THE BESSY VSR PROJECT FOR SHORT X-RAY PULSE PRODUCTION*

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Abstract

The Helmholtz-Zentrum Berlin (HZB) is proposing an innovative, challenging upgrade scheme for the storage ring BESSY II to generate simultaneously 15 ps and 1.7 ps (rms) long electron bunches, the Variable pulse length Storage Ring BESSY VSR [1]. Intense pulses of synchrotron radiation of corresponding length are emitted. Both the short and long X-ray pulses are supplied to all beam ports and can be separated by pulse picking methods. With picosecond X-ray pulses of 1.25 MHz to 250 MHz repetition rate BESSY VSR covers the gap in pulse length between extreme brilliant pulses of diffraction limited storage rings and ultrashort pulses of Free Electron Lasers, leading to improved and new experimental opportunities for time resolved experiments [2]. Main results of the recently performed, extended "Technical Design Study BESSY VSR" [1] are presented here.

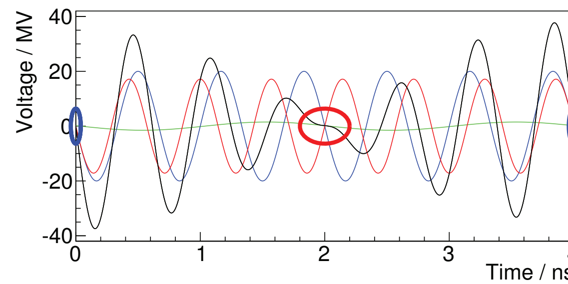

Figure 1: Scheme of the voltage oscillation during one beating period and positions of long (red) and short (blue) bunches, indicated by the colored ellipses. The colored sinusoidal oscillations represent the individual voltages, green 0.5 GHz, blue 1.5 GHz and red 1.75 GHz. The black line shows the resulting sum voltage, which defines both the length and position of each bunch.

INTRODUCTION AND PROJECT OVERVIEW

BESSY II has a long tradition in short-bunch operation for user applications. Two pioneering methods were developed: a low-α optics to produce picosecond bunches [3] and "femtoslicing" to produce 50 fs long undulator X-ray pulses [4]. A continuation in this field was quite natural and a machine upgrade scenario for short and intense, brilliant X-ray pulses for various time resolved experiments was proposed.

The basic idea of BESSY VSR applies a beating of an enhanced longitudinal focusing gradient, with gradients up to 80 times stronger than the present configuration, Fig. 1. This is achieved by superconducting (SC) five-cell cavities of harmonic and sub-harmonic radio frequencies (RF) of 1.5 GHz and 1.75 GHz, and the existing, normal conducting (NC) 0.5 GHz RF system. The beating creates alternating places for 200 long and 200 short bunches in the fill pattern. The current in these buckets is filled by machine requirements and user demands. Long bunches filled with nearly all the beam current ensures a continuation of the present user mode with high average brilliance including full use of insertion devices and TopUp operation. The transverse beam optics is practically not affected by this scheme. Additional, short bunches can be populated independently. By different methods to separate long and short photon pulses users can select different pulses on demand.

BESSY VSR addresses several innovative topics of storage ring operation, specifically:

- the alternating bunch length scheme generated by voltage beating,
- the continuous wave (CW) operation of SC multi-cell cavities at high currents of 300 mA in a storage ring,
- very short bunches of high currents:
  - bunches of 1.7 ps length of up to 0.8 mA (0.64 nC) in the BESSY VSR standard user optics
  - bunches of 0.4 ps length and currents of 0.04 mA (0.03 nC) in the BESSY VSR low-α optics.

For an overview of relevant BESSY II parameters see Table 1, for the BESSY VSR RF cavities parameters see Table 2 and their placement into the cavity straight see Fig. 2.

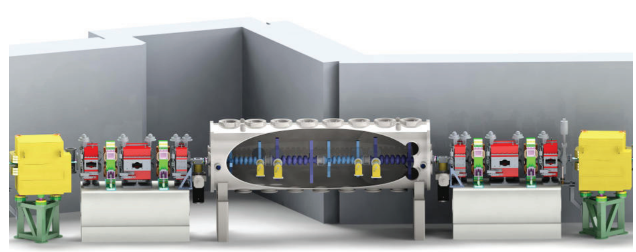

Figure 2: Schematic view of the BESSY VSR cavities straight with the cryo module.

Key project targets are the expected bunch currents and lengths, defining the achievable peak brilliance of short pulses, as discussed in section 2 together with general beam dynamic aspects. The lay out of the superconducting RF

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Table 1: Overview of Relevant BESSY II Parameters

Parameter	Value
Energy E	1.7 GeV
Emittance ϵ	5 nm rad
Beam optics, DBA cells	2×8
Circumference	240 m
Max. beam current I	300 mA
Harmonic number h	400
RF frequency f_{rf}	500 MHz
RF sum voltage V_{rf} at 500 MHz	1.5 MV
Landau cavities frequency	1.5 GHz
Landau cavities sum voltage	0.225 MV
Momentum compaction factor α	7.3×10^{-4}
Synchrotron frequency f_s	7.6 kHz *
Longitudinal radiation damping time τ_z	8 ms
Transverse radiation damping time $\tau_{x,y}$	16 ms

* without Landau cavities

Table 2: Main Cavity Parameters for BESSY VSR

Cavity	Frequency f/GHz	Voltage V/MV	Number of cavities
NC	0.5	1.5	4
SC_1	1.5	20	2×5 cells
SC_2	1.75	17.14	2×5 cells

(SRF) cavities and beam cavity interactions are subject of section 3. Some general remarks on the project development are presented in section 4.

BUNCH CURRENTS AND SHORT BUNCHES

One of the promises of BESSY VSR lies in the higher peak current of short bunches as presently available with the BESSY II low-α optics, limited by the microwave instability [5]. Within simple scaling laws, such as the "Keil-Schnell criterion", the threshold current for a given bunch length increases in proportion to the applied momentum compaction factor α. Due to the 80-times stronger longitudinal focusing gradient, short bunches can be achieved for larger α-values, yielding an up to 80-times increased current threshold. However, in the ps-bunch length range the simple scaling could deviate from more accurate predictions [5, 6]. The bunch length current relation based on experimental data and multi particle tracking was carefully analyzed and applied for the values of Table 3. The expected threshold current is used as a figure of merit for various fill patterns, Fig 3. The zero current bunch lengths σ_0 are multiplied by an estimated factor of 1.5 to account for the potential well lengthening to achieve the presented bunch length values σ_z. Beyond this threshold bunches become unstable with respect to the microwave instability and degrade in quality. They gradually blow up in length and energy spread.

Table 3: Bunch Lengths and Bunch Threshold Currents for the Standard User and low-α Optics of BESSY VSR

	Bunch length σ_z / ps	Threshold current I_{th} / mA
Standard optics		
long bunch	15	1.8
short bunch	1.7	0.8
low-α optics		
long bunch	3	0.045
short bunch	0.4	0.04

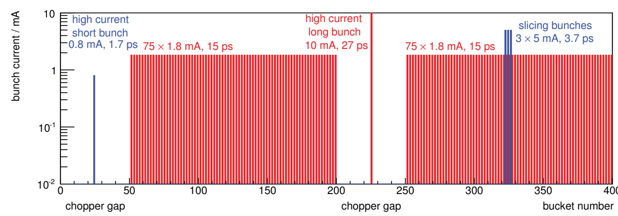

Figure 3: Example of bunch fill pattern with long (red) and short (blue) bunches. There are 400 buckets with 2 ns separation.

The BESSY VSR scheme can be further applied to the well-established BESSY II low-α optics to generate alternating 150 bunches of 3 ps length and 150 short bunches of 400 fs length [7], populated with up to 0.045 mA/bunch. Practically, the lengths of these ultra-short bunches are limited, but not yet at their fundamental limit, as discussed in [8]. Because the ultra-short bunches have a reduced peak current to avoid bursting, this operation mode has a small Touschek loss rate and is additionally very stable with respect to coupled bunch instabilities. Cavity jitter excited by typical mechanical noise spectra will not deteriorate the short bunch lengths [9].

Various bunch fill pattern are possible, the reference scheme is shown in Fig. 3, where bunch lengths and current values are indicated. Different methods are available to separate long and short pulses, like a mechanical chopper [10] or resonant bunch excitation [11]. Additionally, transversely displaced resonance islands are presently studied at BESSY II and MLS with promising results [12, 13]. The advantage of this last method is that a filling gap is no longer required and transient beam loading problems are avoided [14]. As a variant of the reference fill pattern, additionally up to 150 short bunches of 1.1 ps length can be populated to produce intense THz radiation and further options for time resolved measurements.

Bunch charge and bunch length define the peak brilliance of the photon beam. The peak brilliance values of a typical BESSY II undulator like the UE49 will improve by a factor 2 to 10 towards the 1.0×10^{22} ph/s/mrad^2/mm^2/0.1%BW to 5.0×10^{22} ph/s/mrad^2/mm^2/0.1%BW range for nearly all different bunch types of BESSY VSR.

The increased peak current and short bunch operation will affect the impedance load depending on the fill pattern. About 4 times more resistive wall losses for BESSY VSR compared with the present situation are expected but still stay below 10 kW. This value can be compared with incoherent power emission of 50 kW in dipoles and the same amount emitted by SC wigglers and wave length shifters. The power losses by coherent synchrotron radiation are estimated to be less than 10 kW.

Bunches are injected into the storage ring from the full energy booster and are typically 70 ps long. These are a factor 3 too long to maintain the required > 90% TopUp injection efficiency if injected into the short BESSY VSR buckets. To overcome this limitation various schemes are presently studied [15].

TECHNICAL REALIZATION AND BEAM CAVITY INTERACTION

The prominent elements of the BESSY VSR upgrade are two pairs of SC cavities cooled to 1.8 K, Table 2. These cavities with a highly damped HOM spectrum are presently under development at the HZB [16]. The SC cavities are only used for bunch focusing; no source power is extracted by the beam. A small external RF power supply controls the cavities, which simplifies the operation. It is also required to load the cavities for low current operation. The energy lost by synchrotron radiation is recovered from the present NC 0.5 GHz cavities.

The chosen RF harmonics of 1.5 GHz and 1.75 GHz are well within the range of current operating SRF cavities. An optimized, HOM damped five-cell design, was chosen as a reasonable compromise between conflicting requirements to maximize HOM damping while minimizing the installation length and operating field. The design of the 1.75 GHz system will follow the 1.5 GHz design.

Studies of coupled bunch instabilities, based on a calculated HOM spectrum of the 1.5 GHz cavity, have shown that the present active feedback systems can control the instabilities in all desired operation modes [17, 18]. In case of problems, parking of the cavities is required. Even when the cold, SC cavities are maximum detuned, the beam still induces a voltage in the order of 0.3 MV. Two equal cavities of each type can be detuned in such a way, that the fundamental accelerating modes compensate each other, thus not affecting the beam.

The rather high CW field level of about 20 MV/m at a high loaded quality factor Q_L allows operation at power levels within the 10 kW range. This is a power range where reliable coupler designs are available and also the cost for RF transmitters can be kept within acceptable limits. Operating SRF cavities at high Q_L, thus narrow bandwidth requires a precise tuning and therefore compensation of micro phonics and coupled Lorentz-force detuning driven instabilities. Precise regulation of CW driven RF fields at high loaded Q_L was already demonstrated and CW field levels of 20 MV/m are within reach. Nonetheless, routine CW detuning compensation still needs to be demonstrated [19].

Beam loading is a second major challenge the SRF system faces [20]. As the cavities are operated in zero-crossing of the RF field with respect to the beam, they experience strong reactive beam loading leading to a phase shift of the field. This will be compensated by detuning in the kHz range, so that only the power to maintain the cavity field and some compensation for unwanted detuning is required. Finally, given the high impedance of the SRF system and the high current stored in the ring, special attention must be paid to DC and AC Robinson instabilities. In the BESSY VSR concept, the 1.75 GHz frequency system is intrinsically operated in the Robinson unstable regime. However, the combined system of all frequencies is stable again, but it needs to be studied how robust this combined system is to any perturbation. To some extent, this effect can be controlled by high gain amplitude and phase control, reducing any deviation to a minimum, so that any rise towards this instability is suppressed.

OUTLOOK

The upgrade project will start with a preparatory phase by using the existing cryogenic infrastructure of BESSY II. By moderate modifications of the existing cryo system the two 1.5 GHz cavities can be operated at 4.4 K for first proof of principle operations with stored beam. Two R&D projects, one addressing the development, manufacturing and testing of fully equipped BESSY VSR 1.5 GHz SC cavities, the other the bunch by bunch diagnostic necessary to monitor and control the individual parameters of the complex BESSY VSR fill pattern, have been started and will be completed 2018. While the preparatory phase aims to verify the technical setup with beam and to study further aspects concerning beam dynamics, the final phase will focuses on upgrading the required 1.8 K cryogenic system and RF infrastructure for full BESSY VSR user operation.

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