Opportunities in FEL Physics with C3 Technology

Agostino Marinelli
Accelerator Research Division
FEL Physics Department

Assistant Prof.
Photon Science and
Particle Physics and Astrophysics

Outline

1) Intro to FEL R&D
2) Opportunities for FELs driven by cold copper linac
3) Opportunities for the LCLS complex

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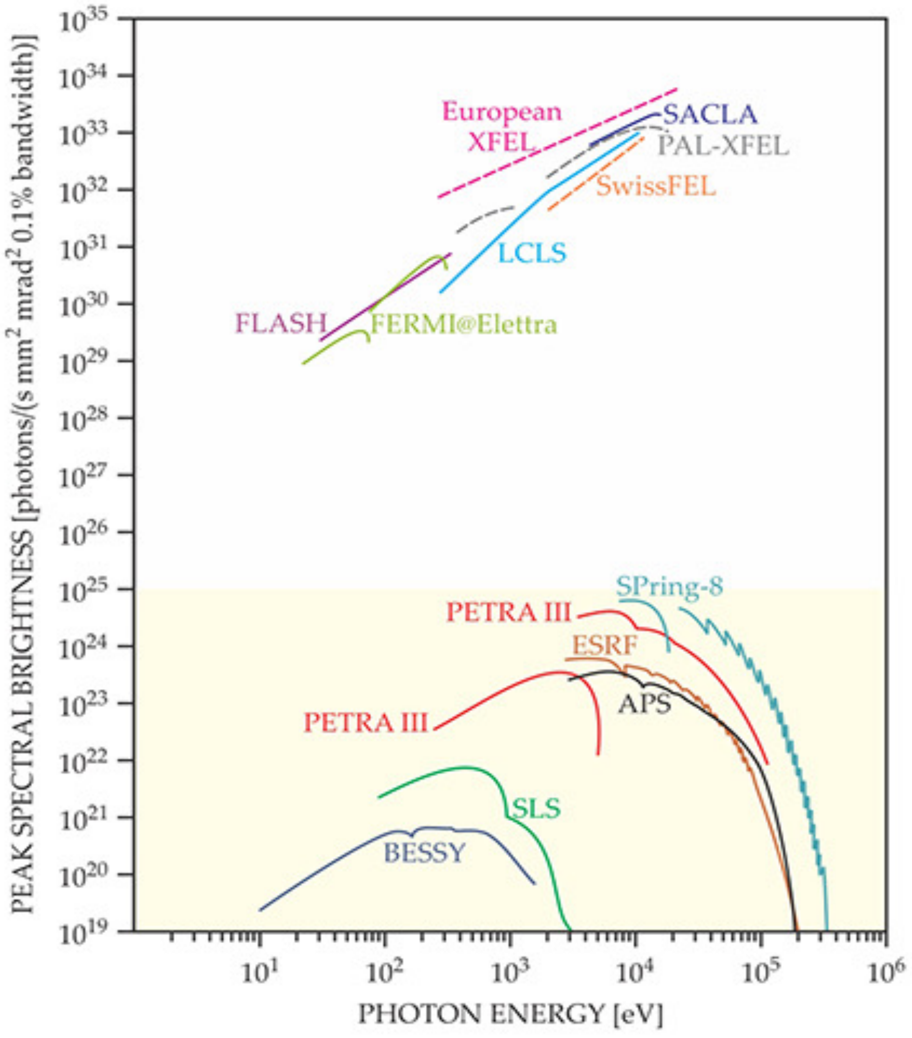
1) Intro to FEL R&D
2) Opportunities for FELs driven by cold copper linac
3) Opportunities for the LCLS complex

Disclaimers:

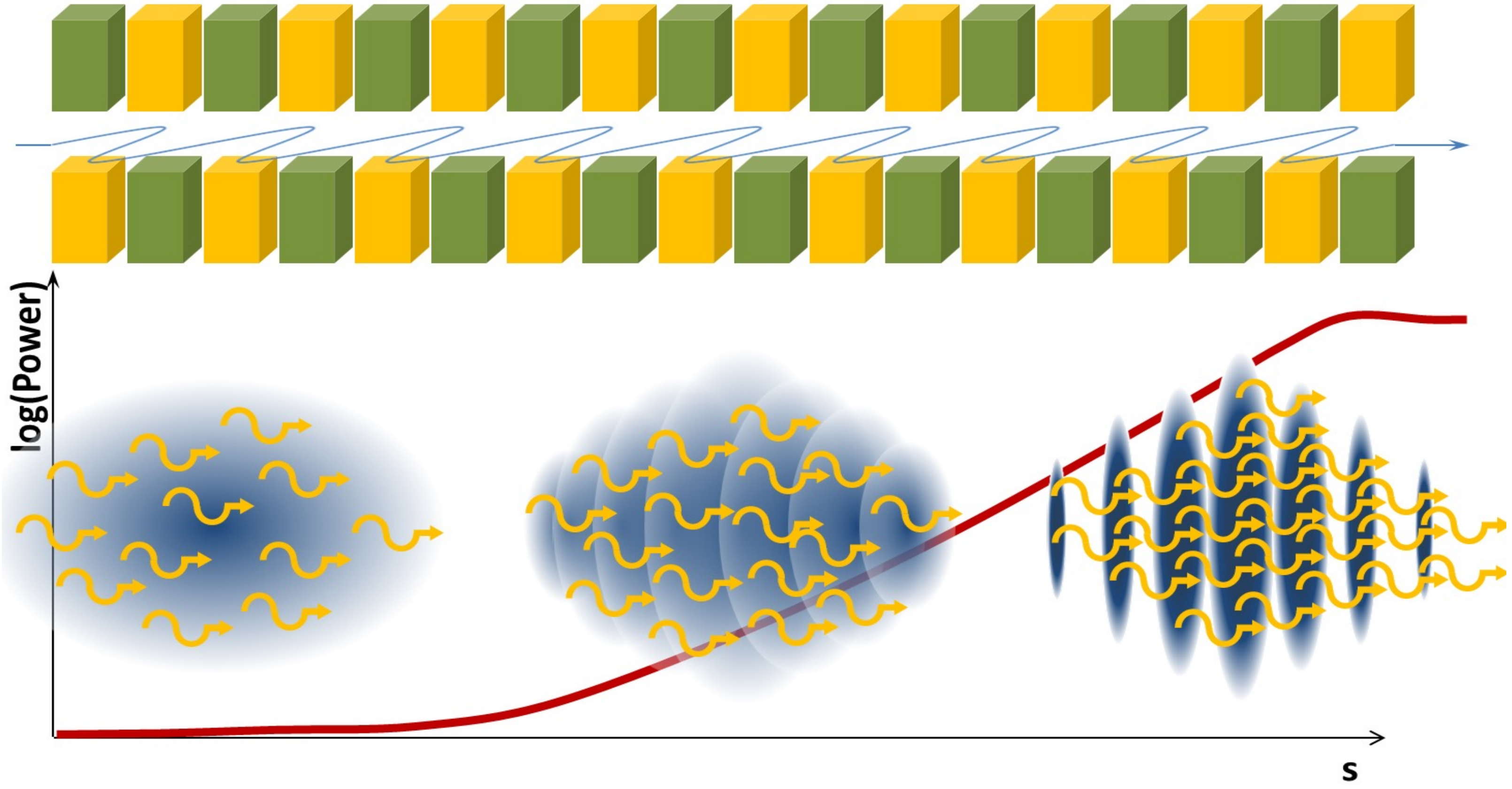
I am here on behalf of myself
Discussing potential opportunities, no in-depth studies

X-ray Free-Electron Lasers



P. Bucksbaum, Nora Berrah *Physics Today* **68** (7), 26–32 (2015);

Free-Electron Laser



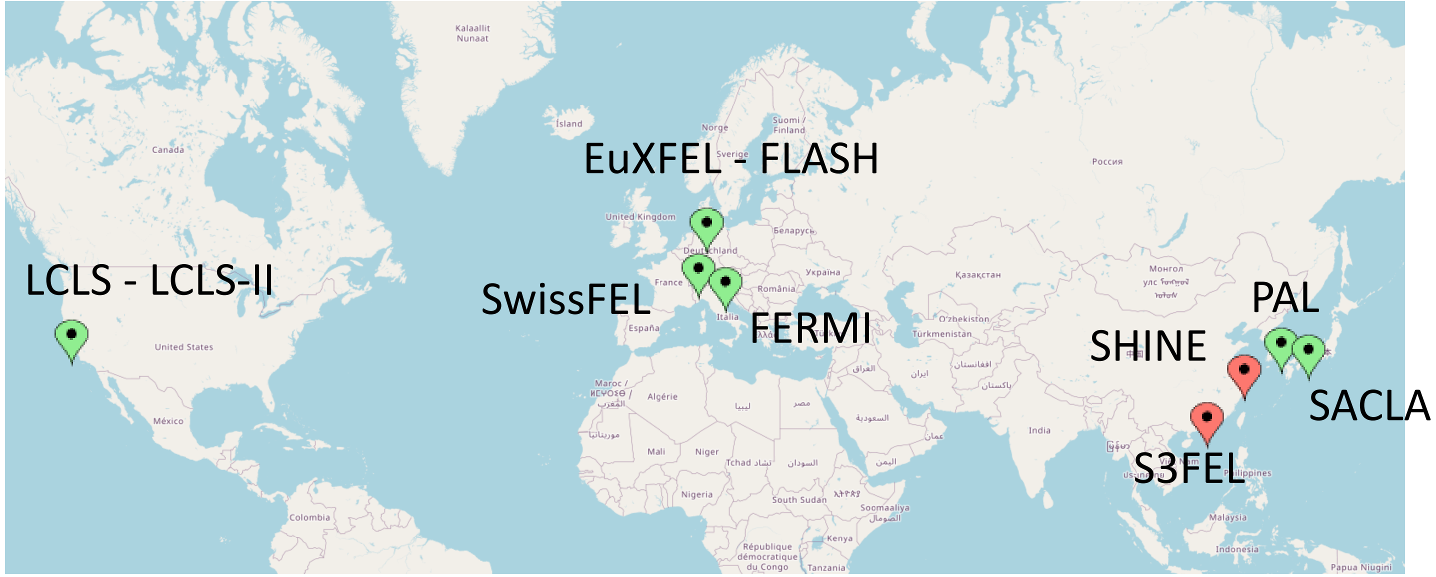
Incoherent Radiation

Coherent Radiation

$$\lambda_w \left(\frac{1}{<\beta_z>} - 1 \right)$$

Source: https://www.helmholtz-berlin.de

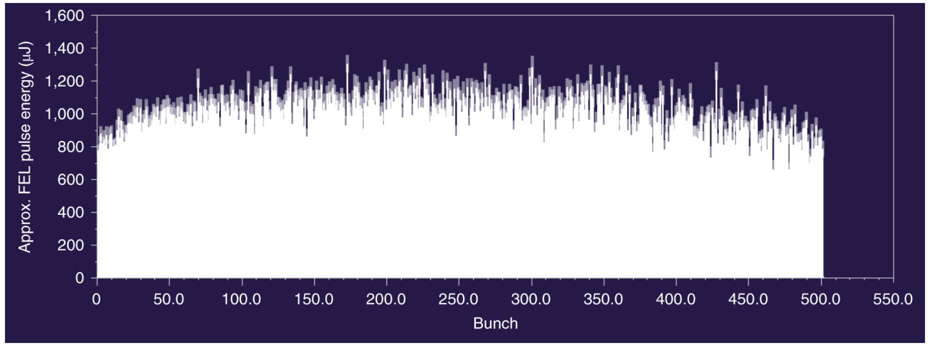
X-ray Free-Electron Lasers



First proposal: Pellegrini, C. A 4 to 0.1nm FEL based on the SLAC linac. Proc. of the Workshop on 4th Generation Light Sources (1992)

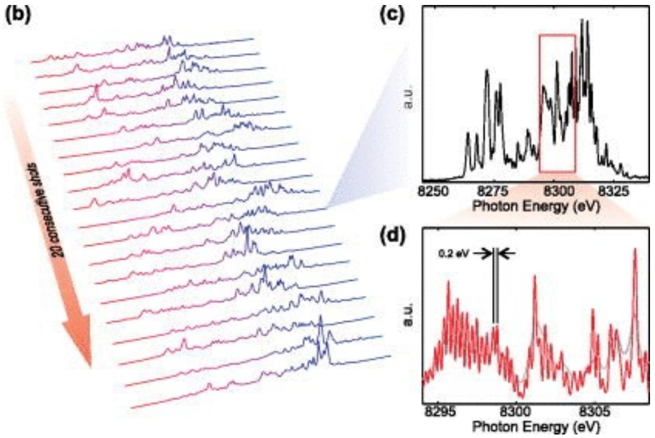
Standard X-ray FEL operation

Pulse energy ~ 0.5 to few mJ



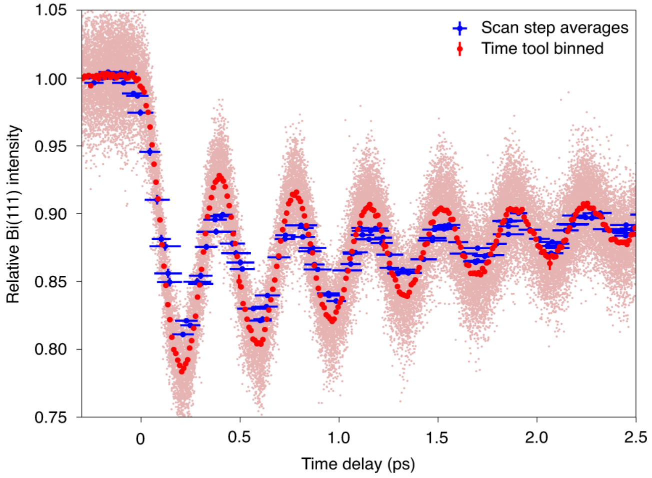
W. Decking et. al.
Nature photonics 14.6 (2020): 391-397.

SASE FEL: partial temporal coherence

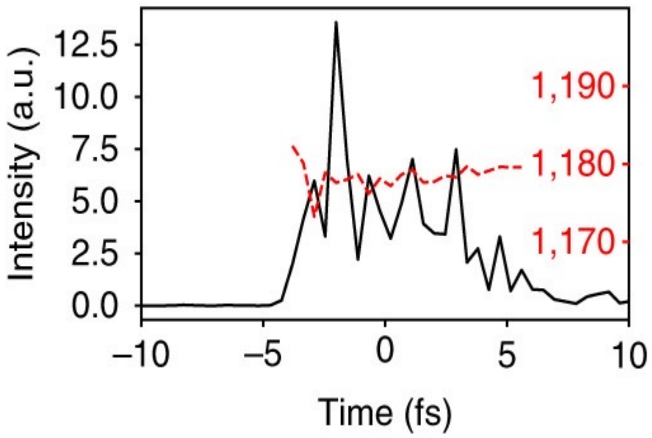


D. Zhu et al.
Applied Physics Letters 101.3 (2012): 034103.

Temporal resolution ~ tens of femtoseconds



E. Prat et al. Nature Photonics 14.12 (2020): 748-754

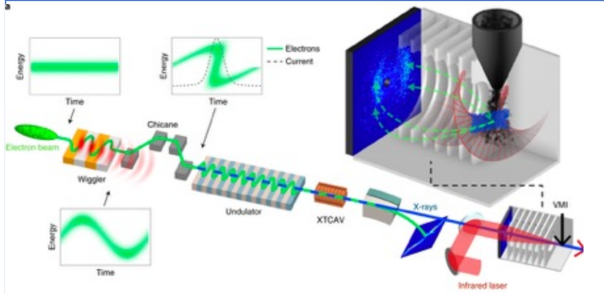


N. Hartmann et al.
Nature Photonics 12.4 (2018): 215-220.

FEL R&D

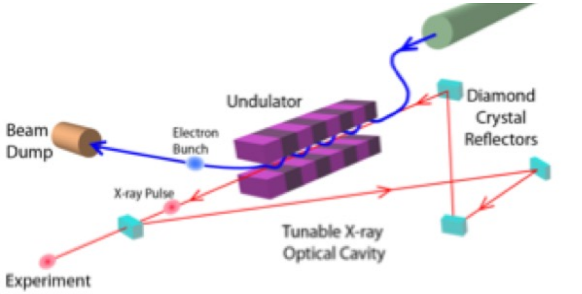
Improving FEL facilities

Time-resolved Capabilities



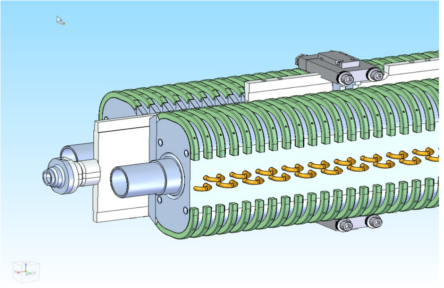
Nature Photonics 14.1 (2020): 30-36

Seeded FELs



G. Marcus Phys. Rev. Lett. **125**, 254801

Enhanced Performance



FEL R&D

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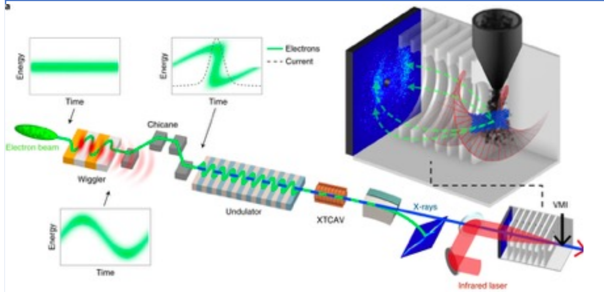

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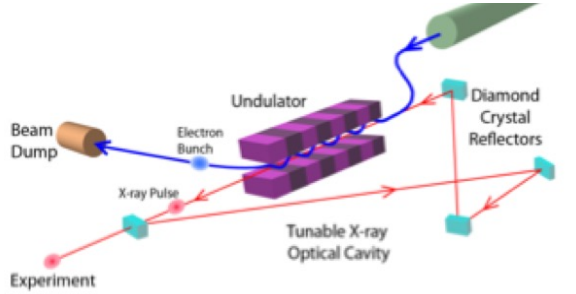

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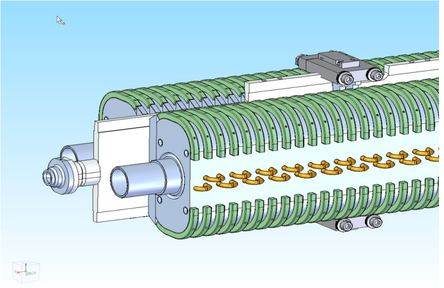
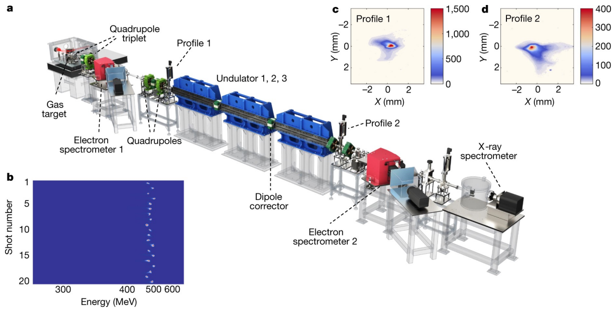


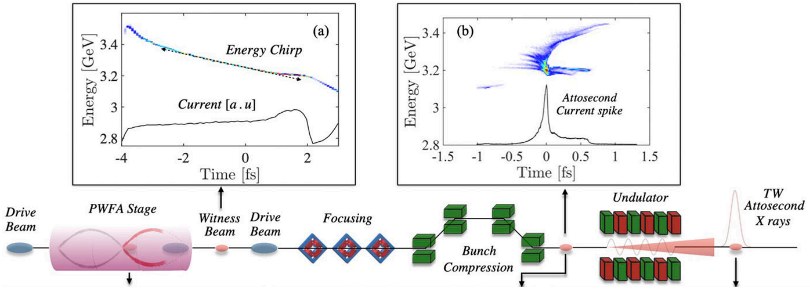
New kinds of FELs

Compact FELs



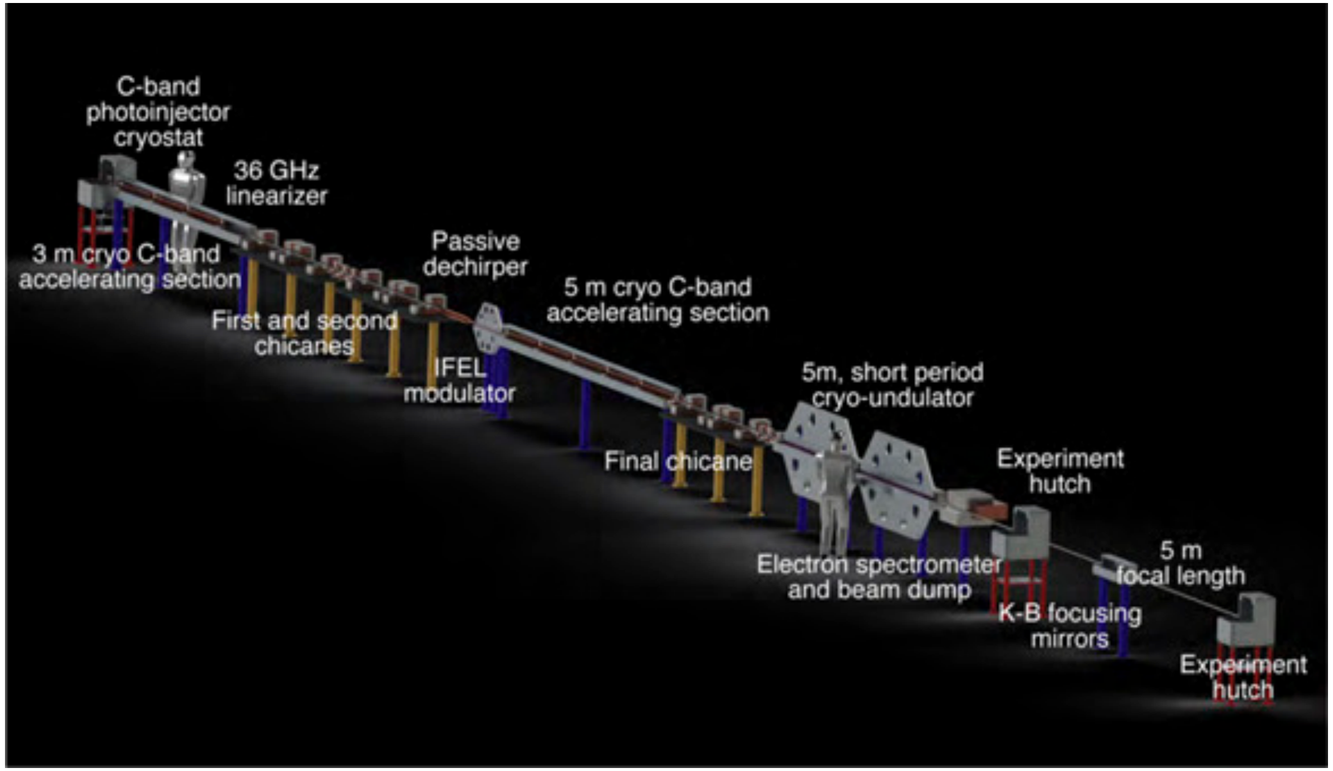
Wang, Wentao, et al. *Nature* 595.7868 (2021): 516-520

Extreme performance



C. Emma et al. APL Photonics 6.7 (2021)

Why an FEL Driven by Cold Copper Linac?   Compactness



J B Rosenzweig *et al* 2020 *New J. Phys.* **22** 093067

Credible path towards university-scale FEL system

Based on largely proven beam dynamics concepts. Undulator is a challenge

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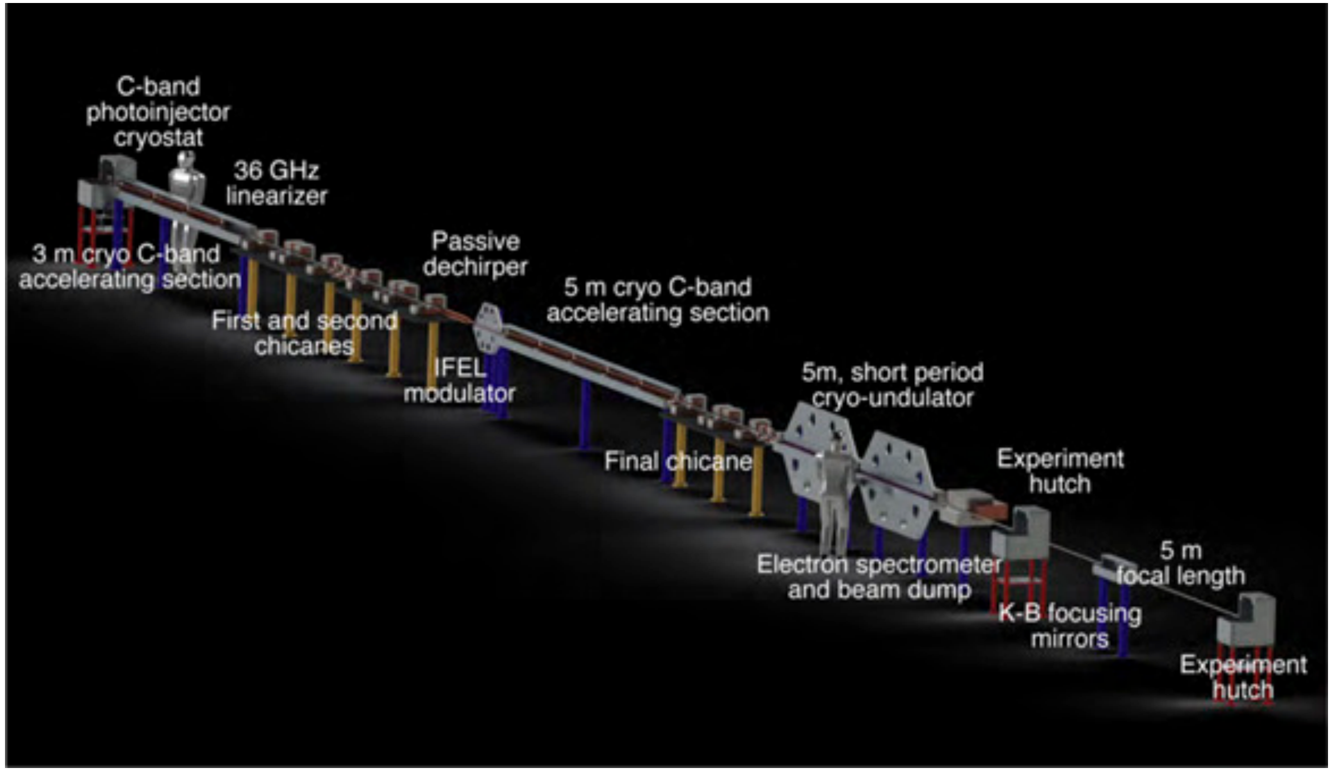

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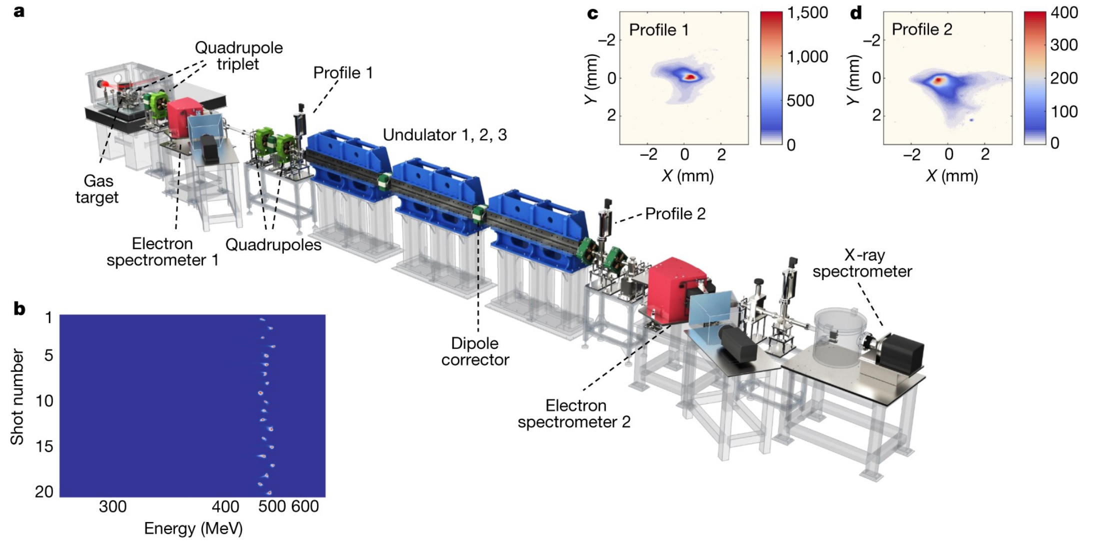

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Credible path towards university-scale FEL system

Based on largely proven beam dynamics concepts. Undulator is a challenge

Competition from laser-plasma community

Why an FEL Driven by Cold Copper Linac? Performance

10 x reduction in emittance

$$L_g \propto \epsilon^{5/6}$$

Operation at higher energy and/or with more compact undulators

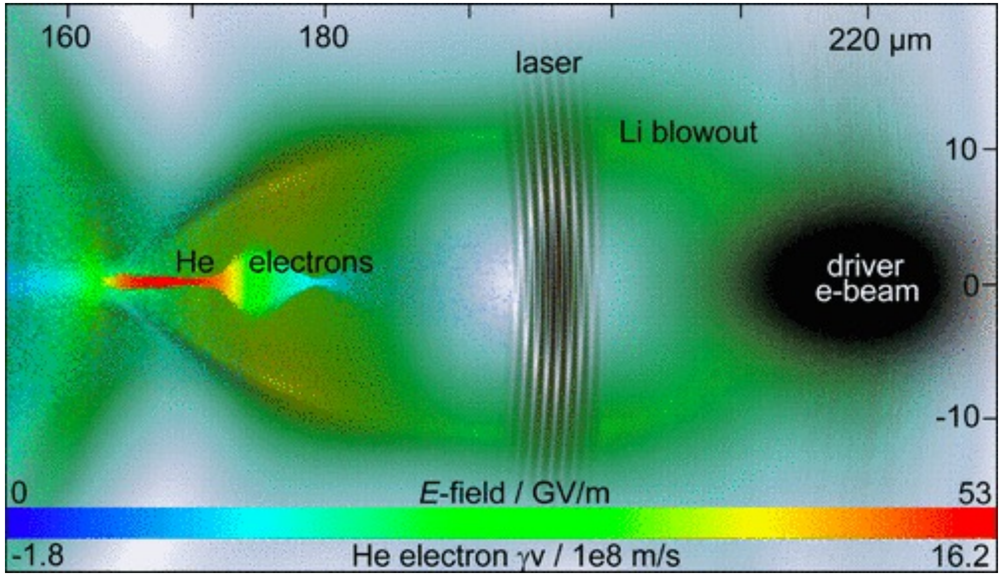
$$\Delta t_{min} \propto \epsilon^{5/6}$$

Improve pulse duration
(Competition from plasma-wakefield acceleration)

Saldin, Evgeny L., Evgeny A. Schneidmiller, and Mikhail V. Yurkov.

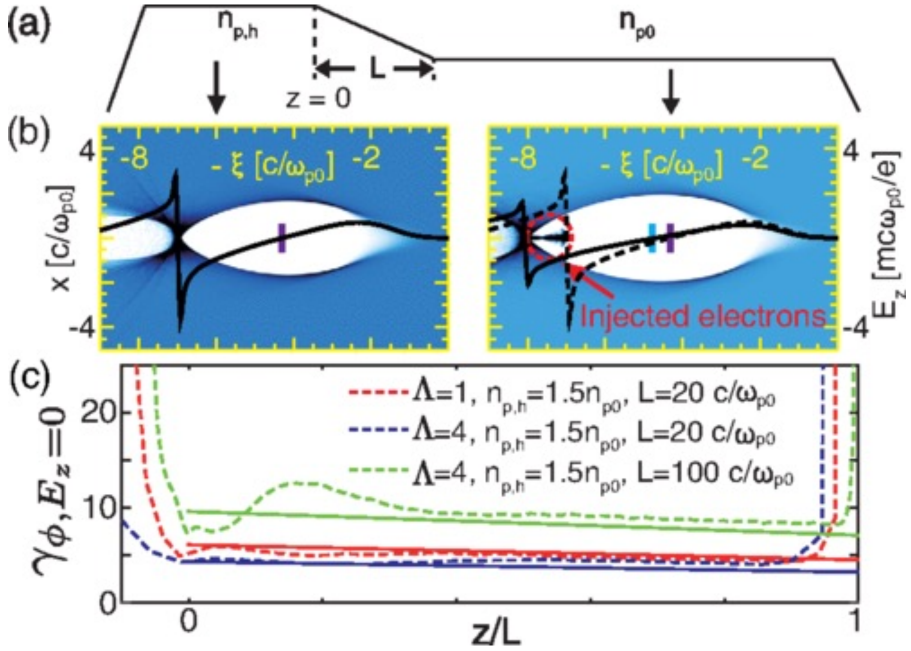
"Design formulas for short-wavelength FELs." *Optics communications* 235.4-6 (2004): 415-420.

Competition from Plasma Wakefield Accelerators



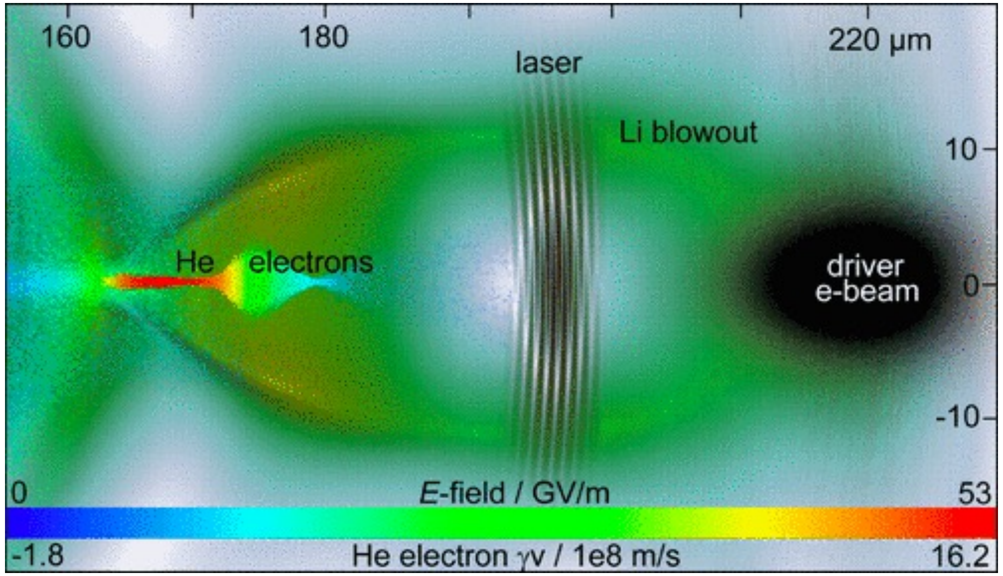
B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller,

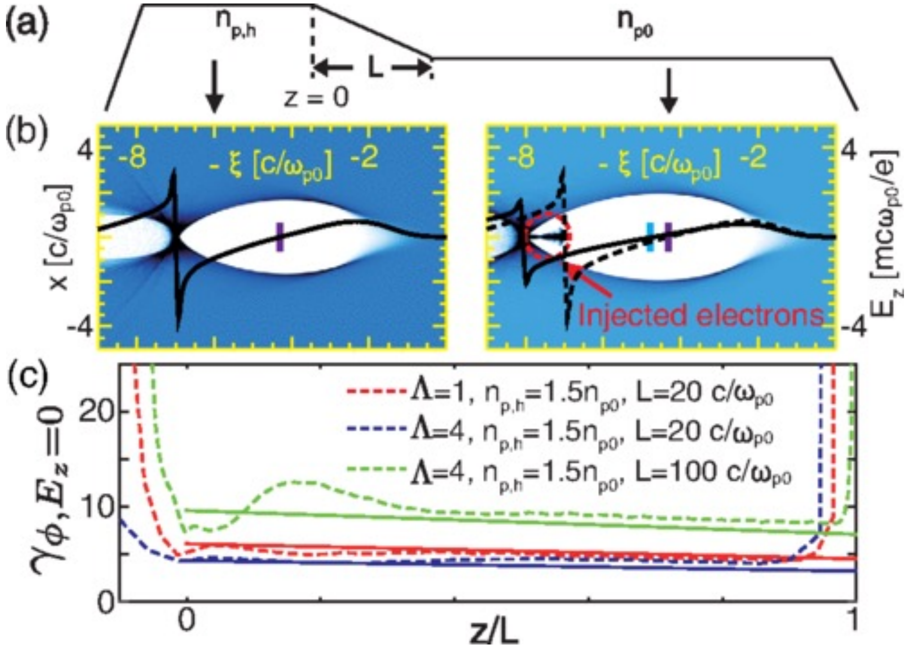
and D. L. Bruhwiler Phys. Rev. Lett. **108**, 035001



X. Xu et al. PRAB 20.11 (2017): 111303.

Competition from Plasma Wakefield Accelerators





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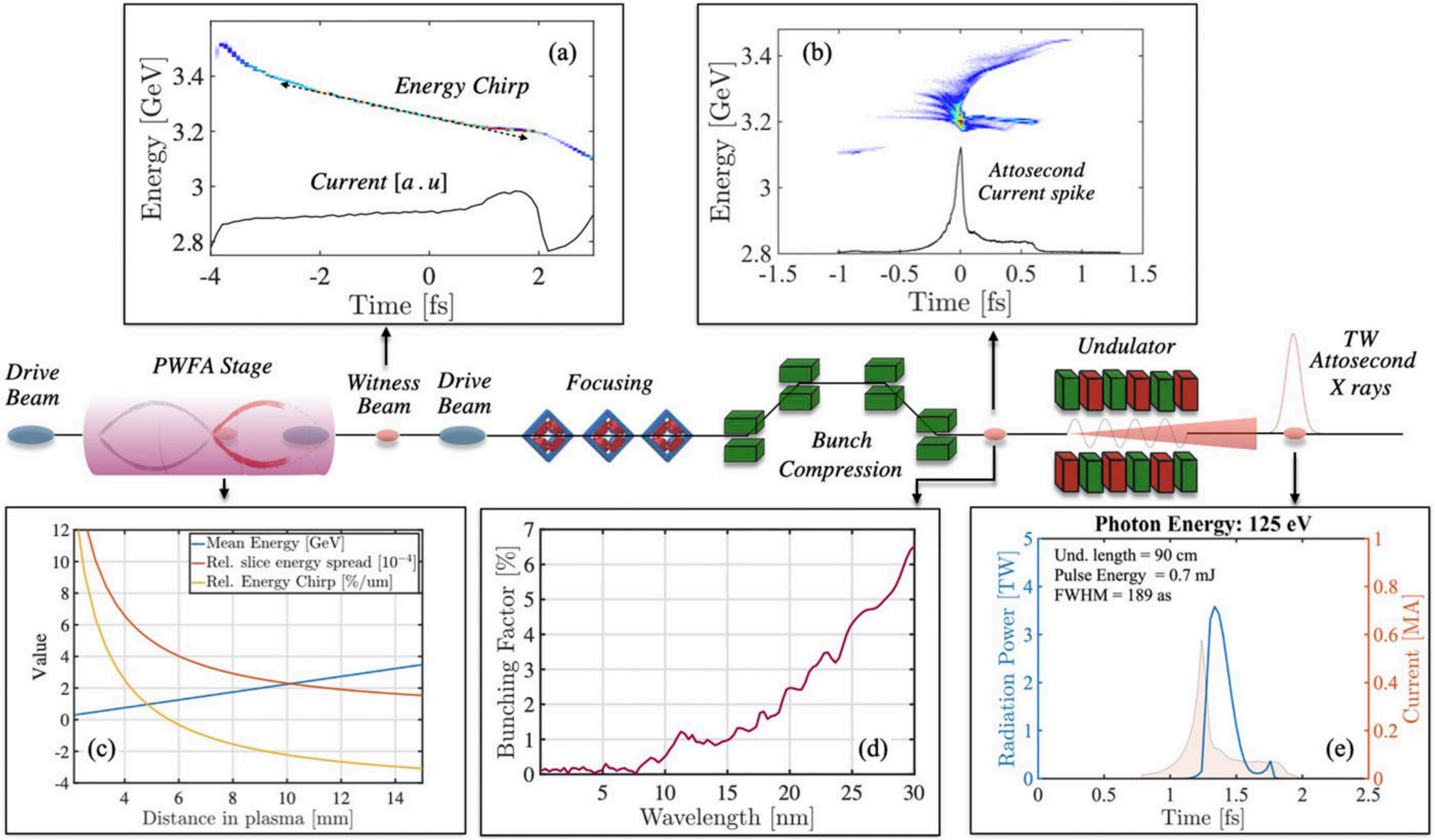
X. Xu et al. PRAB 20.11 (2017): 111303.

Beam generated at ~1-10 kA peak current at the injector!



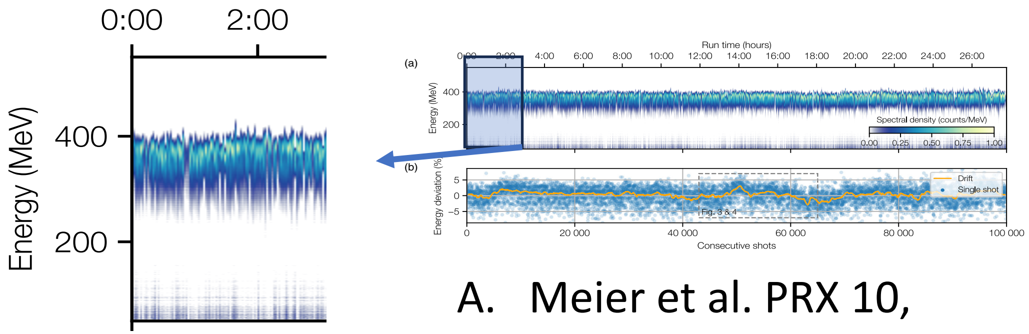
C. Emma et al. APL Photonics 6.7 (2021)

My Opinion: C3 vs Plasma

General considerations

- C3 technology relies on proven beam dynamics concepts and highly developed technology.

- Plasma and laser wakefield pose challenges in terms of stability and reliability.



A. Meier et al. PRX 10, 031039 (2020)

In the context of FELs

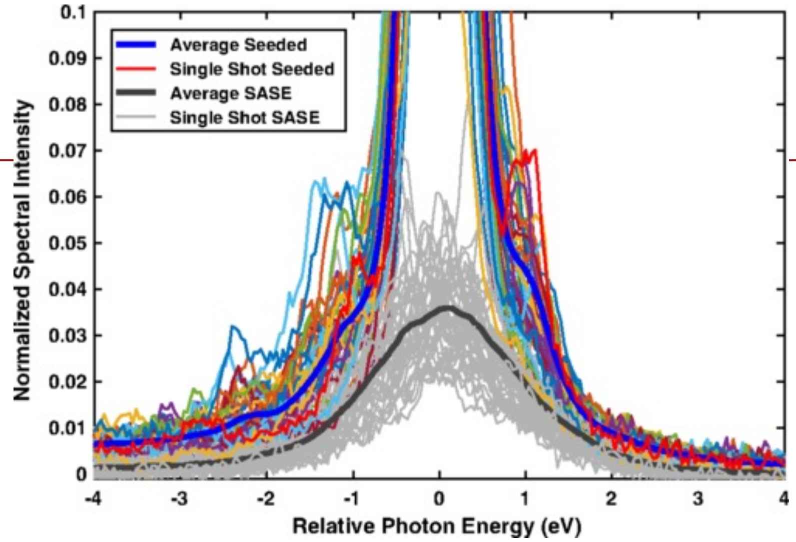
C3 probably best bet for a compact XFEL **today**

Plasma holds more promise for future extreme performance scenarios (e.g. single-cycle x-ray pulses)

Seeded FELs

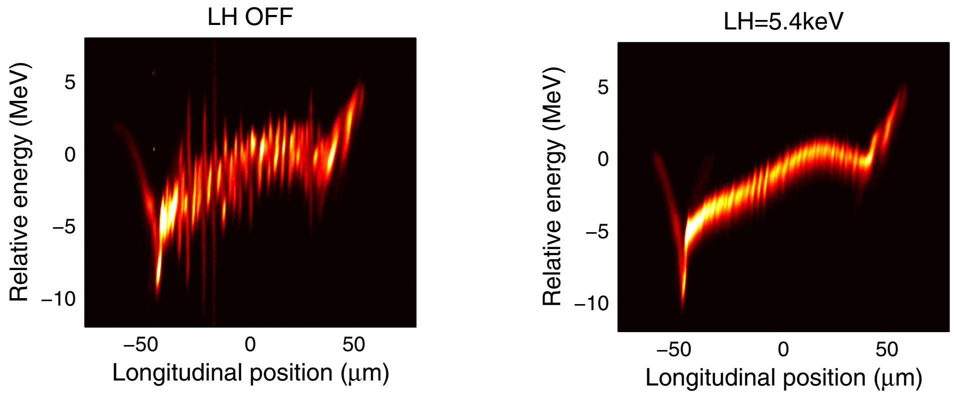
Main limitations of seeded XFELs:
- slice energy spread
- microbunching instability

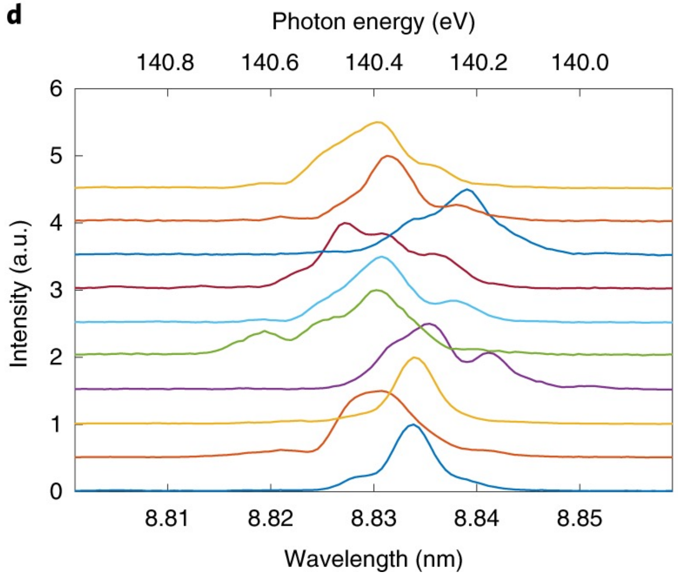
Seeded FEL limited to <~ 500 eV
Hemsing et al. 22.11 (2019): 110701.



G Marcus et al. Phys. Rev. Accel. Beams **22**, 080702

D. Ratner et al. Phys. Rev. ST Accel. Beams **18**, 030704





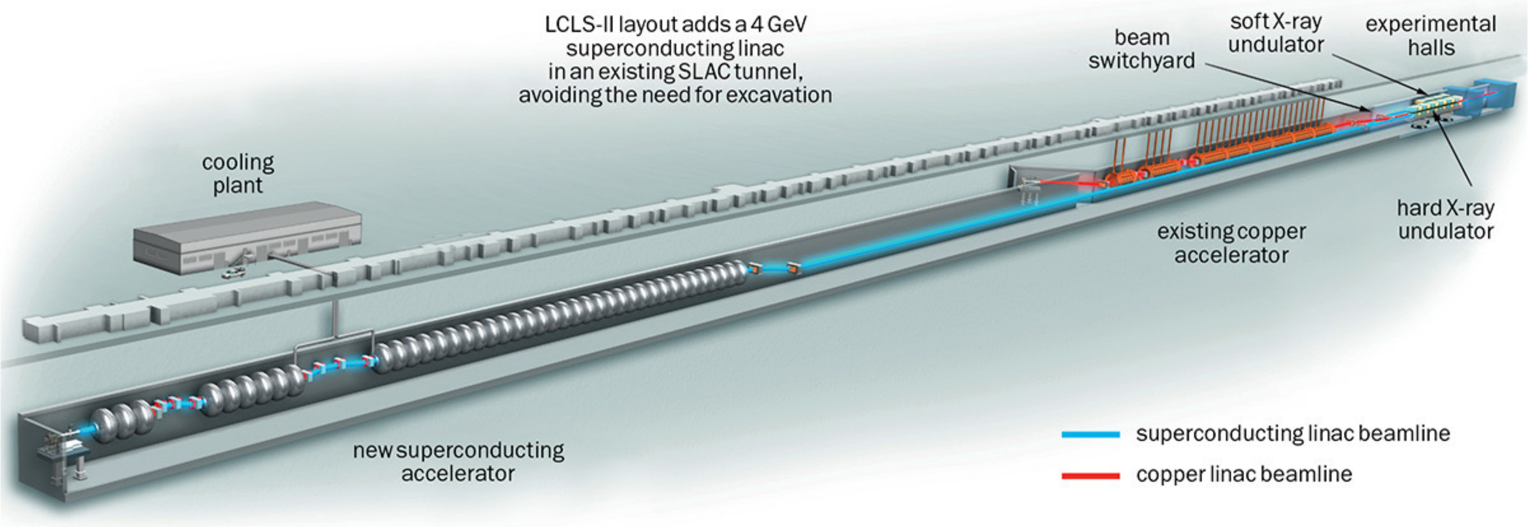
Nature Photonics **volume 13**, pages555–561 (2019)

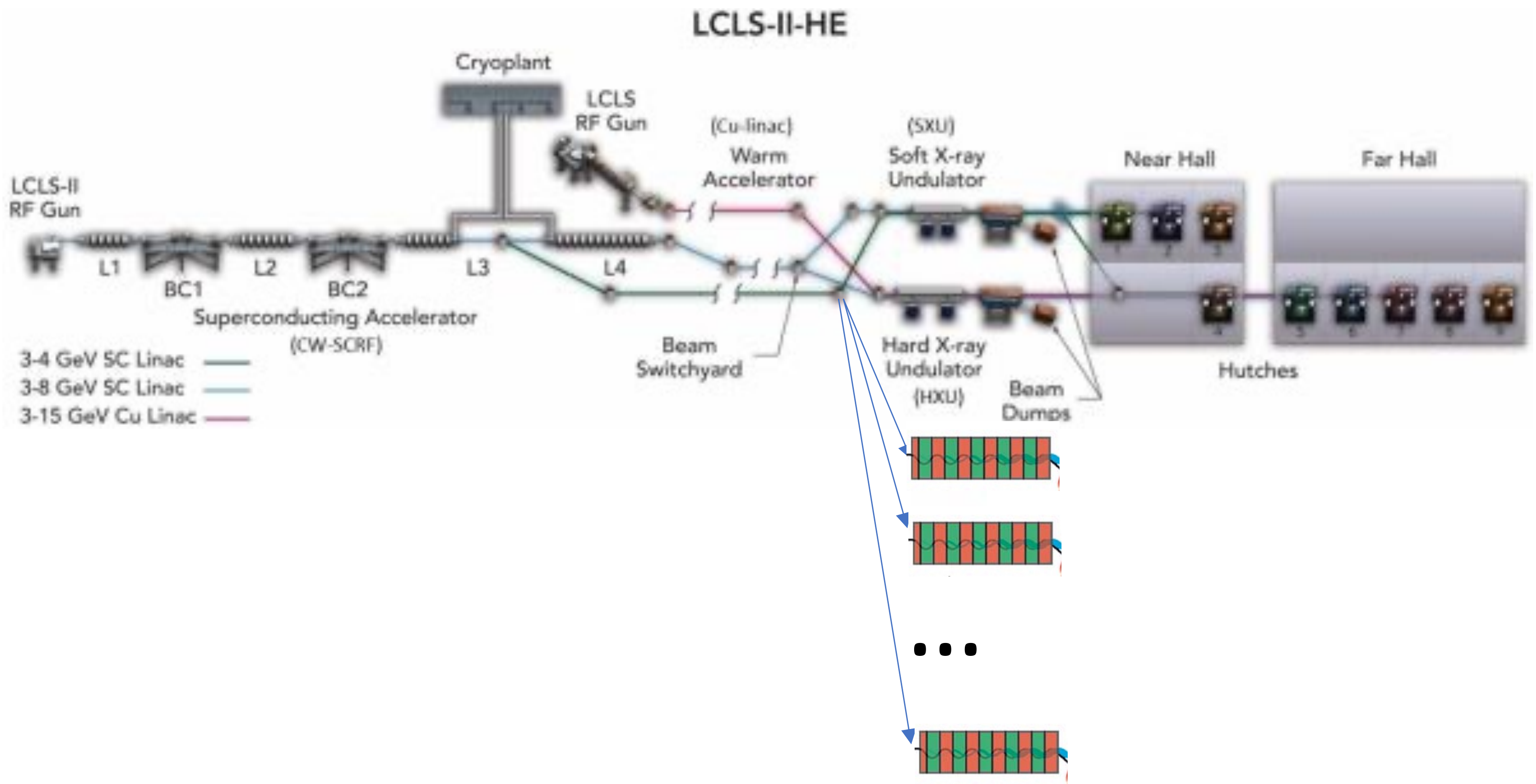
Microbunching gain

$$\frac{b_f}{b_i} \propto 1/G$$

Strong reduction with cold copper

The LCLS Complex



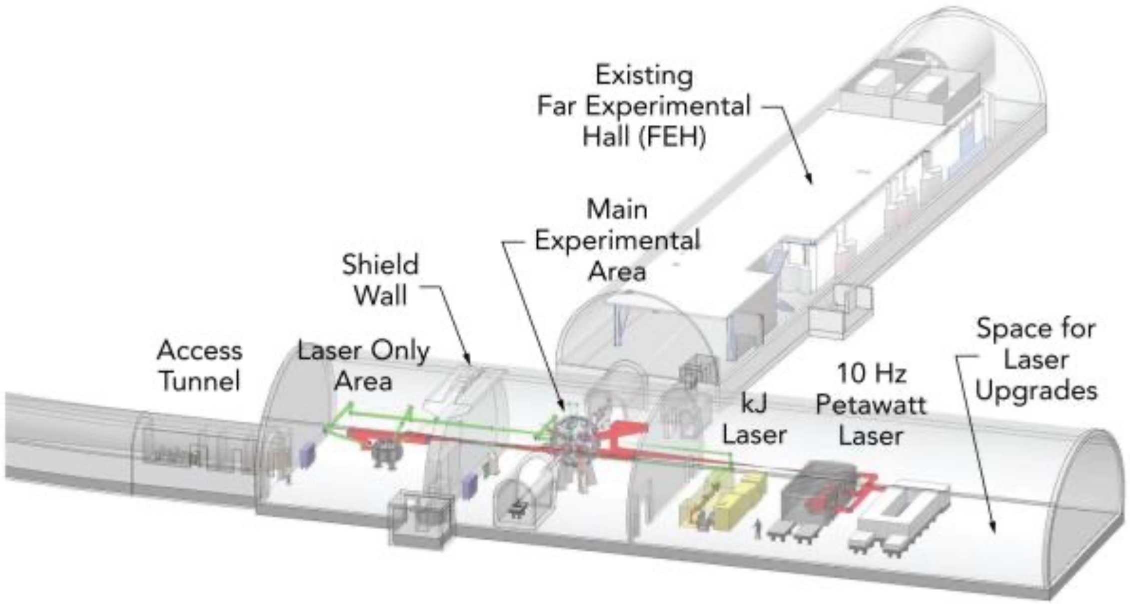


Maximize utilization of superconducting linac infrastructure
Undulator farm with multiplexed undulators

R&D Priorities:

- High brightness operation with cavity-based XFELs
- Beam “a la carte”
- Undulator multiplexing

MEC Upgrade



https://lcls.slac.stanford.edu/mec-u

10 Hz Petawatt laser for the
Matter under Extreme Conditions LCLS lab

Strong interest in > 50 keV X-rays for high-Z materials

Potential path forward for C3 technology:
Multi GeV upgrade of LCLS copper linac

Double linac energy in ~100 m (150 MV/m)
4x increase in available photon energy
(might require gun upgrade…)

Conclusions

Opportunities for C3 technology:

1) Compact FEL (high-gradient acceleration)

2) Improved beam brightness
   10x better emittance -> - 7x shorter pulses
   - Improved photon energy range
   - Improved peak power

3) Improved seeded FEL performance
   Reduced microbunching gain -> Extend externally seeded FELs to > 500 eV?

4) Potential opportunities for LCLS complex with MEC upgrade