# RF SYSTEM PERFORMANCE IN SwissFEL

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### *Abstract*

The Hard X-ray FEL machine SwissFEL at the Paul Scherrer Institut in Switzerland is commissioned and transiting to user operation smoothly. FEL operation requires stringent requirements for the beam stability at the linac output, such as the electron bunch arrival time, peak current and beam energy. Among other things, a highly stable RF system is required to guarantee the beam stability. RF performance often dominates the overall performance and availability of FELs, and for this reason the SwissFEL RF system has been designed based on the state-of-the-art technologies that have enabled excellent RF stability, resulting in an arrival time jitter of 10 fs rms and relative beam energy stability of 10-4 rms. This paper aims to provide an understanding of the peak performance of the RF systems and to highlight possible limitations currently faced, focusing on the S-, C- and X-Band systems.

## INTRODUCTION

SwissFEL [1] has been operational for regular users since early 2019, and over these past 3 years the linac operation in terms of both reliability and stability has been vastly improved. Through a better understanding of the instabilities, individual RF system performance and a gradual improvement of the infrastructure has been routinely carried out, with a long-term plan to increase the operational performance and reliability of the injector. RF stability is one of the most influential aspects of linear accelerator driven FELs, and often determine the achievable performance of the lasing capabilities. Operationally it is crucial to find a compromise between reliability and performance, however PSI have developed an RF system, which is capable of delivering low amplitude and phase jitter, whilst maintaining a highly reliable linac. The accelerator operates almost exclusively at 100 Hz, and consists of a 2.6 cell S-band photo-injector (electron source), four S-band accelerating modules (6 RF structures) and a single X-band station to linearise the energy-time curvature produced in the S-band injector stations and the non-linearities of the magnetic bunch compressors. Immediately following the injector and the first magnetic bunch compressor is the main C-band linac. SwissFEL is unique such that it operates in dual electron bunch mode that can provide a maximum beam energy up to 6.2 GeV to the Aramis undulator line, and 3.2 GeV to the Athos undulator line simultaneously. A schematic of the SwissFEL layout can be seen in Fig. 1.

## RF SYSTEM OVERVIEW

All RF stations (S-, C- and X-band) have the same overall RF system architecture with an individual LLRF feedback system controlling a solid state amplifier, which drives a 45 MW short-pulsed power klystron, which itself is powered by a high-voltage (HV) solid state modulator. A reference clock is distributed to components in the accelerator, with the trigger signal coming directly from the LLRF to the modulator and pre-amplifier.

### *Injector*

The injector operates five accelerating stations (during user operation) and an X-band lineariser. At present due to limitations of the available RF power, configuration and mode of operation, each accelerating station operates at a different setpoint, whilst the specific energy gain of SINSB03/04 are regulated by the energy feedback system. Typical operating parameters for the Injector are displayed in Table 1. In the injector, each accelerating station (besides the gun) drives 1 or 2, 4-m long travelling wave (TW) accelerating structures. Due to excessive arcing in the SINSB04 klystron, the energy gain in SINSB04 has been compensated with SINSB03, to reduce the overall stress in the klystron and minimise downtime.

Table 1: Typical Injector Operating Parameters

| **Station** | **Energy Gain** (MeV) | **RF Phase** | **HV Stab.** (ppm) |
|---|---|---|---|
| RF Gun (2.6 cell) | 7.1 | 90° | 19 |
| SINSB01 (1x4m) | 70.5 | 90° | 15 |
| SINSB02 (1x4m) | 62.4 | 90° | 45 |
| SINSB03 (2x4m) | 100 | 70° | 19 |
| SINSB04 (2x4m) | 79.5 | 70° | 60 |
| SINXB01 (1x0.9m) | -19.6 | 270° | 27 |

### *Linac*

The main C-band linac is composed of three linacs as shown in Fig. 1. Between linac 1 and linac 2 is the second magnetic bunch compressor (BC2) while between linac 2 and linac 3 is the switchyard where the second bunch is extracted for the Athos beamline. The linac has a total of twenty six RF modules each feeding four accelerating structures, ~40 MW is required to achieve the specified 240 MeV energy gain per station. In the Athos beamline, there is an additional RF station to adjust the beam energy for the undulator chain by ±240 MeV. Each C-band station utilises an

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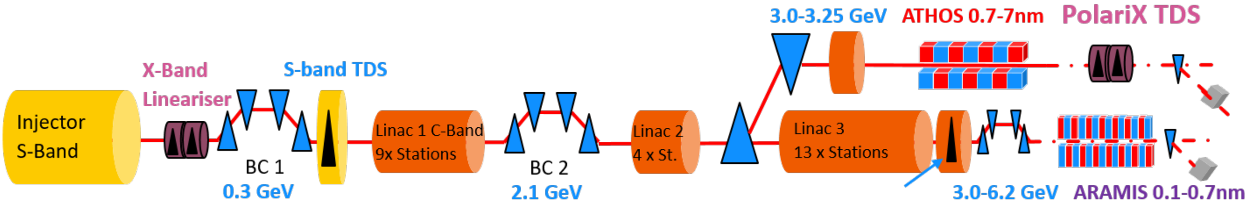


Figure 1: SwissFEL schematic layout.

RF pulse compressor to increase the peak RF power. It is a Barrel-Open Cavity (BOC) using the $TM_{18,1,1}$ mode designed to operate at 5712 MHz with a maximum input power of 50 MW for 3 µs and 100 Hz. This then feeds the four 2-m long travelling wave structures. The BOC increased the peak input power into the structure resulting in an accelerating voltage multipaction factor of around 2.1. Table 2 lists the typical operating parameters for the twenty seven (almost) identical RF stations.

Table 2: Typical Linac Operating Parameters

| | Spec. | Typical |
|---|---|---|
| Frequency (GHz) | 5.712 | 5.712 |
| Klystron voltage (kV) | 370 | 310-340 |
| Klystron current (A) | 344 | 260-300 |
| Klystron Peak output power (MW) | 50 | 33-42 |
| RF Pulse Duration (us) | 3 | 3 |
| Accelerating gradient (MV/m) | 28 | 30 |
| Energy gain per station (MeV) | 240 | 220-250 |
| Modulator pulse-to-pulse voltage stability (ppm) | <15 | 11-13 |

## RELIABILITY

The reliability of the accelerator is of primary importance for uninterrupted beam time for the scientific users. The most crucial and important activities that were carried out in recent years were the upgrade and modification of the RF systems with the aim of reducing downtime and thus considerably improving the availability of the user facility, whilst still achieving the specified beam parameters. Breakdowns and klystron trips in large and complex accelerators are unavoidable, however by optimisation of the individual RF station setpoints and natural conditioning of the RF components, a vast improvement of the trip rate in SwissFEL has been observed. This is emphasised in the yearly trip rate statistics in Fig. 2. Over the past 12 months SwissFEL has experienced 3.3 trips, per station, per week in the injector, and 1.3 trips, per station, per week in the linac. SwissFEL operates a fully automated fault detection and recover system that requires little human intervention.

### *Injector Fault Analysis*

Throughout 2021 (Fig. 3a), a large percentage (80%) of the faults with the SwissFEL Injector were due to the HV modulator failures and klystron trips. Over the past few years a programme to replace ageing klystrons, and routine inspections/assessments of the modulating power supplies, have assisted in the overall availability of the machine. The SwissFEL currently operated without any redundancy in the injector section, therefore any fault in the injector resulted in downtime for the whole ma-chine, until the failed station is able to resume operation.

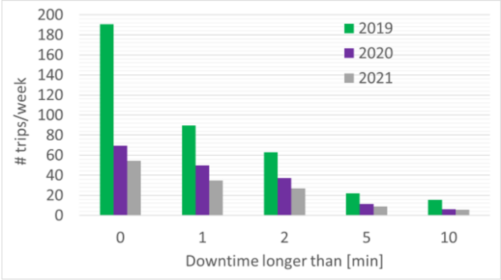
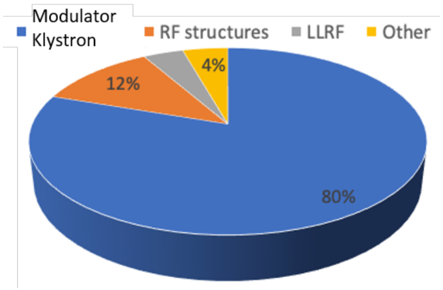


Figure 2: SwissFEL yearly trip rate statistics.

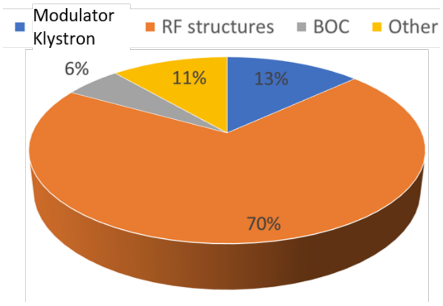
### *Linac Fault Analysis*

For the main linac, due to the overhead in available RF power, operational redundancy is possible. We work at the maximum possible electron beam energy of 6.2 GeV (giving best FEL performance). At this energy all RF stations are required, and therefore we have limited overhead in RF power to try and compensate if a station has to be removed from operation. Only if we deliver below 10 keV photons, can we take RF stations off-beam as "reserve" and can then quickly exchange if there is a long failure. This allows mostly uninterrupted operation for the users. Figure 3b shows the linac fault analysis for 2021 and we can observe that a large percentage of the faults in the C-band linac is due to RF breakdown (70%) in the RF structures. The linac almost immediately recovers from these types of trips, and we have seen vast improvement in the trip rate as the structures have naturally conditioned during operation. Flexibility and significant overhead in the RF power requirements allow individual stations susceptible of faults to operate at a reduced stress. The fault rates in the modulators and klystrons, have significantly improved, due to a number of reasons:

- Reduced charging voltage improves the Mean Time Between Failures (MTBF) for the modulator switches (IGBTs).



(a) Injector



(b) Linac

Figure 3: 2021 fault analysis for a) injector and b) linac.

- Klystron arcing rate significantly reduced at lower klystron voltage.
- Reduction in RF breakdowns at a reduced accelerating gradient.

### *Downtime Analysis*

Studying only the number of trips leads to a false assumption regarding the overall cause of downtime. Whilst the number of RF breakdowns in the Linac is significantly higher than the number of modulator/klystron faults, the breakdowns only account for a small fraction of the accumulated downtime. The accumulated downtime recorded in 12 months of operation (June 2021 to June 2022), see Fig. 4, indicated ~10 days combined downtime from the injector alone, in which 6 days were due to a single klystron arcing, that required several hours of reconditioning (on multiple occasions) before operation could resume. In the absence of operational redundancy or offline spare systems, faults and trips become a significant risk to user operation. Modulator and klystron faults, were also the significant cause of downtime in the main linac, and as a result, SwissFEL experienced several days of downtime. In the event that a long fault occurs, it is sometimes possible that operation can continue by removing the station from beam operation. The total downtime due to the Linac can be seen in Fig. 4.

## STABILITY

The HV solid state modulators were developed to operate with the highest achievable pulse-to-pulse amplitude stability in order to minimise the contribution of the total beam energy jitter. Since most stations operate on-crest, the contribution of phase jitter can largely be ignored. However, amplitude and phase jitter from SINSB03 and 04, contribute towards the compression and arrival time jitter at the exit of the bunch compressor [3]. The rms amplitude and phase jitter for the specific frequency bands in SwissFEL are displayed in Table 3.

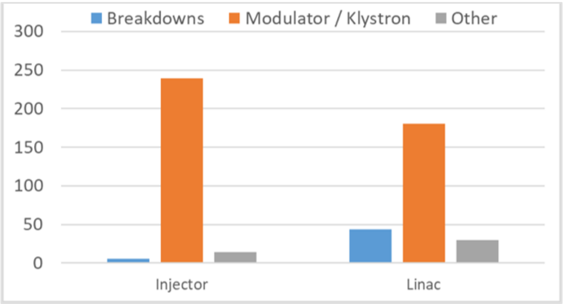


Figure 4: Accumulated station downtime in hours over 1 year by source.

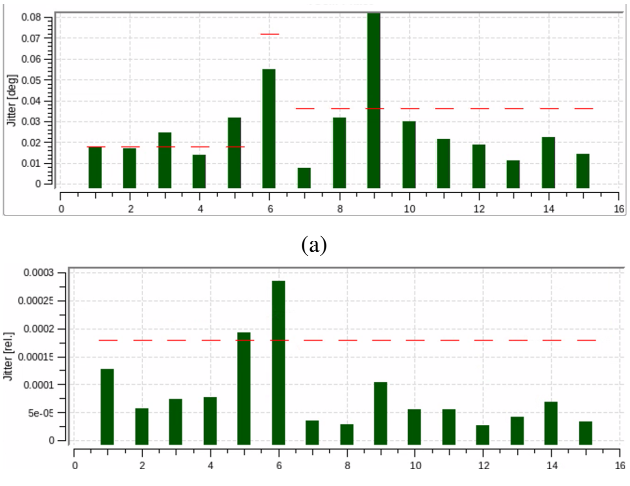
Table 3: Peak to Peak Relative Amplitude and Phase Jitter Measurement (RMS Values)

| | **Relative Amplitude Jitter** | **RF Phase Jitter** |
|---|---|---|
| S-Band | 0.01-0.02% | 0.025° |
| C-Band | 0.01-0.02% | 0.035° |
| X-Band | 0.05% | 0.058° |

Since the overall rms amplitude and phase jitters for the accelerator exceeds the specifications, this allows some tolerance on operation for sub-optimal stations. A measurement of the amplitude and phase jitter of the more critical stations, during a typical user operation set-up highlights stations that are contributing largely to both the arrival time and compression jitter. Figures 5a and 5b show a plot of the measured phase and amplitude jitter observed over 1000 consecutive RF pulses, taken during a user operation shift. The x-axis displays the station numbers where 1 is the gun, 2 to 5 are the S-band stations, 6 is the X-band lineariser, and 7 to 15 are the 9 stations in linac 1. Also displayed on the charts are the associated specification, for amplitude and phase jitter for the different frequency bands (red dashed line).

### *S10CB03*

During the measurement window taken, it was observed that S10CB03 (x = 9) in Fig. 5a displayed high phase jitter, essentially contributing more so to the compression jitter. This is due to a known issue with this station which is multipacting (MP) inside the BOC. Since the remaining stations in Linac 1 are operating much below the specification, the overall contribution to the compression jitter was not compromised, however the instability is observed during operation, and to mitigate MP in the BOC, the station would have then been set to a higher operating point, away from the MP onset.



(a)

(b)

Figure 5: Measured (a) phase jitter and (b) amplitude jitter vs. station position (horizontal axis) for injector and linac 1.

### SINSB04

The amplitude and phase jitter for SINSB04 (x = 5) in Fig. 5b shows higher than specified amplitude and phase jitter, and due to the function of the station, this station is currently dominating the longitudinal beam jitter. A contributing factor to the jitter on this station is presumed to be due to the higher pulse-to-pulse amplitude jitter of 60 ppm (displayed in Table 3), which was measured during normal operation. In an effort to improve the performance of the station, an optimisation of the stability was investigated during a scheduled maintenance window.

For the stability measurements, an average stability (in ppm) of 100 pulses are measured and the trend of the 100 pulses are displayed as a single point on the trend curve (Fig. 6). Here we observed a considerably improved performance, with a measured amplitude stability of 14 to 20 ppm. As adjacent stations were switched on, we then witnessed a gradual increase in the stations amplitude jitter as more stations were placed back into operation, and ramped up to their nominal operating voltage. Plotting 100 consecutive pulses, highlighted a 50 Hz contribution from the neighbouring stations, through the mains supply (Fig. 7). A feed-forward system is planned that should compensate for the 50 Hz, considerably improving the jitter currently experienced on this station.

### Klystron Instabilities

All klystron transfer curves are measured at discrete charging voltages steps. These curves are then used to set the charging voltage and RF drive for each station, such that we automatically operate in saturation, regardless of the desired output power. An automated tool scans the klystron and generates the curves. The automation allows fine steps in the measurement settings that highlighted a potential concern with our klystrons. In October 2018, all klystrons were scanned, ready for routine user operation. With the exception of five stations, we observed discontinuities in nearly all klystron curves reminiscent of multipacting. These multipacting bands mostly occurred at a fixed RF drive setpoint, and the discontinuity was typically in the range 50-100 Watts drive, suggesting an issue in the klystron input cavity. In the low power region, the pre-amplifier also displays significant amplitude and phase jitter, however it is not a region of concern, since we would not be able to operate at these settings. In addition, manual measurements of the klystron curves, may not have highlighted the issue, due to a larger step size in RF drive normally taken. On three of the 26 klystrons, we measured a much broader discontinuity that changed with respect to the RF drive, which is a more common feature of MP in subsequent bunching cavities, and it is these klystrons that affected the achievable amplitude jitter.

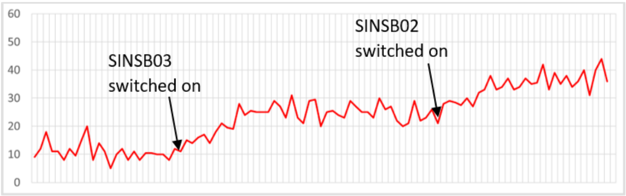


Figure 6: Trend plot: stability in ppm.

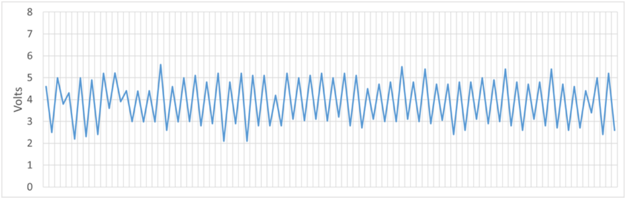
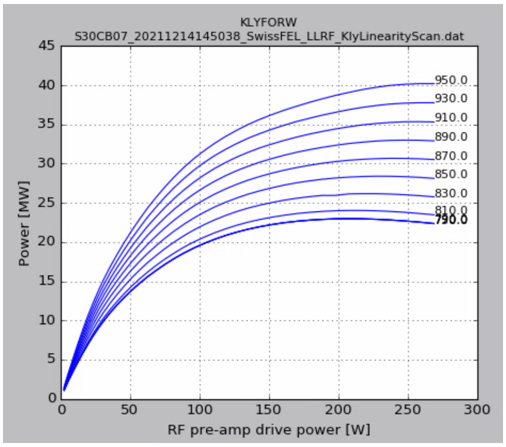


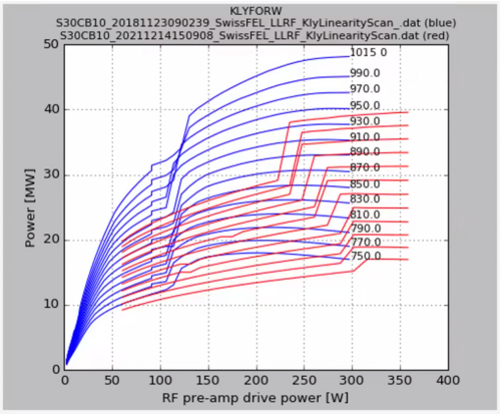
Figure 7: Gated voltage average for 100 consecutive pulses.

Figure 8a displays an ideal klystron transfer curve, as measured on five currently installed linac stations. The value at the end of the curve indicates the charging voltage for the HV modulator. During 2019 to present, we have experienced continuing unstable behaviour of additional stations, with a simple fix of increasing the RF drive to move away from the unstable operating point. Finally in December 2021, we rescanned all klystron curves, to update the operating points for all stations. Here we observed several stations had undergone a significant change in the MP bands, see Fig. 8b. In this plot we have a direct comparison of the klystron transfer curves taken in October 2018 (blue traces), with those taken in December 2021 (red traces). For completeness, we plotted the Multipacting bands of all linac klystrons, to compare the general trend of each station. Figure 9 shows a plot of the multipacting bands measured at each station. At present none of the current klystrons are limiting operation, although the plot would advise caution for S30CB10, 11 and 12.

The linac operates each station with pulsed compression with identical setting for the phase inversion. Over time, we believe this may be the cause of the measured degradation in the klystron performance. We measure the output power after the phase jump for our scanning tool. By observing the RF waveform, we have often seen that during the MP onset, the pre-inversion output power level, was more stable than the post in version power level. Figure 10 displays the RF waveform during regular klystron behaviour and during



(a) S30CB07



(b) S30CB10

Figure 8: Klystron curve with multipacting in stations a) S30CB07 and b) S30CB10.

Figure 9: MP bands by station, blue: 2018, green: 2021, red: current 2022 operating point.

MP. The measurement for the klystron output power is gated with the red and blue vertical lines, directly after the phase inversion (at 2.6 µs). This observation would suggest that the phase inversion initiates the MP onset, however the long term degradation still requires confirmation.

The current phase inversion settings (180°, 50 ns rise time) is equivalent to a frequency shift of around 10 MHz, this may produce unstable operation in the klystron output power. Therefore, it is planned to study the settings, to further understand the characteristics of the multipacting, to mitigate the issue.

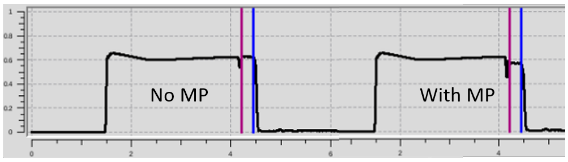


Figure 10: RF waveform without MP.

## SWISSFEL PERFORMANCE

Despite experiencing a number operational issues, the availability for user operation during 2021 was around 95.5%, with an overall improvement of the weekly trip rate observed throughout the year. The long term strategy is to replace underperforming klystrons in the injector to improve the availability of the injector. We also expect natural conditioning in the RF systems to reduce the overall trip rate, which will improve the overall availability of the main linac. The beam stability requirements for the Aramis beam line have been exceeded in terms of beam arrival time jitter and beam energy spread, as can be seen in Table 4. Weaknesses in the key stations driving the performance have been identified, with a strategy for upgrading/improving the stations now introduced.

Table 4: Beam Jitters in Aramis Beamline (RMS Values)

| | **Requirement** | **Measurement** |
|---|---|---|
| Relative peak current | <5% | 6.4% |
| Arrival time | <20fs | <10 fs |
| Relative beam energy | < 5E-4 | 2E-4 |

## CONCLUSION

Beam stability requirements for the Aramis beam line is largely driven by the performance of the RF system, and as a result of the exceptional (rms) amplitude and phase jitter within the RF system the machine is able to operate far below the overall beam stability requirements. Planned improvements in the injector, with the Lineariser, SINSB03 and SINSB04 specifically, will provide vast improvements in the beam energy spread and arrival time. The trip rate of the accelerator, has shown a considerable improvement, and planned system upgrades, specifically for the injector, would see further gain in machine availability. In addition to this, we also fore-cast improvements to the overall, compression and timing jitter for both beam lines.

## REFERENCES

[1] E. Prat *et al.*, “A compact and cost-effective hard X-rayfree-electron laser driven by a high-brightness and low-energy electron beam”, *Nature Photonics* , vol. 14, pp. 748-754, 2020. doi:10.1038/s41566-020-00712-8