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BEAM LOADING IN THE BESSY VSR SRF CAVITIES

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Abstract

In this paper the results on the beam loading analyses for BESSY VSR SRF cavities are presented. Based on wakefield theory a technique is developed to calculate the beam loading for different bunch filling pattern of the BESSY II storage ring. The beam loading for parked cavities as well as for VSR operation mode are discussed.

INTRODUCTION

The BESSY Variable pulse length Storage Ring (VSR) project [1-3] is a future upgrade of the 3rd generation BESSY II light source. This challenging goal requires installation of four new 4-cell SRF cavities (2x1.5GHz and 2x1.75GHz) in one module for installation in a single straight. As far as the authors are aware of, this is the first installation of multi-cell L-Band cavities in a CW high-current storage ring. These cavities [4-8] are equipped with newly developed waveguide HOM dampers necessary for stable operation. Up to 2 kW of HOM power must be absorbed [6,7,9]. Operating two SRF cavities for each frequency will also enable transparent parking of the cavities for the beam.

The application of the SRF cavities in the storage ring requires special attention on the low level RF system to ensure the stable operation. One of the important aspects here is the transient and steady state beam loading [10,11] at different operation regimes and bunch filling patterns to be stored in the ring. In order to evaluate the beam loading a technique based on wakefield theory [12,13] is developed. It implies analytical calculation of induced voltage in the cavity resonant mode by the periodically circulating single bunches. The resulting voltage contains the complete time structure in terms of amplitude and phases. Then the beam loading for arbitrary bunch train is obtained by sum of the individual bunch contributions. Furthermore this technique was applied to study the beam loading for transparent parked cavities and VSR modes. As a result important aspects like the restriction in the tuning range during operation of those SRF cavities are discussed.

BESSY VSR SRF CAVITIES & FILLING PATTERNS

The realisation of the BESSY VSR project implies installation of a single superconducting module with four SRF cavities in one of the low beta straight sections of the existing BESSY II ring (Table 1).

Each of those superconducting 4-cell elliptical cavities [4-8] are equipped with five waveguide dampers and one coaxial fundamental power coupler (FPC) [14,15] as depicted in Fig. 1.

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Table 1: BESSY II Storage Ring Parameters

Lattice	DBA
Circumference	240 m
Energy	1.7 GeV
Current	300 mA
RF Frequency	500 MHz
Bunch Length	15 ps
Revolution Time	800 ns
Number of RF buckets	400
Emmitance	6 nm rad

The cross sections of the waveguide dampers are design to have cut-off frequencies above the fundamental TM_{010} mode frequencies (1.5 GHz & 1.75 GHz) and the different orientations ensures optimum HOM damping for different polarisations. The coupler has a power overhead of 16 kW, the main fraction of which is taken by any deviation of the estimated reactive beam loading compensation from the real beam current and cavity voltage.

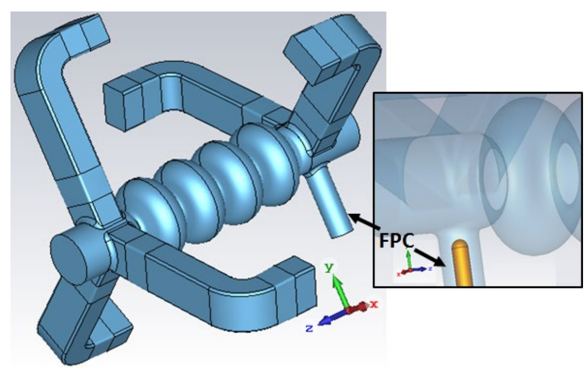

Figure 1: BESSY VSR SRF cavity layout.

In Table 2 the accelerating mode properties are summarized.

Table 2: RF Properties of SRF Cavities

Cavity type (TM_{010} π-mode)	**1.5 GHz**	**1.75 GHz**
Number of cells	4	
Active length	0.4 m	0.344 m
Frequency [GHz]	1.4990	1.7489
Q_{ext}	5*10^7	4.3*10^7
Geometry factor – G [Ω]	277	275
E_{peak} / E_{acc}	2.32	2.30
B_{peak} / E_{acc} [mT/(MV/m)]	5.05	5.23
R/Q [Ω]	386	380
Field flatness - μ_{ff}	97 %	99 %

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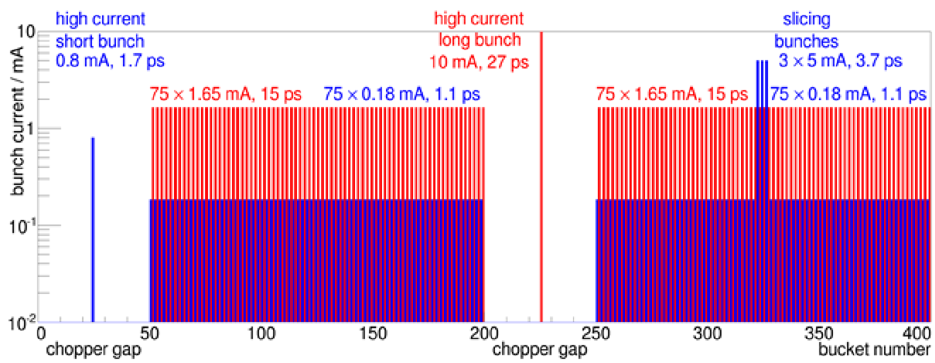

Figure 2: BESSY VSR filling pattern including short (blue) and long (red) bunches.

Since the cavities will operate in a storage ring, the cavity HOM spectrum was designed to fulfil off-resonance condition with respect to the circulating beam harmonics located at multiples of 1.25 MHz revolution frequency [3-7].

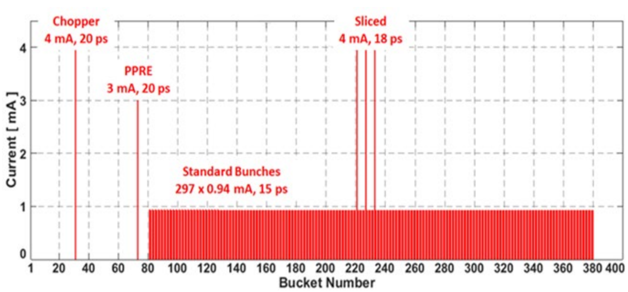

Figure 3: Standard BESSY II filling pattern.

The BESSY VSR filling pattern of the 240m circumference ring is shown in Fig. 2 where the short and long bunches will be stored simultaneously. In total 400 RF buckets with 2ns bunch spacing are available. Two type of bunch filling patterns are considered: the so-called "extended" shown in Fig. 2 and the "baseline" with omission of 150 short-pulse, low-charge bunches. The repetition rates of 500MHz and 250MHz are defined by the bunch spacing in each pattern, respectively.

In order to enable the standard BESSY II mode (Fig. 3) operation the SRF cavities will be parked being transparent for the beam. This requires to have pairs of cavities of the same frequency symmetrically detuned in a range of ± 350 kHz to ensure beam stability. The computation of the beam loading and analyses of parking regime are discussed in the sections bellow.

APPLICATION OF WAKEFIELD THEORY FOR BEAM LOADING CALCULATIONS

Following wakefield theory [12,13] the voltage excited in cavity resonant mode by the ultra-relativistic Gaussian bunch with charge q_0 and r.m.s. length of σ_t is given as

$$\boldsymbol{V_s(\omega,t) = q_0 \cdot 2 \cdot K_{loss} \cdot cos[\omega \cdot t] \cdot e^{-\frac{\omega}{2*Q_L}t} = }$$
$$\boldsymbol{= Z \cdot I_b\, e^{-0.5\cdot\omega^2\sigma_t^2} \cdot \frac{\omega\, T}{2\, Q_L} cos[\omega \cdot t] \cdot e^{-\frac{\omega}{2*Q_L}t}} \quad (1)$$

Where ω is the resonant mode angular frequency, $K_{loss} = \frac{1}{4} \cdot R/Q \cdot \omega \cdot e^{-0.5\cdot\omega^2\sigma_t^2}$ and Q_L are the corresponding loss factor and loaded quality factor. The formula is then rewritten in more convenient terms for storage ring application, i.e. impedance $Z = R/Q \cdot Q_L$ and bunch current $I_b = q_0/T$ with T revolution time of the ring. Note that in this paper linac definition is used for impedance and resonant mode parameters, i.e. $P = V^2/(R/Q * Q_L)$.

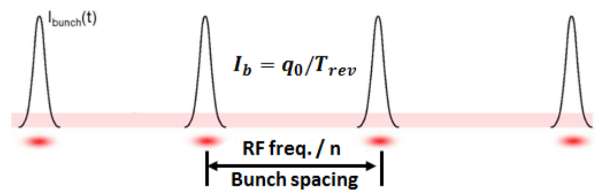

Figure 4: Periodic bunches.

In case of periodic bunch excitation shown in Fig. 4 the steady state cavity voltage read as

$$\boldsymbol{V(\omega,t) = \sum_{n=0}^{\infty} V_s(\omega, t + n \cdot T) = V_s(\omega,t) \cdot} \quad (2)$$
$$\boldsymbol{\cdot Re\left[\left(1 + \frac{e^{-\frac{\omega}{2*Q_L}T}}{e^{i\,\omega\,T} - e^{-\frac{\omega}{2*Q_L}T}} + \frac{e^{2\,i\,\omega\,t}}{1 - e^{i\,\omega\,T - \frac{\omega}{2*Q_L}T}}\right) / (1 + e^{2\,i\,\omega\,t})\right]}$$

In case the cavity resonant frequency coincides with one of the harmonics of the revolution frequency this formula simplifies to

$$\boldsymbol{V(\omega,t) \xrightarrow{\omega\,T = 2\,\pi\,N} V_s(\omega,t) \cdot \frac{1}{1 - e^{-\frac{\omega}{2*Q_L}T}}},$$

where N is integer.

The periodic bunch excitation (Eq. 2) can be represented by single bunch formula (Eq. 1) when $f_{rev} \ll f/(2 \cdot Q_L)$ condition is fulfilled. Typically this is the case for normal conducting cavities in the large storage rings where the excited fields in the cavities are damped during one revolution period. For high Q superconducting cavities this is typically not the case. In further calculations the BESSY II machine parameters given in Table 1 are used.

In the following example VSR 1.5 GHz cavity parameters (Table 2) are taken with lower $Q_L = 10^4$ which is typical

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value for the cavities in the normal conducting state and is determined mainly by cavity wall losses. This particular case is chosen to illustrate the decay of the cavity voltage during one revolution time.

In Fig. 5 the time-profile of the steady state voltage excited by periodic single bunch located at the central RF bucket is presented. It represents the fine structure of the induced voltage and respective damping defined by loaded quality factor. The voltage amplitudes and phases can be easily extracted as well.

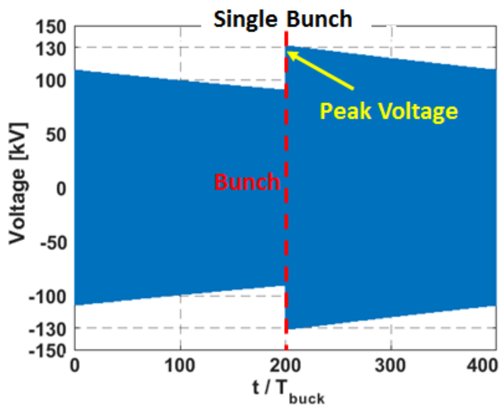

Figure 5: The time-profile of cavity ($Q_L = 10^4$) voltage induced by periodic single bunch.

Then the cavity peak voltage versus resonant frequency detuning is illustrated in Fig. 6. Here the peak voltage is defined as the maximum of the steady state voltage profile within time window of one ring revolution (Fig. 5).

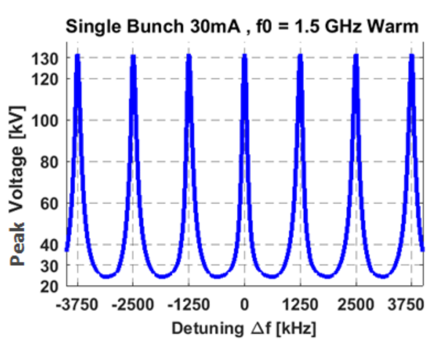

Figure 6: Peak voltage versus frequency detuning.

As was expected the resonances are located exactly at harmonics of revolution frequency. The introduced technique of beam loading calculations based on wakefield theory is identical to the commonly used equivalent circuit approach [10-12].

Further the introduced technique is used to evaluate the induced cavity voltage for arbitrary bunch filling pattern by superposing the voltages excited by individual bunches (2) in the train.

BEAM LOADING FOR PARKED CAVITIES

In this section the transparent parking of SRF cavities is discussed. Here only pair of 1.5 GHz cavities are considered. Since for parked cavities the machine will operate in the standard BESSY II mode the respective bunch filling (Fig. 3) in beam loading calculations is used.

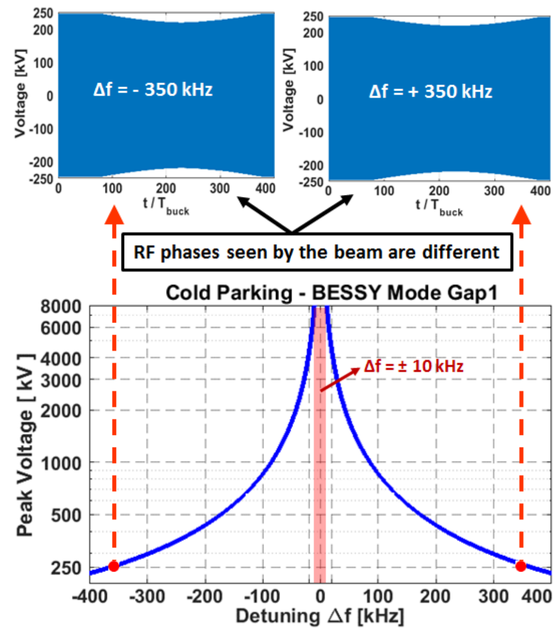

Figure 7: Peak voltage versus detuning (bottom) and voltage time-profiles at detuned ± 350 kHz frequencies (top).

The parking of the cavity implies detuning the pair of cavities in opposite directions by +350 kHz and -350 kHz respectively. In Fig. 7 the calculated steady state voltage induced in the cavity by the circulating BESSY II bunch filling pattern for different cavity detuning is presented.

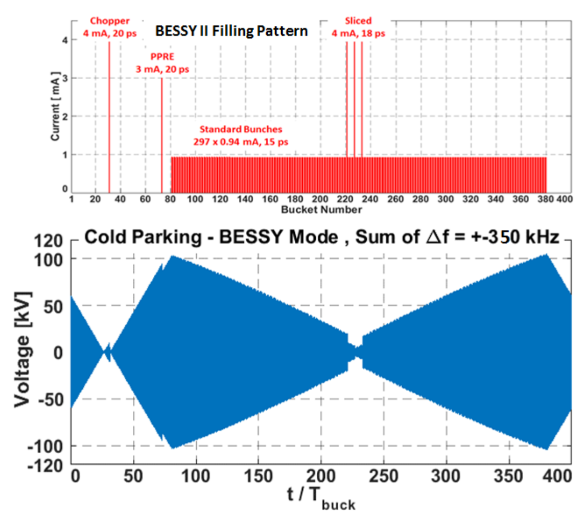

Figure 8: The time-profile of the net voltage seen by the beam (bottom) and the BESSY II filling pattern (top).

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As can be seen at ± 350 kHz detuned frequencies the peak voltage of 250 kV will be induced. Although the voltage amplitude and time profile seems to be identical at those both detuned frequencies, the phases seen by the bunch are near opposite leading to a significant degree of compensation.

The net voltage of both detuned cavities seen by the beam is presented in Fig. 8. As can be seen the net voltage amplitude is significantly decreased in comparison with individual cavity voltages. Nevertheless, the time profile of the residual net voltage indicates that the individual bunches in the train will see different RF voltages and should be considered for beam dynamic studies. Particularly it may lead to shortening of the certain bunches in the train and reduction of the lifetime.

BEAM LOADING IN BESSY VSR OPERATION MODE

For stable operation of the storage ring strong HOM damping must obtained from the design of the BESSY VSR SRF cavities. In order to handle the effects caused by higher order modes with currently operating BESSY II feedback system, the cavity HOM impedances should not exceed the measured impedance threshold of the machine. The mode atlas of 1.5 GHz SRF cavity is presents in Fig. 9.

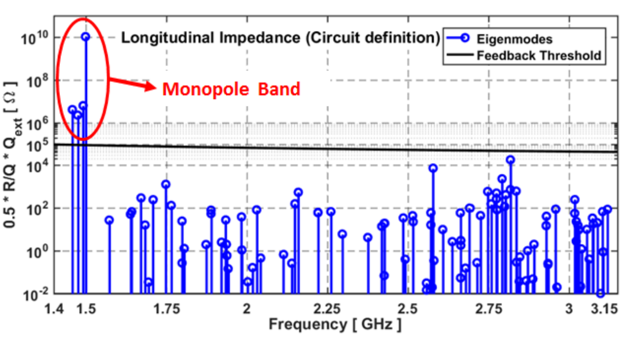

Figure 9: Mode atlas of 1.5 GHz SRF cavity (blue) and feedback threshold (black) of BESSY II storage ring.

As was expected only four monopole band modes with high Q_L are exceeding impedance threshold and can't be handled by active feedback system. Thus those modes should be considered for beam loading. The RF properties of those monopole modes are summarised in Table 3.

Table 3: The Properties of Monopole Band Modes of 1.5 GHz Cavities

Frequency [GHz]	R/Q [Ω]	Q_{ext}	Mode Type
1.49866	386	$5.00{\cdot}10^7$	π
1.49134	0.41	$2.98{\cdot}10^7$	2π/3
1.47424	0.09	$4.74{\cdot}10^7$	π/2
1.45785	0.05	$1.60{\cdot}10^8$	2π

In Fig. 10 the induced voltages of cavity monopole band modes versus frequency detuning is presented. In this case the beam loading is evaluated for BESSY VSR filling pattern (Fig. 2). As can be seen the first three monopole modes have asymmetric behavior with respect to the detuning range of the frequency defined by accelerating mode. At about -180 kHz frequency detuning of the cavity the 2π/3 mode will hit one of the beam harmonics and induce about 335 kV voltage being on comparable level with accelerating mode voltage. Due to the asymmetric character of the 2π/3 mode in respect to the direction of cavity detuning no compensation is possible. Thus the detuning range of ± 20 kHz around the 2π/3 mode resonance will be excluded during normal operations. Another exception in the tuning range lays within ± 10 kHz range which is defined by the maximum allowed gradient of 20MV/m for the fundamental mode. The latest requires special attention for the cavity control system, since at zero detuning even 1mA beam current will exceed the cavity threshold gradient.

In the VSR operation mode the cavity will be actively controlled by external source providing 16 kW RF power through the CW high power fundamental coupler [14, 15]. It will be used also to control transient beam loading during injection and ramp up of the storage ring current.

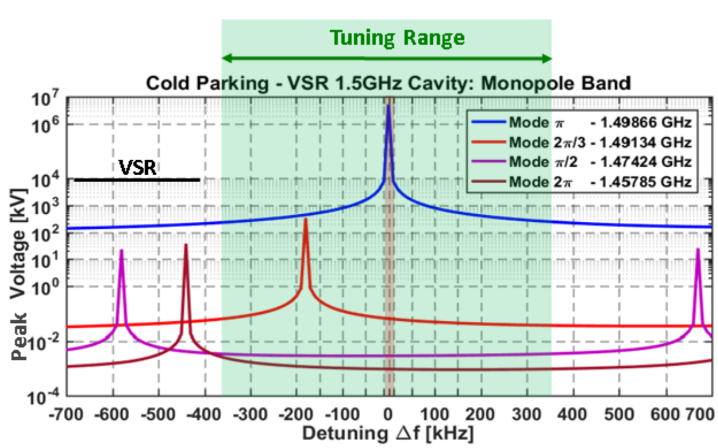

Figure 10: Induced peak voltages versus frequency detuning of 1.5 GHz SRF cavity monopole band modes.

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CONCLUSIONS

In this paper the beam loading computation technique based on wakefield theory is presented. This technique was used to analyse the beam loading effects for the BESSY VSR superconducting cavities. As a result some dangerous zones in the cavity tuning range should be excluded to ensure stable operation of the BESSY II storage ring. The presented results are corresponding to the passive cavity control and does not reflect the transient beam loading effects. Nevertheless, the described technique can be applied also to analyse transient beam loading.

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