FAILURE MODE AND EFFECTS ANALYSIS OF THE BEAM INTENSITY CONTROL FOR THE SPIRAL2 ACCELERATOR

C. Jamet [#], S. Leloir, T. André, B. Ducoudret, G. Ledu, S. Loret, C. Potier de Courcy,
GANIL, Caen, France

Abstract

The first phase of the SPIRAL2 project includes a driver and its associated new experimental areas (S3 and NFS caves). The accelerator, located in Caen (France), is based on a linear solution composed of a normal conducting RFQ and a superconducting linac. Intense primary stable beams (deuterons, protons, light and heavy ions) will be accelerated at various energies for nuclear physics.

The beam intensity monitoring is a part of the control of the operating range. A high level of requirements is imposed on the intensity control system. In 2013, a Failure Mode and Effects Analysis (FMEA) was performed by a specialized company helped by the GANIL's Electronic Group. This paper presents the analysis and evolutions of the electronic chain of measurement and control.

INTRODUCTION

In the first phase, the SPIRAL2 driver will be able to accelerate and deliver beams of protons, deuterons and ions with q/A=1/3 to NFS (Neutron for Science) and S3 (Super Separator Spectrometer) experimental rooms. Table 1 shows the main beam characteristics.

Table 1: Beam Specifications

Beam	P	D+	Ions (1/3)
Max. Intensity	5 mA	5mA	1 mA
Max. Energy	33 MeV	20 MeV/A	14.5 MeV/A
Max. Power	165 kW	200 kW	43.5 kW

Beam diagnostics are installed along the accelerator in order to measure and control continuously beam parameters and transmission losses [1],[3]. Beam intensity and transmission levels are measured by non-interceptive transformers ACCT and DCCT.

To obtain the commissioning authorization, the SPIRAL 2 project has to demonstrate and prove to the French Safety Authority that these devices which monitor the operating range of the facility are built in respect of the quality assurance rules.

To respond to this request, a FMEA (Failure Mode and Effects Analysis) of the intensity and transmission monitors was performed in 2013 by a French company, Ligeron®, specialized in the safety system developments.

Results, conclusions of this FMEA and the uncertainties of the measurement chains are presented in this paper.

REQUIREMENTS

Global Functions

The functions of the non-interceptive intensity measurements are:

- ✓ Tune the beam,
- ✓ Control and monitor the beam intensity at the LINAC exit,
- ✓ Control and monitor the intensity between several points of the accelerator (transmissions),
- ✓ Control the intensity quantity sent to the Beam Dump Linac over 24 hours.

Tuning Requirements

The initial operating ranges for beam intensity were:

- ✓ for proton and neutron beams: from 0,15 to 5 mA
- ✓ for heavy ions (Q/A=1/3) : from 0,15 to 1 mA

"Voltmeter" function: Measure the beam intensity average

"Oscilloscope" function: Visualize the beam intensity in time. Time resolution: few µs

MPS Requirements

The SPIRAL2 Machine Protection System is based on three technical subsystems [2], [4]:

- ✓ One dedicated to thermal protection (TPS), which requires a fast electronic protection system,
- ✓ One dedicated to enlarged protection (EPS), based on robust technologies consisting of a PLC associated with a redundant hard-wired system. It controls the operation domain of the facility from the safety point of view (beam intensities and energies)
- ✓ One dedicated to classified protection (CPS), which protects the vacuum safety valves of the facility.

Enlarged Protection System Requirements

Beam intensity control at the linac output:

- ✓ Intensity levels: 5 mA on the Linac Beam Dump, 1 mA in the S3 experimental room, 50 µA in the NFS experimental room
- ✓ Response time: 1 s

Beam intensity transmission:

- ✓ Level: 250 µA (maximum losses to limit the radiologic level outside the accelerator area)
- ✓ Response time: 1 s

Intensity at the linac output for the activation control of the Linac Beam Dump:

- ✓ Intensity levels: from 11 µA to 5 mA
- ✓ Response time: 10 s

ISBN 978-3-95450-141-0

Thermal Protection System Requirements

Beam intensity control:
- ✓ Intensity levels: 10 µA to 5 mA
- ✓ Response time: 10 ms

Beam intensity transmission:
- ✓ Levels: less 1 µA to 5 mA
- ✓ Response time: from 35 µs (5 mA)

BEAM INTENSITY AND TRANSMISSION CONTROLS

A DCCT and three ACCT-DCCT blocs will be installed along the accelerator. These diagnostics measure the intensity in the LEBT, MEBT, and in the HEBT at the linac exit and at the entrance of the Beam Dump.
The transmissions of the MEBT, Linac and Linac added to HEBT will be also monitored.

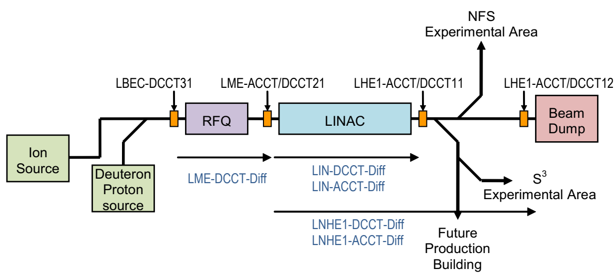

Figure 1: Beam Intensities and transmissions.

ACCT and DCCT diagnostics are complementary. The DCCT, a commercial device, measures the intensity of continuous and chopped beams (response time around 50 µs for a bandwidth of 10 kHz). The minimum intensity measured is around a few dozens of µA without offset compensation.

The ACCT chain is faster with a response time inferior to 1 µs (bandwidth superior to 300 kHz). Its intensity accuracy is better than 10 µA. However, against these benefits must be weighed a disadvantage, a chopped beam is necessary.

MEASURING CHAIN DESCRIPTION

ACCT-DCCT bloc

Two kinds of transformers are used to measure the beam intensity by a non-interceptive method, DCCT (NPCT) and ACCT. A Bergoz NPCT and a homemade ACCT, inside a magnetic shield, compose an ACCT-DCCT bloc.

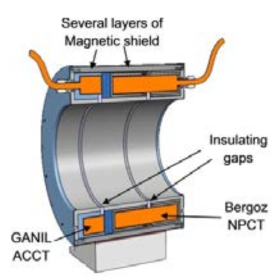

Figure 2: ACCT-DCCT bloc section.

Transformer descriptions:
DCCT: NPCT-175-C030-HR
ACCT: Torus: Nanocristaline, Turn ratio: 300:1
Internal diameter: 184 mm, External diameter: 220 mm

Three shielding layers (Armco, Mu-metal and copper) protect the sensors from external electromagnetic fields.
A vertical shield plate between AC and DC sensors is installed to minimize the disturbance produced by the DCCT magnetic modulator on the ACCT.

ACCT Measuring Chain

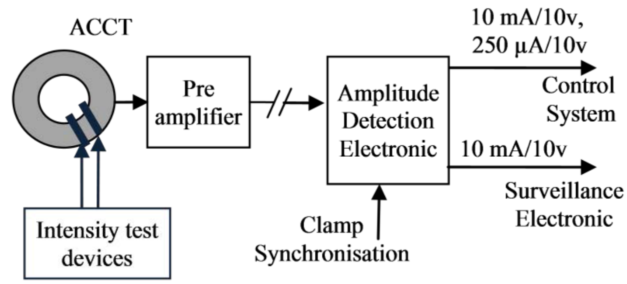

Figure 3: ACCT chain.

The preamplifier was developed to reduce the ACCT low frequency cut-off up to few 10 mHz and decrease the low drop.
The low drop is the gradual fall of the ACCT signal during a constant pulse beam. The low drop uncertainty is proportional to the pulse duration.

The amplitude detection electronic is synchronized to a signal “Clamp synchronization” which memorizes the voltage level when the beam is not present and subtracting the memorized value.
The board has different outputs with two gains 1 and 40 and two bandwidths: 0,5 Hz (low frequency) and 250 kHz (high frequency).

DCCT Measuring Chain

A thermal regulation maintains the temperature at 40 °C ±1°C in order to decrease the effect of the temperature variation on the offset value.

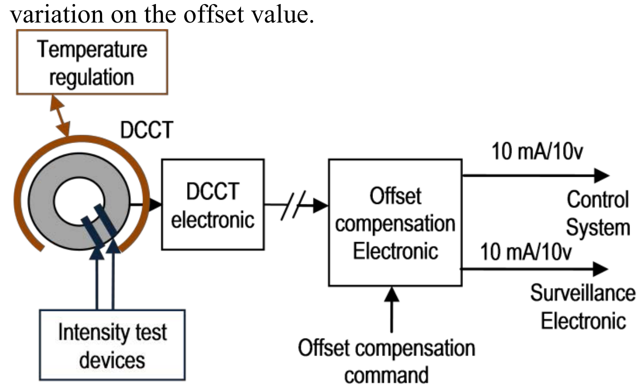

Figure 4: DCCT chain.

ISBN 978-3-95450-141-0

An electronic offset compensation is planned to reset the offset at each start of a new beam tuning. The command is done manually.

INTENSITY SURVEILLANCE BOARD

Requirements

The main board requirements are the following:

- ✓ The surveillance of the average current independently of the duty cycle of the beam chopper (duty cycle period of 200 ms or 1s)
- ✓ a response time of 35 µs with an input level of 5mA

To respond to these 2 requirements, the chosen solution was to build an electronic which integrates the current over a duty cycle period.

Operating Principle

The electronic board realizes a moving integration by using a VFC, a delay of 200 ms or 1 s and a pulse down/up counter [5].

The ACCT or DCCT signal is converted into a pulse frequency. Continually, a counter adds up the pulses and removes the delayed pulses (Figure 5). The delay corresponds to the time interval of integration. This time is equal to a multiple of the chopper period. The counter value is then representative of the input average signal.

A microcontroller is used to perform the counting function and monitor the other thresholds with less reliability but more flexibility. The microcontroller manages the other functions like the communication between the electronics and the control system.

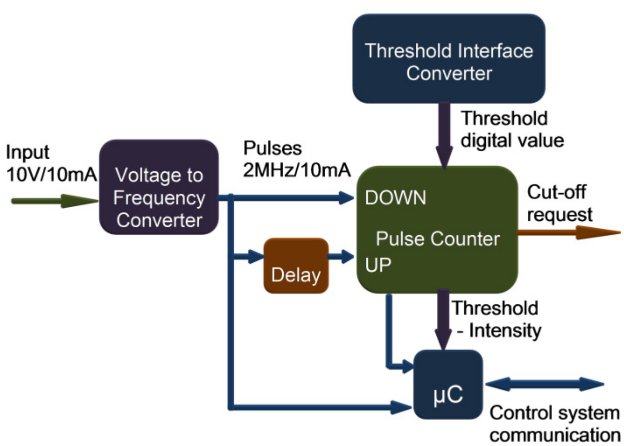

Figure 5: Integrator synoptic.

To generate the alarm signal, the counter starts at the threshold value and its inputs are inverted (count down the pulses and count up the delayed pulses). Therefore, the counter value is equal to the threshold value minus the integrator value.

A negative value of counter is equivalent to the threshold exceeded. In that case, the cut-off request is the sign bit of the counter.

MEASUREMENT RESULTS

Measurement Uncertainty

The MPS controls require knowing the absolute value of the beam intensities. The threshold values must take into account the measurement uncertainty.

The influence quantities in the total uncertainty are:

- ✓ Offset
- ✓ Noise
- ✓ External Electromagnetic field
- ✓ Linearity and accuracy of the gain
- ✓ Temperature drifts (only DCCT)
- ✓ Low drop (only ACCT)
- ✓ Slew rate
- ✓ Time lag between two chains (for transmission measurements)

The measured uncertainties for ACCT and DCCT are presented in the Table 2.

Table 2: Uncertainties

Sources of uncertainty	ACCT	DCCT
Linearity*	0.1%	0.6%
Offset vs. Temperature* ΔT = 1°C	-	10 µA
Integrator Offset	0.5 µA	0.5 µA
External magnetic field max. **	1,5 µA	-
Noise	3nA/√Hz	200nA/√Hz
Low drop ***	-	-
Slew rate	5µs	50µs

* measured by the GANIL test bench
** Measured with the I surveillance board
*** Low drop effect removed by an optimised sample & hold

Noise and fluctuations

For the beam tuning, the ACCT devices will be used to measure the low beam intensity. The main characteristic concerns the resolution the fineness of measurements limited by the noise.

The global chain with the detection board and the "I surveillance" board gives these first results.

The ACCT range of fluctuation is ±1,5 µA with a scale of ±10 mA. These fluctuations are due mainly to the 50 Hz perturbation (in laboratory).

The DCCT fluctuation value is ± 1,5 µA in a short time (few minutes). The offset changes slowly in function of the temperature. The offset variation is measured at ±10 µA for a regulated temperature of ±1°C.

ISBN 978-3-95450-141-0

With a scale of ±250 µA and a 50 Hz reduction, the first ACCT measurements give a resolution better than ±0,5 µA.

The gain dispersion between the different chains limits the transmission accuracy. Tests are underway to adjust the gains in order to obtain the smallest gain difference.

FAILURE MODE AND EFFECTS ANALYSIS RESULTS

The Aim of the FMEA consists to verify that the intensity and transmission control respond to the requirements of the EPS. The risks are to underestimate the beam intensities and transmissions.

The determinist analysis consisted to study the effects of failure modes on the safety functions. The failure mode identification was realized from functional and physical descriptions of the control chains.

The FMEA results show dangerous failures and give three categories of recommendations:

- ✓ Technical recommendations
- ✓ Recommendations to establish periodical controls
- ✓ Recommendations to establish operating procedures

Technical Recommendations

The main technical recommendations are to add surveillances of the hardware functions (saturation detections, timing controls, power supply controls, and temperature regulation control) and add verifications by the microcontroller of the correct writing of the thresholds in the surveillance boards. All these surveillances are added and set off the cut-off request in case of activation. All these recommendations were taking account in the new design of the electronic devices.

An authorisation is now necessary to send a test, to enter a threshold and to deduct the DCCT offset. This authorisation is given when the beam is stopped in the LEBT.

Periodical Controls

These controls are the following:

The control of the measurement chain consists in injecting test currents in the test coil. The measured values and the threshold overrun have to be controlled.

Each hardware control has to be tested. In the new electronic design of the surveillance boards, a connection between each board and a test box is planned.

A control of the thermal regulation is also asked.

Operating Procedures

After each intervention on the beam pipe near ACCT-DCCT blocs, a verification of the beam intensity measurement is intended with the beam presence.

After each threshold modification, a remote verification of the threshold value is done by an operator.

CONCLUSION

The FMEA performed in 2013 and the conception review organised in the beginning of 2014 validated the final design of the intensity and transmission controls. The last prototypes are currently under test. The definitive manufacturing of the overall chain is planned for the end of this year.

The experience of FMEA is quite positive. The analysis has helped to define precisely the requirements, to develop an electronic more robust and to adapt this design to the recommended controls.

REFERENCES

[1] C. Jamet *et al.*, "Injector Diagnostics Overview of SPIRAL2 Accelerator", DIPAC2007, Venice, Italy.

[2] M-H. Moscatello *et al.*, "Machine Protection System for the SPIRAL2 Facility", IPAC2012, New Orleans, Louisiana, USA.

[3] C. Jamet *et al.*, "Beam Intensity and Energy Control for the SPIRAL2 Facility", LINAC2012, Tel-Aviv, Israel.

[4] C. Berthe *et al.*, Machine Protection System for the SPIRAL2 Facility, ICALEPS2013, San Francisco, CA, USA.

[5] S. Leloir *et al.*, Measurement and control of the beam intensity for the SPIRAL2 Accelerator, IBIC 2013, Oxford, England.

ISBN 978-3-95450-141-0