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Machine protection system for coherent electron cooling experiment

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DISCLAIMER

MACHINE PROTECTION SYSTEM FOR COHERENT ELECTRON COOLING EXPERIMENT*

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Abstract

The coherent electron cooling (CeC) experiment employs a 15 MeV electron beam with up to a few milliamperes current which is capable of destroying the vacuum equipment or intercepting beam diagnostics. The high-current beam can be delivered to two different dumps. RF systems include normal conducting and superconducting cavities which also require protection from abnormal conditions. In this paper, we describe in detail the design and operation of the machine protection system for the CeC accelerator.

ACCELERATOR DESCRIPTION

The layout of the CeC accelerator is shown in Fig. 1 [1]. The electron beam is generated by a 113 MHZ superconducting RF gun with a photocathode. Normal conducting copper cavity provides energy chirp for ballistic compression of the electron beam. 704 MHz SRF linac provides final acceleration and removes residual energy chirp in the central part of the electron bunch. The beam parameters are measured in the diagnostics line placed after the first dipole. The diagnostics line comprises a pulsed deflecting cavity for measurement of the temporal characteristics of the accelerated beam including slice emittance and slice energy spread. The energy spread is measured with a diagnostics line dipole placed after the deflecting cavity.

With an energized first dipole the beam is deflected into the dogleg section serving for the merge of the hadron and electron beams in the common section. At the end of the common section, the exhaust dipole deflects the electron beam toward the high-power dump.

The beam current is monitored with three integrating current transformers (ICT) by Bergoz, model ICT-CF6”-60.4-40-UHV-ARB-H. One of them is placed after the gun and two others are placed in front of the high-power dumps. The signal from ICT is amplified and processed with Zynq FPGA. The current measurement system is self-triggered by a signal from the gun ICT on the slew rate of the rising edge. The charges of the individual pulses are accumulated until the signal from the timing system resets the system. The Zynq FPGA then reports the current in all ICTs and losses. Beam losses are calculated as the difference between gun current and beam current into the dump. The current losses are continuously monitored and once the accumulated losses exceed the safe level fault signal is provided to the MPS. In the Low Power Beam mode, the gun current is also continuously monitored for not exceeding the safe level. FPGA provides logical outputs to describe the status of the system. A low threshold limit of 2.5 microamperes is used to indicate that the accelerator is in safe mode. The high thresholds are used to limit the current extracted from the gun. The allowable loss level is equal to the low threshold.

The beam position is monitored with Libera Brilliance Single Pass E units with preloaded limits on the beam position.

ARCHTECTURE OF THE MPS

The MPS is implemented using a NI Compact RIO which has a real-time processor and an FPGA inside. The real-time processor is mainly responsible for communicating with the rest of our control system infrastructure via an Accelerator Device Object (ADO) manager. The FPGA is programmed to perform the fast computations necessary to control the permit signals and respond quickly when conditions change.

The FPGA uses a 40 MHz system clock from a local oscillator to supply all the necessary clocks to the rest of the logic. The permit signals include permits for the Laser, 113 MHz gun cavity, 500 MHz cavity, and 704 MHz cavity. The laser has a Pockels cell and a shutter which are controlled and monitored by the FPGA. The laser and all cavities have sensors to detect the water flow, cryogenic cooling, airflow, and vacuum status of each system. The 500 MHz and 704 MHz cavities also include an arc detector signal. The fault time of each status input is recorded in microseconds to tell which input caused a particular permit drop.

FPGA allowed flexibility of MPS configuration (easy to add/remove inputs and change the MPS logic) and very fast reaction time of the system.

RF SYSTEMS PROTECTION

The RF systems are protected by individual subsystems that monitor the environmental conditions (vacuum, cooling water, airflow, cryogenic systems status) and the status of the components (RF window temperatures, arc detectors, cavity body temperature).

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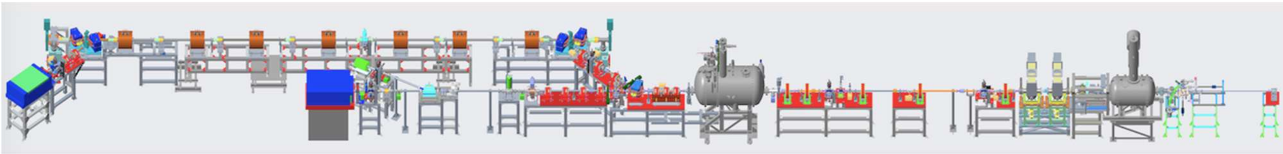

Figure 1: Layout of the coherent electron cooling accelerator.

113 MHz SRF Gun

The CeC superconducting quarter-wave RF gun operates with a photocathode at room temperature. The cathode is placed inside the stalk which serves as field pick-up. The stalk as well as the fundamental power coupler (FPC) are water-cooled.

To prevent freezing of the water and destruction of piping the water flow is constantly monitored. If no water flow is detected during a certain time duration the pipes are blown out with compressed helium to free them from the residual water.

The FPC serves as a fine tuner for the gun cavity and has a bellow around it to allow FPC movement. The bellow is cooled with forced air. The airflow switch inhibits RF power to the gun in abnormal conditions.

The cryogenic system monitors helium temperatures, helium vapor pressure, and insulating vacuum pressure in the critical subcomponents and provides the summary signal to MPS.

500 MHz Buncher Cavity

The 500 MHz copper cavity is protected from overheating body temperature gauge and summary signal from water flaw switches in each of the following water loops: tuner, cavity body, RF window. The temperature of the RF window is monitored with a contactless IR sensor.

The RF power to the cavity is inhibited if vacuum pressure is too high or if an arc is detected in the circulator.

704 MHz SRF Linac

Cryogenic system for 704 MHz cavity monitors cavity temperatures, helium vapor pressure, and insulating vacuum pressure in the critical subcomponents. The beam vacuum interlock is provided by the vacuum system.

The water flow switch monitors water flow in the FPC window.

There are three arc detectors employed in the 70 MHz system: two on the RF window (one on the vacuum side and one on the air side) and the third on the circulator.

Deflecting Cavity

A deflecting cavity was installed recently and its protection is performed by a dedicated PLC which is part of the RF system. The interlocks include a vacuum, two temperature sensors, water flow in the cavity body, a tuner, a circulator, and an amplifier.

The only interface is when the deflecting cavity is inhibited in certain operation modes.

MODES OF OPERATION

There are six modes that the operator can select according to the needs. Each mode facilitates different operational modes either for testing individual systems with others disabled or running with all systems enabled to support the beam during normal operations.

System Off

This mode is used to bring the accelerator to a shutdown state. All RF systems are disabled, and the laser shutter is closed.

Laser Test

Laser test mode is used for aligning the laser beam and laser tuning. The laser shutter is opened, and gun RF is inhibited to suppress the generation of the photoemission current. There are no restrictions on the other RF systems since there is no electron beam.

RF Test

The testing and tuning of all RF systems is the main goal of this mode. The laser shutter is closed to prevent the generation of the photoemission current.

Low Power Beam

Measurement and tuning of the electron beam parameters is the main goal of this mode. All RF systems are enabled, and the laser shutter is opened. If the beam current exceeds 2.5 microamperes the laser shutter is closed.

High Power Beam

The CeC experiment is carried out in this mode. The electron beam should be delivered into the common section and then to the high-power dump, therefore, the current in the first dipole should exceed a certain level. If the orbit is outside the preset boundaries or current losses exceed 2.5 microamperes the laser shutter is closed. Closing the vacuum valves as well as insertion of the intercepting diagnostics will cause the closure of the laser shutter.

High Current from The Gun

Test of the high current from the gun is the main purpose of this mode. The beam is delivered to the second high-power dump in the diagnostics line. In this mode, the linac voltage is limited not to exceed the power rating of the dump. The deflecting cavity is disabled. Current in the first dipole and diagnostics line dipole should be at zero, otherwise the laser shutter will be closed.

PROTECTION FROM DAMAGE BY THE ELECTRON BEAM

High-power beams can easily damage the vacuum chamber, the vacuum valves, and intercepting diagnostics. To prevent the failure the summary signal of the vacuum valves, the profile monitors summary, and pepper-pots are used as inputs to MPS for the High-power Beam and High Current from Gun modes. The following ICT signals are monitored Beam Transmission (losses below safe level) and ICT High Limit (the administrative limit on the maximal current extracted from the gun, the current level is 500 μA).

The beam power is dissipated in the high-power dumps where its water flow and temperature are part of the MPS inputs.

MPS Reaction Time

CeC System can generate a 6 kW electron beam (400 μA, 15 MeV). The electron beam can be focused into the spot size as small as 100 microns and beam energy losses in the stainless steel in the 1-15 MeV electron beam energy range is 15 MeV/cm. Therefore, the volumetric density of the deposited energy is around 9.5×10^3 W/mm^3. With a steel density of 7.8 g/cm^3 and specific heat of 500 J/(kg K) the local temperature increase by 200 K can occur over 82 microseconds.

The electronics (including Zynq FPGA and Libera Brilliance) provide a delay of a few microseconds but the mechanical shutter's closer time is a few milliseconds. Therefore, the mechanical shutter is complemented by a Pockels cell with tens of nanosecond reaction time due to the cable delay with an extinction ratio of 1000:1.

MPS TESTING

Before the start of the operation functionality of the machine-protecting system is tested. Each MPS mode is exercised fully, and each signal assigned to the specific permit is tested individually. MPS testing is performed with the help of subsystem experts (RF, cryogenic, vacuum, instrumentation, etc.).

First, the intercepting diagnostics is actuated, and corresponding inputs and outputs are monitored. Then, the utilities (water, airflow, cryogenics) are tested. Testing of the current levels is performed with a pulse generator, driving ICTs. Vacuum inputs are tested by changing the trip level in the control system.

The final test of the MPS is performed with the electron beam. The current threshold for high-power operation is reduced below the safe level to mimic high-current operation without actual danger of equipment damage. Then, the boundaries for beam position are changed for each BPM, and beam disappearance is observed. Similarly, the threshold for beam loss is reduced and the reaction of MPS is observed.

ASE BOARD

The Accelerator Safety Envelope (ASE) board is not part of the MPS but substantially relies on machine protection system hardware. The goal of the board operation is to prevent unwanted interaction of the electron and hadron beams. There are two working modes of the board: 1) dedicated when the electron beam is allowed to interact with hadrons, and 2) parasitic, when the electron beam can be propagated through a common section inside of the abort gaps of both hadron beams.

In dedicated mode, the hadron bunches are allowed only in the yellow ring. The number of bunches is limited to 12 and the bunch intensity to 10^9 gold ions. In parasitic mode, there are no limits on the number of bunches and their intensity, and the board monitors the location of the abort gaps. If abnormal conditions occur the logical output from the board inhibits laser pulses.

Insertion of the profile monitor in the dogleg prevents the electron beam from entering the common section and disables the ASE board.

Testing and tuning of the ASE board is performed with the de-energized first dipole. In such conditions, the board functionality is preserved while the interaction of the electron beams is impossible. The test is performed with the help of the oscilloscope by observing hadron signals from BPM pick-up in the common section and a fast photodiode for laser (the time offset between two channels is measured with an electron beam when no hadrons are present).

REFERENCES

[1] I. Pinayev *et al.*, "Performance of CeC PoP Accelerator," in *Proc. 10th Int. Particle Accelerator Conf. (IPAC2019)*, Melbourne, Australia, May 2019, pp. 559-561, doi:10.18429/JACoW-IPAC2019-MOPMP05