# SIS100 AVAILABILITY AND MACHINE PROTECTION

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## *Abstract*

For the future FAIR driver accelerator, SIS100, a detailed System-FMEA (Failure Modes and Effects Analysis) according to IEC 61508 has been done. One the one hand, this has been done to identify possible shortcomings for machine protection and on the other hand to predict the machine's availability for beam on target. The methodology for the analysis and the main failure modes currently known for the machine and its environment are described in detail. An estimate of the total machine's availability is given.

## INTRODUCTION

In view of the series release progress of components with long delivery times for SIS100 (e.g. dipoles, quadrupoles, RF acceleration systems, etc.), some of these are related to the machine's overall safety in the one or other way. Therefore, a study on safety related functions has been done. These functions must be clearly distinguished between machine safety related topics (i.e. protecting the machine from destruction by the high intensity ion beam or electrical / pressure related hazards) and personnel safety topics.

This article concentrates on the electrical functional safety of the SIS100 alone, i.e. experiment / detector protection is not addressed. Errors introduced by the machine operator personnel, setting value generation software and beam instabilities (and failures not found by analysis) are dealt with the use of a mandatory low-intensity pilot beam, locking of critical settings and the beam loss monitoring system.

A failure mode and effects analysis on the system level (S-FMEA) has been done. The failures have been assessed using the procedure for simplified system architecture analysis described in EN ISO 13849 (a subset of the DIN EN 61508), using the tool "SISTEMA" [1]. Each failure mode and effect is assessed by its severity, the stay time of personnel in the hazardous area, the probability of avoidance and the likelihood of occurrence. This leads to a *SIL*[1] category necessary for safe detection of this failure. Afterward, the system is characterized by its MTTFd[2], the probability to detect the failure and its MTTR[3]. Later, when details on its architecture do exist, it is scrutinized on a part level using FIT[4] values. Finally, for all subsystems leading to the failure, PFH[5] and DCavg[6] values are calculated. Some part of this work has been published already and is not repeated here [2].

## MACHINE PROTECTION

Compared to accelerators like LHC, the destruction capability of the ion beam in SIS100 itself is low. The maximum total beam energy for $2 \times 10^{13}$ protons is 91.1 kJ and for $5 \times 10^{11}$ $U^{28+}$ ions 51.5 kJ. This is comparable to the CERN PS which has a maximum total proton beam energy of 97 kJ and no destructive event recorded in history. If the beam would be strongly focused in both vertical and horizontal planes, one could reach an energy density just large enough to melt metal, but e.g. the magnet coil structure made from G11 could be severely damaged already by a rather normal focus.

Shock waves created by the beam impact could damage the material by repeated impact of the beam [3]. Therefore, failures leading to this effect have only to be detected and ensured that they do not happen repeatedly. Therefore, only the following failure effects have been identified to be potentially dangerous for the machine already at their first occurrence:

1. Quench of magnets/busbars,
2. Helium supply line pressure rise, leakage or rupture,
3. Horizontal "spiraling" of the beam towards the outside of the synchrotron.

Further (non-destructive) events have been found to be the effect of other failures:

- Focusing of the beam onto a perpendicular thin wall (e.g. vacuum chamber),
- Beam blow up (which will hit the halo collimators),
- Horizontal closed orbit distortion to the inside of the synchrotron (which will hit the cryocatchers) and
- Vertical beam loss (which will hit the halo collimators)

Most of these events will lead to beam loss in a short amount of time ($\mu$s. . .ms). If the beam is not lost completely, its emittance is blown up or distorted in a way that it is not longer usable by the designated experiment (or even can destroy sensible detectors, etc.). Therefore, an emergency dump will be initiated by a fast fail safe optical signal. For failures which are not critical in this meaning, a simple interlock will be generated to stop further injections into the synchrotron and a post-mortem analysis can be done. Some effects will be addressed in the following sections.

### *Quench detection and protection*

The QD/QP system of SIS100 consists of a quench detection system utilizing voltage taps on each half of the main

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[1] SIL = Safety Integrity Level.

[2] MTTFd = Mean Time To dangerous Failure

[3] MTTR = Mean Time To Restauration

[4] FIT = Failures in Time = failures in $1 \times 10^9$ h

[5] PFH = Probability of dangerous failures per hour

[6] DCavg = Diagnostic coverage

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magnet coils, busbar soldering connections and a mutual inductance detector in the corrector coils. The system has been analyzed and must fulfill the *SIL3* criteria to protect the magnets. When a onset of a quench is detected for 10 ms, a fail safe signal is sent from the QD system to start the emergency beam dump. Shortly (1 ms) afterward, the magnet current dump resistor is switched on. Table 1 shows the result of the preliminary system architecture analysis for a single dipole (the values for the other magnet families differ only slightly). The desired safety level *SIL3* is reached.

Table 1: Dipole QD/QP analysis results.

| **Component** | **PFH / h$^{-1}$** | **DCavg / %** |
|---|---|---|
| Voltage taps | $2.29 \times 10^{-7}$ | 90 |
| Quench detection card | $9.34 \times 10^{-8}$ | 70 |
| Current dump resistor | $2.29 \times 10^{-7}$ | 90 |
| Overall QD/QP system | $5.51 \times 10^{-7}$ | |

Another possible method to prevent beam induced quenches is the use of the beam loss monitoring system as described in [4].

### *Failure induced beam movements*

For failures of the main dipole magnets (e.g. through a magnet quench or a power converter fault) or a loss of the acceleration RF voltage during the ramp, the beam is typically lost over many turns at a single position of smallest acceptance, with a very small amplitude increase ($\mu$m/turn). This leads to the deposition of the beam energy in a very small volume and a corresponding thermal stress which may destroy sensitive equipment (e.g. the wires of the electrostatic septa or halo collimator foils).

According to the present design, SIS100 has four different ion optical settings, see Tab. 2. Due to the different optical properties of these settings ($\beta(s)$, $D(s)$) as well as the different beam parameters ($\epsilon_{x,y}$, $\epsilon_l$), device failures have different effects. For instance, if the beam is lost due to a failure of the acceleration RF voltage, the loss position depends on dispersion and beam size. If an injection kicker fails, depending on $\beta(s)$ and beam size, one may either lose part of the beam or just create emittance blow-up. Therefore, the failure scenarios have to be investigated for all operation modes.

Furthermore, deviations from the ideal machine must be considered, e.g. closed orbit distortions or distortions of the beta functions due to alignment or field errors. As an example of how the analysis is done, the analysis of main dipole quench is sketched below.

Table 2: Ion optical settings of SIS100 and their tunes / transition energies.

| Setting | Tune $\nu_{x,y}$ | Transition $\gamma_t$ |
|---|---|---|
| Ions, slow extraction | $(17.31, 17.80)$ | 14.2 |
| Ions, fast extraction | $(18.88, 18.80)$ | 15.4 |
| Protons, $\gamma_t$-shift | $(21.80, 17.70)$ | $18.3 \ldots 45.0$ |
| Protons, $\gamma_t$-jump | $(10.40, 10.35)$ | 8.9 |

**Quench of the main dipoles** For SIS100, all 108 SC main dipoles are powered in series by a single power converter. If the main dipole string fails during the cycle and the quench protection switch is closed at $t_0$, the actual current will decay exponentially with the time constant $\tau = L/R$ being $L$ the inductance and $R$ the resistance of the dipole string including the dump resistor. Using a linear expansion of the magnet calibration curve and ignoring eddy current effects for simplicity, one can obtain an expression for the actual field deviation from the field $B_0 = B(t_0)$ after the quench:

$$\frac{\Delta B}{B}(t) \approx -\left(\frac{1}{\tau} + \frac{\dot{B}}{B_0}\right)(t - t_0) \tag{1}$$

We further assume that the accelerating RF voltage remains unaffected by the dipole failure, i.e. the RF voltage and frequency follow their set values and the beam remains completely bunched. Under these conditions, the field deviation $\Delta B/B$ leads to a momentum error $\delta$ given by:

$$\delta = -\frac{\alpha_c}{\eta}\frac{\Delta B}{B} \tag{2}$$

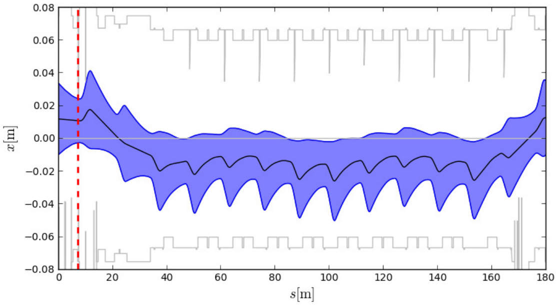
The total change in orbit radius is given by the effect of both the momentum and field change:

$$\frac{\Delta R}{R} = -\alpha_c\left(\frac{\alpha_c}{\eta} + 1\right)\frac{\Delta B}{B} = -\alpha_c\frac{1}{1 - (\frac{\gamma}{\gamma_t})^2}\frac{\Delta B}{B} \tag{3}$$

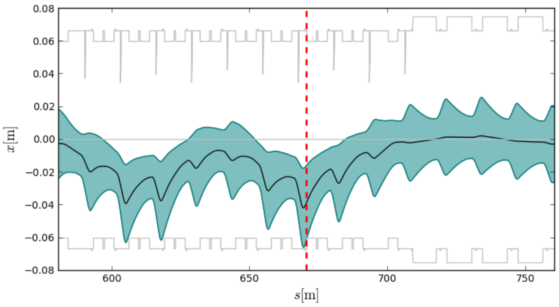
This expression would diverge in the non-adiabatic region around transition energy, where our first order derivation is not valid, too. However, this effect is negligible for SIS100 $U^{28+}$ operation. When the field starts to deviate from the set value $B(t)$, the beam will spiral radial outwards on an orbit determined by dispersion. Two examples of optics calculations showing the onset of beam loss using the dump resistors (and *not* using any beam abort system) can bee seen in Fig. 1.

For the worst case, the maximum of eq. 3 in a typical SIS100 cycle is near injection energy just before reaching the full ramp rate of $\dot{B} = 4\,\mathrm{T/s}$, which is $\Delta B/B = 0.01$. Taking into account an average aperture size of 50 mm, we expect the time for touching the aperture to be ≈1 ms and total beam loss to be on the order of 2 ms, which can be easily handled by the fast beam abort system (FBAS).

**Horizontal beam loss onto electrostatic septum** As the electromagnetic septum for slow extraction is situated at the outside of the synchrotron and defines its acceptance, its 100 $\mu$m thin tungsten wires could be heated by beam energy deposition up to a loss of mechanic stability [5]. This in turn will produce a large downtime of the accelerator for repair



(a) Setting for slow extracted ions. $\Delta B/B = -0.017$, beam just touches ion halo stripping foil (red dashed line).



(b) Setting for fast extracted ions. $\Delta B/B = -0.023$, beam just touches the dipole chamber in sector S2 (red dashed line).

Figure 1: Horizontal envelopes for a $U^{28+}$ beam with two optic settings at $E = 290$ MeV/u defined by the maximum of $\dot{B}/B$. The horizontal emittance is reduced from the initial 34 $\mu$m to 28 $\mu$m by adiabatic damping.

which has to be avoided. The safety function to avoid this event must fulfill the *SIL2* criterion.

Failures leading to a slow, spiraling movement of the full beam into the septum wires are: Quenches of horizontal steerers, chromaticity sextupoles, octupoles or failures of their corresponding power converters, resonance sextupole and IPM magnet failures as well as acceleration RF failures.

An emergency dump will be initiated whenever a failure is detected directly by the devices itself or indirectly by the beam loss monitoring system. The power converter values have been estimated, an example can be seen in Tab. 3. As some system architectures are currently not designed, PFH rates are not available yet.

Table 3: Dipole power converter failure rates.

| Component | FIT | DCavg / % |
|---|---|---|
| Media sensors | 595 | 60 |
| Current control loop | 714 | 91 |
| Parallel feed in | 1 369 048 | 90 |
| Primary voltage | 357 | 90 |
| Ground fault | 83 | 99 |
| Sum | 1 371 393 | |

### *Emergency dump of SIS100*

To use the emergency dump during the whole cycle of SIS100, the extraction kickers are ramped, bipolar devices. If they kick upwards, the beam will enter the 3-stage magnetic septum and extracted to the experiments. If they kick downwards, the beam will hit the emergency dump, which is situated below the magnetic septum #3, see fig. 2. The emergency beam dump will be triggered by the fast beam abort system (FBAS), which incorporates fail-safe links to the magnet power converters and RF systems and will react in less than 50 µs.

If one of the kickers fail, the emergency dump will still be hit by most of the beam. It has been shown that the remaining dose of beam fragments will not lead to a quench of the following quadrupoles [6].

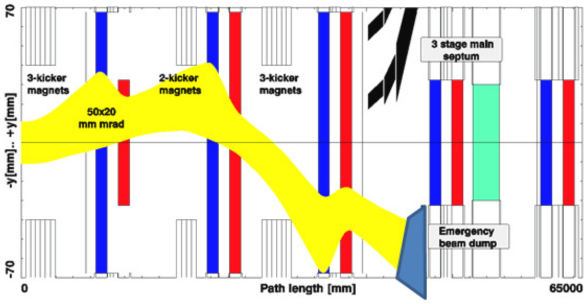


Figure 2: Vertical optics of SIS100. Emergency dump (blue) at bottom, magnetic septum (black) at top.

## CONCLUSION

Taking into account the already analyzed probabilities of failures (i.e. safe and dangerous failures), the availability of SIS100 can be calculated. Assuming an interruption time of 1 h after quenches and 2 min after emergency beam dumps, the overall availability per year has been estimated to be ≈ 3916 h out of 6000 h (65 %), see Fig. 3.

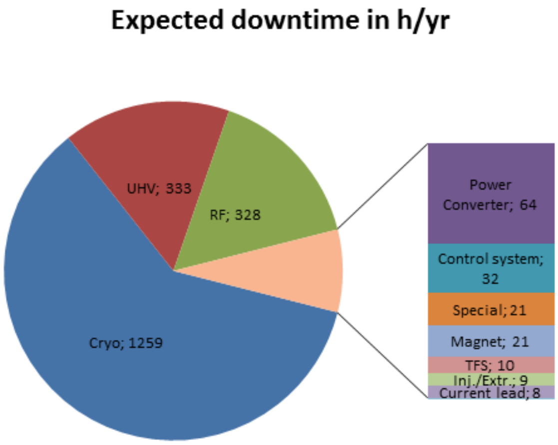


Figure 3: Sum of expected SIS100 downtime per year by systems.

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