

OPERATION OF THE APS-U INJECTORS WITH HIGH SINGLE BUNCH CHARGE*

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Abstract

The APS-Upgrade uses swap-out injection, which means the injectors must supply a full charge bunch (up to 16 nC) to replace a depleted one in the storage ring. The APS injector chain consists of a linac, particle accumulator ring (PAR), and booster synchrotron. These machines were kept in place for the APS-U, with several improvements to support high charge operation. Major upgrades include a new timing system, improved diagnostics, and a new amplifier for bunch compression in the PAR. So far, the injectors have supported up to 140 mA storage ring current in the high charge (48 bunch) mode. This paper will summarize the work needed to achieve high injector charge, and report on operational experience so far.

INTRODUCTION

The APS-Upgrade (APS-U) is a 4th generation electron storage ring (SR) light source, which began operating in April 2024 [1]. It makes use of a seven-bend hybrid multi-bend achromat lattice with reverse bends to achieve a natural emittance of 42 pm at 6 GeV. The dynamic aperture of this lattice is too small to simultaneously accommodate both the stored and injected beam, which precludes top-up injection. As a result, a depleted bunch in the storage ring must be fully replaced by a high charge bunch from the injector, a process known as “swap-out” injection.

The APS-U has two modes of operation: a “brightness” mode with many (presently 216) low charge bunches, and a “timing” mode with 48 high charge bunches. Both modes have a desired storage ring current of 200 mA. In brightness mode, the highest injector charge required is about 5 nC, which is not difficult for the APS-U injectors. In timing mode, up to 17 nC injected charge is required, which is very challenging.

For the APS-Upgrade, it was decided to leave the old APS injector chain in place, and make individual improvements when needed. The injector chain consists of three machines, shown in Fig. 1), which operate at a 1-Hz rep rate:

- A linear accelerator (linac), which generates bunches of ~ 1 nC charge, and accelerates them to ~ 425 MeV.
- A particle accumulator ring (PAR), which captures and accumulates linac bunches in a single rf bucket, up to the desired charge. A 12th harmonic cavity (RF12) turns on 750 ms into the PAR cycle, which compresses the bunch before injection into the booster.

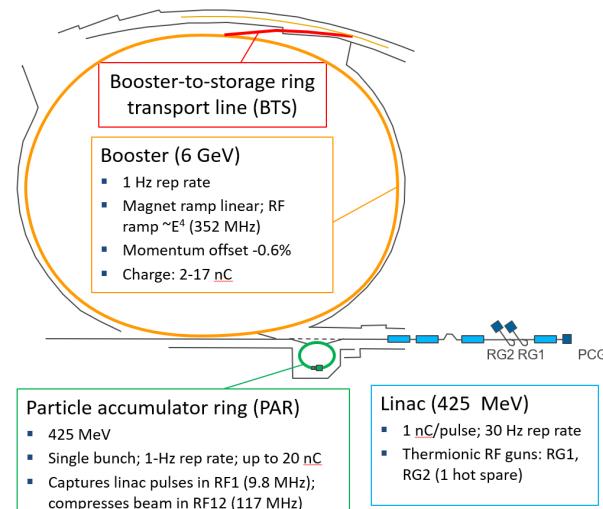


Figure 1: APS-U injector complex.

- A booster synchrotron, which accelerates the bunch up to 6 GeV before extraction to the storage ring. To reduce the extracted beam size, the booster is operated with a momentum offset of -0.6%.

There were many challenges in adapting these three machines for APS-U high charge operation.

LINAC CHALLENGES

For APS-U high charge mode, the linac must produce up to 20 bunches of at least 1 nC charge at a 30 Hz rate at 425 MeV or higher. The linac was nominally capable of meeting this requirement, but not with the consistency and reliability demanded by the APS-U. To close this gap, a linac refurbishment plan was implemented. Key items of this project include:

RF Upgrades

New 50 MW RF stations composed of a klystron and solid state modulator were procured, to provide higher linac energy and improved reliability. The first new RF station was procured and installed in an RF Test Stand for testing. Two additional new RF stations (Fig. 2) have been procured, installed and commissioned to support APS operations [2].

Along with the 50 MW RF stations, the RF control and diagnostic system was upgraded to a new digital LLRF system. A new Micro TCA.0 based digital low level RF (LLRF) system provides lower RF power and phase jitter levels.

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Figure 2: 50 MW RF station at K2. Supporting linac operation since September 2022.



Figure 3: The prototype gun at APS linac RG2 slot, which provides beam for APS-U operations.

Thermionic RF Guns

New RF guns [3] were designed, tested and installed to replace the deteriorating Gen-III guns, ensuring stable charge delivery and improved performance. The prototype gun, shown in Fig. 3, is in operation at RG2 slot providing beam for the upgraded APS. The three production guns are being tested and commissioned.

Other Upgrades

Obsolete power supplies were replaced by fast bipolar units. The response time of 1–18 seconds for the old power supplies has been reduced to 20–150 ms for the new ones. 42 new bipolar supplies have been installed.

A modern timing system was implemented to improve timing accuracy and reliability. The new system with event master and receivers by Micro Research Finland was commissioned in September 2023. It has higher resolution, with 8 ns, 200 ps, 10 ps options (compared to microseconds in the old system). It also has higher channel density (up to 24 channels per VME) and a flexible configuration that is easy to expand.

Taken together, the linac refurbishment projects have significantly enhanced the linac's performance and reliability. Additional RF stations and power supplies in the future will further enhance energy capacity and operational flexibility.

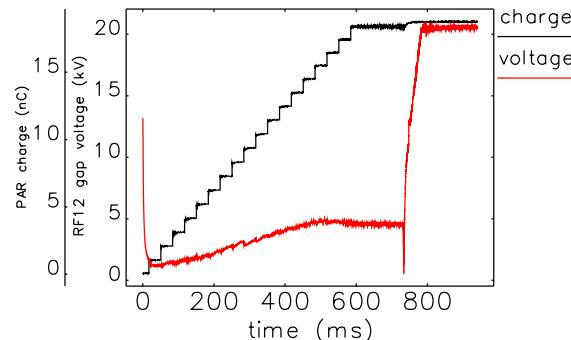


Figure 4: PAR charge (black) and 12th harmonic RF voltage (red) in a 1 Hz cycle.

PAR CHALLENGES

The PAR must accumulate up to 20 bunches from the linac with high efficiency, then compress this bunch in a single 12th harmonic bucket. This process is illustrated in Fig. 4. Accumulation up to 20 nC was accomplished relatively early in the project [4]. Maintaining good PAR injection efficiency up to high charge required optimization of the orbit and injection trajectory, as well as tuning of the LLRF parameters controlling the 12th harmonic voltage and tuner waveforms.

Bunch Lengthening

While 20 nC could be extracted from the PAR, it was not readily accepted by the booster. One of the primary reasons for this is that PAR bunch length more than doubled between low and high charge, from ~350 ps to more than 700 ps. The beam was also longitudinally unstable. These effects result in losses at booster injection.

The bunch lengthening and instability is a result of the PAR longitudinal impedance, and is a combination of potential well distortion and microwave instability. These effects were analyzed first with a circuit model [5], then with detailed particle tracking simulations [6]. These calculations lead to the development of a three part plan to mitigate the bunch lengthening: reduce the PAR impedance where possible, develop a high-power amplifier for the 12th harmonic cavity to allow for increased bunch compression, and run the PAR at higher energy to mitigate the microwave instability.

Kicker Chambers

Through detailed modeling of each PAR impedance element [7], the kicker chambers were identified as a large (and relatively easy to mitigate) source of longitudinal impedance. New kicker chambers were developed which made a use of a patterned Ti coating, shown in Fig. 5 [8]. The pattern was designed to reduce the impedance, while simultaneously limiting the eddy current effect.

12th Harmonic Amplifier

To reduce the overall bunch length, a 10 kW solid state amplifier was designed for the 12th harmonic cavity. It has

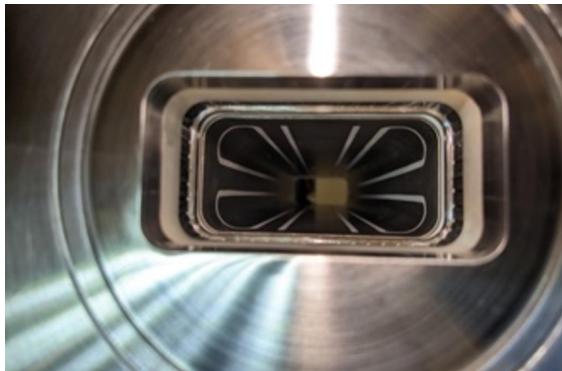


Figure 5: PAR kicker chamber with patterned Ti coating.

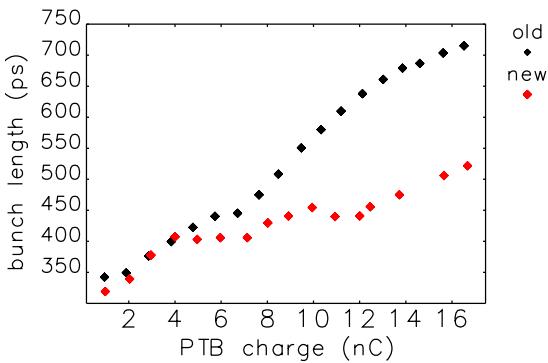


Figure 6: Comparing PAR bunch length with the old (black) and new (red) 12th harmonic amplifier. The new amplifier is set to 22 kV below 10 nC, and 26 kV above it.

been installed, commissioned, and is presently in use for APS-U operations. The old amplifier supported 22 kV RF12 voltage at low charge, but was unable to maintain this at high charge. The new amplifier was designed to provide 30 kV RF12 voltage up to high charge, though it is presently operated at 26 kV.

As shown in Fig. 6, the combination of higher RF12 voltage and reduced PAR impedance has resulted in a dramatic reduction of the PAR bunch length at high charge. In addition, a new LLRF system for the PAR allows for more precise control and better stability of the RF12 voltage.

The PAR has been operated up to 450 MeV during machine studies. Recent linac upgrades make it plausible to do so during operations, though this has not been tested yet. Presently, the dipole power supply limits the PAR energy to 470 MeV. Operation at higher energy would require significant upgrades to both the PAR and linac.

BOOSTER CHALLENGES

The booster must capture high charge bunches from the PAR with good efficiency, accelerate them to 6 GeV, and maintain relatively small transverse emittance for injection into the storage ring. In addition, the booster and storage ring are operated at different RF frequencies, making synchronization challenging.

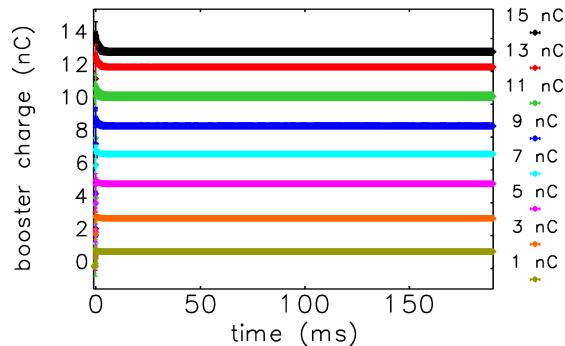


Figure 7: Booster charge along the ramp, for different injected charge. The width of each line represents the standard deviation of 20 measurements. Injecting more than 15 nC does not result in a significantly higher booster charge.

Injection Efficiency

Low booster injection efficiency at high charge has been the most difficult challenge to overcome. Initially we used a lower emittance booster lattice, but the maximum captured charge we could achieve was 6 nC [9]. After switching to a higher emittance lattice, which has low dispersion in the straight sections, we were able to increase the limit to 12 nC [10]. Key improvements that enabled this increase include orbit correction, new current-controlled sextupole power supplies, improved diagnostics (including a photodetector for bunch length measurements [11]), and improvements to control of the injection trajectory [12].

Despite these upgrades, we found that the booster efficiency dropped sharply above 10 nC, limiting the captured charge to 12 nC. Particle tracking simulations were employed to help identify the source of these losses. The simulations showed good agreement with the measured injection efficiency vs charge for both lattices [10]. Most of the losses occur shortly after injection. The simulations pointed to two major sources of loss: bunch lengthening in the PAR, and heavy transient beam loading in the booster cavities.

The recent reduction in PAR bunch length has helped improve the high charge booster injection efficiency, allowing for capture of over 13 nC (Fig. 7). The charge stability is very good (3% rms or less), even at high charge.

As seen in Fig. 7, no charge loss is observed except at injection. Both measurements and simulations show no transverse instability or blowup at high charge extraction. We observe a small (~5%) bunch length increase at booster extraction at high charge [11].

Timing System

The APS-U SR is slightly shorter than the old one, and so requires a higher RF frequency. To avoid a costly realignment of the booster, the PAR, booster, and SR RF frequencies were decoupled for the APS-U. The three RF sources, and the transfer of beam between the machines, are handled by a new Injection/Extraction Timing and Synchronization

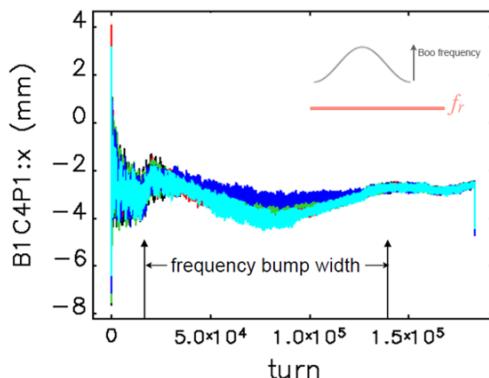


Figure 8: Horizontal beam position in a dispersive location during the booster ramp. The positive frequency bump (required so the booster frequency does not cross the cavity resonance f_r) results in a larger negative momentum offset for the beam. The different colors represent different measurements with different frequency bump heights.

system (IETS) [6]. Bucket targeting in the storage ring is accomplished by varying the booster frequency during the ramp. This changes the amount of time the beam is in the booster, so it aligns with the correct SR RF bucket at 6 GeV extraction. The height of the bump is automatically calculated for each shot, based on the relative phase of the booster and SR and the desired SR bucket. This frequency variation is observable in dispersive BPMs in the booster (Fig. 8).

The IETS system also supports an overall frequency ramp between booster injection and extraction. This would allow us to simultaneously optimize booster injection (which favors on-momentum injection), and storage ring injection (which favors off-momentum extraction, since this results in smaller horizontal emittance) [13]. Since the frequency ramp brings the booster cavities further out of tune, it results in a large reflected power at extraction. This is a risk for the present booster couplers, so the frequency ramp is not currently in use.

High Power Couplers

Handling the high reflected power at extraction requires specially designed high power couplers (HPCs). A prototype HPC was designed, tested, and installed in one of the four booster cavities in 2021. While there were no issues operating with this coupler, a potential weakness was discovered in the design (water-vacuum joints), and it was eventually descoped from the APS-U project.

More recently, the HPC project was restarted, this time based on the modification of a CERN 500 kW coupler design (Fig. 9). It utilizes a cylindrical ceramic with copper brazing rings and a corona geometry to minimize electric field breakdown. For integration into the APS, the coupler was modified for magnetic loop coupling to accommodate matching adjustments with the cavity. Mechanical stress mitigation was incorporated to minimize tensile stresses on the ceramic and enhance its integrity. A first-article coupler has been installed in the APS test facility and is currently

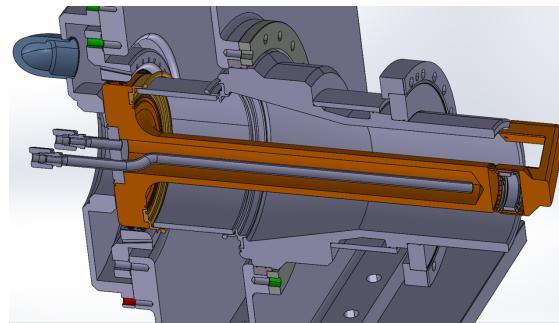


Figure 9: CERN HPC design with magnetic loop coupling.

being prepared for high-power tests. Upon successful completion of the testing, additional couplers will be received for each of the injection and extraction Booster cavities.

The HPCs will be installed with a high coupling factor ($\beta = 3$), which will help mitigate beam loading and allow for higher detuning. They will also enable the use of a frequency ramp in the booster.

INJECTOR RE-COMMISSIONING

The APS-U dark time began in April 2023. All machines, including the injectors, were shut down for several months. Linac and PAR restarted in September 2023 [8], and the booster in February 2024 [14]. Overall, injector re-commissioning went relatively smoothly. The biggest challenge we faced was poor vacuum in the PAR, after it was vented for installation of the new kicker chambers. The high vacuum pressure lead to multipacting in the fundamental RF cavity, which initially limited the voltage to 10 kV, less than half the nominal voltage of 22 kV. This issue was resolved by storing beam in the PAR to process the vacuum chambers. Over the course of a few months, the vacuum slowly improved and we were able to raise the voltage to the nominal value.

Injector re-commissioning was completed in March 2024, in time to support APS-U SR commissioning in April. High charge operation with the IETS system was checked out, up to 12 nC booster charge.

OPERATIONAL EXPERIENCE

During swap-out operation, a SR bunch is fully replaced by a new one delivered by the injector. This is repeated at a set interval. Presently, the injection interval is set to 10 seconds, but the swap-out shot is skipped if the SR current is still above a set target. This results in an effective swap-out interval between 10–40 seconds, depending on the injector charge, beam lifetime, target current, etc.

The injector machines are enabled several (presently 5) seconds before a shot is extracted from the booster into the SR. This is done because the first few shots after the injector is enabled tend to have lower efficiency. We plan to investigate the cause of this, and reduce the number of shots needed before SR injection.

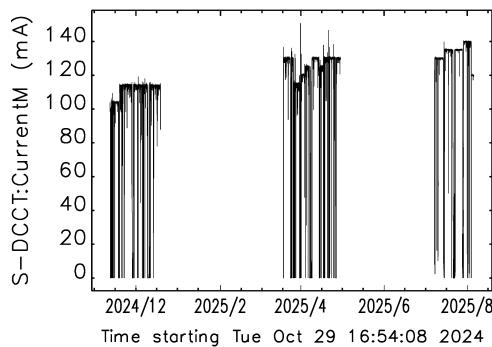


Figure 10: Storage ring current during APS-U timing mode operation.

Storage Ring Current Limit

The APS-U operates with three runs of three months each per year, with a one month maintenance period in between them. The first run of APS-U (2024-2) focused on commissioning and initial operation in brightness mode. Since then, the runs have been roughly equally divided between brightness and timing mode. We began the first run with timing mode (2024-3) with 100 mA SR current, then increased it to 115 mA. We increased the current limit to 130 mA in run 2025-1, and 135 mA in 2025-2, with several days at 140 mA near the end of the run (Fig. 10).

When the injectors are well tuned, they operate with good efficiency and very good charge stability. The charge in each injector machine and transfer line are recorded for each swap-out shot. For the last week of operations at 135 mA, the following values were measured:

- Linac-to-PAR (LTP) transfer line: 14.2 ± 0.2 nC
- PAR-to-booster (PTB) transfer line: 13.6 ± 0.2 nC
- Booster charge before extraction: 12.9 ± 0.3 nC
- Booster-to-SR transfer line (BTS): 11.6 ± 0.3 nC

At each step, the efficiency is better than 90%, and the charge stability is better than 3% rms. Unexpectedly, there is some apparent charge loss at booster extraction. This was not observed in high charge studies at the old APS, and is not presently understood.

The maximum storage ring current achievable is a function of the BTS charge and charge variation, SR efficiency, beam lifetime, and injection interval. Table 1 gives the average injection interval required for a given BTS charge and desired SR current, using measured values for the other parameters. The minimum injection interval allowed is 10 seconds, though 20 seconds or higher is preferable.

Operational Challenges

The biggest operational challenge so far has been failures of components in the injector pulsed magnet power supplies, especially in the PAR injection kickers. Failures include a damaged HV triaxial cable, thyratron heater failure, a faulty control power supply, and a shorted sensor cable.

Table 1: Required Injection Interval for a Given SR Current and BTS Charge

mA:	100	120	140	160	180	200
10 nC	91	14				
12 nC	169	77	20			
14 nC	227	125	77	23		
16 nC	270	175	111	59	24	
17 nC	303	200	125	77	38	13

The injector pulsed PS are nearly 30 years old. Swap-out operation requires more frequent operation of the injectors, increasing wear on the supplies. This is especially true of the PAR injection kickers, which must fire up to 20 times a second to inject linac bunches into the PAR. A plan is under development to replace the PAR kickers, starting with the control racks and long haul cables, then the pulsers.

We have also encountered issues running the PAR 12th harmonic amplifier at high voltage and high charge. The cavity voltage, detuning, and phase are controlled by a feed-forward process which takes one cycle to respond to a change in PAR charge. Thus there is a mismatch when the charge changes (i.e. during swap-out), which can lead to high forward and reverse power. We partially mitigated this effect by running with a lower voltage and moderate detuning when beam is not present, to reduce the transient when beam first appears. Despite these precautions, we recently discovered that several of the modules in the amplifier have been damaged over the course of the past year. This prevented us from finishing run 2025-2 at 140 mA.

Reaching Higher Charge

The biggest improvement that will help us achieve higher charge is the high power booster couplers. These will allow us to overcouple/detune the cavities, and/or inject on momentum, both of which should help booster injection efficiency. In recent studies, we achieved 14.5 nC booster charge by operating on momentum and slightly detuning the cavities. Other future improvements include:

- Continuing the linac refurbishment project.
- Increasing linac/PAR energy.
- Improving operation of PAR RF12, making use of the new LLRF system, and further increasing the voltage.
- Replacing old pulsed power supplies.
- Investigating the source of apparent charge loss at booster extraction.

CONCLUSION

Upgrades and intensive studies in the linac, PAR, and booster have raised the maximum charge injected into the storage ring from ~ 3 to ~ 12 nC. These improvements have enabled APS-U operation in 48 bunch timing mode up to a storage ring current of 140 mA. Further studies, upgrades, and operational improvements are underway to achieve the design goal of 200 mA operation.

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