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PSR Beam-Pulse Formation and Control*

R. A. Hardekopf
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Introduction

The Proton Storage Ring (PSR) is a major addition to the Weapons Neutron Research Facility (WNR) at LAMPF. It will act as a bunch compressor for the relatively long linac macropulses from LAMPF, tailoring them into short, intense pulses ideally suited for neutron-scattering research. This paper concentrates on the methods used to form these pulses before injection into the linac, to multiplex the PSR beam with other LAMPF users, and to synchronize the storage ring with pulse arrival time at injection and with the WNR mechanical neutron chopper at extraction.

WNR Pulse Characteristics

To understand the pulse structure required by the PSR, it is useful to begin with the operation of WNR in its present configuration. The LAMPF accelerator produces 800-MeV proton beams with a 750-µs-long macropulse structure at a 120-Hz repetition rate. Within the macropulses are many 200-MHz micropulses, each containing 3-5 x 10^8 protons. WNR operates in one of two modes, micropulse or microsecond.

For high-energy neutron work, single micropulses at a minimum spacing of 1 µs throughout an entire macropulse are selected. Thus, this is a low-intensity mode, wasting the capability of the LAMPF accelerator during that macropulse. Furthermore, because other LAMPF users must be satisfied, only one macropulse in ten can be diverted to WNR, resulting in a maximum 12-Hz overall rate. As Fig. 1 depicts graphically, this combination provides very narrow pulses but with low peak intensity and only about 0.25-µA average current.

For slow-neutron (thermal and epithermal) work, much longer pulses can be used, up to 10 µs in length, and these are taken at the end of each LAMPF macropulse. To maintain high average intensity, both the pulse width and the repetition rate must be higher than desired for many experiments. A typical 5-µs-long pulse, as depicted in Fig. 1, contains 1000 micropulses and gives an integrated intensity of 5 x 10^{11} protons/pulse for an average current of about 10 µA.

PSR Pulse Characteristics

The PSR will remove the limitations imposed by compromise between intensity and resolution, converting much more of the LAMPF beam to pulses suitable for neutron work without seriously impacting other LAMPF users. It operates both as a pulse compressor, squeezing the 750-µs-long LAMPF pulses into much shorter ones (270 ns), and as an accumulator and repetition-rate shifter, accepting pulses at the normal LAMPF rate of 120 Hz and ejecting them at 720 Hz. It accomplishes these operations with a significant gain in time-averaged beam intensity.

Figure 1 depicts graphically the gain in integrated protons/pulse for the two operating modes of PSR compared with the two WNR modes discussed earlier. The short bunch (SB) mode, shown on the left, will replace the existing WNR micropulse mode for high-energy neutron applications. In this mode, protons are accumulated in six equally spaced 1-ns bunches during the last 108 µs of each LAMPF macropulse. The LAMPF beam is modified during this injection period by a chopper buncher system in the low-energy linac transport to form a sequence of pulses spaced at 60-ns intervals. The ring circulation period is synchronized with this incoming pulse train so that 300 micropulses are accumulated in each of the six ring bunches. The 1-ns bunch width is maintained during accumulation and storage by a 503-MHz buncher system in the ring. Individual bunch extraction takes place between LAMPF injection cycles at a constant 720-Hz rate. Each bunch contains 1 x 10^{11} protons, yielding an average current in the SB mode of ∿ 12 µA.

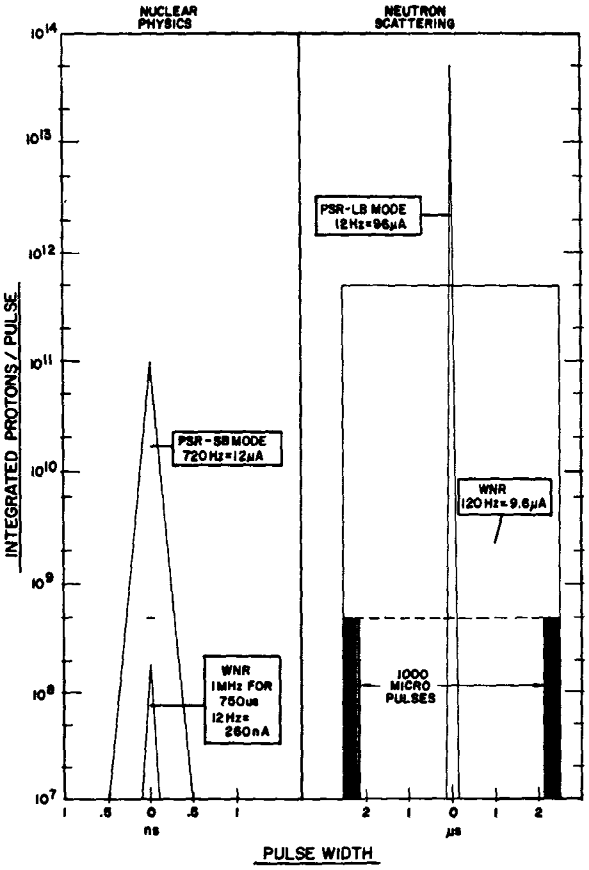

Fig. 1
Comparison of WNR and WNR/PSR pulse characteristics for the two modes of operation. On the left (nanosecond time scale) is the SB mode used for high-energy nuclear physics experiments and on the right (microsecond time scale) is the LB mode used for slow-neutron scattering experiments. The peaks are schematic representations of the important parameters for neutron production: integrated protons per pulse versus pulse width. Overall repetition rates and average beam currents for these operational modes are indicated in the labeled boxes.

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The long-bunch (LB) mode, shown on the right in Fig. 1, replaces the WNR microsecond mode for low-energy neutron applications. Here the gains are even more dramatic as the bunch width is decreased to 270 ns, the protons/pulse is increased to 5 x 10^{13}, the repetition rate is lowered to 12 Hz, and the average current is increased to about 100 μA. For this PSR mode, one out of ten LAMPF macropulses are chopped at the injector into 270-ns-long segments at a 360-ns period, synchronous with the ring circulation period. The entire macropulse is accumulated by the PSR into a 270-ns-long pulse with a 46-A peak circulating current. The pulse width is maintained by a 2.8-MHz harmonic buncher in the ring, and the pulse is extracted about 100 μs after injection is complete.

PSR Control Summary

It is clear that PSR operation places new requirements on beam preparation and transport at LAMPF, including synchronization and timing aspects that are crucial to successful operation. Figure 2 is a schematic of the accelerator, storage ring, and WNR target area showing major components that affect PSR operation. Here I will mention only briefly these components, with more detailed descriptions of some of the active components to follow.

The injection scheme for PSR requires H^- beam produced in a new, intense H^- source at LAMPF. The beam is chopped and bunched in the low-energy transport line, accelerated to 800 MeV in the linac, kicked into Line D in the LAMPF switchyard, and bent into the PSR injection line where it is magnetically stripped to neutral atoms just before entering the ring orbit. A foil stripper in the first section fully strips the beam to protons. A PSR injection kicker magnet and foil stripper in the Line D by-pass allow multiplexed operation between PSR and direct LAMPF beam for WNR. Thus the old modes of WNR operation can be provided to experimentors while PSR operates at a low duty cycle for tune up and machine physics tests. After accumulation of the pulse in PSR is complete, the bunches are kicked out by two extraction kickers that perturb the orbit so that the pulse passes into the extraction septum magnet. The firing circuit for the extraction kicker allows synchronizing the target pulses with a WNR mechanical neutron chopper operating at 30000 rpm.

Low-Energy Beam Chopper

One of the keys to PSR operation is preparation of the pulse structure before the beam is accelerated so that incoming bunches are synchronized with the ring period and active bunchers in the ring. A traveling-wave beam chopper has been designed for the H^- injector transport line to provide pulses not only for the two PSR modes, but also for the existing WNR direct modes and other LAMPF users of H^- beam. The design is a careful balance between several factors that influence chopping efficiency and state-of-the-art pulsed electronics capability. To achieve clean micropulse selection with high intensity, a pulse rise time of <5 ns is required, and the chopper must be coupled with a subharmonic prebuncher

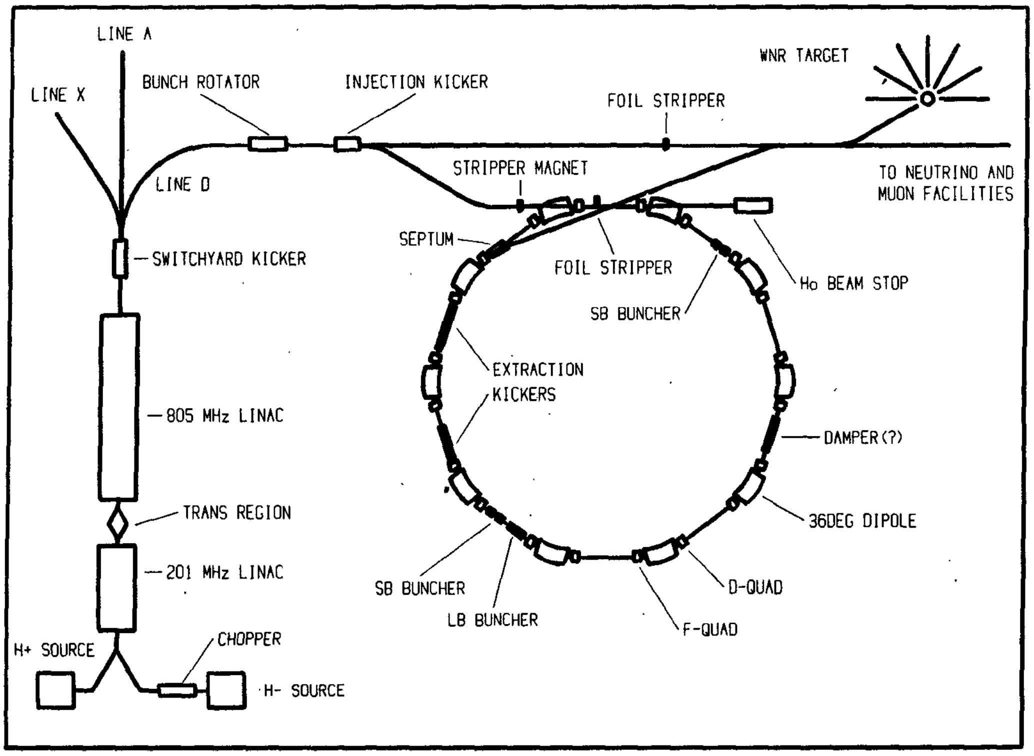

Fig. 2.
Overview of the LAMPF/WNR facility showing how the PSR interacts with other LAMPF beams. New equipment at LAMPF being built for the PSR includes the intense H^- source, the chopper, and the switchyard kicker magnet. The injection kicker allows beam to be multiplexed between PSR and WNR-direct during PSR tune-up. A tune-up beam dump under the PSR extraction line can receive up to 5-μA average beam.

to compress transmitted beam into the acceptance of LAMPF's 201-Mz bunching system. The beam optics of the newly designed H^- transport system dictated 20-mrad deflection as a minimum for complete separation of the chopped beam, taking into account the expected 2π cm•mrad emittance from the ion source. For this deflection angle and for pulses of less than 1 kV, a deflector $\sim$1-m long is required. The 750-keV ions travel at 1.2 cm/ns, taking about 80 ns to traverse this distance. Therefore, a traveling-wave principle must be used, with the deflecting pulse longitudinal velocity matched to the beam velocity.

Figure 3 shows the coax-plate deflecting structure that we have designed for the chopper. It uses flat plates on the structure's beam side soldered to and supported by short lengths of coaxial cable that connect adjacent plates across the back of the ground plane. The lengths of the cables are adjusted to match pulse propagation to beam velocity. The plate width and spacing thus can be chosen to give the best compromise between efficiency and coupling. Because the coaxial cable provides most of the path length, deleterious effects from mismatch at the corners are avoided, as well as coupling between turns on the structure's back. The shape of the plates and their spacing from the ground plane are adjusted empirically, providing $50\text{-}\Omega$ impedance with minimum perturbation at the coaxial-cable transition. Individual plate replacement is accomplished easily without disturbing the rest of the structure.

The thickness of the plates influences plate-to-plate coupling; therefore, we used 0.4-mm-thick spring steel for desirable stiffness, with copper plating for better conductivity. We can thus maximize efficiency by making the plates 7.9 mm wide on a 10.2-mm center-to-center spacing for a 78% aspect ratio and a 94% calculated dc efficiency. The chopper's bandwidth with an assumed spacing of 2.8 cm between deflecting structures is $\sim$200 MHz.

Two power amplifiers (positive output and negative output) with the following characteristics are required for driving the deflection structures.

Rise and fall times	<5 ns
Voltage output into $50\ \Omega$	>600 V
Pulse width	<15 ns to > 1 ms
Duty factor	10% maximum
Time jitter	<1 ns

An amplifier configuration using eight paralleled planar triodes has been developed to meet these requirements.

A paper[1] describing this development, including the POISSON calculation studies and laboratory measurements, was presented at the 1983 Particle Accelerator Conference in Santa Fe. Completion of the two power amplifiers, the deflecting structures, and the vacuum box is scheduled for completion in the spring of 1984.

Switchyard Kicker Magnet

The change from protons to H^- beam for PSR/WNR has necessitated a complete redesign of the LAMPF switchyard area, where beams are directed into the major experimental areas. The positive and negative beams, simultaneously accelerated by LAMPF, are first spatially separated by a vertical bending magnet. Low-intensity negative beam is directed into Line X (nuclear physics) while the chopped, high-intensity negative beam is bent into Line D (PSR/WNR) by a fast kicker magnet and a septum magnet.

In the SB mode of PSR operation, each macropulse is shared with other LAMPF H^- users; therefore it is desirable to minimize the kicker rise time, during which time no beam can be transmitted (the chopper

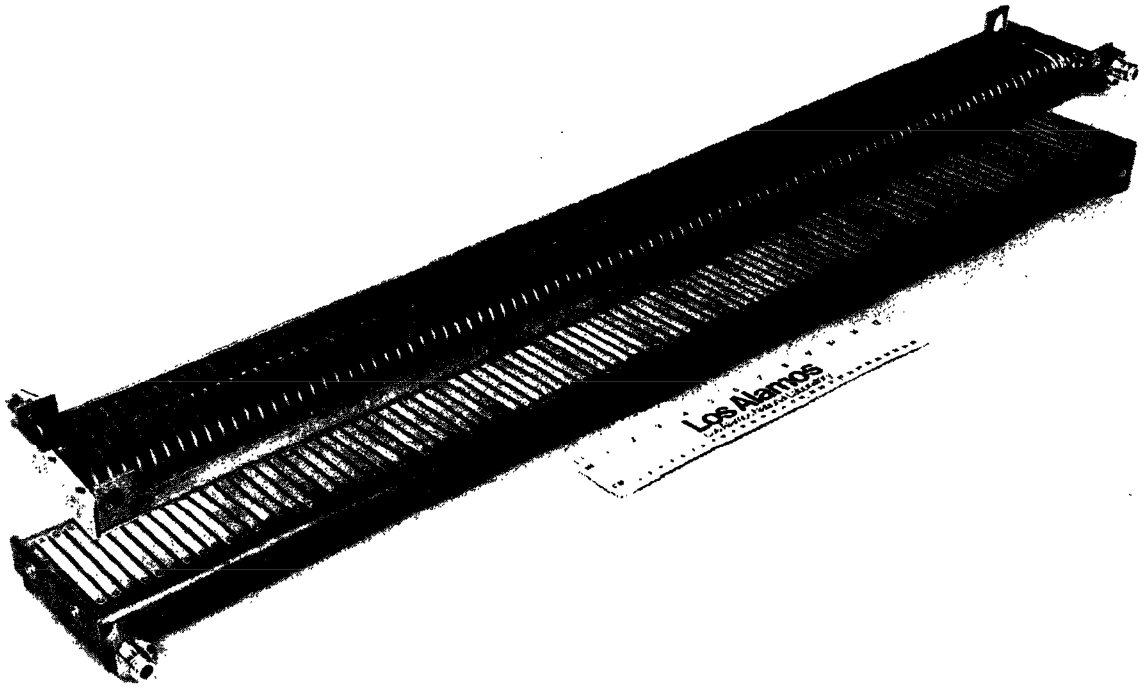

Fig. 3
Photograph of coax-plate traveling-wave deflection structure used in the beam chopper. This device, located in the H^- linac injection line, must product a variety of pulse patterns with <5-ns rise time for both WNR and PSR beams.

provides the gap required). A time of 40 μs was chosen as a reasonable compromise between beam efficiency and driver capability. The magnetic field must be established and settled to within 0.3% during this period.

The fast rise time, variable pulse length (100 to 1000 μs), high duty factor, and high degree of amplitude regulation required by the kicker magnet have determined the design. We have chosen a single-turn conductor, lumped-inductance ferrite magnet for the basic element, partly in order to use existing ferrite bricks and support equipment. However, to have the required current in the range of 2 kA where solid-state regulator circuits are applicable and at the same time keep the magnet inductance and peak voltage to low values, we chose to construct the kicker magnet in two identical sections with separate drivers. The mechanical construction of each section is a 1-m-long stack of ferrite blocks with a 5-cm-high by 10-cm-wide aperture. The unit has a calculated inductance of 3 μH, and both sections together yield a 1.2° kick for 2-kA current.

The modulator design uses a three-loop current driver to supply current to the kicker magnet. The circuit uses a high-current transistor amplifier in conjunction with a dual pulse forming network (PFN) to establish, sustain, and regulate the required current wave. The transistor amplifier/regulator and the dual PFN energy store share in the overall current development; the amplifier supplies 10-15% of the total while the PFNs supply the remainder. Active feedback is used in the amplifier/regulator to deripple the PFN contribution and provide a constant current to the kicker during the required pulse interval. Adjustment of the pulse length is achieved by a PFN line-length-changing circuit that couples appropriate sections of the PFN together through semiconductor switches. Kicker magnetic-field level is set by adjusting the PFN charge voltage and a reference voltage level supplied to the feedback circuit.

PSR Extraction Kicker

Once the injection cycle is complete, the extraction process can begin. Long-bunch extraction takes place soon after injection at the same rate. Short-bunch extraction is at six times the injection rate and takes place at equal intervals throughout the 8.3 ms between LAMPF cycles. The short-pulse mode of PSR operation requires the extraction of single 1-μs proton bunches from up to six bunches circulating at 60-ns intervals in the ring. This requires the kicker magnet to turn on and off quickly and to turn off cleanly so as not to disrupt the remaining proton bunches. These requirements led to the choice of a kicker "magnet" that is a carefully terminated strip transmission line. For transverse electromagnetic waves, the pulse must propagate through the electrodes in the direction opposite to the beam propagation so that the electric and magnetic forces deflect the beam in the same direction.

The pulse power supplies[2] provide ±45-kV pulses to the plates with rise times of 30 ns (SB mode, 720 Hz) or 50 ns (LB mode, 12-24 Hz). For the LB mode, the pulse must be sustained for 300 ns with a flat-top specification of ±1%. These power levels are obtained by resonant charging of an intermediate energy-store capacitor bank that is switched into a Blumlein PFN a few microseconds before extraction time. Discharge of the PFN into the load is through high-voltage thyratrons especially developed for this application.

Extraction pulses must be synchronized within 1 ns of the circulating beam and, for the SB mode, must provide complete flexibility in the extraction sequence. This will allow nonuniform loading of the bunches, extraction of alternate bunches to reduce instabilities, and possibly nonuniform extraction times for experimental purposes. For the LB mode, the circuit provides a 200-μs window during which time a fire signal synchronized with the WNR mechanical chopper can extract the pulse, subject to the 360-μs ring period.

Timing and Synchronization

The interaction with LAMPF is complicated by the many pulse-selection options required: 800-MeV or dual-energy LAMPF operation, PSR and/or WNR running in either of two basic modes with possible multiplexed operation, tune-up of PSR with reduced repetition rate and modified pulse structure, and simultaneous chopping of H^- beams for LAMPF experimenters when required. As indicated schematically in Fig. 4, the system is intimately connected with LAMPF timing, and close coordination is essential.

A computer-to-computer link is envisioned to establish the basic mode requests between PSR and LAMPF operations. The LAMPF master timer then provides the appropriate timing gates as indicated in Fig. 4. Independently of these "slow" gates, PSR establishes the fast chopping patterns through CAMAC commands to the chopper control and pattern generator (CCPG) located in the LAMPF injector area near the H^- chopper. These patterns are synchronized to the two basic PSR frequencies, 2.8 MHz and 16.7 MHz, which are transmitted by the frequency and synchronization generator (FSG) to the CCPG, to the PSR master synchronization system, and to a new low-frequency buncher (16.7 MHz) in the H^- injection line. The patterns are selected and multiplexed within the CCPG by the LAMPF master timer gates and applied to the amplifiers driving the fast H^- chopper.

There are three levels of control that provide the needed flexibility: first, the frequency of the indicated gate patterns on a macropulse basis (for example 12 Hz for LB mode, 120 Hz for SB mode); second, the length of the gates that establish the PSR or WNR portion of the macropulse; and third, the synchronized pattern structure produced by the CCPG. Selection at all three levels will be provided at the PSR control console within boundaries established by LAMPF.

Although the bunchers in the ring are synchronized to the same frequencies (or multiples) used in pulse selection, there is a phase uncertainty because of the different transit times for the beam pulses and rf signals. The PSR master synchronization system will establish the correct phase relationship by comparing the arrival time of beam in the PSR injection line with the rf signals in the buncher cavities. Synchronized operations, such as position monitors and beam extraction, will derive their signals from these phase-locked reference frequencies. Slower operations, such as turn on of the injection kicker magnet and start of orbit-bumper programming, will be gated by pulses from the PSR timing processor, which receives trigger pulses from the LAMPF master timer.

Figure 5 displays the relation between LAMPF beam gates for a few macropulses in the two basic PSR modes. The patterns indicated in the figure on a nanosecond time scale are developed by the chopper for the two modes during the enable time determined by the gates. Low-intensity H^- beam can be accelerated simultaneously with the high-intensity H^+ beam from LAMPF. Thus the SB mode, in which only one out of twelve micropulses is admitted, does not impact meson production in Area A. However, H^- beam in the LB mode will be nearly equal in intensity to the H^+ beam, and rf-cavity loading precludes simultaneous acceleration. Up to 10% of LAMPF production (12 out

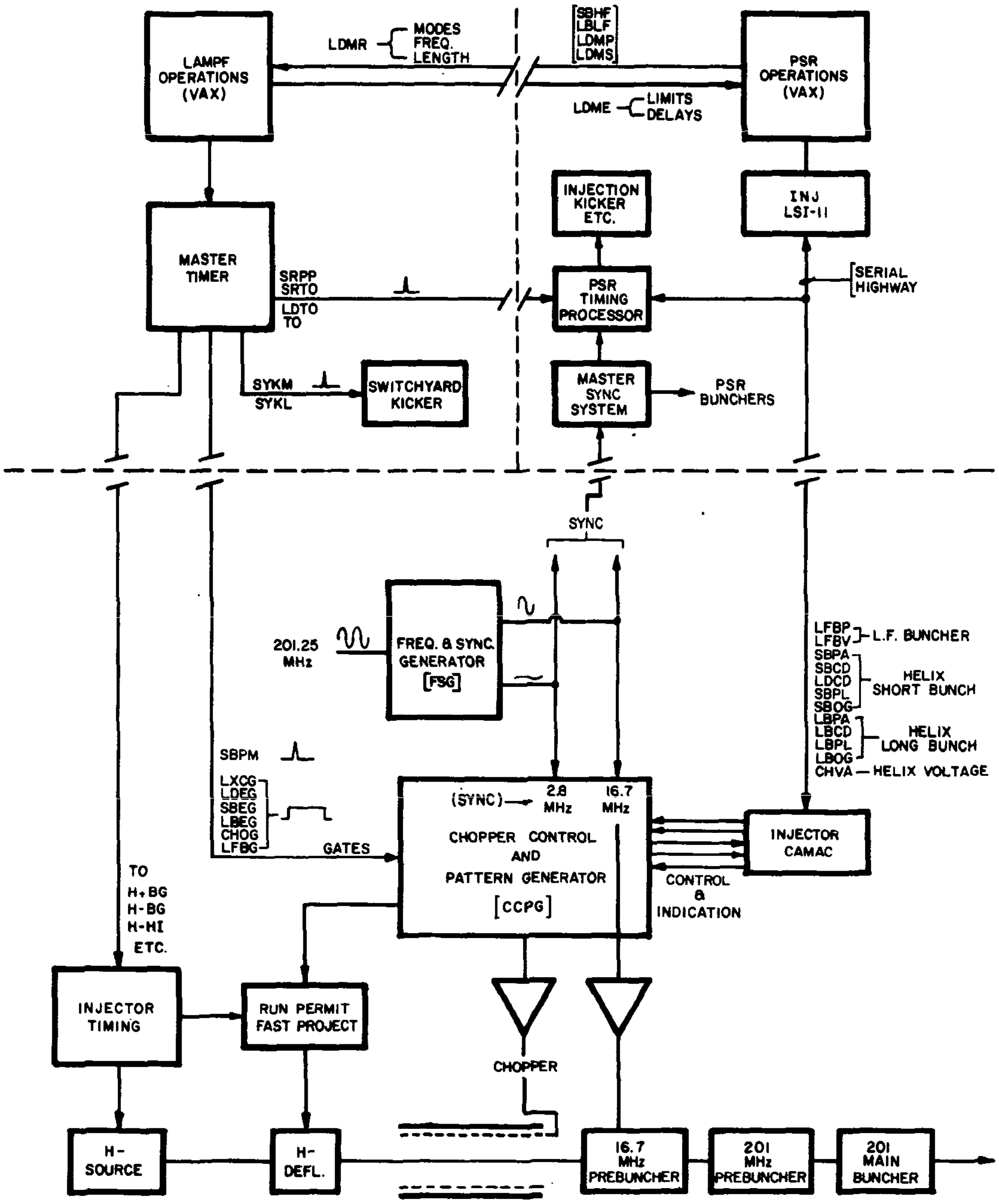

Fig. 4
Schematic diagram to illustrate timing and synchronization communication between PSR, LAMPF, and the H$^-$ injector area. The focus of the control for PSR is the CCPG which generates pulse trains to drive the chopper amplifier. Although the patterns are controlled from PSR, overall timing gates must be provided by LAMPF through the master timer. The FSG derives the rf needed to synchronize chopper patterns with the PSR bunchers.

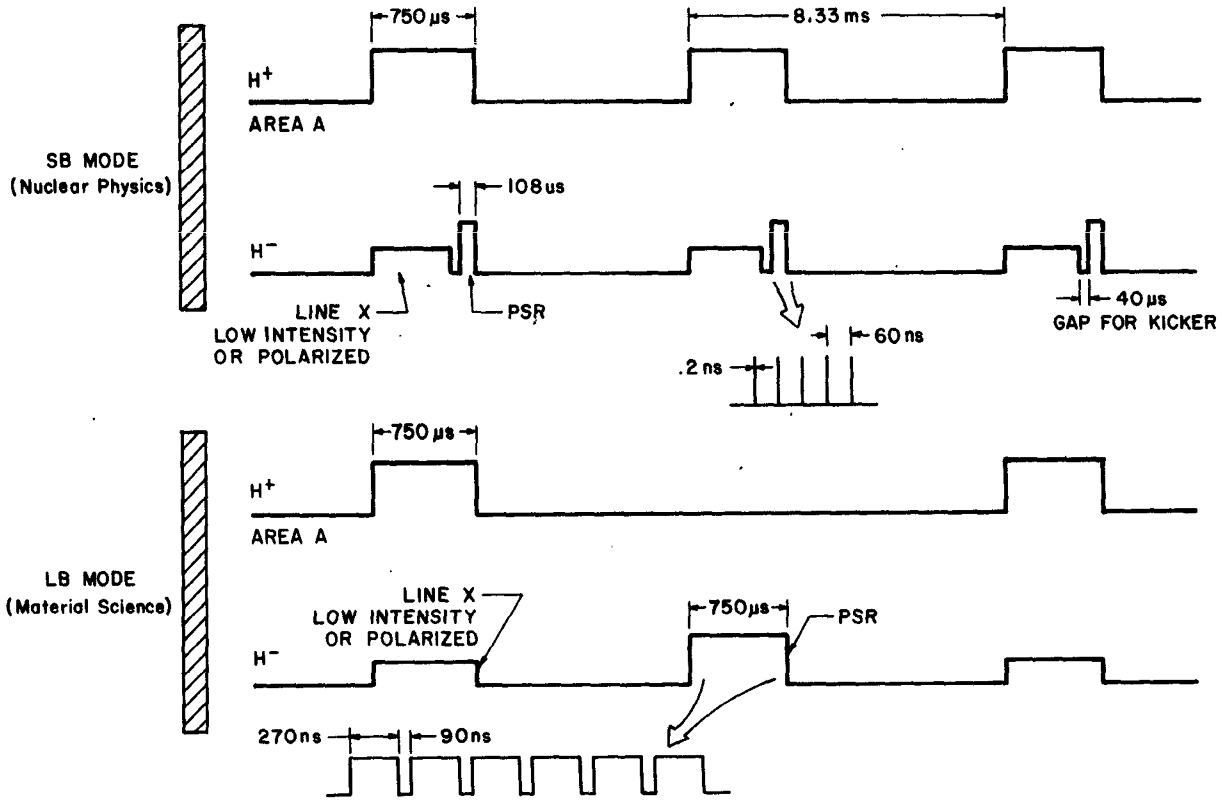

Fig. 5.
This diagram shows the interlacing of PSR beam with other LAMPF beams for the two basic modes of operation. Low intensity H^- beam, either from the H^- or polarized source, or chopped for the SB mode, can be accelerated simultaneously with the high-intensity H^+ beam. In the SB mode, PSR takes the last 108 μs of each (nominal) 750-μs-long macropulse. For the LB mode, the chopping pattern retains much of the intense H^- beam, requiring that H^+ macropulses be skipped during PSR injection. Many other combinations are possible, including multiplexed operation with different types of chopped beams.

of 120 Hz) will be made available for PSR in the LB mode.

Conclusion

Four different kinds of pulse structures are required for chopped beam destined for the PSR/WNR complex. Within these types, a great deal of flexibility must be provided so that WNR can operate in a stand-alone mode, or with PSR, or multiplexed during the PSR commissioning period. PSR beams must be fully synchronized with the ring bunchers and must be adjustable in frequency, length, and micropulse selection pattern for tune-up operations. The beam chopper, kicker magnets, and synchronization scheme necessary to achieve these aims have been described. Close coordination with the LAMPF linac rf and timing system will be required to successfully implement all of the beam requirements.

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