10.5 BCD Proposal: Machine Protection System

1. Overview

The ILC Machine Protection System (MPS) is that collection of devices intended to keep the beam from damaging machine components. With nominal average beam power of 20 MW, consisting of 14000 bunches of 2e10 ppb each per second, and typical beam sizes near 10 x 1 micron, both the damage caused by a single bunch and the residual radiation or heating caused by small (fractional) losses of a many bunches are important for MPS. The MPS consists of 1) a single bunch damage mitigation system, 2) an average beam loss limiting system, 3) a series of abort kickers and dumps, 4) a restart ramp sequence, 5) a beam permit system, 6) a fault analysis recorder system, 7) a strategy for limiting the rate with which magnetic fields (and insertable device positions) can change, 8) a sequencing system that provides for the appropriate level of protection depending on machine mode or state, and 9) a protection collimator system. The systems listed must be tightly integrated in order to minimize time lost to aberrant beams and associated faults.

Several of the systems listed below provide redundant protection mechanisms. The BCD recommendation is to adopt them all as listed. Alternate designs with less redundancy are proposed as 'ACD'.

2. Baseline Configuration

a. Single Pulse Damage

Single bunch damage will be mitigated by systems that check the preparedness of the machine before the high power beam passes by. Single bunch damage control is only necessary in the 'damped-beam' section of the ILC, where the beam area is less than 50 micron^2 (2e10). Single bunch damage mitigation will be done using two basic subsystems: 1) a leading benign pilot bunch and 2) a beam permit system that surveys all appropriate devices before damping ring beam extraction begins and provides a permit if each device is in the proper state. In addition, some exceptional devices (damping ring RF and extraction kickers for example) will need fast monitoring systems and redundancy.

The pilot bunch is one percent of nominal current and is spaced 10 usec ahead of the start of the nominal train. The pilot bunch must traverse the machine properly before the rest of the train is allowed to pass. Indeed, each bunch must traverse properly or the abort system will be triggered. Proper passage is sensed using the beam position monitors and beam intensity monitors as these are the only beam diagnostics with true single bunch response time. It is important to note the resolution requirements: BPM's must have resolution and systematic offsets not more than 10 times worse at the low end of the intensity range 2e9 ppb to 2e10 ppb. (Availability and failed reading rates must also be very good). The actual required pilot beam BPM resolution may depend on the performance of the RTML/BDS collimation. If an errant trajectory is sensed, the nearest upstream abort system is triggered. Assuming the latency for detecting the fault is 500 ns, the upstream signal effective propagation speed is 0.7 c, and the abort kicker latency time is 1 us, the maximum kicker spacing should be 1000m. This ensures that the kicker can be turned on quickly enough to dump or spoil the high intensity bunches that follow the pilot bunch. Only those bunches extracted from the damping ring before the abort signal is sensed and received at the ring need to be dumped and the damping ring extraction sequence will be terminated, leaving what is left of the partially

extracted beam train stored. Given that the time needed for the beam to go from the damping ring to the main beam dump is 67 us, in the worst case, (when the downstream most sensor detects a fault condition from the pilot), and the signal return time to the damping ring is another 100 us, roughly 450 bunches need to be dumped. The detailed timing will depend on the ring / linac transfer line geometry. Since there is more than one dump line, not all of these need to be dumped in one place.
The injector complex must include systems that reliably generate the pilot bunch. Extraction from the ring should not begin unless the pilot is within allowed limits; its intensity should be high enough for the trajectory sensors to read and respond reliably yet below the single damage threshold, expected to be around 1% for bunches which are intended for the whole machine. There may also be a need for a benign pilot bunch of nominal intensity but much larger emittance.

b. Average beam loss limiting system

Average beam loss will be limited, throughout ILC, using a combination of radiation, thermal, beam intensity and other special sensors. This system will function in a manner similar to other machines, such as SLC, LHC, SNS and Tevatron. If exposure limits are exceeded at some point during the passage of the train, damping ring extraction or source production (e+/e-) will be stopped. For stability, it is important to keep as much of the machine operating at a nominal power level. This is best done by segmenting it into operational MPS regions. For the BCD, there will be 11 of these regions, as noted in table 1. Since the fault response can (and will) occur during the train, and since there will be 9 full power shut-off points, each with an extraction system and a full capacity dump, and we can expect to have trains of different lengths in the machine on any given pulse. The average beam loss MPS will be applied throughout the complex, including the source, damping ring injector and the damping ring itself.

	Region name	Begin	End
1	e- injector	Source (gun)	e- Damping ring injection (before)
2	e- damping ring	Ring injection	e- Ring extraction (after)
3	e- RTML	Ring extraction	e- Linac injection (before)
4	e- linac	Linac injection	Undulator (before)
5	Undulator	Undulator	BD; e+ target
6	e- BDS	BD start	e- Main dump
7	e+ target	e+ target	e+ damping ring injection
8	e+ damping ring	Ring injection	e+ ring extraction
9	e+ RTML	ring extraction	e+ linac injection
10	e+ linac	linac injection	e+ BDS
11	e+ BDS	e+ BDS	e+ main dump

Table 1: beam shut off points. Each of these segmentation points is capable of handling the full beam power, i.e. both a kicker and dump are required. These systems also serve as fast abort locations for single bunch damage mitigation.

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c. Abort kickers and dumps

Abort systems are needed to protect machine components, especially the superconducting cavities, from single bunch damage. It is expected that a single bunch impact on a niobium iris will leave a small hole, roughly the diameter of the beam, through which the helium will flow. The minimal abort system consists of a spoiler / collimator / absorber block (copper) and a kicker. The kicker rise time should be fast enough to produce a guaranteed displacement of more than the pipe radius in an inter-bunch interval. In any given fault, at most 450 bunches would then strike the copper block. It is expected that the upstream block surface would be marred with a sequence of small impact holes, but that the block would not fracture and would not require cooling. If the block is thick enough to absorb the full shower, the energy associated with 450 bunches should be less than 400kJ (250 GeV) and the block temperature will rise about 4 degrees. Since each abort precedes a cool down interval, a post-mortem evaluation of the fault, response to the fault and the restart sequence, (total time to recover may be close to a minute) the average power on the block should be very low. Even if the abort recovery sequence is made fast, care must be taken to avoid a rapid sequence of identical fault events. If this occurs, the block thermal interlock may trip. The block volume should be more than one cubic foot. RD is needed to validate this general concept. The beam aperture should be less than 20mm as defined by nearby protection collimators.

In the baseline configuration five abort systems are needed on the electron side (four on the e+ side): 2 upstream of the linac, one upstream of the undulator and 2 in the beam delivery. An alternative is an additional abort per kilometer of linac. ACD RD will be required to determine if additional abort systems are required. This may depend on the linac straightness. The required kicker deflection is 10 mm, for the radius, and a relatively small additional amount for margin. With a kicker volume of 20 * 20 mm, about 25 MW of peak power would be required for a 50 m long kicker system [1]. RD is needed to reduce this requirement and to make a system with an appropriate safety factor.

The total length associated with abort systems is 200 m per side (BCD), an additional 400 m / side for ACD. In the beam delivery and the RTML, 2 of the abort system can be integrated with the tune up dumps. The abort system can also be triggered during the train, if a serious trajectory distortion is detected. The kickers must be triggered as close as possible to the preceding bunch so that no bunch is kicked incompletely.

d. Restart Ramp sequence

Depending on the beam dynamics of the long trains, it may be advisable to program short trains into a restart sequence. There may also be single bunch, intensity dependent effects that require an intensity ramp. In order to avoid relaxation oscillator performance of the average beam loss MPS, the system will be able to determine in advance if the beam loss expected at the next stage in the ramp sequence is acceptable. Given the number of stages and regions, the sequence controller must distribute its intentions so that all subsidiary controls can respond appropriately and data acquisition systems are properly aligned.

The sequence may need to generate a ‘benign’ bunch sequence with the nominal intensity but large emittance. The initial stages of the sequence will be used to produce ‘diagnostic’ pulses to be used during commissioning, setup and testing.

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e. Beam Permit System

For all of the ILC, there will be a controls-based survey of critical subsystems, about 1 ms before the pulse begins, in order to determine readiness. All magnet systems, key RF and controls systems and collimators will be included in the survey. For the damped beam part of the system, this is redundant with the pilot bunch.

f. Fault analysis recorder system

A post mortem analysis capability is required that will capture the state of the system at each trip. This should have enough information to allow the circumstances that led to the fault to be uncovered. Data to be recorded on each fault should include: bunch by bunch trajectories, loss monitor data, machine component states (magnets, temperature, RF, insertable device states), control system states (timing system, network status, diagnostic) and global system status (sequencer states, PPS, electrical, water and related sensors). The fault analysis system should automatically sort this information to find what is relevant.

g. Rapidly changing fields

In addition to the above, there are critical devices whose fields (or positions) can change quickly, perhaps during the pulse, or (more likely) between pulses. These devices need 1) special controls protocols, 2) redundancy or 3) external stabilization and verification systems.

1) Depending on the state of the machine, there should be programmed (perhaps at a very low level) ramp rate limits that keep critical components from changing too quickly. For example, a dipole magnet should not be allowed to change its kick by more than a small fraction of the aperture (few percent) between beam pulses during full power operation. This may have an impact on the speed of beam based feedback. Some devices, such as collimators should be effectively frozen in position at the highest beam power level. There may be several different modes, basically defined by beam power, that indicate different ramp rate limits.

2) There are a few critical, high power, high speed devices (damping ring kicker, RF, linac front end RF, bunch compressor RF and dump magnets) which will need some level of redundancy in order to reduce the consequence of failure. In the case of the extraction kicker, this will be done by having a sequence of independent power supplies and stripline magnets that have minimal common mode failure mechanisms. In the case of the front end and bunch compressor RF, there will be more than one klystron / modulator system powering a given cavity through a tee. The LLRF feedback will be used to stabilize the RF in the event that one of sources fails 'mid-pulse'. There are alternate methods of doing this, for example using a sequence of modestly powered devices controlled completely in parallel, as in the case of the critical damping ring extraction system.

3) There are several serious common mode failures in the timing and phase distribution system that need specially engineered controls. This is necessary so that, for example, the bunch compressor or linac common phase cannot change drastically compared to some previously defined reference, even if commanded to do so by the controls, unless the system is in the benign – beam tune up mode.

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h. Sequencing system depending on machine state

The ILC will be divided into segments delineated by beam stoppers and dump lines. There may be several of these in the injector system, two beam dumps in each RTML, and 2 (or 3) in the beam delivery and undulator system. In addition, the ring extraction system effectively operates as a beam stopper assuming the beam can remain stored in the ring for an indefinite period. This part of the MPS assumes that the beam power in each of these segments can be different and reconfigures the protection systems noted above accordingly.

i. Protection collimators

The entire ILC will require protection collimators that effectively shadow critical components. In the main linac, for example, there should be a few collimators per betatron wavelength, with an aperture of about ½ of the nominal aperture. These devices must be engineered to withstand innumerable single pulse impacts. There is a collimation system that defines the launch into the main linac.

j. Supporting Documentation

[1] Mattison, T. NanoBeam 2005 presentation. http://atfweb.kek.jp/nanobeam/files/presen//presen-WG2a-12.pdf

[2] Ross, M., http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-8605.pdf.

[3] http://www-project.slac.stanford.edu/ilc/MPS_design_rules.htm

[4]http://alcpg2005.colorado.edu/alcpg2005/program/accelerator/GG3/peter_tenenbaum20050812215847.ppt

[5] http://lhc-mp-review.web.cern.ch/lhc-mp-review/Review-Programme.html

k. Required Research and Development

RD is needed to:

1) determine the abort kicker and spoiler system. Tests indicating the single pulse damage threshold were done in 2000 and need to be extended to study effects of single pulse impacts in niobium, related ILC vacuum chamber construction materials (titanium, stainless steel and aluminum) and on thicker samples (such as the proposed absorber block. RD is also needed to determine how to resurface the material 'in-situ' so that an accumulation of many small impact holes does not reduce its integrity. Systems of the highest value (cryo-cavities, collimators and instrumentation) need specific testing in order to determine the threat posed by single bunch impact. Components such as vacuum chambers and associated hardware may be protected by much simpler means and tests are needed for these also.

2) to develop the kicker system. The system is fairly high power (25MW) and must have some degree of redundancy and fail-safe performance. It should be designed to reduce the possibility of partial-kicks. RD is also needed to determine the effect of small holes in the niobium cavities. It may be possible to protect the most vulnerable section of the cavity (iris) with some backing material.

3) An evaluation of possible failure modes must be made in order to determine the risk associated with the lack of abort systems in the linac.

4) Controls RD is needed to determine the integration strategies for the ramp rate limit and mode distribution system.

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3. Alternative lower cost Configuration

a. Description

Alternate MPS designs, with lower initial investment cost, involve the removal of one or more of the above systems. For example, the pilot bunch may not be needed if the possibility of strong transverse kicks in the linac is shown to be acceptably small, and the BDS / BC systems are shown to be robust enough. Since the pilot bunch is primarily an operational choice, its direct cost impact is small, so this alternate is not very compelling. Other systems, such as redundant upstream RF and abort kicker/ dump systems may also be eliminated as part of an ACD evaluation. These have substantial costs and will need careful evaluation.