AN AUTOMATED STATISTICAL ANALYSIS PACKAGE FOR THE STUDY OF SYNCHROTRON LIGHT SOURCE OPERATION

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Abstract

Machine faults and interruptions to user beam at Diamond Light Source are recorded in a Fault Log Database running under Microsoft Access. A data analysis package has been written in Matlab to automatically analyze machine faults. Performance data is presented for Diamond for the latest year of operation and since user beam began in 2007, and the impact of different technical groups is considered. Failure distributions and the underlying hazard functions are produced and compared with standard statistical models.

DIAMOND LIGHT SOURCE OPERATION

Diamond is a 3 GeV third-generation light source. User operation began in January 2007 in decay mode, with 125 mA storage ring current [1]. Top-up operation was introduced in October 2008 [2] and beam current has been gradually increased to the present 250 mA. The number of operational beamlines has risen from an initial eight to a planned 22 by the end of 2011. User beam is provided in multiple-week runs, most starting with a two day start-up/machine development period and usually including one day per week of machine development. Allocated hours from 2007 to 2011 are broken down in Figure 1.

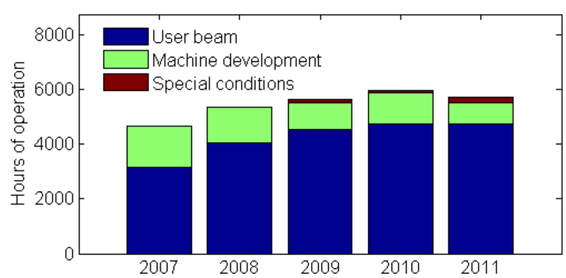

Figure 1: Machine operation at Diamond.

Machine availability and reliability is of critical importance, and so since the beginning of machine commissioning a fault database logging system has been used to track and process all machine faults and trips.

FAULT LOGGING AND ANALYSIS

When a fault is recorded, a fault report is sent to the Technical Group responsible for the relevant area, and a copy of the report is recorded in a Microsoft Access Fault Log Database (FLDB). Access is a relational database management system that enables the efficient management of data and the simple generation of easy-to-use interfaces, but has limited data processing capability. In order to address this problem, a Matlab tool called the "MTBFometer" has been developed to use the analytical power of Matlab to analyse the fault data into clearly presented summary charts and reports.

Fault information and run data from the FLDB are brought into Matlab by the creation of an ActiveX automation server which is deleted once the information has been transferred; freeing the Access database for other users while the analysis is carried out within Matlab. MTBFometer is available as a native Matlab application, or as a compiled Windows executable.

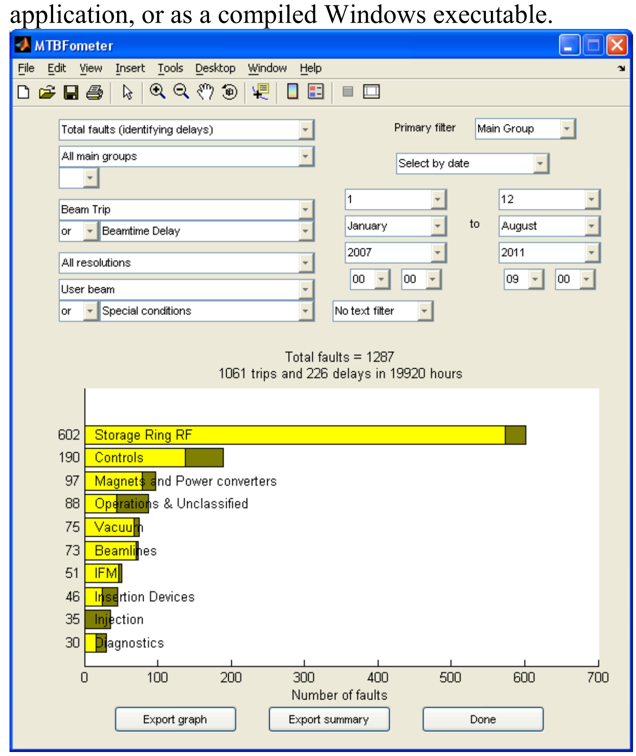

Figure 2: Default interface to the MTBFometer.

The MTBFometer interface is shown in Figure 2. The default display shows faults (in yellow) and delays to beam restoration (in brown) for each Technical Group. A selection of drop-down menus allows all fault data to be sorted by date (specified by calendar date or run number), impact, fault resolution, beam mode (user beam, machine development or special conditions) or Technical Group. An optional text filter allows finer specification of faults.

GLOBAL PERFORMANCE INDICATORS

Many different analyses are possible with the MTBFometer: one of the most fundamental figures of merit is the percentage up-time of user beam, shown in Figure 3 as a year-on-year summary. This clearly illustrates the improvement in beam availability since operations began.

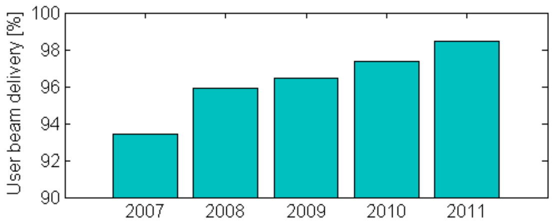

Figure 3: Percentage of beam time delivered to users.

Machine reliability can be characterised by the Mean Time Between Failures (MTBF), shown in Figure 4. Again, performance has improved, with a sharp jump in MTBF at the start of 2011: this is discussed further below.

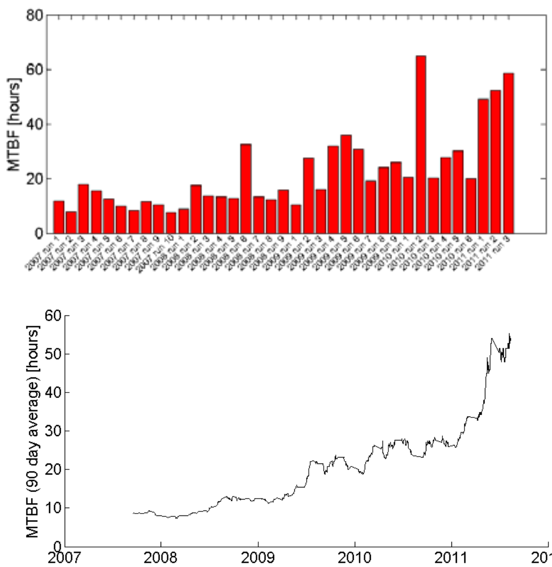

Figure 4: MTBF by run and by 90-day rolling average.

If the reliability of a system is invariant with time, then the instantaneous failure rate, or hazard function, is constant and the failure rate follows an exponential distribution characterised by the rate parameter, λ. Figure 5 shows all Diamond beam-loss or delay faults in user beam or special conditions since 2007, sorted by median rank, plotted against the time between faults, in hours. The fit to a cumulative exponential is very poor and so the hazard function is clearly not constant. A Weibull distribution, with probability density function

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-(t/\eta)^{\beta}}$$

with scale parameter η and shape factor β, provides a much better fit, particularly for times in excess of 1 hour, where recording of fault times in the FLDB is less subject to rounding errors. Best fit parameters and errors calculated at the 90% confidence level are generated by MTBFometer and are shown in the figure. Distributions with $\beta < 1$ indicate a decrease in failure rate with time, characterised by the monotonically decreasing hazard function shown on the figure. In general, β is less than 1 for all Technical Groups in any defined period.

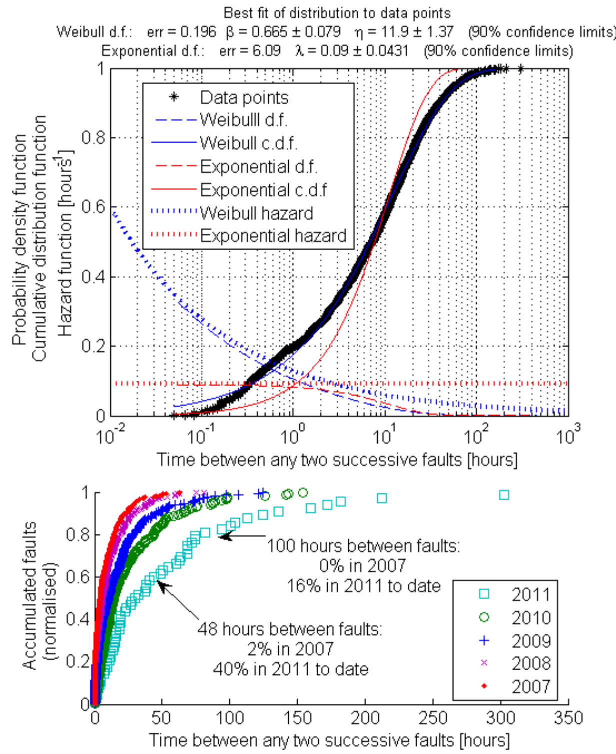

Figure 5: Cumulative distribution of time between faults compared to two model distributions, and year-by-year record of cumulative fault distribution.

Figure 5 also shows a plot of accumulated faults broken down into operating years. Machine reliability has increased as detailed on the figure, with Weibull η (analogous to $1/\lambda$ in the exponential distribution) increasing from 7 to almost 50, and β rising from 0.65 to around 0.85, indicating that failure now has a weaker time dependence. The five longest periods between faults have all occurred in 2011, with the longest fault-free time of over 300 hours this year.

CONTRIBUTION OF INDIVIDUAL GROUPS

Down-time is logged and assigned for each trip or delay, as shown in Figure 8 and summarised for all times since top-up began. This allows a Mean Time To Recovery (MTTR) to be calculated for each group: Installation and Facilities Management (IFM), dealing with site services, has an MTTR of 1.5 hours, whereas the RF MTTR is only around 0.5 hours.

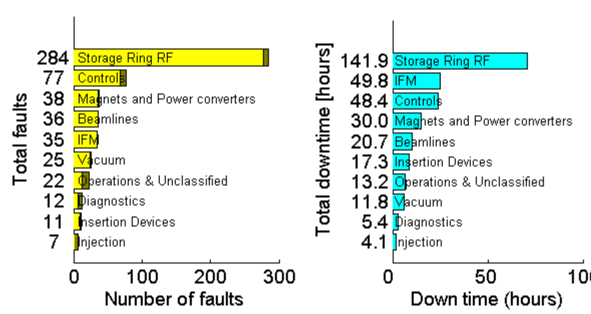

Figure 6: Pareto chart of faults and downtime.

A plot of accumulated faults against run days reveals that beam trips have always been dominated by the storage ring RF, and that the rate of accumulation of faults for individual groups is generally decreasing. A text filter in the MTBFometer allows the fault reports to be interrogated, leading to the breakdown of RF faults shown in Figure 7. Most RF faults are cavity vacuum trips, with the division of trips amongst the three cavities dependent on the balance of power and voltage amongst them.

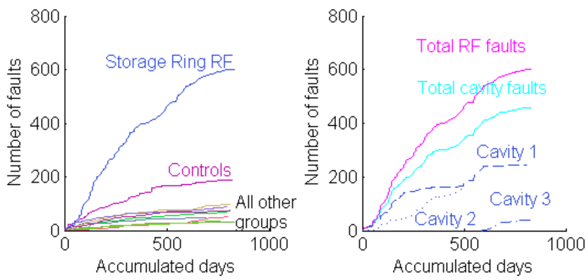

Figure 7: Accumulated faults.

Cavity 1 fault rate was high when it ran alone at high voltage between the removal of cavity 2 in January 2010 and the installation of cavity 3 in July 2010. The plot of accumulated faults against time to failure is shown in Figure 8. Again, the distribution is far from the cumulative exponential: the smoothed hazard function derived from the time-to-failure data is inset in the figure.

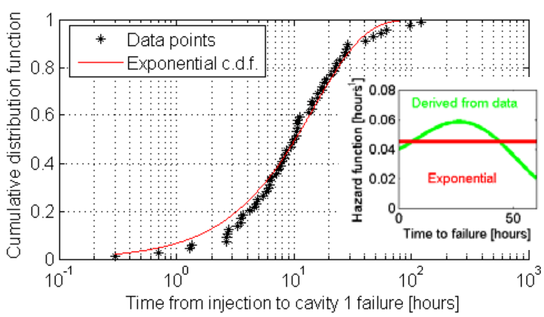

Figure 8: Cavity 1 time-to-failure distribution.

In order to address the RF reliability issue, titanium sublimation pumps were installed in the RF straight in mid 2010 and a programme of full and partial cavity warm-ups was instigated [3, 4]. The effect on cavity MTBF was immediately apparent following the full warm-up of cavities 1 and 3 in November 2010, between runs 5 and 6 of that year, as shown in Figure 9.

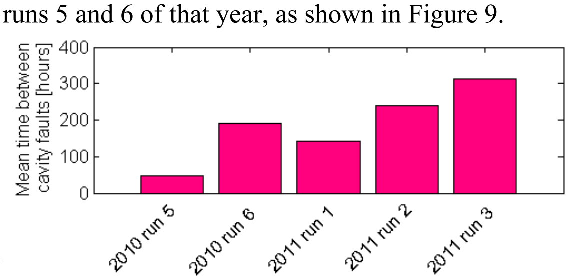

Figure 9: MTBF for cavities 1 and 3 operating together.

Further partial warm-ups of cavity 3 to temperatures up to 35 K throughout 2011 and regular firing of the TSPs has maintained the high cavity MTBF, and led to the significant increase of global MTBF shown in Figure 4.

RELIABILITY IN 2011

The improved reliability of the RF cavities has led to an MTBF of 53 hours for 2011 to date. The RF contribution to the total fault number no longer dominates as strongly as it did from 2007 to 2010. All beam trips and delays are charted in Figure 10, illustrating the reduced RF dominance compared to Figure 7 and also the increasing effect of beamline faults on Diamond reliability.

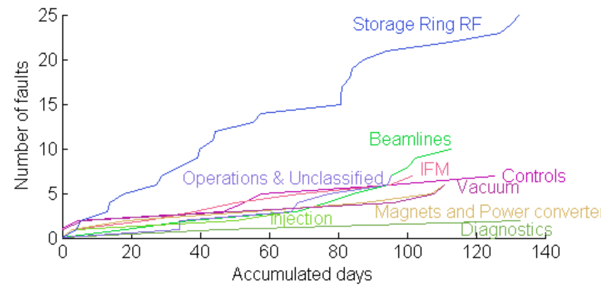

Figure 10: Accumulated faults in 2011 so far.

High machine reliability has allowed Diamond to provide beam to users for an unbroken week between machine development periods on more than one occasion. Figure 11 shows the beam current over one user-week of operation in 2011, showing the beam current maintained between 249 mA and 251 mA for the entire period.

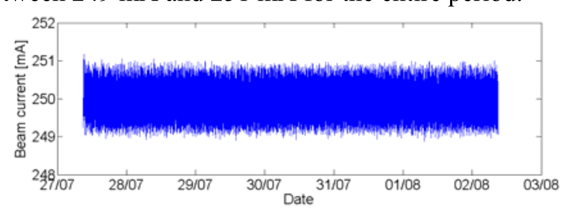

Figure 11: Uninterrupted beam delivered to users for a complete week of top-up operation.

SUMMARY AND CONCLUSIONS

Fault-logging and automatic data analysis software has been developed at Diamond to track machine faults, quantify performance and identify areas of concern. Accurate and thorough monitoring of machine performance has resulted in year-on-year improvements in reliability and availability, enabling Diamond to be a dependable and consistent light source for the user community.

REFERENCES

[1] V. C. Kempson et al., Proc. EPAC'08, p. 2051.
[2] R. P. Walker et al, Proc. EPAC'08, p. 2121.
[3] The contribution here of Pengda Gu and Morten Jensen from the Diamond RF group is greatly appreciated.
[4] P. Gu et al, Proc. SRF 2011, in press.