

HIGH CHARGE OPERATION AND FUTURE UPGRADES OF THE APS-U INJECTOR CHAIN*

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Abstract

For swap-out operation in the APS-Upgrade storage ring, the injector must supply a full charge bunch in one shot. For 200 mA operation in 48 bunch timing mode, the required charge per bunch is 16 nC, which is challenging for the injector chain. In this paper we report on the present status of high charge operation and discuss upcoming improvements to increase the charge limit. We also propose two future upgrades to the APS-U injector chain: a high charge photoinjector for direct injection into the booster, and a high energy accumulator ring in the booster tunnel.

INTRODUCTION

The APS-Upgrade (APS-U) is a 4th generation electron storage ring (SR) light source, which has a natural emittance of 42 pm at 6 GeV [1]. Achieving this ultralow emittance requires strong focusing and nonlinearities, which results in a small dynamic aperture, precluding accumulation. Instead, the APS-U uses swap-out injection [2, 3]: a depleted bunch in the SR is replaced by a full charge bunch from the injector.

For 216 bunch brightness mode, the injector chain can easily deliver the required charge (up to 5 nC), and the full SR current of 200 mA has been achieved. In 48 bunch timing mode, the injector must deliver at least 16 nC to the SR, 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 3 machines (Fig. 1), which operate on a 1 Hz cycle: a linac, Particle Accumulator Ring (PAR), and booster. The PAR accumulates 1 nC pulses from the linac (up to 20 nC), and compresses the bunch with a 12th harmonic cavity (RF12) before injection into the booster. The booster must capture this bunch with high efficiency, accelerate it to 6 GeV, and maintain a reasonably low emittance.

Challenges of the APS-U injector upgrade included aging and obsolete accelerator components, operating the booster and SR at different frequencies [4], and stricter requirements for charge stability [5]. This paper will describe recent progress on the key requirement: delivering a high charge bunch to the storage ring. It will also describe two potential long term upgrades of the injector chain, which would further improve on high charge performance.

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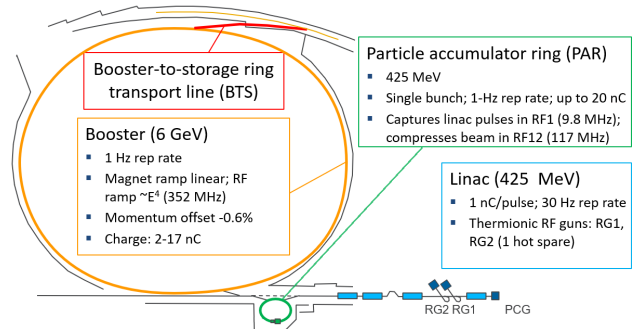


Figure 1: APS-U injector complex.

Other accelerator projects have taken different approaches to the challenge of high charge swap-out injection. ALS-U will use a full energy accumulator ring in the storage ring tunnel [6]. In the HEPS, the booster doubles as an accumulator ring by maintaining a flat top at full energy [7]. These schemes avoid the problem of high charge transport at low energy, at the cost of requiring a complex and high performance machine in the injector chain.

BOOSTER INJECTION

The main bottleneck to high charge transport through the APS-U injector is booster injection efficiency. The efficiency is good at low charge, but quickly drops above ~ 10 nC. Extensive simulations [8] indicated two main reasons for the reduced efficiency: PAR bunch lengthening and beam loading in the booster cavities.

PAR Bunch Length

As previously reported [9, 10], the PAR bunch length increased from 350 ps to more than 700 ps between low and high charge, due to a combination of potential well distortion and microwave instability. One of the largest sources of impedance was the kicker chambers. During the APS-U dark time, new chambers were installed with a patterned Ti coating, which both reduced the impedance (Fig. 2) and limited eddy currents.

In addition, a high power amplifier for the 12th harmonic cavity was installed, to provide increased bunch compression. The amplifier was recently tested up to full power, which provides 30 kV RF12 voltage. Figure 3 plots the measured bunch length vs charge for different RF12 voltages. At 30 kV, the bunch length is kept below 500 ps up to 18 nC.

A method of further reducing the extracted bunch length, by modulating the 12th harmonic rf voltage, is also under investigation, and has recently been demonstrated at low charge.

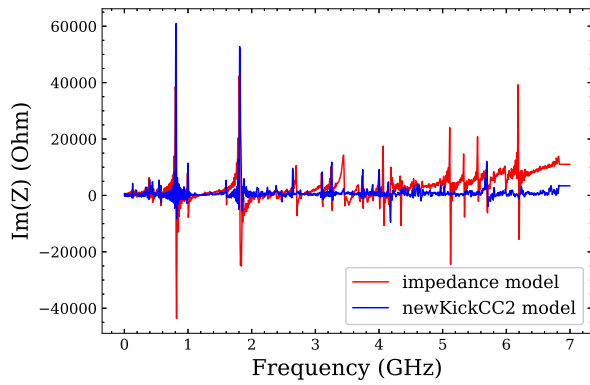


Figure 2: Comparison of imaginary part of the impedance for the old and new kicker chambers. These were calculated by CST Microwave Studio.

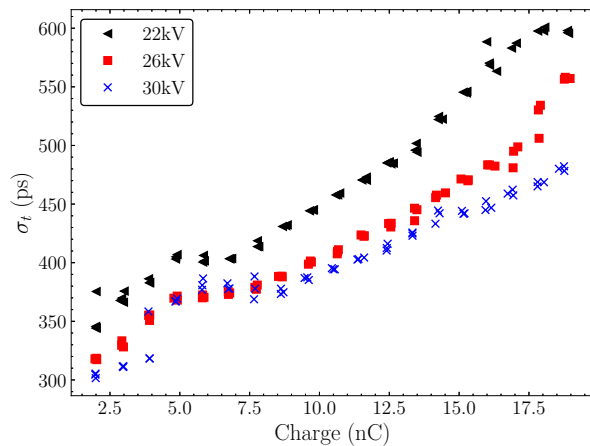


Figure 3: Measured PAR bunch length vs charge, for different RF12 voltage.

Booster Cavity Beam Loading

One way to mitigate beam loading in the booster is by detuning the rf cavities to reduce the total beam-induced voltage. Modest detuning is easily done without any upgrades to either the booster low-level rf or the cavity systems. During high charge (48 bunch mode) operation, they are detuned to around -4 kHz. Simulations [8] have shown that detuning as far as -20 kHz could be beneficial. However, since the present booster cavity couplers were not designed or tested for high reflected power, there is reluctance to operate them this way. During studies, we have detuned as far as ~ -6 kHz. Higher detuning results in faster damping of the longitudinal motion at injection (Fig. 4).

When the effort to increase the APS injector charge first began, the maximum charge that could be captured in the booster was about 5 nC. Through a series of machine upgrades and studies (previously described [8]), this value was increased to 12 nC. In a recent study, with 30 kV in RF12 and -6 kHz detuning, we successfully captured 15 nC in the booster (Fig. 5). Studies and upgrades have been guided by particle tracking simulations, which have generally agreed well with measurements.

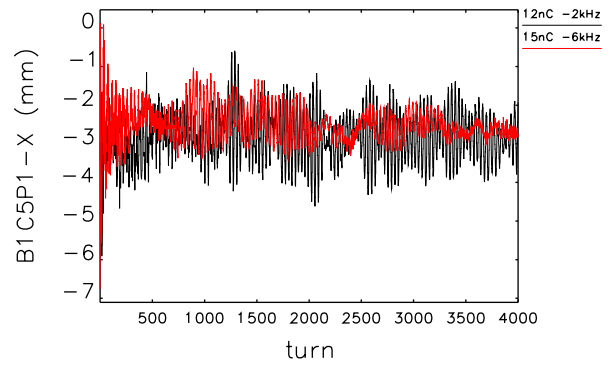


Figure 4: Synchrotron motion observed in a dispersive BPM. Black: 12 nC, -2 kHz. Red: 15 nC, -6 kHz. The motion is damped faster at higher detuning, despite the higher charge.

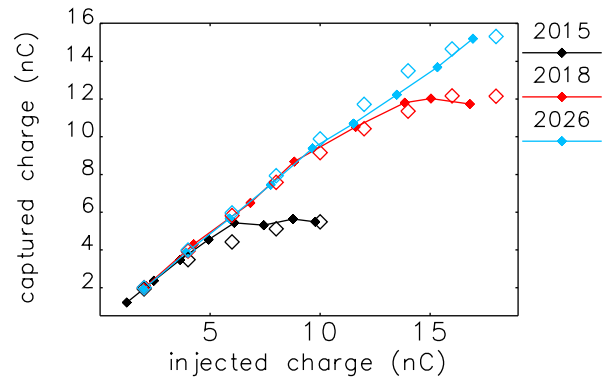


Figure 5: Captured vs injected booster charge, over the years. Connected points are measurements; hollow diamonds are simulation results under equivalent (booster and injected beam) conditions.

ACHIEVING HIGHER SR CURRENT

While 15 nC booster charge is close to our goal of 17 nC, several factors restrict high current storage ring operation in 48 bunch mode. First, there is a charge loss at booster extraction, which can be as high as 10% at high charge. This is not presently understood. Also, as mentioned above, the booster couplers can't be operated with high reflected power for an extended time. Other factors impact injector reliability at high charge. These include trips of RF12 at high voltage due to power transients, and failures of pulsed magnet power supplies (especially the PAR injection kickers).

We have injected 13 nC bunches into the SR, which could in principle support up to 160 mA operation. So far operation has been limited to 130 mA (with a brief period at 140 mA). In general, users prefer reliable operation at lower current to less reliable operation at higher current. Thus, future upgrades must target both higher charge and reliability.

Near Term Upgrades

Several booster rf upgrades are planned. The first of these is high power couplers for the booster cavities. These are based on a 500 kW CERN design, and will allow high cavity detuning [5] as well as a lower loaded Q to reduce the total

beam-induced voltage. Two of these couplers are presently being built, and are expected to be delivered late in CY27. Simulations predict that with -20 kHz detuning in all four cavities, 18 nC can be captured in the booster. We will also have the option of ramping the booster frequency between injection and extraction, which allows for optimizing both injection efficiency and extracted emittance [4].

For historical reasons the present booster analog-based LLRF system uses feed-forward on the klystron drive power while using feedback only on cavity phase. An upgrade to a digital LLRF system is planned that would allow for global amplitude and phase regulation around the cavities. Fast feed-forward and feedback are also being investigated to mitigate the transient beam-loading at injection. However, it is complicated by the rf system configuration of a single klystron driving two sets of booster cavities on opposite sides of the ring. Within the next few years, the klystron will be replaced by a solid state amplifier (SSA) system. There will be a separate SSA for each booster cavity, making feedforward/feedback easier to implement.

An effort is also underway to upgrade the injector pulsed power supplies, starting with the booster injection septum. Diagnostics upgrades are also planned. An former APS storage ring DCCT has been modified to fit the booster chamber (Fig. 6), and will be installed in an upcoming shutdown. This will give a much more precise reading of the booster charge.

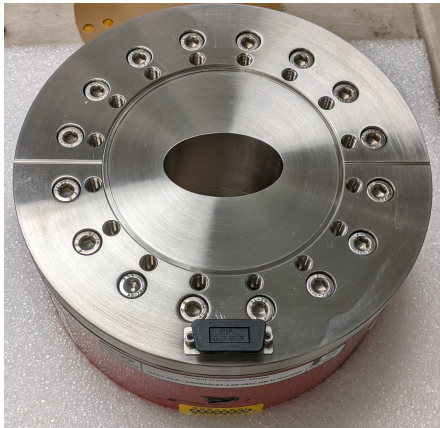


Figure 6: Old SR DCCT, modified to fit the booster chamber.

HIGH CHARGE PHOTOINJECTOR

In addition to the thermionic rf gun [11] presently in use for operations, the APS linac is equipped with a photoemission source [12]. The recent installation of a new laser system will enable robust operation of this source [13]. The photoemission source can be optimized for either high brightness or high charge. In the high charge mode, a high power UV laser pulse will be split into four pulses with spacing 350 ps. These pulses will generate 4 electron bunches from the photocathode, which are accelerated by the S-band linac. Initially these bunches will be about 1 nC each, though this could be increased to 5 nC with a laser upgrade.

These bunches can be injected directly into the booster, skipping the PAR. Relative to the beam extracted from the

PAR, the pulse train has higher energy spread, but shorter effective bunch length (since there are no Gaussian tails). This makes it a better fit for the booster bucket, which has high energy acceptance but a shorter rf period than the PAR.

The viability of this scheme was studied using elegant simulations [14, 15]. The booster simulation model includes transverse and longitudinal impedance, cavity beam loading, and booster lattice errors. The input beam is generated by Astra simulations of the linac. We also found it necessary to include CSR in the simulation, since the individual bunches have very short bunch length (~ 4 ps rms).

The simulated longitudinal phase space at different turns is shown in Fig. 7. In this simulation, each mini-bunch contains 5 nC, so the total charge is 20 nC. The mini-bunches rotate through phase space and decohere, but without causing significant instability or charge loss. The simulation used a high rf voltage at injection (1.5 MV), but only modest cavity detuning (-4 kHz). The overall efficiency was 90% .

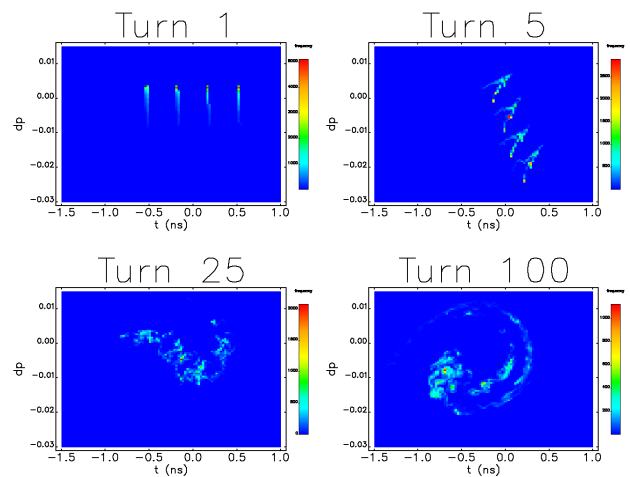


Figure 7: Simulated longitudinal phase space of photoinjected bunches in the booster. The total charge is 20 nC.

One challenging aspect of this project is synchronizing the linac (and laser) with the booster, rather than the PAR. Timing jitter is a concern, so a timing scan was performed (Fig. 8) with simulations. The efficiency is above our goal of 85% for a range of ± 330 ps.

HIGH ENERGY ACCUMULATOR RING AND OTHER OPTIONS

Another potential long term injector upgrade is to build a high energy accumulator ring, similar to ALS-U [6]. The ring would be installed in the booster tunnel, attached to the outside wall. Medium charge bunches (5 – 10 nC) would be accelerated in the booster, then injected into the accumulator ring. These bunches could be stacked up to 20 nC (or potentially higher). Injection and accumulation will be easier at high energy, due to the more rigid beam and increased radiation damping. This ring would also have lower emittance than the booster, improving SR injection and perhaps allowing further optimization of the ring.

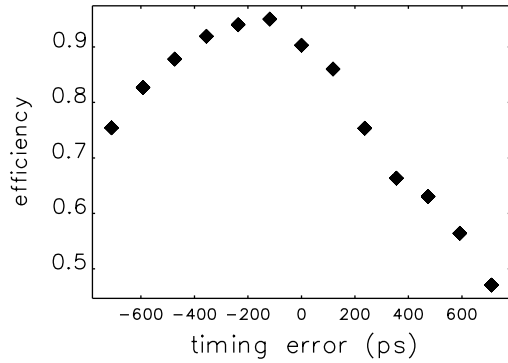


Figure 8: Sensitivity of booster efficiency to timing error of the photoinjector beam.

A potential lattice for the accumulator ring has been developed. Like the APS booster, it uses a FODO structure with dispersion suppression in the straight sections (using a missing magnet scheme), but it also includes dipole fields in the defocusing elements. The lattice has a natural emittance of 11 nm at 6 GeV, compared to 97 nm for the booster lattice. Twiss functions for a section of the lattice are shown in Fig. 9, and a frequency map analysis (without errors) in Fig. 10. The dynamic aperture is reasonably large. An alternate lattice, similar to the Australian Synchrotron Source booster [16], is also being considered.

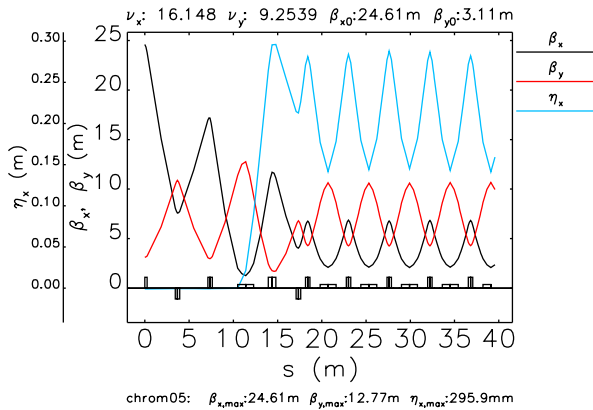


Figure 9: Twiss functions for one section of the accumulator ring lattice.

Preliminary simulations of injection into this lattice were performed, using the booster rf cavities and impedance model (Fig. 11). Two 10 nC bunches are injected 10 mm off-axis, 15,000 turns apart. The rf voltage is 9.2 MV, and the detuning is -2 kHz. Horizontal oscillations are quickly damped, and there is no transverse beam size blowup. The longitudinal impedance does cause a shift of the beam centroid, and slight bunch length increase. The simulated injection efficiency is 99%.

Other options under discussion include a full-energy linac in various configurations. For example, a 6-GeV CW superconducting linac could deliver high-rate beam to a large FEL (Free Electron Laser) farm, while occasionally providing bunches to fill an accumulator ring. Alternatively, the

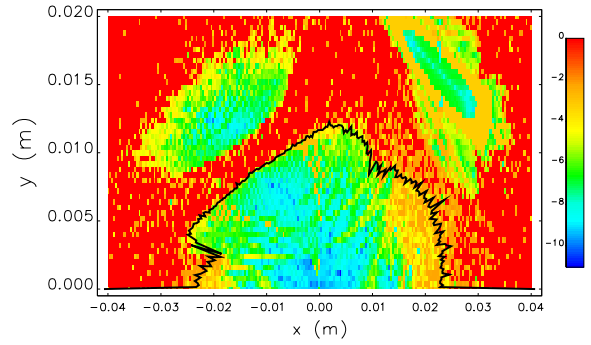


Figure 10: Frequency-map analysis and 1000-turn DA in the absence of errors for the accumulator ring lattice.

linac could have dual front ends, one providing low-charge, high-brightness beams to an FEL farm and another providing single, high-charge bunches for direct injection into the storage ring. The advantage of these schemes is that we could enhance the capabilities available at Argonne for ultra-fast x-ray science on two fronts (FEL and high-charge ring), while addressing the obsolescence challenges of the existing injector.

Another possibility is a 6-GeV LPA (Laser Plasma Accelerator) coupled with a 6-GeV accumulator ring, similar to what's under discussion for DESY's PETRA IV ring [17]. Unlike PETRA IV, we would require an accumulator because we can't accumulate in the storage ring. Still, this would represent a dramatic reduction in the complexity of the injector systems.

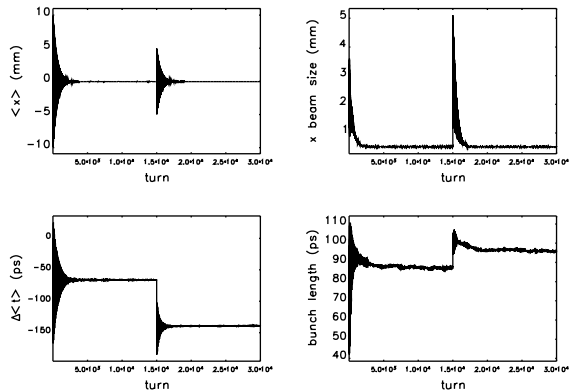


Figure 11: Simulation of two 10 nC bunches injected into the accumulator ring.

CONCLUSION

Injector upgrades and intensive studies have raised the maximum charge captured in the APS booster from 5 to 15 nC. In principle, this can support 160 mA operation with 48 bunches. However, operational considerations have limited the SR current to 130 mA. Further upgrades are underway to achieve the design goal of 200 mA operation.

At the same time, two potential reconfigurations of the APS-U injector chain are being considered. A high charge photoinjector, already under development, could produce a 20 nC S-band bunch train that would skip the PAR, and provide a better match to the booster. A full energy accumulator ring in the booster tunnel could accumulate up to 20 nC (or more) with high efficiency, and provide a lower emittance for SR injection. In the long run, a 6 GeV linac could deliver medium charge bunches directly to the accumulator ring, skipping both the PAR and booster.

REFERENCES

- [1] V. Sajaev *et al.*, “APS upgrade: Commissioning the world’s first light source based on swap-out injection”, in *Proc. NAPAC’25*, Sacramento, California, USA, Aug. 2025, pp. 1–7. doi:10.18429/JACoW-NAPAC2025-MOXP02
- [2] L. Emery and M. Borland, “Possible Long-Term Improvements to the Advanced Photon Source”, in *Proc. PAC 2003*, pp. 256–258, 2003. <http://cern.ch/AccelConf/p03/PAPERS/TOPA014.PDF>
- [3] R. Abela *et al.*, “Design Considerations for a Swiss Light Source”, in *EPAC 92*, pp. 486–488, 1992.
- [4] J. R. Calvey *et al.*, “Plan for Operating the APS-Upgrade Booster with a Frequency Sweep”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 201–204. doi:10.18429/JACoW-IPAC2021-MOPAB046
- [5] J. Calvey *et al.*, “Operation of the APS-U injectors with high single bunch charge”, in *Proc. NAPAC’25*, Sacramento, California, USA, Aug. 2025, pp. 20–26. doi:10.18429/JACoW-NAPAC2025-MOYN01
- [6] M. Ehrlichman *et al.*, “Three-dipole kicker injection scheme for the advanced light source upgrade accumulator ring”, *Phys. Rev. Accel. Beams*, vol. 24, no. 12, p. 120702, Dec. 2021. doi:10.1103/PhysRevAccelBeams.24.120702
- [7] Z. Duan *et al.*, “The Swap-Out Injection Scheme for the High Energy Photon Source”, in *Proc. IPAC’18*, Vancouver, Canada, Apr.-May 2018, pp. 4178–4181. doi:10.18429/JACoW-IPAC2018-THPMF052
- [8] J. R. Calvey, J. C. Dooling, K. C. Harkay, K. P. Wootton, and C. Yao, “Measurements and Simulations of High Charge Beam in the APS Booster”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 197–200. doi:10.18429/JACoW-IPAC2021-MOPAB045
- [9] K. C. Harkay *et al.*, “High-Charge Injector for on-Axis Injection Into A High-Performance Storage Ring Light Source”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 3423–3426. doi:10.18429/JACoW-IPAC2019-THYYPLM3
- [10] J. R. Calvey, T. Fors, K. C. Harkay, and U. Wienands, “Progress on the APS-U Injector Upgrade”, in *Proc. NAPAC’22*, Albuquerque, NM, USA, Aug. 2022, pp. 859–862. doi:10.18429/JACoW-NAPAC2022-THYD4
- [11] J. W. Lewellen *et al.*, “Operation of the APS RF Gun”, in *Proc. LINAC’98*, Chicago, IL, USA, Aug. 1998, pp. 863–865, 1998. <https://jacow.org/198/papers/TH4042.pdf>
- [12] Y.-E. Sun *et al.*, “Commissioning of the Photo-Cathode RF Gun at APS”, in *Proc. FEL’14*, Basel, Switzerland, Aug. 2014, pp. 803–806. <https://jacow.org/FEL2014/papers/THP039.pdf>
- [13] Y. Sun, P. Piot, J. Dooling, T. Berenc, R. Hong, and Y. Yang, “High-Charge and High-Brightness Beam Generation at the Advanced Photon Source Photoinjector”, presented at IPAC’26, Deauville, France, May 2026, paper TUP2329, this conference.
- [14] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source, Rep. LS-287, Sep. 2000. doi:10.2172/761286
- [15] Y. Wang and M. Borland, “Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking”, *AIP Conf. Proc.*, vol. 877, pp. 241–247, Nov. 2006. doi:10.1063/1.2409141
- [16] G. Georgsson, N. Hauge, and S. P. Møller, “A State-of-the-Art 3 GeV Booster for ASP”, in *Proc. EPAC’04*, Lucerne, Switzerland, Jul. 2004, pp. 2317–2319. <http://accelconf.web.cern.ch/e04/papers/THPKF024.pdf>
- [17] I. Agapov *et al.*, “The Plasma Injector for PETRA IV”, DESY, Rep. PUBDB-2024-06078, 2023. doi:10.3204/PUBDB-2024-06078