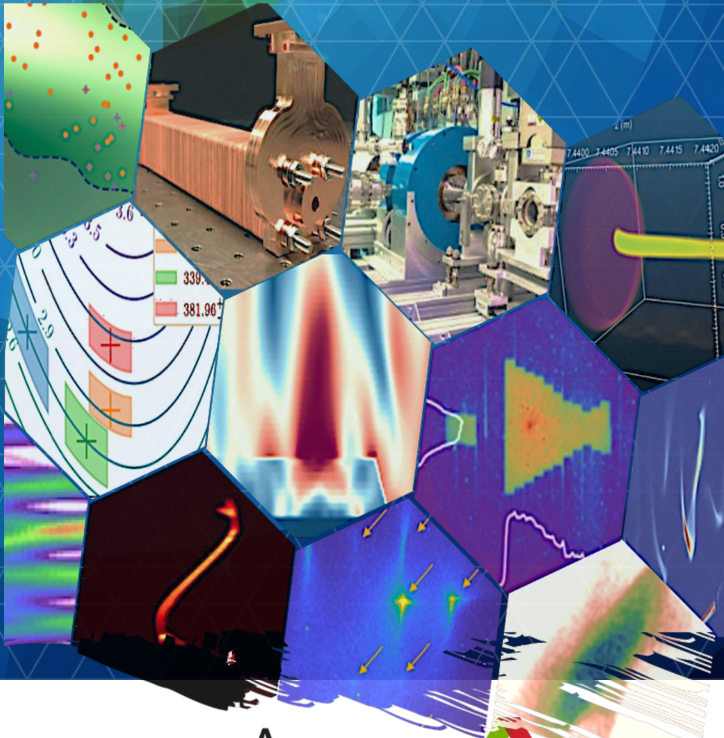
NOVEMBER 15, 2024

PAVING THE WAY FOR NEXT-GENERATION ELECTRON ACCELERATORS AT ANL

PHILIPPE PIOT, FOR THE AWA TEAM
Argonne Accelerator Institute
& Argonne Wakefield Accelerator



U.S. DEPARTMENT OF ENERGY

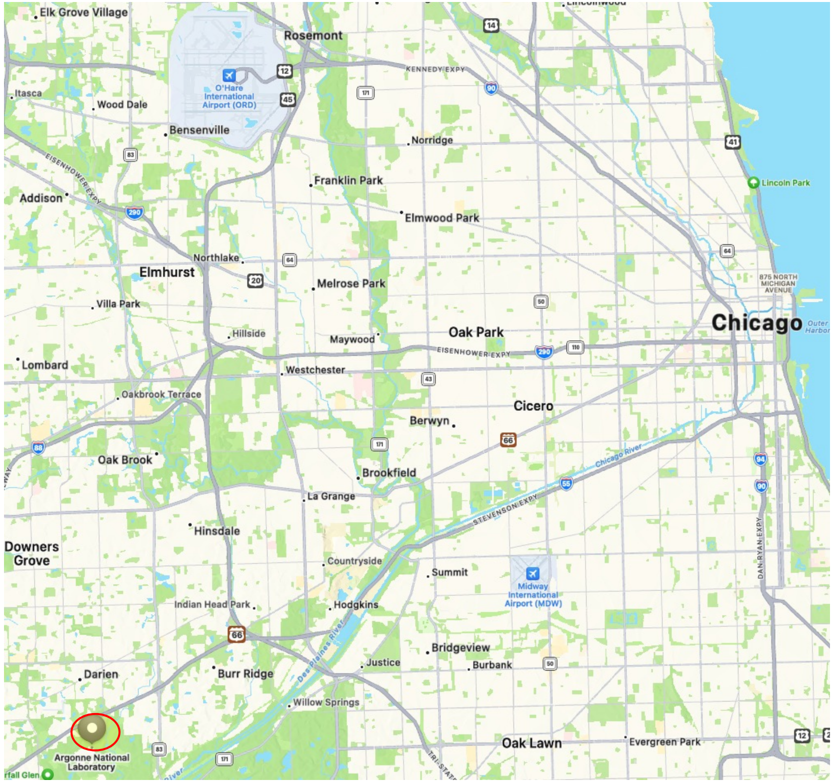
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

PREAMBLE…

Talk outline

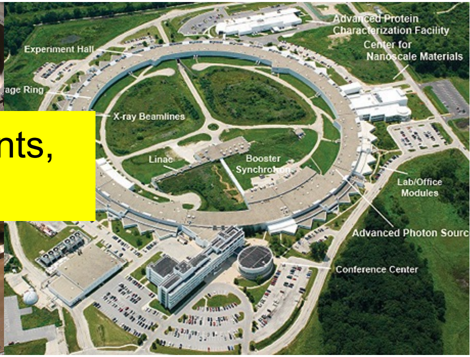
- Introduction & Background
  - Bright beams
  - Applications
- Research on e-beam @ANL
  - Why & roadmap
  - Some highlights
  - Opportunities
- Doing research @ANL
  - Visiting us (~4 hr from MSU!)
  - Working with us



OVERVIEW OF ARGONNE

An Ecosystem with Opportunities for Synergistics Research



Argonne: 3500 Staff, 475 Joint Faculty, 800 postdocs and students, 1600 visiting scientists + 6000 users

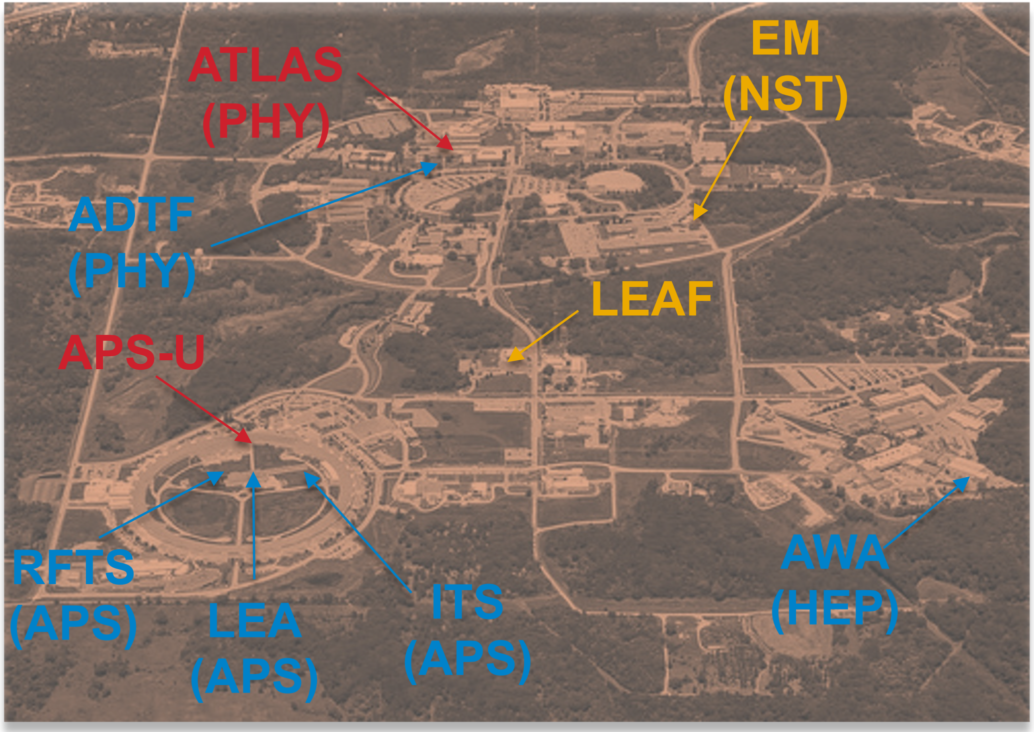
- Materials, Nanoscience
- Leadership Computing
- Nuclear & High-Energy Physics
- Photon Science

- Multidisciplinary national laboratory
- Several particle accelerators that serve as backbone for research: from flagship user facilities to “sandbox” facilities

ACCELERATOR PORTFOLIO AT ANL

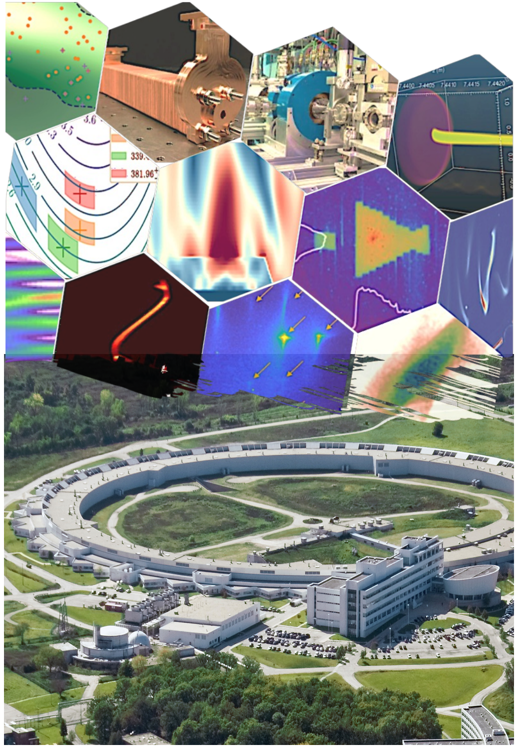
A unique and broad set of accelerator facilities & expertise

- National user facilities: APS & ATLAS
- Accelerator accessible to collaborators: LEAF, EM
- Facility that supports lab R&D:
  - **A**ccelerator **D**evelopment **T**est **F**acility
  - **RF** **T**est **S**tand
  - **L**inac **E**xtension **A**rea
  - **I**njector **T**est **S**tand
  - **A**rgonne **W**akefield **A**ccelerator



THE ARGONNE ACCELERATOR INSTITUTE (AAI)

Advancing Particle-Accelerator Science & Technology



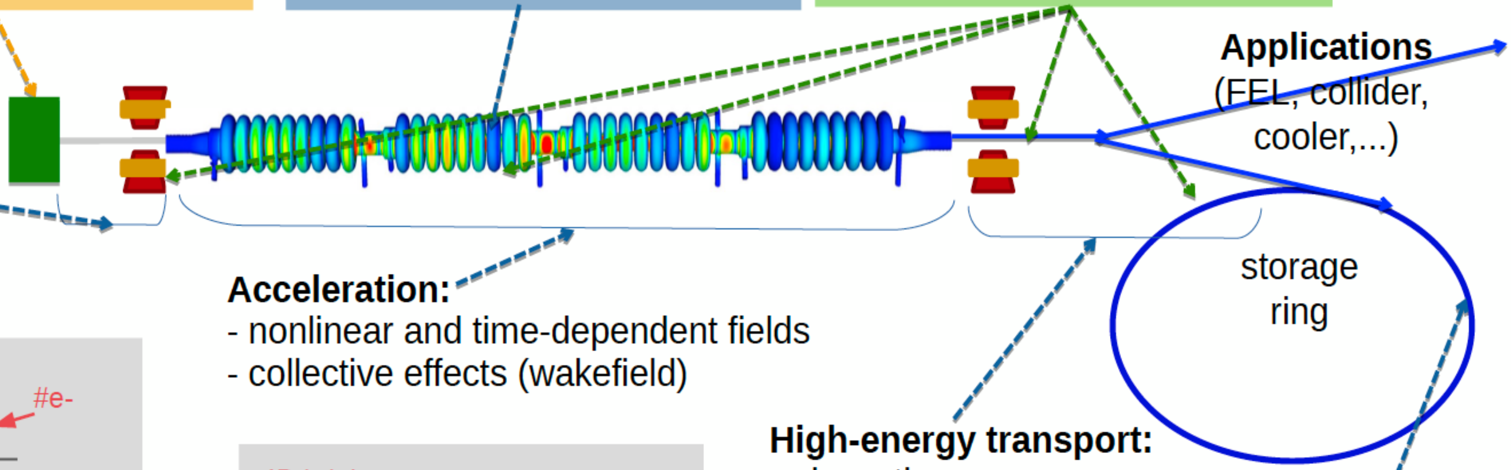
- Much of Argonne research, and the scientific community at large, depends on particle accelerators
- AAI's mission is to advance the science and technology of particle accelerators
- AAI's areas of focus include:
  - **Education:** Build a steady stream of accelerator scientists and engineers
  - **Accelerators for discovery:** Develop next-generation accelerator-based instrument for fundamental research
  - **Accelerators for society**: Explore societal use of particle accelerators

INTRODUCTION & BACKGROUND

BRIGHT BEAMS

Some definition & concepts

Beam Production | **Beam Acceleration** | **Beam Dynamics & Control**



Low energy transport:
- space-charge
- aberration

Acceleration:
- nonlinear and time-dependent fields
- collective effects (wakefield)

High-energy transport:
- aberration
- collective effects

Storage:
- instabilities
- heating+**cooling**

6D brightness; #e-

$$B_{6D} = \frac{N}{\varepsilon_{6D}}$$

6D emittance; 4D emittance

$$\varepsilon_{6D} = \varepsilon_{4D}\varepsilon_{nz}$$

4D brightness

$$B_{4D} = \frac{N}{\varepsilon_{4D}} \propto \frac{1}{MTE}$$

ELECTRONS FOR MICROSCOPY/DIFFRACTION

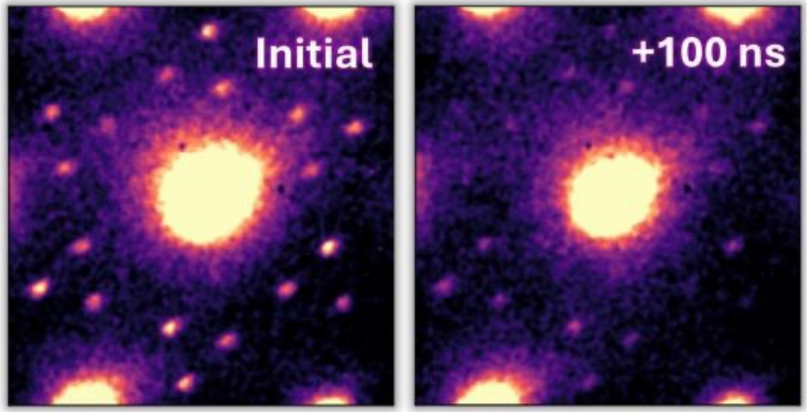
Electrons to probe the structure of matter

- Low energy (keV to MeV) bright electron beams behave as wave, figure of merit is brightness and lateral coherence

$$L_{\perp} \simeq \frac{\hbar}{mc} \frac{\varepsilon_{\perp}}{\sigma_{\perp}}$$

transverse emittance & beam size

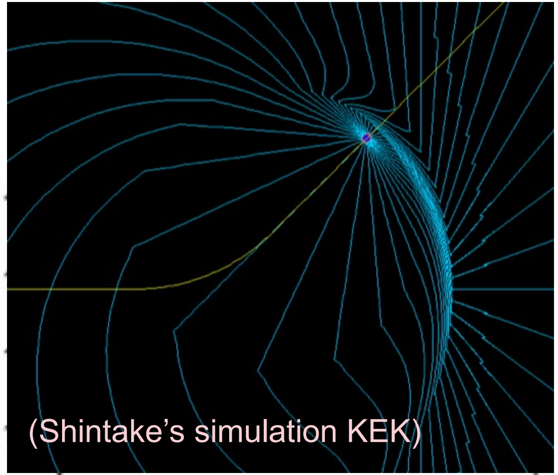
(Image by Argonne National Laboratory.)



- $L_{\perp} \sim a$ lattice spacings of the sample
- Serves as primary probe to explore structure of matter at the atomic scale
- On going step is to produce fs-scale bunches for high-resolution time-resolve molecular movies

ACCELERATOR-BASED LIGHT SOURCES

Electrons as source of photons

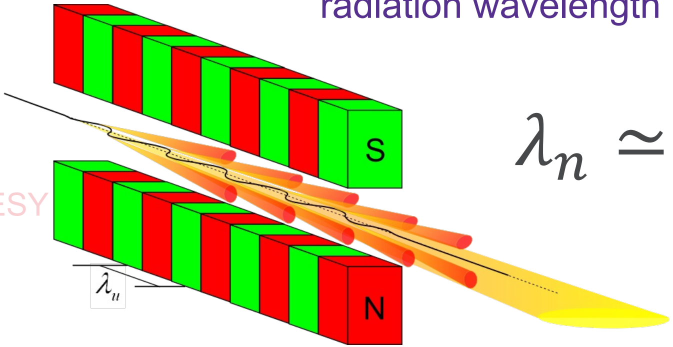


- Radiated power due to centripetal acceleration (i.e. in B field) scales as

$$P \propto \mathcal{E}^4$$

e- beam energy

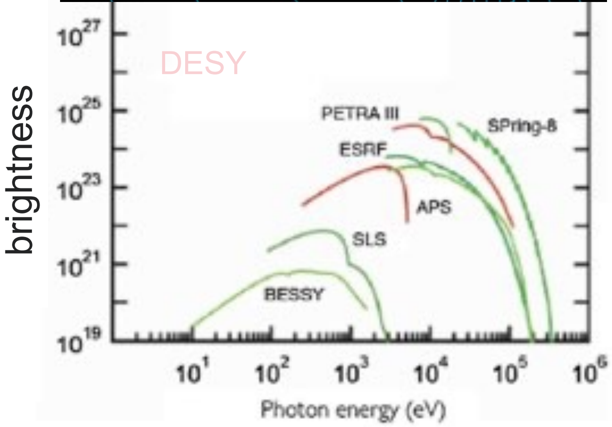
- Synchrotron radiation emitted in bending magnet
- Synchrotron radiation emitted in undulators



radiation wavelength, undulator period

$$\lambda_n \simeq \frac{n\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Lorentz factor, undulator parameter

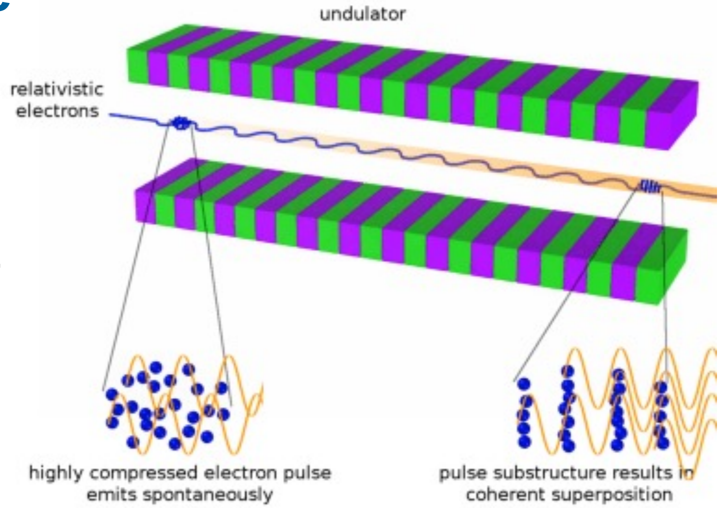


ACCELERATOR-BASED LIGHT SOURCES

The free-electron laser: enabling coherence

Bright electron sources

FEL performances scales with e- beam brightness $\rho_p \propto \mathcal{B}$



(adapted from ETH Zurich)

Short-period undulators

undulator period

$$\lambda \propto \lambda_u/\mathcal{E}^2$$

radiation wavelength

High-gradient accelerating structures

accelerator length

accelerating gradient

$$L \propto \mathcal{E}/G_{acc}$$

final e- beam energy

- High-frequency conventional accelerators
- Wakefield accelerators

ENERGY-FRONTIER LINEAR COLLIDERS

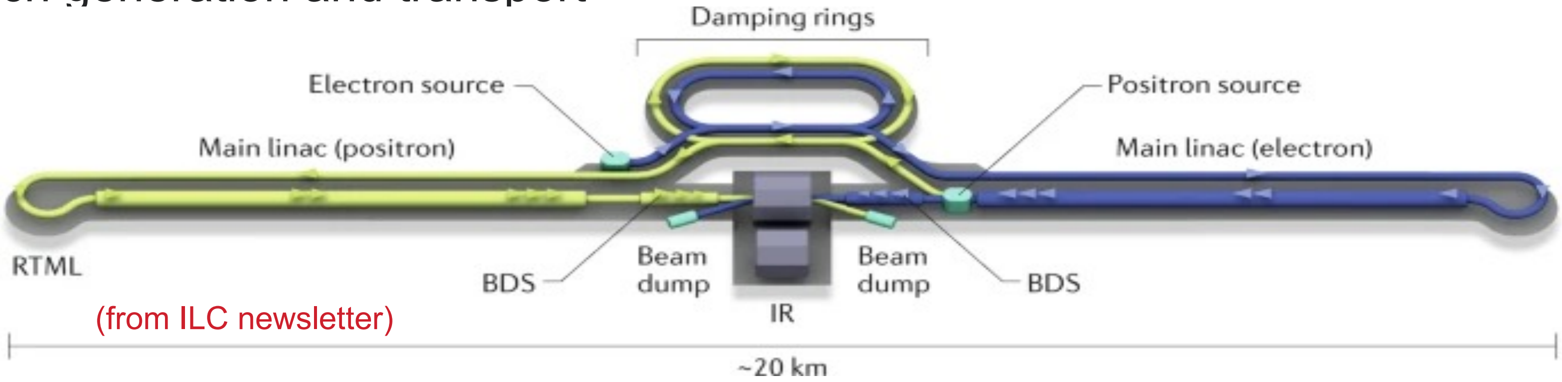
Probing the standard model and beyond

- Figure of merit is luminosity

$$\mathcal{L} \propto \frac{P}{\mathcal{E}} \frac{N}{\sigma_x \sigma_y}$$

P: beam power
σ: beam sizes
N: number of particle/bunch

- The luminosity is ~proportional to the beam 4D brightness programs
- Next-gen collider at the energy frontier 10 TeV center-of-mass relies on bright bunch generation and transport

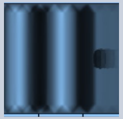


(from ILC newsletter)

RESEARCH ON ELECTRON ACCELERATORS: MOTIVATIONS & HIGHLIGHTS

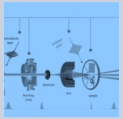
RESEARCH ON E-BEAM

Motivations



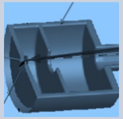
Long-term research

- Advanced acceleration: high-gradient high-efficiency acceleration
- Beam production: brightness & high charge
- Beam manipulation & diagnostics: shaped-beam distribution, emittance control and repartitioning



Midterm research with immediate impact

- Preparing for next accelerator facilities
- Enabling new mode of operation/capabilities for current facilities
- Developing a testbed for R&D Accelerator Science and Engineering



Short term research with immediate impact

- Improving beam diagnostics & controls
- ML-driven Autonomous operation
- Upgrade/enhancement of current facilities

INTRA-LAB COLLABORATION

Example of autonomous control of particle accelerators

User facility: reliability/efficiency

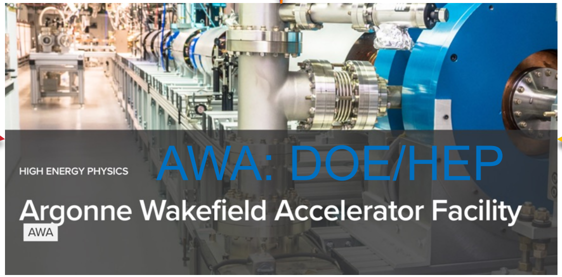
User facility: high demand broad operating parameters

shared expertise EPICS, LLRF

Tests of AIML algorithm

ML-based diagnostics

Funding from DOE/NP



Flexible "sandbox" facility

Extramural collaborators

- **Outcomes:**
  - joint proposal
  - APS test/staff at AWA
  - Expertise from APS & ATLAS to help AWA

SHORT TERM RESEARCH OPPORTUNITIES

Enabling APS at its full performance

- The APS storage ring was recently upgraded and is in its commissioning phase
- Lowest emittance ring in the world! Operate in the diffraction limited mode

$$\varepsilon_u \simeq \lambda/(4\pi)$$

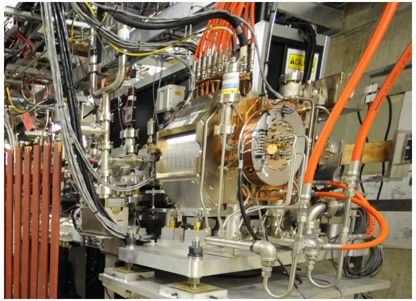
- It will take a few years to fully deploy APS capabilities
  - New fast (>kHz) feedback system for beam stabilization
  - R&D on phase-space diagnostics
  - Autonomous operation enabled by Machine Learning (on going)

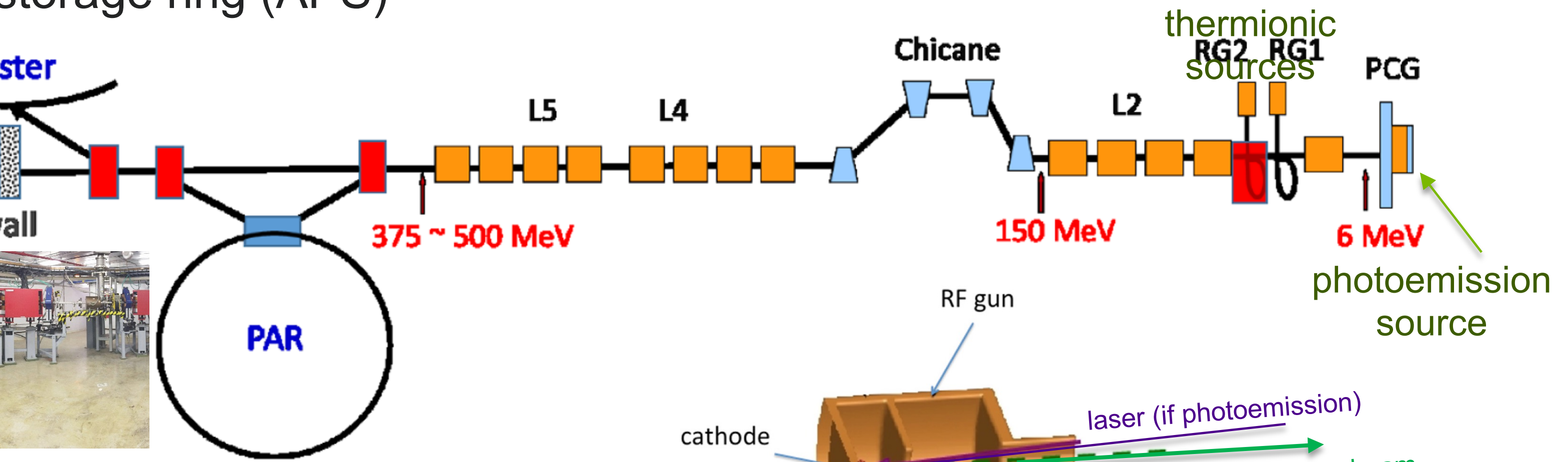
RESEARCH ON E-BEAMS

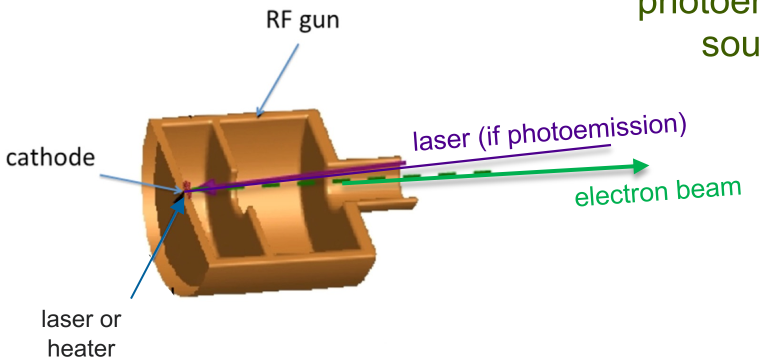
Opportunities at APS

- **BOOSTER**: energy ramp to 6 GeV for injection in the main storage ring (APS)

- **Linac**: generates ~400-MeV electron bunches organized as a 15-ns train of bunches





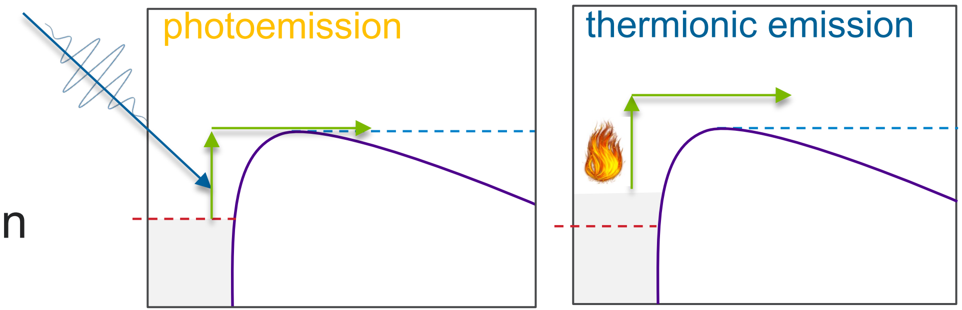


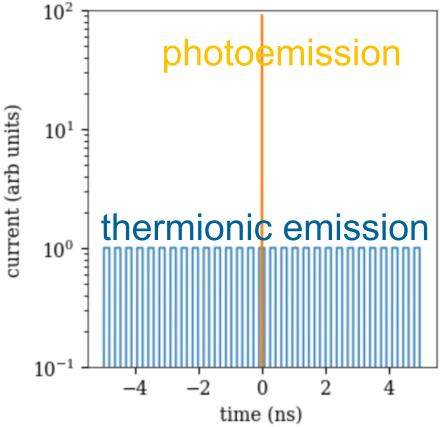
- **PAR**: particle-accumulator ring: beam cleaning and pulse shortening final bunch duration is 1 ns

SHORT TERM RESEARCH OPPORTUNITIES

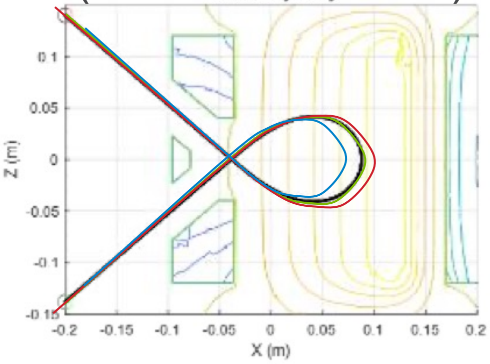
Electron sources developments

- Improving injector chain to support reliable high charge operation
- Current electron sources are based on thermionic emission slow turn on/off
  → fills many RF bucket
  → large energy spread
  → need alpha magnet to reduce spread and microbunches duration
- Alternate electron photoemission electron source available and will be restarted in the summer 2025
- Paths & limits to ultimate brightness?





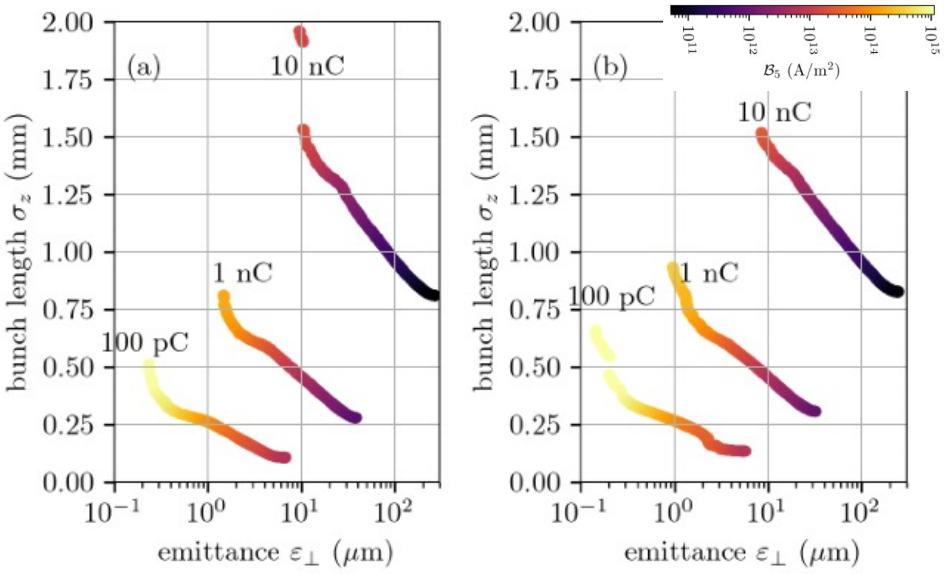
alpha magnet (from RadiaBeam)

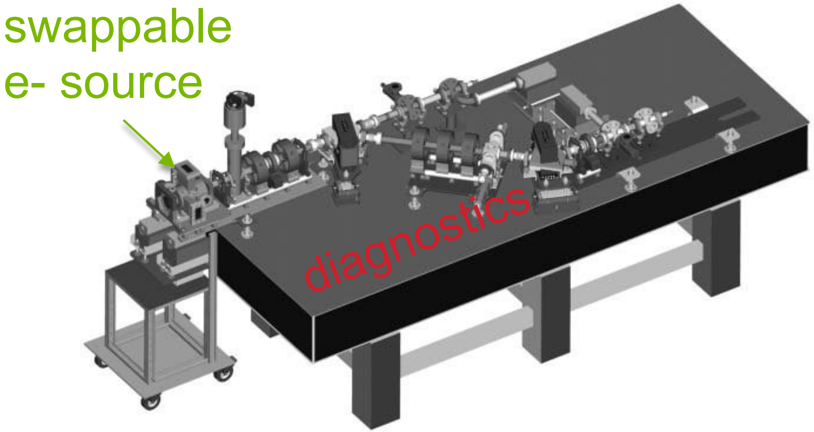


SHORT TERM RESEARCH OPPORTUNITIES

Electron sources R&D @APS

- Photoemission can generate high charge bunches
- Optimization of laser shaping and accelerator parameters → potential for bright beam generation → R&D on future light source (FLS) concepts





- Synchronization of laser with RF at the 100-fs time scale, nonlinear optics, and physics of photoemission using the Injector Test Stand (ITS)

PATH TO BRIGHTER BEAMS?

Experimental opportunities at APS

- Scaling of beam brightness:

$$\mathcal{B} \propto \frac{E_0^{\nu}}{\mathrm{MTE}}$$

4D beam brightness (*ideally* invariant) → $\mathcal{B}$

field experienced at emission (controlled by applied accelerating field) → E_0

depends on ab-initio aspect ratio of the beam → ν

mean-transverse energy [a property of the emitting surface (photocathode)] → MTE

- Two R&D directions:
  - R&D new photocathodes (decrease MTE)
  - **Work on electron source to support higher E-fields** (typical E~100 MV/m)
    - Limited by breakdown
    - Other limitation comes from photocathode physical and chemical topologies (e.g. surface roughness, or non uniform quantum efficiency)

GENERATING GV/M FIELDS IN STRUCTURES

Short-pulse regime – pushing CLIC technology

- Idea pioneered at the CERN linear collider (CLIC) facility: use very short RF pulse
- Short pulse acceleration → reduces **B**reak**d**own **r**ate

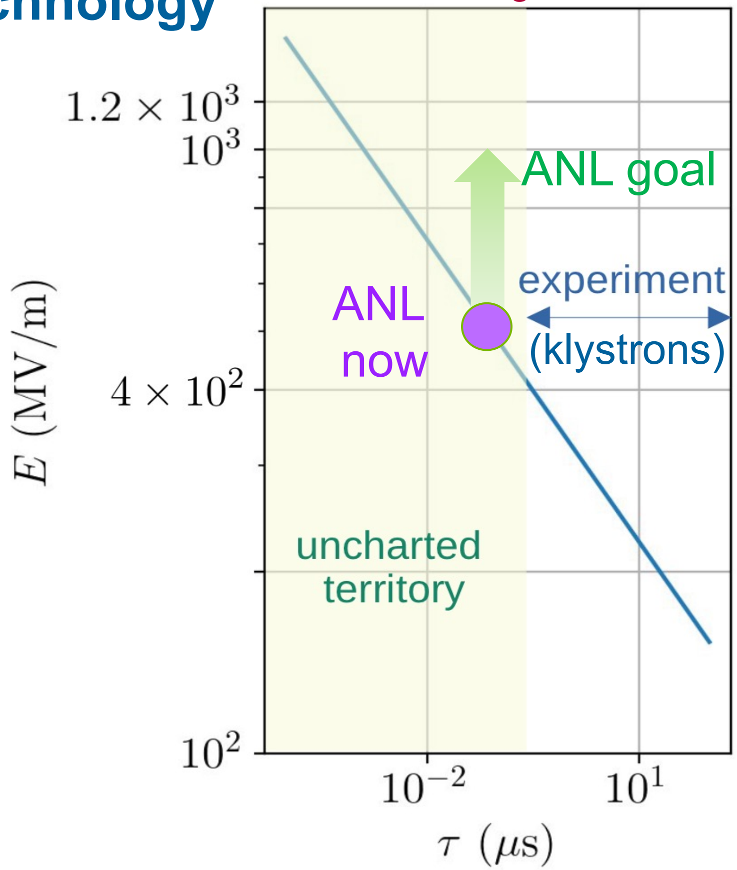
$$BDR \propto E^{30}\tau^{5}$$

RF pulse duration (τ)

accelerating field (E)

- **Impact:** GV/m accelerating fields, and eco-friendly accelerators

E vs τ for a given BDR

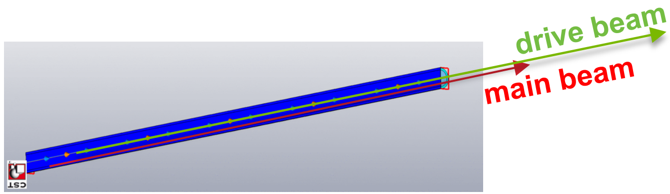


GENERATING HIGH FIELD WITH WAKEFIELDS

Wakefield: radiation field generated due to boundary conditions

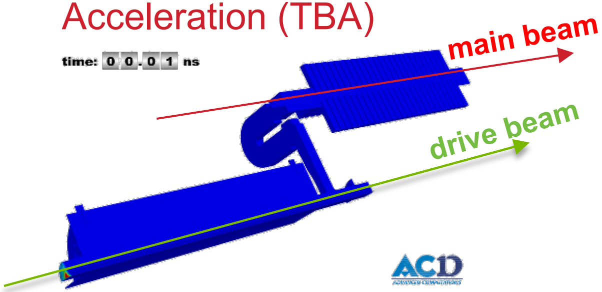
Two methods for producing high-peak electric field

- Collinear Wakefield Acceleration (CWA)
  - On-beamline for both bunch
  - **Near-field interaction scalable to THz**
  - E fields ~GV/m demonstrated



- Two-beam Acceleration (TBA)
  - Based on a conventional approach
  - High-power e.m. pulses generation based on wakefield
  - **Far-field interaction need technologies**
  - Two parallel beamlines

Two-Beam Acceleration (TBA)



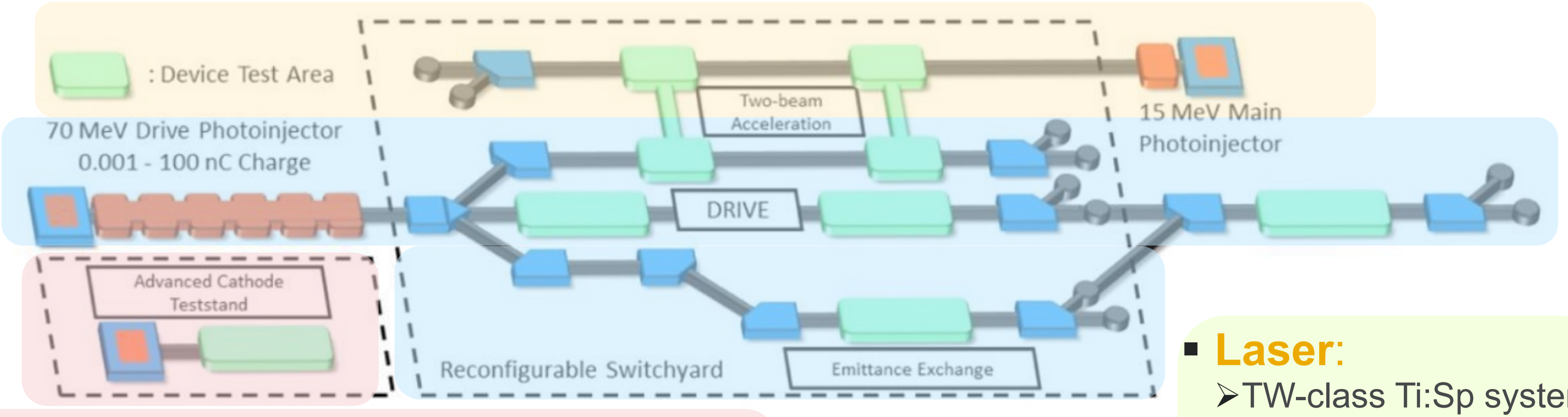
- All these techniques are [part of Structure Wakefield Acceleration (SWFA)

OVERVIEW OF AWA

A facility with unique capabilities

- **Drive beam:**
  - **Backbone accelerator**
  - ~60 MeV, bright or high-charge (1 pC ~100 nC) bunches

- **Main beam:**
  - High-quality 15 MeV bunches
  - nC-level charges



- **Laser:**
  - TW-class Ti:Sp system
  - 300 fs + laser shaping
  - <100 mJ IR pulses
  - 5 mJ UV pulses
  - Pulse train (GHz, THz)

- **Advanced Cathode Teststand (ACT):**
  - Cathode research (photo- and field-emission)
  - Physics of breakdown
  - Low energy diagnostics

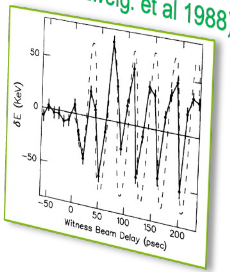
AWA: HISTORICAL NOTES

Groundbreaking Science paired with Technological Advances

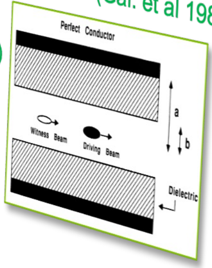
1st demo of beam-driven collinear wakefield acceleration in plasmas and dielectrics

Discovery of breakdown-insensitive acceleration regime

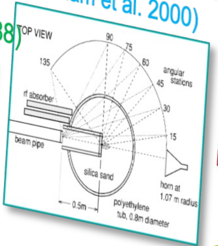
Plasma wakefield acceleration (Rosenzweig. et al 1988)



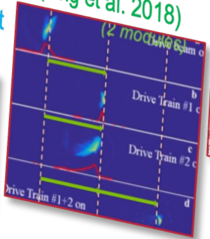
Dielectric wakefield acceleration (Gai. et al 1988)



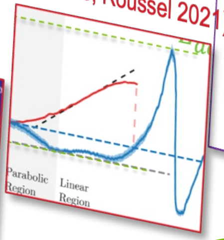
Astrophysics experiment (Gorham et al. 2000)



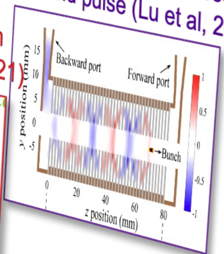
Staging of SWFA (Jing et al. 2018)



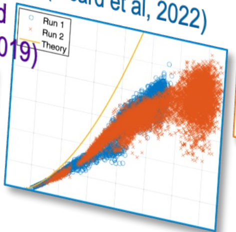
High-efficiency wakefield acceleration (Gao, 2018, Roussel 2021)



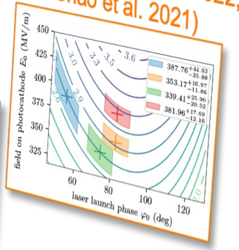
Observation of reversed wakefield pulse (Lu et al, 2019)



600 MW RF power (Picard et al, 2022)



Ultra-high gradient XRF guns (Tan et al, 2022, Shao et al. 2021)



Drive and witness bunch production

High-charge bunch generation via photoemission

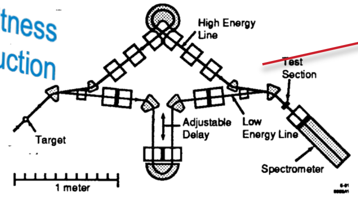
Schottky-enabled photoemission

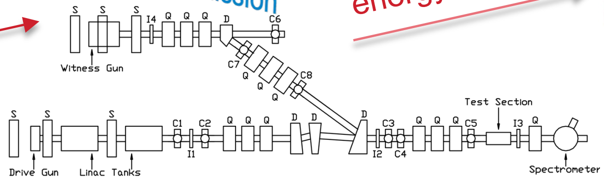
High-charge bunch train generation

Cross-plane phase-space manipulation & shaping

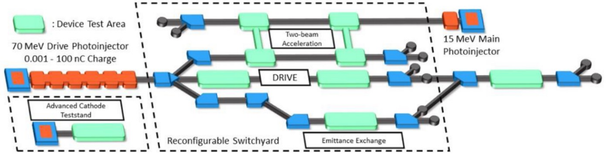
High-power RF pulse manipulations

"High-brightness" upgrade (gun, linac, LLRF, laser)





energy upgrade

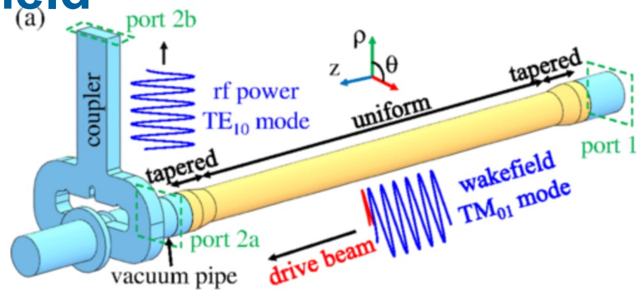


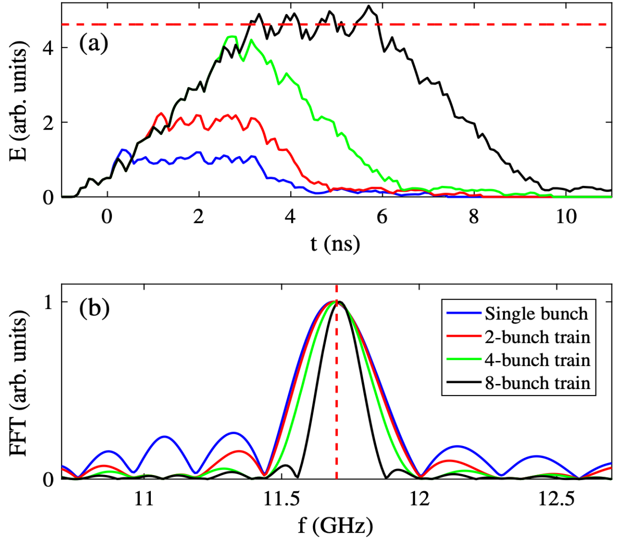
RF GENERATION

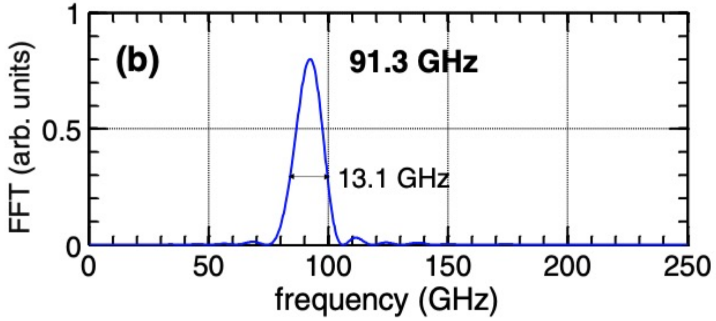
J. Shao et al., 10.1103/PhysRevAccelBeams.23.011301 (2020)]

High-peak-power short RF pulse from wakefield

- Principle: Coherent stacking of wakefield pulse produced by bunches within a train
  - Routinely produces 300 MW peak power (can generate up to 600 MW) at 11 .7 GHz
  - Can generate power at harmonic of 1.3 GHz (7.8 and 11.7 GHz done) other frequency need R&D
- Can generate sub-THz/THz frequency pulses





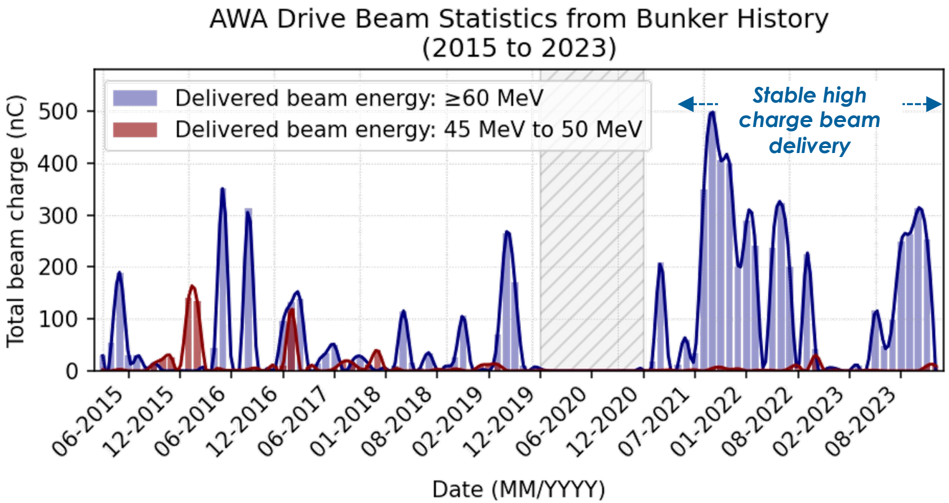


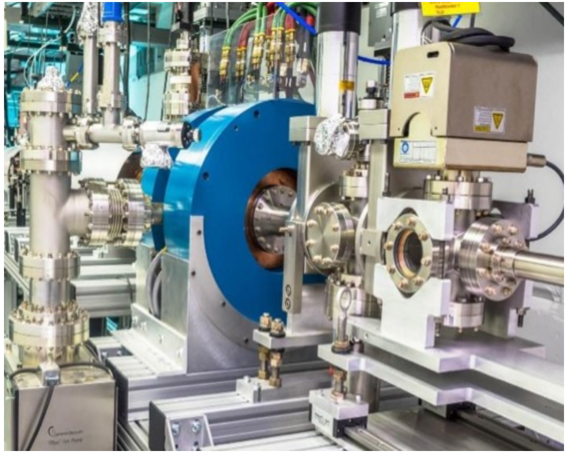
D. Wang, et al., 10.1103/PhysRevLett.116.054801 (2016)

HIGH CHARGE BUNCHES

The enabling technology for high-power RF pulses

- In-house research often require high-charge bunches
  - ~50 nC/bunch in single-bunch mode
  - Trains of 8 (possibly 16) high-charge bunches with 769 ps spacing (1.3-GHz RF period)





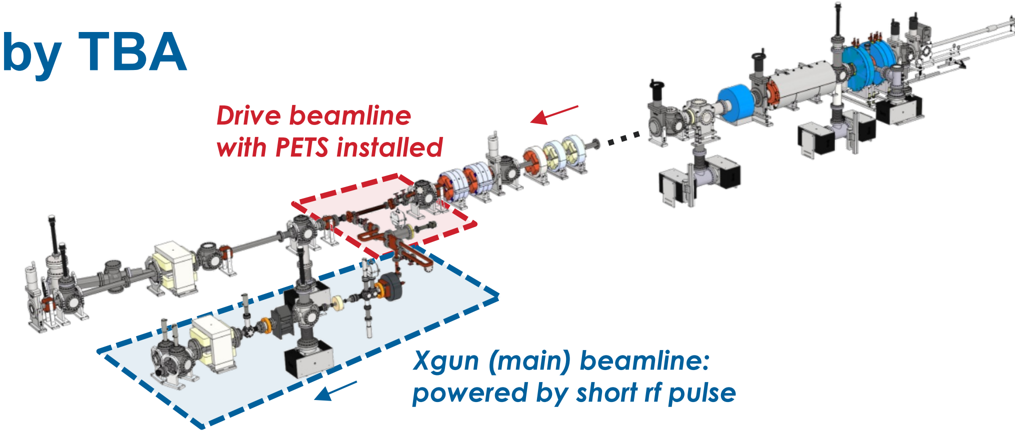
- Bunches are produced from a 1.3 GHz RF gun with ~80 MV/m field with Cs_2Te photocathode
- Photocathode laser up to 5 mJ UV pulses

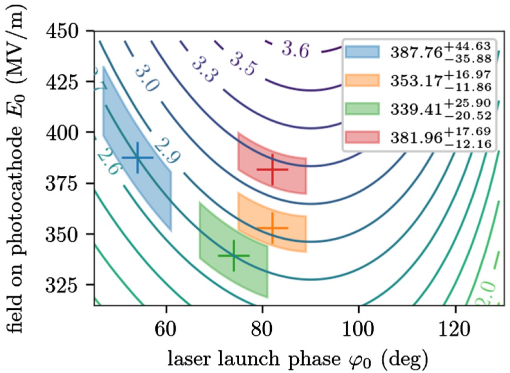
HIGH-GRADIENT X-BAND GUN

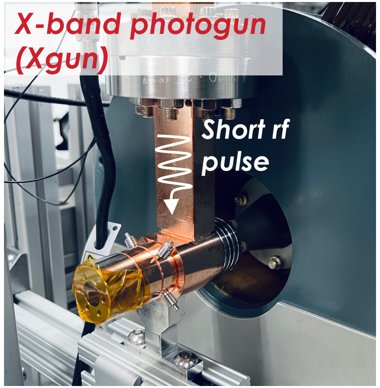
A path to bright beams enabled by TBA

- Development of a 1.5-cell X-band photogun (Xgun) powered by short rf pulse (9 ns), via TBA technique.
- High gradient (>350 MV/m) achieved in 2020, estimated from RF calibration.
- Stable beam produced in 2021, with highest gradient (**388 MV/m**) achieved and verified by beam energy measurements.

Note: *the current state-of-the-art S-band gun operates at a gradient of 140 MV/m.*







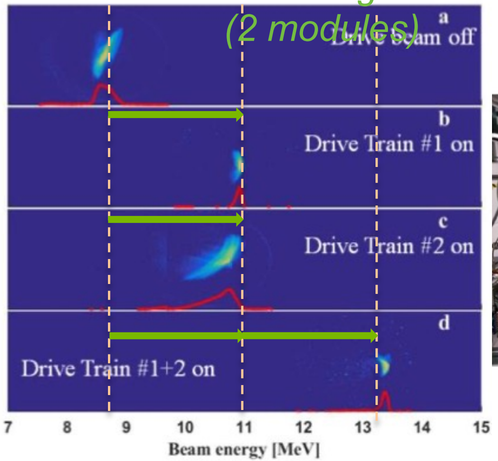
W.H.Tan et. al., 10.1103/PhysRevAccelBeams.25.083402 (2022)

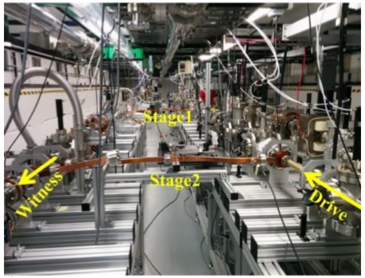
STAGING OF TWO-BEAM ACCELERATION

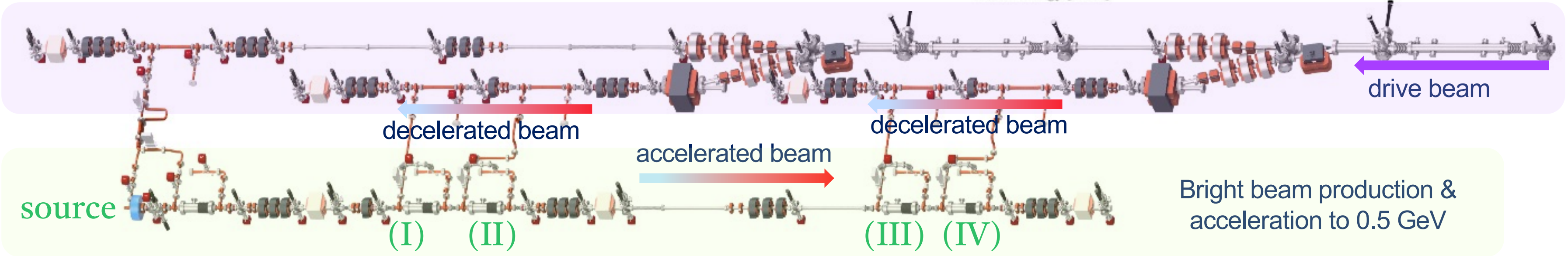
A large integrated experiment combining two beamlines

- Excitation of high-field in various structures via two beam acceleration or collinear wakefield field acceleration.
- Demonstrated staging in two subsequent accelerating module power.
- Staging scalable to any number of accelerating modules w/ proper RF distribution.

Demonstration of staged acceleration (2 modules)







Planned multi-staged acceleration experiment to 500 MeV

C. Jing et al. 10.1016/j.nima.2018.05.007 (2018)

SYNERGIES OF SWFA APPLICATIONS

Address Linear collider and future light source needs

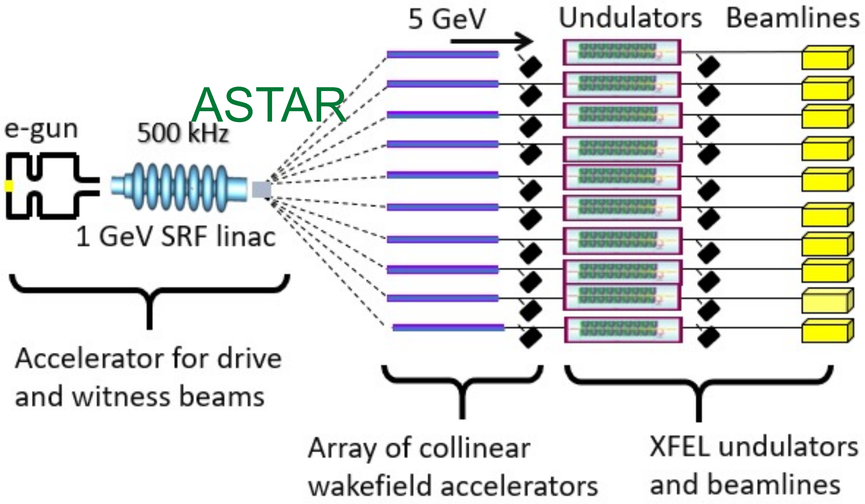
- SWFA is a viable candidate for a wakefield acceleration at kHz driven by an SRF linac – ASTAR project based on collinear wakefield acceleration.

- SWFA in two-beam acceleration configuration offers a pathway toward a compact ”semi-conventional” FEL -- work on electron source and FEL design in progress.

PREPARED FOR SUBMISSION TO JINST

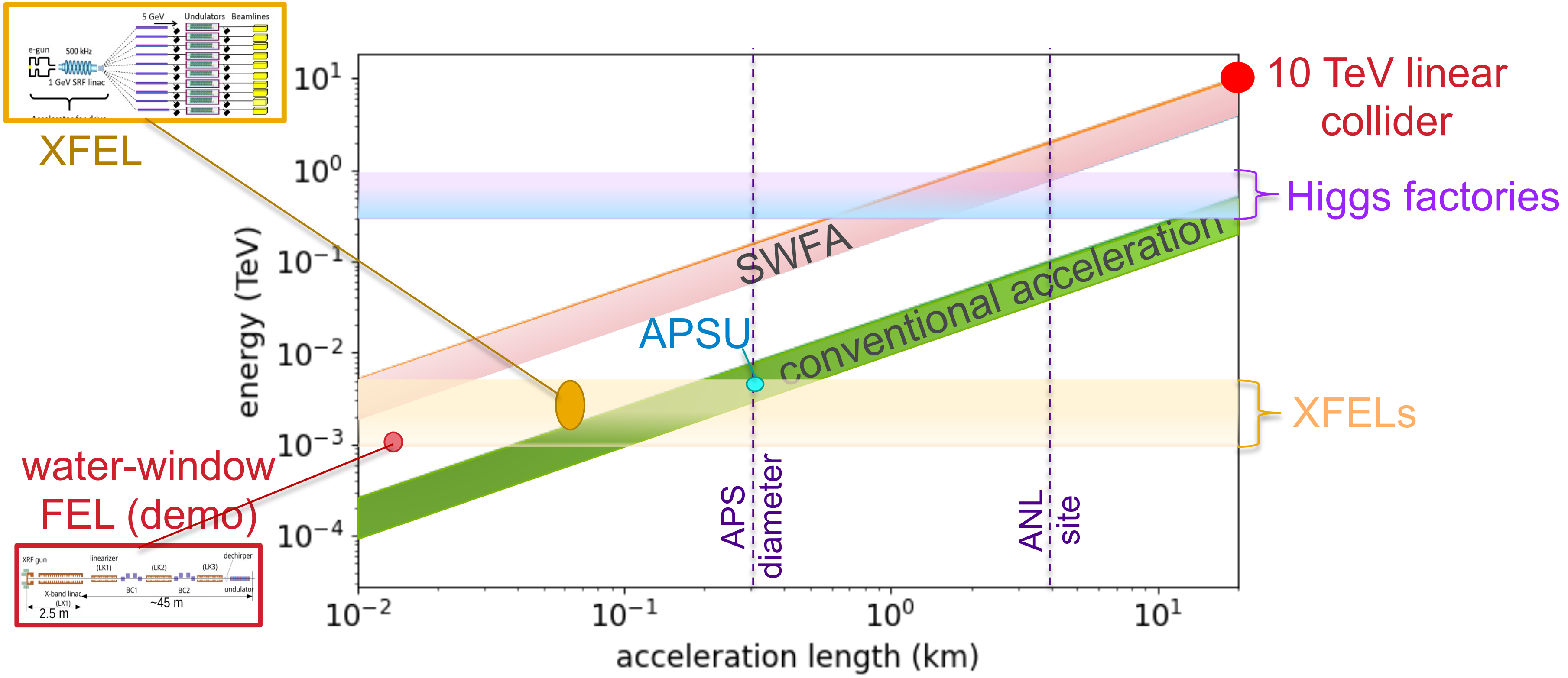
A high repetition rate millimeter wavelength accelerator for an X-ray free-electron laser

A. Zholents,[a,1] S. Baturin,[b,c] S. Doran,[a] W. Jansma,[a] M. Fedurin,[d] M. Kasa,[a] K. Kusche,[d] S. Lee,[a,e] A. Nassiri,[a] P. Piot,[a,b] B. Popovic,[a] M. Qian,[a] A. Siy,[a,f,g] S. Sorsher,[a] K. Suthar,[a] E. Trakhtenberg,[a] G. Waldschmidt,[a] J. Xu[a]



OPPORTUNITIES

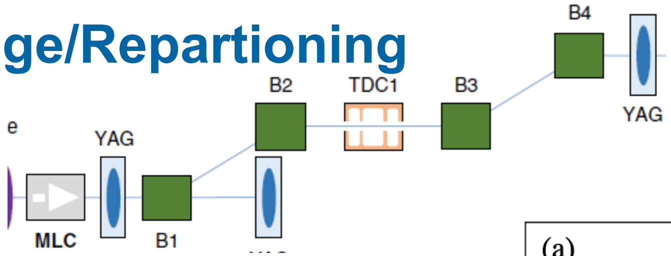
Applications to photon science and high-energy physics



BEAM ON DEMAND

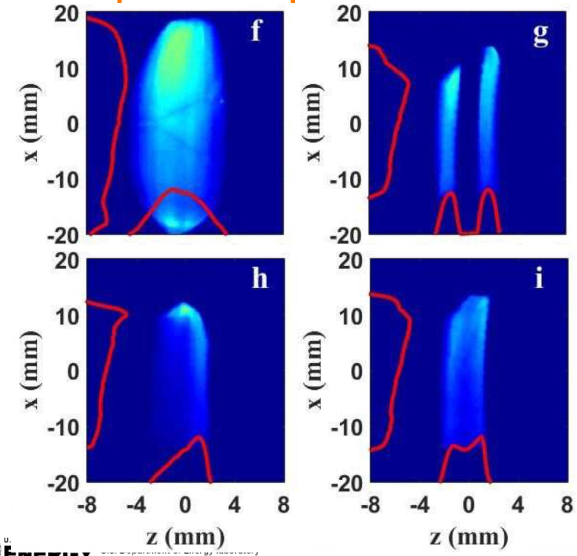
[G. Ha, et al., 10.1103/PhysRevLett.118.104801 (2017)]

Beam Shaping & Phase-Space Exchange/Repartioning

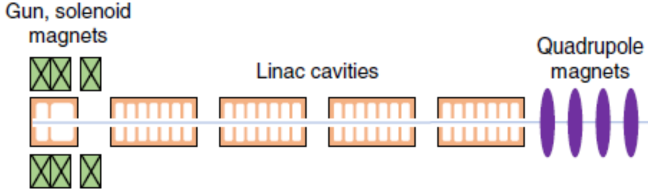


- **Transverse-to-longitudinal phase-space exchanger (“emittance exchange”)**
  - Shape (*x,x’*)
  - Exchange (*x,x’*) with (*z,δ*)

→ shaped temporal distribution

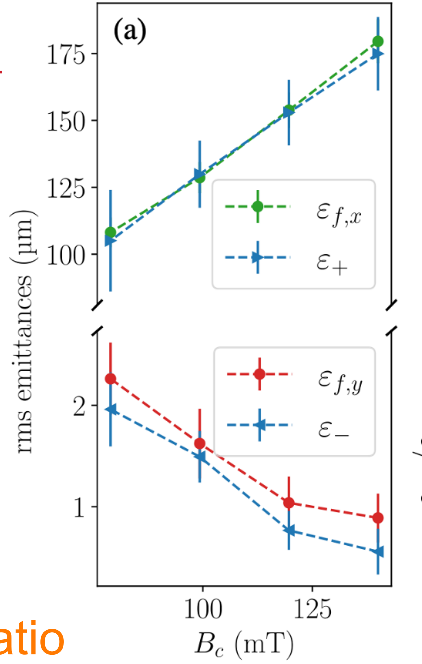


[T. Xu et al., 10.1103/PhysRevAccelBeams.25.044001 (2023)]



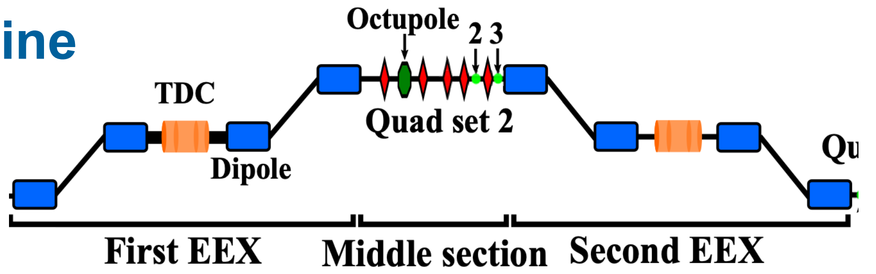
- **Flat-beam generation**
  - Produce a magnetized beam (with angular–momentum)
  - Apply torque with skew quadrupoles

→ control of transverse emittance ratio



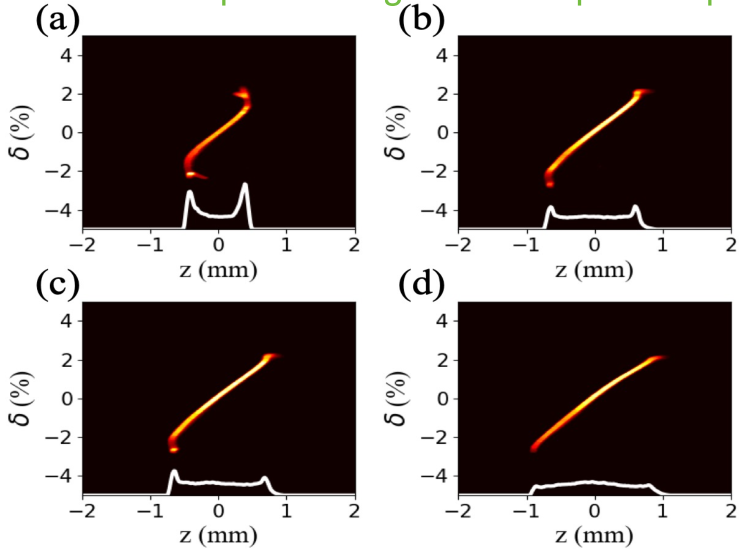
LONGITUDINAL PHASE-SPACE SHAPING

Cascaded emittance-exchange beamline



- Two consecutive EEX beamline with quadrupole/multipole-magnet insertion
- The strength of the magnets provides precise control over the longitudinal phase space distribution
- Experiment:
  – Demonstrated chirp LPS-chirp control using quadrupole magnets (no RF!)
  – Controlled 3rd nonlinear correlation in the LPS using an octupole magnet
- Applications:
  - Improve transformer ratio
  - Mitigation of beam break-up instability

Effect of octupole strength on final phase space



J. Seok, et al., 10.1103/PhysRevLett.129.224801 (2022)

ML-BASED DIAGNOSTIC

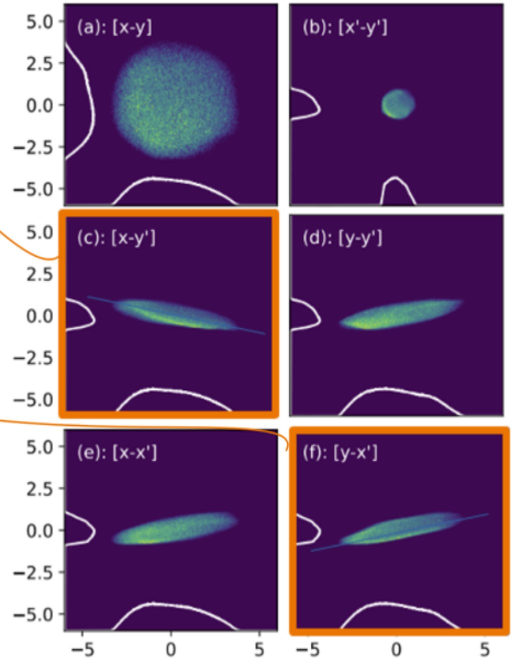
ML-based 4D phase-space reconstruction

- Demonstrated AIML-based generative reconstruction to infer 4D phase-space distribution → direct access to all 2D projections (including inter-plane ones)

$$\Sigma = \begin{bmatrix} \epsilon_{eff} T_x & \mathcal{L}J \\ -\mathcal{L}J & \epsilon_{eff} T_y \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

- Experiment:
  - Applied to characterization of magnetized beam (e.g. critical for e- cooling of hadron beams)
- Impacts:
  - Unprecedented knowledge on the full phase space distribution
  - Expanded to 6D → inform how to correct aberration/coupling



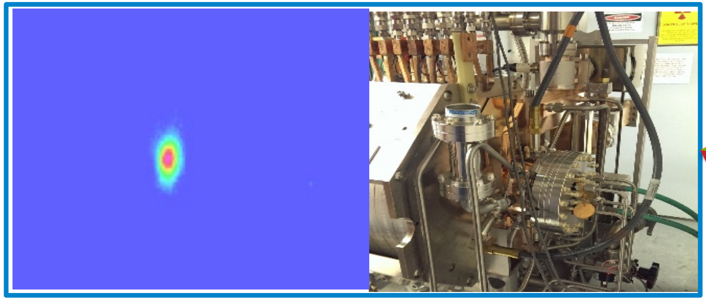
Reconstructed 4D phase-space projection

S. Kim et al., 10.1103/PhysRevAccelBeams.27.074601 (2024)

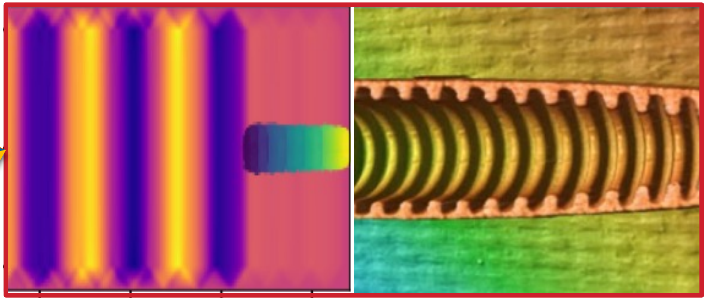
R. Roussel et al., 10.1103/PhysRevAccelBeams.27.094601 (2024)

EMERGING NEW OPPORTUNITIES

Transdisciplinary expertise enables *exciting* opportunities



Enabling new opportunities within the APS complex (ASD/HEP)



Next-gen accelerators for energy frontier & light sources (HEP. APS)

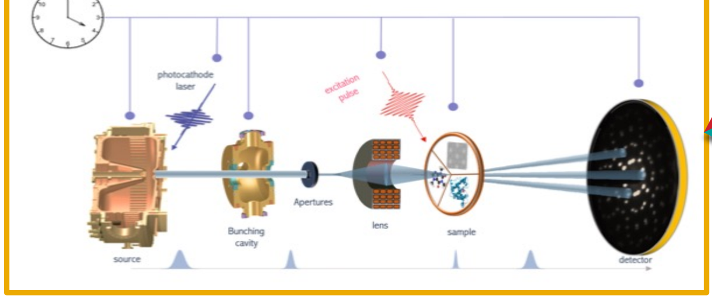
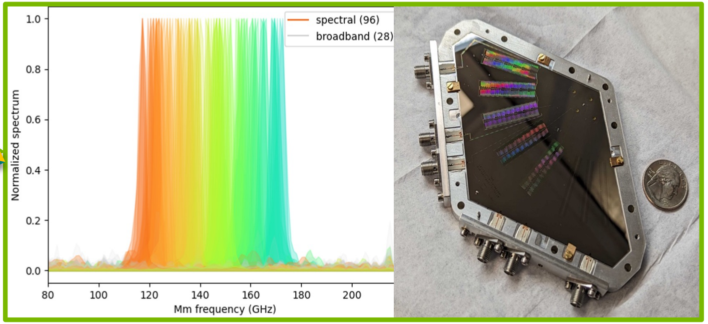


Image from D. Filippetto, LBNL

Exploring technologies for ultrafast electron scattering (NST, HEP, PHY)



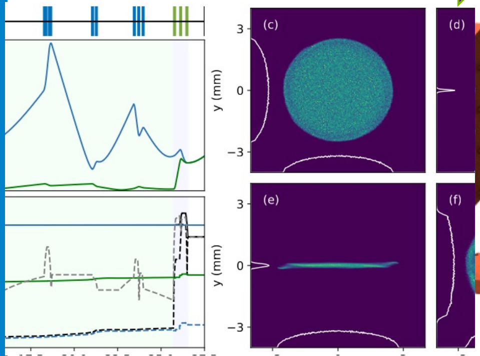
Applying cosmic-frontier detectors to accelerator (HEP, APS)

DOING RESEARCH IN ACCELERATOR SCIENCE & ENGINEERING AT ANL

OPPORTUNITIES

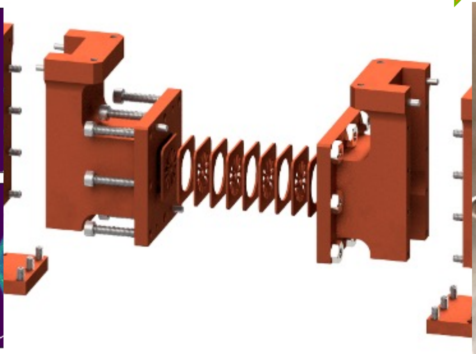
Collaborations (lab- versus university-driven)

Modeling



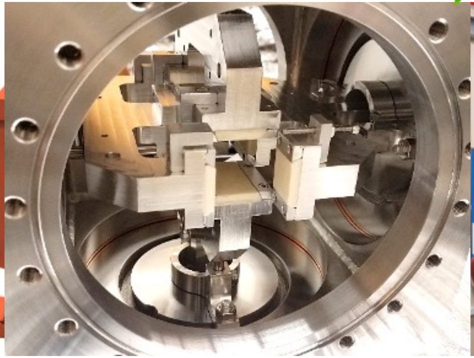
- Beam dynamics & electromagnetic modeling
- Beam dynamics models

Design



- Mechanical engineering, beamline design
- Electrical engineering e.g. PCB layout

Fabrication



- Magnet fabrication
- UHV installation
- Sample preparation (e.g. cathode) or cleaning

Operation

- Beamline operation (ML)
- Collaborate on DAQ (python+EPICS)

▪ Broad infrastructure and expertise

▪ All topics mentioned have opportunities for MS or PhD research

INITIATING COLLABORATION

Students are integral part of the ANL fabric

- Students provide a path to expanding research at the lab; either to work ANL-driven projects or as part of broader collaboration with university & industry
- Possible paths for graduate students:
  - SCGSR (DOE): usually work with university (faculty/student) to write a proposal (the AAI can support few weeks visit for preparing such proposal)
  - University-funded/university-driven collaboration to perform research in one of ANL groups: more flexibility on project selections (as long within ANL competencies, and related to ANL mission) – AAI can help with proposal
  - University-funded ANL-driven collaboration – usually joint proposal to a funding agency
  - AAI-supported Ph.D: research needs to focus on a project aligned with ANL strategic planning
- **If you have any interest let us know accelerator@anl.gov !**

Thank you for your attention.

This research was conducted at Argonne National Laboratory and supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.