BESSY VSR: A NOVEL APPLICATION OF SRF FOR SYNCHROTRON LIGHT SOURCES

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Abstract

CW SRF Cavities have been used very successfully in the past in synchrotron light sources to provide high power acceleration. Here we present a novel application of higher harmonic systems of two different frequencies (1.5 GHz and 1.75 GHz) to generate a beating of accelerating voltage. With such a system it is possible to store "standard" (some 10 ps long) and "short" (ps and sub-ps long) pulses simultaneously in the storage ring. This opens up new possibilities for light source users to perform picosecond dynamic and high-resolution experiments at the same facility. The demands on the SRF system and RF control are substantial and a new design, based on waveguide damping, is currently being developed. This system will be used for a major upgrade of the BESSY II facility to the BESSY Variable Pulse length Storage Ring (BESSY VSR) for a next-generation storage-ring light source. We will discuss the concept, challenges and designs for BESSY VSR from the SRF point of view.

INTRODUCTION

Storage ring sources represent very useful and reliable tools for scientist due to the broad spectrum of photon beam parameters available when designing a dedicated experiment: wavelength, flux, peak and average brilliance, coherence, and pulse length. Regarding this last parameter storage rings like BESSY II dedicate most of their beam time to produce long bunches while short bunch operation is provided only during a few days per annum to all beam lines. During the years, BESSY II has been developing a broad community of users working in the THz to hard X-RAY range interested in performing dynamic measurements by means of short pulses (ps to fs). For this reason BESSY has implemented 2 different modes of operation able to satisfy the short pulse demand (low α mode and femto-slicing facility). Nevertheless, short pulses can only be provided to all beam-lines during dedicated low α mode (12 days/year). Although the femto-slicing facility can be operated along the whole year only 1 beam-line is available. In addition, both techniques offer limited flux capabilities. Motivated by this fact HZB's presents the upgrade project of BESSY II by offering the possibility to supply all users simultaneous operation with short (ca. 1.7 ps rms) and long (ca. 15 ps rms) bunches while maintaining a high average brilliance at 300 mA bunch current. Opposite to the upgrade plans in the direction of reducing transverse beam emittance (Difraction Limited Storage Rings, DLSRs) for many facilities like ERSF or Spring-8, BESSY VSR presents a complimentary facility able to supply shorter bunches by an increase in the RF focusing. This RF gain compensates the expected flux reduction due to bunch shortening and a factor 100 increase in bunch current can be potentially obtained with no change in the machine optics. Thus users will be then able to choose the required photon beam for the individual experiments by implementing the proper bunch separation technique in a dedicate beamline. Therefore this paper presents the currents status of the BESSY II SCRF upgrade in order to address the needs of increasingly diverse users community.

BESSY VSR, THE CONCEPT

The original concept of BESSY VSR was proposed in 2006 [1] and further developed in 2011 [2]. It relies on 1.5 GHz CW superconducting RF (SRF) cavities to provide 80 times more longitudinal focusing than from the normal-conducting RF system in BESSY II. The additional installation of a second 3.5 harmonic SRF system (1.75 GHz) leads to a beating of the induced cavity voltages while bunches can be compressed by roughly a factor of √80 into the low picosecond range. Therefore a combination of long and short buckets can be simultaneously generated. Then, long bunches can be then stored to provide the high photon flux while only a few short-bunch buckets are populated with high charge for short-pulse experiments. This procedure successfully avoids eventual impedance and Touschek lifetime problems. Figure 1 shows the voltage beating created by the three cavity system in time domain for a factor 10 bunch shortening. The long bunches are placed within the low gradient buckets, while the short bunches appear 2 ns shifted.

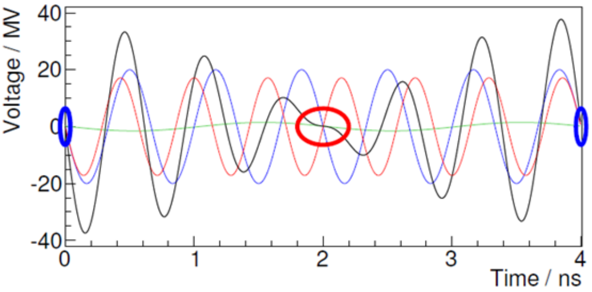

Figure 1: Representations of the 3 cavity system BESSY-VSR concept showing the voltage beating in time domain for a factor 10 bunch shortening. The sum voltage is shown in black. Short bunches are placed at t = 0 and t = 4 ns, long bunches at t = 2 ns.

SRF DEVELOPMENTS

Cavity Design

The SRF cavity system designed to provide bunch compressions and the proper beating is composed by two higher harmonics (3 and 3.5) cavity sets (2x1.5 GHz and 2x1.75 GHz). Since the cavities will be operated CW providing high accelerating field values (E_{acc}=20MV/m), requirements for the cavity geometry impose fine tuning in order to avoid dangerous high peak fields potentially leading to discharges, quenching or field emission. Moreover high beam current (I_{beam}=300mA) imposes special care to be devoted to the implementation of the high order modes (HOM's) damping strategy in order to avoid coupled bunch instabilities (CBI's). Calculations considering the complete BESSY-VSR filling pattern and feedback show very challenging impedance budget specifications: R/Q • Q_{ext} ~ 10e5 for monopole modes and ~ 10e7 for dipole modes [3]. These restrictive low impedance thresholds make fulfilment of damping specifications an extremely challenging design goal. In addition, the presence of ion clearing gaps and some sets of single bunches in the BESSY VSR filling pattern (see Fig. 2) compromise the correct choice and application of the damping strategy because of the amount of HOM power to be extracted.

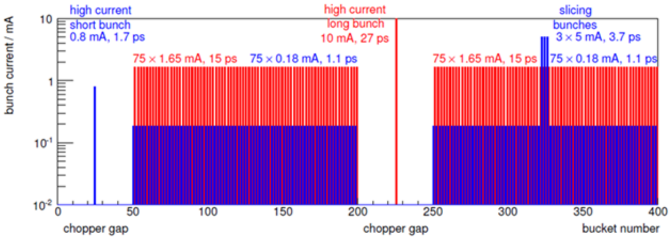

Figure 2: BESSY VSR filling pattern including short (blue) and long (red) bunches [4].

In order to accomplish this goal the design process of two different heavily HOM damped cavities is under progress. A first prototype for the 1.5 GHz 5-cell cavity has been designed with fulfilment of the SRF specifications (see Table 1) while maintaining HOM impedances below the specified thresholds [5]. The cell's base geometry for this cavity consists on an HZB own design inspired on the JLAB [6] and Cornell [7] mid-cell designs. HZB's mid-cell geometry has been optimized in order to maximize the cell to cell coupling factor (3.3%) and therefore increasing HOM propagation on the later 5-cell cavity prototype. Table 1, shows the comparison between the imposed SRF specifications for the 5-cell cavity prototype and the results obtained from EM. Simulations in CST Microwave Studio [8]. These results are obtained after tuning the end-cells in order to obtain a field flat response. Figure 3 shows a layout of the 1.5GHz 5-cells cavity geometry after end-cell tuning for field flatness.

Table 1: BESSY-VSR SRF Goal Specifications and Results Achieved with CST [8] after Tuning.

Parameter	**Goal**	**Simulation**
Eacc	20MV/m	
Ibeam	≤ 300mA	
Epk/Eacc	≤ 2.3	2.29
Bpk/Eacc	≤5.3mT/(MV/m)	4.4mT/(MV/m)
R/Q	≥ 100Ω	105Ω
K for TM_{010}	≥ 3%	3.3%
μff for TM_{010}	≥ 97%	98.2%

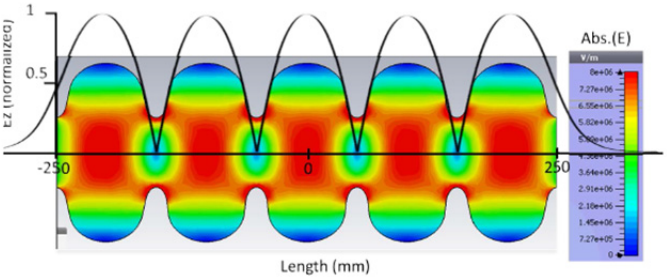

Figure 3: Cavity layout and field flatness characteristics for the fundamental TM_{010} mode. Black curve shows the normalized on axis accelerating electric field for the presented structure.

Because of the high damping specifications needed to avoid CBI's waveguide-loaded end-groups are chosen as damping technique [6]. This technique has been proved to efficiently perform due to its tested damping capabilities and low risk of dust contamination when compared to the use of beam tube absorbers.

HZB design consists on end-groups loaded with 5 waveguide dampers (3+2) [9] combined with enlarged beam-pipes [9, 10] in order to improve the overall HOM propagation. An intensive study of the waveguide dampers size (height and width of the waveguide) has been performed in order to tune the waveguide cut-off to conveniently damp HOMs depending on their natural orientation (transverse/longitudinal) as described in [5,9]. As a result an improvement in the waveguide damping technique has been developed where both waveguide sides (height and width) must be tuned in order to efficiently transport to the loads all different TM and TE high order modes.

As in the case of bERLinPro cavities [10] it was also demonstrated that the combination of tuned waveguide dampers with enlarged beam-tubes significantly improves damping performance showing a high reduction level in the calculated Q_{ext} for HOMs. Damping performance (Q_{ext}) for the 1.5 GHz cavity is depicted in Fig. 4 compared to the JLAB case using the standard waveguide damping technique combined with extended beam tubes.

Regarding the impedance budget specifications it has been proved that by means of the presented technique the

R/Q*Q_{ext} demands are successfully fulfilled and therefore the 1.5GHz cavity design represents a good candidate save from coupled bunch instabilities for its application to BESSY-VSR. Figure 5 shows a representation of the impedance spectrum for the longitudinal and transverse HOMs up to the 3GHz computed frequency [4].

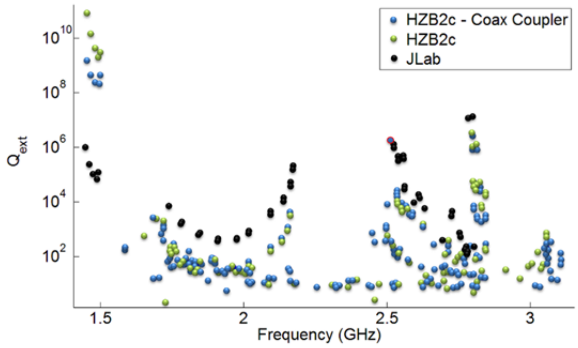

Figure 4: Computed Q_{ext} for the 1.5 GHz cavity compared with the Jlab standard waveguide case (black). 6 WG damper model (green). 5WG dampers+1 coax. fundamental power coupler.

Although enlarged beam-tubes help reducing the loaded Q, their main drawback is the propagation of a significant amount of HOM power downstream the beam tube. Therefore, in case that no beam-tube based damper can be foreseen, this might lead to unwanted heating. Wakefield calculations performed for different bunch lengths (δ=3mm, δ=15mm) in CST Microwave Studio show that a high amount of the energy lost by the bunch for the 1.5 GHz prototype (52%) is propagated out of the cavity. From this energy, 67.6% is efficiently propagated via WG dampers to the ferrite loads. Nevertheless, the remaining 32.4% can freely travel through the beam-pipe reaching the neighbour cavities or out to the BESSY ring. The variated BESSY VSR filling pattern (see Fig. 2) causes this effect to be of special relevancy since not negligible power levels may be reached (~ 350 W in worst case scenario).

When operating the cavities at two different frequencies zero-beam loading can´t be obtained, existing a strong reactive beam loading. Nevertheless this can be compensated by means of tuning. The cavity coupling is chosen for minimum power at a given detuning. Weak RF coupling and therefore high external quality factors can be used ($Q_{ext} \geq 5 \times 10e7$) with relatively low power requirements $P \leq 10$ kW [11]. These low power requirements allow to make use of a coupler concept similar to the Cornell 60 kW adjustable power coupler [12] which adds flexibility and improves system capabilities.

Regarding RF feeding, each cavity will be feed by an individual transmitter. Thus individual phase and amplitude control is possible when needed. The expected required power level for each transmitter is 16 kW including losses in the RF distribution including some power overhead required for microphonics compensation. The type of RF power source is still to be chosen with option for klystron or solid state amplifiers (SSA). Nevertheless, SSAs represent a convenient alternative since their performance at 1.3 GHz has been already tested by HZB at the HoBiCaT test facility.

In order to validate the results obtained for the designed 1.5GHz cavity with proper standard bead-pull measurements a copper model prototype is currently on fabrication process. Figure 6 shows the construction layout for the first 1.5 GHz Copper prototype with waveguide dampers and the FPC port.

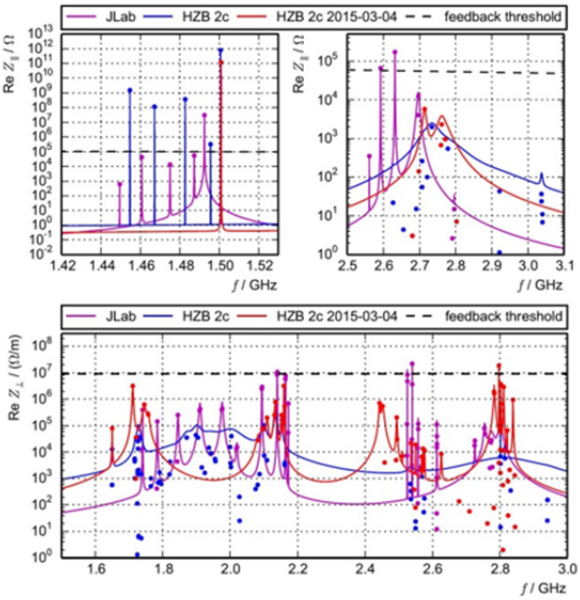

Figure 5: Computed longitudinal (a) and transverse (b) R/Q*Qext for the 1.5 GHz cavity. Impedance threshold with feedback included is represented in dashed line. (Courtesy of M.Ruprecht).

Rotatory damping end-groups have been included in order to test different WG damper orientations. In addition, once the first later Niobium based prototype is received a cavity characterization procedure based on "cold bead-pull" measurements is foreseen [13]. This test consists on performing a standard bead-pull field characterization under superconducting conditions (1.8K) in a dedicated test stand inside HoBiCat [14].

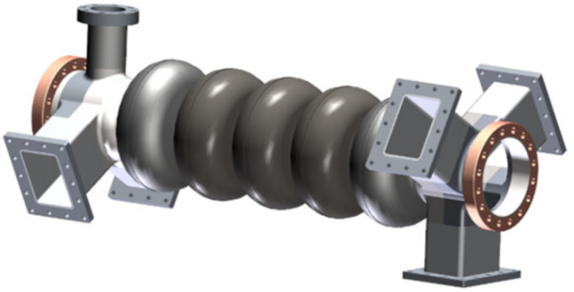

Figure 6: 1.5 GHz 5-cell cavity prototype.

Design works for the 3.5 harmonic cavities (1.75 GHz) are currently under development based on the same techniques developed for the 1.5 GHz model. Due to the different working frequencies cavity arrangements inside the module must be analysed in detail. The beam-tube diameter of the two different frequency cavities must be chosen different in order to ensure isolation through cut-off for the both fundamental TM_{010} mode spread as well as to avoid overlapping of the 1.75 GHz TM_{010} and the 1.5 GHz first dipole band. Therefore, a tapered beam-tube transition between cavities is required. As a consequence, unwanted beam-tube modes might appear consequently leading to CBI's. Thus concatenation studies are currently under development in order to determine the most efficient cavity distribution and orientation in order to maximize damping efficiency for the available module length [15].

Cryogenics and RF Systems

The whole SRF multi-cavity system is foreseen to be installed in a single cryomodule to be located in one of the available BESSY II ring straight sections. The total length available for the module installation is 4.6 m and therefore the use of extra safety elements as beam-tube based dampers might not be possible due to space limitations. As a solution, design alternatives such as the combined used of beam tube absorbers with below sections can be considered [16]. The BESSY-VSR cryomodule will utilize only helium as the cooling media for the cavities, thermal intercepts and shields and will be driven by a new ad hoc built BESSY-VSR cryogenic plant. Figure 7 shows a tentative distribution of all the elements inside the VSR module including the waveguide damping sections, fundamental power couplers, two RF shielded gate valves and 7 bellows sections. In total, three temperature levels are used in the module: 1.8K for cooling the SC cavities, 5K for thermal intercepts and 50K for thermal intercepts and the thermal radiation shield of the module. In addition the BESSY-VSR cryo-plant has to be capable of providing liquid Helium for the operation of the superconducting wave length shifter magnets (WLS) installed at BESSY II. Cryogenic load values have been calculated assuming an accelerating field of 20MV/m for all the cavities with $Q_0 = 8 \times 10e9$ and $Q_0 = 7 \times 10e9$ for both 1.5GHz and 1.75 GHz cavities. Calculated cryo-load at 1.8K is 146W. These estimated Q values include losses due to field emission and are based on CEBAF specifications [17].

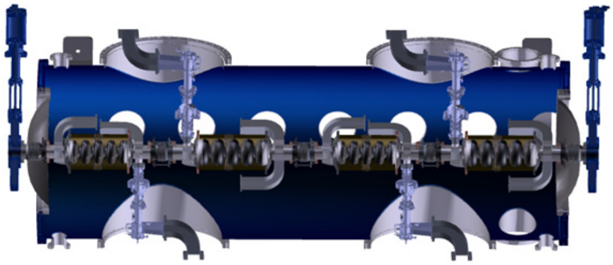

Figure 7: Tentative module arrangement with the 4 cavity system distribution including waveguide damping and FPC.

CONCLUSION

The present work discusses the BESSY VSR project concept, needs and current developments as an upgrade for the 3rd generation light source BESSY II ring in order to open new possibilities for time resolved experiments. From the SRF technology point of view several challenging goals generated by the use of high beam current values (I_{beam}=300mA) and high accelerating fields (20MV/m) have been presented. Some of those such as the damping specifications imposed by impedance threshold limits needed to avoid CBIs have been proved to be solved by applying the proper cavity design and improved damping techniques. As a consequence the design of a first 1.5GHz cavity prototype is about to be finalized and ready for production. At the present state the developed design techniques are utilized in the design of the 1.75GHz system. Moreover, an overall cryo-module description has been presented as well as the power and thermal requirements needed by BESSY VSR.

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