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FUTURE DIRECTIONS FOR RF BUNCHER AT LANSCE PROTON STORAGE RING*

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Abstract

Los Alamos Neutron Science Center (LANSCE) is evaluating options for refurbishing the Proton Storage Ring (PSR). An important component of this is the ring RF bunching system at h=1 for one circulating bunch. It has operated with high availability since an upgrade was installed in 1999 to raise the gap voltage [1]. A second RF system at h=2 is planned to improve the bunching factor, reducing the peak beam current at the center of the bunch resulting from space charge forces, helping mitigate effects of electron cloud and leaving an avenue for circulating two bunches in the future. The unique low output impedance RF system for h=1 is based on a cathode follower configuration using push-pull triode vacuum tubes. This feature provides automatic beam loading compensation without active feedback or feedforward systems. The triodes are no longer produced, and suitable replacements are unavailable. The ferrite materials used in the h=1 system are also obsolete. Our goals include determining a suitable replacement amplifier configuration that can work at either frequency, and developing a replacement resonator for each harmonic that uses current production ferrite material.

PRESENT RF BUNCHER SITUATION

The PSR is an accumulator that circulates a single 290 ns proton bunch with a beam-free notch of ~68 ns to allow time for the stripline extraction kicker to operate. An h=1 RF buncher system creates a sinusoidal RF barrier waveform at 2.795 MHz, a period of 358 ns. This is the circulating time of the bunch plus notch. The RF system has been operating 25 years with very few problems (Fig. 1).

Figure 1: PSR Buncher.

There is no need for active beam loading compensation as it uses a low output impedance RF system, based on a cathode-follower configuration using push-pull triode vacuum tubes [2]. There is minimal beam-induced RF voltage as the full charge circulates and crosses the bunching gap [3]. The cathode-follower configuration provides low effective output resistance at the expense of lower stage gain, less than unity voltage gain. At PSR the output resistance of the amplifier was measured to be <11 ohms from 1 – 10 MHz. To accomplish this, the amplifier is positioned directly below the buncher gap, in a radiation zone. The 400 kW triodes (E2V BW1643J2 or Philips 8918/YD1342) are no longer produced, and suitable replacements are unavailable. Many large low frequency industrial triodes have been made obsolete due to the availability of solid-state low frequency (< MHz) converters for industrial RF generators. A quantity of triodes was purchased prior to discontinuance and will work as a stop-gap for a limited period of years at LANSCE.

A pair of TH555A tetrodes drive the input to the triodes, and operate with high power gain of 31 dB (Fig. 2). They are current production devices and are also used at the Facility for Rare Isotope Beams for the K500 and K1200 cyclotrons. In addition, they are designed into the SIS100 bunch compressor at GSI for the Facility for Antiproton and Ion Research project. It is desirable to reuse this versatile amplifier stage in any upgrade.

The NiZn ferrite cores used in the existing buncher resonator are obsolete Ferroxcube type 4H. The buncher system clearly needs to be upgraded in the near term to continue running, and there is a desire to add a second buncher operating at a harmonic.

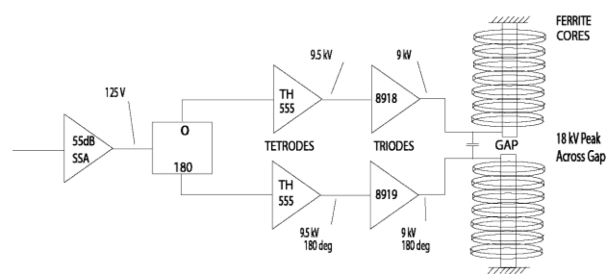

Figure 2: High Power Portion of PSR Buncher.

POSSIBLE CONFIGURATIONS

Final Amplifier Replacement

Replacement of the triode cathode-follower amplifier with an alternative tube design requires investigating multiple solutions. Conventional high frequency power amplifiers are typically operated in the grounded cathode topology. These have higher output resistance when driving the gap resonator. This complicates the beam/amplifier interaction leading to a coherent instability originally defined

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by Robinson [4, 5]. In order to prevent this disruption the shunt impedance (R_{sh}) across the gap/resonator must be reduced by one of various methods discussed here. Specifically,

$$R_{sh} \leq V_g/(I_b \sin\phi),$$

where $\phi = 90°$, V_g is gap voltage and I_b is beam current.

In addition to the triode cathode-follower method used at PSR, various approaches have been used to meet the requirement:

1) Loading the gap with high-power resistor [6].
2) Using low Q resonator with iron-based nano-crystalline magnetic alloy (MA) inductive material such as Finemet, Victrovac, and Nanoperm. This approach is more popular for wideband synchrotron RF systems to avoid fast ferrite tuning using DC bias [7, 8].
3) Reducing the output resistance of a conventional grounded cathode tetrode amplifier using fast local feedback.
4) Compensating for beam-loading by using a one turn delayed feedback or direct feed-forward signal developed from the beam current in the ring to sum with the RF drive into the amplifier tube.

The TH555A tetrode intermediate amplifier installed in 1998 has been very reliable and has tube life of over 40,000 hours. It is desirable to continue to use this amplifier in whatever approach is chosen. The first two approaches may require replacement of that power amplifier to be able to supply the extra power from the lossy MA or added shunt resistance. This approach requires further analysis.

The third approach has been used frequently in large synchrotrons. An example is the AGS accelerating system at BNL, where wideband RF feedback is developed using a high gain preamplifier to lower the resistance of high-power RF amplifiers [9]. To maintain RF amplifier stability the feedback loop is physically short to reduce delay within the amplifier passband. CERN used a similar technique for the PS Booster earlier [10]. GSI proposed a similar fast feedback system for the RF system for SIS18 in 2000 [11].

This method has become problematic recently as the availability of ceramic-metal high gain tetrodes of lower power (<2 kW) became limited. Tubes have been used as they can be placed close to the high-power amplifier, adjacent to the accelerator. The traditional high power tube manufacturers have dropped most of these products, leaving questionable second-tier sources or nothing. CERN has had similar concerns for the PS machine. In both cases, a hybrid development has ensued using rad-tolerant solid-state preamplifiers co-located near the high-power tube amplifiers. This work is ongoing at CERN, BNL, and JPARC. This approach is also feasible at PSR as it is a small ring of 14.4m radius where a shielded alcove in the center could provide partial shielding from protons and neutrons. This will require radiation testing of candidate preamplifiers in this location.

The fourth approach is also feasible, especially with digital low level RF controls. Either one-turn delayed feedback from a beam pickup [12] or a feed-forward method is possible. The latter approach was considered for the SNS accumulator ring [13] but hasn't been needed for 1 GeV operation. It is being considered, however, for the proton power upgrade that increases average beam current by 50% [14].

One might consider using a 100% solid-state amplifier as an alternative to high-power tubes. The accelerating system at CERN PS Booster uses this approach after considerable development of an elegant solution [15]. Each cell of compact MA cores is driven by a local DMOS solid-state amplifier that has been designed for improved radiation tolerence. It can be quickly removed and replaced if damaged and provides less than 1000 Volts of RF, so that a number of cells are inserted in series in the structures. At PSR, the sinusoidal voltage is adjustable up to 18 kV peak. The ambient radiation field precludes survival of large scale solid-state amplifiers close to the gap, and remote location of the amplifier is undesirable due to the same output resistance consideration as a tube.

Ferrite-Loaded Resonator Replacement

As the ferrite cores used in the existing buncher are obsolete, any replacement or build of a second unit requires new inductive material. Furthermore, the PSR refurbishment has established the need for having a higher harmonic buncher in the ring. A single frequency buncher eventually leads to high peak current density resulting in increased space charge tune shift. Eventually this limit prevents further proton stacking and extracted current. Raising the h=1 sinusoidal bunching voltage also contributes to momentum spread in the bunch. A more constant longitudinal current profile is obtained by superposition of two harmonically related Fourier voltage components, creating a flatter RF bucket. This helps overcome space charge limits while increasing beam current. This was proposed in 1998 [16], but effort at the time focused on a passive space charge compensation scheme using embedded ferrite rings [17] and the second harmonic design was not completed. Second harmonic bunchers is well proven in a number of machines and was tested at PSR in 1999. Figure 3 shows the resultant gap voltage of two sinusoids, at 2.8 and 5.6 MHz, in a special wideband test, from [3]. The second harmonic sinusoid is shown in-phase with the fundamental cavity voltage in the oscilloscope waveform capture but was actually inverted in phase to create the composite voltage waveform. This experiment demonstrated that the improvement in bunching factor was reachable with the addition of a second harmonic voltage. The resulting bunch shapes became flatter as seen in the difference between Fig. 4 and Fig. 5.

We have created a full EM model of the existing h=1 resonator/gap for simulation using CST-Microwave Studio. The last step has been to obtain accurate complex permeability for the 4H ferrite cores, which was never documented in the old literature. We accomplished this using small toroids cut from a scrap of the old material.

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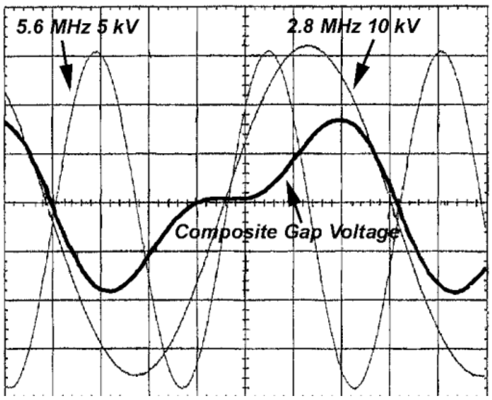

Figure 3: h=1 and h=2 at 2:1 voltage ratio.

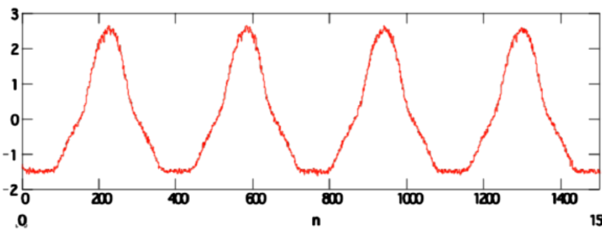

Figure 4: bunch shape for h=1 buncher, 4 turns shown.

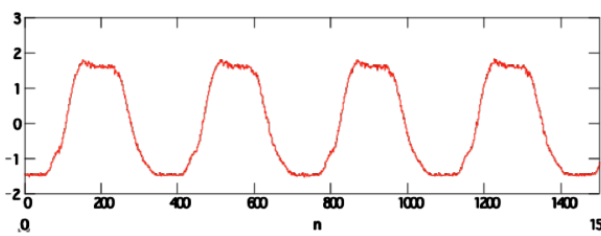

Figure 5: bunch shape for h=1 + 2, 4 turns shown.

A second harmonic buncher would also allow operation of two shorter bunchers in the PSR, beneficial for certain physics if one could be extracted at a time. In 2023, we temporarily converted the exiting h=1 buncher to operate at the second harmonic to verify that the amplifiers were capable. The test was successful. Development of a second harmonic buncher would benefit from the same tetrode amplifier as presently used. New ferrite cores such as Ferroxcube 4M2 appear to be viable for the new resonator, as tested for a different program in 2000 [18]. The same development would also be configured for operation at the h=1 (present) frequency of 2.795 MHz. This would eventually provide two separate bunchers, one being spare for the old buncher plus a second for the h=2 system.

An alternative design for a PSR upgrade has been recently discussed that would operate with 6 short bunches, to provide more intense protons (and subsequent fast neutrons from the target) for nuclear studies. This capability presently depends on the LANSCE linac, limited in peak proton current by configuration to share the same linac RF macro-pulse as isotope production. Using PSR to develop intense short bunches requires a new extraction kicker and a fast kicker magnet. Along with this technology is a need for a higher frequency buncher. This development may require a change from low frequency NiZn ferrite to a lower-loss material such as nickel or aluminium-doped yttrium-iron-garnet. This buncher may require a fast tuner to cope with transient beam loading. It could be an on- or off-beam axis tuner using perpendicularly biased garnet. This concept was developed at LANL in 1982 [19] and later a high-power resonator was constructed for one of the booster synchrotrons at SSC [20]. This higher frequency buncher requires a different RF amplifier circuit than the low frequency h=1 and 2 systems discussed earlier and is an alternative approach under preliminary discussion. The SSC prototype is in storage at Fermilab (Fig. 6).

Figure 6: 50 MHz accelerating cavity with on-axis tuner.

In the proposed scheme, multiplexing the long- and short-pulse modes is required. The effect of the quiescent cavities for one bunch mode to the other is expected to be problematic; the circulating bunches from short bunches could excite the long bunch resonator to produce spurious longitudinal fields across the gap. Similarly, the long bunches could excite the short bunch resonator to create microwave instabilities. Mechanical shorting devices of low inductance and resistance may be difficult to implement at the speed of 20 pulses per second. Other possibilities may include a passive (dissipative) coupler off the resonator or a version of active feedback to maintain zero voltage on the quiescent cavity.

CONCLUSION

The LANSCE PSR requires upgrades to the RF buncher, to address obsolescence and add capability. There are multiple approaches being investigated to handle high peak beam loading as the original cathode-follower triode amplifiers are not sustainable for the future. New gap/resonators are being considered as the original ferrite is obsolete. The addition of a second harmonic buncher RF system is being planned. There are discussions underway on whether the ring can be made capable of accumulating 6 bunches with a different RF bunching system.

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