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OPERATION EXPERIENCE WITH SESAME RF SYSTEM

D. Foudeh, N. Sawai, A. Kurdi, SESAME Synchrotron, Allan, Jordan

Abstract

SESAME RF system has been in operation for five years during which the operational beam current has been increased from 100 mA to 300 mA. The higher operational beam current with the need to have longer beam lifetime to reduce number of injections per day, required higher forward RF power, on the other hand; more attention needed to be paid to monitor and tackle the current driven High Order Modes and to respect the limitation on the forward RF power coming from the solid-state amplifiers. In this paper we describe the RF system and report on the challenges we faced in addition to the operational experience we had with the RF system.

INTRODUCTION

SESAME is an international third-generation light source that has been hosting users since Jul.2018. The storage ring (Table 1) is filled with current that reached 300 mA in the last year, at 1Hz repetition rate using 800MeV injector, then its energy is ramped up to 2.5 GeV. Due to the long beam lifetime, around 24h at 300 mA, one injection per day is sufficient for users.

Table 1: Operational Main RF Parameters

parameter	unit	value
Circumference	m	133.2
RF	MHz	499.671
Energy	GeV	2.5
Current	mA	300
Filled buckets		≈198
Harmonic number h.		222
Energy Losses per turn	keV	603
Momentum compaction factor		0.00828
No of cavities		4
RF Voltage	MV	1.8

SESAME storage ring RF system is composed of four identical plants where each has one Elettra cavity powered by 80kW solid state amplifier (SSA) through WR1800 waveguide (Fig.1). The RF plant is controlled via digital low level RF (D-LLRF) system from DIMTEL. The RF system had been installed and commissioned in 2016 while the first beam stored beginning of 2017 [1].

Figure 1: Top view for 4x80 kW RF plants.

MASTER OSCILLATOR

In the commissioning period of the machine there was a frequent need to change the master oscillator (MO) frequency which was unfortunately causing a trip in the RF system even with steps of tens of hertz. It appeared that MO was losing its phase at the frequency change leaving the D-LLRF with no reference signal, consequently creating a high reflected power tripping the RF system. Figure 2 shows the amplitude and phase of RF signals relative to the reference channel, where forward and reflected jumps are associated with the frequency change at about 106 µs into the record, resulting in an interlock trip at 110 µs [2].

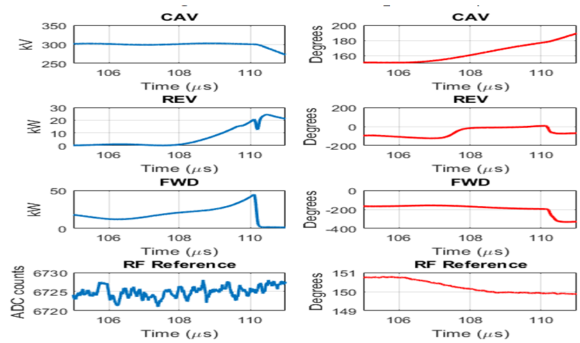

Figure 2: Post-mortem showing FWD phase change.

To avoid this situation; a temporary setup had been implemented to change frequency via FM DC-coupled modulation which preserves phase continuity. This setup required a frequency counter to keep measuring the MO frequency. Later, the old MO was replaced by a new phase-coherent signal generator model HS9001B manufactured by Holzworth which is free of phase glitch regardless to the step size of frequency change with about -10 dB phase noise improvement.

80 KW SOLID STATE AMPLIFIER

The 80 kW SSA is composed of 160x550 W RF modules whose outputs are combined using a set of coaxial combiners arranged in (8x10x2x1) scheme. Similarly, the driving signal is buffered by another 5 modules and then split into 1x5x4x8 scheme. Operational voltage of modules ranges from 46 to 50 VDC which is chosen as the default operational DC voltage. The power supplies are assembled in 5 groups, installed on the top of SSA cabinet, each has 16x2kW power supply modules. The SSA showed high reliability during machine operation, only 30 out of 660 RF modules had transistors repaired and one 2 kW power supply was found defected out of 340 rectifiers. Due to the proven performance of SSA, an in-house 4 kW SSA was assembled from the spare modules to be used for booster RF plant. The new amplifier replaced the old 2 kW commercial TV amplifier.

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DIGITAL LOW-LEVEL RF

SESAME uses LLRF9 from Dimtel for Booster and Storage rings, many features are available in the system that allow better control and diagnose for the RF plant, i.e., network and spectrum analysers are used for cavity tuning and feedback loops calibration, time data acquisition to clarify the behaviour once a trip happened and a klystron phase loop correction is used to handle all phase disturbances between LLRF9 output and cavity forward power to keep the cavity phase constant. Feedback loops settings are optimized for the machine operational current 300 mA while voltage calibration of LLRF9 were based on synchrotron measurement at low current, beside these features; LLRF9 voltage is programmable to follow designed patterns consisted of 512 points.

A good example of diagnostic time acquisition tool is the post-mortem feature which had proven to be extremely beneficial for diagnosing RF trips, Fig. 3 shows an arc interlock event captured by LLRF9.

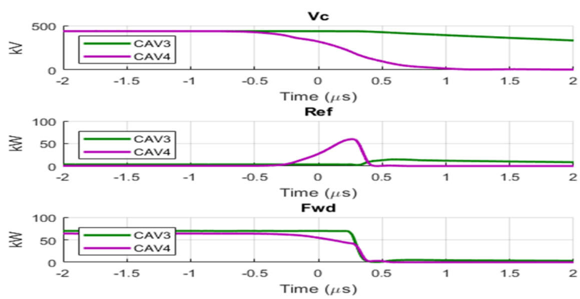

Figure 3: captured interlock with an arc in cavity4.

At about –0.5µs into the record, an RF arc generates reflected power in cavity4, resulting a trip at -0.11 µs since ref power trips at 15 kW, note the rapid decay in cavity4 probe signal as compared to cavity3 that complies with the expected loaded quality factor ≈12000, after RF drive is removed due to machine protection; cavity3 generated reflection as expected. For safety and machine protection, beam dump is performed through LLRF9 interlock I/P.

RF CAVITIES

Four Elettra RF cavities are used for SESAME storage ring. In normal operation; gap voltage used is 430kV/cavity to accommodate 300 mA in the SR. Elettra cavity does not support damping system for High Order Modes (HOM), instead; it utilizes the ability to operate the cavity at specific temperature intervals where HOM's will not be excited. A precise temperature control of the cavity is achieved by a special cooling rack that is connected to the main cooling circuit through a heat exchanger on its primary side while the cavity is on its secondary side within a closed circuit. Cavity temperature regulation accuracy should be within ±0.05C°, however, the regulation accuracy reached so far is ≥±0.15 due to the long distance between the cavity and its cooling rack (≈12m) with many 90^{o} elbows, nevertheless, temperatures windows found for the four cavities (49.7, 56, 63.5, and 51 respectively) are good enough to operate the machine with good stability conditions. In addition to temperature control method; a plunger system is used to shift the HOMs that hardly can be moved by temperature, HOM shifter was needed only for cavity3 by inserting the plunger 8mm while others are fully out.

Due to SSA's thresholds levels; cavity RF power conditioning in the pulse mode was limited to values less than 380kV due to the high RF power transients that tripped SSA, that could be worked around by using the beam itself as will come later.

Recently, cavities coupling factors were increased from 1.9 in average to 2.3 to minimize the reflected power at 300 mA, as this process requires breaking the vacuum to rotate the cavity main coupler, Nitrogen gas were used instead of air to break the vacuum and showed the possibility to condition the cavities by RF power without the need for baking out.

RF OPERATION WITH BEAM

Minimum required voltage/cavity for injection is 70 kV but with increasing injected current; more voltage is needed to compensate for the beam loading, after many trials; 130 kV were chosen for injection process, higher voltages would lower injection efficiency.

As the cavity HOMs are the main source of the machine instabilities, it was very important to adapt a system that can track all instability modes and display it graphically as in Fig. 4, the first adapted system was based on the scope LC574A1-500 MHz digitizer, the raw data of the BPM hybrid measured signal is sent to a PC with MATLAB code [3] to analyze it and present the whole 222 beam modes, Fig. 5 illustrates the setup of the instability monitor. Later, the scope was replaced by Libera Bunch-by-Bunch processors (one per plane) upgraded with Diamond Light Source firmware & EPICS drivers, the instability monitor helped in optimizing cavities temperatures [3].

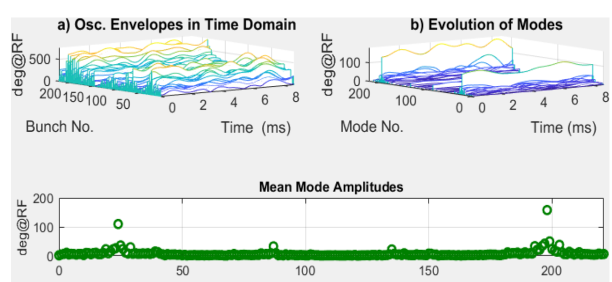

Figure 4: longitudinal instability during injection.

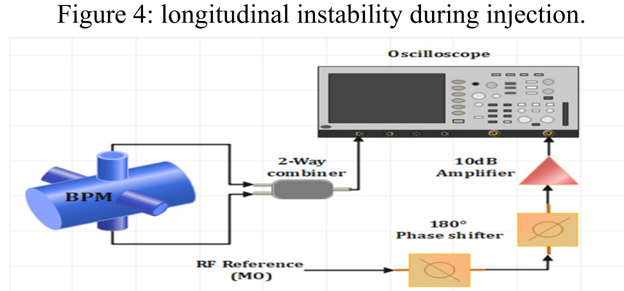

Figure 5: Schematic of initial setup of instability monitor using LC574A1 oscilloscope at 500MS/s sampling.

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During injection, the coupled bunch instabilities are clearly seen on the instability monitor, nevertheless, these instabilities at low energy are not critical where injection up to 350 mA was achieved. The energy ramp starts directly after reaching the desired current, where a set of scripts load and trigger ramping curves for both magnet and RF systems. Figure 6 shows the SR filling and energy ramp processes.

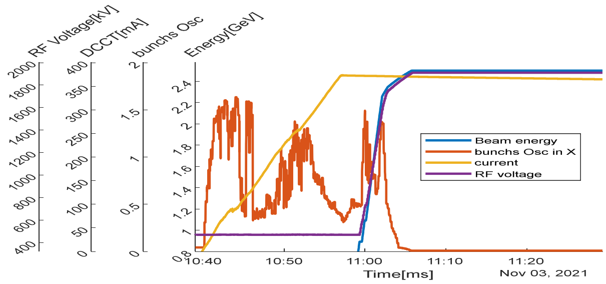

Figure 6: SR injection and ramping process.

On the way to 2.5GeV, excited modes can be seen clearly on the instability monitor up to 1.8GeV then start to get weaker up to about 2.48GeV where all excited modes are strongly suppressed due to shorter machine damping times $\tau x/\tau y/\tau z$: 2.7/2.3/3.7msec, respectively.

As SESAME machine runs in the decay mode; it was very important to optimize the RF in order to increase the stored beam and lifetime, that goal was achieved by two approaches:

1st.: increasing the stored beam to 300mA after improving the vacuum in cavities, since RF conditioning in the pulse mode was not possible for more than 380kV we had to get use of the beam itself as a load to clean the cavities by controlling the energy ramping process manually, one can see the effect on vacuum spikes during energy increase as in Fig. 7 when 250mA limit was exceeded, this process would be repeated every time more current is required since pressure will be excited then energy ramping process would become straight forward with no interruptions.

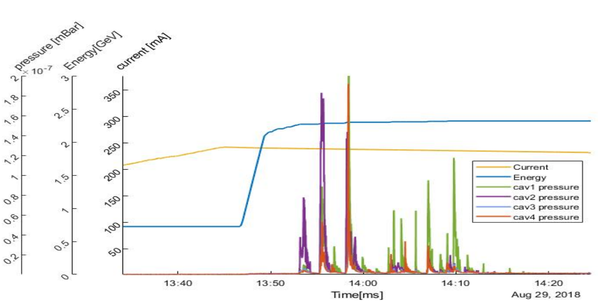

Figure 7: Vacuum spikes during energy increase with 250mA stored beam for the first time.

2nd.: getting use of the available power while the beam is decaying; by running a script that keeps checking every RF station forward power which once is less than a specific value, i.e.; 75kW the code will increase the voltage gradually but not to exceed 540kV, this active increment of voltage during beam decay helps to increase the beam lifetime with good number of hours, i.e.; before code; lifetime at 200 mA was 36h as in Fig. 8 while with the script is ON reaches 52h as in Fig. 9.

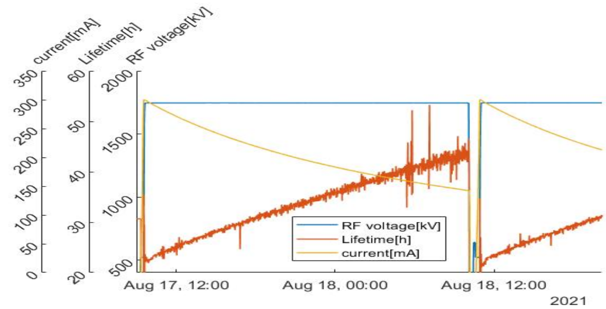

Figure 8: Lifetime with RF voltage fixed 430KV/cavity.

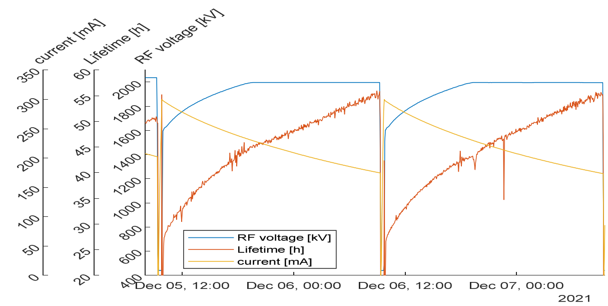

Figure 9: Lifetime during RF voltage increase up to 500KV/cavity.

ACKNOWLEDGEMENTS

Thanks to Diamond and Australian synchrotrons for their donation of retired Bunch-by-Bunch electronics [3], also thanks to Dmitry Tytelman and Cristina Pasotti for the discussions and continuous help.

CONCLUSION

The SESAME system has performed very well, 300mA beam is routinely stored at 2.5GeV with very good stability and look forward for 325mA in the near future which might require implementing Bunch-by-Bunch feedback for any possible instabilities.

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