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ESRF-EBS 352.37 MHz RADIO FREQUENCY SYSTEM

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Abstract

The ESRF 352 MHz Radio Frequency (RF) system has been upgraded and tailored to the new 4th Generation Extremely Brilliant Source EBS that was installed in 2019 and commissioned in 2020. The five former five-cell cavities were replaced with 13 single cell strongly HOM damped cavities that were developed in house, 10 of which are powered from existing 1.1 MW klystron transmitters. The remaining three cavities are individually fed by three 150 kW solid state amplifiers. All this required a reconstruction in record time of an elaborate WR2300 waveguide network. The low level RF system as well as the cavity and transmitter control system have been rebuilt. The RF design, commissioning and operation experience is reported, including plans for a 4th harmonic RF system for bunch lengthening to further improve the performance of the new EBS ring.

INTRODUCTION

The ESRF operates a 6 GeV storage ring light source that was taken into operation in 1992. In December 2018 the existing storage ring (SR) was shut down, then fully dismantled and replaced with a new 4th Generation 6 GeV ultra-low emittance ring, the Extremely Brilliant Source ESRF-EBS. The new ring was taken into operation one year later on 28 November 2019 and commissioned until end of February 2020. After commissioning of the X-ray beam lines, standard user operation was resumed as scheduled on 25th August 2020 [1, 2].

The 352 MHz Radio Frequency (RF) system was upgraded and tailored to the needs of the new EBS ring. While a precise temperature control of the former five-cell cavities allowed detuning the higher order modes (HOM) and escaping longitudinal coupled bunch instabilities (LCBI) up to the nominal current of 200 mA, the factor two lower thresholds for LCBI on EBS required the installation of 13 HOM damped single-cell cavities that were developed at the ESRF [3, 4]. Figure 1 shows a string of five such cavities in cell 5 of the EBS ring. The control synopsis in Fig. 2 illustrates the EBS RF system layout. By means of waveguide switches 10 cavities can be connected to either 1.1 MW klystron transmitter SRRF1 or transmitter SRRF2 [5, 6]. Each klystron transmitter can also be connected to one string of five cavities. The three cavities in cell 25 are individually powered by three 150 kW solid state amplifiers (SSA) [7, 8]. The waveguide switches, the -7 dB hybrid and -3 dB magic Tee splitters with water loads on their idle arms are not shown in Fig. 2.

The implementation required the reconstruction of an elaborate waveguide network including splitters, waveguide switches, phase shifters and a number of water cooled loads. Also the low level RF and the control of the klystron transmitters and of the cavities were rebuilt.

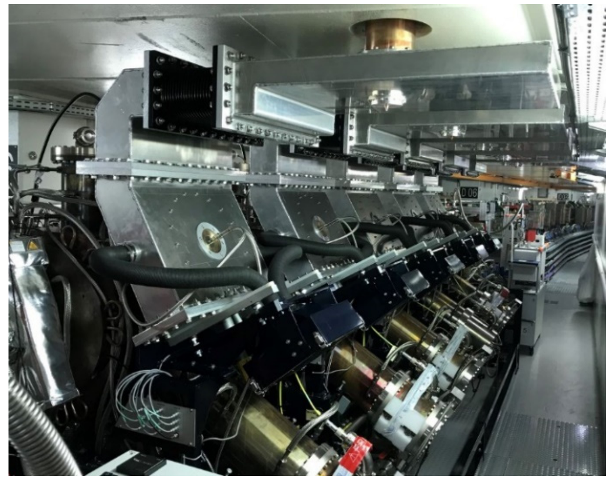

Figure 1: String of five HOM damped 352.37 MHz cavities in the EBS storage ring. Per cavity: $R/Q = 145\ \Omega$, $Q_0 = 35700$, $R_s = 5\ M\Omega$, $V_{acc\text{-}nom} = 500$ kV, Vacc-max = 750 kV. Longitudinal HOM impedances for 13 cavities remain well below threshold for LCBI [4].

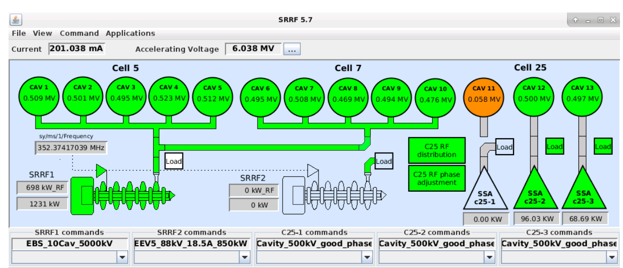

Figure 2: Graphical control synopsis of the EBS RF system, here in a fall back configuration with only 12 cavities in operation at 200 mA.

Table 1 summarizes the main RF parameters for the former ESRF SR and EBS. The insertion device (ID) beam lines could be kept in place thanks to an increase of the RF frequency by 170 kHz for the slightly shorter EBS ring, which was well within the available frequency range of all existing RF components, including the 1.1 MW high power klystrons. The dipole radiation loss per turn U_0 is lower by almost a factor two, resulting in a 30% reduction of the total RF power consumption at the nominal beam current of 200 mA. It allowed dismantling the no longer needed former 3rd klystron transmitter [9]. The nominal accelerating voltage of 6 MV was determined by lifetime optimization during EBS beam commissioning.

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EBS COMMISSIONING

All the cavities had been pre-conditioned in the RF power test stand up to 750 kV and needed only short in situ re-conditioning after their installation on EBS [4]. The nominal RF voltage was therefore available from day one of EBS commissioning on 28 November 2019 [1, 2]. Substantial ramping of the beam current started in January and 200 mA were reached well ahead of schedule on 28 February 2020 after an easy beam conditioning of the 13 HOM damped cavities and their power couplers. Not counting the cavity vacuum trips experienced during the few shifts dedicated to current ramping, only 6 beam trips were attributed to RF failures during the whole EBS commissioning period until 1st March 2020.

From 2nd March 2020 the EBS SR started to be routinely operated for beamline commissioning, and SR optimization was carried on during machine dedicated time (MDT shifts). In this period the ID gaps were gradually closed, thereby steadily increasing the additional radiation losses up to 0.7 MeV/turn. The further conditioning of the RF cavities to additional 140 kW of beam power was straightforward as well. This period ended with the start of the summer shut down on 28 July 2020. Only 13 beam trips were attributed to RF failures during this early operation phase, and their root causes were all mitigated.

Early RF Faults

The total of 19 RF failures that caused beam trips during the commissioning from December 2019 to July 2020, had the following causes:

- 9 Due to vacuum burst or field breakdowns in the freshly beam conditioned cavities.
- 4 Caused by minor RF controller and LLRF bugs.
- 2 Mechanical issues with the new tuners due to errors in the assembly at the factory: each time systematic corrective actions were taken on all the tuners.
- 4 Arc detections within a short period of time at one waveguide switch (S24), for which a first inspection didn't reveal any trace of arcing. After the 4th detection, S24 was finally replaced and tiny hidden arc traces were found on an RF finger strip, which could easily be repaired. These were the only arc detections since the start of EBS.

For EBS the waveguide run was equipped with a slightly modified version of the CERN/LHC arc detectors [10]. They so far provided an excellent protection:

- High sensitivity: i.e. excellent equipment protection by triggering before arcs could damage e.g. the waveguide switch S24.
- No spurious detection so far: i.e. no impacting on the MTBF of the machine, as is often the case with sensitive arc detectors.

EBS OPERATION IN USM

Photon beam delivery in user service mode (USM) was resumed as scheduled on 25th August 2020. During the nine months until today, only two RF failures have tripped the stored beam. This confirms the outstanding reliability of the EBS RF system. The first trip was due to a glitch on the RF input of one SSA. The cause of the other trip was a breakdown at the input of cavity 12 in January, shortly after the replacement of its input coupler, i.e. still during its conditioning phase.

Indeed, in October 2020 a tiny leak had opened on the ceramic window of the cavity 12 input coupler, which induced a rise in pressure of the cavity of less than 3 10^{-10} mbar. To avoid any risk, the cavity 12 was removed from operation and tuned to its parking position. At 200 mA, the pressure of the passive cavity was about 1 10^{-9} mbar. The coupler was replaced during the Christmas shut down.

Table 1: Main RF Parameters; (*) the Generator Power P_{gen} Includes Measured 8% Transmission Losses

	Former SR	**ESRF-EBS**
ε_h [pm rad]	4000	133
ε_v [pm rad]	4	1 (10 in oper.)
f_{RF} [MHz]	352.20	352.37
U_0 [MeV/turn]	4.88	2.56
U_{ID} [MeV/turn]	0.7	0.7
h (harmonic nb.)	992	992
τ_s [ms]	3.5	8.9
Mom. Comp. α	17.8 10^{-5}	8.6 10^{-5}
σ_E/E	1.06 10^{-3}	0.94 10^{-3}
$V_{RF\text{-}nom}$ [MV]	9	6
ΔE/E, incl. ID	3.5 %	4.6 %
f_s [kHz]	2.04	1.20
Number cavities	6 x 5-cell	13 HOM damped
Cavity coupl. β	4.4	2.8
$P_{Cu\text{-}loss}$ /cav [kW]	42	22
P_{gen}/cav [kW] * @ 200 mA	250	79
$P_{gen\text{-}total}$ [kW] * @ 200 mA	1500	1020

FALL BACK RF CONFIGURATIONS

A few MDT shifts were used to test various fall back configurations allowing to store beam if one RF device has a major fault that needs substantial time for repair. The example of Fig. 2 shows that 200 mA can easily be stored at the nominal RF voltage if one of the cavities in cell 25 is removed from operation. However, in case of a major fault on one of the cavities of cell 5 or cell 7, the complete string

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of five cavities needs to be removed from operation, leaving only 8 active cavities. Such a configuration was successfully tested at 200 mA with open ID gaps, the cavities of cell 7 in passive and the other 8 cavities at 0.6 MV, providing 4.8 MV of total accelerating voltage. The configuration was tested again later with 0.7 MeV/turn additional ID radiation loss, however, only at 150 mA to avoid any unnecessary risk. In case this configuration would need to be set in USM, it could probably be operated at or close to 200 mA. Note that when reducing the RF voltage from 6.0 to 4.8 MV at 200 mA with closed ID gaps, the lifetime drops from 21 to about 16 hours. Below 4.8 MV the drop in lifetime becomes unacceptable, in particular because of the radiation load from the correspondingly high electron loss rate.

PROJECT - ACTIVE 4TH HARMONIC RF SYSTEM FOR BUNCH LENGTHENING

While design performance is achieved in mutlibunch 200 mA operation, including 7/8 + 1 filling, with a lifetime above 20 hours, the few bunch operation is still limited [2]. Due to overheating of the ceramic kicker and shaker chambers, the beam current is limited to 35 mA in 16 bunch mode, well below the nominal 90 mA, and to 20 mA in 4 bunch filling instead of the nominal 40 mA. With the installation of new ceramic chambers presumably early 2022 these few bunch fillings should again be operated at nominal current. However, even with a vertical emittance set to 20 pm, the Touschek lifetime will be around 3.5h in 16 bunch and 2.5h in 4 bunch filling.

The development within 3 to 4 years of an active 4th harmonic 1.41 GHz RF system for bunch lengthening by a factor 2.5 to 3 has been launched in order to reduce Touschek and intra-beam scattering (IBS), and mitigate impedance heating of critical vacuum vessels in few bunch operation. It will provide a corresponding increase in Touschek lifetime as well as a reduction of the emittance blow up due to IBS and of the energy blow up due to the microwave instability (threshold at 1.4 mA/bunch).

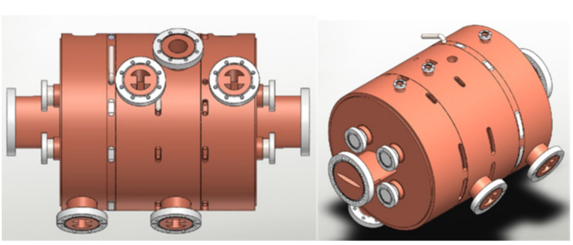

Figure 3: TM020 4-cell harmonic cavity for EBS [11].

Two TM020 4-cell cavities as shown in Fig. 3, equipped with two couplers each, are foreseen to provide up to 1.49 MV harmonic voltage, which corresponds to optimum bunch lengthening for 6.5 MV main accelerating voltage and all ID gaps open [11]. With its 2.3 times lower R/Q and 1.7 times higher Q_0 the TM020 mode generates less transient beam loading for non-symmetric filling patterns than the TM010 mode, at the expense of a about 30% more power needed to obtain a given voltage [12]. The total shunt resistance of the two cavities is 8.8 MΩ.

Critical coupling ($\beta_h = 1$) and, as for the main RF system, tuning for zero load angle provide the most efficient working point for the active harmonic RF system. At zero beam current, 31.5 kW must be fed through each of the four couplers to obtain 1.49 MV. At the phase for optimum bunch lengthening, the beam loading is negative, i.e. the generator power needed to obtain the desired voltage decreases when injecting beam. This beam power is taken from the main RF system and can reach several 10 kW, depending on the tuning of the harmonic RF system.

Including a 25% overhead for losses and RF feedback, four 40 to 45 kW 1.41 GHz solid state amplifiers are foreseen to power the harmonic cavities. To protect the SSA against possible substantial reverse power, circulators and loads in isolator configuration are also foreseen.

The novel compact TM030 mode aluminium cavity combiner in Fig. 4 has been designed at the ESRF to combine the power from 60 modules of 700 to 750 W. Their power is coupled via 7-16 connectors and 60 simple rod antennas to the E-field of the TM030 mode. The tunable E-field antenna on the axis couples the total power to a WR650 waveguide. The combiner can be tailored to the actual power needs by removing RF modules and retuning the output coupler. A piston at the bottom is used to tune the centre frequency. Total combiner losses of 2% to 4% were computed. A prototype is in fabrication.

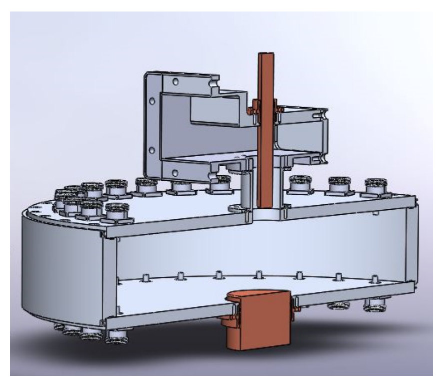

Figure 4: ESRF 1.41 GHz TM030 cavity combiner.

CONCLUSION

The upgraded RF system with its new HOM damped cavities has allowed commissioning the new EBS ring and reaching the nominal beam current in record time. The reliability of the RF system is outstanding with only 2 beam trips in 9 months of user operation. It will be complemented by a 4th harmonic RF system for bunch lengthening: first priority is to improve the EBS performance for few bunch modes with high currents per bunch.

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