SNS CREDITED BEAM POWER LIMIT SYSTEM PRELIMINARY DESIGN*

C. E. Deibele†, K. L. Mahoney††
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Controls Section at the Spallation Neutron Source (SNS) is designing a programmable signal processor based credited safety control that calculates pulsed beam power based on beam kinetic energy and charge. The system must reliably shut off the beam if the average power exceeds 2.145 MW averaged over 60 seconds. This paper discusses architecture and design choices needed to develop the system under the auspices of a programmable radiation-safety credit control.

PROBLEM DESCRIPTION

The SNS is reliably operating at its initial design beam power of 1.4 MW, which is well below the facility safety envelope of 2 MW for the First Target Station (FTS), and therefore no requirements for monitoring and controlling the power of the facility have been implemented. After the Proton Power Upgrade (PPU) at the SNS, the machine will be capable of producing a beam power of up to 2.8 MW, well above the FTS safety envelope of 2 MW. Harmonization of PPU requirements with the accelerator safety envelope results in a requirement for a credited system that can be implemented through the Personnel Protection System (PPS) to halt operations if the delivered beam power to the target is too high. This system is known as the SNS Beam Power Limit System (BPLS) and requires the design discipline equivalency of a Safety Integrity Level (SIL) 2 certification.

A table of relevant BPLS PPU beam parameters is shown in Table 1.

Table 1: PPU Beam Parameters

Nominal Current Pulse Width	0.75 ± 0.1 μsec
Kinetic Energy	1.3 GeV
Nominal Rep Rate	60 Hz
Peak Current	130 A
Average Current	2.15 mA
Bandwidth	≤ 22 MHz

For background, the power delivered to the target is calculated as follows:

$$P = R_{rate}E_b \int_{t_o}^{t_o+w} I(t)dt \quad (1)$$

where R_{rate} is the repetition rate of pulses on the target, E_b is the beam energy, t_o is the time domain start of the beam, w is the current pulse width, and I(t) is the time domain current distribution.

The PPU plan is to operate the First Target Station (FTS) at a 60 Hz repetition rate until the Second Target Station (STS) comes online, then operate the FTS at 45 Hz and the STS at a 15 Hz repetition rate. Additionally, when the STS comes online, a second BPLS system to limit the STS beam power is required. This preliminary design for PPU, outlined in this paper, is envisioned to work with both PPU and STS beams.

Traditional protection and safety systems that interface with the PPS system are controlled via a Safety Programmable Logic Controller (Safety PLC). The nature of the dynamic range of currents that are expected to be measured and the relatively narrow beam pulse width make the implementation challenging using a PLC. Additionally, the known electrical noise environment creates further complications since the geographically nearby beam extraction kickers induce a large signal on the ground when the beam is extracted out of the accumulator ring.

IMPLEMENTATION

An examination of Eq. (1) shows that three parameters control the power delivered to the target. These parameters are explored below

Repetition Rate

The repetition rate is a function of the timing system at the SNS. This is can vary between <1 and 60 pulses per second and an algorithm that works within these constraints is required. It is also necessary for the system to perform correctly independent of this timing reference signal.

Beam Energy

The kinetic beam energy is the second parameter. For this measurement, it is necessary to measure the current through the dipole magnets that steer the beam to the FTS. The current in this magnet is easily mapped to the energy in the beam as it exits the linac. For implementation purposes, the dipole magnets in the Ring-To-Beam-Target (RTBT) beamline are measured [1]. Since the magnetic field necessary to steer the trajectory (θ) of the beam is a function of the beam energy (T), and the magnetic field is

a function of the magnet current ($BL(I)$), an independent measurement of the magnet current to calculate energy is possible.

$$T = \sqrt{E_0^2 + \left(\frac{cBL(I)}{\theta}\right)^2} - E_0 \qquad (2)$$

The magnet current will be measured with a PLC using two sets of three Direct Current-Current Transformers (DCCTs). A single measurement of the magnet current requires three DCCTs for two reasons:

- The magnet has six cables going to and six cables returning from the magnet
- The DCCT dimensions can only accommodate two of the cables.

To achieve a SIL 2 equivalency, two sets of measurements of the magnet current are performed. This results in a One-out-of-Two (1oo2) voting scheme for the magnet current measurement.

A schematic implementation of the DCCT measurement scheme is shown in Fig. 1.
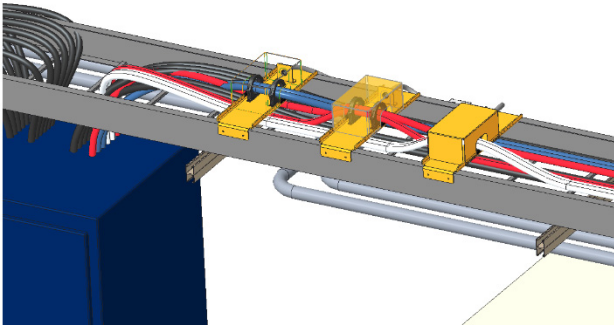

Figure 1: Schematic picture of the DCCT measurement of dipole magnet current.

The cables are grouped in sets of two through a single DCCT.

Beam Current Measurement

Traditional means to measure the charge delivered to the FTS utilize a series of analog integrators connected to a current transformer on the beamline. The integrators not only require attention to calibration, which the BPLS system requires, but also require the timing system to be used to control when the gate for the integration takes place. Additionally, the use of the timing gates implies that it is known with certainty that the beam falls within the gate. Use of a longer gate is one possible design solution, but it comes at either the risk of intercepting some of the environmental noise or of an upstream amplifier having a modest DC offset that can cause the measurement to introduce additional error.

Overcoming these potential sources of error and implementing a robust design guided the team to utilize Analog-to-Digital-Convertors (ADCs), and a sliding window integrator to measure the beam charge. The maximum value of beam charge for a single pulse is then retained over each beam pulse and used in the beam power calculation. An internal timer is used to verify the timing system reference signal is present. When a loss of reference is detected, the BPLS system uses the internal timers to keep charge measurements occurring at the required 60 Hz interval.

Two fast current transformers (FCTs) will be deployed in the beamline. A schematic of the current transformers is shown in Fig. 2. Each FCT is connected to an independent ADC thereby implementing a 1oo2 architecture that will be implemented into the overall system. Calculations were performed which drove the requirements of the FCT are outlined in [2]. Measurements of the beam bandwidth under different accelerator configurations verify the results in [2] are found in [3].
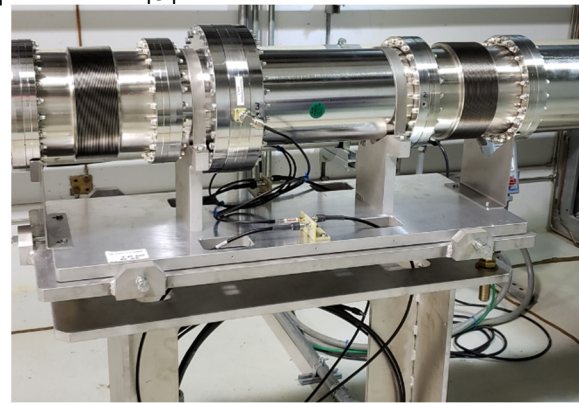

Figure 2: Installation of single FCT.

The parameters of the FCTs are listed in Table 2.

Table 2: Fast Current Transformer Parameters

Applicable Frequency Range Main Winding	1 kHz – 22 MHz
Applicable Frequency Range Cal Winding	1 kHz – 16 MHz
Main Magnitude Flatness	±0.5 dB
Cal winding Magnitude Flatness	±0.5 dB
Main Winding Phase	±10 degrees
Cal Winding Phase Flatness	±10 degrees
Peak Current	150 A
Transfer Impedance Main	0.25 V/A
Cal – Main Turns Ratio	1:100
Connectors	Type N, Isolated
Shielding of CT	≥ -80 dB
Droop	≥1±0.1 msec

The calculation of charge, however, requires a broader understanding of the system and how it is implemented. This is described in the following block diagram section of this paper.
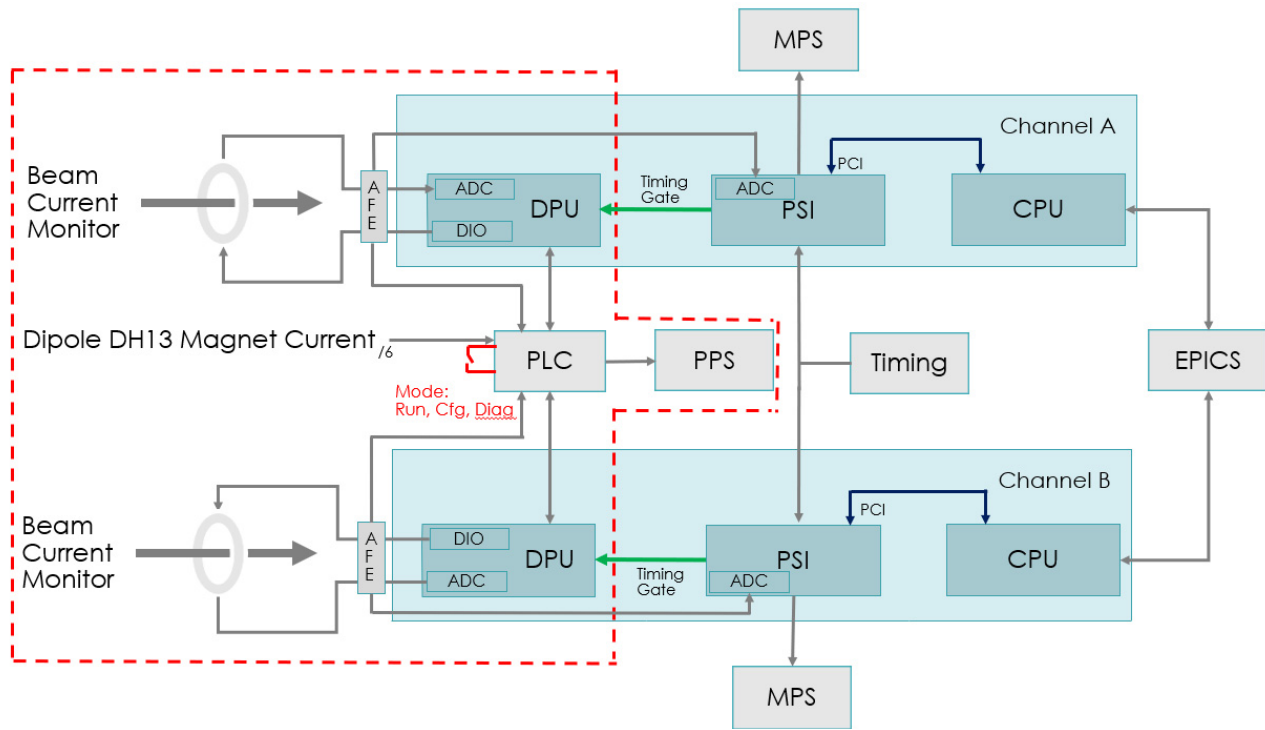
Figure 3: Block Diagram of the Beam Power Limiting System.

BLOCK DIAGRAM

The functional components for understanding the mechanics of the measurement in the different elements of Eq. (1) have been described. The overall block diagram of the system is shown in Fig. 3. In Fig. 3, one sees that there are two measurements of beam current, implementing a 1oo2 measurement of beam current. Also, a PLC performs a 1oo2 measurement of the magnet current thereby performing a beam energy calculation. The dashed red line shows the safety-critical components of the design.

Connected to the FCT is the Analog Front End (AFE) chassis. The AFE conditions the signals so it is at a level and bandwidth appropriate for the ADCs in the Digital Processing Unit (DPU). It also provides a self-test mechanism so that the DPU can pass a test pulse through the FCT via the calibration winding, the pulse is received by the AFE and FCT and is used to validate the system integrity. The power to the AFE card is also monitored by the PLC to ensure a failed power supply is detected and can be reported.

The DPU is connected to the PSI via a timing Gate. The connection to timing is used so that when a new beam cycle starts, the DPU can calculate the previous beam pulse charge. The DPU monitors and reports timing reference errors to the PLC. The DPU performs the sliding window integration during the beam pulse, recording the maximum value over the beam pulse. It compares the calculated charge to a threshold that the PLC communicates and notifies the PPS when the threshold is reached. The DPU design is governed by [4]

The Safety PLC, designed under [5], serves several functions. First, it monitors the different DPUs for system integrity (proper power, proper timing, heartbeat, proper test pulse). It is also used to measure the beam energy by measurement of dipole magnet. The PLC performs the 1oo2 voting to determine if a particular DPU or set of DCCTs is discarded due to system integrity issues. It also contains the calibration data for the DPU and PSI AFE cards so it can calculate the appropriate charge thresholds for the DPU and PSI. The PLC is also responsible for sending a signal to the DPU to do a test pulse.

Additionally, the PLC interfaces directly to the RTBT PPS system. The output of the voting from the 1oo2 is implemented and drives the PPS to permit beam operation. The PLC will also report on the health of the subsystems of the BPLS.

CONCLUSION

The BPLS system is at a preliminary design phase at the Spallation Neutron Source as part of the Proton Power Upgrade project. BPLS is a system of high pedigree qualified for use in a personnel safety system. It uses FPGA based digital processor to implement integration and diagnostic functions that are not possible to perform within analog signal processing alone. This, coupled with the use of a certified safety PLC, mean the BPLS can reliably calculate beam power on a pulse-to-pulse basis.

REFERENCES

[1] K. Mahoney, "Basis for Beam Power Limit System Energy Calculation", Oak Ridge National Laboratory, Oak Ridge, TN, USA, Rep. PPUP-406-TD0002-R00, Oct. 2020.

[2] C. Deibele and N. Evans, "Background Calculations for the Beam Power Limiting System", Oak Ridge National Laboratory, Oak Ridge, TN, USA, Rep. PPUP-406-CA0003-R00, Dec. 2020.

[3] C. Deibele and Y. Tan, "Beam Bandwidth Measurements for the Beam Power Limiting System", Oak Ridge National Laboratory, Oak Ridge, TN, USA, Rep. PPUP-406-CA0002-R00, Dec. 2020.

[4] *RTCA/DO-254 Design Assurance Guidance For Airborne Electronic Hardware*, RTCA, Washington, DC, 2000, pp. 1-137, `https://standards.globalspec.com/std/927681/RTCA%20DO-254`

[5] *IEC 61508-1:2010 Functional safety of electrical/electronic/programmable electronic safety-related systems*, IEC, Geneva, Switzerland, 2010, pp. 1-127, `https://webstore.iec.ch/publication/5515#additionalinf`