ENABLING TECHNOLOGIES TOWARDS COMPACT X-RAY FREE ELECTRON LASERS

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Advanced Photon Source

Future Light Sources, Lucerne
30 August, 2023

QUICK UPDATE ON THE APS UPGRADE

Argonne’s 4th generation light source is being installed with commissioning in February 2024

Completed modules ready for transport.

Installed in APS tunnel, July 2023

- New ring is being installed since shutdown in April 2023
- Projected emittance of ~40 pm, 200 mA current, bunch patterns of 324/48 bunches.
- On-axis swapout injection, 4th harmonic SCRF passive cavity
- Many new IDs including full-straight SCUs
- Old ring magnets planned to be part of EIC ESR.

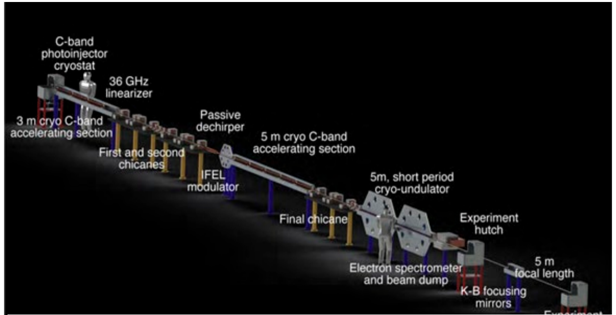
HOW CAN WE DEMOCRATIZE ULTRAFAST X-RAY SCIENCE

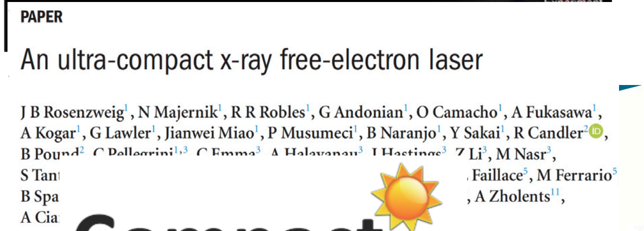
Find ways to reduce the cost/experiment while expanding bandwidth

- Ultrafast X-ray science is now an established field with several hard and soft x-ray FELs in operation around the world.
- Unlike the synchrotron, most of the XFEL facilities operate with a single or few experiments at a time, making the cost/experiment much higher than for synchrotrons.
- Most XFELs use relatively conventional accelerator technology (both RT and SCRF) to simplify operations and to derisk project proposals. Furthermore, low emittance electron sources have not seen significant improvement over the past decade. Therefore, lasing at higher photon energies requires higher beam energy for the electron emittance to match the photon emittance.
- Argonne has some unique capabilities to address these issues.

SEVERAL COMPACT XFEL CONCEPTS

Based a multiple advanced technologies and techniques, some of which have never been demonstrated.

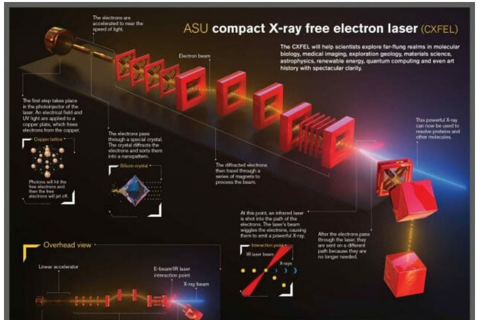



PAPER

An ultra-compact x-ray free-electron laser

J B Rosenzweig[1], N Majernik[1], R R Robles[1], G Andonian[1], O Camacho[1], A Fukasawa[1], A Kogar[1], G Lawler[1], Jianwei Miao[1], P Musumeci[1], B Naranjo[1], Y Sakai[1], R Candler[2], B Pound[2], C Pellegrini[1,3], C Emma[3], A Halavanau[3], J Hastings[3], Z Li[3], M Nasr[3], S Tan Faillace[5], M Ferrario[5] B Spa , A Zholents[11], A Cia

Conceptual Design Report of the CompactLight X-ray FEL



The CXFEL will help scientists explore far-flung realms in molecular biology, medical imaging, exploration geology, materials science, astrophysics, renewable energy, quantum computing and even art history with spectacular clarity.

The electrons are accelerated to near the speed of light.

The first step takes place in the photoinjector of the laser. An electrical field and UV light are applied to a copper plate, which frees electrons from the copper.

Photons will hit the free electrons and then the free electrons will jet off.

The electrons pass through a special crystal. The crystal diffracts the electrons and sorts them into a nanopattern.

The diffracted electrons then travel through a series of magnets to process the beam.

At this point, an infrared laser is shot into the path of the electrons. The laser's beam wiggles the electrons, causing them to emit a powerful X-ray.

After the electrons pass through the laser, they are sent on a different path because they are no longer needed.

This powerful X-ray can now be used to resolve proteins and other molecules.

CXFEL: Compact X-ray Free Electron Laser

Our strategy is to focus on developing accelerator technologies that can be implemented in 5-10 year time frames on existing and future facilities.

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

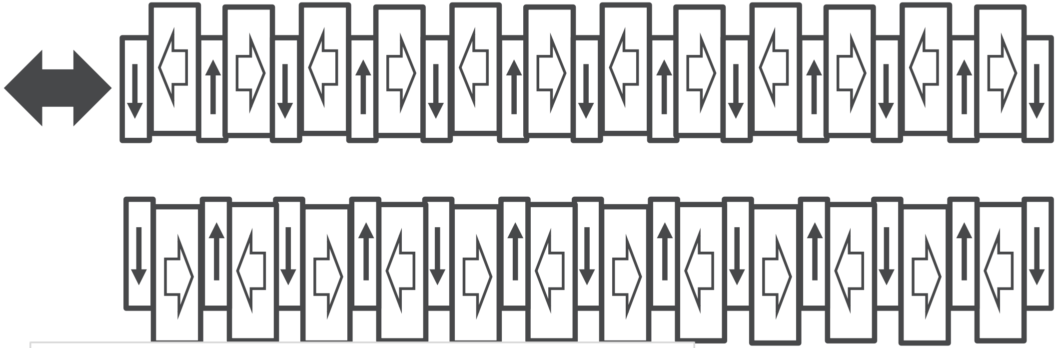
Allows reduced cost/experiment and overall facility cost

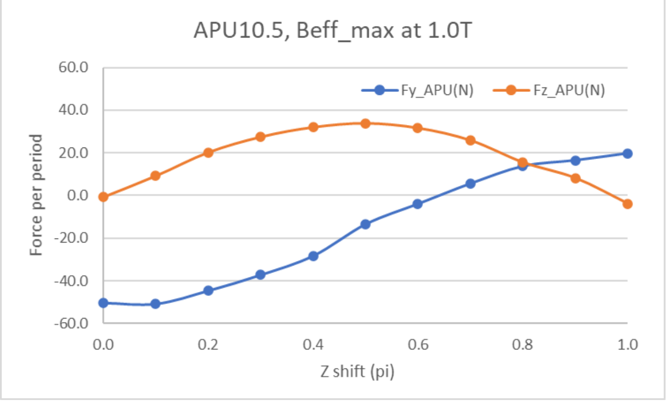
- **High-field short period undulators: reduce undulator length and beam energy**
- **Multiline FELs: allow multiple simultaneous users**
- **High field injectors: reduce source emittance to lase at lower energies**
- **High gradient acceleration-reduce tunnel length**

- Develop compact undulator arrays to allow independent FELs for multiple beam lines.
  - Hybrid Permanent Magnet Undulators using the new concept of adjustable phase undulator
  - Short-period high-field Superconducting Undulators (SCUs)
  - Multiline SCUs with multiple independent cores in a single cryostat
- A new concept for an ultralow emittance electron source based on the CLIC two-beam accelerator scheme using short (<10 nsec) RF pulses.
- Investigation of high gradient linear accelerator technology, including the CLIC TBA scheme but excluding superconducting RF.

THE ADJUSTABLE PHASE UNDULATOR (APU)

An old idea with a new twist to cancel magnetic forces





A 3m long 10mm period APU has 280 periods. It experiences over a metric ton force in Z and two metric tons in Y. Both forces vary with phase change.

- Highly compact with potentially smaller gaps than adjustable gap undulator (AGU).
- The magnetic forces vary significantly, especially when the length of the device scales beyond 2-meter.
- Force in Y varies twice as much as that of the AGU.

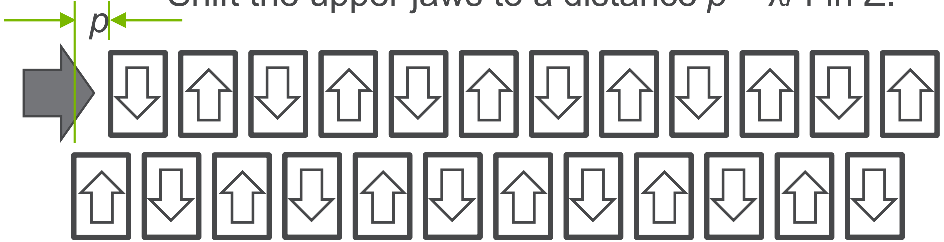
Led by Joe Xu

Roger Carr, “Adjustable phase insertion devices as X-ray sources,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 306, p. 391, 1991.

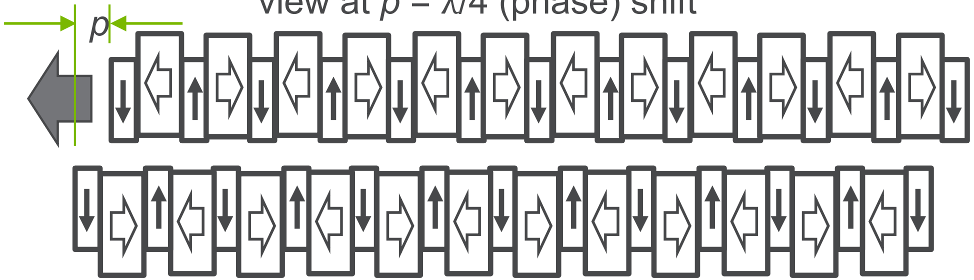
USE FORCE COMPENSATION MAGNETS TO NEUTRALIZE THE FORCES

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

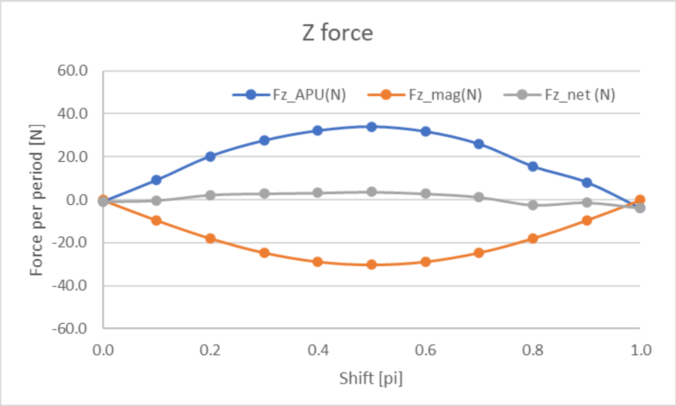
Shift the upper jaws to a distance *p* = λ/4 in Z.



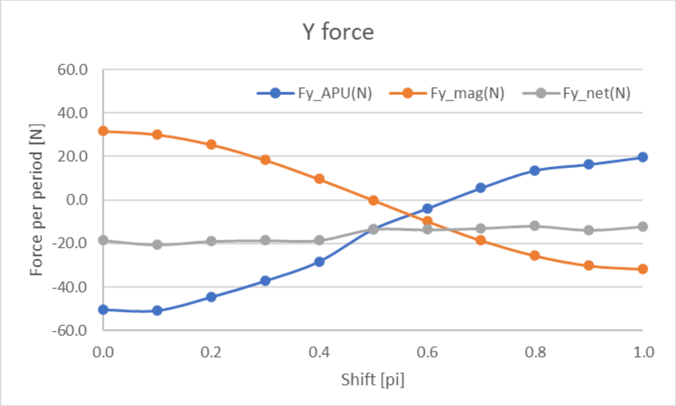
Force compensation magnet structure side view at *p* = λ/4 (phase) shift



Main undulator magnetic structure side view at *p* = λ/4 (phase) shift



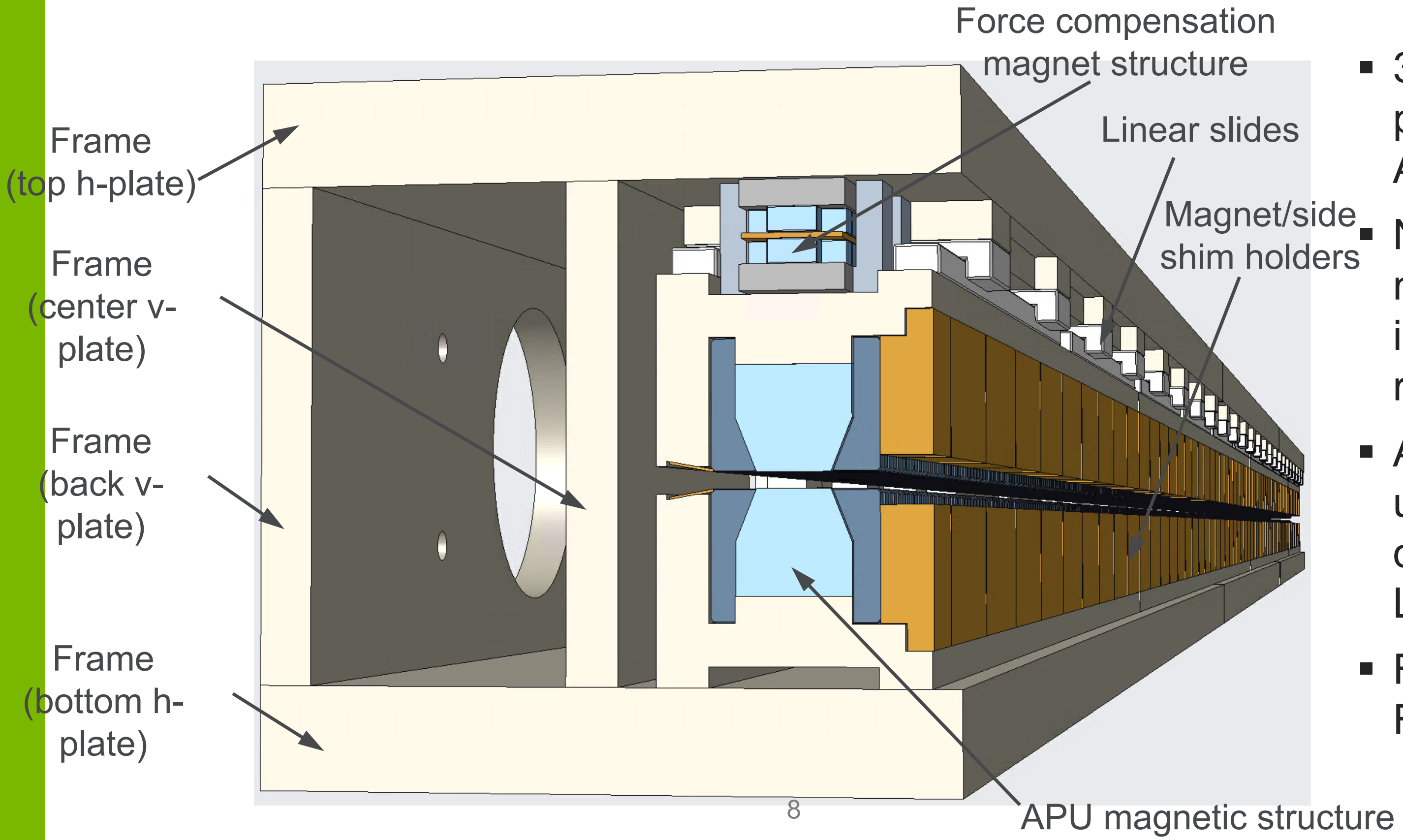
Simulated forces in Z vs. phase shift. The net force in Z is neutralized.



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

CONCEPTUAL DESIGN OF A FORCE-NEUTRAL APU

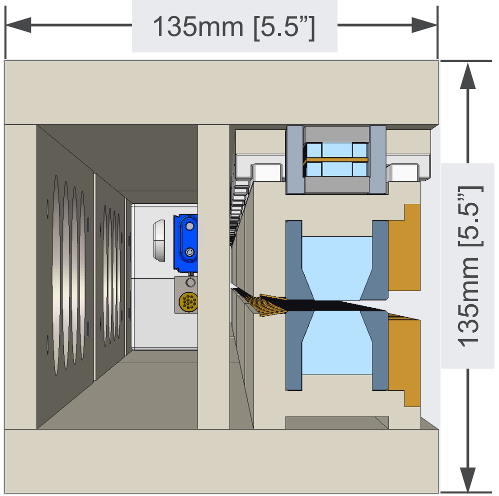
Under development using internal R&D support



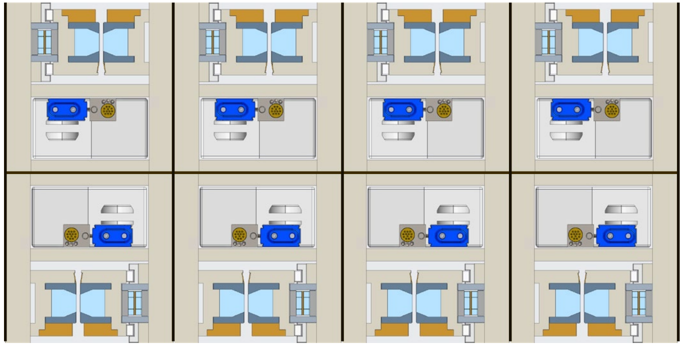
- 3-meter long, 10.5mm period, 3mm fixed gap APU.
- Neutralized forces allow more COTS components improving reliability and reducing cost.
- A prototype of this undulator is being developed using Argonne LDRD funds.
- First results expected in FY24.

THE COMPACT APU DESIGN ALLOWS FOR UNDULATOR ARRAYS FOR FELS OR RINGS

One can arrange the undulators for multiline FEL operation or for swapping undulators in the ring

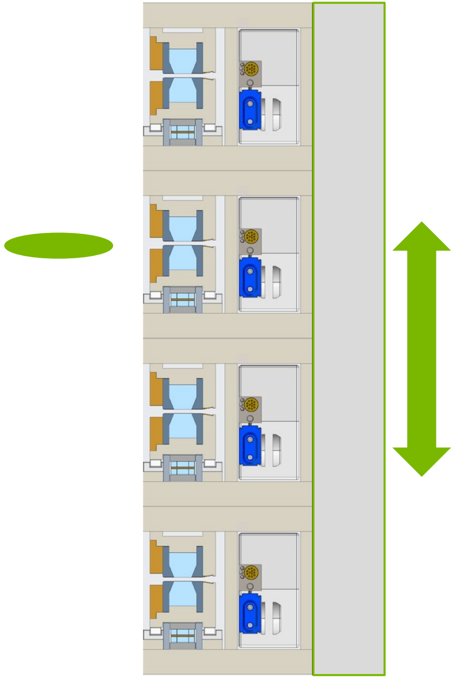


Cross section of a 3-meter long 10mm period with 3mm fixed gap compact FEL-APU. It can be rotated 90-degree to be an horizontal gap vertical polarizing undulator (HGVPU.)



Multiple APUs with different period length can be stacked to form multiplex undulators (undulator array). Conceptual only.

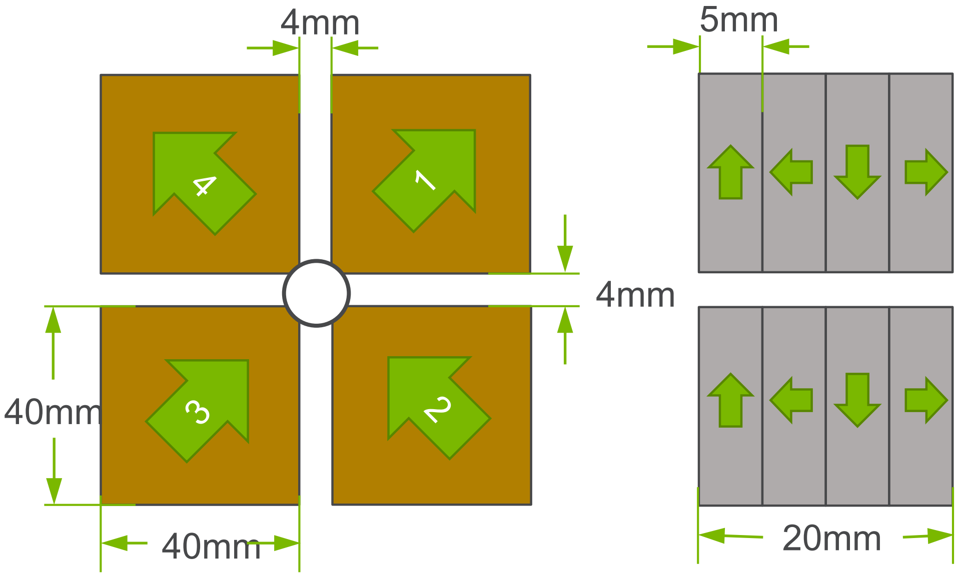
Multiple APUs with different period length can be stacked to form multiplex undulators (undulator array). Conceptual only.



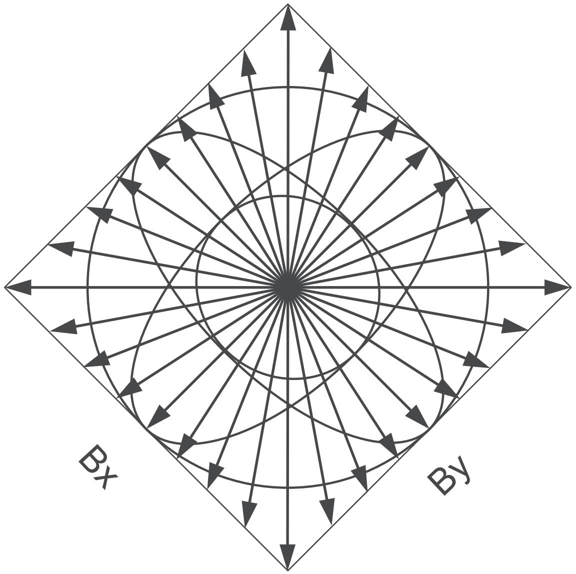
Multiple APUs can be stacked for ring operation.

APPLYING THE FORCE-NEUTRAL CONCEPT TO A DELTA-TYPE UNDULATOR

Our version is called the X-Undulator (XU)



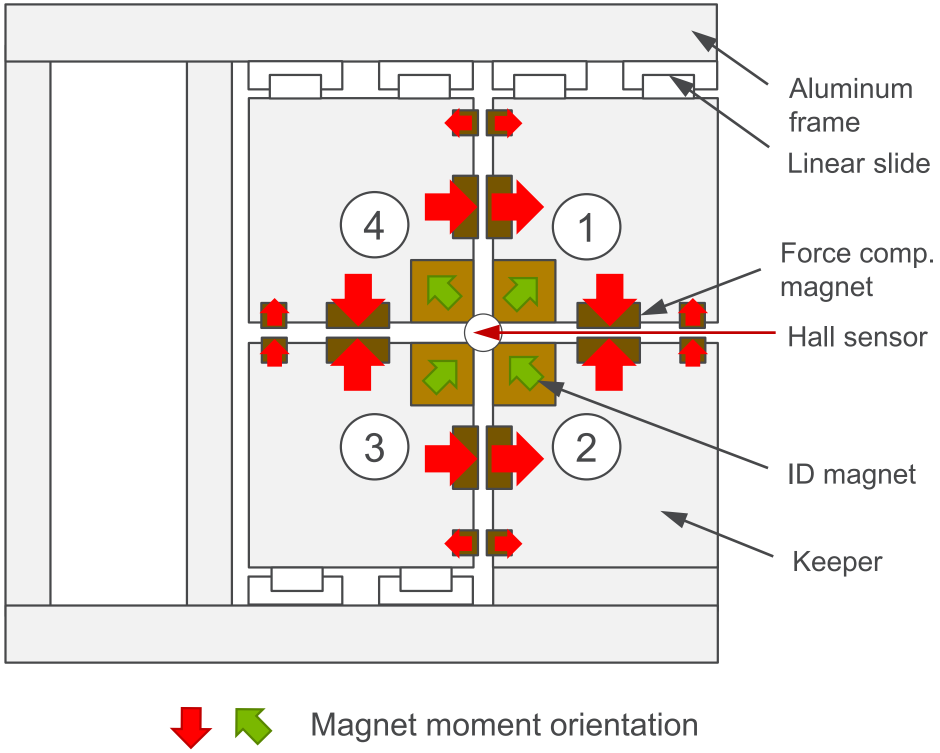
Jaw 2 stationary. Shift jaws 3 and 4 to tune X-ray energy (adjust ID k value). Shift jaw 1 and 3 to adjust X-ray polarization.



When they are in phase, it produces linear polarizing light in any transvers direction. When they are shifted by +/- half pi, it produces right/left elliptical (circular) polarizing light in any shape (ellipticity).

FORCE NEUTRAL X-UNDULATOR (XU) STRUCTURE

Prototype under development in FY24



- All the magnetic forces and torques are neutralized.
- Hall sensors can access and map out the X-undulator field directly. Therefore, it can be measured precisely and tuned to much higher specifications.
- It is compact.
- It can achieve much faster polarization mode switching.
- Multiple XUs with different period length can be stacked to form multiplex undulators (undulator array).

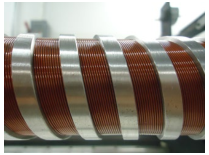
TOWARDS MULTILINE COMPACT SCUS

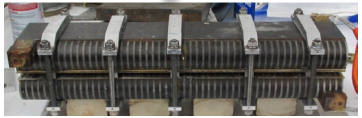
We believe that SCUs are the best path to ~10 mm period, high field undulators

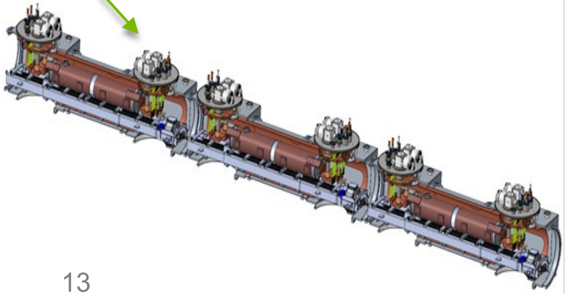
- After several decades of development, SCUs have only been adopted in a few light sources. They are difficult, expensive and require significant infrastructure just to get started. Furthermore, operation in the beam environment presents more challenges.
- However, we believe that many of the fundamental engineering challenges have been addressed (fabrication, cryogenic systems, SC wire, measurement and correction techniques).
- With the renewed interest in IC fusion, there has been accelerated growth in the development of high temperature superconducting wire (tape). This will be ideal for development of a ~10 mm period undulator with K~1-2 with a few mm magnetic gap.
- The size of the SCU magnet cores allows the possibility of multiple SCUs/cryostat.

ARGONNE HAS A DEEP HISTORY IN SCU R&D AND OPERATION

Built on a strong investment in scientists, engineers and facilities







2000: Start of SCU R&D

2012: SCU0

2015: SCU1

2017: Helical SCU

2021: SCU-FEL Demo (w/SLAC)

2022: Nb3Sn SCU

2024: APS-U Full-straight SCUs

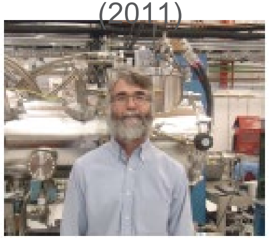
2028?:

Holy Grail: λ~10 mm, K~1-2, HTS, cryo-free

APS SCU TEAM COVERS ALL BASES

Physics, engineering, design, cryogenics, fabrication, measurement, commissioning and operation

Susan Bettenhausen (2011)



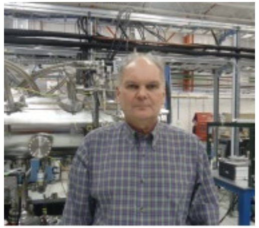
Joel Fuerst (2010)

Chuck Doose (2011)

Matt Kasa (2008)

Quentin Hasse (2007)

Efim Gluskin



Yury Ivanyushenkov (2007) – team leader

Yuko Shiroyanagi (2012)

Ibrahim Kesgin (2014)

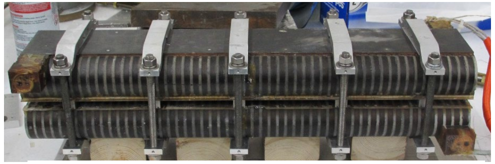
Heisenberg (2008-13)

Accelerator Physics support: *Yipeng Sun, Vadim Sajaev, Aimin Xiao* ---lattice design and beam dynamics; *Ryan Lindberg, Xiang Sun*--- wakefied analysis; *Kathy Harkay*---ray tracing and beam heat load; *Michael Borland* --- device parameters optimization;
Magnetic Devices support: *Mike Merritt, John TerHaar, Kurt Boerste, Joe Gagliano, Jr., Eric McCarthy* --- technical support; *Roger Dejus* --- radiation calculations;
Engineering Design support: *E.Trakhtenberg, D.Skiadopoulos, E.Anliker.*
Controls: *Marthy Smith*
Alignment: *W.Jansma, Rendering: O.Schmidt*

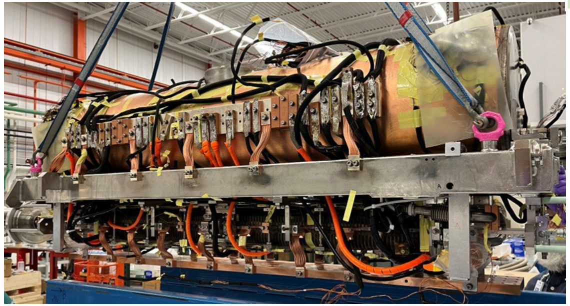
DEVELOPMENT OF NB$_3$SN UNDULATORS

First Nb3Sn magnet installed in an accelerator

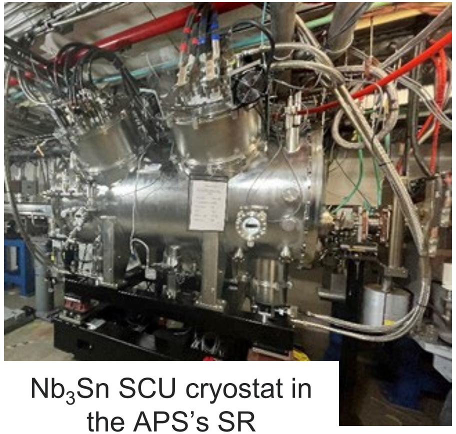
- A 3-year project supported by the DOE's Accelerator & Detector Research Program.
- Collaboration among three US National Labs:
  - ANL (lead institution),
  - FNAL (heat treatment),
  - LBNL (protection system).



Cold mass assembly with the 1.1 m long Nb3Sn magnets



Undulator specifications	Nb$_3$Sn	NbTi
Undulator Field, T	1.17	0.97
K value	2	1.6
Design current, A (~70 and ~80% of the I_c) at 4.2 K	820	450
Period length, mm	18	18
Magnetic gap, mm	9.5	9.5
Magnetic length, m	1.1	1.1
Vacuum gap, mm	7.2	7.2



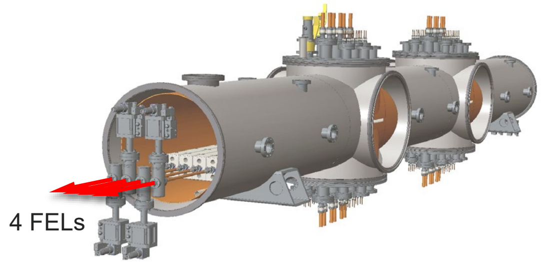
Nb$_3$Sn SCU cryostat in the APS's SR

Nb$_3$Sn SCU replaced NbTi SCU in APS's Sector 1 and successfully delivered x-ray beams as the first Nb$_3$Sn-based SCU. Operated flawlessly until the start of the APS upgrade on April 17th, '23.

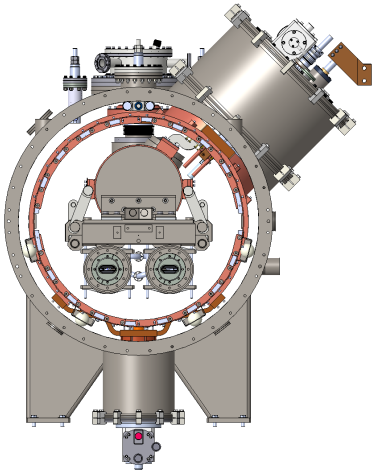
STATUS OF MULTILINE FEL SCU R&D

3-year program funded by internal R&D funds

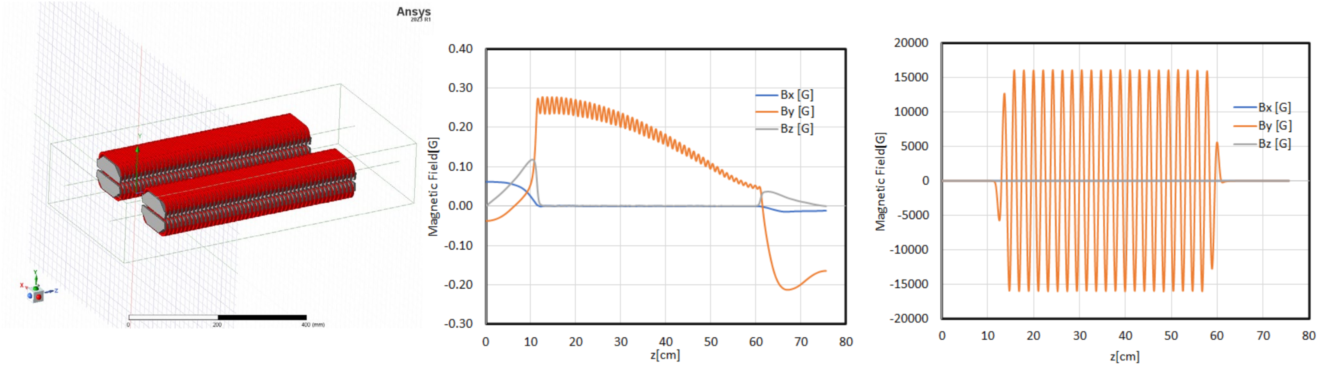
- Several SCU magnets can be installed side-by-side in a single cryostat
- This enables a multiline FEL SCUs
- Design and test of such a cryostat prototype is the goal of Laboratory funded R&D project “Multiline Free Electron Laser Superconducting Undulators”



A concept of a cryomodule with four FELs.
Courtesy of J. Fuerst, ANL



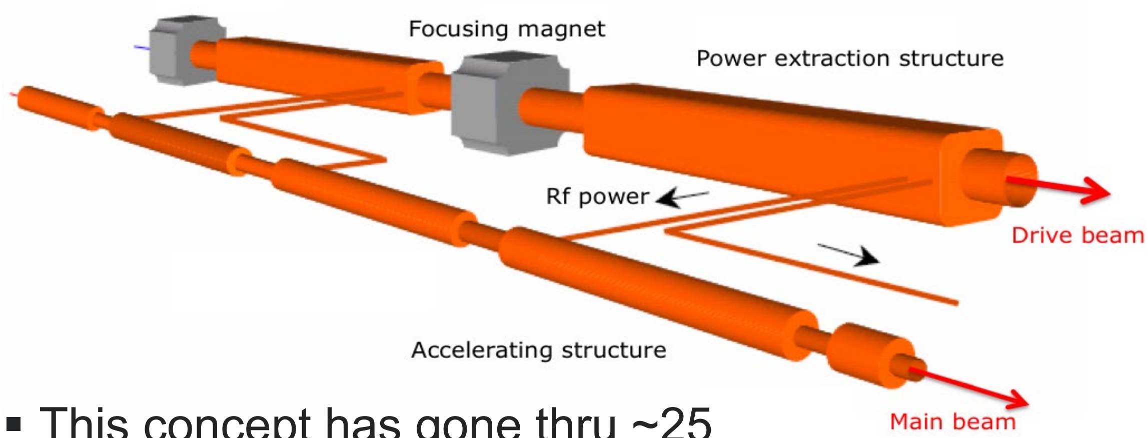
Design of an APS-style cryostat prototype with two SCU magnets.
Courtesy of J. Fuerst, ANL



Simulation of magnetic interference in a two-magnet system (left) predicts the magnetic field in the neighboring magnet is less than 1 gauss (middle) when the other magnet is powered to a full operation current (right).
Courtesy of Y. Shiroyanagi, ANL

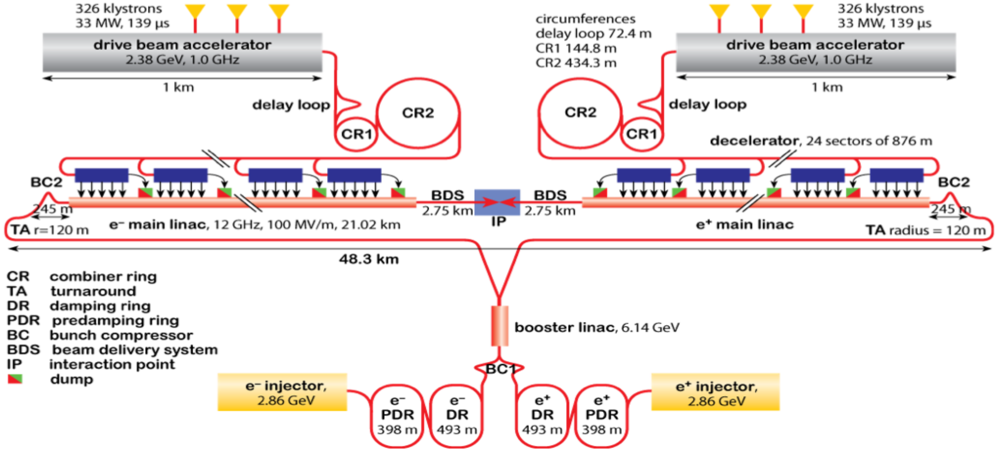
THE CLIC TWO-BEAM ACCELERATOR CONCEPT

A potential path to a high-gradient linac



- A low-frequency, high-current linac (drive beam) is used to generate the RF pulse for a high-frequency, low-current (12 GHz) linac.

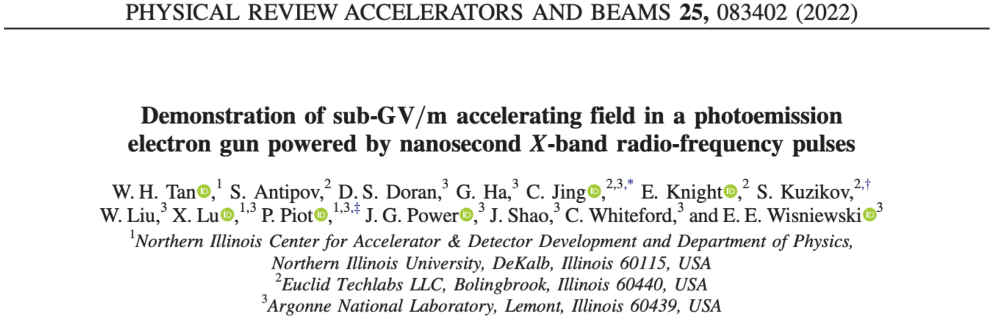
- This concept has gone thru ~25 years of R&D at CERN with an existing test facility and CDR and TDR produced. Many years of effort have gone into sophisticated RF design. It is not clear if CLIC will go forward in the current CERN strategy.



WHY DO WE CARE ABOUT CLIC?

A recent breakthrough at the Argonne Wakefield Accelerator opens the possibility for very high gradient acceleration.

- The main beam RF pulse length is set by the length of the bunch train in the drive beam.
- The CLIC design was focused on acceleration of a bunch train in the main beam and didn’t consider short (<10 nsec) RF pulses.
- This was tested last year and produced ~400 MV/m gradient with little or no dark current.
- This is now an interesting option for a compact XFEL linac.



PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 083402 (2022)

Demonstration of sub-GV/m accelerating field in a photoemission electron gun powered by nanosecond *X*-band radio-frequency pulses

W. H. Tan,[1] S. Antipov,[2] D. S. Doran,[3] G. Ha,[3] C. Jing,[2,3,*] E. Knight,[2] S. Kuzikov,[2,†]
W. Liu,[3] X. Lu,[1,3] P. Piot,[1,3,‡] J. G. Power,[3] J. Shao,[3] C. Whiteford,[3] and E. E. Wisniewski[3]
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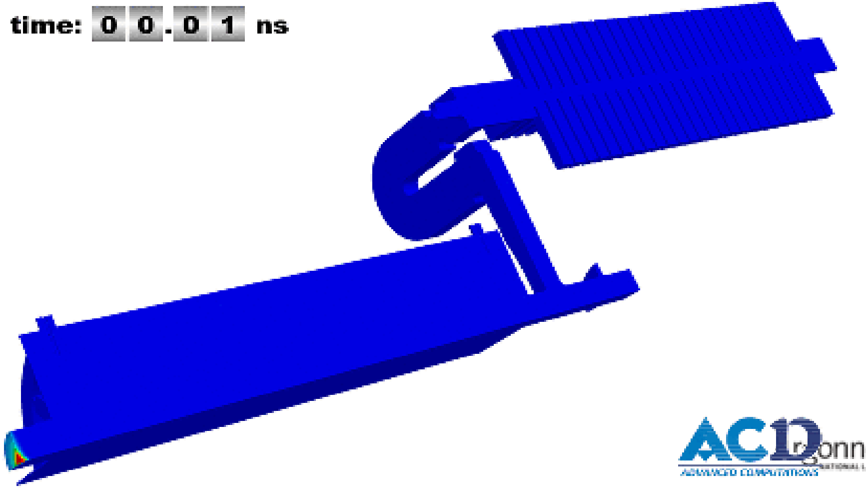
[3]*Argonne National Laboratory, Lemont, Illinois 60439, USA*



ULTRAHIGH GRADIENT RF GUN

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

- LCLS gun is 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 (published on ***Phys. Rev. Accel. Beams*** *25, 083402, August 2022*).
- With higher gradient, a reduction of emittance is expected and to be measured as the next step.

GOAL: High brightness beam

To achieve low emittance

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

To overcome breakdown at high E

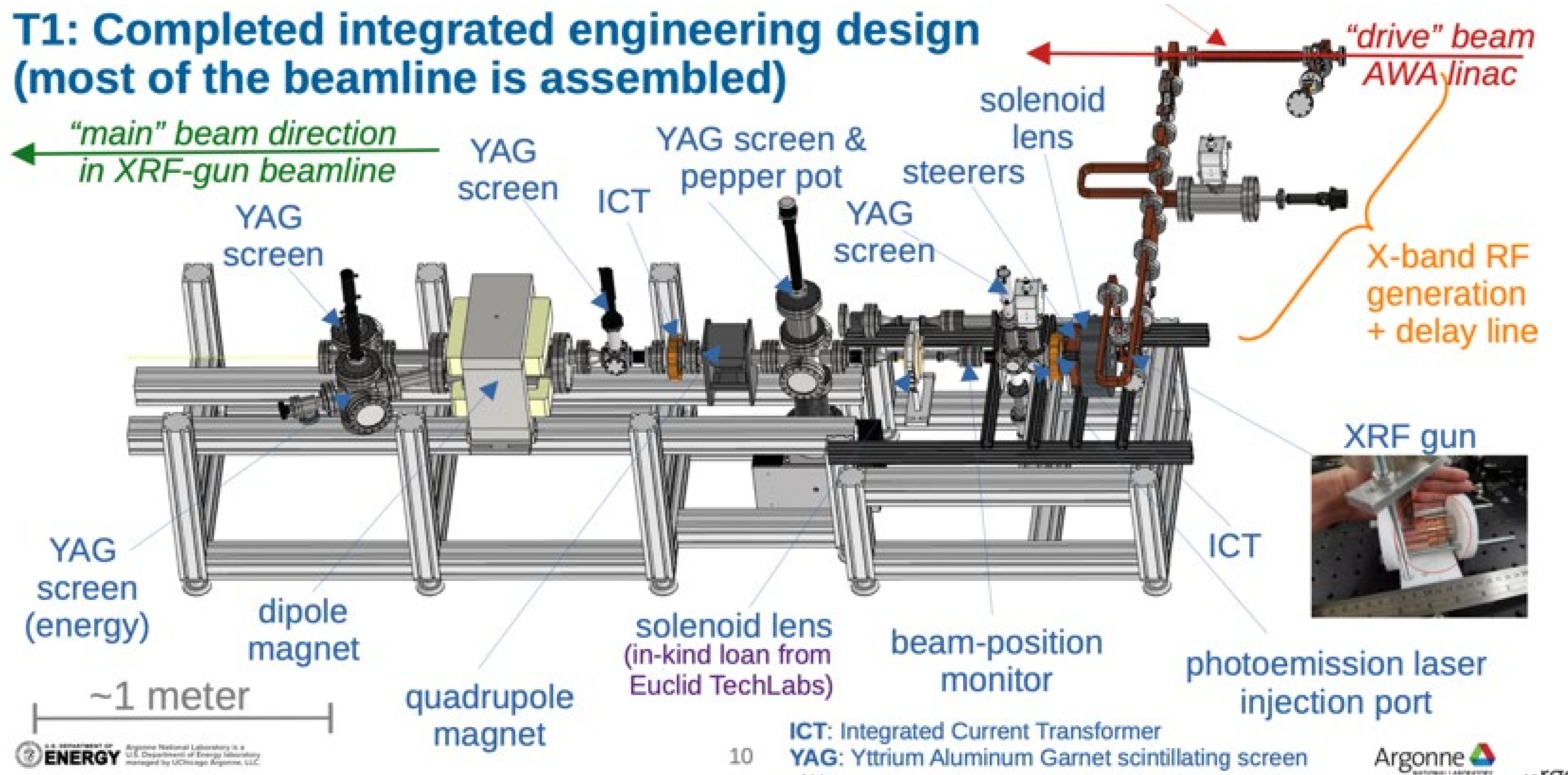
Short rf-pulse operation ($BDR \propto E^{30}\,\tau^{5}$)

High brightness beam is critical for reducing the footprint of future X-ray free-electron lasers (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



T1: Completed integrated engineering design (most of the beamline is assembled)

"main" beam direction in XRF-gun beamline

"drive" beam AWA linac

X-band RF generation + delay line

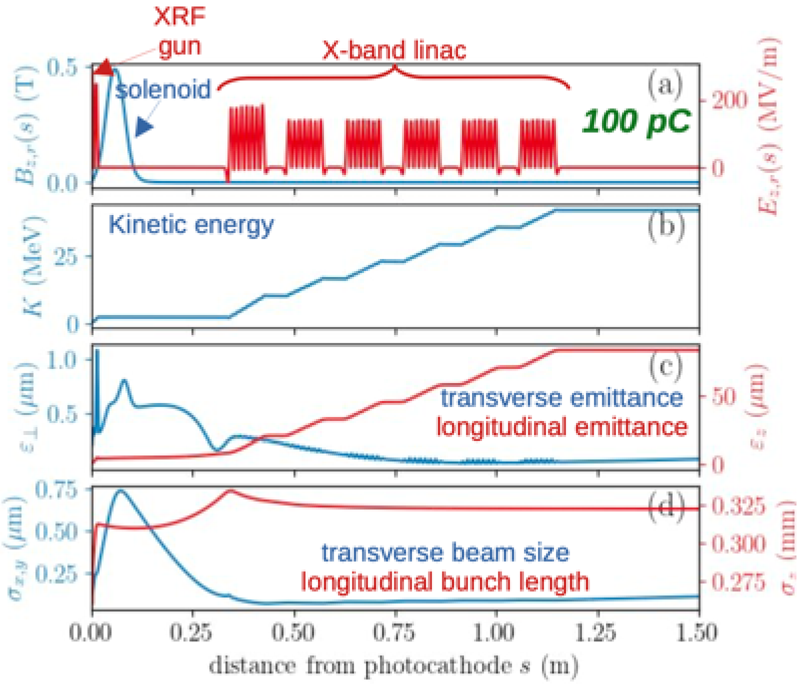
ICT: Integrated Current Transformer

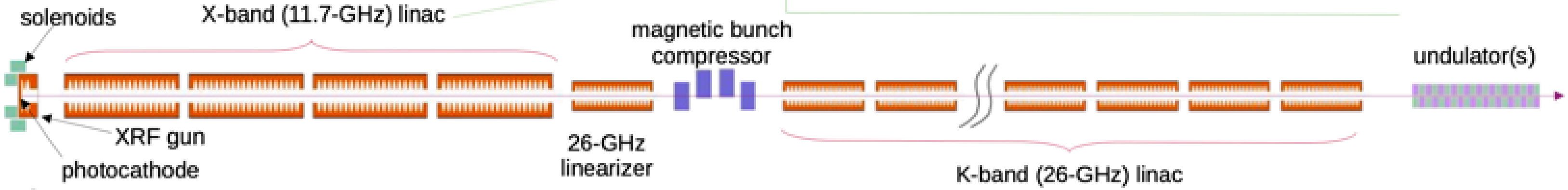
YAG: Yttrium Aluminum Garnet scintillating screen

PRELIMINARY MODEL IS PROMISING FOR COMPACT FEL

Still significant work to be done

- Preliminary simulations show a beam brightness of $\mathcal{B} \simeq 3 \times 10^{15}$ A/m^2.
- Similar performance to the ultra-compact XFEL proposal (UCLA) or LCLS-II-HE (SLAC) specifications.
- The parameters are compatible with injection in a 26-GHz linac for further acceleration stages.





SUMMARY

- With the scientific success of the current generation of FELs, we believe there is still significant room for optimizing and fully utilizing existing and future FEL facilities to open access to more user science.
- We have concepts for HPMUs and SCUs for creating compact undulator arrays that would allow simultaneous user operation.
  - Force-neutral Adjustable Phase Undulators are very promising in the near term
  - Short-period, high-field SCUs are under development as well as combining multiple SCUs in a single cryostat.
  - Demonstration of SCUs in a FEL is in process at SLAC/DESY over the next few years.
- New concepts for high gradient acceleration can improve the beam brightness and reduce the linac FEL driver length. The BrIAR regime for short pulse (<10 nsec) appears to renews interest in NRF acceleration. Argonne is actively pursuing R&D in this area.

CO-AUTHORS AND COLLABORATORS

Thank you very much!

APUs

- Joe Xu
- Maofei Qian
- Yinghu Piao
- Isaac Vasserman
- Wei Lu
- John TerHAAR

SCUs

- Yury Ivanyushenkov
- Susan Bettenhausen
- Maofei Qian
- Matt Kasa
- Ibrahim Kesgin
- Efim Gluskin
- Joel Fuerst
- Yuko Shiroyanagi
- Chuck Doose
- Quentin Hasse

High Gradient RF

- Gongxiaohui Chen
- Scott Doran
- Philippe Piot (NIU/ANL)
- John Power
- Emily Frame (NIU)
- Chunguang Jing (Euclid)
- Sergey Kuzikov (Euclid)
- Ryan Lindberg
- Xueying Lu (NIU/ANL)
- Eric Wisniewski