Accelerator Reliability and Availability

F. Willeke

Joint Accelerator School

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Overview

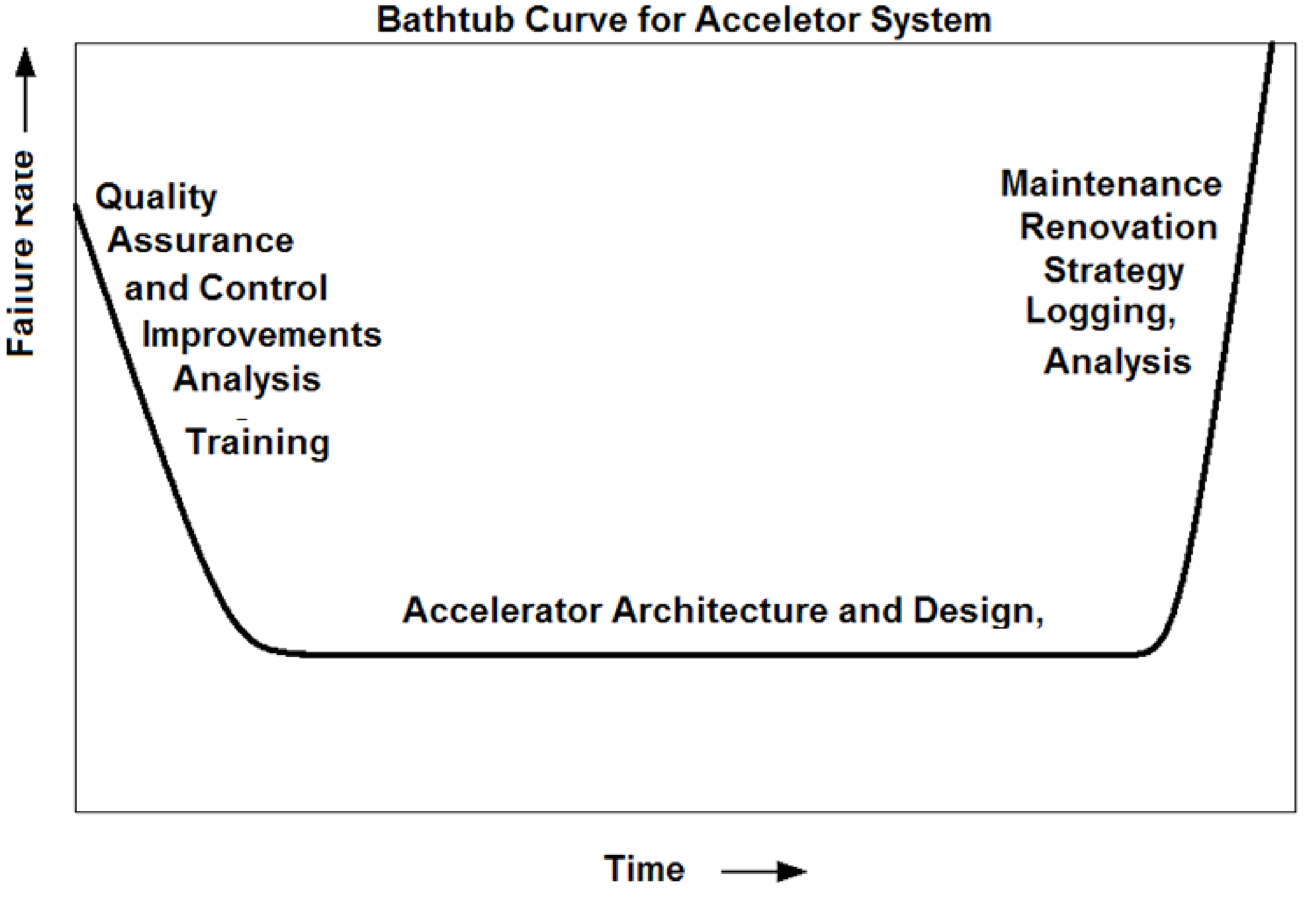
- Introduction
- Short summary of definitions and relationships
- Elements of high reliability design
- Achieving and maintaining high reliability in operations
- NSLS-II reliability estimate component reliability
- Availability simulations

Introduction

- Accelerators of multiple user facilities are required to be highly reliable and the beam is required to be available at scheduled times.
- Typical requirement of beam availability at scheduled times **Availability > 95%**

- The motivation for understanding reliability issues in accelerators is to
  - design accelerators for high reliability
  - develop (preventive) maintenance programs
  - Predict performance

Understanding Reliability



Understanding Reliability

- Methods for assessing reliability have been developed in and for industry and are well suited to assess reliability and lifetime of mass-produced units.
- Basis of modeling are idealizing assumptions: such as that failures interpreted as statistical events
- Accelerator systems are complex and very heterogeneous but the number of components of a single type is not as large as industrial production numbers (<~1000). Due to number of components being relatively small and the number of samples for assessing reliability even smaller need to be careful to draw conclusions..
- In reality failures are not uncorrelated related and it is complicated to include such coupling into reliability modeling.

Reliability modeling is a powerful tool, but you need to be ware of the limitations of the modeling,

Short Summary of definitions and relationships

MTBF (mean time between failures)

Average time between two failures of a repairable system

MTTR (mean time to repair)

Average time to recover from a failure

AVAILABILITY = 1 – MTTR/ (MTBF+MTTR)

Failure of Composite System

In case of a system is composed of multiple systems labeled “i”
Availability of the entire system is

$$A = \prod_{i=0}^{N} \left(1 - \frac{MTTR_i}{MTBF_i + MTTR_i} \right)$$

Statistical Model

Failures are considered statistical events

Which are uncorrelated to previous failures or failures of other components of subsystems

➔ Obviously a simplification, has to remembered when analyzing failures

Failure Rate and Failure Density Distribution

$p = \lambda \cdot \Delta t$:

probability for system to fail within any small time interval of length Δt

If *λ is constant in time*, the failure density distribution function probability for system to fail within a certain time interval n of length Δt :

$f_n \cdot \Delta t = (1-p)^{n-1} p$

f_n is a normalized distribution function $\Sigma f_n \Delta t = 1$

Failure Function and Survival Function

The failure function F_n gives the probability per unit time that the component fails once in the time interval [0·Δt, n·Δt] is

$$F_n = \sum_{k=1}^{n} f_k$$

The survival function S_n is related to F_n by:

$$S_n = 1 - F_n$$

Mean Time Between Failure

Given a system with a constant failure rate p

What is the meantime between failure:

$$MTBF = \langle n \rangle \Delta t = \Delta t \cdot \sum_{n=0}^{\infty} (1-p)^{n-1} \cdot p \cdot n$$

$$MTBF = \Delta t \cdot \lim_{N \to \infty} \left(\frac{1}{p} \left(1 - (1-p)^{N} \cdot \left(1 - Np \right) \right) \right) = \frac{1}{\lambda}$$

Systems with N identical components

Given a system with **M** identical components, each having a constant failure probability p=$\lambda\cdot\Delta$t,

What is the probability for failure of **n** components in any interval of time Δt?

$$P_{M,m} = \binom{M}{m} \cdot (1-p)^{M-m} p^{m}$$

What is the average numbers of failures to be expected in any time interval Δt

$$\langle m \rangle = \sum_{m=0}^{M} P_{M,n} \cdot m = M \cdot p$$

➔ **$\mathbf{MFBF_M = \Delta t/(Mp) = 1/(M\lambda)}$**

Non-constant failure rates and survival function

- There are many reasons why a constant failure rate is not describing sufficiently well the system reliability over an extended period:
- Enhanced early failure rates (early mortality)
- Replacement or repair of components which fail often
- Changing external conditions: temperature, humidity, thermal stress during start-up, shut-down
- Ageing
- Wear-out

➔ The failure rate depends on time and in order to analyze failures and predict system behavior from sample behavior, the model must be extended to time dependent rates.

Non-constant failure rates and survival function

Non-constant failure rate

$$p \to p_n = \lambda_n \Delta t$$

Failure density

$$f_n \cdot \Delta t = \lambda_n \cdot \Delta t \cdot \prod_{k=1}^{n} (1 - \lambda_k \Delta t)$$

$$f_n = \lambda_n \cdot \exp[\sum_{k=1}^{n} \ln(1 - \lambda_k \Delta t)]$$

$$\Delta t \to 0$$

$$f(t) = \lim_{\Delta t \to 0} \left[\lambda_n \cdot \exp[-\sum_{k=1}^{n} (\lambda_k \Delta t)] \right]$$

$$\Rightarrow f(t) = \lambda(t) \cdot \exp\left[-\int_0^t \lambda(t')dt' \right]$$

Failure Function

$$F(t) = \int_0^t f(t')dt' = 1 - \exp(-\int_0^t \lambda(t')dt')$$

Survival Function

$$S(t) = 1 - F(t) = \exp(-\int_0^t \lambda(t')dt')$$

Failure rate

$$\lambda(t) = \frac{\frac{d}{dt} F(t)}{S(t)}$$

MTBF Non-constant Failure Rate

$$MTBF = \int_0^\infty dt \cdot t \cdot f(t)$$

$$MTBF = \int_0^\infty dt \cdot t \cdot \lambda(t) \cdot \exp\left[-\int_0^t d\tau \cdot \lambda(\tau)\right]$$

$$MTBF = \lim_{x \to \infty}\left[t \cdot \exp\left[-\int_0^t d\tau \cdot \lambda(\tau)\right]\right]_0^x + \int_0^\infty dt \cdot \exp\left[-\int_0^t d\tau \cdot \lambda(\tau)\right]$$

$$MTBF = \int_0^\infty dt \cdot S(t)$$

Survivaltime

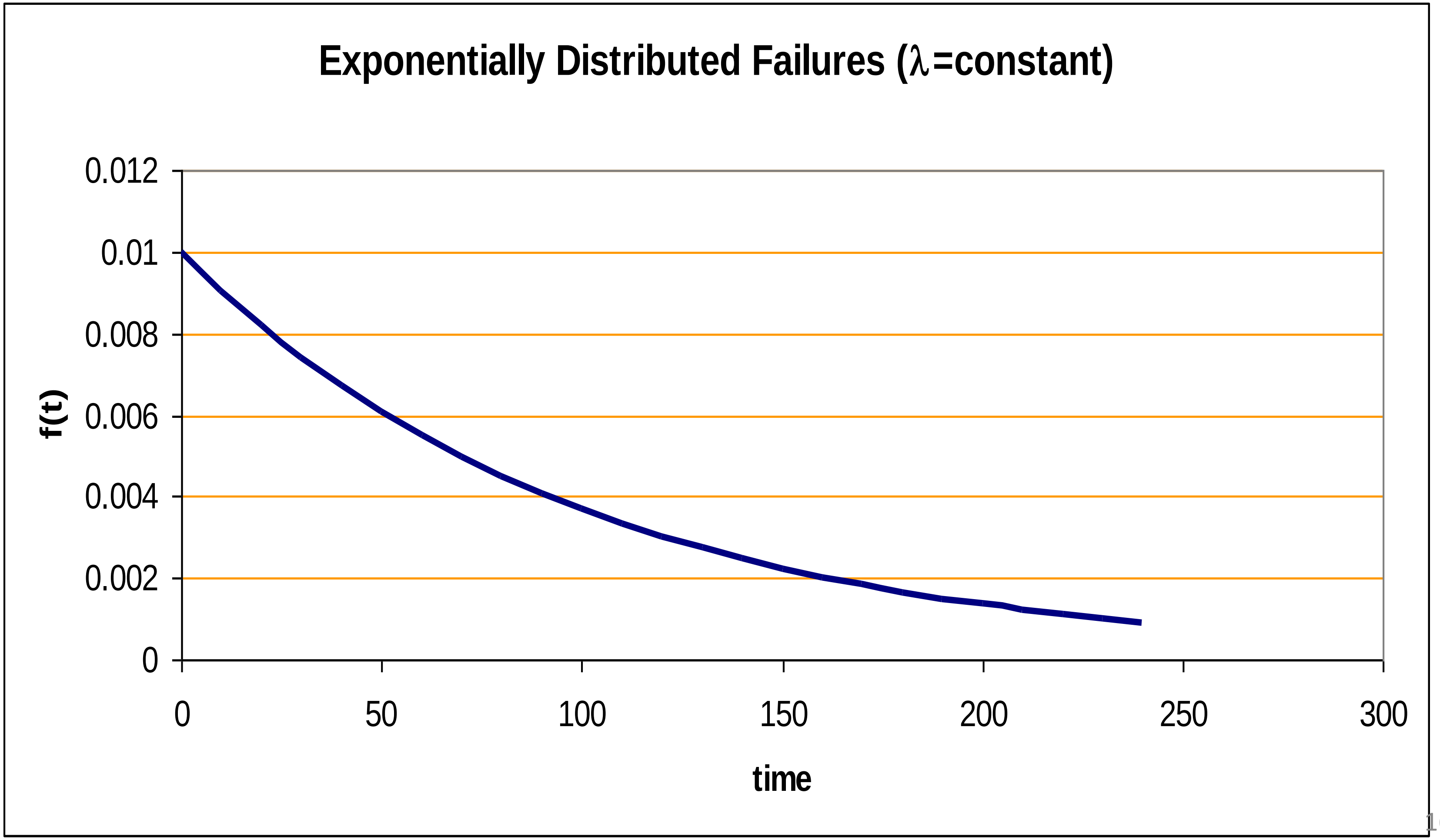
$$MRL(t) = \frac{\int_0^\infty d\tau \cdot S(t+\tau)}{S(t)}$$

$$\lambda = const$$

$$\Rightarrow f(t) = \lambda \cdot \exp(-\lambda \cdot t)$$

$$\Rightarrow S(t) = \exp(-\lambda \cdot t)$$

$$\Rightarrow MTBF = 1/\lambda$$



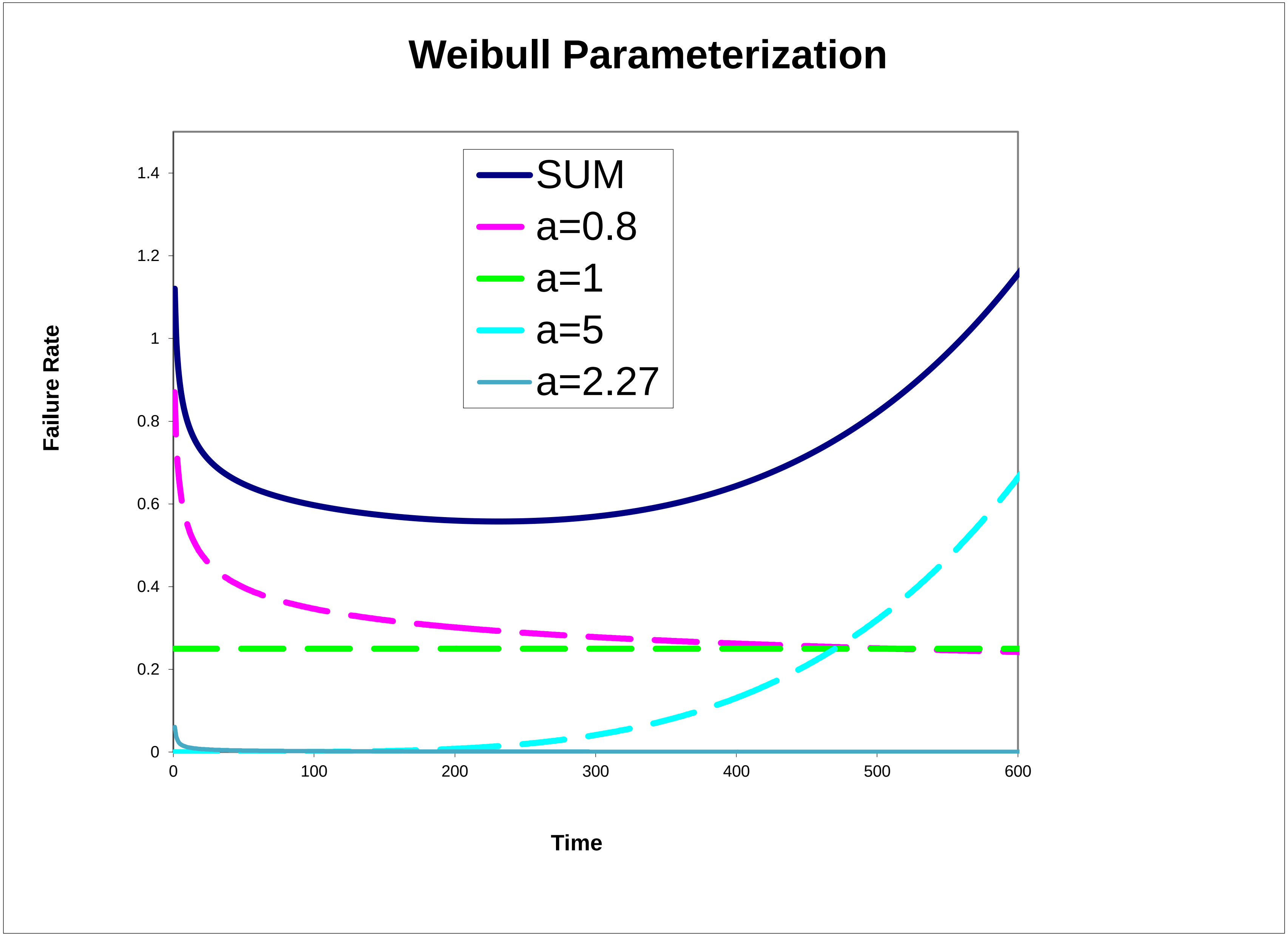
Parameterizing Systems with time dependent failure rate (Weibull Parameterization)

$$\lambda(t) = \frac{a}{b}\left(\frac{t}{b}\right)^{a-1}$$

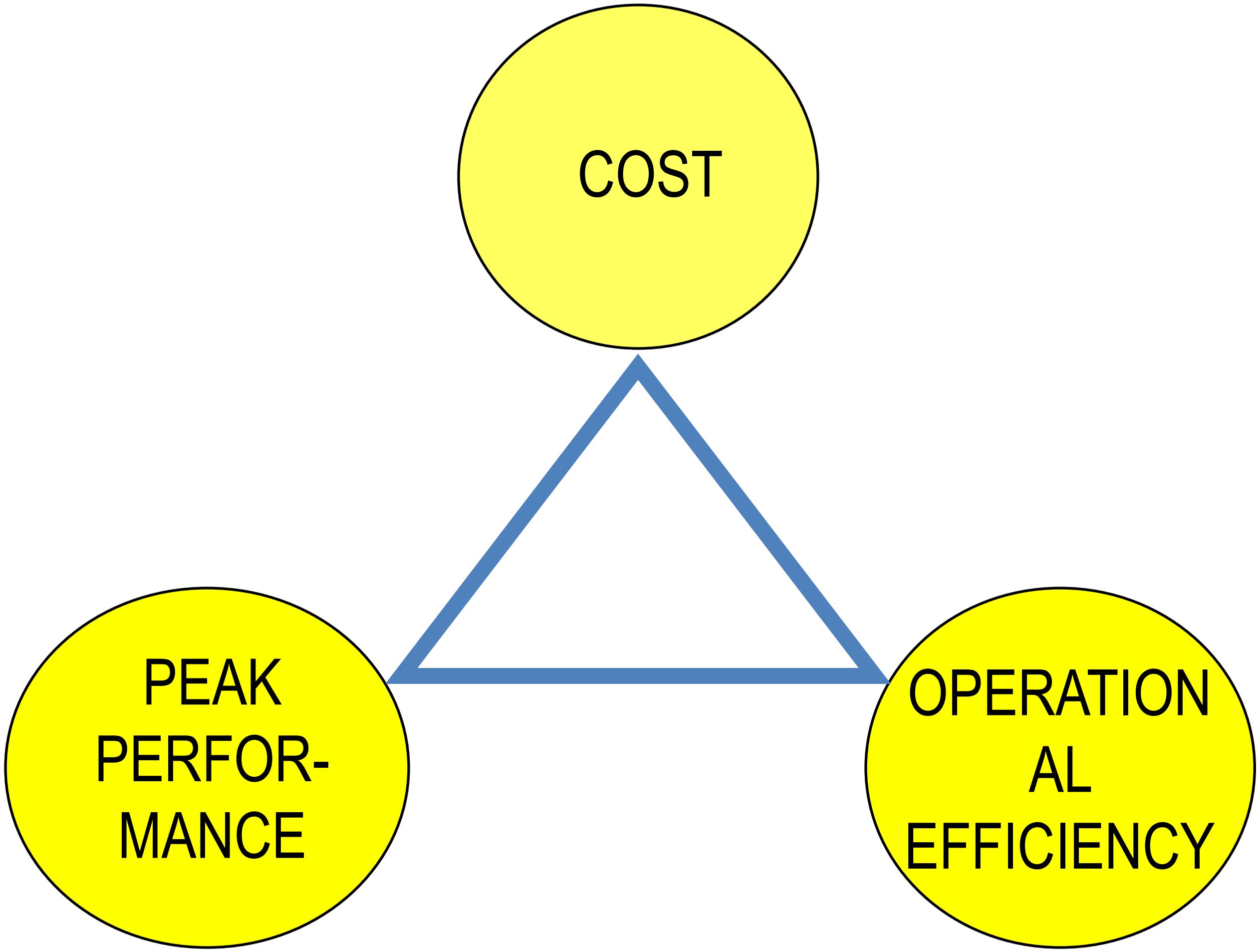
$$\Rightarrow \; f(t) = \frac{a}{b}\left(\frac{t}{b}\right)^{a-1} \cdot \exp\left[-\left(\frac{t}{b}\right)^{a}\right]$$

$$\Rightarrow S(t) = \exp\left[-\left(\frac{t}{b}\right)^{a}\right]$$

$$MTBF = b \cdot \Gamma\left(1 + \frac{1}{a}\right)$$


Weibull Parameterization
SUM
a=0.8
a=1
a=5
a=2.27
Failure Rate
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
Time

Accelerator Design



Design for High Availability

<u>Considerations:</u>

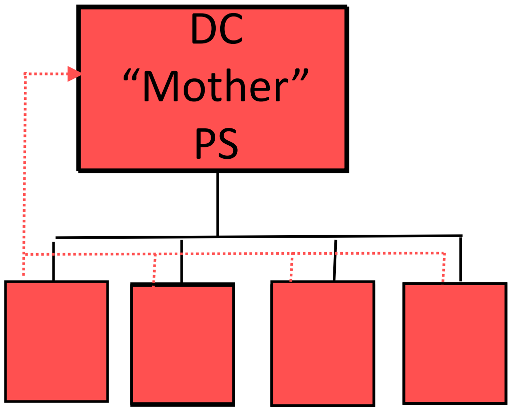
- Overall Complexity
- Unavoidable Weakness
- Subsystem Architecture
- Fail Safe Design
- Overrated Design
- Environmental Impact
- Error Prone Solutions
- Build-in Redundancy and Hot Spares
- Built-in Diagnostics
- Repair and Maintenance Friendly Design

Subsystem Architecture

Monolithic versus Modular Design ➔

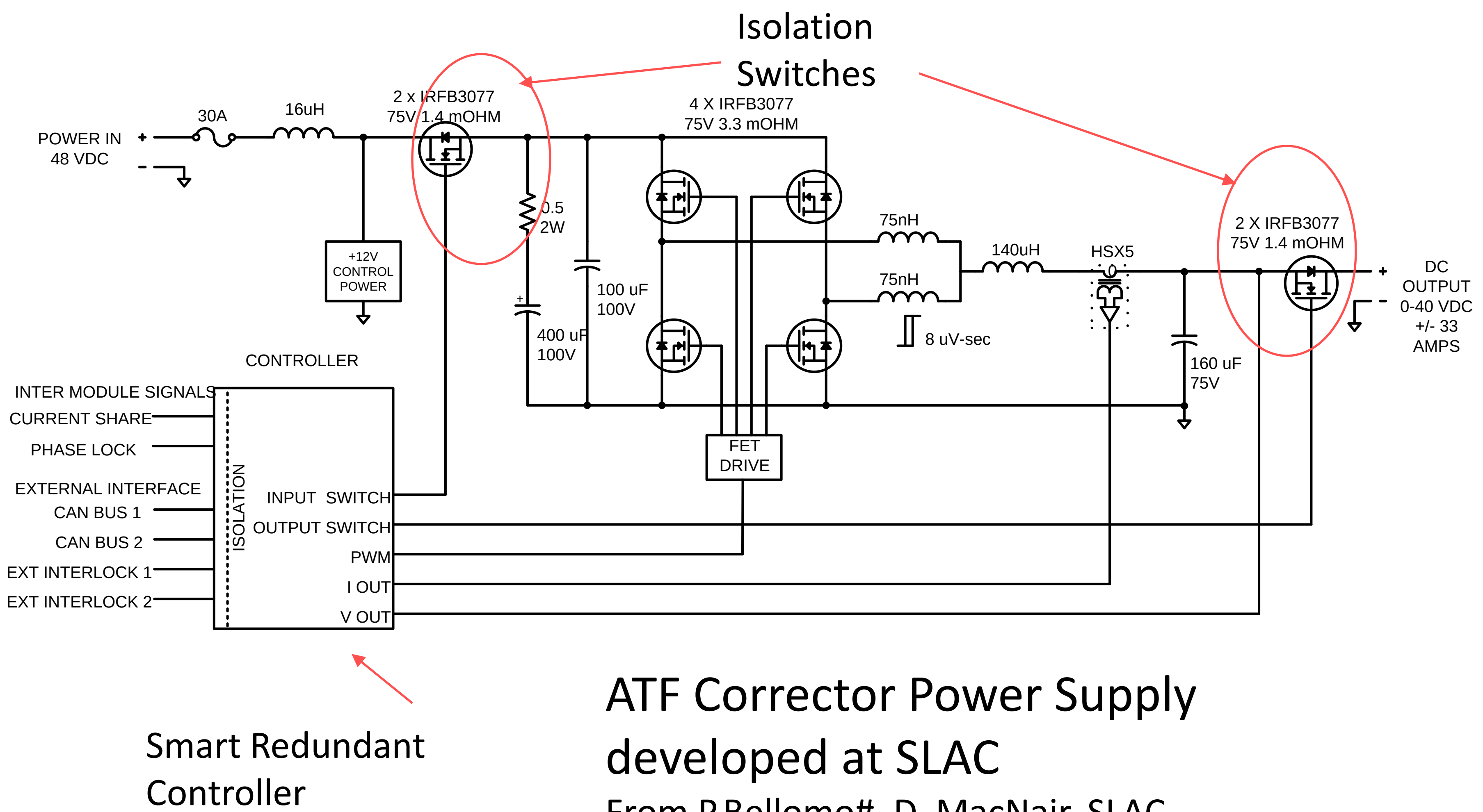
Case to Case Decision

Avoid coupling of the two types of architecture



Switched Mode “Daughter” PS

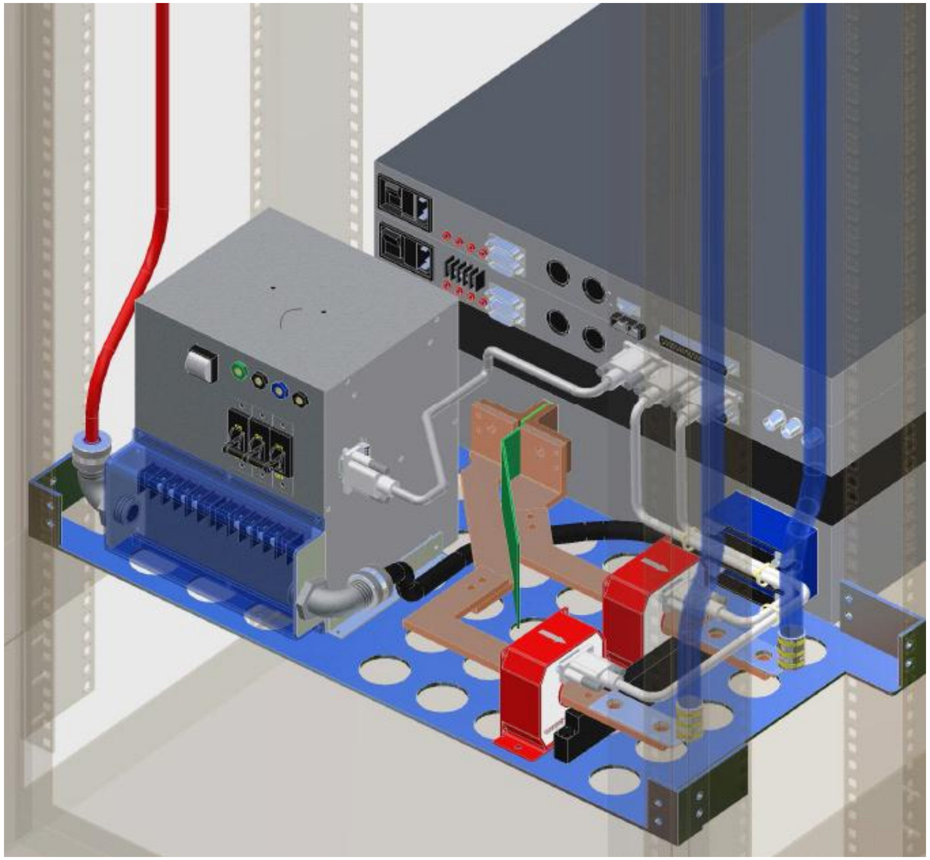
High Reliability Switched Mode PS

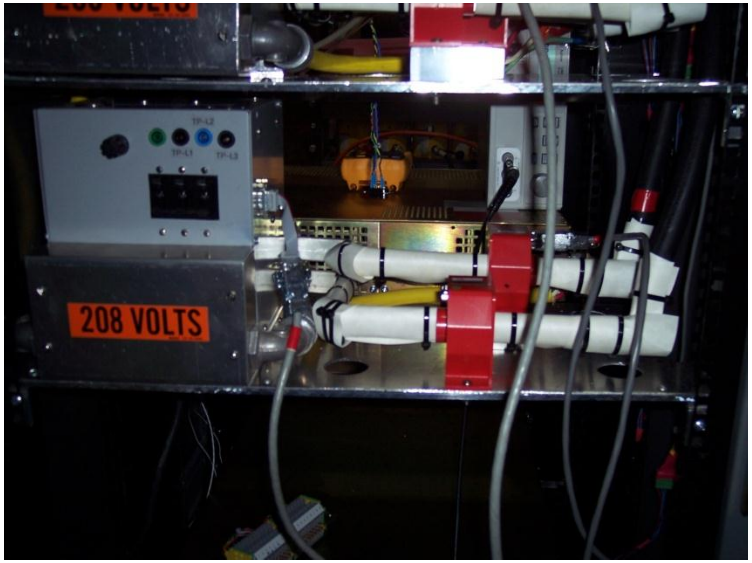


ATF Corrector Power Supply developed at SLAC

From P.Bellomo#, D. MacNair, SLAC http://indico.triumf.ca/contributionDisplay.py?contribId=5&sessionId=7&confId=749, Vancouver 2009

NSLS-II Solution: Small AC/DC Supplies



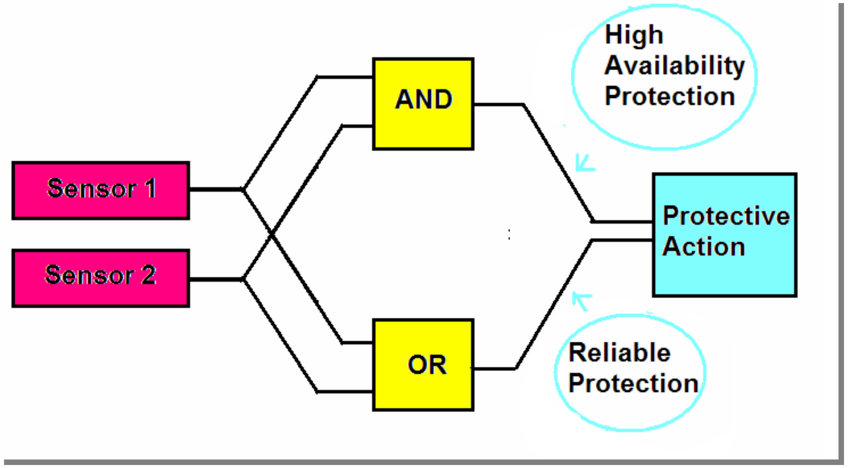


Courtesy G. Ganetis, BNL

Smart Fail Safe Design

Fail Safe Design = Good Engineering Practice

<u>However:</u> System Trips are an important factor in operational efficiency esp for accelerator with long injectin cycles



Need to be conservative in early operation phase → High false trip rate,

but

Trip Thresholds could be higher with growing experience and confidence

- Need flexible internal trip thresholds
- Need flexible protection logics
- Needs to be included in the design phase
- Safe administration and management of the threshold must be integrated upfront!

Overrated Design

Thermal Cycling

Thermal Stress

$$\frac{\lambda}{\lambda_0} = \left(\frac{\Delta T}{\Delta T_0}\right)^2 \cdot \exp\left[-\frac{E}{k} \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

Temperature Failure Enhancement Factor for Electronics

Overrating of Power Components:

- Reduced operating temperature

-Reduced temperature change when switching on/of

-Less mechanical and thermal stress on Components

- Operating further away from internal trip thresholds

➔Lower Failure Rate

Difficult to optimize overrating

For magnet power supply gain in reliability varies from vendor to vendor

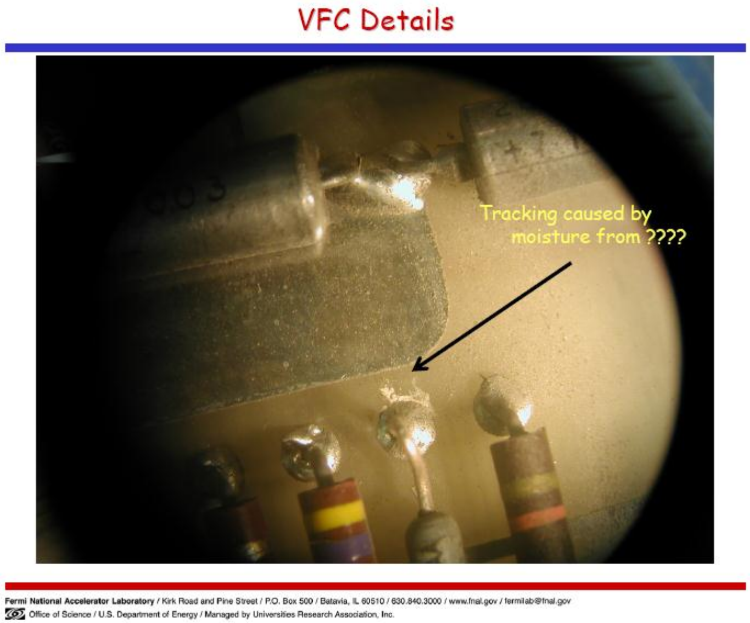
Example HERA Experience:

Beam Current @ 1996 Limited by RF Trip Rate <1996

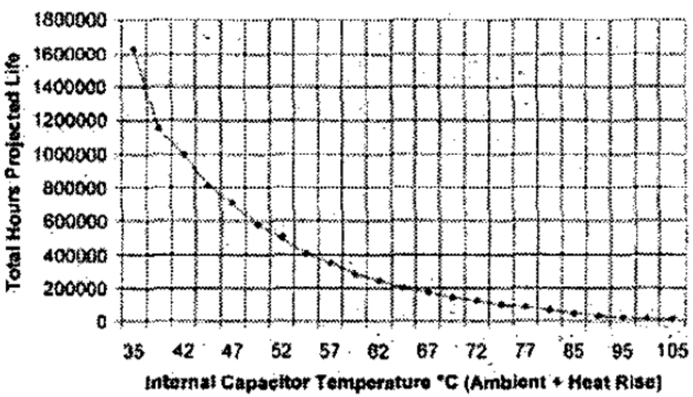
After RF power margin of ~30% was added by adding an 8^{th} 1.5MW klystron transmitter and fixing SC RF cavity problem

➔ Beam current increased from 35mA ➔ 50mA

Environmental Impact: Dust, Humidity, Temperature

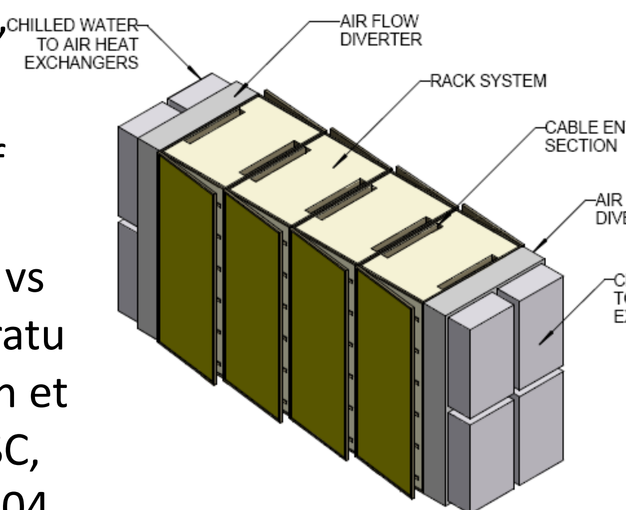


Dust causing frequent failures on TEVATRON QP electronics)copied from H. Edwards/P. Czarapata, FNAL, Groemitz Miniworkshop 2005



Lifetime of film capacitors vs int.temperature C. Chen et al IEEE PESC, Aachen 2004

NSLS-II Electronics/PS Rack Solution



This avoids error prone design

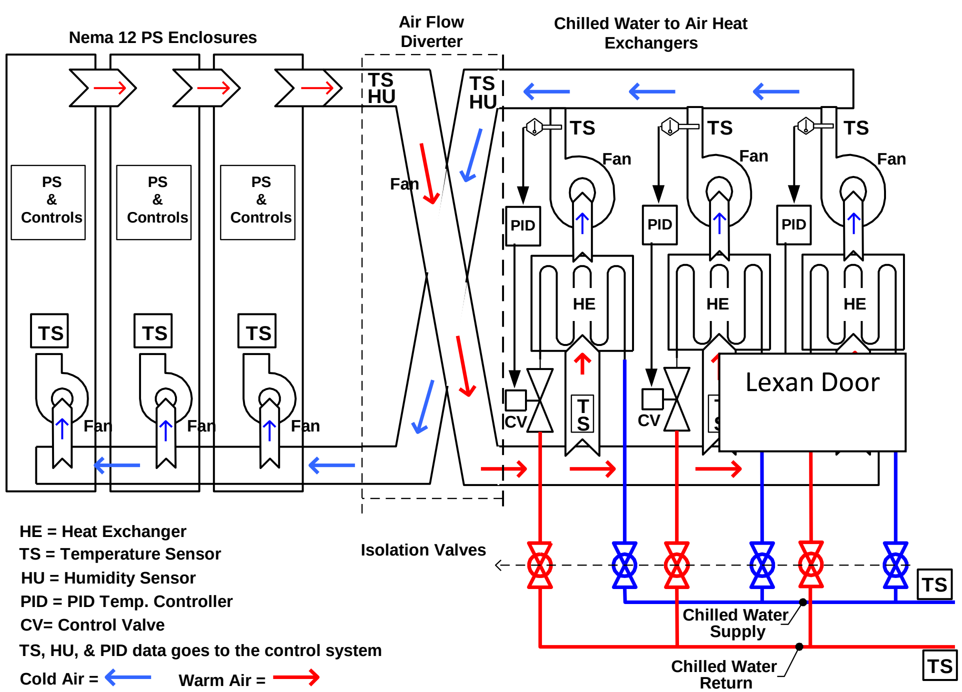
Error Prone Solutions

- **Water Cooling**
- **Electrical Connectors**

Replace analog cable connections by serial digital links where ever feasible (gain reliability, save costs)

Example of air-cooled PS design at NSLS-II

Equipment Enclosures Cooling Scheme



Reliability of Redundant Safeguards

Consider a number N of independent safeguard to protest a system. Each may fail unnoticed which reduces redundancy. Assume constant failure rate

- ➔ Need to check safeguards to ensure proper protection.
- ➔ Checking period Δt is a crucial parameter of system protection.

Let **F(Δt)** be the probability for system protection failure within **Δt:** $\mathbf{F}(\Delta \boldsymbol{t}) = \mathbf{1} - \boldsymbol{exp}(-\lambda \Delta \boldsymbol{t})$

Each safeguard i has a probability to fail $F_i\ (\Delta \boldsymbol{t}) = 1\ - \exp(-\lambda_{\boldsymbol{i}} \Delta \boldsymbol{t})$ i=1…N

$$\mathbf{F}(\Delta \boldsymbol{t}) = \prod_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} [1\ - \exp(-\lambda_{\boldsymbol{i}} \Delta \boldsymbol{t})]$$

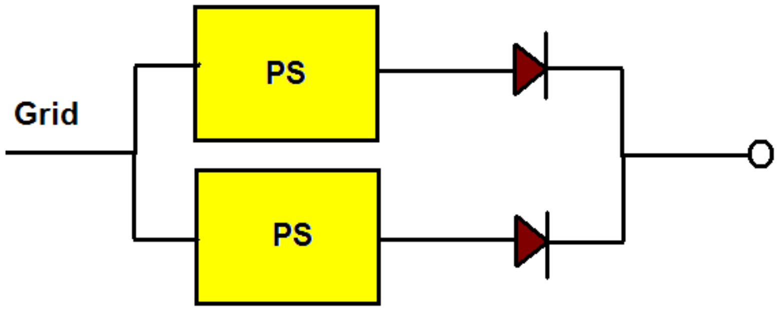
For $\lambda_{\boldsymbol{i}}\ \Delta \boldsymbol{t} << 1$: $\lambda \Delta \boldsymbol{t} = \prod_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} [\lambda_{\boldsymbol{i}} \Delta \boldsymbol{t})]$

or

$$\frac{\Delta \boldsymbol{t}}{MTBF} = \prod_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} \left[\frac{\Delta \boldsymbol{t}}{MTBF_i}\right] \rightarrow MTBF = \frac{\prod_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} [MTBF)]}{\Delta \boldsymbol{t}^{N-1}}$$

Build-in Redundancy and Hot Spares

Build in Redundancy will increase reliability significantly --If failed modules are replaced continuously
➔ needs access!
➔ "Hot Swap" Capability helps

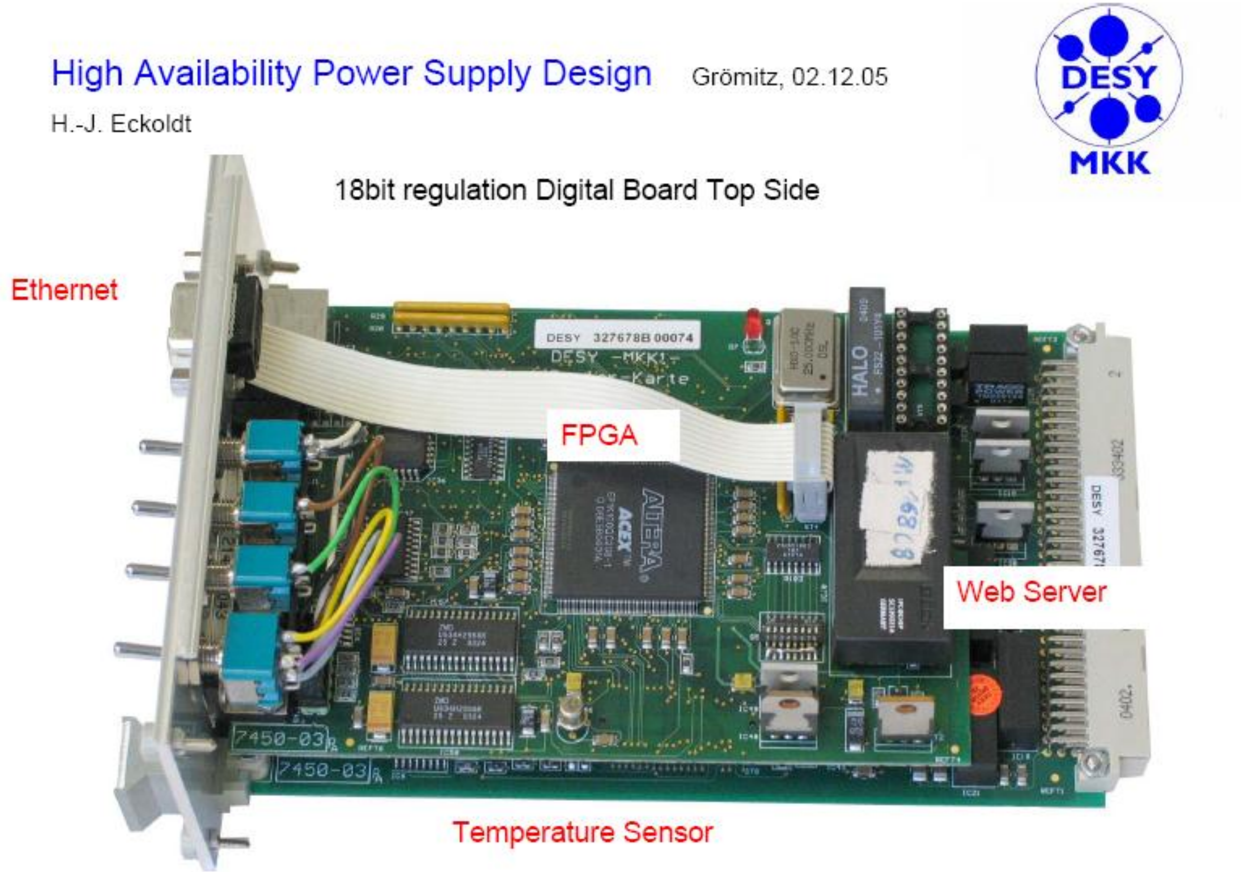


Example:

TESLA/XFEL Switched Mode PS with Hot Spare Redundant Power Modules

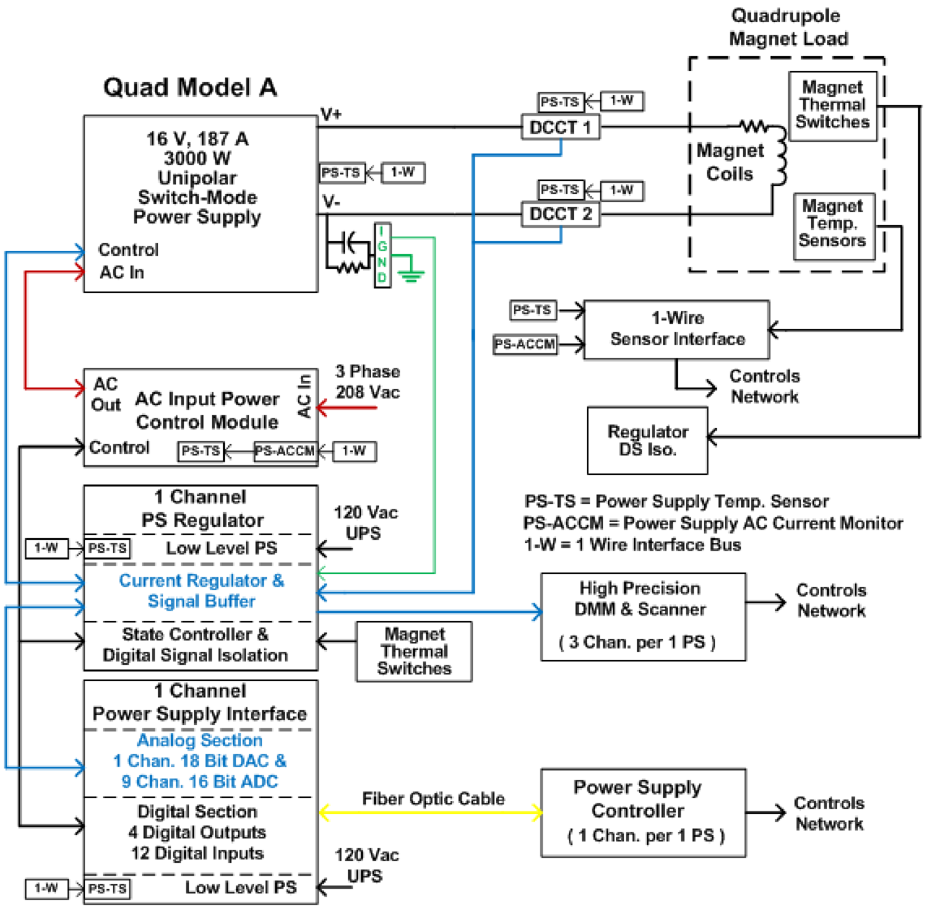
Built-in Diagnostics

Built-in diagnostics
- long term monitoring and onset of failure detection
- trouble shooting
-Cross correlations with external factors



NSLS II Power Supply Reliability

Configuration is used for Quadrupole magnet circuits.



The large number of power supplies (~ 997) in the NSLS II storage ring required a stagey to enhance their reliability.

The stagey was to incorporate **built-in diagnostic features into the power supply design**.

Expert controls **software applications have been developed for testing and monitoring** each power supply.

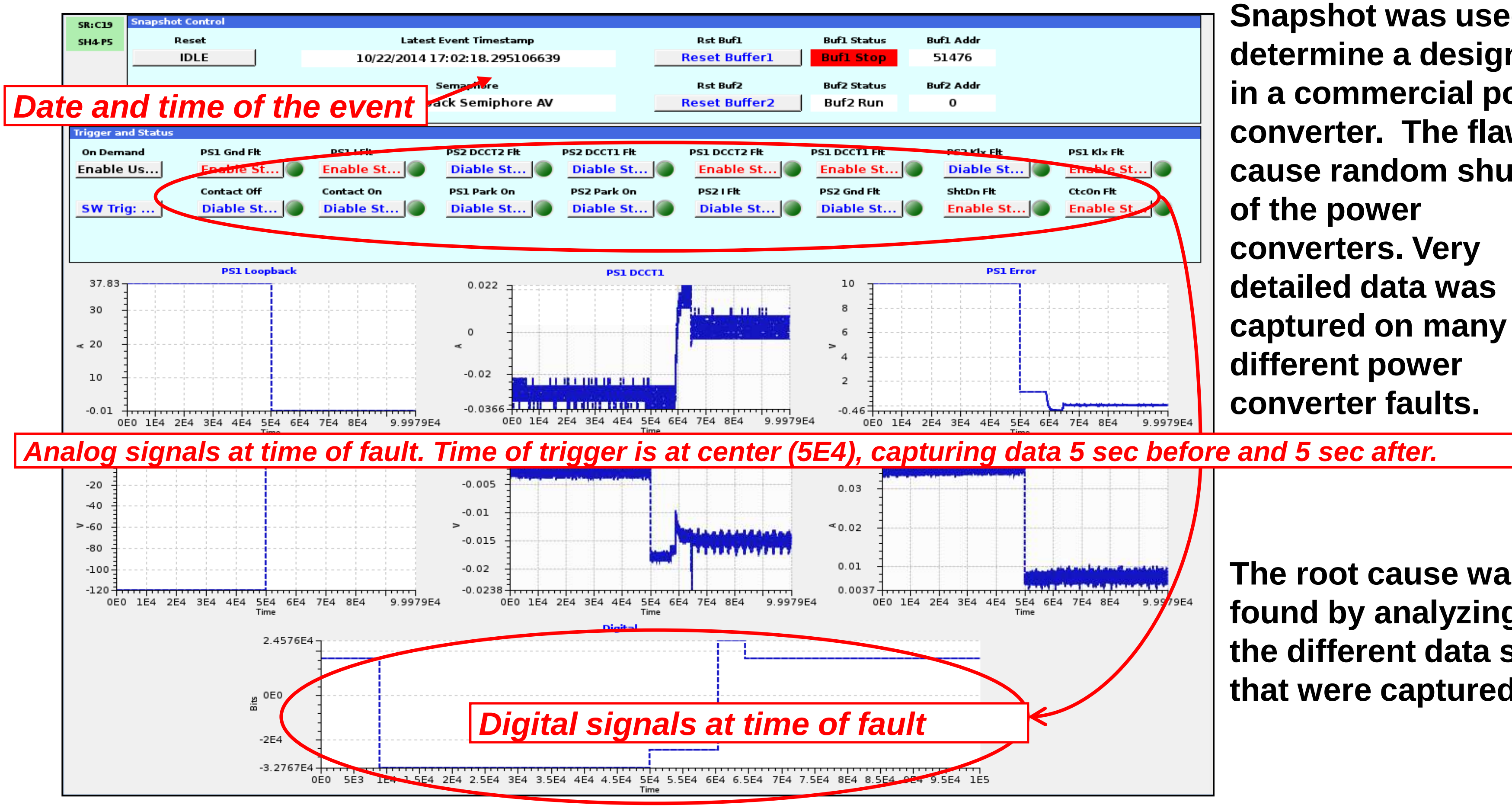
Transient recorder features have been implemented for each power supply. A large number of signals are recorded when a fault has happened. .

There are **9 fast and 3 slow analog signal, 8 temperature sensors, ~8 digital I/O**
(~ 27,916 signal for the storage ring power supplies)

NSLS II Power Supply Reliability

Snapshot is a Transient Recorder Software Application

Snapshot control/viewer panel



Snapshot was used to determine a design flaw in a commercial power converter. The flaw cause random shut offs of the power converters. Very detailed data was captured on many different power converter faults.

The root cause was found by analyzing all the different data sets that were captured.

Repair and Maintenance Friendly Design

Power Supply Rack System with Docking ➔System for **fast replacement** of the entire unit

Good **accessibility** of components important to minimize trouble shooting and repair. However, is often compromised

HIGH AVAILABILITY OPERATIONS

Continuous Improvement

Data Logging (time stamped, well accessible on/off site)

Data Analysis Tools and Cross Correlation

(*Example: check A/V on each magnet cycle*)

Root Cause Analysis mandatory for large incidents

Commercial Software tools available t extent this technique for all failure

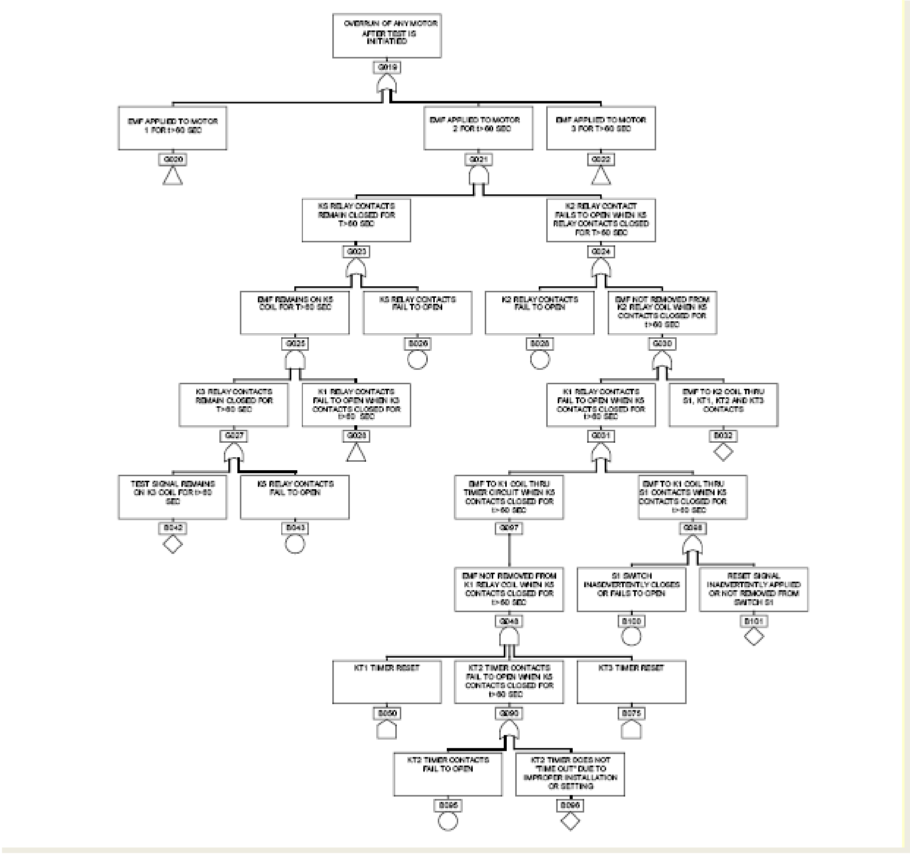


Illustration of Root Cause Analysis using Fault Tree Analysis

http://www.hq.nasa.gov/office/codeq/doctree/fthb.pdf

High Availability Operations

Operational Strategy to mitigate Impact of Failure

- Scheduled Maintenance: Opportunity for repair and preventive maintenance
- Back-up programs to operate with limited performance

(accelerator studies)

- Management:

- Cleary defined roles and accountabilities

- Escalation strategy

- Experts On-call

HIGH AVAILABILITY OPERATIONS

- **Preventive Maintenance**

Necessary: Rotating machinery (compressors)

Air Filters

UPS-systems

Desirable: clamped, bolted support systems in PS)

Cooling Water Hoses

Difficult: Connectors

Was used successful to improve HERA PS system
Some supplies: MTBF 15000h → 50000h

- **Preventive Refurbishment**

Fans, EL capacitors, small DC supplies, thyratrons,

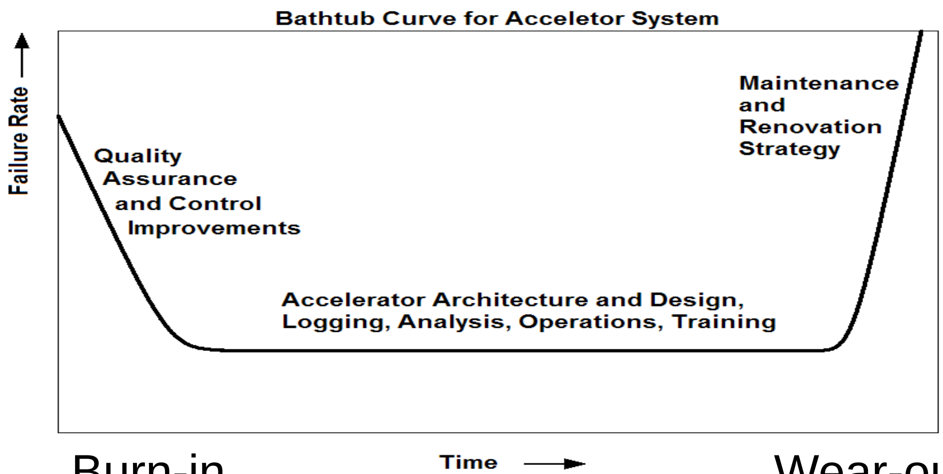
→ Fix before Fail

Residual Lifetime Prediction

$$MRL = \frac{1}{S(t)} \cdot \int_0^{\infty} dt' \, S(t+t')$$

Preventive Maintenance

Maintenance is labor intense and is one of the highest cost elements in operating an accelerator. It is important that precious resources are used in the most effective way. This requires that maintenance needs to focus on components with a high failure probability. Error and failure analysis supported by modeling can be helpful tools to develop and effective maintenance program.



Burn-in phase

Stable operations

Wear-out phase

Preventive Maintenance makes no sense during productive phase with constant hazard function (as failures occur statistically) or in burn-in phase ➔ Use during ear-out phase

Mean Residual Lifetime

The following quantify is useful for preventive maintenance planning:

If a component has operated without failure for a time t_0 , what is the residual MTBF called ***mean residual life*** (**MRL**) ?

For constant hazard function λ, the answer is simply

$$MRL = 1/\lambda = MTBF$$

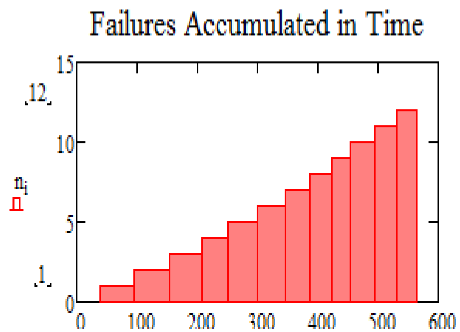
For time varying hazard function the result is different:

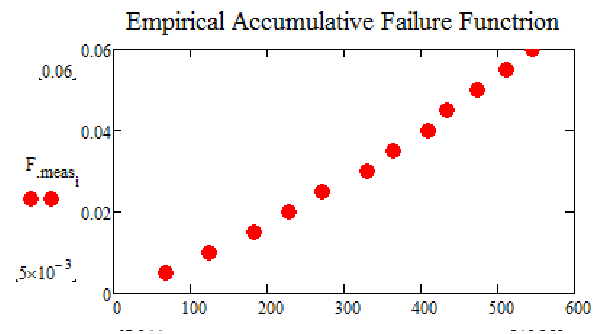
$$MRL(t) = \frac{1}{S(t_0)} \int_0^{\infty} dt\, f(t + t_0) \cdot t$$

$$MRL(t) = \frac{1}{S(t_0)} \int_0^{\infty} dt\, S(t + t_0)$$

Statistical Analysis to optimize Preventive Maintenance

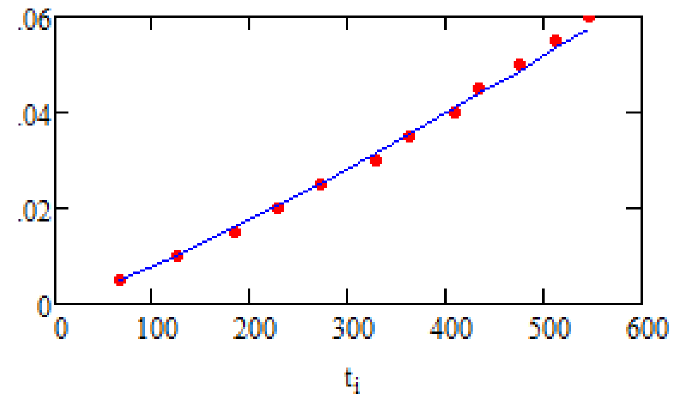
Consider a system with 200 wearing-out constituents





Describe by 2-par Weibull failure distribution function

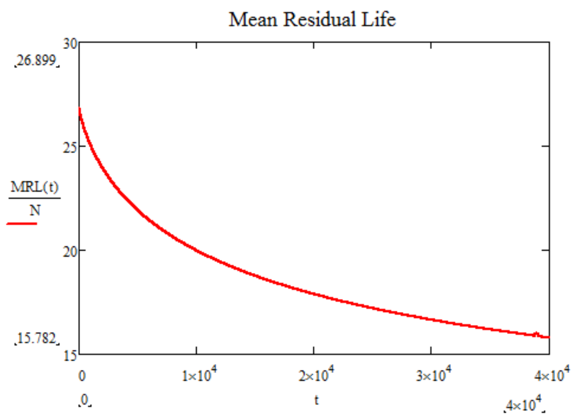
$$F(t) := 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

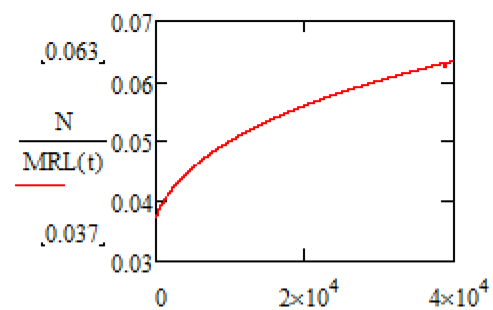


Fit the parameters β and η in a linear fit:

Calculate MRL function

$$MRL(t) := \frac{\int_t^{\infty} S(\tau)\, d\tau}{S(t)}$$





Failure rate is increasing factor 2 In 8y

HIGH AVAILABILITY OPERATIONS

<u>Speed Up Repair</u>

- Transient Recording
- Integration of Operational Data Base and Asset Management
- Remote Access to Build-in Diagnostics
- Logged Data Analysis Tools
- Failure Scenario Data Base
- Start-up Check List

…

Human Factor

Human errors are unavoidable
but can be minimized with reasonable effort

- Clear line of command in operating and maintaining accelerator
- Well defined roles and responsibilities
- Distribution of information, operation briefings at shift change
- Written, reviewed and approved instructions and procedures
- Clearly defined line of command for routine/non-routine
- Automation of operating procedures wherever safe and possible
- Software Interlock System to prevent operator mistakes
- Operator Training and Qualification, Motivation
- On-line Technical and Procedural Information
- Ergonomic Operation Software
- Functional alarm system (limit false alarms)
- Management of access to accelerator controls
- Management of access to accelerator equipment
- Unambiguous naming
- HPI training

➔ **Well implemented conduct of operations**

Operational Efficiency Simulation

…will allow to assess reliability using complex realistic operation models

thereby

- helps to specify reliability of components
- helps to provide guidance and to decide on operational strategies
- may validate simplified reliability assessment

Complementary Figure of Merit

Average Performance

Performance = Beam Current / Effective Beam Size

D: Relative Performance Reduction Due to Failure

Maintenance Interval

$$\langle P \rangle = \prod_{n=1}^{N} \left[1 - \frac{1}{2} \cdot \frac{\Delta T}{MTBF_n} \cdot D_n \right]$$

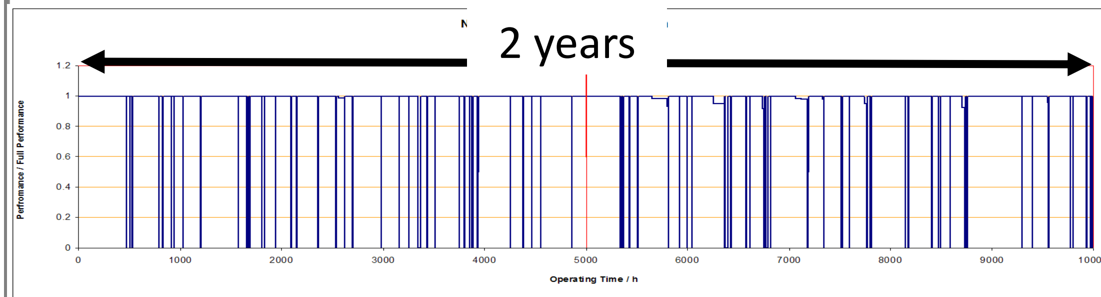
Analysis of Component Reliability Data

name	count	MTBF(c0mp)	MTTR	MTTR_R	maxpf	minpf	System P	System MTBF	Calc. Failures/500 0h	Repair time	Repairtime/runtime	Calc.Lost performance	1/log(mtbfs)
quadrupole ps	300	800000	0	8	1	0.5	0.000375	2666.7	1.9	14.70	0.00293948	14.70	0.2919
quadrupole ps trip	300	200000	0	0	0	0	0.0015	666.7	7.5	8.25	0.00165	8.25	0.3541
sextupole ps	60	820000	0	8	1	0.6	7.32E-05	13666.7	0.4	2.31	0.000461687	2.31	0.2418
sextupole ps trip	60	220000	0	0	0	0	0.000273	3666.7	1.4	1.50	0.0003	1.50	0.2806
corrector ps	204	450000	0	2	1	0.8	0.000453	2205.9	2.3	8.17	0.001634514	8.17	0.2991
corrector ps trip	204	340000	0	0	1	0	0.0006	1666.7	3.0	3.30	0.00066	3.30	0.3104
dipole ps	1	150000	0	8	1	0.4	6.67E-06	150000.0	0.0	0.18	3.64343E-05	0.18	0.1932
dipole ps trip	1	80000	0	0	0	0	1.25E-05	80000.0	0.1	0.07	0.00001375	0.07	0.2040
BPM	240	500000	0	2	1	0.95	0.00048	2083.3	2.4	8.76	0.001751613	8.76	0.3013
RF-PS	2	600000	0	8	0	0.3	3.33E-06	300000.0	0.0	0.09	1.78607E-05	0.09	0.1826
RF-trip	2	2500	0	0	0	0	0.0008	1250.0	4.0	4.40	0.00088	4.40	0.3229
RF-transm	2	50000	0	8	0.7	0	0.00004	25000.0	0.2	1.20	0.000239777	1.20	0.2274
RF Cavity	4	100000	8	24	0.7	0.4	0.00004	25000.0	0.2	4.62	0.000924	4.62	0.2274
quad-magn	300	1500000	0	8	1	0.4	0.0002	5000.0	1.0	7.10	0.00142	7.10	0.2703
sext -magn	300	1000000	0	8	1	0.4	0.0003	3333.3	1.5	11.32	0.002264847	11.32	0.2839
Dipole-magn	60	1000000	0	24	1	0.4	6E-05	16666.7	0.3	4.50	0.000899842	4.50	0.2369
controlsmod	1000	2000000	0	1	1	0.4	0.0005	2000.0	2.5	6.80	0.001359017	6.80	0.3029
instrumentation	100	1000000	0	1	1	0.9	1E-04	10000.0	0.5	1.05	0.00021	1.05	0.2500
water pump	25	300000	0	6	1	0	8.33E-05	12000.0	0.4	2.17	0.000434836	2.17	0.2451
miscl electronic	500	2000000	0	1	1	0.4	0.00025	4000.0	1.3	2.99	0.000597642	2.99	0.2776
klixon	1000	5000000	0	1	0	0	0.0002	5000.0	1.0	2.31	0.000461421	2.31	0.2703
Vacuum Seal	400	2000000	4	24	0	0.4	0.0002	5000.0	1.0	21.10	0.00422	21.10	0.2703
Vacuum Pump	200	2000000	4	24	0.7	0.5	0.0001	10000.0	0.5	9.96	0.001992843	9.96	0.2500
AC distribution sw	25	500000	2	8	1	0	5E-05	20000.0	0.3	2.08	0.000416237	2.08	0.2325
septa	3	50000	2	24	1	0.7	0.00006	16666.7	0.3	5.14	0.001028963	5.14	0.2369
kicker	6	50000	1	24	1	0.7	0.00012	8333.3	0.6	10.14	0.002027142	10.14	0.2550
pulser trips	9	30000	1	0	1	0.5	0.0003	3333.3	1.5	4.99	0.000997423	4.99	0.2839
Booster	1	2500	0	4	1	0.5	0.0004	2500.0	2.0	10.20	0.00204	10.20	0.2943
Linac	1	2500	0	4	1	0.5	0.0004	2500.0	2.0	10.20	0.00204	10.20	0.2943
cryo-system	1	10000	0	48	0	0	0.0001	10000.0	0.5	14.28	0.00285641	14.28	0.2500
central power	2	2500	0	12	1	0	0.0008	1250.0	4.0	48.00	0.009599184	48.00	0.3229
safety systems	100	2000000	0	2	0	0	5E-05	20000.0	0.3	0.65	0.00013	0.65	0.2325
Count	32												
Total									44.7	232.52	4.65%	232.52	0.0465
Availability										0.95		0.95	

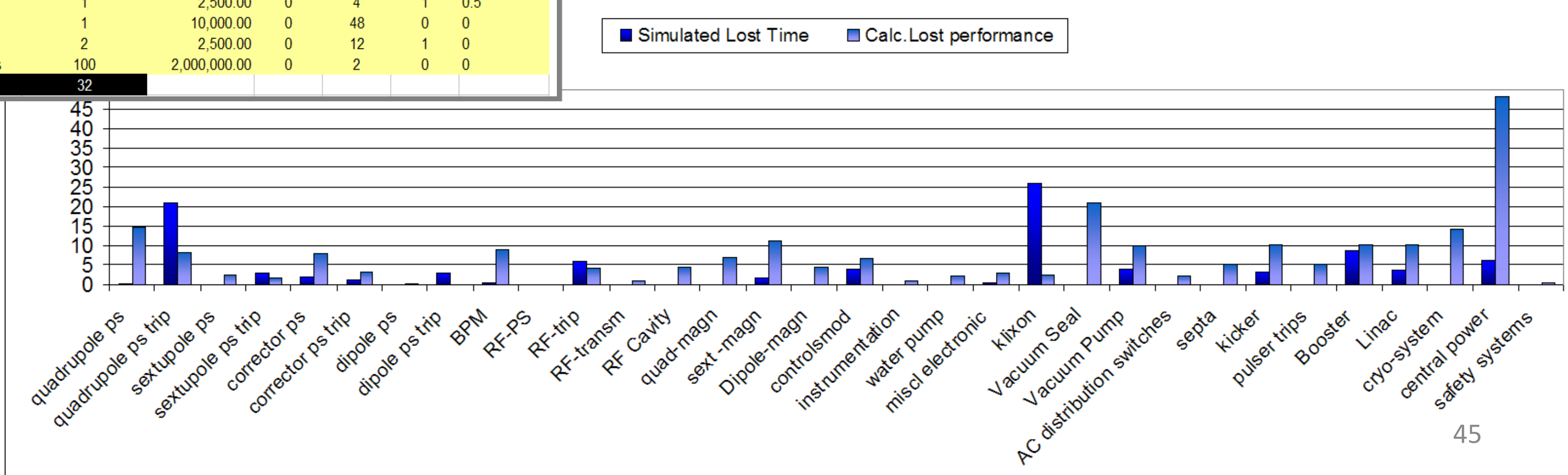
NSLS-II Performance Simulation

system	Count	mtbf	mttr	range	pr-max	pr-min
quadrupole ps	300	800,000.00	0	8	1	0.5
quadrupole ps trip	300	200,000.00	0	0	0	0
sextupole ps	60	820,000.00	0	8	1	0.6
sextupole ps trip	60	220,000.00	0	0	0	0
corrector ps	204	450,000.00	0	2	1	0.8
corrector ps trip	204	340,000.00	0	0	1	0
dipole ps	1	150,000.00	0	8	1	0.4
dipole ps trip	1	80,000.00	0	0	0	0
BPM	240	500,000.00	0	2	1	0.95
RF-PS	2	600,000.00	0	8	0	0.3
RF-trip	2	2,500.00	0	0	0	0
RF-transm	2	50,000.00	0	8	0.7	0
RF Cavity	4	100,000.00	8	24	0.7	0.4
quad-magn	300	1,500,000.00	0	8	1	0.4
sext -magn	300	1,000,000.00	0	8	1	0.4
Dipole-magn	60	1,000,000.00	0	24	1	0.4
controlsmod	1000	2,000,000.00	0	1	1	0.4
instrumentation	100	1,000,000.00	0	1	1	0.9
water pump	25	300,000.00	0	6	1	0
miscl electronic	500	2,000,000.00	0	1	1	0.4
klixon	1000	5,000,000.00	0	1	0	0
Vacuum Seal	400	2,000,000.00	4	24	0	0.4
Vacuum Pump	200	2,000,000.00	4	24	0.7	0.5
AC distribution sw	25	500,000.00	2	8	1	0
septa	3	50,000.00	2	24	1	0.7
kicker	6	50,000.00	1	24	1	0.7
pulser trips	9	30,000.00	1	0	1	0.5
Booster	1	2,500.00	0	4	1	0.5
Linac	1	2,500.00	0	4	1	0.5
cryo-system	1	10,000.00	0	48	0	0
central power	2	2,500.00	0	12	1	0
safety systems	100	2,000,000.00	0	2	0	0
Count	32					

Efficiency	simulation	0.957	Analytic	0.953495
Availability	Simulation	0.958	Analytic	0.953495
Failures	Simulation	45.000	Analytic	44.65032
Time Without beam	Simulation	210.000	Runtime	5000

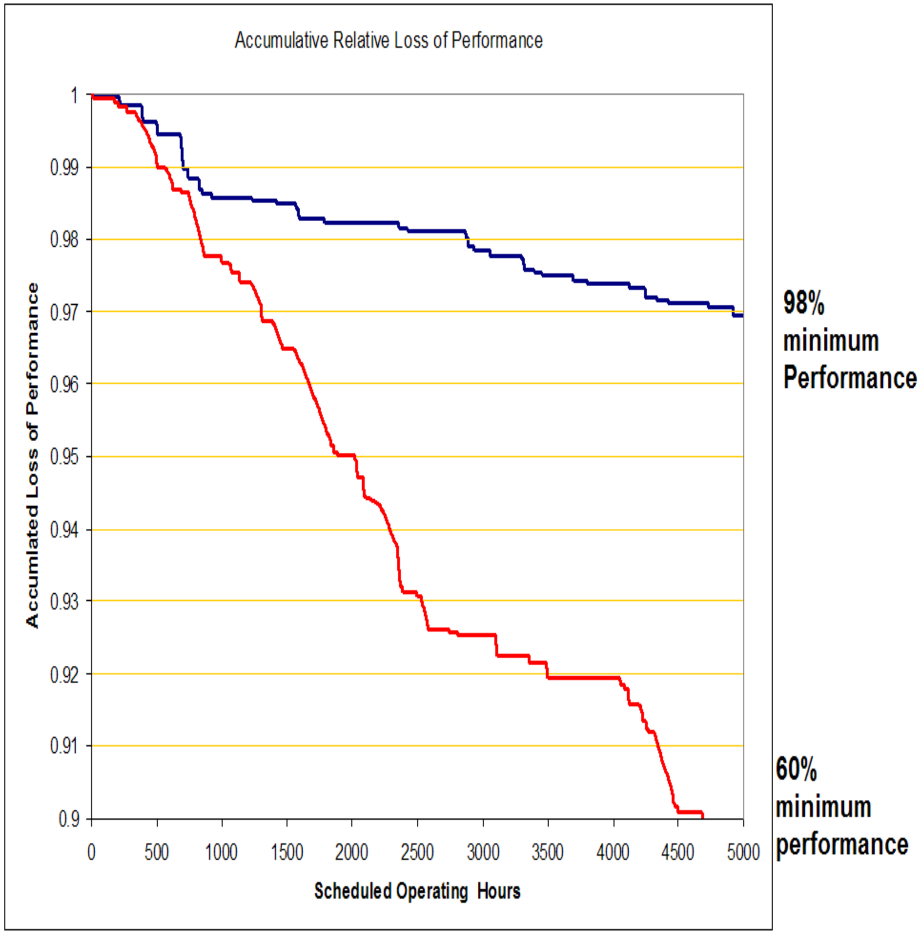


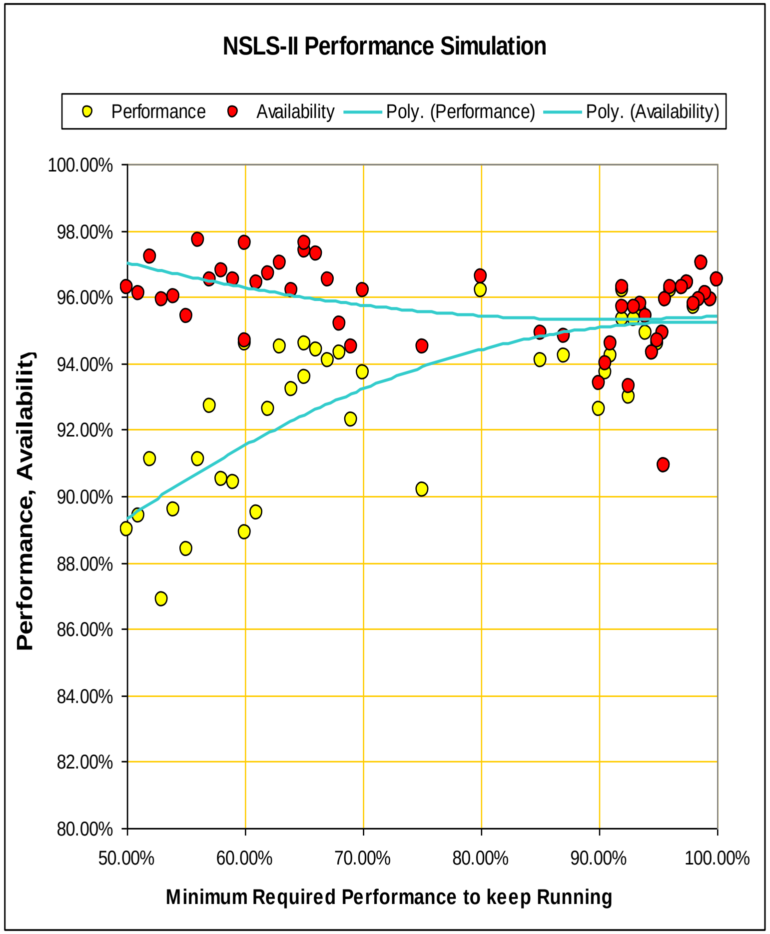
Lost Performance per System



NSLS-II Performance Simulations

Question: Keep Running with Reduced Performance –OR- Break for Repair?

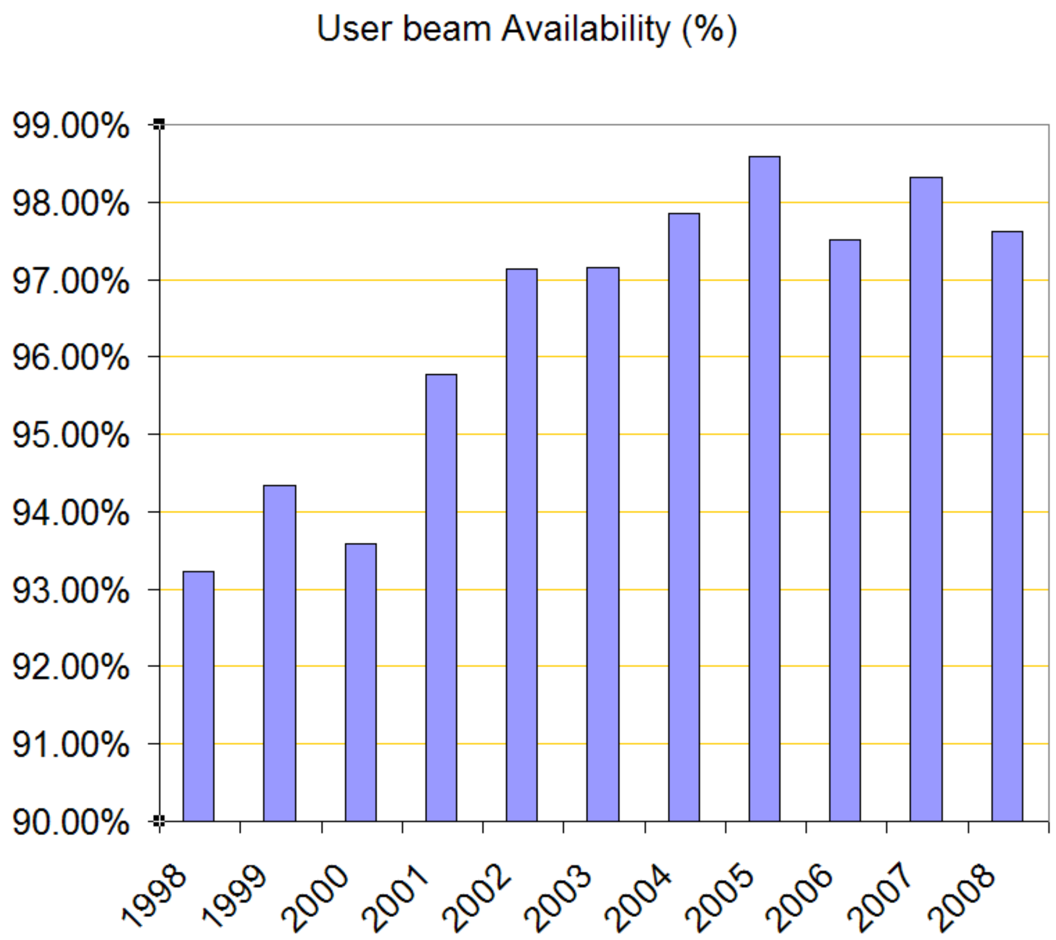




Answer (for NSLS-II assumptions): Don't accept more than 10% reduction in performance, Don't expect substantial increase in schedule safety by accepting running with reduced performance

Achieved Availabilities

Synchrotron Light Sources, Example APS



http://www.aps.anl.gov/Accelerator_Systems_Division/Operations_Analysis/logging/MonitorDataReview.html

Conclusion

- High operational reliability is for many accelerator facilities of equal or even larger importance than high performance
- High Reliability needs t
- o be built into accelerator design. Same as high performance, high reliability comes with a cost tag which requires careful optimization
- Operational procedures and analysis is an extremely import factor in achieving reliable accelerator operation