Feasibility Study of Short-Wavelength and High-Gain FELs in an Ultimate Storage Ring

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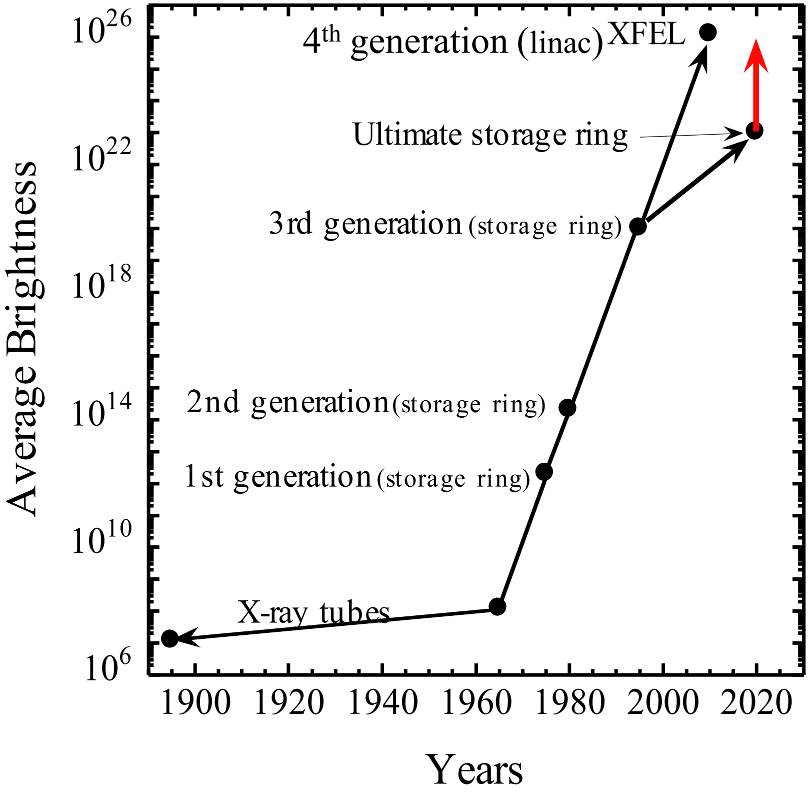
- Introduction
- Ultimate Storage Ring
- Analysis
- Simulation
- Summary

Introdution



- **3rd Generation Light Source**
  - **Storage ring**
  - **Average brightness $B_0 \sim 10^{20}$ (ph/s/mrad2/mm2/0.1%bw)**
- **4th Generation Light Source**
  - **Linac**
  - **Average brightness $B_x \sim 10^{26}$ (ph/s/mrad2/mm2/0.1%bw)**
- **Storage-Ring-Based Light Sources finished?**
  - **stability, reliability, variety of bunch pattern, many photon beam line, matured technology**
  - **Ultimate storage ring**

    Average brightness $B_u \sim 10^{23}$ (ph/s/mrad2/mm2/0.1%bw)

    $\sim(10^2\text{-}10^3)B_0$
- **Objective**
  - **To increase the average brightness of an ultimate storage ring to $10^4\text{-}10^6 B_0$**

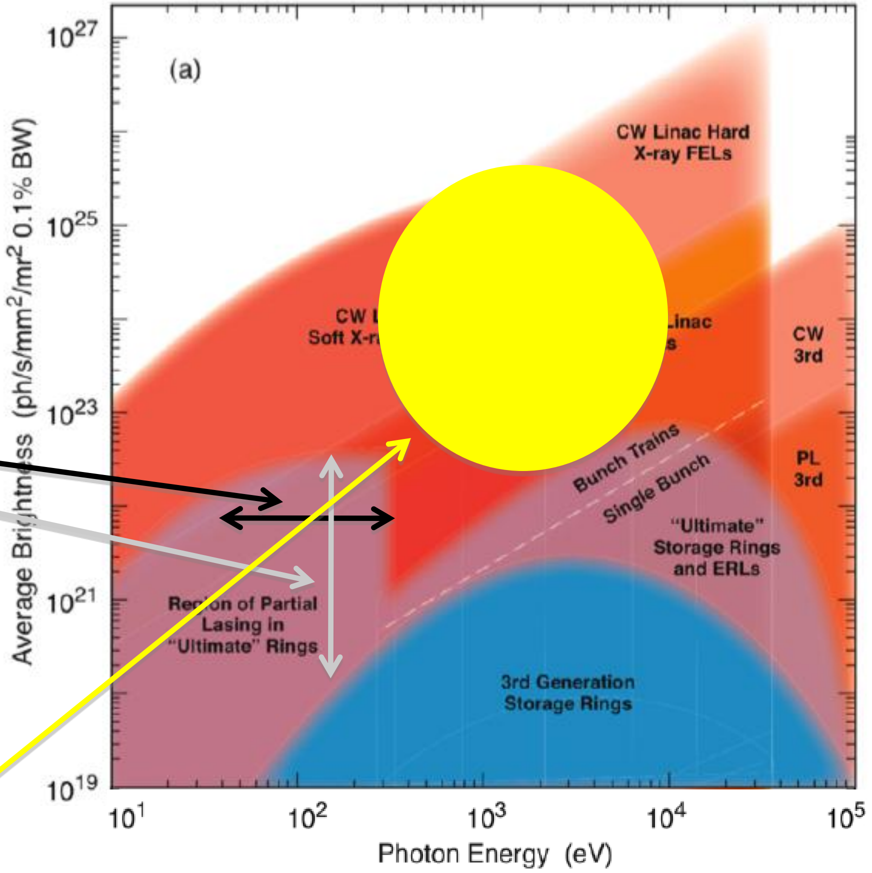
Introduction

■ Partial Lasing

- Z. Huang et al[1] showed that short-wavelength high-gain FEL is possible in PEPX storage ring
- λ=3.3 nm-30 nm
- Average Brightness 10^2-$10^3 B_0$

■ Wavelength Region

- Is shorter wavelength FEL in storage ring impossible?



The approximate range of average brightness.[2]

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[1] Z. Huang et al., Nucl. Instr. and Meth. A 593 (2008) 120.

[2] J. Corlett and R. Hettel, PAC09.

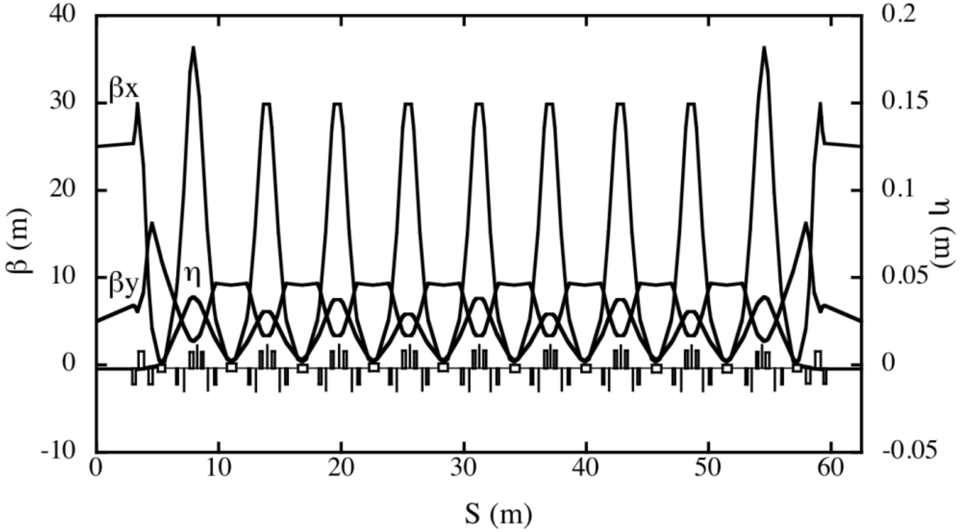
Ultimate Storage Ring

Main Parameters of Storage Ring

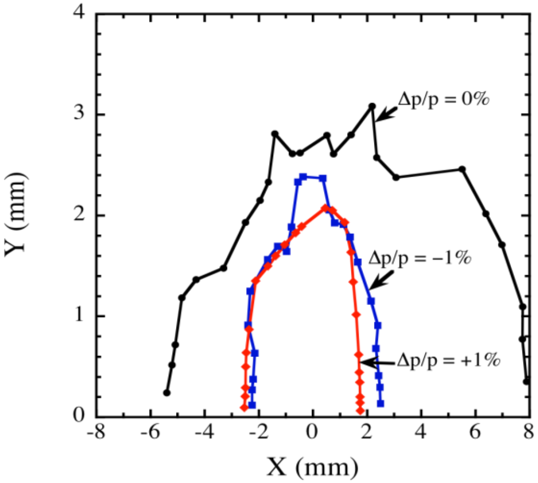
Parameter	Symbol	Value
Energy	E	6 GeV
Natural emittance	ε_o	34.5 pm
Full coupling	$\varepsilon_{x,y}$	17.3 pm
Normalized	$\gamma\varepsilon_{x,y}$	0.20 um
Energy spread	σ_e	0.89×10^{-3}
Bunch length	σ_l	1.23 mm
Circumference	Lc	1999 m
Lattice		10 bend achromat
Number of cells	Nc	32

[1] K. Tsumaki et al., Nucl. Instr. and Meth. A 565 (2006) 394.

Ultimate Storage Ring – Betatron function and dynamic aperture



Betatron and dispersion functions in a cell



Dynamic aperture

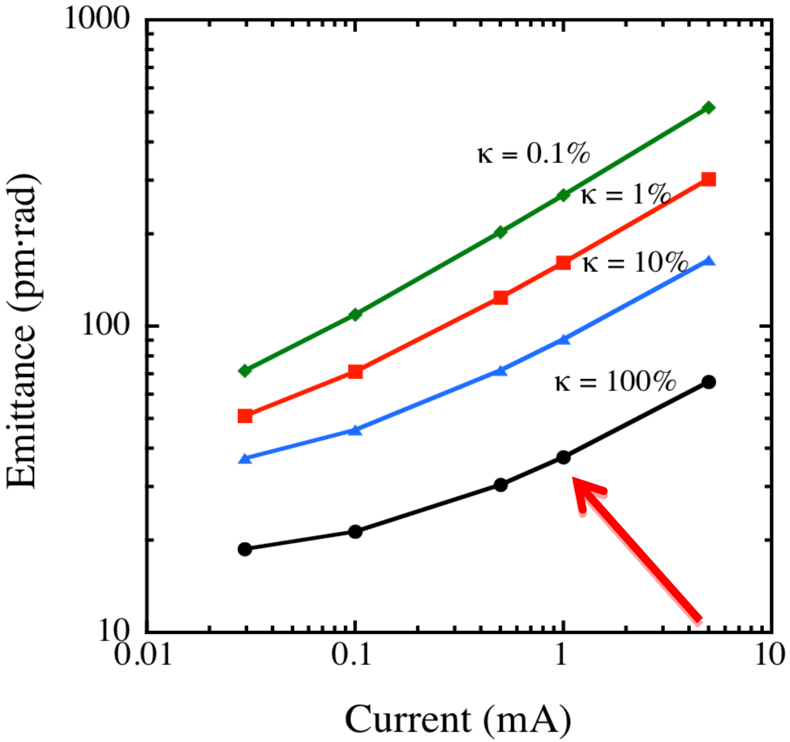
- Dynamic aperture is small, but enough to store the beam.
- Long straight section length is 6 m and βx=25m, βy=5m.
- But it is easy to change the straight section length without changing the main parameters.

Ultimate Storage Ring – Emittance and bunch length

- **Effect of intrabeam scattering at 1mA bunch current**
  - **Emittance growth at 100 %coupling**

    $\varepsilon_{x0}=\varepsilon_{y0}=17$ pm → $\varepsilon_x=\varepsilon_y=37$ pm
  - **Bunch lengthening**

    Negligibly small



- **Emittance in an actual machine**
  - **Emittance $\varepsilon_x=\varepsilon_y < 37$ pm**
  - **Damping effect of undulator**
  - **Use of damping wiggler**

Analysis

- **Analisis was done as follows.**[1]

Energy spread in a storage ring

Rate-of-change of energy spread
= (quantum excitation) – (radiation damping)
+ (FEL excitation)

$$\frac{d\sigma^2}{dt}=\frac{\sigma_0^2}{\tau_e}-\frac{\sigma^2}{\tau_e}+\frac{2P}{\rho P_{beam}T_0}$$

$$\sigma_0=\sigma_{e_0}/\rho,\sigma=\sigma_e/\rho$$

FEL Power

$$P\approx P_n\exp(Z/L_G)$$

$$L_G=L_{G0}(1+\Lambda)$$

$$\Lambda(\sigma_e,\varepsilon,\beta,\cdots)$$[2]

$$\rho=\left[\frac{1}{8\pi}\frac{\hat{I}}{I_A}\left(\frac{K[JJ]}{1+K^2/2}\right)^2\frac{\gamma\lambda_r^2}{\Sigma_x}\right]^{1/3}\quad\hat{I}\propto\frac{\sigma_{e_0}}{\sigma_e}$$

- **Solving these equations numerically for σ_e, energy spread σ_e, FEL power P, and power gain length Lg are obtained.**

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[1] Z. Huang et al., Nucl. Instr. and Meth. A 593 (2008) 120.

[2] M. Xie, Nucl. Instr. and Meth. A 445 (2000) 59.

Analysis - Undulator

- **In the calculation, the following undulators are assumed.**

Undulator Parameters

λ_r	λ_u	K	
0.10 nm	15 mm	1.3	SPring-8 XFEL[1]
0.18 nm	18 mm	1.9	SPring-8 XFEL[1]
0.49 nm	37 mm	2.3	SPring-8 storage ring[2]
0.90 nm	45 mm	3.0	
1.86 nm	50 mm	4.3	PEP-X[3]

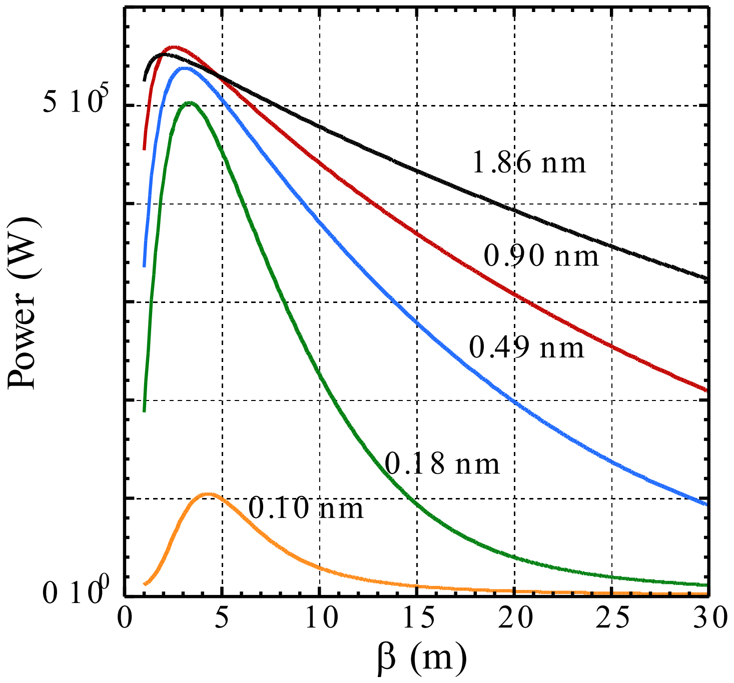
[1] T. Tanaka et al., Proc. the 27th Inter. FEL Conf., 370.

[2] H. Kitamura, Insertion Device Handbook'96, SPring-8 OPSRR 1996-0003.

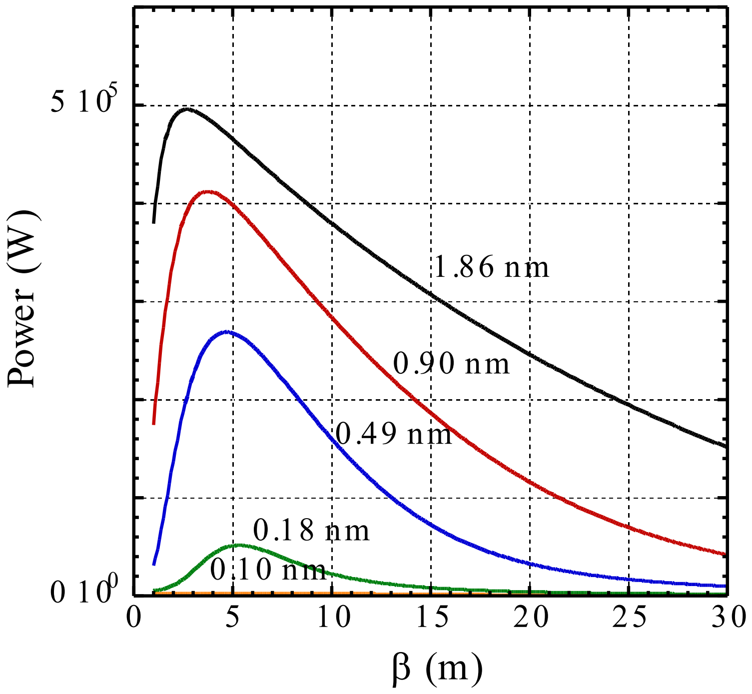
[3] Z. Huang et al., Nucl. Instr. and Meth. A 593 (2008) 120.

Analysis – Beta dependence of FEL power

- **Assumption : Undulator length 100 m, Bunch current 1mA($\hat{I}_0 = 648A$)**
- **For 17 pm emittance, 2 m < β < 4 m and for 37 pm, 2 m < β < 5 m.**



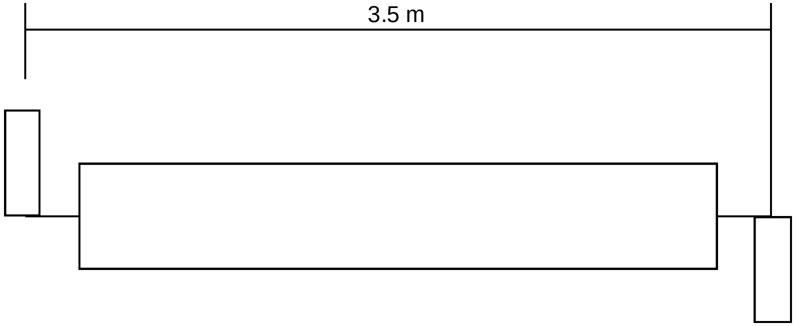
(a) $\varepsilon_x=\varepsilon_y=17$ pm



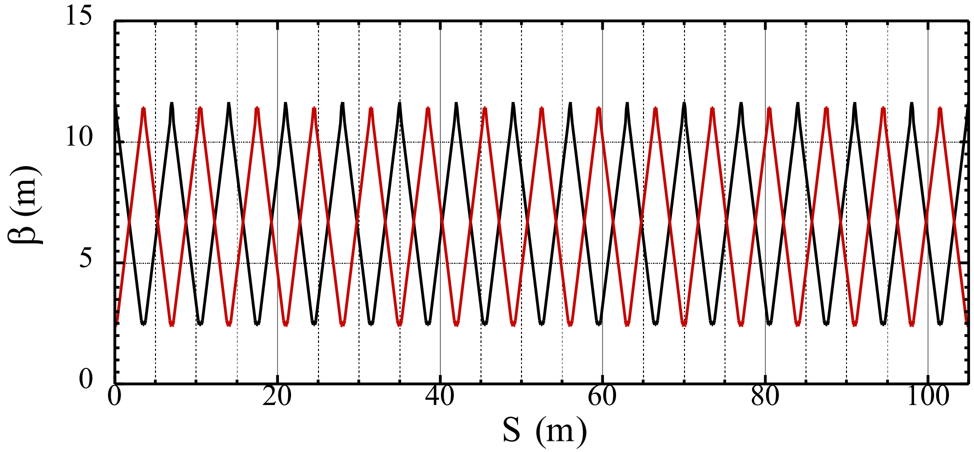
(a) $\varepsilon_x=\varepsilon_y=37$ pm

Analysis – Betatron function at undulator section

- FODO cell was chosen as the lattice in the undulator section
- Betaron function should be less than 5 m.
- The shorter the cell length, the smaller the average betatron function.
  But, the undulator's occupation ratio in the undulator section becomes small.
- 3.5 m cell length is determined. Average betatron function value became 6.7 m.



(a) FODO cell

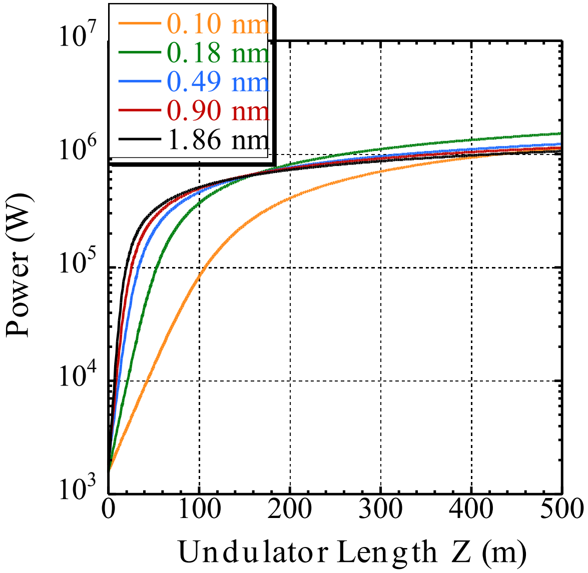


(b) Betatron function

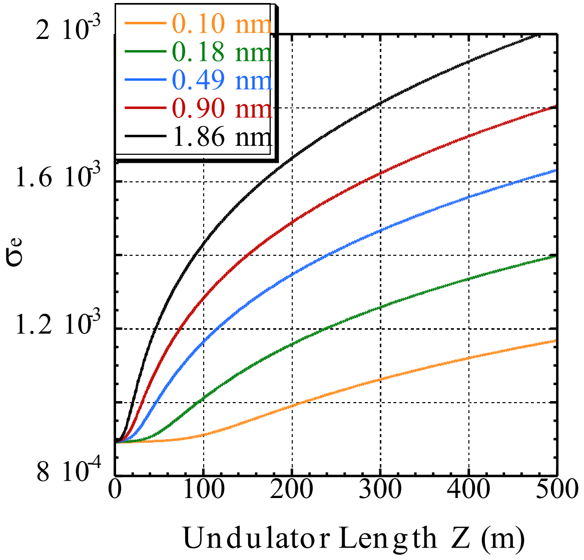
Analitical Results

Undulator length dpendence of power, enrgy spread, gain length at $\varepsilon_x=\varepsilon_y=17$pm

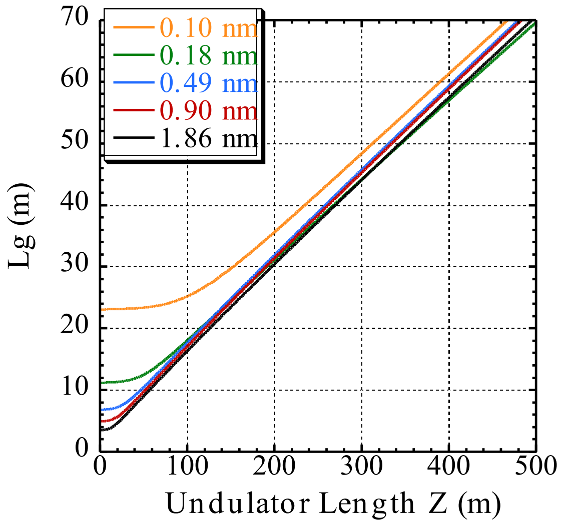
- **Achievable maximum power in the storage ring is ~ 1 MW.**
- **Increase of FEL power : Increase of FEL Interaction → Increase of energy spread → Degradation of gain length → Saturation of FEL power**



(a) Undulator length dependence of FEL power



(b) Undulator length dependence of energy spread

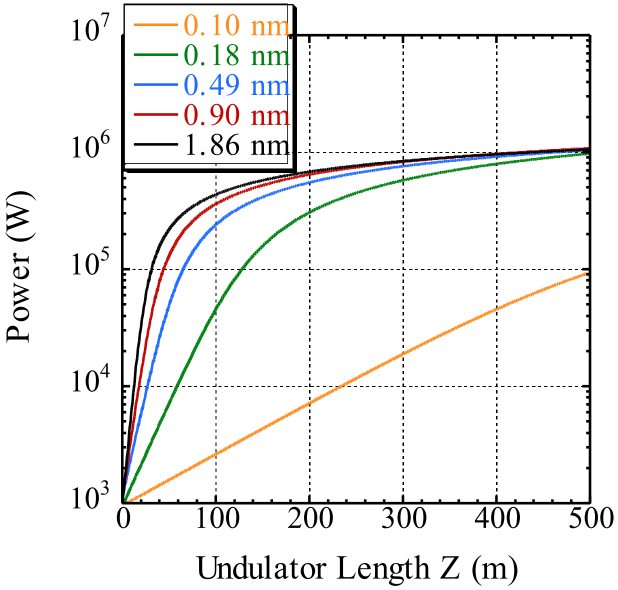


(c) Undulator length dependence of gain length

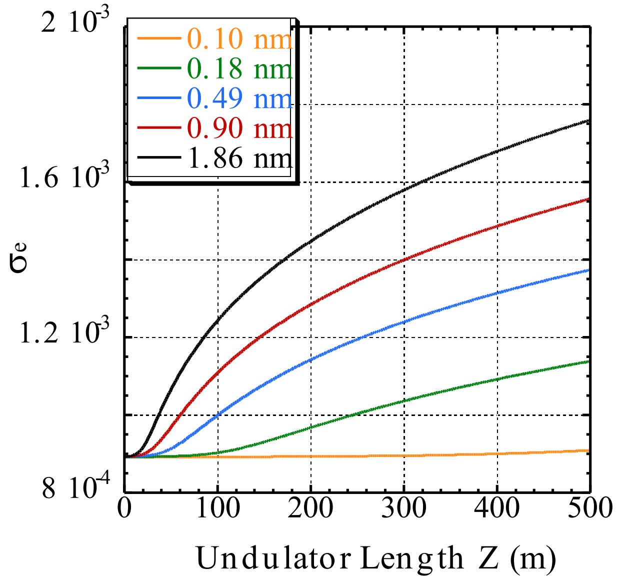
Analitical Results

Undulator length dependence of power, energy spread, gain length at $\varepsilon_x=\varepsilon_y=37\text{pm}$

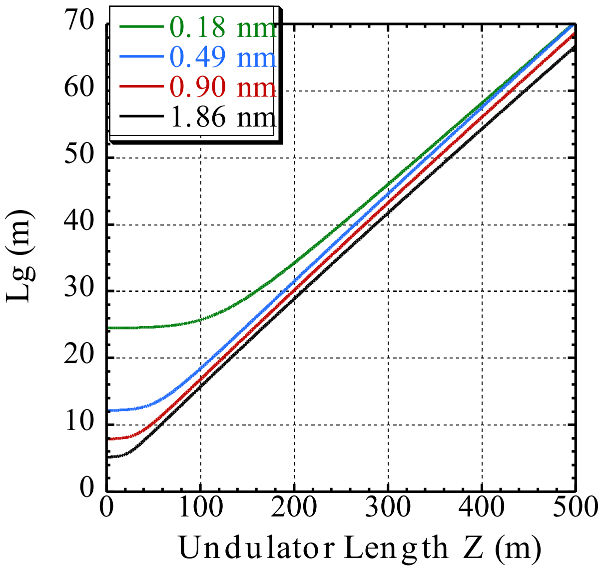
- **Achievable maximum FEL power is ~1 MW.**



(a) **Undulator length dependence of FEL power**



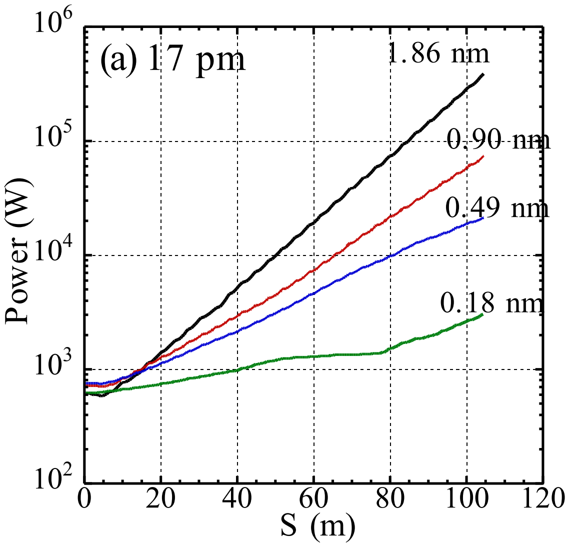
(b) **Undulator length dependence of energy spread**



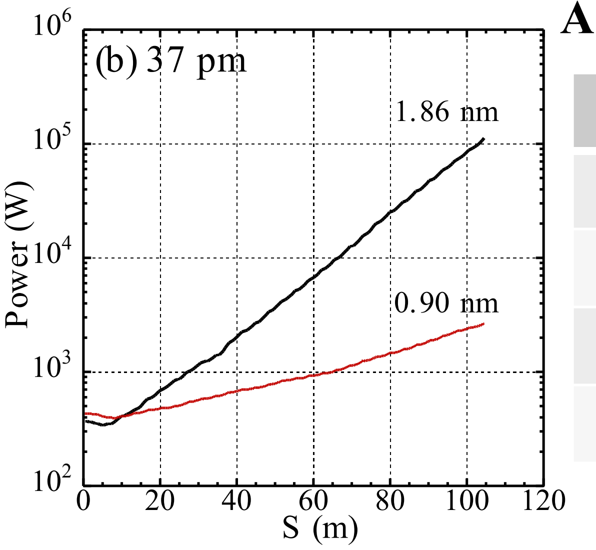
(c) **Undulator length dependence of gain length**

Simulation

- Numerical simulations have been done using SIMPLEX[1].
- For 1.86 nm, maximum power 400 kW (17pm) and 100 kW(37pm).
- For 0.90 nm, maximum power 70 kW (17pm) and 3 kW(37pm).
- Amplification from ~ 300 times to ~ 600 times is possible at 1.86 nm.
- At 0.90 nm, amplification from ~ 10 to ~ 100 is possible.



(a) $\varepsilon_x = \varepsilon_y = 17$ pm



(b) $\varepsilon_x = \varepsilon_y = 37$ pm

Amplification Factor of FEL Power

λ_r	17 pm	37 pm
1.86 nm	~ 600	~ 300
0.90 nm	~ 100	~ 10
0.49 nm	~ 30	—
0.18nm	~ 5	—

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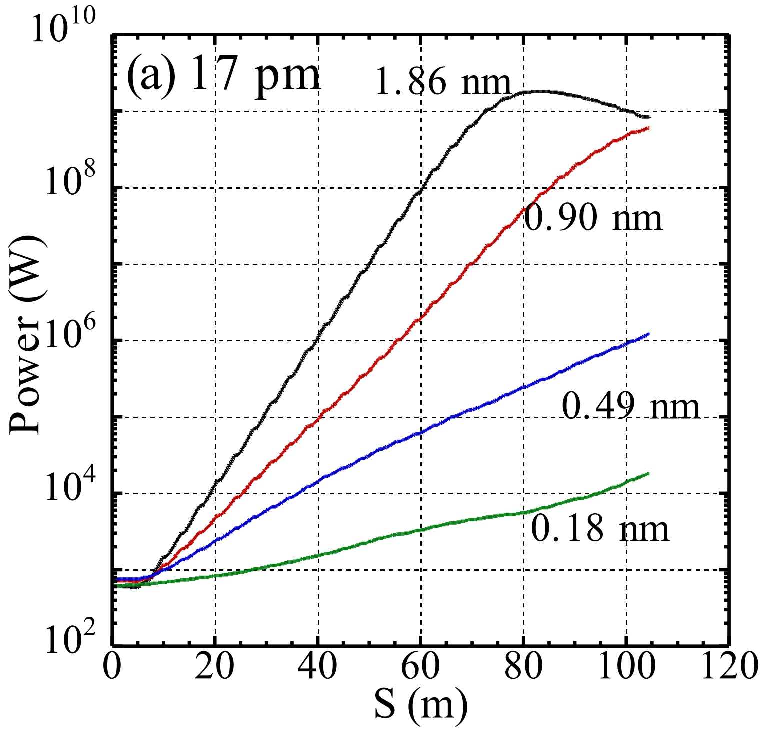
[1] T. Tanaka, http://radiant.harima.riken.go.jp/simplex

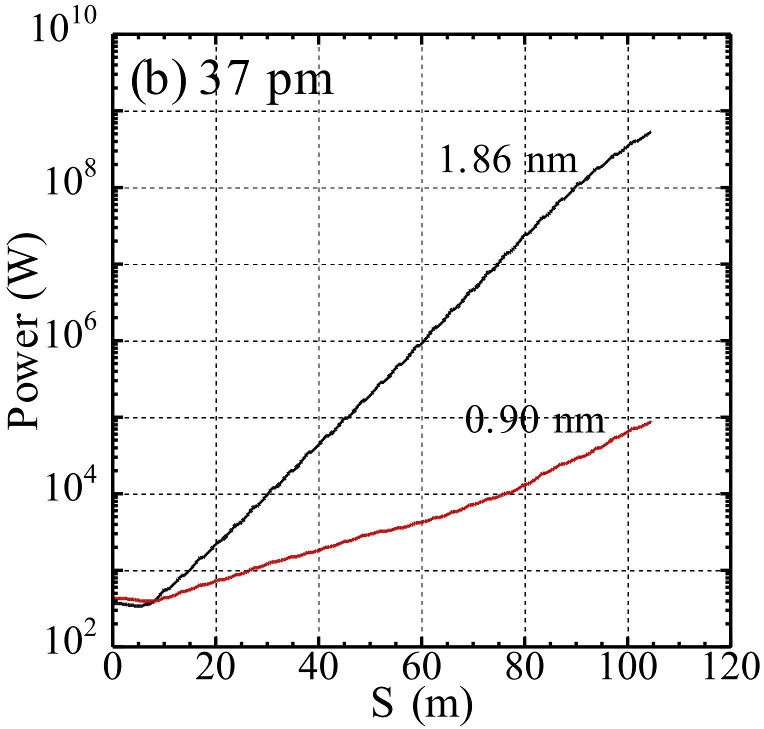
Simulation

FEL with a bypass

- For a 17 pm emittance beam, we can achieve saturation at 1.86 nm and 0.9 nm.
- For a 37 pm emittance beam at 1.86 nm, FEL power nearly reached saturation.
- FEL power is about 1 GW.



(a) $\varepsilon_x = \varepsilon_y = 17$ pm



(b) $\varepsilon_x = \varepsilon_y = 37$ pm

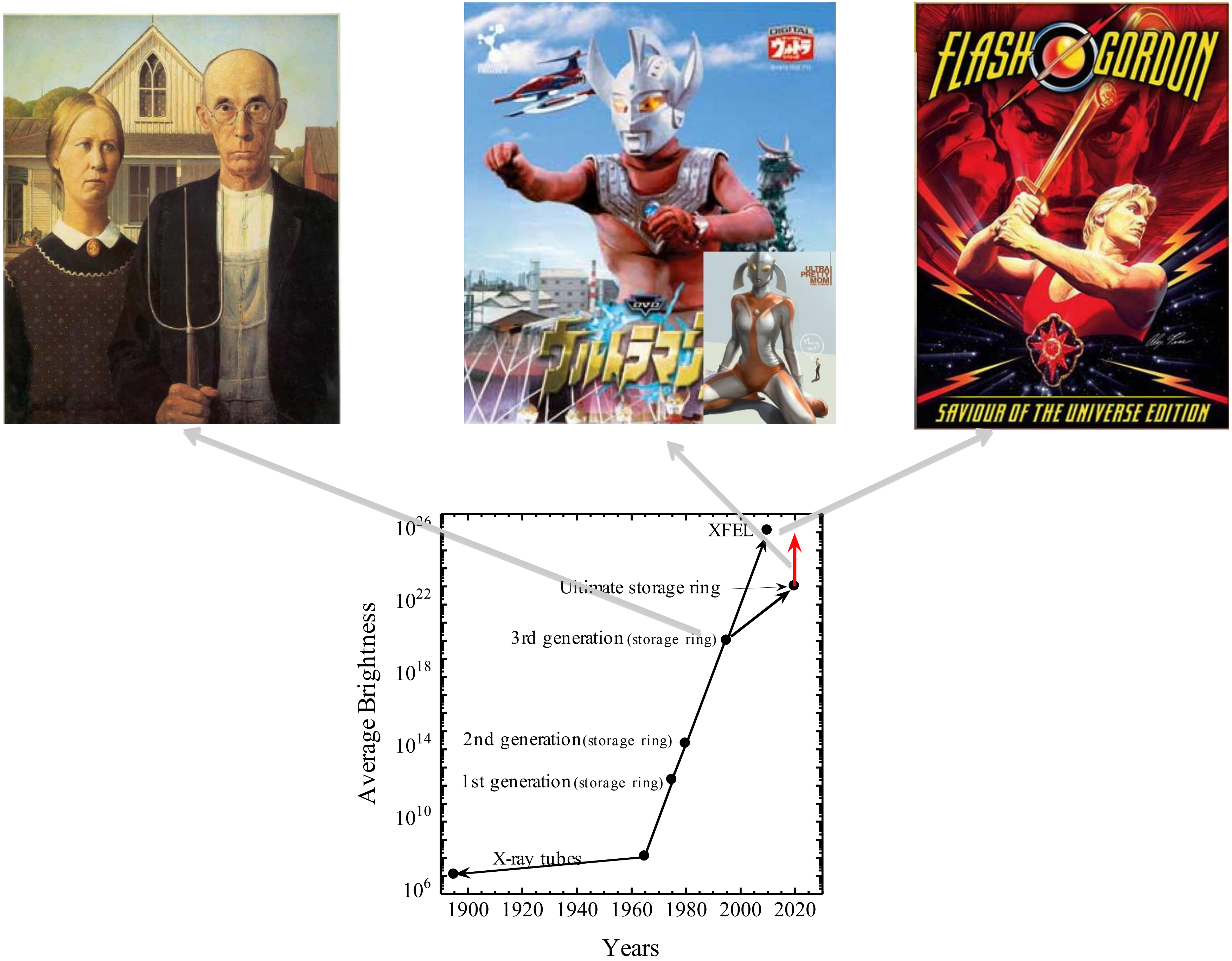
Summary

- **We studied the viability of the high-gain FELs in wavelengths ranging from 0.10 nm to 1.86 nm, assuming 1 mA bunch current in an ultimate storage ring.**

- **Analytical results showed that the achievable maximum FEL power in the storage ring is on the order of 1 MW.**

- **Assuming a 90 m effective length undulator, we carried out the simulations using SIMPLEX.**
  - **At 1.86 nm, the maximum achievable power is 100-400 kW and we can expect about 300-600 times power amplification.**
  - **At 0.90 nm, the maximum achievable power is 3-70 kW and we can expect about 6-100 times power amplification.**
  - **We also carried out simulations with a bypass and found that FEL saturation is possible at 1.86 nm.**

- **These results show that FEL in the ultimate storage ring is promising for wavelengths longer than 0.9 nm.**


DIGITAL
ウルトラ
DVD
ウルトラマン
ULTRA PRETTY MOM
FLASH GORDON
SAVIOUR OF THE UNIVERSE EDITION
Average Brightness
10^{6}
10^{10}
10^{14}
10^{18}
10^{22}
10^{26}
1900
1920
1940
1960
1980
2000
2020
Years
XFEL
Ultimate storage ring
3rd generation (storage ring)
2nd generation (storage ring)
1st generation (storage ring)
X-ray tubes