to 10-nC beam charge. Issues addressed in this design are efficient beam capture and acceleration to 7 GeV while maintaining adjacent bunch purity. Tolerances on various rf system parameters are presented in order to maintain bunch purity to better than 1 part in 100,000.

REQUIREMENTS

Successful operation of the APS storage ring (SR) in top-up mode requires a reliable injector system that efficiently delivers beam at 7 GeV to the SR. One way to possibly improve injector reliability is to inject the linac beam directly into the booster and bypass the PAR. Direct injection into the booster imposes several requirements on the booster rf system. First, the rf must capture the complete linac beam or at least a large fraction of it. Second, bunch purity must be preserved. Third, the whole acceleration process from injection to extraction at 7 GeV must be as efficient (as measured by particle loss) as possible at up to 10 nC of extracted charge. Finally, the rf system parameters should be chosen to preserve the present linear ramp profile used in the booster (0.325 to 7 GeV in 225 ms). The last requirement minimizes the required recommissioning effort since the magnet family ramps are left unchanged.

These requirements can be achieved by adding a subharmonic rf system in the booster at the appropriate frequency and gap voltage. The subharmonic system in combination with the present booster 352-MHz rf system act together to accelerate the beam to 7 GeV while minimizing beam loss and preserving bunch purity. The central problem of this design is to determine the proper subharmonic and 352-MHz rf system parameters to satisfy these requirements. The acceleration and capture process is achieved by using the subharmonic system to capture the linac macropulse and turning on the 352-MHz system at about 3 GeV to quickly capture and accelerate the beam to 7 GeV. The subharmonic system will also support future booster upgrades as well as a new, recently commissioned low-emittance booster lattice [1].

SUBHARMONIC FREQUENCY AND GAP VOLTAGE GENERAL CONSIDERATIONS

The thermionic gun macropulse length drives the choice of subharmonic frequency. The rf thermionic guns have nominal pulse lengths of 40 ns (gun 1) and 10 ns (gun 2). The subharmonic period sets the maximum macropulse length that can be captured in a stationary bucket. This maximum length is further reduced by a factor for nonstationary buckets [2]. For the booster, the beam is injected into an accelerating bucket so the achievable linac macropulse length that can be captured by the booster is approximately 30 - 50% less than the subharmonic period.

To capture the complete macropulse for both guns would require a < (1/40 ns) = 25 MHz subharmonic frequency. Due to the difficulty of building high-voltage, low-frequency rf cavities, this requirement can be relaxed so that at least the 10-ns pulse from gun 2 can be captured. Finally, the subharmonic frequency must be an integer subharmonic of 352 MHz (h = 432). Table 1 lists the subharmonic frequencies and numbers considered in this study. All four frequencies can completely capture the macropulse generated by gun 2. The exact choice of subharmonic frequency can be made based on rf considerations such as ease of construction and maximum gap voltage obtainable.

Table 1: Booster Subharmonic Capture Cavity Parameters

Frequency (MHz)	Subharmonic Number	Subharmonic Gap Voltage (kV)	Minimum Bunch Length (ns)
29.327	12	650	2.44
39.103	9	500	2.57
43.991	8	450	2.57
58.665	6	400	2.33

The subharmonic gap voltage required depends on the linac macropulse length and the bunch length required to efficiently capture and accelerate the beam by the 352-MHz rf system. The linac macropulse must be damped to < 2.84 ns before it can be captured and accelerated by the 352-MHz rf system. However, radiation damping is very small up to about 3 GeV where the damping time is 17.2 ms (at the injection energy of 0.325 GeV the damping time is 13.5 seconds). For energies less than approximately 3 GeV, adiabatic damping of the energy

---

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

spread is the dominant mechanism for reducing the bunch length since the bunch length is (nearly) proportional to the energy spread [2,3]. The proportionality is not exact since it is scaled by the synchrotron frequency, which changes as the synchronous phase and energy change.

The gap voltage needs to be large enough to provide an adequate overvoltage factor at 3.25 GeV to compensate for acceleration (36.4 keV/turn) radiation loss (296.7 keV/turn) as well as beam loading. This requires a subharmonic gap voltage of somewhere around 400 to 600 kV (depending on choice of frequency) to insure adequate overvoltage. The exact value of the gap voltage is explored via simulation described in the next section.

DETERMINATION OF SUBHARMONIC GAP VOLTAGE FROM TRACKING

Initial elegant [4] tracking simulations were performed to determine the gap voltage required for each frequency listed in Table 1 to capture and bunch the linac macropulse to < 2.84 ns. The initial linac macropulse length was varied depending on the subharmonic frequency, and the energy spread was taken to be ±1% (hard edge full width) at 0.325 GeV. These initial beam parameters resulted in ~ 0.5% particle losses at injection. The simulation used 35,000 particles to estimate the worst-case capture efficiency as well as bunch purity during capture and acceleration. Beam loading was simulated for the subharmonic cavity by using the standard resonator impedance model with Q_o = 40,000, β = 1, and Rs = 5 MΩ. Finally, elegant has the capability to simulate radiation damping and quantum excitation, and these effects were included in the simulations.

Table 1 shows the total gap voltage required for each subharmonic cavity frequency to achieve a 2.3- to 2.5-ns full width bunch length (defined as the difference in arrival time of the most downstream and most upstream particles in the bunch). The table clearly shows the tradeoffs involved in the choice of subharmonic frequency. One would like to use the lowest frequency possible to capture the longest possible linac pulse. A lower subharmonic frequency would require a much higher gap voltage to achieve the bunch length required for efficient 352-MHz capture. In general it is more difficult to design low-frequency cavities with high gap voltage (> 200 kV) because of voltage breakdown [5,6]. Next we explore a way to reduce the required total gap voltage yet still use a low-frequency cavity for capture of a long linac macropulse.

SIMULATIONS USING TWO SUBHARMONIC CAVITIES WITH DIFFERENT FREQUENCIES

Table 1 illustrates the tradeoff between subharmonic frequency and gap voltage. This is understood simply: the bunching required is inversely proportional to the time derivative of gap voltage, which is the product of the subharmonic frequency and peak gap voltage in the frequency domain [2]. One can increase the effective gap voltage time derivative by using a combination of low-frequency subharmonic cavity and high-frequency subharmonic cavity (both cavity frequencies need to be harmonically related to each other as well as to 352 MHz). This has the effect of reducing the total gap voltage required for a given desired final bunch length (~ 2.5 ns for efficient capture by the 352-MHz booster rf system).

The subharmonic frequencies chosen for this study were the twelfth subharmonic (29.327 MHz) previously described and the third subharmonic (117.310 MHz) of 352 MHz. The twelfth subharmonic was kept powered at a constant 200 kV throughout the ramp and the third subharmonic was ramped (linearly) to 250 kV in 10 ms to capture and bunch the beam when the beam energy reached approximately 2.40 GeV. After the beam was captured and compressed by the subharmonic cavities to <~ 2.5 ns (which occurred at a beam energy of approximately 3.16 GeV), the primary 352-MHz system was turned on and ramped to full power. The cavity mode parameters for the unloaded Q, shunt impedance, and coupling from the last section were used for the 3rd and twelfth subharmonic cavities. The design parameters Q_o = 40,000 and Rs = 221 MΩ were used for the quality factor and total shunt impedance of the four 352-MHz booster cavities. In all the simulations, elegant modeled tuning the 117- and 352-MHz cavities on resonance instantaneously at a given turn after injection when the bunch length was short enough for efficient capture.

Figure 1 shows the results of the simulation where 110,000 particles were used. The figure shows the beam captured and accelerated to 7 GeV by both subharmonic and 352-MHz systems without particle loss. The full-width bunch length plotted shows a transient at injection due to longitudinal phase-space mismatch where the initial momentum spread of the beam was ± 1%. Particle losses at injection were about 0.5% due to the mismatch. To reduce beam loss and enhance bunch purity, the 352-MHz system ramp profile was chosen to be a two-term, fourth-order polynomial (linear and quartic terms used), which guarantees a near linear ramp for approximately 50 ms after system turn-on. The full power level of the 352-MHz system is 10 MV.

The most critical point where particle loss can occur is when the 352-MHz system is turned on. Eight simulations were performed where the phase of the 352-MHz system was varied, which showed that particle loss starts to occur when the phase differs by more than ± 1 degree from nominal. The phase tolerance for the 117-MHz system at turn-on was found to be somewhat more relaxed at ± 5 degrees from nominal. A crucial design issue for the 352-MHz system is how to achieve ± 1-degree phase stability at system turn-on.

CONCLUSION

The studies presented here indicate that a subharmonic system optimized using both third and twelfth

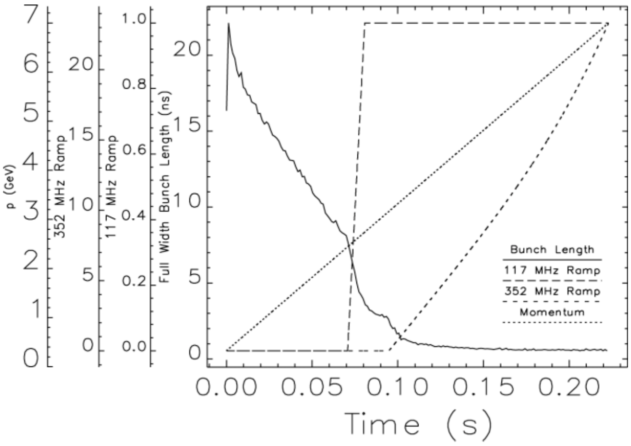

Figure 1: Full-width bunch length, 117- and 352-MHz ramps, and momentum as a function of time. Shown is the rapid bunching when both 117- and 352-MHz rf systems are powered. In this simulation no particles are lost when the ramped rf systems are powered. Not shown in the figure is the constant ramp profile (200 kV) of the twelfth subharmonic system. The 117-MHz and 352-MHz ramps are in arbitrary units. The peak gap voltage for 117- MHz and 352-MHz systems was 200 kV and 10 MV, respectively. Both 117-MHz and 352-MHz systems were tuned to resonance instantaneously when the ramp profile first becomes greater than zero.

subharmonic cavities (117.3 and 29.3 MHz) provides the minimum total gap voltage required to capture and accelerate a 15-ns linac macropulse at up to 10 nC with ± 1% energy spread. The simulations also show particle losses less than one part in 110,000 when including radiation damping, quantum excitation, and rf cavity beam loading. The only particle losses were found to be at injection due to phase-space mismatch. Optimization of the subharmonic capture idea requires knowledge of the gap voltage that can be achieved with an actual cavity. In general, the lower the cavity frequency the harder it is to engineer a cavity that can sustain a given gap voltage without breakdown. Phase and amplitude control of both subharmonic and 352-MHz systems also need to be carefully considered so that bunch purity is preserved and operational flexibility is maintained. Phase stability is particularly important for the high-power 352-MHz system, which preliminary simulation studies show needs 1-degree regulation at turn-on. Future optimization studies need to include amplitude stability tolerance studies for each ramped rf system at turn-on. In addition, elegant has recently been modified to include realistic modeling of cavity tuning using a ramp profile.

The two-frequency, subharmonic capture system considered here has both advantages and disadvantages. On the one hand, up to a 20-ns pulse can be captured while requiring only a single 29-MHz cavity. This cavity would be very large and difficult to build and operate at up to 200-kV gap voltage. Operationally, a two-frequency subharmonic system would be more difficult to operate and manage spares. A good compromise and the focus of ongoing simulation studies is to use one or two sixth subharmonic cavities operating at 58.7 MHz and a total gap voltage of 400 kV. Using this frequency, most if not all of an 8- to 10-ns pulse can be captured. With two sixth subharmonic cavities, a degree of redundancy can be achieved; if one cavity becomes inoperable, the other can be used to fill the storage ring at the expense of bunch purity.

ACKNOWLEDGEMENTS

The author wishes to acknowledge many valuable discussions with M. Borland on rf capture and PAR rf experience. Thanks go to D. Horan, A. Nassiri, and R. Kustom of the APS RF Group and K. Kleman of the Univeristy of Wisconsin Synchrotron Radiation Center, who provided valuable comments on rf cavity, amplifier, and low-level rf design of the subharmonic capture system. Finally, thanks to APS management for encouraging this study as a possible way of increasing injector efficiency and reliablity for top-up operation.

REFERENCES

[1] N. S. Sereno, M. Borland, “APS Booster Low Emittance Lattice Commissioning Results,” these proceedings.

[2] H. Wiedemann, Particle Accelerator Physics: Basic Principles and Linear Beam Dynamics, Springer-Verlag, pp. 290-291, 1993.

[3] J. Murphy, Synchrotron Light Source Data Book, Version 4 NSLS/BNL, pp. 18, May 1996.

[4] M. Borland, elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation, APS Light Source Note LS-287, September 2000.

[5] R. Kustom, 38.9 MHz Capacitively-Loaded Coaxial Cavity Design for the Booster, APS Light Source Note LS-26, June 1985.

[6] R. Kustom, Folded Coaxial Line Design for the 38.9 MHz Booster Cavity, APS Light Source Note LS-28, July 1985.