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IBS STUDIES FOR BESSY II, MLS AND BESSY VSR

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Abstract

Intrabeam Scattering (IBS) effects will become a limiting factor for the attainable emittances and single-bunch currents in future electron storage rings and light sources. IBS studies were performed for BESSY II at the Helmholtz-Zentrum Berlin (HZB) and for the Metrology Light Source (MLS) at the Physikalisch-Technische Bundesanstalt (PTB) to quantify the IBS contributions to equilibrium beam sizes in these machines and make predictions for the BESSY II upgrade project, BESSY VSR. The energy dependence of IBS effects (γ^{-4}) makes especially the MLS machine susceptible to IBS effects due to the relatively low energy ranges at which it can be operated (50 MeV-630 MeV). We compare experimental data with simulations and present IBS simulation results for BESSY VSR.

INTRODUCTION

Intrabeam scattering or IBS is elastic Coulomb scattering of charged particles in a confined space, like a particle bunch, which directly influences the phase-space volume of that bunch. As users of light sources ask for increasingly smaller emittances and bunch lengths with higher repetition rates and brightness, IBS is expected to become a more and more relevant effect due to its contribution to the equilibrium beam sizes. At HZB we are interested in quantifying this effect for user operation for BESSY VSR, the upcoming upgrade of BESSY II where we expect to have very short bunches (1.2 ps zero-current RMS [1]). At PTB's synchrotron source MLS, a growth of the beam size in all three planes with increasing single bunch current was observed in low emittance mode. Figure 1 shows part of the evolution of the bunch length (blue), horizontal emittance (magenta) and vertical emittance (green) for the MLS, where the vertical beam excitation (black) was first turned on (region before the black dashed line) and was then turned off (at the vertical dashed line) resulting in a clear increase in bunch length and horizontal emittance [1]. This points towards IBS as a cause for the observations and motivates an IBS analysis. Table 1 shows some typical emittances and bunch lengths for BESSY II in standard user mode and for the MLS in low emittance mode. The last line gives some expected values in standard user mode for the short bunches in BESSY VSR, the long bunches are expected to be similar to the present BESSY II bunches. In our studies, we considered several IBS models

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[1] Amplified white-noise, generated by a noise generator, is fed to a strip line. This excites the beam in the vertical plane, resulting in an increased vertical beam size.

Table 1: Typical Beam Size Values for BESSY II, MLS and Expected Values for BESSY VSR

	ϵ_x [nmrad]	ϵ_y [nmrad]	σ_s [mm]
BESSY II	7.5	0.057	5
MLS	36	0.18	7
BESSY VSR (short)	7.5	0.057	0.4

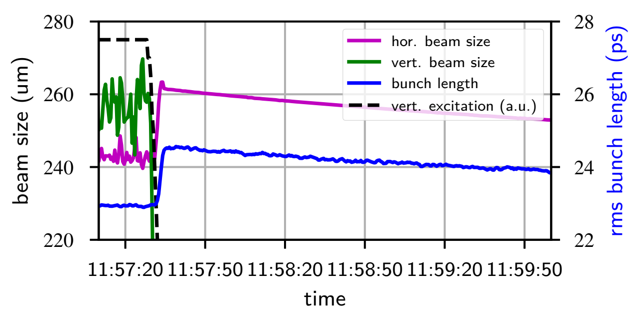

Figure 1: MLS: vertical noise excitation (black dashed), bunch length (blue), horizontal (magenta) and vertical emittance (green) measurement with and without vertical noise excitation

available in the literature [2–8] and used two different simulation methods [9–11], an ordinary differential equations (ODE) and a particle tracking method. The following sections will discuss the simulations methods, measurements and discuss the results.

ODE APPROACH

In the ODE approach we used a set of coupled ordinary differential equations (Eq. 1,2), similar to the approach in [12], to describe the evolution of the horizontal emittance ϵ_x, the vertical emittance ϵ_y and the square of the energy spread σ_δ^2. The ODE model takes three effects into account: radiation damping, quantum excitation and IBS. The contributions of radiation damping are captured by the terms containing the radiation damping times $\tau^{\mathrm{RAD}}_{\epsilon_x}, \tau^{\mathrm{RAD}}_{\epsilon_y}, \tau^{\mathrm{RAD}}_{\sigma_\delta^2}$, those of quantum excitation by the terms with the radiation equilibrium values $\epsilon_x^\infty, \epsilon_y^\infty, \sigma_\delta^\infty$ and finally those of IBS by the terms containing the IBS lifetimes $\tau^{\mathrm{IBS}}_{\epsilon_x}, \tau^{\mathrm{IBS}}_{\epsilon_y}, \tau^{\mathrm{IBS}}_{\sigma_\delta^2}$. The IBS lifetimes can be calculated using different IBS models [2–8].

$$\frac{d\epsilon_i}{dt} = -\frac{1}{\tau^{\mathrm{RAD}}_{\epsilon_i}}\left(\epsilon_i - \epsilon_i^\infty\right) + \frac{\epsilon_i}{\tau^{\mathrm{IBS}}_{\epsilon_i}}, \text{ with } i = x, y \quad (1)$$

$$\frac{d\sigma_\delta^2}{dt} = -\frac{1}{\tau^{\mathrm{RAD}}_{\sigma_\delta^2}}\left(\sigma_\delta^2 - \sigma_{\delta,\infty}^2\right) + \frac{\sigma_\delta^2}{\tau^{\mathrm{IBS}}_{\sigma_\delta^2}} \quad (2)$$

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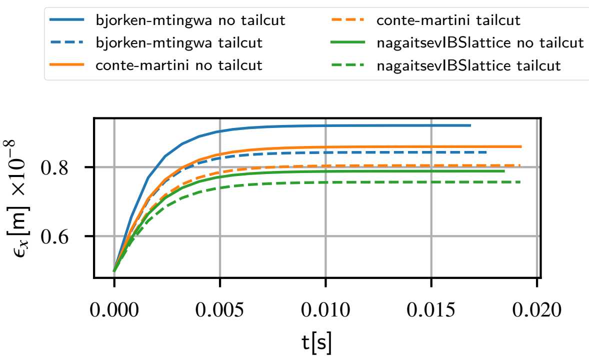

Figure 2: Horizontal emittance evolution using a Coulomb logarithm with and without a tail-cut procedure, for different IBS models (Bjorken-Mtingwa [2] (blue), Conte-Martini [6] (orange) and Nagaitsev approximation [7] (green).

As is the case in most IBS papers a short discussion on the Coulomb Logarithm (clog), defined as the logarithm of the maximum impact parameter $b_{\max}$ over the minimum impact parameter $b_{\min}$ i.e. clog = $\log\left(\frac{b_{\max}}{b_{\min}}\right)$, is needed. The choice of these impact parameters is often a highly discussed topic. As far as we are aware the only model not depending on this clog is described in [13]. For our simulations two methods were considered regarding the calculation of the clog [2], in a first method we used the formulae from [14] to evaluate the clog and in a second method [15] its value was evaluated with a tail cut using [16, Eq. 18]. The clog was calculated at each simulation step and a significant difference in equilibrium beam sizes was observed for the two methods, for the same IBS algorithm. Figure 2 shows the difference for the evolution of horizontal emittances between the two methods to evaluate the clog, for different IBS models for BESSY II, with initial beam parameters given by $\epsilon_x = 5$ nm, $\epsilon_y = 37.5$ pm, $\sigma_s = 4.5$ mm and corresponding damping times of 7.8 ms, 7.7 ms, 3.8 ms respectively.

PARTICLE TRACKING APPROACH

In the particle tracking approach, a bunch is represend by a distribution of macro particles [3] which is generated to fit the input beam parameters (bunch length, emittances,...). This distribution is tracked and updated on a simulation turn-by-turn basis, applying sequentially the selected physical processes. Available update routines are : betatron motion, synchrotron motion, radiation damping, quantum excitation, IBS (with Coulomb log calculation), simple damping wiggler module changing the radiation damping integrals [17] and artificial beam blowup. The code is based on the original Collider Time Evolution code [9, 18], adapted for electron machines, available in FORTRAN[4], C++/CUDA and Python (3.6) [5].

[2] These methods differ in the calculation for the maximum impact parameter $b_{\max}$, see [14–16] for details.
[3] Each macro particle representing a certain number of real particles.
[4] Some IBS models are not available yet in FORTRAN, but will be in the near future.
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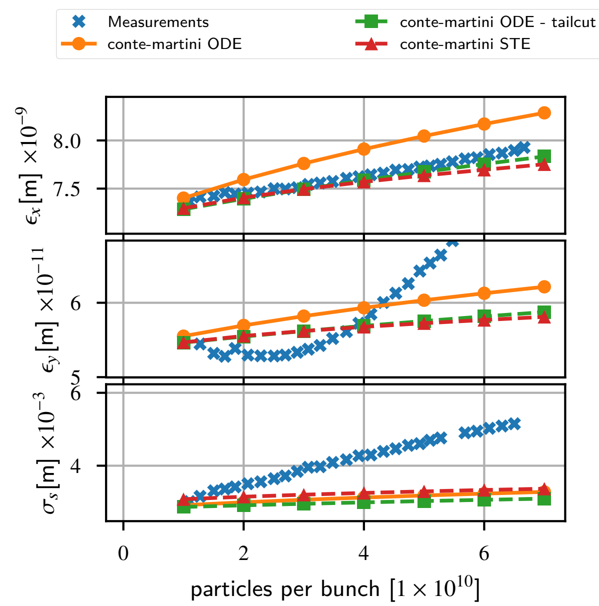

Figure 3: Comparison BESSY II measurements (blue) with ODE simulations (with (red) and without (orange) tail cut) and particle tracking simulations (green) using Conte-Martini as IBS model.

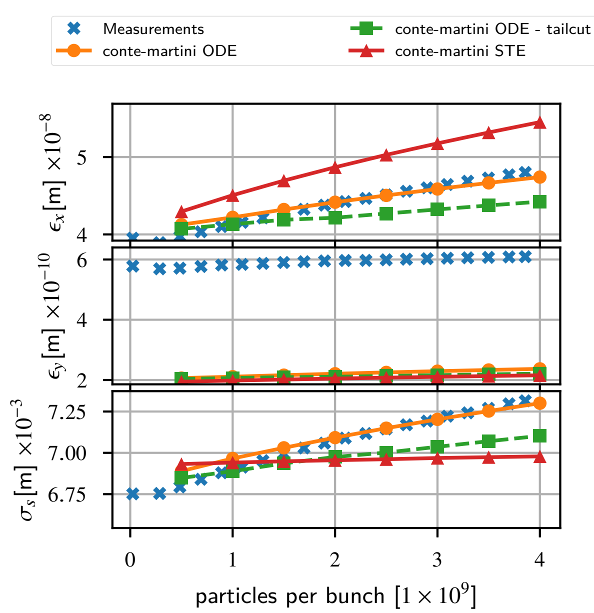

Figure 4: Comparison MLS measurements (blue) with ODE simulations (with (red) and without (orange) tail cut) and particle tracking simulations (green) using Conte-Martini as IBS model.

MEASUREMENTS

Measurements at BESSY II were performed using standard user optics in single bunch mode, with the 7 Tesla wiggler turned on. A current of 15 mA ($\approx 7.5 \times 10^{10}$ particles) was injected into a single bunch, after which it was let to decay down to 0.5 mA. The bunch length and transverse beam sizes were continuously measured during this process. Similar measurements at the MLS date back to 2015, and

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were performed using a low emittance lattice setup in single bunch mode. For both machines, bunch lengths were measured using a streak camera and transverse emittances using a pinhole system [19, 20]. The measured vertical beam size is not well know due to resolution limitations and other systematic errors of our pinhole system, therefore we used weak coupling between the transverse planes in the simulations to evolve the vertical emittances, using 0.75 percent coupling for BESSY II and 0.5 percent for the MLS.

MEASUREMENTS VERSUS SIMULATIONS

After comparing the different IBS models, we decided to report only using the Conte-Martini model. Results with other models are different but not significantly compared to expected measurement errors. Figure 3 shows the results for BESSY II, where we observe that IBS simulations seem to agree for the horizontal plane. However for the vertical plane a quadratic growth is observed, inconsistent with IBS. Furthermore, the bunch length data shows a much stronger growth than predicted by IBS. A confirmation of our suspicion that the measured growth of the beam parameters at BESSY II are not due to IBS came from increasing the vertical beam size using noise excitation (similar to what was done for the measurements at MLS) and observing that the measured bunch length did not change. We conclude that for BESSY II IBS is negligible and we are in a regime dominated by collective effects (potential well distortion, impedance effects,...).

For the MLS case, Fig. 4, we observe a strong discrepancy between simulation data and measurement data in the vertical plane, where in the simulations the values are due to coupling to the horizontal plane, in other words they are the horizontal emittance times a coupling factor (0.005). Nevertheless, assuming this vertical size, a good agreement is observed for the horizontal and longitudinal plane between data and simulations. During the measurements special care was taken to exclude Coherent Synchrotron Radiation as cause for the observed growth in beam size and the idea that the observed growth with current is due to IBS is further supported by the observation shown in Fig. 1, as discussed before.

BESSY VSR

The ODE approach was used to predict the effect of IBS on the expected long and short bunches for BESSY VSR, using the optical lattice from BESSY II assuming a coupling between the horizontal and vertical plane equal the one used for the BESSY II simulations. For the particle tracking simulations a triple RF system has been implemented, that for the moment, only allows to track the short bunches. Results of both types of simulations, again with and without tail cut for the ODE approach, are shown in Fig. 5. The simulations indicate a possible increase of 25 percent in bunch length compared to the zero-current RMS bunch length of 1.2 ps for the short bunches with a current of 1 mA, which is the

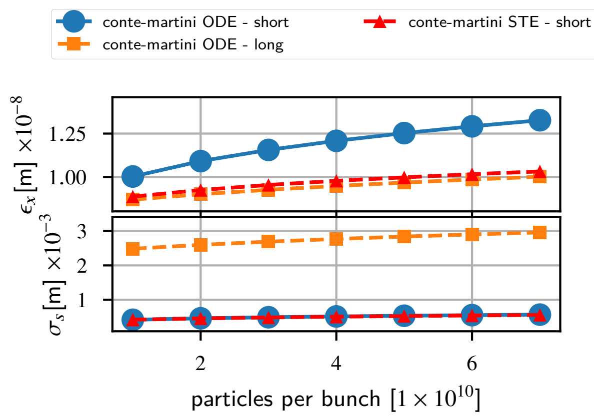

Figure 5: BESSY VSR ODE simulations (with (red) and without (orange) tail cut) and particle tracking simulations (green) using Conte-Martini as IBS model.

expected operational current in these bunches. These simulations do not take current dependant effects into account such as bunch lengthening due to potential well distortion or Coherent Synchrotron Radiation effects, which are expected to contribute about a factor of one and a half to the bunch length, therefore also reducing IBS effects. Moreover, during user operation vertical noise excitation is applied to the beam, increasing the vertical beam size roughly by a factor of three, further reducing IBS effects. We conclude that for BESSY VSR IBS will not affect user operation, but that we will have the opportunity to study the effect during dedicated experiments.

CONCLUSION

Two different types of simulation codes have been implemented to investigate the effects of IBS on the present and future machines at HZB and PTB. Both simulation approaches agree fairly well and were compared with BESSY II and MLS data. We concluded that at the BESSY II machine there is currently no indication of IBS effects, while at the MLS we observe an agreement with IBS simulations assuming that the vertical beam size is dominated by coupling and roughly a factor three smaller than indicated by the pinhole measurement system. More dedicated experiments are needed to confirm or reject if the observations are due to IBS. Using the discussed simulation tools the IBS effect for expected bunch parameter for BESSY VSR have been quantitatively studied, and we conclude that IBS will have a negligible impact compared to other effects in user operation, but can be studied during dedicated experiments.

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