

# XFELはどのように実現すべきか

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先端放射光源に関する研究会

— 第3世代放射光リング／SASE-FELを越えて

日本が選択すべき放射光源ロードマップに向けて(1)

5年前の研究会にて

# X線光学素子用ダイヤモンド 結晶の現状と展望

玉作 賢治 理研播磨

ERLサイエンスワークショップ @KEK 7/10/2009



共振器型XFEL (XFEL-O) の原理と光源特性

羽島良一

日本原子力研究開発機構

ERL光量子源開発研究グループ

ERLサイエンスワークショップ

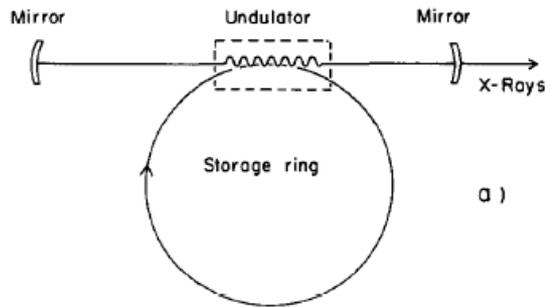
2009年7月10日

<http://pfwww.kek.jp/pf-seminar/ERL/workshop/>

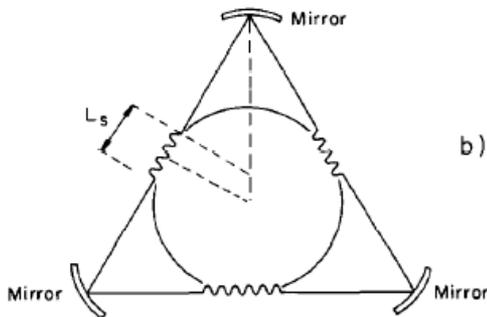
# 内容

- XFEL の概要
- ERL に併設 (7 GeV) の例
- 電子エネルギーを下げる
  - バンチ圧縮
  - 高調波発振
- SASE-XFEL に併設の可能性
  - LCLS-II
  - European XFEL
- 要素技術

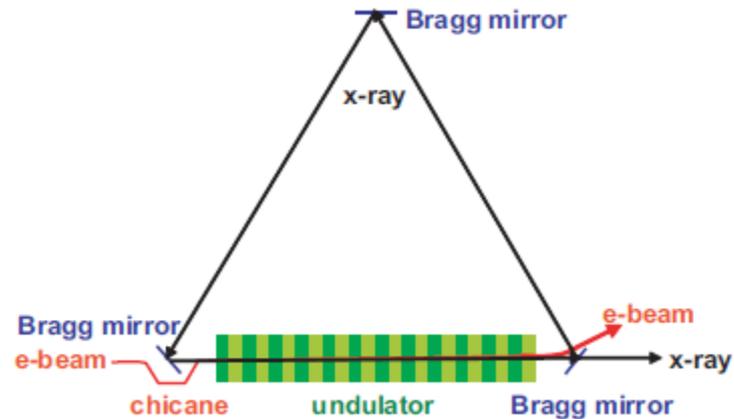
# 共振器型X線FELの提案



a)



b)



Z. Huang, D. Ruth  
Phys. Rev. Lett. (2006).

SLAC-LCLSの電子ビームパラメータで  
再生増幅型XFELを提案。(10パス程度で飽和)

R. Colella, A. Luccio,  
Opt. Comm. (1984)

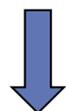
蓄積リングの電子ビームで  
2-3 ÅのXFELを提案。

1. X線領域で利用可能な“反射率の高い”ミラー
2. 高品質、かつ、“高繰り返し”の電子ビーム

この両者がそろわない限り、実現は不可能！

# K-J. Kimらによる共振器型X線FELの提案

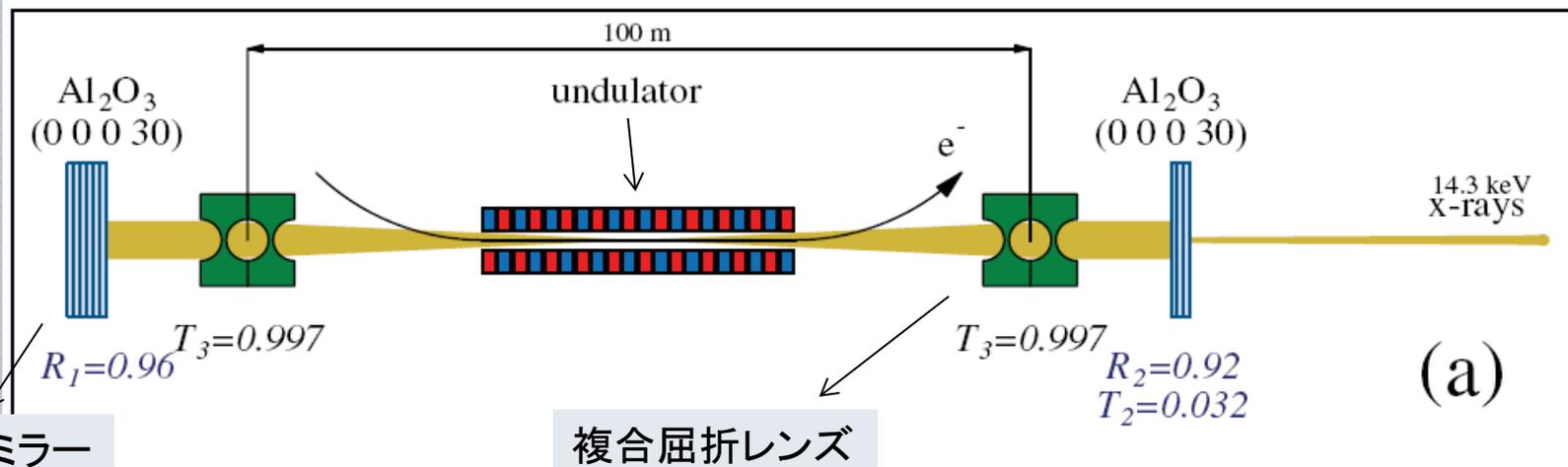
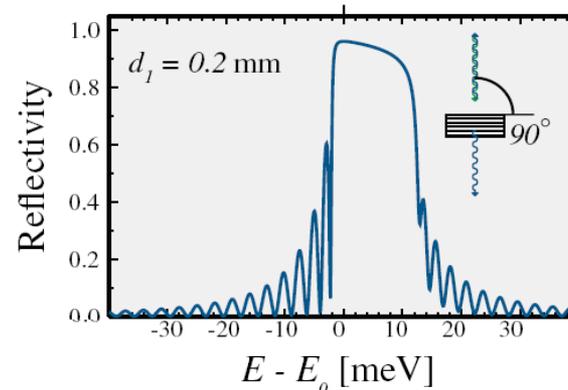
完全結晶によるX線のBragg反射を利用。  
“ERL quality”の電子ビームを利用。



K-J. Kimら ERL-2007 WS  
PRL 100, 244802 (2008)

SASEとは異なるX線レーザ  
空間・時間コヒーレンスに優れる  
高輝度電子バンチ >1MHz  
ERL放射光源に組み込み可能

Al<sub>2</sub>O<sub>3</sub>によるBragg反射(14.3keV)

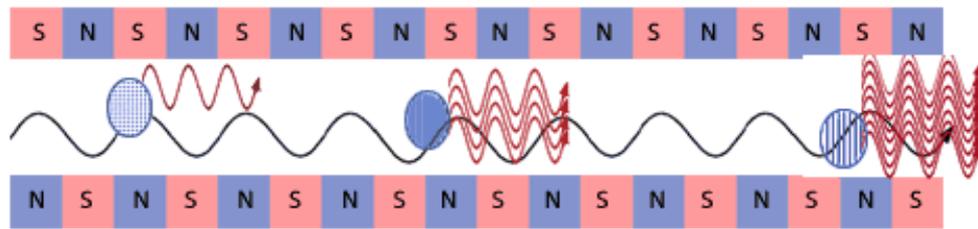


Braggミラー

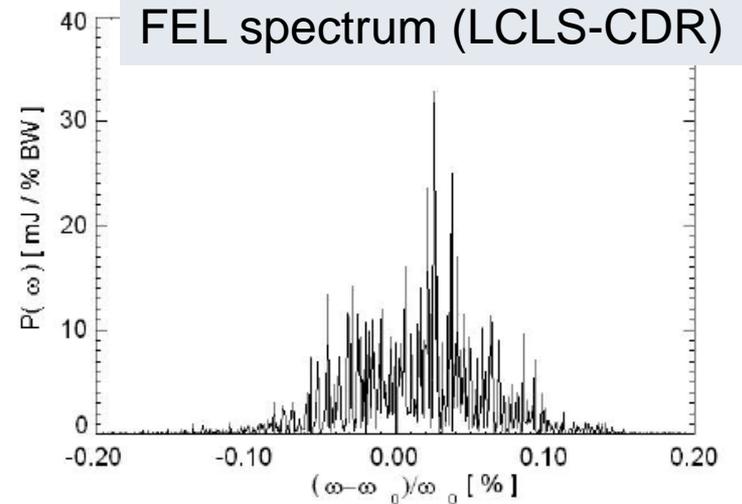
複合屈折レンズ

# SASE-XFELとXFELOの比較

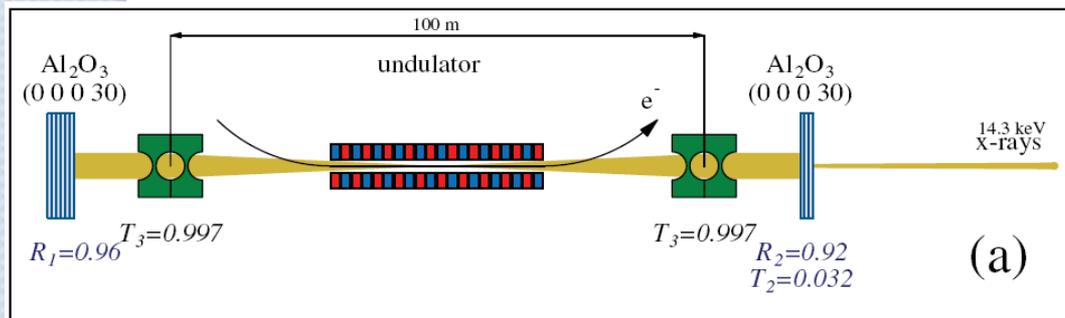
SASE = Self-Amplified Spontaneous Emission



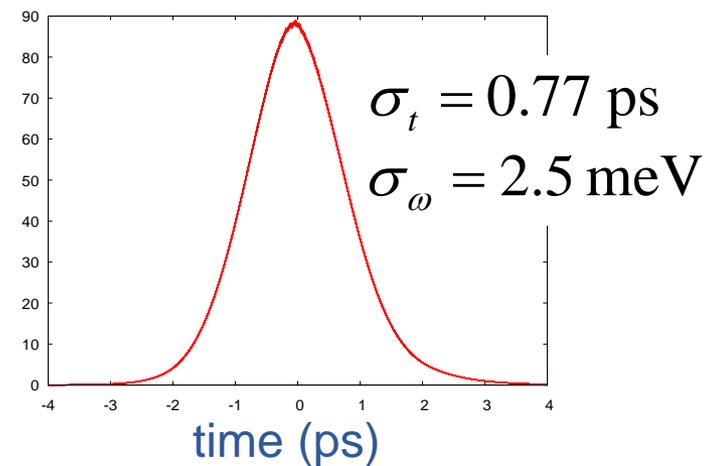
1パスでノイズから飽和まで(>10<sup>7</sup>倍)増幅  
電子バンチ = 1nC, 100fs, 1mm-mrad, 10<sup>-4</sup>



## XFEL- Oscillator



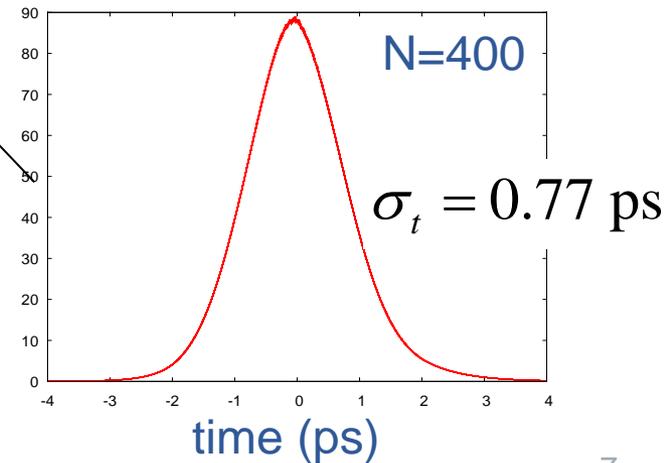
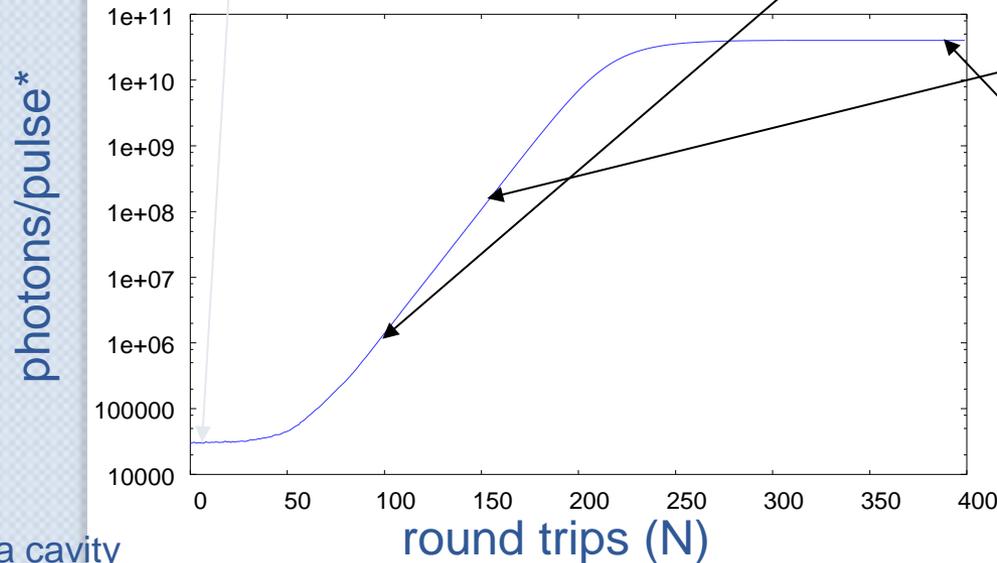
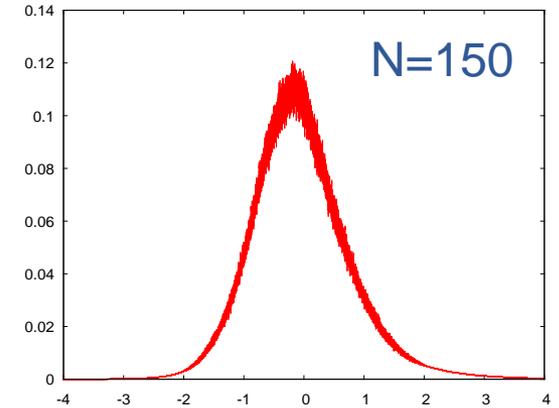
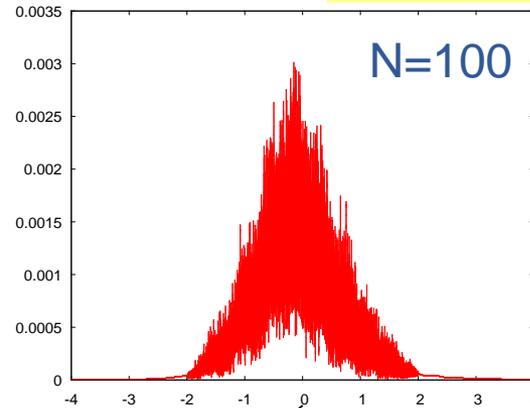
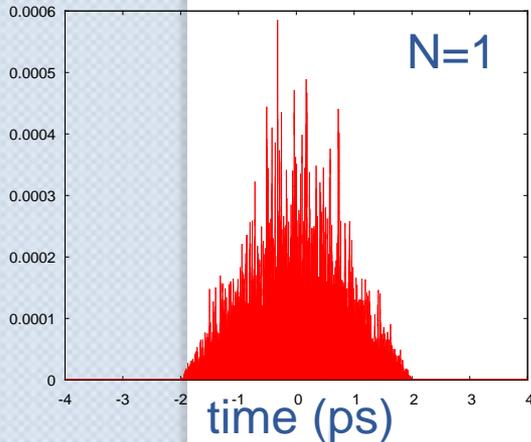
1パスの増幅率 > 1 (損失 < 増幅の条件)  
電子バンチ = 20pC, 2ps, 0.1mm-mrad, 10<sup>-4</sup>



# Bragg反射の位相シフトを含んだ計算 FEL発振に伴うX線パルス波形の変化

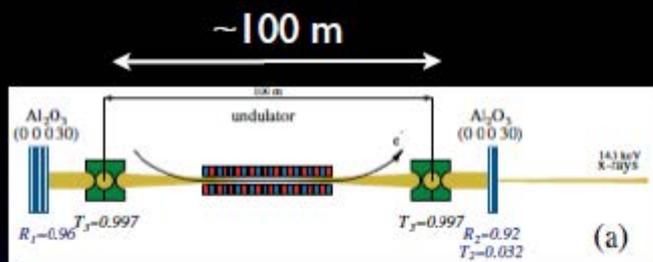
Darwin curve に基づく位相シフトを考慮  
共振器長  $\delta L = -100 \mu\text{m}$

パルスの増幅と狭帯域化が同時に起こる。  
飽和後は Gaussian-like な時間波形



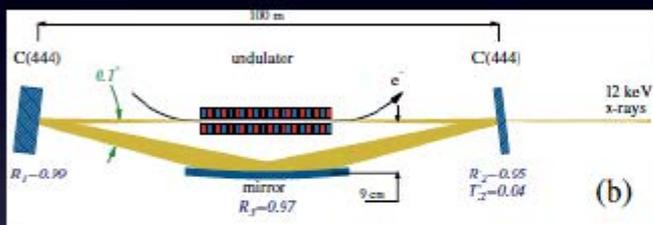
\* intra cavity

# 共振器の具体的な配置



## サファイアを使った共振器

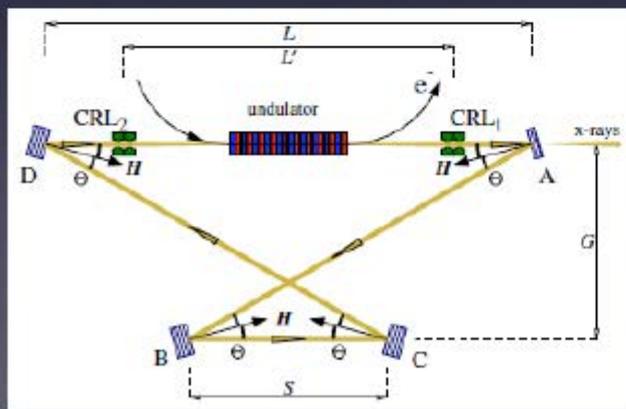
- ☉ 広いエネルギー範囲をカバー
- ✕ 結晶性
- ✕ 反射率



## ダイヤモンドとミラーを使った共振器

- ✕ 離散的なエネルギーでしか機能しない
- ☉ 結晶性
- ☉ 反射率

K. J. Kim et al., PRL 100, 244802 (2008).



## 4枚のダイヤモンドを使った共振器

- ☉ エネルギー選択の自由度が比較的高い
- ☉ 結晶性
- ☉ 反射率
- ✕ 高い角度安定性(nrad以下)が必要

K. J. Kim & Y. Shvyd'ko, PR-ST 12, 030703 (2009).

# XFELにおける波長の可変性は？

Bragg ミラーの角度を調節することで K-J. Kim et al., PR ST-AB 12, 030703 (2009).  
波長可変を実現できる

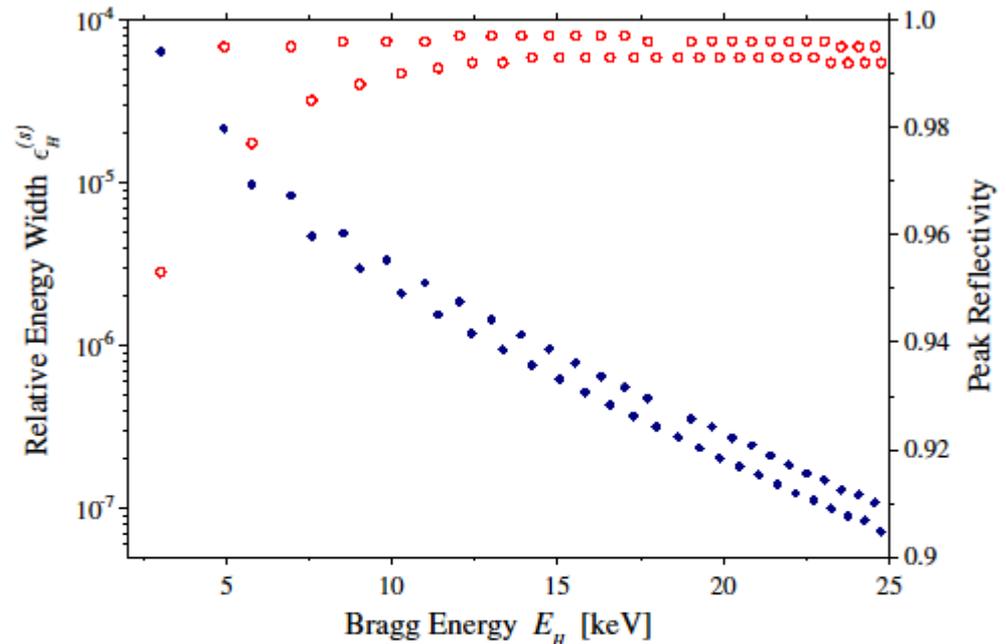
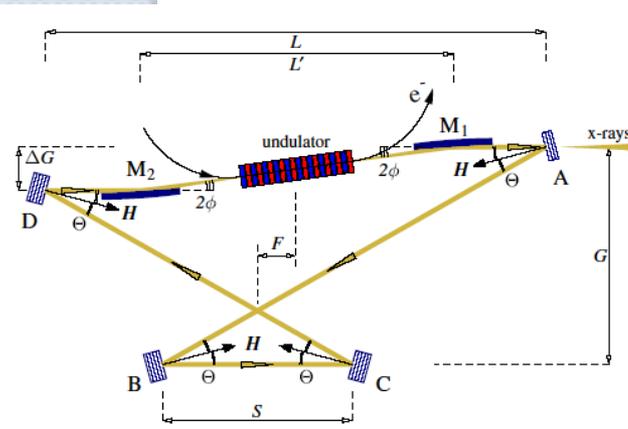
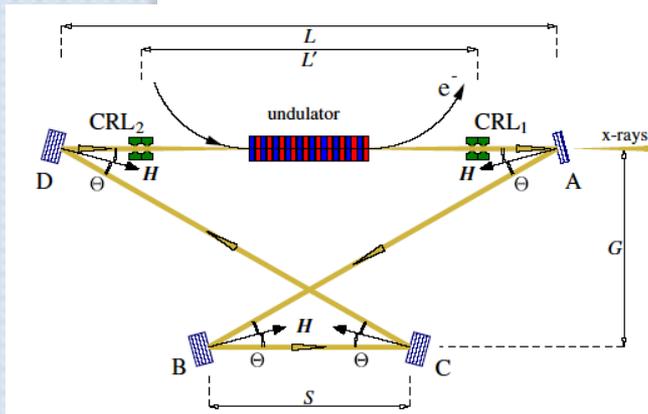


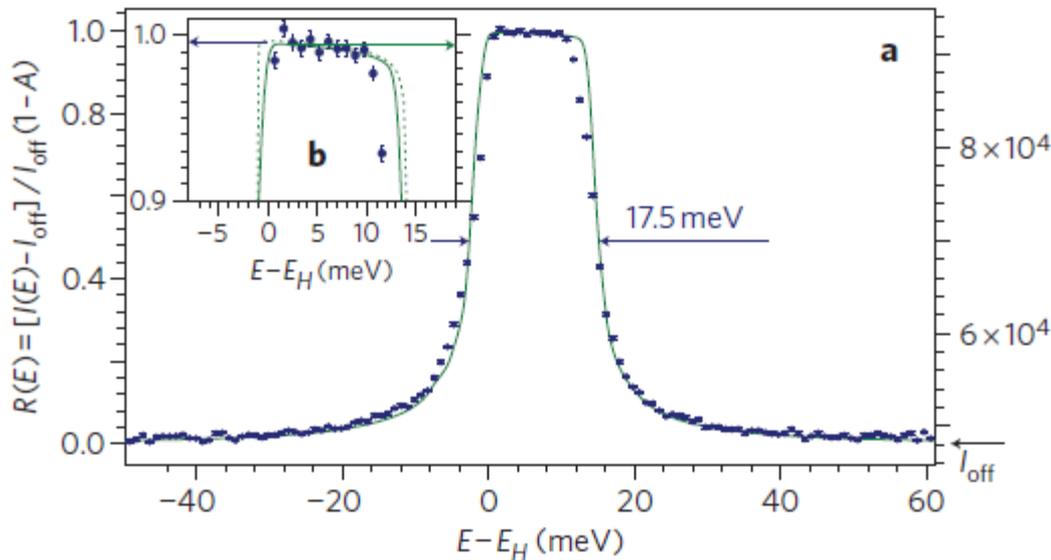
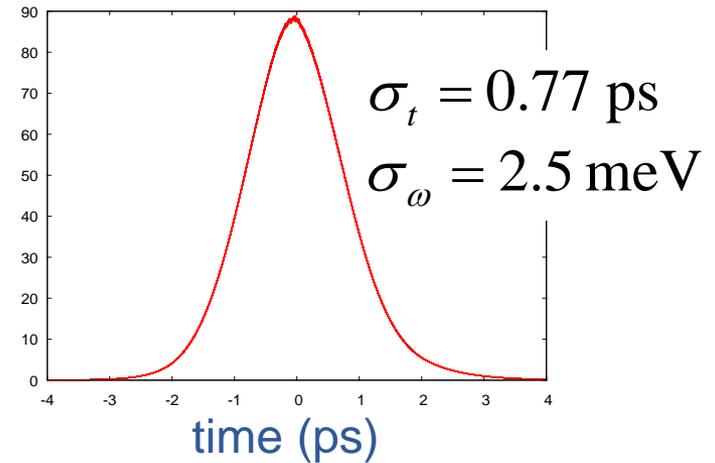
FIG. 5. (Color) Closed circles: relative energy width  $\epsilon_H^{(s)}$  of all allowed Bragg reflections in diamond (C) crystals, in the symmetric scattering geometry, for Bragg energies  $E_H$  up to 25 keV. Open circles: the same for the peak reflectivity. Calculations are performed with dynamical theory of x-ray diffraction in thick crystals as described in [11]. Debye-Waller factors are calculated using 2200 K Debye temperature.

# XFELOの発振帯域は何で決まるのか？

$$\sigma_{\omega} = \frac{1}{2\tau} = \frac{g^{1/4}}{\sqrt{8\tau_{el}\tau_M}}$$

$$\tau_M = \frac{1}{2\sigma_M} \quad \text{Bragg ミラーの帯域}$$

$\tau_{el}$  電子バンチ長



Bragg mirror  
for 13.9 keV X-ray

Yuri Shvyd'ko et al.,  
Nat. Phot. 5, 539 (2011)

# ERL に併設する場合

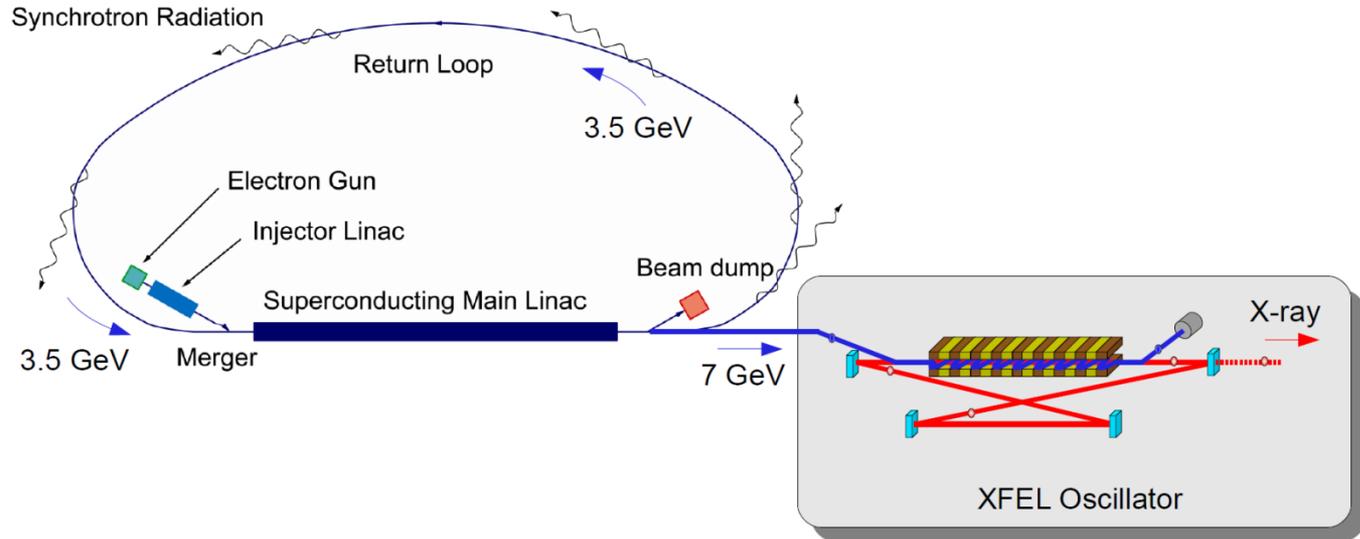


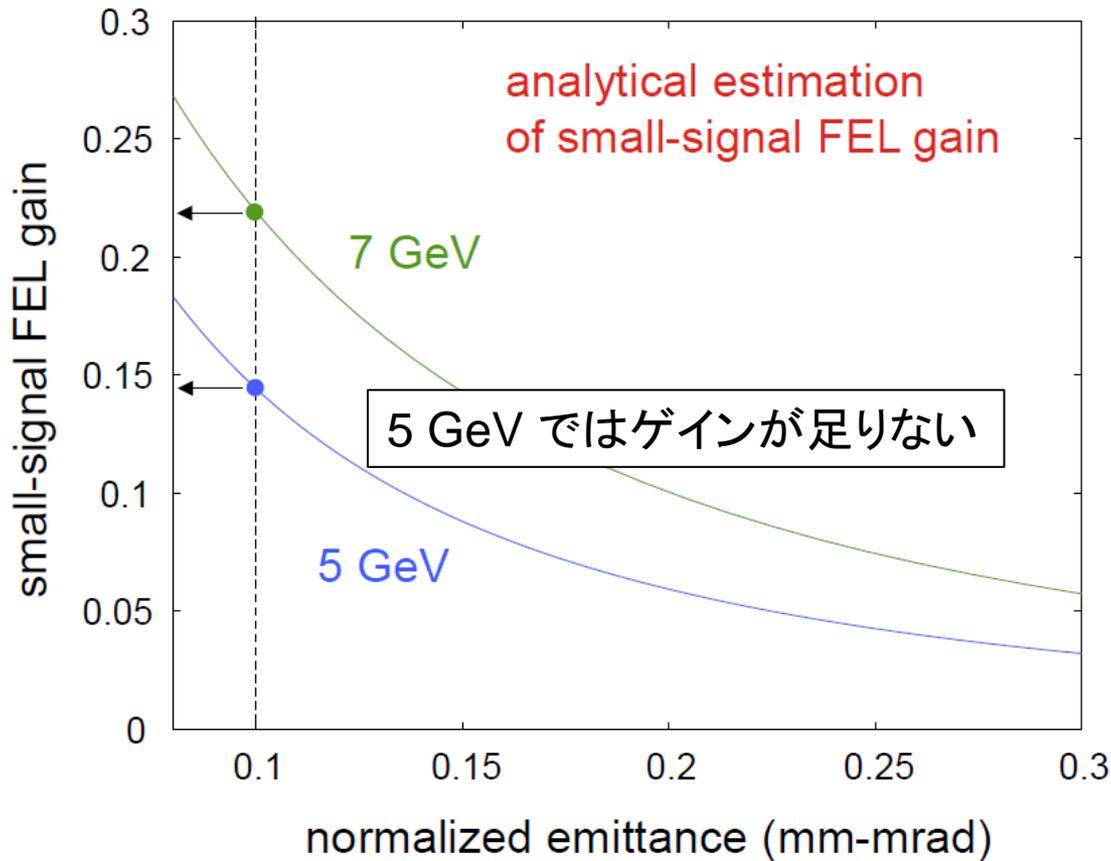
TABLE I. Performance of X-FELO. See text for explanation of symbols.

$\lambda_1$ (Å)	$E$ (GeV)	$Q$ (pC)	$K$	$\lambda_U$ (cm)	$N_U$	$Z_R$ (m)	$g_{th}$ (%)	$g_{sim}$ (%)	$r$ (%)	$P_{sat}$ (MW)
1	7	19	1.414	1.88	3000	10	26	28	90	19
1	7	40	1.414	1.88	3000	12	55	66	83	21
0.84	7.55	19	1.414	1.88	3000	12	26	28	90	20
0.84	10	19	2	2.2	2800	10	42	45	83	18

K-J. Kim ら PRL 100, 244802 (2008)

7-10 GeV, 19-40 pC の電子ビーム → ERL と近いパラメータ

# XFELO with 5 and 7-GeV ERLs

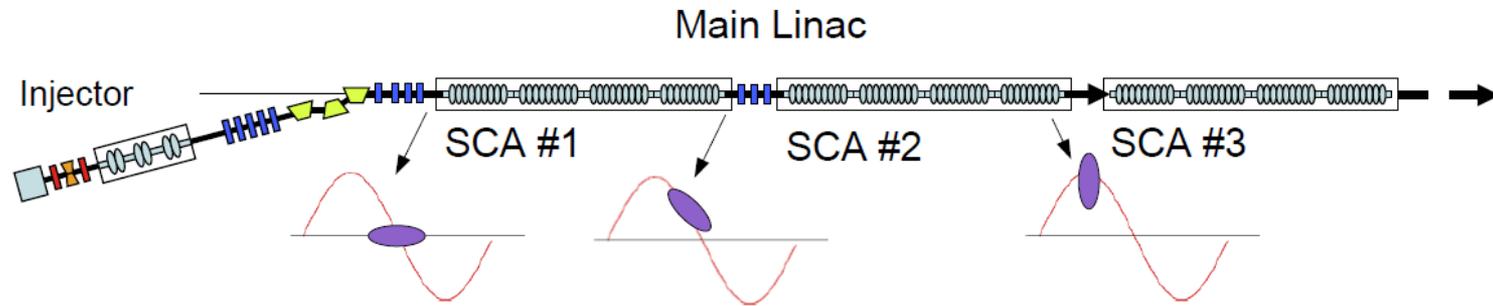


1Å X-FELO

Energy	5 GeV	7 GeV
charge	20 pC	→
$\sigma_t$	2 ps	→
$\sigma_E/E$	1e-4	→
$a_w$	0.59	1.0
$\lambda_u$	1.43 cm	1.88 cm
$N_u$	3000	→
$\beta^*=Z_R$	10 m	→
$\varepsilon_n$	0.1 mm-mrad	→
gain	14 %	22 %

The above calculations are based on a Halbach-type undulator. DELTA undulator gives 1.4 times larger FEL gain.

# Velocity bunching in an ERL main linac



Velocity bunching for a SASE-FEL injector [L. Serafini and M. Ferrario, AIP-Porc. \(2001\)](#)

Velocity bunching for an ERL light source [H. Iijima, R. Hajima, NIM-A557 \(2006\)](#).

Velocity bunching for an X-FELO [R. Hajima, N. Nishimori, FEL-2009](#)

- (1) no additional component is required
- (2) only 2-3% SCAs are used for the velocity bunching
- (3) residual energy spread is smaller than magnetic compression
- (4) moderate emittance growth for low bunch charge

# Gain reduction by bandwidth mismatch

K-J. Kim et al., PRL 100, 244802 (2008).

$$\Lambda_m = (g - \alpha)/2 - (u/2\tau_M)^2 - 0.5\sqrt{g}(2m + 1)(\tau_M/\tau_{el})$$

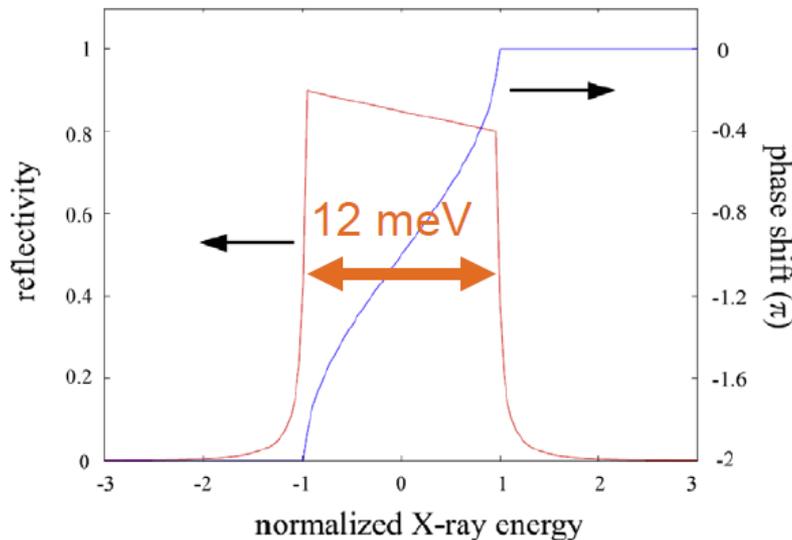
growth rate  
of the  $m$ -th mode

gain

loss

cavity length  
detuning

bandwidth mismatch



reflectivity and phase shift  
for a cavity round trip

$$\sigma_{\omega}^M \gg \sigma_{\omega}^{el} \quad \text{or} \quad \tau_M \ll \tau_{el}$$

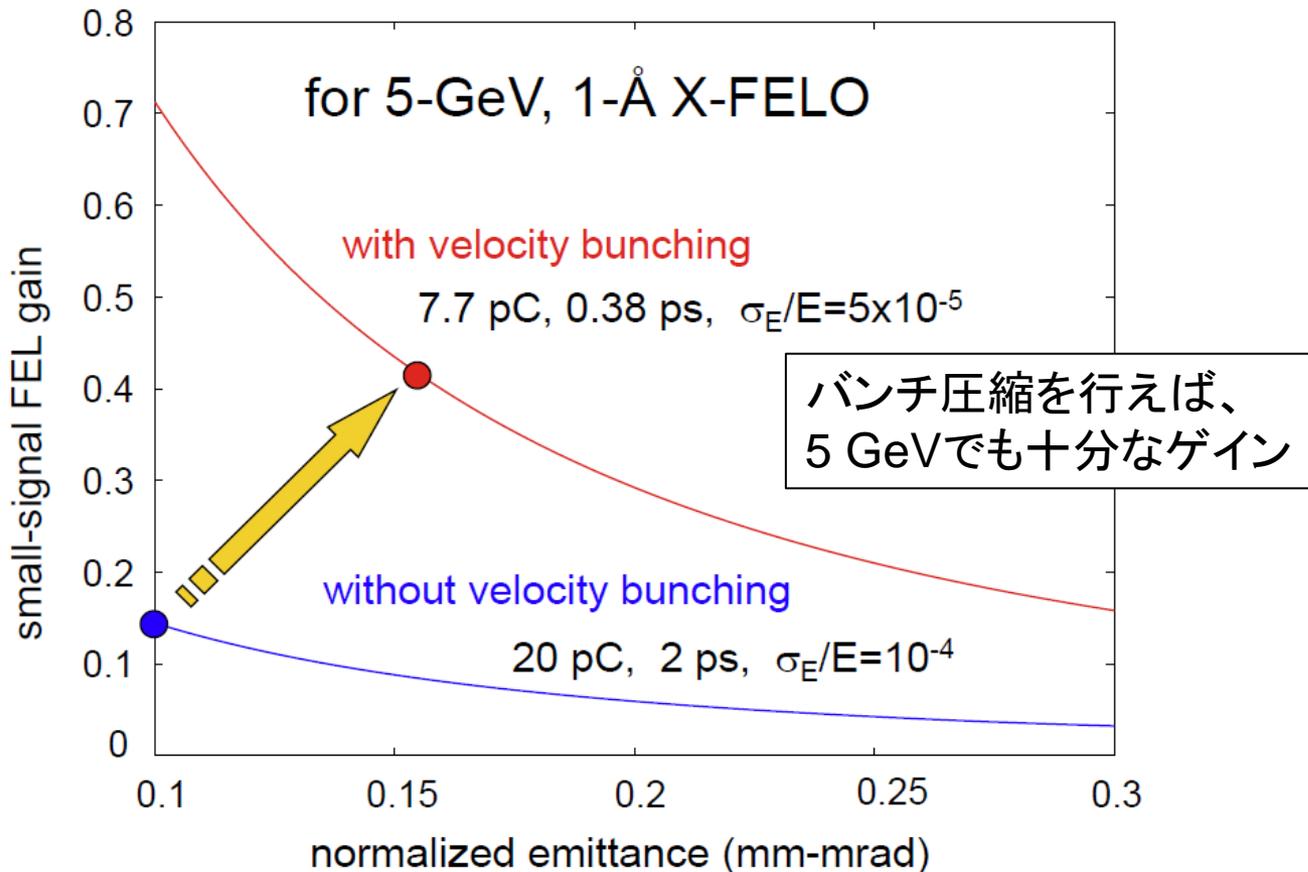
bandwidth of the Bragg mirrors = 12 meV

$$\tau_M = 100 \text{ fs}$$

$$\tau_{el} \gg 100 \text{ fs}$$

In the following calculations,  
we choose  $\tau_{el} = 400 \text{ fs}$

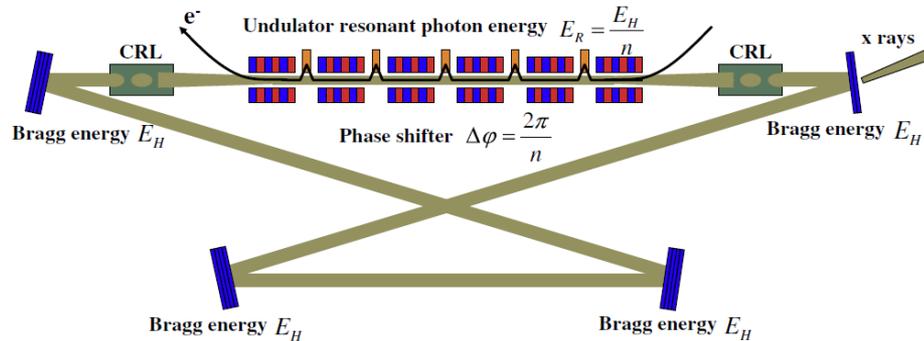
# Enhancement of the FEL gain by velocity bunching



Significant enhancement of the FEL gain by velocity bunching.  
Gain~40% is possible even with emittance growth during the bunching.

# 高調波によるXFELO

J-H. Dai, H. Deng, Z. Dai, Phys. Rev. Lett. 108, 034802 (2012).

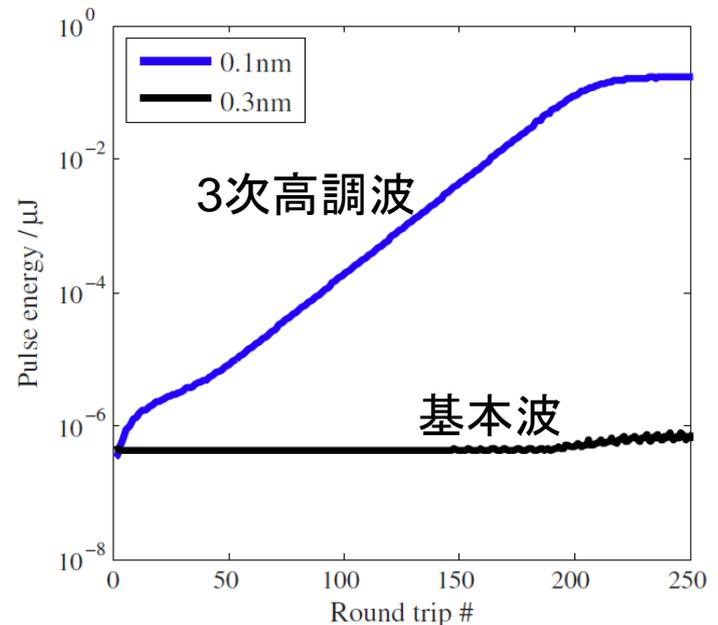


アンジュレータ間の位相シフトを適切に選んで、高調波のみを発振

3.5 GeV で 1 Å の XFEL

TABLE I. The main parameters of harmonic lasing XFEL.

Parameters	Third harmonic	Fifth harmonic
Crystal Bragg energy $E_H$	12.42 keV	20.71 keV
Phase jump $\Delta\varphi$	$4\pi/3$	$6\pi/5$
Undulator period $\lambda_u$	15 mm	15 mm
Undulator number $N_u$	1200	1200
Undulator parameter $K$	1.3244	1.3244
Beam energy $E$	3.5 GeV	3.5 GeV
Slice energy spread $\sigma$	100 keV	100 keV
Beam peak current $I$	20 A	100 A
Slice emittance $\varepsilon_n$	$0.083 \mu\text{m}\cdot\text{rad}$	$0.083 \mu\text{m}\cdot\text{rad}$
Single-pass gain $g_h$	65%	72%
Total cavity reflection $r$	80%	80%
Cavity length $L_c$	150 m	150 m
Bragg crystal	C(4,4,4)	C(5,5,9)
FWHM spectral width	5.5 meV	24.6 meV
FWHM temporal width	463 fs	107 fs
Photons/pulse	$0.86 \times 10^8$	$0.24 \times 10^8$
Output peak power	0.35 MW	0.74 MW



# LCLS-II に併設の提案

K.-J. Kim et al.,  
FEL-2014

## Harmonic XFELO performance (R. Lindberg, with a new code with exact total energy conservation)

Input

Electron beam

$\gamma mc^2$	4 GeV
$\sigma_\gamma/\gamma$	0.0125%
$I$	120 A
$\varepsilon_{x,n}$	0.2 $\mu\text{m}$

Undulator

$\lambda_u$	2.6 cm
$K$	1.69
$N_u$	2500

Cavity

$Z_R$	11 m
$R$	75%

Radiation

$\lambda_{\text{rad}}$	1
------------------------	---

harmonic

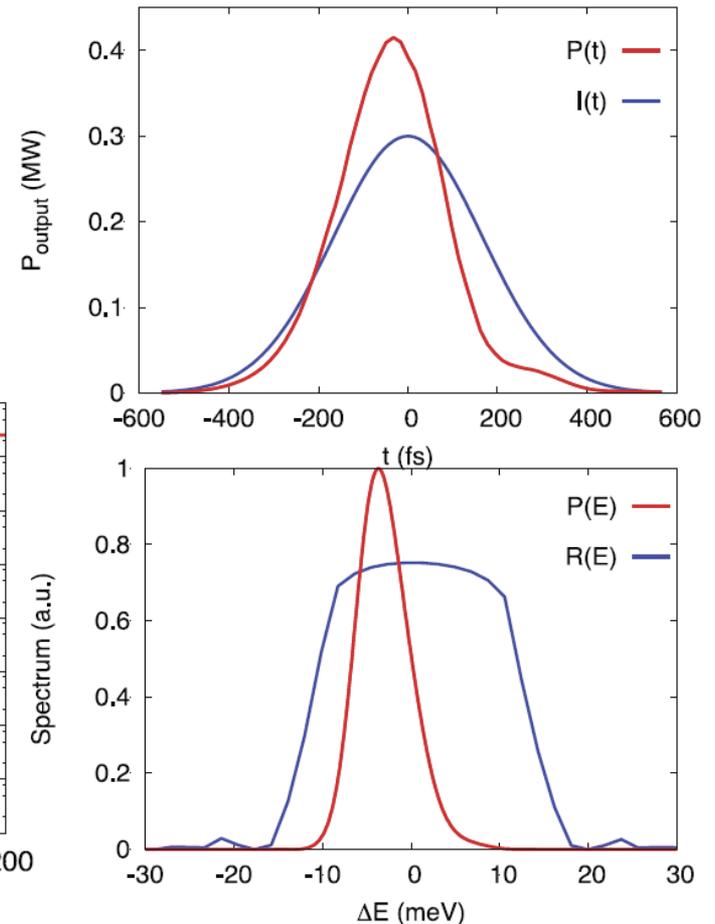
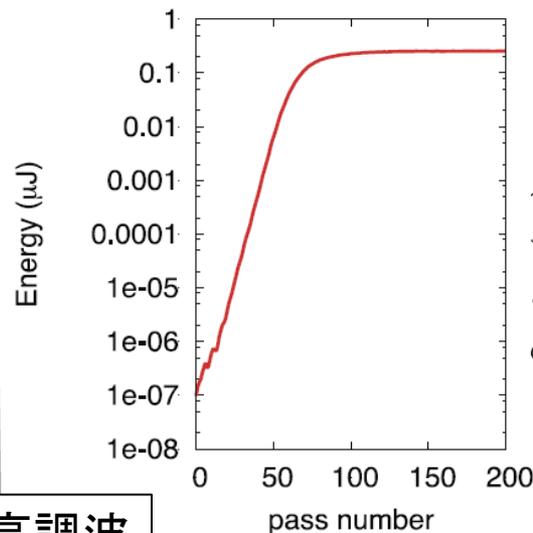
5

5次高調波

50 pC/  
140 fs (rms)

Output

Parameter	Value
Power	0.42 MW
# photons	$1.6 \times 10^8$
$\Delta T_{\text{FWHM}}$	265 fs
$\Delta E_{\text{FWHM}}$	6.8 meV



# European XFEL に併設の提案

マクロパルスモード  
SASE-FEL で使用した後の電子

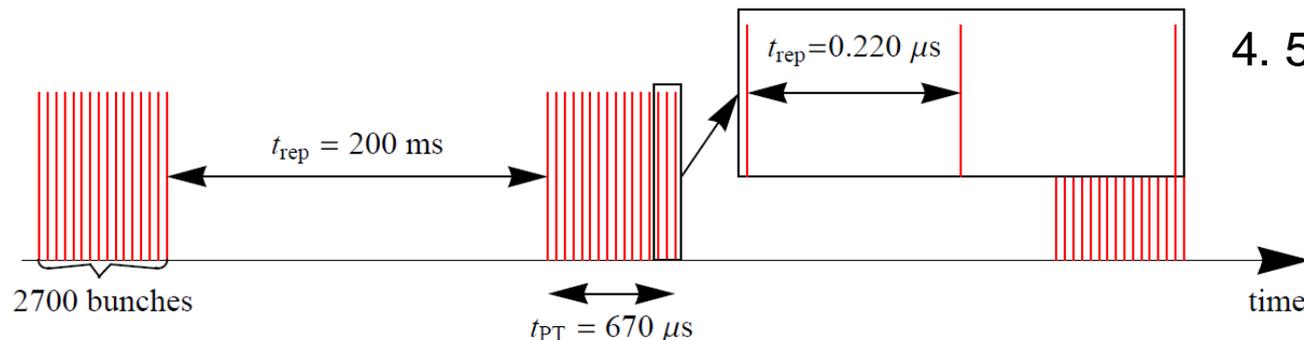
J. Zemela et al., FEL-2012

マクロパルス内で飽和

spent beam

beam energy $E_B$	GeV	14.5
bunch charge $q$	nC	1.0
bunch length (rms) $t_B$	fs	75.6
peak current $I_A$	kA	4.9
normalized emittance $\varepsilon_n$	mm mrad	1.0
slice energy spread $\sigma_E$	MeV	0.45 resp. 10
energy chirp $E_{\text{Chirp}}$	MeV	10.0
betafunctor $\beta_{x,y}$ at $\omega_0$	m	6.0
radiation wavelength $\lambda_R$	nm	0.1029
undulator length $L_U$	m	15.0
undulator periode $\lambda_U$	m	0.03
cavity length $L_{\text{Cav}}$	m	66.62
focal length $f$	m	18.82
round-trip reflectivity $R_{\text{Cav}}$	%	87.5
output coupling $T_{\text{Cav}}$	%	4

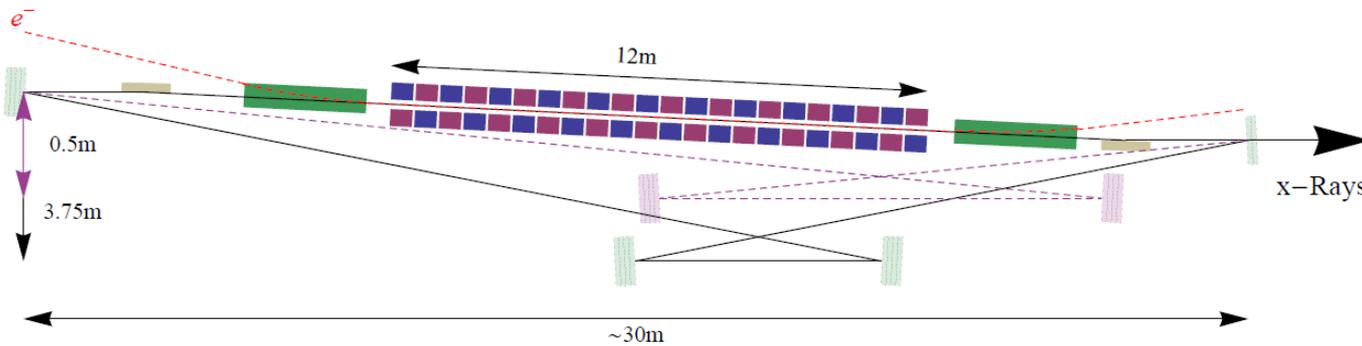
rms slice energy spread $\sigma_E$	MeV	0.45	10.0
detuning parameter $\eta$	$\cdot 10^{-4}$	0	6.36
gain per passage		1.1	0.105
round-trips to saturation		26	190
photon pulse energy $E_P$	$\mu\text{J}$	286	211
rms photon pulse length $t_P$	fs	42.8	52.2
relative spectral width $f_{\text{rel}}$	$\cdot 10^{-7}$	8.17	7.6
time bandwidth product		0.64	0.73
photon beam size at $\omega_0$ $\sigma_{\omega_0}$	$\mu\text{m}$		14.0
photon beam size at $L_1$ $\sigma_{L1}$	$\mu\text{m}$		39.2
opening angle $\theta_R$	$\mu\text{rad}$		2.33
couple out photon per pulse	$\cdot 10^9$	5.93	4.37
peak brilliance PB	$\text{B} \cdot 10^{34}$	1.1	0.69



4.5 MHz x 2700 bunches

# トンネルサイズと波長可変範囲

J. Zemela et al., FLS-2010

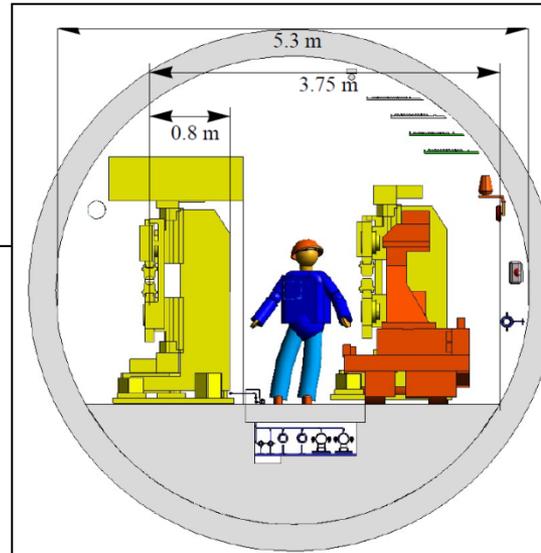


$$\lambda = 2d \sin(\theta_B), \quad \Delta\lambda = 2d (\sin(\theta_B + \Delta\theta) - \sin(\theta_B))$$

**Resonator length  $\sim 67$  m**

$h_{min}$ :	0.50 m
$h_{max}$ :	3.75 m
$\Delta\theta$ :	97 mrad
$\frac{\Delta\lambda}{\lambda}$ :	$6.2 \cdot 10^{-3}$

波長を変えるには  
それなりのスペースが必要



Here  $h_{min}$  not suitable small because of the undulator brace.

**Assumptions:**

$$h_{min} = 0.5 \text{ m}$$

$$h_{max} = 3.75 \text{ m}$$

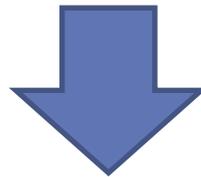
# 要素技術 – 電子銃、加速器

## 電子ビーム

10-50 pC, 1-10 MHz,  $< 0.2$  mm-mrad

## 加速器

超伝導、CW、4-7 GeV、 $< 1$  mA



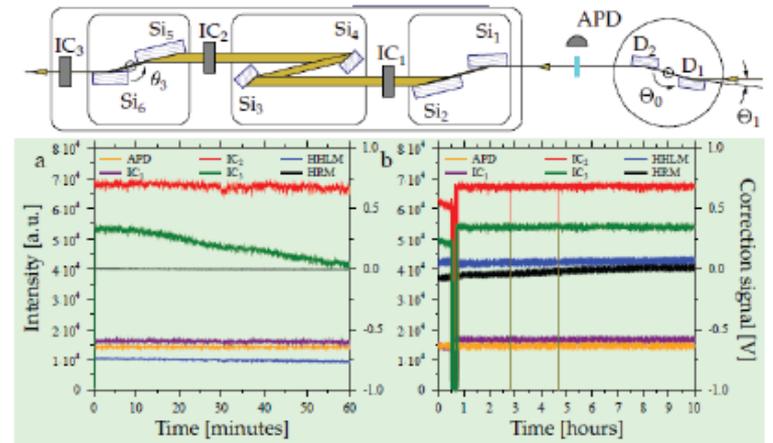
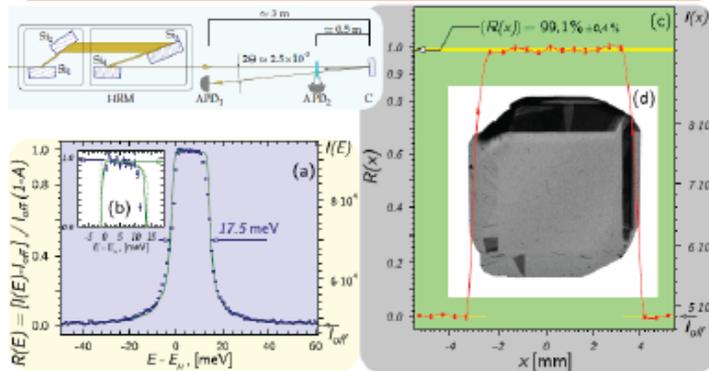
ERL、CW-FEL 用の電子銃、加速器がそのまま利用可能

# 要素技術 - X線共振器

K.-J. Kim et al.,  
FEL-2014

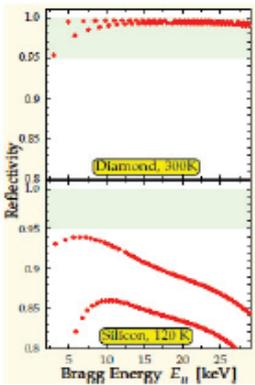
## Diamond Crystal is well-Suited for XFELO

Diamond Reflectivity Studies: C(008) @ 14.3 keV



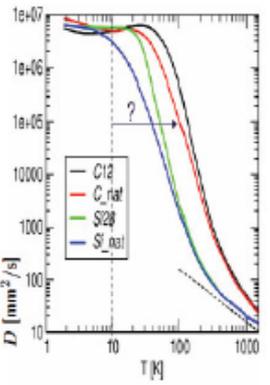
Record high reflectivity  
for hard x-rays

Theory: > 99%



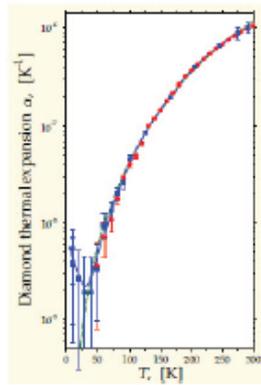
Ultra-high thermal diffusivity  
at low temperatures

$\approx 10^5 \text{ mm}^{-2}\text{s}$  @ 100 K



Ultra-low thermal expansion  
at low temperatures

$\approx 10^{-8} \text{ K}^{-1}$  @ 100 K



- Null-detection FB achieving 50 nr stability  $f < 2 \text{ Hz}$
- Nano-radian stage
- Strain-free crystal holder
- experience with LCLS SS

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# どのように実現するか？

- ユーザーの強い要求が前提
- 加速器コンポーネント
  - 現在進行中の研究開発で、ほぼ実現
- X線共振器
  - 国内で具体的な活動はない？
  - 潜在的な技術、研究者はいるはず
- 装置の建設
  - 他の光源と組み合わせて設置