IBS Effects in a Wiggler-Dominated Light Source

Boris Podobedov
Brookhaven National Lab
National Synchrotron Light Source

Lingyun Yang
Indiana University

IBS'07, Daresbury, UK
August 29, 2007

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Outline & Preliminaries

- Introduction
  - Motivation and light source specifics
  - Wiggler-dominated LS
- Effects of wigglers/undulators (No IBS)
- Analytical results on IBS through Bane's formalism
- ZAP simulations
- SAD simulations (preliminary)
- Summary and conclusions

IBS results are described in our PAC'07 paper

- I only talk about Multiple Intra Beam Scattering
- Collective effects (such as potential well distortion, etc) are ignored
- I don't include harmonic RF (which reduces IBS even further)
- Most estimates are for CDR DBA30 NSLS-II lattice
- We looked for worst case estimate

Motivation

Why IBS is important?

- IBS is viewed to be one of the fundamental show-stoppers in achieving very low storage ring emittances at high single bunch current

Light Source Quality Factors

ID Capacity $N_{ID} >> 1$	**Ave Flux** $\Phi \sim I\,E$	**Stability** $\frac{\Delta_{x,x',\ldots}}{\sigma_{x,x',\ldots}} < \Delta_{limit}$
Ave Brightness $B \propto \frac{I\,N_u}{\left(\varepsilon_x \oplus \lambda/2\right)\left(\varepsilon_y \oplus \lambda/2\right)}$	**Short Pulse** $\tau_{ring} \approx 0.1-50\text{ps}$	**Cost** $\$ < \$_{limit}$

Try to break new ground on the first 5 without violating the last!

IBS in Light Sources

What is special about IBS in a modern LS?

- Brightness is important figure of merit (don't want ε blow-up)
- Main customers are hard X-ray (think 1 Å or 12 keV)
- Diffraction-limited ε_y is routinely achieved
- To provide 1Å don't need to go lower than ε_y=1Å/4π
- Need to control E-spread, esp. for undulator users (typ. <0.1%)
- While top-off is becoming widespread, Touschek-dominated lifetime is still an issue (defines the injector, shielding, etc.)
- (Often) superconducting RF provide adequate rf acceptance => we can assume const. RF bucket

Implications for IBS calculations set LS apart from high energy physics machines

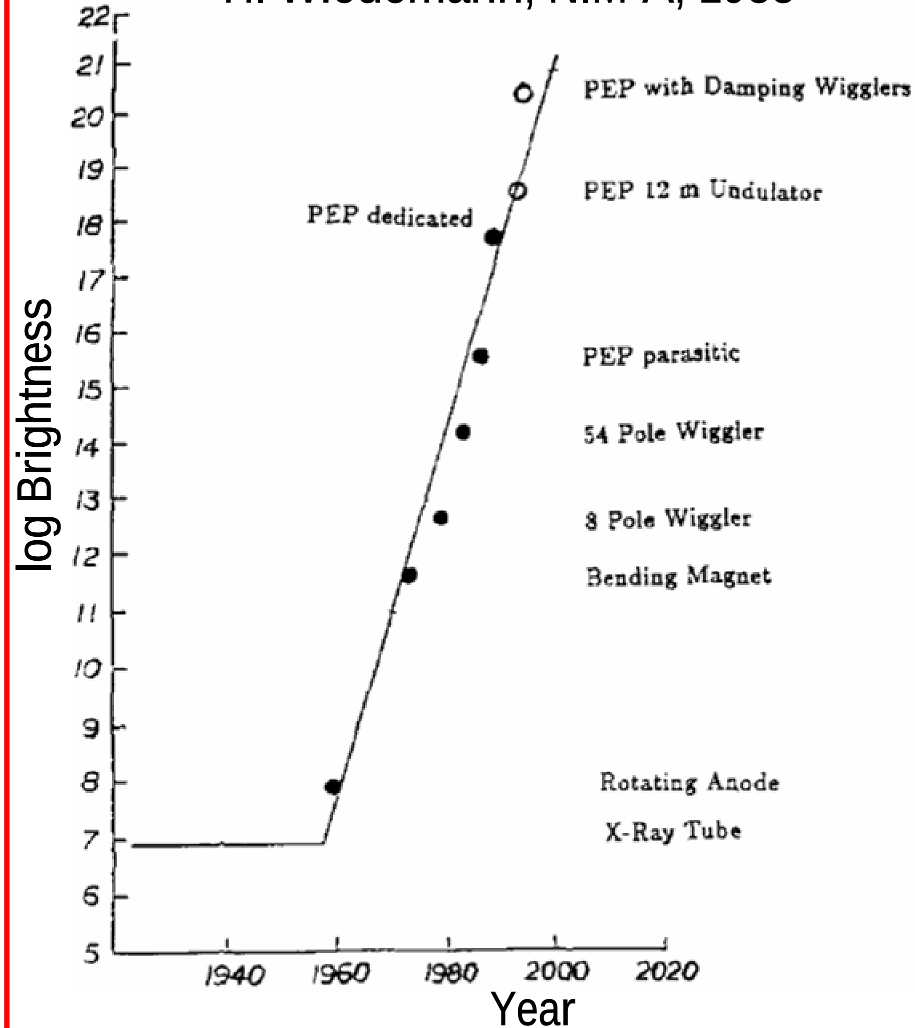
Wiggler-Dominated Light Source

- Damping Wiggler (DW) in a LS idea H. Wiedemann

$$\frac{\varepsilon_x}{\varepsilon_{x0}} \approx \frac{U_0}{U_0 + U_w}$$ ultra-simplified!

- Several LS in design, construction, i.e. NSLS-II and PETRA-III
- Many more have considered DW option
- DW concept is proven in colliders (i.e. CESR)

H. Wiedemann, NIM-A, 1988



Effects of IDs on Beam Properties

ID	λ [cm]	K	L [m]	δE[KeV]	$\delta\nu_y$
SCU	1.4	2.2	5	80.6	0.028
SCW	6.0	19.6	1.0	71.1	0.024

Assume: 18-SCU & 2-SCW in 1.4 nm lattice

Effects of IDs

- Energy loss/turn, $U_{tot} \rightarrow$ 2.445 MeV = 2.86 x U_o
- Energy spread, $\sigma_e \rightarrow$ 0.10% = 1.09 x σ_{eo}
- Equilibrium emittance, $\varepsilon \rightarrow$ 0.488 nm = ε_o /2.8
- RF voltage, V $\rightarrow$ 3.7 MV = 1.97 x V_o
- Bunch length, $\sigma_L \rightarrow$ 3.2mm = 0.83 x σ_{Lo}

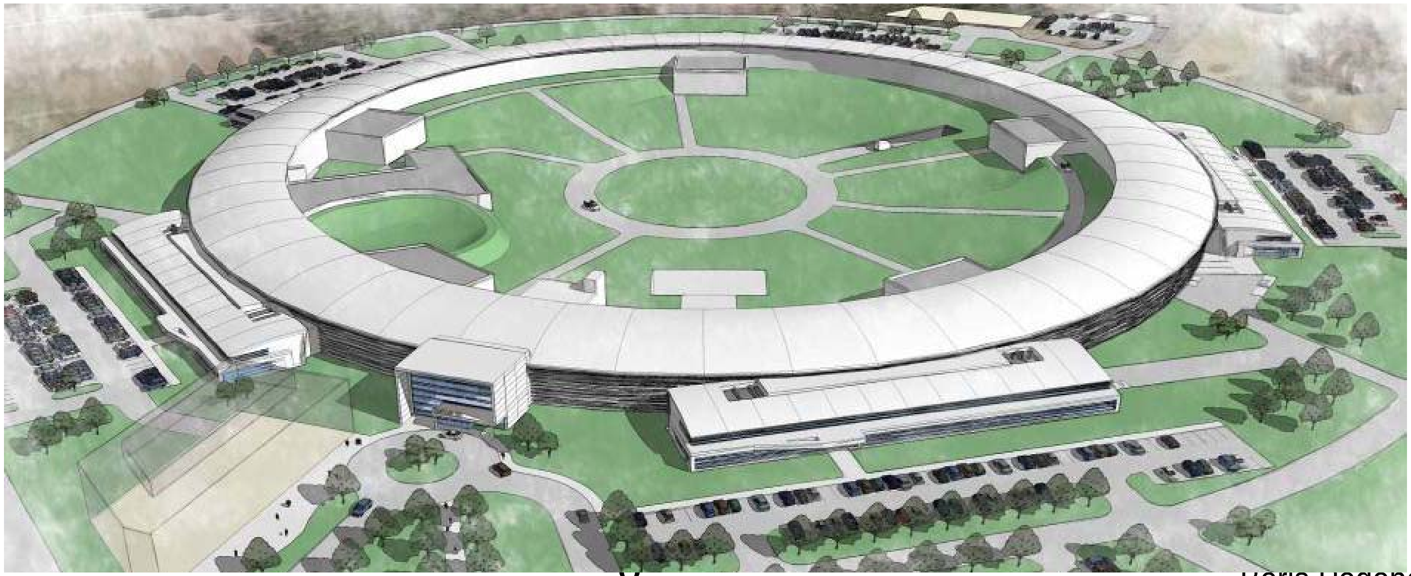
This is obsolete NSLS-II lattice ~Dec 04 (TBA24, 630 m) before the switch to DBA + damping wigglers

U_{tot} is convenient measure of ID effect on beam dimensions (for IBS)

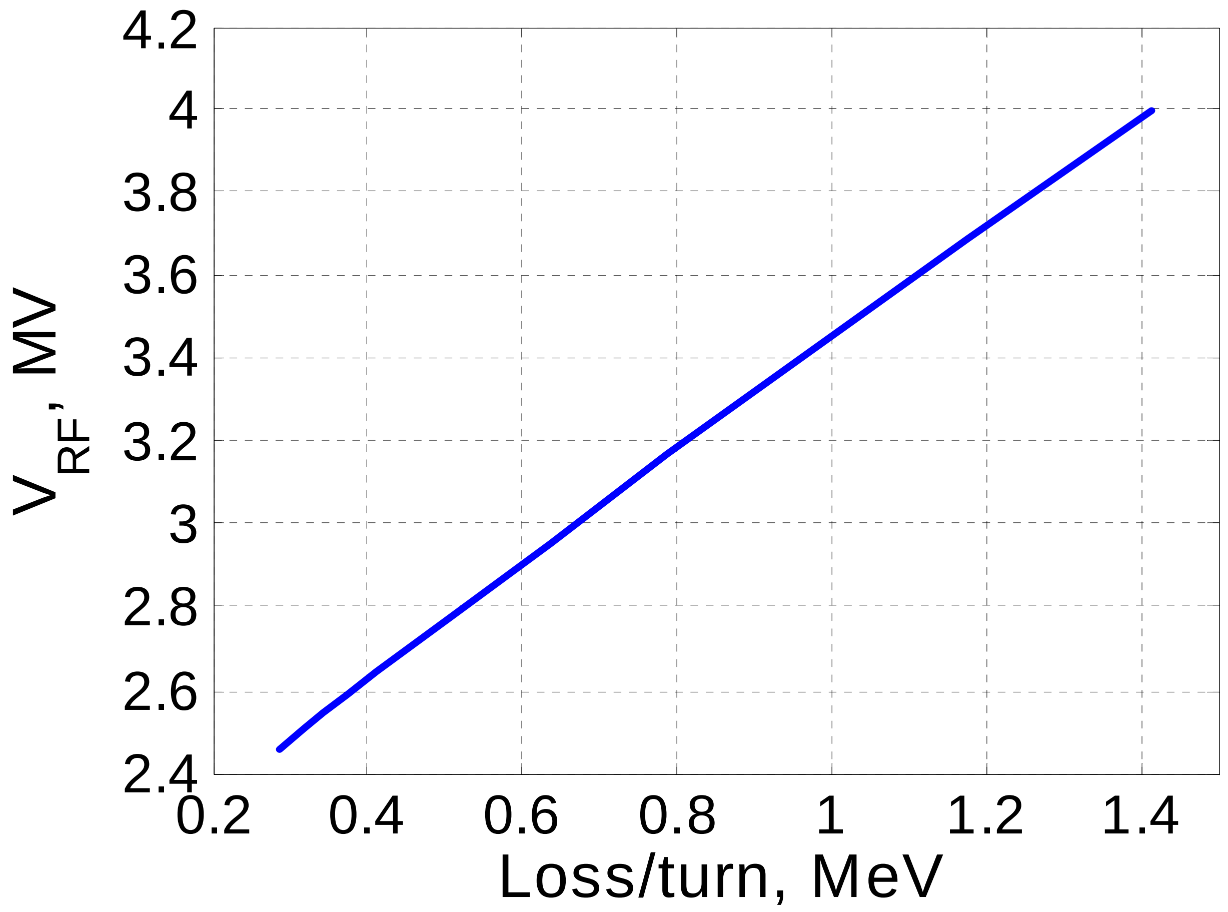
Parameters for NSLS-II IBS Calculations

Energy	3.0 GeV	Energy Spread	<0.1%
Circumference	~800 m	RF Frequency	500 MHz
Number of Periods	30DBA	RF Bucket Height	3%
Length Long Straights	8.6 & 6.6 m	Synchrotron Tune	~0.009
Emittance (h,v)	2-0.5 nm, 8 pm	RMS Bunch Length	15ps
Betatron Coupling	>0.5%	Maximum Current	500ma
Dipole Bend Radius	25m	Current per Bunch	0.48ma

More details at http://www.bnl.gov/nsls2/project/CDR



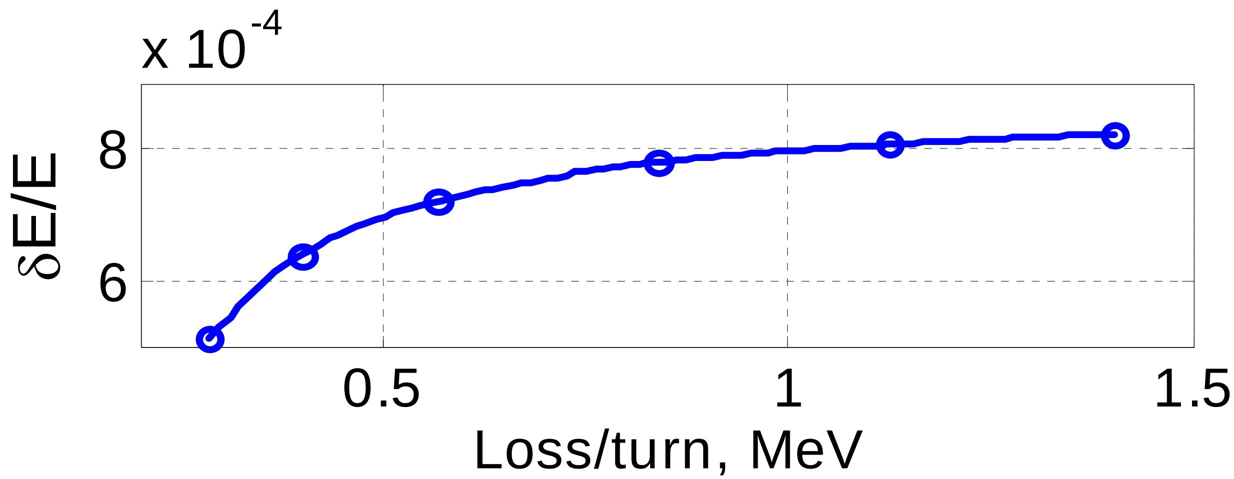
Fixing RF Bucket Height at 3%

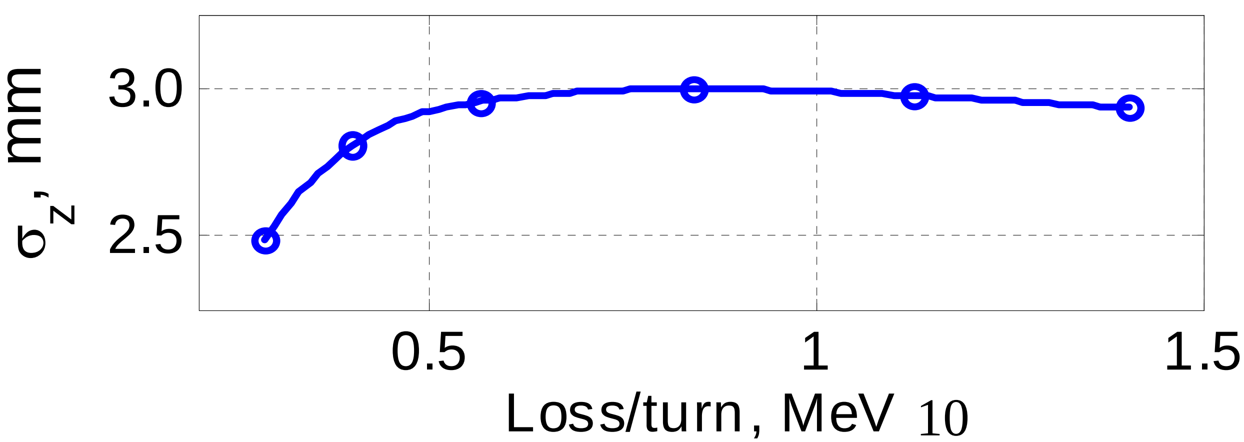


CESR-B 500 MHz SC
RF Cavity

Zero Current Energy-spread and Bunch Length

$$\frac{\delta E/E}{(\delta E/E)_0} = \sqrt{\left(1 + \frac{2L\rho_b^{\,2}}{3\pi^2\rho_w^{\,3}}\right)\Bigg/\left(1 + \frac{L\rho_b}{4\pi\rho_w^{\,2}}\right)} > 1 \quad (\rho_b > \rho_w)$$





L is wiggler length

ρ_b dipole bend radius

ρ_b wiggler bend radius

δE/E always grows!

σ_z is approx. constant

IBS via Bane's Formalism

- Equilibrium emittances $\varepsilon_{x,y}$ & E-spread σ_p depend on SR damping times (τ) and IBS growth times (T),

$$\varepsilon_x = \frac{\varepsilon_{x0}}{1-\tau_x/T_x}, \quad \cancel{\varepsilon_y = \frac{\varepsilon_{y0}}{1-\tau_y/T_y}}, \quad \sigma_p^2 = \frac{\sigma_{p0}^2}{1-\tau_p/T_p},$$

- Starting with B-M theory, K. Bane derived [EPAC02] simple expressions for $T_{x,y,p}$

$$T_x^{-1} \approx \frac{r_0^2\, c\, N\,(\log)}{16\gamma^3 \varepsilon_x^{7/4}\,\varepsilon_y^{3/4}\sigma_z\sigma_p}\left\langle H_x\,\sigma_H\, g\left[\sqrt{\frac{\varepsilon_y\beta_x}{\varepsilon_x\beta_y}}\right](\beta_y\,\beta_x)^{-1/4}\right\rangle, \qquad T_x^{-1} \approx \left\langle \sigma_p^{\,2}\, H_x\,\varepsilon_x^{-1} T_p^{\,-1}\right\rangle$$

$$\sigma_H^{-2} = \sigma_p^{-2} + H_x/\varepsilon_x + \cancel{H_y/\varepsilon_y}, \qquad g[\alpha]=\alpha^{(0.021-0.044\ln\alpha)}.$$

$$\boxed{\frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_{x,y}}{\varepsilon_{x,y}}} << 1}$$

high energy approx.

- K. Bane and others observed good agreement with more general methods.

- We studied how these IBS rates behave in a wiggler-dominated LS as a function of energy losses (or zero-current emittance). So far we consider ε_y dominated by (weak) coupling, i.e. $\boxed{\varepsilon_y = \kappa\,\varepsilon_x}$.

IBS via Bane's Formalism: Main Result for Wiggler Dominated LS

- Turning on the damping wigglers increases U_{tot} reducing the emittance. What happens to the IBS effect?

$$\varepsilon_x = \frac{\varepsilon_{x0}}{1-\tau_x / T_x}, \qquad \tau_x \propto 1/U_{tot}, \quad T_x(U_{tot}) = ?$$

- Let's observe the scaling with U_{tot} with of Bane's IBS growth time:

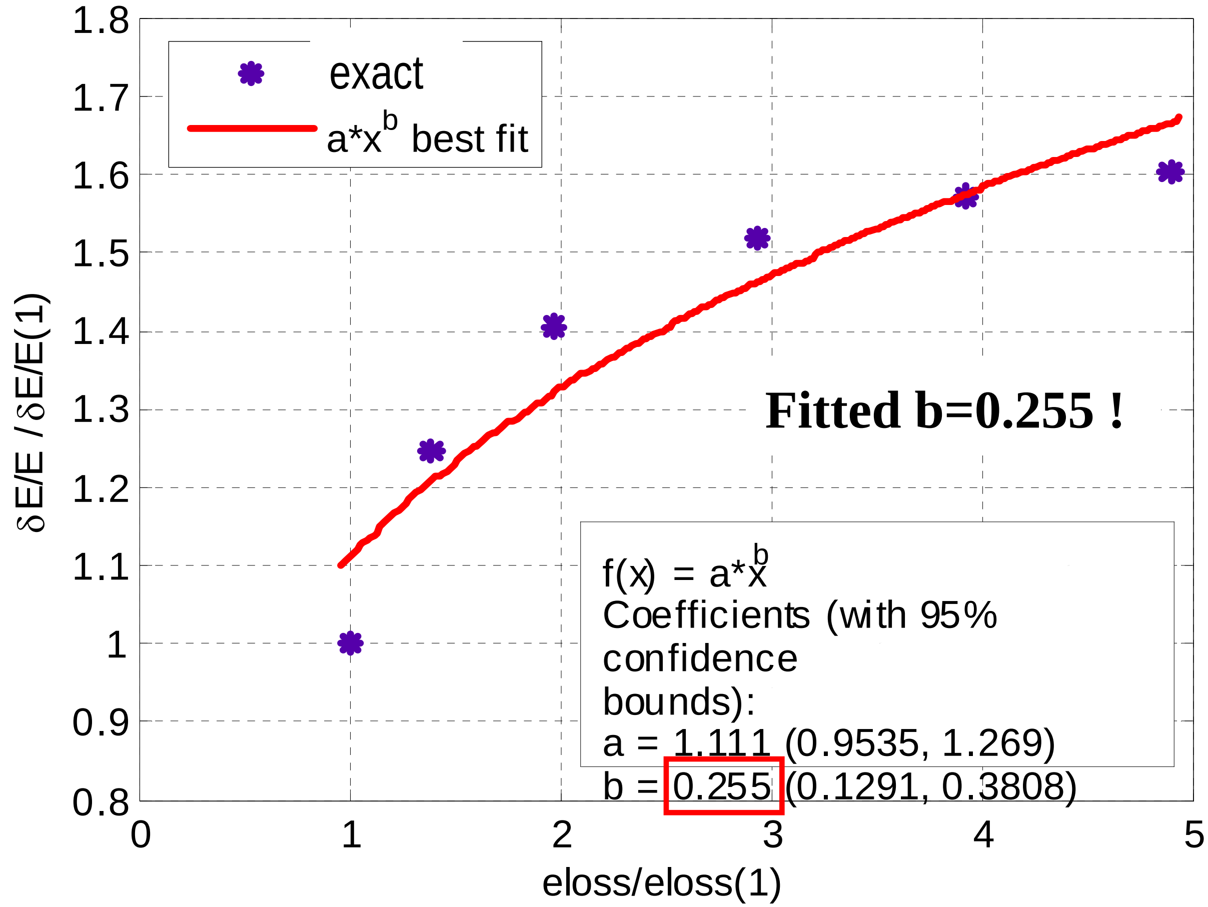
$$T_x^{-1} \approx \frac{r_0^2\, c\, N\,(\log)}{16\gamma^3 \varepsilon_x^{7/4} \varepsilon_y^{3/4} \sigma_z \sigma_p} \left\langle H_x\, \sigma_H\, g\left[\sqrt{\frac{\varepsilon_y \beta_x}{\varepsilon_x \beta_y}}\right] (\beta_y\, \beta_x)^{-1/4} \right\rangle, \Leftarrow$$

rapidly and slow-varying functions of U_{tot} shown in color

- ε_y=1Å/4π=constant (increase κ for lower ε_y); also we ignore the variation of σ_z
- For couplings 0.5%<κ<1 and β_x~β_y, g[$\kappa^{1/2}$] changes slowly => ignore
- dominant contribution $\quad \sigma_H^{-2} \approx \sigma_p^{-2} + H_x/\varepsilon_x \approx H_x/\varepsilon_x \propto U_{tot},$
- Assume $\sigma_p \sim U_{tot}^{1/4} \sim \varepsilon_x^{-1/4}$ (approx.!) we obtain $T_x \sim \varepsilon_x \sim 1/U_{tot}$. $\Rightarrow \varepsilon_x / \varepsilon_{x0} \approx const.$

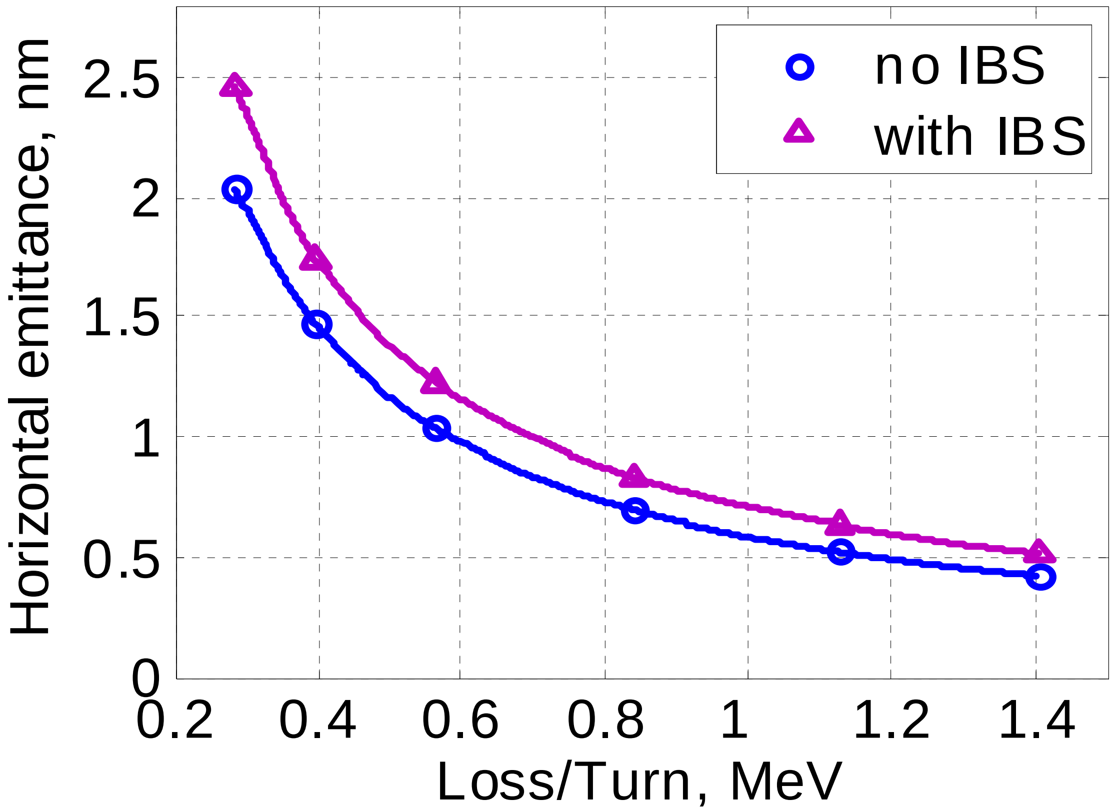
IBS-induced emittance blow-up is ~independent of energy loss U_{tot}!

Approximating Wiggler Effect on Energy Spread



Approximation is good enough for us. One could use exact formula for $\delta E/E(U_{tot})$; for reasonable wigglers it shouldn't change much.

ZAP Calculations



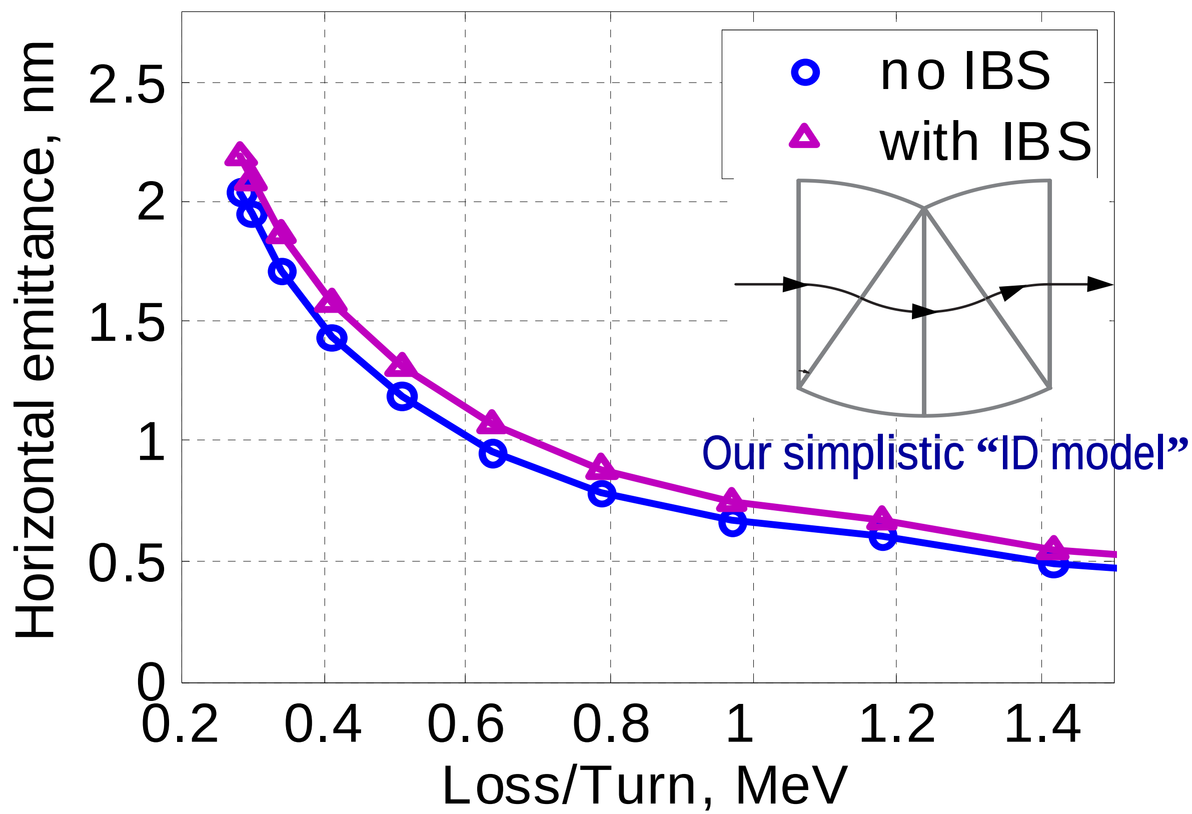
- ZAP uses 2D B-M algorithm (OK for flat beams in a LS).
- Computes growth rates, then iterates to find the equilibrium.
- for wiggler ε_x, $\delta E/E$, τ_{rad}, scaled "by hand" for radiation losses
- No tail cut in the Coulomb (log)=~17

IBS-induced emittance blow-up is ~20% and it is ~independent of energy loss!

Adding SAD (accelerator code by K. Oide)

WHY SAD ?

- Comprehensive (and well documented) IBS treatment, allows for full 3D coupling
- Full-blown lattice code
- Put ID model in the lattice and get self-consistent beam sizes



IBS-induced emittance blow-up is ~10% and it is ~independent of energy loss! Much of the difference ZAP/SAD is due to Coulomb log.

Work in progress with more realistic wiggler models.

Summary and Conclusions

- In a wiggler-dominated light source increased IBS rates due to denser bunches are offset by the increase in radiation damping.
- The magnitude of the IBS-induced emittance blow-up in a wiggler-dominated light source appears to be fairly independent of the emittance.
- IBS-induced relative emittance blow-up for NSLS-II should not exceed 20% at nominal bunch intensity (and several conservative assumptions) and therefore it should not present a problem.
- Want to repeat SAD calculations for realistic ID models; also check the case when vertical beam size is controlled by dispersion (not coupling).
- Experimental verification (at least when wiggler-dominated) is still lacking.

Acknowledgements

Many thanks to

K. Bane, A. Fedotov, J. Murphy, S. Krinsky, and J. Wei

for insightful discussions and/or help with cross-checking the results with other codes or analytic approaches.