TOWARDS SUB-PICOSECOND ELECTRON BUNCHES: UPGRADING IDEAS FOR BESSY II *

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Abstract

Sub-picosecond electron bunches are achieved with the BESSY low alpha optics and their lengths are measured [1]. The current in these short bunches is limited to the micro Ampere level, to avoid current dependent bunch lengthening. An upgrade of the BESSY II rf system is suggested to overcome this low current limitation by 2 orders of magnitude. Intense, picosecond bunches could then be achieved already at the regular user optics. The resulting short and very intense electron bunches are useful to generate short X-ray pulses and powerful THz radiation. Expected parameters of bunch length and current are discussed.

INTRODUCTION

There is an increasing interest in short electron bunches in storage rings as sources of synchrotron radiation [2]. These bunches are versatile tools to generate intense, coherent THz radiation and short X-ray pulses for time resolved measurements. At the 1.7 GeV synchrotron radiation light source BESSY II, the typical bunch length of the user optics is 13 ps rms at 0.7 mA bunch current (0.5 nC), with a filling of 350 out of 400 buckets. By applying the low alpha optics, bunches can be shortened to the sub-ps range. Bunches of different lengths and currents are measured and analyzed [1]. These data show excellent agreement with the bursting instability theory [3] and the Haissinski equation [4, 5], derived from the synchrotron radiation impedance. A scaling relation between bunch length and current describing these results is summarized here.

A limitation of this short bunch mode is the low current to avoid bunch lengthening, i.e. 3 μA at 1.3 ps rms bunch length. To overcome this limitation it is suggested to install a superconducting (sc) rf structure into one of the straight sections of the storage ring. This structure strongly enhances the longitudinal bunch focusing, like a Landau cavity in bunch shortening mode. It is not intended to use it as an accelerating device. We extrapolate the bunch length and current scaling relation, which is expected, if such a sc structure is included. Critical technical issues of this scheme are not discussed.

The results are applied to the 'user'- and the 'THz'-optics. These are settings of the magnet strength of the BESSY lattice, independent on the longitudinal rf-focusing. With the presently installed rf system, the bunch lengths in the user and THz optics are 13 ps and 3 ps, respectively.

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SCALING EQUATION

The bunch length in the storage ring is described by two limiting cases. One is the "zero current limit", where the length is independent on the current. This length σ is a function, beside typical machine parameters, on the momentum compaction factor α,

$$\sigma = \alpha c \sigma_e/(2\pi f_s),$$

with

$$f_s^2 = \frac{e\alpha}{2\pi R m_e \gamma}\frac{dV_{rf}}{ds},$$

and the speed of light c, rms energy spread σ_e, the synchrotron frequency f_s, the electron charge e, the average ring radius R, the electron mass m_e, the Lorenz factor γ and the rf-gradient dV_{rf}/ds, respectively. This relation follows from single particle beam dynamics.

The second limiting case is derived from the bursting instability [3]. From this instability follows, that bunches above a threshold current, start to emit stochastically pulsed THz radiation ("bursting"). For a given machine, this current I_{th} is related to bunch length and voltage gradient V'_{rf} as,

$$I_{th} \sim \sigma^{7/3} V'_{rf}.$$

Empirically, both results can be summarized to fit our data over bunch length variations by a factor of 10 and current variations by 3 orders of magnitude,

$$(\sigma/\sigma_0)^4 = (f_s/f_0)^4 + (I/I_0)^{3/2},$$

with σ_0=13.1 ps, f_0=7.5 kHz and I_0=1.18 mA as fit parameters, [1].

From our measurements follows, that at the instability threshold the "zero current" bunch length growths by about 50 % due to potential well lengthening. We will use the threshold current as an indication of tolerable bunch lengthening. For high currents the experimental bunch length in our parameter range scales as $\sigma \sim I^{3/8}$ [6]. For the bursting threshold an exponent of $3/7$ is predicted, leading to only small deviations with respect to our data. For the scaling we will apply the theoretical value.

The threshold of bursting scales finally as,

$$I_{th} = I_0(\sigma/\sigma_0)^{7/3} V'_{rf}/V'_{rf0},$$

for the present BESSY II rf-cavities we have V'_{rf0} = 0.75 GHzMV/c. The bunch length in this formulae can be expressed as a zero current length, the common 50 % factor cancels out (if not differently stated, all bunch lengths are expressed as zero current values). For a fixed bunch length, which can be controlled by tuning the alpha value, the threshold current is proportional to the rf-gradient. This leads to a very efficient process to generate powerful, coherent radiation. The emitted coherent radiation power growth with the square of the applied rf-gradient. In the bursting range, we expect an even stronger power increase.

BUNCH SHORTENING CAVITY

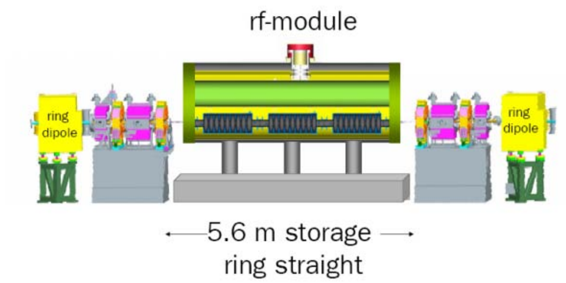

Figure 1: Scheme of a superconducting TESLA structure placed into one of the BESSY II straight sections.

It is suggested to install a strong, superconducting rf-cavity into one of the straight sections of the BESSY ring, Fig. 1. This sc cavity acts only as a longitudinal focusing, not as an accelerating device. The rf multi-cell cavity could be similar to the TESLA type, producing an integrated field gradient of up to 50 MV at 1.5 GHz. The accelerating voltage of 1.5 MV for the beam is still supplied by the existing, normal conducting 0.5 GHz cavities. The maximum beam current which can be used in this bunch focusing mode is not estimated. At lower currents it would be advantageous, to control the excited voltage by an external power source.

There are many open questions, when running the machine with this structure, such as coherent instabilities, multi bunch instabilities, emitted radiation power, effects of bunch jitter and so on. They are left for future investigations.

At DAΦNE (Frascati) [7] presently a sc structure is studied in detailed, to test the longitudinal, strong focusing regime. This cavity of 0.8 m length is designed for a voltage of 8 MV at 1.3 GHz. It will operate at multi bunch currents of up to 1 A. This cavity is close to the parameters which fit our upgrading suggestion. Therefore, as a first example, scaling values of the bunch length-current relation will be derived for a 10 MV device, in a second example a 50 MV unit is assumed.

APPLICATIONS

Three numerical examples for the scaled bunch length current relation achieved from different gradients are presented in this section. For each case, we compare the user optics and the THz optics plus the additional longitudinal rf-focusing. Compared to the user optics, the THz optics

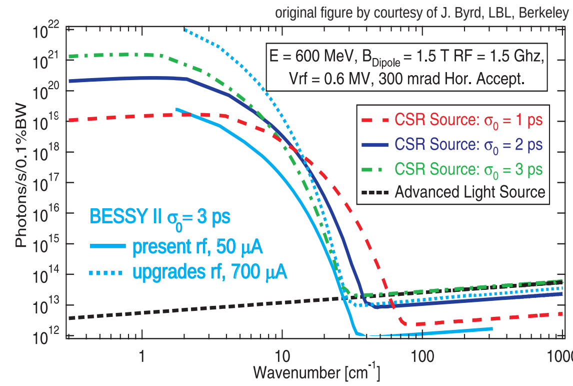

Figure 2: Comparison of scaled THz flux at BESSY by 3 ps bunches with simulated CIRCE parameters.

further reduces the bunch length by an additional factor of 4.5. Two examples are related to BESSY II, in the 3^{rd} example, it is assumed, that the 10 MV unit is placed into the MLS ring, presently constructed next to the BESSY site [8].

In a first step we assume a voltage of 10 MV, corresponding to a gradient increase of a factor 20. Without any change of the transverse machine optics, the bunches in the user optics become 3 ps long. From the scaling relation we expect a current threshold of 0.75mA per bunch, 250 mA multi bunch current. This is at least 10 times more than in the present THz optics, leading to a power increase in the coherent range of a factor of 100. A comparison of the expected flux with CIRCE [9] is plotted in Fig. 2. This moderate bunch shortening structure leads to an enormous THz radiation peak power in the kW range. If, as a further step, the machine is tuned to the THz optics, the bunches become 700 fs long, at currents of 23 μA per bunch.

In a second example we suppose a voltage of 50 MV to achieve a 100 times larger gradient. In the user optics the bunches become 10 times shorter, 1.31 ps in the zero current limit. The threshold increases from presently 5 μA to 0.5 mA. If the THz optics is applied, we expect 300 fs short bunches of 17 μA, 6 mA ring current. The scaling results are summarized in Tab. 1, the bunch length-current relation plotted in Fig.3.

In this figure the red colored, upper left area indicates combination on length and currents which are possible at BESSY II by the low alpha manipulation. The characteristic bunch length-current line of the user optics is indicated by a red line, and similar for the THz optics and a 'ps' optics (for bunches of picosecond length). Bunches outside this area exist only in a short transition mode. The green arrow indicates the bunch current of the 250 mA multi bunch filling, presently the upper limit of the injected current. By an 100x upgrading of the rf-gradient,the present limitation is expanded into the blue area, yielding 100 times more current for a given bunch length. The characteristic scaling relations of the user and the THz optics are plotted as blue lines.

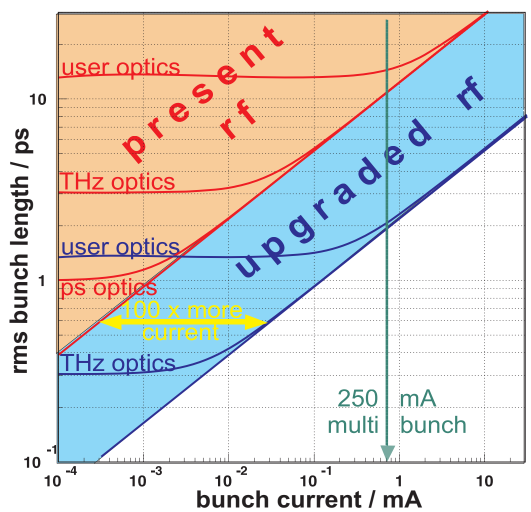

Figure 3: Bunch current relation for the present BESSY II ring (red) and extrapolated version with an 100x upgraded rf-gradient (blue).

If the 10 MV rf-structures is placed into the MLS ring, where the beam is accelerated by a 0.5MV, 0.5 GHz cavity. Because of the relatively low acceleration gradient, the 10 MV structure becomes very effective, it enhances the longitudinal focusing by a factor of 60. The bunch length in this ring at 600 MeV is 13 ps for the user optics and 3 ps for the THz optics (same as the BESSY II values). The values for the compressed bunches are given in Tab. 1. Tracking simulations in the THz optics including 100 times enhanced focussing (corresponding to 300 fs bunch length) were performed, the particles are stable over several damping times [8].

Table 1: Summary of bunch and current relation for the BESSY II and MLS ring. Different rf-gradient upgrades are applied. The relations are calculated for the user optics and the THz optics. The bunch length values include 50 % potential well lengthening.

user optics					
BESSY II			MLS		unit
1.5	**10**	**50**	**0.5**	**10**	**MV**
20	4.4	2.0	20	2.5	ps
1.20	0.72	0.55	2.8	1.5	mA

THz optics					
BESSY II			MLS		unit
1.5	**10**	**50**	**0.5**	**10**	**MV**
4.5	1.0	0.44	4.5	0.58	ps
40	20	16	90	45	μA

CONCLUSION

Different methods of bunch shortening are under discussion [2], like LASER slicing, crab cavities and bunch compression by a focusing rf-cavity. This last scheme has the advantage, that short bunches are supplied to all beam line ports. The repetition rate will be the same as the accelerating cavities, 0.5 GHz in the BESSY II case. It is expected that it can be operated with a high average current. Typically, picosecond bunches of 40 mA multi bunch current seem to be possible. A moderately upgraded optics will become comparable with THz intensities as proposed for CIRCE, with fluxes up to 10^{22} photons/s/0.1%BW.

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