Proposal of An X-ray Free-Electron Laser Oscillator based on Diffraction Limited Storage Ring

Weilun QIN

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Hamburg, 10.10.2025

Outline

- Introduction
- Gain optimization
- Simulation framework
- Preliminary results
- Summary

A brief history of XFELO

- 1984, R. Colella & A. Luccio
  - First propose to use Bragg crystal for x-ray cavity

PROPOSAL FOR A FREE ELECTRON LASER IN THE X-RAY REGION*

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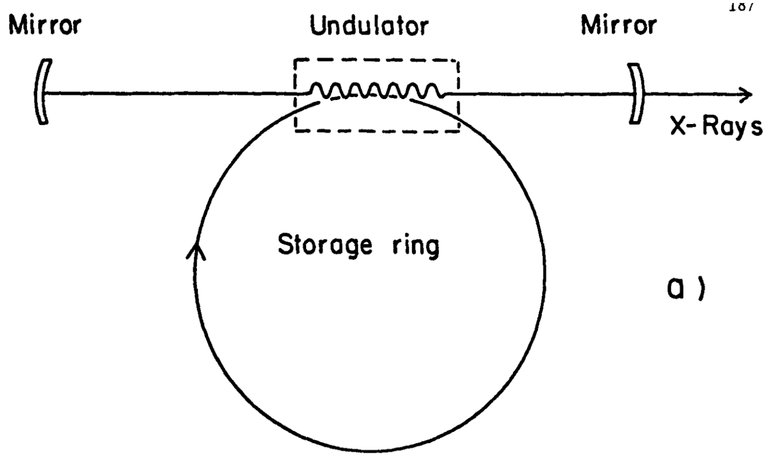
National Synchrotron Light Source
Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

It is proposed that a free electron laser can be operated in the X-ray region, in the range 2 - 3 Ångstroms. An analysis is presented of the machine parameters and the characteristics of the mirrors that are required for operation in the Ångstrom region.



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PRL **100**, 244802 (2008) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2008

A Proposal for an X-Ray Free-Electron Laser Oscillator with an Energy-Recovery Linac

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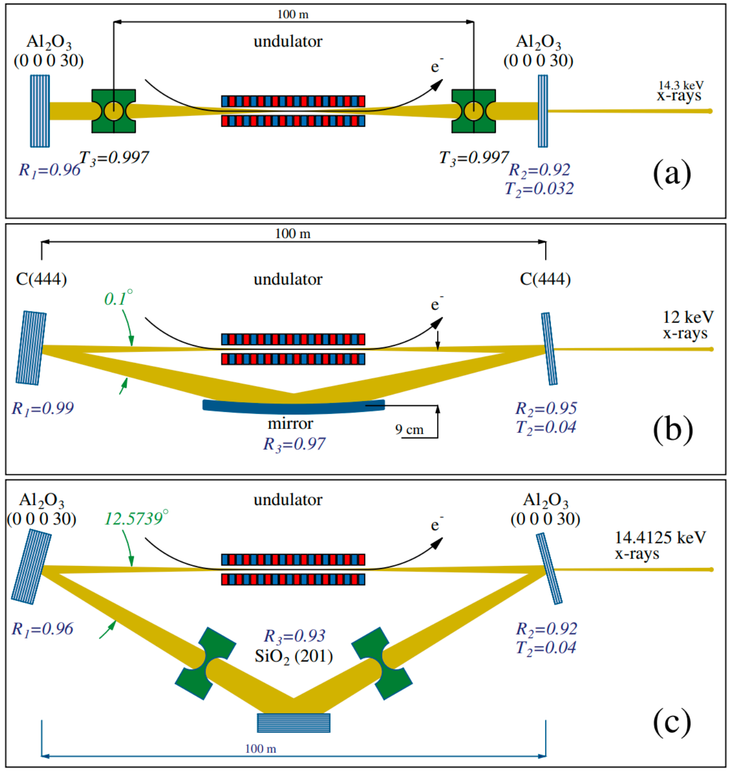
(Received 14 March 2008; published 17 June 2008)



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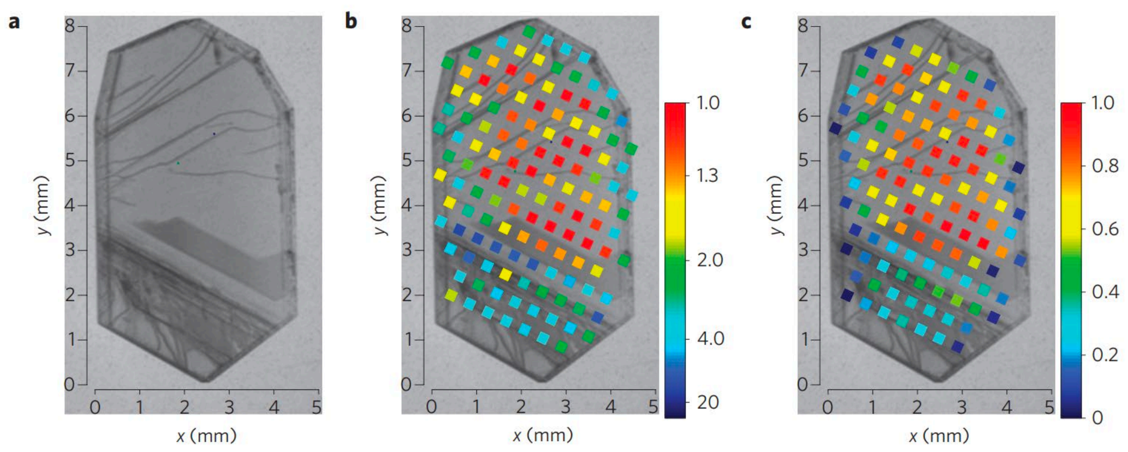

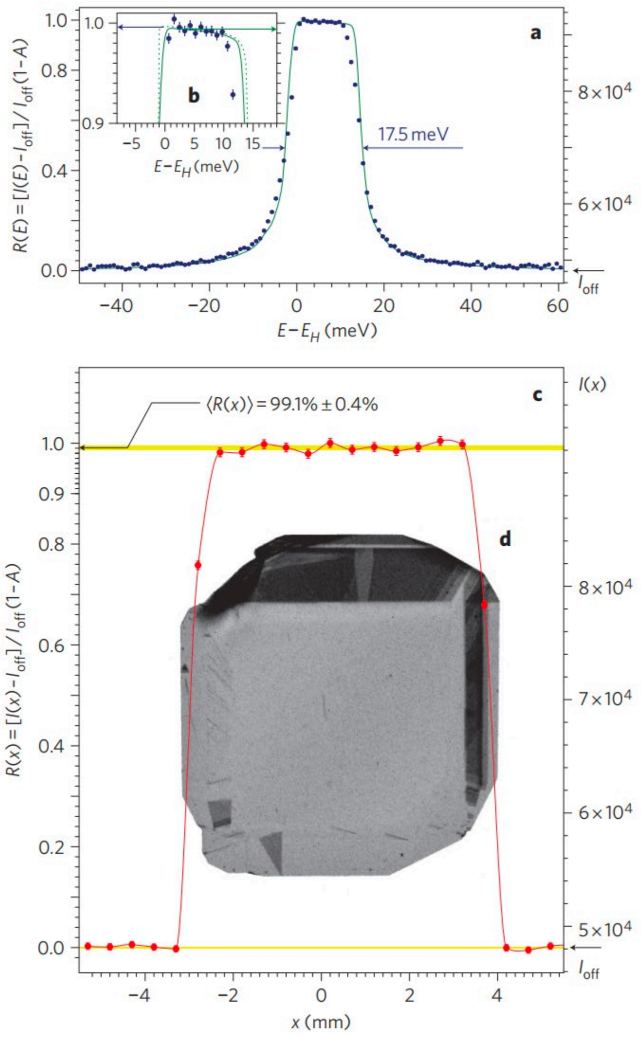

*Shvyd'ko, Y. et al., Nature Physics **6** (2010); Nature Photonics **5** (2011)*

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- 2015+, SLAC, EuXFEL, SHINE etc
  - ➢ Proposal of SRF-linac based XFELO
  - ➢ Proposal of DLSR-based XFELO

38th International Free Electron Laser Conference FEL2017, Santa Fe, NM, USA JACoW Publishing
ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUC05

START-TO-END SIMULATIONS FOR AN X-RAY FEL OSCILLATOR AT THE LCLS-II AND LCLS-II-HE

W. Qin*, S. Huang, K. X. Liu, IHIP, Peking University, Beijing, China
K.-J. Kim, R. R. Lindberg, ANL, Argonne, USA
Y. Ding, Z. Huang, T. Maxwell, K. Bane, G. Marcus, SLAC, Menlo Park, USA

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 895, 1 July 2018, Pages 40-47

Systematic design and three-dimensional simulation of X-ray FEL oscillator for Shanghai Coherent Light Facility

Kai Li [a b], Haixiao Deng [a]

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26**, 020701 (2023)

Cavity based x-ray free electron laser demonstrator at the European X-ray Free Electron Laser facility

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Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany

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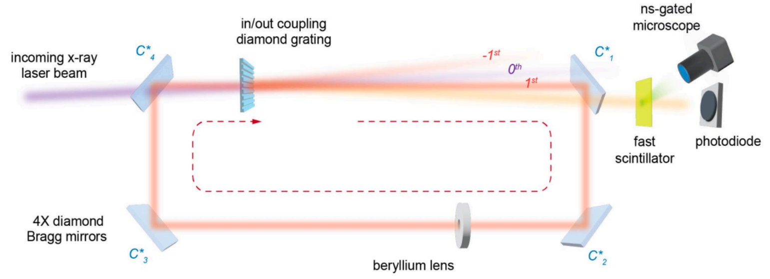
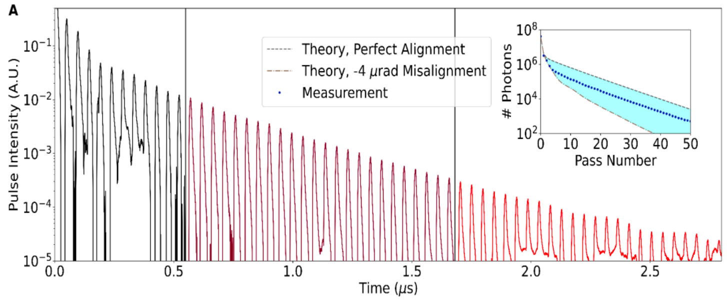
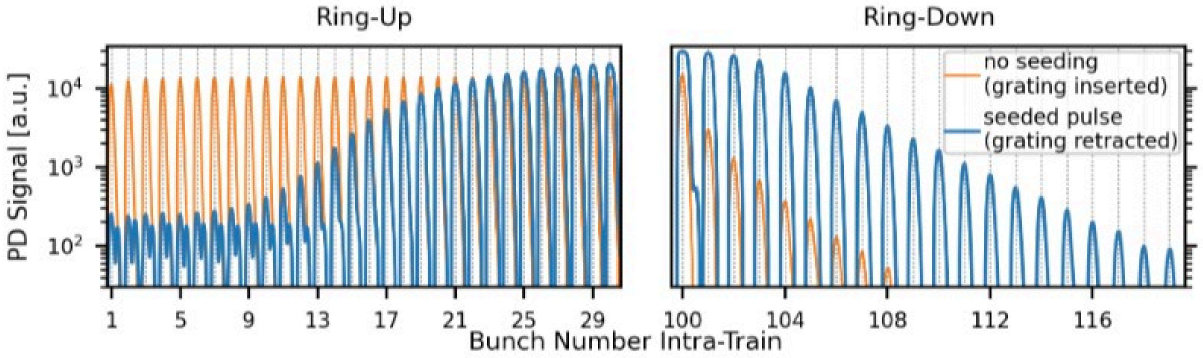
- 2020+
  - ➢ 2023, SLAC, cold cavity demonstration
  - ➢ 2025, EuXFEL, lasing demonstration

R. Margraf et al., Nature Photonics ***17*** *(2023)*

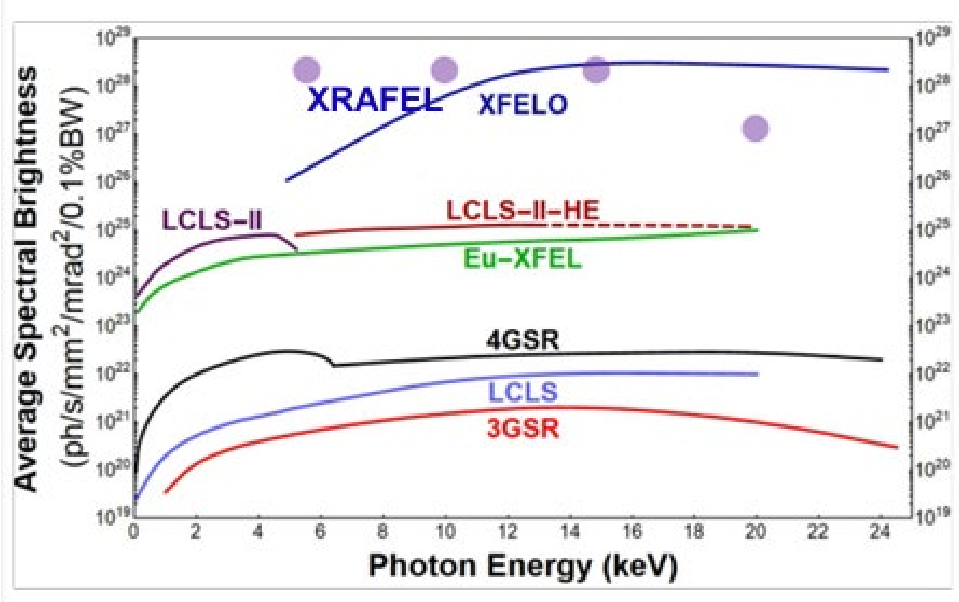






Patrick Rauer et al., available at Research Square [https://doi.org/10.21203/rs.3.rs-7274597/v1]

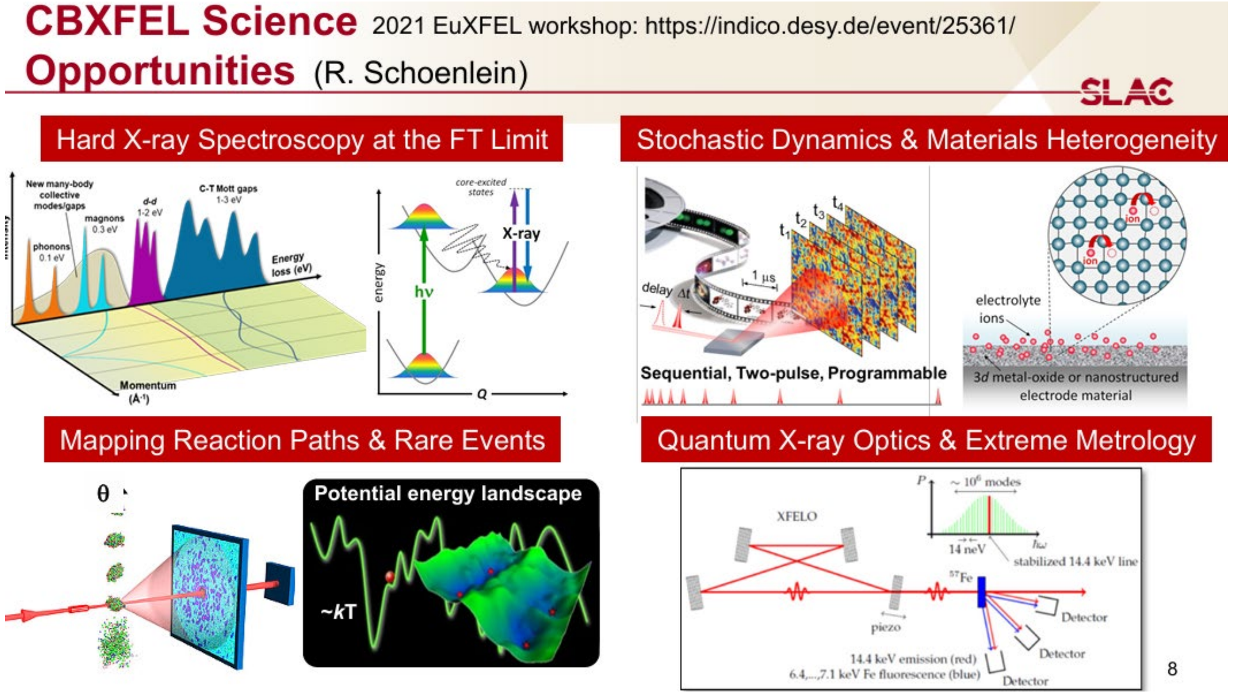
Scientific opportunities



- Ultra-high spectral brightness
- Ultra-fine spectral resolution

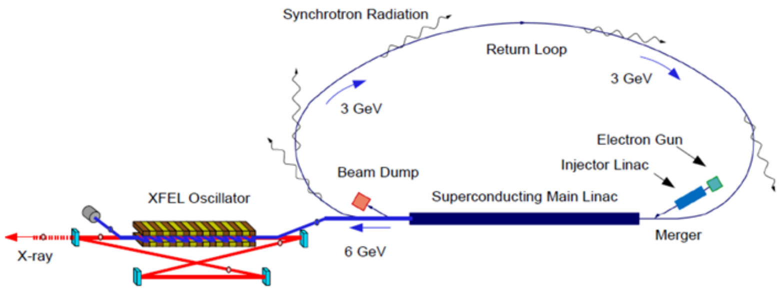
Scientific Opportunities with an X-ray Free-Electron Laser Oscillator

Bernhard Adams,[1] Gabriel Aeppli,[2,3,4] Thomas Allison,[5] Alfred Q. R. Baron,[6] Phillip Bucksbaum,[7,8,9] Aleksandr I. Chumakov,[10] Christopher Corder,[5] Stephen P. Cramer,[11] Serena DeBeer,[12] Yuntao Ding,[13] Jörg Evers,[14] Josef Frisch,[13] Matthias Fuchs,[15] Gerhard Grübel,[16,17] Jerome B. Hastings,[13] Christoph M. Heyl,[16,18,19] Leo Holberg,[8] Zhirong Huang,[13] Tetsuya Ishikawa,[20] Andreas Kaldun,[7] Kwang-Je Kim,[21] Tomasz Kolodziej,[22] Jacek Krzywinski,[13] Zheng Li,[7,23] Wen-Te Liao,[24] Ryan Lindberg,[21] Anders Madsen,[25] Timothy Maxwell,[13] Giulio Monaco,[26] Keith Nelson,[27] Adriana Pálffy,[14] Gil Porat,[18] Weilun Qin,[28] Tor Raubenheimer,[13] David A. Reis,[7,9] Ralf Röhlsberger,[16,17] Robin Santra,[23,29,17] Robert Schoenlein,[13] Volker Schünemann,[30] Oleg Shpyrko,[31] Yuri Shvyd'ko,[21] Sharon Shwartz,[32] Andrej Singer,[31] Sunil K. Sinha,[31] Mark Sutton,[33] Kenji Tamasaku,[20] Hans-Christian Wille,[16] Makina Yabashi,[20] Jun Ye,[18] and Diling Zhu[13]

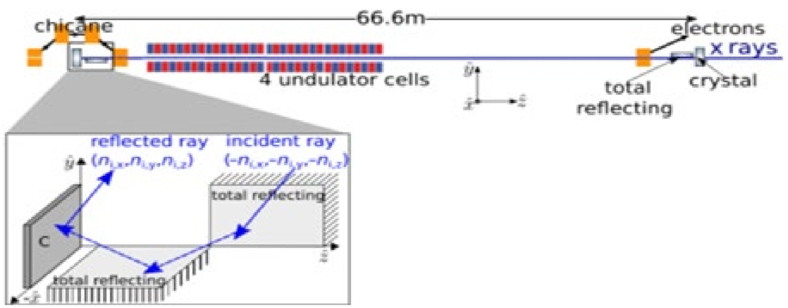


Drivers of an XFELO

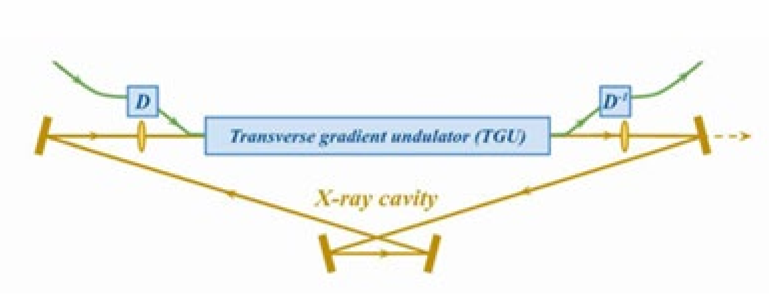
R. Hajima et al., FEL2012



P. Rauer et al., PRAB, 2023

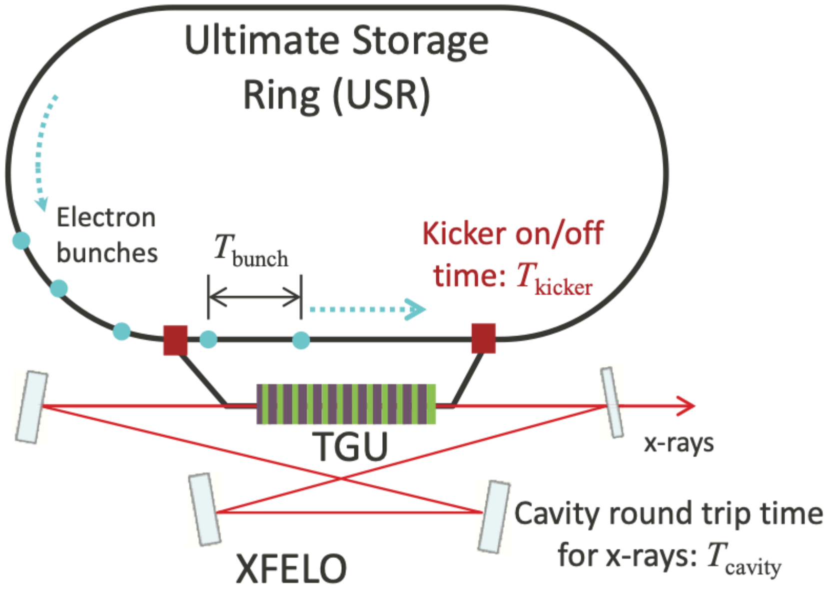


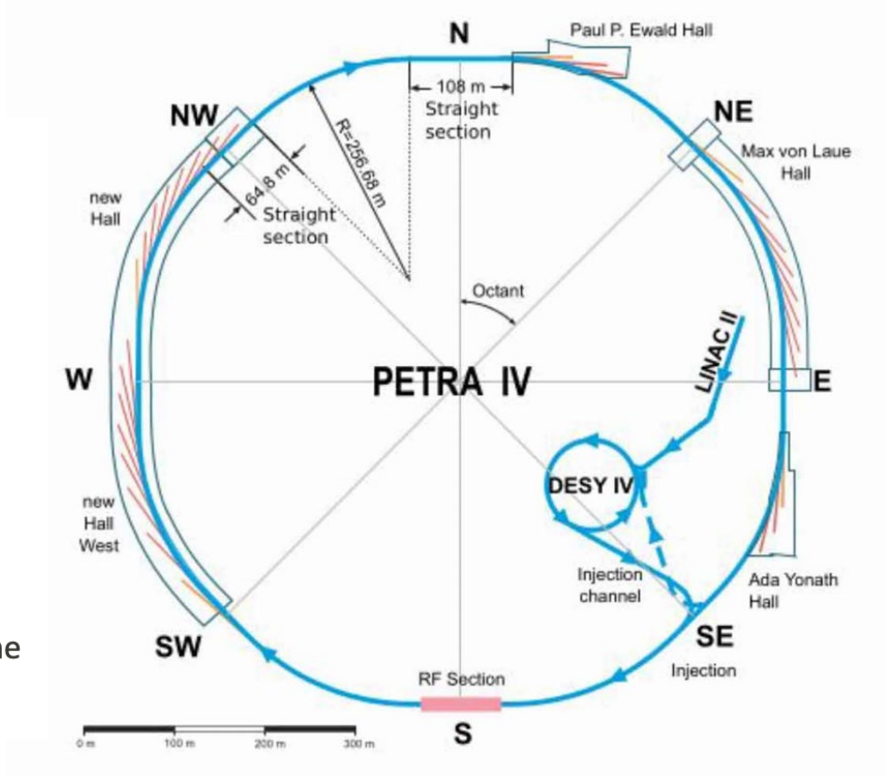
Y. Li et al., PRAB, 2023

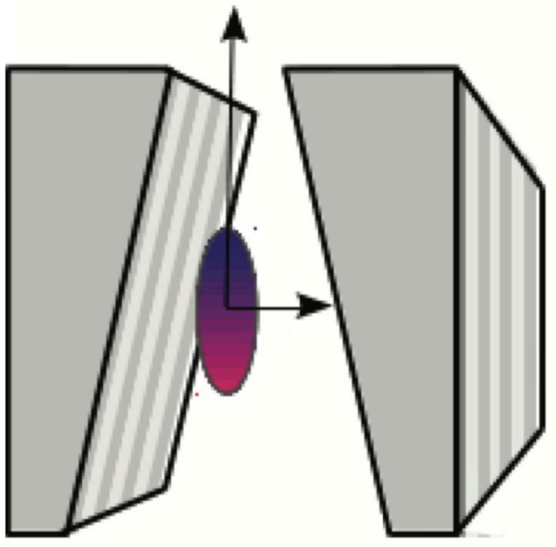


	ERL	SRF linac	DLSR
Emittance	√	√	√
Energy spread	1e-4	1e-4	**1e-3**
Peak current	100s A	100 – 1000 A	**10s A**
Rep. rate	1-100MHz	1 MHz	100 MHz
Availability	x	EuXFEL, LCLS-II, (SHINE)	（√）

DLSR based XFELO







$$\frac{\Delta K}{K_0} = \alpha x$$

- ➢ R. Lindberg et al., 2013
- ➢ PEP-X parameter
- ➢ **Bypass line**
- ➢ Fast kicker

- ➢ Y. Li et al., 2023
- ➢ PETRA-IV parameter
- ➢ **Long straight section**
- ➢ Current enhancement

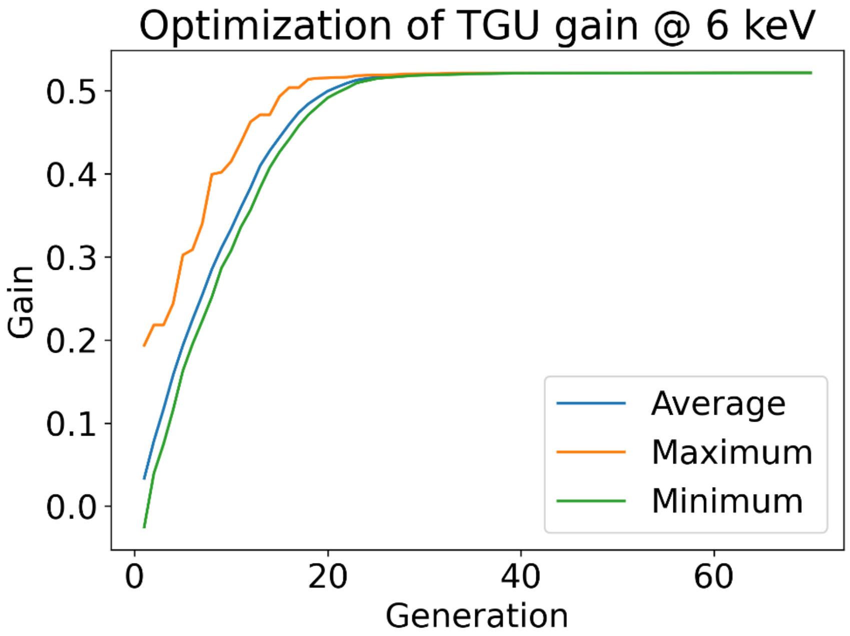
Transverse Gradient Undulator (TGU) for large energy spread

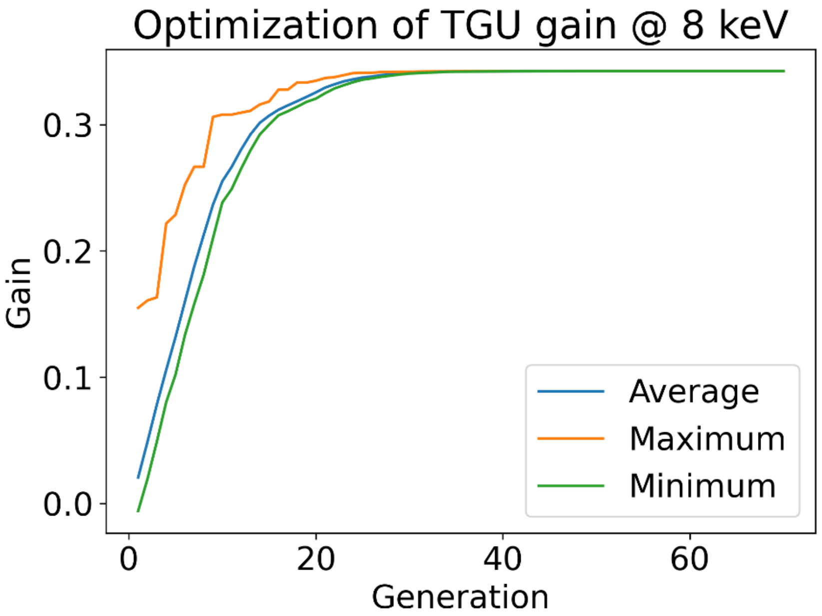
TGU gain in a 6m straight section

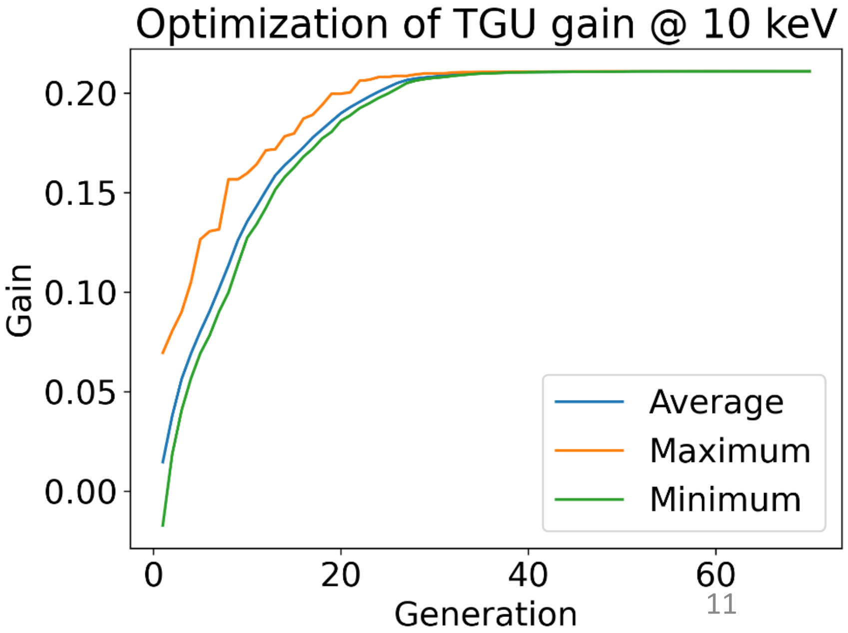
- I_{pk}: 240 A, λ_u: 18 mm, L_u: 5 m, E_b: 6 GeV

Analytical formula from Y. Li et al.

Eph	B [T]	η [cm]	β_x/β_y [m]	ZR_x/ZR_y [m]	TGU α [m^{-1}]	detune	Gain
6 keV	1.237	1.04	4/4	4/4	140	2.01	0.52
8 keV	0.986	1.24	4/4	4/4	140	2.02	0.34
10 keV	0.798	1.51	4/4	4/4	140	2.03	0.21

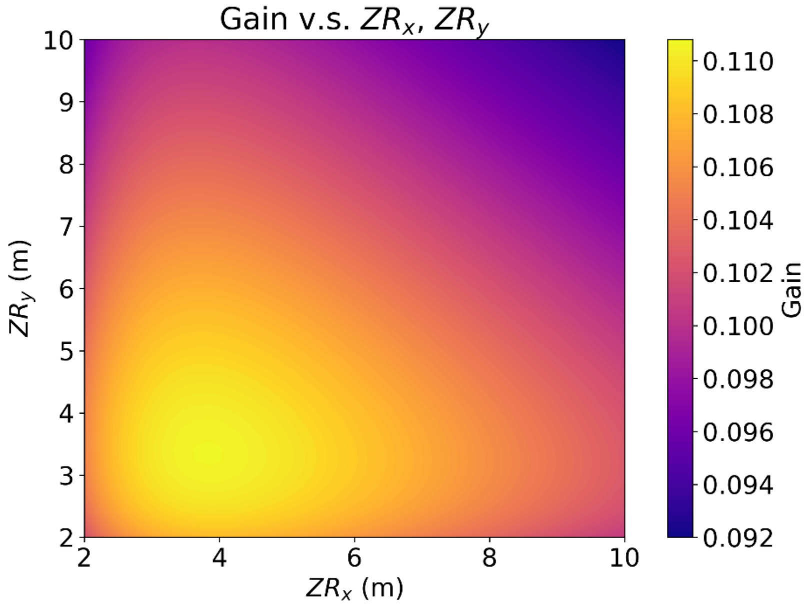


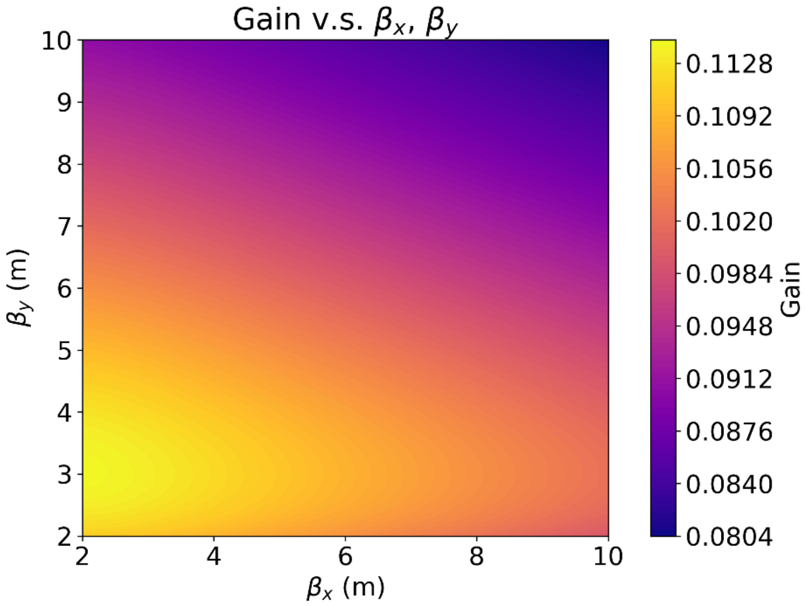


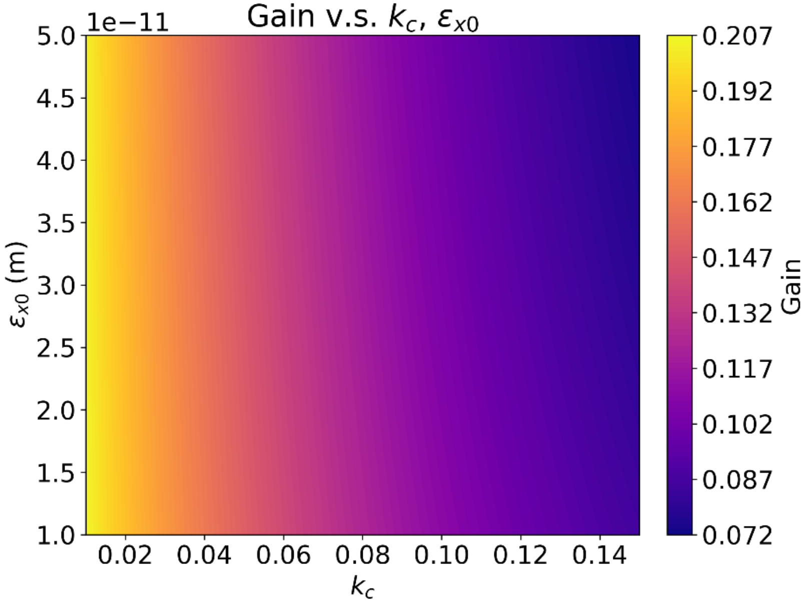


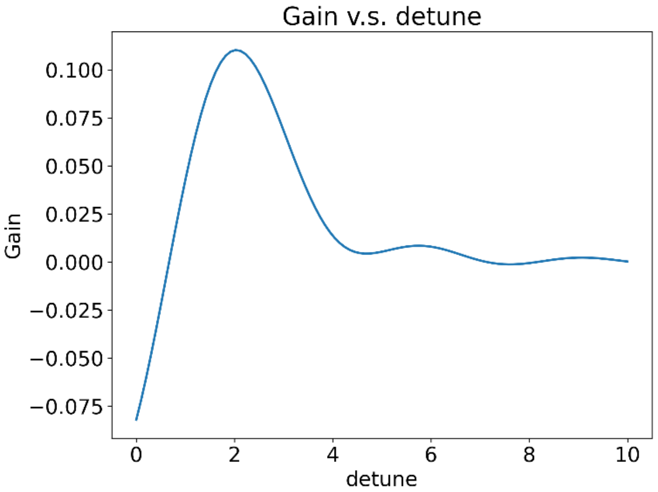
Parameter sensitivity of TGU gain

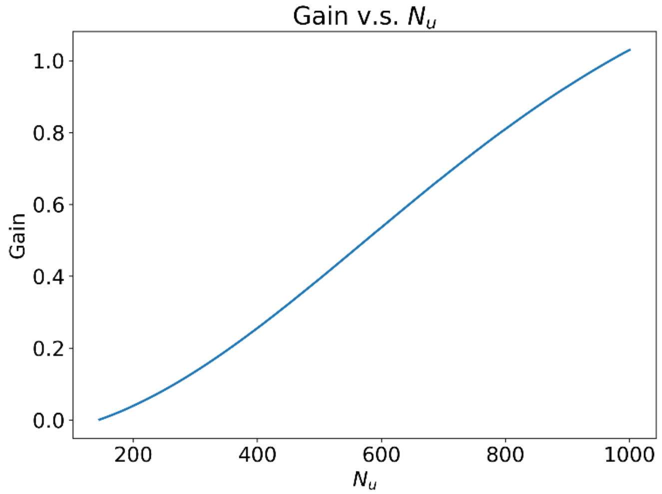
- **Linear with undulator length， peak current**

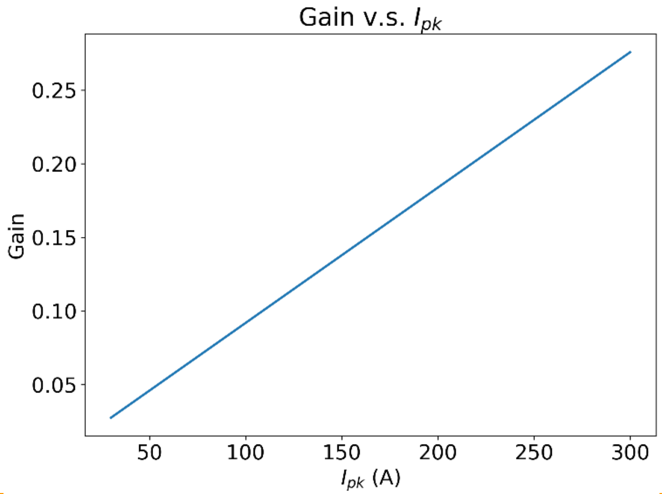






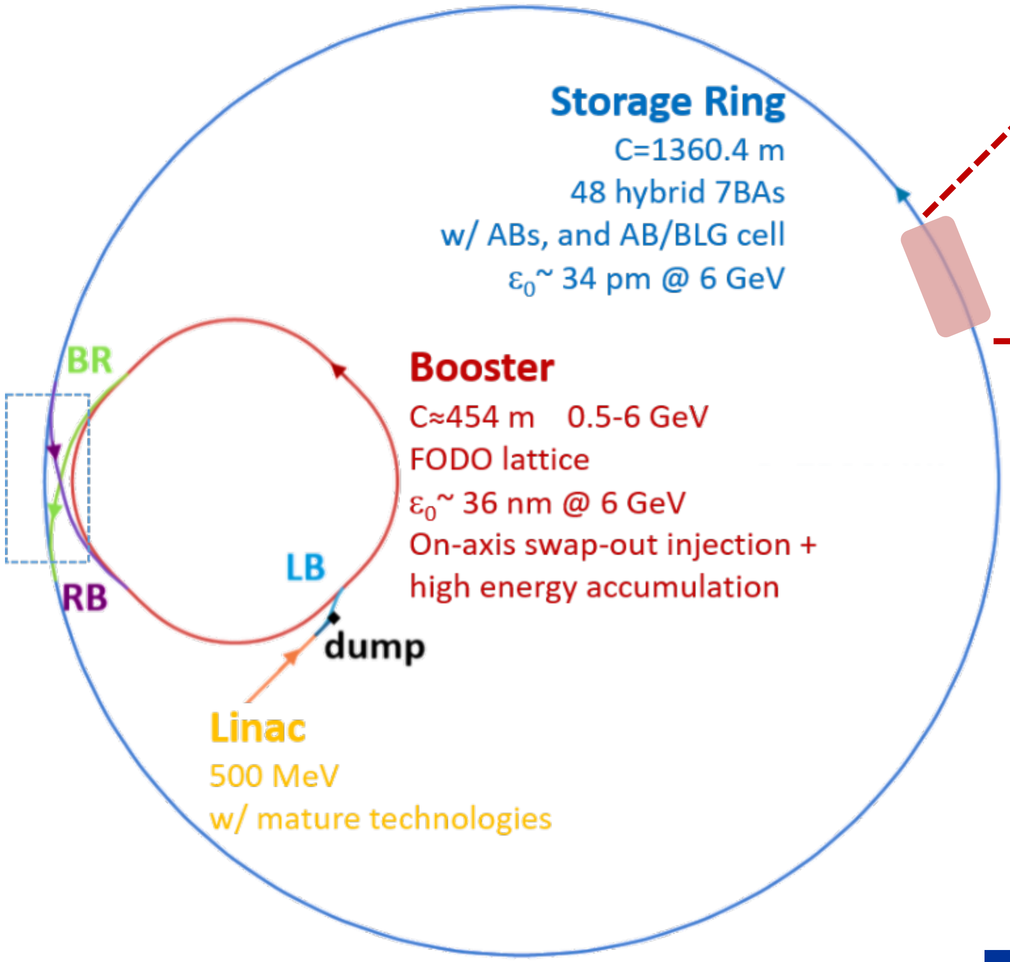


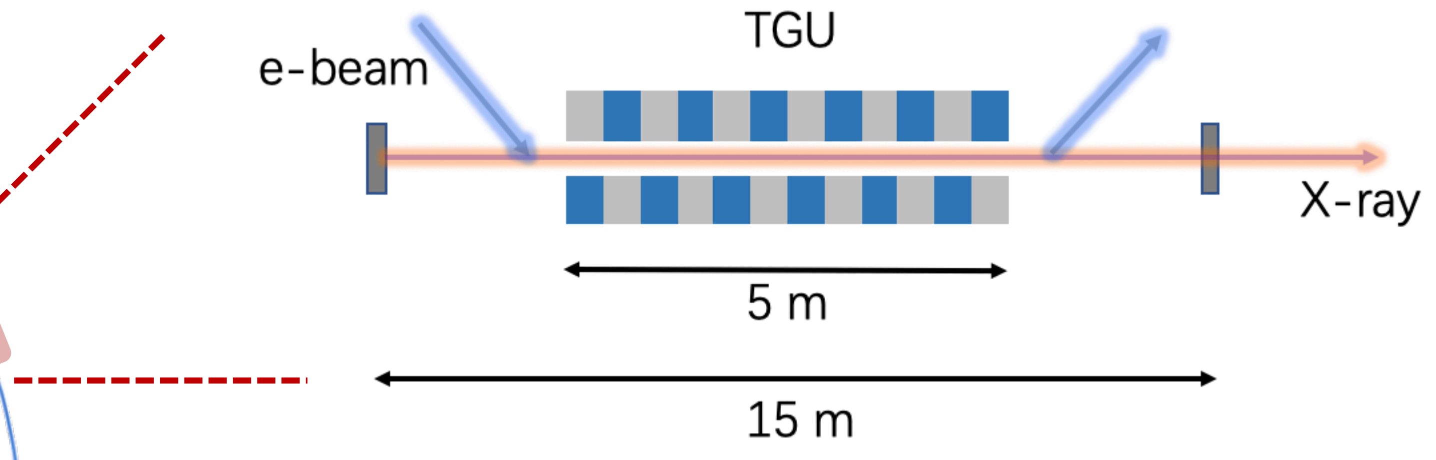




XFELO in a 6m straight section

- **The HEPS accelerator complex**

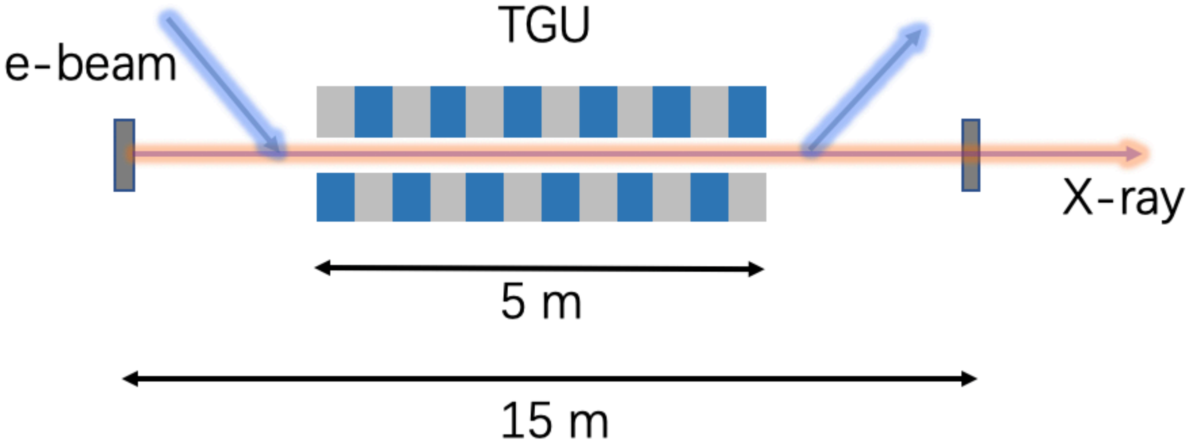


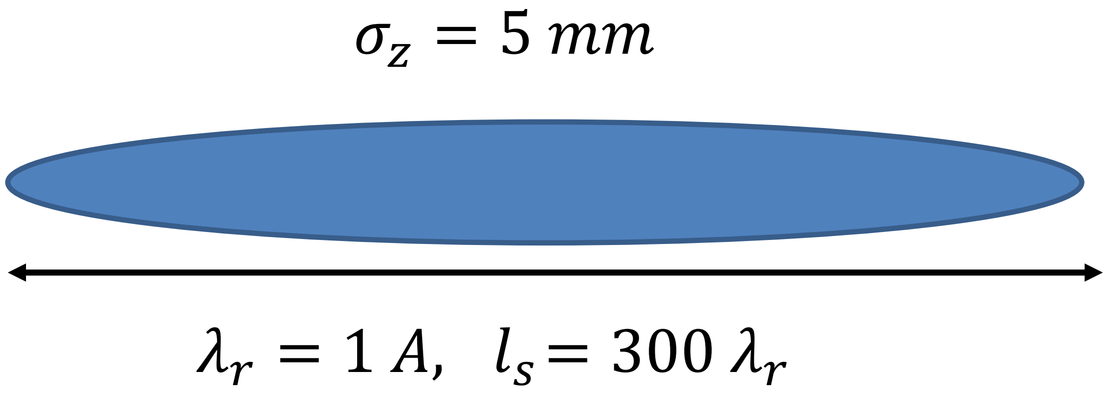


Parameter	Value	Parameter	Value
Undulator length [m]	5	Undulator period [cm]	1.8
Cavity length [m]	30	Undulator field [T]	1~1.5
Rep. rate [MHz]	10	TGU α $[m^{-1}]$	140

- **Short undulator, short optical cavity, high rep. rate**

Simulation challenge

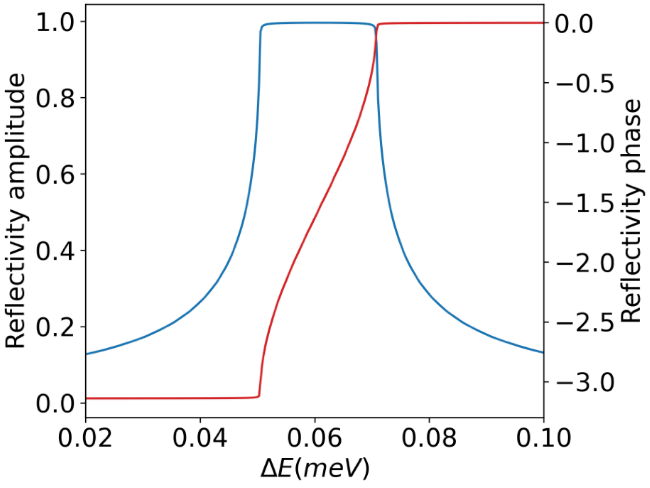




- **Single pass FEL process** — Resolving slippage and whole bunch length requires $> 10^6$ slices
- **Field propagation & filtering** — Same number of field slice, bragg reflection process
- **Ring tracking** — Compatability of Genesis & Elegant
- **Hundreds of pass or even more**

A (maybe over-) simplified model

Bragg filtering



FEL process

$$G = \frac{G_0}{4\pi}\int_{-1/2}^{1/2} dz\, ds \frac{i(z-s)}{\sqrt{\mathfrak{D}_x \mathfrak{D}_y}} \exp$$

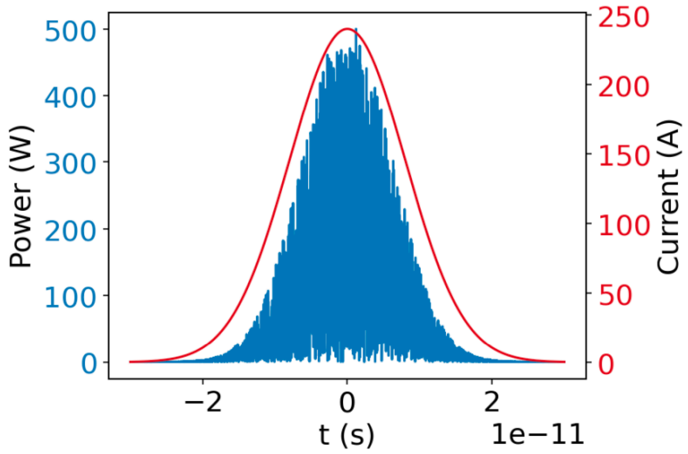
$$\left[-2i\delta(z-s) - \frac{2\tilde{\sigma}_\eta^2 (z-s)^2}{1+\Gamma^2} - \left(\frac{\Gamma}{1+\Gamma^2}\frac{\tilde{\sigma}_\eta}{\tilde{\beta}_y}\right)^2 \frac{(z^2-s^2)^2}{2}\frac{\mathfrak{d}_y}{\mathfrak{D}_y}\right]$$

$$\Delta\eta = \frac{K[JJ]}{\gamma_0^2}\frac{L_u}{\sigma_r}\sqrt{\frac{P}{P_{rel}}} \qquad \Delta y = \eta\Delta\gamma/\gamma$$

Ring tracking

- One turn map
- Damping
- RF focusing

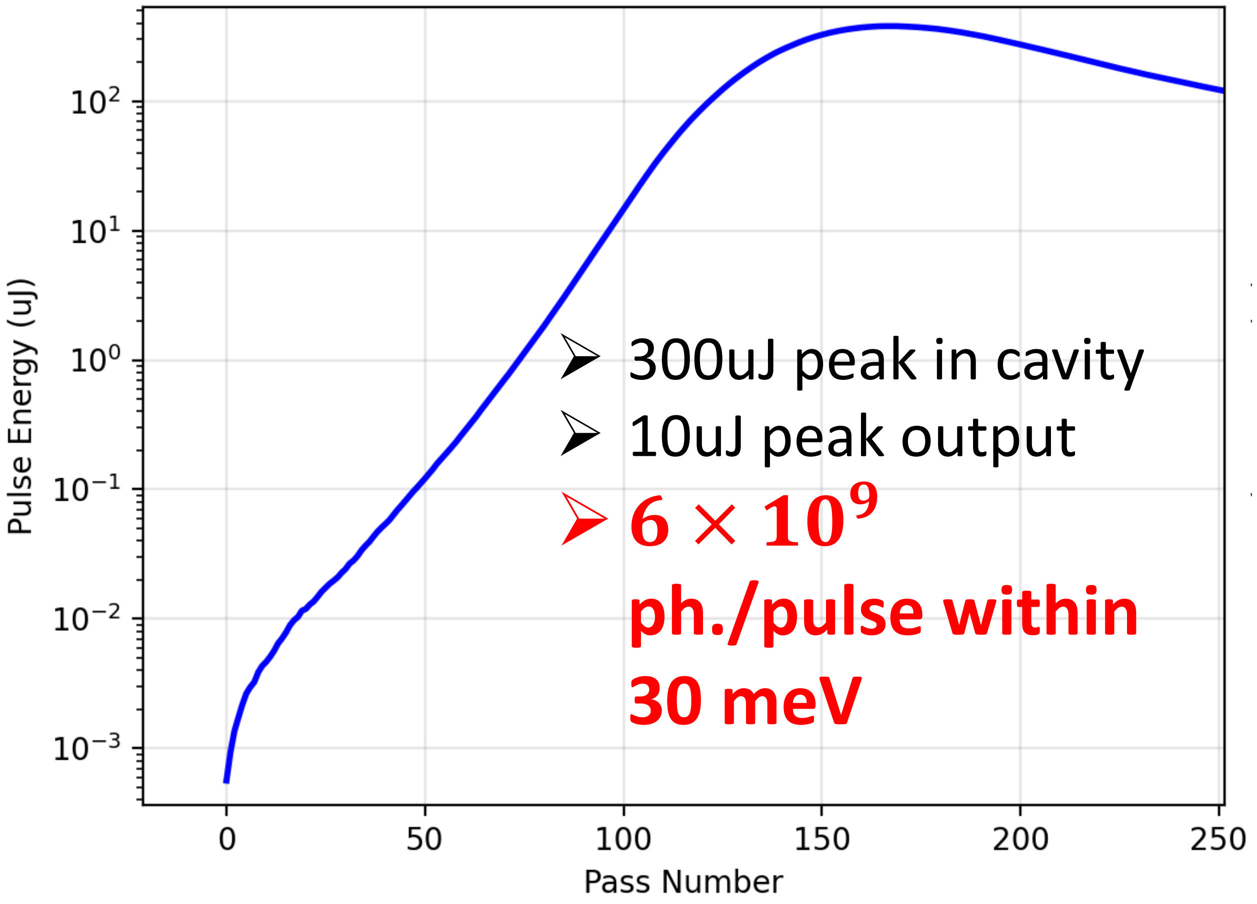
Update field



Update beam

A (maybe over-) simplified model

In-cavity pulse energy evolution

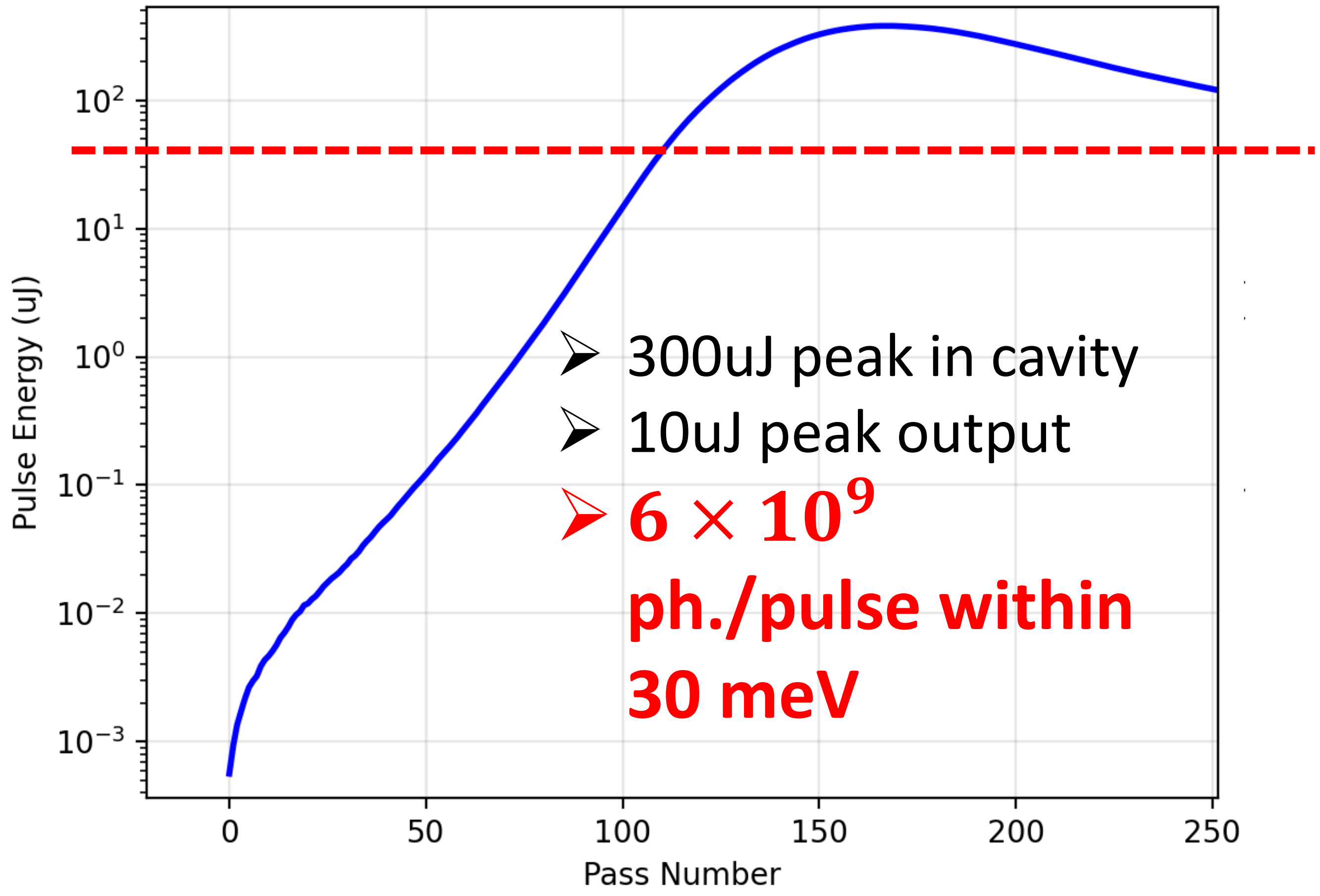


- 300uJ peak in cavity
- 10uJ peak output
- **6×10^9 ph./pulse within 30 meV**

Parameter	Value
Beam	
Beam energy [GeV]	6
Peak current [A]	240
Coupling	0.06
$\varepsilon_x/\varepsilon_y$ [pm]	32/2
TGU	
Undulator period [mm]	18
α [m^{-1}]	131
Number of periods	280
Estimated gain	0.21
Photons	
Photon energy	9.83keV
Total loss (loss + outcoupling)	11%

A (maybe over-) simplified model

■ **In-cavity pulse energy evolution**

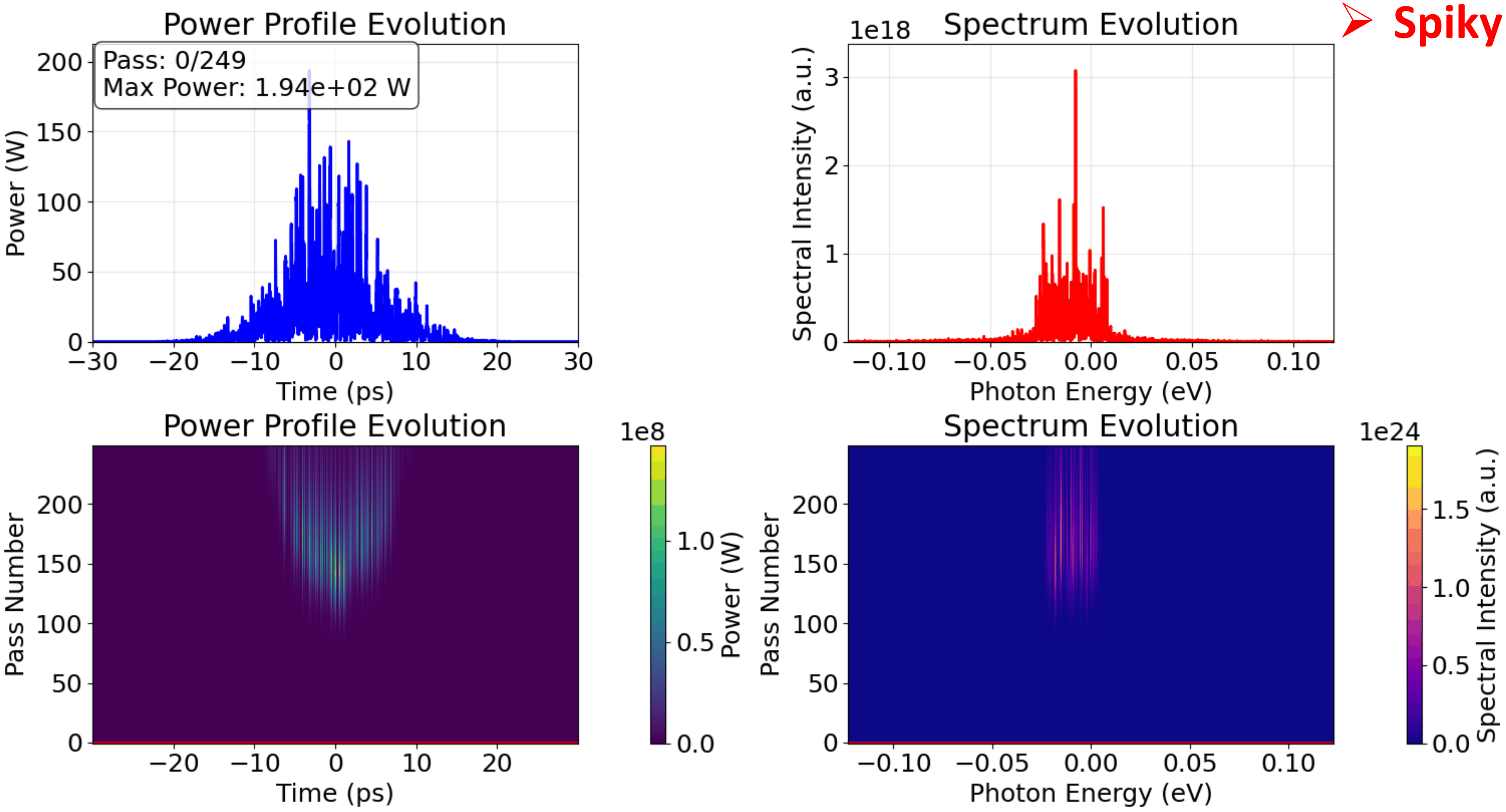


- 300uJ peak in cavity
- 10uJ peak output
- **6×10^9 ph./pulse within 30 meV**

- Assuming 50ms for beam to damp ➔ 20Hz
- Limit passes above 1uJ output ➔~200 bunches
- **4k Hz with 6×10^8 ph./pulse**
- For comparison, LCLS-II 8 GeV linac beam based simulation:
- 1 MHz with 1×10^{10} ph./pulse

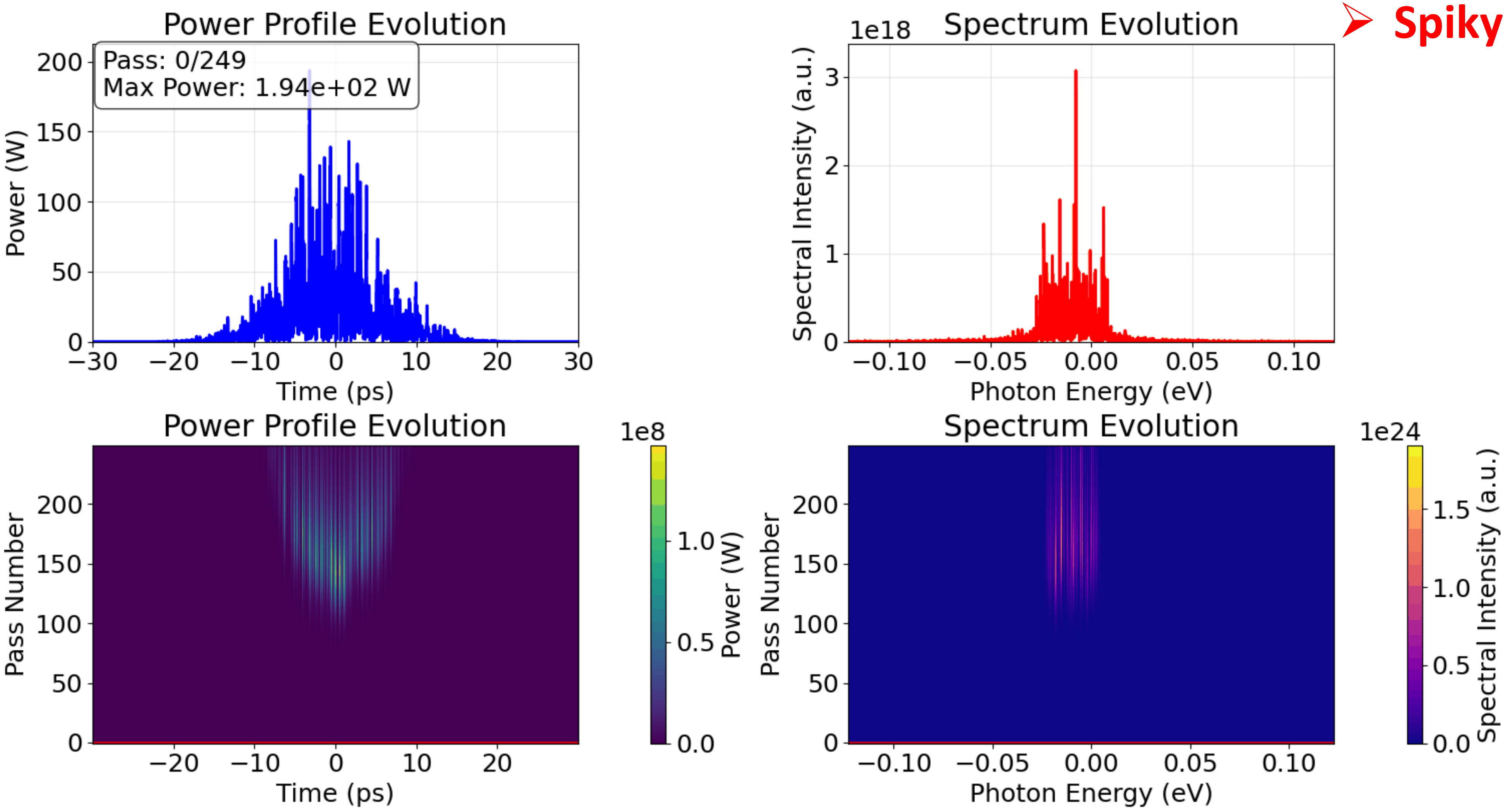
Weilun Qin, FEL2017, TUC05

A (maybe over-) simplified model

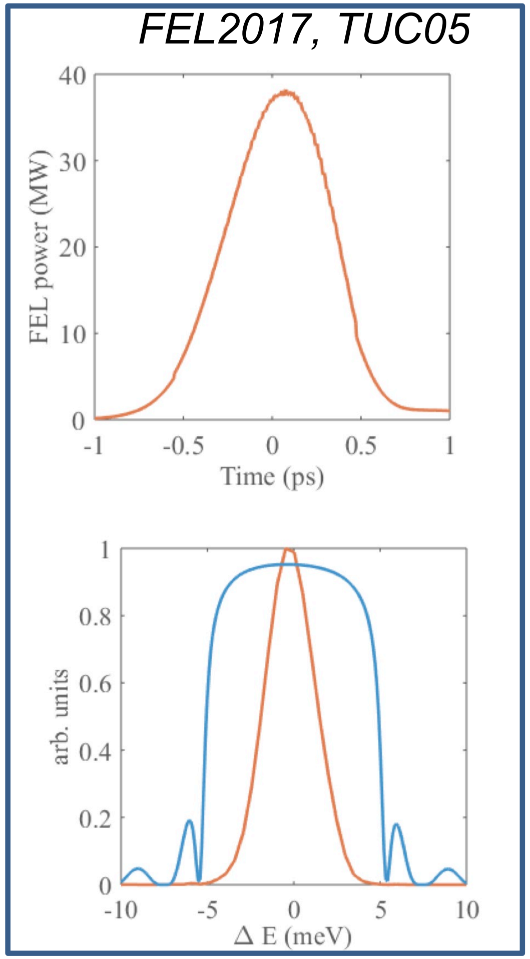


- **Spiky profile and spectra**

A (maybe over-) simplified model

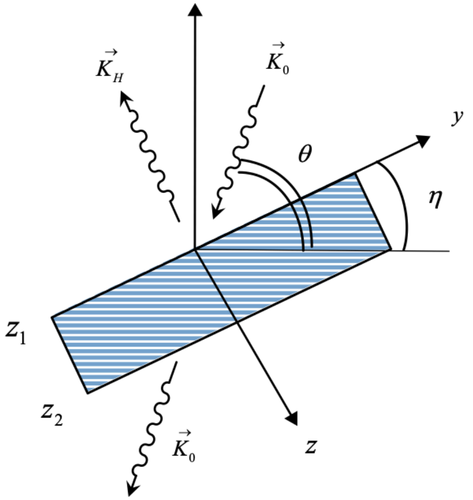


➢ **Spiky profile and spectra**



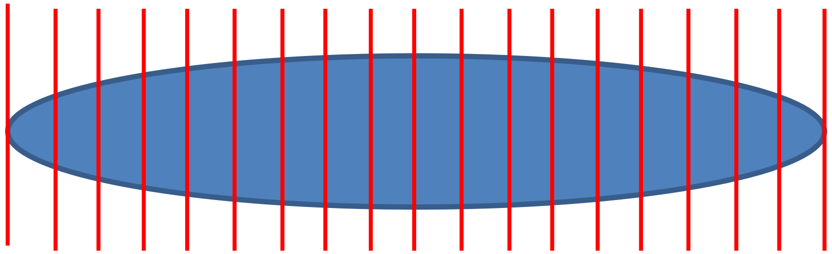
A more involved model： Genesis + Bright + Ring

- **BRIGHT**



Update field

- **Genesis**



- Ignore slippage, large sampling
- Each slice has same 8192 particles
- Dump field file
- Dump beam distribution

- **Ring tracking**

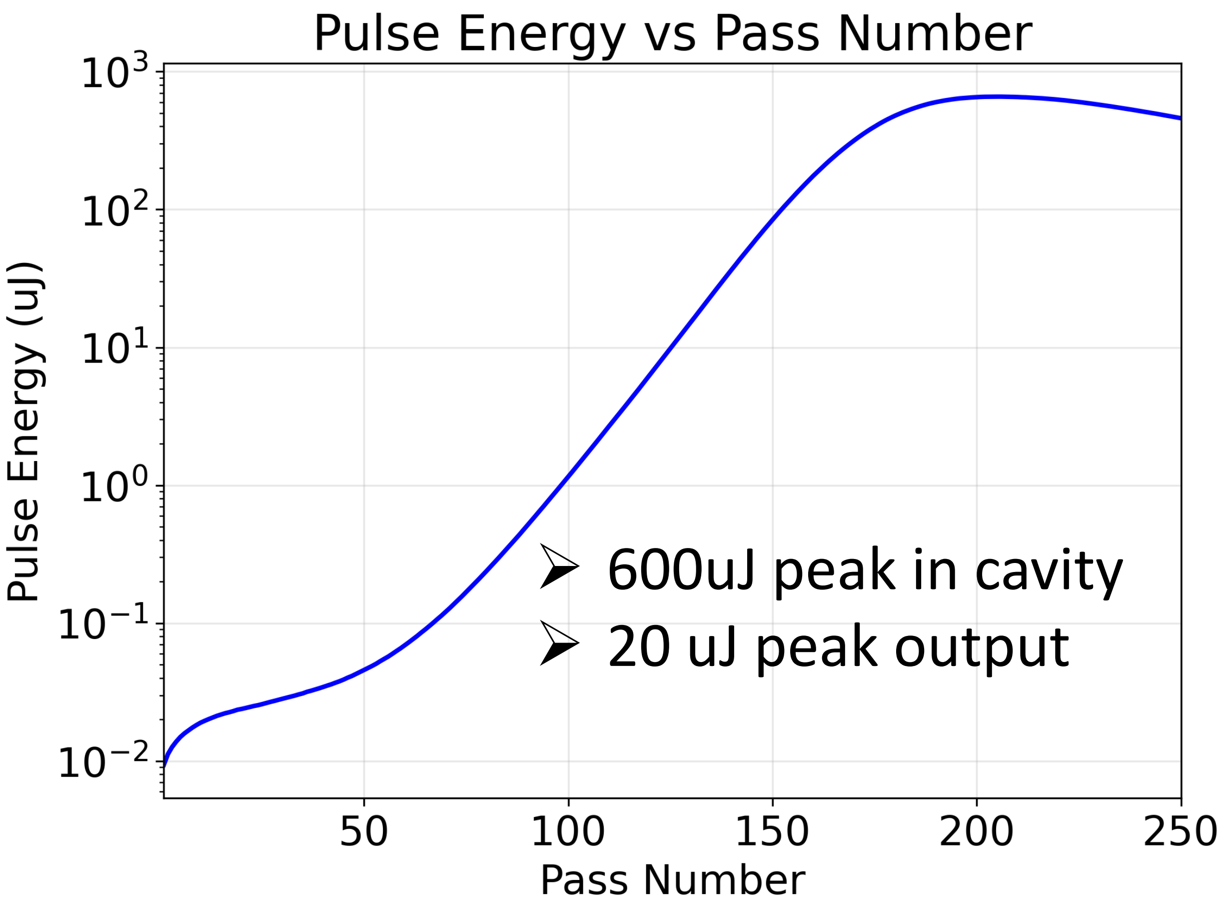
- One turn map
- Damping
- RF focusing

Resampled distribution

- **More realistic FEL process and field handling**

Performance

In-cavity pulse energy evolution



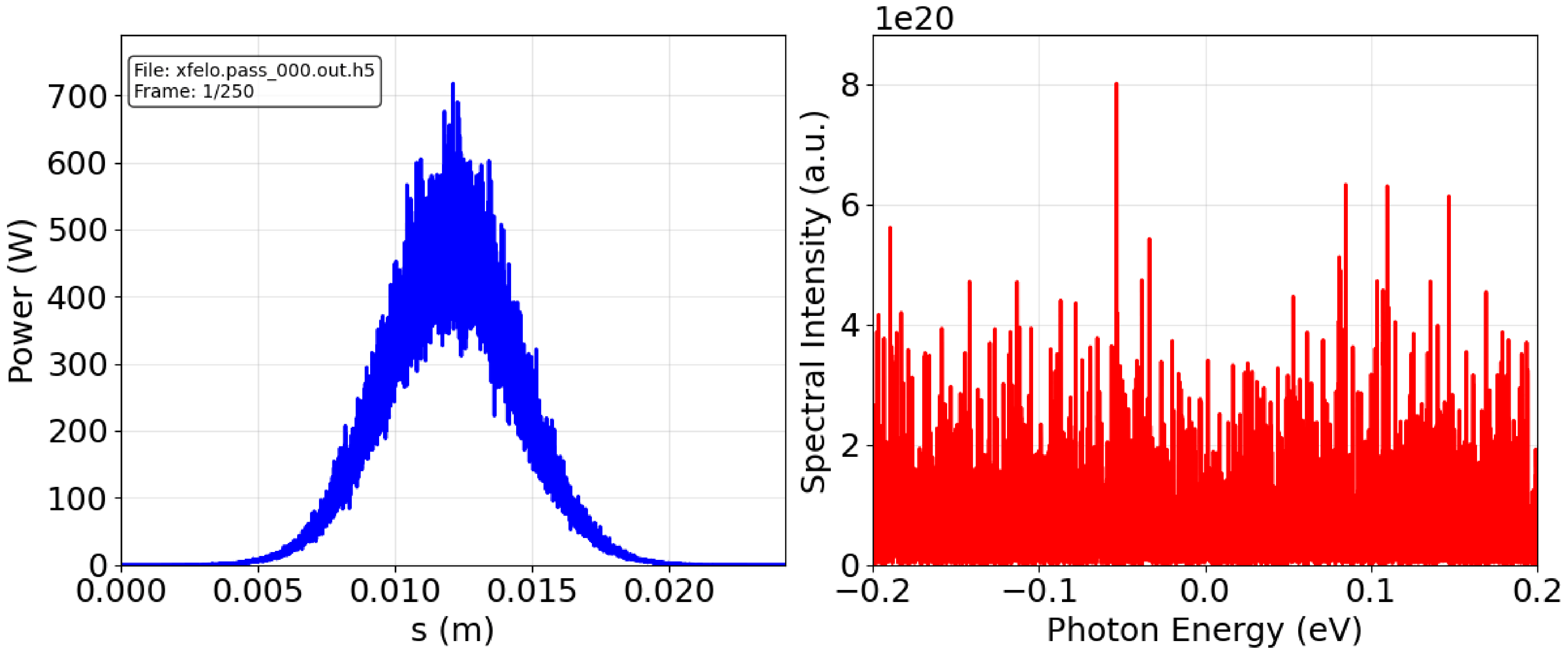
- ~ 1 day run time with 1e4 slices

- Similar level of saturation pulse energy
- Start-up takes longer time
- Saturation is slower

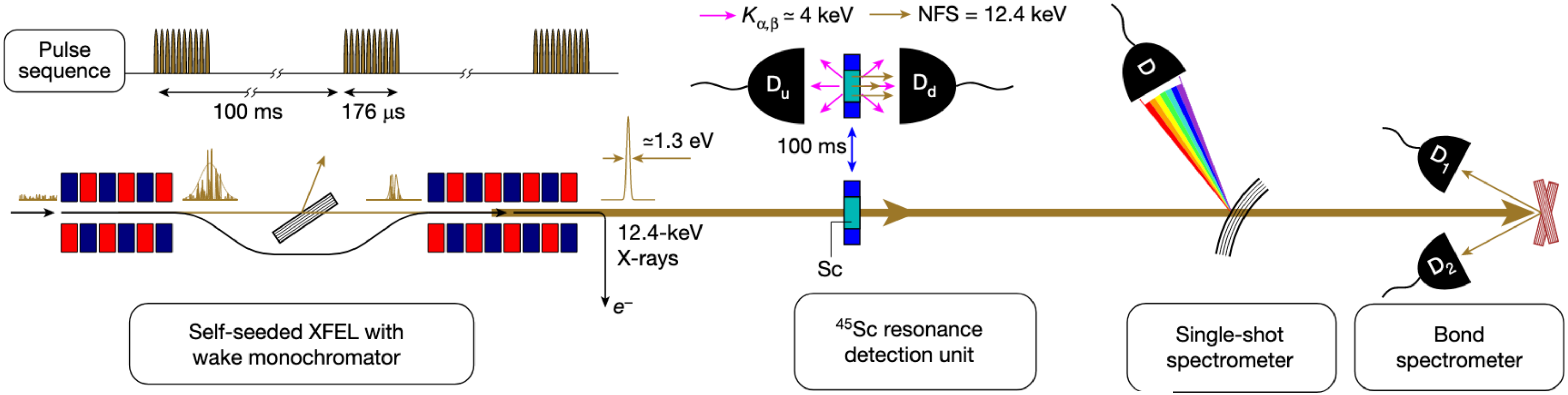
- Total pulse energy higher mainly due to a different reflection used.

Performance

- **Relatively good agreement with simplified model**



What can we do with it?



Article

Resonant X-ray excitation of the nuclear clock isomer ^{45}Sc

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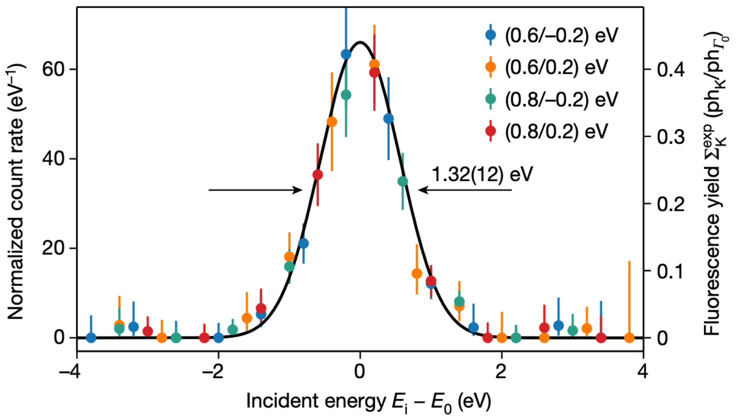
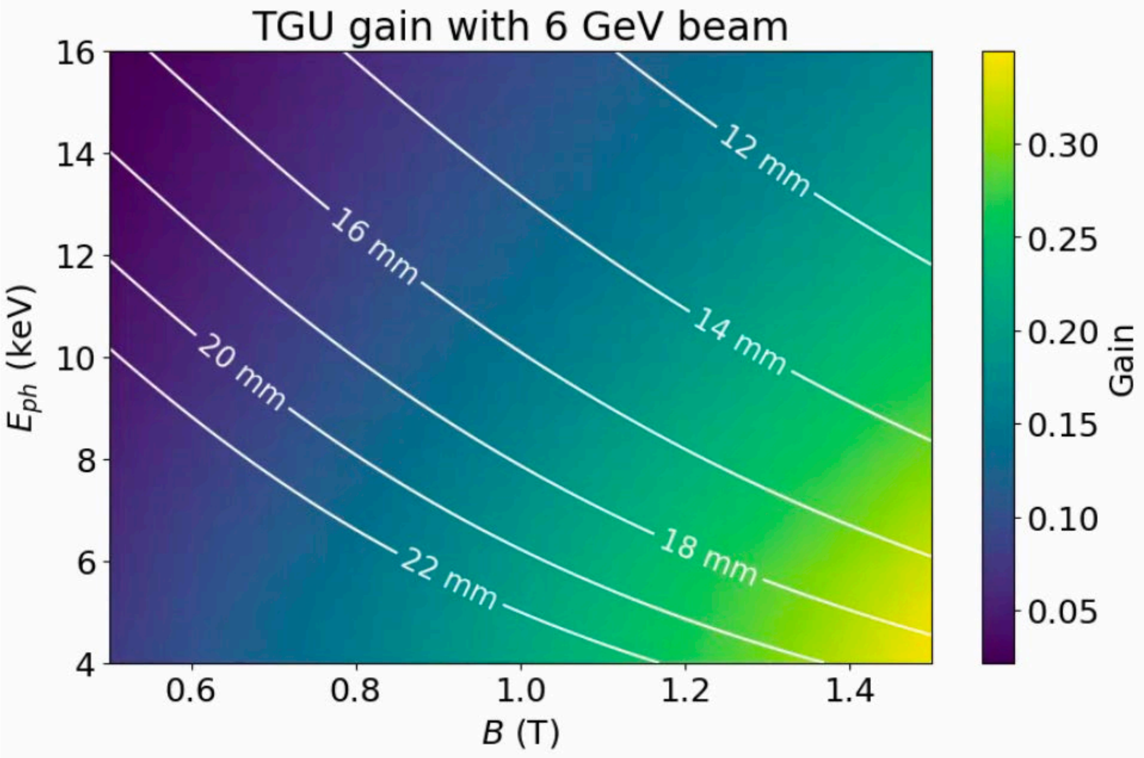


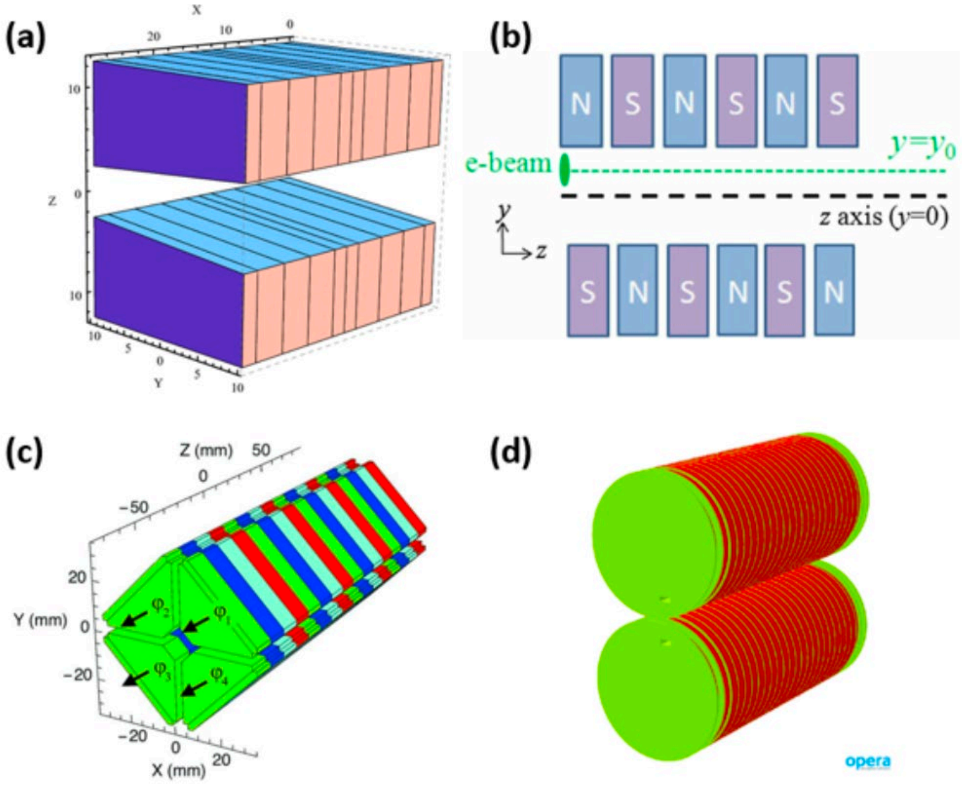
- **4k Hz, 350uJ, 2eV**
- **5×10^{14} ph/s/eV**

- **In our case: 4k Hz, 1uJ, 30meV ➔ 8×10^{13} ph/s/eV**

In real life, challenges in all aspects

- **Undulator: Short period, high field, high transverse gradient**

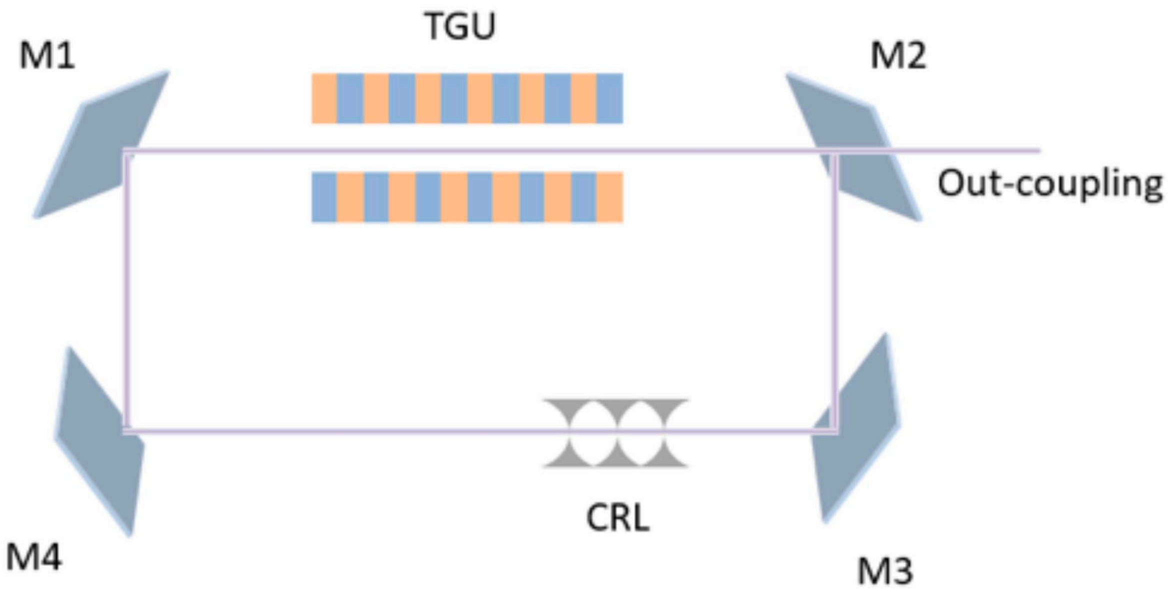




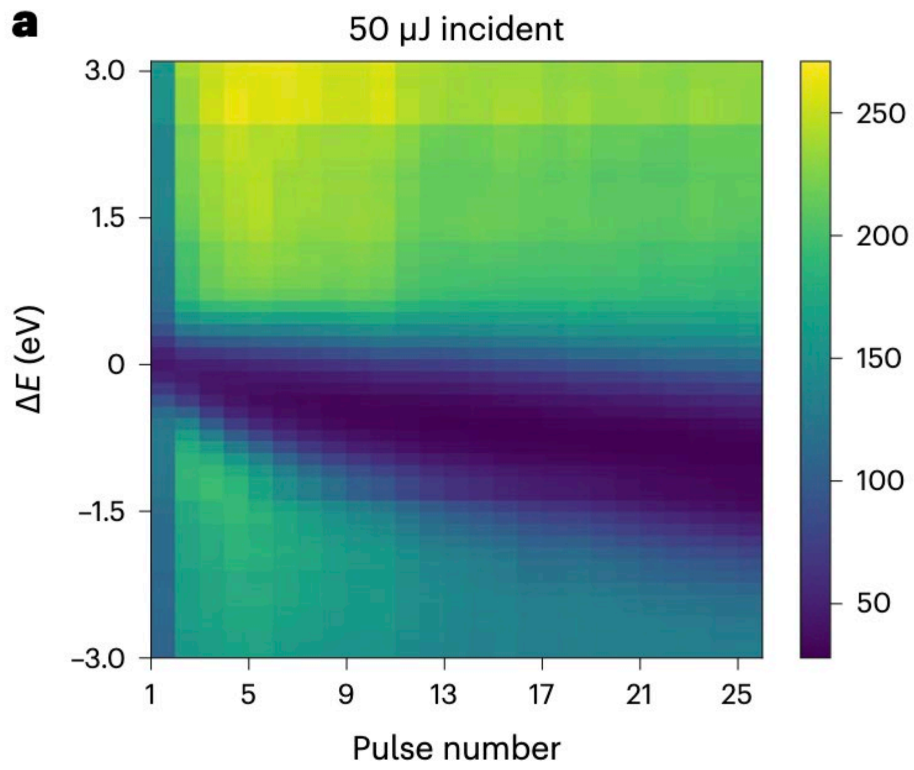
- Wavelength coverage
- Technology for high transverse gradient?

In real life, challenges in all aspects

- **Bragg cavity: very low loss, stable at 10 MHz rep. rate**



➢ Round trip loss < 10%

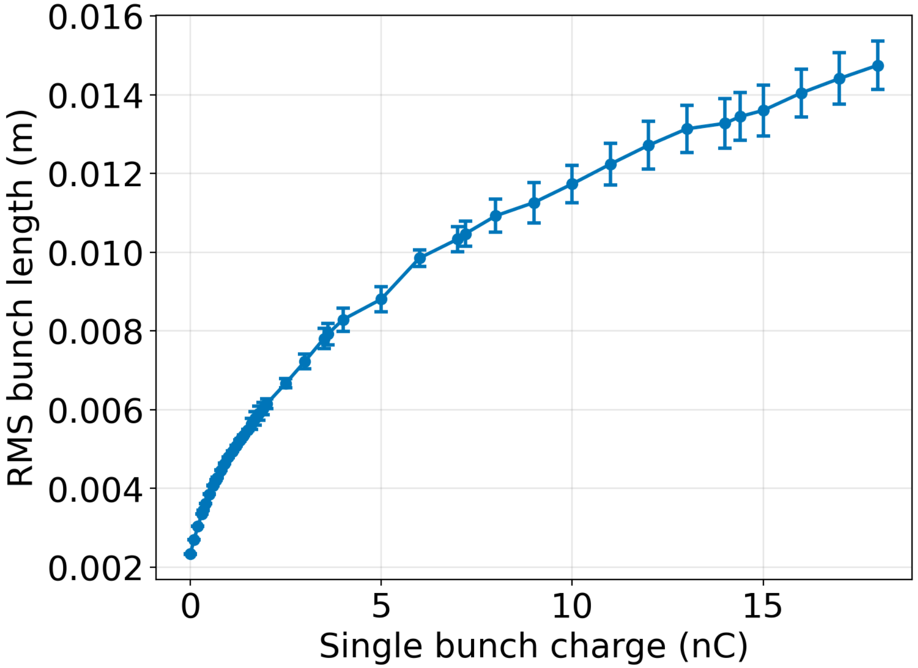


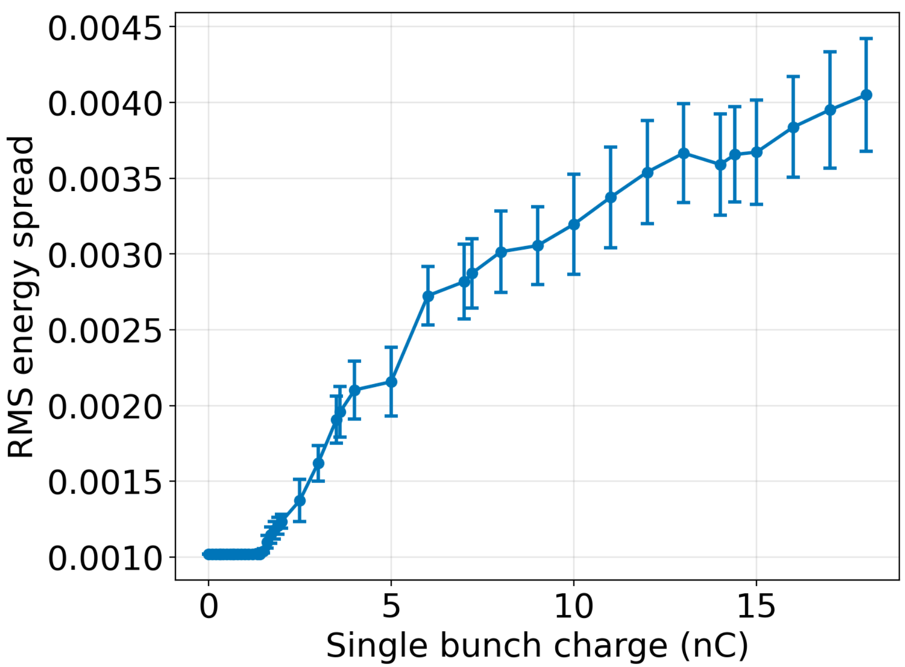
➢ Thermal response at **6keV**, 50uJ, 2.25MHz XFEL pulse

S. Liu et. al., Nat. Photonics (2023)

In real life, challenges in all aspects

■ Ring: high peak current operation





Data from Haisheng Xu

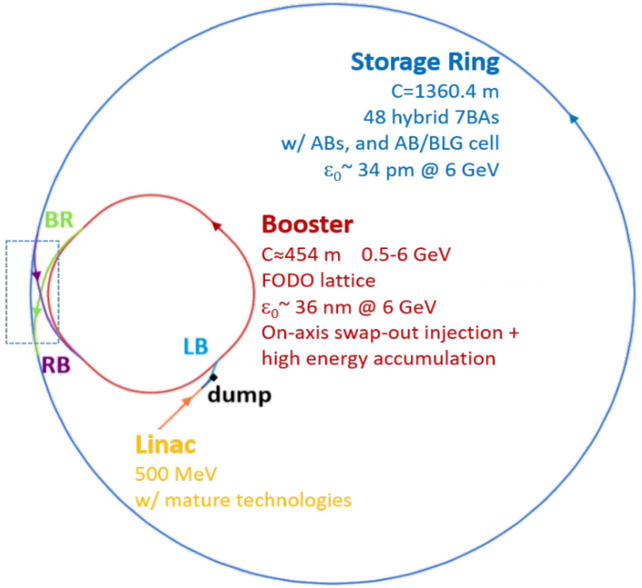
➢ HEPS lattice, with only 500MHz cavity, with impedance, single bunch limit

Summary

- Ring-based XFELO produces high flux hard x-ray photons within 10 meV level bandwidth, this can enable new applications that requires high spectral flux

- We studied the possibility to implement XFELO in a 6-m long straight section, analysis indicated 10^8 to 10^9 ph./pulse output at 10keV within 30meV bandwidth.

- Requirements on the electron beam and x-ray cavity place big challenges to undulator technology, x-ray optical elements, and ring dynamics.



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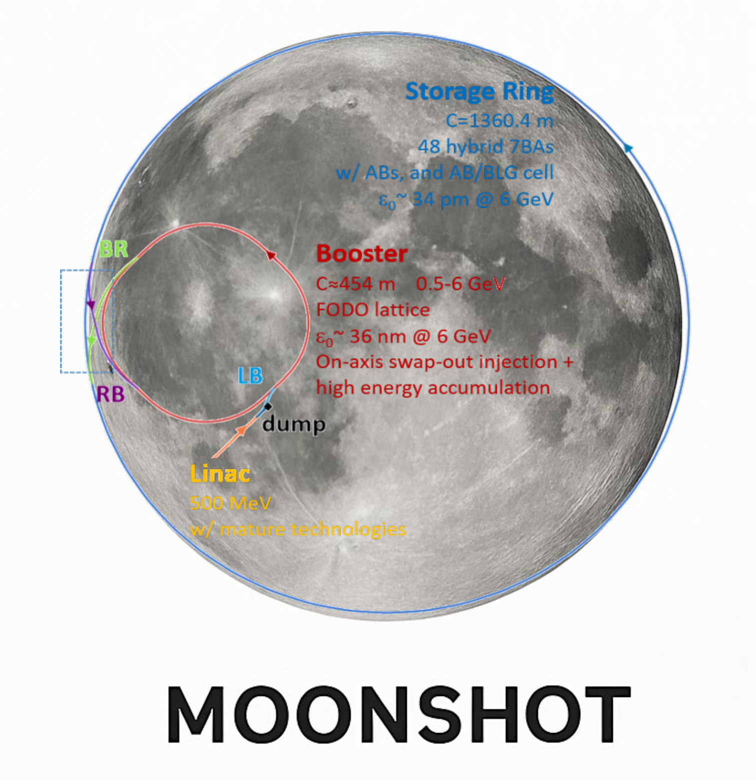

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■ **Thanks for your attention!**