ILC - Operations
2nd International Accelerator School on Linear Colliders

ETTORE MAJORANA FOUNDATION AND
CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE
AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

WORLD FEDERATION OF SCIENTISTS
Founded in Erice
Beijing Geneva Moscow New York

Integrated luminosity is the goal – peak luminosity is only a demonstration

Marc Ross, FNAL

Integrated luminosity:

- Integrated luminosity = Peak luminosity x time x derating factors

- Peak luminosity requires charge (power) and low emittance
  - At specified energy
- Integrated performance requires
  - reliability
  - stability
  - controls
  - diagnostics
  - system understanding

- Operations, as a field in itself:
  - ‘operations engineering’ or ‘industrial engineering’
  - describes how to assess and optimize the utilization of a facility

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 these as ‘lost’ time)

    - Budget dividing lines – used for planning

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

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

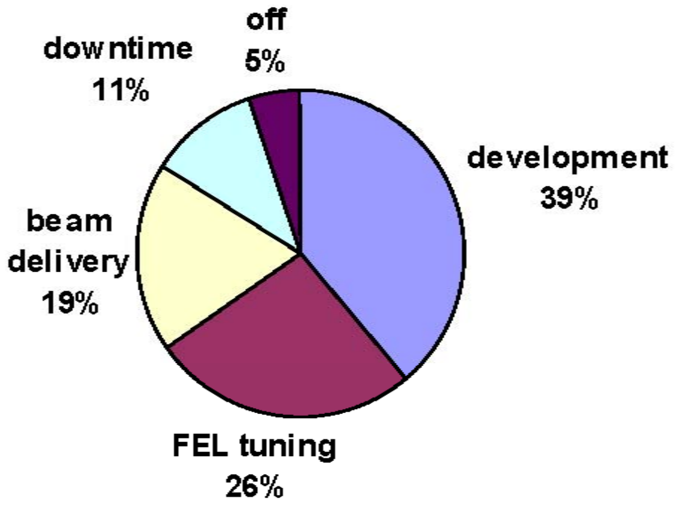
T_T= tuning

Typical numbers →

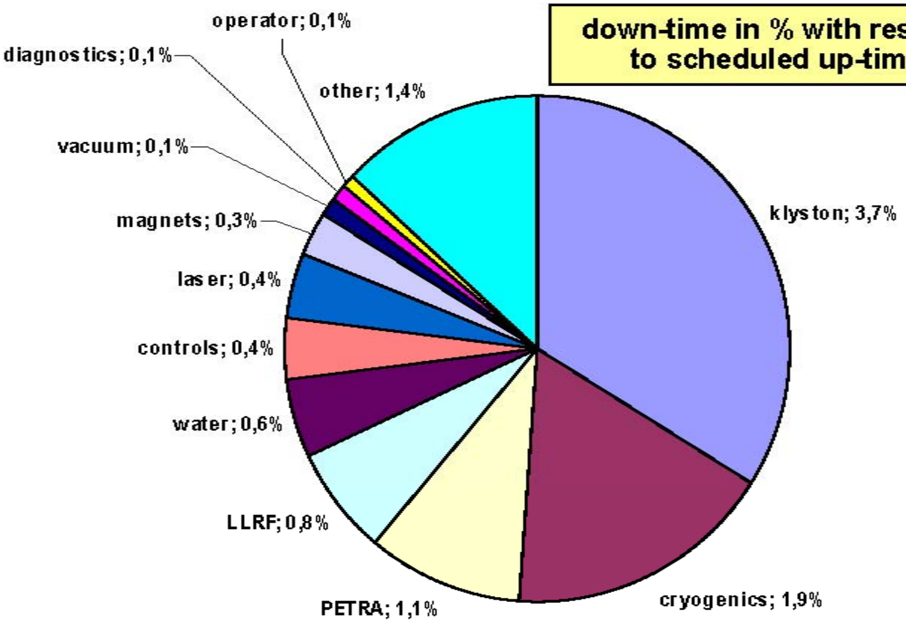
Red line indicates the '5000 hour' point

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

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 managed, 10% contingency
  - Use that goal to apportion a budget and evaluate system designs
  - this is required by size of the system.
- Typical synchrotron light machine:
  - $T\_UM + T\_R = 4\%$
  - requirements are different from ILC; the long term goal is serving users promptly, not integration

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

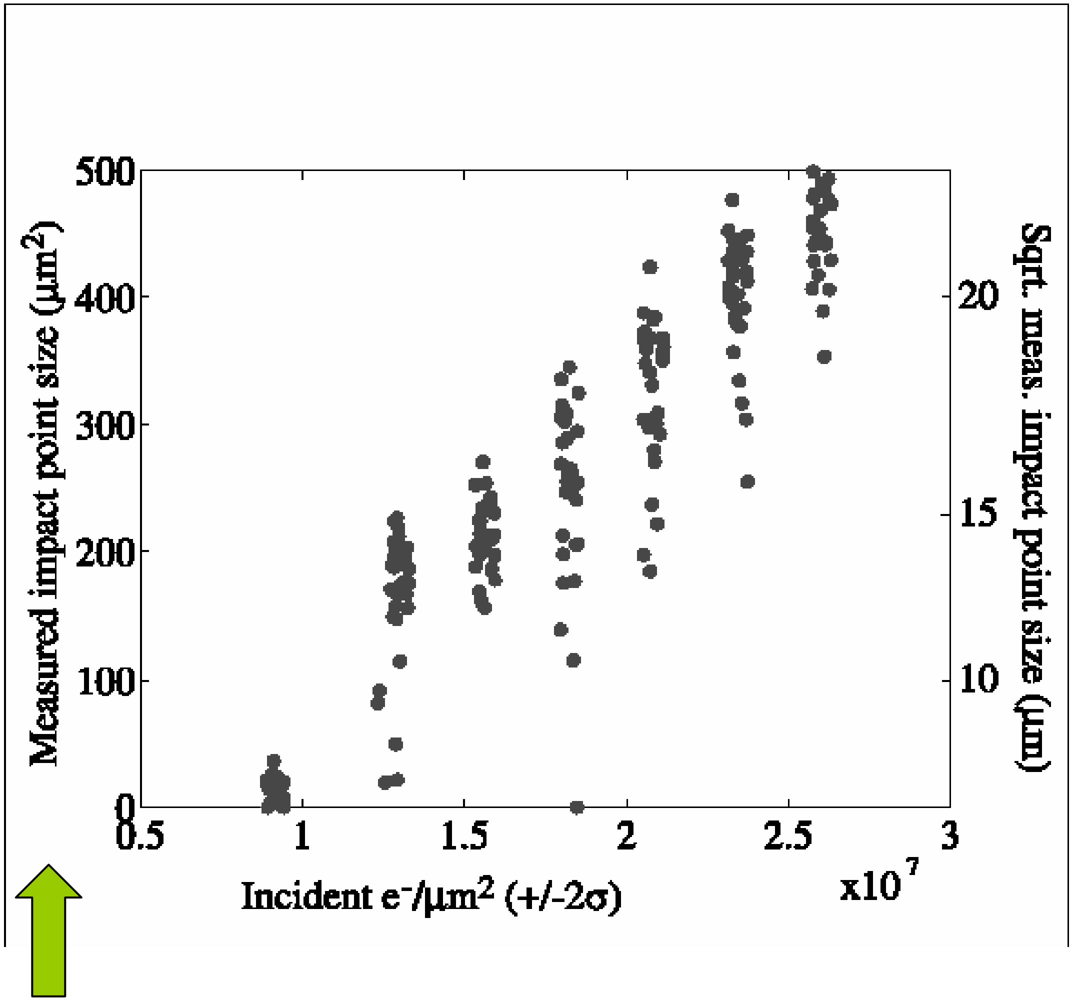
- Mean time to failure (MTBF)
  - Mean time between failures; of a single device or of a system
- Mean time to replace (MTTR)
  - Time to fix it and restart operation
- Recovery time
  - Time to restore conditions to pre-fault state
- Tuning time
  - Nothing broken, but unsatisfactory operation
  - routine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

Startup process

- How is the ILC started, after a short interruption? (T_R)
  - 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

Results from the FFTB single bunch damage test

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



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 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
- 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…)
- 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

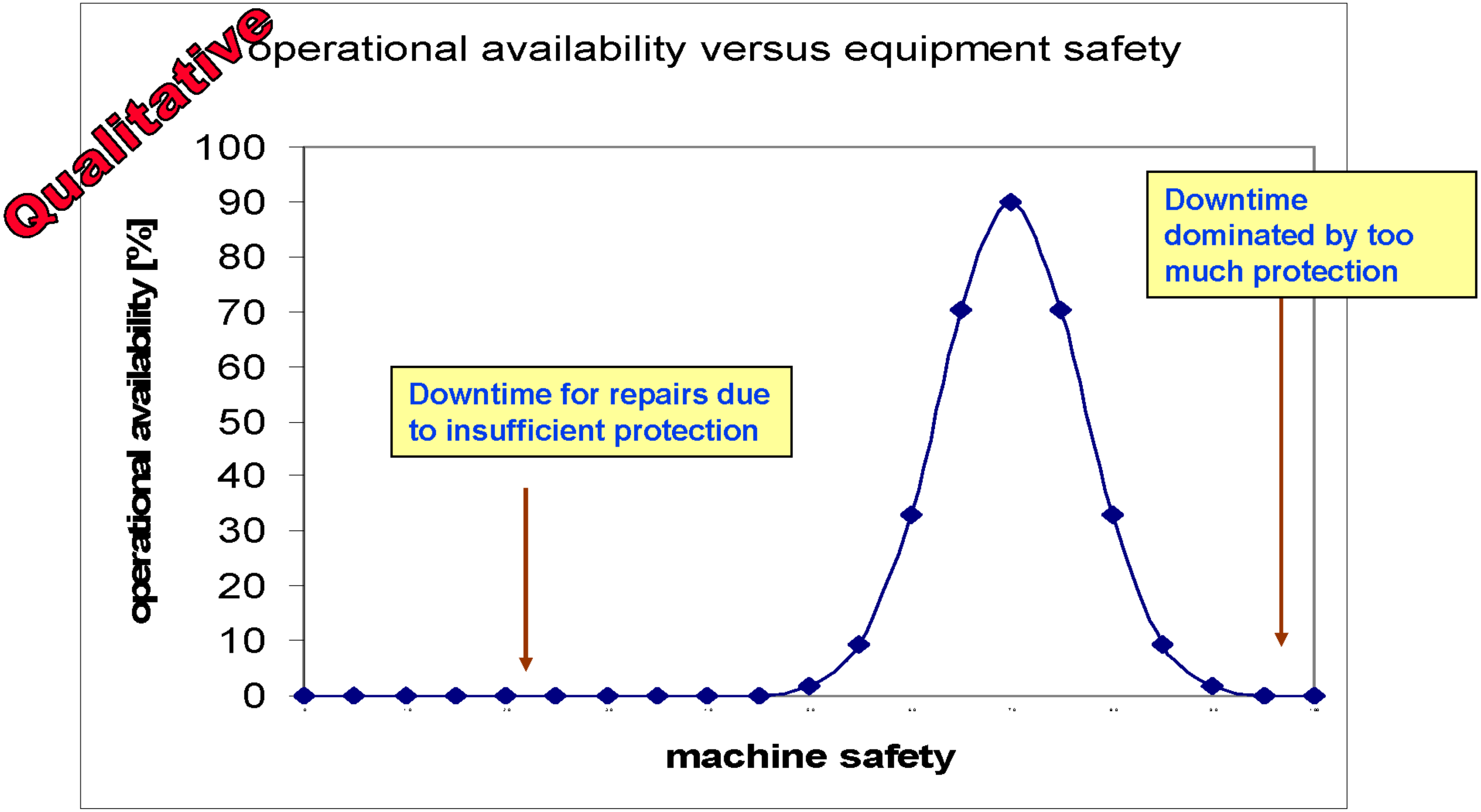
- Machine Protection system manages the above functions
- Consists of
  - device monitors (e.g. magnet system monitors; ground fault, thermal sensors)
  - beam loss and beam heating sensors
  - interlock network with latching status
- Also
  - keeps track of T_{MPS}
  - tests and calibrates itself
 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

Machine Protection at LHC

- MPS is complex and detailed, and 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
  - 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…….



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
  - 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

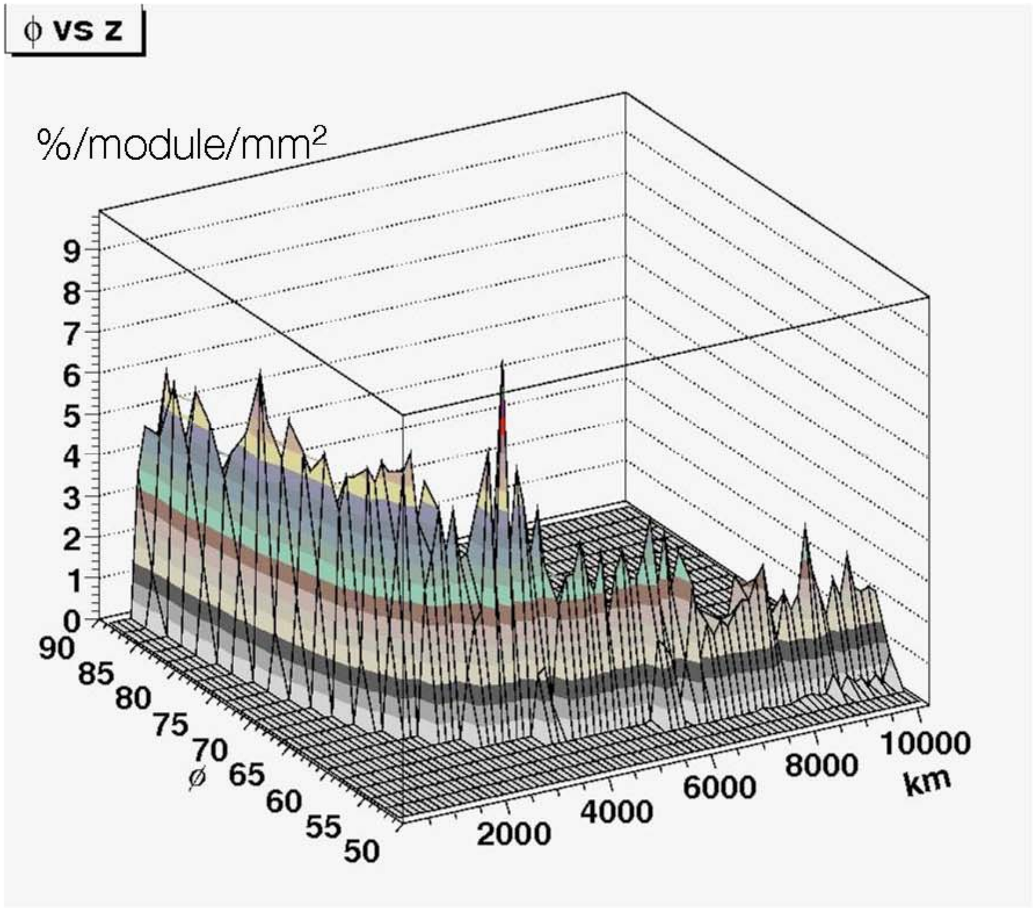
Extreme beam deflections in the linac

- 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

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 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.

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

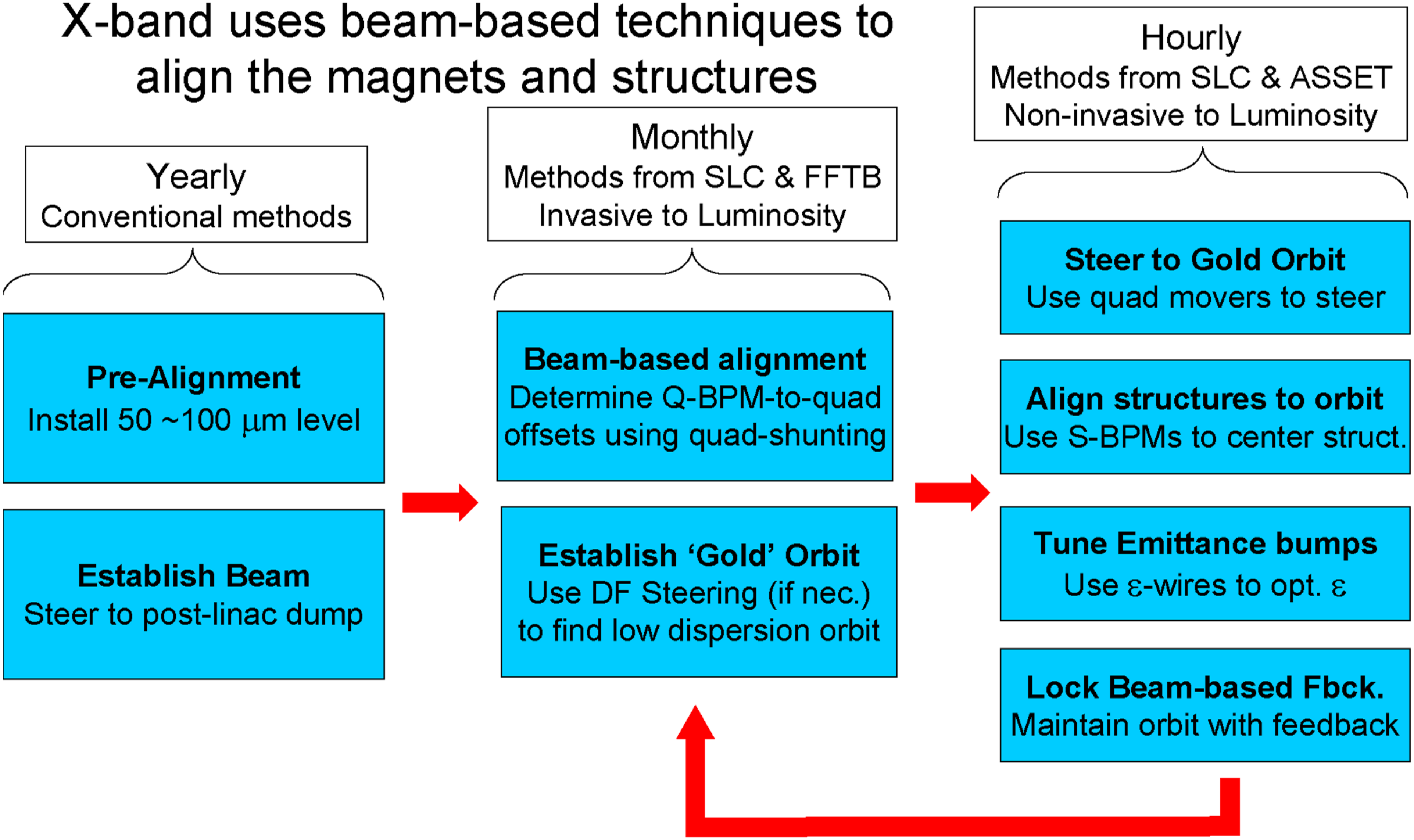
Time scale for repeating BBA

- 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

The alignment flow chart (for the warm machine)

X-band uses beam-based techniques to align the magnets and structures



Yearly
Conventional methods

Pre-Alignment
Install 50 ~100 µm level

Establish Beam
Steer to post-linac dump

Monthly
Methods from SLC & FFTB
Invasive to Luminosity

Beam-based alignment
Determine Q-BPM-to-quad offsets using quad-shunting

Establish 'Gold' Orbit
Use DF Steering (if nec.) to find low dispersion orbit

Hourly
Methods from SLC & ASSET
Non-invasive to Luminosity

Steer to Gold Orbit
Use quad movers to steer

Align structures to orbit
Use S-BPMs to center struct.

Tune Emittance bumps
Use ε-wires to opt. ε

Lock Beam-based Fbck.
Maintain orbit with feedback

LEP approach to BBA

- Use sub-tolerance synchronous excitation
  - 17 Hz on quad windings
- synchronous beam response proportional to actual beam offset
- compare beam response observed to that predicted by offset estimated from nearby BPM
- similar to ‘dither’ feedback used at SLC
- requires extra precision margin
  - beyond that required for normal beam tuning

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

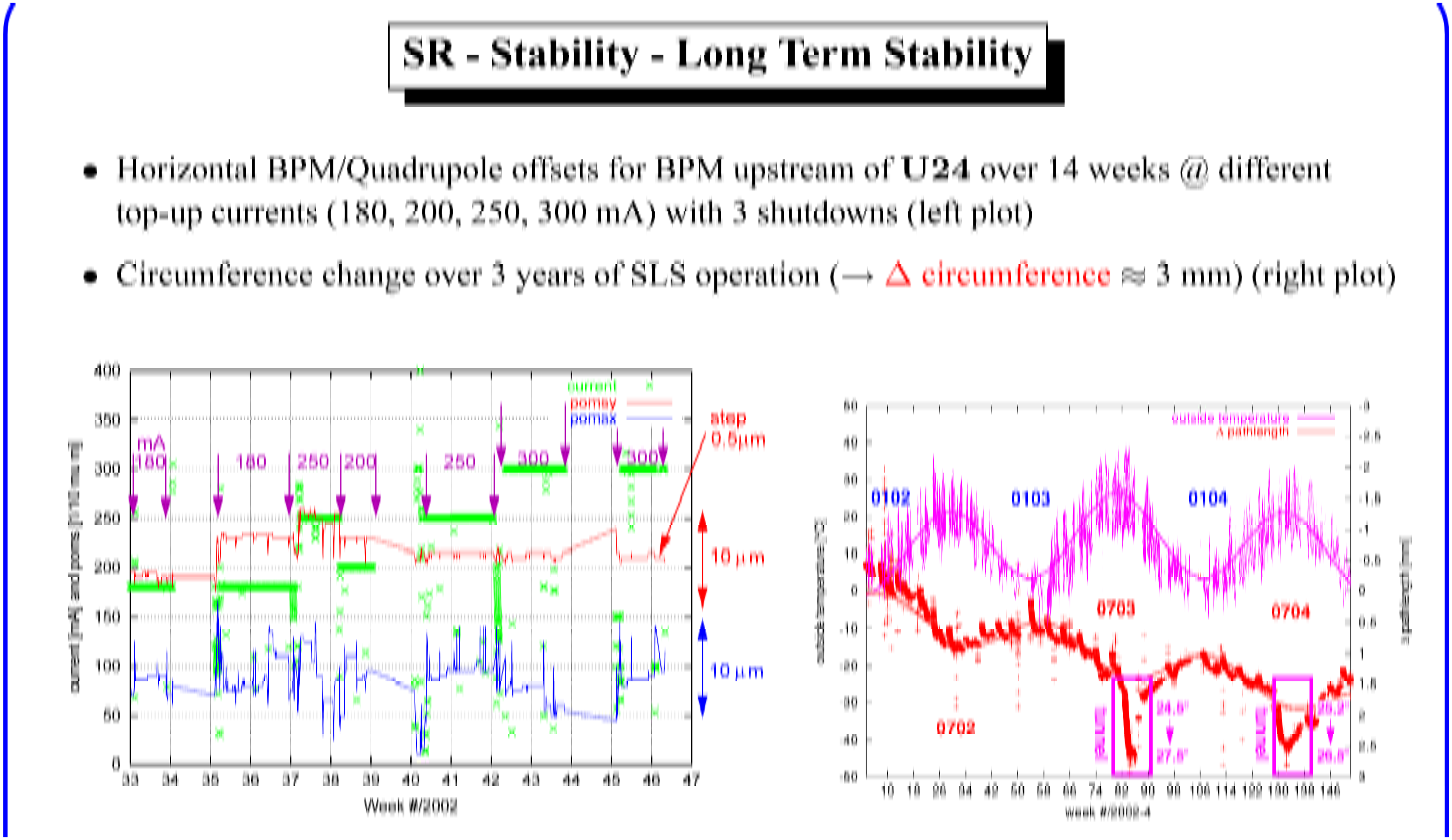
hours

days

weeks

years

Data from the Swiss Light Source (PSI)

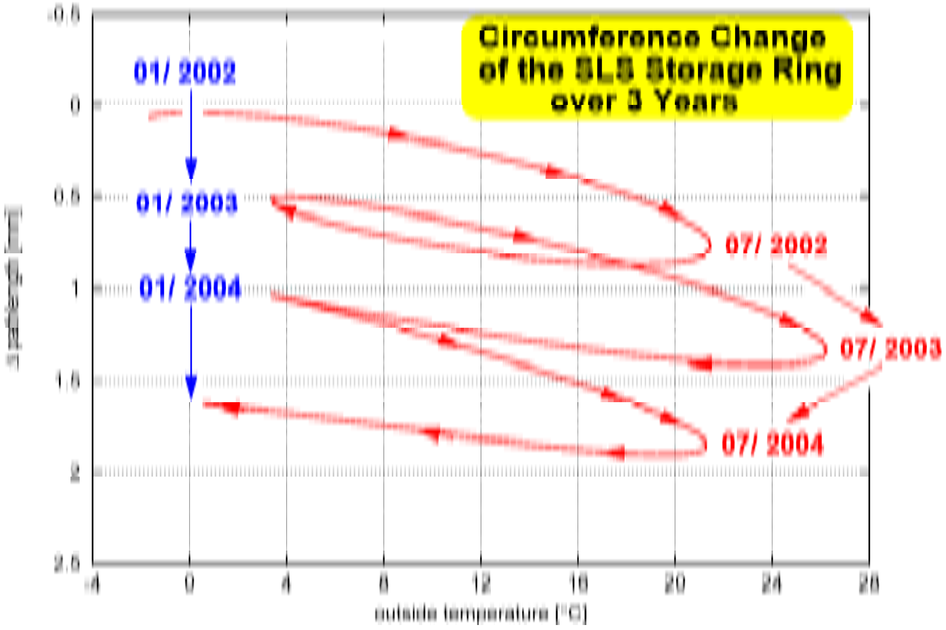


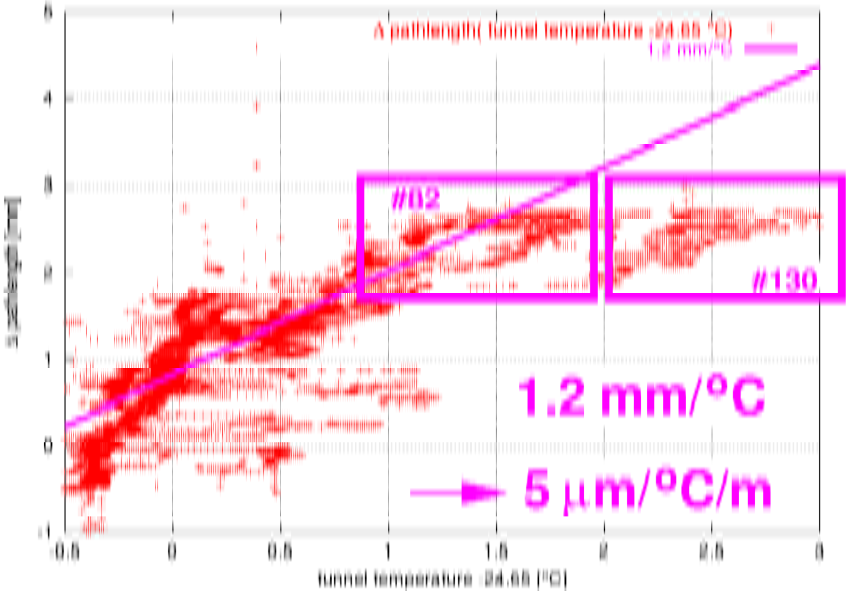
SR - Stability - Long Term Stability

- 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)

SR - Stability - Long Term Stability

- Fitted circumference change over 3 years of SLS operation (→ Δ circumference ≈ 2 mm) as a function of the fitted **outside temperature** (left plot)
- Circumference change as a function of the average **tunnel temperature** (right plot)



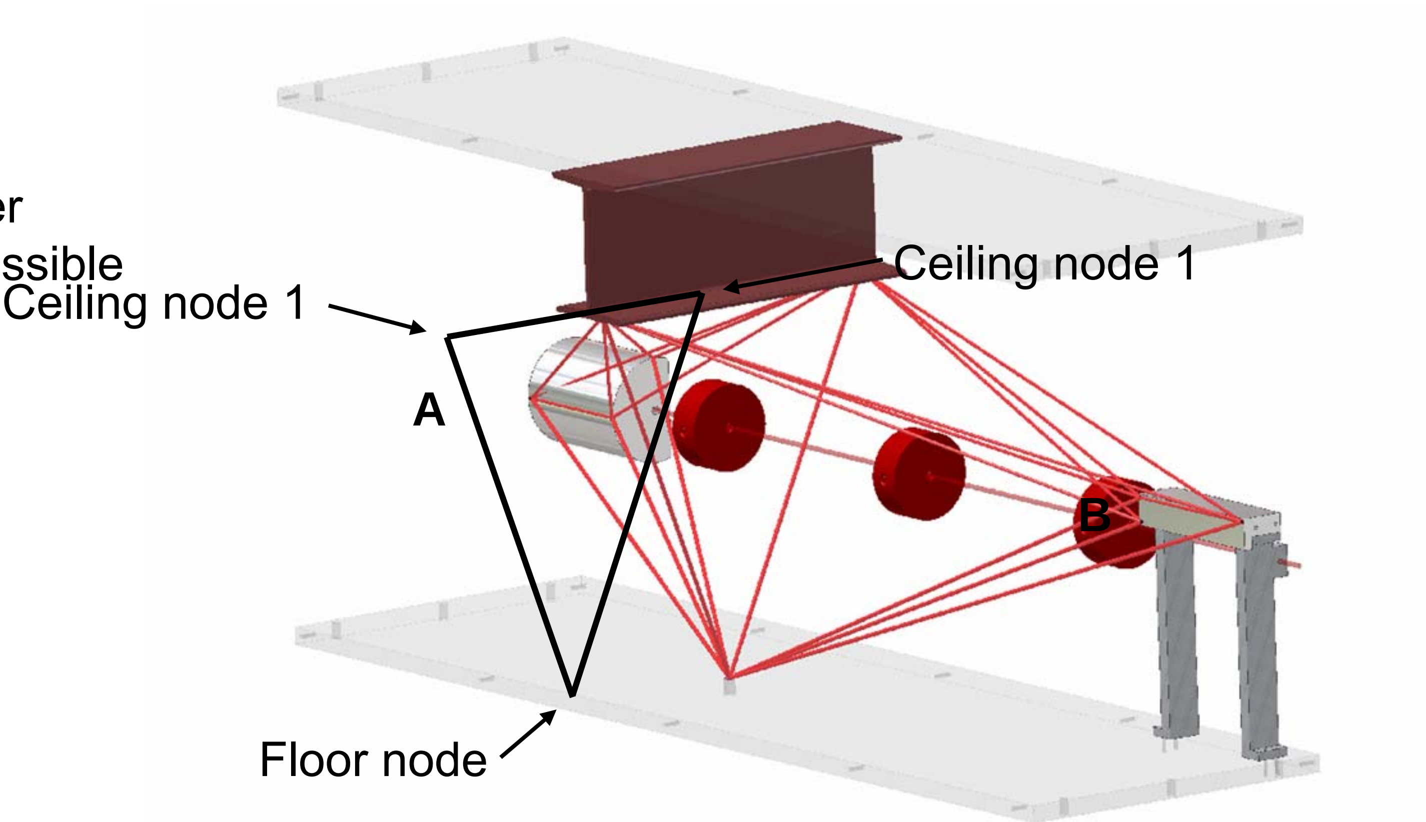


- Stabilization of the **tunnel temperature** to ≈ ±0.1° is needed to guarantee sub-micron movement !

Using laser interferometers to connect beamline systems:

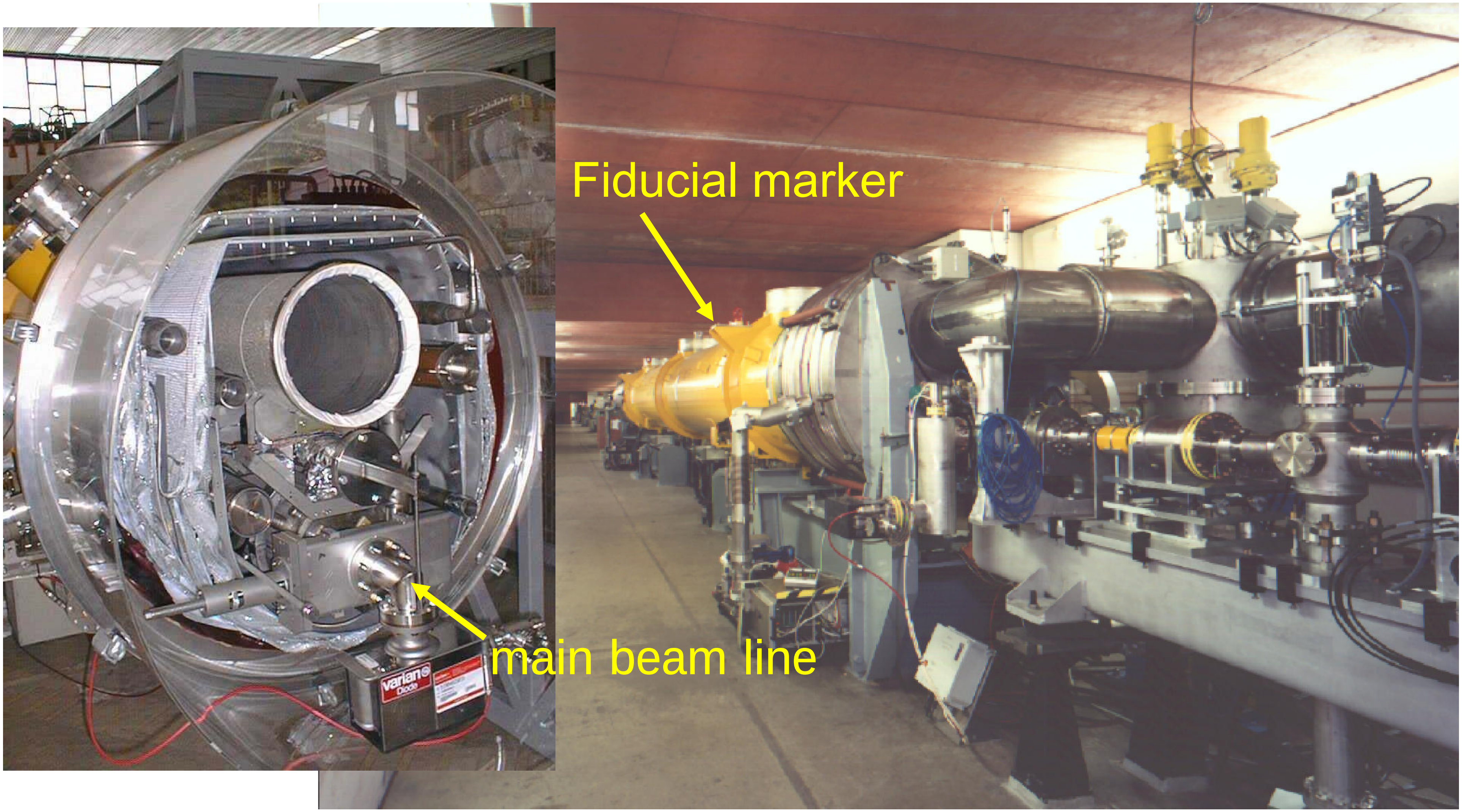
Automatic alignment:

10 nanometer resolution possible

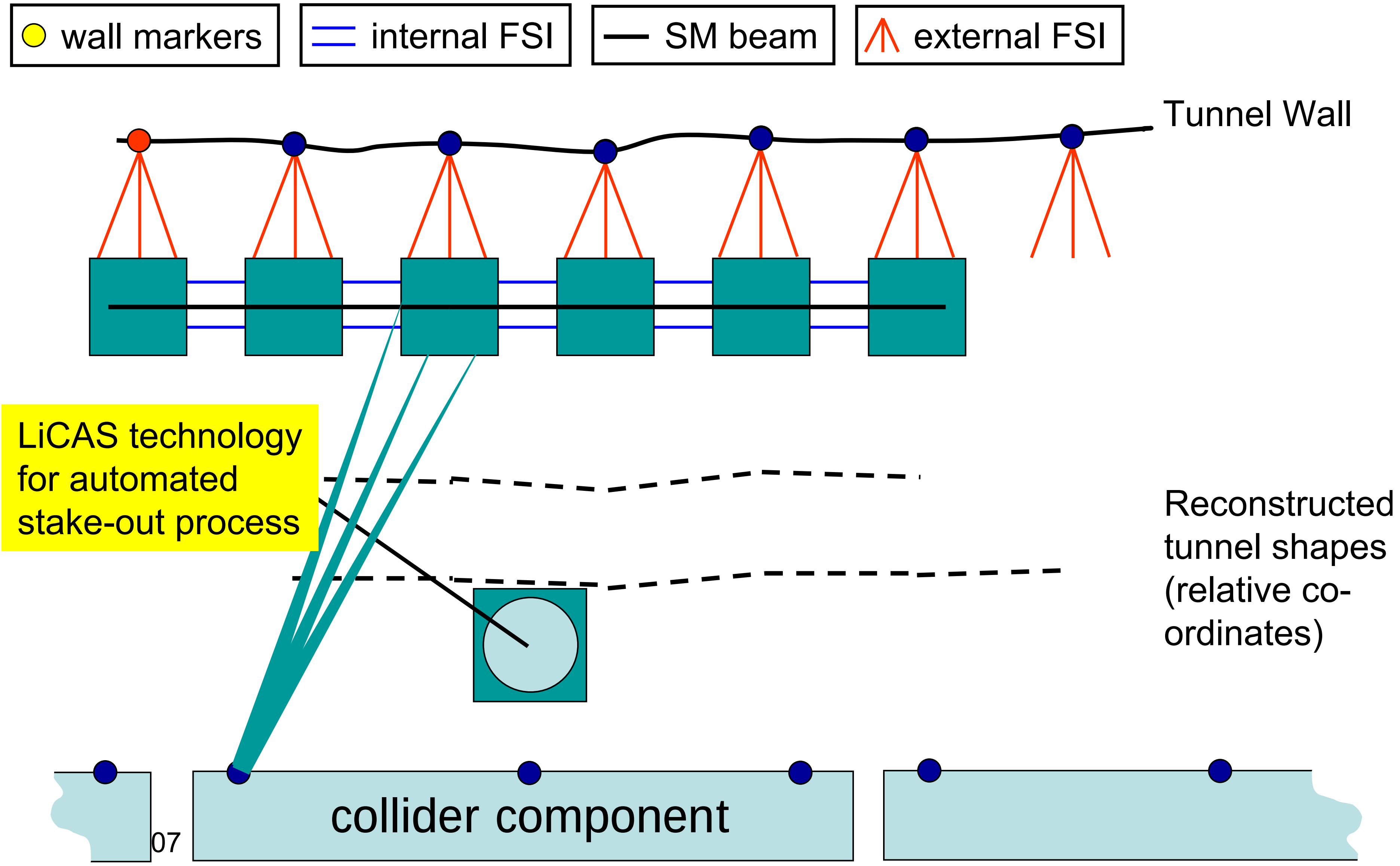


- A sequence of nested tetrahedra; forms a sort of infinitely stiff truss
- Information related via central triangle

LC Survey Problem



Another idea: use a train of cars, locked to each other with laser interferometers

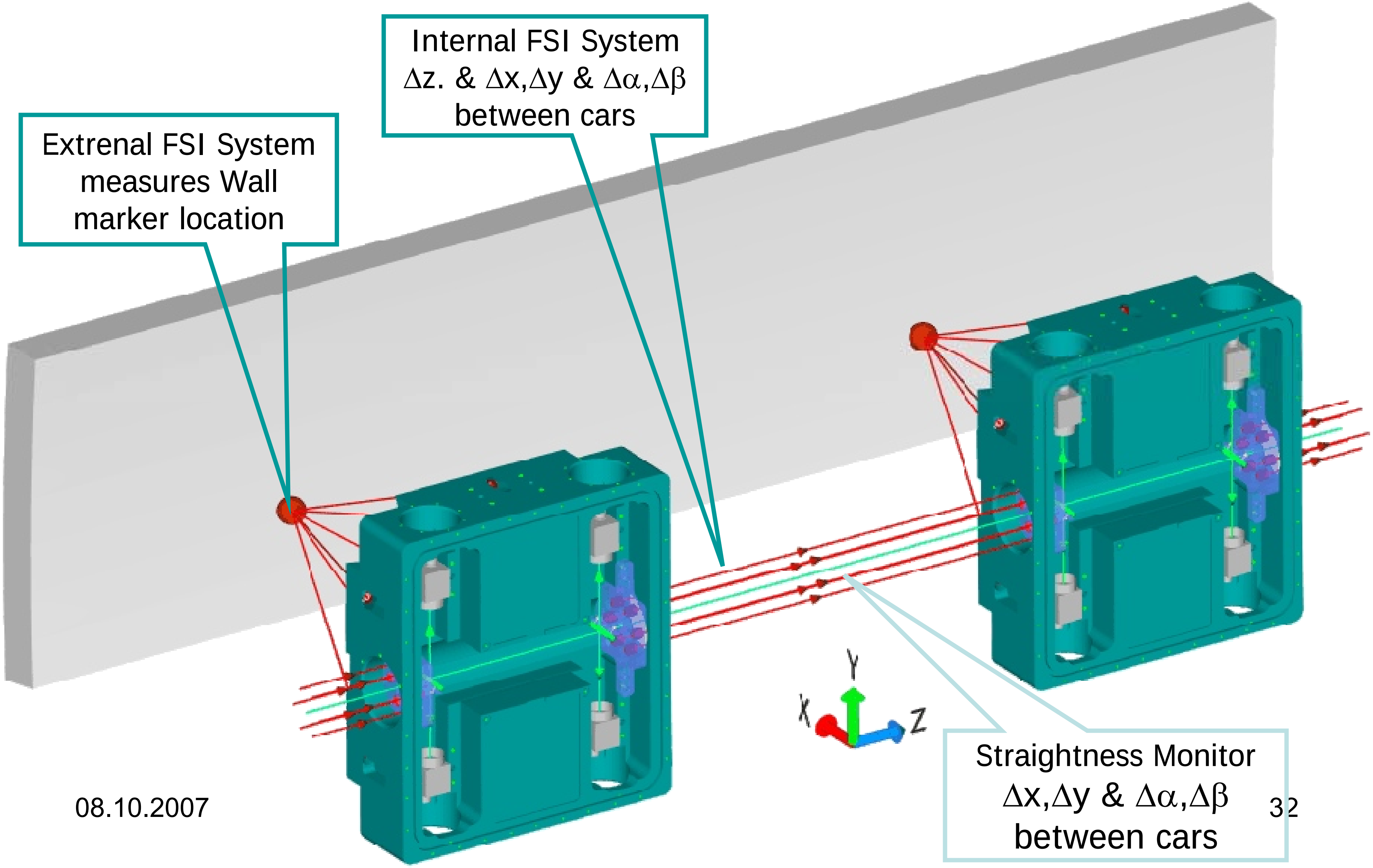


LiCAS technology for automated stake-out process

Reconstructed tunnel shapes (relative co-ordinates)

Developed for LHC
'ATLAS'

Measurement Principle: Frequency Scanning Interferometry (FSI)



Extrenal FSI System
measures Wall
marker location

Internal FSI System
Δz. & Δx,Δy & Δα,Δβ
between cars

Straightness Monitor
Δx,Δy & Δα,Δβ
between cars

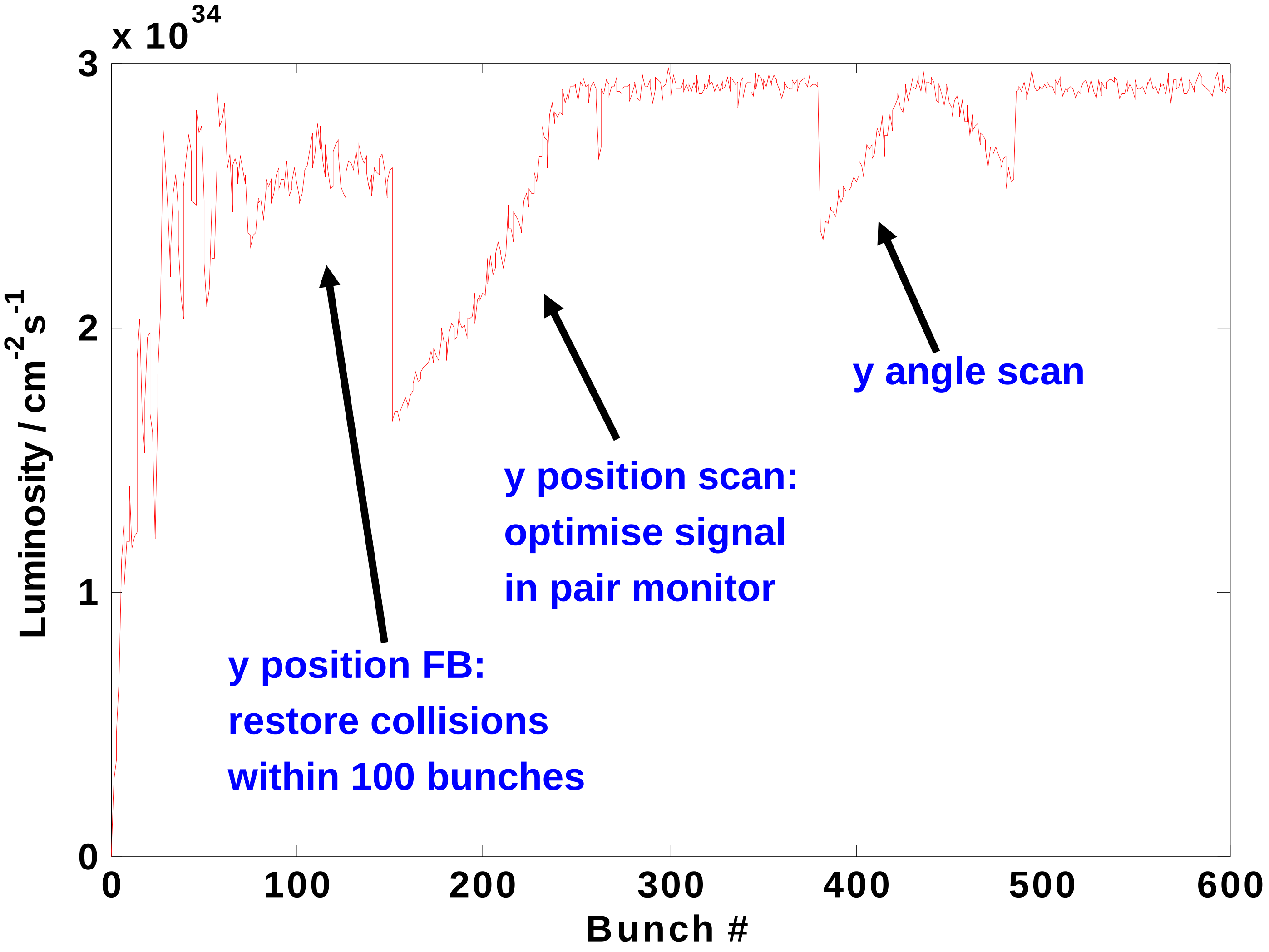
Tune up process – beyond BBA Diagnosis and other procedures:

- 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

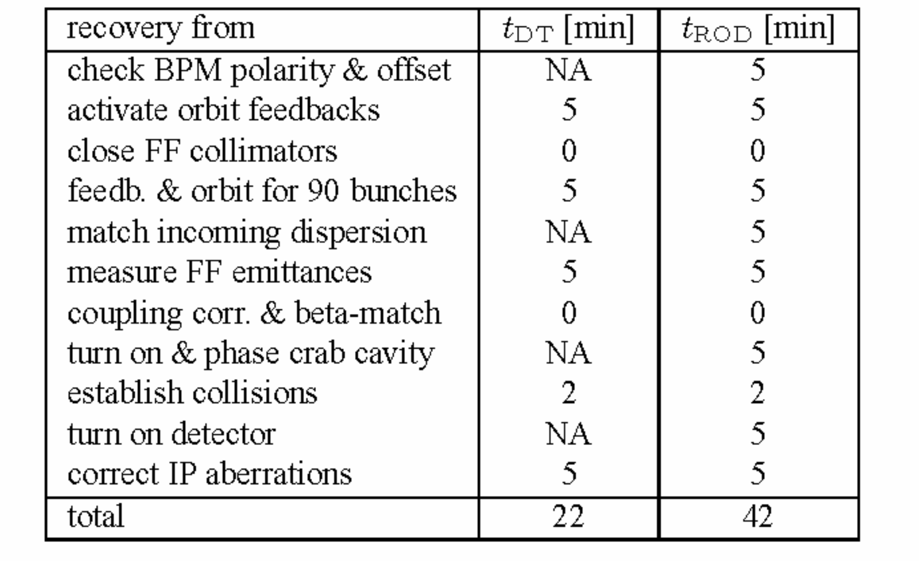


y position FB:
restore collisions
within 100 bunches

y position scan:
optimise signal
in pair monitor

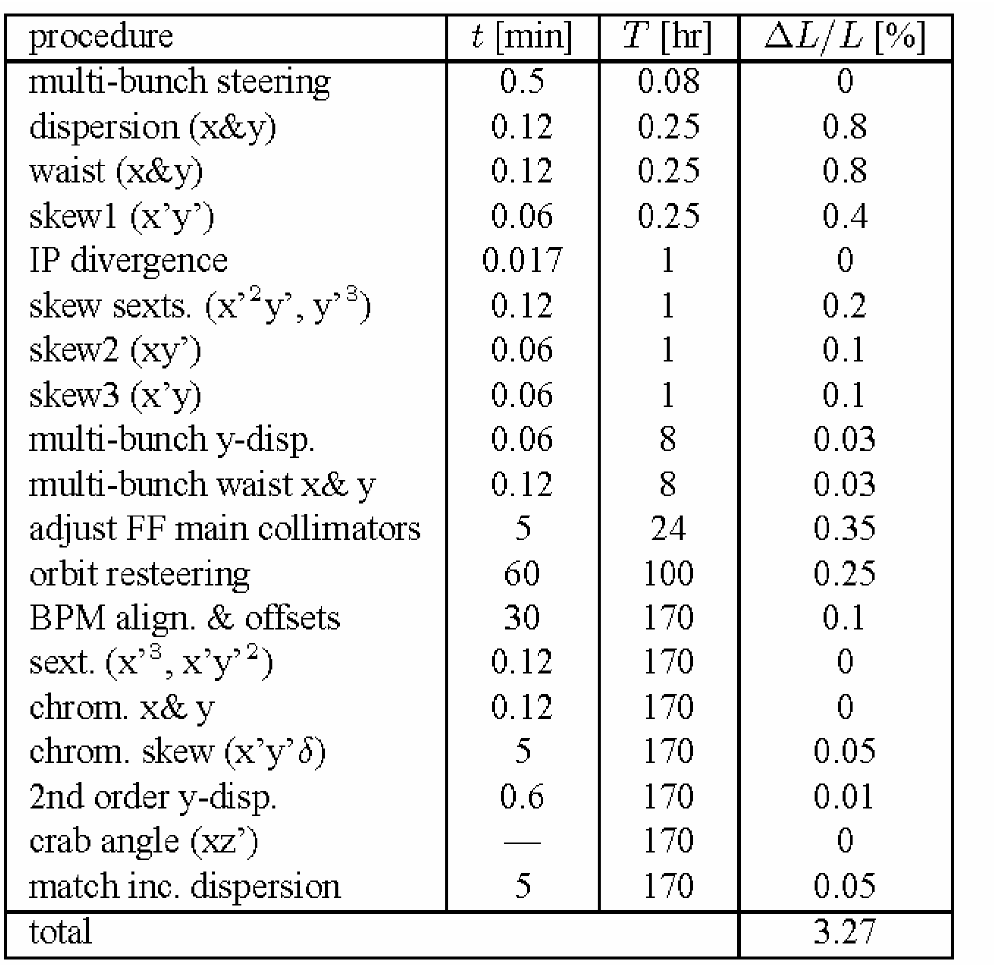
y angle scan

Tables of tuning process - BDS



recovery from	t_{DT} [min]	t_{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

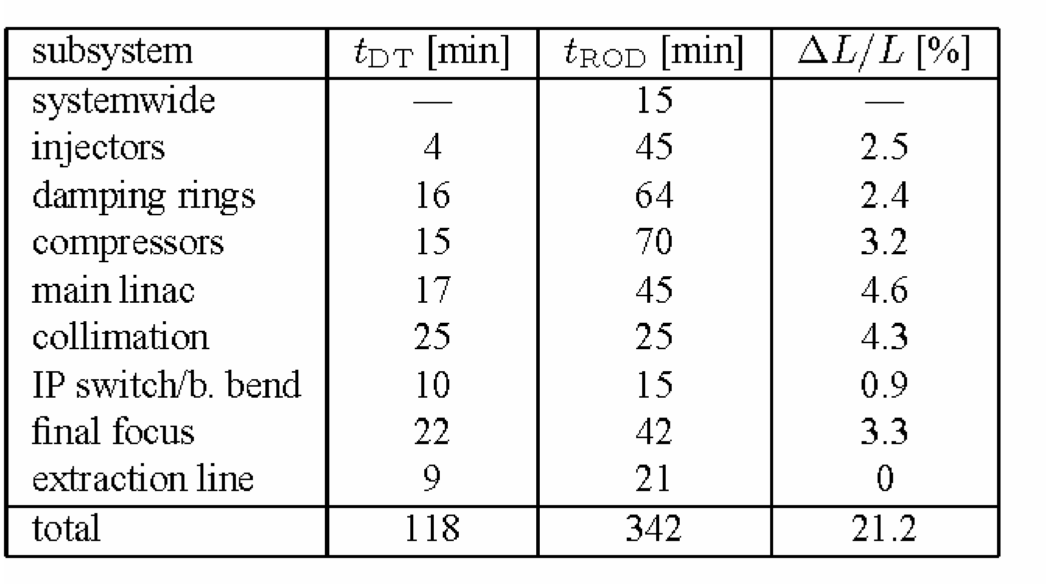
- Showing
  - the time it takes per BDS procedure after 1) short downtime and 2) day-long downtime
  - continual BDS tuning required – the time it takes; associated interval and expected luminosity impact



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'^2y', 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 ($x'y'\delta$)	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 - LHC example

- much of the tuning time at SLC was adjusting collimators to reduce detector backgrounds
- typical distances between collimators is large, position tolerances are tight and relative alignment tolerances are also tight

- LHC will have primary, secondary and tertiary collimation
  - positions of the secondary/tertiary collimators will depend on the position of the primary and the trajectory between
  - the standard process of ‘touch’ and move back will be possible at LHC because of MPS
  - collimation tuning will require a special machine mode; with low power pseudo-benign beam

Sensitivity example:

- In the BD system, the un-normalized vertical emittance is 4 fm-rad
- with 40000 m beta, sigma_y~ 50 um
- rms transverse momentum is 250 eV

- The largest source of electric field in the BD is the beam itself
  - 250 V is quite small

Availability

- Separate T_{UM}=*unscheduled maint and* T_R=*recovery* from MPS and tuning
  - These are directly related to the engineering / hardware effort
  - Subject to analysis to evaluate level of required performance and impact of basic design decisions:
    - One tunnel vs two
    - Damping rings in the same enclosure as linac
- Typical components:
  - accelerator power supply MTBF 2e5 hours (at SR sources)
    - 1000 → one failure per week
  - Dried electrolytic capacitors

Availability and large systems:

- accelerators are some of the most complex machines ever built.
- in ILC we have 1,000,000 components, with varying failure effects
  - there are 120 motors per RF unit (80000 motors total in the linac alone)
  - assume typical MTBF of 500,000 hours – two failures per hour
  - if each takes ½ hour to repair – there will be no operation
  - (neglecting recovery time)
- We don’t expect to make perfect components with infinite lifetime
  - Redundancy is our strategy – exp for critical items
  - (e.g. many BPMs, but design so accel doesn't break when one is broken
  - (can mention difficulty of keeping lying BPMs from causing downtime due to steering and feedbacks),
  - energy headroom with energy feedbacks,
  - redundant regulators in power supplies,
  - hot spare water pumps).
- recovery time may be extended due to thermal time constants

Availability evaluation - based on simulation

- for simple systems, like a small accelerator, combine the single component performance, a simulation is not needed – spread sheet is ok.
- for complex systems, with large scale sub-systems (DR, linac, positron), develop an ‘operations availability’ simulation
- based on a machine description ‘deck’, which includes:
  - redundancy and ‘overhead’
  - recovery
  - machine time management (machine development, use of repair personnel)
    - for example, in the one tunnel model, can only replace a limited number of klystrons per day.
  - failures that only degrade, as well as more serious failures that terminate operation
  - access constraints (e.g. the beam can be on in zone A with people in zone B)
    - this is used to determine civil layout constraints
  - actual MTBF and MTTR from existing machines (DESY, SLAC and Fermilab)
- simulation is best suited for sequencing tasks
  - this is operations engineering
  - complex ‘management’ simulation code

Jobs on the May 21, 1996 ROD list

#	Area	ROD #	* ONGOING	Work Title	Person Resp.	Shop1	Shop2	Access	L & T	O H P S	E S W C F	R S W C F	A S W C F	R W P	R R S	Time [hrs]	CATER	STATUS	Start Time
4445	Sect. 0/1	142		Check alignment of E+/E- recombiner magnet & section dnstrm.	M Pietryka	MEA		Permitted	☒	☒	☒	☐	☐	☐	☐	4		Scheduled ML	
4460	Sect. 0/1	142		Inspect all PROF's in LI00/01 for remoting of cameras	V Brown	CTL		Permitted	☒	☐	☒	☐	☐	☐	☐	0.5		Scheduled ML	
4487	Sect. 0/1	142		Replace G10 insulator and jumper on Q142 coils.	Gaxiola/G. Craft	MFD		Permitted	☒	☐	☒	☐	☐	☐	☒	.5		Scheduled ML	
4492	Sect. 0/1	142		Remove spare Sec2-30 Feducial Generator from Sec.0 for repair	D Bernstein	CTL		Any	☐	☐	☐	☐	☐	☐	☐	0.25		SCHEDULED ML	
4047	NDR	142		Inspect DIP Pigtails and Replace as Needed	Weinberg/Ratcliffe	MFD	ME	Permitted	☒	☐	☐	☐	☐	☒	☒	3		Scheduled ML	
4099	NDR	142		Install Lead Bricks to Shield Pre-amp for DR13 toroid 040	Thompson	CTL		Controlled	☐	☒	☐	☐	☐	☒	☐	2		Scheduled ML	
4254	NDR	142		Replace RF Cavity HIPs with Faster Ones (Requires Venting and Pulling HV Cables)	Gaxiola/Zdarko	MFD	CTL	Permitted	☒	☒	☒	☐	☐	☒	☐	6		Scheduled ML	
4255	NDR	142		Replace Reference Plane #7 in Vault girder 6 (pulls down SAM)	Nguyen/Tavares	CBL	CTL	Permitted	☐	☒	☐	☐	☐	☒	☐	2		Scheduled ML	
4256	NDR	142		Restore TCs 59X_NCAV and B350_AIR to Their Normal Locations	Rack/Tavares	CBL	AM	Permitted	☐	☒	☐	☐	☐	☒	☐	0.5		Scheduled ML	
4267	NDR	142		Run a New Signal Cable for DR12 AMPL 79 (RF monitor)	Mitchell/Tavares	AMRF	CBL	Controlled	☐	☒	☐	☐	☐	☒	☐	4	44945	Scheduled ML	
4296	NDR	142		Replace Lens for NDR SLM Optics	Vergne Brown	CTL		Controlled	☐	☒	☐	☐	☐	☒	☐	0.3		Scheduled ML	
4297	NDR	142		Tune PFN for NRTL Compressor 1-8 (Today 5/23/96)	Hilliard	AMW		No	☐	☐	☐	☐	☐	☐	☐	2		Standby ML	12:00
4319	NDR	142		Install New Holding Ion Pumps Near the Ring Kickers	Gaxiola	MFD		Permitted	☒	☒	☒	☐	☐	☒	☐	6		Scheduled ML	
4320	NDR	142		Supply Cables to New Holding Ion Pumps Near the Ring Kickers	Tavares/Zdarko	CBL	CTL	Permitted	☒	☒	☒	☐	☐	☒	☐	6		Scheduled ML	
4323	NDR	142		RGA Scan - Requires Closing Ring Valves and Turning Pumps	Gaxiola	MFD		Any	☐	☐	☐	☐	☐	☐	☐	1		Standby ML	
4371	NDR	142		Install Valves Near Septa for Future RGA (while vented)	Ratcliffe/Eriksson	MFD	ME	Permitted	☐	☐	☐	☐	☐	☐	☐	1		Scheduled ML	
4373	NDR	142		Re-install Old Growler Magnet (while vented)	Gaxiola/Stege	MFD	AM	Controlled	☐	☒	☐	☐	☐	☒	☐	1		Scheduled ML	

Availability evaluation –

- based on monte-carlo random event generation
  - have to perform several runs to get a ‘reliable’ result
- includes operational requirements
  - machine development
  - entry requirements (radiation cool down)
  - limited number of people
- used to compare alternatives
  - common errors may cancel

Tunnel Configuration Study

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

Sensitivity Study

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
ILC5	ILC2 but with undulator e+ and keep alive e+ source 2	17.0	83.0	78.3	4.8	2.8	14.2	3.4
ILC17	ILC5 but no hot spare klystron/modulator where there are single points of failure	18.8	81.2	77.0	4.2	3.3	15.5	3.3
ILC18	ILC5 but 'commissioning' (0.5xMTBF, 2xMD, 2xTuneTime)	44.9	55.1	45.5	9.6	4.9	40.0	4.2
ILC19	ILC18 but no keep-alive e+ source	52.8	47.2	25.4	21.8	2.7	50.1	3.5
ILC20	ILC5 but MTTRs twice as fast	12.9	87.1	81.8	5.3	2.2	10.7	3.4
ILC21	ILC5 but recovery time halved	12.6	87.4	82.5	4.9	2.6	10.0	3.6
ILC22	ILC5 but 3 hour cooldown instead of 1	18.2	81.8	77.1	4.7	2.8	15.4	3.3
ILC23	ILC5 but with DR in separate tunnel	16.9	83.1	79.0	4.1	3.4	13.5	3.4

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%

LEP: Reliability of magnet power converters

CERN power converter = power supply

- Faults during beam operation were considered for all fills that led to physics (seen from accelerator operation)
- MTBF: based on all faults
- MTBF1: do not count multiple f … short period, assuming that the PC … the first fault
- Comment: without power converters for orbit correc…
- For the high current power converters, MTBF somewhat less
- Comparison with other numbers – be careful

Hot from the press

F.Bordry: main Q and B power converters at LEP 35-40 khours

SPS orbit corrector converters: 300-400 khours

Year	Running time (h)	# PC faults	MTBF (kh)	MTBF1 (kh)
1998	2481	13	150	200
1999	2554	25	80	110
98 & 99	5035	38	110	150

J.Wenninger

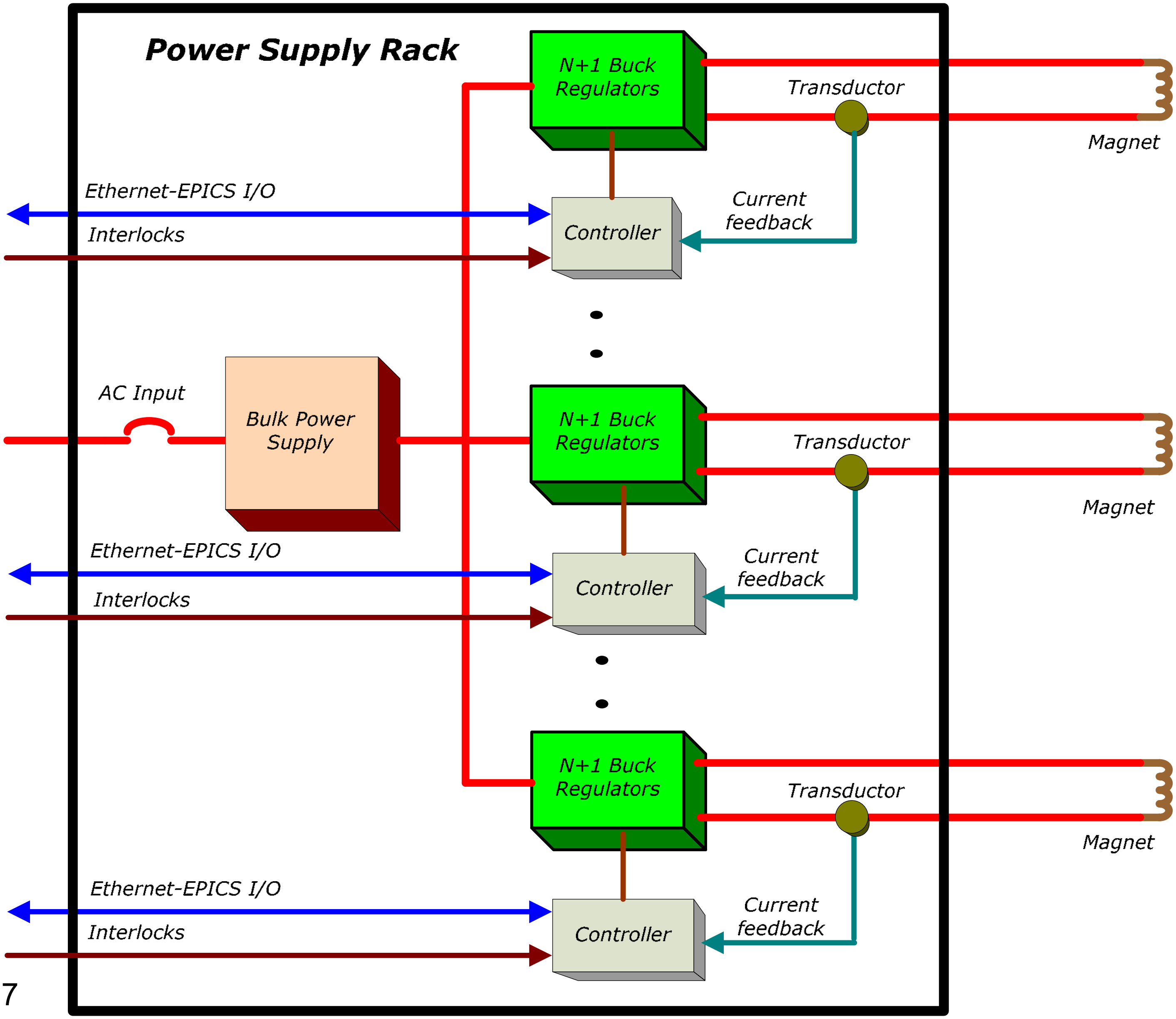
Klystron management

- 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.

ATF2 project and redundancy

- Target performance for ILC is far beyond present performance
- 5 x for power supplies (10 x for SLAC power supply performance)
- Solution is not to reduce MTBF of a given power supply, rather to reduce to zero the time to replace

Phase 1 - Typical System Block Diagram



Example of component failure – SCRF tuner

- the stepping motor for the blade tuner can fail
  - has happened at TTF (‘human error’… design flaw)
- Failure mode: stuck motor
- Failure effects:
  - cavity resonance is shifted from nominal, usually
    - pretty benign; but there is no acceleration
  - sometimes – may be stuck on resonance (not really so unlikely)
    - keeps working
    - If, in addition, this is a ‘low field’ cavity, the passage of the beam may cause breakdown
- Repair scenario
  - take out the module
- CEBAF linac – uses a mechanical shaft feedthrough so the motor is not in the cold volume
  - typically, the shaft connection fails

Main linac failure modes

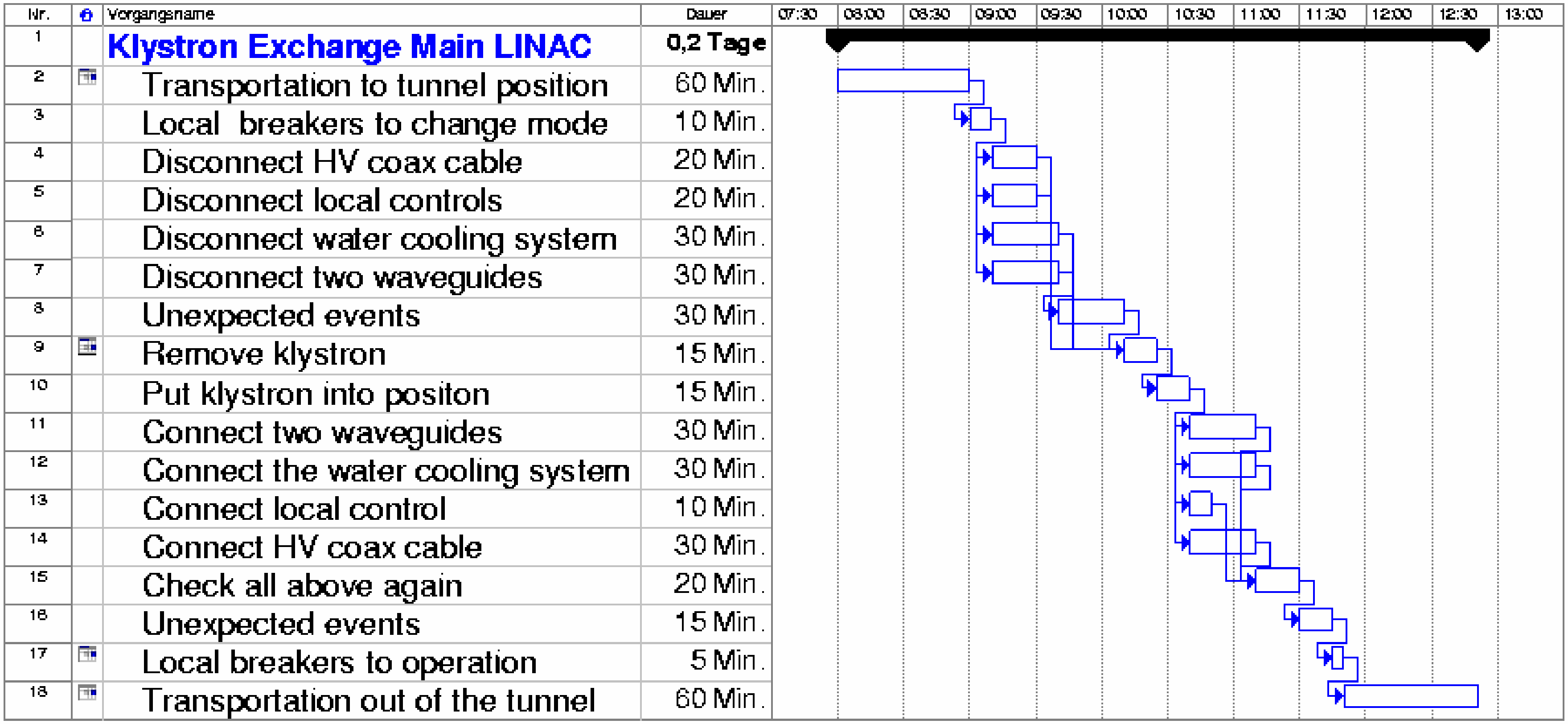
- The primary linac function is to add energy
- redundancy is applied with klystron ‘overhead’
  - typically a few percent
  - losing a klystron or two does not cause linac ‘failure’
- more serious failure modes:
  - cryo cavities – also can lose a few
  - cryo system
  - vacuum leaks
  - tuner systems
  - coupler breakdown
  - waveguide faults
  - magnet / power supply failures

Consumables

- 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 target itself
  - Hoses, cables,

Klystron Replacement for the TESLA Linear Collider

- teams of 3-4 people will exchange a klystron within a few hours; klystrons will be equipped with connectors (HV, controls, cooling, waveguides) which allow fast exchange of a klystron



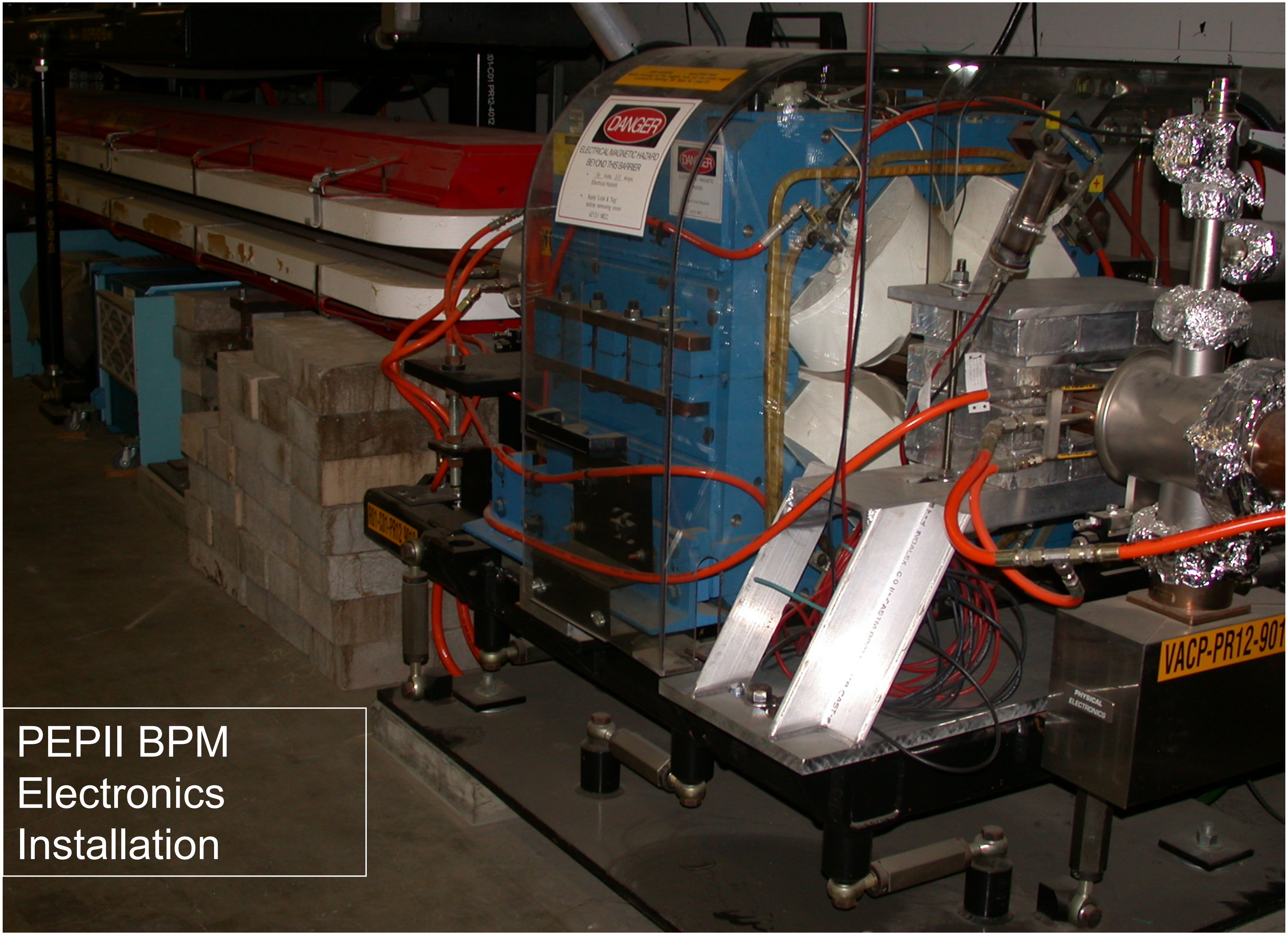
Nr.		Vorgangsname	Dauer
1		**Klystron Exchange Main LINAC**	**0,2 Tage**
2		Transportation to tunnel position	60 Min.
3		Local breakers to change mode	10 Min.
4		Disconnect HV coax cable	20 Min.
5		Disconnect local controls	20 Min.
6		Disconnect water cooling system	30 Min.
7		Disconnect two waveguides	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.

Radiation in the main linac tunnel

- Typical cavity performance will be limited by field emission
  - an electron beam is generated, which usually does not go beyond the next focusing magnet
- the field emitted beam will cause radiation in the tunnel – beyond that caused by high power primary beam halo
  - for a 10 um beam, the Nb cavity vacuum enclosure is at 3000 sigma
- Field emission is an exponential function of the accelerating gradient
  - some cavities have field limits close to the onset of field emission
  - others can go well beyond
  - These can cause substantial radiation in the tunnel
  - SNS: 100 Sv/hour

PEPII BPM Electronics Installation → after 2004 …

PEPII BPM Electronics Installation



PEPII BPM
Electronics
Installation

Controls

- Purpose of controls to establish equilibrium
  - In a storage ring, the closed orbit condition helps to do this directly
- Controls makes precision machines like LC possible because the extreme spatial tolerances, stability tolerances
- ever-growing list of responsibilities:
  - optimization ‘feedback’
  - failure effect mitigation
  - remote diagnosis → the scale of the ILC prevents ‘quick checkout visits’
  - trend analysis
  - model / simulation integration at all levels

Remote diagnosis and operation

- Global Accelerator Network Project: Led by DESY

Imagine …

You are a non-local expert and you have to assist a local technician, engineer or accelerator scientist in

- Trouble shooting
- Remotely assisted repair
- Accelerator studies
- Tune-up (components or beam parameters)
- Setting-up a test (new equipment or entire accelerator)
- Commissioning (new equipment or entire accelerator)
- Equipment maintenance

Imagine …

You are sitting in front of your desktop computer and your local partner is at or in

- an accelerator control room
- a laboratory or workshop
- a test-stand
- a power supply hall or klystron gallery
- an accelerator tunnel
- …

Imagine …

- You have been called up on short notice.
- You have to access the local control system and data services, but
  - the appropriate controls software client is not installed on your computer.
  - firewall settings prevent you from accessing the local network.
- You have to analyze a trace on a scope recently connected to the local test-stand.
- You have to inspect visually a fault or to view a document.
- You have to guide your local partner to press the right button.
- …

MVL - A Virtual Room

- Provides communication with good audio and video quality
- Provides familiar look-and-feel and simple handling
- Grants access based on world-wide standards

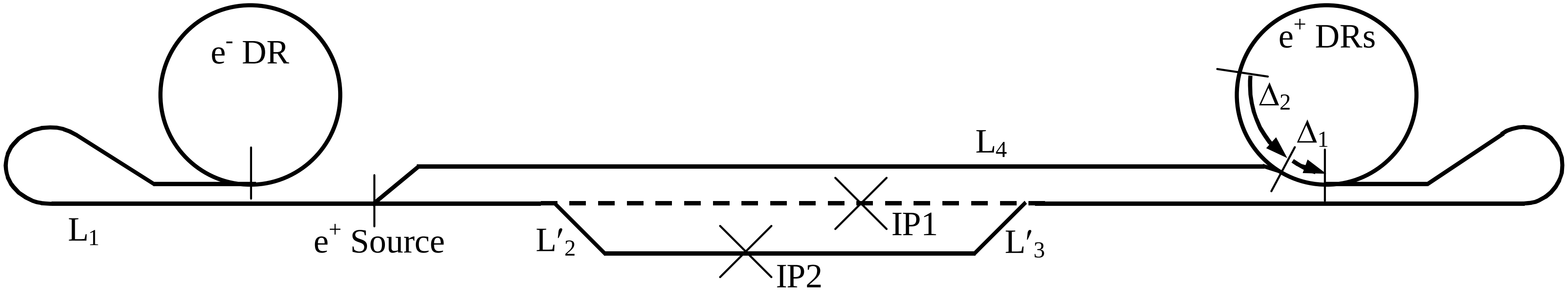
- Generates the impression of being at the same location
- Provides proper awareness of remote presence

- Provides access to control system(s) and data services
- Provides seamless integration of mobile measurement equipment

- Provides access to groupware and information services

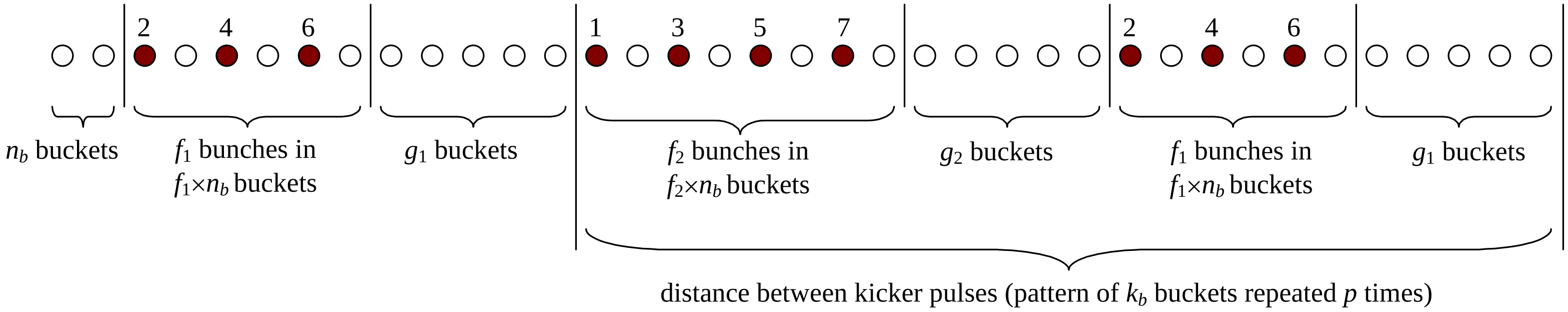
Timing system

- Constraints on layout
  - bunches must collide at IP
    - (there are 2 – with different path lengths)
  - freshly made e+ must go into the space recently vacated by collision bunch –
    - ~ arbitrary initial constraint
    - (must operate in single bunch mode)
  - *The integrated path length must be an integer number of ring turns*
  - Damping ring kicker performance is a key part
  - there are other solutions – an exercise in numerology



Timing constraints:

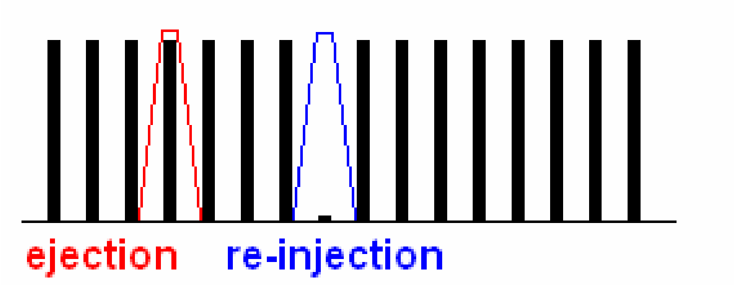
- the damping rings' circumference and RF frequency;
- the fill patterns in the damping rings (e.g. presence of ion-clearing gaps); (here is a non-functional example)

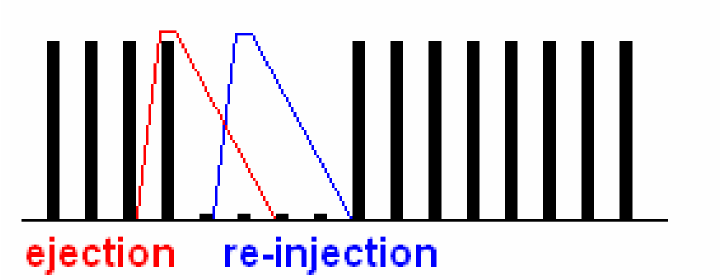


- the lengths of the beamlines connecting the damping rings with the sources (particularly the positron source) and with the main linacs;
- the longitudinal separation of the two interaction points;
- the locations of the damping rings within the accelerator complex.

Damping ring injection and extraction

- Typical kickers have much longer fall time than rise time
  - e.g. due to parasitic capacitance / inductance
- injection / extraction into the same bucket forces symmetric behavior
- sliding gaps





Safety – primarily radiation

- Radiation is proportional to beam power
  - residual activity also, with a different coefficient for proton beams and for different materials
    - Aluminum is very good,
    - Copper, iron, nickel are about the same
    - Nb ?
    - Rare earth materials (permanent magnets) can become very radioactive
- Prompt exposure and residual activity
- Comparison with other machines (LHC, MI)
  - typical proton machine limiting losses are 1W/m
- At ILC energies, synchrotron radiation can be above the neutron - liberating giant resonance
  - there is a lot more synchrotron radiation power than beam loss power
    - residual activity can be large

Maximum Allowable Radiation Levels

	DESY (*1)	TESLA TDR	KEK (*2)	SLAC (*3)	FNAL (*4)
Standard	20 mSv/yr	**1.5 mSv/yr**	20 mSv/yr		50 mSv/yr
Fertile women	2 mSv/month		6 mSv/yr 2 mSv/3months		
Pregnant women	1 mSv /pregnancy		1 mSv /pregnancy		5 mSv /pregnancy
Operating Conditions					
Normal			20 uSv/hr (1 mSv/week)	5 uSv/hr (10 mSv/yr)	
Mis-steering			20 mSv/event (20 mSv/yr)	4 mSv/hr	
System failure				**250 mSv/hr for max. credible beam** (30 mSv/event)	

(*1) Radiation Protection Instructions, DESY, June 2004
(*2) Radiation Safety Instructions, KEK, in Japanese, June 2004
(*3) Radiation Safety System, SLAC, April 2006
(*4) Fermilab Radiological Control Manual, FNAL, July 2004

Cost of operations

- People
- Power
- Water
- Consumables
- Overhead

- typical numbers:
    - people 80% of the total
    - power 80% of the remaining part (16% of the total)
    - consumables the rest

    - Overhead 30% of the total - a tax.

Power flow in the ILC

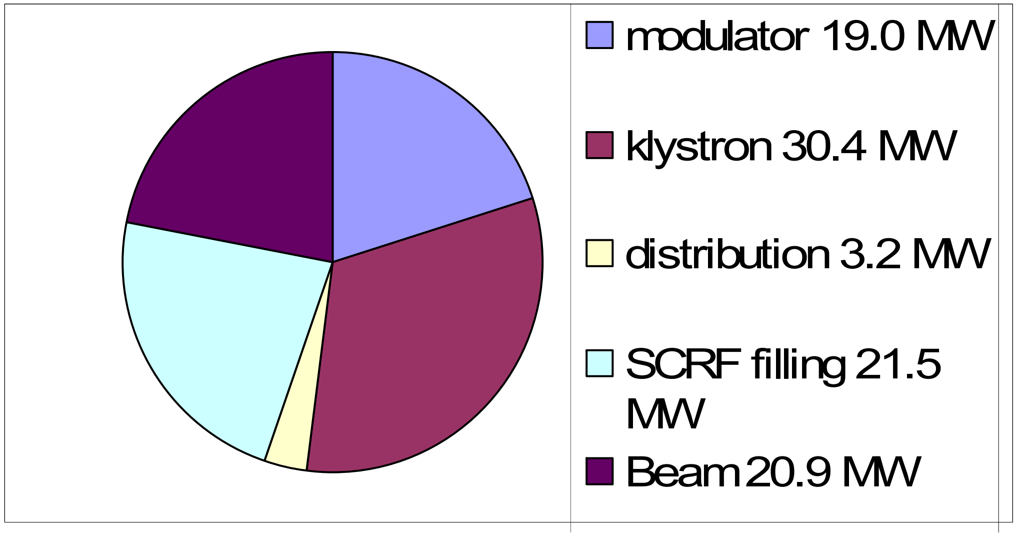
- Primary external cost; also a critical engineering effort
- ILC → 250 MW
  - Linac power 95 MW:
    - 15% loss for power modulators
    - 40% loss for RF source
    - 5% loss for distribution
    - 35% loss for SCRF filling (where does this power go?)
    - 21 MW for the beam
  - (The rest ?)
  - Two linacs combined have ~650 10MW peak power klystrons

    - 17% efficient → 10.5 MW beam at the end of each linac

Subsystem power

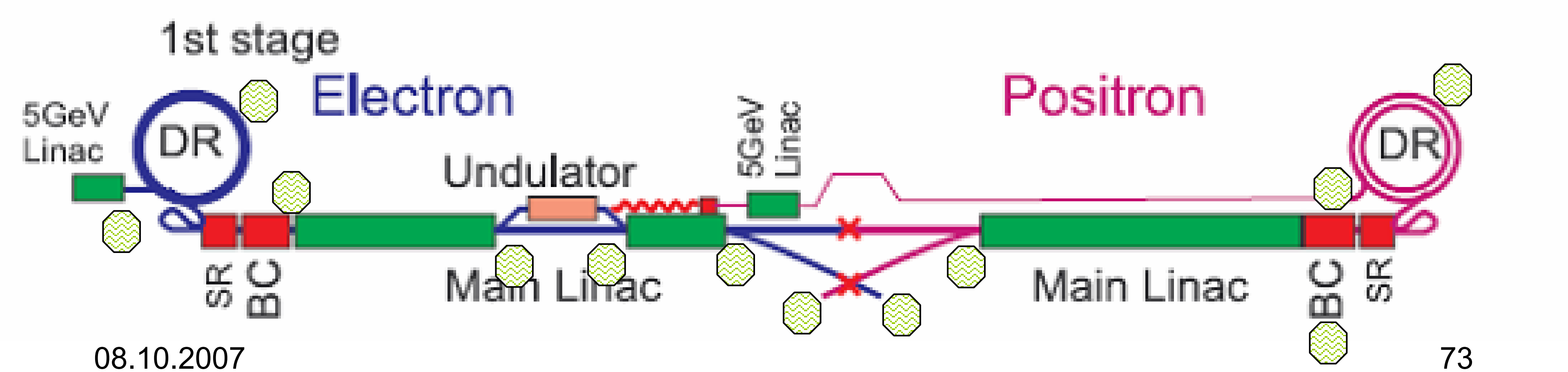
- Power to water: 75MW (for both 250 GeV linacs)
  - 3.6 KW / meter with full beam power
    - rises to 4.5 kW with 0 beam current → explain how the heat flow is changed…
  - Installed cooling is 82 MW
  - Usually can capture 90 to 95% with water system: 360 W/meter to air.
    - This is about 3 x worse than a typical synchrotron light source

- Air conditioning / air temperature control is required



Beam dumps

- Concentrated power and radiation
- Used to segment the system
  - 25 dumps; 12 over 0.25 MW capacity
- Installed capacity ~ 35 MW total
  - Almost 2 times the system power capability (why?)
  - Most ‘localized’ power deposition system



The water-based dump

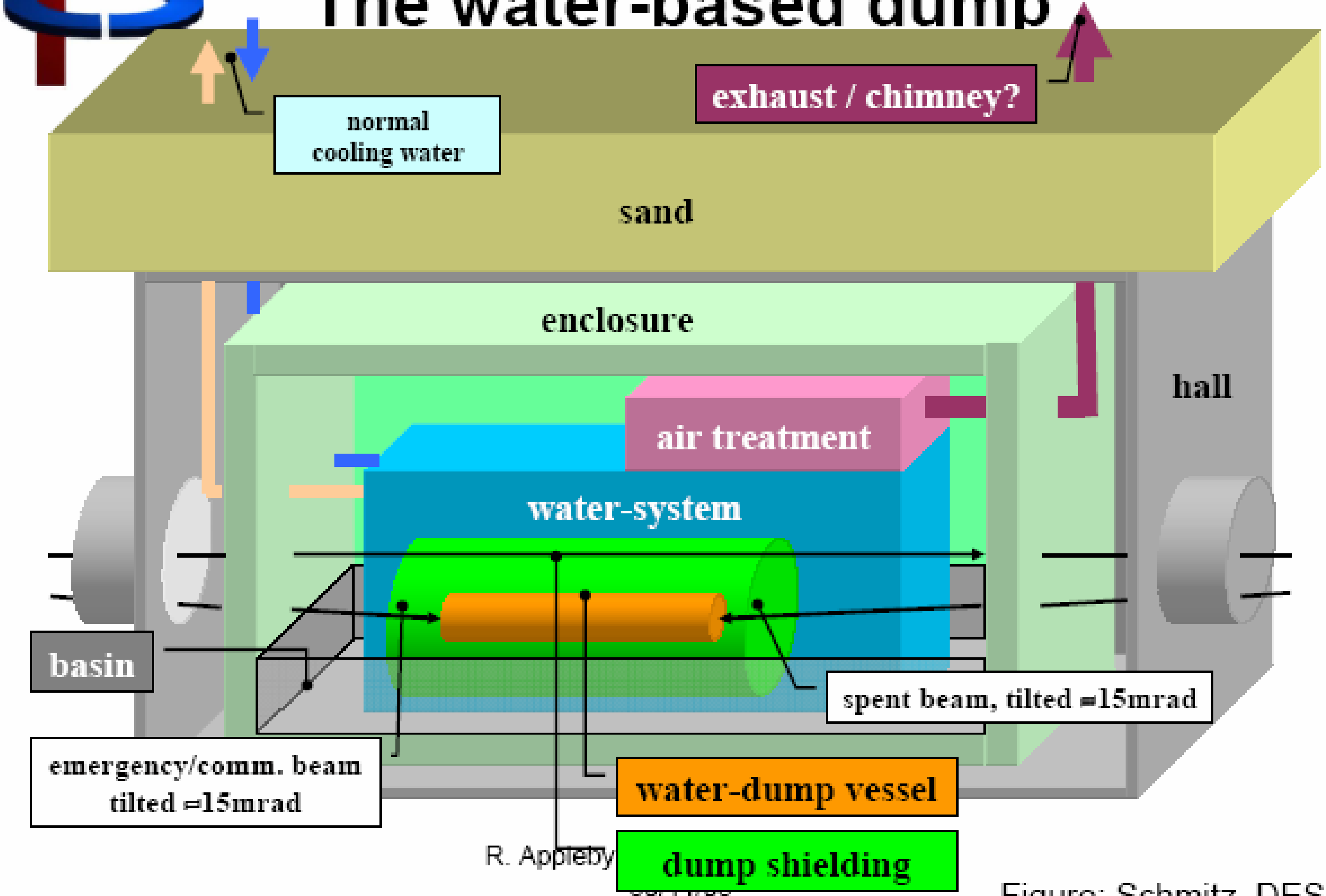


Figure: Schmitz, DESY

Material from:

- Nick Walker
- Eckhard Elsen
- P.Tenenbaum
- Tom Himel
- Phil Burrows
- Hans Weise
- Michael Boge
- Junji Urakawa
- Nobuhiro Terunuma
- Tor Raubenheimer
- Frank Zimmermann
- David Urner
- Armin Reichold
- Glenn White
- Rob Appleby
- Tom Lackowski
- Paul Bellomo
- Reinhard Bacher