



Intra-beam Scattering in the Low
Energy MAX-IV Storage Ring

H. Tarawneh

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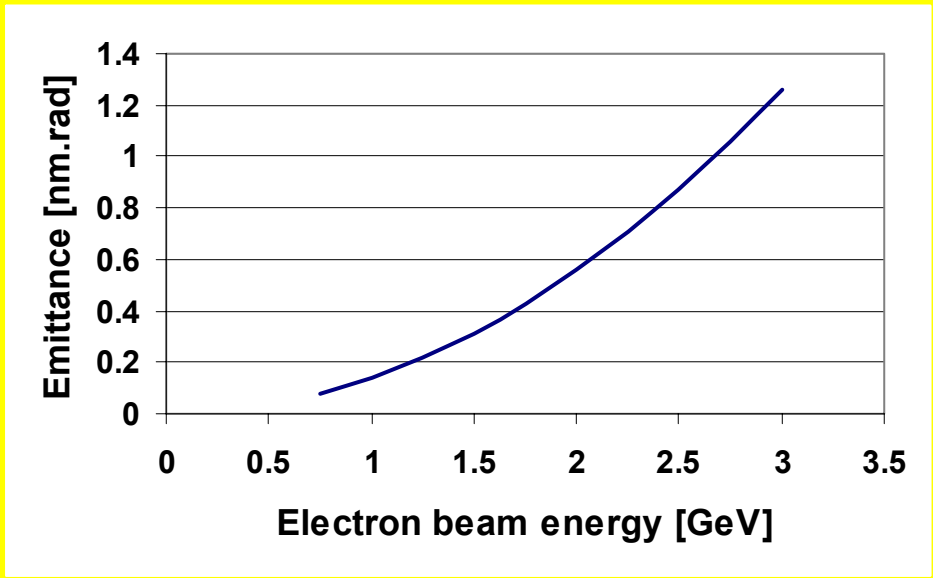
The MAX-IV Lattice

The equilibrium of the excitation and the damping of the betatron oscillations determines the emittance of the stored beam with the result:

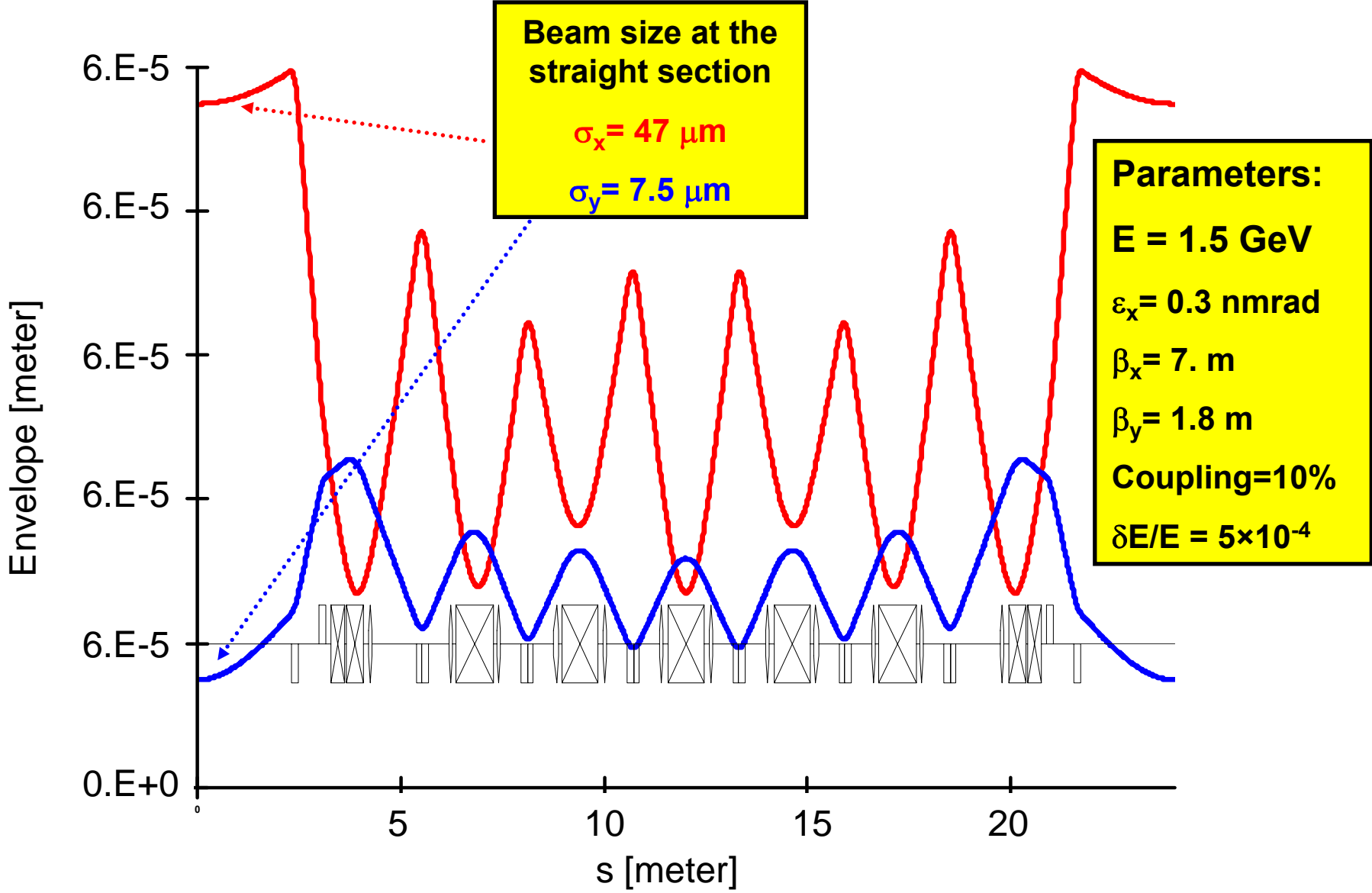
$$\varepsilon_x = C_q \frac{\gamma^2}{\rho J_x} \frac{1}{2\pi\rho} \int_{Dipoles} H ds$$

$$H = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta_x'^2$$

⇒ The emittance is determined by the behaviour of the dispersion - and the horizontal betatron function within the bending magnets. The emittance is given by the lattice of the machine.



Beam cross sections at the MAX IV

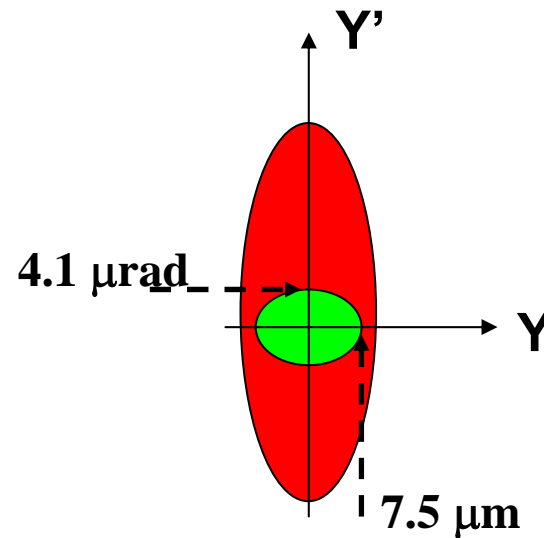
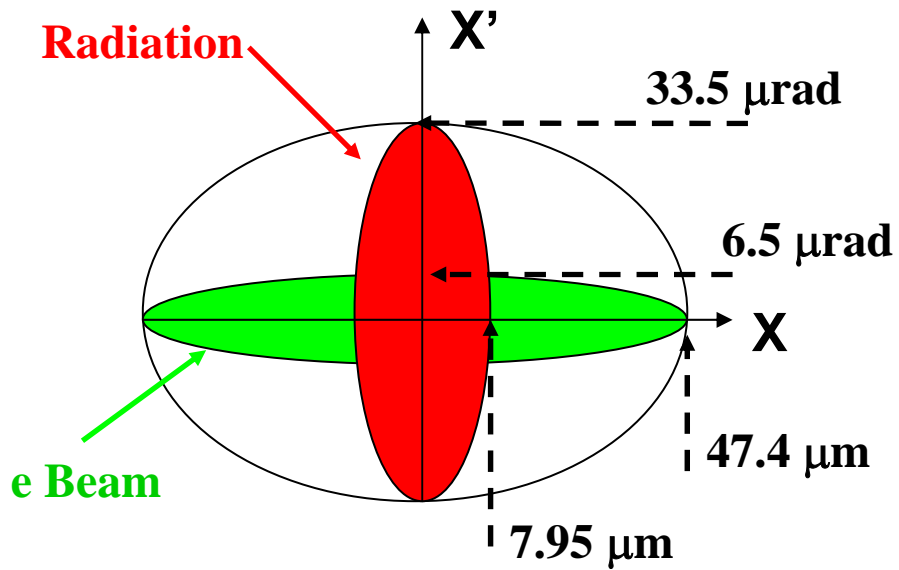


Phase space of electron beam and undulator radiation

Soft X-ray 1.5 GeV electron beam, 10% Coupling

Horizontal direction

Vertical direction

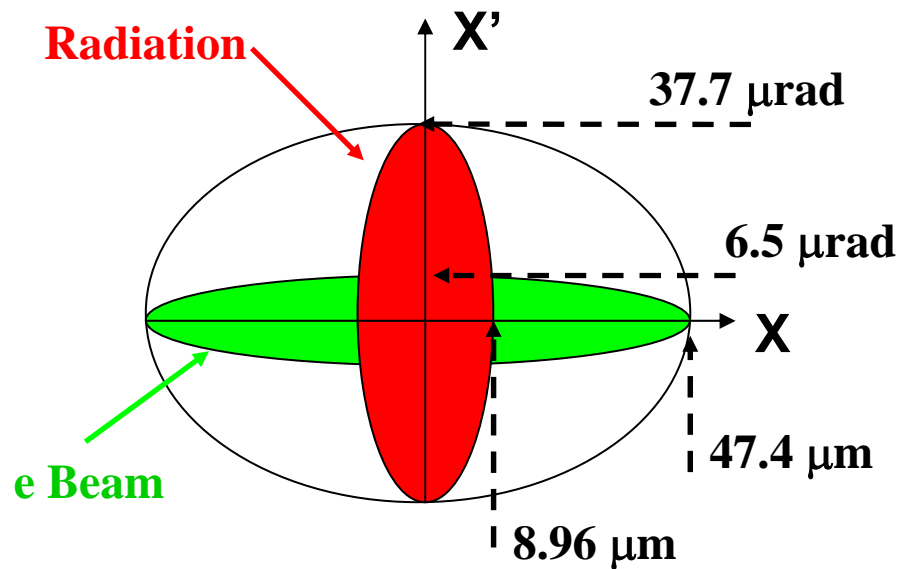


SC undulator: $\lambda_u=16.5$ mm, $N=181$, $L=3$ m, $n=1$, $\lambda=33\text{\AA}$ (375 eV)

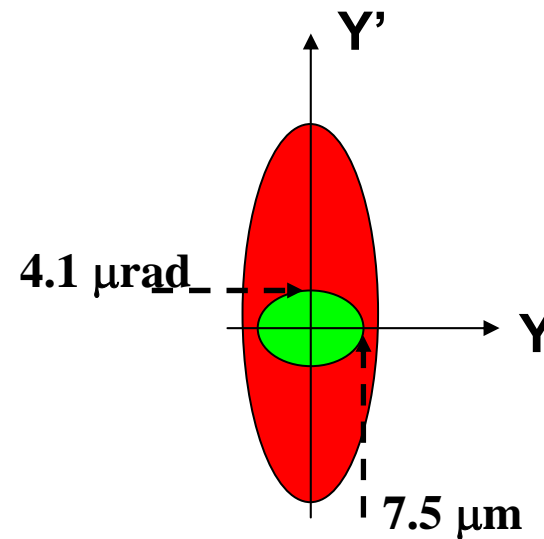
Phase space of electron beam and undulator radiation

Soft X-ray 1.5 GeV electron beam, 10% Coupling

Horizontal direction



Vertical direction



CPM undulator: $\lambda_u = 21.5 \text{ mm}$, $N = 139$, $L = 3 \text{ m}$, $n = 1$, $\lambda = 42.5 \text{ \AA}$ (295 eV)

The Touschek Losses

- The high bunch densities and the electrons betatron & longitudinal oscillations lead to enhanced rate of elastic collisions between electrons in all planes.

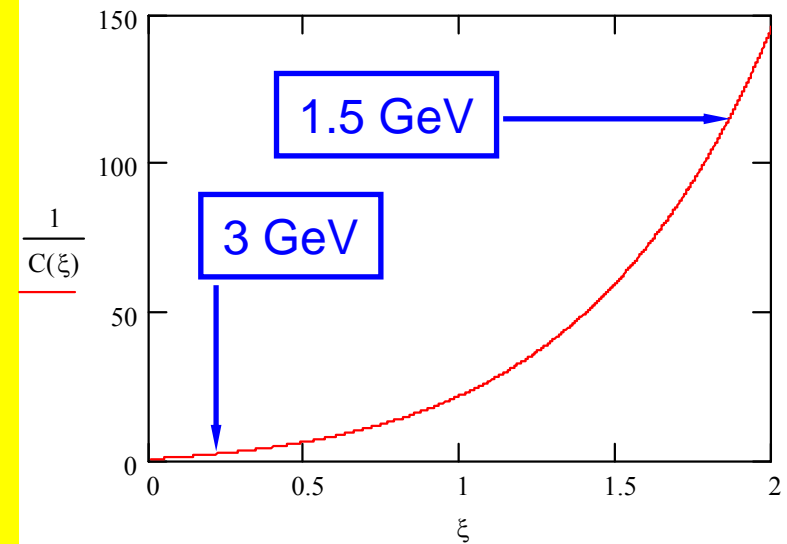
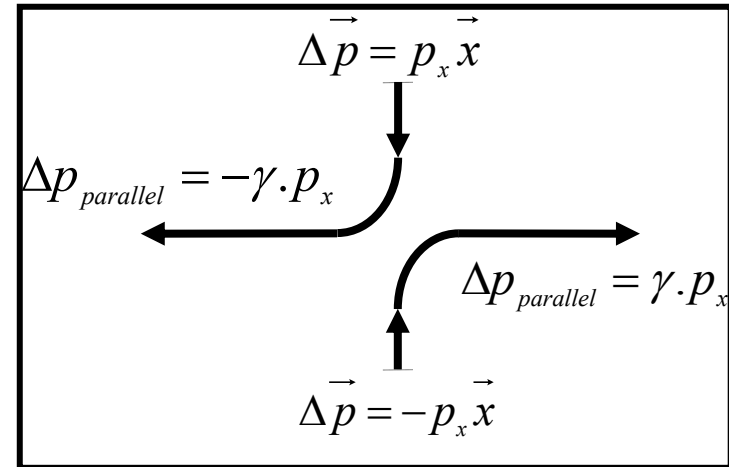
⇒ Energy transfers due to collisions in all planes.

Touschek event :

$$p_x, p_y \gg p_z$$

- Energy transfer of transverse momenta into longitudinal one can lead to the loss of both electrons.
- A displacement of 50 μm at a point with $\beta_x=5\text{ m}$ and beam energy of 1.5 GeV gives $\Delta p=44\text{MeV}$, i.e. $\sim 3\%$ energy deviation.

- Lifetime
$$\tau_{\text{Tou}} = \frac{\gamma^2 V_B \epsilon_{\text{acc}}^3}{\sqrt{\pi} r_e^2 c N_e} \frac{1}{C(\xi)}$$



Intra-beam Scattering - Theory



Intra-beam scattering (IBS) is the result of multiple small angle collisions between particles in the beam leading to diffusion.

IBS increases the equilibrium emittance until the additional diffusion is countered by the synchrotron radiation damping.

Diffusion or Emittance Growth $\implies \epsilon_{x,y} = \frac{\epsilon_{x0,y0}}{1 - \tau_{x,y}/T_{x,y}} \quad \sigma_{\epsilon}^2 = \frac{\sigma_{\epsilon0}^2}{1 - \tau_{\epsilon}/T_{\epsilon}}$

- IBS event will first heat the longitudinal plane ($p_x, p_y \gg p_{\epsilon}$).

$$\frac{1}{T_{\epsilon}} \approx \frac{r_0^2 c N}{32 \gamma^3 \epsilon_x \epsilon_y \sigma_l \sigma_{\epsilon}^2} \left(\frac{\epsilon_x \epsilon_y}{\langle \beta_x \rangle \langle \beta_y \rangle} \right)^{1/4} \ln \left(\frac{\langle \sigma_y \rangle \gamma^2 \epsilon_x}{r_0 \langle \beta_x \rangle} \right)$$

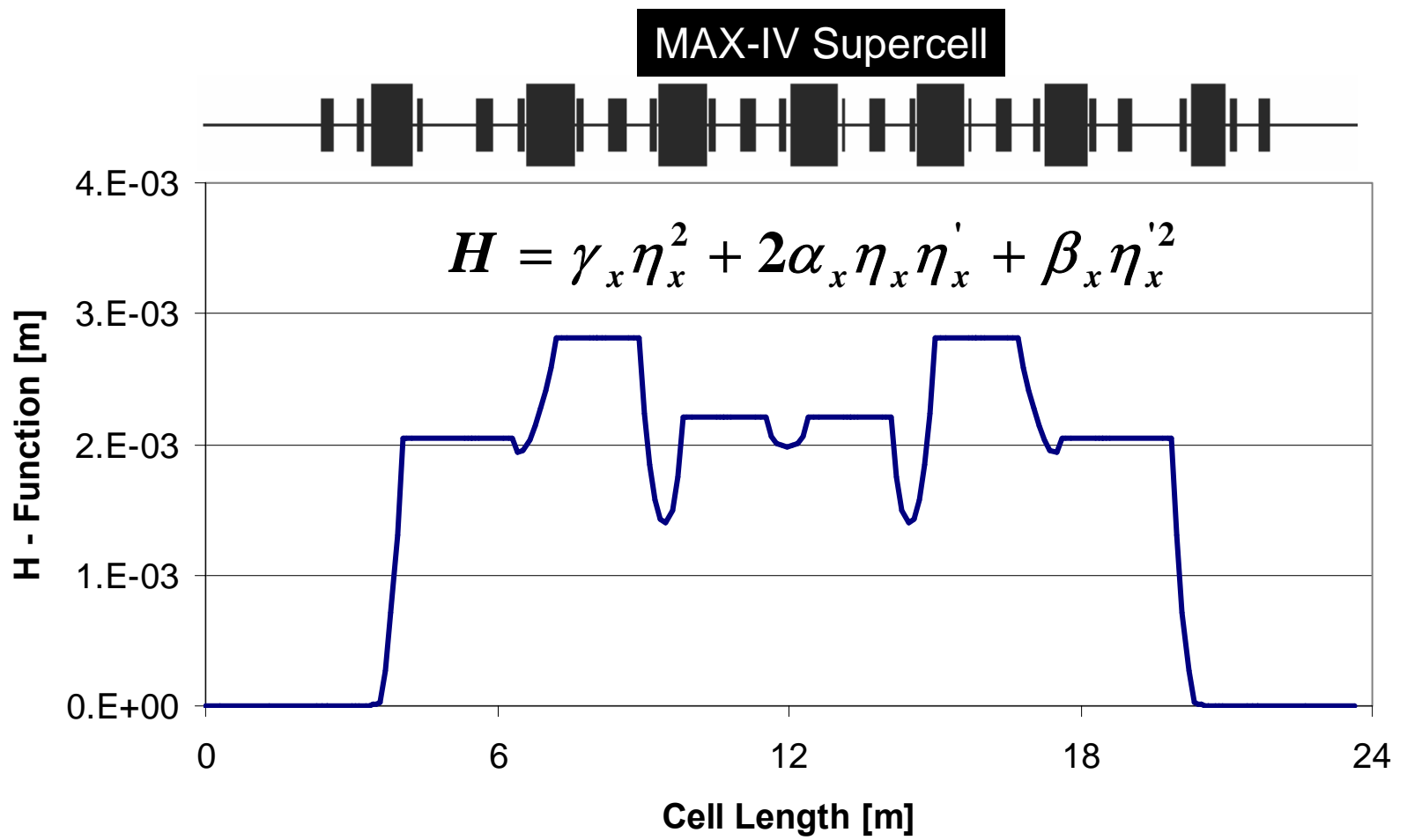
- An increase of the transverse emittance through the H - function, similar to SR.

$$\frac{1}{T_{x,y}} \approx \frac{\sigma_{\epsilon}^2 \langle H_{x,y} \rangle}{\epsilon_{x,y}} \frac{1}{T_{\epsilon}}$$

IBS vs. Betatron Functions



IBS increases the emittance everywhere along the accelerator whereas SR only in the bending magnet and the ID's.



Intra-beam scattering in the 1.5 GeV ring



$\varepsilon_0 = 0.34 \text{ nmrad}$
Nat. $\sigma_\varepsilon = 5 \times 10^{-4}$
Nat. $\sigma_l = 0.99 \text{ cm (400kV)}$
No. of bunches = 95

Short bunches

$\sigma_\varepsilon = 1 \times 10^{-3}$
 $\sigma_l = 1.98 \text{ cm (400kV)}$

Lengthening:

- BB impedance.

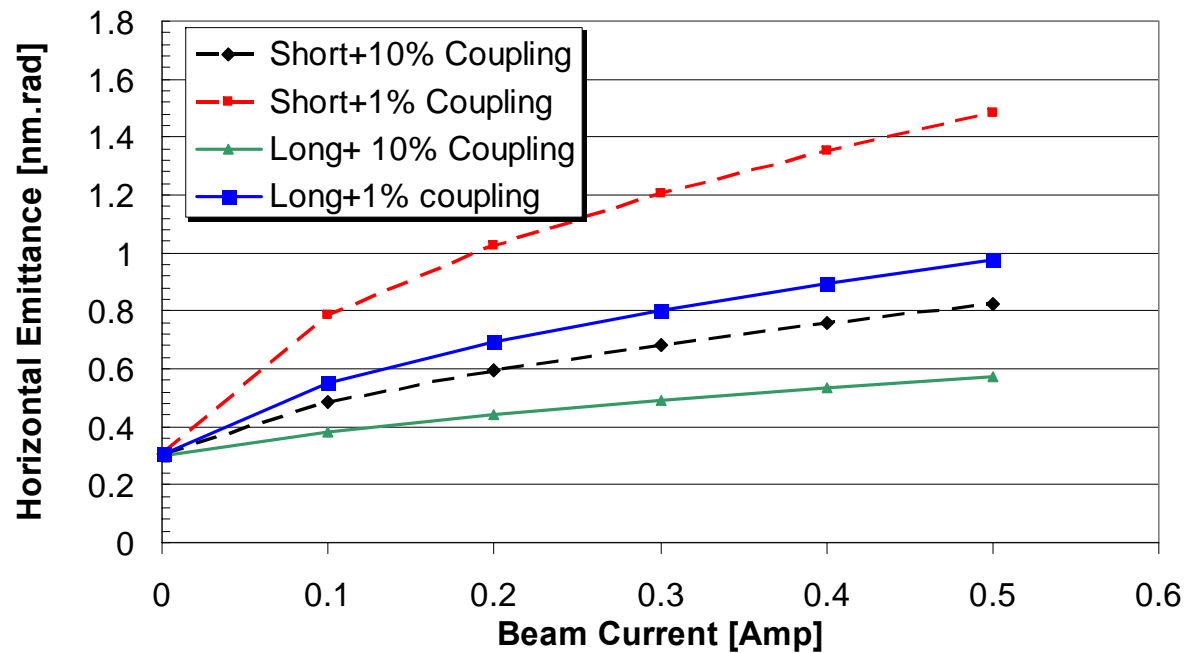
Long bunches

$\sigma_\varepsilon = 1 \times 10^{-3}$
 $\sigma_l = 5.66 \text{ cm (400kV)}$

Lengthening:

- BB impedance.
- Passive cavities.

Emittance Growth due to IBS



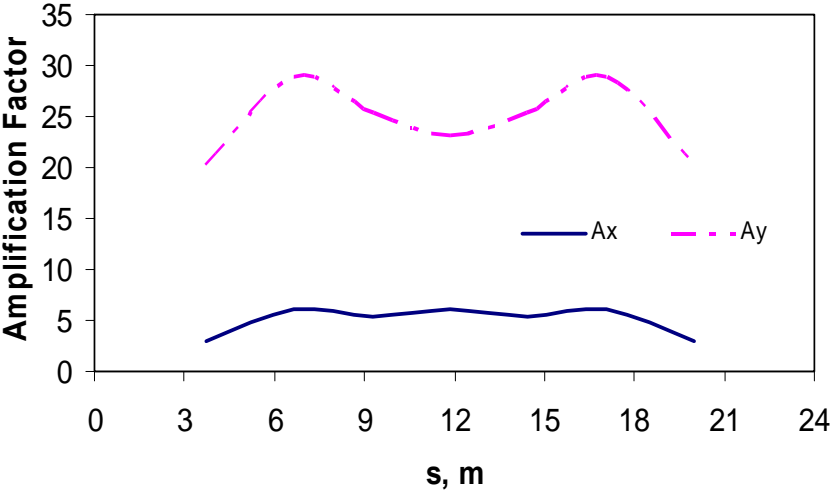
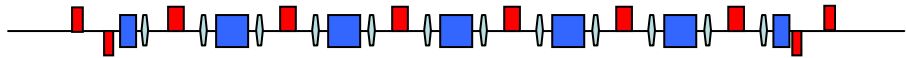
Dipole Misalignment



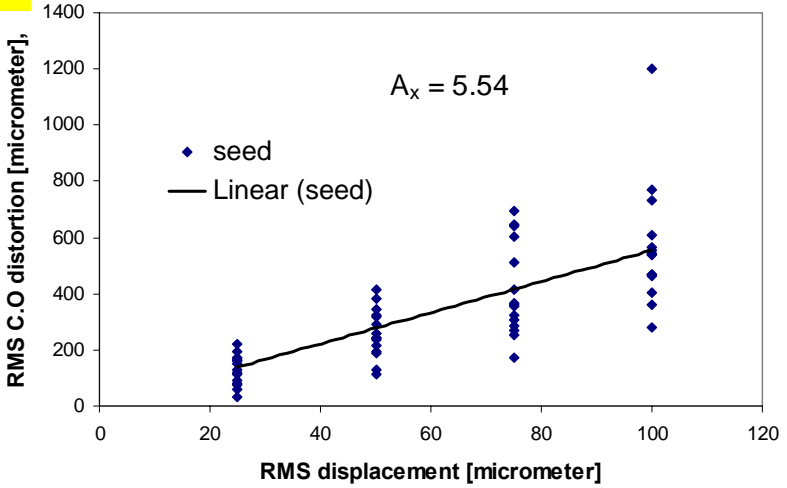
- Vertical dispersion due to magnets misalignment

-Contribution of each dipole to different Amp. factor $A_{x,y}$
 -Random Misalignment error over 120 seeds.

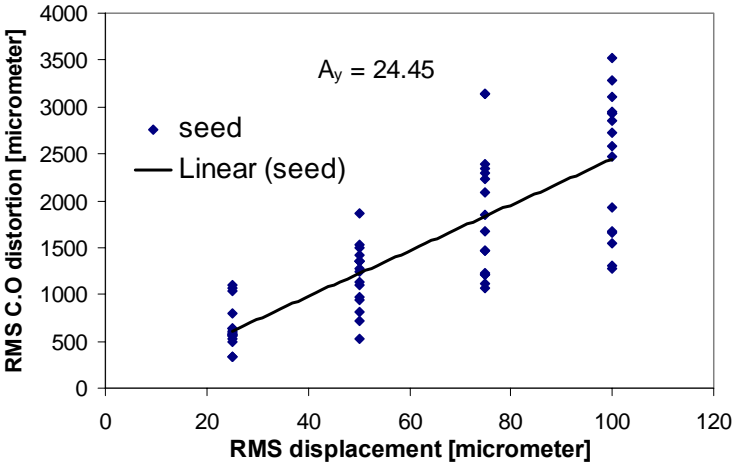
$$A_{x,y} = \frac{\langle \Delta u^{CO} \rangle_{RMS}}{\langle \Delta i \rangle_{RMS}}$$



Random dipole misalignment (Hor.)



Random dipole misalignment (Vert.)



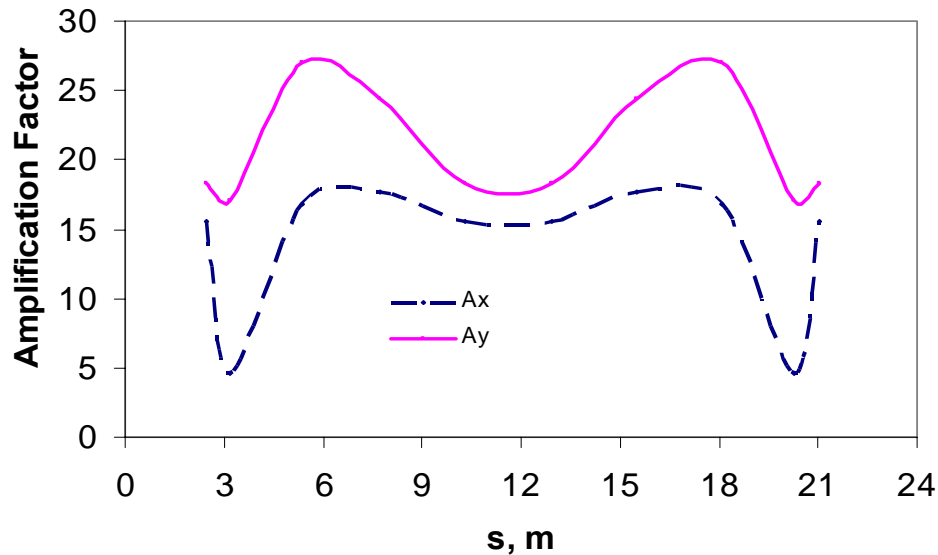
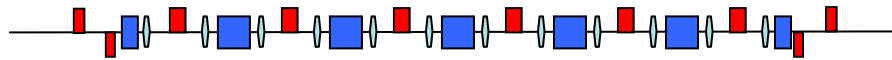
Quadrupoles Misalignment



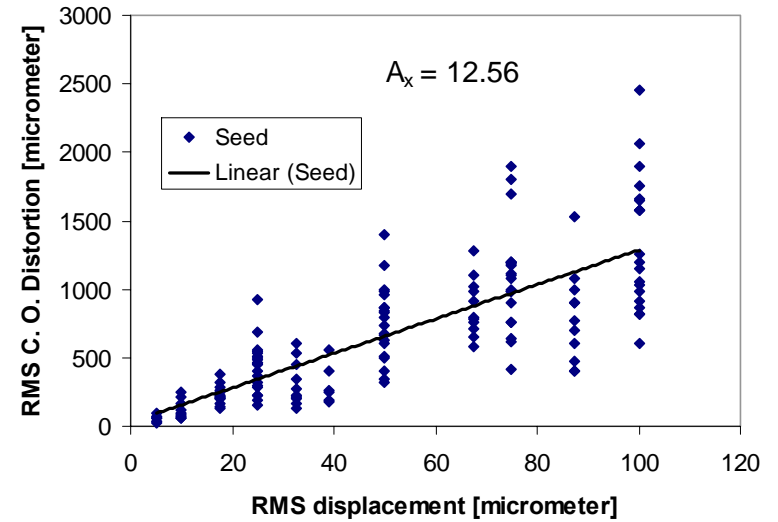
- Vertical dispersion due to magnets misalignment

-Contribution of each Quad. to different Amp. factor

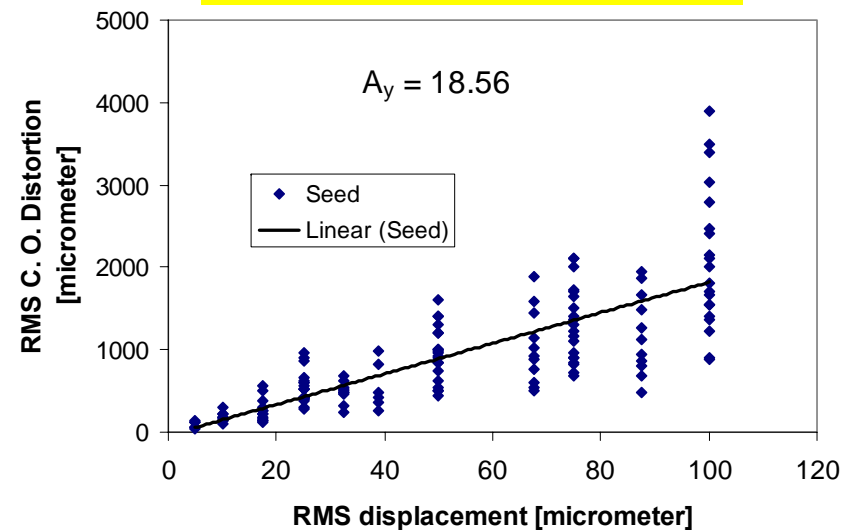
-Random misalignment errors over 150 seeds.



Random Quad. Misalignment (Hor.)



Random Quad. Misalignment (Vert)

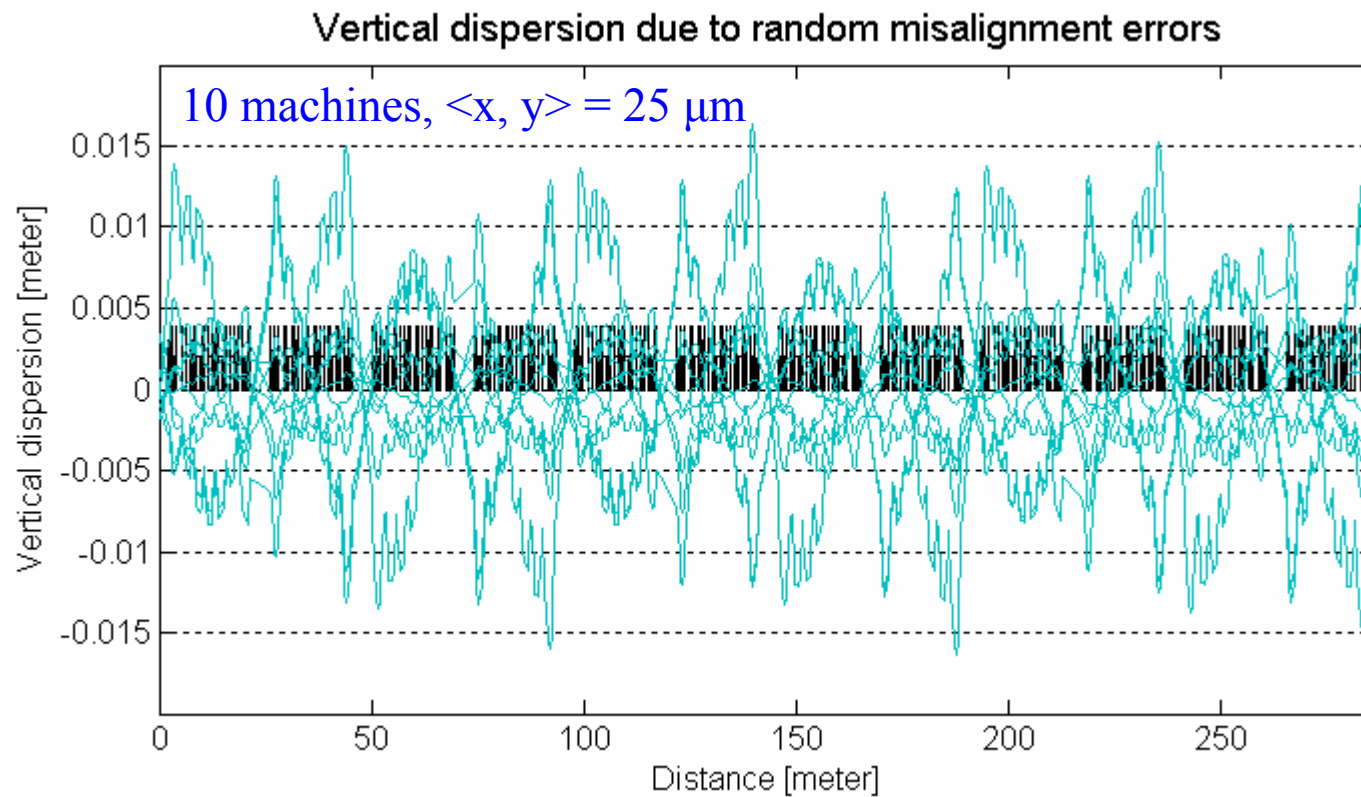


Vertical Dispersion



Two sources for vertical emittance:

- **Betatron coupling**
- **Vertical dispersion**



Intra-beam Scattering with 2 GeV Energy



$\varepsilon_x = 0.56 \text{ nmrad}$
Nat. $\sigma_\varepsilon = 6.6 \times 10^{-4}$
Nat. $\sigma_l = 1.3 \text{ cm (550kV)}$
No. of bunches = 95

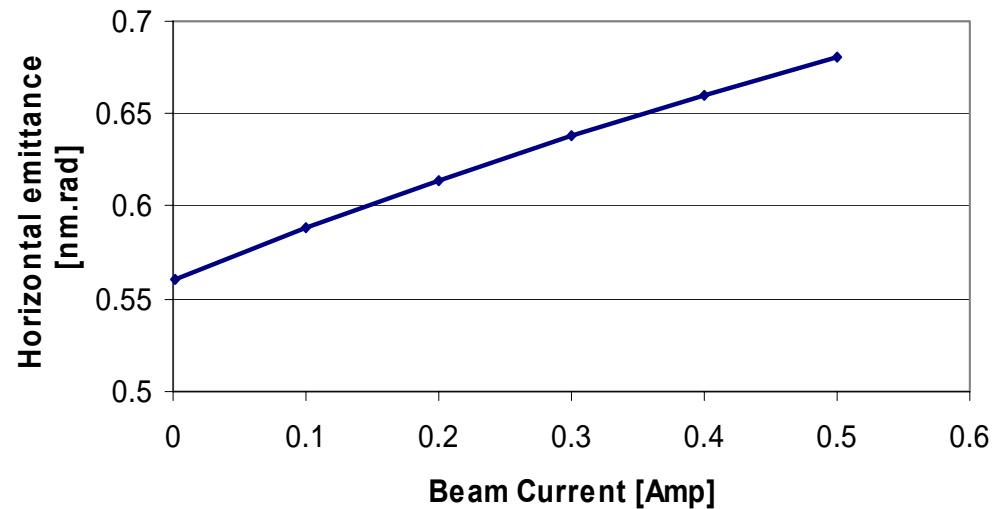
Parameters Used

$\sigma_\varepsilon = 1 \times 10^{-3}$
 $\sigma_l = 1.975 \text{ cm (550kV)}$
5% coupling

Lengthening:

•BB impedance.

Emittance growth due to IBS at 2 GeV



Undulator Spectra vs. Beam Energy

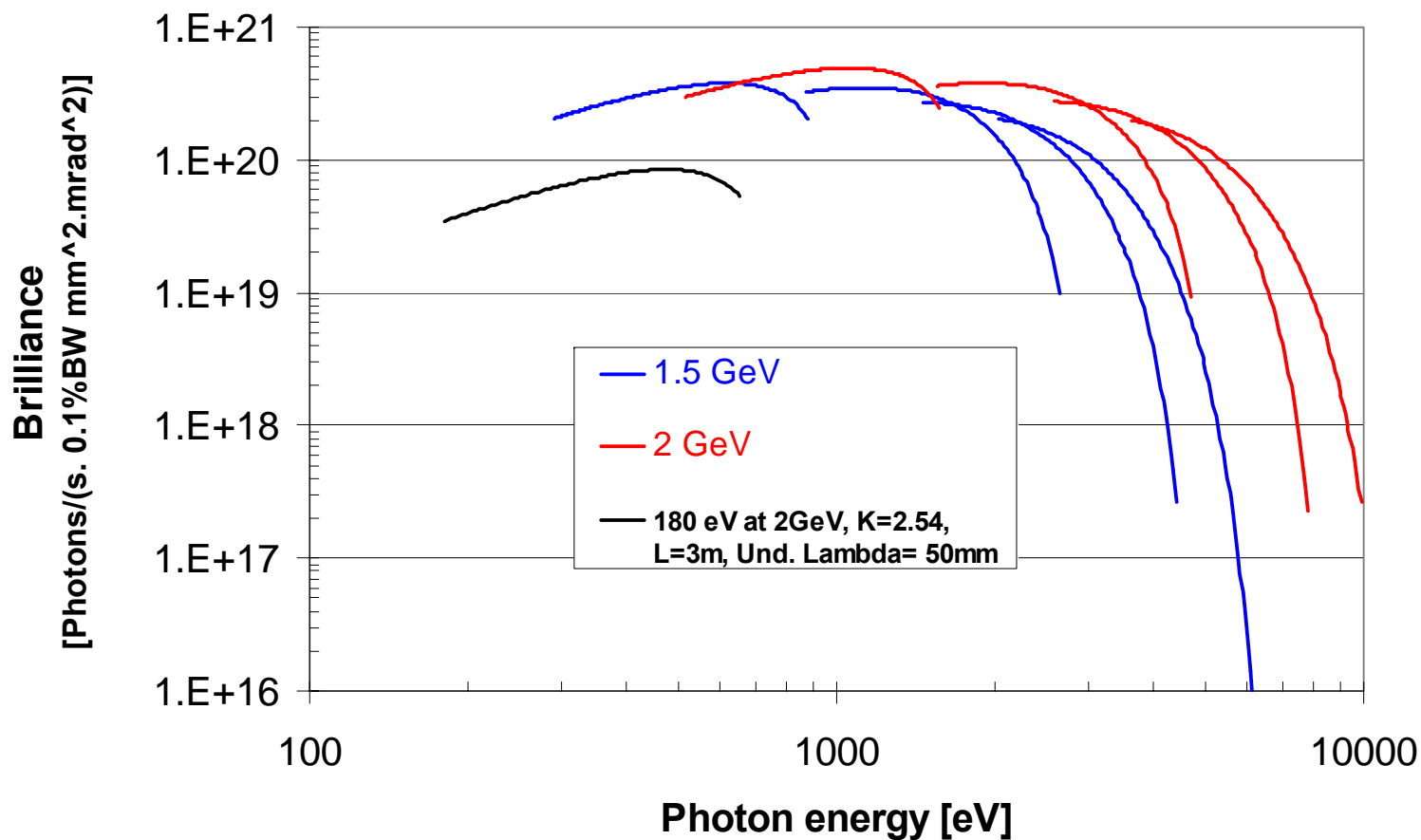


- CPM undulator at 1.5 GeV & 2 GeV:

$\lambda_u=21.5$ mm, $N=139$, $L=3$ m, $n=1,..,7$, $K=0.5-2.2$

- Low energy photons at 2 GeV:

$\lambda_u=50$ mm, $N=60$, $L=3$ m, $n=1$, $K=0.5-2.54$



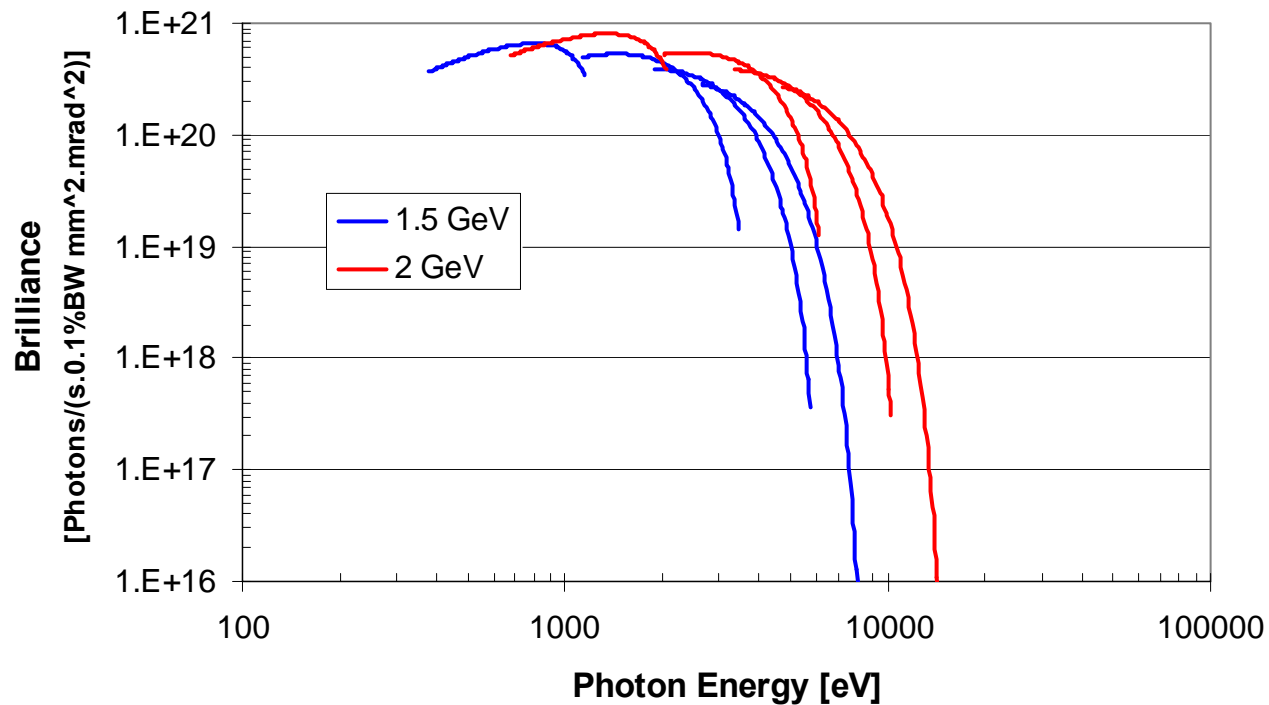
Undulator Spectra vs. Beam Energy



SC undulator at 1.5 GeV & 2 GeV

$\lambda_u=16.5$ mm, $N=181$, $L=3$ m, $K=0.5- 2.2$

$\epsilon_{1.5 \text{ GeV}} = 375$ eV, $\epsilon_{2 \text{ GeV}} = 673$ eV



Conclusions

- **The emittance of the low energy MAX-IV ring is defined by the interplay of quantum excitation, SR damping and intra-beam scattering.**
- **Vertical emittance is limited by betatron coupling, Intra-beam scattering, and vertical dispersion (magnets misalignment).**
- **Low frequency RF system with passive cavities is feasible cure to reduce the IBS growth rates.**
- **Raising the beam energy could be an option ($1.5 \text{ GeV} < E < 2 \text{ GeV}$).**