PSI Center for Accelerator Science and Engineering

ARW 2024

History of Maintenance and Reliability Strategy for the SLS Operation

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Accelerator Reliability Workshop, Helsingborg, June 25th, 2024

History of Maintenance and Reliability Strategy for the SLS Operation - Outline

1 **Introduction Swiss Light Source**
- Chronology
- The Accelerator
- The Light Source

2 **Swiss Light Source Operation**
- Statistics
- Scheduling Strategy
- Reliability Strategy

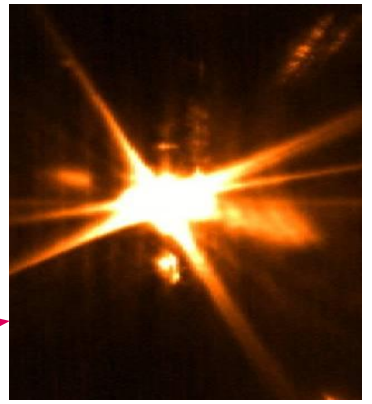
3 **Maintenance and Reliability Strategy**
- Magnets
- Machine Safety PLCs
- Diagnostics
- BPMs
- Power Supplies
- Cryo System
- Mains
- RF
- Controls
- Cooling
- Racks

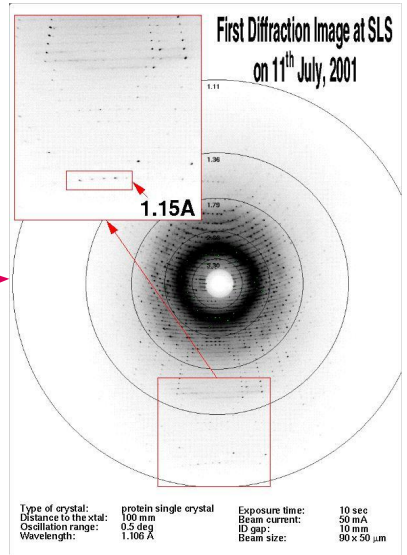
Introduction Swiss Light Source

Introduction Swiss Light Source

Chronology

1.	1993	Conceptual Design Report
2.	September 1997	Project approved by Swiss Government
3.	1998	Construction work begins
4.	June 1999	Accelerator installation begins
5.	**Christmas 2000**	**First stored beam**
6.	June 2001	**Top up operation at design current 400 mA**
7.	**July 2001**	**First user experiment**
8.	August 2001	Design specifications reached, start of user operation
9.	January 2005	Femto Slicing
10.	May 2006	3 T Superbends
11.	January 2012	Commissioning of 19th and last beamline PEARL
12.	**September 2023**	**Final Beam Dump**

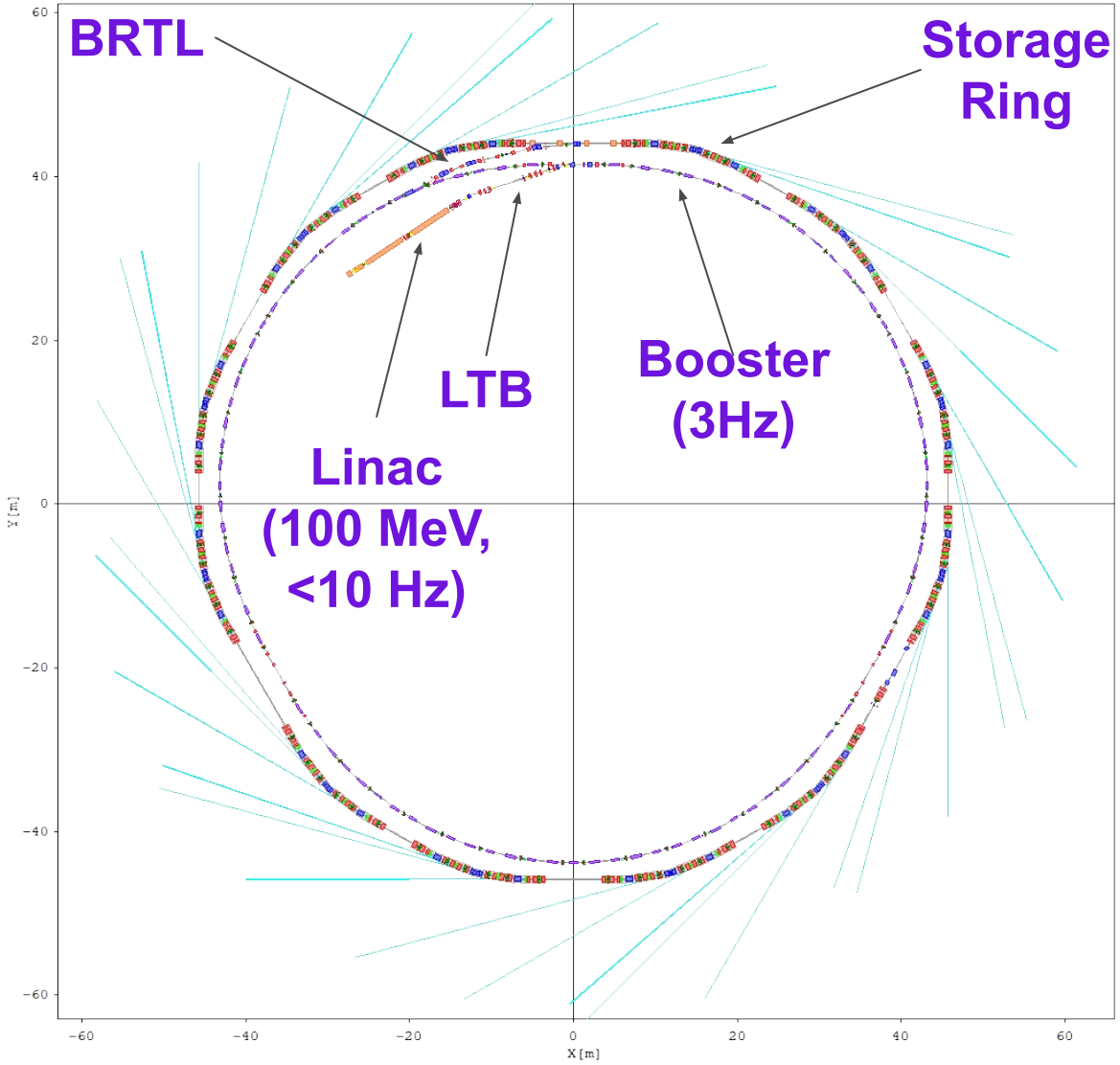




Introduction Swiss Light Source

The Accelerator

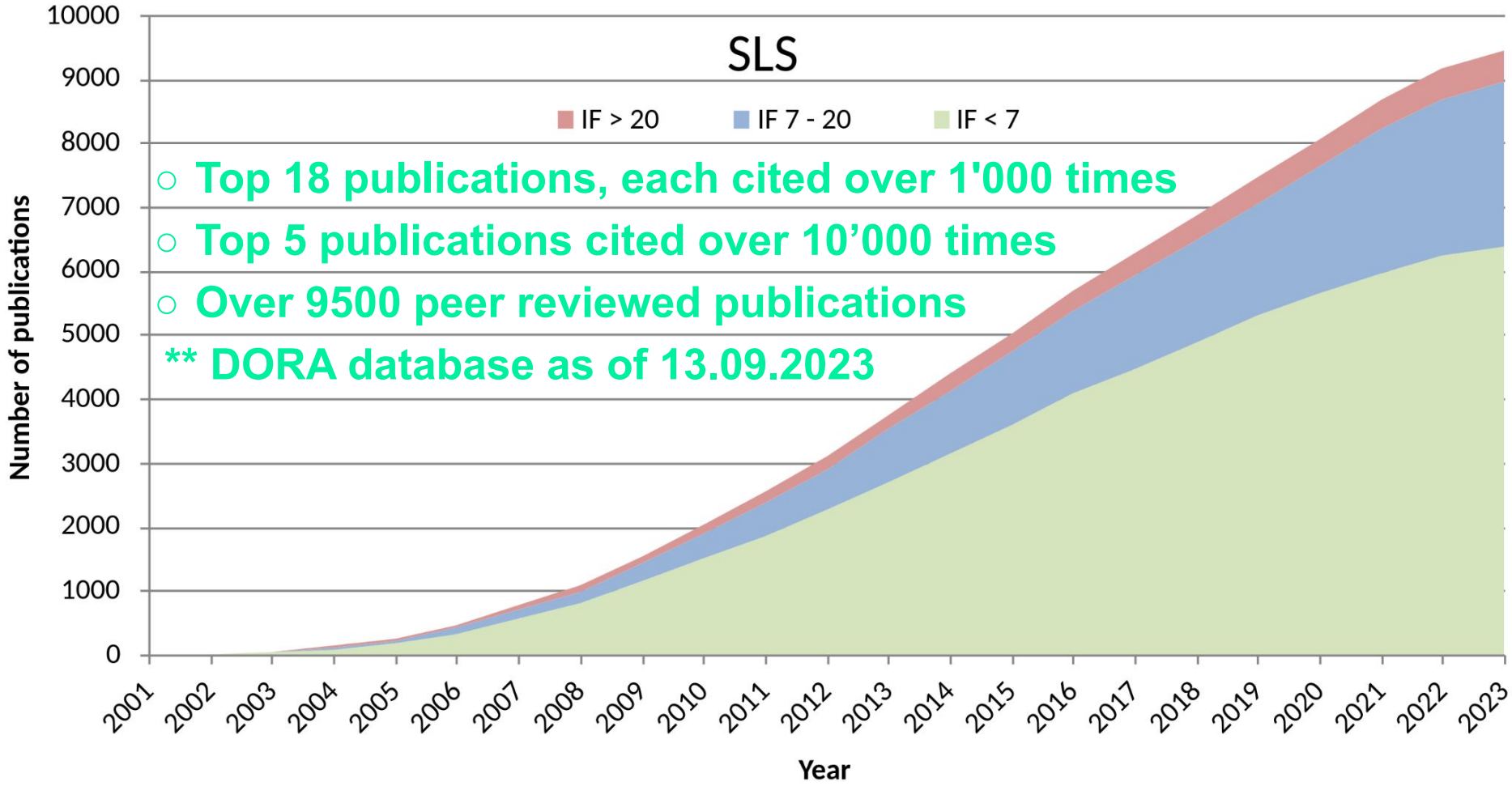
Circumference	288 m
Straights	3 × Long
	3 × Medium
	6 × Short
Straight Length	~80 m
Beam Current	400 mA
Beam Energy	2.41 GeV
Horizontal Emittance	5.5 nm rad
Vertical Emittance	1.9 … 7 pm rad
Coupling	0.03 … 0.1 %
Energy Spread	0.09 %
Lifetime	~12 h
Stability (photon beam at FE)	< 1 µm



Introduction Swiss Light Source

The Lightsource

Over 22 years of user operation delivering photons from 16 source points to 18 beamlines



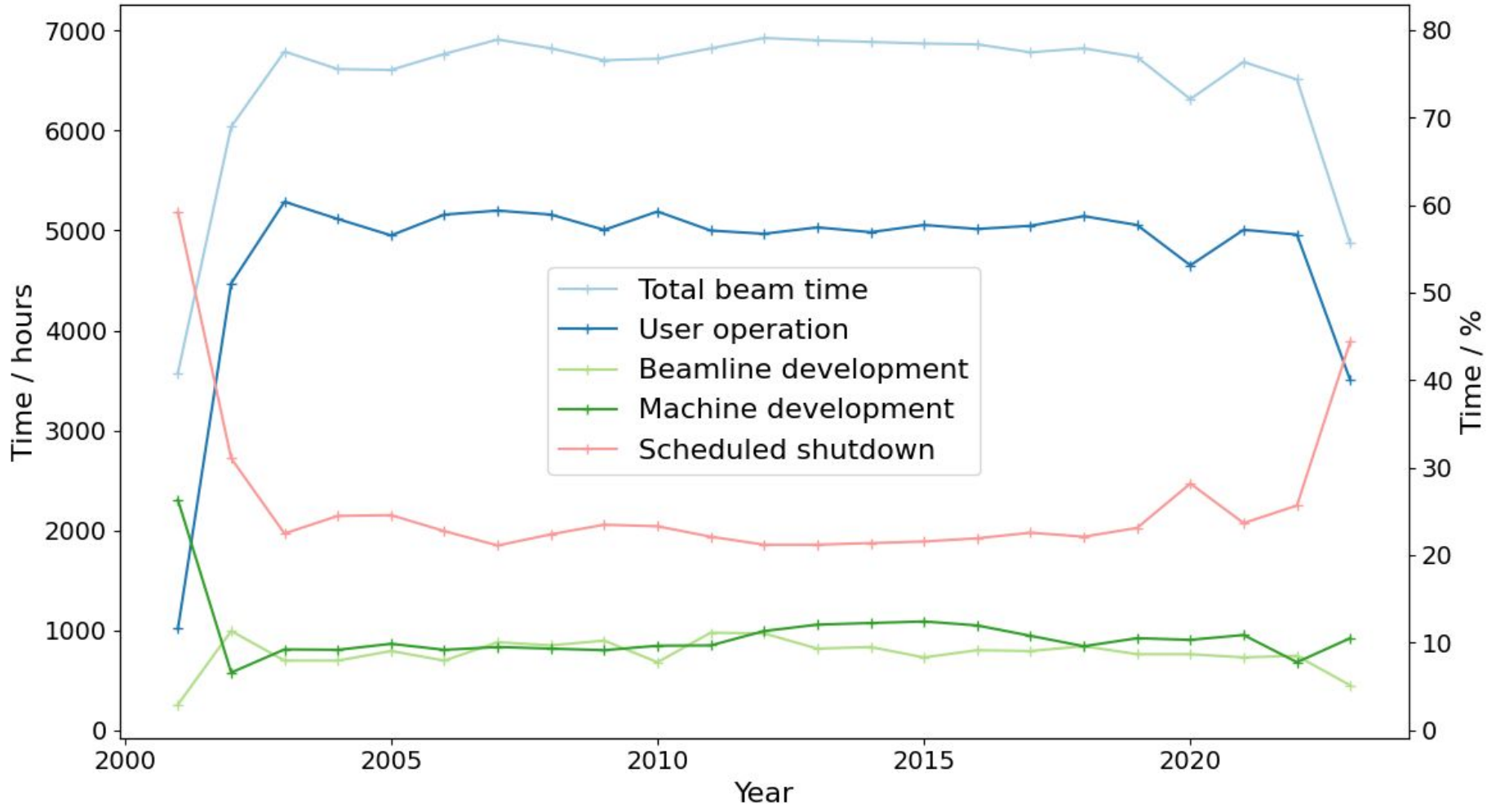
Operation Swiss Light Source

The Swiss Light Source was in user operation between August 2001 and September 2023

- The presented statistics are limited to the time range from 2002 until 2023 due to limited historic data

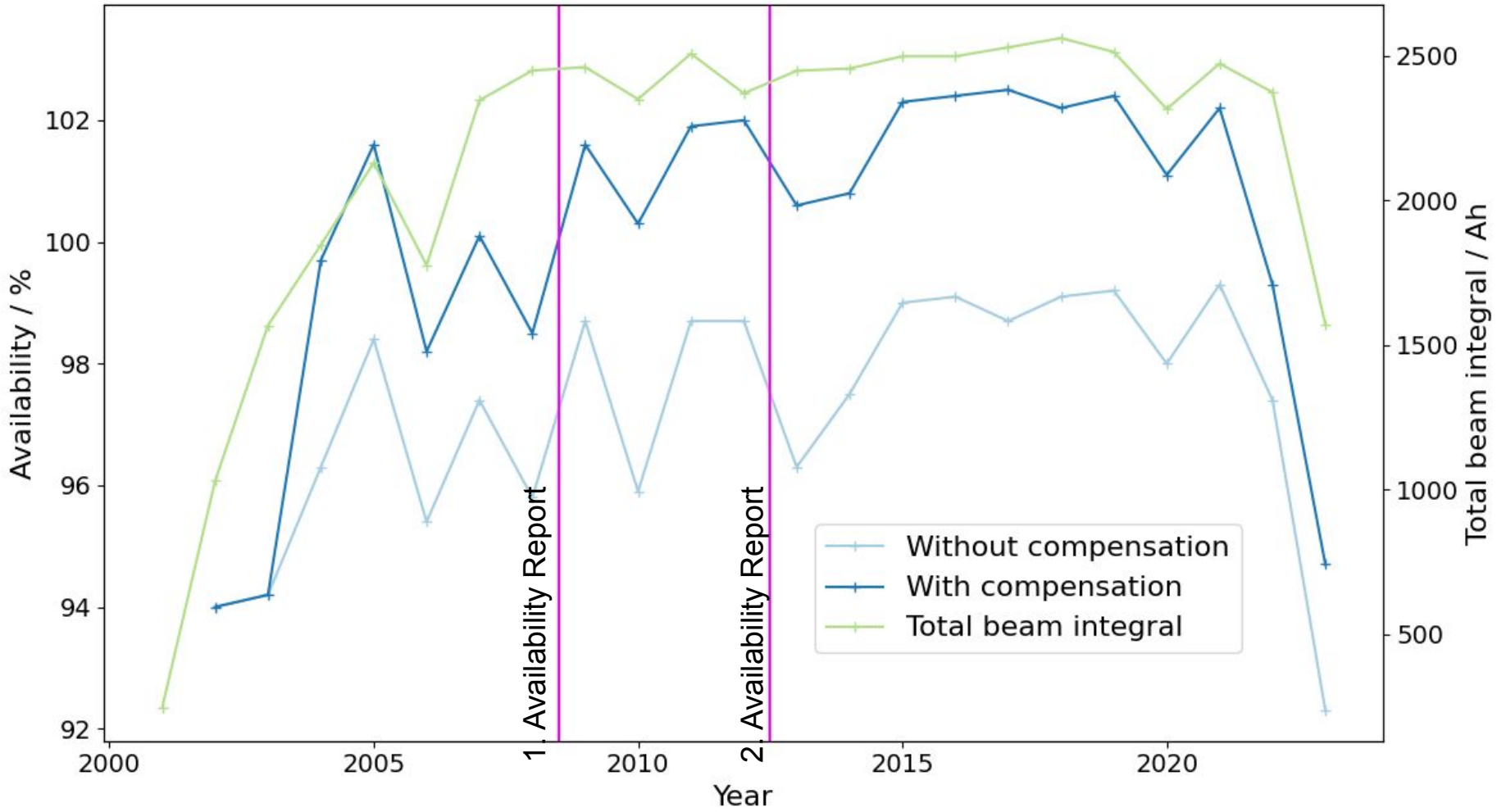
Operation Swiss Light Source

Statistics - The Bathtub Curves - Scheduled Time



Operation Swiss Light Source

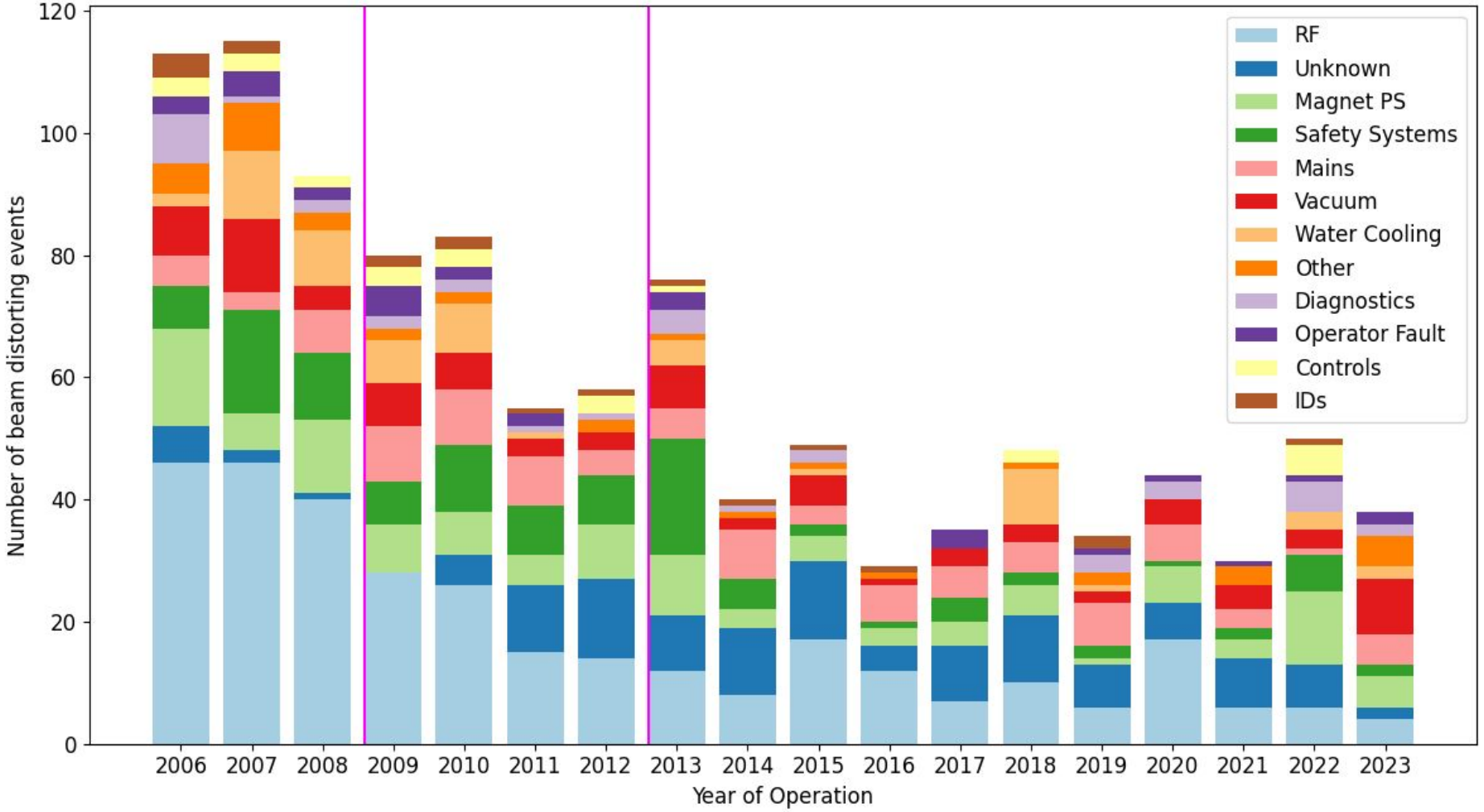
Statistics - The Bathtub Curves - Availability



Reduced reliability in last years due to expert groups shifting focus to upgrade project SLS 2.0

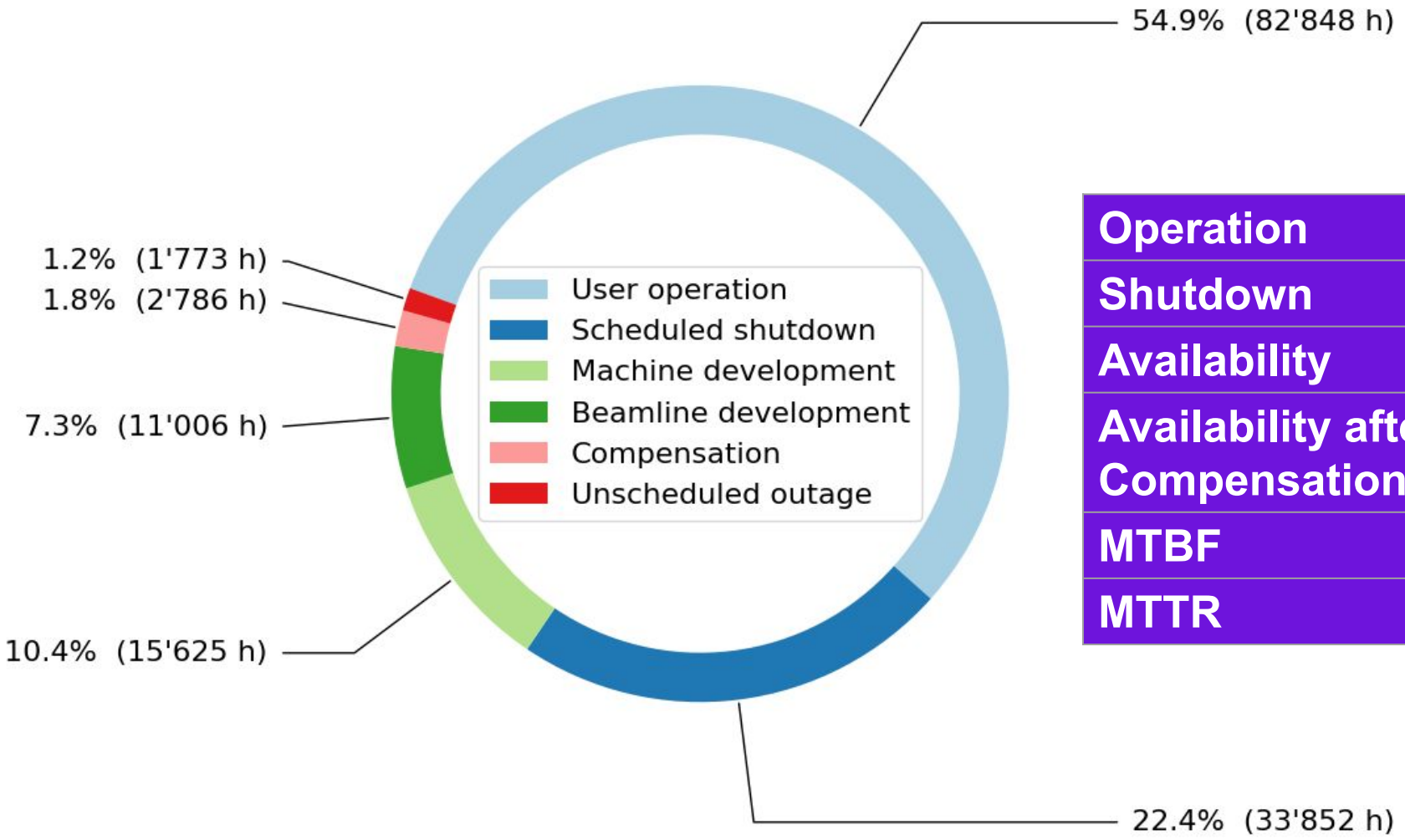
Operation Swiss Light Source

Statistics - Cause Distribution by Nr. of Incidents



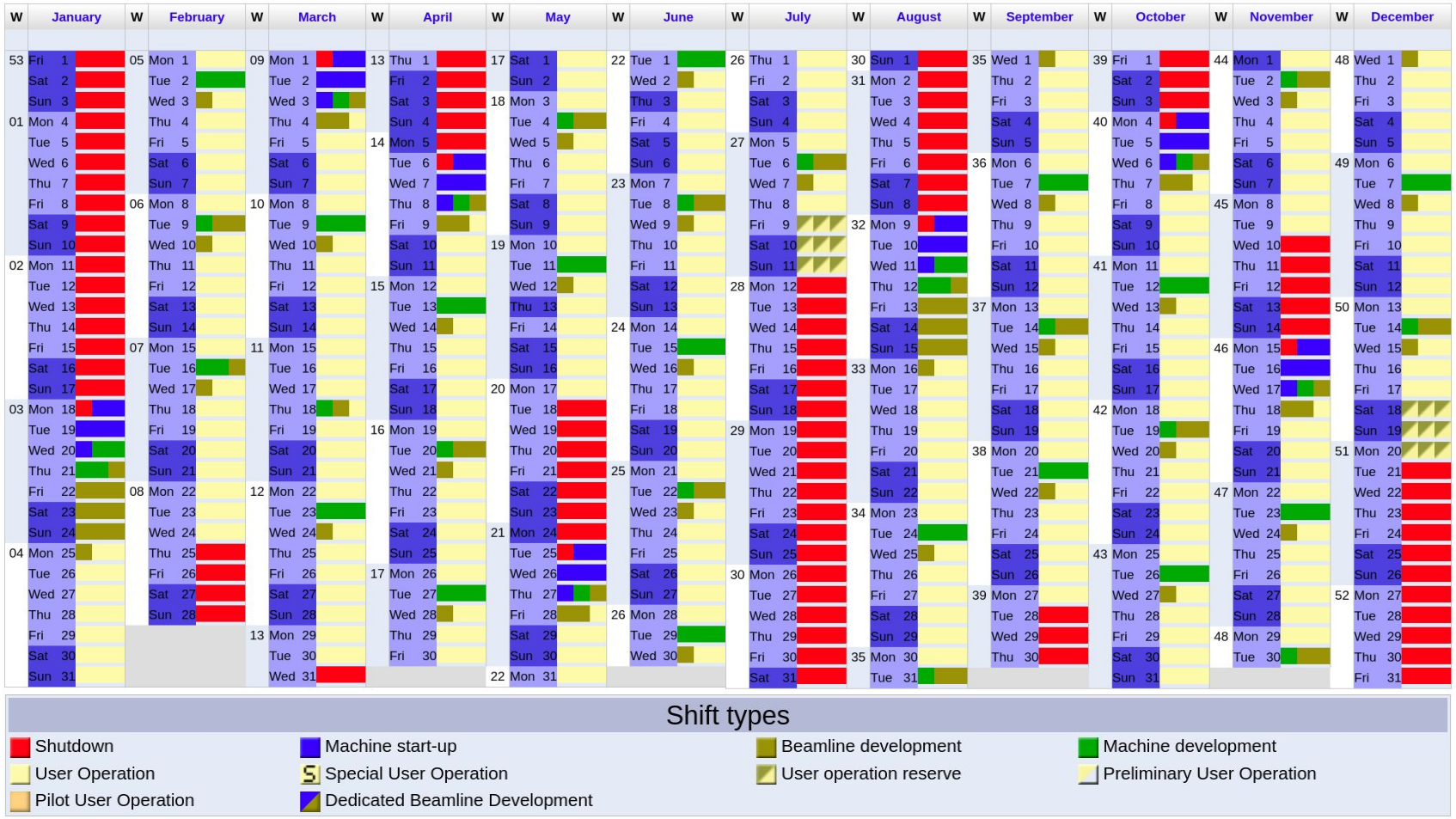
Operation Swiss Light Source

Overall Statistics Jan. 2005 - Dec. 2021



Operation	**115’051 h (76.3 %)**
Shutdown	**35’625 h (23.6 %)**
Availability	**97.9 %**
Availability after Compensation	**101.2 %**
MTBF	**90.6 h**
MTTR	**1.9 h**

Operation Swiss Light Source
Scheduling Strategy



- 3 days user operation reserve before long shutdowns (summer / christmas)
- Machine and beamline development shifts scheduled before reset of weekly dose limit (20 µSv) on Wednesday morning
- Machine and beamline development shifts are canceled to compensate unscheduled downtime exceeding user operation reserve
- Buffer of beamline- and machine development after shutdown

SLS Operations Planning for 2021

Operation Swiss Light Source
Reliability Strategy

- **24/7 occupied control room** with well-trained and experienced operators (70 % shift)
  - Regular hands-on training for
    - machine standard procedures
    - recovering from automated sabotage
- **24/7 On-call service**
  - Machine Physicist, RF, Power Supplies, Vacuum, Cooling, Feedbacks, Controls, (Cryo), Radiation Protection, Experimental-Hall-Service
- **Operations Manager**
  - Highlighting required resources for accelerator systems to management
    - Yearly operations report for management and regulatory authority
    - Availability reports, highlighting systematic failures
    - Providing easy access to accelerator performance/reliability data
      - Web interface to predefined archive data plots
      - Web interface to operation event logging system
      - Web interface to operation logbook

Maintenance and Reliability Strategy

Maintenance and Reliability Strategy Swiss Light Source

Magnets - Operational Strategy

Operational Strategy

One spare for each magnet type is held in reserve

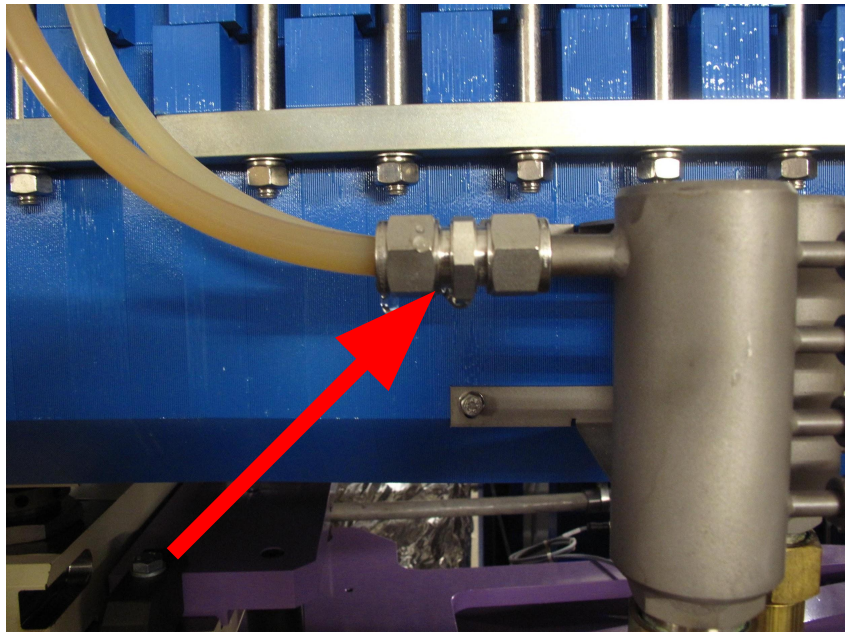
Preventive maintenance

Check for water leaks each shutdown

(radiation damage to plastic hoses → yellowed)

Maintenance and Reliability Strategy Swiss Light Source

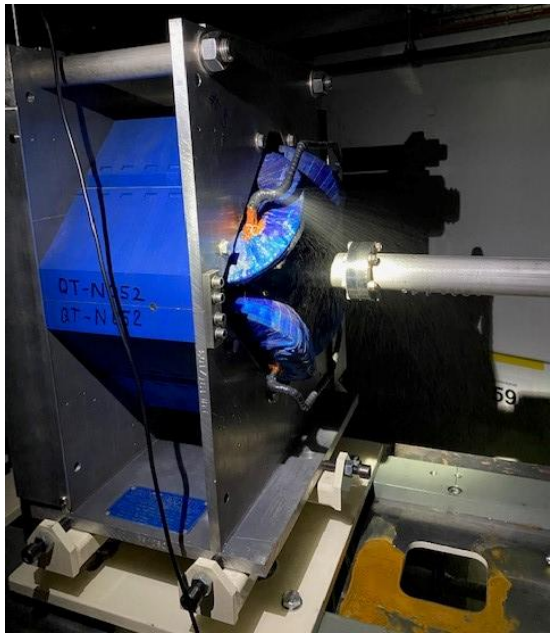
Magnets - Observed Magnet Failures



Common

Slight water leaks at plastic hose connectors

→ Due to thermal expansion
→ Retightening at next opportunity is sufficient



Rare

Water leaks in copper conductor

→ Due to erosion

→ Beam time interruption

Maintenance and Reliability Strategy Swiss Light Source

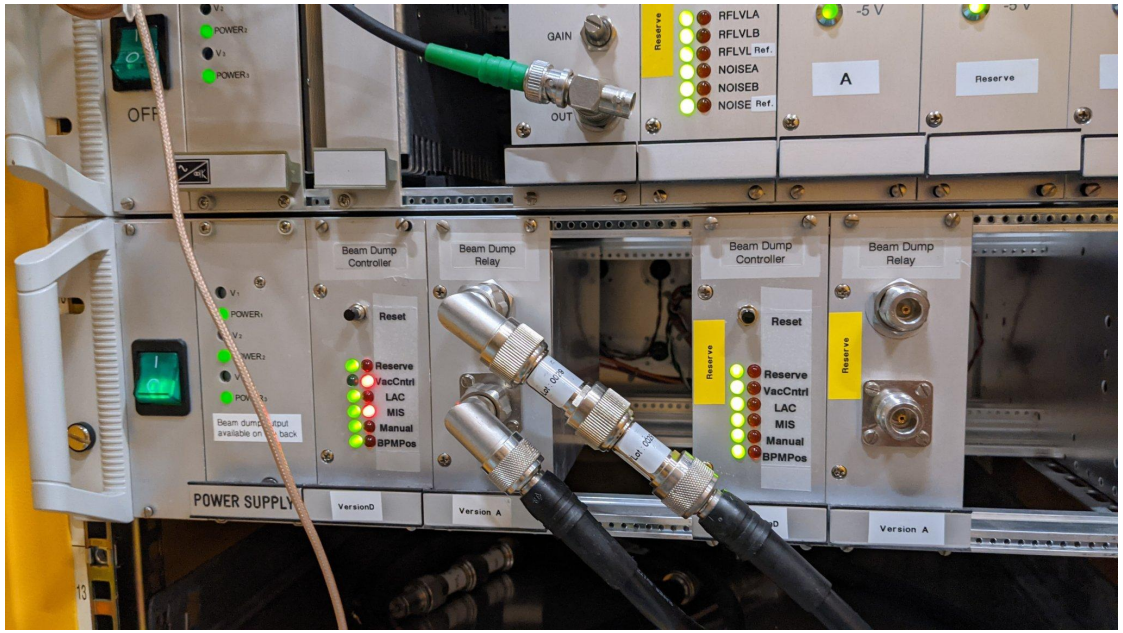
Cooling Strategy SLS 2.0

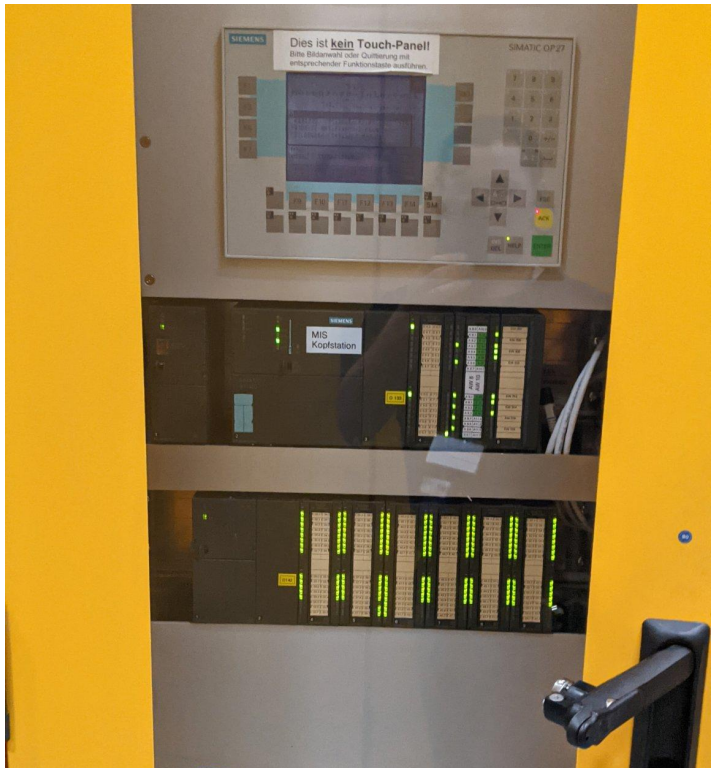
- Reduced water pressure of 4 instead of 8 bar
  - ➢ Sufficient for cooling
  - ➢ Less erosion / cavitation / water leaks
  - ➢ More energy efficient
- Avoid usage of chillers

Maintenance and Reliability Strategy Swiss Light Source
Machine Safety PLCs

- Interlock beam dumps due to temporary communication breakdowns between head and sector stations of MIS

  ➢ Introduction of allowed dead time between head and sector stations





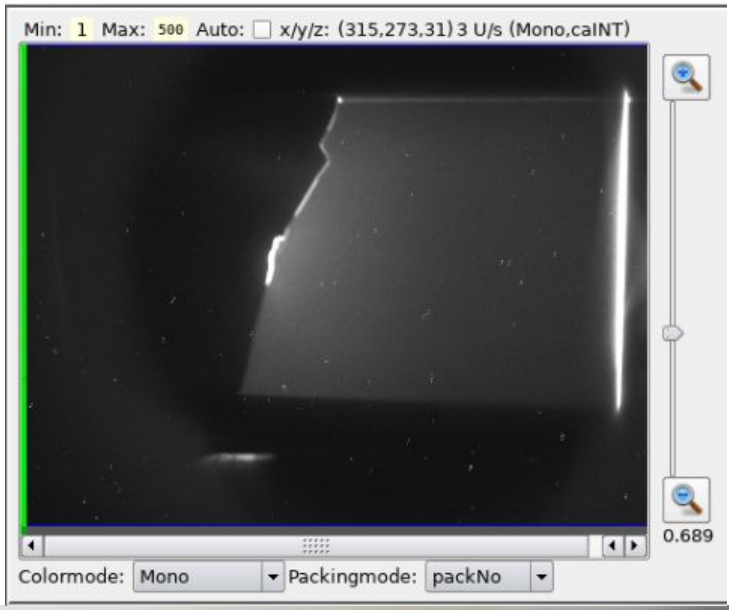
Maintenance and Reliability Strategy Swiss Light Source

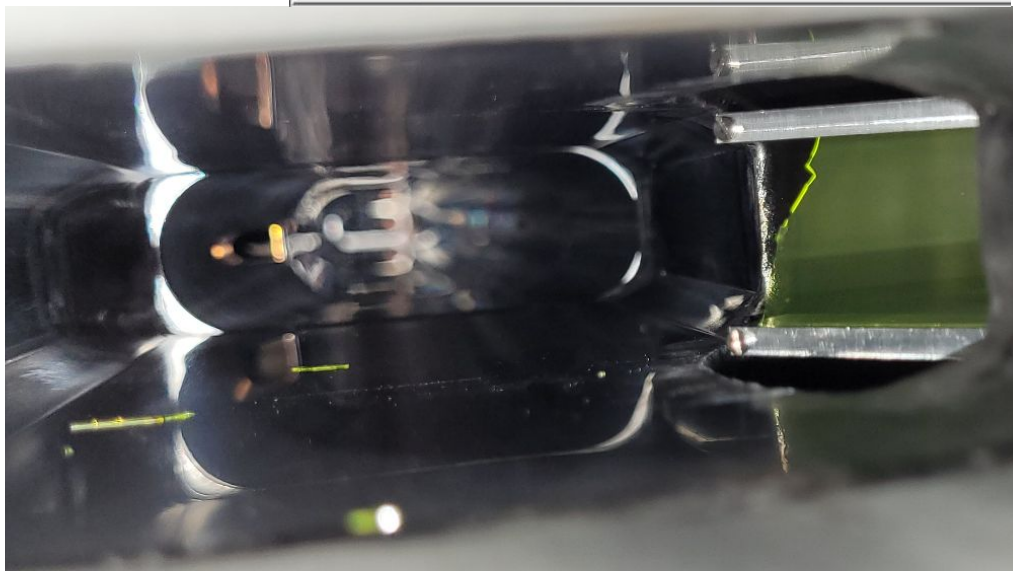
Diagnostics

- Shutdown tasks
  - Lubricate motors
  - Electronics power cycle
  - Check encoders, electronics in tunnel for radiation damage
  - Re-commissioning after changes to related systems
  - Check optical elements for degradation → replace

- Operational tasks: checklist diagnostics
  - Screens: move in/out
  - Cameras: reference image

- Electronics → Too few prototype-iterations
  - Compatibility of design with production procedures
  - Design adjustment often advisable
  - Burn-in tests





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BPMs

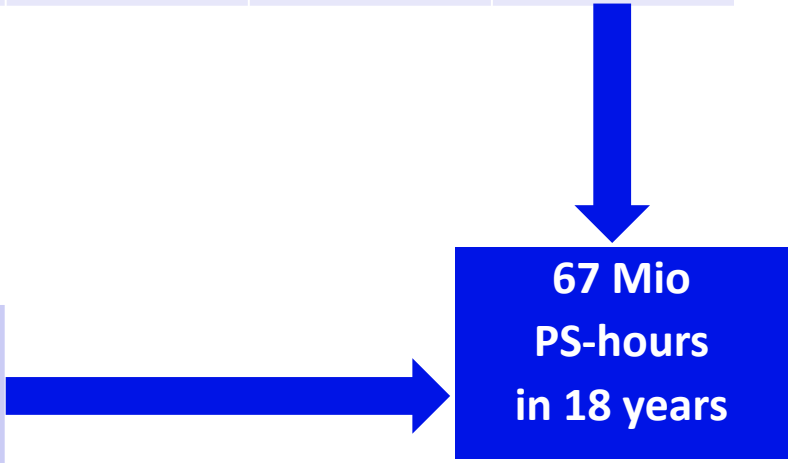
- Options: off-the-shelf Bergoz vs. **in-house DBPM**
  - Aiming for better performance and functionality
  - Providing closed orbit and turn-by-turn-data
  - Limited local storage preventing rollout of new features
- 50% of BPMs lost in just 3 years (bad soldering joints)
  - Large scale deployment of unskilled personnel for resoldering the circuit board contacts
  - Booster BPMs misused as spare parts stock
    → only 2 working booster BPMs left
- Automatic testing of DBPM systems introduced after 2019

Maintenance and Reliability Strategy Swiss Light Source

Power Supplies - Portfolio and Operation 2005 - 2022

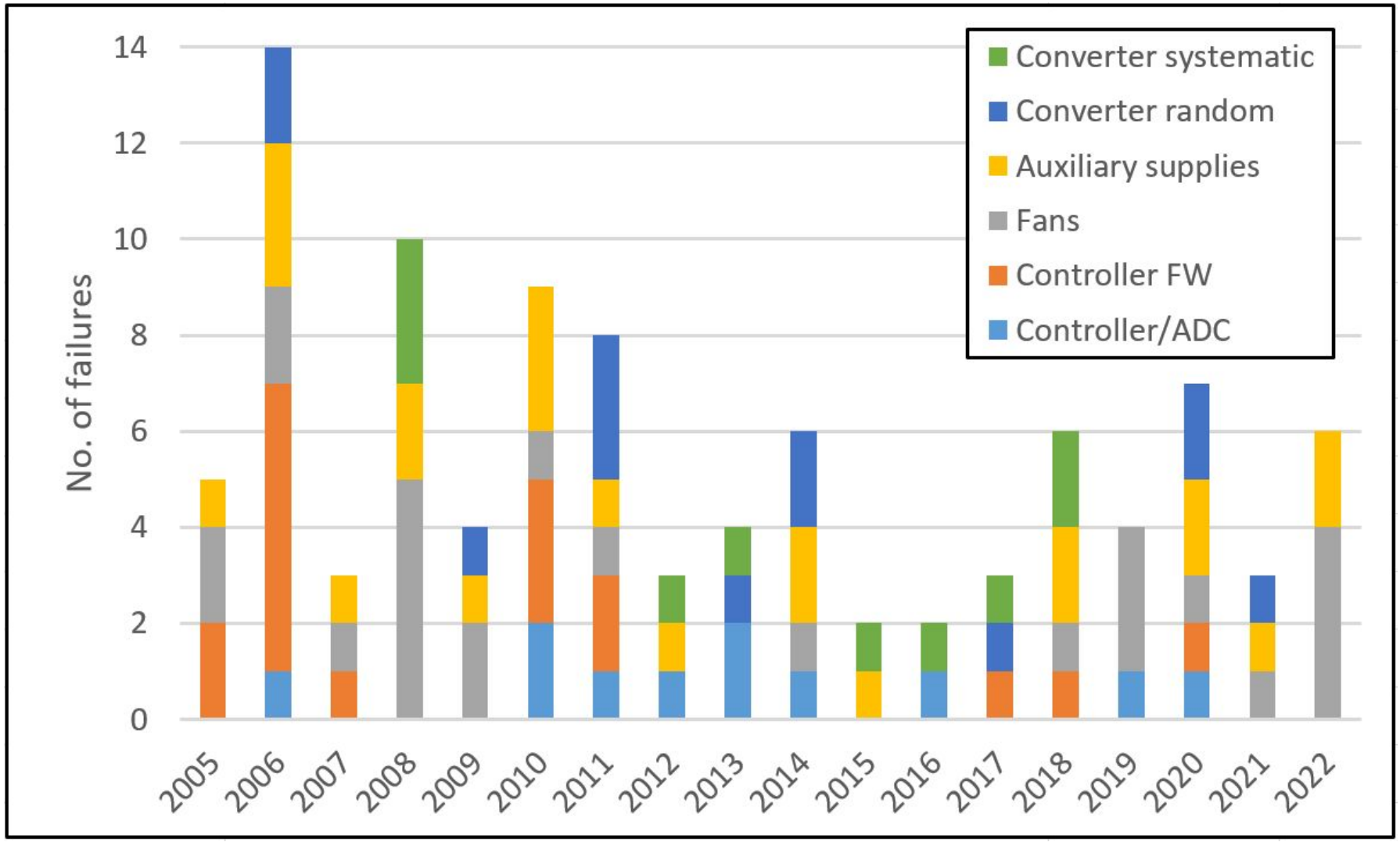
Power Supply	Type	Injector	Ring	IDs	Total
Booster Dipole	900 A, 1000 V, 3 Hz	1			
Storage Ring Dipole	500 A, 880 V, 1Q		1		
Storage Ring Superbend	500 A, 200 V, 1Q		1		
Bipolar for IDs	150 A, 90 V, 4Q			9	
Quadrupole, low voltage	120 A (140 A), 15...60 V, 1Q	22	177		
Quadrupole, high voltage	120 A, 75...240 V, 1Q		9		
Miscellaneous		12	1		
Corrector	7 A (10 A), 24 V, 4Q	119	197	86	
Total		**154**	**386**	**95**	**635**

Shutdown		
Startup		
Machine Development		
Beamline Development	**Approx. 5800 hours / year**	**105’000 hours 2005 - 2022**
User Operation		



Maintenance and Reliability Strategy Swiss Light Source

Power Supplies - Portfolio and Operation 2005 - 2022



Maintenance and Reliability Strategy Swiss Light Source

Power Supplies - Systematic Failures

Fans

Overall 1’126 installed with 25 failures

→ Regular patrol for and exchange of noisy fans

→ New PS design: avoid fans or use redundant fans

Auxiliary Supplies

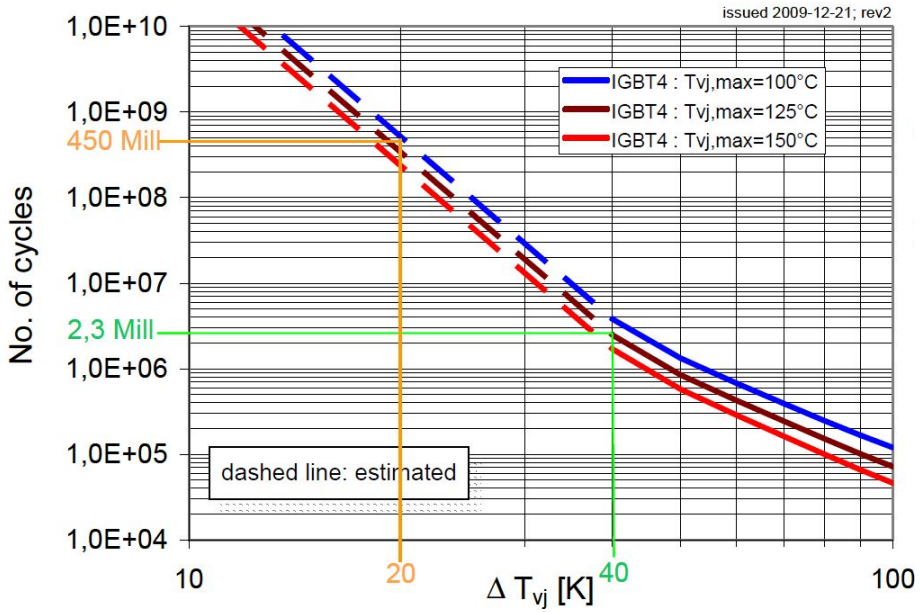
Overall 550 installed with 23 failures

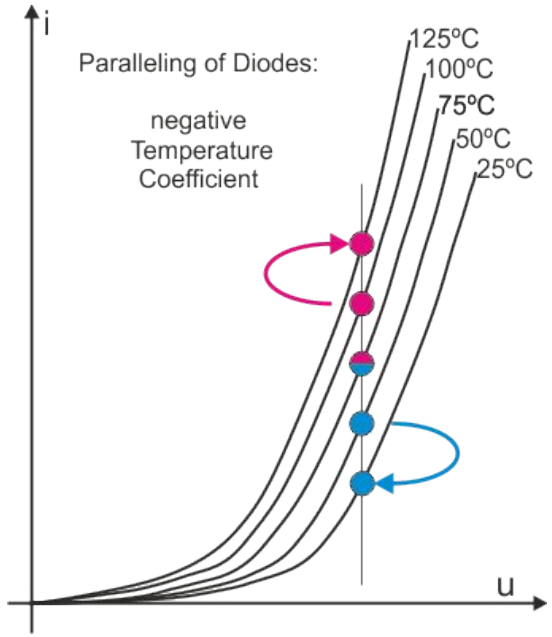
→ Quick repair strategy

→ New design: Redundancy enabling relaxed repair during next shutdown

Maintenance and Reliability Strategy Swiss Light Source

Power Supplies - Design Deficiencies





Limited power/thermal cycling capability for IGBTs

Relevant for booster main dipole PS with overall 3 failures

→ Replacement of power semiconductors every 3 years

Unbalanced load when paralleling diodes

Overall 7 failures

→ Quick repair strategy

Maintenance and Reliability Strategy Swiss Light Source

Power Supplies - Beam losses due to PS failures 2005-2022

PS operating time in 18 years
66’690’240 hours

	Controller / ADC (HW)	Controller FW	Water Cooling	Fans	Auxiliary PS	DCCT	Converter random	Converter systematic	Wiring	Unknown
Failures per Category	11	17	2	25	23	1	13	10	7	4
Total Failures over 18 years	113									
Average nr. of failures per year	6.3									
MTBF / hours	590’179									

Maintenance and Reliability Strategy Swiss Light Source

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Preemptive Maintenance & Design Improvement

	Controller / ADC (HW)	Controller FW	Water Cooling	Fans	Auxiliary PS	DCCT	Converter random	Converter systematic	Wiring	Unknown
Failures per Category	11	17	2	0	0	1	13	0	7	4
Total Failures over 18 years	55									
Average nr. of failures per year	3.1									
MTBF / hours	1’212’550									

→ Same PS failure rate despite 2x PS for SLS 2.0

Maintenance and Reliability Strategy Swiss Light Source

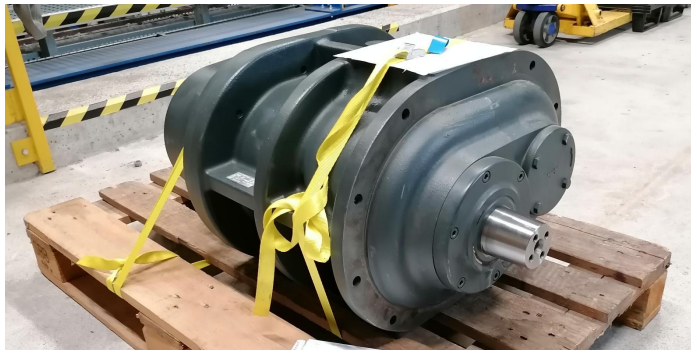
Cryo System

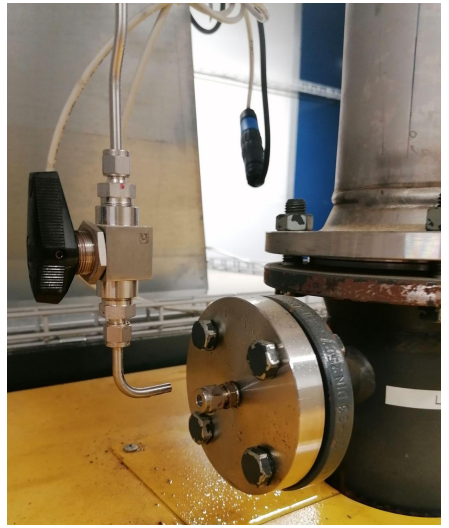
General Situation

- Super-3HC critical for operation
- Failures usually imply multiple hours beam interruption

Risk

- Failure-duration and general condition of cryogenic system determine downtime
- When cold box temperature rises too high
  - ➢ Helium system contaminated by foreign gases / water (frozen out during operation)
  - ➢ Warm-up and cleaning procedure (=downtime) over several days



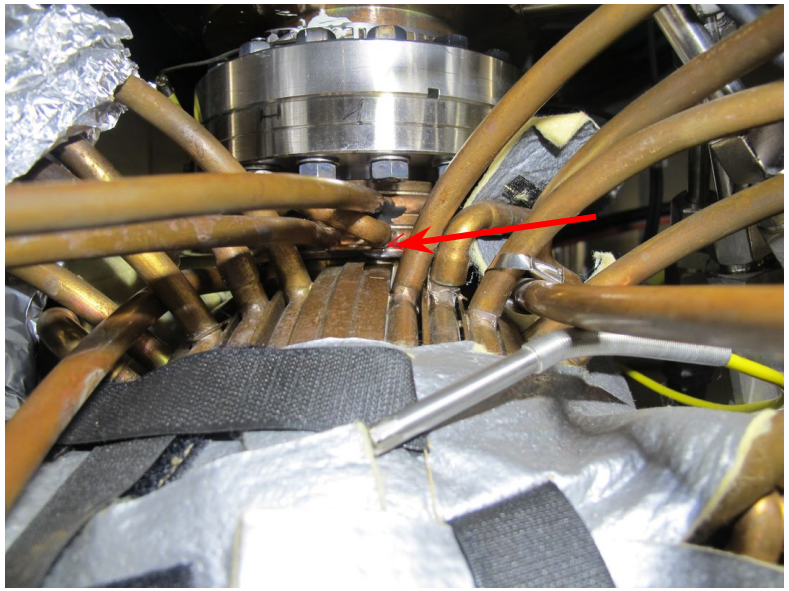


Maintenance and Reliability Strategy Swiss Light Source
Mains

- In total 6 defective mains transformers (16 kV → 220 V)
  - ➢ Problem linked to bad production series → all replaced
  - ➢ Switching from star to ring topology of mains transformers enables maintenance (used for SLS 2.0)
- Signature of RF station 2 after power glitch always caused switching of 16 kV transformer safety switch

Maintenance and Reliability Strategy Swiss Light Source

RF

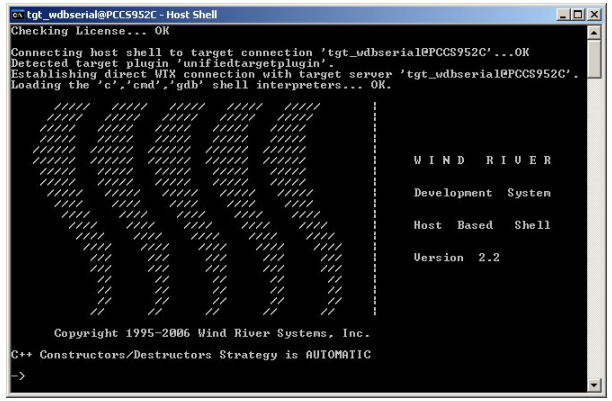


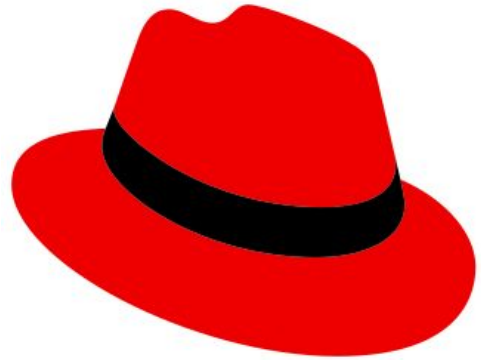
- Cavity water leaks and clogging issues
  - ➢ Reduce flow to prevent cavitation
  - ➢ Emergency water valves prevent water contamination in cavities
  - ➢ Prevent corrosion with chemical additives / degassing unit
  - ➢ Test stand enables quality control for spare parts
- HOM tuning
- Coincidence arc detectors to suppress false interlocks
- Replacement of cavities and power couplers
- Improving RF filter bank (i.e., thresholds, dead times, …) of every RF signal able to trigger a beam dump
  - ➢ E.g., reflected power after beam losses triggers RF beam dump making fault detection difficult
    → increase reflected power threshold
    → automatically reduce RF input power in dependance of reflected power
    → quicker restart of accumulation

Maintenance and Reliability Strategy Swiss Light Source
Controls

- Generally few problems during user operation
  - Problems usually occur during startup → Scheduling Strategy
  - Most problems due to new versions of VxWorks, EPICS or Linux

➢ Software development / maintenance / upgrade procedures with rollback capability





Maintenance and Reliability Strategy Swiss Light Source
Racks in Technical Gallery

Overheating racks due to failing fans

- ➢ Retrofit fan failure detection
- ➢ Preemptive maintenance strategy: replace noisy fans
- ➢ Design strategy SLS 2.0: passively cooled racks (punctured roof & double floor)

Summary

Summary

Operation Swiss Light Source

In Operation	Peak Availability (2005 - 2021)	MTBF	MTTR
~23 years (2001 - 2023)	~98 % … 101 % with / without compensation	~91 h	~2 h

Reliability and Maintenance Strategy

- **Staff, i.e.,** dedicated, well-qualified and well-trained physicists, engineers and **technicians**
  - Experts to design, procure, commission and upgrade their systems (also off-the-shelf commercial systems!)
  - Specialised technicians for maintenance and vertically integrated system tests
  - Experienced and well-trained operators to diagnose, document and solve problems or escalate them to the piquet
  - 24/7 piquet service staffed with experienced experts for efficient fault diagnosis and quick repair
- **Preemptive maintenance**
  - Identify and tackle systematic failures → Invest in good first fault detection / post-mortem system
- **Quick repair strategy**
  - Modular service-friendly design including good self-diagnostics for all systems
  - Complete spare parts inventory on site (10% spare units << 10% of cost but large reliability gain)

Summary

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Machine reliability / availability requires dedicated expert groups with sufficient resources
→ Giving expert groups the resources and personnel required to take responsibility for their systems and improve, maintain and upgrade these will pay off increasing reliability and avoiding time- and cost-intensive post mortem repairs


PSI
Center for Accelerator Science
and Engineering
SINQ
Thank you for your attention
And thanks to the many colleagues
who provided slides and input
for this presentation
Swiss Light Source

Maintenance and Reliability Strategy Swiss Light Source

Definitions

- Downtime: time between beam loss (I_{beam} < 20mA) and full recovery (I_{beam} >= $I_{nominal}$ = 400 mA).
- Short-uptime-rule: if two beam outages have less than 1 hour of uptime in between, it is counted as one long downtime.
- Scheduled-user-time: this time is distributed between the accepted user proposals
- Scheduled-user-reserve-time: additional user time, provided to compensate for beam outages
- User-Time: Scheduled-user-time + Scheduled-user-reserve-time
- Delivered-beam-time: User-Time - Downtime
- Total-downtime: Sum over all individual Downtime of one year
- Number-of-faults: Count of all individual Downtimes
- Number-of-distortion = Incidence count of Downtimes, beam drops and orbit feedback failures (introduced 2004)
- Availability: Delivered-beam-time / User-Time.
- Availability after compensation: Delivered-beam-time / Scheduled-user-time.
- MTBF: Mean Time Between Failures = User-Time / (Number-of-faults + 1)
- MTTR: Mean Time To Recover = Total-downtime / Number-of-faults
- MTBD: Mean Time Between Distortions = User Time / Number-of-distortions

Swiss Light Source Maintenance and Reliability

Disaster Photo Competition

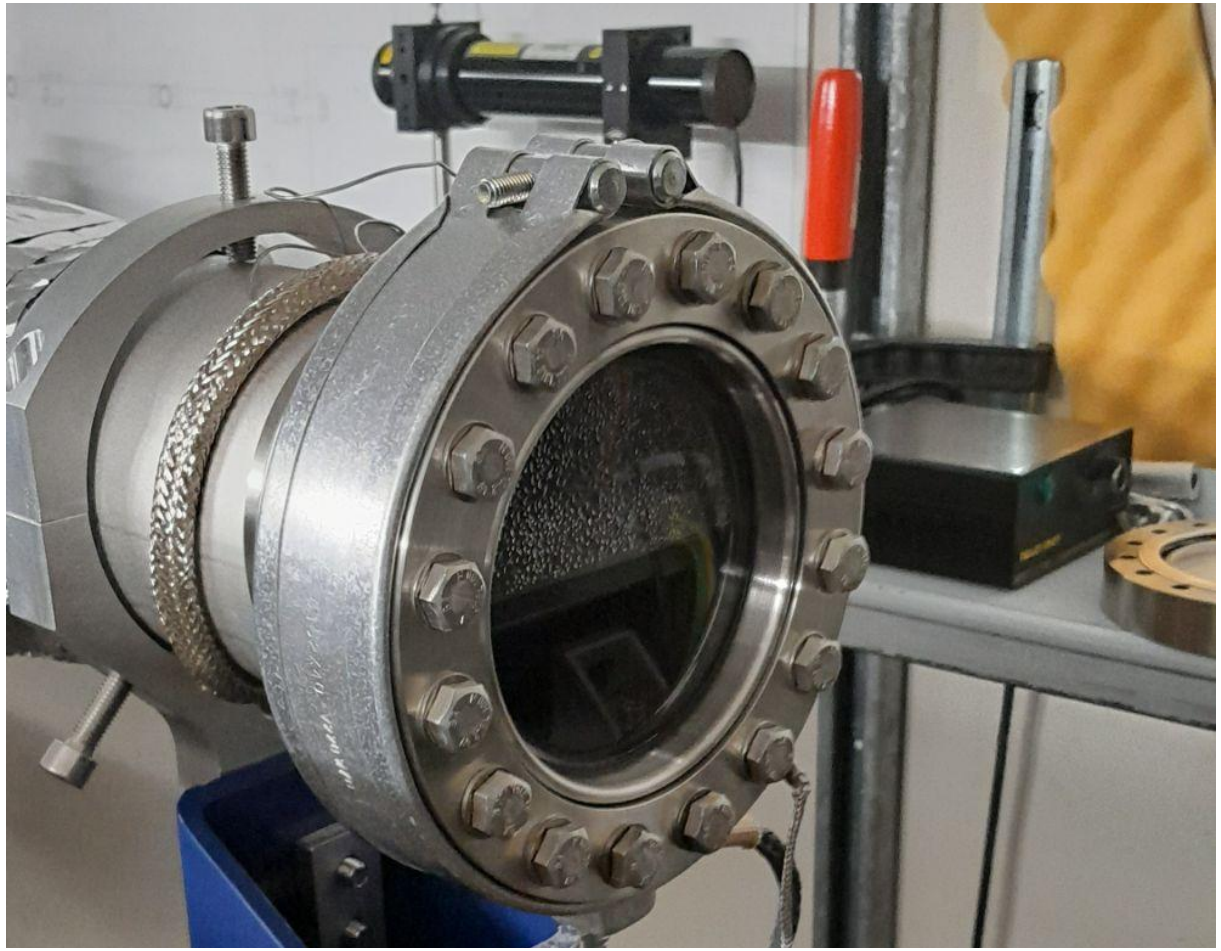
March 2006

After heavy snow damage to the wooden roof construction was observed indicating that the maximum roof load had been exceeded. Fire Brigade and Swiss Military joined forces to free the 14'000 sqm from snow.

Swiss Light Source Maintenance and Reliability
Disaster Photo Competition

December 2019
Reverse engineering of an oil capacitor that was failing inside the pulser of the booster kicker during initial testing.

Swiss Light Source Maintenance and Reliability
Disaster Photo Competition



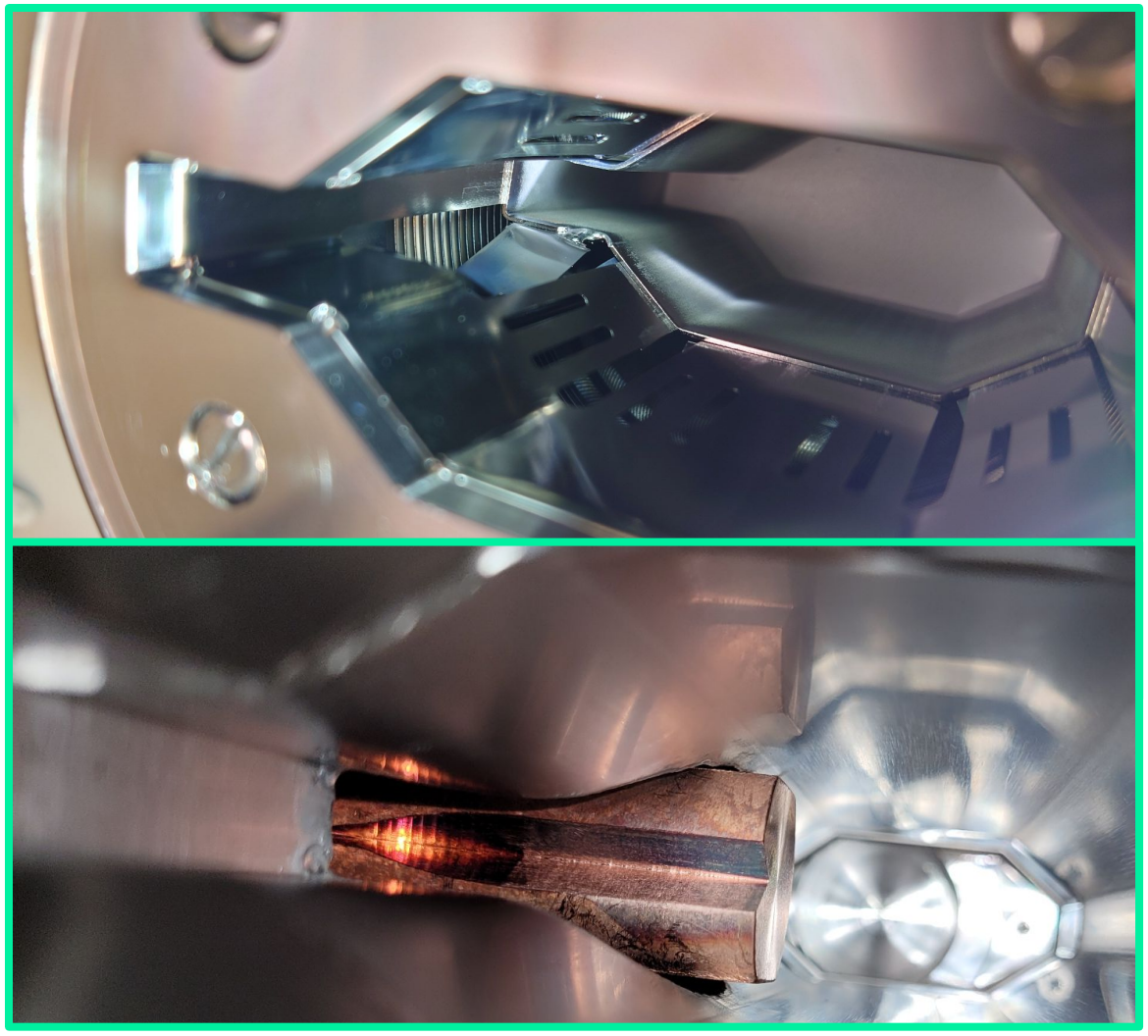
February 2023
Front End X09DA of the diagnostic beamline was flooded due to erosion/radiation induced leakage of copper cooling pipe for pinhole holder.

1. FE isolated from ring due to bad vacuum
2. Two days later 100 l water missing
3. Decision for no repair before SLS 2.0
4. No beam size measurement for user operation

For SLS 2.0 switch to stainless steel cooling pipes and reduced water pressure.

Swiss Light Source Maintenance and Reliability

Disaster Photo Competition

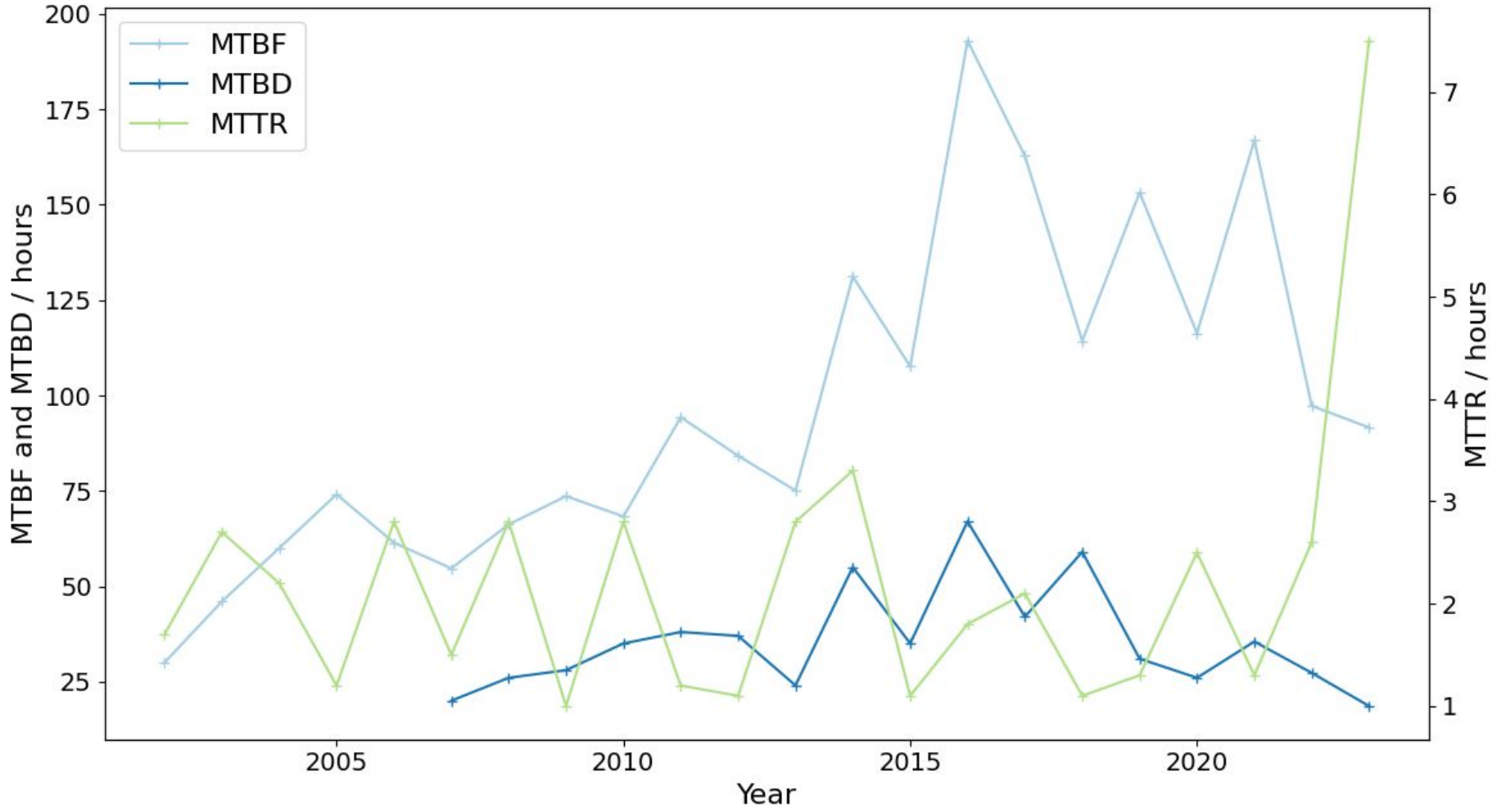


SLS Dismantling

Upstream bellow and absorber of Super-3HC show damage from large offset orbit event enabled/created by combined failures from amongst others BPM/OFB and vacuum Interlock.

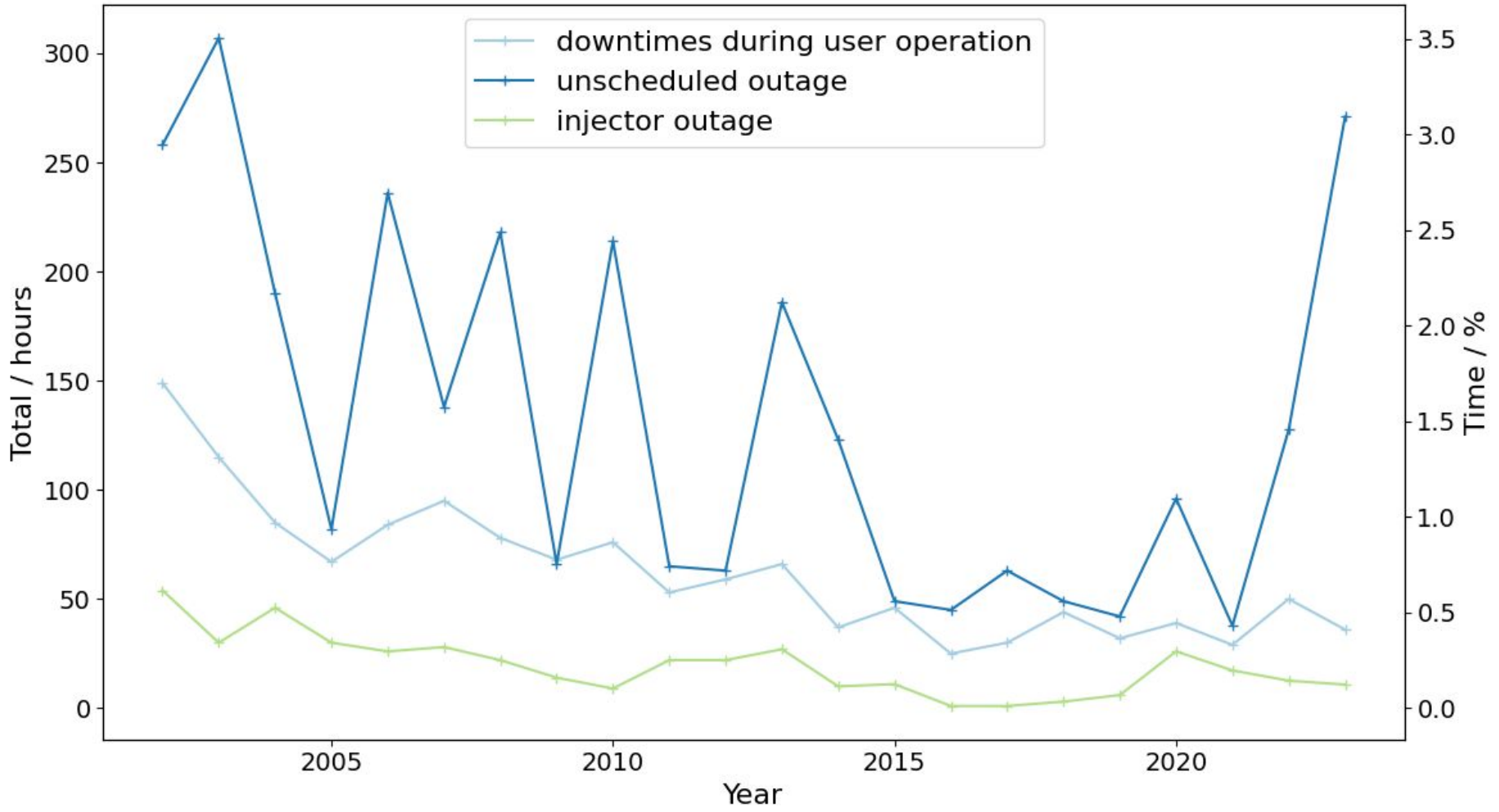
Operation Swiss Light Source

Statistics - The Bathtub Curves - Mean Times



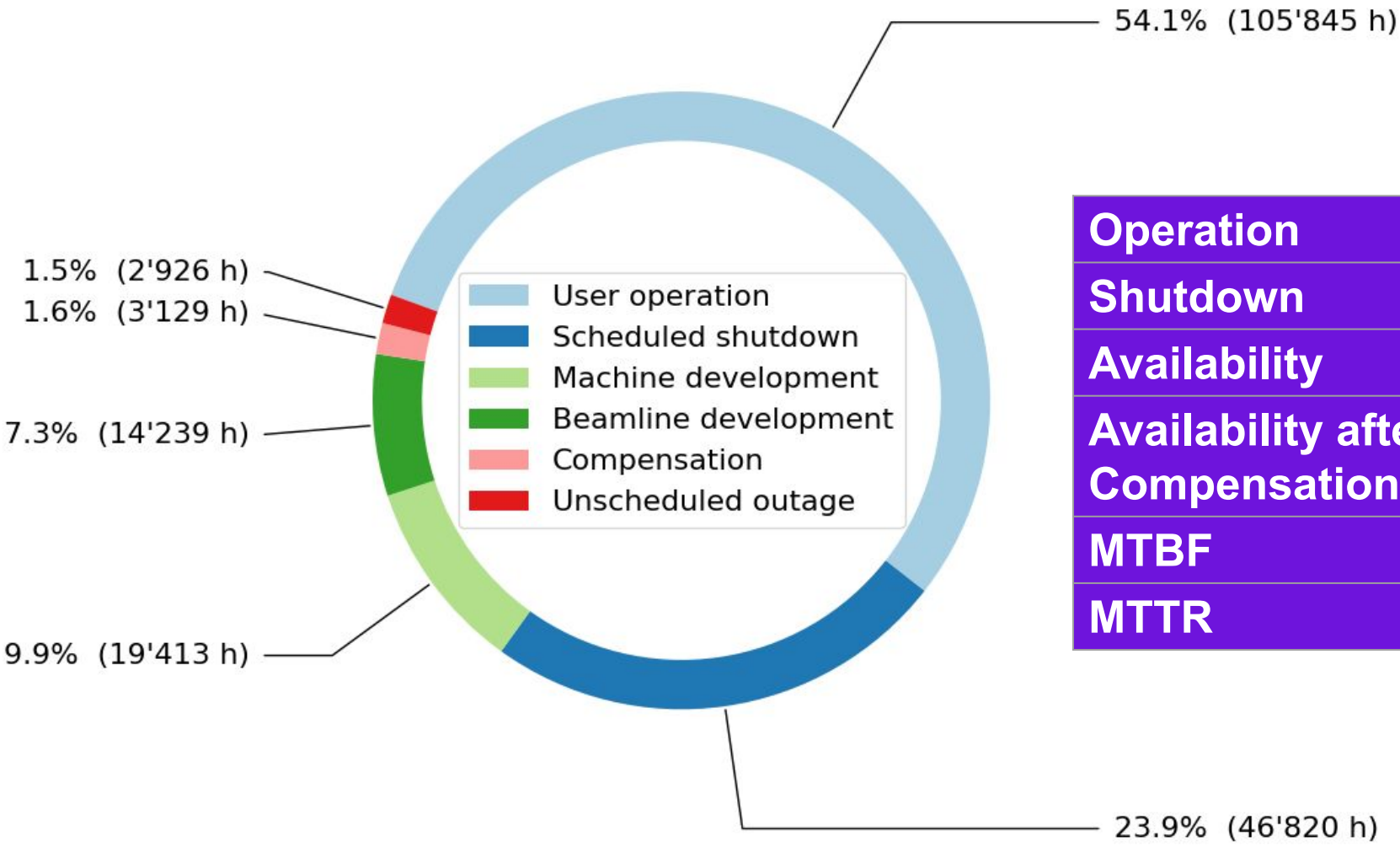
Operation Swiss Light Source

Statistics - The Bathtub Curves - Lost Time



Operation Swiss Light Source

Overall Statistics Jan. 2002 - Sep. 2023



Operation	**145’755 h (74.5 %)**
Shutdown	**49’746 h (25.4 %)**
Availability	**97.3 %**
Availability after Compensation	**100.2 %**
MTBF	**78.7 h**
MTTR	**2.2 h**

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Statistics - Cause Distribution by Nr. of Incidents