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PROGRESS TOWARD DUAL-PULSE OPERATION AT THE PROTON STORAGE RING OF LANSCE*

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Abstract

Significant progress has been made in both hardware development and simulation capability to shorten the proton bunch width delivered to the Lujan Center at LANSCE via the Proton Storage Ring (PSR). We have successfully demonstrated operation of the PSR RF buncher at 5.6 MHz, doubled from the standard running condition, in preparation to accumulate a shorter beam pulse. A quick switch between two modes is under consideration. To extract the beam properly, a prototype kicker test stand has been established, and the measurement of the pulse width, rise time, and charging time will be demonstrated. On the simulation front, beam dynamics models have been refined using both ELEGANT and pyORBIT codes to optimize dual-pulse stacking. We have performed detailed studies of longitudinal phase space evolution, space charge mitigation, and bunch separation fidelity, which guide ongoing design efforts and beamline integration. These advancements will be the foundation for future development of shorter pulses for the Lujan Center.

INTRODUCTION

The PSR delivers an intense, 290-ns-long proton beam that drives neutron scattering experiments at the Manuel Lujan Center user facility. The role of the PSR, which has a revolution time of 360 ns, is to "stack" a 625-µs-long train of 290-ns minipulses, each separated by a 70-ns gap to allow for extraction from the ring. Experiments relying on neutron time-of-flight (TOF) information benefit from the short pulse, as the TOF resolution depends on the duration of the proton pulse that creates the neutrons [1–4].

We have proposed a novel method of pulse stacking to generate two 120-ns pulses in the PSR, instead of a single 290-ns-long pulse [5]. The timing structures used to generate the 290-ns pulse and proposed dual 120-ns pulses are shown in Fig. 1. Achieving the dual pulse configuration requires efforts on three fronts: doubling the operating frequency of the RF buncher from 2.8 MHz to 5.6 MHz; modifying the timing structure of the extraction kickers; and investigating bunch compression techniques via simulation. An update on the status of work in each of these areas is reported in the following sections.

RF BUNCHER FREQUENCY DOUBLING

The PSR buncher currently operates at 2.8 MHz for 1 ms at a repetition rate of 20 Hz. The buncher cavity consists of

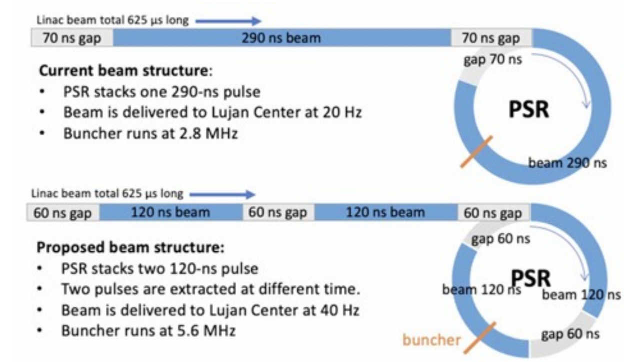

Figure 1: Timing structure for stacking one 290-ns pulse (top) and two 120-ns pulses (bottom), taken from [1].

a series inductor-capacitor-inductor, where the RF voltage is applied to the beam across the capacitor. The inductors are composed of a series of ferrite discs. The amplifier consists of two stages. The first is a Final Power Amplifier (FPA) in a cathode follower configuration, which minimizes the voltage induced by the high peak beam image current. The second is a tetrode Intermediate Power Amplifier (IPA), which enhances the input signal to the 16-kV AC signal required between the capacitor ends. The entire amplifier, IPA, FPA and cavity, shown in Fig. 2, was tested at 5.6 MHz and full voltage in 2023.

The IPA is a tetrode-based amplifier with a tuned input circuit that matches the tetrode grid-cathode capacitance to the incoming 50-Ω line and produces 180° de-phased signals feeding each side of the amplifier. The output circuit similarly matches the tetrode output to 500-Ω coaxial lines feeding each final amplifier triode. The IPA requires changes to several capacitors and inductors of its input circuit (shown in Fig. 3) to produce equivalent tuning at 5.6 MHz. Additionally, the π-shaped capacitor-inductor-capacitor output

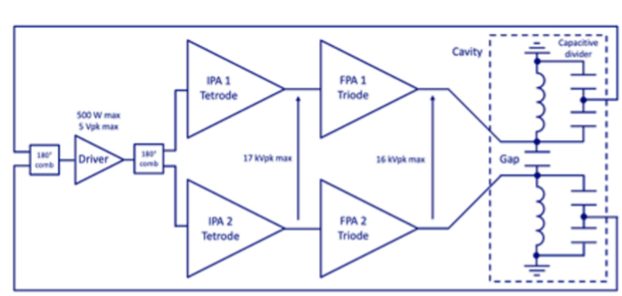

Figure 2: Schematic depicting the amplifier chain and connection to the buncher cavity.

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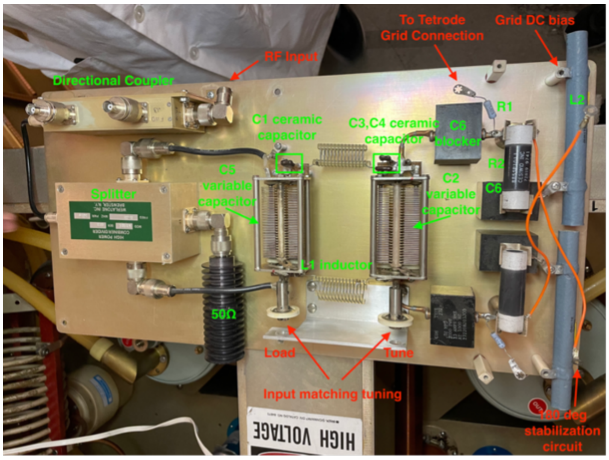

Figure 3: IPA input circuit and component descriptions.

circuit requires the disconnection of the inductor leads from one of the capacitors and the connection at an intermediate point. Other components, such as feedthrough capacitors and choke inductors for the anode and grid connections, were tested to verify no resonance or anomalous behavior was observed at 5.6 MHz, and the screen choke inductor was replaced with a version better suited to the higher frequency operation. Nominal functioning into a 500-Ω resistive load was verified at 5.6 MHz. Since the FPA possesses no tuned circuits, it was only verified that no system components presented a resonance or significant change of behavior at 5.6 MHz. The IPA was originally designed (1998–2000) to be operated at 2.8 MHz and 5.6 MHz, and the design documentation was consulted for the necessary changes.

Tuning the buncher cavity proved more difficult than expected, as removing the parallel capacitors produced only a small change in the tuning frequency. To lower the magnetic permeability of the ferrite and set the resonant frequency of the cavity to 5.6 MHz, the only alternative was to increase the biasing current for the ferrite via a temporary, high-current power supply with shortened connections. This allowed the amplifier and buncher to operate at their nominal voltages of 16 kV peak across the gap electrodes. Unfortunately, some connections inside the cavity were unable to handle the higher current in the biasing circuit, which limited testing of the amplifier and buncher cavity to a couple of hours. In 2023–2024, higher capability wiring was installed inside the cavity and between the amplifier and cavity. This will enable testing of the buncher amplifier and cavity at 5.6 MHz for extended durations to simulate full operational conditions.

EXTRACTION KICKER TESTING

To evaluate the feasibility of generating two 120-ns pulses with a 1-ms separation in the PSR, a prototype kicker test stand was established to explore novel kicker configurations. Currently, the only method available to adjust the extraction kicker pulse width is through modifying the lengths of the Blumlein coaxial cables.

The PSR extraction kicker system utilizes RG17/14U Blumlein cables to generate pulses, with the SRFK71 modulator employing cable lengths optimized for a 300-ns flattop pulse and the SRFK81 for a 500-ns flattop pulse. Under standard operation, longer cable lengths are used to produce wider flattop pulses. For short-pulse operation, it was estimated that approximately 143 ft of Blumlein cable per section would be required to achieve a 120-ns flattop. Initial testing with shortened Blumlein cables confirmed that pulse width can be tuned by adjusting cable length. The modified configuration produced a flattop pulse of approximately 129 ns (Fig. 4). Further optimization will be necessary to achieve the target pulse width of 120 ns.

A second design objective is to achieve a gap of 1 ms or less between the two extracted 120-ns pulses. This is critical, as beam current losses begin to occur in the PSR after approximately 1 ms. Currently, the minimum achievable gap is 2 ms, limited by the charging time of the existing high-voltage power supply. The present system requires approximately 2 ms to recharge the pulse forming network (PFN) to 50 kV and delivers a maximum power of 10 kW and (Fig. 5). To create the 1-ms gap, a higher-power, faster-charging power supply is necessary. We estimate that the power supply must be capable of delivering at least 20 kW at 50 kV.

BEAM DYNAMICS SIMULATIONS

The dual pulse stacking has been simulated [5]. In this update, we evaluate two different bunch rotation methods to achieve a short pulse: the slow and fast rotation methods. Both methods attempt to manipulate the ϕ-E space of the already stacked PSR beam to compress it in the longitudinal direction by exchanging the phase spread with an energy spread. The slow method uses a lower RF buncher voltage, while the fast method uses a higher buncher voltage. Both

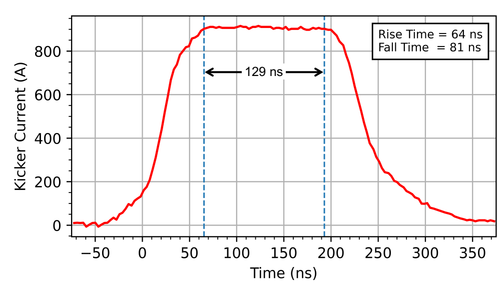

Figure 4: Current for 50-Ω load with 129-ns flattop.

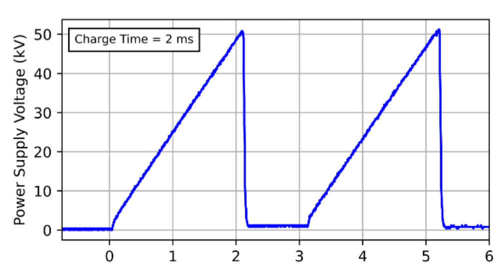

Figure 5: PFN charge time with shortened Blumlein cables.

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assume the beam can be stacked with a buncher voltage that high enough to capture the beam. This way, we obtain a bucket in longitudinal phase space with the minimum energy spread height necessary to contain the stacked beam.

The final pulse length depends monotonically on the bucket height, with smaller heights producing shorter pulses. The synchrotron oscillation period inside the PSR sets the time scale for beam manipulations. The synchrotron period of 700 μs, or about 2000 turns, is given only as an estimate, as the period is proportional to the square root of the buncher voltage. Presently, it seems that a buncher voltage as low as 2 kV is adequate for dual-pulse stacking.

The slow method to compress the stacked beam is by adiabatically capturing each particle, i.e., the height of the longitudinal phase space bucket must increase slowly in a synchrotron period. This means that adiabatic capturing requires a long time (tens of milliseconds) to produce a short bunch. The particles will follow a spiral-like trajectory in longitudinal phase space, decreasing their distance from the center of the bunch while increasing the energy difference from the central energy in such a way that the phase space area is conserved. The drawback of this scheme is that the stacked/stored beam must survive in the PSR for tens of milliseconds, which may be difficult to attain due to the onset of the various instabilities common in storage rings. The advantage is the loose constraint on the RF buncher rise time, which may be on the order of tens of milliseconds.

The fast method produces a faster rotation of the stacked beam in longitudinal phase space. In this technique, the height of the RF bucket (buncher voltage) must increase as fast as possible compared to a quarter period of the synchrotron oscillation (175 μs). The drawback of this scheme is that it may not be possible to generate such a fast rise of the buncher voltage. The advantage is that the fully stacked beam must survive inside the PSR only slightly longer than the time it takes to stack it. Presently, the voltage of the RF buncher can be increased at a rate of 150 V/μs, meaning the final buncher voltage will be ~26 kV for the ~175 μs it takes the stacked beam to complete a quarter of a synchrotron oscillation.

To quantify the fast method of bunch compression, we show the pulse length (containing 95% of the particles) as a function of turns around the ring (Fig. 6) and the beam current profiles at maximum compression for the cases when the buncher voltage is raised at the present rate of 150 V/μs and at a faster rate of 1130 V/μs (Fig 7). These calculations assume the buncher voltage is set at 2 kV while the beam is accumulated/stacked over 1726 turn. After the beam is fully accumulated/stacked, the buncher voltage is raised from 2 kV to 15 kV or 100 kV, depending on which case is considered, in 87 μs (241 turns). After turn number 1967, the voltages stay constant at their final values. These plots show the fast rotation option for the PSR can produce shorter bunches than are presently obtained. In fact, the example with a rise time of 0.15 kV/μs could be tested in the present operational configuration of the PSR.

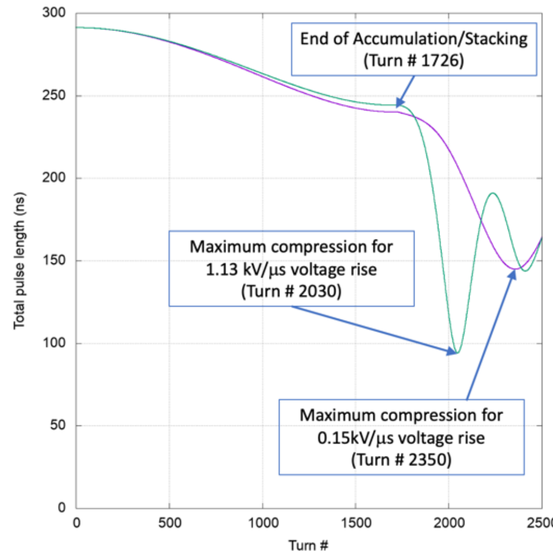

Figure 6: Pulse lengths as function of time of stored beam during accumulation/stacking and after applying a fast-rotation compression for two rates of buncher voltage rise times.

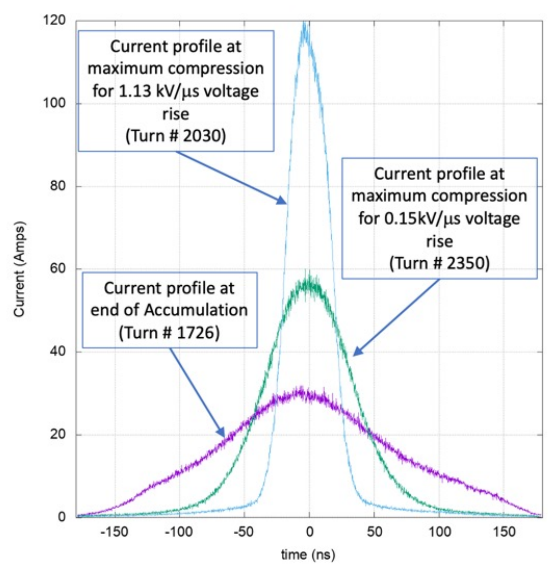

Figure 7: Current profiles at end of accumulation and at maximum fast-rotation compression for two rates of buncher voltage rise times.

CONCLUSION

Significant advancement has been made towards enabling dual short pulse operation at the PSR. We have successfully demonstrated 5.6-MHz operation for the existing RF buncher, double the normal operating frequency of 2.8 MHz. We have achieved an extraction kicker flattop width of 129 ns, close to the required 120 ns, and there is a clear path forward to achieving the 1-ms pulse separation. Simulation studies of two options for compressing the stacked pulse have been conducted, and one of the methods could be tested with the present operational configuration of the PSR.

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