Argonne NATIONAL LABORATORY | APS

ENABLING TECHNOLOGIES TOWARD COMPACT X-RAY FREE ELECTRON LASERS

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HOW CAN WE DEMOCRATIZE ULTRAFAST X-RAY SCIENCE?

Find ways to reduce the overall construction cost by building shorter linacs and use multiplexed FEL beamlines to reduce cost/experiment

- Ultrafast X-ray science is established, with several hard X-ray free electron lasers (FELs) operating globally
- Unlike the synchrotron, most XFEL facilities operate with a single experiment at a time, making the cost/experiment much higher than for synchrotrons
- Most XFELs use conventional accelerator technology to simplify operations and de-risk project proposals
- Low emittance electron sources have not seen significant improvement over the past 15–20 years. Lasing at higher photon energies requires higher beam energy for the electron emittance to match photon emittance
- Argonne has unique capabilities to address these issues

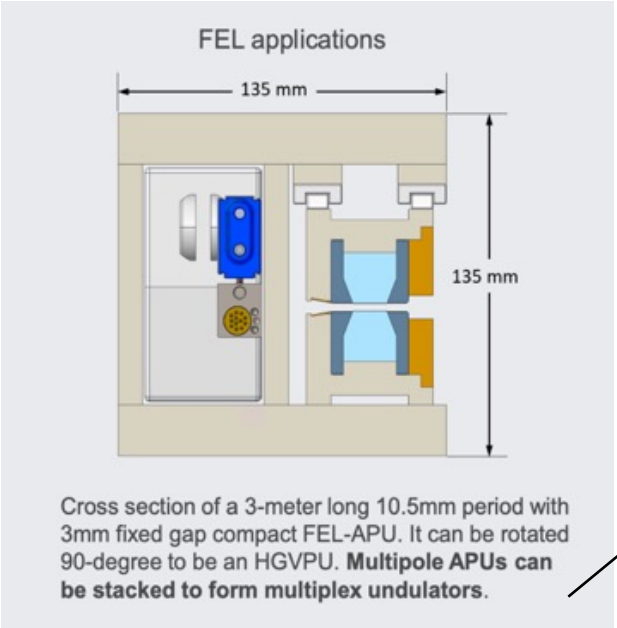
ARGONNE'S COHERENT X-RAY SCIENCES: STRATEGY TOWARD COMPACT XFELS

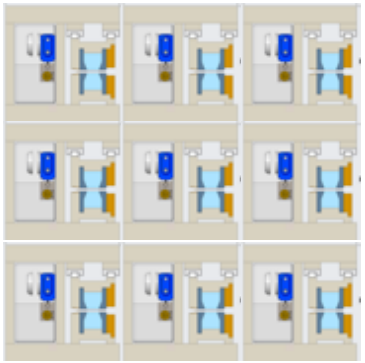
One of the pillars of the Argonne lab plan since 2022

- Develop compact undulator arrays to allow independent FELs for multiple beam lines
  - Hybrid permanent magnet undulators using adjustable phase undulator
  - Multi-line superconducting undulators with multiple independent cores in single cryostat
- A new concept for an ultralow emittance electron source based on the Compact Linear Collider (CLIC) two-beam accelerator scheme (<10 nsec) RF pulses
- Investigation of high gradient linear accelerator technology, including the CLIC two-beam accelerator scheme but excluding superconducting RF
- The first two bullets have been funded via LDRD starting in FY23 ($900K)

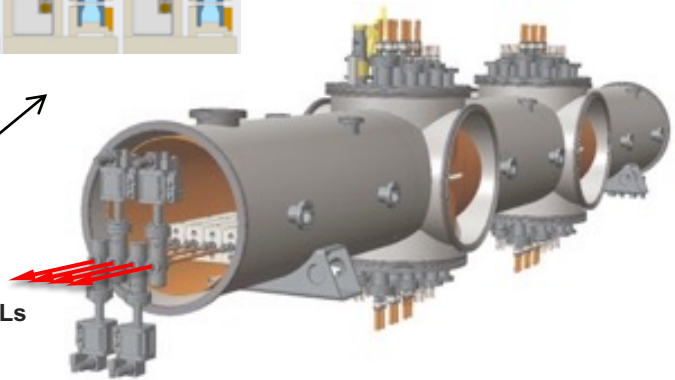
COMPACT UNDULATOR TECHNOLOGIES

Both permanent magnet and superconducting options





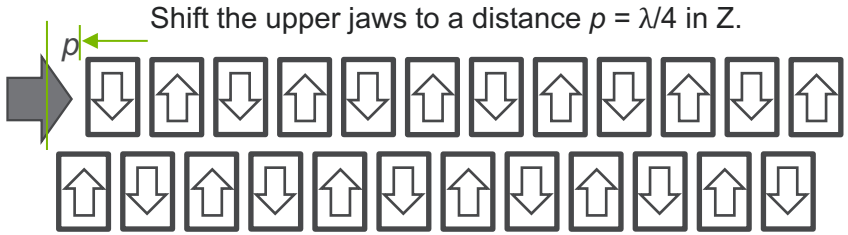
A cryomodule with four FELs



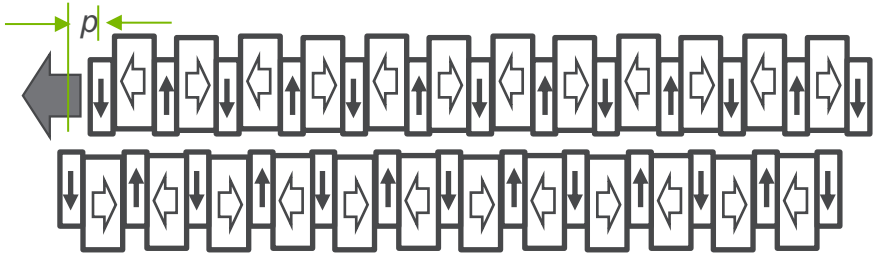
COMPACT PERMANENT MAGNET UNDULATOR

Adjustable phase undulator uses force compensation magnets to neutralize the forces, allowing compact structure

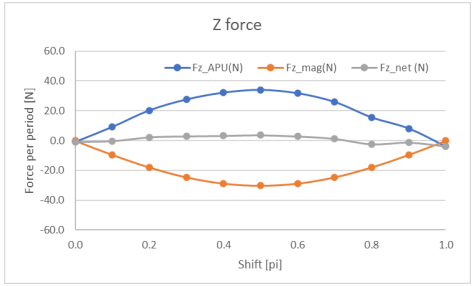
A secondary magnet array nearly cancels the forces in the primary undulator structure



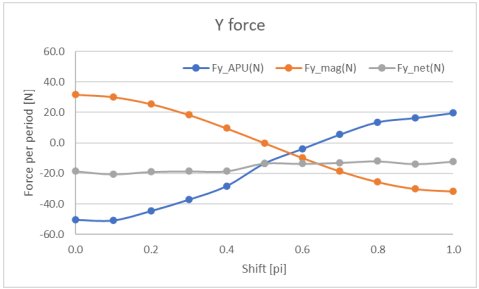
Force compensation magnet structure side view at $p = \lambda/4$ (phase) shift



Main undulator magnetic structure side view at $p = \lambda/4$ (phase) shift



Simulated forces in Z vs. phase shift. The net force in Z is neutralized.

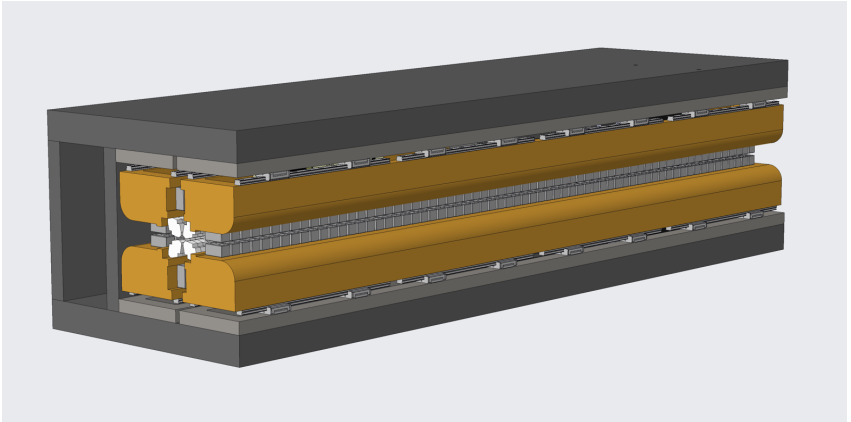


Simulated forces in Y vs. phase shift. The net force in Y is a constant

A FORCE-NEUTRAL PLANAR APU PROTOTYPE IS ALREADY COMPLETE

In MM1 now for magnetic testing. Mechanical design for “DELTA-style” APU with adjustable polarization in progress.

Planar FNAPU prototype undergoing magnetic testing



The X undulator allows independent force neutral motion of 3/4 jaws, allowing arbitrary polarization

HONEY, I SHRUNK THE XFEL (J. ROSENZWEIG)

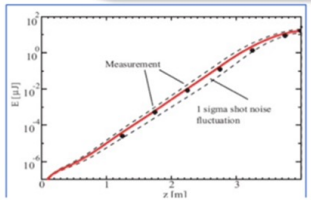
- ***Shrink the accelerator and undulator interaction***
- Joins two pillars of advanced beam physics community

Advanced Light Sources

- New SASE FEL concepts
- Experimental explorations in XFEL
- Ultra-high brightness beam sources
- Advanced instrumentation
- Micro-undulators, MEMS devices

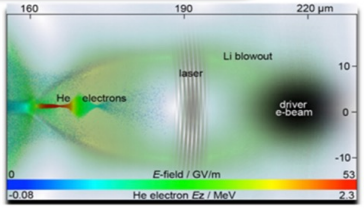
Advanced Accelerators

- Plasma wakefield accelerators
- Dielectric wakefield accelerators
- Dielectric laser accelerators
- Inverse free-electron lasers
- *Very high gradient RF acceleration*



The 5th generation light source

Ultra-compact X-ray FEL



HIGH(ER) GRADIENT RF ACCELERATION IS KEY TO MAKING COMPACT(ER) XFELS

Active international effort to reduce XFEL size using modern high-gradient linac concepts borrowed from high energy physics projects

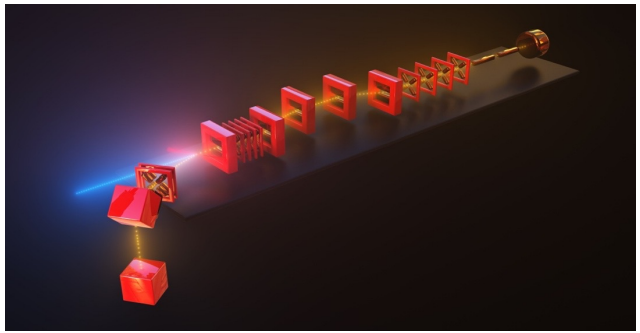
- Most XFEL design focus has been on optimizing the operation of LCLS-I and the design and fabrication of the LCLS-II/HE
  - The LCLS-I Cu Linac (~20 MV/m)
  - The LCLS-II SRF Linac (~20-25 MV/m with 100% duty cycle)

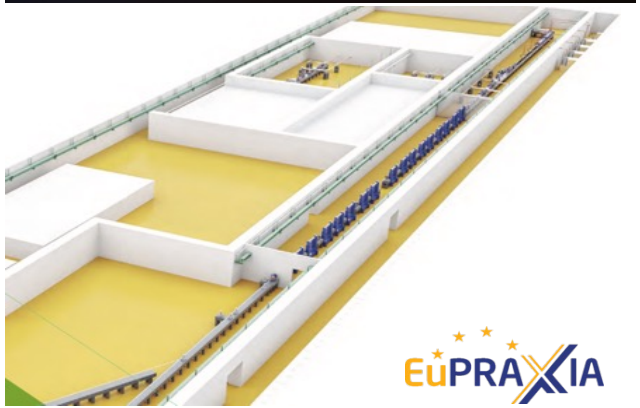
HIGH(ER) GRADIENT RF ACCELERATION IS KEY TO MAKING COMPACT(ER) XFELS

Significant developments in Linac/photogun design reduce Linac length and source emittance, allowing compact FEL designs

- Cool Copper Collider uses low-temperature copper, which has improved performance and distributed coupling (~150-200 MV/m)
- CompactLight, an EU-funded study uses x-band RF optimized for XFELs (65 MV/m)
- Two-beam acceleration based in the CLIC collider design. Short RF pulse regime (>400 MV/m)

Very few of these enhancements for particle physics applications have been adopted or demonstrated yet for light source applications





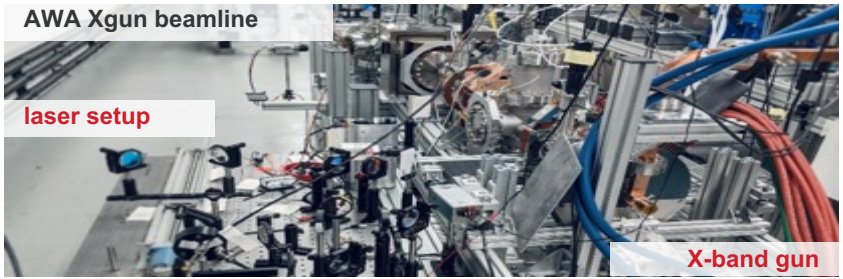
WHAT IF WE COULD MAKE A HIGH GRADIENT COMPACT LINAC?

Lower the cost of construction and operation to allow more multiplexed XFELs, lowering the overall cost/experiment

BREAKTHROUGH IN ULTRAHIGH GRADIENT OF 400 MV/M COULD BE THE ANSWER

Recent breakthrough result at the Argonne Wakefield Accelerator using two-beam accelerator technology with <10 nsec RF pulses

- LCLS gun, today's standard, operates at 120 MV/m to produce the beam of 100 pC at emittance ~150 nm
- AWA demonstrated gun gradient of **400 MV/m** with an X-band RF gun powered by ns-scale short RF pulses (***Phys. Rev. Accel. Beams*** *25, 083402, August 2022*)
- With higher gradient, a reduction of emittance is expected



GOAL: High brightness beam

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To achieve low emittance

High electric field ($\mathcal{B} \propto E^{\alpha}$)

↓

To overcome breakdown at high E

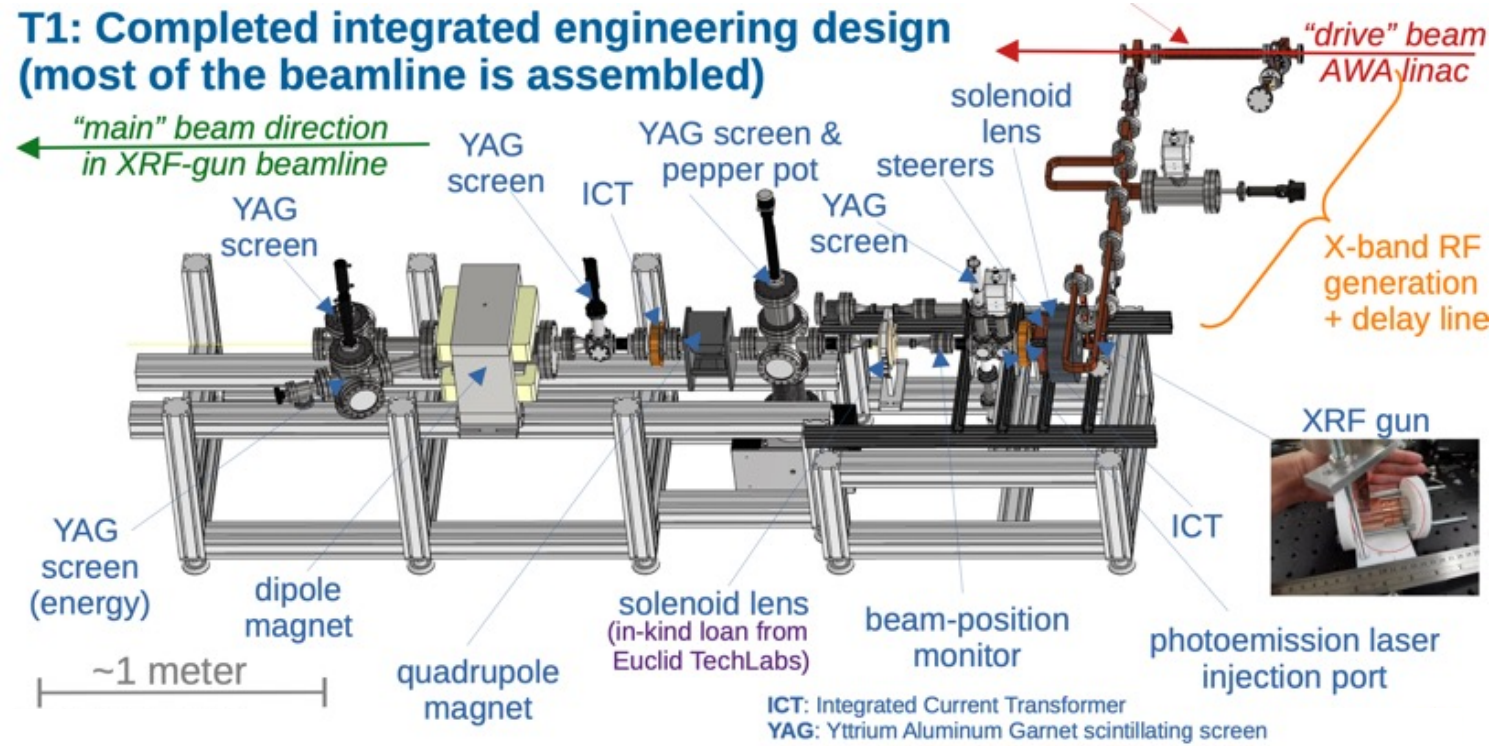
Short RF-pulse operation ($BDR \propto E^{30}\,\tau^{5}$)

High brightness beam is critical for reducing the footprint of future XFELs

A variation of the CLIC TBA scheme which uses a drive beam for creating the short RF pulse

- John Power
- Philippe Piot
- Xueying Lu

EXPERIMENT IN PROGRESS TO DEMONSTRATE EMITTANCE SCALING IN HIGH FIELD REGIME



SUMMARY AND NEXT STEPS

“Democratize” ultrafast X-ray science by reducing the cost/experiment and the cost of next generation XFELs

- Significant progress on compact undulator concepts that can enable multiplexed XFEL operation
- Several high gradient linac options exist, including potential breakthrough option at Argonne, that could result in a 5-10x reduction of XFEL length, significantly reducing new construction cost
- With LCLS-II and LCLS-IIHE well underway, there may be interest in future XFEL capability not covered by these machines
- We believe we have the basis for a study of a unique concept for a compact XFEL. More studies planned following the commissioning of the upgraded APS!

SUGGESTIONS WELCOME!