# SIMULTANEOUS LONG AND SHORT ELECTRON BUNCHES IN THE BESSY II STORAGE RING

G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, HZB, Berlin, Germany

*Abstract*

We present first ideas of a scheme to develop BESSY II into a variable electron pulse length storage ring. The final goal is, to fill BESSY II with short bunches of 1.5 ps length (rms) and long bunches of 15 ps length simultaneously in the presently applied user optics. All insertion devices are operated as usual, i.e. the helical undulators and 7 T-field insertions. Long bunches of 1.5 mA current per bunch, twice the value of the present user optics, are filled in each second bucket. The other buckets can be filled with short bunches of up to 0.8 mA. The lower current value is required to avoid increase in the bunch length and bunch energy spread, predicted by scaling laws. The total current is e.g. limited by the HOM damping capabilities of the sc-cavities and the machine impedances.

This scheme is achievable with recent developments in sc-rf cavity technology driven by requirements of high current cw applications like for the energy recovering linacs (ERLs). These developments seem to make it feasible to install high gradient HOM damped multi-cell cavities in electron storage rings. With an appropriate choice of the cavity resonance frequencies a beating of the effective longitudinal focusing voltage at the stable fixed points can be introduced and leads to different zero current bunch lengths. Basic parameters of this scheme are presented.

## INTRODUCTION

Since 10 years, the 1.7 GeV storage ring BESSY II offers a dedicated short electron bunch mode, the 'low-$\alpha$ shifts', were $\alpha$ is the momentum compaction factor, for production of coherent THz radiation and short X-ray pulses [1, 2]. These bunches are about 5 times shorter than in the normal user mode. The bunch shortening is achieved by applying a low-$\alpha$ optics. The current in these bunches is low, typically 40 $\mu$A per bunch at 3 ps length. The current is limited by single bunch instabilities, i.e. the bursting instability induced by the coherent synchrotron radiation [3]. These low-$\alpha$ shifts have the draw back, that they are addressed to few user groups, applying THz radiation or short X-ray pulses, and therefore restricted to 12 days per year.

To overcome this limitation, we suggest a simultaneous storage of short and long bunches, to satisfy all user demands, an extended version of an earlier presented proposal [4]. For this scheme, short bunches are produced by 100 times stronger rf-voltage gradients, achieved by superconducting cavities, similar as presently developed at the HZB for the BerlinPro project [5]. By choosing cavities of different resonance frequencies we get a beating pattern of the voltage at the different stable fixed points locations, leading to alternating short and long bunches. At the high voltage gradient locations the bunches become shorter, a kind of longitudinal 'rf-focusing'.

From the zero current bunch length calculations we expect 10 times shorter bunches by this rf-focusing. The maximum achievable current is kept just below the bursting instability threshold, derived by scaling laws. For a fixed bunch length, the predicted threshold current for bursting is increased by a factor 100 compared to the present situation. The transverse beam optics does not change, the BESSY user optics or the BESSY low-$\alpha$ optics can be applied. For the coherent THz radiation a power increase of up to $10^4$ is expected. In this note, we estimate bunch length and current limits from a set of rf-cavity parameters.

## ALTERNATING BUNCH LENGTH SCHEME

In case of low currents ("zero current limit") the bunch length $\sigma_0$ can be reliably predicted. This length is a function of $\alpha$ and the rf-voltage gradient taken with respect to the longitudinal position $\partial V/\partial z = V' = 2\pi V f_{rf}/c$, given by the voltage amplitude V, the rf-frequency $f_{rf}$ and the speed of light $c$,

$$\sigma_0 = \alpha c \delta_e/(2\pi f_s), \text{ with } f_s^2 = f_{rev}\alpha e V' c/(4\pi^2 E_0),$$

and the rms energy spread $\delta_e$, the synchrotron oscillation frequency $f_s$ and the electron charge e. This relation follows from single particle beam dynamics. It further states, that the bunch length $\sigma_0 \propto \sqrt{\alpha/V'}$ remains constant, if the voltage gradient and $\alpha$ are increased by the same factor.

For a bunch length reduction of a factor 10, a 100 times stronger gradient is required, a typical value to get pico second and sub pico second bunches. To achieve this strong bunch focusing, superconducting cavities, similar to the presently developed high current HOM damped ERL cavities for BerlinPro [5] of 1.3 GHz rf frequency and electric fields of 20 MV/m are required. For a consistent set of parameters for the BESSY machine two types of cavities are considered, energy replacement cavities and focusing cavities. The present $f_0 = 0.5$ GHz and $V_0 = 1.5$ MV cavities replenish the energy lost by the emitted synchrotron radiation. This rf-frequency defines the fill pattern of the 400 buckets. For the focusing cavities several schemes are possible, we suggest here two different frequencies. The first one, the harmonic cavity, is chosen as $f_1$=1.5 GHz ($f_1 = nf_0, n = 3$) and a voltage amplitude of $V_1 = 25MV$, a higher harmonics to 0.5 GHz. The second one, the sub harmonic cavity, is chosen as $f_2$=1.75 GHz ($f_2 = (m + \frac{1}{2})f_0, m = 3$) and a voltage amplitude of

$V_2$=21.43 MV, a higher harmonics to 0.25 GHz. For simplicity, we place the cavities at the same location inside the ring, to avoid phase tuning adjustments.

By labeling the buckets or stable fixed points from 1 to 400, we get each second even numbered and the others are odd numbered. The voltages produced by the two super conducting cavities are tuned with respect to phase and amplitude in such a way, that they add up at even fixed points leading to an enhanced, strong focusing, and cancel at the odd fixed points. The focusing gradient at the even points is

$$V' = 2\pi(f_0V_0 + f_1V_1 + f_2V_2)/c$$

and at the odd positions, where $f_1V_1 + f_2V_2 = 0$,

$$V' = 2\pi f_0V_0/c.$$

Because the voltage gradient is proportional to the frequency, the voltage amplitudes have to be chosen such, that $|V_1/V_2| = f_2/f_1$ to achieve a proper cancelling. This oscillation of the voltage leads to alternating places with short and long bunches, independent of the transverse beam optics. Figure 1 shows the voltages for the chosen cavities as

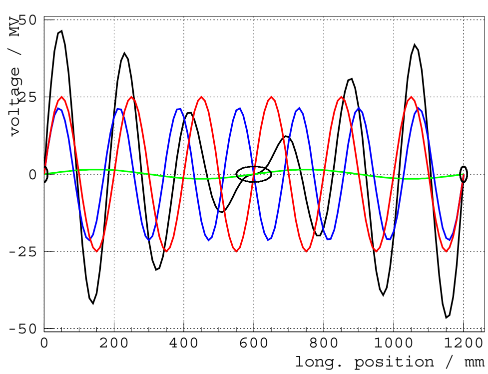


Figure 1: Voltage beating of the 3 cavity scheme. The sum voltage in MV as a function of the longitudinal displacement in mm is shown in black. Voltages of the 0.5 GHz, 1.5 GHz and 1.75 GHz are shown in green, red and blue, respectively. Short bunches are placed at the longitudinal position 0 and 1200 mm, long bunches are placed at 600 mm, indicated by the circles.

a function of the longitudinal position. Short bunches are placed at longitudinal positions of even multiples of 600 mm, long bunches at odd multiples of 600 mm. Close to the odd fixed points, where the two voltages of the sc-cavities become zero, one additionally wants that the sum voltage is increasing (as expected for the even fixed points), to keep particles with larger oscillation amplitudes inside the focusing potential. This is achieved, if the sub harmonic cavity has a higher frequency than the harmonic cavity, i.e. $f_2 > f_1$.

As seen in Fig. 1, there exist more stable fixed points, where the sum voltage becomes zero. However, at the presently discussed places each voltage contribution of the sc-cavities vanishes and in turn also the sum. At the other places the voltage vanishes, as a difference of two larger contributions. These places seem to be more sensitive in case of small jitter, from the cavity phase or amplitude or from the particle arrival time at the cavity and could lead to bunch lengthening.

In a more advanced step, we can combine this scheme with a low-$\alpha$ optics, to go to even shorter bunches, into the sub pico second range. With this optics, bunches of 700 fs length were produced and characterized already at BESSY [1]. To avoid bunch lengthening of these ultra short bunches by coupling effects, zero dispersion is required at the cavity location. Additionally, a two bucket scheme can be applied in a low-$\alpha$ optics [6]. These buckets are displaced by few percent in energy. Therefore, the short bunch can be placed in the high energy bucket and the long one in the low energy bucket, separated by dispersive orbits. In this way, the emitted X-rays can be spatial separated and users can choose at the beam port between long and short X-ray pulses.

## TRACKING RESULTS

Single particle tracking calculations where performed with MAD [7] to simulate the longitudinal phase space of the present user optics with the two focusing cavities added. Figure 2 (top) shows that particles with momentum deviation up to 4 % are still stable at the long and short bucket locations. Figure 2 (bottom) shows a long term

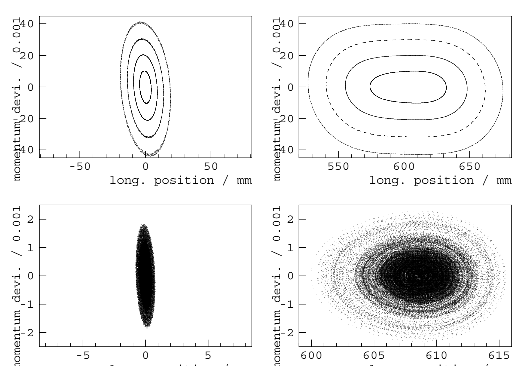


Figure 2: Results of longitudinal phase space tracking. Vertical axis indicates the momentum deviation, the horizontal axis the longitudinal displacement. Upper part, tracking of particle momenta $\Delta p/p$ of 1% to 4%. Lower part, equilibrium distribution from long term tracking including damping and radiation quantum excitation.

tracking of 10 damping times, achieved by the same optics, where particles are started at a long and short bucket location, yielding a factor 10 difference in the resulting equilibrium bunch length.

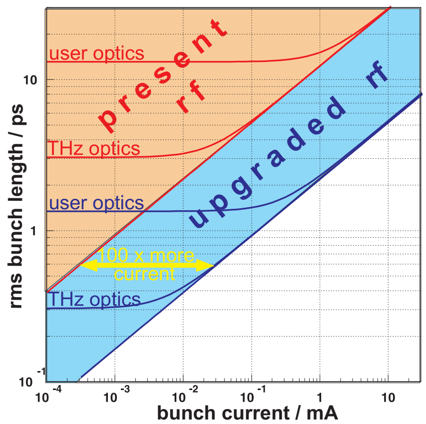


Figure 3: Characteristic plot of bunch length (vertical axis) and bunch current (horizontal axis) relation derived from BESSY II measurements [1, 11]. The red coloured area shows the present situation, the blue coloured part the expected gain by a 100 times stronger rf-gradient.

## CURRENT LIMIT FOR SHORT BUNCHES

The zero current bunch length and the related energy spread can be easily estimated. However, if the bunch current increases, we expect a bunch lengthening by potential well effects and, beyond an instability threshold, even an additional increase in the energy spread of the bunch. Theoretical studies [3, 8, 9] predict that this threshold is proportional to $\alpha$. For a fixed bunch length $\sigma_0$, the fraction $\alpha/V'$ remains constant, according to the zero current bunch length calculations. If $\alpha$ and $V'$ are increased by a factor 100, the bunch current can be increased by the same amount, without exciting an instability. The spectrum of the interacting impedance should be independent of the bunch current as long as the bunch shape and its length stay unchanged. It is shown by [10] that the bunch shape disturbed by its own coherent synchrotron radiation field is invariant close to the bursting threshold for a given bunch length. Beyond the threshold, the energy spread of the bunch increases, which could degrade the width of the undulator harmonics. It might be possible to tolerate a limited energy spread and a moderate bunch lengthening and profit from the increased bunch current.

The theoretically predicted bursting threshold and measurements performed at BESSY II agree well [1]. The bursting threshold is indicated in Fig. 3 as the red, straight line, separating the red and the blue area and following the theoretical scaling $\sigma_0^{7/3} \propto I/V'$, where $I$ is the average bunch current. Bunches in the red coloured area remain stable, whereas bunches beyond the red line can only exist in a short transition stage. If the bunch charge is higher than the threshold limit, the energy spread and bunch length will blow up. This threshold is shifted by the increased rf-focusing and bunches of a given length can store 100 times more current without blow up. Furthermore, the characteristic curve of the user optics will be shifted to 10 times shorter bunches of 1.5 ps length. Any intermediate tuning between the user and THz optics is possible. The alternating bunch length scheme can be varied in a more or less challenging way, limited by the sc-cavities and the machine impedance, as long as the overall current stays below the radiation safety limit of 300 mA. Table 1 shows typical examples of expected bunch lengths and currents. The impedance related bunch lengthening of 50% close to the bursting threshold [1] is not taken into account.

Table 1: Bunch length and current relation

| $\sigma_0$ ps(rms) | max. expected current mA |
|---|---|
| 3.0 | 4.0 |
| 1.5 | 0.8 |
| 0.7 | 0.14 |
| 0.3 | 0.020 |

## SUMMARY

A scheme is presented to operate the BESSY II ring with simultaneous short and long bunches. The short bunch currents can be increased 100 times compared to the present values. There are issuses to be adressed for a detailed technical study, like beam stability and interactions of short and intense bunches with the sc-cavities and the surrounding chamber.

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