2.12 Machine Protection

Overview

Both the electron and x-ray beams in the ERL have great power densities. Protection of the electron and x-ray beamline components will require great care. The electron beam transit time through the ERL is about 6.7 μs. The per pass stored energy in the beam is about 3.3 kJ, enough to do significant damage to machine components if deposited therein via accidental beam loss. Such loss can be due to a failure of the control system or to failure of any one of the many beamline components. In addition, there is continuous loss of beam particles due to intra-beam scattering, and this requires that the undulator permanent magnets be protected from the scattered electrons. Thus the machine protection system (MPS) requires both passive and active components. The passive system consists of protective collimators located upstream of each undulator as described in §2.6 and §2.1.17. The active protection system includes interlocks and fast failure detection using several different kinds of devices as well as means for removing the beam in a time comparable to the ERL transit time and depositing the beam energy harmlessly into a beam stop designed for that purpose. Similarly, there must be an x-ray beamline component protection system to avoid overheating and damage by a suitable system of interlocks and monitors.

Other important protection systems, not directly connected with the beams, are not included here. Examples would be internal heating in electronic and magnetic components and power supplies, water pumps, and ventilation equipment.

State of the art

Several electron accelerators with greater stored energy and multi-microsecond beam times have successful machine protection systems, e.g. the B-Factories with ampere level circulating beams and higher beam energies than the ERL, plus the large synchrotron radiation machines, SPring-8, ESRF, APS and PETRA III, and NSLS-II ([1], under construction). Thus we have several examples of machine protection systems in existence to emulate. For some perspective we give here the circulating electron beam power density of several of these machines, normalized to the same value of $\beta_{h/v} \sim 10\,\text{m}$:

ERL (target) : $5.3 \cdot 10^{11}\,\text{W/mm}^2$;

KEK-B: $8.9 \cdot 10^{10}\,\text{W/mm}^2$;

SPring-8 : $1.7 \cdot 10^{11}\,\text{W/mm}^2$;

NSLS-II (target): $7.5 \cdot 10^{11}\,\text{W/mm}^2$.

The ERL target values are comparable to those already achieved in the B-factories and synchrotron radiation storage rings, and almost identical with the NSLS-II target values. What makes ERL different is the rather small horizontal aperture of 5 mm (round) at the IDs. As the brightness of the x-ray beam reflects that of the electron beam, the ERL will require and benefit from systems similar to those designed and developed for SPring-8 and NSLS-II. Triggering times at circular machines tend to be rather long (for example $\sim 22\,\mu$s for PEP-II), partly due to their large circumference, the wait time for an abort gap, and electronics delay times. Once triggered, the abort kickers turn on in less than 1 μs (see [2]).

MPS performance parameters

Relevant performance targets for the electron beam can be found in §2.1. As the electron transit time is about 6.7 μs, it will be important to trigger the beam extraction system in a time shorter than this. The layout of the Cornell ERL electron beamline consists of long, nearly parallel sections that are relatively close together, which should allow triggering of the extraction kickers and laser beam stop quickly if the electronics and logic are properly designed. Extensive simulations will be required to optimize the protection system design for minimum response time.

2.12.1 Equipment to be protected

Vacuum chambers and interconnections

Vacuum chambers have to be protected from overheating by synchrotron radiation and the direct electron beam, as well as from excess HOM deposition caused by hardware failure, e.g. in an expansion joint. Each sliding joint and any irregularities in the vacuum chamber will have an attached thermocouple, with readout connected to the interlock system.

Undulators

Even the best grade NdFeB permanent magnet material has a radiation sensitivity of about 1×10^4 Gy for less than 1% demagnetization as discussed in §2.7. Thus it is necessary to prevent the undulators from exposure to synchrotron radiation and direct electron beam loss. To this end, each undulator is protected by a heavy collimator as described in §2.1.17.

X-ray mirrors and lenses

Potential damage to mirror elements as well as thermal distortion that would affect the x-ray beam coherence is of great concern. Protection will require that coolant flow interlocks and temperature sensors be used extensively.

Accelerating cavities

Very low energy deposition in the SRF cavities is essential to their proper operation. If the beam is aborted by the machine protection system, excessive beam loss in the cavities has to be avoided, and the RF system turned off in a controlled fashion so that the RF field in the cavities does not become too large. Field and phase monitoring and beam loss monitors will trigger the beam extraction and removal of RF power drive as appropriate.

Injector complex

The injector system will utilize a protection system similar to the one already implemented on the Phase 1a injector currently in operation.

Main beam stop

Up to 1.5 MW of electron beam power are expeted to be deposited. It will utilize a protection system similar to the one already implemented on the Phase 1a injector currently in operation. This system also monitors H_2 buildup in the cooling water.

2.12.2 Interlocks

It is important to abort the beam in response to any faulty condition, and to prevent beam turn-on if the system is not ready. The interlocks will also abort the beam if any sub-system fails during operation. At the highest level, a master interlock system will ensure that all of the sub-system chains are ready. Sub-systems consist of sensors attached to equipment, vacuum, pressure, cooling flow and temperature sensors, voltage, current, cavity field level and phase value monitors (one at each cavity) to name a few. All of these and more will have to be included in the overall interlock chain.

2.12.3 Triggering of fast beam extraction

A number and variety of monitors will provide trigger signals for fast beam abort (FBA) to avoid damage to beamline components (both x-ray and electron). In addition to stopping the beam, the laser beam illuminating the photocathode is turned off at the same time.

Interlock unready

If any subsystem interlock fails during beam operation, or for some reason is not in its ready state, the FBA has to be activated. This system will be redundant so that if one of the elements fails, the beam can be aborted safely.

Fast change in cavity field or phase

The LLRF, system will be used to monitor cavity behavior, and check for any failures or quenches.

Electron beam loss

Fast-beam loss monitors positioned along the entire electron beam path will monitor any abnormal losses. Currenlty, 200 monitors are planned, one approximately every 10 meters. The monitors will be located at positions where beam losses are most likely to occur, e.g. at the collimators that protecting the undulators. As the expected losses due to IBS will vary markedly along the ERL, the FBA trigger thresholds will have to be set individually. Further, the thresholds will need to be conditional, and recognize beam ramp-up, initial tuning, and other circumstances. A useful guide to such systems can be found in a thesis that describes the FLASH machine protection system ([3]. Wide dynamic range beam loss monitor detectors have been developed at accelerator laboratories and by industry ([4])

Radiation level

Radiation levels in the user areas must be kept below 'public at large' levels as discussed in §4.6. While the shielding provided by the ratchet wall enclosure is intended to be conservatively designed, it will be necessary to monitor and control the radiation levels in user areas. A level in excess of the allowed maximum value will result in a FBA with a location indication of the recorded excess.

Orbit deviation

A significant deviation from the saved orbit can be used to trigger the FBA using the BPM system.

Gun spark

If there is a high voltage discharge at the gun, the beam will necessarily be interrupted at the injector, and result in unsatisfactory acceleration and beam energy recovery conditions. Thus a gun spark will be detected and used to trigger the FBA.

Laser Failure

Similarly, a failure involving laser timing or light intensity or of the beam current regulating feedback that controls laser intensity will result in unsatisfactory acceleration and energy recovery conditions and will trigger the FBA.

Other trigger signals

Additional channels will be provided as experience dictates and operating conditions encountered in practice will occur.

2.12.4 Fast beam extraction system

As mentioned above, the challenge of stopping a high energy, high power density beam has been dealt with at other laboratories, and gives confidence that this can be done reliably. Many details have to be worked out prior to a preliminary engineering design. Nevertheless one can form a general idea of what the system will look like for planning and costing purposes. In what follows, we present such a concept, based on a specially designed 'collimator' that functions as beam stop and fast kicker to drive the beam into the "collimator". To be conservative at this stage of planning, we foresee up to four in-line beam absorbing collimators as indicated in Fig. 2.12.1. Details can be found in [5]

Collimator

Schematically, a beam stop-collimator is shown in Fig. 2.12.2. In this case, D is taken as 7 cm, and the separation of kicker and stop, L is adjusted by matching to the optics. . A conservative choice of 10 mrad is used for the kicker estimate. In Fig. 2.12.3 a conceptual sketch of an actual collimator-stop is shown.

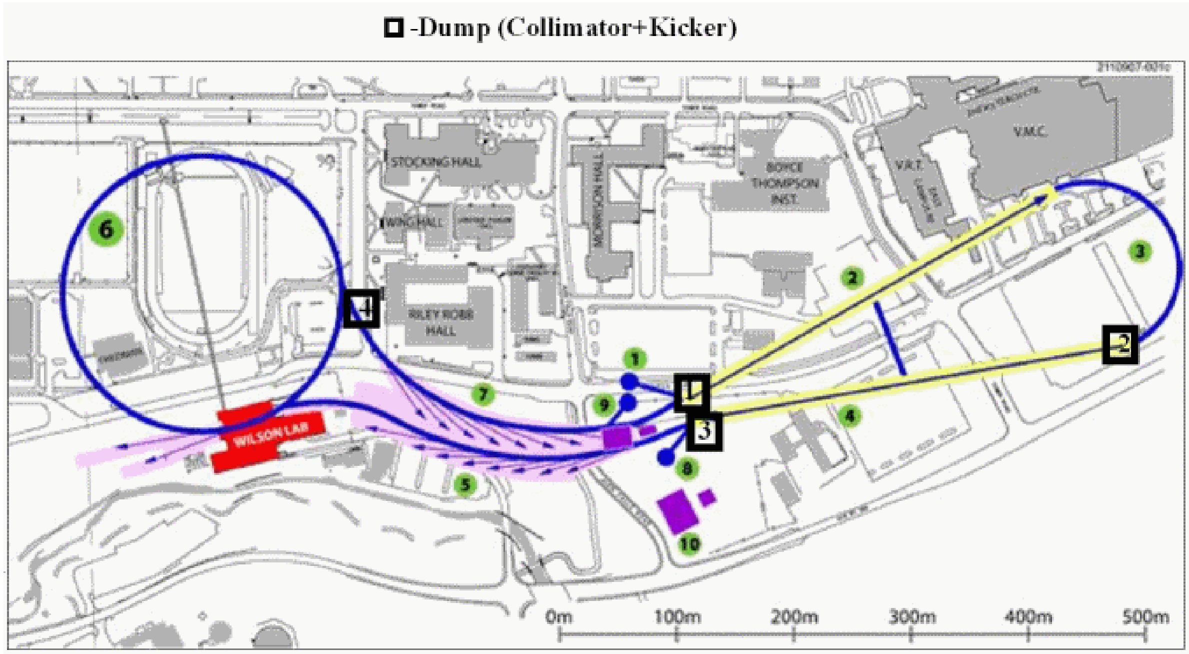

Figure 2.12.1: Schematic layout with potential locations for the beam absorbing collimator and kicker combinations

Various schemes for fast-kicker magnets have been successfully produced in the past. One scheme, based on a high-resistivity, metalized, ceramic tube vacuum chamber is shown in Fig. 2.12.4. Using available materials, it seems practical to make a system with a 10 ns risetime and a pulse length approaching 8 μs using six, 10 cm long kicker units each pulsed at 30 kV, 2.5 kA [6]. The driving pulse can be provided by a standard pulse-forming network discharged by a thyratron. Figure 2.12.5 shows an arrangement of four of the six kicker magnets arranged in series. The assembly could be less than 1 m long.

2.12.5 Next design steps

To understand the full consequences of the various component and sub-system failures, and how to detect them, a simulation model will be used. Adding IBS physics to the simulation will permit an evaluation of the dynamic range and variety of threshold settings that will be needed for the beam loss monitors and readout electronics. Adding detector properties and discriminator electronics with logic and signal paths will permit a design that minimizes the time from trigger event detection to FBA [7].

Before the design is finished, it will be important to integrate the equipment protection system and personnel protection system designs, particularly in the injector region, due to its critical nature, and in the user areas to assure that maximum protection is afforded to the users and general public at the laboratory.

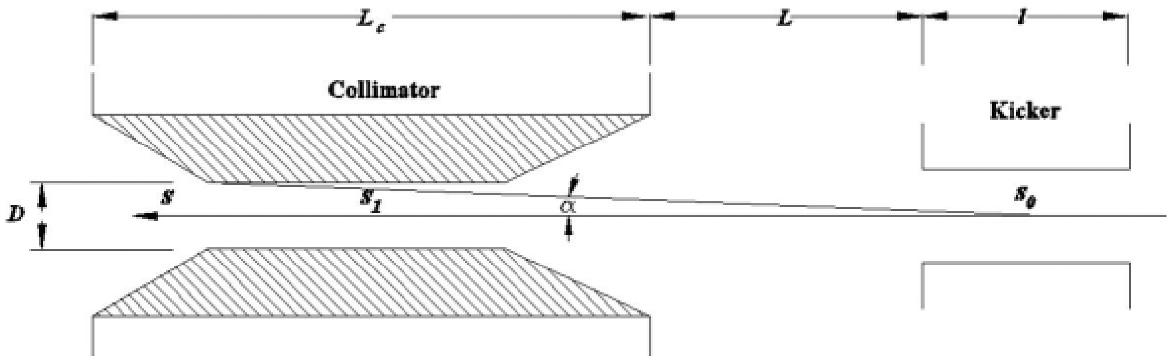

Figure 2.12.2: Principle of a beam absorber based on a fast kicker followed by a specially designed collimator.

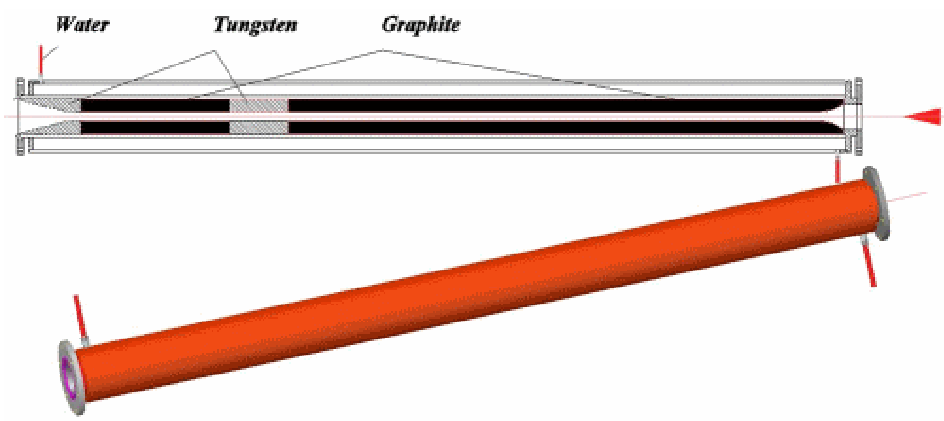

Figure 2.12.3: Beam collimator-stop based on pyrolitic graphite with additional collimation for safety and a water chamber to remove the absorbed hea.t

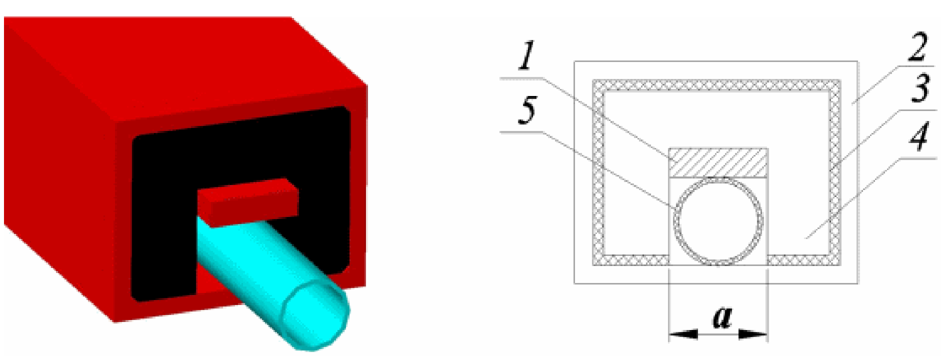

Figure 2.12.4: Crosssection of a kicker magnet: 1) central electrode; 2) enclosure; 3) insulation; 4) laminated iron or ferrite; 5) ceramic chamber.

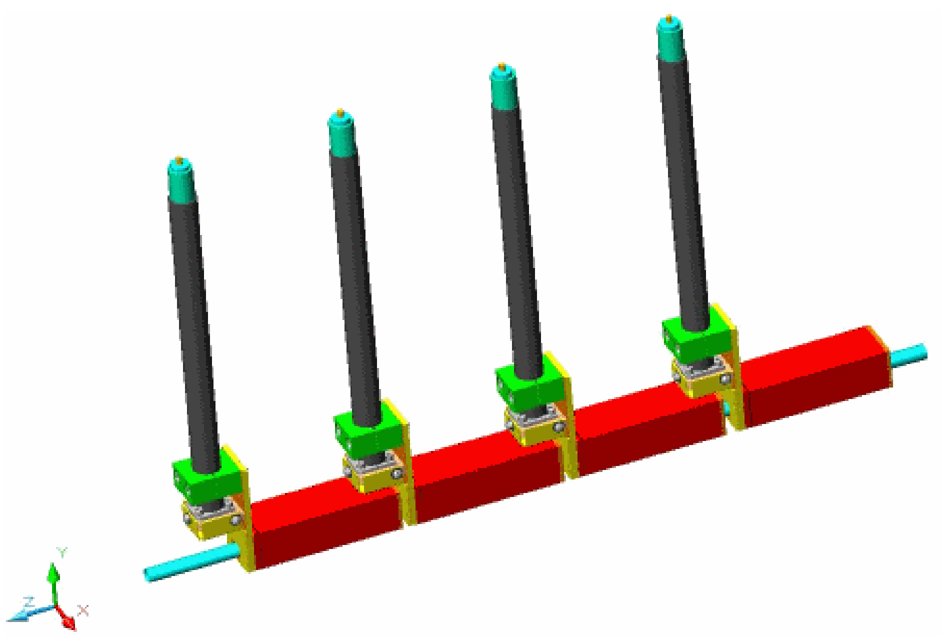

Figure 2.12.5: A series of kickers (each about 10 cm in length) with a common ceramic vacuum tube passing through. Four of six are shown.

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