Availability – Tom Himel
MPS – Marc Ross
Safety – Vic Kuchler

Availability

- Availability is a concern because ILC will be the largest most complex accelerator ever built.
- If we don’t do better on typical components than present HEP accelerators, it will be down all the time.
- Have done extensive studies with a simulation to determine required MTBFs and effects of various layouts
- Have started developing high availability components

Are 2 tunnels needed?

Run Number	LC description	Simulated % time down incl forced MD	Simulated % time fully up integrating lum or sched MD	Simulated % time integrating lum	Simulated % time scheduled MD	Simulated % time actual opportunistic MD	Simulated % time useless down	Simulated number of accesses per month
ILC8	everything in 1 tunnel; no robots ; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	30.5	69.5	64.2	5.3	2.2	28.3	18.1
ILC9	1 tunnel w/ mods in support buildings; no robots; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	26.5	73.5	68.1	5.5	2.0	24.4	11.1
ILC10	everything in 1 tunnel; with robotic repair ; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	22.0	78.0	73.0	5.1	2.4	19.5	5.9
ILC11	2 tunnels w/ min in accel tunnel; support tunnel only accessible with RF off; undulator e+ w/ keep alive 2	22.9	77.1	72.3	4.8	2.7	20.2	3.7
ILC12	2 tunnels with min in accel tunnel; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	17.0	83.0	78.3	4.8	2.8	14.2	3.4
ILC13	2 tunnels w/ some stuff in accel tunnel; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	21.3	78.7	73.8	4.8	2.7	18.7	9.7
ILC14	2 tunnels w/ some stuff in accel tunnel w/ robotic repair; undulator e+ w/ keep alive 2; Tuned MTBFs in table A	17.0	83.0	78.2	4.8	2.8	14.3	3.5
ILC15	ILC9 but table B MTBFs and 6% linac energy overhead	14.7	85.3	79.4	6.0	1.5	13.1	5.6
ILC16	ILC15 but table C MTBFs and 3% linac energy overhead	15.2	84.8	79.2	5.6	1.9	13.3	6.5

The need for a Keep-Alive e+ source

- The fact that high energy e- are needed to make e+ hurts the availability of the undulator e+ source for 4 reasons
  - Can’t do MD simultaneously in e.g. e+ and e- DR
  - Can’t do opportunistic MD in e.g. e+ linac when the e- linac is broken
  - Can’t keep e+ system “hot” when e- are down, so extra tuning time is needed.
  - e- linac must have correct energy at both undulator and at the end.
- A keep-alive e+ source can ameliorate 3 of these problems.
- Increases time integrating luminosity from 68% to 78%
- Any e+ keep-alive source with bunch intensity high enough for diagnostics to work **well** is OK

Should e+ and e- DR be in one tunnel?

- Pros
  - Less tunneling cost
  - Rings would probably be near IPs and central site, so transport time would be less when repairs are needed
- Cons
  - When access needed to one ring, no beam can be in other. Availsim says Int Lum decreases 0.7%
  - 2 or 3 rings in 1 tunnel could make maintenance difficult if not very carefully engineered.
- Prefer 2 separate tunnels, but both in 1 not a killer.

Needed MTBF Improvements: Requirements for Tech Systems

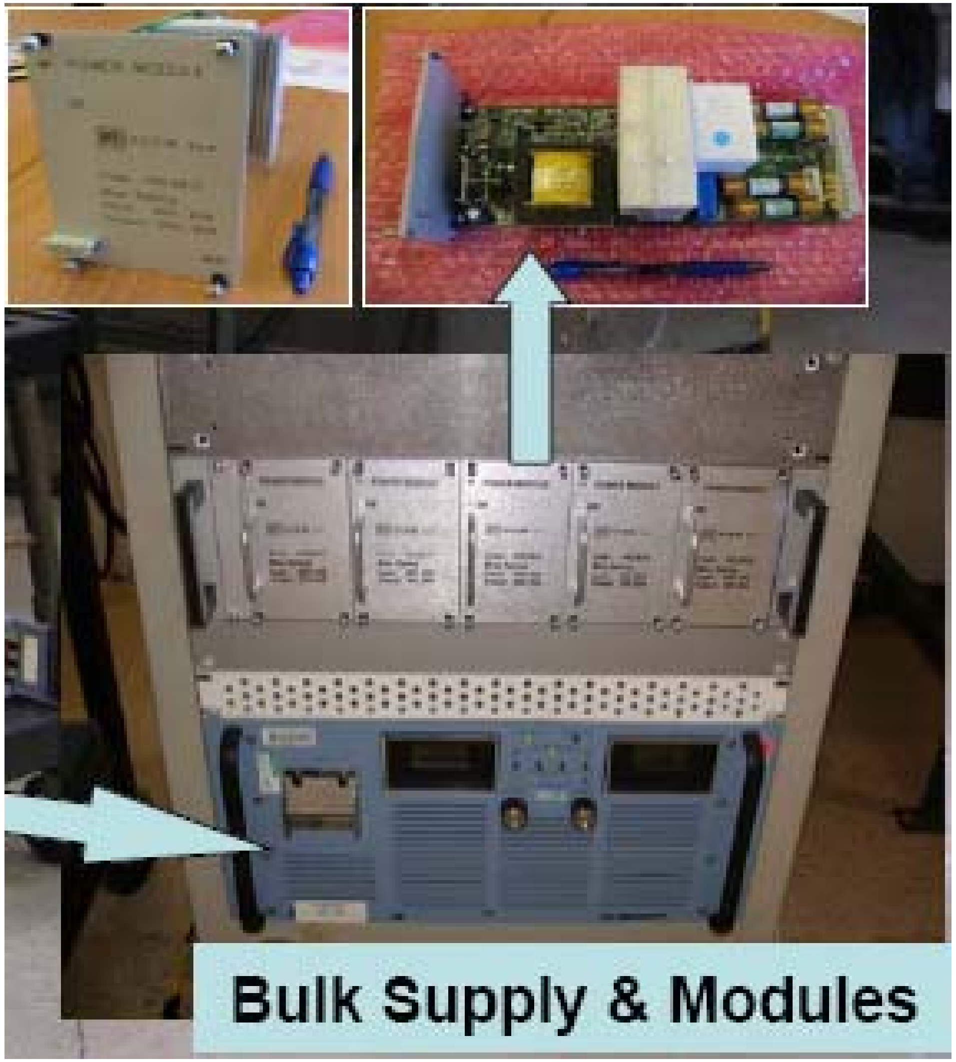
Device	Improvement factor **A** for 2 tunnel conventional e+ source	Improvement factor **B** for 1 tunnel undulator e+ source, 6% energy overhead	Improvement factor **C** for 1 tunnel undulator e+ source, 3% energy overhead	Nominal MTBF (hours)
magnets - water cooled	**20**	20	20	1,000,000
power supply controllers	**10**	**50**	50	100,000
flow switches	**10**	10	10	250,000
water instrumention near pump	**10**	10	**30**	30,000
power supplies	**5**	5	5	200,000
kicker pulser	**5**	5	5	100,000
coupler interlock sensors	**5**	5	5	1,000,000
collimators and beam stoppers	**5**	5	5	100,000
all electronics modules	**3**	**10**	10	100,000
AC breakers < 500 kW		**10**	10	360,000
vacuum valve controllers		**5**	5	190,000
regional MPS system		**5**	5	5,000
power supply - corrector		**3**	3	400,000
vacuum valves		**3**	3	1,000,000
water pumps		**3**	3	120,000
modulator			**3**	50,000
klystron - linac			**5**	40,000
coupler interlock electronics			**5**	1,000,000
linac energy overhead		**3%**		3%

Magnets MTBF not as bad as it appears

- Factor of 20 above our average MTBF of 1,000,000 hours seems formidable.
- However, a few magnet systems have been built with >10 million hour MTBFs. (Fermilab main ring, HERA e- ring)
- Labs' magnet engineers are working together to develop a set of HA design rules
  - No braze joints in the conductor
  - Pot the coils…
- Four HA prototypes (FMEA design method) have been built at SLAC and are running in the linac.

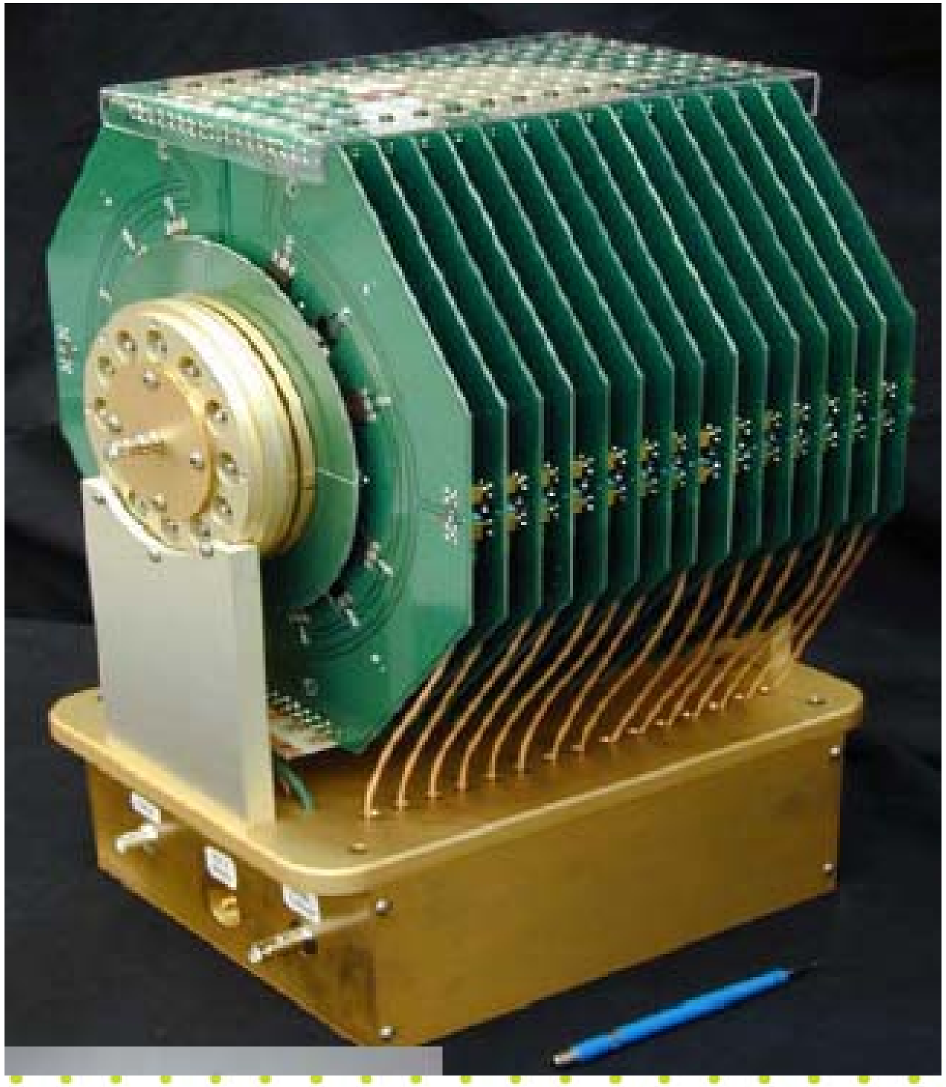
Power Supply work

- Building 40 HA PS for ATF2.
- Based on commercial design of n+1 regulators with current summing
- Prototyping small diagnostic boards that can be used in many places (incl PS) to remotely diagnose impending problems.



Kicker pulser

- Have prototyped and tested a DR kicker pulser that is modular. A card can die and it keeps running.

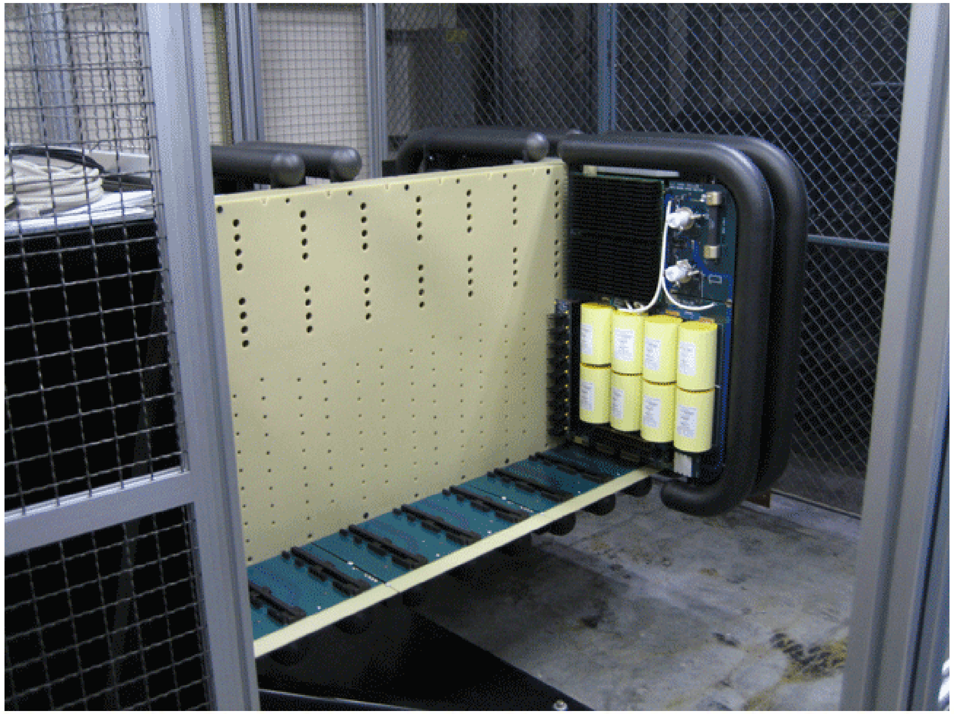


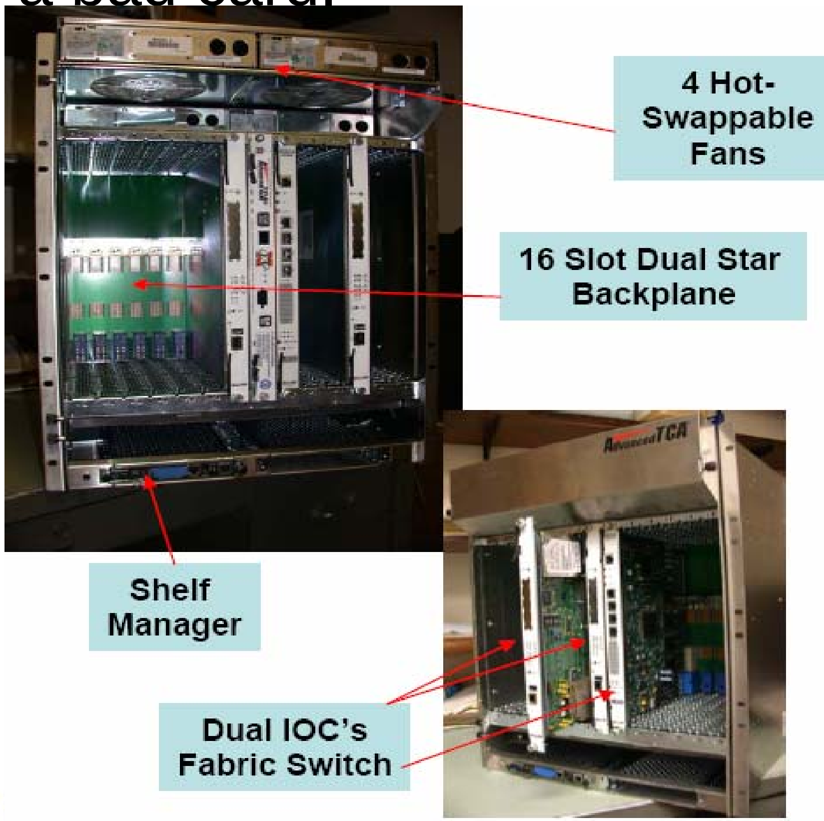
Electronics Modules – ATCA

- Have adopted the Advanced TeleCommunications Architecture for the electronics
- This is a commercial HA standard for the telecom industry.
- Has redundant PS, redundant fans, redundant network links, redundant CPUs along with software to manage it all.
- Has true hot-swappable modules.
- We have bought a few shelves and are talking to companies to learn how to use ATCA.

Marx Modulator

- The Marx modulator is expected to be both cheaper and more reliable than the bouncer modulator.
- Each card is made so it can keep running with a few IGBTs or capacitors blown.
- Full voltage can be maintained with a bad card.





Summary

- + Have early, reasonably good grasp of what is needed to get high availability
- - required MTBF/MTTR improvements are significant
- + Have gotten started on some of the more important improvements
- - Others are not started yet
- - It is difficult to test enough items for long enough to be sure we have achieved necessary MTBFs.
- Need to take advantage of accelerators built for other reasons to aid this testing.
- Need to continue HA effort, but expect will still have some problems which need to be remedied after ILC is built.

Machine Protection (MPS)

Marc Ross

GDE

Machine Protection: LHC / ILC

- LHC:
  - 3000 bunches each with 1e11 protons
  - Damage at 3e-5 of nominal I
  - Loss of a small fraction of each bunch is a concern
- ILC
  - 3000 bunches each with 2e10 e+/e-
  - Damage at 3e-6 of nominal I
  - Loss of a single bunch (with I > 1% of nominal) is a concern
    - e.g. first bunch…
- Difference is emittance, stored energy vs single pass

What are the most fearsome failure scenarios?

- LHC
  - Full train with COD = aperture
  - Single turn widespread damage (90us)
  - Only one abort kicker
- ILC
  - Full train with oscillation amplitude=linac aperture
  - BUT: full train is 300 km long (30 times linac length)
  - No abort within linac (2 up / 1 down stream/ undulator)
- ILC linac indicated component / system failure:
  - Multiple (~10) quad failures
  - Common mode phase error > 50 degrees
  - Typical failure causes beam ‘blowup’
- In both ILC / LHC fast transients must be prevented

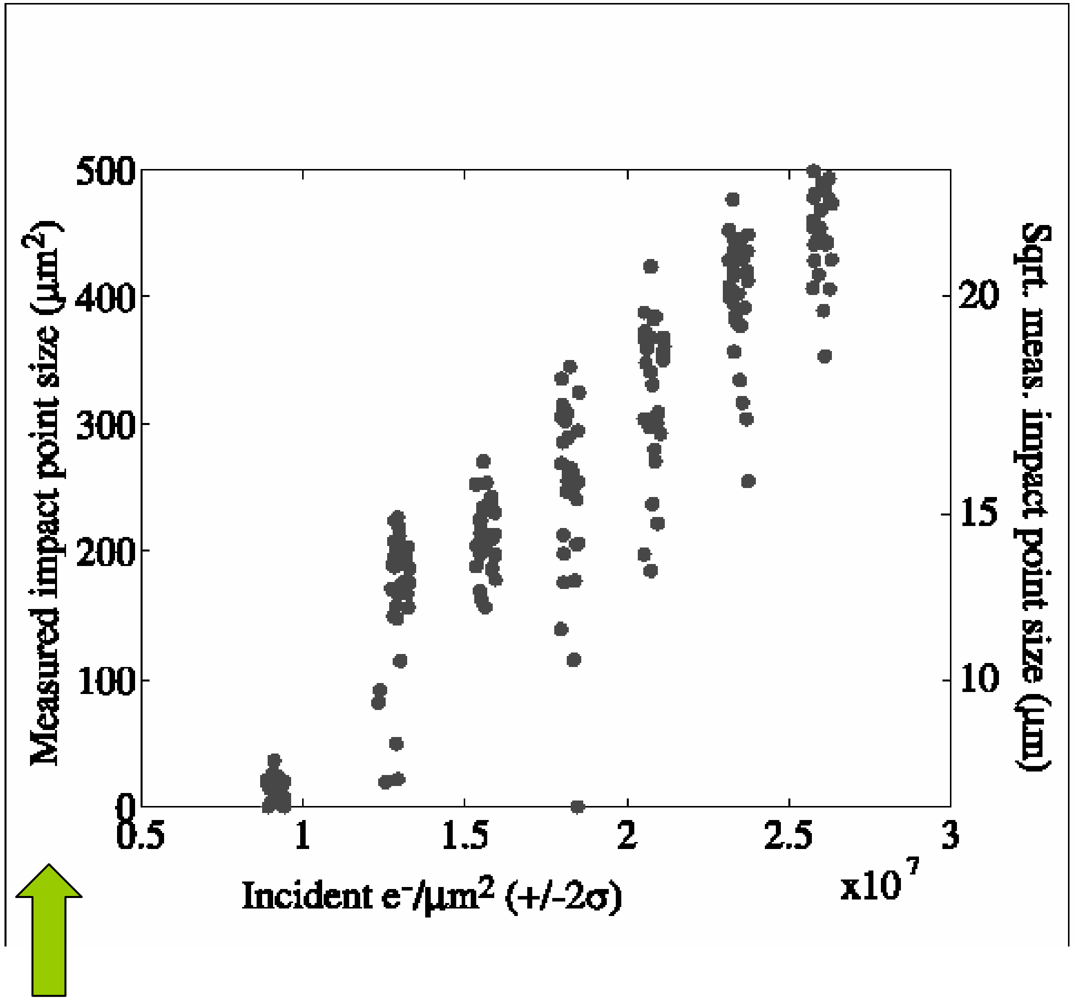
MPS has:

1) *<u>single bunch damage mitigation system: (pilot bunch)</u>*
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,
9) a protection collimator system

<u>Italics → not in traditional MPS</u>

Results from the FFTB single bunch damage test

- Observed 'puncture threshold' vs particle density
- Cu tests Cu / Nb similar
    - Nb tests not done
- ILC linac density tests not done
- energy independent



1% pilot bunch at linac end (0.13 e7)

Pilot bunch

- Each startup sequence begins with an analysis of hardware / set point / controls software readiness
  - This is the 'summary interlock check' (-100 us)
  - beam checks in DR
- then benign 'pilot bunch' traverses the system and is used to validate subsystem performance
  - incapable of causing 'single pulse' damage
  - 1% of the charge
  - or 100 x the cross section
- the time elapsed since the last successful pulse is important
  - many systems remain static during 200ms interpulse period
- pilot bunch 'leader' for each machine pulse is possible

Machine Protection at LHC

- MPS is complex and detailed, and lessons learned are expensive in time and money.
  - ILC can learn from LHC
- The LHC will have more stored beam energy than any previous machine – 350 MJ
  - total energy is similar to a 747 at 1/3 of takeoff speed
  - the beam is so energetic, it is hard to deflect its trajectory quickly
  - the MPS is based on beam loss sensors
- There are several (relatively simple) failure modes that result in the destruction of the ~ machine (one of the rings) in one turn
  - the beam 'cuts' the vacuum chamber open along the mid-plane symmetry surface
- LHC MPS makes extensive use of redundancy and machine 'mode' controls
  - allowing flexibility only when the power is low
  - Locks components (software mostly) at high energy
  - Collimator control and tune-up is a major challenge

Collimation

- ‘Closest hardware’
- BDS Sacrificial spoiler / absorber design
  - optics and simulation studies mature
- R and D US / UK equal partners
  - damage and associated monitoring
  - beam tests within ~ 2 years
- design goal: aperture defining collimation upstream of linac

MPS within GDE:

- RDR 'Operations' Global System Leaders:
  - Himel, Elsen, Terunuma
- RDR Abort Technical System Lead (within Magnets):
  - Mattison
- Components: RDR Area System Leaders

- Basic concept in baseline
- Recent (EuroTeV) report on linac failure modes
- Costing complete 2006

- MPS → system integration challenge
  - ranked single highest risk subsystem in 2003 US Tech. Option
    - difficult to test

Startup process

- We must protect beamline components from simple beam-induced failure:
  - puncture – this effect is new with ILC; older machines have lower charge density
  - heating
  - radiation
- A single nominal (2e10, ~few micron bunch) is capable of causing vacuum chamber puncture
- The full single beam 11 MW power has much more destructive capability
  - 1e14 W/cm^2 at the end of the linac
  - (2e23 W/cm^2 at the IP)
  - But there is time to detect and prevent this extreme power from damaging expensive hardware -→ 1 ms train length
  - BDS entrance fast abort system

Transition from a single pilot pulse to full power operation (1)

- Neglect injector / source details
  - (actually very important with the undulator – driven source)
- Require system checks before each pulse
  - depending on effects of various failure modes; may have a pilot every machine pulse
  - to be effective the pilot should be early enough to allow controlled beam shutoff in case a problem is discovered
  - during the pulse, 50 us or 1/20 of the beam has been extracted and not yet dumped…
    - the ILC BC, linac and BDS are long enough to hold 1/20 of the bunches
- If a problem occurs:
  - ring extraction must be stopped
  - the beam upstream of the problem location must be deflected to a protection dump
- fast, large amplitude deflecting kicks are not expected to occur in the linac itself.

Transition from a single pilot pulse to full power operation (2)

- once we know the path is clear,
  - 1) produce the nominal single bunch
  - 2) start to increase the number of bunches over a sequence of machine pulses (30 x 1/5 second…)
- As soon as the power becomes ~ kilowatts, average heating from (fractionally) small beam losses will be observed
  - Stop the sequence,
  - identify the mechanism
  - fix it
  - check it
  - Restart
  - (this could take time, and could result in a relaxation oscillator)

Injector startup

- parallel startup sequence using ‘e+ keep-alive’ backup source
  – e+ / e- to DR and BDS dump independently
- series startup using undulator source
  – e- to linac dump before e+ are made
- injector beam power ~ 0.25 MW
  – undamped beam tails are less well controlled
  – e+ normalized emittance 1e-2

MPS transient 'history'

- MPS can cause large changes in beam intensity
  - TTF experience
- Key components change depending on average beam power:
  - positron capture section RF
    - heated by target radiation
  - damping ring alignment
    - heated by synchrotron radiation
    - many SR sources and B-factories use 'trickle charge' to maintain stability
  - collimator position
    - beam heating will move the edges of the collimator jaws
  - Others? – see homework question
- Performance will depend on thermal history
  - what happens on pulse *n* depends on *n-1*…

Machine Protection

- Machine Protection system manages the above functions
- Consists of
  - device monitors (e.g. magnet system monitors; ground fault, thermal sensors)
  - beam loss and beam heating sensors
  - interlock network with latching status
- Also
  - keeps track of T_{MPS}
  - tests and calibrates itself
  - is integrated into the control system

- Most vulnerable subsystems:
  - Damping ring, ring extraction to linac, beam delivery, undulator
- Most expensive (but not so vulnerable because of large cavity iris diameter):
  - linac

Failure modes

- Subsystem failures can direct the beam outside its nominal path
  - failed dipoles - deflected trajectory
  - ‘run away’ movers
  - loss of accelerator RF – incorrect energy
  - Also: damping ring coherent beam instabilities or
  - increased generation of beam halo
- Usually the control system will be aware of these conditions, but not always

Extreme beam deflections in the linac

- Failed dipoles
  - Dipole strength limited to correct ~3 mm offsets of quadrupole misalignment at 500 GeV (Bdip/(∂B/∂x))
  - this is ~10 σalignment
  - same dipole at low energies could correct for >30 times (500/15) that displacement
  - ⇒ beam outside of aperture
  - current limitation Imax(L) has to be built into hardware (firmware)
- Mis-steering / mis-adjusted dipole correctors
- Failed quadrupoles
  - need ~30 to fail before the aperture is hit, and beam becomes large before hitting the cavity surfaces

Average power losses

- Limiting average power loss is set by personnel radiation exposure concerns
  - typical limit for normal materials (Copper, Steel) ~ 100 W/m
  - (100 x the limit for protons)
  - 100 w is 1e-5 of the nominal power
  - this is extremely low compared to existing electron machines
  - beam dynamics can contribute to this loss, in addition to small mis-alignments etc.
  - 5 sigma (probably beyond present – day simulation code performance)
- component heating from beam loss is also a concern, also at 100 W level
- beam loss monitors with this degree of sensitivity are available.

Regional Overview

- Each Region (Asian, European and Americas) has Varying Requirements that Determine Criteria for Life Safety and Egress
- These Differences have been Reviewed by the CFS Group and Used to Develop the Current Strategy for Life Safety and Egress for the ILC Project
- While Differences do Exist, Progress has been Made in Reaching International Consensus on Requirements for this Aspect of Conventional Construction
- All of the Requirements have the Same Intent, Safe Evacuation of all Occupants During Normal Operations or Emergency Conditions

Overview of Existing Guidance

- *Current Codes and Standards do not Directly Apply to Underground Installations like the ILC, but Progress Has Been Made in Code Development*
  - ***NFPA 101-2003, Life Safety Code***
  - ***International Building Code 2003***
  - ***NFPA 130-2003, Transit Systems***
  - ***NFPA 520-1999, Subterranean Spaces***
- *The Current ILC Design is Based on a Reasonable Interpretation on the Available Guidance with Input From Consulting Safety Engineers*
- *Cited Codes are Recognized in all Regions However the Authority Having Jurisdiction in Each Region will have the Final Authority for Approval*

Life Safety & Egress

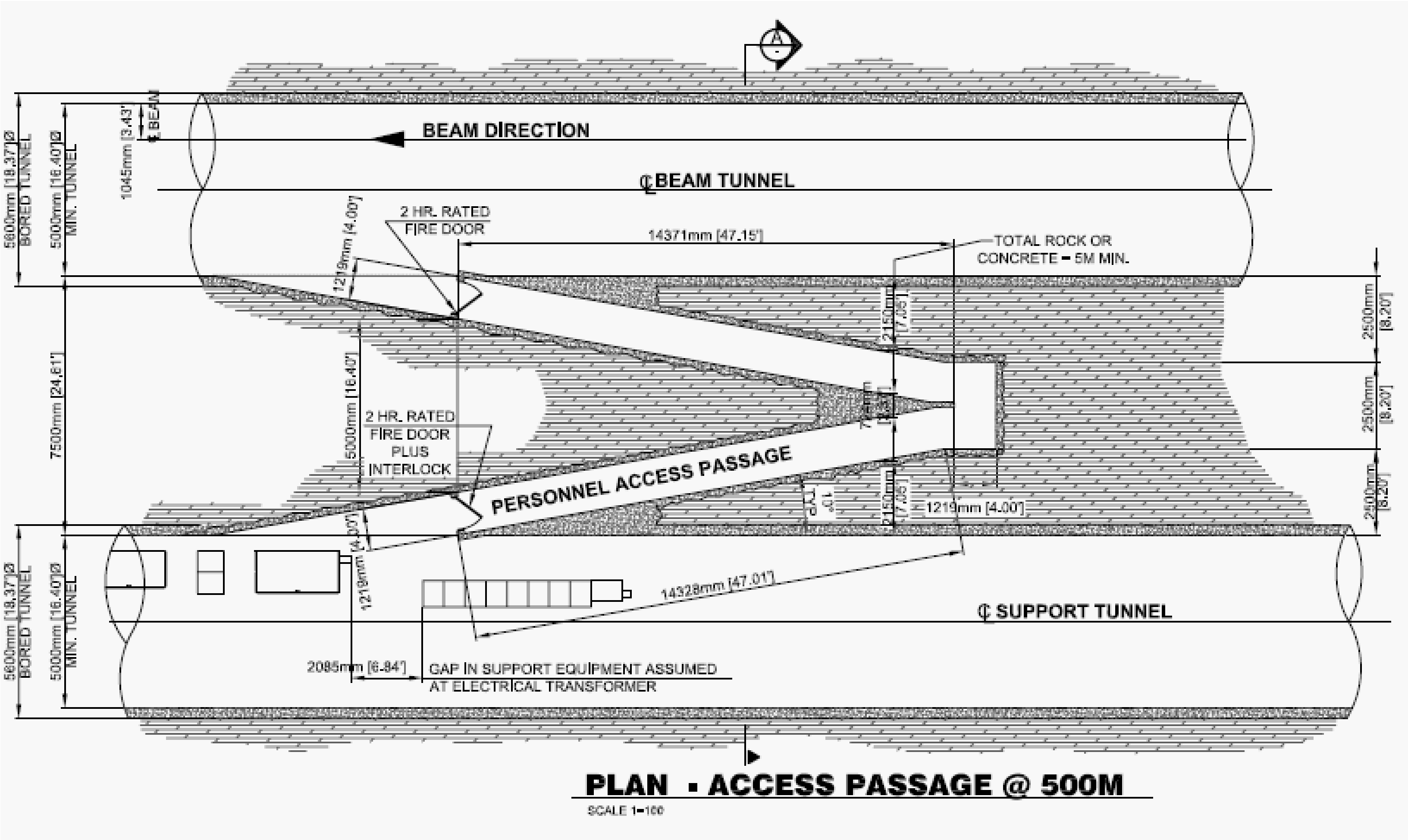
EXIT DISTANCE OF VARIOUS EXISTING ACCELERATORS (FOR INFO ONLY)

Regions	Laboratory	Name of Enclsoure / Tunnel	Year Designed	Maximum Distance between exits	*Exit to Discharge* (see Note A)	Remarks
Americas	FNAL	TEV	1968	243.84 m (800 Ft)	30.48 m (100 Ft)	Fire alarm and smoke detection at service buildings
		Main Injector	1992	182.88 m (600 Ft)	21.336 m (70 Ft)	Fire alarm and smoke detection throughout enclosure; sprinkler protection at Alcoves and Service Buildings.
		NuMI - MINOS	1999	0.91 Km (3000 Ft)	182.88 m (600 Ft)	Exit is to Passageway and exludes elevator travel distance. Passageway has automatic sprinkler protection
	SLAC	SLAC Linac	1962	200 m (330 ft)	~9 m (~30ft)	Opening to shaft ladder - 30ft up to Klystron Gallery- excludes travel distance up ladder.
		PEP tunnel	1975	360 m (1,180 ft)	~6 m (~20ft)	PEP Tunnel diam. ~700 m (2,300 ft). Exits at 5 interaction regions (IR-12, -2, -4, -6, and -8).
Europe	CERN	LHC	1996	3 Km (1.86 mi)	100 m average	Use of oxygen masks is compulsary
		SPS	1971	1.1 Km (3608 Ft.)	0 m (direct, no sas)	Use of oxygen masks is compulsary
	DESY	HERA	1984	1.5 Km		
Asian	KEK	KEKB	1985	~200m	~15m	Circumferernce: 3 km, 20 exits total. Thermo-detection at tunnel, smoke-detection at service buildings. Oxigen alarm at SCRF sector. Full ventilation of experiment halls at fire detection.

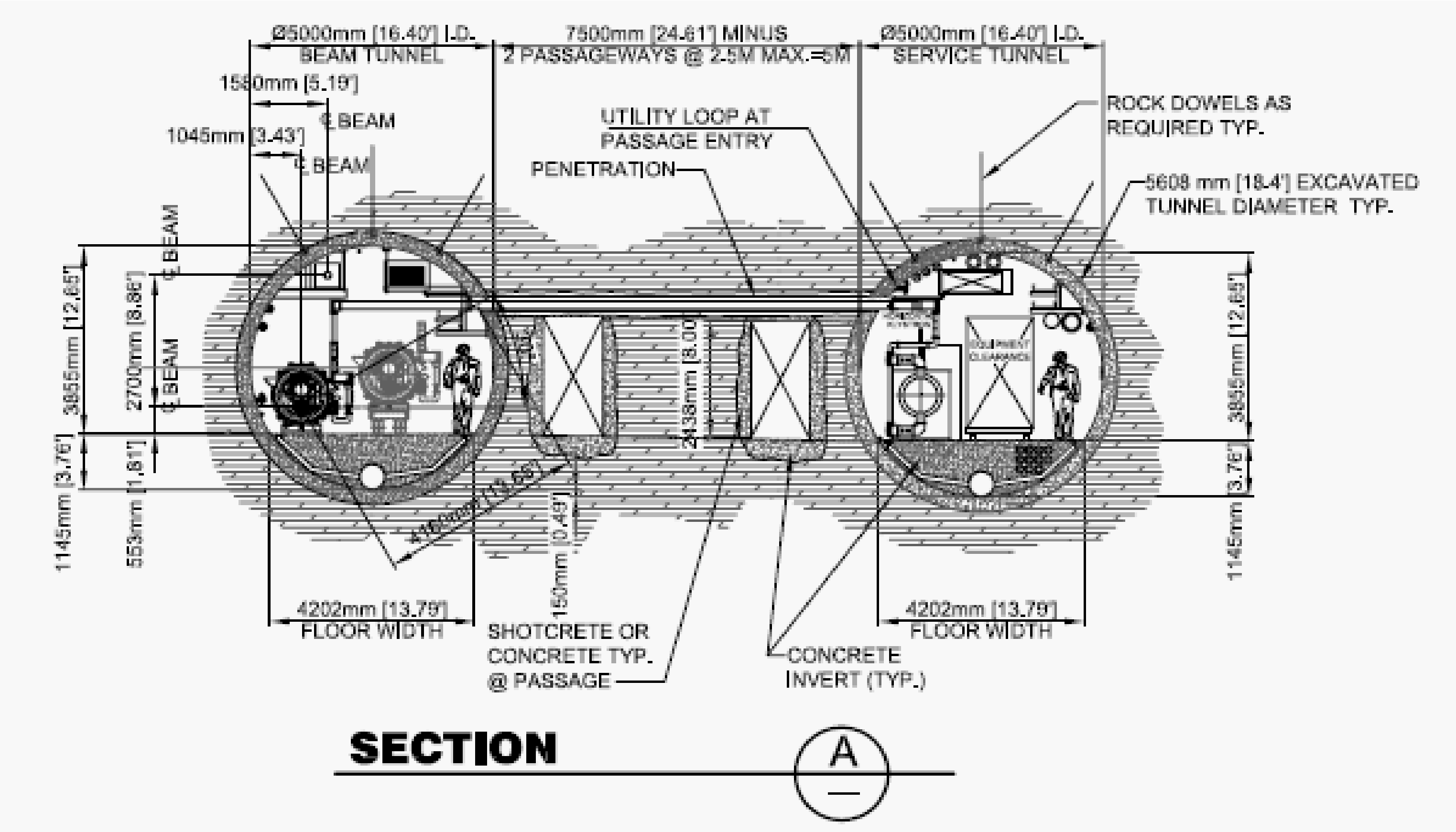
Salient Features of Existing Design

- *Twin Tunnel Configuration Provides a Reasonable Basis for an Appropriate Exiting Strategy*
- *Electrical Distribution Cables and Power Supply Equipment Comprise the Largest Hazard to the Underground Enclosures*
- *Crossover Passageways are Provided Between the Service Tunnel and Main Linac Accelerator Tunnel at Intervals of Approximately 500 m*
- *Shafts to Grade Levels (Vertical or Horizontal) are Spaced at 5 km Intervals Primarily to Accommodate Cryogenic Requirements*

Life Safety and Egress



Life Safety and Egress



Salient Features of Existing Design cont

- Fire Detection and Alarm System
  - Smoke Detectors for Each 150 m^2 Floor Area
  - Manual Pull Alarms at 100 m Intervals
- Fire Suppression Equipment
  - Portable Fire Extinguishers at 25 m Intervals
- Evacuation Support
  - Connecting Passageways Between Twin Tunnel Layout
  - Smoke Control/Exhaust System Using Differential Pressure and Fresh Air Input to Provide Safe Means of Egress to Surface Areas
  - All Shafts to Surface Areas are Pressurized with Fresh Air to Maintain Air Quality in Exit Elevators and Stairways
  - Emergency Lighting at 10 m Intervals
  - Exit and Directional Signage in Accordance with Code Requirements

Salient Features of Existing Design cont

- Communication Equipment
  - Public Address Systems
  - Phone System
  - Closed Circuit Monitoring and Security Camera System
- Emergency Power Equipment
  - Emergency Power System (Transition Time < 10 sec)
  - Standby Power System (Transition Time < 60 sec)
- He and N_2 Considerations
  - Differential Pressure with Ambient Pressure in Accelerator Tunnel Lower than in Service Tunnel
  - Oxygen Monitoring System with Auto Shut-off Capability
  - Self Contained Breathing Apparatus Equipment
- Fire Command Center
  - Dedicated and Protected Area with Status Condition Displays and Manual System Control

Summary

- The Current Design Solution Provides a Defendable Configuration and Addresses the Fundamental Intent of the Existing Code Guidance
- The Current Design Solution has Input from Consultant Fire Protection and Safety Engineers
- Most Code Guidance Allows "Equivalency" to Stated Requirements
- The Current Design Solution Affords Enough Detail to Provide a Credible Cost Estimate at This Time
- Further Refinement of Specific Aspects of the Design are Still Needed
- Interaction with Regional JHA's will be Required for Final Approval of Fire Protection and Life Safety Egress Designs