HIGH DYNAMIC RANGE CURRENT MEASUREMENTS WITH MACHINE PROTECTION

D. Thompson, D. Bartkoski, C. Deibele, J. Patterson, C. Sibley, SNS*, Oak Ridge, TN, USA

Abstract

At the SNS a beam current measurement technique, called CHuMPS (Chopper Machine Protection System) has been developed that is fast, has a large dynamic range, and is droop free. Combined with the LEBT (Low Energy Beam Transport) chopper controller, a beam in gap measurement is possible that can accurately measure the beam in the chopper gaps. The beam in gap measurement can then provide machine protection in the case of chopper failure. The same application can also measure waste beam from the ring injection stripper foil and provide fast protection from stripper foil failure.

SYSTEM DESCRIPTION

The SNS is a pulsed neutron source using a linear accelerator to provide 1 Gev protons to a storage ring and to a mercury target. The storage ring stacks the beam over a period of 1 ms to provide a single 700 ns pulse to the target at 1000 times the linac operating current. In order to obtain low loss extraction the beam is chopped into mini-pulses at low energy in the LEBT and at 2.5 Mev in the MEBT (Medium Energy Beam Transport). Each mini-pulse is separated by a gap that is preserved in the ring and synchronized with extraction timing. A poor chopping extinction ratio, slow rise and fall times of the chopped beam and any chopping artifacts are all detrimental to the goal of maintaining low losses at the extraction kickers and throughout the machine.

Chopping is done in the LEBT at low energy where chopping is effective but provides poor rise and fall times, and at medium energy where the rise and fall times as well as any chopping "islands" can be cleaned up. The MEBT target is power limited and is not capable of absorbing an un-chopped beam pulse from the LEBT and RFQ (Radio Frequency Quadrupole) at 2.5 MeV.

The CHuMPS system was first proposed and deployed as a means of both measuring the beam and protecting the MEBT chopper target and the ring extraction area from LEBT chopper failures.

The SNS LEBT chopper as seen in Figure 1 has four vanes, each of which is alternately driven positive or negative in a pattern that repeats every fourth pulse. The vanes are driven in pairs, and both pairs are driven when

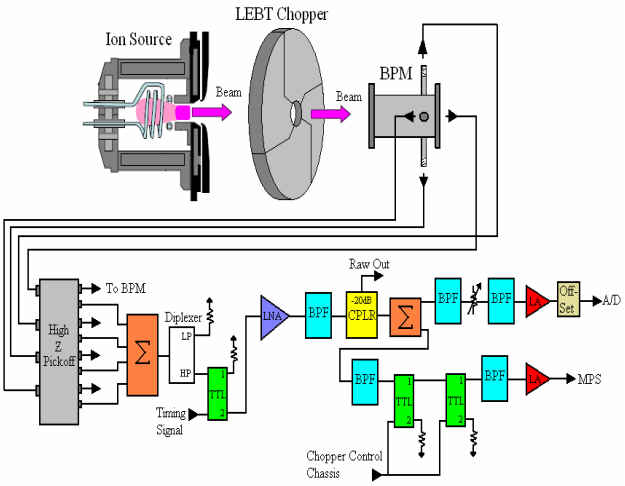

Figure 1: Layout of CHuMPS circuit.

the beam is being cut off by deflecting it to one of four spots on the LEBT target. There are two high voltage switches per vane for a total of eight high voltage switches. At least one pair of vanes must switch polarities every microsecond because vanes are AC coupled to the power electronics. This additional switching causes islands in the beam blanking period before and after the main beam pulse.

The first CHuMPS system is described in [1]. Changes in the system have been made to further optimize system dynamic range. A schematic diagram of the new circuit is shown in Figure 1. The salient changes in the system are the addition of a voltage offset circuit, additional band-pass filters, use of a higher gain LNA (low noise amplifier), and use of multiple TTL switches.

The voltage offset circuit was deployed to match the intrinsic behavior of the log-amp circuit to the range of the A/D converter. Since the A/D has a range of +/-1V, and the log amp has a total range of about 1.6V, use of the offset circuit now permits us to take full advantage of the dynamic range of our A/D. Figure 2 shows the calibrated voltage versus power curve for the log amp and offset circuit that we used.

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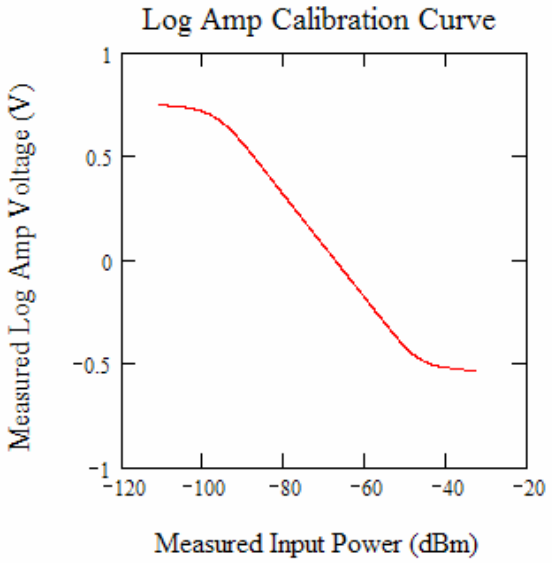

Figure 2: Log amp output voltage offset circuit versus input power.

As can be seen in Figure 2, the analog output of the new CHuMPS system now has an offset which takes advantage of the full dynamic range of the A/D that we use ICS-554D PMC card. This particular A/D converter is a 14 bit, signed, DC coupled, A/D. The raw output from the logarithmic amplifier goes from +2.3V with -60 dBm input, to +0.5V with 0 dBm input. Previously in [1], we simply used an attenuator on the output of the logarithmic amplifier which attenuated the output of the log amp from 2.3V to +0.9V, thereby using only about 30% of the full range of the A/D

This data can then be calibrated against a current transformer to provide the high-dynamic range current measurement tool. The results of this are shown in Figure. 3.

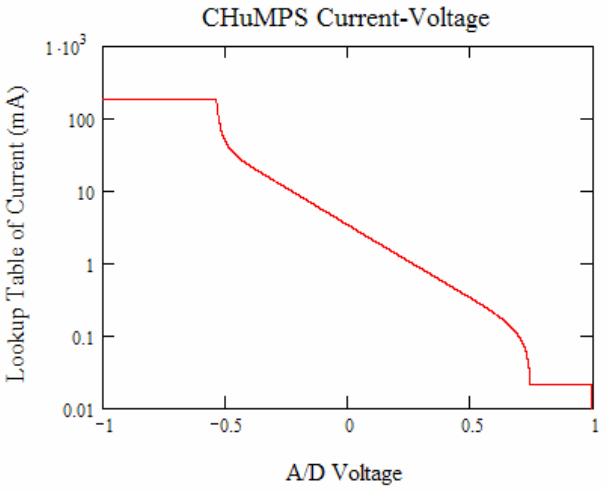

Figure: 3 Lookup table of current, in milliamps versus voltage on the logarithmic amplifier.

SYSTEM CALIBRATION

The entire system is calibrated based on a known current to power relationship in the BPM (Beam Position Monitor). A Labview program is controlling a signal generator and taking data from multiple instruments. A schematic of the circuit is shown in Figure 4, and a full description of the system calibration setup is described in [2].

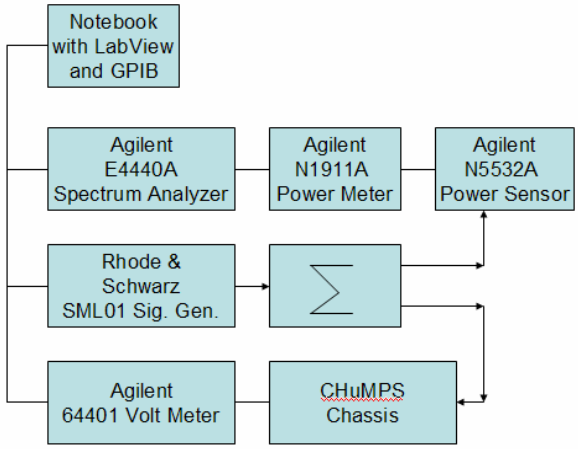

Figure 4: Calibration setup of the CHuMPS system.

The calibration schematic shows a notebook computer is controlling an Agilent spectrum analyzer which is connected to a power meter and power sensor, a signal generator, and an accurate volt meter. The spectrum analyzer has additional software loaded onto it so that it can control the power meter and power sensor. This combination provides an accurate power measurement. The signal generator is controlled and provides power to a splitter, which is measured so an absolute power measurement can be made to correlate the output voltage of the logarithmic amplifier to the RF and microwave power being applied to the system. All the measurements can be averaged and power swept over a general range.

After the calibration is completed a data file is produced with a data point corresponding to each possible A/D count. The real time conversion from the raw A/D count to current is simply a lookup operation in an array done once per sample in the waveform.

NOISE AND DYNAMIC RANGE CONSIDERATIONS

The LNA used in Fig. 1 is the Miteq AMF-4F-00500100-05-10P. It has a NF (Noise Figure) of 0.6 dB, gain of G=45 dB, 1 dB compression point of +10 dBm. The band pass filters have a bandwidth of B=10 MHz. The equivalent Noise Temperature is therefore:

$$T_e = (10^{NF/10} - 1)T = 42.9^\circ K.$$

The output noise power is therefore:

$$N = G + 10\log\left(\frac{kT_eB}{1\times10^{-3}}\right) = -67.3dBm.$$

This means that the amplifier has a dynamic range of 77.3 dB between the noise floor and compression. Since

the logarithmic amplifier has its compression point at 0 dBm and has a dynamic range of 50 dB, the analog part of the system has a dynamic range of 50 dB.

The ENOB (effective number of bits) of the A/D is 12 bits for a dynamic range of 72.2 dB.

The LNA, logarithmic amplifier, and A/D are well matched to one another.

PERFORMANCE IN OPERATION

The best way to demonstrate the performance of the CHuMPS is by way of online screen pictures. In Figure 5, we see a short beam pulse during machine tuning as digitized by a BCM (Beam Current Monitor) using a current transformer. Not only is the signal to noise ratio no better than 30 dB there are artifacts from the droop compensation as well. Part of the shape of this pulse is real and due to the change in ion source current over time and part of it is noise.

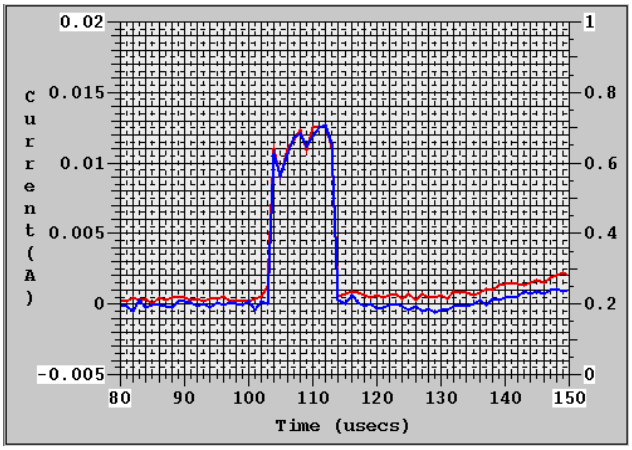

Figure 6: A short pulse as seen on a toroid based beam current monitor.

The CHuMPS waveform in Figure 6 not only shows details of the mini-pulses in the chopped beam but beam leakage in the gap. Islands in the beam before and after the intended pulses where the beam is supposed to be cut off are visible due to the dynamic range. There is also ample bandwidth to see an accurate representation of the rising and falling edges. The "Beam On" and "Beam In Gap" estimates in Figure 6 are based on integrating the A/D waveform over an 800us window. The background charge measured when there is no beam is about 9nC.

Using this CHuMPS display a damaged switch or a beam centering problem in the LEBT can be diagnosed using beam-off leakage and by comparing the pulse shape of any four consecutive mini-pulses.

MACHINE PROTECTION

The MPS (Machine Protection System) output signal shown in the Figure 1 schematic is connected to an input of the SNS machine protection system. The MPS is

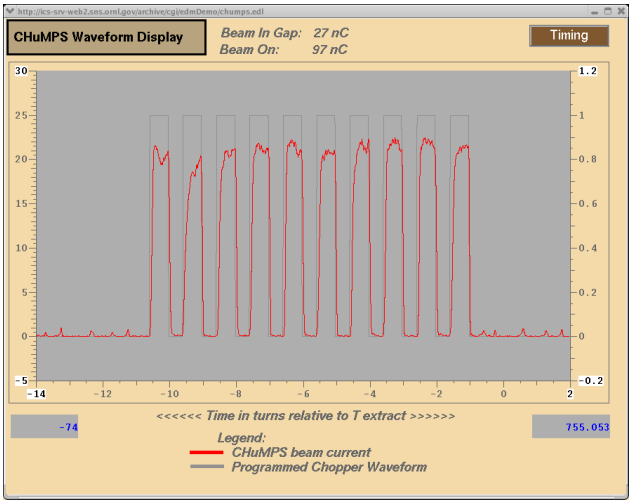

Figure 5: A short pulse as seen on the CHuMPS current monitor.

capable of turning off the beam within about 15 us of receiving a fault. CHuMPS detects a failed chopper switch in mid-pulse and turns the beam off before a damaging amount of un-chopped beam is reaches the MEBT target or is accumulated in the ring. The RF signal from the BPM is gated by a logic signal from the chopper controller such that the RF switch is only on when the beam is supposed to be off. Any significant signal level at the output of the gated RF switch indicates a fault. The fault detection comparator is set to about 3 mA and conditioned with a 200 ns time delay to minimize the number of false alarms during normal operation.

SUMMARY

The improvements described here have enabled CHuMPS to use the full 50 dB dynamic range of the log amp. The system has been in regular use at the SNS since last year. The current waveform display screen provides accurate current and timing information essential to understanding the health of the beam from the ion source to the target. As this is being written the current monitoring application is being enhanced to provide MEBT waveforms. Hardware is being built to deploy a CHuMPS system at the injection foil to protect the injection dump.

REFERENCES

[1] D. A. Bartkoski et. al,, "High Dynamic Range Current Measurements in the Medium-Energy Beam Transport Line at the Spallation Neutron Source," Linac 2006, Knoxville, Tennessee, TUP002.

[2] D. A. Bartkoski, C. Deibele,, "Log Amp Calibration Setup and Procedure,", http://it.sns.ornl.gov/asd/public/pdf/sns0177/sns0177.pdf