BEAM LOSS MONITORING AND MACHINE PROTECTION DESIGNS FOR THE DARESBURY LABORATORY ENERGY RECOVERY LINAC PROTOTYPE

S. R. Buckley and R. J. Smith, CCLRC Daresbury Laboratory, Warrington, WA4 4AD, UK

Abstract

Daresbury Laboratory (DL) is currently constructing an energy recovery linac prototype (ERLP). This is to carry out the necessary research and development of the technology of photo-cathode electron guns and superconducting linacs so that a fourth generation light source (4GLS) can be designed and constructed. Beam loss monitoring and machine protection systems are vital areas for the successful operation of the ERLP. These systems are required, both for efficient commissioning and for hardware protection during operation. This paper gives an overview of the system requirements, options available and details of the final design.

INTRODUCTION

The ERLP accelerator will be a test and development facility for many systems and principles required for 4GLS. It is under construction at Daresbury Laboratory, in the North West of the UK, the site of the UK's current synchrotron radiation source (SRS), due to close in January 2008. The ERLP utilises two superconducting, accelerating modules, each containing a pair of modified TESLA 9 cell cavities to accelerate an electron beam, produced initially from a 360 kV DC electron gun, to ~35 MeV using the energy recovery principle (see Figure 1), The accelerator is principally a technology demonstrator but will also include an FEL and other magnet systems loaned to DL by the Thomas Jefferson National Accelerator Facility (TJNAF), Virginia USA. The FEL will be used both as a beam disruptor and experimental facility to provide experience.

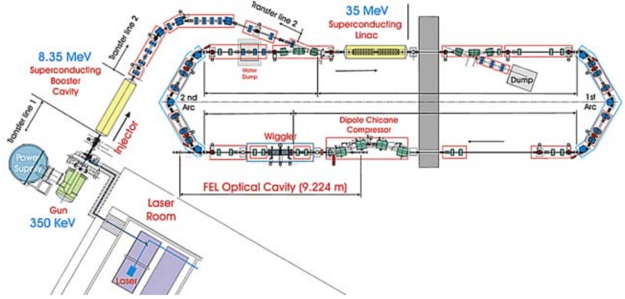

Figure 1: ERLP Accelerator Layout

The scope of the machine protection system is to provide an installation, which will, in the event of a mis-steered electron beam, prevent damage to vital machine components, or produce undesirable excess radiation. The implementation must be able to detect a mis-aligned beam and reduce the ERLP to a safe operating level before damage to the complex hardware can occur. Should the beam continually collide with the beam pipe, mechanical damage (melting) will release particles which will severely reduce the quality of vacuum within the machine causing downtime to enable the vacuum to recover [1]. The system required must be multi-layered and reliable with a simple interface.

OPERATING MODES AND PROTECTION REQUIREMENTS

The ERLP has been designed to operate in several modes to allow the beam to be transported to a different point of the machine and with varying length of the beam pulse train. The system designed must cater for all these variables and ensure that the machine hardware is protected when necessary.

The accelerator RF frequency is 1.3 GHz. Bunches of 80 pC charge and 20 fS duration are produced at a rate of 81.25 MHz, resulting in every 16th RF bucket being filled during a pulse train. Typical modes of operation are:

- Single bunch
- 30 μS short bunch train (typical)
- 100 μS long train (typical)

CW operation is not allowed

All of these modes can be transported to a number of locations including beam dumps and Faraday cup stops by appropriate configuration of the lattice and dumps, resulting in beam transport to varying locations, and due to the nature of ERLP operation, varying energies.

The high average power of the ERLP demands that stringent protection systems are required to protect against a mis-steered beam or beam loss. It should be noted that once a train of electron bunches is inside the machine it cannot be stopped. A single train will not cause a failure; however, multiple trains while the machine is in long train mode will cause considerable damage due to the higher average beam power. The detection of a collision must, therefore, disable the electron gun, the source of the beam, before the next train is produced. This means that a loss must be detected and the gun disabled within 49.9 mS (max.), and the gun output is disabled by the interruption of control signals to the photo-cathode laser system Pockels Cell and a mechanical shutter.

DETECTION TECHNIQUES

The detector stage of the project is most critical; any loss of beam must be detected and compared to a preset safe threshold. In order to decide upon the most appropriate detection method the accelerator must be completely understood. This includes the electrical and radiation characteristics of the machine. To maintain efficiency it is important for the system to only stop the accelerator when it is at risk. This requirement means the system must be reliable and accurate.

There are several methods that can be used to detect beam loss; these techniques use both anticipatory and reactive techniques.

Anticipatory Techniques

As the speed of the system is probably the most critical factor, anticipatory techniques could initially seem to be the best choice for a detector. These detectors could, in theory, anticipate a beam loss by detecting failures of systems relied upon for a successful beam orbit. This would include the monitoring of magnet power supplies, magnet field strength, accelerator vacuum and high power RF systems. Instability in any of theses systems would certainly cause a level of beam loss but the small deviation required would be difficult to detect and act upon before damage could occur.

The monitoring of these systems is quite slow, if a magnet PSU output falls by 1%, the beam will have been mis-steered enough to cause a loss. As electrons are travelling at 99.99 % of the speed of light, electrons would be lost before the instability of the output was detected. Such systems could still prevent the next train of electrons being produced; however, the threshold levels on the monitoring equipment would have to be very tight and would be prone to spurious trips. It is clear that anticipatory methods would be inappropriate for this system.

Reactive Techniques

Reactive techniques react only to an actual loss; measurement of this reduces the possibility of spurious trips. In the event of a beam loss the average beam current is reduced and as a result of an electron's collision with an object, ionising radiation is produced. These properties are measurable and can be used to form a fast and accurate detection system. Also, by the detection of two different properties, a distinct primary and secondary protection system could be used to improve the overall system integrity.

After researching techniques used at other facilities, it was clear as the financial and time constraints were restrictive that the procurement of a proven detector system would be a more viable option to that of the design and construction of an in-house system.

HARDWARE ELECTRONICS

The decision was made to purchase two separate detection systems, both from the Electron Linac for beams with high Brilliance and low Emittance (ELBE) Research facility in Rossendorf, Germany. Both, Current Difference Monitoring (CDM) and Long Ionisation Chamber (LIC) systems were manufactured by ELBE within budgetary and time constraints.

Current Differencing System (CDM)

The CDM system measures the quantity of beam lost in the accelerator. In order to provide this function, each channel of the system measures the average beam current at two points of the machine (see Figure 2). The downstream value is subtracted from the upstream value and if the resulting current difference is above a preset threshold the system will trip an interlock to the controller [2].

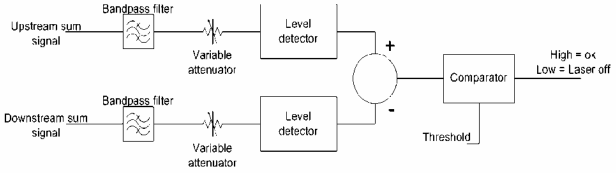

Figure 2: Current Differencing System Principle

In order for the system to perform the current difference calculation, the beam current must be measured. The beam current signal originates from the Beam Position Monitoring system (BPM) and by the collection of the electrons in the beam dumps. No additional machine hardware is required for the CDM system. This is important to avoid machine congestion.

Long Ionisation Chamber System (LIC)

The LIC system measures the quantity of ionising radiation generated by the accelerator. In order to provide this function ionisation chambers are distributed around the machine at uniform distance from the beam pipe. The radiation level is monitored by an electronics module and compared against a preset threshold, if this threshold is exceeded, the system will trip an interlock to the injector controller.

The Ionisation Chamber principle has been used in radiation detection for many years. An ionisation chamber is an enclosure filled with inert gas (air filled coaxial cable:- Andrew HJ4-50, 50 Ω is used) and configured with positive and negative electrodes (see Figure 3). The ionising radiation that passes through the enclosure causes a current to flow; this current can then be measured [3].

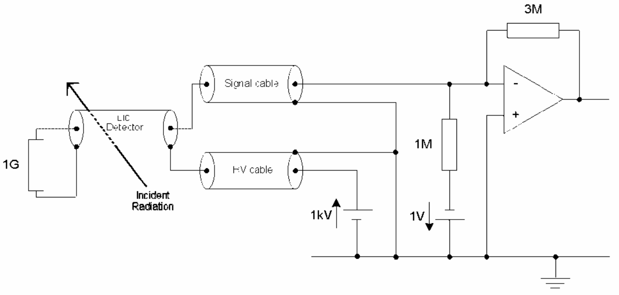

Figure 3: LIC Detection System Principle

As the ionising radiation passes through the gas within the enclosure, ion pairs are produced. The ionised gas molecules are attracted to the positive electrode (1 kV) forming a current flow, which although very small, can now be measured.

SYSTEM CONTROLS

The logic controller is a critical component of the Machine Protection System (MPS). It is essential that the controller is fast, reliable and allows expansion flexibility. There are two main approaches that can be considered in the design of a logic controller: hardware or software. Both options have several positive and negative attributes that relate to this project.

Software Based controller

The software option considered utilises a Programmable Logic Controller (PLC), which is widely known for its versatility and ease of configuration. PLC's offer a wide range of control possibilities ranging from simple logic control to Proportional, Integral, Derivative (PID) and motor speed control. PLC's can be constantly updated to perform a new function if required by the user by simple program modification and subsequent download. Additional input and output modules can be added as the system expands.

There are two main negative characteristics of PLC's are performance (speed) and cost. The performance of a PLC is directly related to the complexity of its program, therefore the more complicated the program the slower the PLC becomes.

Hardware based controller

The use of logic Integrated Circuits (IC's) offers a less expensive alternative to the PLC. Though this must be balanced against development and build costs. The speed performance of logic IC's is a major attribute; a standard TTL gate will have a typical propagation delay of 10 ns. This enables complicated gate arrays to be constructed whilst ensuring that the controller propagation delay is kept to a minimum.

The major negative point in the use of logic IC's is that there is little or no flexibility. Once the circuit is built it can only perform the task for which it was designed. If a change of purpose were required a new circuit would have to be designed and constructed. This would prove costly in the long run for progressive systems.

Controller Design

As the MPS for the ERLP needs to be fast and reliable, and does not require any great flexibility, the decision was made to construct the logic controller using the hardware option with a dedicated hard logic design.

In order to define a controller, the machine itself must be fully understood, including the way in which it will be operated. Once the operational requirements were fully understood; a list of inputs and outputs, that will satisfy these requirements, can be produced. The logic diagram, based upon these inputs and outputs can then be designed.

IMPLEMENTATION OF MPS SYSTEMS

There are 27 BPM stations installed on the machine; their locations were studied to find the optimum arrangement of the CDM channels. The layout of the CDM system can be seen in Figure 4 and the positioning of these channels enhanced the resolution of the overall system.

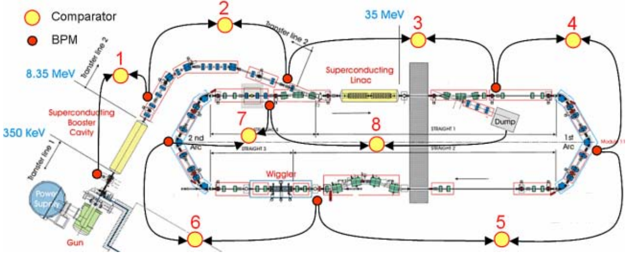

Figure 4: Current Difference Monitor Implementation

The position of the LIC is flexible as the coaxial cable can be cut to length to fit any arrangement. As the positioning is flexible (see Figure 5) the decision was made to terminate the chambers at each of the four beam dumps as high doses of radiation will be emitted during operation due to the extreme deceleration of the electrons. This layout will ensure that the machine will be protected in any of the operating modes.

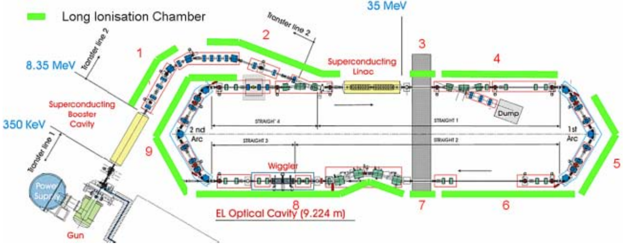

Figure 5: Long Ionisation Chamber Layout

. This radiation must not be detected as it would be interpreted as a collision and prevent the next train of electrons from being produced.

CONCLUSIONS

The proposed implementation of an MPS will ensure that the machine will be protected in any of the four operating modes. The enhanced resolution of the system was achieved by over-lapping the ionisation chambers and the CDM channels. It is clear that each system independently protects the machine; whilst overlapping the systems will allow a more precise analysis of where the collision occurred, and allow effective loss analysis.

REFERENCES

[1] Zerlauth, Goddard, Kain and Schmidt, "Detecting failures in electrical circuits leading to very fast beam losses in the LHC", CERN, Geneva, Switzerland.

[2] Buchner, Voigtlander, Gabriel and Langenhagen, "Machine interlock system improvements by new beam loss monitors", ELBE, Rossendorf, Germany.

[3] Michel, Schurig and Teichert, "Beam loss monitoring with long ionisation chambers at ELBE", ELBE, Rossendorf, Germany.