Compensation of emittance and beam size variations induced by insertion devices

Fernando Sannibale

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ALS ADVANCED LIGHT SOURCE

Content

- Problem definition.
- Possible compensation schemes:
  - Use a variable gap wiggler to generate emittance.
  - Use of a “dispersion bump” inside a wiggler with gap at a fixed position.
  - Compensation by small variation of the beam momentum.
  - Using intra-beam scattering (IBS).
  - Compensation by “White Noise” Excitation in the Transverse Plane
- Final Considerations.

The MBA Lattice Revolution

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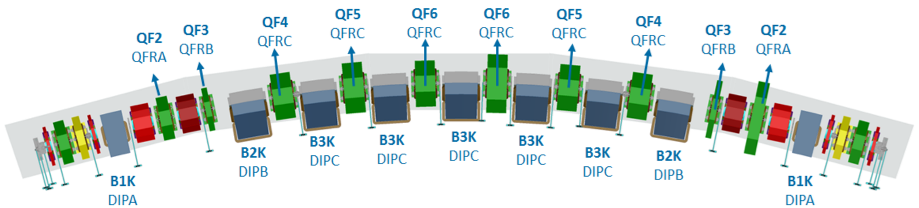
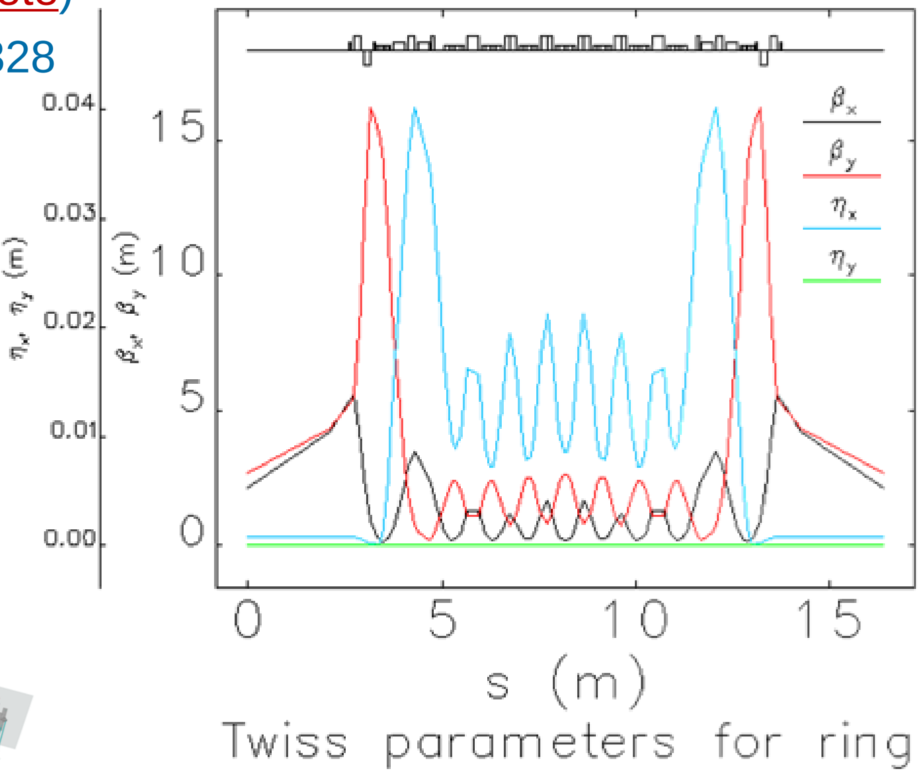
Tens of pm emittances, orders of magnitude brightness increase, approaching fully photon coherence in the transverse plane!

Ultra-Low Emittance MBA Lattices

Example: ALS-U 9BA Lattice v18_127 (obsolete)

- 1.15 nC/bunch - 2 GeV - L = 196.5 m - h = 328
- Dipole: ρ = 8.6 m ; k_1= -7 m^{-2}; θ = 3.33 deg
- ε_0 = 109 pm (no IBS) – 12 super-periods
- Full coupling:
- $\varepsilon_x = \varepsilon_y$ = 81.32 pm (with IBS and harm. cav.)
- σ_z = 14.56 mm (with IBS and harm. cavities)
- δ_0 = 0.0828% - U_0 = 181.9 keV (no IDs)
- α_c= 2.68 10^{-4} - j_x=1.865





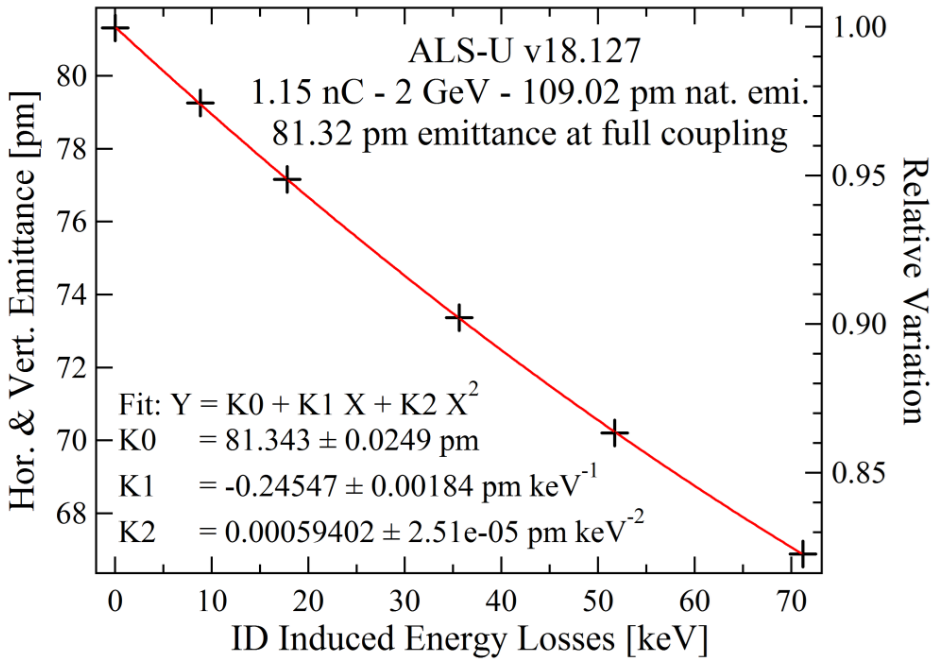
In such lattices, the typically large bending radius decreases the energy radiated in the bends making it comparable to that radiated in insertion devices (IDs).

In this situation, the IDs' contribution significantly contributes to radiation damping and hence in defining the ring natural emittance.

Significant Emittance Dependence on IDs

Energy losses induced by IDs increase damping decreasing emittance

(ELEGANT simulations).



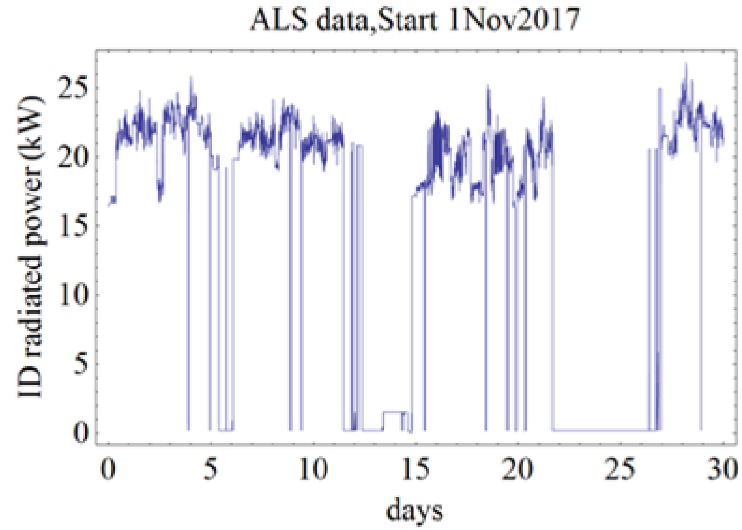
In this particular example using the ALS-U lattice v18.127, a 20 keV energy loss induced by IDs decreases the emittance by about 5 pm equivalent to ~6% of emittance reduction.

How large are ID induced energy losses in a real ring?

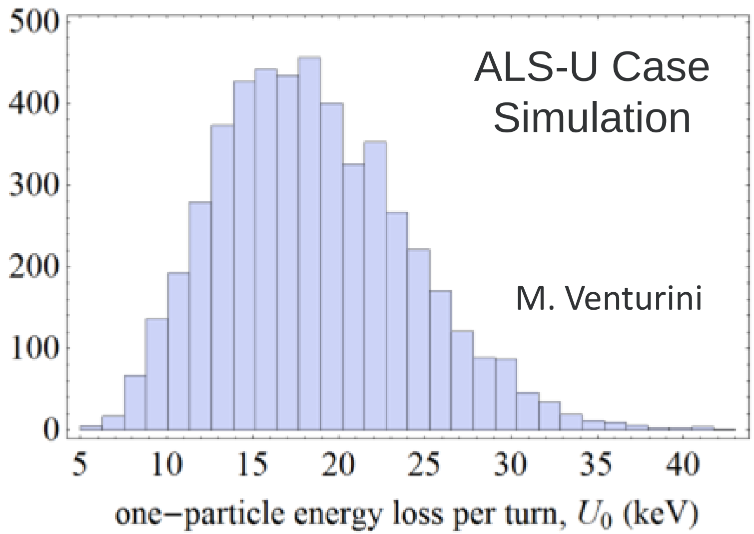
Example of ID Induced Energy Losses in a Ring

ALS Insertion Devices

Name	Alias	BL	New?	λ_u (mm)	BX_{max} (T)	BX_{min} (T)	BY_{max} (T)	BY_{min} (T)	No. periods
EPU50		4.0.2	No	50	0.58	0.1	0.8	0.1	37
QEPU90	MERLIN	4.0.3	No	90	0.78	0.06	1.18	0.06	20.5
U114		5.0.1	No	114	1.94	0.03	0	0	29
EPU38	COSMIC	7.0.1	No	38	0.89	0.11	0.67	0.11	44.5
EPU70	MAESTRO	7.0.2	No	70	1.18	0.07	0	0	26.5
U50		8.0.1	No	50	0.85	0.1	0	0	80
U100		9.0.1	No	100	0.98	0.05	0	0	43
U100		9.0.1	No	100	0.8	0.05	0	0	43
EPU50		11.0.1	No	50	0.85	0.1	0.57	0.1	36.5
EPU50		11.0.2	No	50	0.85	0.1	0.58	0.1	37
U80		12.0.1	No	80	0.8	0.07	0	0	55



Random ID gaps variation generates random beam radiated power variations.

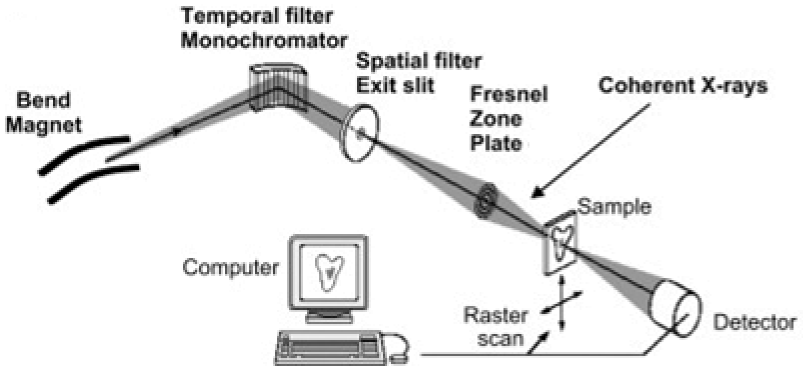


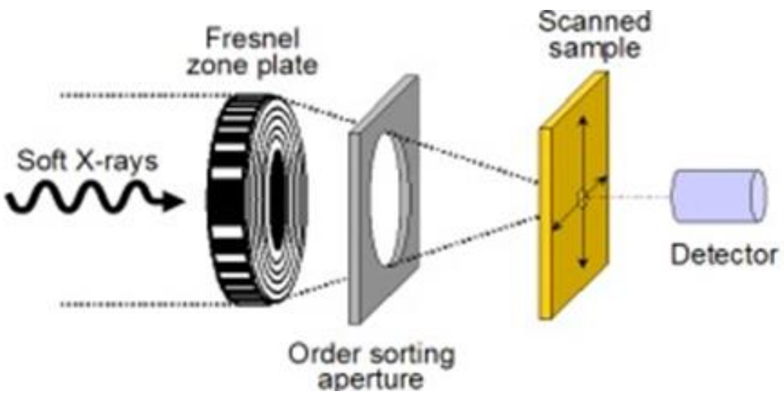
$$\langle U_0 \rangle = 18.5 \text{ keV}, \ \sigma_{U0} = 5.6 \text{ keV}$$

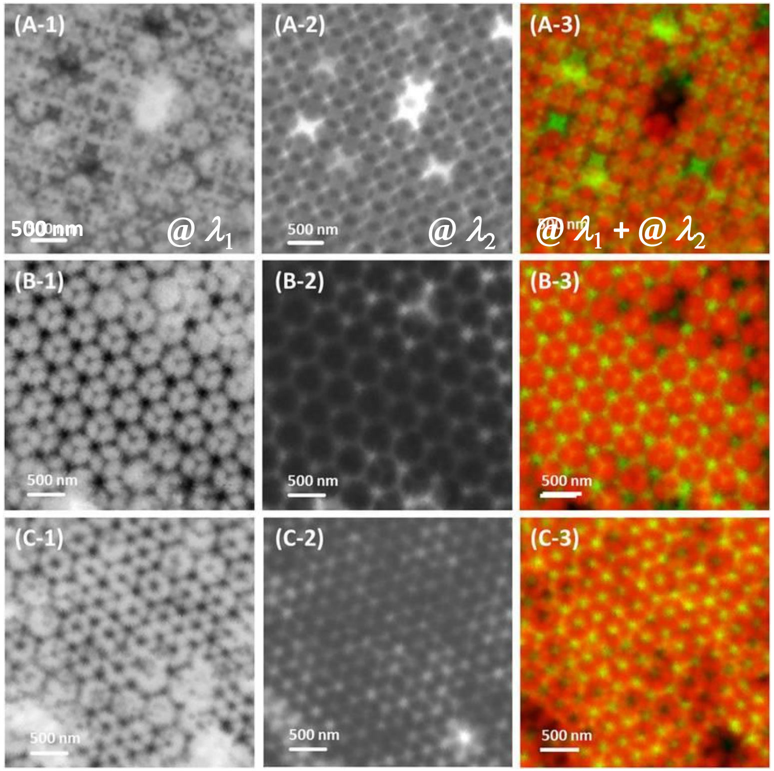
$$\Delta\varepsilon/\varepsilon \sim 7\ \% \quad (4 \text{ sigma})$$

How important such an emittance variation to experiments?

Example: STXM- Scanning Transmission X-Ray Microscopy







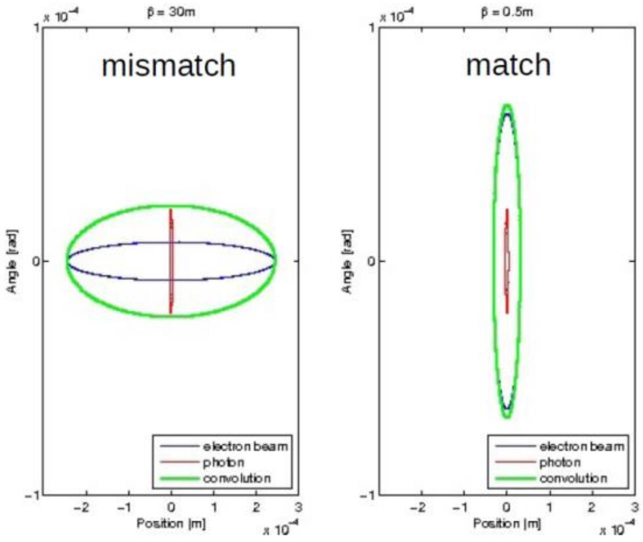
Colloid Crystal STXM Image. H. W. Nho, T. H. Yoon, (2017). Scientific Rep. 7. 10.1038/s41598-017-12831-4.

X-ray microscopy/spectroscopy technique very sensitive to beam size and hence to emittance variations.

In general, experiments where beam size variations induce amplitude modulation that cannot be normalized by real time I_0 measurements can be affected by emittance variations.

Additional Considerations

Experiments using photon energies where the beam is diffraction limited are less sensitive to electron beam emittance/ size variations.



In rings with transverse electron beam sizes with high aspect ratio (flat beams), compensating vertical beam sizes variations induced by moderate emittance variations by global coupling control can suffice.

Possible Compensation Techniques

- Variable gap wiggler
- Dispersion bump in a wiggler
- Small beam momentun variation
- Intra-beam scattering (IBS).
- Transverse plane “white noise” excitation

Compensation by Variable Gap Wiggler

$$U_0 = \frac{C_\gamma}{2\pi} E^4 I_2 \qquad C_\gamma = 8.846\ 10^{-5}\ m/GeV^3 \qquad I_2 = \oint \frac{ds}{\rho^2} = \frac{B^2\, L_w}{2\,(B\rho)^2} \quad (wiggler)$$

$$B = 2\pi \frac{mc}{e} \frac{K_w}{\lambda_w} \quad (wiggler)$$

$$U_0 = \pi\, C_\gamma \left(\frac{m\, c^2}{e}\right)^4 \gamma^2 \left(\frac{K_w}{\lambda_w}\right)^2 L_w$$

The gap of the compensating wiggler is closed when the other IDs are open, and is gradually opened to keep the emittance constant when the other IDs close.

ALS Wiggler example: λ_W = 0.114 m; $N_{Periods}$ = 29; L_W = 3.3 m; K_W = 20.6; B_W = 1.94 T;

U_0 = 28.3 keV @ 1.9 GeV or 31.4 keV @ 2 GeV

Pros.:
- Allow operating at an emittance value smaller than the one obtainable from the bare lattice without IDs.

Cons.:
- Requires a dedicated wiggler

Compensation by Local Dispersion Bump in Fixed Gap Wiggler

$$\varepsilon_0 = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2}$$

$$I_2 = \oint \frac{ds}{\rho^2} \qquad C_q = \frac{55}{32\sqrt{3}}\frac{h}{2\pi\, mc} \approx 3.832 \times 10^{-13}\, m$$

$$J_x = 1 - \frac{I_4}{I_2} \qquad I_4 = \oint \frac{\eta_x}{\rho}\left(\frac{1}{\rho^2} + 2k_1\right) ds \qquad k_1 = \frac{e}{p}\frac{\partial B_y}{\partial x}$$

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds \qquad \mathcal{H} = \gamma_x {\eta_x}^2 + 2\alpha_x \eta_x \eta'_x + \beta_x {\eta'_x}^2$$

Assuming a horizontal dispersion bump Inside the wiggler with η_x constant and $\eta'_x = 0$

$$\rightarrow \Delta I_{5W} \sim \frac{4}{3\,\pi}\frac{{B_W}^3}{(B\rho)^3} L_W \langle\gamma_x\rangle\, {\eta_x}^2, \qquad \Delta I_{2W} = 0, \qquad \Delta I_{4W} \sim 0$$

$$\rightarrow \frac{\Delta\varepsilon}{\varepsilon} \sim \frac{\Delta I_{5W}}{I_5}$$

Using the ALS wiggler and $<\gamma_x> = 1/2.5\ \mathrm{m}^{-1}$ (ALS-U 18.127) and η_x = 1 cm $\rightarrow \Delta\varepsilon/\varepsilon \sim 5\%$

Pros.:

- Potentially compatible with user operation of the wiggler at fixed gap (if wiggler users can accept horizontal beam size variations)

Cons.:

- Requires extra knobs to perform the local dispersion bump.
- Bump size not negligible. Possible effects on beam dynamics should be evaluated.

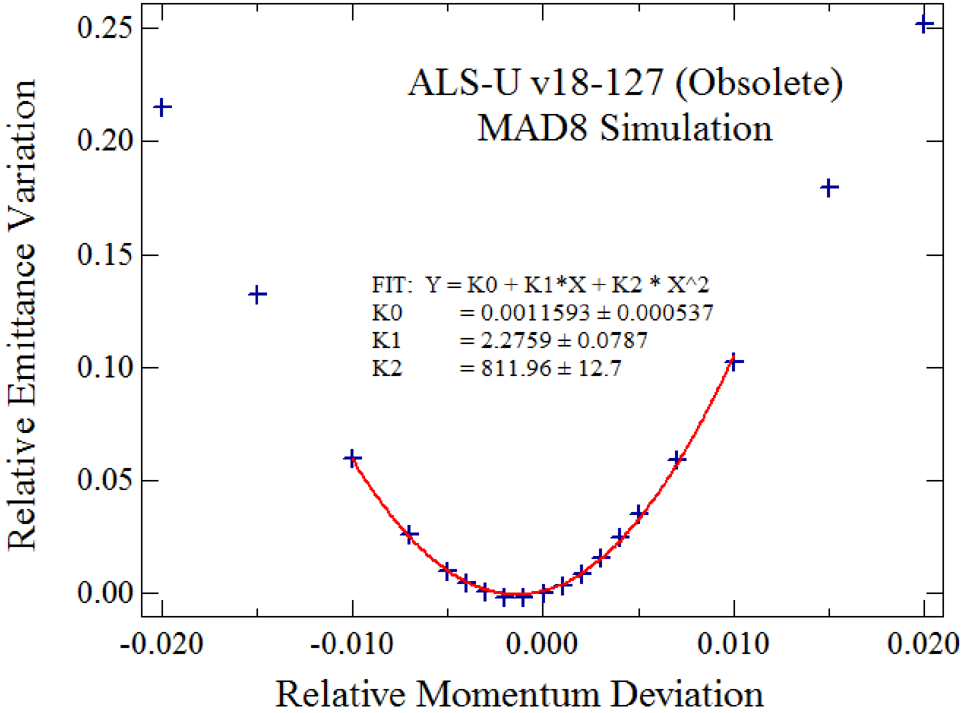
Compensation by Small Beam Momentum Variations

The beam momentum can be modified by varying the RF frequency

$$\delta p = \frac{dp}{p_0} = -\frac{1}{\alpha_C}\frac{df_{RF}}{f_{RF}}$$

And due to the dependence of the emittance terms on energy, we can change the emittance

$$\varepsilon_0 = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2}$$



In the ALS-U v18.127 example, a 5% emittance variation can be obtained with ~ 1% momentum variation (~ 1.3 kHz RF variation)

The scheme it is not practical because it moves source points in dipoles, change the energy of the radiated photons, and can challenge the ring momentum acceptance.

Using Intra-beam Scattering (IBS) to Compensate Emittance

$$\varepsilon'_{x0} = \frac{1}{1 - \frac{\tau_x}{T_x}} \varepsilon_{x0}$$

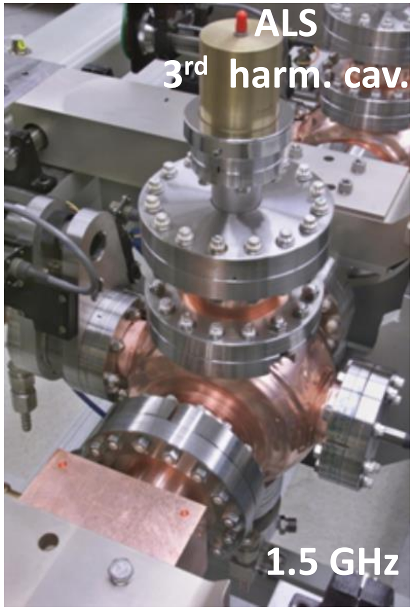
$$\frac{1}{T_x} \approx 2\pi^{3/2} A \left\langle \frac{\mathcal{H}_x \sigma_H^2}{\varepsilon_x} \left(\frac{1}{a} g\left(\frac{b}{a}\right) + \frac{1}{b} g\left(\frac{a}{b}\right) \right) - a\, g\left(\frac{b}{a}\right) \right\rangle (\log)$$

$$A = \frac{r_e^2 c N_0}{64 \pi^2 \gamma^4 \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta}$$

Bjorken-Mtingwa

$$\Rightarrow \frac{\Delta\varepsilon'_{x0}}{\varepsilon_{x0}} \sim \frac{\tau_x}{T_x} \propto A \propto \frac{1}{\sigma_z} \qquad \text{for} \frac{\tau_x}{T_x} \ll 1$$

The last expression shows that bunch length can be used for generating emittance variations and hence to compensate for ID induced emittance variations.

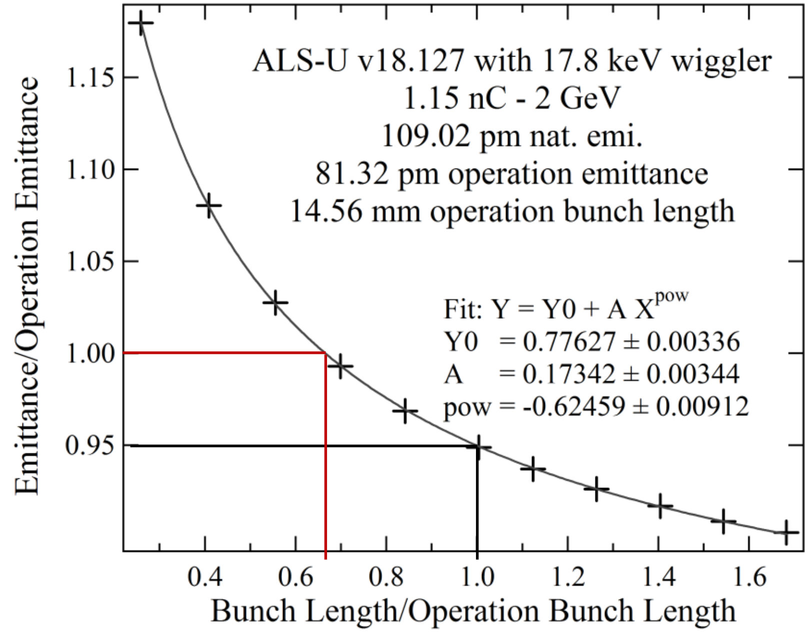


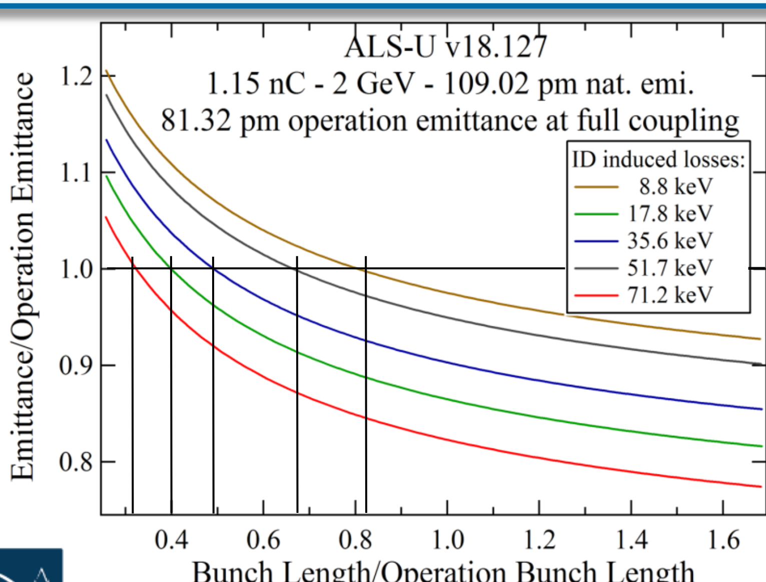
Harmonic cavities, when present, can be used for that purpose

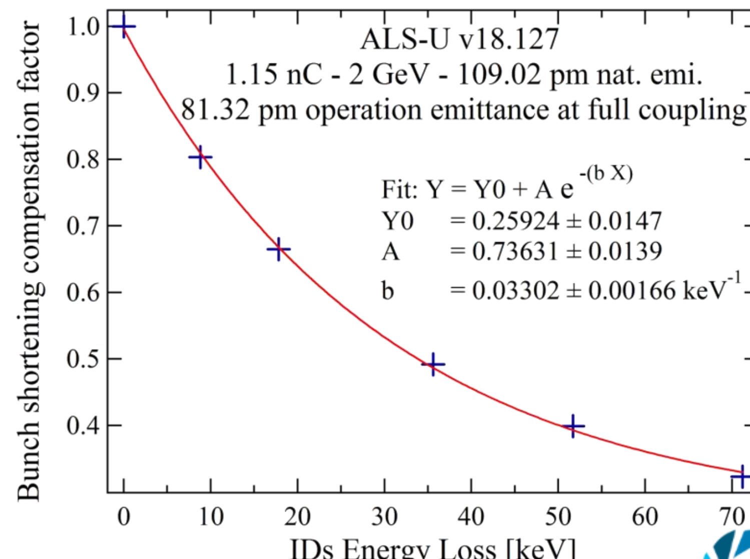
Using Intra-beam Scattering (IBS) to Compensate Emittance

IDs losses simulated with ELEGANT by adding 12 wigglers to the ALS-U v18.127 lattice : λ_W=7.63cm, L_W = 4.196 m, Np=55, variable K_W

Example: Wigglers tuned for ~ 18 keV losses.
Emittance decreases to ~95% of the no ID value if the bunch length is not changed.
To reestablish the emittance to the original value the bunch must be shortened to ~ 66% of the no ID value (using the harmonic cavities).
Lifetime will be also reduced by the same factor!
Possible intensity modulation on high harmonics…







Compensation by "White Noise" Excitation in the Transverse Plane

ARTIFICIAL BEAM ENLARGEMENT

Philip L. Morton
Stanford Linear Accelerator Center
Stanford, California

P. Morton, Trans. Nucl. Scie. 20, 862 (1973)

The beam is constantly excited in the transverse plane by uniform noise over a proper bandwidth centered on one of the betatron tune harmonics.

Field non-linearities generate tune shift on amplitude making the beam particles' oscillation incoherent resulting in an increase of the transverse r.m.s. beam size.

Pros.:

- If part of a feedback and properly tuned the system demonstrates good beam size stability. For example, at SURF (Arp et al., Rev. Scie. Instr. 73, 2002)

Cons.:

- If not properly tuned can lead to beam instabilities.
- The excitation introduces noise in the beam that can affect time resolved experiments.

Final Considerations

- In most of presently proposed/built low emittance MBA lattices, insertion device and bend magnet radiation losses are now comparable.
- ID gaps variations during user operation generate significant emittance variations that ultimately translate on electron and photon beam size variations.
- Such variations can negatively affect some of the users' experiments and should be preferably compensated.
- Several compensation schemes with respective pros and cons were discussed:
  - A variable gap wiggler can maintain a constant operation emittance but requires a dedicated wiggler.
  - ALS-U ? → A dispersion bump in a fixed gap wiggler does not require a dedicated wiggler but requires knobs for the bump control, significant size bumps, and could affect beam dynamics.
  - Small electron beam momentum variations can be used but they move dipole source points, shift photon energy and can affect the ring dynamic aperture.
  - Control by IBS requires significant bunch length shortening using harmonic cavities, affecting lifetime and stressing cavity tuning control.
  - Excitation of incoherent transverse oscillations by "white noise" allow for beam size control but introduces beam noise that can affect time resolved experiments