First Thoughts on Fast MPS

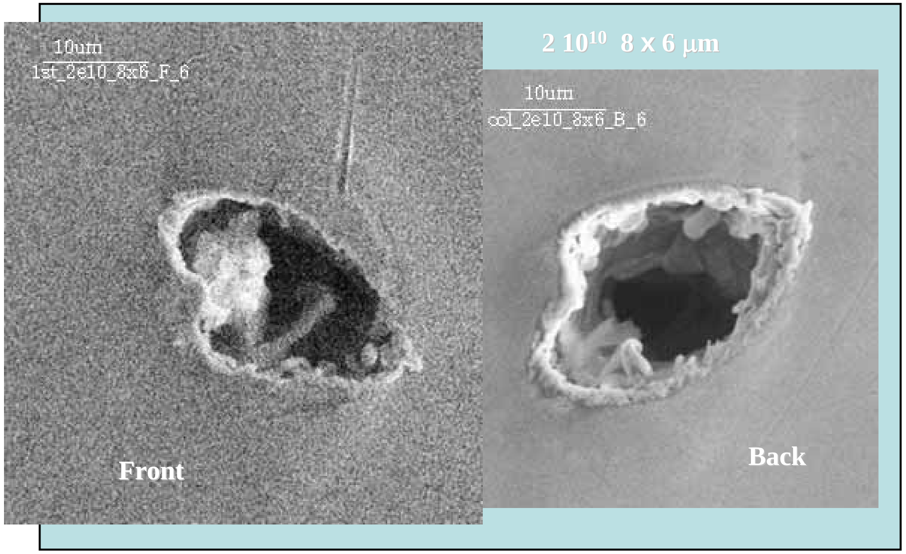
Snowmass Global Group 3

Introduction

- Like most (all?) other accelerators, ILC has "conventional" (average power) MPS requirements
  - Limit radiation damage to components and detector
  - Prevent overheating of electromagnet windings
  - etc etc etc
- ILC also has MPS requirements related to peak or instantaneous power
  - Beam power is ~10 MW
  - Transverse bunch sizes ~a few μm^2
  - Potential for damage from a single bunch or a single train
- Nomenclature:
  - Average power MPS = "conventional MPS"
  - Instantaneous power MPS = "Hazard Avoidance Logic" (HAL)

Setting the Scale

- Damage from beam impact at normal incidence
  - Niobium: threshold is around 5×10^{14} e^-/cm^2
  - Copper is about the same (collimators)
  - Titanium can take ~15x higher density
- At glancing incidence
  - High-z materials: about the same as normal incidence
  - Low-z: factor of a few higher density can be tolerated
- For β ~ 100 m, 2e10 e-/bunch, single bunch density:
  - $\sim8\times10^{13}$ @ 5 GeV
  - $\sim4\times10^{15}$ @ 250 GeV



Electron micrograph of single electron bunch "silhouette of passage" through 0.25 RL Cu target; courtesy of Doug McCormick, SLAC

Takeaway message: Even at DR extraction energy of 5 GeV, cavities can potentially be damaged by 6 bunches hitting at a given point!

ILC Problem is Hard to Solve!

- Other facilities have high instantaneous power
  - B-factories, light sources
- Circular accelerators can continually monitor status via beam signals
  - ILC LET duty cycle 0.5%
  - “A lot can happen in 200 msec”
- Circular accelerators typically have small bunch spacings
  - ILC LET spacing ~300 nsec
  - More can happen in 300 nsec than in 2 nsec
- Circular accelerators are smaller than ILC
  - Path length to abort kicker typically a couple of microseconds
  - ILC: 50 usec or more
  - LHC: 90 usec (1 round trip)

Two Parts to the Problem

- Detecting a developing fault
  - Want to minimize the number of inputs to maximize robustness
    - Hardware monitoring
    - Monitoring with beam
      - preferred – single monitoring point can detect large number of failures
- Responding to a developing fault
  - Want to simplify the number of response points for robustness and cost
    - Abort dumps
    - Inhibit beam extraction from damping ring
- For both parts, time is key issue
  - How fast can a fault develop?
    - Defines frequency + timing of monitoring strategy
  - How fast can HAL respond?
    - Defines how many bunches will get through between failure and halting of beam, thus how many out-of-control bunches LET has to tolerate

Response: Inhibiting DR Extraction

- DR bunches extracted one at a time
- In principle, can decide to stop extracting with a few nsec warning
  - In practice, probably should plan on ~100 nsec
- Most effective for responding to problems which occur in DR extraction itself
  - LET length ~27 km @ 1 TeV CM (180 usec round trip time)
    - For faults which manifest themselves in BDS or at the end of the linac, 20% of the train is already "in the pipeline" before extraction switched off

Response: Beam Abort Dumps

- Anticipate abort dumps at end of BC, end of linac
  - Dumps can probably operate within 1 bunch spacing
    - Which presents certain hazards, as we will see!
- What are the abort dumps good for?
  - BC length ~2 km (13 usec round trip time)
  - BDS length ~1.5 km (10 usec round trip time)
  - Linac length ~23 km (150 usec round trip time)
  - Conclusion:
    - BC and BDS can be dump-protected from faults which take 15 usec or more to develop
    - Linac can only be dump-protected from faults which take 150 usec or more to develop
      - Do we need more abort dumps in the linac? They don't need to take a very high average power

Detection: Hardware Monitoring

- ILC will contain a lot of hardware channels
  - magnet power supplies, cavity tuners, cryo controls, and don’t get me started about the number of control points for the RF!
  - Letting any of them inhibit the beam probably not practical
    - Huge number of channels need to approve beam in a couple of msec before extraction
    - We’ll always be down from channels giving false inhibits for various reasons or not getting their approval to the control system in time
    - Can’t detect “cockpit errors”
      - “Whoops, I just steered the beam into the wall!”
      - Can’t distinguish a deliberate (but bad) change from a deliberate (but safe) change
  - Might be useful for a small number of key devices
    - Example: final doublet current can be a HAL input

Detection: Beam Monitoring

- Can use a limited number of channels to detect a wide variety of hardware errors
  - A few BPMs can monitor orbit, energy
  - A couple of phase monitors can detect errors in the bunch compressor
  - Radiation monitors around collimators
- Probably can't use one train to generate permission to extract next train
  - Trains are 200 msec apart
    - a lot can happen in that time
    - Probably can't slow hardware down enough to make 200 msec a safe interval
    - Provides no protection against pulsed device failures
- Current train can't generate early warning
  - ie, can't verify that BC is safe for beam before beam arrival if beam arrival is the signal that it's safe!

Detection:
Pilot Bunches

- Consider the following scenario:
  - In addition to the luminosity bunches, every train has 1 pilot bunch
    - low charge density
    - completely benign – can hit anywhere without damaging it
  - Pilot bunch is launched from DR a short time before luminosity bunches
    - Monitor pilot bunch energy, orbit, etc to ensure that the system is safe for high-density bunches
  - Pilot bunch doesn’t need to be massively degraded from luminosity bunches
    - Lumi bunches ~10x “safe” density
    - Use 1×10^9 charge, nominal emittances
    - Use larger charge and degraded emittances
      - Reduce store time of pilot bunch by injecting into DR late

Pilot Bunch (2) – Pilot Interval

- How early should pilot bunch be launched relative to luminosity bunches?
  - Want pilot bunch to verify safety of BDS so that detector is well protected
    - BDS abort signal has ~ 10 usec response time
    - If pilot interval < 10 usec then pilot can’t do this
  - Increasing pilot interval has 2 negative consequences
    - Loss of efficiency
      - Linac needs to reach full voltage for pilot, then stay there during pilot interval
    - Loss of effectiveness
      - Errors which can happen in time short compared to pilot interval are no longer trapped by pilot bunch

Errors and their Characteristic Times

- Made a list of failures that can result in unacceptable beam conditions
  - Excel spreadsheet format
- Looked at the minimum possible interval between status==OK and status==bad
  - A few percent voltage droop in RF systems with ~1 usec fill time: ~0.01 usec
    - typically normal-conducting dipole mode structures at S-band
  - Systems that operate bunch-by-bunch: ~150 nsec
    - including emergency aborts and DR extraction
  - A few percent voltage droop in RF systems with 500 usec fill time: ~10 usec
  - Significant change in “train straightener” system: ~50 usec
  - HOM buildup time: ~100 usec
  - DR synchrotron period: ~200 usec
  - Decay time for dipole correctors: ~500 usec
  - Decay time of large electromagnets: ~1000 – 3000 usec
  - Mechanical system response time: ~5000 usec
  - DR store time: 200,000 usec

The big list (subsection)

ordinal	Region	System	Failure	Bad sigz	Bad sigE	Bad sig x	Bad Energy	Bad Orbit @ eta==0	safe → unsafe [usec]	Failures / year
1	BC	LLRF	hardware/software/crate failure	1	1	3	1	4	10	20
2	BC	LLRF	wrong bunch pattern	3	3	3	1	4	10	1
3	BC	LLRF	Master phase/timing/oscillator fault	1	1	3	1	4	10	5
4	BC	LLRF	Phase/Ampl/Timing cockpit error	1	1	3	1	4	10	50
5	BC	Injection	Beam from MDR inadequately damped	3	3	1	4	3	0	1
6	BC	Injection	Extraction prior to cavity fill completed	1	1	3	1	4	10	1
7	BC	Injection	Bad phase/freq from MDR	1	1	3	1	4	0	5
8	BC	Injection	MDR FeedForward broken or wrong	3	3	3	1	4	10	5
9	BC	Injection	MDR bad orbit at extract time	5	5	3	5	1	0	100
10	BC	Injection	MDR extraction kicker strength/timing error	5	5	3	5	1	0	10

Or just look at the whole thing at:

http://www-project.slac.stanford.edu/ilc/acceldev/ops/MPS/talks/Copy2%20of%20mps_hal_faults2.xls

How HAL Might Work

- DR extraction can go wrong within 1 bunch time
  - must be continually monitored by BPMs
    - also need safe channel defined by collimators?
  - bad pulse → extraction inhibit
- Abort kickers can go wrong within 1 bunch time
  - Definitely need collimators defining safe channels
  - Continual monitoring during train required
- NC dipole cavities can go wrong within 1 bunch time
  - Can we make them so weak that it doesn’t matter?
  - Or convert them all to SC cavities?

How HAL Might Work (2)

- RF systems can fail within a train, and possibly during the pilot interval
  - Need to continually monitor the energy at a couple of points
    - Maybe 2 points in BC and at end of linac
  - Put monitoring points close to abort points
    - minimize response time
    - Monitor beam phase as well?
  - Energy collimators near monitoring points
    - Need to be able to be hit by a few bunches at full intensity
  - Linac and BC need to be able to function while voltage is drooping
    - ie, last transmitted off-energy bunch is much more off energy than the one which triggers the abort
    - Probably not an issue for BC (short)
    - Do we need an additional abort in the center of the 1 TeV CM main linac?
- Individual HOM failures probably don’t make enough kick to be dangerous
  - Not an MPS issue at all?

How HAL Might Work (3)

- Train straightener and dipole correctors can go unsafe during 1 train
  - Dipoles are slow compared to linac travel time
    - Can handle cumulative effects of all dipoles at the end of the linac
  - Train straightener is comparable to linac travel time
    - Put system at end of linac near abort dump
  - Monitor orbit at a point near abort dump
- All other magnets are slow compared to train length
  - Safe passage of pilot implies rest of train is safe from these sources
    - Particularly important in BDS

How HAL Might Work (4) -- Summary

- Pilot bunch on every train
  - Verifies that lumi bunches will reach end of linac safely
  - Verifies that any bunch that gets thru BDS collimators will reach main dump safely
- Some additional intra-train monitoring and response necessary
  - Energy at end of linac, maybe middle/end BC
  - Orbit at end of linac
  - Orbit at DR extraction
- Intra-train abort kickers present special hazards
  - Probably need sacrificial collimators downstream of each one
  - What happens if a kicker fails to come on when HAL tells it to?
    - How often do abort kickers at storage rings fail?

Additional Layers of Protection (Optional)

- Continually monitor current through final doublet magnets
- Mode-sensitive control system
  - "Luminosity mode" – excursions of component parameters highly constrained
  - "Setup mode" – component excursions unconstrained, beam parameters limited
    - Only pilot bunches produced
    - only a few bunches per train

Additional Work

- Need to check characteristic times of all catalogued failures
  - Esp. SC magnets – author doesn’t know much about their failure modes
- Study each failure mode much more carefully
  - ie, can linac really tolerate 10’s of usec of beam with voltage continually drooping?
- Study production of pilot bunches
  - Source / DR implications?
- verify that detection-to-kicker distances are acceptable
- Can we really abort in 1 bunch time?
- Can we really protect against a failure in the abort system?
  - What’s the real-world history of these systems?