Fully Coherent Hard X-ray Free-Electron Lasers

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Thomas Jefferson National Accelerator Facility
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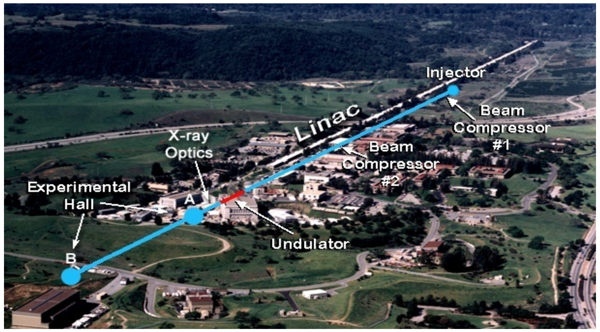
Outline

- Intro: two paths to completely coherent hard x-rays
  - Apply monochromator to self-amplified spontaneous emission and amplify the result in downstream FEL (self-seeding)
  - Form x-ray cavity using Bragg mirrors for x-ray FEL oscillator
- Operating principles of self-seeding
- "Wake monochromator" as a simple self-seeding scheme
- An alternative approach: the x-ray FEL oscillator (XFELO)
- XFELO performance and scaling
- Stability concerns
- Physics of Bragg scattering for oscillators and wake monochromators
- Performance of high-quality diamond crystals
- Conclusions

FELs based on self-amplified spontaneous emission (SASE) are now producing hard x-rays for science



LCLS pioneered bright, hard x-ray sources based on SASE, with many more projects underway

- SPring8 SACLA in operation, Euro XFEL under construction, LCLS II under development, Swiss FEL designed, PAL XFEL (Korea) in planning stages, …

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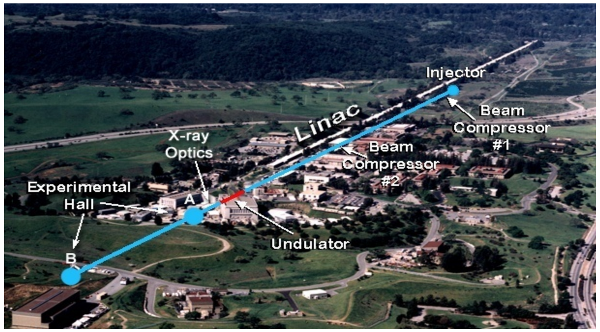
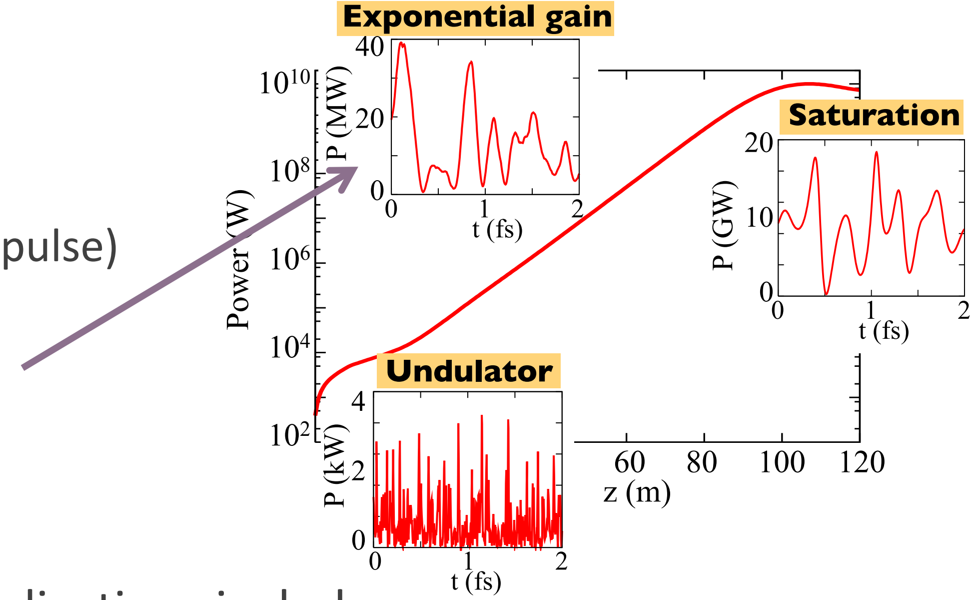


Characteristics

- High pulse intensity (~ 10^{12} photons/pulse)
- Temporally chaotic

  Normalized bandwidth $\Delta\omega/\omega \sim 10^{-3}$
- Sub-femtosecond pulses possible



Flagship applications include:

Single shot x-ray imaging, Nonlinear physics, and Atto-second dynamics

Brightness limits of SASE

- Because the FEL gain is initiated by electron beam shot noise, the SASE radiation comprises many longitudinal modes (temporally chaotic)
- In the frequency domain, the shot noise seeds radiation over the entire FEL bandwidth, so that $\Delta\omega/\omega \approx \rho$

⇒ Either the pulse is not Fourier limited/coherent
OR
The x-ray pulse is short ($\sim\lambda/c\rho$) with $\sim$100% shot-to-shot fluctuations in energy ("single spike")[1]

- Longitudinal coherence/spectral brightness can be improved by initializing the interaction with a coherent signal at the wavelength of interest

Harmonics of induced current modulation
(High Gain Harmonic Generation[2], Echo-Enabled Harmonic Generation[3])

Coherent radiation sources (using, e.g., High Harmonic Generation)

SASE + monochromator + radiator FEL ("self-seeding")

Oscillator using Bragg crystal mirrors

1. R. Bonifacio, L. De Salvo, N. Piovella, and C. Pellegrini, *Phys. Rev. Lett*. **73**, 70 (1994).
2. L. H. Yu, *Phys. Rev. A* **44**, 5178 (1991).
3. G. Stupakov, *Phys. Rev. Lett*. **102**, 074801 (2009).

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Harmonics of induced current modulation
(High Gain Harmonic Generation[2], Echo-Enabled Harmonic Generation[3])
Coherent radiation sources (using, e.g., High Harmonic Generation)

Appear to be limited to soft x-rays

SASE + monochromator + radiator FEL ("self-seeding")
Oscillator using Bragg crystal mirrors

Applicable to hard x-rays

1. R. Bonifacio, L. De Salvo, N. Piovella, and C. Pellegrini, *Phys. Rev. Lett*. **73**, 70 (1994).
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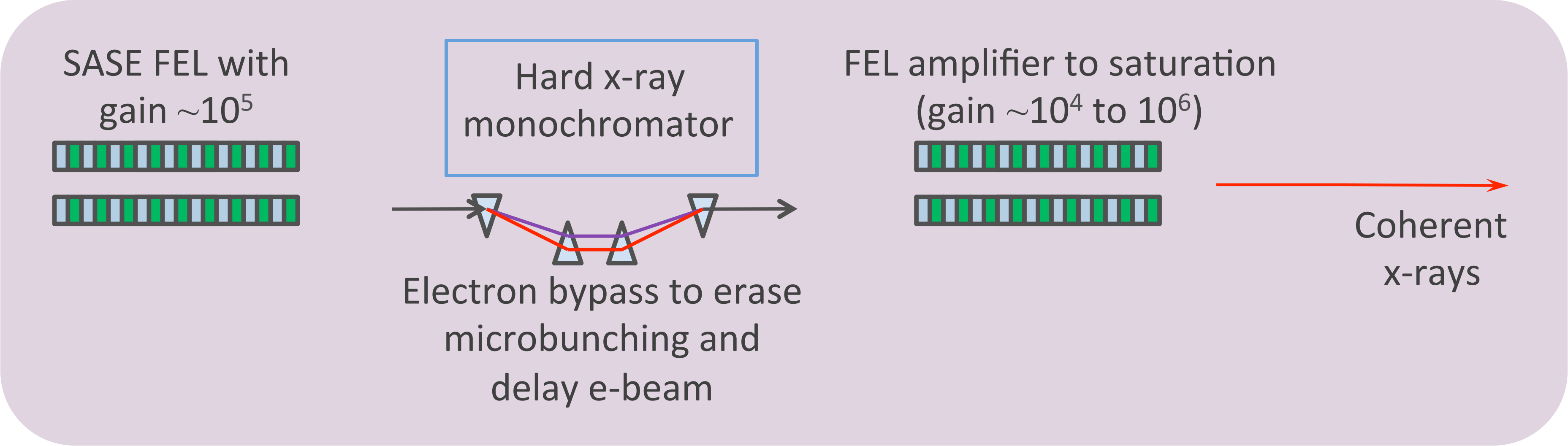
3. G. Stupakov, *Phys. Rev. Lett*. **102**, 074801 (2009).

Self-seeding schematic



SASE FEL with gain ~10^5

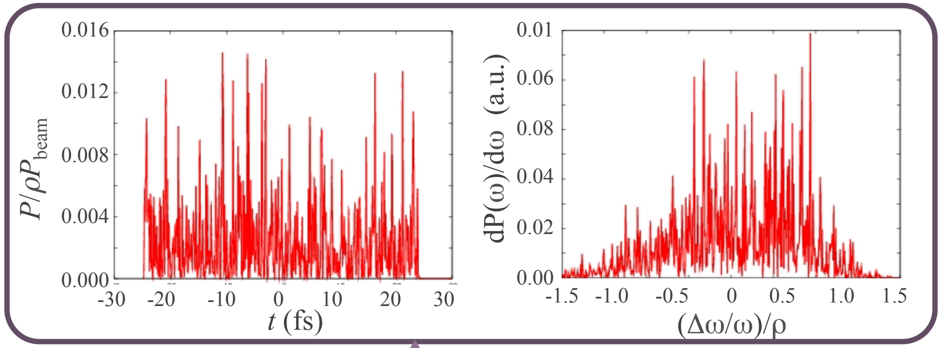
Hard x-ray monochromator

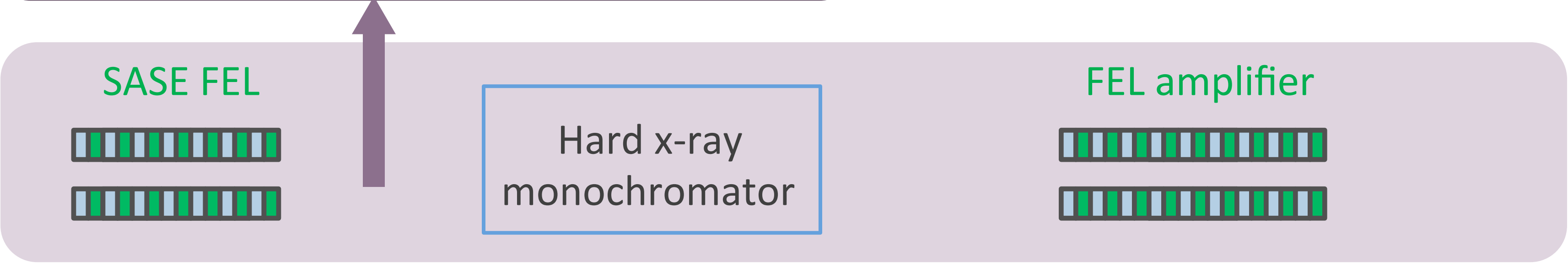
FEL amplifier to saturation (gain ~10^4 to 10^6)

Electron bypass to erase microbunching and delay e-beam

Coherent x-rays

Self-seeding power evolution




SASE FEL

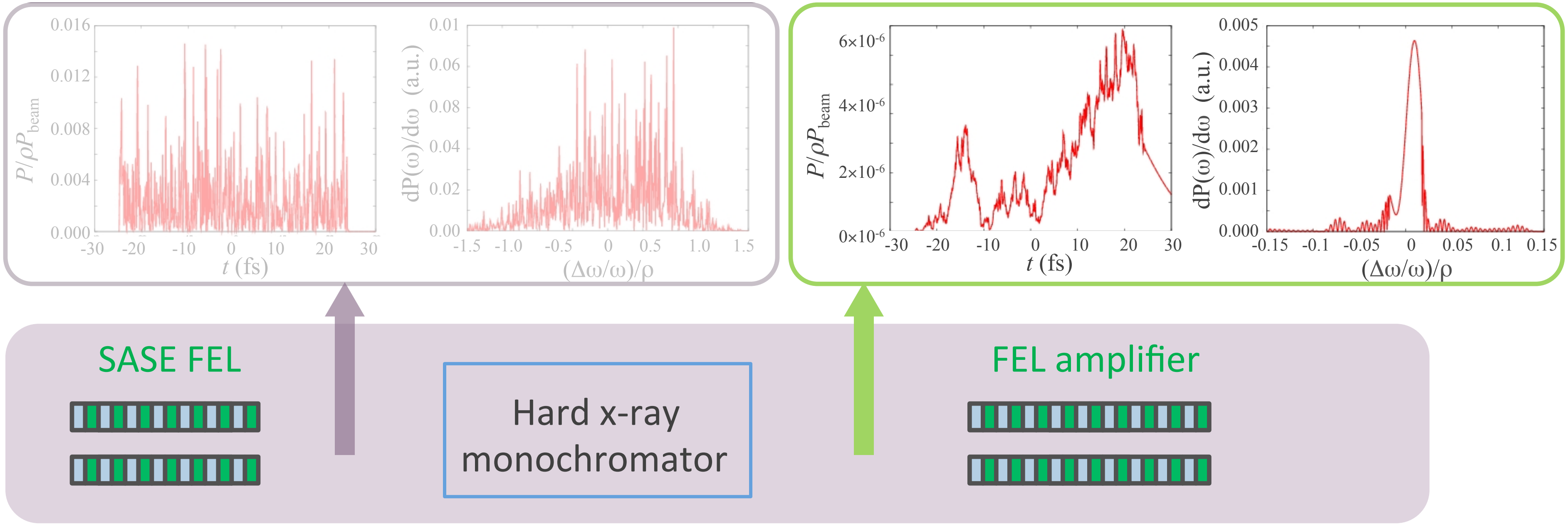
Hard x-ray monochromator

FEL amplifier

- Power large enough so that monochromatic signal dominates the seeding of SASE by electron beam shot noise
- FEL-induced energy spread on beam must remain small (well before nonlinear regime)

Example uses LCLS-type parameters with
$\rho = 5\times10^{-4}$, $\sigma_e \approx 12$ fs and $(\Delta\omega/\omega)_{\mathrm{mono}} = 2\times10^{-5}$

Self-seeding power evolution



SASE FEL

Hard x-ray monochromator

FEL amplifier

- Monochromator selects narrow bandwidth seed whose energy fluctuates by ~100%
- Electron beam must be delayed to overlap and amplify radiation in downstream undulator

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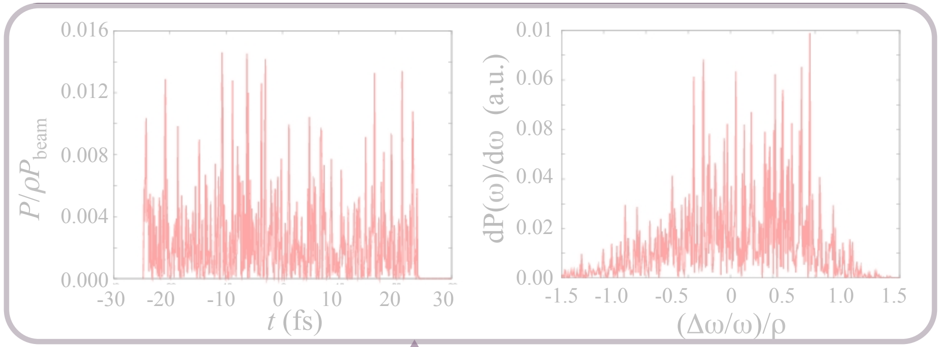
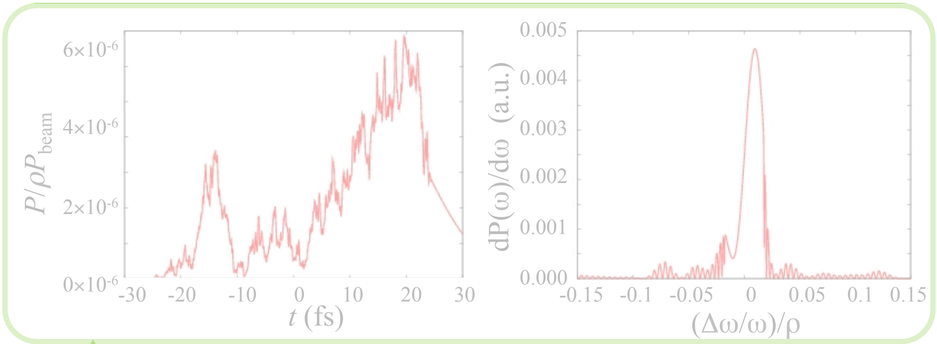
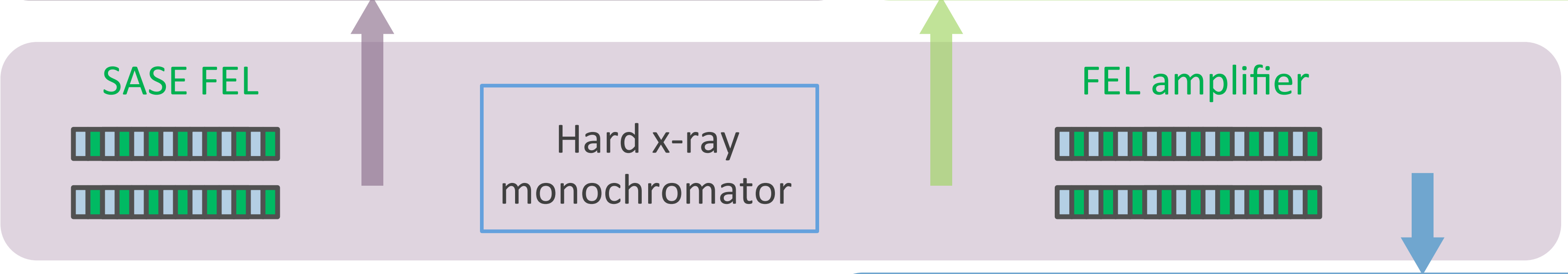
Self-seeding power evolution



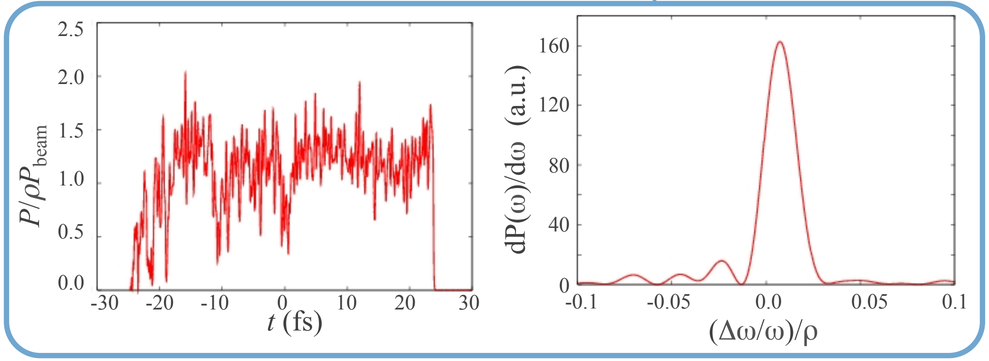




SASE FEL

Hard x-ray monochromator

FEL amplifier

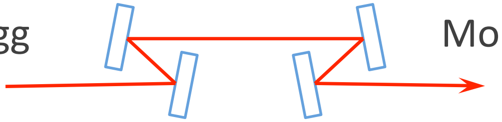


- Initial ~100% fluctuations of seed are reduced to ~20% at saturation
- Additional energy can be efficiently extracted by tapering the undulator strength

Example uses LCLS-type parameters with $\rho = 5\times10^{-4}$, $\sigma_e \approx 12$ fs and $(\Delta\omega/\omega)_{mono} = 2\times10^{-5}$

The monochromator and e-beam bypass (chicane)

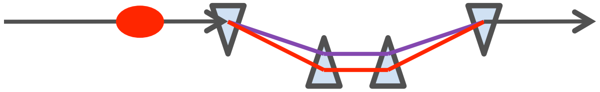
- Standard 4-bounce monochromator delays monochromatic seed ~30 ps



High heat load first pair of Bragg crystals (Si, Ge, diamond, …)

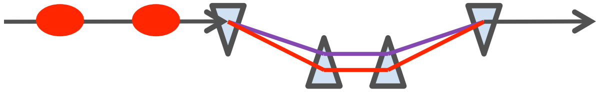
Monochromatizing second pair

- Chicane delays radiation for overlap and washes out the SASE-induced microbunching



Single bunch self-seeding[1]

Delaying the e-beam ~30 ps requires ~40 m chicane



Two bunches produced with beam splitter at photocathode[2]

Trailing bunch amplifies seed from leading bunch. Microbunching eliminated with ~3-4 m chicane

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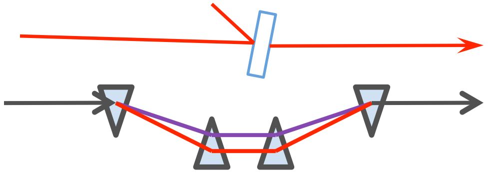
1. E.L. Saldin, E.A. Schneidmillera, Yu.V. Shvyd'ko, and M.V. Yurkov, *Nucl. Instrum. Methods Phys. Res., Sect. A* **475**, 357 (2001)
2. Y. Ding, Z. Huang, and R. D. Ruth, *Phys. Rev. ST Accel. Beams* **13**, 060703 (2010)

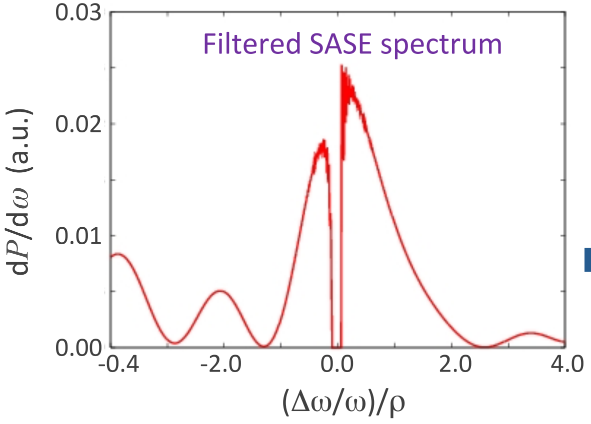
The “wake” monochromator for small delays from temporally short beams

- Uses time dependence of forward Bragg diffraction from a single crystal, i.e., time response of the crystal transmission function[1]

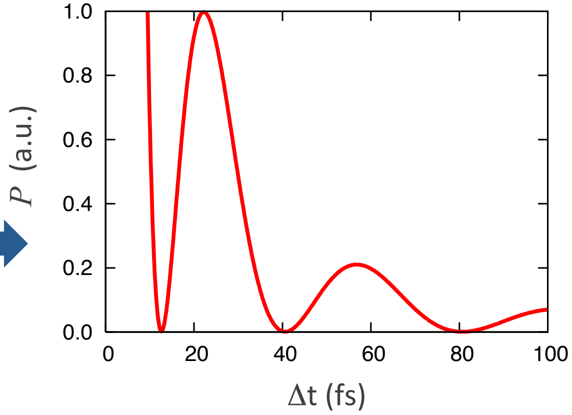
Single crystal wake mono



~3-4 m chicane washes out microbunching and delays electrons requires tens of fs



Spectral “notch” gives rise to broad temporal feature delayed by causality



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1. G. Geloni, V. Kocharyan ,and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011)

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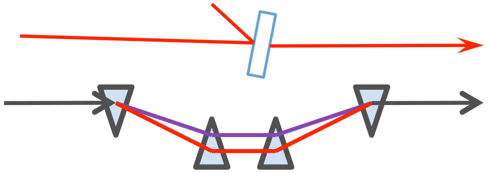

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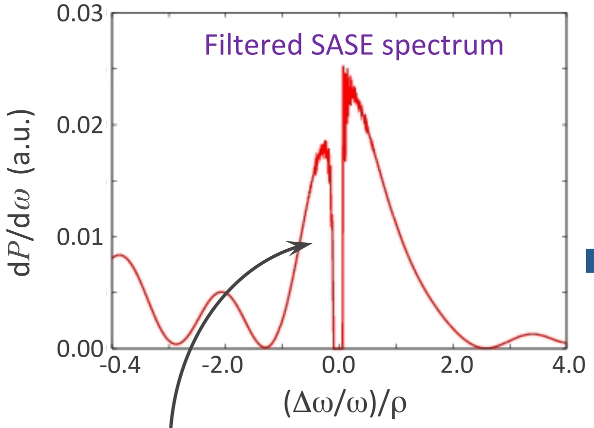

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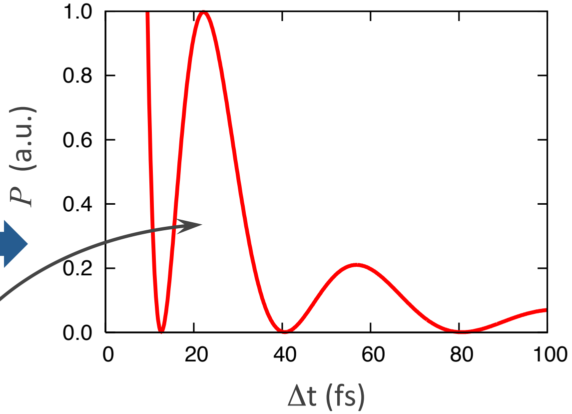


For broad initial spectrum and optimal seeding overlap, best suited to short ~fs pulses

1. G. Geloni, V. Kocharyan ,and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011

Post-saturation taper of undulator can result in significant gains in field energy

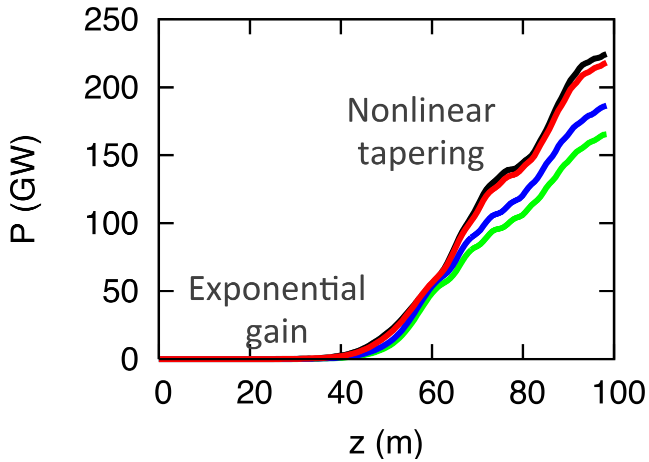
- Tapering the undulator strength (or period) lowers the ponderomotive potential, so that particles can continue to lose energy to the field
- In SASE, different coherent regions of the electron beam do different things

Can maintain synchronism
with only some particles
➔ Moderate energy gains

- In seeded FEL, the average phase of particles is uniform across the bunch

Single taper can be used to extract more energy across entire bunch

➔ Significant increase in FEL power and efficiency



SLAC-ANL-TISNCM collaboration has demonstrated a reduction of bandwidth ~10 to 40 using the wake monochromator at the LCLS

- Configuration proposed by scientists at DESY[1]
- **SLAC**: project lead; designed and built chicane; built monochromator; prepared control systems; installed hardware; designed and built spectrometer; …
- **ANL**: designed and built the vacuum chamber and YAG diagnostic; designed monochromator tank; procured and tested diamond crystals
- **TISNCM**: grew high-quality diamond crystals of 100 and 150 µm thickness
- Data still being analyzed and prepared for publication

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1. G. Geloni, V. Kocharyan ,and E.L. Saldin, “Cost-effective way to enhance the capabilities of the LCLS baseline”, DESY 10-133, arXiv:1008.3036 (2010)

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Basic idea has been confirmed
Significant reduction in the bandwidth has been measured
Time delay scan agrees with theory

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Decrease in fluctuations yet to be observed
Additional tapering has not improved performance to date

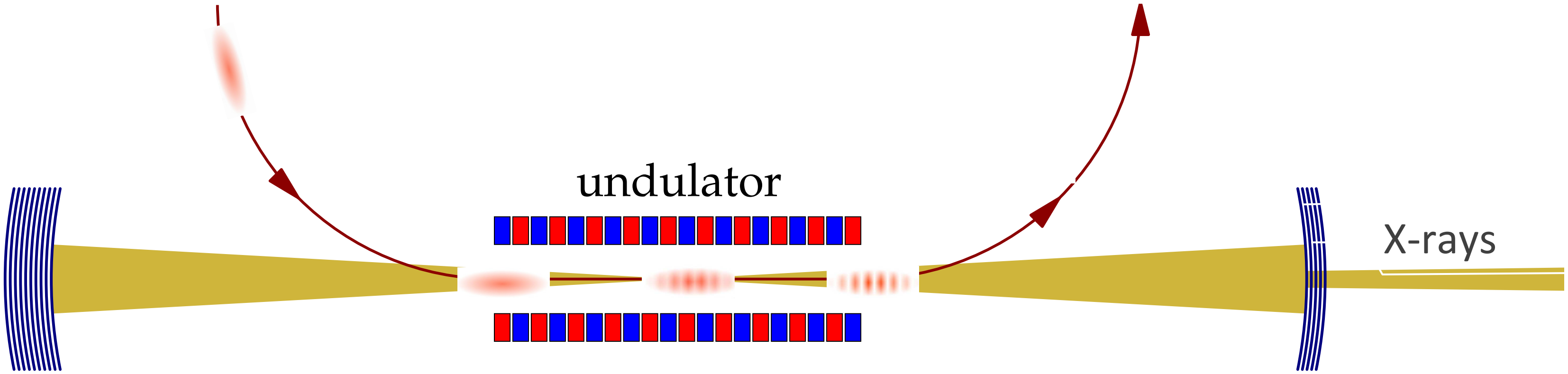
Nonlinear saturation not yet reached

1. G. Geloni, V. Kocharyan ,and E.L. Saldin, DESY 10-133, arXiv:1008.3036 (2010)

X-ray FEL oscillator for fully coherent hard x-rays

First proposed by Colella and Luccio using Silicon mirrors, but without detailed understanding of the FEL physics the idea went dormant as SASE came into prominence[1]

Interest in the oscillator was renewed recently when concrete, realizable parameters for the undulator, the electron beam and the x-ray optical cavity were presented by Kim, Shvyd’ko, and Reiche[2]



1. R. Colella and A. Luccio, *Optics Comm.* **50**, 41 (1984).
2. K-J. Kim, Yu. Shvyd’ko, and S. Reiche, *Phys. Rev. Lett.* **100,** 244802 (2008)

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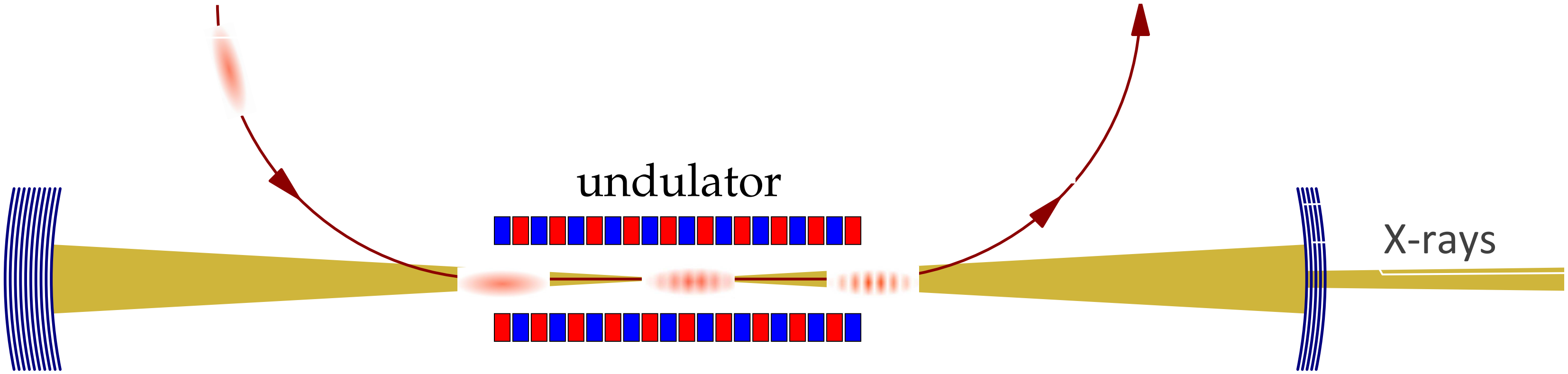
Energy recovery linac-type electron beam @ 1 MHz:
$Q = 25$ pC, $E = 7$ GeV, $\Delta E = 1.4$ MeV, $\varepsilon_{x,n} = 0.2$ mm-mrad



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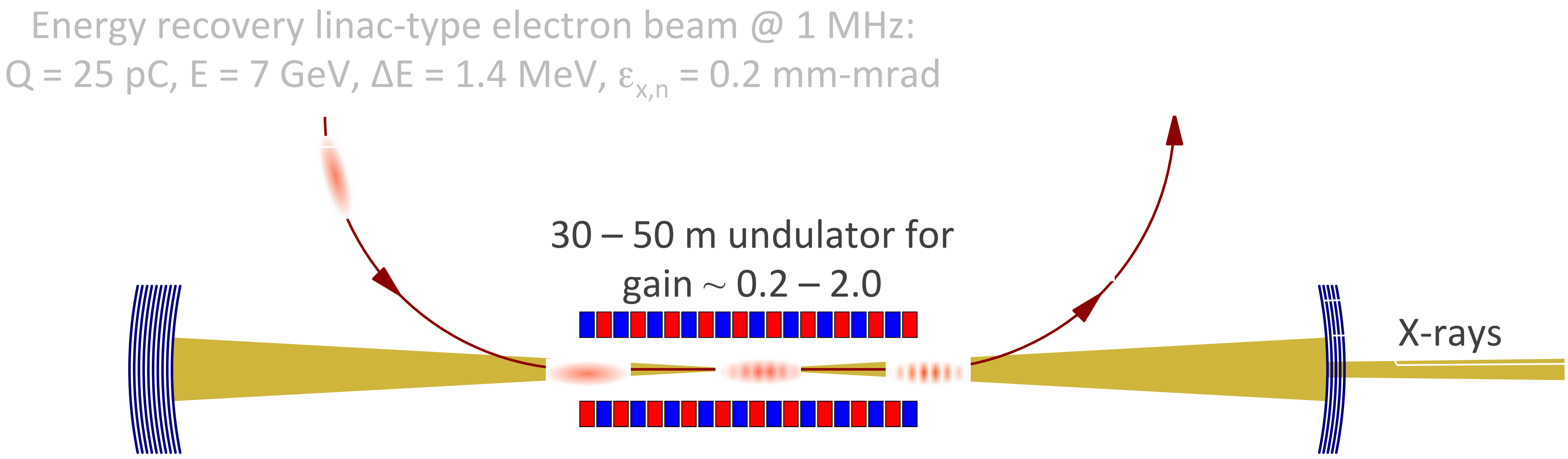

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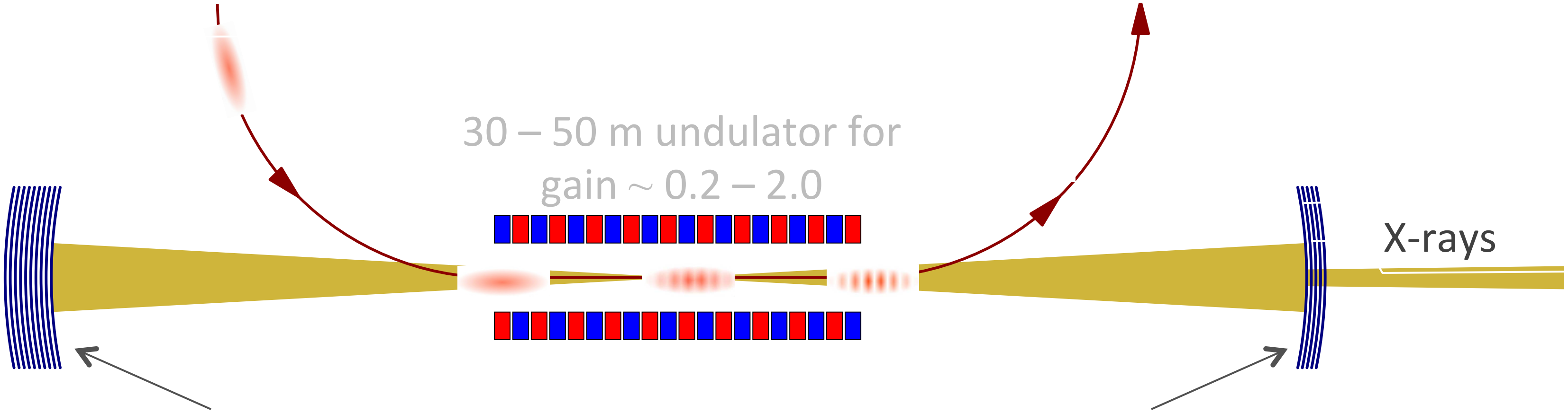


Energy recovery linac-type electron beam @ 1 MHz:
$Q = 25$ pC, $E = 7$ GeV, $\Delta E = 1.4$ MeV, $\varepsilon_{x,n} = 0.2$ mm-mrad

30 – 50 m undulator for gain ~ 0.2 – 2.0

X-rays

High reflectivity (R > 95%) Bragg crystal mirrors to trap appropriate optical mode

1. R. Colella and A. Luccio, *Optics Comm.* **50**, 41 (1984).
2. K-J. Kim, Yu. Shvyd'ko, and S. Reiche, *Phys. Rev. Lett.* **100,** 244802 (2008)

Parameters

Cavity length ~ 100 m ➔ Repetition rate ~ 1 MHz

Peak Currents ~ 10 – 100 A
Bunch Lengths ~ 2 – 0.1 ps ➔ Low charge ~ 10 – 50 pC

High quality electron beam:
$\varepsilon_{x,n} \sim$ 0.1 – 0.3 mm-mrad, $\Delta\gamma/\gamma \sim$ 0.01 – 0.03%

Low single pass gain, losses:
$G \sim$ 0.3 – 1.0, $R_{tot} \sim$ 0.85 – 0.5 > $(1 + G)^{-1}$

Example @ 1 Å

E_{beam}	7 GeV
I_{peak}	10 A
$\varepsilon_{x,n}$	0.2 mm-mrad
$\Delta\gamma/\gamma$	0.02%
L_{und}	52 m
G	0.36
R_{tot}	0.85
crystal	C(4 4 4)

Performance

Cavity power ~ 10 – 200 MW ➔ Output power ~ 0.5 – 10 MW

Output ~ 10^9 – $5\text{x}10^9$ photons ➔ Spectral brightness ~ 10^{31} – 10^{34}

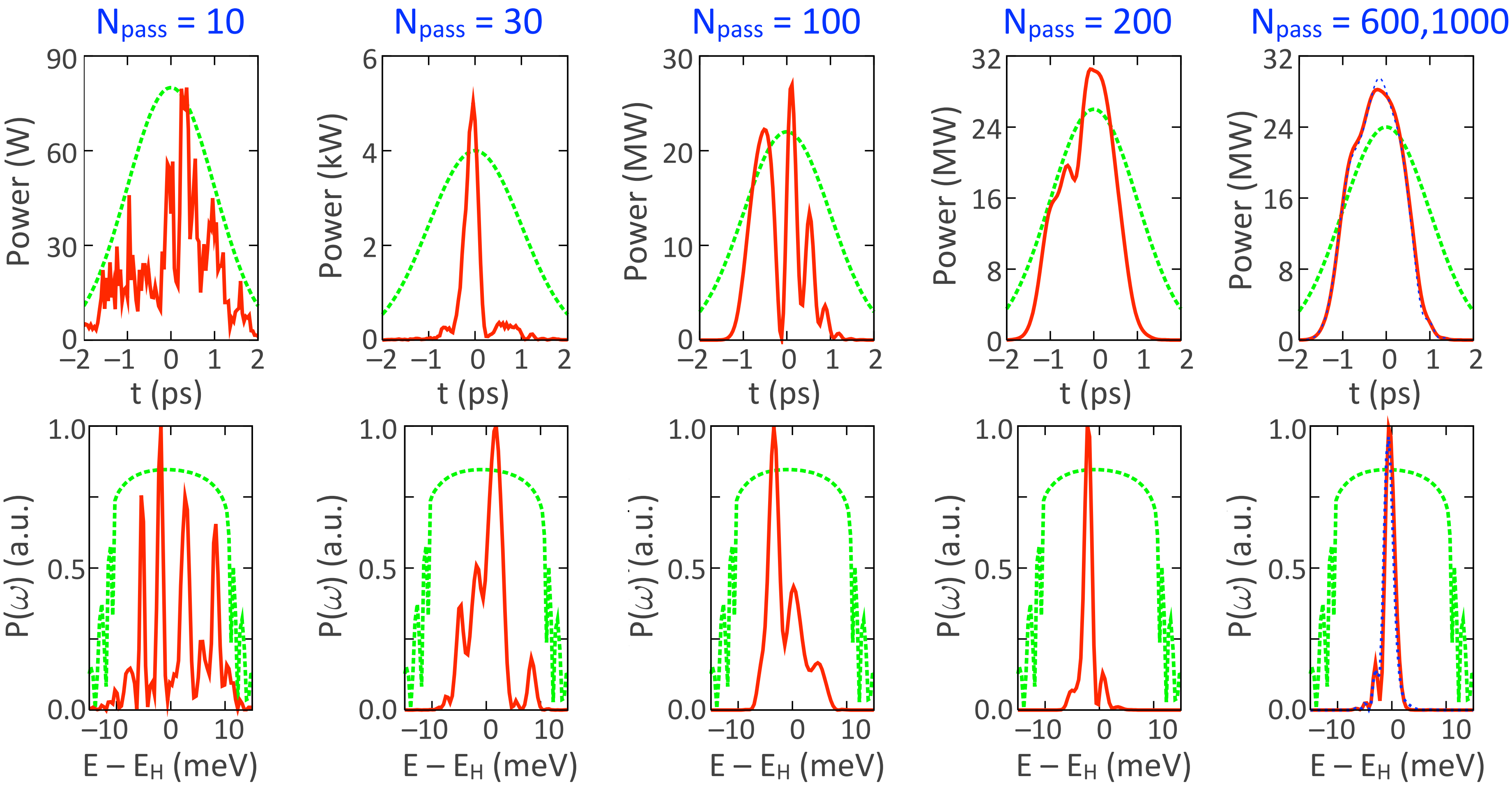
Nearly Fourier limited pulses ➔ ΔE ~ 1 – 10 meV, $\Delta\omega/\omega \sim 10^{-6} - 10^{-8}$

Example @ 1 Å

P_{out}	1.7 MW
Photons/ pulse	1.1×10^9
ΔE	1.29 meV
Δt	0.51 ps

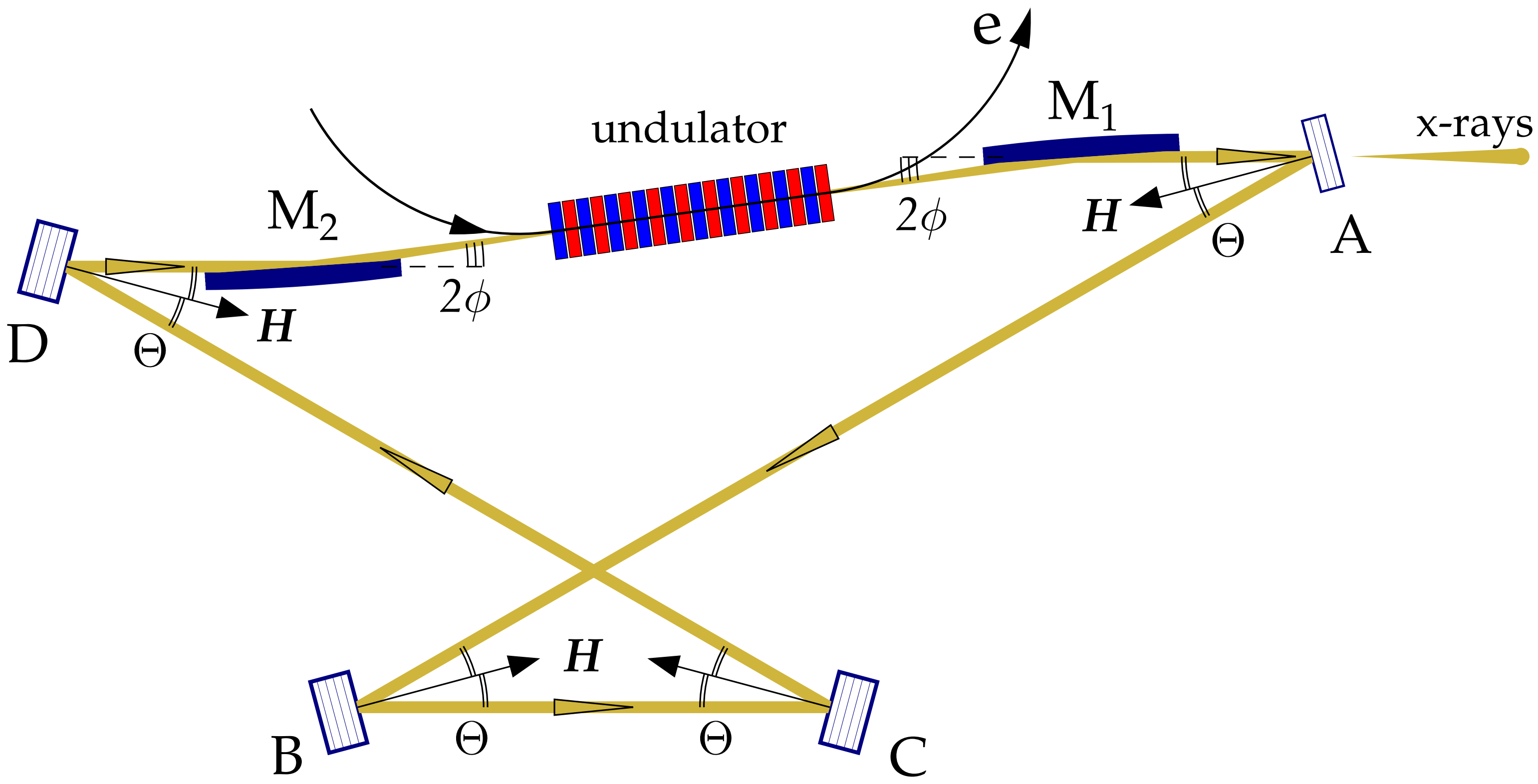
R.R. Lindberg, K-J. Kim, Yu. Shvyd'ko, and W.M. Fawley, *Phys. Rev. ST-AB.* **14,** 010701 (2011)

Temporal and spectral evolution of XFELO



R.R. Lindberg, K-J. Kim, Yu. Shvyd'ko, and W.M. Fawley, *Phys. Rev. ST-AB.* **14,** 010701 (2011)

Tunable source of hard x-rays



By varying the incidence angle Θ, one can obtain a wide range of photon energies that satisfy Bragg's law $E = E_H \cos\Theta$

Tunability allows one to pick a single crystal for all wavelengths of interest

R.M.J. Cotterill , *Appl. Phys. Lett.* **12**, 403 (1968)
K.-J. Kim and Yu. Shvyd'ko, *Phys. Rev. ST-AB* **12**, 030703 (2009)

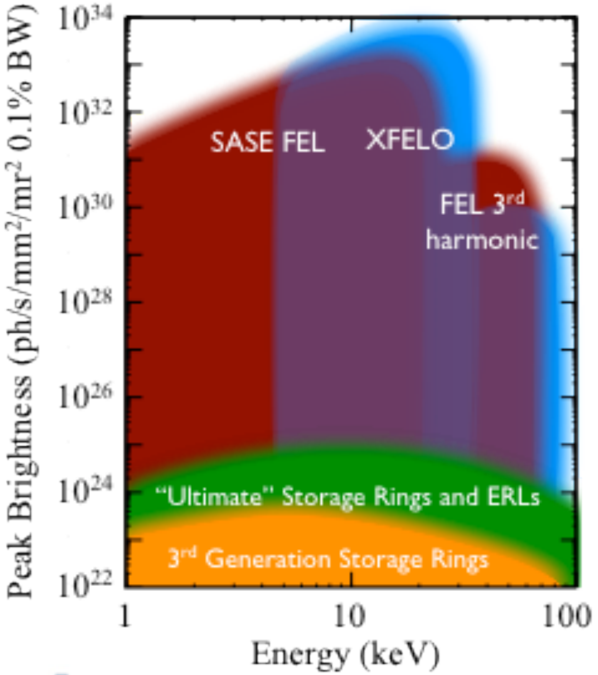
X-ray FEL oscillator: a complementary hard x-ray source

Characteristic	SASE	XFELO
Pulse duration (fs)	1 to 100	100 to 1000
Photons/pulse	10^{12}	10^{9}
ΔE (eV)	10	10^{-3}
Coherence	Transverse	Fully

Science:

Inelastic x-ray scattering,
Nuclear resonant scattering,
X-ray photoemission spectroscopy,
Hard x-ray imaging,
X-ray photon correlation spectroscopy

Will revolutionize techniques pioneered at 3rd generation light sources, and complement the science of SASE FELs



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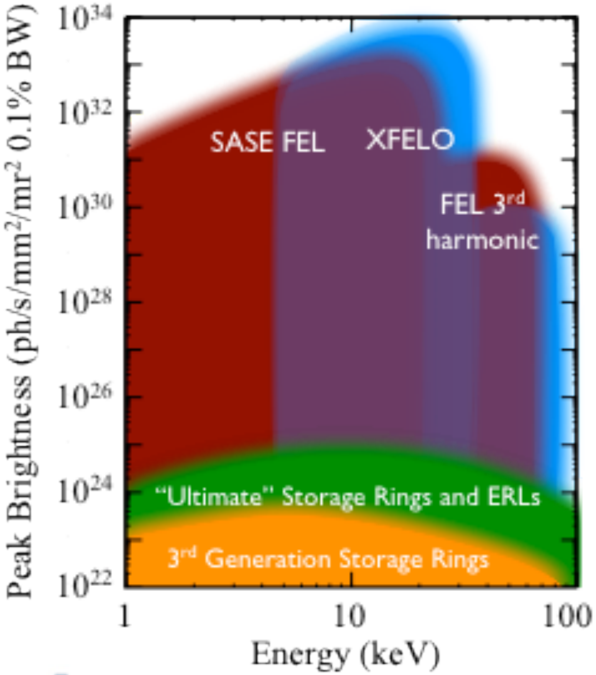

Science Opportunities with an XFELO Workshop, APS, May 5th, 2010

XFELO scales well to extremely low electron beam charge and emittance

As an extreme example, consider a suitably modified version of the parameters first proposed for the ultra-short, “single spike” regime of high-gain FELs[1]:

Q = 1 pC ε_{xn} = 0.062 mm•mrad ΔE = 250 keV

σ_e = 250 fs ➔ I = 1.6 A

Using the same undulator (N_u = 3000) and optical cavity, G = 74%

R = 85% ➔ P_{out} = 9.5 MW, $N_{\text{ph}} = 10^8$

R = 50% ➔ P_{out} = 600 kW, $N_{\text{ph}} = 5\text{x}10^6$

$$\Delta\omega/\omega \approx 2 \times 10^{-6} \qquad \hbar\Delta\omega \approx 3 \text{ meV}$$

Reduced heat load on crystals ➔ Increase repetition rate

1. J.B. Rosenzweig, et al.,, *Nucl. Instrum. Methods A.* **593,** 39 (2008)

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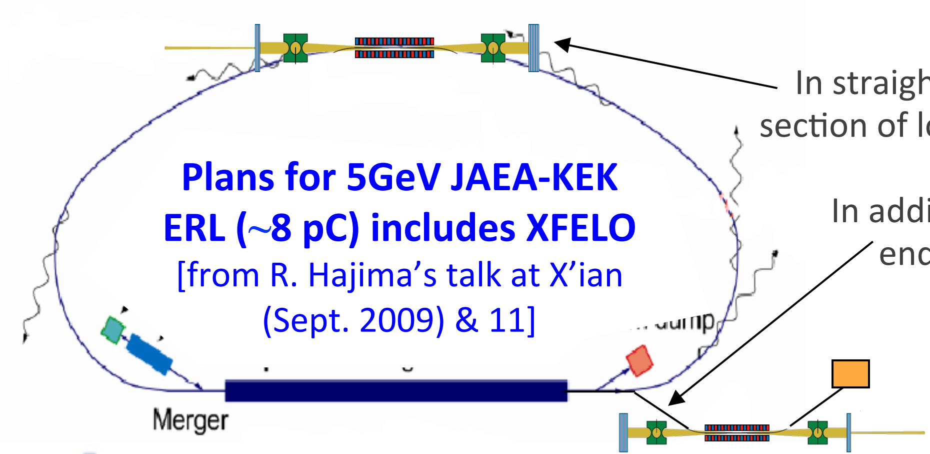
Using the same undulator (N_u = 3000) and optical cavity, G = 74%

R = 85% ➔ P_{out} = 9.5 MW, $N_{\mathrm{ph}} = 10^8$

R = 50% ➔ P_{out} = 600 kW, $N_{\mathrm{ph}} = 5\text{x}10^6$

$$\Delta\omega/\omega \approx 2\times10^{-6} \qquad \hbar\Delta\omega \approx 3\ \mathrm{meV}$$

Reduced heat load on crystals ➔ Increase repetition rate up to ~GHz



Plans for 5GeV JAEA-KEK ERL (~8 pC) includes XFELO
[from R. Hajima’s talk at X’ian (Sept. 2009) & 11]

In straight section of loop

In additional single-ended branch

The beam energy can be significantly decreased by lasing at the 3rd harmonic if the emittance is sufficiently small[3]

1. J.B. Rosenzweig, et al.,, *Nucl. Instrum. Methods A.* **593,** 39 (2008)
2. R. Hajima and N. Nishimori, Proc. of 2009 FEL Conf.
3. J. Dai, H. Deng, and Z. Dai, Phys. Rev. Lett. **108**, 034802 (2012).

Stability

- Self-seeding
  - Intrinsic: 100% fluctuations in linear regime $\sim$20% fluctuations at/after saturation
- Oscillator
  - Intrinsic: Ratio of spontaneous to saturated power $\sim 10^{-5} - 10^{-6}$
  - Stability likely dominated by crystals + mirrors angular tolerances $\sim$10 nrad
- Output of both are affected by
  - Variations of beam energy $\sim 10^{-4}$
  - Energy/current uniformity of beam
    (E/I modulations create sidebands that can be amplified)
  - Heating issues of crystals
  - Etc.

Long term drifts → Compensated using feedback

Fast time scale fluctuations → Directly mapped onto seeded output

→ Reduced in XFELO by the effective quality factor of the cavity

“Favored” parameters/performance of fully coherent hard x-ray FELs

Self-seeding with wake monochromator $\mathcal{B}_{\text{sat}} \approx \rho \frac{\gamma mc^2}{\hbar\omega\mathcal{V}_{\text{coh}}} \frac{Q}{e}$

Constraints: $T_{\text{FWHM}} \sim$ 5 fs (T_{FWHM} >> T_{coh} SASE) – 50 fs (to maintain overlap in radiator)

$Q \sim$ 20 – 150 pC (to produce necessary current)

Output: $P_{\text{FWHM}} \sim$ 20 – 1000? GW

$N_{\text{photons}} \sim 10^{10} - 10^{14}$?

(depending on length of taper)

$\Delta\omega/\omega \sim 10^{-4} - 10^{-6}$

X-ray FEL oscillator $\mathcal{B}_{\text{sat}} \approx \frac{T}{1-R} \frac{1}{2N_u} \frac{\gamma mc^2}{\hbar\omega\mathcal{V}_{\text{coh}}} \frac{Q}{e}$

Constraints: $T_{\text{FWHM}} \sim$ 0.1 ps ($T > /\Delta E_{\text{refl}}$) – 2+ ps

$Q \sim$ 1 – 50+ pC (to produce necessary gain, depending on ε_x)

Output: $P_{\text{FWHM}} \sim$ 1– 10 MW

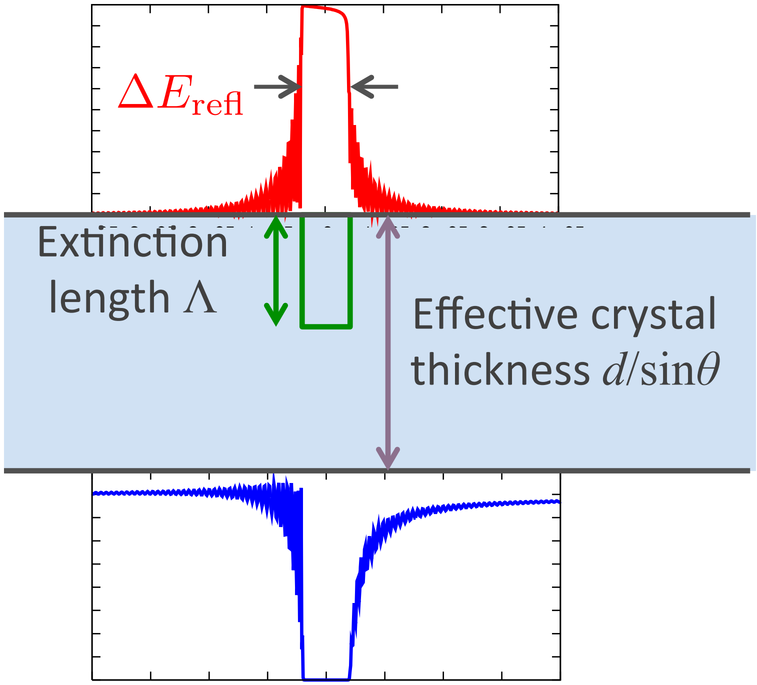
$N_{\text{photons}} \sim 10^{8} - 10^{10}$

$\Delta\omega/\omega \sim 10^{-6} - 10^{-8}$ and below

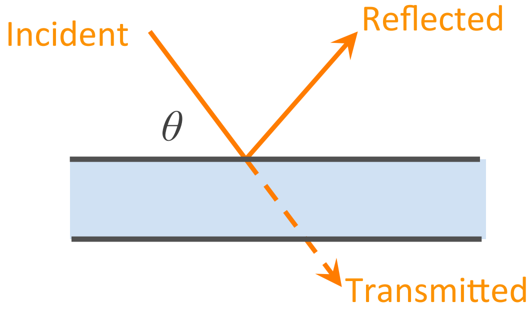
Bragg crystals in reflection for XFELO

Bragg's law defines central energy of reflection $\lambda = \lambda_B \sin\theta$

Reflection $|R(E)|^2$



Transmission $|T(E)|^2$



- Extinction length Λ gives depth into crystal over which x-rays near Bragg's law are reflected

$$\Delta E_{\text{refl}} \sim \frac{\hbar c}{\Lambda}$$

- XFELO radiation has $\hbar/T_{\text{rad}} \lesssim \Delta E_{\text{refl}}$ to minimize reflection losses

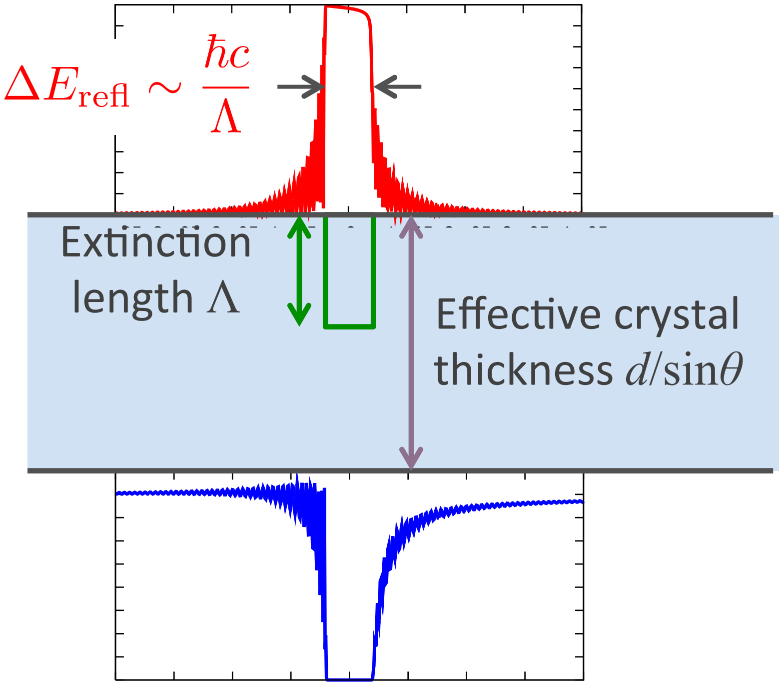
  ➔ Narrow region of R, T contributes

- Decreasing thickness to few Λ allows for transmission to users

Bragg crystals in transmission for “wake” self-seeding

Bragg’s law defines central energy
of reflection $\lambda = \lambda_B \sin\theta$

Reflection $|R(E)|^2$

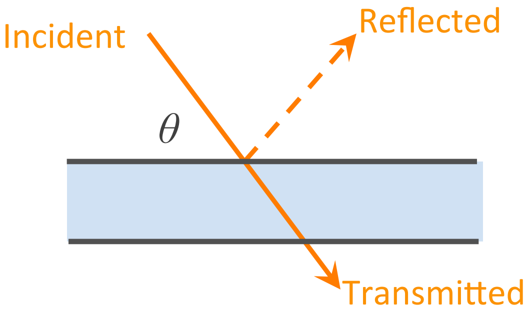


$\Delta E_{\text{refl}} \sim \frac{\hbar c}{\Lambda}$

Extinction length Λ

Effective crystal thickness $d/\sin\theta$

Transmission
$|T(E)|^2$



- Radiation has $\hbar/T_{\text{rad}} \gg \Delta E_{\text{refl}}$

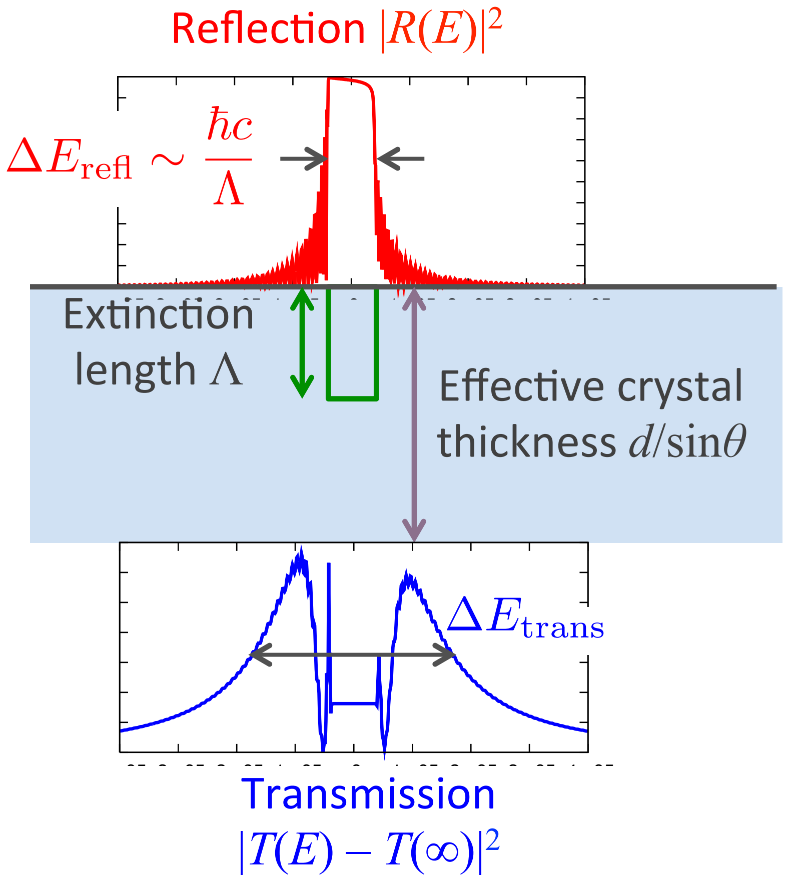
  ➔ Large Region of T contributes

- Seeding “wake” is determined by the difference $T(\mathrm{E}) - T(\infty)$

R.R. Lindberg and Yu. Shvyd’ko, submitted to *Phys. Rev. ST-AB.*, eprint arXiv:1202.1472 (2011)

Bragg crystals in transmission for “wake” self-seeding

Bragg’s law defines central energy of reflection $\lambda = \lambda_B \sin\theta$



Reflection $|R(E)|^2$

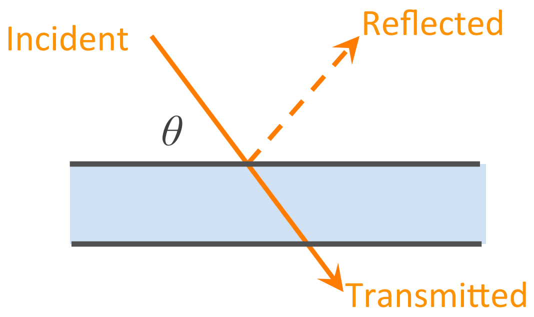
$\Delta E_{\text{refl}} \sim \frac{\hbar c}{\Lambda}$

Extinction length Λ

Effective crystal thickness $d/\sin\theta$

ΔE_{trans}

Transmission $|T(E) - T(\infty)|^2$



- Radiation has $\hbar/T_{\text{rad}} \gg \Delta E_{\text{refl}}$

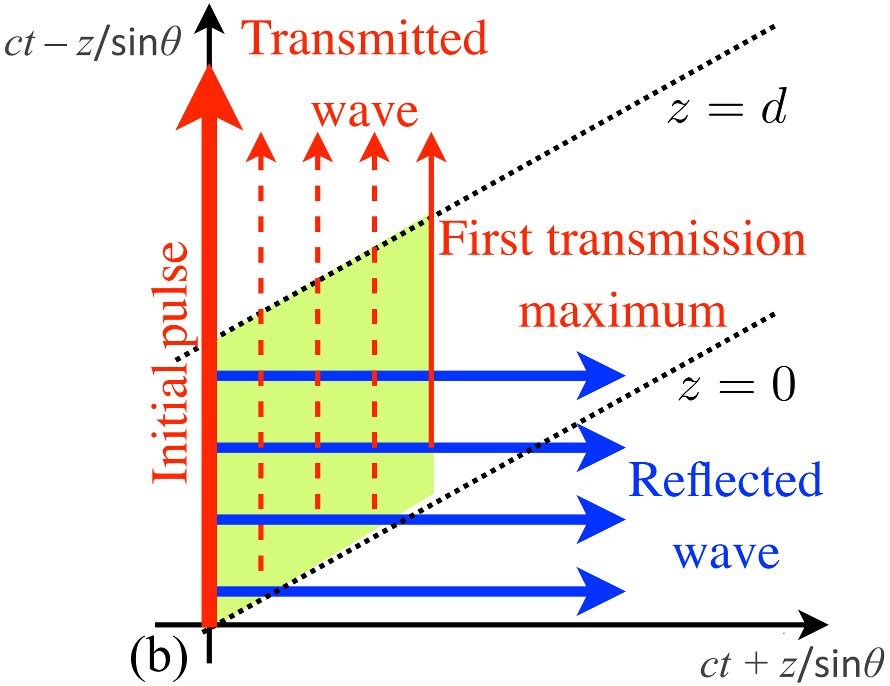
  ➔ Large Region of T contributes
- Seeding “wake” is determined by the difference $T(\mathrm{E}) - T(\infty)$
- Relevant spectral components interact over entire crystal thickness

$$\Delta E_{\text{trans}} \sim \frac{d}{\Lambda \sin\theta} \Delta E_{\text{refl}}$$

$$\Delta t_{\text{trans}} \sim \frac{\Lambda^2 \sin\theta}{cd}$$

R.R. Lindberg and Yu. Shvyd’ko, submitted to *Phys. Rev. ST-AB.*, eprint arXiv:1202.1472 (2011)

Time domain picture of wake monochromator



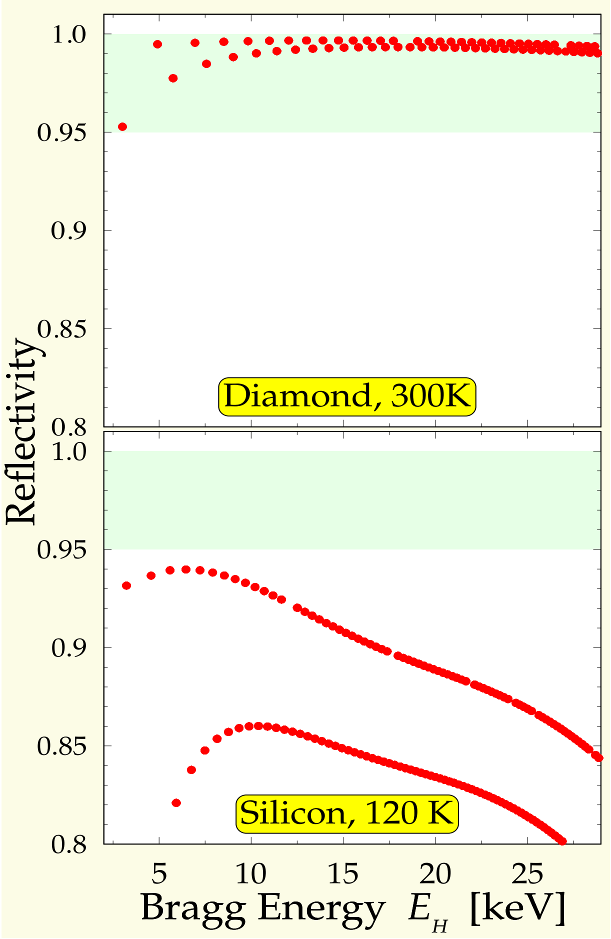
Position of first peak proportional to interaction area: $\Delta t\, d$ = constant
Δt scales inversely with crystal thickness

Seed power scales quadratically with crystal thickness

Diamond crystals have superlative material properties

Record-high reflectivities

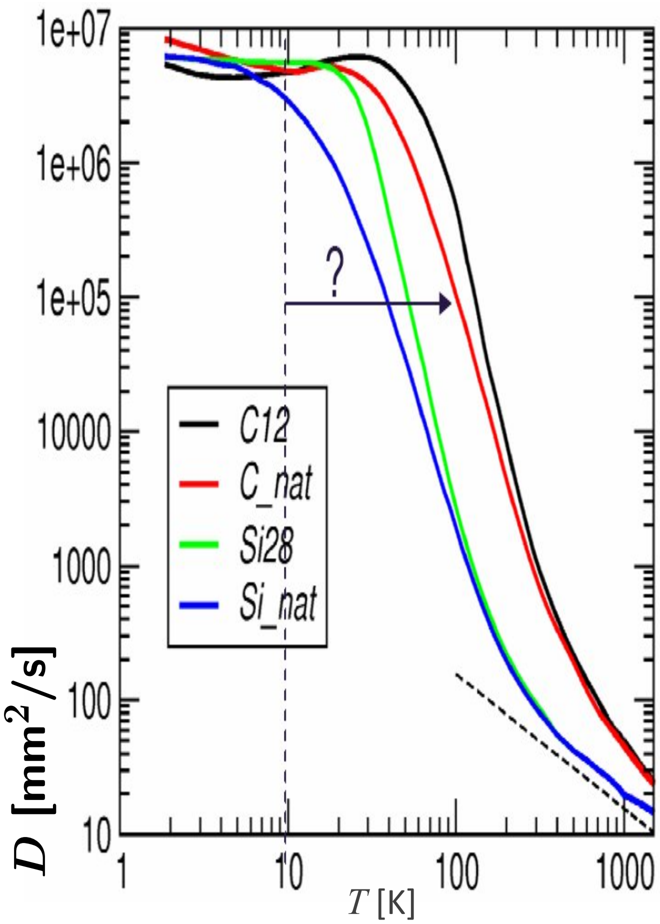
Theory: > 99% possible



Yu. Shvyd'ko, S. Stoupin, A. Cunsolo, A.H. Said, and X. Huang, *Nature Phys.* **6**, 196 (2010)

Ultra-high thermal diffusivity

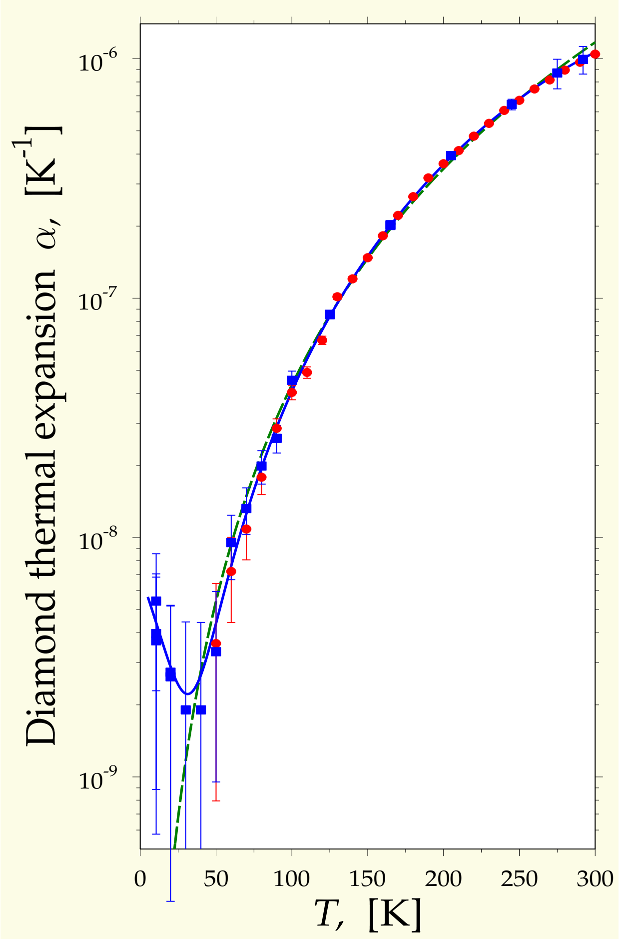
~ 10^5 s/mm^2 @ 100 K



Courtesy H. Sinn

Ultra-low thermal expansion

~ 10^{-8} K^{-1} @ 100 K



S. Stoupin and Yu. Shvyd'ko, *Phys. Rev. Lett.* **104**, 085901 (2010)

Reflectivity of TISNCM† synthetic diamond was measured to be > 98% @ the APS

† Technological Institute for Superhard Novel Carbon Materials, Russia

Yu. Shvyd'ko, S. Stoupin, V. Blank, and S. Terentyev, *Nature Photonics* **5**, 539 (2011)

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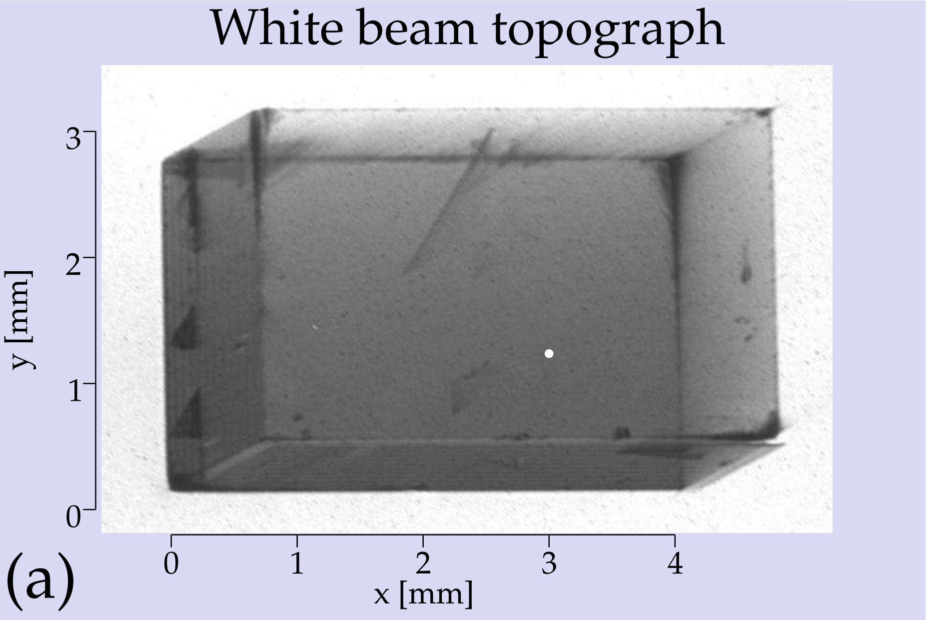


There exist regions whose area > 1 mm^2
that are free of dislocations and stacking faults.

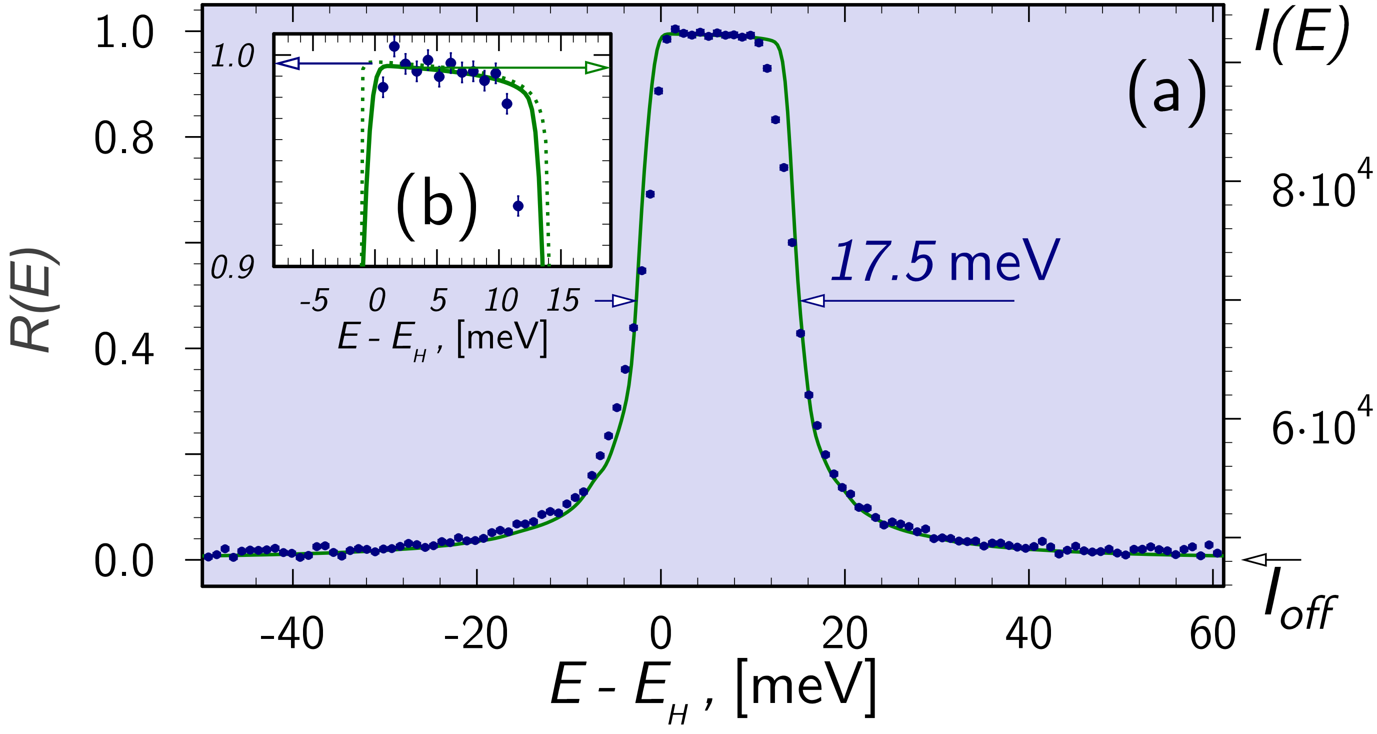
Suitable for FEL applications

Yu. Shvyd'ko, S. Stoupin, V. Blank, and S. Terentyev, *Nature Photonics* **5**, 539 (2011)

Reflectivity of TISNCM† synthetic diamond was measured to be > 98% @ the APS

† Technological Institute for Superhard Novel Carbon Materials, Russia

Measured Reflectivity = 99.1% ± 0.4%



Reflectivity curve width and maximum match that predicted by theory

Yu. Shvyd'ko, S. Stoupin, V. Blank, and S. Terentyev, *Nature Photonics* **5**, 539 (2011)

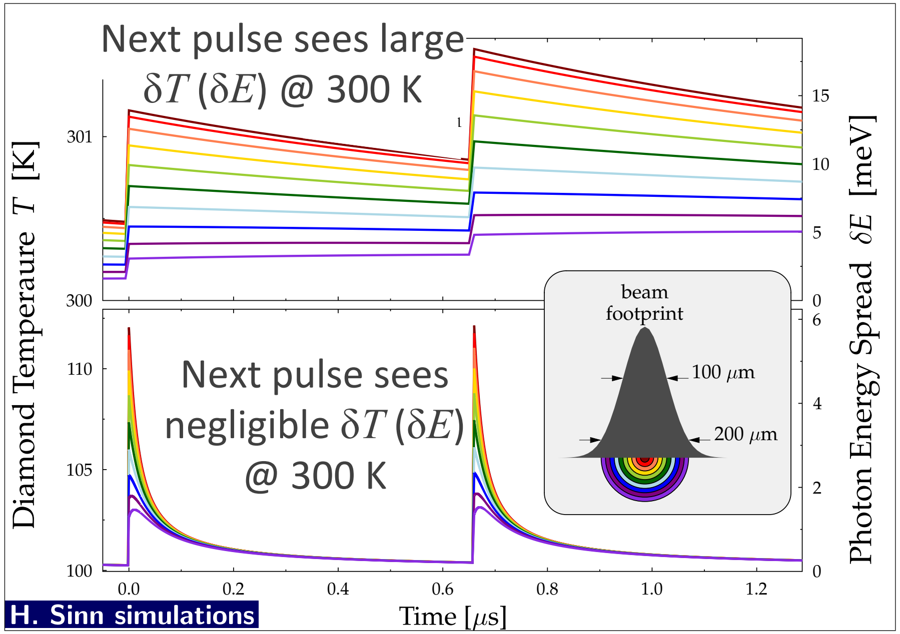
Crystal heating

Crystal temperature rise δT ➔ Crystal expansion $\delta a = \beta a \delta T$

➔ Variation in atomic spacing ➔ Variation in Bragg's law $\delta E/E = \beta\delta T$

How does the variation δE compare to the bandwidth ~ meV?

Thermal diffusivity sufficiently high and thermal expansion sufficiently low @ 100 K

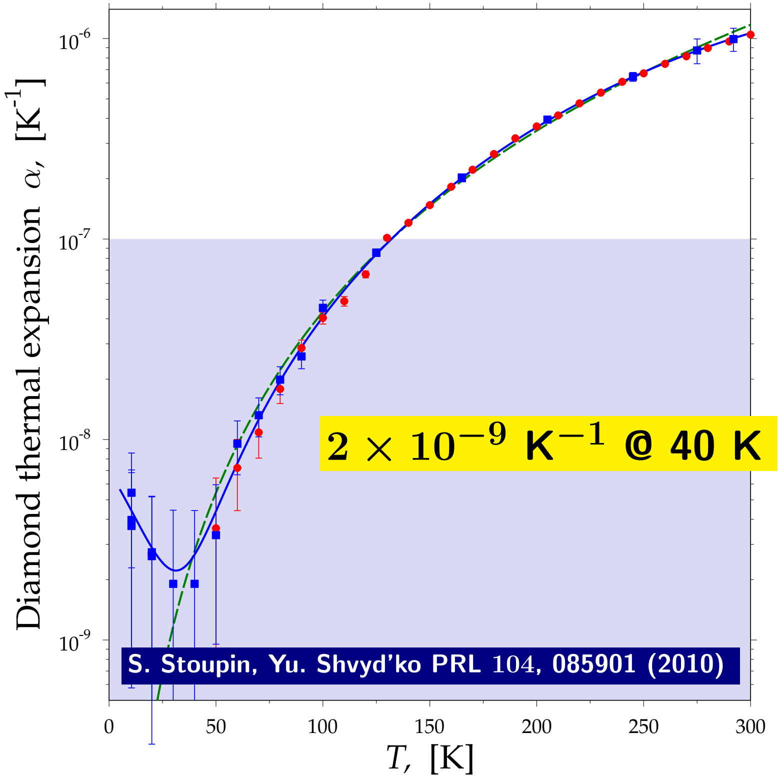


Next pulse sees large δT (δE) @ 300 K

Next pulse sees negligible δT (δE) @ 300 K

H. Sinn simulations

Cryogenic cooling results in very small expansion coefficient < 10^{-8}/K below 70 K

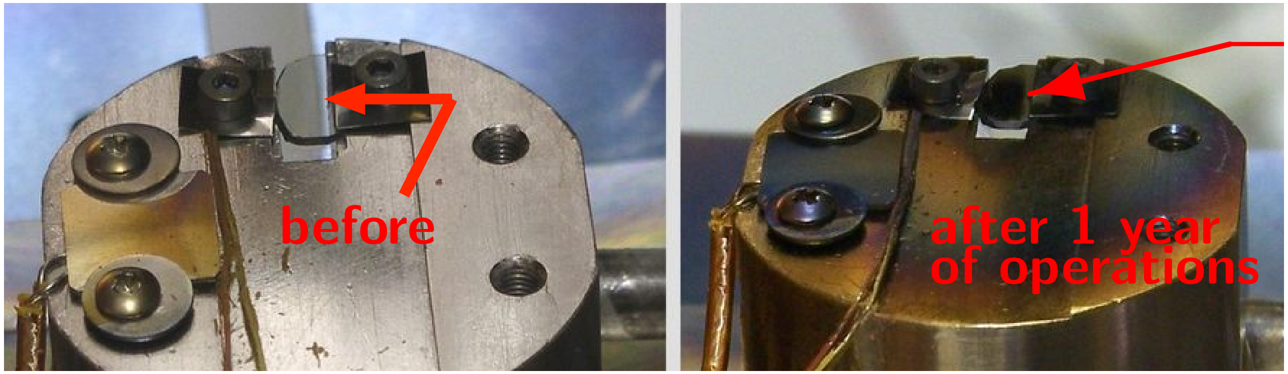


2×10^{-9} K^{-1} @ 40 K

S. Stoupin, Yu. Shvyd'ko PRL 104, 085901 (2010)

Crystal Damage

- There are significant unknowns regarding exact damage limits of x-ray crystals
- Present thinking is that time averaged photon intensity is main concern
  - Photoabsorption can produce high energy ``free'' electron and secondary Auger electron which can lead to lattice deformations/damage
- Graphitization of diamond crystals seen at synchrotrons



Graphitization seen after a few days, but no significant performance degradation after one year

APS undulator power flux $\sim$0.15 kW/mm^2

XFELO with 50 pC @ 1 MHz provides $\sim$4 kW/mm^2 on crystal (scales with charge)

Self-seeding typically has $\sim$0.5 kW/mm^2 × f[MHz] × T_{FWHM}[fs]

There is evidence that diamond exposed to 3.5 kW/mm^2 survives[1]

1. J. Als-Niesen, A.K Freund, and S. Terentyev, *Nucl. Instrum. Methods Res. Sec. B* **94**, 348 (1994)

Conclusions

- Fully coherent hard x-ray FELs are possible
- Self-seeding with the wake monochromator can dramatically improve SASE
  - Route to Fourier limited short pulses (< 50 fs or so)
  - Increase power with efficient nonlinear undulator tapering
  - Early experimental results are quite promising
- X-ray FEL oscillator offers complementary approach to small linewidths
  - Revolutionize techniques developed at 3rd generation light sources
  - Scales quite favorably to low charge
  - Natural fit in ERL based light source
- Diamond Bragg crystals are the future of high-intensity hard x-ray optics
  - Low absorption, high reflectivity, narrow bandwidth, low thermal expansion, high thermal conductivity, high damage threshold, …
  - Near perfect crystals are now routinely grown at a few companies/institutes

Acknowledgements

At the APS:

- Kwang-Je Kim
- Yuri Shvyd'ko
- Stanislav Stoupin
- Deming Shu
- Sasha Zholents

- Vladimir Blank (TISNCM)
- Sergey Terentyev (TISNCM)
- Gunn-Tae Park (UC graduate student)
- Bill Fawley (FEL free agent)
- Harald Sinn (Euro XFEL)

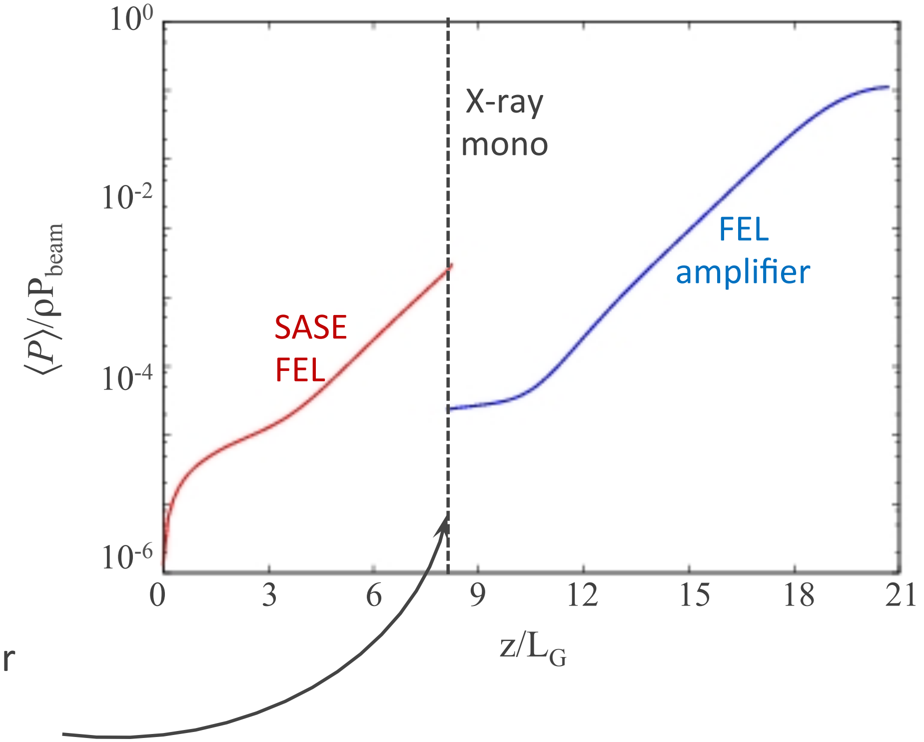
Other members of the HXRSS collaboration:

J. Amann
W. Berg
F.-J. Decker
Y. Ding
P. Emma
Y. Feng
J. Frisch
D. Fritz
J. Hastings
Z. Huang
J. Krzywinski

H. Loos
A. Lutman
H.-D. Nuhn
D. Ratner
J. Rzepiela
S. Spampinati
E. Trakhtenberg
D. Walz
J. Welch
J. Wu

Extra slides

Self-seeding power evolution



Power drops by ~10^2 when monochromator reduces SASE bandwidth of ~10^{-3} to Fourier limited bandwidth ~10^{-5} → Increases undulator length ~ 30%

Example uses LCLS-type parameters with $\rho = 5\times10^{-4}$, $\sigma_e \approx 12$ fs and $(\Delta\omega/\omega)_{mono} = 2\times10^{-5}$

Parameters

Cavity length ~ 100 m ➔ Repetition rate ~ 1 MHz

Low charge ~ 1pC
Bunch Lengths ~ 0.25 ps ➔ Peak currents ~ 1.6 A

High quality electron beam:

$\varepsilon_{x,n} \sim$ 0.082 mm-mrad, $\Delta E \sim$ 250 keV

Low single pass gain, losses: (Nu = 2000)

$G = 0.4$, $R_{tot} \sim 0.85$

Example @ 1 Å

E_{beam}	7 GeV
I_{peak}	10 A
$\varepsilon_{x,n}$	0.2 mm-mrad
$\Delta\gamma/\gamma$	0.02%
L_{und}	52 m
G	0.36
R_{tot}	0.85
crystal	C(4 4 4)

Performance

Cavity power ~ 12 MW ➔ Output power ~ 0.6 MW

Output ~ 10^8 photons ➔ Spectral brightness ~ $10^{31} – 10^{34}$

Nearly Fourier limited pulses ➔ ΔE ~ 5.0 meV FWHM
$\Delta\omega/\omega \sim 10^{-6} – 10^{-8}$

Example @ 1 Å

P_{out}	1.7 MW
Photons/ pulse	1.1×10^9
ΔE	1.29 meV
Δt	0.51 ps

9. R.R. Lindberg, K-J. Kim, Yu. Shvyd'ko, and W.M. Fawley, *Phys. Rev. ST-AB.* **14,** 010701 (2011)

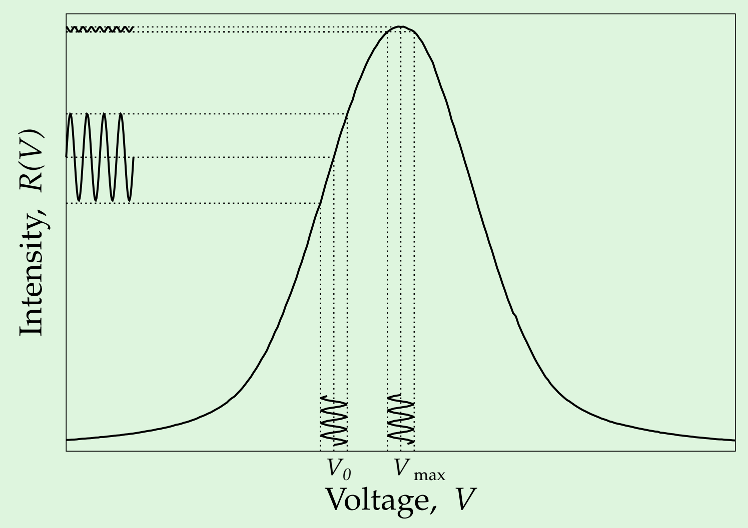
Cavity tolerances and stability

To preserve radiation-electron beam overlap and FEL gain, we require:

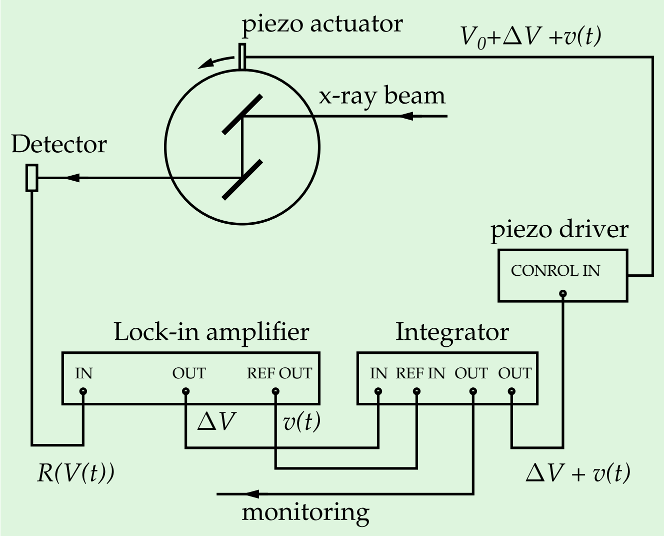
Cavity length stability $\delta L < 3\ \mu\text{m}$ rms

Crystal angular stability $\delta\theta < 10$ nrad rms

Null detection feedback (similar to that used at LIGO)



Variation in output signal is proportional to deviation from maximum



Feedback correction signal is extracted using a lock-in amplifier

Stoupin, Lenkszus, Laird, Goetze, Kim, and Shvyd'ko, *Rev. Sci. Instrum.* **81**, 055108 (2010)

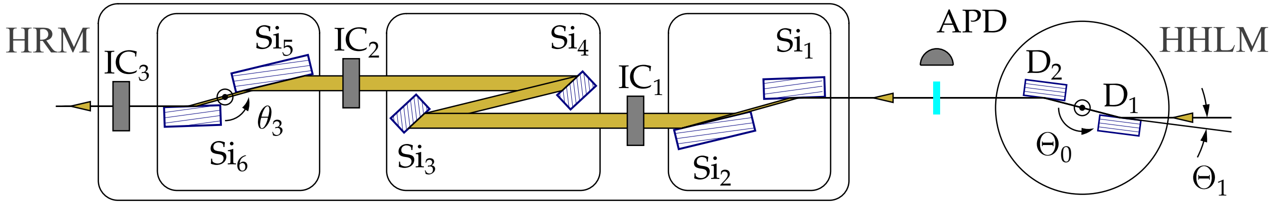
Cavity tolerances and stability

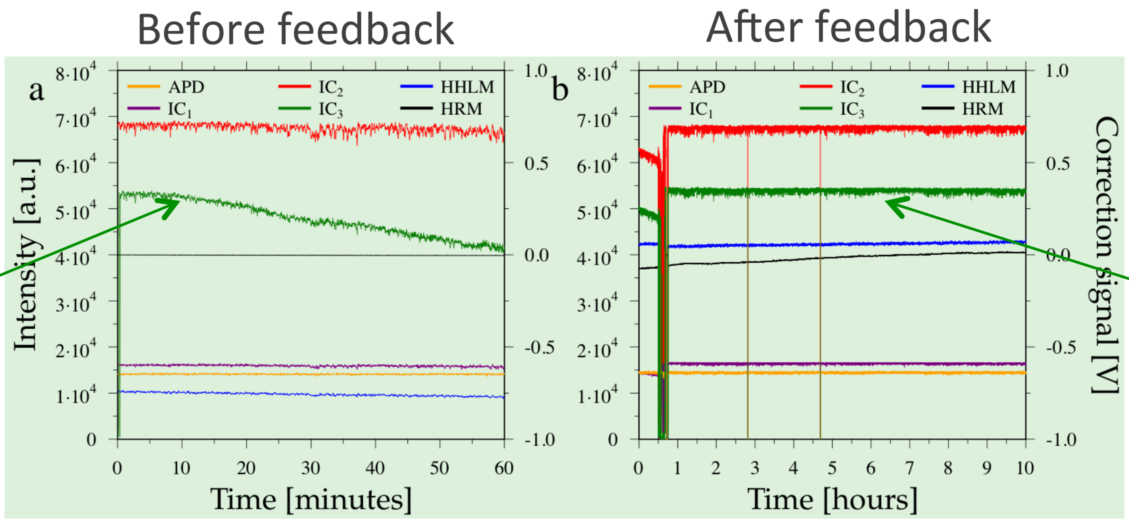
To preserve radiation-electron beam overlap and FEL gain, we require:

Cavity length stability $\delta L < 3\ \mu\text{m}$

Crystal angular stability $\delta\theta < 10$ nrad

Null detection feedback: proof of principle experiment @ APS




Before feedback

After feedback

"Wandering" crystal

Stabilized crystal

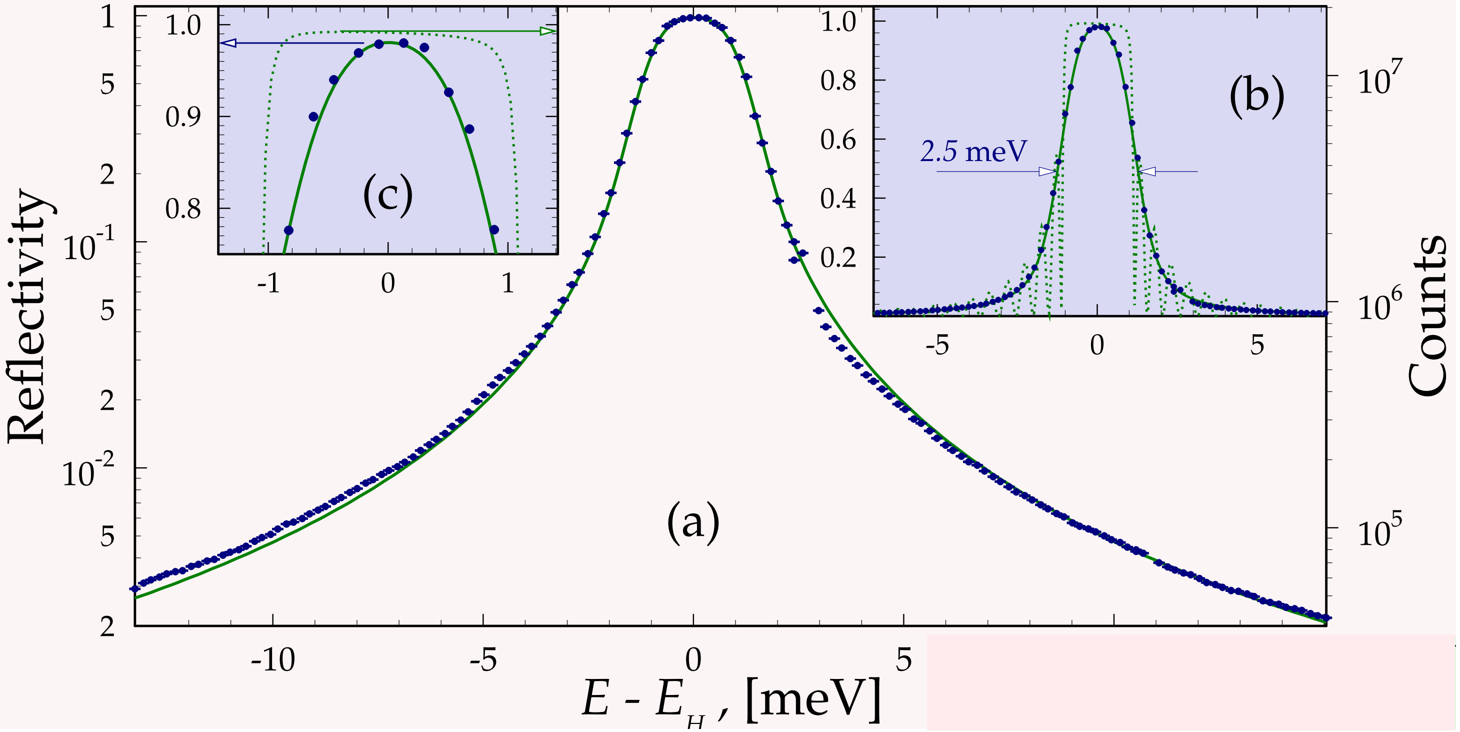
Crystal stability of ~ 15 nrad rms was shown at the APS HERIX monochromator

Stoupin, Lenkszus, Laird, Goetze, Kim, and Shvyd'ko, *Rev. Sci. Instrum.* **81**, 055108 (2010)

Reflectivity of TISNCM† synthetic diamond was measured to be > 98% @ the APS

† Technological Institute for Superhard Novel Carbon materials, Russia

Measured R = 98% ➔ 99% including measurement function



Reflectivity curve width and maximum match that predicted by theory

Shvyd'ko, Stoupin, Blank, and Terentyev, accepted to *Nature Photonics* (2010)

Crystal Heating

Crystal temperature rise δT ➔ Crystal expansion $\delta a = \beta a \delta T$

➔ Variation in atomic spacing ➔ Variation in Bragg's law $\delta E/E = \beta \delta T$

Two heatings:

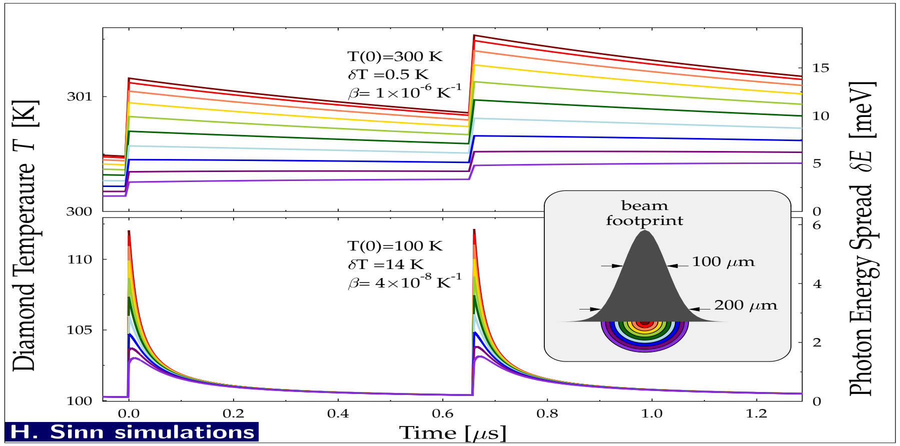
- Intra-pulse: source of differential lattice expansion

  Expansion time $\sim L/c_{\text{sound}}$ >> pulse duration

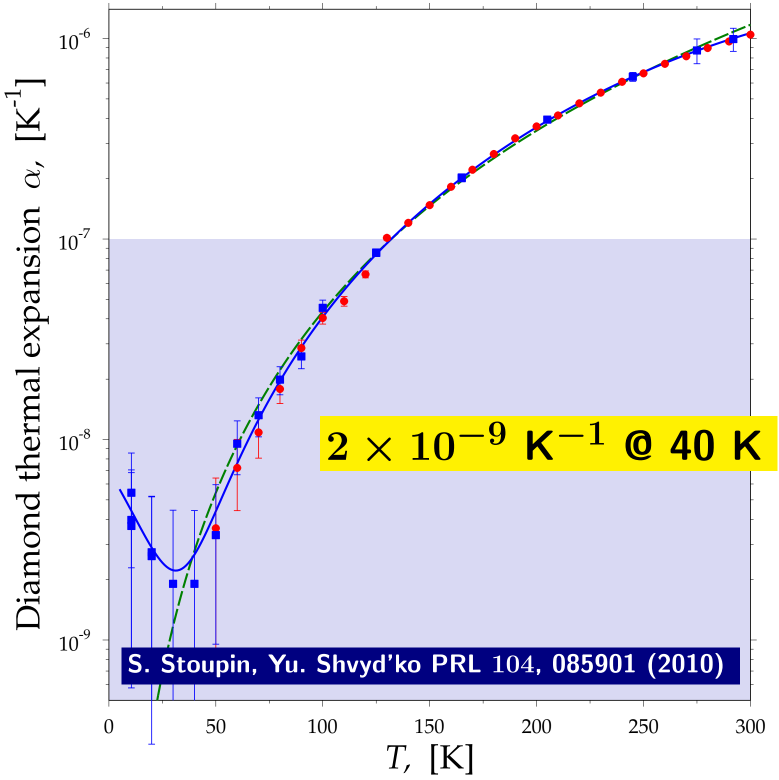
  Further mitigated by small thermal expansion ($< 10^{-8}$/K) below 70 K

- Inter-pulse: results in long-term heating

  Mitigated by high conductivity + external cooling



H. Sinn simulations

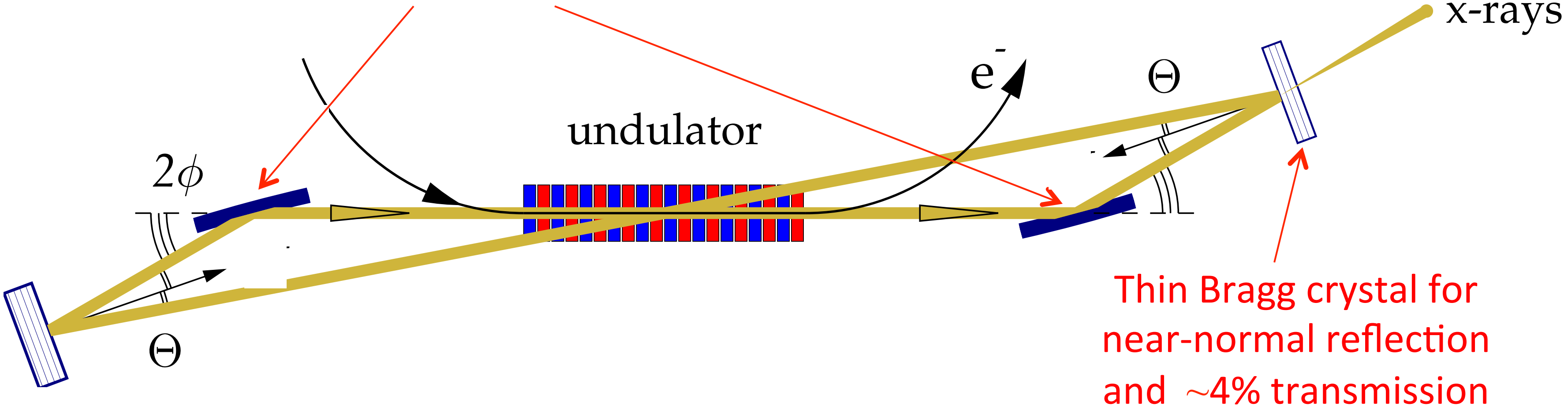


2×10^{-9} K^{-1} @ 40 K

S. Stoupin, Yu. Shvyd'ko PRL 104, 085901 (2010)

The Advanced Photon Source is an Office of Science User Facility operated for the U.S. Department of Energy Office of Science by Argonne National Laboratory

Hard x-ray optical cavity



Grazing incidence mirrors for focusing

Thin Bragg crystal for near-normal reflection and ~4% transmission

Bragg crystal for near-normal reflection of x-rays in a narrow energy range around $E = E_H \cos\Theta$

Total external reflection of grazing incidence mirrors require $\phi << 1$

➔ Requires $\Theta << 1$ which leads to a limited tuning range