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SNS CREDITED PULSE ENERGY LIMIT SYSTEM CONCEPTUAL DESIGN*

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Abstract

The Controls Group at the Spallation Neutron Source (SNS) is designing a programmable signal processor based credited safety control that calculates pulsed beam energy based on beam kinetic energy and charge. The SNS Pulsed Energy Limit System (SPELS) must reliably shut off the beam if the average power exceeds 2.145 MW averaged over 60 seconds. This paper will cover the architecture and design choices needed to develop the system under the auspices of a programmable radiation-safety credit control. The authors will also introduce the concept of a graded failure approach that allows the credited system to continue operation in the presence of some faults.

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. 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 although the safety envelope will remain at 2MW. The disparity results in a requirement for a credited system that can be implemented through the Personnel Protection System (PPS) to shut down the beam if it is too high. This system is known as the SNS Pulsed Energy Limit System (SPELS) or the Beam Power Limit System (BPLS).

A table of 2.8 MW beam parameters is shown in Table 1.

Table 1: PPU Beam Parameters

Nominal Current Pulse Width	$0.75 \pm 0.1\ \mu sec$
Kinetic Energy	1.3 GeV
Nominal Rep Rate	60 Hz
Peak Current	100 A
Average Current	2.15 mA
Bandwidth	$\leq 22\ MHz$

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

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

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.

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The present plan is to operate the 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, it is envisioned to deploy a second BPLS system to limit the STS beam power.

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 makes for a challenging implementation with a Safety PLC. Additionally, the known electrical noise environment is challenging since the near by beam extraction kickers induce a large signal on the ground when the beam is extracted out of the accumulator ring.

IMPLEMENTATION

Repetition Rate

An examination of Eq. (1) reveals that three separate measurements are needed to measure the beam power. The first measurement of the repetition rate is a function of the timing system at the SNS. This is can vary between 1 and 60 pulses per second. The accelerator can only be run in a setup that is less than or equal to 60 pulses per second, and so an algorithm that works for 60 pulses per second is needed.

Beam Energy

The next necessary measurement is the kinetic beam energy. In normal operation, the beam energy is determined by a measurement of the time-of-flight (TOF) using a beam position monitor system in the Linear Accelerator (linac). This is then used to set the main dipole magnets in both the accumulator ring and in the Ring-To-Beam-Target (RTBT) beamline. Since the magnetic field necessary to bend 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 Safety PLC using three Direct Current Current Transformers (DCCTs). Each DCCT has a 4-20 mA output for a fail-safe connection. This is required so that the Safety PLC can sense if the DCCT amplifier is working correctly or if it has lost power.

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A conventional Two-out-of-Three (2oo3) voting scheme for the magnet current will be implemented, and the average of the voting channels will be used to calculate the beam energy.

A schematic picture of an envisioned implementation of the DCCT measurement scheme is shown in Figure 1. The magnet power supply is used to power DH-13, which has six individual cable pairs used to power the magnet.

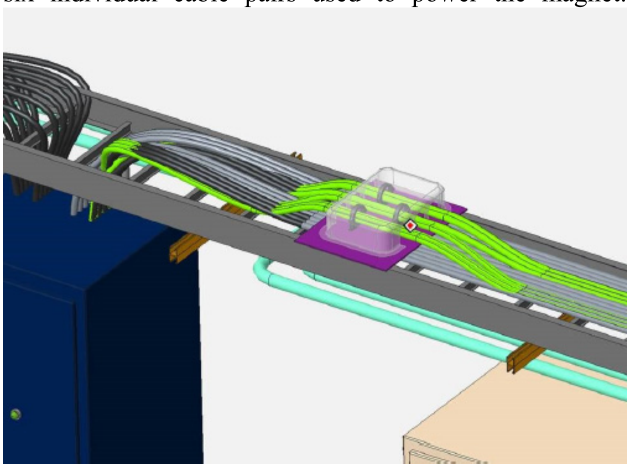

Figure 1: Schematic picture of the DCCT measurement of dipole magnet current.

The cables will be grouped in sets of two cables into a single DCCT. It is noteworthy to mention that the DCCTs are covered to keep the DCCT connections to amplifiers under configuration control.

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.

Before discussing the current transformer, it is noteworthy to discuss issues with past work. The previously mentioned analog integrators not only require attention to calibration, which the BPLS system requires, but also requires the timing system be used to control when the gate for the integration takes place. This poses a particular problem for the measurement of charge since the timing system is not a credited engineered control device, and the timing gates are not under configuration control. Additionally, 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 and the DC offset cause the measurement to introduce additional error.

To circumvent these potential sources of error and reduce the project risk is to utilize Analog-to-Digital-Convertors (ADCs), and a sliding window integrator to measure the beam charge. The maximum value of beam charge is then retained over each beam pulse and used in the beam power calculation.

It is envisioned to use two fast current transformers (FCTs) in the beamline. A schematic of the current transformers is shown in Figure 2. Each FCT is connected to an independent ADC thereby implementing a One-out-of-Two (1oo2) architecture that will be implemented into the overall system.

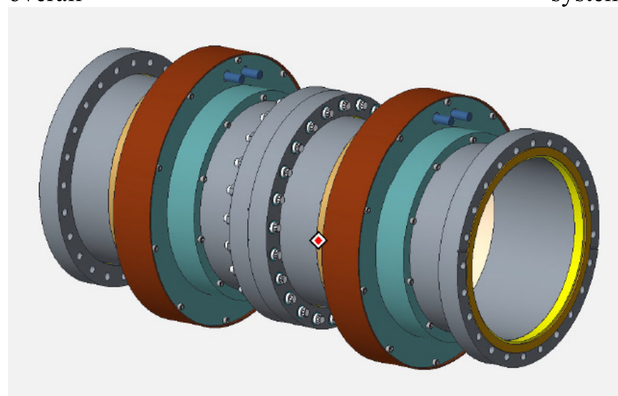

Figure 2: Schematic of two current transformers.

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 Winding Magnitude Flatness	±0.5 dB
Cal winding Magnitude Flatness	±0.5 dB
Main Winding Phase Flatness	±10 degrees
Cal Winding Phase Flatness	±10 degrees
Peak Current	150 A
Transfer Impedance	0.25 V/A
Calibration – Main Winding Turns Ratio	1:1
Connectors	Type N
Isolation	Connectors are galvanically isolated from beamline
Cal and Main Winding Impedance	50±1 Ω
Shielding of CT assembly to outputs of CT	≥ -80 dB to 100 MHz
Droop	≥1±0.1 msec (≤0.1±0.01%/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.

BLOCK DIAGRAM

The functional components of understanding the mechanics of measurement of the different elements of Eq. (1) have been described. The overall block diagram of the system is shown in Figure 3. In Figure 3 one sees that there are two measurements of beam current, implementing a

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1oo2 measurement of beam current. Also, the Safety PLC performs a 2oo3 measurement of the magnet current thereby performing a beam energy calculation.

Connected to the CT is the Analog Front End (AFE) card. The AFE conditions the signal so it is at a level appropriate for the ADCs in the Digital Processing Unit (DPU). It also provides a self-test mechanism so that the DPU can send a test pulse down to the CT via the calibration winding. The DPU can then sense the test pulse and verify that the cabling, AFE, and CT are functioning within specification. Also, the power to the AFE card is monitored so that a failure of power is detected and can be reported.

The DPU is connected to timing, to the Machine Protection System (MPS), and to the Safety PLC. The connection to timing is used so that when a new beam cycle starts, the DPU can calculate the previous beam pulse energy, read the beam energy from the Safety PLC, and send waveforms from the previous pulse to the Machine Protection System. The DPU contains a timer that is used to determine if loss of timing occurs. Loss of timing indicates a failure in the system and is reported to the Safety PLC

Functionally, however, the DPU performs one necessary function, namely measure the beam charge. It performs a sliding window integrator during the beam pulse, recording the maximum value over the beam pulse.

The Safety PLC serves several functions. First, it monitors the different DPUs for system integrity (proper power, proper timing, heartbeat). It is also used to measure the beam energy by a measurement of dipole magnet. This measurement occurs at a 10 Hz rate and the magnet current is averaged over 10 seconds.

The Safety PLC does the voting (1oo2) to determine if the a particular DPU is masked due to system integrity. A set of system rules has been established how long the system can run with a valid single measurement of beam power.

Additionally, the Safety PLC interfaces directly to the Ring To Beam Target (RTBT) PPS system. The output of the voting from the 1oo2 is implemented and drives the PPS to permit beam operation.

CONCLUSION

The BPLS system is at a conceptual design phase at the Spallation Neutron Source as part of the Proton Power Upgrade project. BPLS is a credited control qualified for use in a personnel safety system. It uses FPGA based digital processor to implement integration and diagnostic functions not possible to perform with 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. Further development is needed to prove the efficacy of the BPLS in a noisy environment. Overall, the BPLS will advance state of the art in credited safety instrumentation.

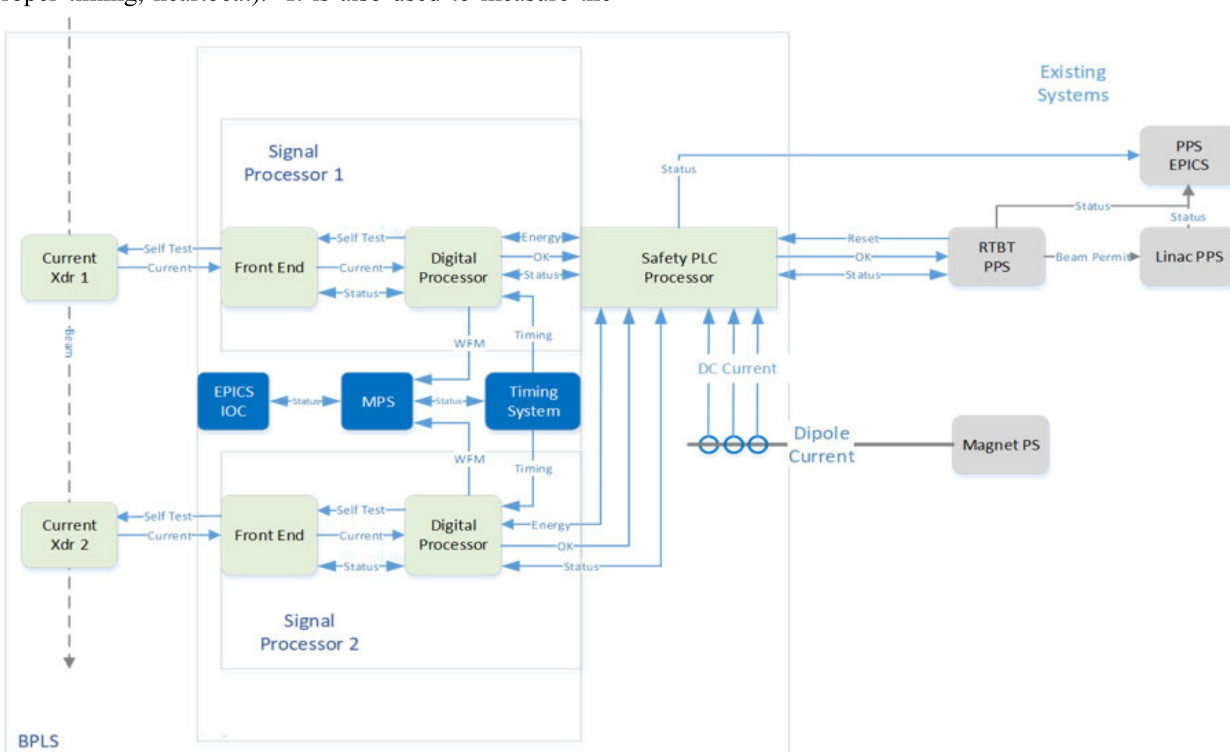

Figure 3: Block diagram of the BPLS system.