ILC - Operations

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Credits

- I “stole” material from many people and places.
- A lot came from Marc Ross who has given this lecture in the previous 2 LC schools.
- He in turn, “stole” much of it from other people, including me!

What is Operations?

- Things that turn peak luminosity into integrated luminosity
  - **Reliability/Availability, redundancy**
  - **PPS**
  - **MPS**
  - **Stability, Tuning algorithms, diagnostics, Feedbacks**
  - **Maintenance**
  - **Control System**
  - **Operating expenses**
- Much of this should be designed in.

Integrated luminosity

- Time accounting
  - **Impact of lost time can be substantial**
    - How long is a year?
      - Operating fraction typically 5000/8760 – 57%
      - The difference sometimes includes ‘ scheduled maintenance’
    - How much maintenance is required?
    - (many don’t consider this as ‘lost’ time)

Simple budget:

$$T_L = T_y - T_D - T_S - T_{SM} \Big| - T_{UM} - T_R - T_{MPS} - T_{AP} - T_T$$

T_L=time integrating L_{nom}

T_y=total time in year

T_D=long downtimes – upgrades, no budget

T_S=recovery from the above

T_{SM}=scheduled maintenance

T_{UM}=unscheduled maint

T_R=recovery from the above

T_{MPS}=machine protection

T_{AP}=accelerator physics

T_T= tuning

Typical numbers →

Red line indicates the ‘5000 hour’ point

Reliability/Availability, redundancy

- Define Reliability and Availability
- Many parts makes this hard
  - Give simple example
- Redundancy is biggest weapon
  - Energy gain with many RF stations
- Careful design and maintenance is also important.
  - APS power supply example
- Try to design in high availability: Availsim

Definitions

- Availability = (1-Unavailability)
  - **Unavailability is the time luminosity is not produced because hardware is broken plus the recovery time after hardware is repaired.**
  - **=MTBF / (MTBF+MTTR)**
- Reliability

$$R(t) = e^{-N\lambda t}$$

Probability of success until time t

λ =1/MTBF

- Mean time to failure (MTBF)
  - **Mean time between failures; of a single device or of a system**
- Mean time to replace (MTTR); μ = 1/MTTR
  - **Time to fix it and restart operation**
- Recovery time
  - **Time to restore conditions to pre-fault state**
- Tuning time
  - **Nothing broken, but unsatisfactory operation**
  - **routine or non routine tasks required to fix it**

Availability of Repairable systems Formulas

		A for MTBF=100, MTTR = 5, n=2
Single device	$A=\frac{\mu}{\lambda+\mu}$	0.950
n devices all must work	$A=\prod_{i=1}^{n}\frac{\mu_i}{\lambda_i+\mu_i}$	0.907
n devices one must work	$A=1-\prod_{i=1}^{n}\frac{\lambda_i}{\lambda_i+\mu_i}$	0.996

Availability Arithmetic

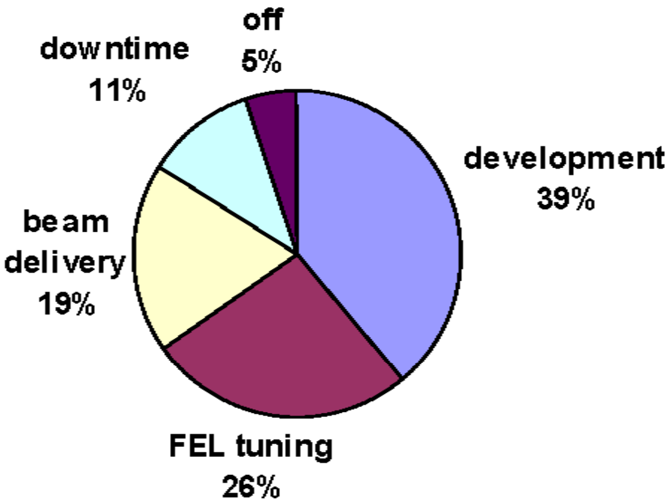
- Consider typical part with MTBF = 100k hours
  - **This is 11.4 years.**
  - **Assume MTTR = 2 hours**
  - **Availability = 99.998% – Excellent**
- Consider 500k such parts.
  - **MTBF of combined system = 0.2 hr.**
  - **Availability = 9% – Disaster**
- Consider 2 for 1 redundancy for each part
  - **Availability for single pair = 1 – 4e10**
  - **And for 500 k pairs = 99.8%**
- Redundancy really helps.
  - **ILC uses it for energy. A linac has 280 RF units of which 8 can be broken and still get to 3% under design energy**

Careful design and maintenance help too

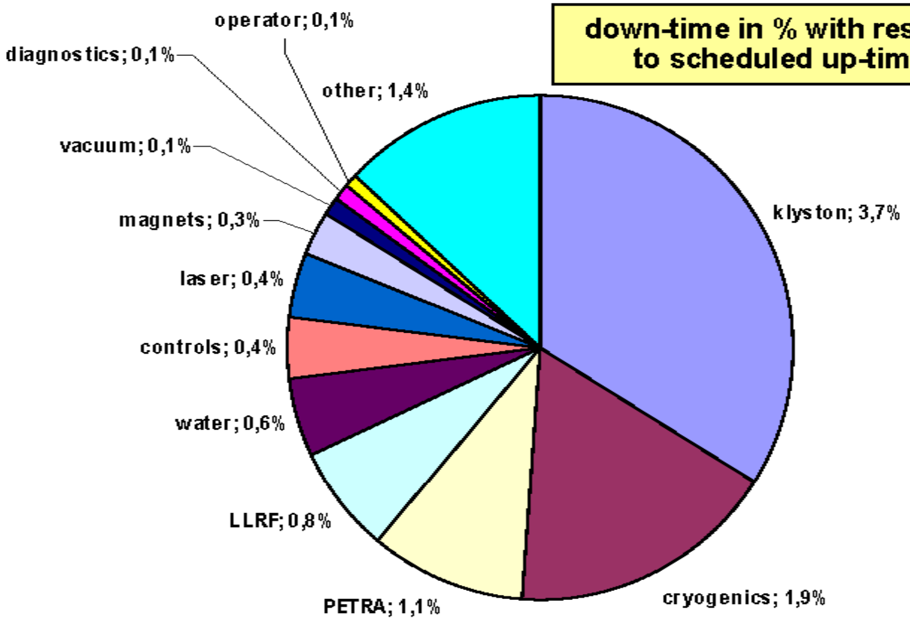
- Typical Magnet PS MTBF is 50k hours.
- APS has achieved 10 times that.
- How?
  - **Needed it because each magnet on separate supply, so more supplies than normal and need 95% uptime**
  - **Burn in before each run at 20% over needed current**
  - **Inspect with IR camera during downtimes**
  - **Analyze *every* failure and upgrade supplies to fix that failure mode.**
  - **Watch trends in IGBT, water and capacitor temperatures**

2005 Downtime statistics

TTF/VUV-FEL operation between
January 6th and November 1st, 2005



down-time in % with respect
to scheduled up-time



The TTF/VUV-FEL downtime over 10 months was approx. 11%.

During this period we had

- **user operation**
- **accel.studies**
- **system R&D.**

3.7% klystron	mostly problems with the prototype MBK
1.9% cryogenics	clearly dominated by one event connected with the use of the small/local refrigerator
1.1% PETRA	PETRA ramping disturbs the TTF/VUV-FEL operation
0.8% LLRF	clearly driven by system ‚improvements‘ since failures often shortly after R&D efforts

Accelerator Availabilities (from NLC ZDR)

ANL (APS)	95	68.30%
CERN (SPS)	94	69.30%
CERN (SPS)	93	72.00%
CERN (SPS)	92	74.00%
CERN (SPS)	91	72.00%
CERN (SPS)	90	74.00%
CERN (SPS)	89	71.20%
Fermi	91	72.64%
Fermi	92	65.86%
Fermi	93–94	63.71%
Fermi	93–94	63.71%
SLAC (SLC)	92	81.00%
SLAC (SLC)	93	84.53%
SLAC (SLC)	95	80.87%

SLAC (ESA)	92	87.01%
SLAC (ESA)	93	93.25%
SLAC (ESA)	94	93.33%
SLAC SSRL	94	97.04%
SLAC SSRL	95	96.60%
AGS,	FY95Q3	86.30%
AGS,	FY94Q4	86.70%
Cornell	91–92	74.10%
Cornell	92–93	77.90%
Cornell	93–94	84.00%
KEK photon factory Linac		
	92–93	98.70%
	91–92	98.40%
	90–91	97.70%

Accelerator availabilities

- From above slide notice:
  - Photon sources mostly available >95%
  - HEP machines mostly 65-85%
  - No clear size dependence
- Conclusion
  - Photon sources need higher availability because of few shift run lengths
  - Each machine is designed and then gets reliability problems fixed until it is good enough.
- Since ILC has many pieces will have to design in high availability.

ILC Downtime budget

- to the right of the line.
  - **controversy over scheduled maintenance**
  - **Goal is 25% downtime … max.**
    - this goal must be reconciled with impact on capital cost and operating costs; may change as ILC project matures
    - split this: 15% target to be budgeted now, 10% contingency
  - **Use that goal to apportion a budget and evaluate system designs**
  - **Learn which devices would cause large downtimes and hence need to be improved.**
- This work is required by size of the system.
- A quantitative tool is needed to design a high availability ILC.

Introducing Availsim (1 of 2)

- The ILC will be an order of magnitude more complex than any accelerator ever built.

- If it is built like present HEP accelerators, it will be down an order of magnitude more.
- That is, it will always be down.
- The integrated luminosity will be zero.
- Not good.

Introducing Availsim (2 of 2)

- Availsim is a Monte Carlo simulation developed over several years.
- Given a component list and MTBFs and MTTRs and degradations it simulates the running and repairing of an accelerator.
- It can be used as a tool to compare designs and set requirements on redundancies and MTBFs.

Availsim includes:

1. Effects of redundancy such as 21 DR kickers where only 20 are needed or the 3% energy overhead in the main linac
2. Some repairs require accelerator tunnel access, others can't be made without killing the beam and others can be done hot.
3. Time for radiation to cool down before accessing the tunnel
4. Time to lock up the tunnel and turn on and standardize power supplies
5. Recovery time after a down time is proportional to the length of time a part of the accelerator has had no beam. Recovery starts at the injectors and proceeds downstream.
6. Manpower to make repairs can be limited.

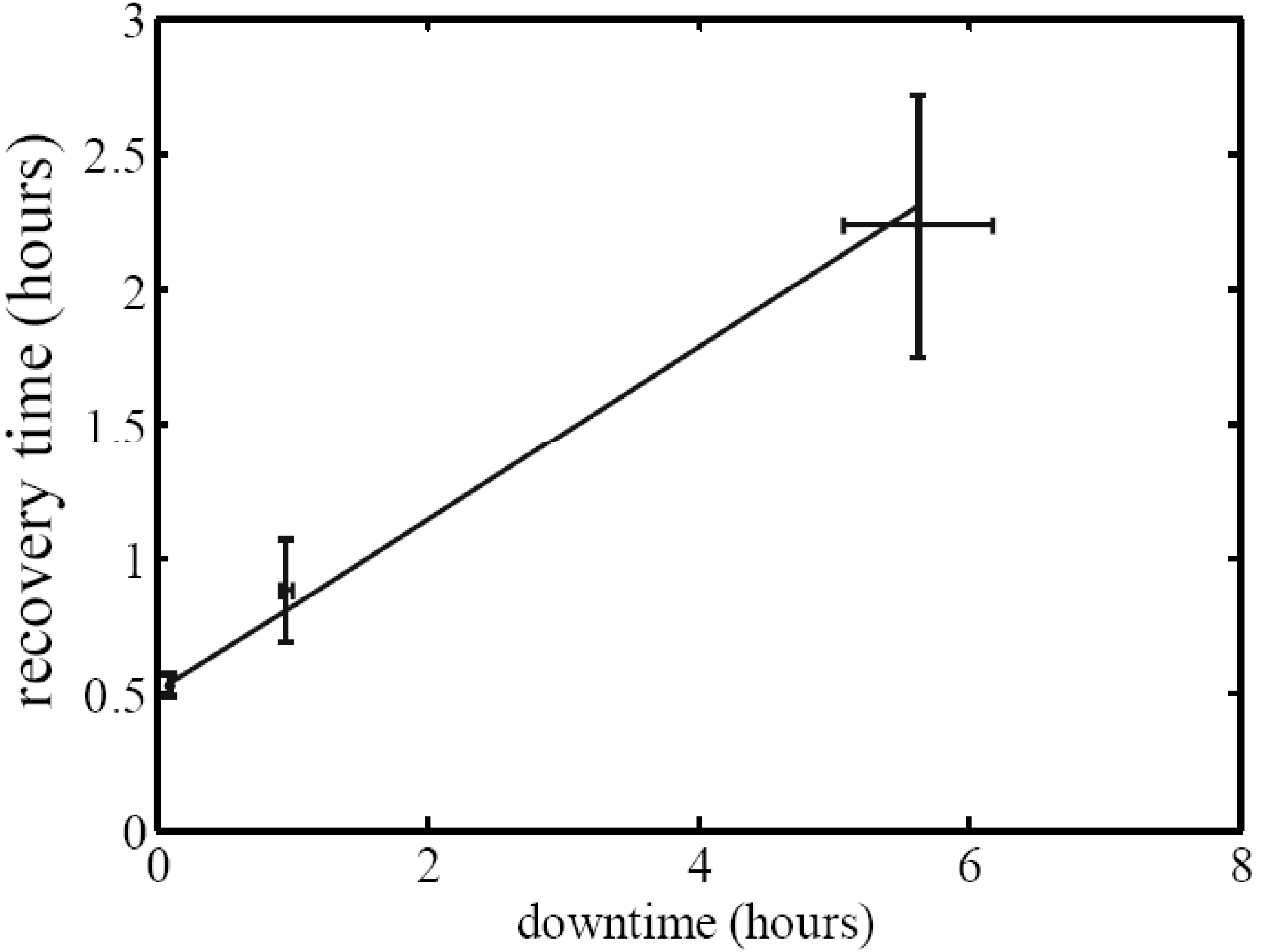
Availsim includes:

7. Opportunistic Machine Development (MD) is done when part of the LC is down but beam is available elsewhere for more than 2 hours.
8. MD is scheduled to reach a goal of 1 - 2% in each region of the LC.
9. All regions are modeled in detail down to the level of magnets, power supplies, power supply controllers, vacuum valves, BPMs …
10. The cryoplants and AC power distribution are not modelled in detail.
11. Non-hot maintenance is only done when the LC is broken. Extra non-essential repairs are done at that time though. Repairs that give the most bang for the buck are done first.

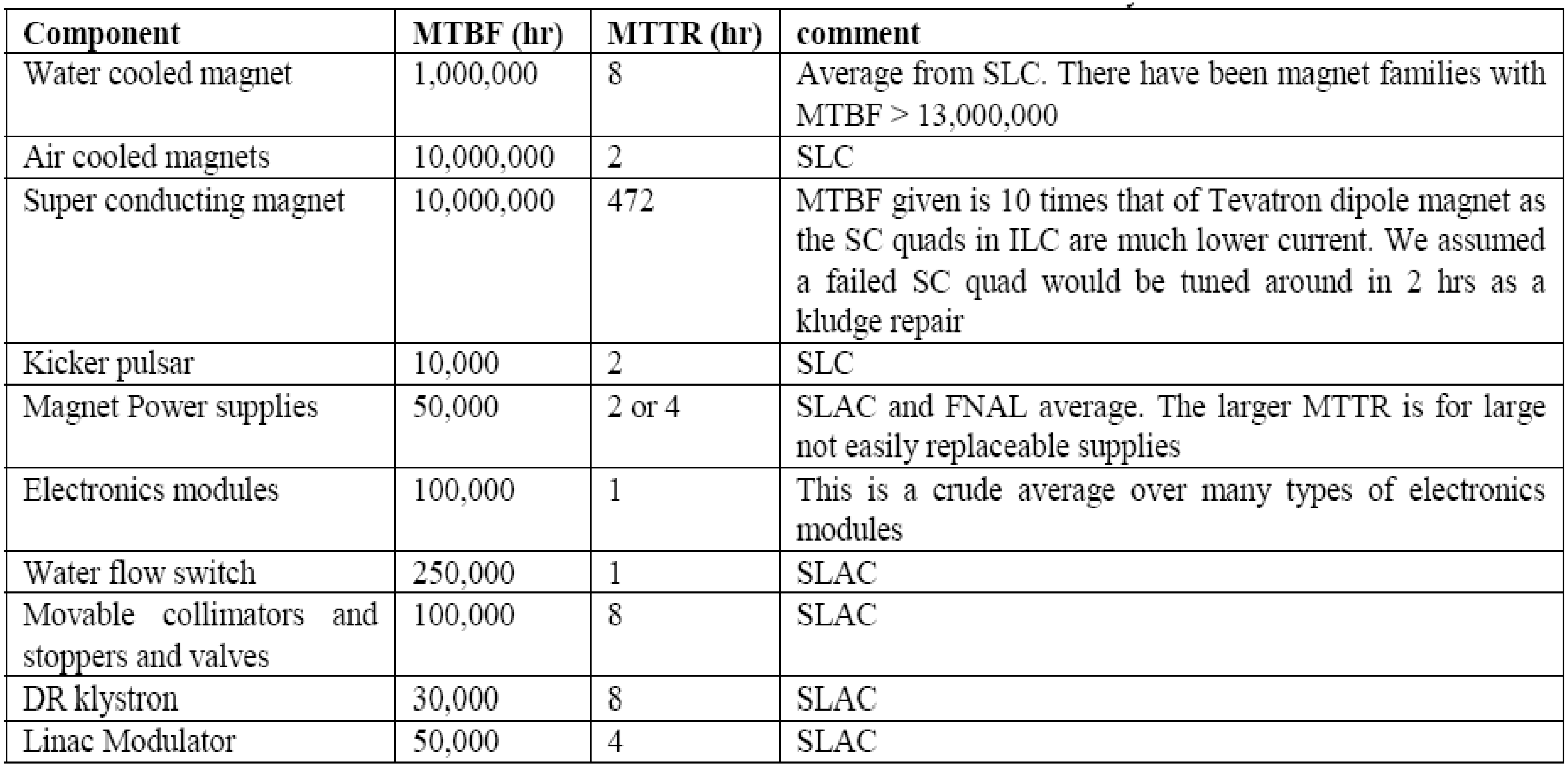
Availsim includes:

12. PPS zones are handled properly e.g. can access linac when beam is in the DR. It assumes there is a tuneup dump at the end of each region.
13. Kludge repairs can be done to ameliorate a problem that otherwise would take too long to repair. Examples: Tune around a bad quad in the cold linac or a bad quad trim in either damping ring or disconnect the input to a cold power coupler that is breaking down.
14. During the long (3 month) shutdown, all devices with long MTTR's get repaired.

Recovery Time for PEP-II



Mined data from old accelerators



Component	MTBF (hr)	MTTR (hr)	comment
Water cooled magnet	1,000,000	8	Average from SLC. There have been magnet families with MTBF > 13,000,000
Air cooled magnets	10,000,000	2	SLC
Super conducting magnet	10,000,000	472	MTBF given is 10 times that of Tevatron dipole magnet as the SC quads in ILC are much lower current. We assumed a failed SC quad would be tuned around in 2 hrs as a kludge repair
Kicker pulsar	10,000	2	SLC
Magnet Power supplies	50,000	2 or 4	SLAC and FNAL average. The larger MTTR is for large not easily replaceable supplies
Electronics modules	100,000	1	This is a crude average over many types of electronics modules
Water flow switch	250,000	1	SLAC
Movable collimators and stoppers and valves	100,000	8	SLAC
DR klystron	30,000	8	SLAC
Linac Modulator	50,000	4	SLAC

MTBF data for accelerator components is scarce and varies widely

Availsim answers 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

Needed MTBF Improvements:

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%

Used as input for many design decisions

- Putting both DR in a single tunnel only decreased int lum by 1%. -- OK
- Is a hot spare e+ target line needed? -- Not if e+ target can be replaced in the specified 8 hours
- Confirm that 3% energy overhead is adequate in the linac.
- Showed that hot spare klystrons and modulators are needed where a single failure would prevent running.
- Availsim is available at:
  - www-project.slac.stanford.edu/ilc/acceldev/ops/avail/source_code.htm

PPS

- Mostly straight forward:
  - Redundant interlocks on doors
  - Key-banks and/or card-keys/RFID
- Multiple regions
  - With shielding, allow one part to run while another part is under repair.
  - Reduces recovery time
    - PEP-II study (like DR)
  - Allows MD to be done during repairs
  - Without shielding, lose 1.7% in availability
- Multiple search zones
  - Keep search time down

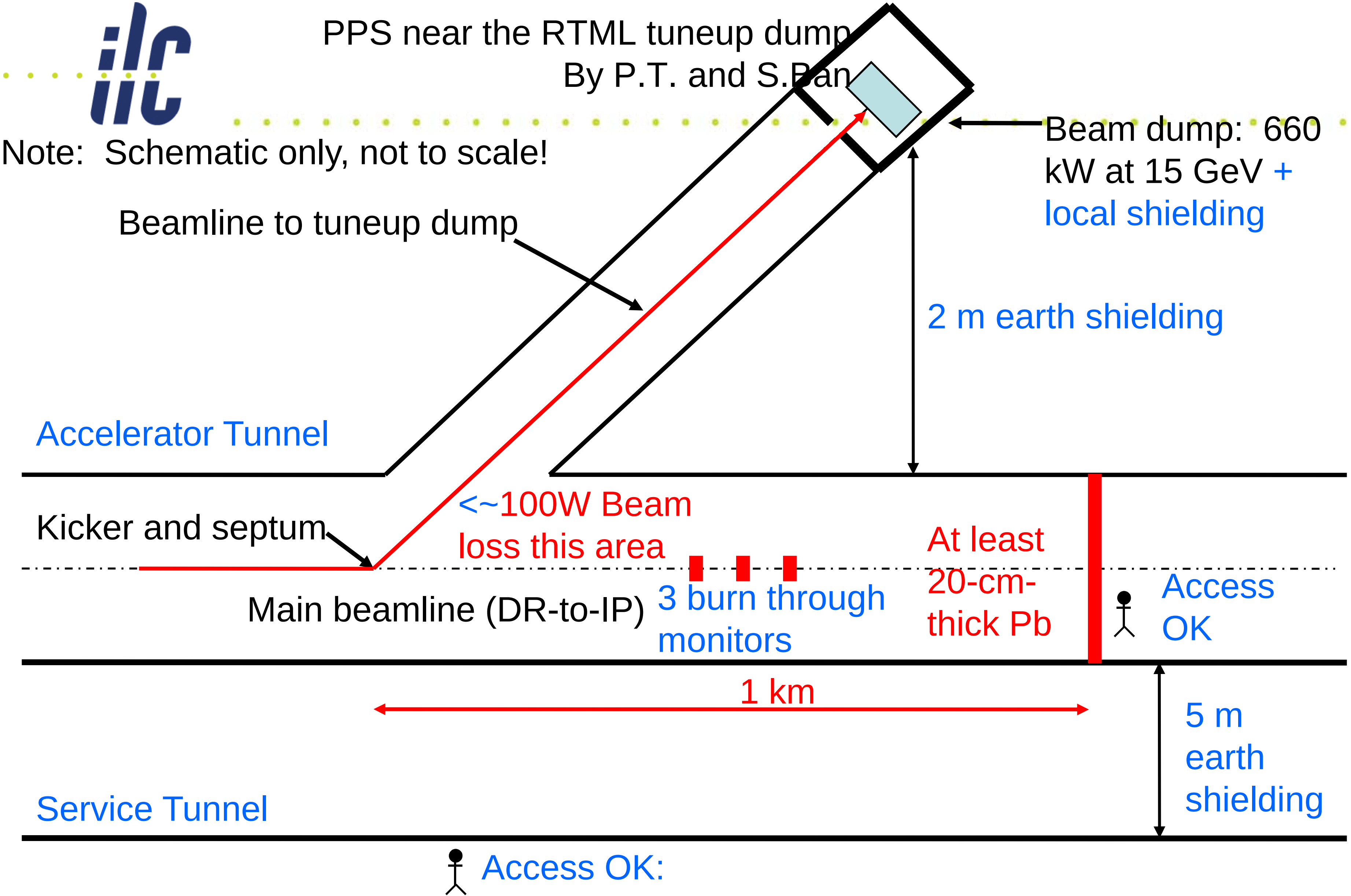
Radiation Safety Rules

- Complex and different at different labs. Here list amount a lab worker can be exposed to.
- SLAC: Normal operation < .005 mSv/hr or **10** mSv/yr; misteering < 4 mSv/hr; worst failure (18 MW loss) < 250 mSv/hr and < 0.1 mSv/incident (that is a 1.5 second loss at full power) (shield to < **0.014** mSv/hr/kW-loss)
- DESY: Average operation < **1.5** mSv/yr. Assume losses dominated by miss-steering causing 100 W/m loss for 100 hours/yr (shield to < **0.03** mSv/hr/kW-loss) (assuming 5 m of line loss is equiv to point loss)
- KEK: Average operation < **2** mSv/yr (what loss to assume not known)
- Conclusion: Rules differ, but limits similar. Will use tightest: shield to < **0.014** mSv/hr/kW-loss.

PPS near the RTML tuneup dump

By P.T. and S.Ban

Note: Schematic only, not to scale!



Beamline to tuneup dump

Beam dump: 660 kW at 15 GeV + local shielding

2 m earth shielding

Accelerator Tunnel

Kicker and septum

<~100W Beam loss this area

At least 20-cm-thick Pb

Main beamline (DR-to-IP)

3 burn through monitors

Access OK

1 km

5 m earth shielding

Service Tunnel

Access OK:
0.14 mSv/hr w/o local dump shielding;
0.025 mSv/hr with local dump shielding

Exit passages between tunnels

- Needed for fire/safety reasons
- Tried many designs to keep radiation in support tunnel below lowest region's limit of 0.014 mSv/hr/kW
- No heavy moving shielding doors
- 7.5 m between the tunnels
- Have found 2 designs that work

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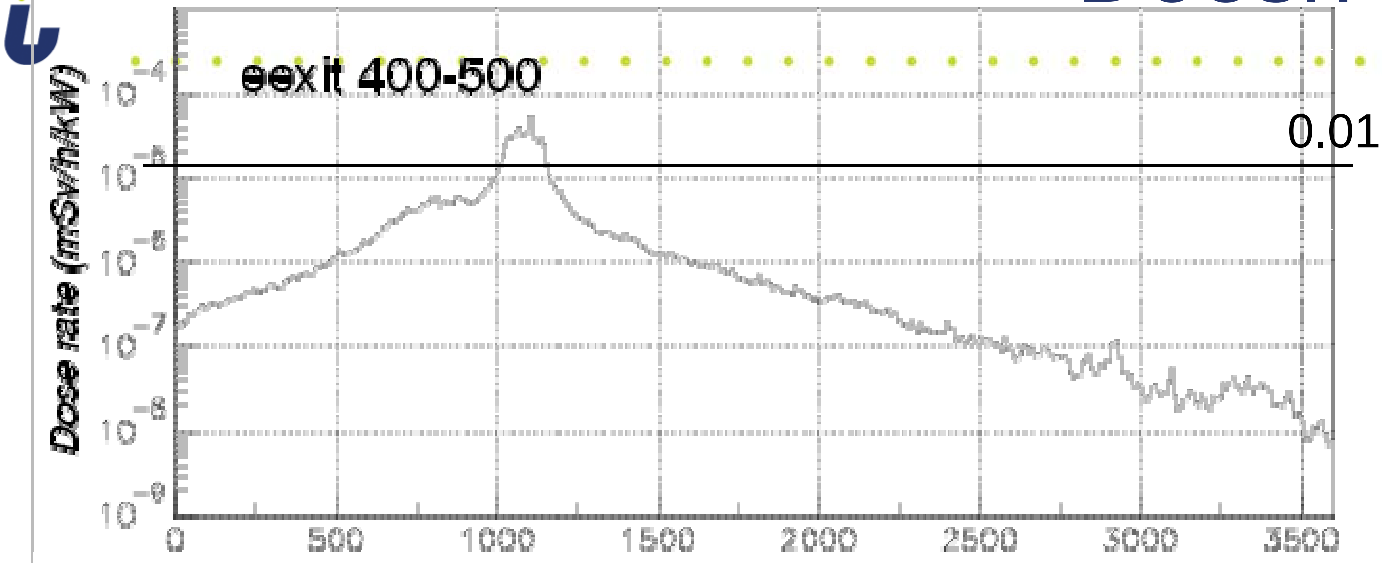
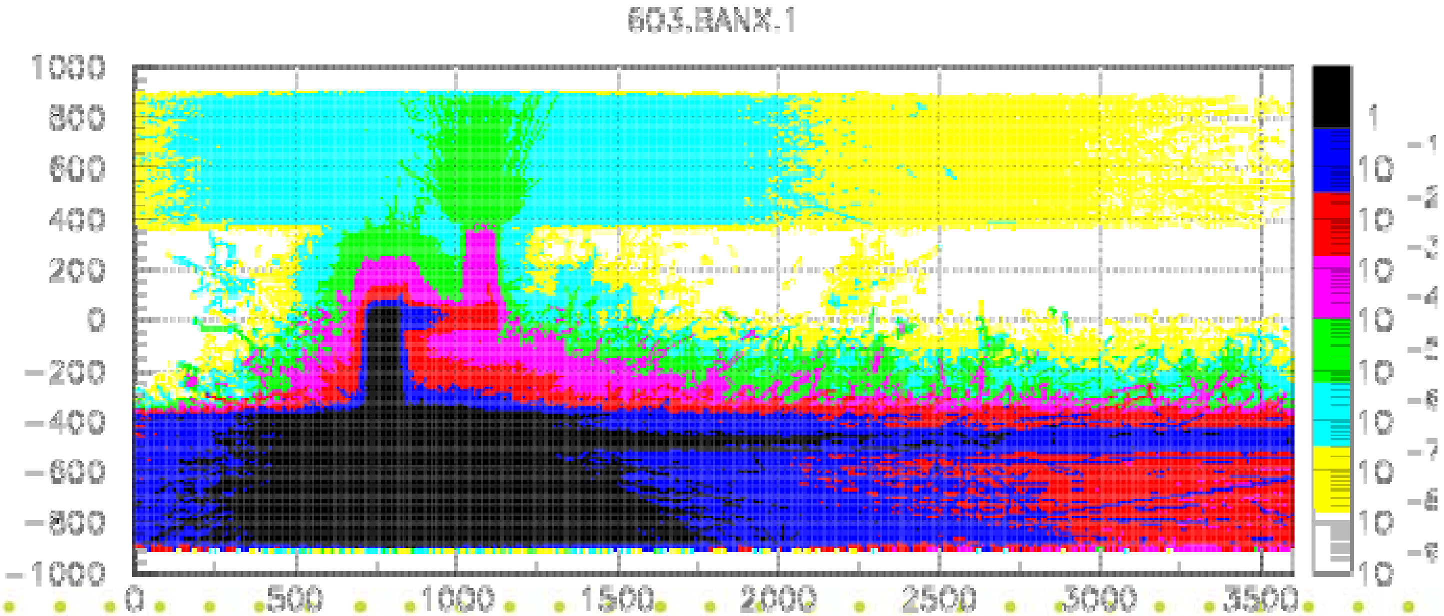
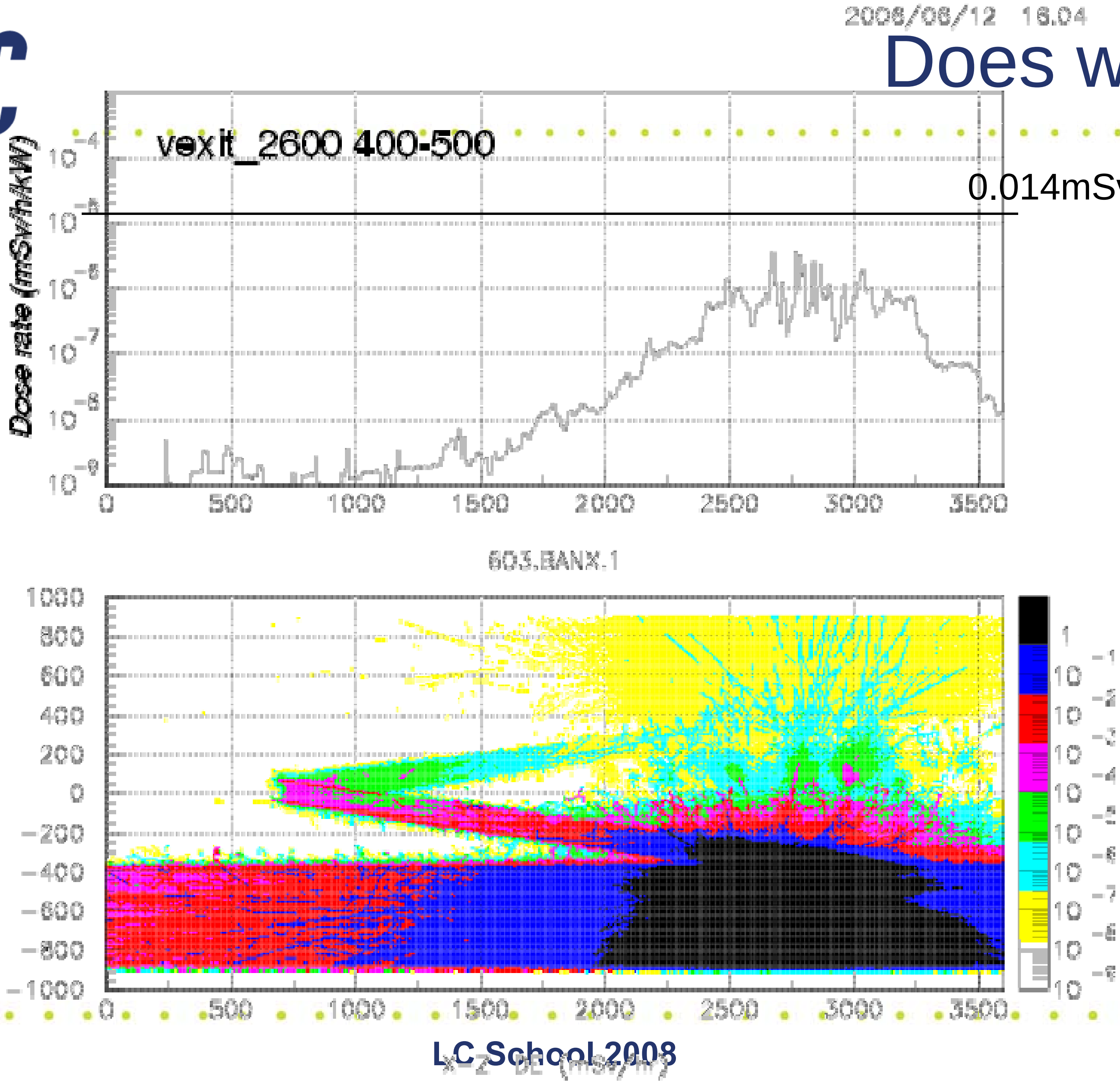
Doesn't work



0.014mSv/kW



Does work



0.014mSv/kW

MPS

- One bunch can drill hole in ILC.
- Must monitor anything which can change between pulses (0.2 seconds)
- Must monitor beam for changes.
- Preferably redundant enough so any problem is caught by 2 systems.
- Reliable enough to not cause many false trips.
- Must gradually turn on after outage in highly automated fashion.

Machine Protection

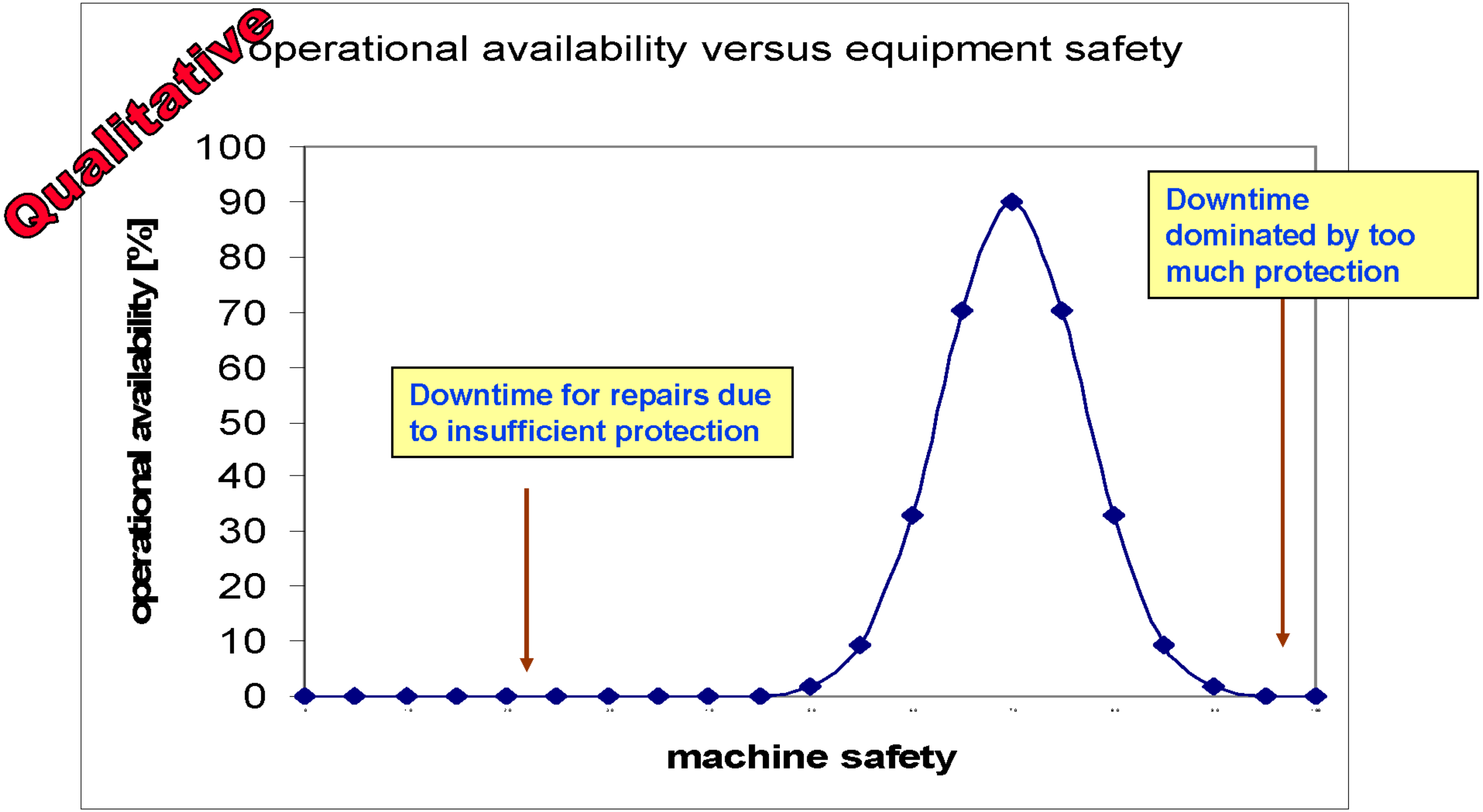
- Machine Protection system manages the above functions
- Consists of
  - **device monitors (e.g. magnet system monitors; ground fault, thermal sensors)**
  - **beam loss and beam heating sensors**
  - **interlock network with latching status**
- Also
  - **keeps track of** T_{MPS}
  - **tests and calibrates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

Machine Protection at LHC

- MPS is complex and details matter. Lessons learned are expensive in time and money.
  - **we 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**
  - **Can melt half a ton of copper**
  - **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 entire machine (one of the rings) in one turn
  - **90 us.**
  - **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**

One way to avoid damage…….



Qualitative

Downtime for repairs due to insufficient protection

Downtime dominated by too much protection

- The protection system must be optimised (more is not equal to better)
- There is no 100% safety

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**
    - This is most common failure mode
  - **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

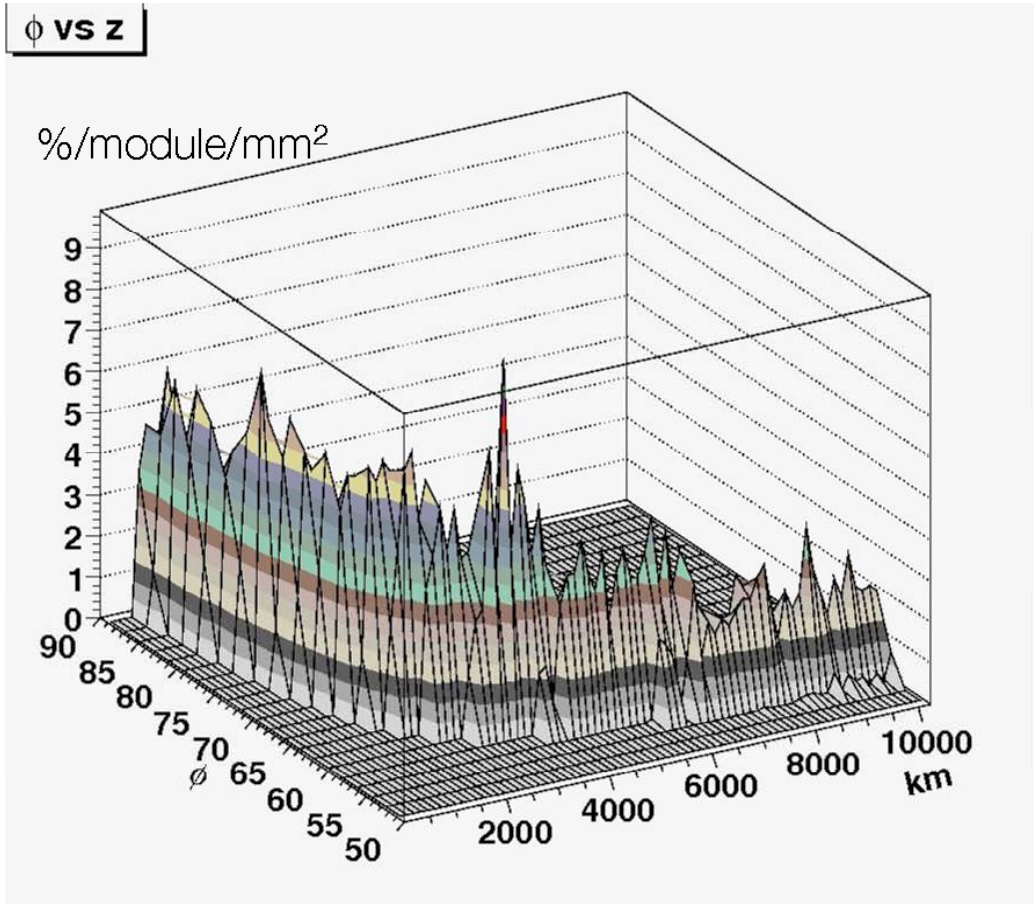
Extreme beam deflections in the linac

- Failed dipoles
  - **Dipole strength limited to correct ~3 mm offsets of quadrupole misalignment at 500 GeV (Bdip/(∂B/∂x))**
  - **this is ~10 σ alignment**
  - **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**

Failed RF phase control

- linac ‘bandpass’ 50%
  - **60 degree phase advance /cell**

- Maximum energy deposit <10%/module/mm^2
  - $10\% \times 2 \cdot 10^{10} \times 3000 / 9 \approx 7 \cdot 10^{11}$ particles
  - typical particle density to generate a hole: 10^{13}/mm^2 (needs confirmation for Nb)
- a train will not pierce a hole
  - phase verified during fill – stable due to large Q_{ext}.
  - early beam abort will increase margin (~300 bunches)



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 miss-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.

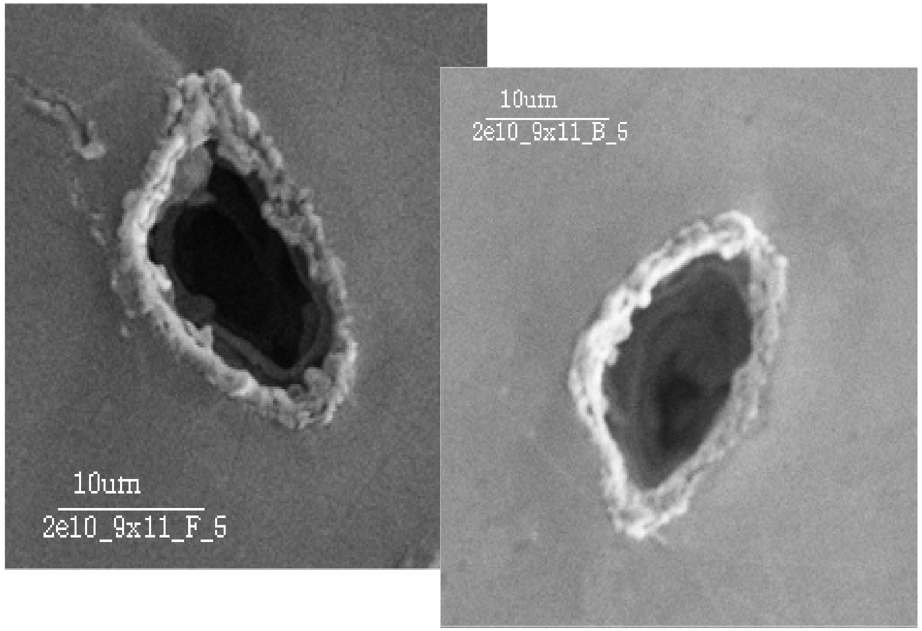
Startup process after MPS trip or longer outage

- Must be automated as part of MPS system
  - **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

Single pulse damage measured at FFTB

- tests done with Cu
- Copper / Nb are similar
  - **Nb tests have not been done**
- energy independent
  - **Electromagnetic showers are a further concern**

Damage from 13 pC/μm^2 (2x10^9 e^-)



Pilot bunch

- Each startup sequence begins with an analysis of hardware / set point / controls software readiness
  - **This is like a ‘summary interlock check’**
- 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**
  - **roughly independent of energy; what matters is at the incoming surface**
  - **Need way to produce this pilot bunch**
- the time since the last successful operation is important
  - **many systems remain fixed over 200ms**

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…)**
  - **3) check that beam loading compensation is working**
- 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)**

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*…**
- Reason to keep as much of machine "hot" as possible
- Reason to recover slowly from MPS faults and have feedbacks

Tuning algorithms, Stability, diagnostics, Feedbacks

- To stabilize a beam parameter (e.g. dispersion) at a desired value, one must
  - **Have a way to measure it**
    - May require special optics
    - Certainly needs diagnostics
  - **Have a way to control it**
    - E.g. RF phase or magnet strength
    - Fast enough to correct (un)known disturbance spectrum
  - **Have an algorithm for the correction**
    - Minimization is more difficult than first order
    - Many dimensional minimization is hardest

Tuning up – Alignment example

- In general following a startup, or at regular intervals
- Controls will only indicate what sensors show
  - **component alignment; sensor calibration or thermal drifts, sub-component deterioration may not be indicated**
  - **beam based checks, beam based tuning is required**
    - steering, offset finding, emittance tuning, phase space checks
- For example: Beam based alignment (BBA)
  - **this process takes time; during which the machine is not integrating luminosity (T_T)**
  - **typically takes ~ 100 pulses per focusing magnet; with ~5 different magnet currents**
    - finds the offset between the magnet center and the BPM
  - **300 magnets: ~ 2 hours per linac**
- Beam based alignment works best if we start with good initial alignment
  - **A major justification for the long downtimes**

Time scale for repeating BBA

- mechanical
  - **forced disturbance (system bumped)**
  - **thermal cycling**
- ‘civil’
  - **concrete cracks**
  - **motion of the floor**

- electronic
  - **replaced electronics**
    - 300,000 hour MTBF (used in the availability simulation) →
    - 2000 cavity BPM’s means one fails (and is replaced) per week
  - **electronic gain drifts**
  - **imperfect calibration**

SR - Stability - Noise Sources

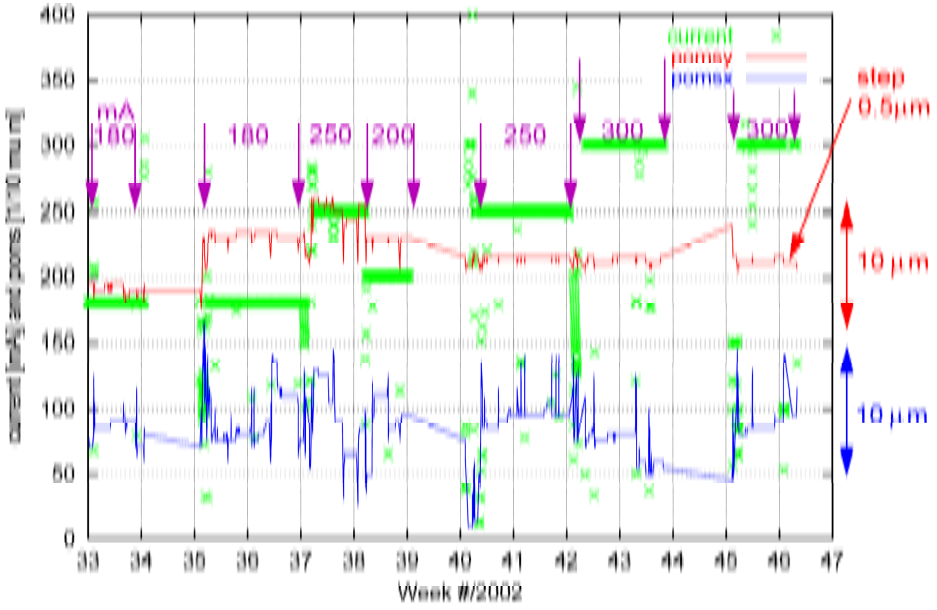
- **Short term (<1 hour):**
  Ground vibration induced by human activities, mechanical devices like compressors and cranes or external sources like road traffic potentially attenuated by concrete slabs, amplified by girder resonances and spatial frequency dependent orbit responses, ID changes (fast polarization switching IDs <100 Hz), cooling water circuits, power supply (PS) noise, electrical stray fields, booster operation, slow changes of ID settings, “top-up” injection.
- **Medium term (<1 week):**
  Movement of the vacuum chamber (or even magnets) due to changes of the synchrotron radiation induced heat load especially in decaying beam operation, water cooling, tunnel and hall temperature variations, day/night variations, gravitational sun/moon earth tide cycle.
- **Long term (>1 week):**
  Ground settlement and seasonal effects (temperature, rain fall) resulting in alignment changes of accelerator components including girders and magnets.

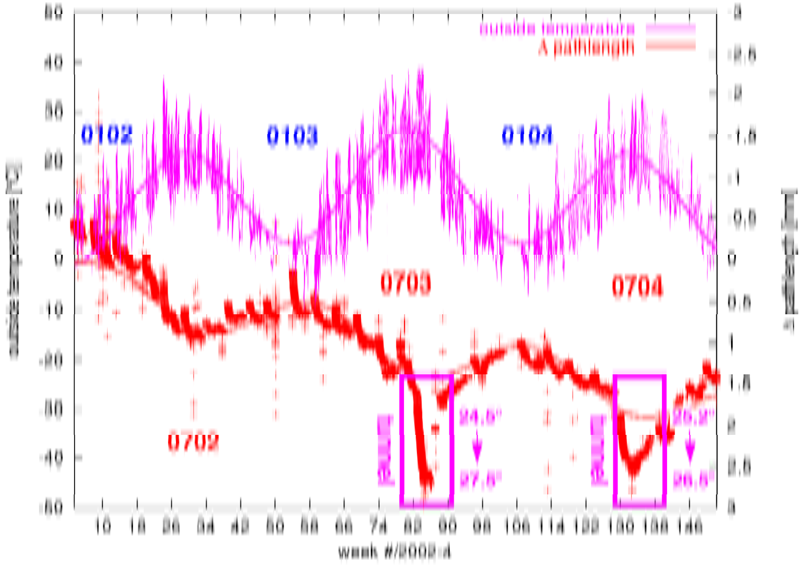
msec
↓
sec
↓
hours
↓
days
↓
weeks
↓
years

Data from the Swiss Light Source (PSI)

SR - Stability - Long Term Stability

- Horizontal BPM/Quadrupole offsets for BPM upstream of **U24** over 14 weeks @ different top-up currents (180, 200, 250, 300 mA) with 3 shutdowns (left plot)
- Circumference change over 3 years of SLS operation (→ Δ circumference ≈ 3 mm) (right plot)





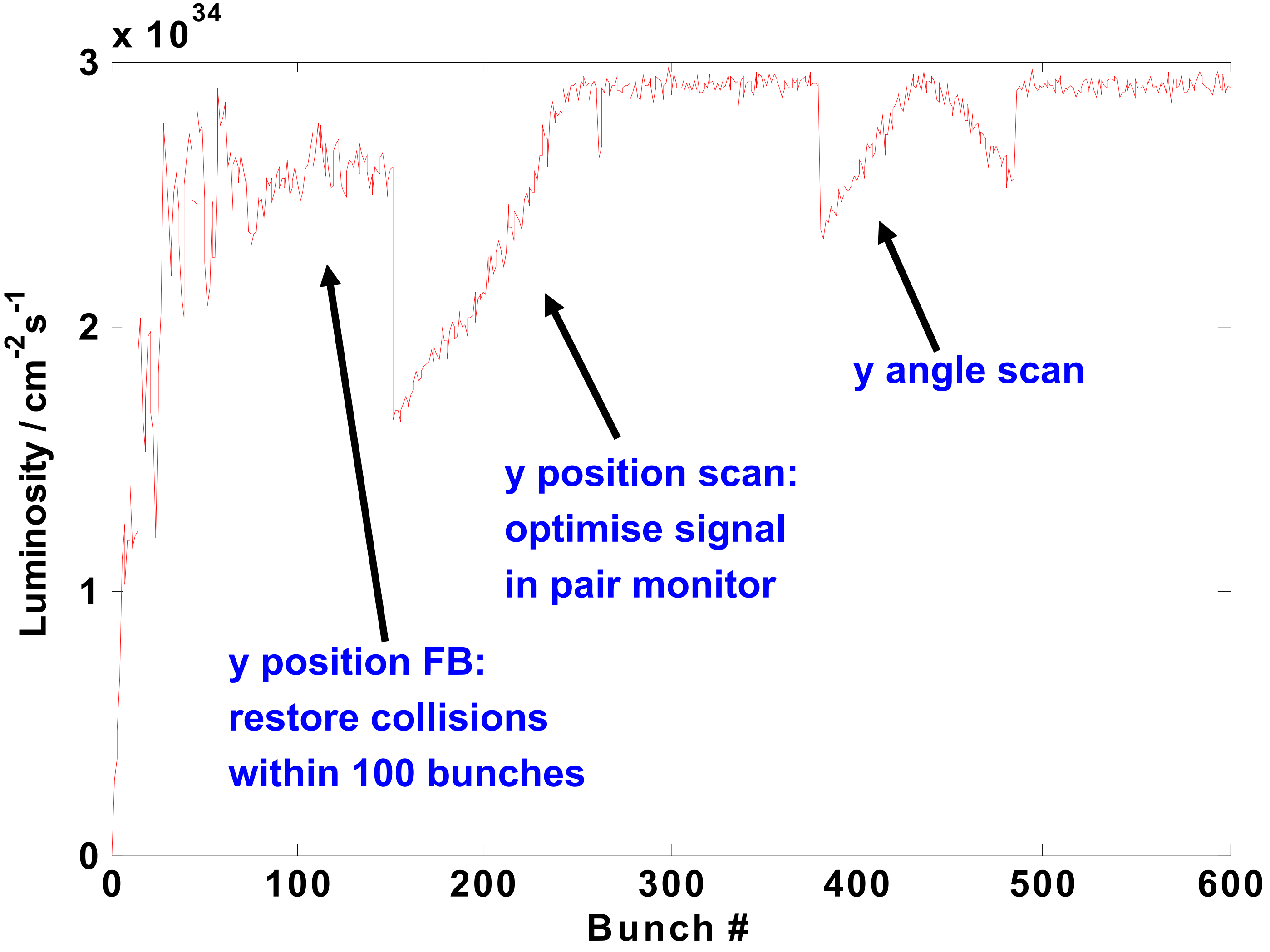
Tune up process – beyond BBA Diagnosis and other procedures:

- Tuning also will take place when none of the routine procedures are indicated
- Everything seems to be ok, but the resulting beam is not satisfactory
  - – **diagnostics / instrumentation fulfill this role**
- Need low power beam for emittance tuning
  - – **relaxes MPS; may also release locks**
- Performance testing and checking procedures
  - – **Software data acquisition package for this:**
    - Correlation ‘plot anything vs anything’ utility is required

Low power ILC

- Single bunch operation of ILC may have no luminosity
  - **ground motion and other instability will cause initial bunches to miss each other**
  - **200 ms is long compared to typical drift amplitude rates**
  - **Thermal: 0.2e-3 degrees**
  - **vibration: 5 Hz amplitude > nm for macroscopic structures**
- Machine tuning will require independent study of emittance and power effects
  - **we must be able to empirically prove the performance of one without the other**
- How many bunches are needed before an effective luminosity can be measured?

Number of bunches needed to establish collisions



y position FB:
restore collisions
within 100 bunches

y position scan:
optimise signal
in pair monitor

y angle scan

Tables of tuning process - BDS

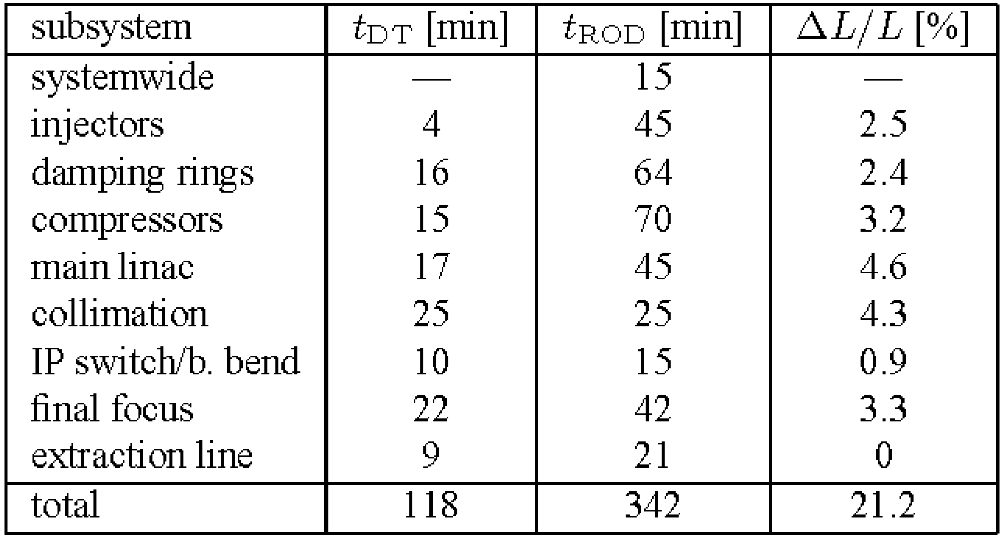
recovery from	$t_{\rm DT}$ [min]	$t_{\rm ROD}$ [min]
check BPM polarity & offset	NA	5
activate orbit feedbacks	5	5
close FF collimators	0	0
feedb. & orbit for 90 bunches	5	5
match incoming dispersion	NA	5
measure FF emittances	5	5
coupling corr. & beta-match	0	0
turn on & phase crab cavity	NA	5
establish collisions	2	2
turn on detector	NA	5
correct IP aberrations	5	5
total	22	42

- Showing
  - the time it takes per BDS procedure after 1) short downtime and 2) day-long downtime
  - continual BDS tuning required – the time it takes; associated interval and expected luminosity impact

procedure	t [min]	T [hr]	$\Delta L/L$ [%]
multi-bunch steering	0.5	0.08	0
dispersion (x&y)	0.12	0.25	0.8
waist (x&y)	0.12	0.25	0.8
skew1 (x'y')	0.06	0.25	0.4
IP divergence	0.017	1	0
skew sexts. (x'^{2}y', y'^{3})	0.12	1	0.2
skew2 (xy')	0.06	1	0.1
skew3 (x'y)	0.06	1	0.1
multi-bunch y-disp.	0.06	8	0.03
multi-bunch waist x& y	0.12	8	0.03
adjust FF main collimators	5	24	0.35
orbit resteering	60	100	0.25
BPM align. & offsets	30	170	0.1
sext. (x'^{3}, x'y'^{2})	0.12	170	0
chrom. x& y	0.12	170	0
chrom. skew (x'y'δ)	5	170	0.05
2nd order y-disp.	0.6	170	0.01
crab angle (xz')	—	170	0
match inc. dispersion	5	170	0.05
total			3.27

Example table of tuning time: system wide

- showing the tuning time required for all systems after a short downtime and after a day-long down with impact on luminosity



subsystem	t_{DT} [min]	t_{ROD} [min]	$\Delta L/L$ [%]
systemwide	—	15	—
injectors	4	45	2.5
damping rings	16	64	2.4
compressors	15	70	3.2
main linac	17	45	4.6
collimation	25	25	4.3
IP switch/b. bend	10	15	0.9
final focus	22	42	3.3
extraction line	9	21	0
total	118	342	21.2

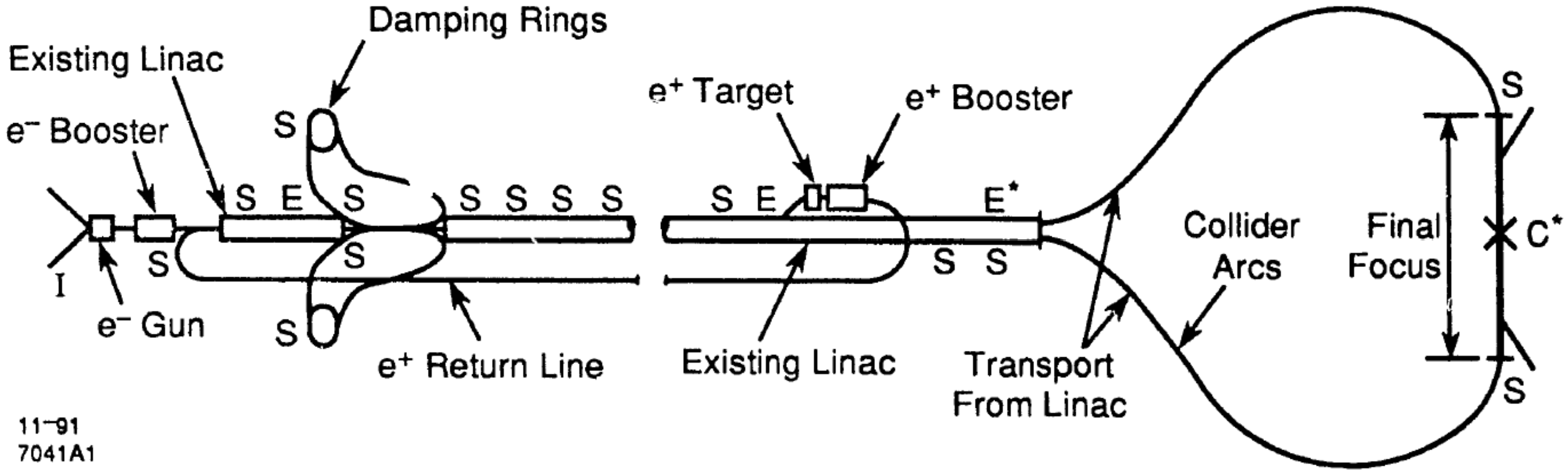
Tuning collimation

- much of the tuning time at SLC was adjusting collimators to reduce detector backgrounds
- typical distances between collimators are large, position tolerances are tight and relative alignment tolerances are also tight
- Beam can have large tails, unlike a storage ring where they are scraped in the early turns.
- MPS has to allow small collimator movements for this tuning while preventing moving the collimator into the beam where it will be destroyed.
- Difficult to automate this tuning as have no model.

Klystron management

- The linac contains spare klystrons, but these may be a long distance away from the one which just failed
  - **complete readjustment of the linac may be required**
  - **including quadrupole strengths - to rematch the linac**
- this should be done quickly, to compensate for the expected (high) failure or fault rate
  - **should be automated**
  - **within a pulse interval? or a few pulses?**
- need an accurate estimate of the energy along the linac and the gradients of the RF units involved in the exchange.

Feedbacks



- The SLC had about 50 feedback loops to stabilize the beam.
- They were crucial to the success of the SLC and will be for the ILC also.

Feedbacks

- Compensate for things can’t control (well enough)
  - **Ground motion**
  - **Vibration**
  - **Temperature’s effects on position, phases …**
  - **Power supply currents (mostly stable enough now)**
  - **Klystron faults**
  - **Unknown sources of change**
- Allow operator tuning by zeroing out downstream effects

Example feedback and diagnostics

- Steering to minimize dispersive and wakefield growth needs good BPMs
- Beam size and tail measurements to add bumps to minimize emittance growth in the linac
- Bunch length monitors needed to adjust compressor phases to control the bunch length
- Energy feedbacks need optics with small beta and large eta with BPMs
- Orbit feed-forward after DR needs turn-around and BPMs. Allows pulse-to-pulse changes to be corrected.
- Beam loading compensation feed-forward can take currents in DR and adjust RF parameters. Needs bunch by bunch current measurements in the DR
- Measure beam deflection and luminosity at the IP to make the beams collide and correct the angle. Bunch-by-bunch feedback.

Maintenance

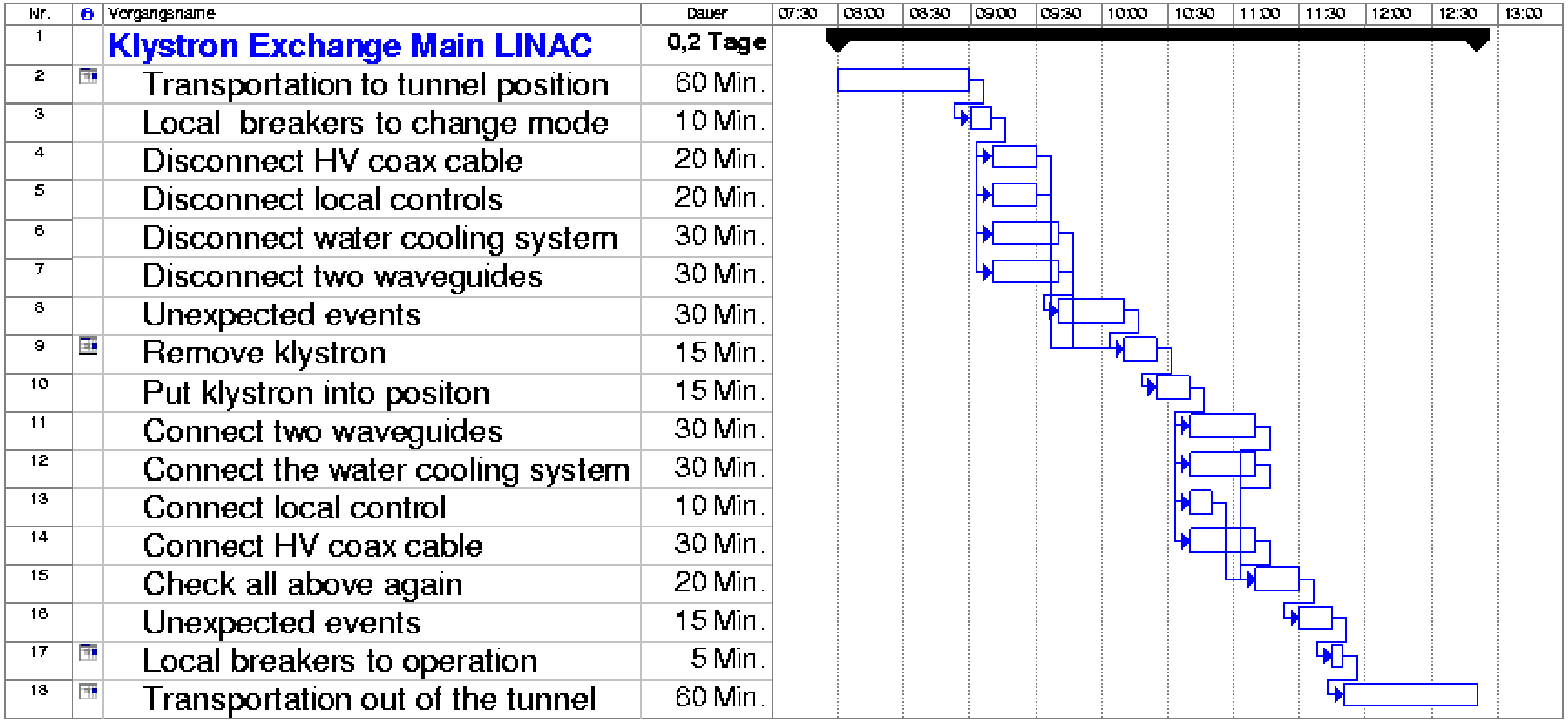
- Unscheduled maintenance
  - Forced when an essential component breaks
  - In facility with short experiments (Sync Rad) makes users more unhappy than scheduled maintenance.
- Scheduled maintenance
  - More efficient because it can be well planned, people and parts ready to go.
  - Can do many nonessential repairs at the same time
  - Still not integrating luminosity during this time

Common maintenance items

- Tubes (klystrons, thyratrons, tetrodes) will fail after ~40000 hours and require replacement
  - **For ILC, the most important consumable is klystron**
  - **Modulators will use modern solid state technology which should have more than 200000 hour life (?)**
  - **700 klystrons with 40000 hour life → 3 replacements / week.**
    - Typical SLAC performance
    - Lifetime is dominated by cathode physics
  - **A main reason for the second tunnel**
- electronics, capacitors, fans
- Radiation damaged components – extreme example is the positron target itself
  - **Hoses, cables,**

Klystron Replacement for the TESLA Linear Collider

- Plan to change a klystron in 5 hours
- Faster than it is done now.



Nr.	ℹ	Vorgangsname	Dauer
1		**Klystron Exchange Main LINAC**	**0,2 Tage**
2	▦	Transportation to tunnel position	60 Min.
3		Local breakers to change mode	10 Min.
4		Disconnect HV coax cable	20 Min.
5		Disconnect local controls	20 Min.
6		Disconnect water cooling system	30 Min.
7		Disconnect two waveguides	30 Min.
8		Unexpected events	30 Min.
9	▦	Remove klystron	15 Min.
10		Put klystron into positon	15 Min.
11		Connect two waveguides	30 Min.
12		Connect the water cooling system	30 Min.
13		Connect local control	10 Min.
14		Connect HV coax cable	30 Min.
15		Check all above again	20 Min.
16		Unexpected events	15 Min.
17	▦	Local breakers to operation	5 Min.
18	▦	Transportation out of the tunnel	60 Min.

Control System

- An accelerator is enormously complex
- Control system
  - **should automate as much as possible**
    - Includes tuning procedures and feedbacks described above.
  - **Be highly available**
  - **Have many built-in diagnostics to detect electronics problems**
  - **Summarize information well**
  - **Allow remote access**

Automation

- Tuning procedures like beam based alignment and steering should be totally automated. Click once and watch and wait.
- Automatic data acquisition, varying settings and recording many readings
- Record everything and provide tools for offline analysis

High availability

- Controls must be HA itself and provide tools for other systems to be HA.
- Looking at new telecom ATCA standard. Allows hot swapping and also redundancy of power supplies, CPUs, and networking.
- Must build diagnostics into hardware and monitor then with the control system.
  - **E.g. in a magnet power supply, measure many temperatures, current from each regulator, ground fault current, voltage across the magnet etc.**
  - **Try to find incipient problem before it breaks totally.**

Remote Access

- ILC is an international effort.
- Different parts will be built in different places
- Experts will be resident all over the world
- Airplane flight is slow compared to photons over fiber optics.
- Provide offsite experts with communications and control system access good enough to diagnose and fix a problem (or run accelerator physics shifts) with help from people onsite.

Remote Access

- Technology is the easy part
  - Control systems are already “remote” in the sense that they pass most if not all data over a network.
  - Even the onsite control room will be “remote”
  - Many times on many accelerators operator consoles have been used remotely to view or even control an accelerator
  - Modern networks have the bandwidth needed.

Remote Access

- Sociology is the hard part
  - **Some countries' radiation safety rules specify that control must be from onsite**
  - **Difficult for remote people to keep up-to-date on the minutia of accelerator operations**
  - **People work better together if they know and trust each other.**
- Some physical presence (collaboration meetings) is necessary
- There are projects to improve remote collaboration
  - **They still have physical meetings, so not totally successful.**

Operating expenses

- May be expensive to run, with limited operating funds, can limit run period.
- Electricity and people tend to be largest operating expenses.
- Can trade-off construction vs operations costs (e.g. amount of copper used in magnet coils)
- Tradeoff coefficients argued (n years operating), operating sometimes easier to get than construction.

Power use in the ILC

AREA SYSTEM	RF	CONV	NC MAGNETS	WATER SYSTEMS	CYRO	EMER	TOTAL (by Area)	NOTES
SOURCES e-	**1.05**	**1.19**	**0.57**	**1.27**	**0.00**	**0.06**	**4.13**	**Valencia**
	Not Included		1.50		0.00	Not Included	1.50	Vancouver
SOURCES e+	**4.11**	**7.32**	**6.52**	**1.27**	**0.00**	**0.21**	**19.43**	**Valencia**
	Not Included		1.50		0.00	Not Included	1.50	Vancouver
DR	**14.00**	**1.71**	**6.78**	**0.66**	**2.56**	**0.23**	**25.95**	**Valencia**
	14.00		6.00		5.40	6.20	31.60	Vancouver
RTML	**8.40**	**3.78**	**3.22**	**1.34**	**2.78**	**0.15**	**19.67**	**Valencia**
	8.00		6.00		0.00	3.90	17.90	Vancouver
MAIN LINAC	**86.47**	**15.43**	**1.41**	**9.86**	**32.20**	**0.40**	**145.77**	**Valencia**
	93.00		63.70		68.80	3.60	229.10	Vancouver
BDS	**0.00**	**1.11**	**18.48**	**3.51**	**0.24**	**0.20**	**23.54**	**Valencia**
	Not Included		71.40		0.00	2.20	73.60	Vancouver
DUMPS	**0.00**	**3.83**	**0.00**	**0.00**	**0.00**	**0.12**	**3.95**	**Valencia**
	0.00		3.20		0.00	0.00	3.20	Vancouver
TOTAL (by System)	***114.0***	***34.4***	***37.0***	***17.9***	***37.8***	***1.4***	***242.4***	**Valencia**
			89.3					
TOTAL (by System)	***115.0***		***153.3***		***74.2***	***15.9***	***358.4***	Vancouver
CHANGE	**-1.0**		**-64.0**		**-36.4**	**-14.5**	**-116.0**	

MW	***242.4***	**Valencia**
MW	***358.4***	Vancouver

Power Cost

- 242 MW instantaneous
- 9 months/year
- $0.11/kWhr
- Cost each year about $175 million
- $1.7 billion per 10 years
- Significant fraction of 6.4 Billion ILCU construction cost
- Worth design work to reduce it.

Summary

- Proper accelerator design includes much more than peak luminosity.
- Must also consider:
  - **Availability, redundancy**
  - **PPS (regions w/ beam others with people)**
  - **MPS**
  - **Stability, Tuning algorithms, diagnostics, Feedbacks**
  - **Maintenance**
  - **Control System**
  - **Operating expenses**