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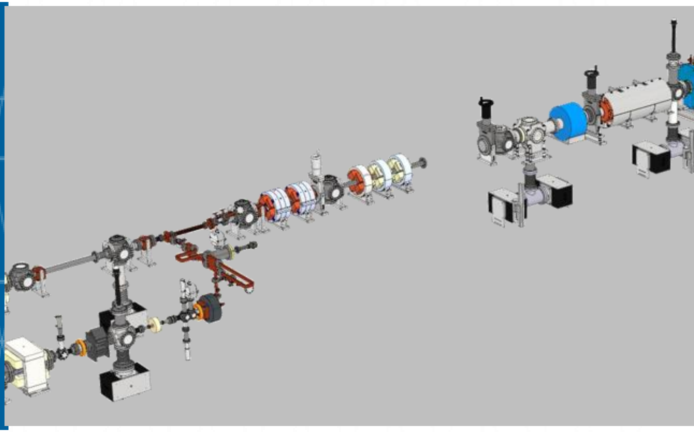
Argonne NATIONAL LABORATORY

DESIGN OF A WATER-WINDOW FREE-ELECTRON LASER USING THE TWO-BEAM ACCELERATION SCHEME



PHILIPPE PIOT
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& Argonne Wakefield Accelerator

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MOTIVATION

Next-gen future light source at ANL

- ANL recently successfully commissioned the Advanced Photon Source upgrade
- In parallel to performance improvements, and to enabling new capabilities at APS, we are also exploring a future light source (FLS) concept
- One of the approaches is based on recent work on two-beam acceleration at the AWA
- First step is to demonstrate the concept in the water-window regime [2,4] nm to support a physics program

INTRODUCTION

Ingredients for a compact Free Electron Laser (FEL)

- Bright electron beams

4D brightness

$$\mathcal{B} \propto E_0^{\nu}$$

E-field during emission

- Short-period undulator

radiation wavelength

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

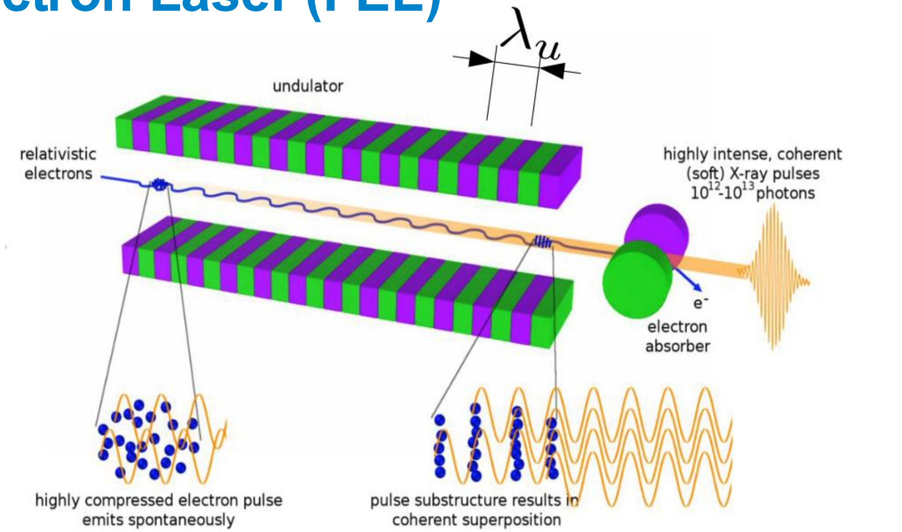
undulator period

- High-gradient accelerator

accelerator length   beam energy

$$L_{acc} \sim \mathcal{E} / G_{acc}$$

accelerating gradient



[Adapted from ETH Zurich]

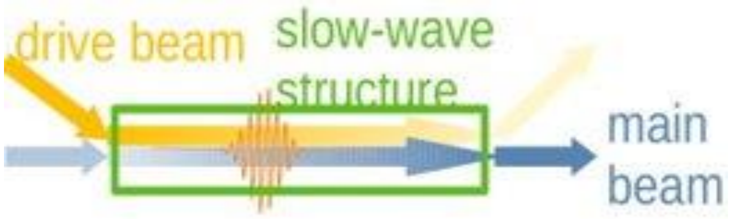
- High-frequency linacs
- Wakefield accelerators
- Two beam accelerators

GENERATING HIGH FIELD WITH WAKEFIELDS

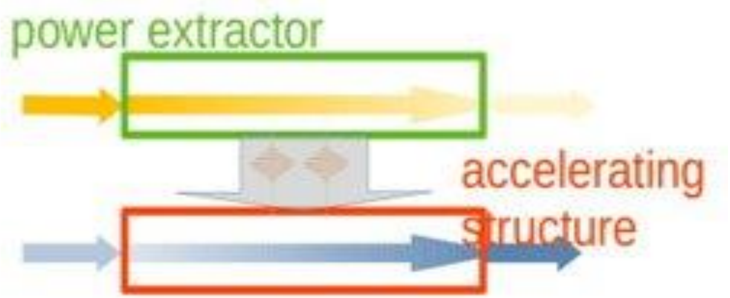
Wakefield: radiation field generated due to boundary conditions

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



- All these techniques can be implemented in Structure Wakefield Acceleration (SWFA)

PATH TO GV/M FIELD IN STRUCTURES W/ TBA

Short high-peak-power RF pulse

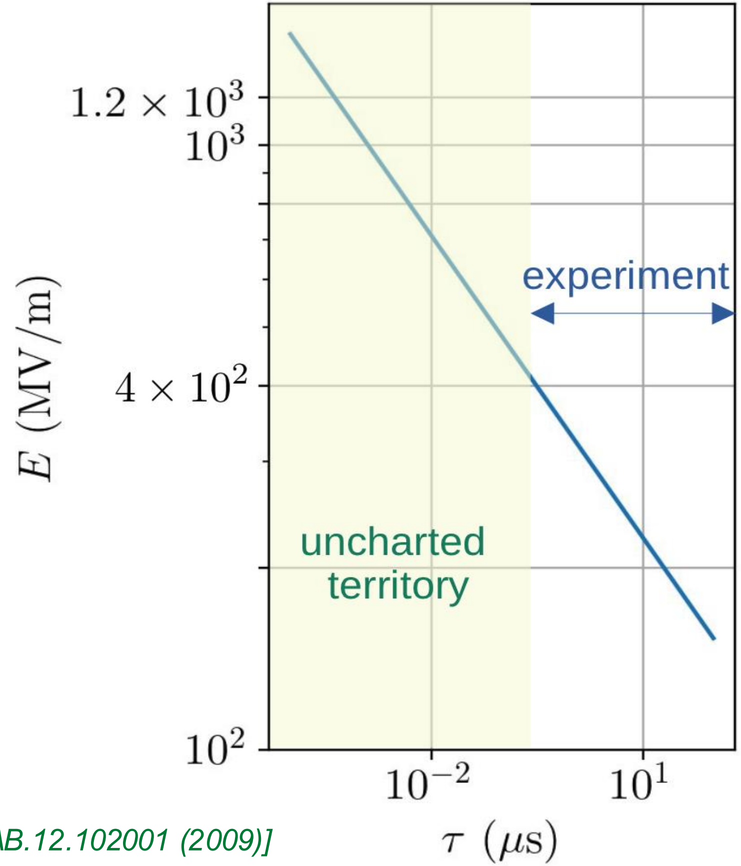
- Breakdown is a major limitation toward producing high electric field in structures
- Phenomenological model based on large data* set suggest a scaling the breakdown rate (BDR)

field → E

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

RF-pulse duration → τ

- So far pulse duration has been limited by available RF pulse duration (typically from Klystron)
- Shorter RF pulses enabled by wakefield provide a path to high accelerating gradient

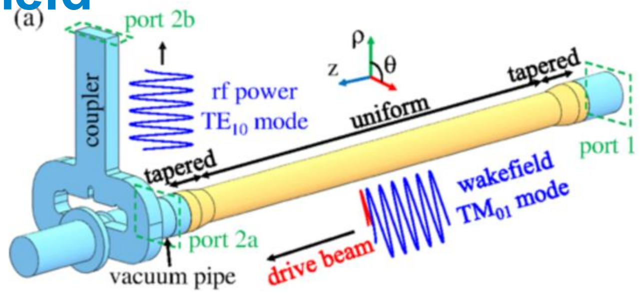


[A. Grudiev, et al. PRAB 10.1103/PhysRevSTAB.12.102001 (2009)]

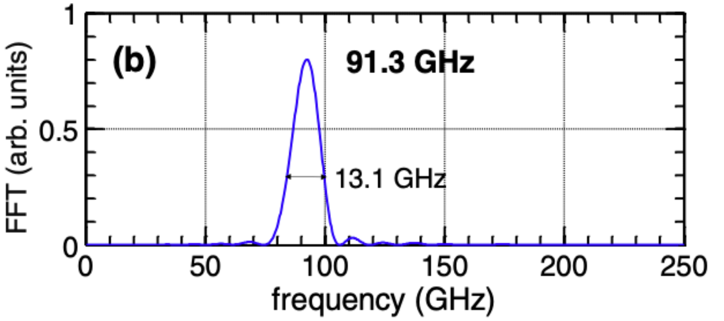
RF GENERATION

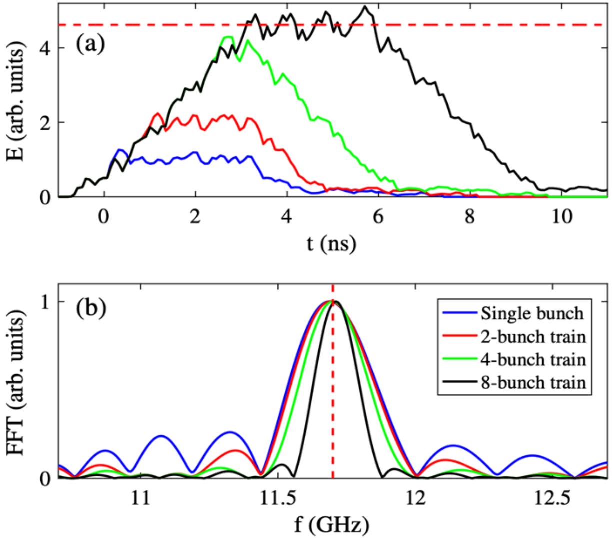
J. Shao et al., 10.1103/PhysRevAccelBeams.23.011301 (2020)]

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



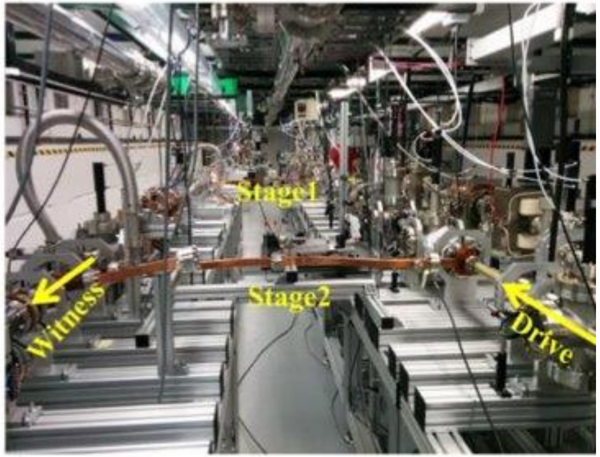


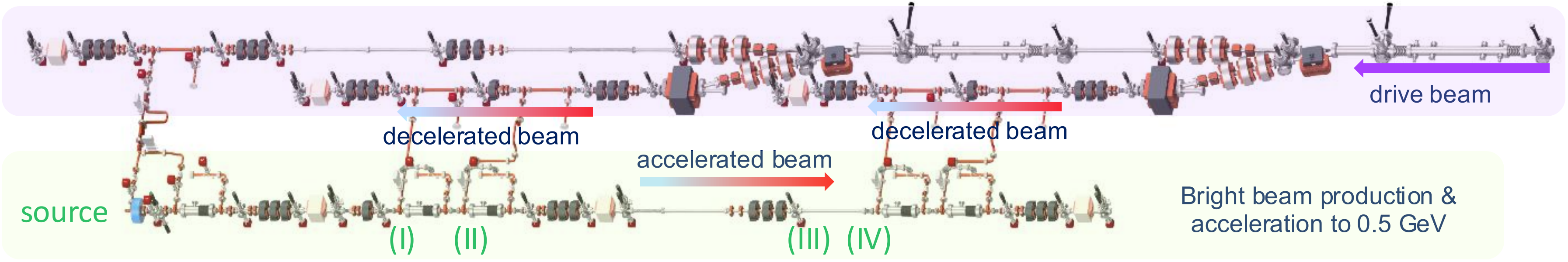
D. Wang, et al., 10.1103/PhysRevLett.116.054801 (2016)

POWER GENERATION & DISTRIBUTION

A large integrated experiment combining two beamlines

- **Drive-beam switchyard:** kicker + septum magnet to direct bunch trains in parallel beamlines
- **Timing control:** high-power phase shifter + power splitter (tested) w/ waveguide delay
- **Staging:** Demonstrated + not challenging in SWFA

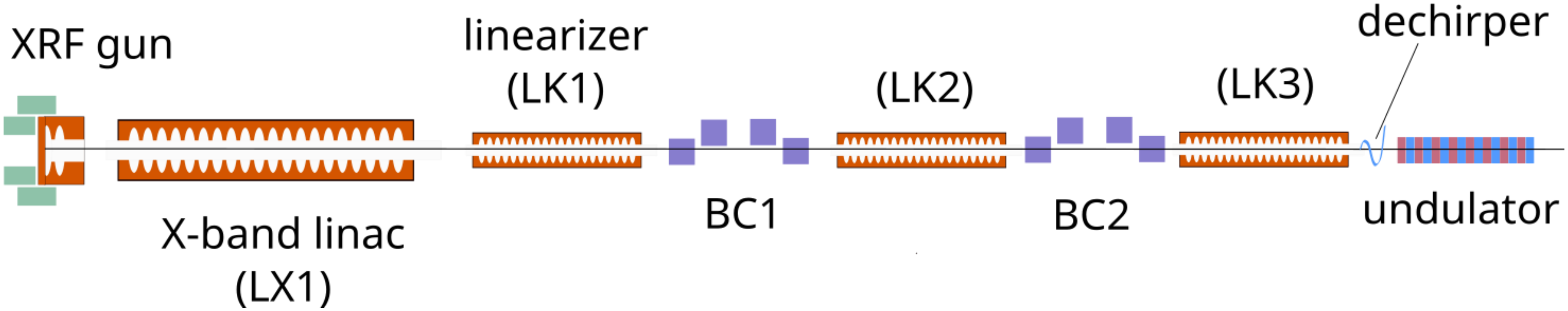




Planned multi-staged acceleration experiment to 500 MeV C. Jing et al. 10.1016/j.nima.2018.05.007 (2018)

GENERAL ARCHITECTURE

Compact light source demo at AWA



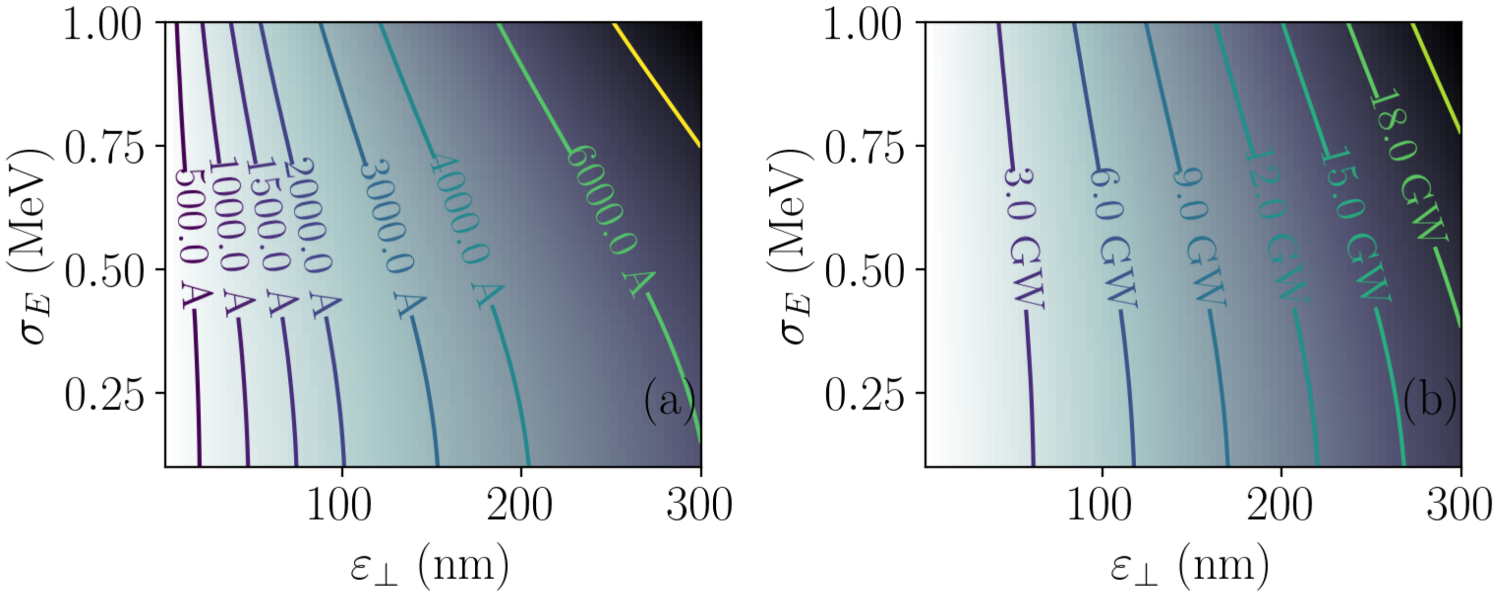
- **High-field photoemission RF gun:** ~400 MV/m on photocathode
- **High-frequency linac:** ~200 MV/m peak field
- **Compact undulators:** superconducting undulator

based on TBA

REACHING THE WATER-WINDOW

Required beam parameters

- Ming-Xie parameterization used to identify range of needed beam parameters

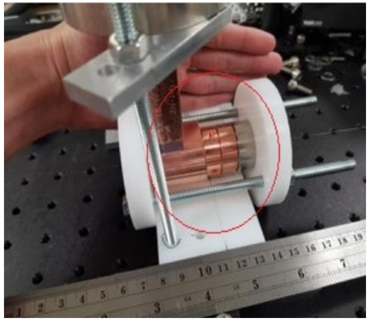


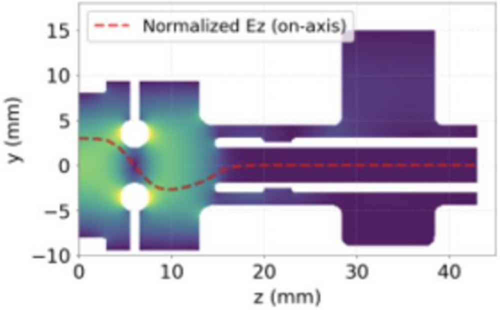
2.10 nm

INJECTOR

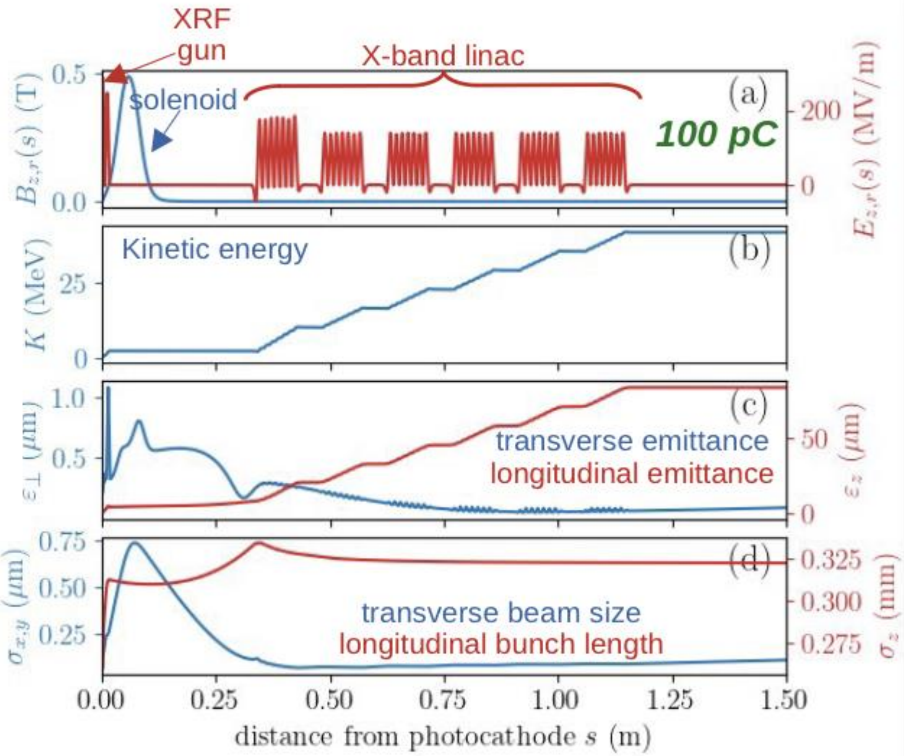
High-gradient gun + linac

- Adopt current XRF gun capable of ~400 MV/m on photocathode





- X-band linac TW 4π/5 phase-advance per cell – max field taken to ~180 MV/m
- Emittance ~ 80 nm

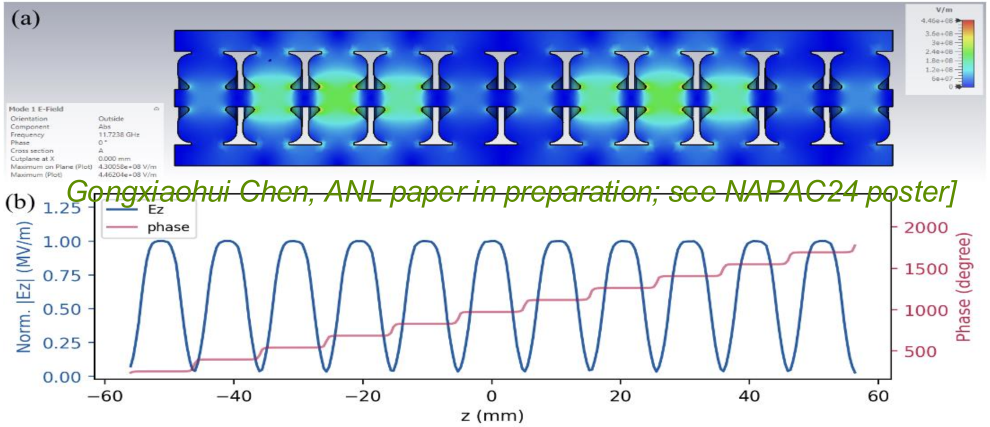


[W. H. Tan, et al. 10.1103/PhysRevAccelBeams.25.083402 (2022)]

1-GEV LINAC

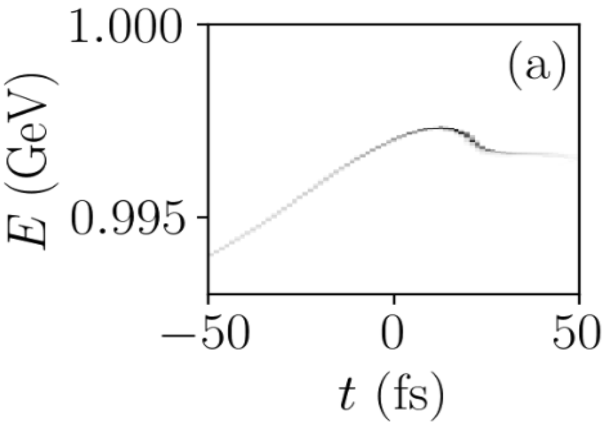
Compact light source demo at AWA

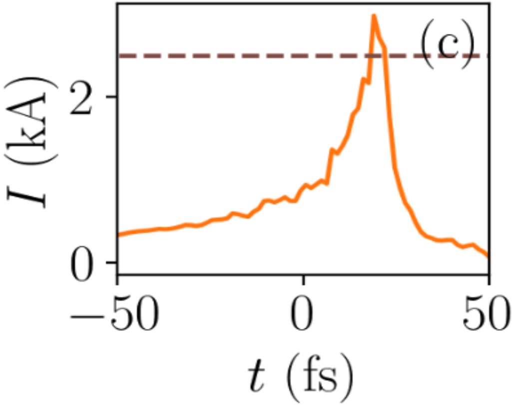
- Initial design assumes X-band linac with W-band linearizer (not designed yet)



Gongxiaohui Chen, ANL paper in preparation; see NAPAC24 poster]

- Simulations performed in a piecewise fashion
- Final emittance close to 150 nm (a factor ~2 increase from photoinjector)



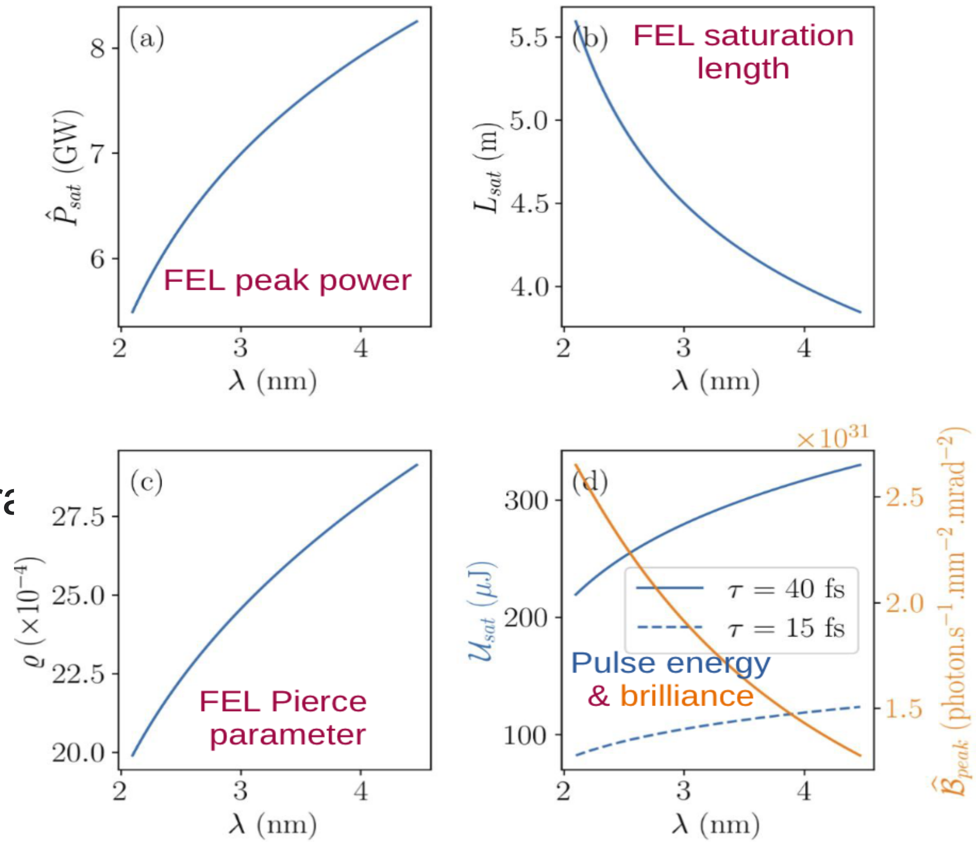


FEL DEMO IN THE WATER-WINDOW RANGE

Expected performances

- FEL-gain calculations performs for a worst-case scenario (lower electron-beam brightness)
- 10-GW peak power over the full water-window range
- Energy/pulse [100, 300] μJ
- Saturation length over the full spectra range is <5.5 m

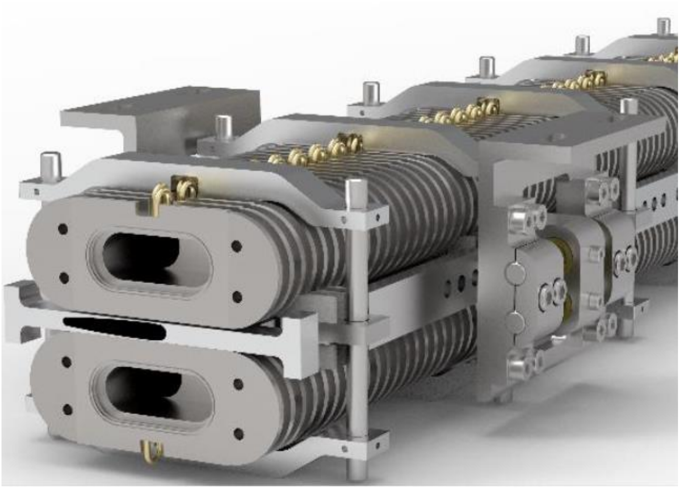
- FEL performances comparable to larger-scale FEL facilities

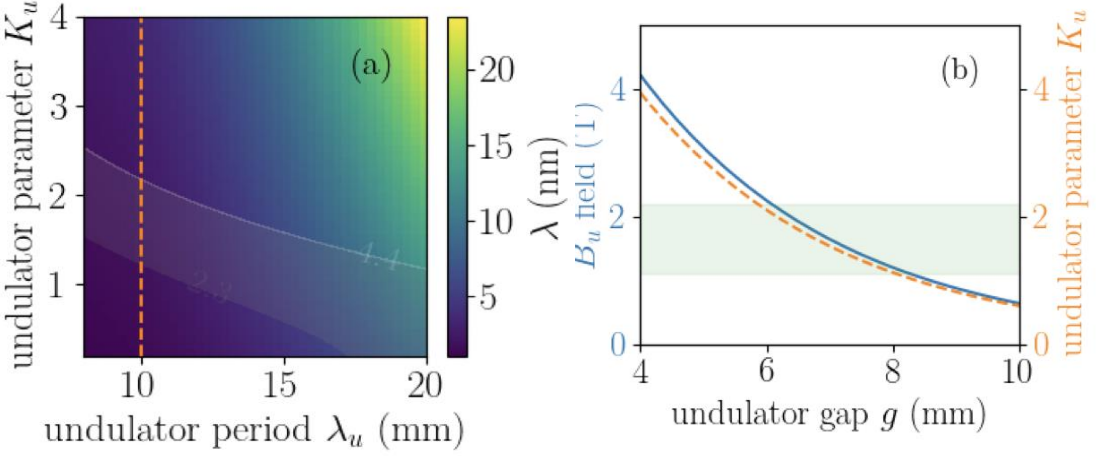


UNDULATOR-DESIGN ASSUMPTION

Based on designs from the APS insertion-device group

- Undulator design assumes a compact undulator based on superconducting undulator (SCU)





- Based on U. Houston, TX high-temperature-superconductor (UH-HTS) tapes which have demonstrated record current density

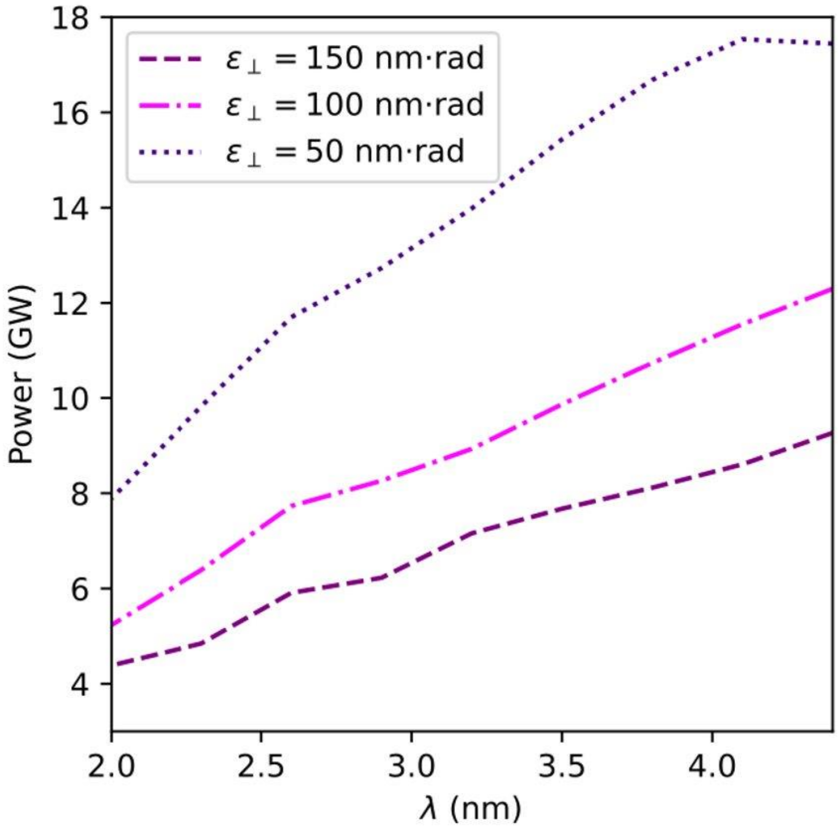
[M. Kasa & Y. Ivanyushenkov, Argonne National Laboratory]

FEL DEMO IN THE WATER-WINDOW RANGE

Genesis Simulations

- Genesis simulations essentially confirm predictions from Ming-Xie's parametrization
- Saturation over the full water-window region over 5 m using a 10-mm period undulator
- Final power P~[4,8] GW for the worst-case scenario of emittance

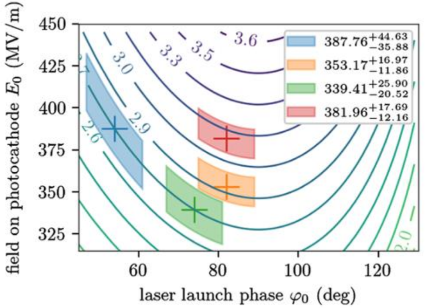
[R. Margraf-O'Neal, et al. In Proc.l Linac 2024 (2024)]

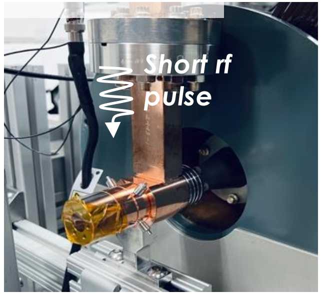


TECHNOLOGICAL PROGRESS

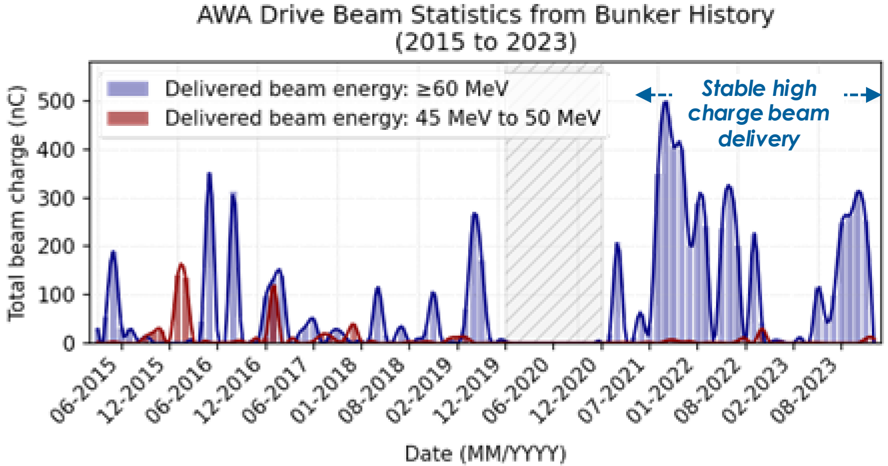
Most of the technologies are demonstrated

- High-charge drive-bunch train generation
- High-peak-power generation demonstrated ~0.5 GW
- High accelerating field (~400 MV/m) in transient-mode





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

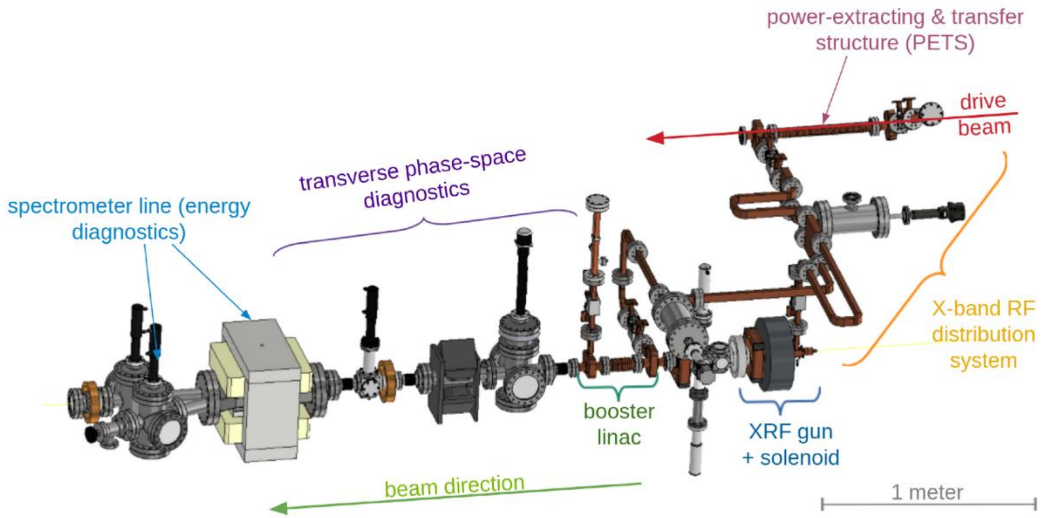


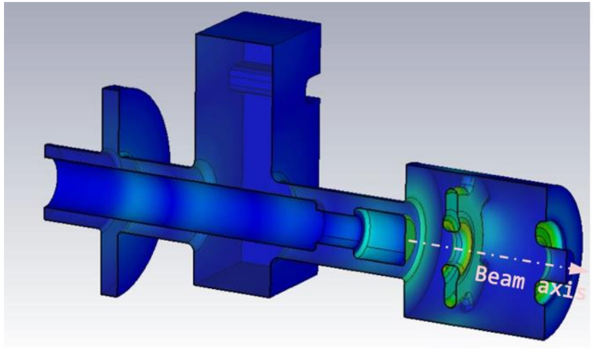
- Main beam from photoinjector not yet characterized (slice emittance experiment recently performed)
- Acceleration in a booster next

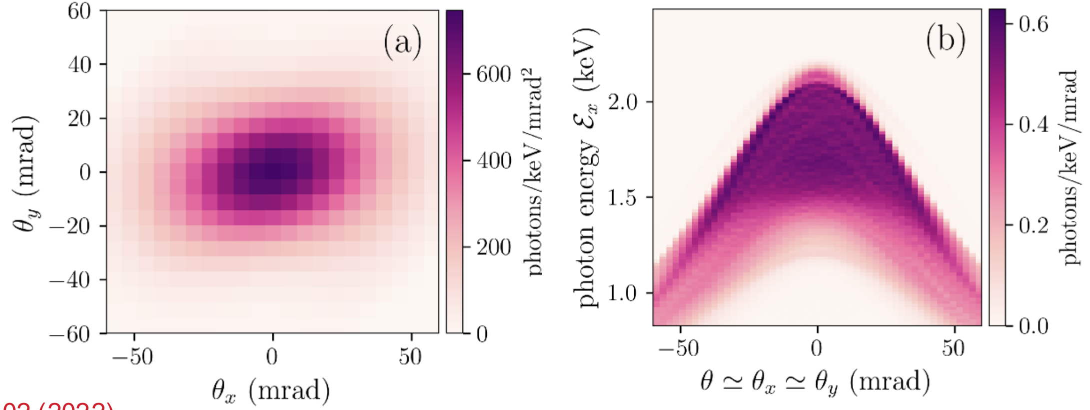
NEXT STEP

100-MeV photoinjector

- New gun + solenoid being for optimal emittance performance
- 10 MeV beamline in ~2 year with application (ICS)
- 100 MeV photoinjector at AWA







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

SUMMARY

- Significant progress has been made on operating RF structure with surface field close to GV/m
- Short (< 10-ns) RF-pulses naturally produced in two-beam accelerators (TBA) are critical to GW peak-power generation at X-band frequencies
- An X-band RF photoemission electron source powered by short pulses was recently commissioned at ANL. It has enabled 400 MV/m on photocathode.
- Near-term R&D include characterization of produced beams and acceleration to ~10 MeV with applications (possibly ICS)
- Mid-term 100-MeV photoinjector with emittance compensated beam
- Longer-term R&D focuses on the design of a 1-GeV linear accelerator to leverage the bright e- beam from the gun and support a FEL in the water-window regime