INTRABEAM SCATTERING STUDIES AT CESRTA*

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Abstract

Intrabeam scattering (IBS) dilutes the emittance of low energy, low emittance rings. Because CesrTA can be operated at low energies with low transverse emittances and high bunch intensity, it is well-suited for the study of IBS. Furthermore, CesrTA is instrumented for accurate beam size measurements in all three dimensions, providing the possibility of a complete determination of the intensity dependence of emittances. Measurements from dedicated IBS machine studies at different emittances, intensities, and species are presented. A model based on analytic IBS theories is developed and compared to the data.

INTRODUCTION

In this paper we document IBS experiments conducted at CesrTA and compare the results to simulation. CESR is a 768 m e^+/e^- wiggler-dominated storage ring. The experiments presented here were conducted at 2.1 GeV beam energy. Measured horizontal geometric emittance ϵ_x is in the 6 to 8 nm range. Vertical ϵ_y is adjustable from about 8 pm up to 150 pm and higher. Nominal bunch length is 10.5 mm and can be adjusted by varying RF voltage. Measurements are on single bunches with charges ranging from 0.10 mA to 10.0 mA (1.6×10^9 to 1.6×10^{11} particles/bunch).

CESR CONFIGURATION

Vertical: xBSM [1] Vertical beam size is measured by x-ray beam size monitors (xBSM), one for positrons and one for electrons. X-rays from a bend magnet are imaged through a pinhole onto a vertical 32 pixel detector array. Data is gathered turn-by-turn, and each turn is fitted separately. Individual fits over 512 or 1024 turns are averaged to obtain the measurement.

Horizontal: vBSM [2] Visible spectrum light from a soft-bend dipole is imaged through a pair of vertical slits onto a CCD camera. The resulting interference pattern is fit to obtain the horizontal beam size. The vBSM images are averages over many turns.

Longitudinal: Streak Camera [3] From the same beam line as the vBSM, visible light is split off to a streak camera that captures the longitudinal profile of the bunch. The streak camera measurements are single shot, but not turn-by-turn. The bunch length is taken as the FWHM or σ of a fit to an asymmetric Gaussian.

Tunes A current-dependent vertical tune shift of -0.5 kHz/mA is observed in CESR, which corresponds to a drop in the fractional tune Q_y of about 0.01 at high current. Thus a significant range of tunes is sampled as the beam current decays. The vertical beam size is affected when Q_y crosses a resonance. The impact of high order resonances, such as $(1, 2, 2, 2)$ or $(0, 2, -4, 1)$, have been observed in the vertical data.

Experimental and simulation tune scans are used identify a region of the tune plane that is clear of resonances. The scans measure the beam sizes as Q_x and Q_y are rastered by adjusting quadrupole strengths. Simulation tune scans are run on misaligned lattices corrected with the CesrTA emittance tuning procedure [4]. An operating point of $(0.624, 0.580)$ was chosen from these scans, where Q_y can change by at least 0.010 without encountering resonances.

MODELING OF BEAM BEHAVIOR

A goal of the CesrTA IBS program is to develop a model of high-current, single-bunch behavior in low-emittance beams. The calculation of IBS growth rates is only part of the task. Horizontal and vertical coupling is included, as well as potential well distortion.

Misaligning Model Lattices In an ideal lattice, coupling and vertical dispersion are zero. Realistic coupling and vertical dispersion are modeled by misaligning lattice elements and applying the same correction procedure as is applied to the machine. The misalignments are randomized, producing several "seeds" from which are selected lattices that have properties similar to those seen in CESR. The lattice used for the simulations presented here has vertical dispersion $\langle \eta_y \rangle = 0.02$ m and coupling $\left\langle \bar{C}_{12} \right\rangle = 0.7\%$. Natural vertical emittance ϵ_{y0} is 14.5 pm.

We use the normal modes of the lattice for our calculations, rather than the horizontal and vertical. At instrumentation source points, the beam is projected from the ab plane into the xy plane to obtain the beam sizes that are compared to data [6]. This approach avoids the question of how to account for coupling. Growth rates are recalculated at 1 m intervals around the ring.

Calculation of IBS Rates Two widely used analytic methods for calculating IBS rates are from either Piwinski or Bjorken-Mtingwa formalisms. These methods and their

* Support from NSF and DOE contracts PHY-0734867, PHY-1002467, PHYS-1068662, DE-FC02-08ER41538, DE-SC0006505, the Japan/US Cooperation Program, and Education and Lifelong Learning, co-financed by Greece and the EU.

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approximations are summarized in [7]. Both are based on a kinetic approach that integrates over many small angle scattering events. Two approximate, and more computationally efficient, methods are an approximation of Piwinski referred to as CIMP and one of Bjorken-Mtingwa done by Karl Bane.

Over the range of ϵ_y explored at CESR, sub-10 pm to 150 pm, the equilibrium emittance obtained from Bjorken-Mtingwa, Bane, and CIMP are very similar. CIMP is the quickest to evaluate, and is the method used in this paper.

Tail Cut IBS calculation methods based on the kinetic approach require a cut-off at the largest and smallest impact parameter. The integral diverges for large impact parameter because the number of particles available for scattering dominates over the diminished angle change from each event. It diverges for small impact parameter because the angle change from each event dominates over the rarity of such events. The largest impact parameter is taken as the vertical beam size. Classically, the smallest impact parameter is that associated with maximum momentum transfer.

It was pointed out in [8] that large momentum transfer scattering events are very rare. If a small number of scattering events occur, the result is non-Gaussian. The core of an IBS-dominated beam is Gaussian because the equilibrium is formed from many random scattering events and radiation damping.

The tail cut consists of ignoring scattering events that occur less frequently than the damping rate, $\sigma \rho v < 1/\tau$. The original method for calculating this cut-off is found in [8]. A more intuitive derivation, found in [9], results in modifying the Coulomb Log in the following way,

$$\log\left[\frac{\gamma^2 \epsilon_x \sigma_y}{r_0 \beta_a}\right] \Rightarrow \log\left[\sqrt{\frac{N c \tau}{4\pi \sigma_x \sigma_y \sigma_z \gamma}}\left(\frac{\epsilon_x}{\beta_x}\right)^{\frac{1}{4}} \sigma_y\right]. \quad (1)$$

Potential Well Distortion (PWD) The field of a bunch interacts with structures in the vacuum system resulting in fields that act back on the bunch. One consequence of this is a voltage gradient along the length of the bunch. The longitudinal focusing seen by the bunch is a combination of this effect and focusing in the RF cavities. The strength of the gradient is proportional to the bunch charge.

A derivation of PWD based on Vlassov theory results in a differential equation for the longitudinal profile [5],

$$\frac{\partial \psi}{\partial \tau} = \frac{-eE_0 \psi}{\sigma_\epsilon^2 \alpha T_0}\left[\frac{V_{rf}\cos(\omega\tau + \phi) + QR\psi - U_0}{1 + \frac{eE_0 Q L \psi}{\sigma_\epsilon^2 \alpha T_0}}\right]. \quad (2)$$

The longitudinal profile is parametrized in terms of resistance R and impedance L. R does not lengthen longitudinal profile, but sweeps it backwards. L increases the bunch length. Matching the slope of the streak camera data, L is found to be about 30.0 nH, though uncertainty in L is very large, pending further model development.

Energy spread in CesrTA IBS conditions has been measured by varying dispersion at the vBSM source point. The result of about 8.5×10^{-4} agrees with the design value. Evidence of microwave instability was not found.

The free parameters in the model are ϵ_{x0}, ϵ_{y0}, R, and L.

DATA & MODEL RESULTS

The experiment is run by setting machine conditions, then filling to high current and taking data as the beam decays. At low currents or large vertical sizes, the decay rate is very slow and a pulsed injection bump is used to scrape the beam. Gaps in the data are when the beam was scraped. Shown in Figs. 1, 2, and 3 is IBS data from a 2.1 GeV e$^+$ run with low ϵ_y. Low-current horizontal and vertical emittance were measured to be 6.75 nm and 15.4 pm.

Above 6 mA the vertical beam size diverges from the model. The cause of this is not yet pin-pointed. The positive curvature and delayed onset suggest it is not an IBS effect. Tune plane effects, space charge, electron cloud, and instrumentation are among the potential causes being investigated.

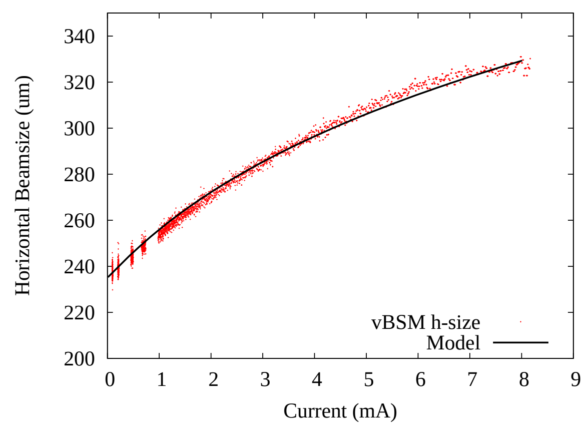

Figure 1: vBSM data from run 4B. $\epsilon_{x0} = 6.75$ nm.

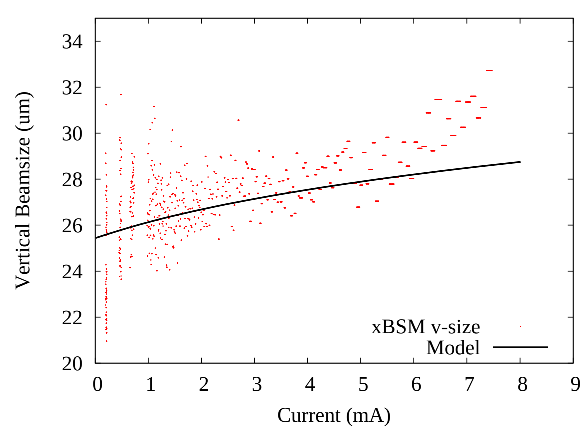

Figure 2: xBSM data from run 4B. $\epsilon_{y0} = 15.4$ pm.

Shown in Figs. 4, 5, and 6 is data from e$^-$ and e$^+$ at different vertical emittances. Vertical emittance is varied by

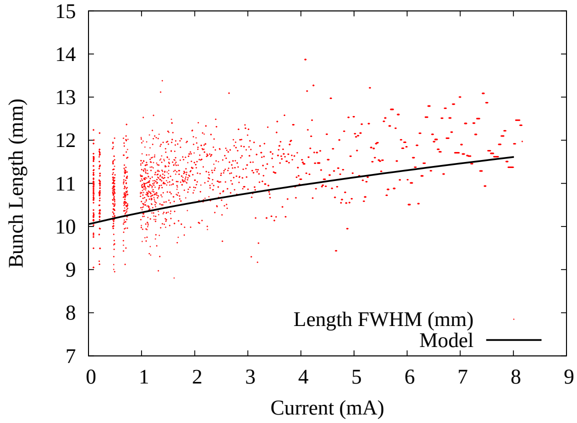

Figure 3: Bunch lengthening in run 4B. Growth is mainly due to potential well distortion.

adjusting a closed coupling and vertical dispersion bump in the wiggler region. These additional runs show that the model agrees with the data over a wide parameter range.

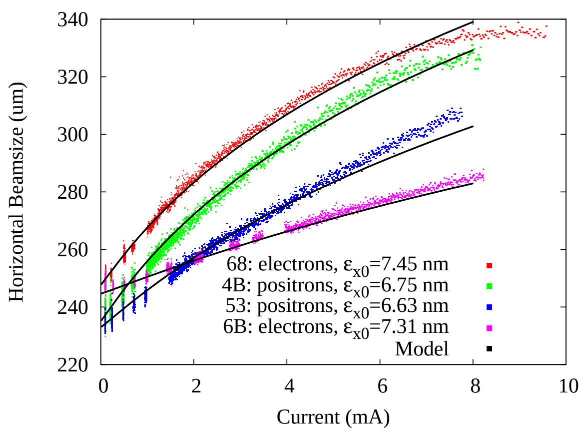

Figure 4: vBSM data with model results for e^+ and e^- at various emittances.

CONCLUSION

Intrabeam scattering is strong in CesrTA, which is well-instrumented to study this effect. Two other collective effects, potential well distortion and current-dependent tune shift, are also observed. Detailed data versus current on all three bunch dimensions have been obtained.

A model that incorporates the commonly used IBS calculation methods, potential well distortion, and realistic coupling is being developed and has obtained reasonable agreement with data at low current. At high current, vertical measurements diverge from the model, the cause of which has not yet been pin-pointed.

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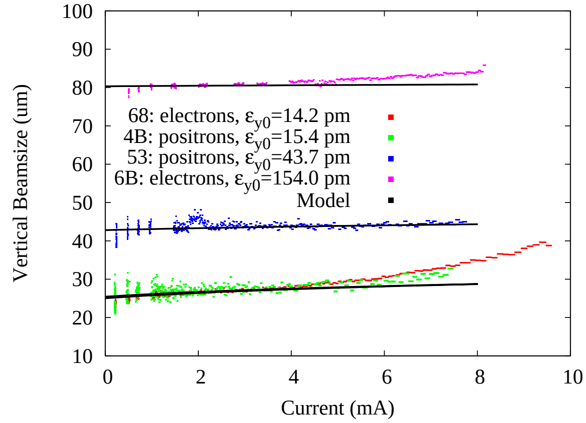

Figure 5: IBS effects in vertical are minimal to to low coupling and vertical dispersion.

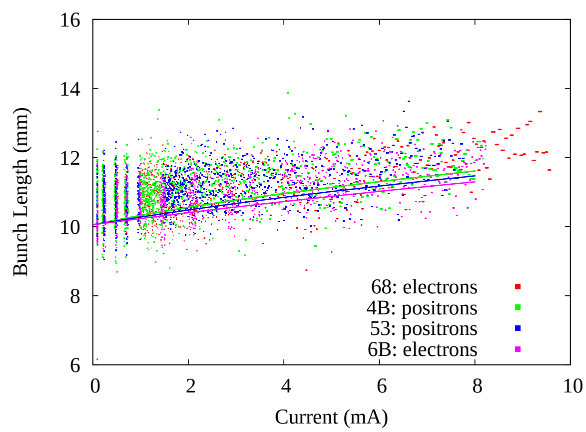

Figure 6: Streak camera data. Solid curves are model results.

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