The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

X-ray FELs based on high-gradient conventional acceleration

Nathan Majernik
UCLA

CBB Compact Light Sources Symposium

2022-06-03

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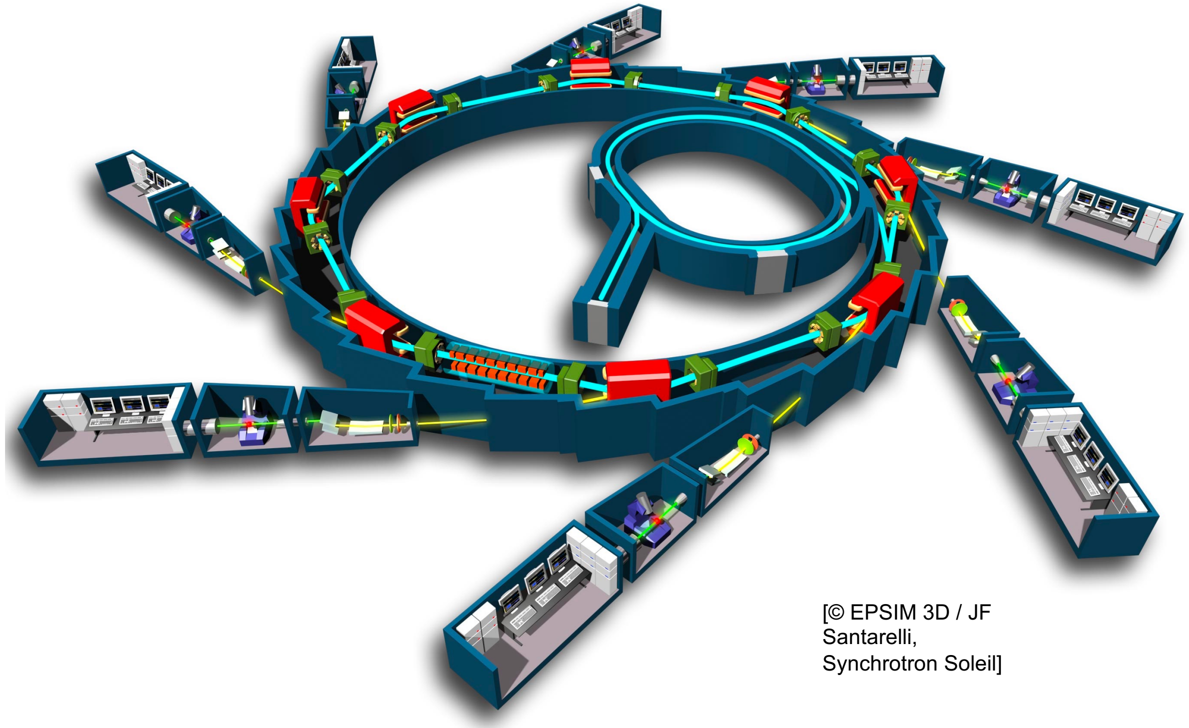
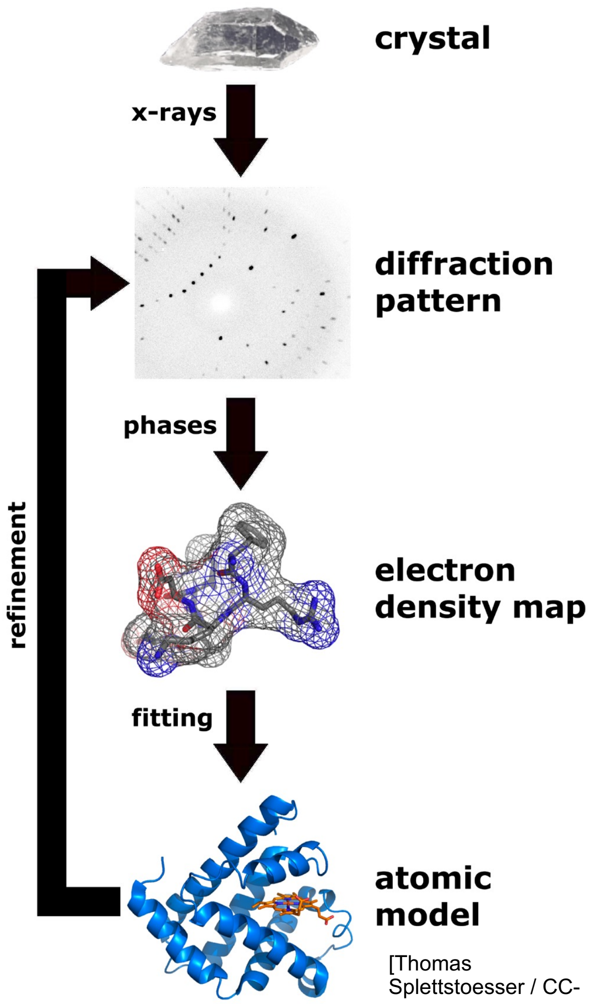
Synchrotrons - 3rd generation light sources

- Originally a parasitic process for HEP
- Now big science: hundreds of beamlines and billions of dollars worldwide
- High brilliance but incoherent



[© EPSIM 3D / JF Santarelli, Synchrotron Soleil]



[Thomas Splettstoesser / CC-BY-SA-3.0]

X-ray protein crystallography has been a powerful tool but it has substantial limitations. What if there's a better way?

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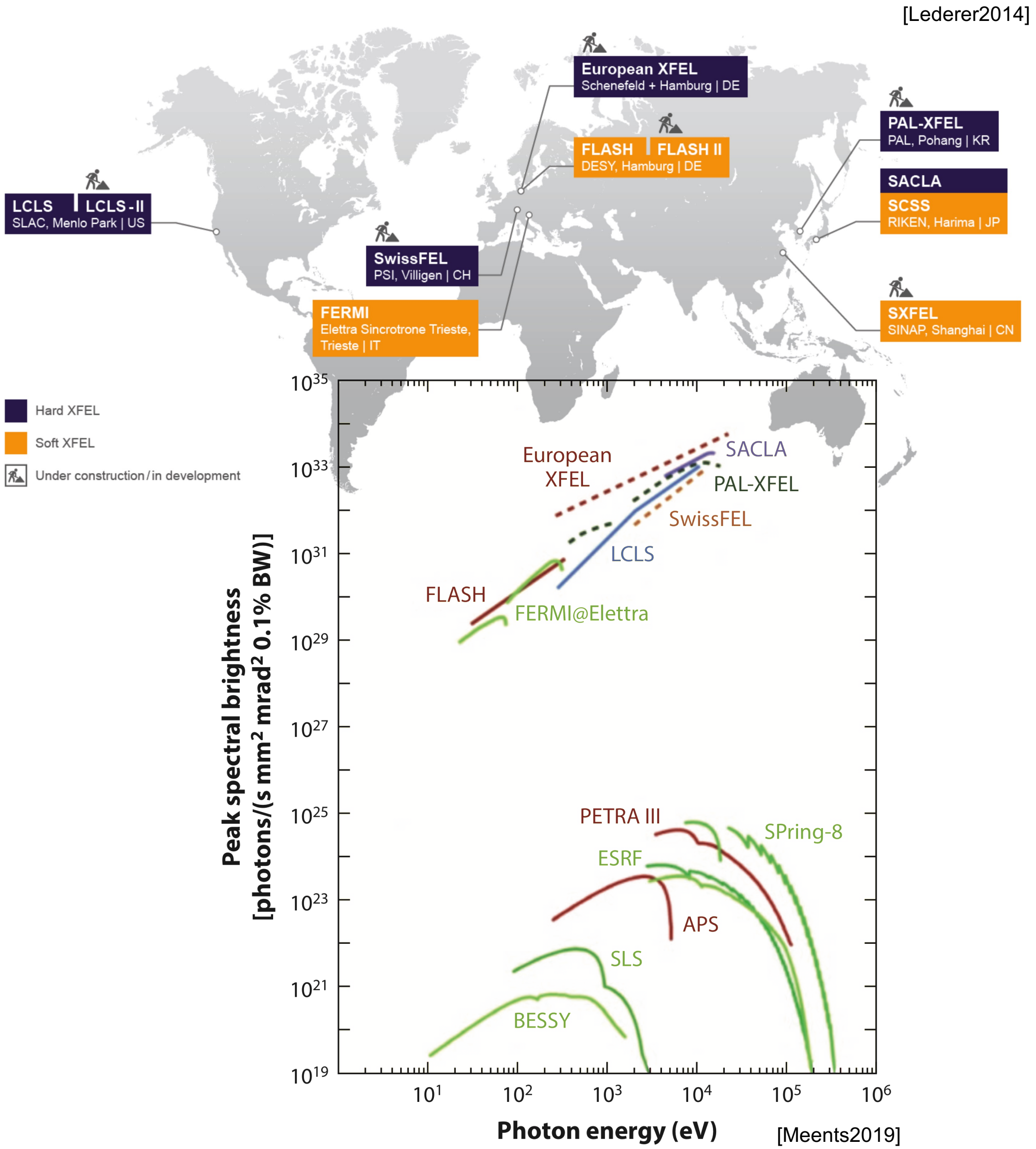
XFELs – 4th generation light sources

- First HXR demonstration: LCLS in 2009
- 10^{10} times brighter than synchrotrons, coherent, and fs-resolution
- ~km footprint, ~10 GeV, and ~$1B price
  - Unlike 3rd gen, no option to scale; go big or go home



Electron beam self-organization: The XFEL instability

Resonant wavelength

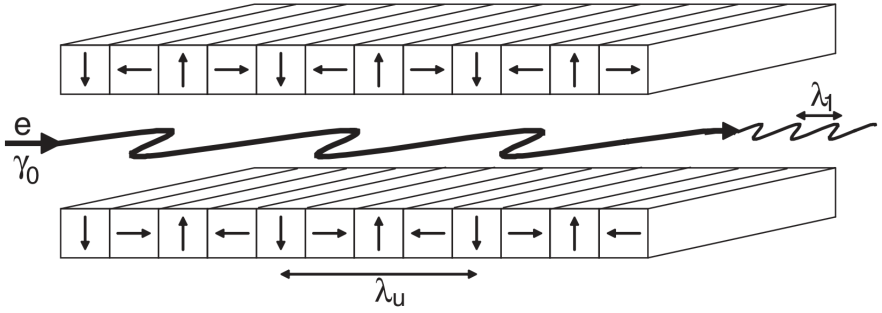
$$\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

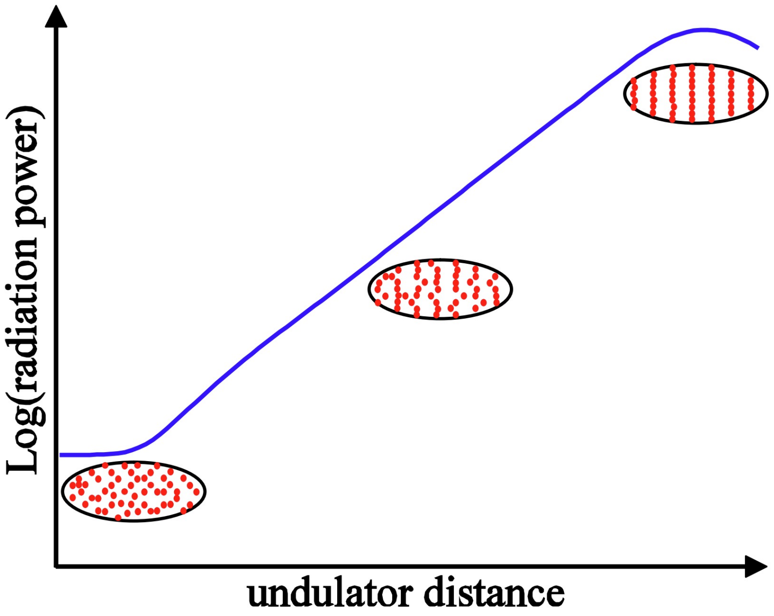
Pierce parameter

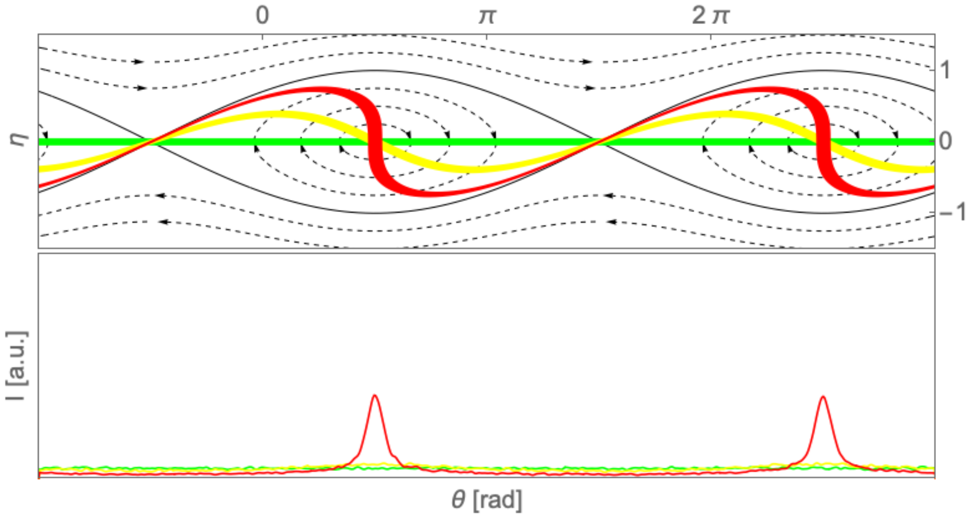
$$\rho = \left(\frac{I_e K_0^2 [\mathrm{JJ}]^2}{16 I_A \gamma_0^3 \sigma_x^2 k_u^2}\right)^{1/3}$$

1D gain length

$$L_{G0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$







Requires very high electron beam quality

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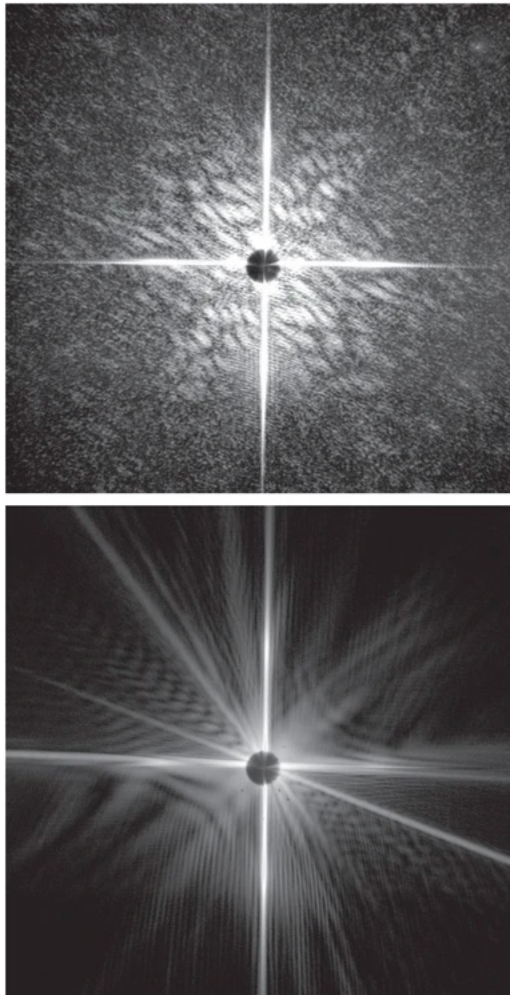
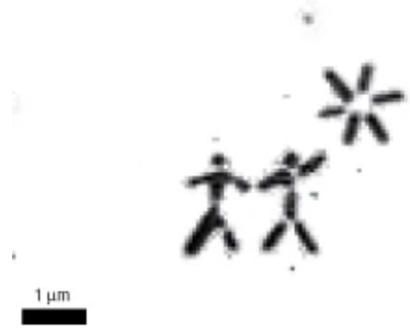
XFEL enabled science

- Coherent, ultra-bright x-rays open up entirely new avenues for research at Å and fs scales
  - Reconstruction of incoherent matter; no need to crystallize
  - “Diffraction-before-destruction” principle
  - Holy grail: single particle imaging
  - Unlike cryo-EM, can study dynamic, non-equilibrium states
  - Important, otherwise impossible, results have been produced in atomic physics, high energy density physics, material science, chemistry, biology (**virology!**), and more
- Dark side: limited access
  - Only small fraction of proposals are granted beamtime
  - Strong incentive to publish results
  - Even harder to get beamtime to validate/reproduce





- [Chapman2006] demonstrates ultrafast, coherent imaging
- Top left: diffraction pattern from single shot
- Top right: computationally reconstructed mask
- Bottom left: diffraction pattern from the second shot, illustrating the obliteration of the mask by the first shot and the “diffraction-before-destruction” principle

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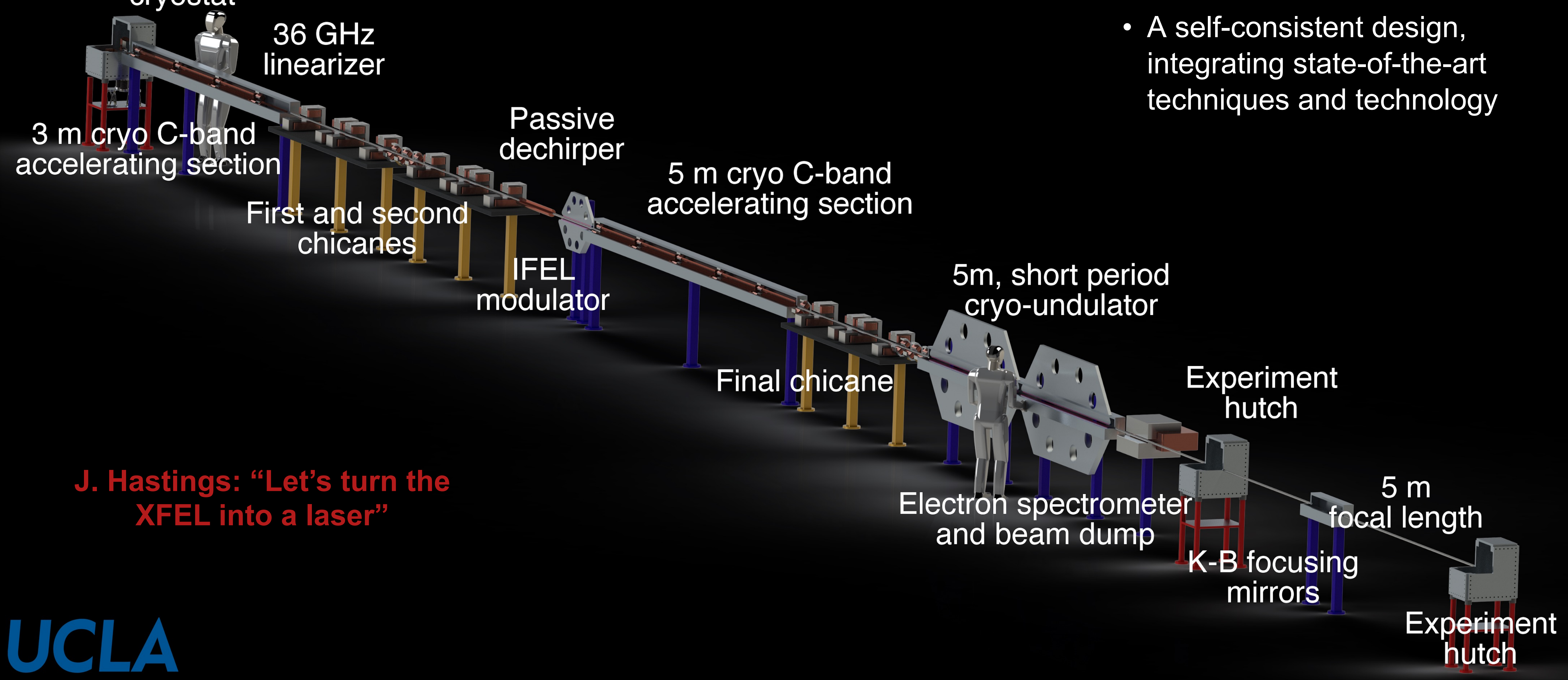
Ultra-compact x-ray free electron laser

- 5th generation light source
- $40M x 40 meters
- A self-consistent design, integrating state-of-the-art techniques and technology



J. Hastings: "Let's turn the XFEL into a laser"

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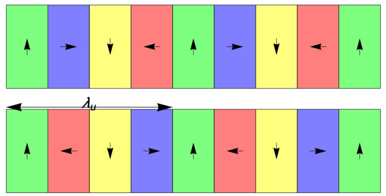
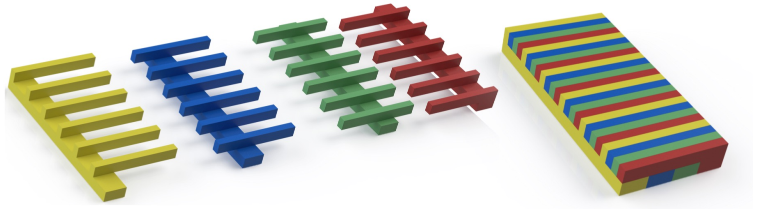
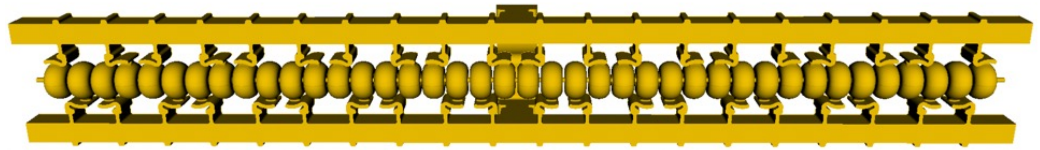
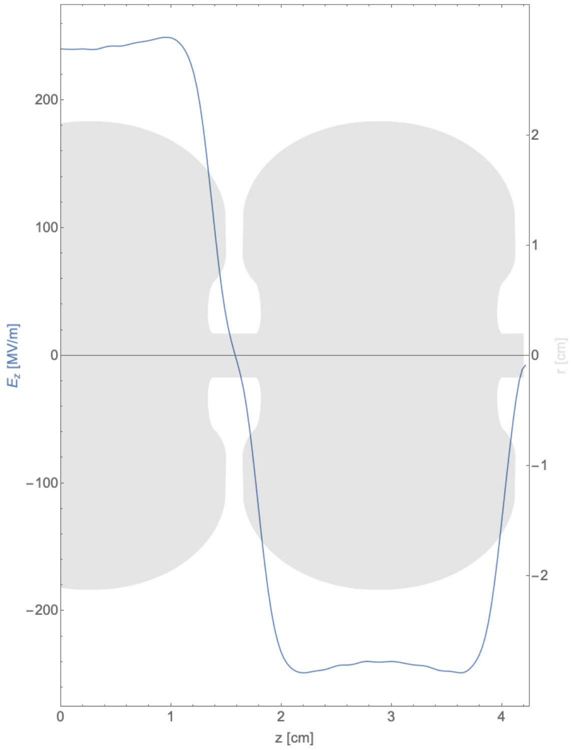
UC-XFEL recipe

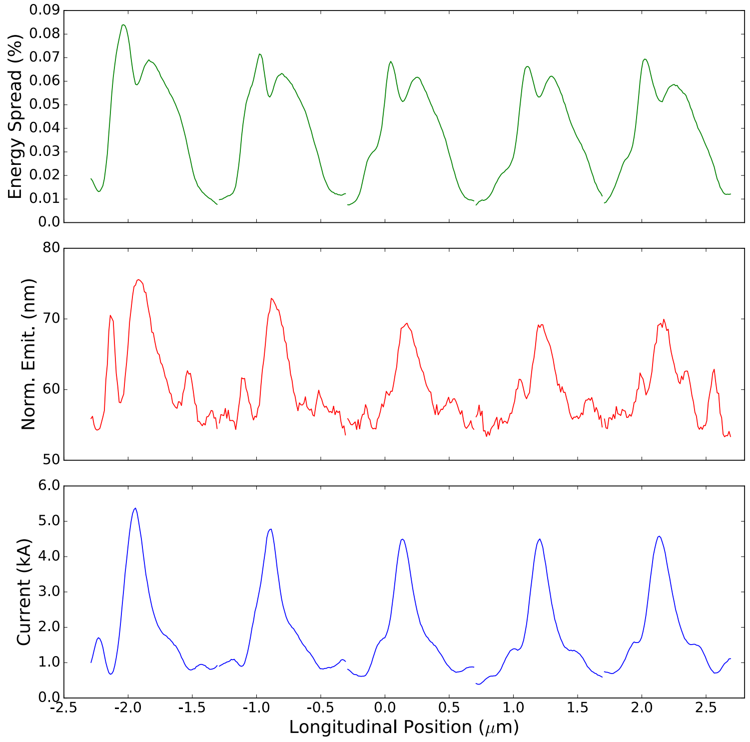
- Short period undulator
  - Linac length $\propto \sqrt{\lambda_u}$, undulator length $\propto \lambda_u^{5/6}$
  - Cryogenic magnets improve K_0
- Start with high brightness beam
  - Need to make up for lower γ
  - Cryo-copper photoinjector
- Increase linac gradient
  - Cryo-cooling and manifold coupling further reduce linac length
- Preserve high brightness
  - Atypical compression via IFEL
  - Short overall length limits collective effects
  - Microbunching mitigates wakes







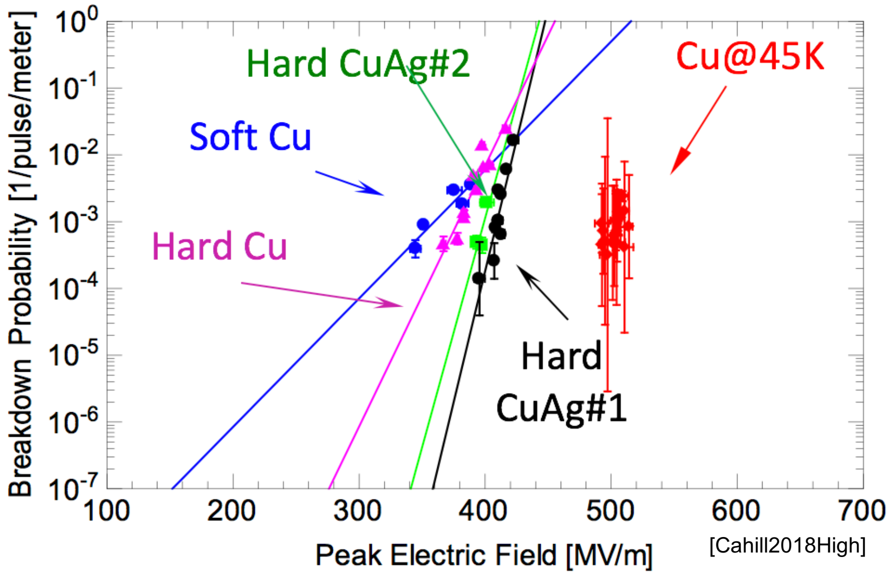




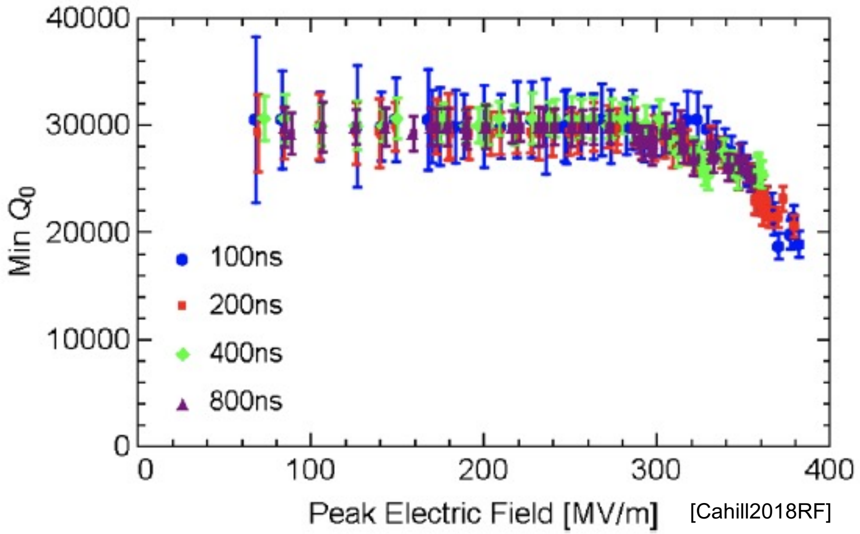
Ultra-compact x-

Cryogenic copper RF cavities

- Cooling copper to cryogenic temperatures enhances a number of material properties
  - Reduced resistivity
  - Higher yield strength
  - Reduced coefficient of thermal expansion
- Net result is to substantially increase breakdown field
  - 500 MV/m threshold
  - Dark current onset limits usable gradient to ~300 MV/m
- Also substantial interest for linear collider



[Cahill2018High]



[Cahill2018RF]

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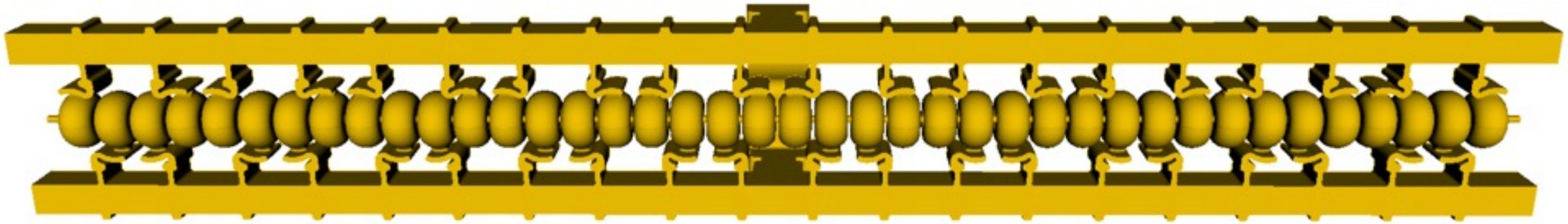
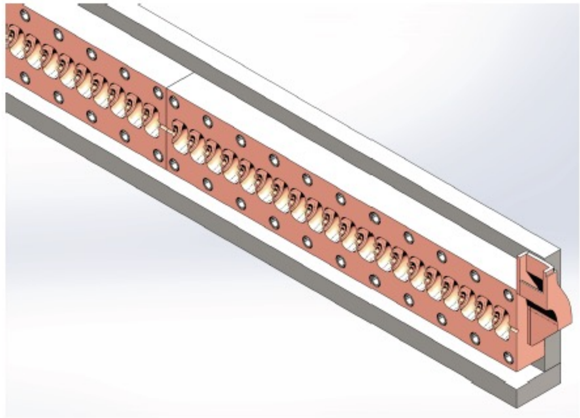
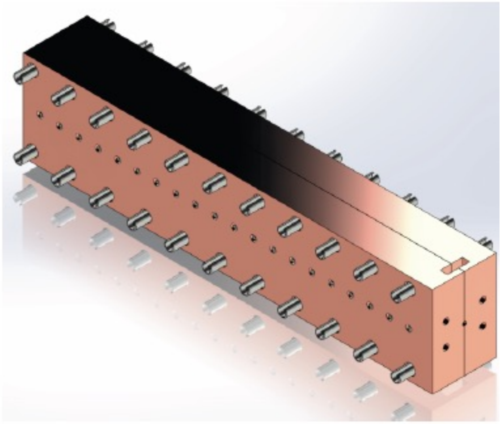
Cryogenic linac

- Cryo-copper linac at c-band designed for 125 MV/m; 1 GeV in 8 meters!
- New “manifold coupling” concept from SLAC
  - Allows more control over linac characteristics, greater performance, and increased shunt impedance
  - Initial tests at 77 K successful







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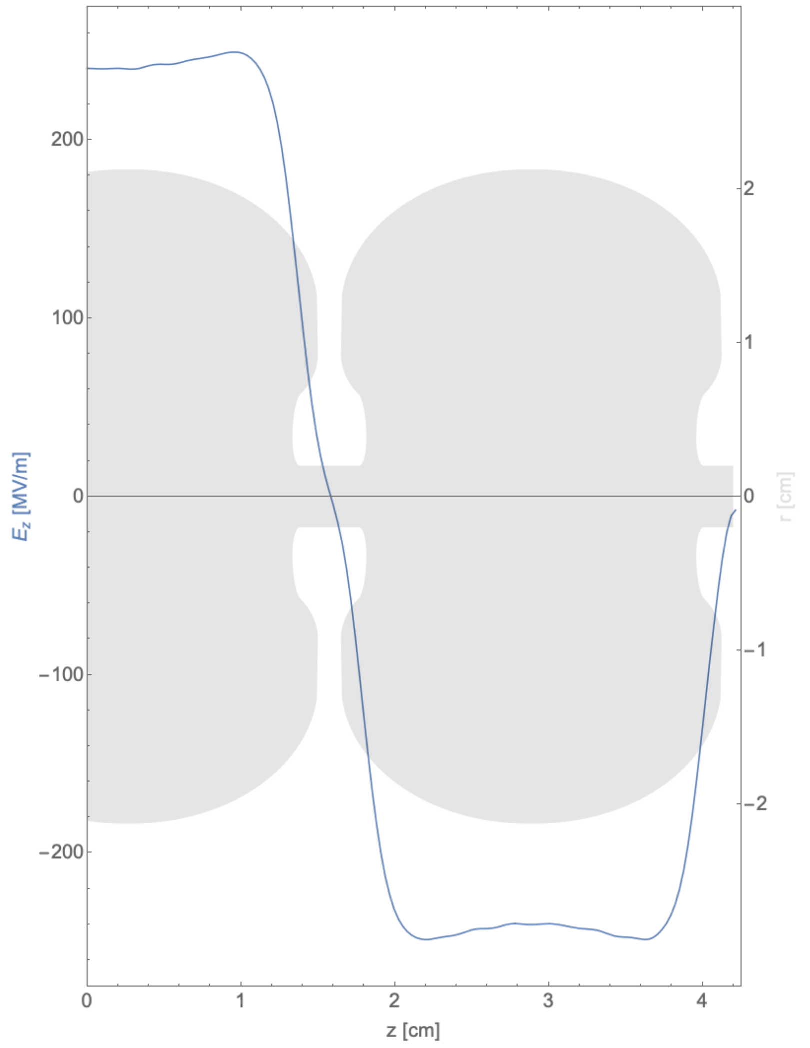
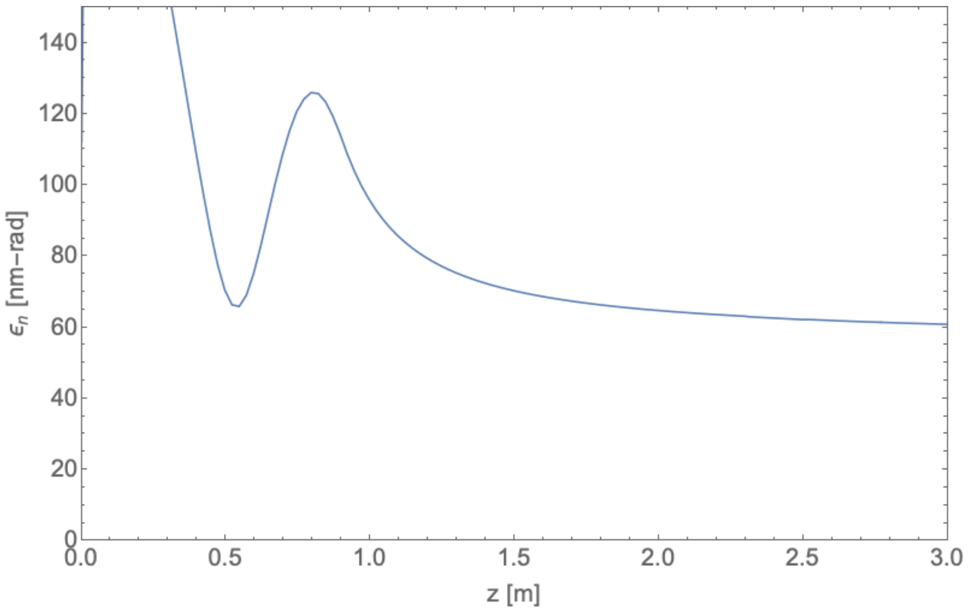
Cryogenic photoinjector

- Cryo cooling the photoinjector enhances brightness in two ways
  - $B \propto E_0^2/T$
- C-band design injects at 240 MV/m
  - Contrast with LCLS at 60 MV/m; anticipate 50x brighter
  - Highly optimized cavity design to minimize surface magnetic fields
  - Substantial higher harmonic content improves RF focusing
  - 100 pC @ 55 nm-rad (38 nm-rad at cathode)





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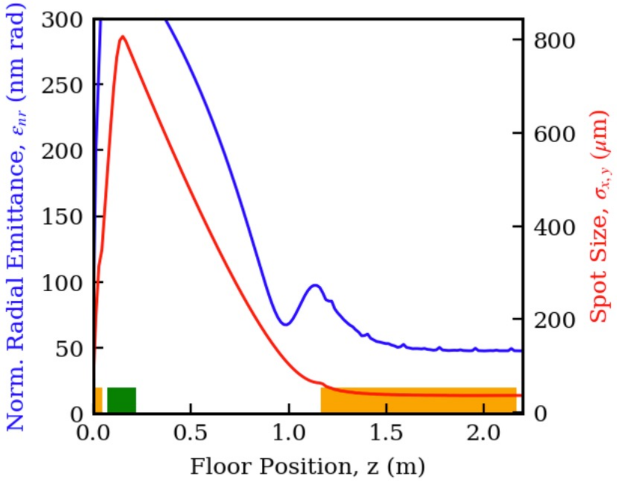
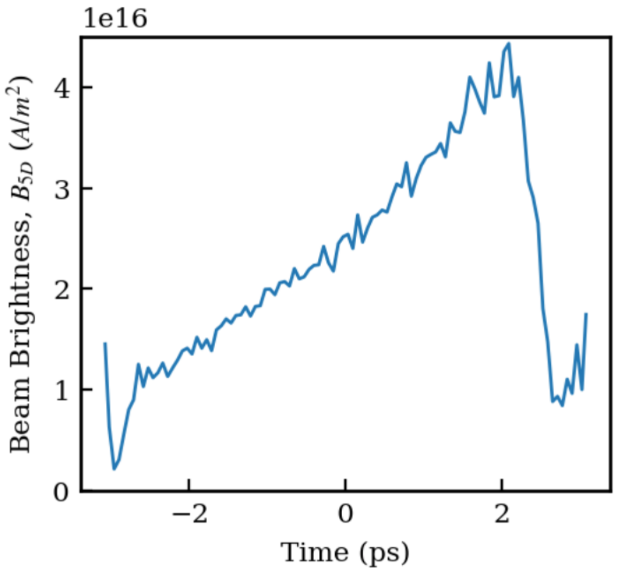
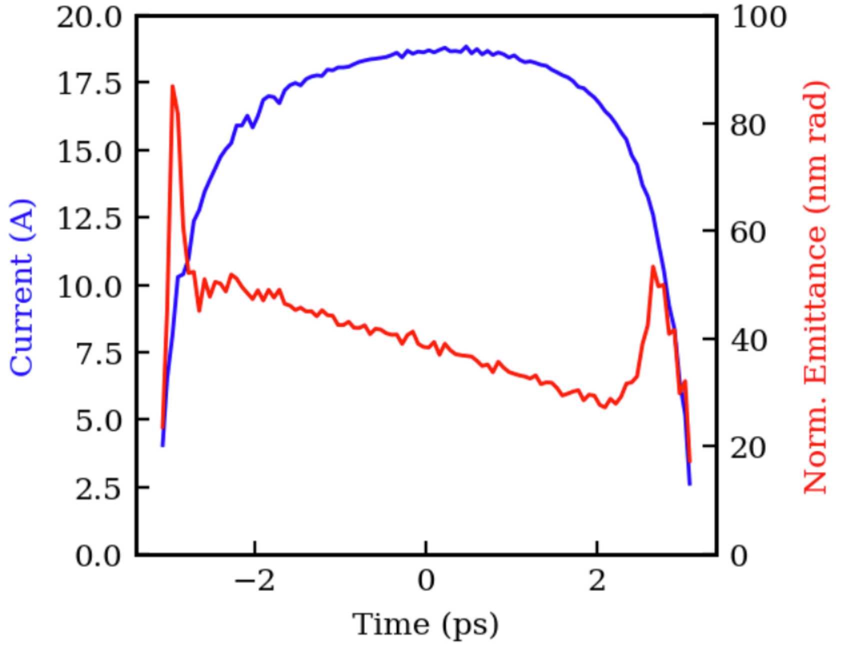
Photoinjector simulations

- More extensive photoinjector simulations
- Spatial harmonics improve launch field to surface field ratio
- Challenges in simulating these relatively high charge (100 pC) but bright beams
  - Short-range effects difficult to capture accurately and computationally efficiently
- Gun can also be magnetized for linear collider and DLA applications







[Robles, R. R., Camacho, O., Fukasawa, A., Majernik, N., & Rosenzweig, J. B. (2021). Versatile, High Brightness, Cryogenic Photoinjector Electron Source. *Physical Review Accelerators and Beams* 24.6 (2021): 063401.]

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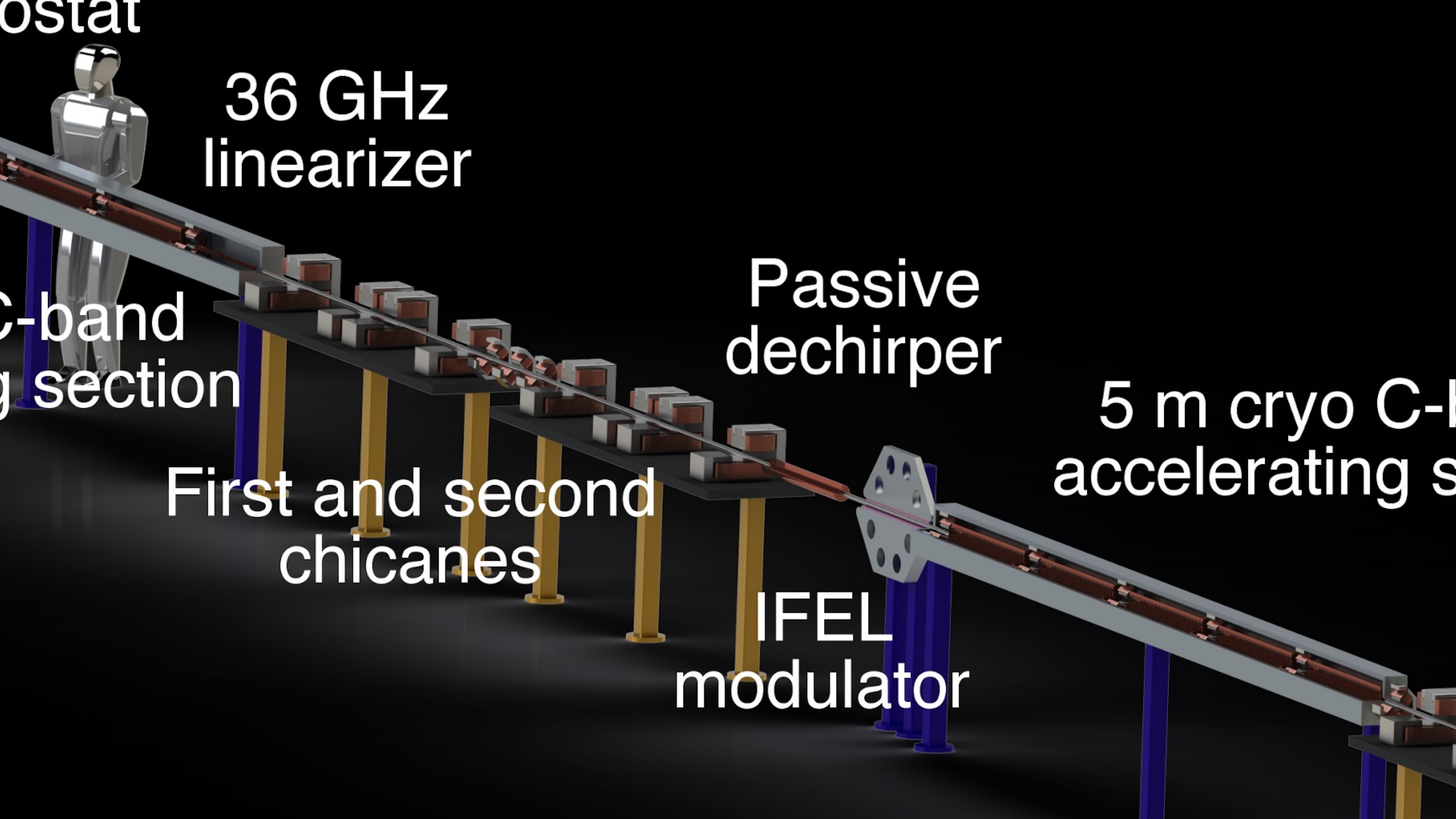
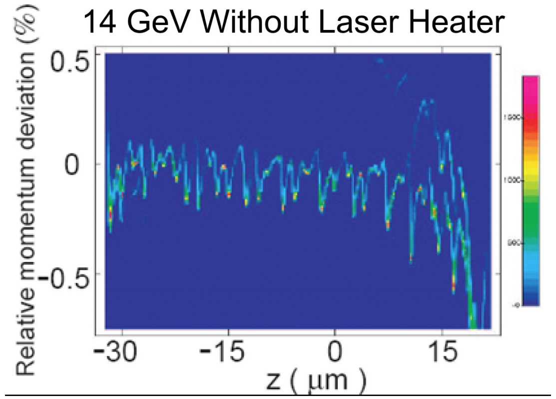
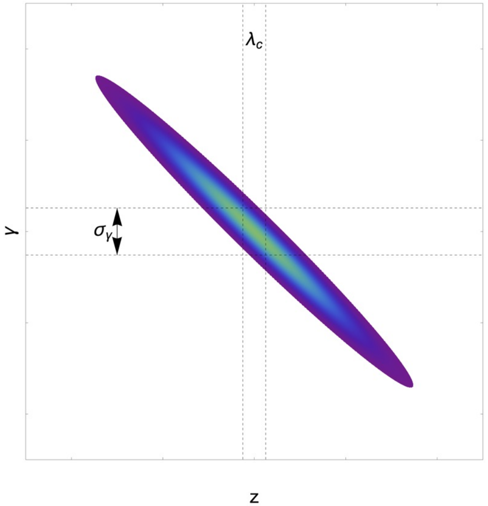
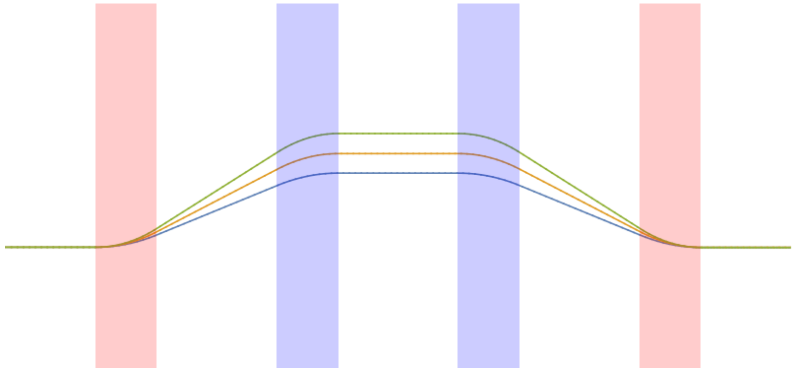

ostat
36 GHz
linearizer
C-band
g section
Passive
dechirper
5 m cryo C-
accelerating s
First and second
chicanes
IFEL
modulator

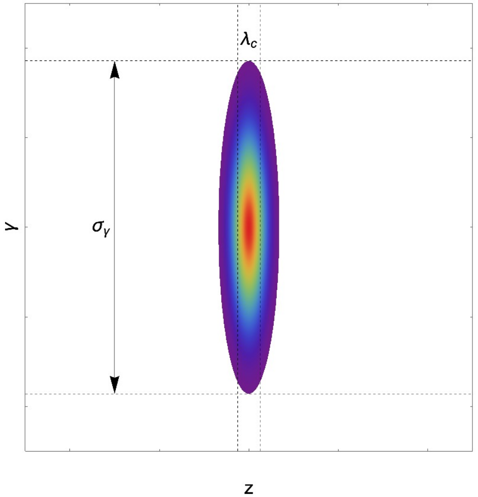
Bunch compression

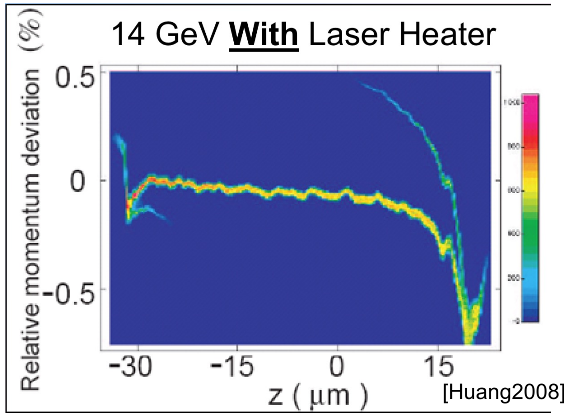
- Conventional approach to bunch compression uses chicanes
  - R_{56} shears longitudinal phase space, compressing chirped beam
  - Major issue is coherent synchrotron radiation (CSR) which induces emittance growth
  - Sometimes tolerable, but we can't afford the loss
- A laser heater is one way of addressing this
  - Introduces an uncorrelated energy spread, reducing MBI growth
  - Although this technique helps, it necessarily adds energy spread which is not ideal







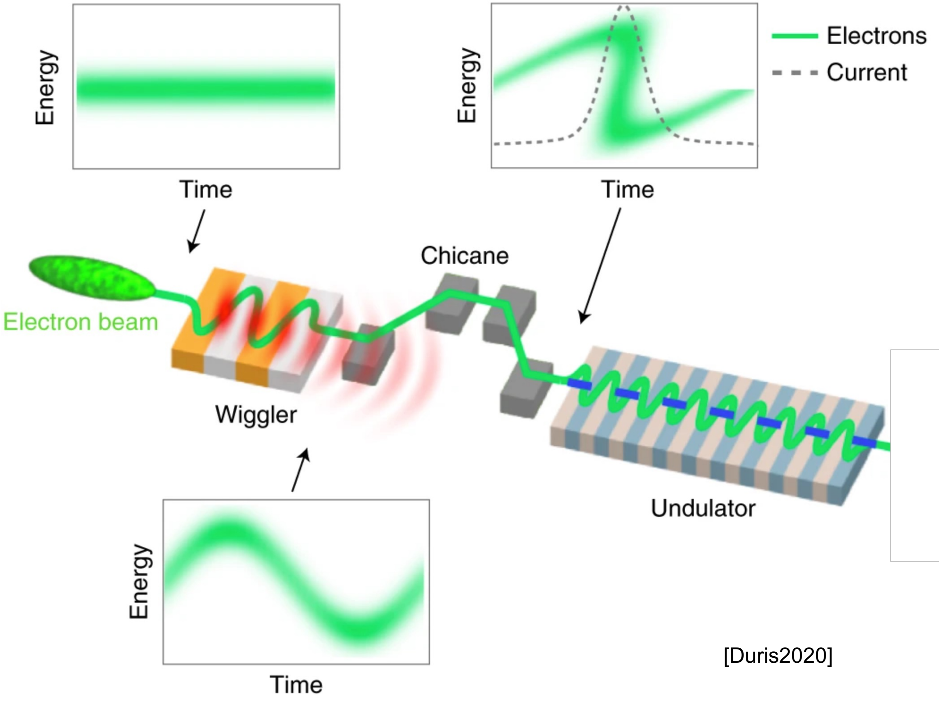




[Huang2008]

IFEL/ESASE

- Inverse FEL (IFEL) and enhanced SASE (ESASE) refer to the same technique described by [Zholents2005]
  - Copropagate resonant laser with beam in wiggler to induce energy modulations
  - Then pass through chicane to convert to current modulations (much lower R_{56} required and conducted at higher energy)
  - Reduced energy spread and emittance growth
  - Bonus: microbunch train mitigates resistive wake effects
- Proof of concept experiment at SLAC: XLEAP

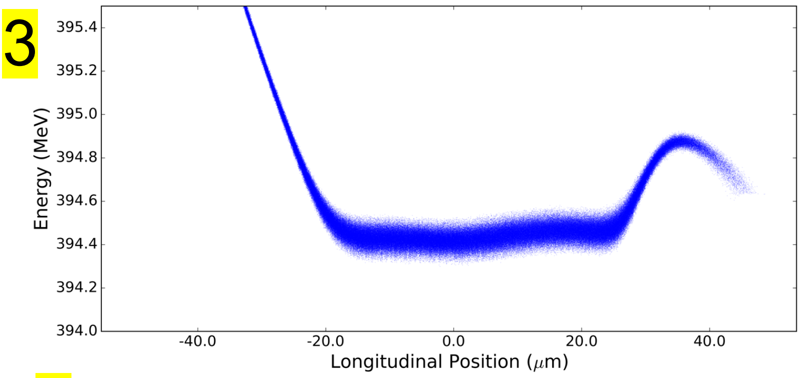


[Duris2020]

Compression for UC-XFEL

1. Beam is accelerated to 400 MeV then linearized by 34 GHz (6th harmonic) structure
2. Opposed chicanes compress from 20 A to 400 A with <15% emittance growth
3. A corrugated structure passively removes remaining chirp
4. Beam is modulated at 10 μm by 145 MW laser and accelerated to 1 GeV
5. Energy modulations are converted to 4 kA microbunches by the final chicane

3



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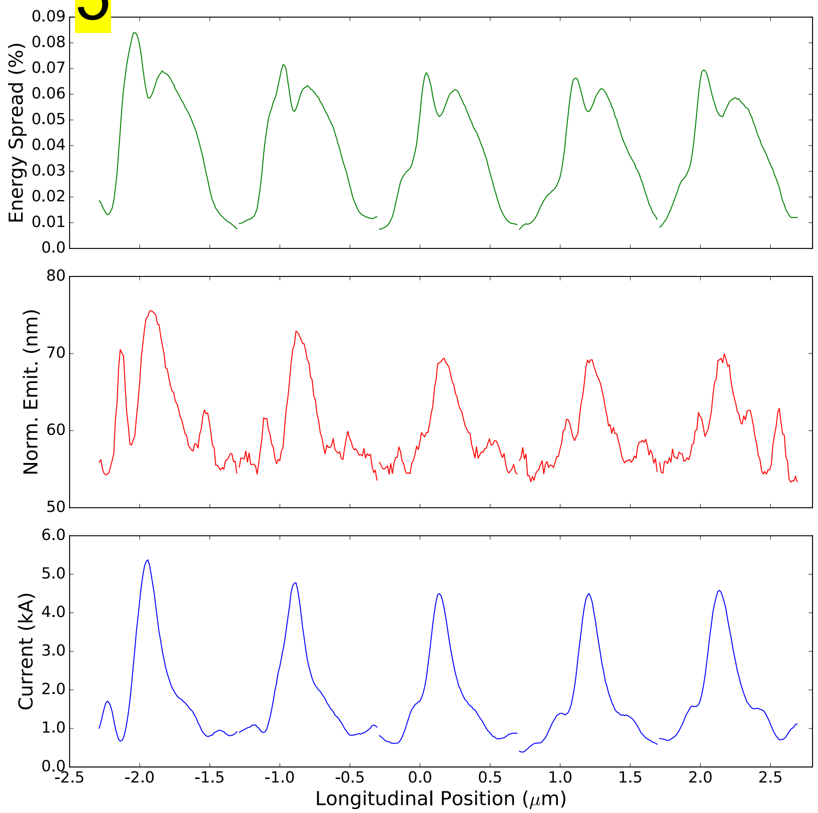

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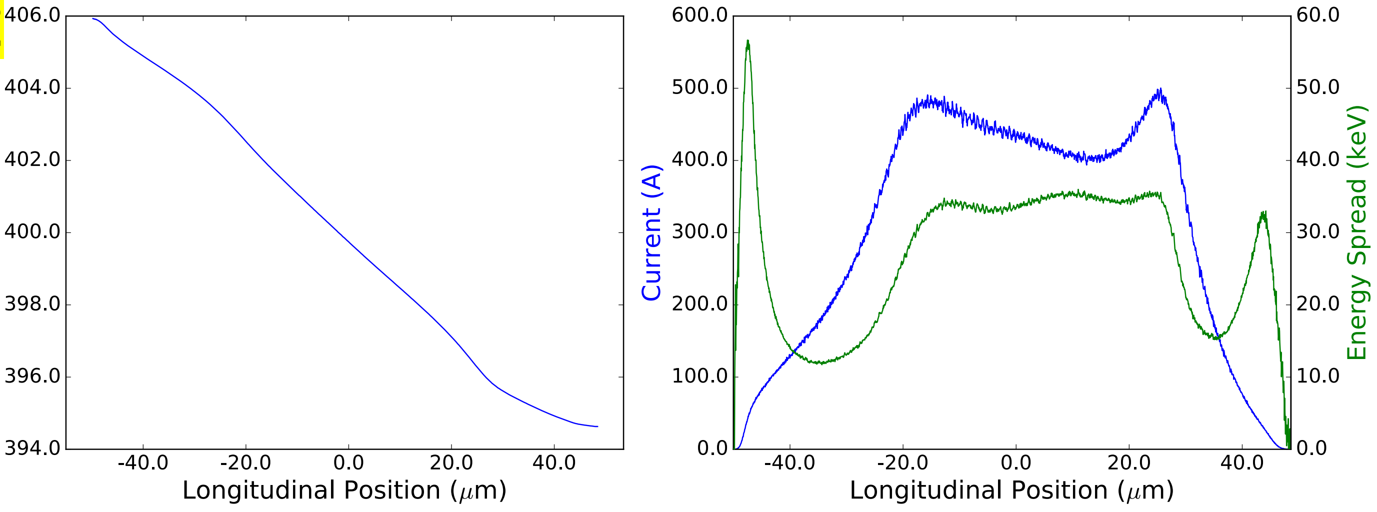
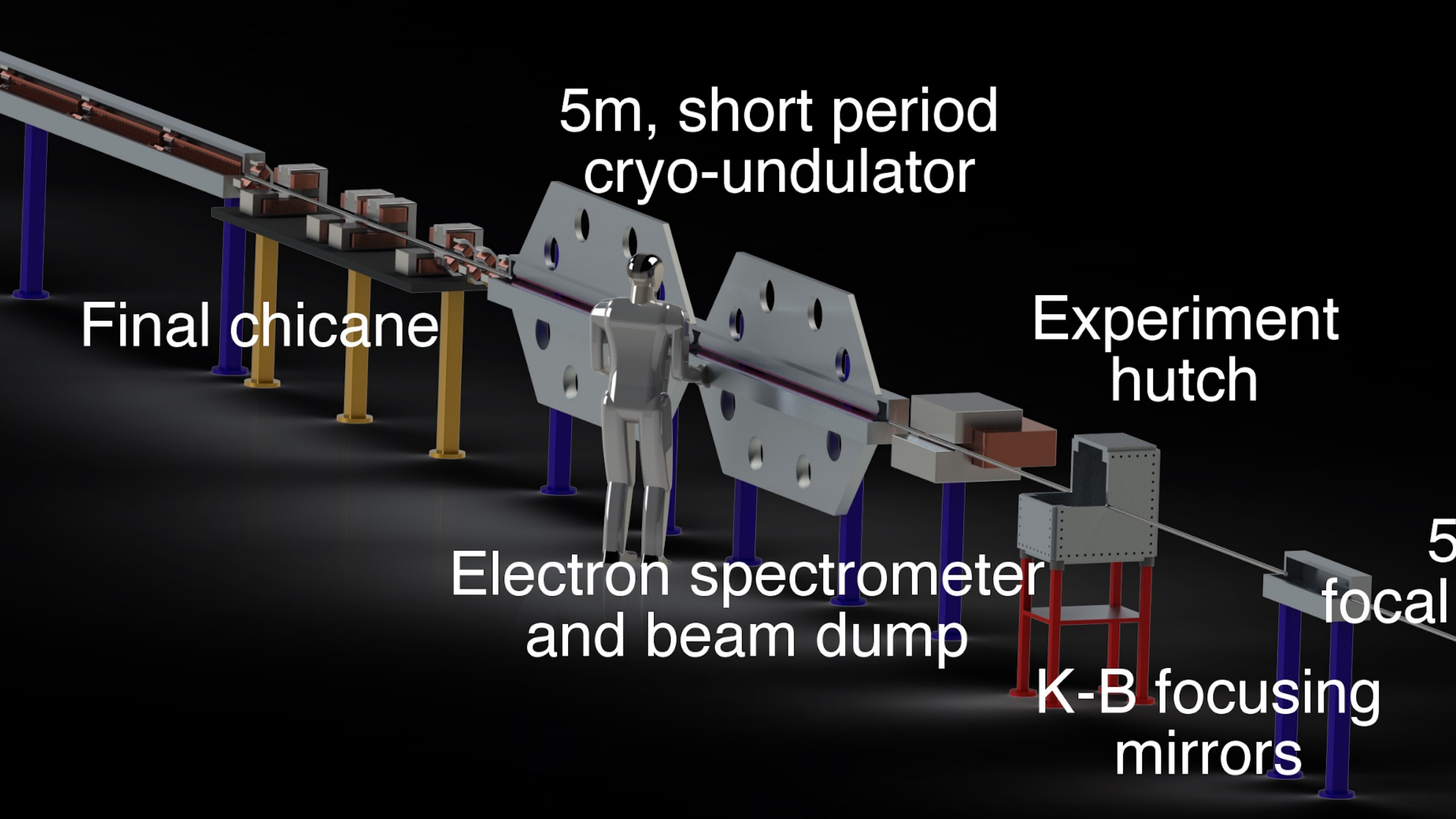



5m, short period
cryo-undulator
Final chicane
Experiment
hutch
Electron spectrometer
and beam dump
K-B focusing
mirrors

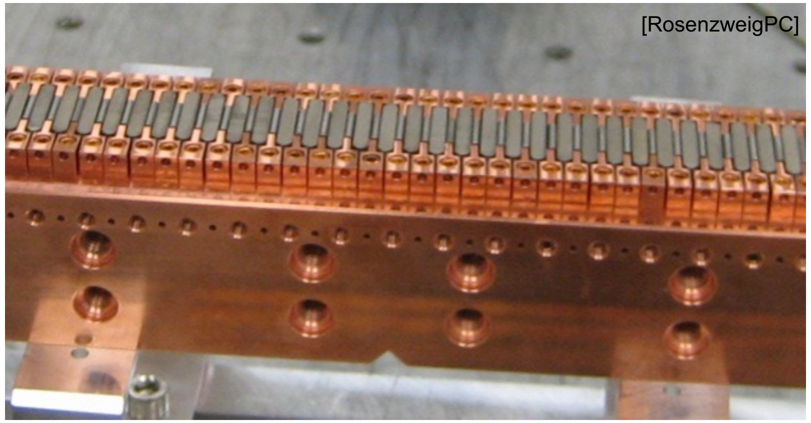
Short period undulators

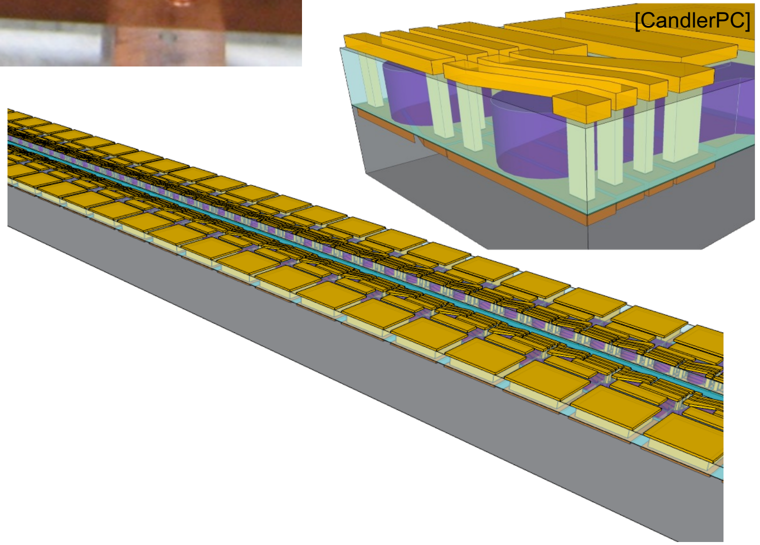
- Extant XFELs use "conventional" undulators
  - Hybrid or PPM Halbach, few cm period, NdFeB or SmCo magnets, room temperature
- Short period undulators
  - Reduce the required energy for target λ_r
    - Linac active length $\propto \sqrt{\lambda_u}$
  - Reduce the gain length
    - Undulator length $\propto \lambda_u^{5/6}$

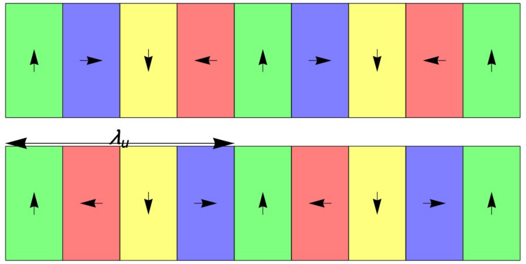
Name	λ_u [mm]	Array type	B_{peak} [T]	K_0
LCLS [5]	30	Hybrid	1.3	3.7
SACLA [118]	18	Hybrid	1.3	2.2
European XFEL (SASE 1) [119]	36	Hybrid	1.0	3.3
European XFEL (SASE 2) [119]	48	Hybrid	0.6	2.8
European XFEL (SASE 3) [119]	80	Hybrid	0.4	3.3
PAL-XFEL (HXU) [120]	26	Hybrid	0.8	2.0
PAL-XFEL (SXU) [120]	35	Hybrid	1.0	3.3
Swiss XFEL [121]	15	Hybrid	0.9	1.2
FLASH [122]	27	PPM	0.5	1.2
Fermi FEL-1 [123]	65	PPM, APPLE-II	0.9	4.0
Fermi FEL-2 [123]	50	PPM, APPLE-II	0.9	2.8

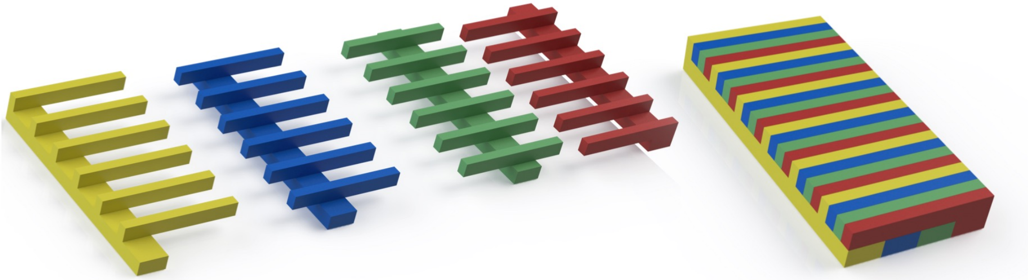
Short period undulators

- What sets the lower bound on λ_u?
  - Beam brightness
  - Fabrication
  - Field strength
  - Resistive wall wakefields
- Past: 9 mm cryo-undulator
  - Demonstrated fields to >2 T
- Present: few mm comb fabrication
  - Our recent paper explored this for both PPM and hybrid arrays
  - EDM machining and larger assembly unit cell
- Future (?): 100s μm MEMS
  - All elements formed in place by photolithography and related techniques









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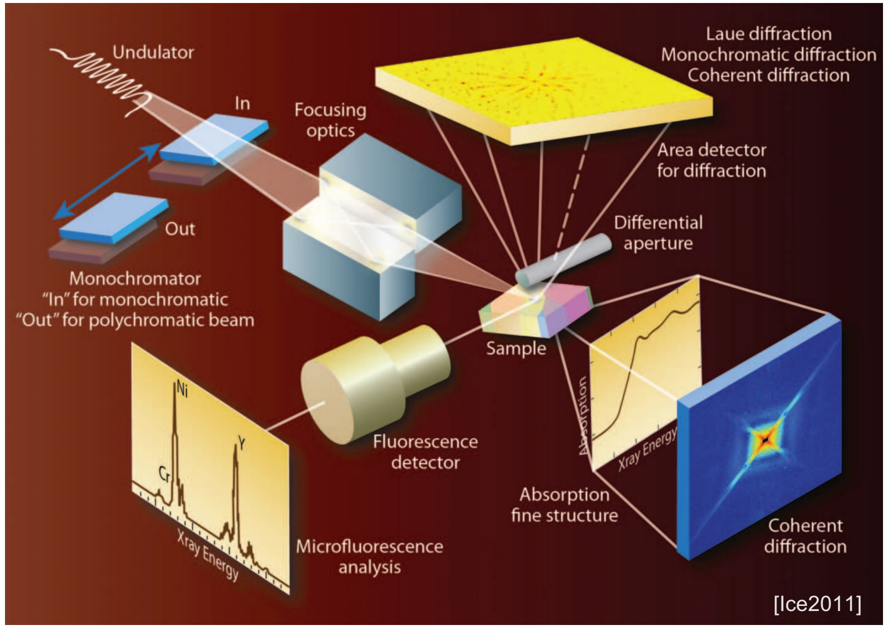
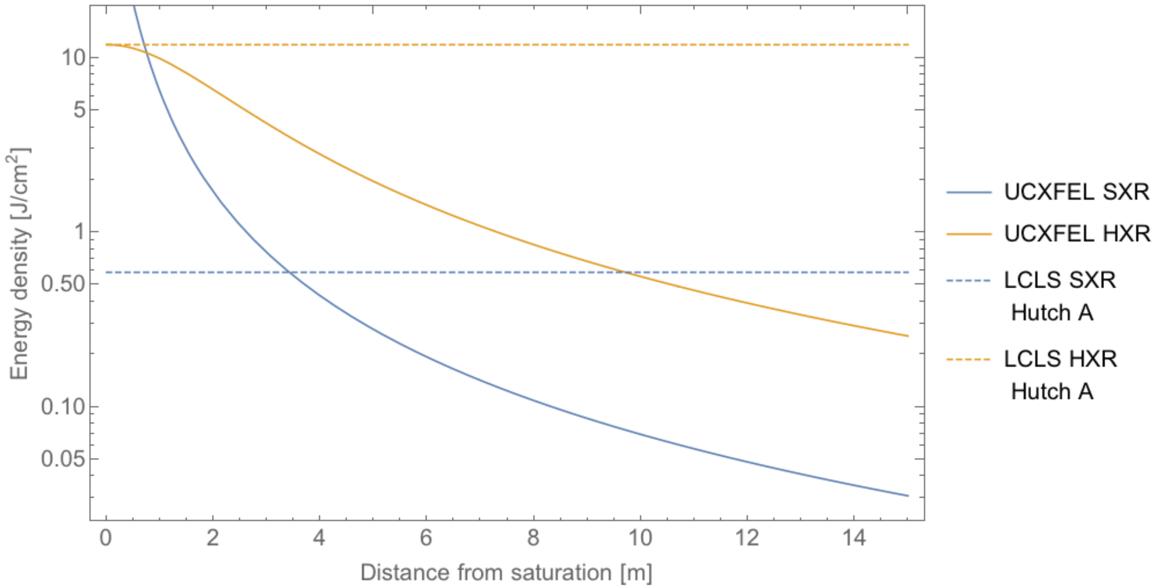
X-ray optics

- LCLS has a 400 m optical baseline for some x-ray optics
  - Dictated by need to avoid damage from high peak fluences over the course of electronic thermalization time
  - Although additional engineering considerations arise from high average power, this is not the determining factor for baseline
- Two factors allow UC-XFEL to employ a much shorter solution
  - Lower per-shot photon counts (<5%)
  - Smaller electron bunches are more diffractive. No brightness is lost but larger spots are present on mirrors sooner
- SXR UC-XFEL requires <10 m





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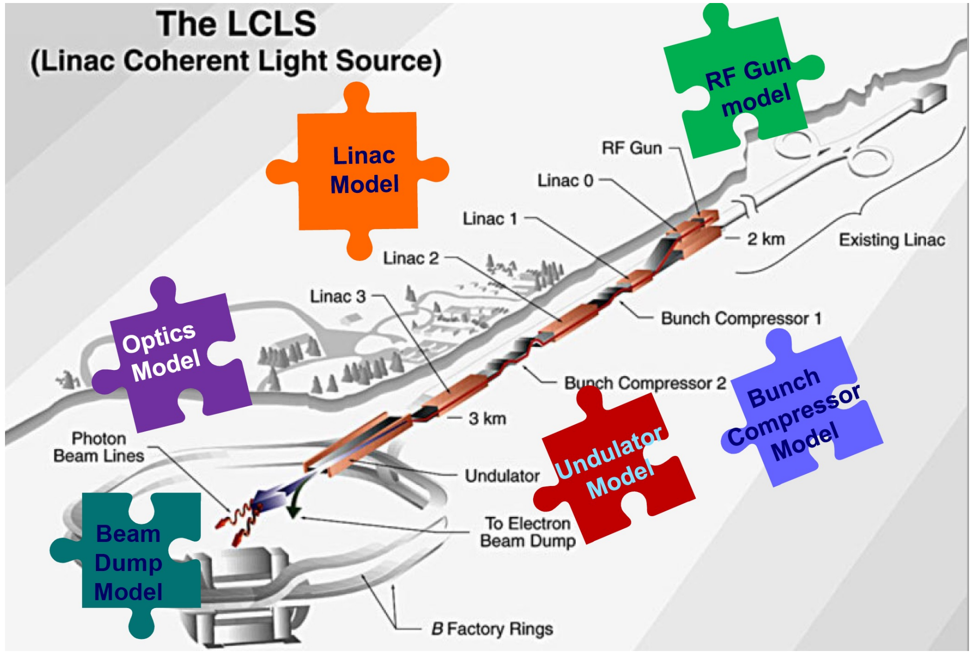
Machine Learning for UC-XFEL

- Start-to-end simulations from photocathode through detector
  - Model-based system engineering and control
- Key aspects
  - Beam dynamics: space-charge, IBS, MBI, CSR, wakefields, BBU
  - FEL performance including strong collective beam effects
  - Multi-physics model of x-ray optical system
- Design *and* control with modern tools
  - **Powerful capabilities with smaller human intervention**



Much existing activity at XFELs worldwide

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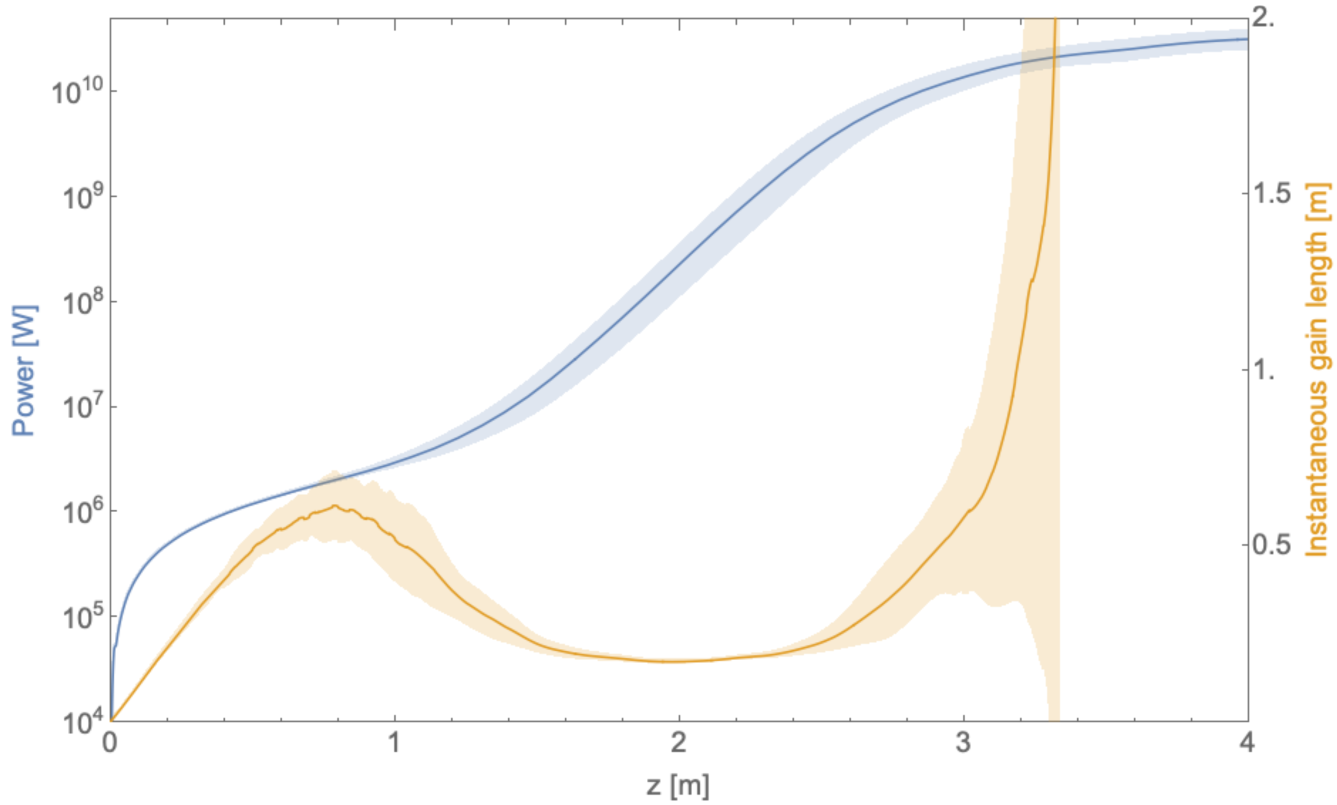
[Courtesy of S. Biedron]

SXR performance

Parameter	Units	Value
Energy	GeV	1.0
Energy spread	%	0.1
Micro-bunch charge	pC	14.2
Micro-bunch rms length, σ_z	nm	424
Peak current	kA	4.0
Normalized emittance, $(\epsilon_{n,x}, \epsilon_{n,y})$	nm-rad	(80, 60)
Mean spot size, σ_r	μm	4.9
Undulator period, λ_u	mm	6.5
Peak undulator field, B_0	T	1.0
Undulator parameter, K_u		0.60
Undulator length	m	4
Radiation fundamental, λ_1	Å	10.0
Photon energy	keV	1.2
Gain length, $L_{g,3D}$	m	0.21
Radiation peak power	GW	25
Radiation rms bandwidth	%	0.046
Radiation pulse energy/μbunch	μJ	19.2
μbunch count		6
Radiation pulse energy/train	μJ	115.2
Number of photons/train		6×10^{11}
ρ	10^{-3}	3.1
ρ_{3D}	10^{-3}	1.4
$L_{g,3D}/L_{g,1D}$		2.2



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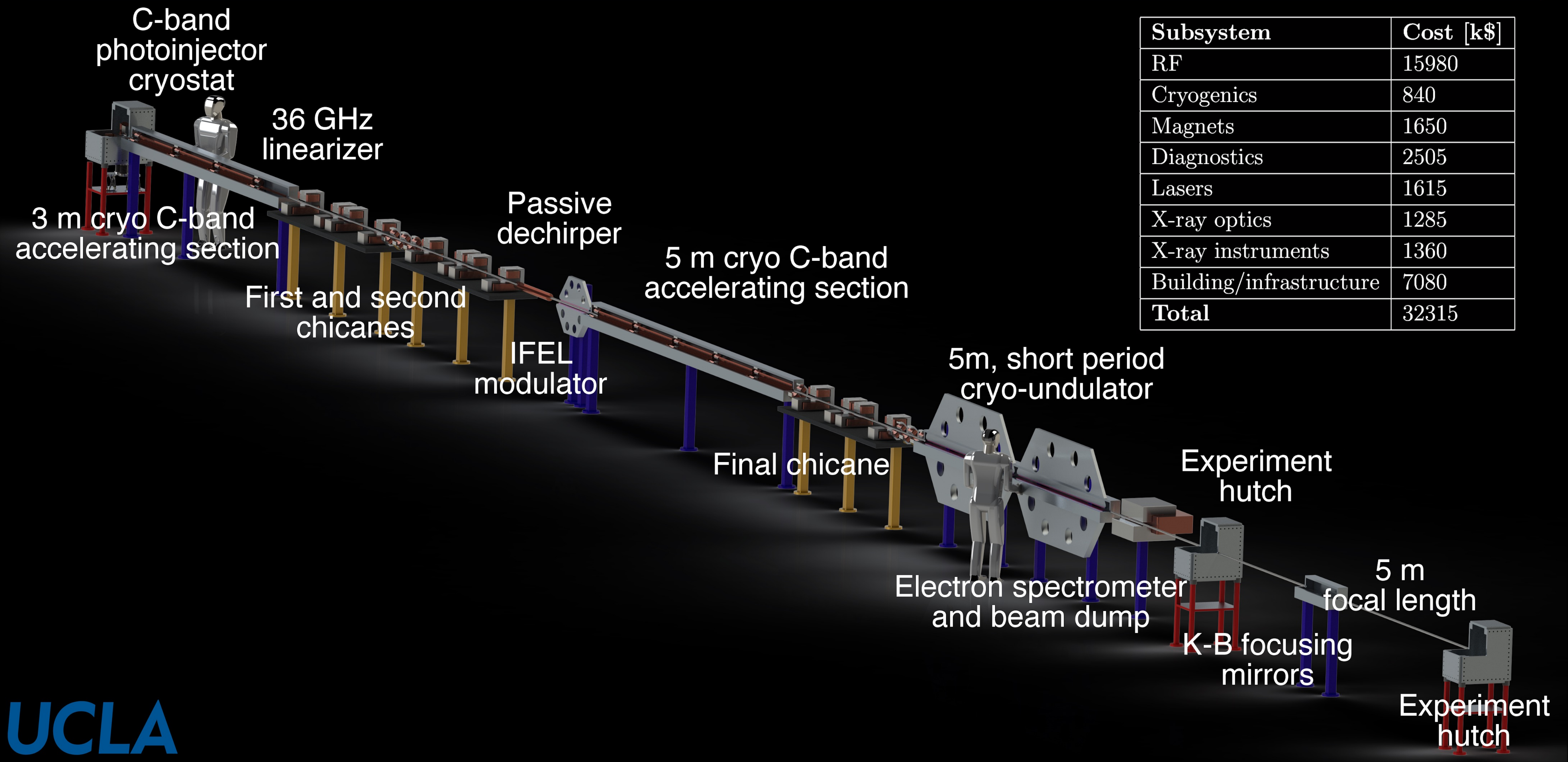
SXR cost and footprint

Subsystem	Cost [k$]
RF	15980
Cryogenics	840
Magnets	1650
Diagnostics	2505
Lasers	1615
X-ray optics	1285
X-ray instruments	1360
Building/infrastructure	7080
Total	32315



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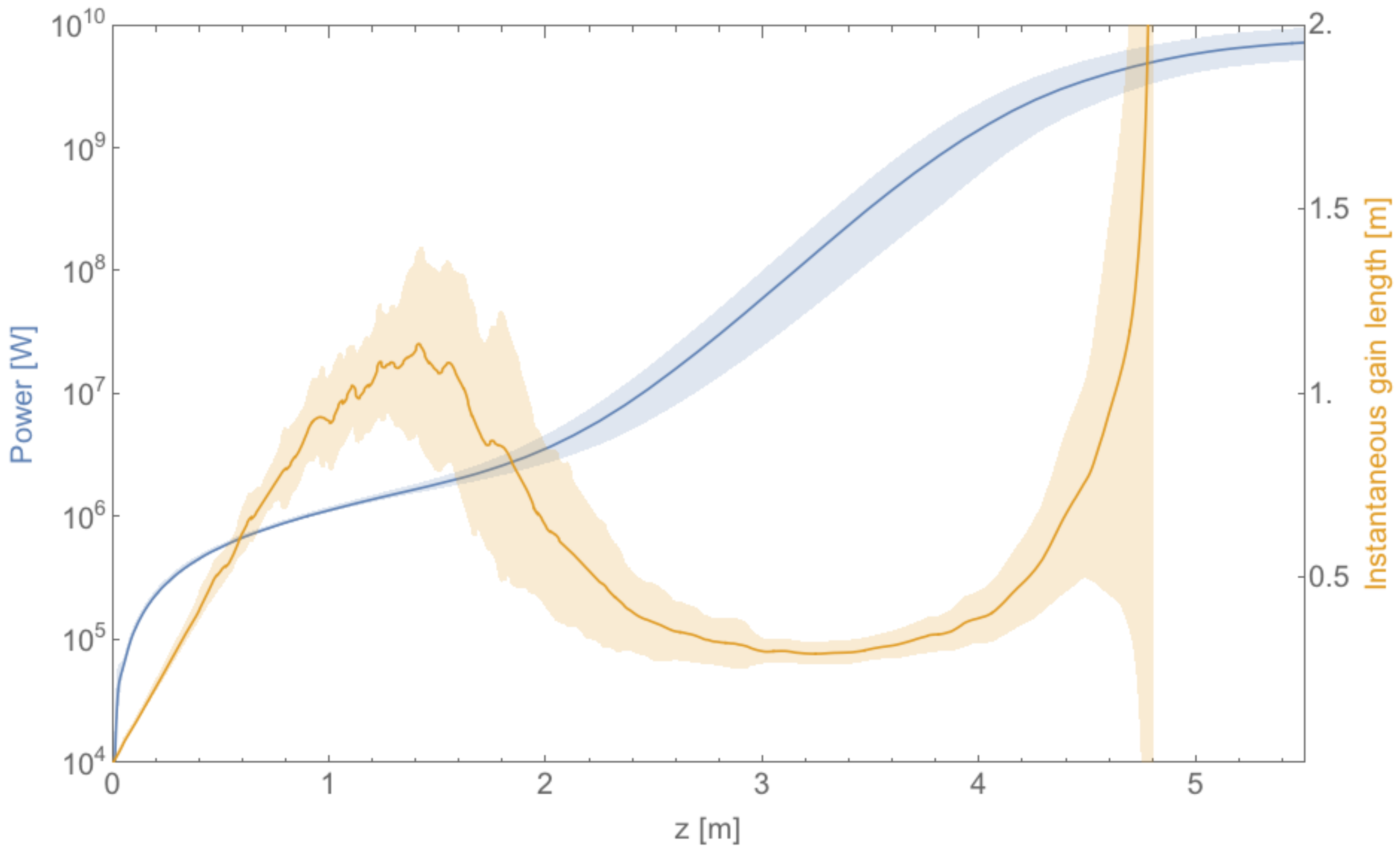
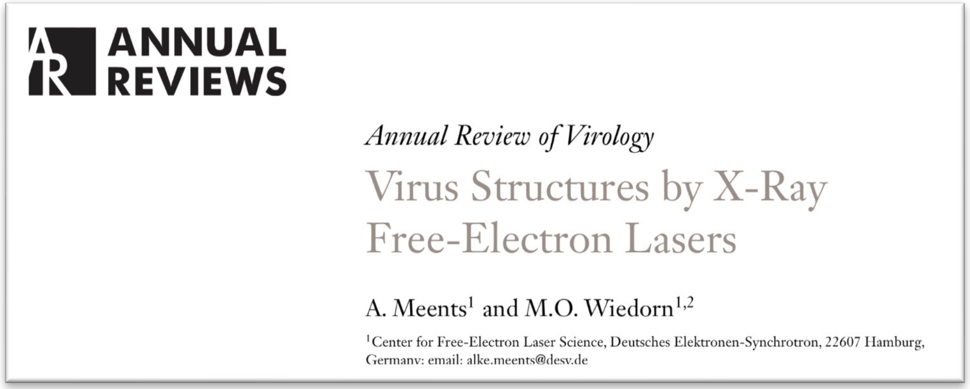
Future direction – 4 keV




ANNUAL REVIEWS

Annual Review of Virology

Virus Structures by X-Ray Free-Electron Lasers

A. Meents[1] and M.O. Wiedorn[1,2]

[1]Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany; email: alke.meents@desy.de

- [Meents2019]: optimal photon energy for viral imaging is 4 keV
- UC-XFEL concept can be extended from SXR
  - 1.2 GeV, λ_u = 3.3 mm
  - 5 m saturation length
  - 5.6 GW, ~10^{10} photons/shot

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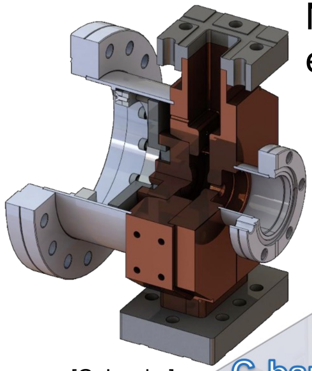
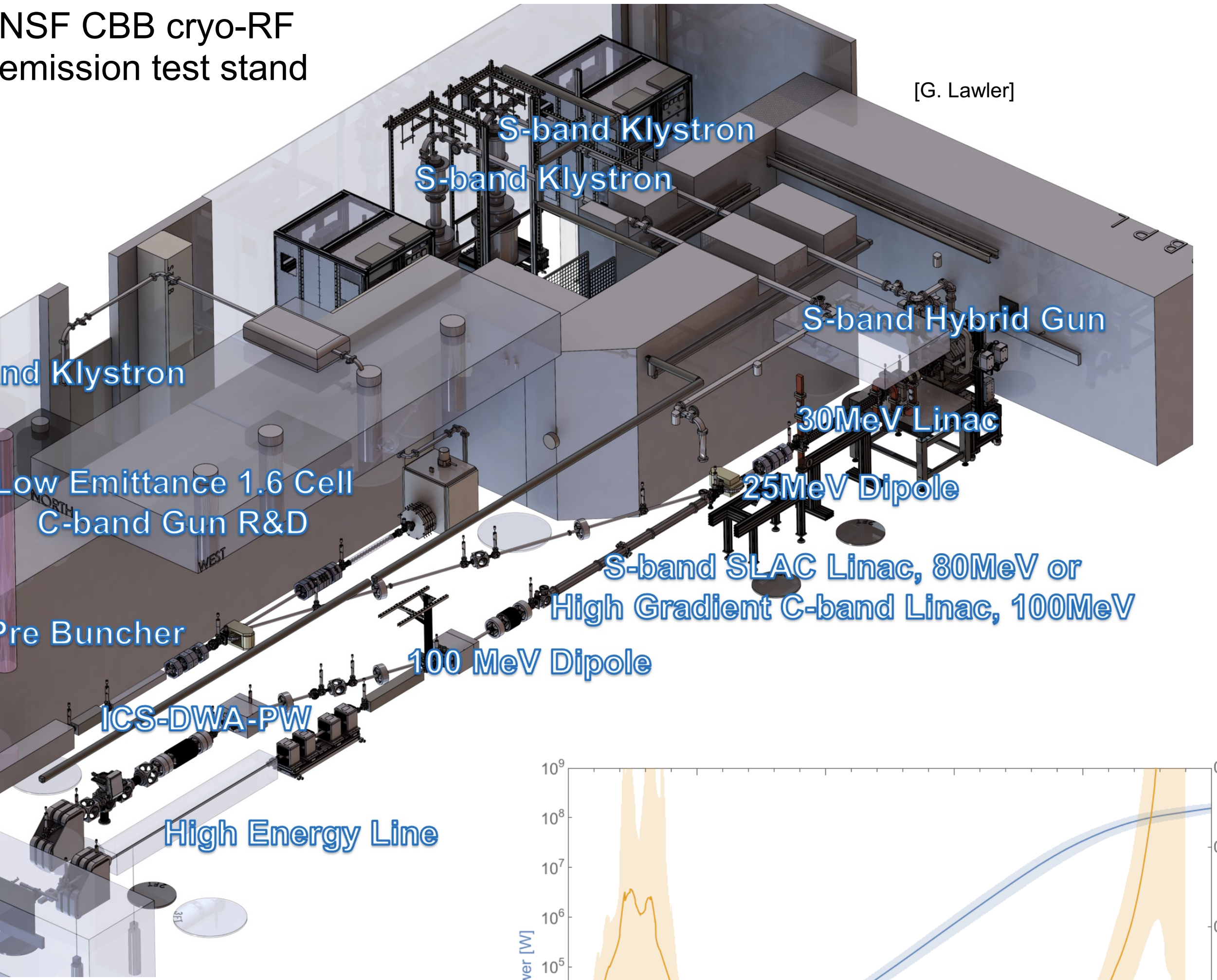
Leveraging the present for the future

- New accelerator lab at UCLA
  - $5M construction, $7M legacy
    - DOE HEP (injector)
    - DARPA (C-band RF)
    - NSF (dynamics, cryo-emission)
    - DOE NNSA (MaRIE FEL)
  - **UC-XFEL research and development**
    - Cryo-RF gun and linac
    - Advanced undulators
    - IFEL and CSR studies
    - Intermediate FELs (IR through EUV)
  - Also: ICS, beam-plasma interaction, interdisciplinary applications
- Bunker complete
  - Laser and RF installation and commissioning ongoing

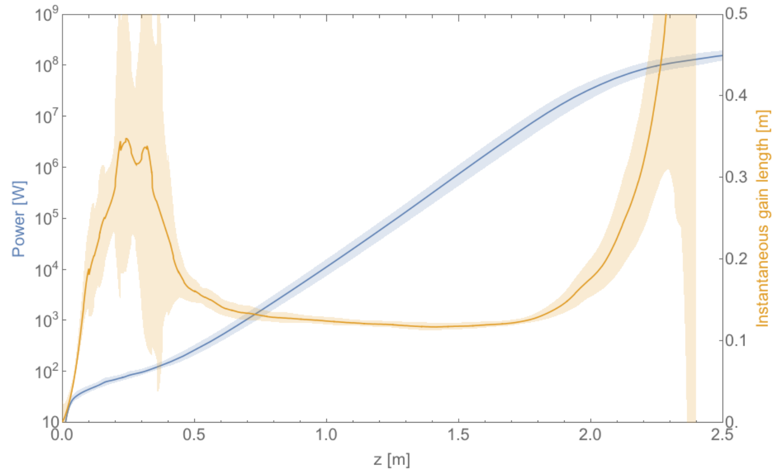


NSF CBB cryo-RF emission test stand

[G. Lawler]



[G. Lawler]



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Demonstrator FELs at SAMURAI

Parameter	Sloan	NSF Mid-scale RI-1	SXR UC-XFEL
Photoinjector	**Cryogenic C-band 1.6-cell**	Existing S-band hybrid	**Cryogenic C-band 1.6-cell**
Acceleration	$1 \times \sim 1$ m **cryogenic C-band linac section**	$3 \times \sim 1$ m **cryogenic C-band linac section**	8×1 m **cryogenic C-band linac section**
Compression	Chicane or **IFEL**	Velocity bunching and long wavelength **IFEL**	CSR compensating chicane pair and **IFEL**
Undulator	Room temperature, conventional	**Cryogenic, short period**	**Cryogenic, short period**
Footprint	12 m	18 m	40 m
Budget	\$3M	\$12.5M	\$40M
Energy [MeV]	90	300	1000
Energy spread [%]	0.02	0.05	0.1
Total beam charge [pC]	100	100	100
Peak current [A]	200	1500	4000
Emittance [nm-rad]	60	400	70
Undulator period [mm]	20.6	6.5	6.5
Undulator field [T]	0.54	1	1
Undulator length [m]	2	4	4
Radiation wavelength [nm]	520	11	1
Radiation energy [eV]	2.4	110	1200
Gain length [m]	0.12	0.23	0.21
Peak power [MW]	160	170	25000

[Majernik, N., *et al.* Demonstration FELs using UC-XFEL technologies at the SAMURAI Laboratory. *12th Int. Particle. Accelerator Conf.*, 2021.]

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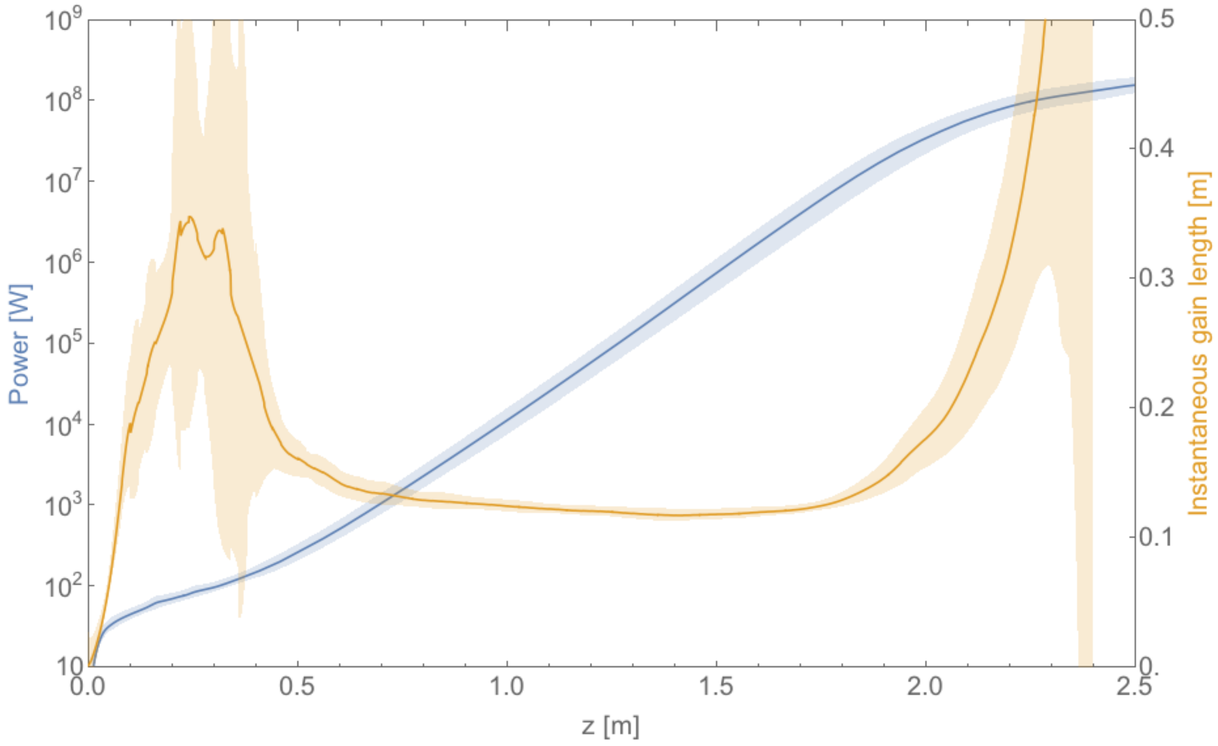
Sloan visible FEL proposal

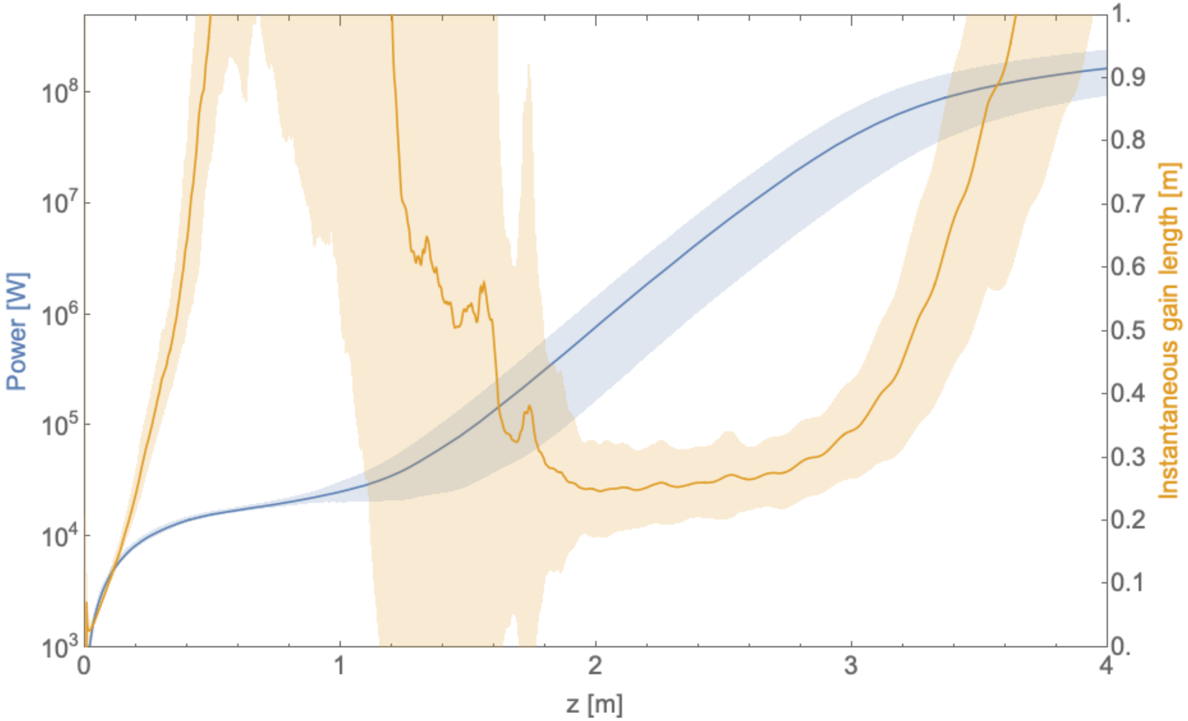
Parameter	Sloan
Photoinjector	**Cryogenic C-band 1.6-cell**
Acceleration	1 × ~1 m **cryogenic C-band linac section**
Compression	Chicane or **IFEL**
Undulator	Room temperature, conventional
Footprint	12 m
Budget	$3M
Energy [MeV]	90
Energy spread [%]	0.02
Total beam charge [pC]	100
Peak current [A]	200
Emittance [nm-rad]	60
Undulator period [mm]	20.6
Undulator field [T]	0.54
Undulator length [m]	2
Radiation wavelength [nm]	520
Radiation energy [eV]	2.4
Gain length [m]	0.12
Peak power [MW]	160



- $3M budget
- 100 MeV beam lasing at 520 nm
- Same 1.6-cell cryogenic gun as SXR
- Compression via chicane <u>or</u> IFEL
- Uses existing 2 meter conventional undulator
- Testing resistive wall wakefields
- Emphasis on pushing limits of cryo-RF

NSF Mid-scale RI-1 EUV FEL proposal

Parameter	NSF Mid-scale RI-1
Photoinjector	Existing S-band hybrid
Acceleration	3 × ~1 m **cryogenic C-band linac section**
Compression	Velocity bunching and long wavelength **IFEL**
Undulator	**Cryogenic, short period**
Footprint	18 m
Budget	$12.5M
Energy [MeV]	300
Energy spread [%]	0.05
Total beam charge [pC]	100
Peak current [A]	1500
Emittance [nm-rad]	400
Undulator period [mm]	6.5
Undulator field [T]	1
Undulator length [m]	4
Radiation wavelength [nm]	11
Radiation energy [eV]	110
Gain length [m]	0.23
Peak power [MW]	170



- $12.5M budget
- 300 MeV beam lasing at 11 nm
- Uses existing S-band hybrid gun
- Several cryogenic linac segments
- Compression via long wavelength IFEL
- Uses same, short period cryogenic undulator as SXR case
- Emphasis on limiting technology risk
- **Only EUV FEL in USA**
  - Useful wavelength for scientific end users
- Potential to access x-rays; first UC-XFEL!

Demonstrator FELs at SAMURAI

Parameter	Sloan	NSF Mid-scale RI-1	SXR UC-XFEL
Photoinjector	**Cryogenic C-band 1.6-cell**	Existing S-band hybrid	**Cryogenic C-band 1.6-cell**
Acceleration	$1 \times \sim 1$ m **cryogenic C-band linac section**	$3 \times \sim 1$ m **cryogenic C-band linac section**	8×1 m **cryogenic C-band linac section**
Compression	Chicane or **IFEL**	Velocity bunching and long wavelength **IFEL**	CSR compensating chicane pair and **IFEL**
Undulator	Room temperature, conventional	**Cryogenic, short period**	**Cryogenic, short period**
Footprint	12 m	18 m	40 m
Budget	\$3M	\$12.5M	\$40M
Energy [MeV]	90	300	1000
Energy spread [%]	0.02	0.05	0.1
Total beam charge [pC]	100	100	100
Peak current [A]	200	1500	4000
Emittance [nm-rad]	60	400	70
Undulator period [mm]	20.6	6.5	6.5
Undulator field [T]	0.54	1	1
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Peak power [MW]	160	170	25000

[Majernik, N., *et al*. Demonstration FELs using UC-XFEL technologies at the SAMURAI Laboratory. *12th Int. Particle. Accelerator Conf.*, 2021.]

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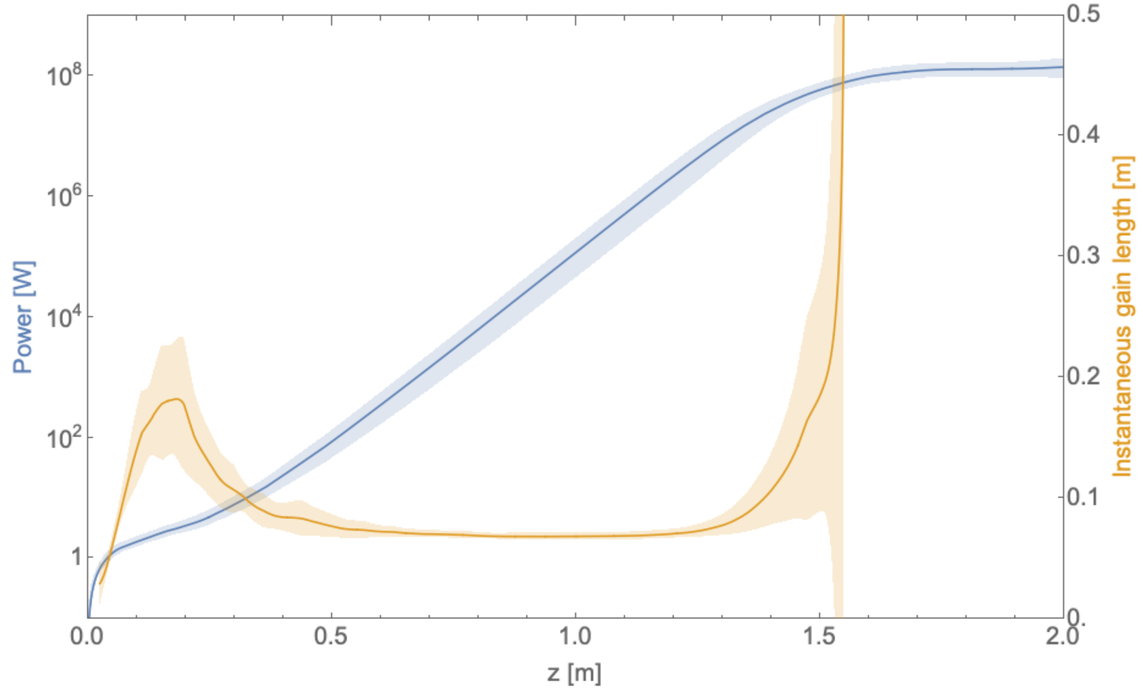
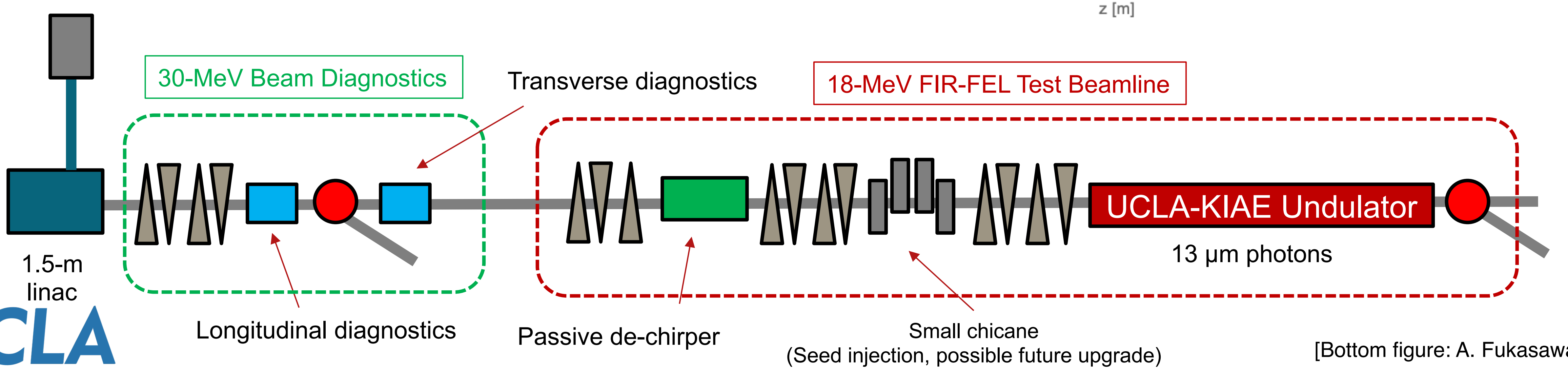
High gain IR FEL

- ~$0M
- Steppingstone[2]
  - No tech overlap with eventual UC-XFEL
  - Strong overlap with both demonstrators
- 18 MeV, compression by velocity bunching
  - Beam from S-band hybrid photoinjector
- Hogan undulator
  - Same energy as original paper [Hogan1998]
    - No upgrade to focusing lattice required
- 136 MW at 13 microns
  - Unlike original, expect to saturate!





[Bottom figure: A. Fukasawa]

Conclusions and future directions

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An Ultra-Compact X-Ray Free-Electron Laser

James Rosenzweig[1], Nathan Majernik[1], River Robles[1], Gerard Andonian[1], Obed Camacho[1], Atsushi Fukasawa[1], Anshul Kogar[1], Gerard Lawler[1], (John) Jianwei Miao[2], Pietro Musumeci[3], Brian Naranjo[2], Yusuke Sakai[4], Robert Candler[5], Ben Pound[6], Claudio Pellegrini[7], Claudio Emma[8], Aliaksei Halavanau[9], Jerome Hastings[8], Zenghai Li[8], Mamdouh Nasr[8], Sami G Tantawi[10], Petr Anisimov[11], Bruce Carlsten[12], Frank Krawczyk[13], Evgenya Simakov[13], Luigi Faillace[14], Massimo Ferrario[15], Bruno Spataro[15], Siddharth Karkare[16], Jared Maxson[17], Yanbao Ma[18], Jonathan S Wurtele[19], Alex Murokh[20], Alexander Zholents[21], Alessandro Cianchi[22], Daniele Cocco[23] and Bas Van der Geer[24] – Hide full author list

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- Promising path for UC-XFEL explored in detail
  - 80 page, 37 author paper published in New Journal of Physics
    - Quasi-CDR
    - Science case strongly emphasized but outside the scope of this talk
  - Enabled by high gradient cryo-RF, a cryo-cooled photoinjector, short period undulators, and advanced beam transport/manipulation
  - **High brightness beams are a central focus and necessity!**
  - Synergistic with other accelerator applications, including HEP
- Future work includes:
  - Extending concept to other parts of parameter space
  - Exploring zero MTE limit
  - Wakefield accelerated drivers

MAJOR PROPOSALS TO NSF, DOE UNDERWAY

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