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AVAILABILITY ANALYSIS AND TUNING TOOLS AT THE LIGHT SOURCE BESSY II*

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Abstract

The 1.7 GeV light source BESSY II features about 50 beamlines overbooked by a factor of 2 on the average. Thus availability of high quality synchrotron radiation (SR) is a central asset. SR users at BESSY II can base their beam time expectations on numbers generated according to the common operation metrics [1]. Major failures of the facility are analyzed according to [1] and displayed in real time, analysis of minor detriments are provided regularly by offline tools. Many operational constituents are required for extraordinary availability figures: meaningful alarming and dissemination of notifications, complete logging of program, device, system and operator activities, post-mortem analysis and data mining tools. Preventive and corrective actions are enabled by consequent root cause analysis based on accurate eLog entries, trouble ticketing and consistent failure classifications with enhanced diagnostics. This paper describes the toolsets, developments, their implementation status and some showcase results at BESSY II.

OVERVIEW

Accelerator based light sources have become indispensable tools within the international scientific infrastructure. These instruments enable photon based cutting edge experiments for a huge variety of scientific disciplines. Even if the number of facilities is still growing, access to suited beamtime is a specific problem. The established "workhorses", the storage ring based light sources (SR), are serving many users at a time. Their detailed requirements on photon flux, energy, stability, coherence, polarization, time structure vary largely. Thus, within their technical limits, SR facilities try to accommodate users needs by offering adjusted operations modes for certain periods of time.

For the application for beamtime users have to decide first place on the best suited facility, the adequate available operation mode, appropriate beamline capabilities and experimental setups. Secondly the SR reliability, i.e. the ability to serve the promised function, over the assigned beamtime at the light source matters.

Independent of the level of sophistication the primary parameter for photon delivery of a light source is the stored beam current. Less obvious cases cover situations where degraded properties turn out to make stored beam not usable for most beamlines. Usually statistics on beam availability or "up-time" are published for most light sources. Conditions under which beam is considered "available" are frequently defined according to some common sense. Handling the rescheduling portions of the whole beamtime calendar due to disaster recovery or unforeseen technical necessities is very facility specific and typically very vague.

In order to improve comparability of light source availability some facilities made the attempt to define a simple, *common operation metric* [1]. Expectation is that application and refinement of such a common metric will improve understanding and comparison of light source performance. This will help to optimize the light source user experience and to assess the improvements of a specific facility over time.

Going through the different modes of operation of a single facility illustrates the difficulties to draw a conclusive picture. The challenge to maintain the desired beam properties is in addition complicated by tight radiation protection prescriptions that impose significant *top-up constraints*. At BESSY II these constraints are implemented in the top-up interlock, generating a number of enforced combinations of decay mode, closure of the beam shutters, restricted refilling modes. *Decay mode* is enforced by insufficient lifetime ($t < 5\,h$) or insufficient injection efficiency – a four hour average of injection efficiency $Eff_{avg} < 90\%$ enforces a $T = 4\,h * (90\% - Eff_{avg}\%)/(100\% - 90\%)$ compensation time of no injection. If a single shot with efficiency $Eff_{shot} < 60\%$, beam current drop $I_{ring} < I_{min}$ or unclear/inconsistent status of the top-up interlock occurs, a *beam shutter closure* is requested to allow for restoration of all top-up conditions and to leave the enforced decay state.

OPERATIONAL MODES

The annual beamtime calendar at BESSY II is organized in weeks of user operation, machine development and beamline commissioning, shutdown and beam scrubbing. A standard week of scheduled user beam time starts Tuesday 07:00 and ends Sunday 23:00 providing 3 basic user operation modes. Every other Sunday two eight hour shifts are dedicated to a single user, the National Metrology Institute of Germany (PTB, 4^{th} mode).

Multi bunch hybrid mode This mode comprises 298 mA total current, kept constant by permanent top-up injections. General bunch pattern is an even filling of 300–350 bunches and a gap of about 100–50 bunches (500 MHz, harmonic number 400). In addition to this 280 mA multi bunch current up to 5 specific bunches are serving dedicated timing experiments.

A long "dark" gap (200 ns) and a higher current (4 mA), purity controlled camshaft bunch in the middle supports pulse picking with mechanical choppers and electronic gating. Three higher current (4 mA) bunches opposite

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of the gap, sequentially sliced with 20 fs laser pulses at a 6 kHz repetition rate are generating 100 fs x-ray pulses [2, 3].

One bunch, typically 3 buckets away from the end of the dark gap, can be resonantly excited in the horizontal plane for pseudo-single bunch experiments at specific set-ups (PPRE bunch) [4].

Problems with the special bunches can affect 3–6 user groups out of 20.

Single bunch mode Top-up Filling of 15 mA into a (purity controlled) single bunch for time resolved experiments (2–3 weeks/y).

Low-α [5] mode Even filling of 100 mA (short pulse mode) or 15 mA (THz mode, non-bursting coherent synchrotron radiation) in an alternating, $3 * 8$ h hour period decaying beam sequence (2–3 weeks/y).

The 128 ns dark gap is filled with a camshaft bunch, in the middle, the horizontally excited PPRE bunch close to the start of the gap, both bunch current equal to the MB train. In addition there is an ultrashort low current bunch (30 μA) close to the end of the gap.

PTB mode Beam conditions according to a single main user's specific experimental requirements. Availability is 100% as long as the facility is functional.

IMPLEMENTATION OF THE METRICS

In the common operation metrics [1] 'no beam' as well as 'low beam' has agreed on to be a *primary failure*. At BESSY II users do not make a big difference between lost beam and closed beamshutters: they do not get, what has been promised, photons on sample are interrupted. Thus, a 'no-beam' event ("dark" time) starts when the beam current is below I_{min} or the moment, the BESSY Top-Up interlock enforced closure of the beam shutters to restore top-up conditions occurs. Whatever happens first will trigger the start of the event.

Short interruptions of the injector system are neglected, as long as the beam current is not decaying to less than 'low beam' I_{tol} = 90% of I_{nom}. Below that threshold we record a 'low beam' event. In multi-bunch mode limits are set to I_{nom} = 298 mA, I_{tol} = 268 mA and I_{min} = 200 mA and in single-bunch mode: I_{nom} = 15 mA, I_{tol} = 13.5 mA and I_{min} = 8 mA. At the moment of writing removal of the third harmonic cavities for repair imposes a temporary (shutdown spanning) lowered I_{nom} = 248 mA (I_{tol} = 223 mA, I_{min} = 150 mA) due to lifetime and impedance heating constraints.

Enforced beam shutter closure can be shifted within limits, and the failure begins at the moment, any no-beam condition has been met. A primary failure ends as soon as top-up conditions are restored, the nominal beam current I_{nom} is reached and beamshutters are released again.

Each *primary failure* is an outage from a user's point of view. All outages are automatically accounted by number and duration to produce a live display of overall availability as well as MTBF and MTTR per week and year (see Fig. 1).

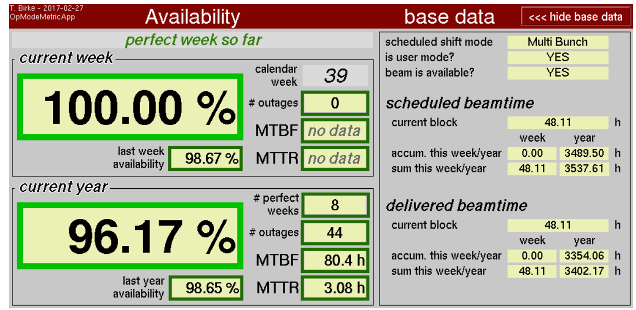

Figure 1: Complete monitoring of failure conditions and continuous evaluation of the metrics allows to display relevant numbers in real time.

Undesired intensity changes at the experiments may be caused by degraded beam conditions. Thus BESSY records *secondary failures* like 'beam-blow-up' events, when the nominal horizontal or vertical beam size is increased by more than 30%, i.e. $\sigma_{\text{act}} >= \sigma_{\text{normal}} * 130\%$ (see Fig. 2).

'Distorted-orbit' events cover all 'orbit-out-of-control' situations. If none of the fast or slow orbit corrections (FOFB/SOFB) is usable/active (orbit-feedback-outage) or if the RMS deviation from the "Golden Orbit" exceeds 0.08 mm. Typical RMS orbit deviation range between 0.00–0.01 mm (installation of Golden Orbit, based on new BBA measurement) and 0.04–0.05 mm year(s) later. An accountable orbit-feedback-outage event lasts longer than 60 sec. Succeeding events are counted as one if the feedback runs for less than 10 min.

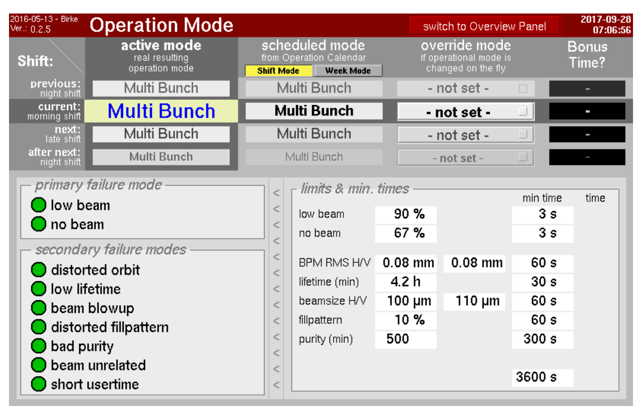

Figure 2: Planned operation mode is read from the beamtime calendar. Failure trigger levels for the requested mode are calculated. Scheduled mode can be overridden as unforeseen schedule changes require.

At BESSY a qualified even MB filling is only of secondary relevance in standard user mode: STXM experiments suffer from phase jumps induced by the high intensity bunches. The long dark gap, needed by the mechanical pulse picking chopper, affects time resolution. In low-α mode this is different. At higher currents even filling translates to the quality

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Table 1: Back Evaluation According to Common Operation Metrics [1]

	2013	2014	2015	2016
Availability	96.5 %	92.9 %	97.6 %	98.7 %
MTBF	42.9 h	39.8 h	43.3 h	70.4 h
MTTR	1.52 h	2.83 h	1.03 h	0.91 h
#Outages	105	136	90	68

of the THz spectrum, close to the CSR bursting threshold, all bunches have to be safely non-bursting.

Due to the relevance for timing experiments the 'low-beam-current' criterion is applied for the specific bunches and accounted for distorted-filling: it starts below 90% of the nominal bucket charge in the camshaft bunch (pump probe) or the slicing bunches (fs-pulse intensity) or the PPRE bunch. A camshaft bunch purity of less than 500 (typically well above 5000) is recorded as a 'bad purity' event.

Beam up-times of less than an hour do not count as available beam. The end of an event is only known after beam is available again for at least one hour.

BESSY II availability has been back evaluated according to the common operation metrics until 2013, the introduction of top-up operation (see Table 1).

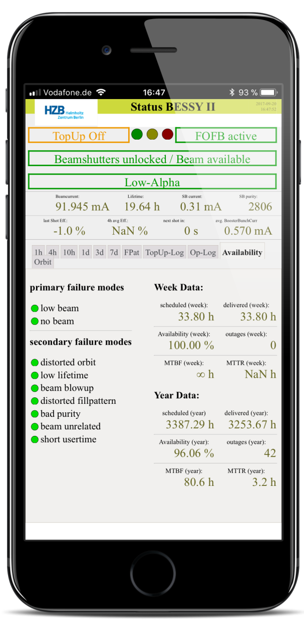

Figure 3: Web-based real time display of current failure modes and accumulated availability data.

Live evaluation of primary and secondary failure modes as well as outages, and resulting MTBF, MTTR and availability of the current week and year are displayed online in real time at [6] where it is accessible via the tab "Availability" (see Fig. 3). Internally the intermediate tag "perfect week" has been introduced for user weeks with 100% availability and no primary failures.

OPERATIONAL TOOLS

Tuning tools are a hierarchical mixture of surveillance and automatic corrective actions. Primary monitoring is provided by alarm handlers reporting malfunctioning devices and out-of-band measurements of specific signals. Notification happens via blinking and by text messages sent to mobile devices. For backtracking all alarms are stored in logging databases (historically: cmlog, current: splunk, future: Elastic Stack) and retrieved via preconfigured retrieval requests and generic filtering browsers.

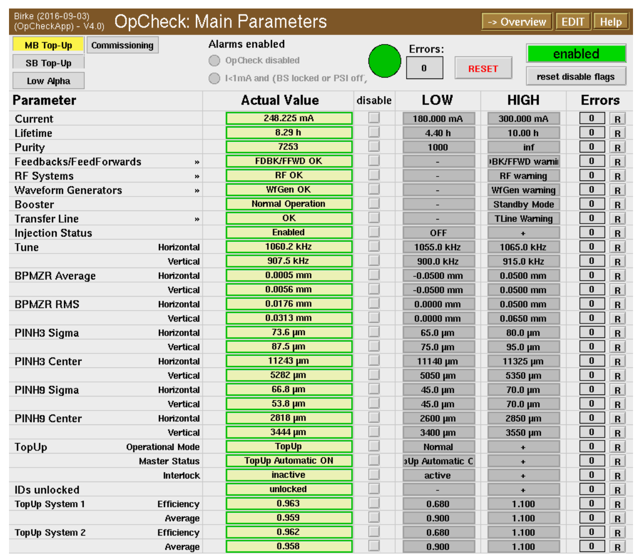

Figure 4: Parameter boundary check.

Parameter Checks Hitting the limits of *secondary failures* is a serious degradation. For an alarm notification this is frequently simply too late. Thus an extended set of parameters is supervised within much smaller boundaries (see Fig. 4). In case of a limit violation, the operators are notified by alarms and take precautions to prevent secondary failures. In prevention of a beam time interruption, e.g. if there is significant danger of a bad shot, injection is software- or hardware-prohibited, to allow for corrective actions first (e.g. trigger pulses are blocked in hardware if the beamcurrent in the booster is too low to allow for an accurate injection efficiency measurement which would be a violation of top-up-constraints).

Analysis of possible trends of these crucial parameters is part of the formal shift hand over procedure (see a preconfigured correlation plot in section **Correlation** with Fig. 8).

Post-Mortem Root cause analysis of failures is the key to mitigation, prevention and repair. Identification of the root cause is not always an easy task, especially if it is a very fast event. Storage and analysis of the post-mortem buffers of the bunch-by-bunch-feedback (BBFB), the fast

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orbit correction (FOFB) and the kicker pulse shape monitor (see Fig. 5) have turned out to be an invaluable source of information. Having these in place allows to decide if e.g. an RF trip on beam loss was the cause or the consequence of a beamloss.

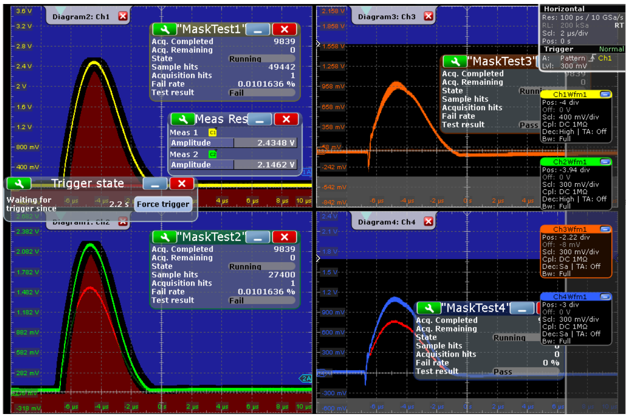

Figure 5: Kicker pulse monitoring system. In this event, one kicker fired a second time while re-charging.

Post-mortem data blocks go to a beam event database together with relevant beam conditions and operational circumstances (see Figs. 6 and 7).

	time	name	current	loss
4	07.09.17 14:59	BEAMLOSS	199,279	0,301409
5	07.09.17 10:16	BEAMLOSS	248,176	99,9454
6	04.09.17 04:44	BEAMLOSS	240,063	99,9483
7	01.09.17 09:46	BEAMLOSS	248,003	99,9432
8	27.08.17 18:25	BEAMLOSS	248,913	99,9494
9	25.08.17 01:15	BEAMLOSS	248,624	99,9437
10	23.08.17 16:55	BEAMLOSS	248,129	0,0322819
11	23.08.17 16:54	BEAMLOSS	248,568	0,0327706
12	19.06.17 15:31	BEAMLOSS	156,422	7,9188

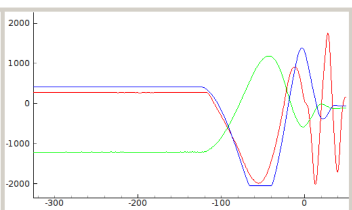

Figure 6: Post-mortem beamloss database. Beammotion in all three planes during the last turns before a beamloss. A loss within ~100 turns indicates RF dropout as cause of loss. In this case due to an interlock-enforced beamdump.

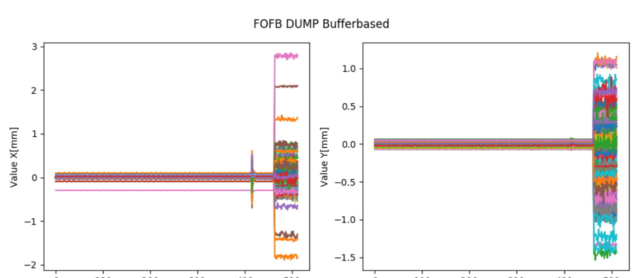

Figure 7: Post-mortem BPM data dump by FOFB. A ring buffer of the 512 latest BPM datasets saved about 1 s after an identified beamloss. BPM dataset are processed at 150Hz. The beamloss occured about 300 ms after an injection shot.

Correlation Operation of a light source can be seen as a complex, long term experiment. In order to be able to find the cause of changes on multiple time scales nearly all beam conditions, direct or mediated, have to be archived with proper frequency, precision and correct time stamp. The methods of comparison and correlation allow to either return to a certain state or to correct for the real perturbation source.

Numerous preconfigured correlation plots (see Fig. 8) cover single shifts, whole user weeks or arbitrary time spans, extract data from the channel archiver and the archiver appliance paint a picture of beam parameters like source size, beam position and pointing, current and fill pattern, beam loss rates and locations, vibration amplitudes, but also equipment conditions vacuum pumps, temperatures, etc.

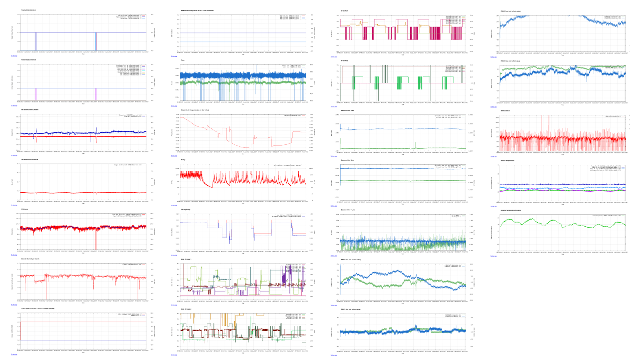

Figure 8: Preconfigured correlation plots provide a quick overview of crucial parameters over a shift/day/week.

These overview-plots provide a useful quick view of all important signals. Unusual behavior of signals is often identified at first glance and can then be further tracked down to find the cause of perturbations or slow drifts and install proper countermeasures.

Logging Actions and findings are documented within appropriate electronic log book entries. Equipment, program and basic operator actions report to the logging data bases (cmlog, splunk, Elastic Stack).

Problems, malfunctions and broken configurations are escalated through a trouble ticketing system and followed up until solved or clarified.

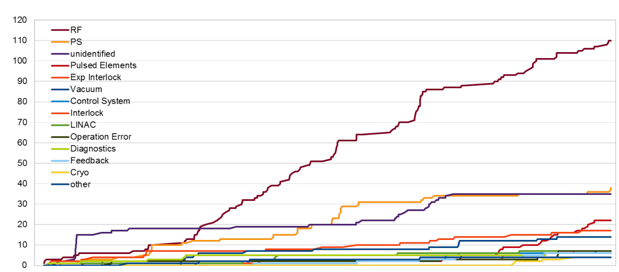

Figure 9: Cumulative assignment of primary failures to root causes.

RESULTS

Extraction of information with strategic relevance still require combination and correlation of information in all available datastores. At BESSY this is still a "manual" iterative process of presentation, analysis and discussions. Significant steps visible in cumulative primary failure graphics plotted

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according to root causes (s. Fig. 9) have been worked on e.g. with a refurbishment campaign of all quadrupole power supplies, improved diagnostics aiming at kicker misfiring or changed RF maintenance procedures. No appropriate software based, automatic data mining approach could be found so far.

SUMMARY

For long term operational light source facilities like BESSY II transparent availability analysis and maintenance are crucial. Potential users as well as regular customers need to know how the facility of their choice handles disaster prevention and recovery. And management has to know if the preservation and modernization activities are adequate or need readjustment.

As a result of the analysis and tuning tools developed at BESSY there has been practically no beam loss for "unkown reasons" within the last years.

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