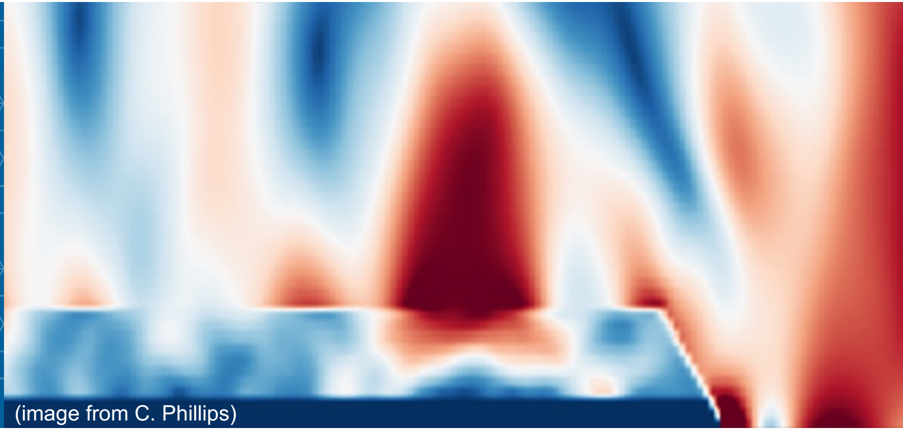
A PATHWAY TOWARD A SWFA-BASED COMPACT COHERENT LIGHT SOURCE



(image from C. Phillips)

PHILIPPE PIOT
Argonne Accelerator Institute
& Argonne Wakefield Accelerator

Contributors:
G. Chen, S. Doran, E. Frame (NIU), C. Jing (Euclid), S. Kuzikov (Euclid), R. Lyndberg, W. Liu, X. Lu (NIU/ANL), J. Power, W. Wisnewski, J. Xu

This research is based on work supported by Laboratory Directed Research and Development (LDRD) funding from Argonne National Laboratory, provided by the Director, Office of Science, of the U.S. DOE under Contract No. DE-AC02-06CH11357.

CONTEXT OF THIS WORK

From high-energy physics to basic energy science

- High-gradient accelerators → path to cheaper, and smaller e+/e- linear colliders
- Several schemes have been proposed e.g. based on plasma or structures based on beam or laser-pulse drivers
- At the Argonne Wakefield Accelerator (AWA) we explore methods for beam-driven acceleration based on structure wakefield acceleration (SWFA) with focus on linear-colliders
- Examples of SWFA include corrugated or dielectric-lined waveguides, photonic bandgap, metamaterials.
- SWFA is closer to “conventional” accelerators also has synergies with PWFA
- ANL currently supports R&D on a potential SWFA-based light source that would complement APS (FEL demo) or enable a future FEL-based facility.

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

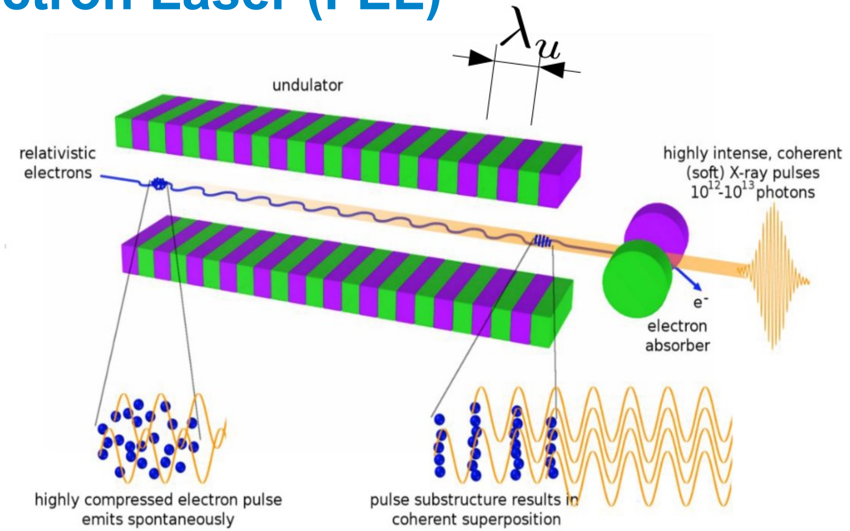
- High-gradient accelerator

accelerator length

beam energy

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

accelerating gradient

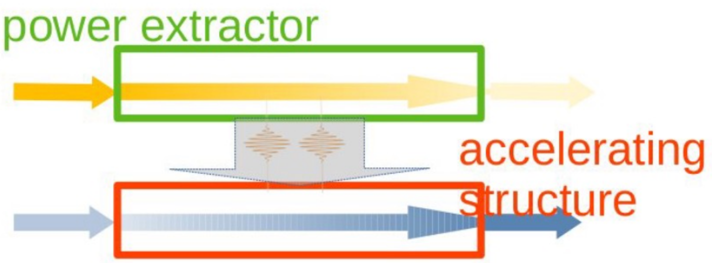


[Adapted from ETH Zurich]

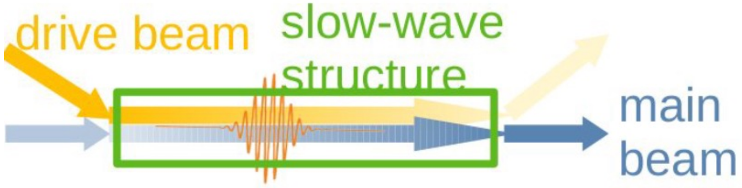
- High-frequency linacs
- Wakefield accelerators
- Two beam accelerators

SWFA APPROACHES

Two-Beam Acceleration vs Collinear Wakefield Acceleration



- Drive beam excites wakefield in power extractor → powerful short RF pulses
- Power is outcoupled and transferred to an accelerating structure
- Main beam is accelerated in structure
- ”far-field” interaction
- 2 beamlines → drive and main bunches are decoupled (independent beam dynamics)

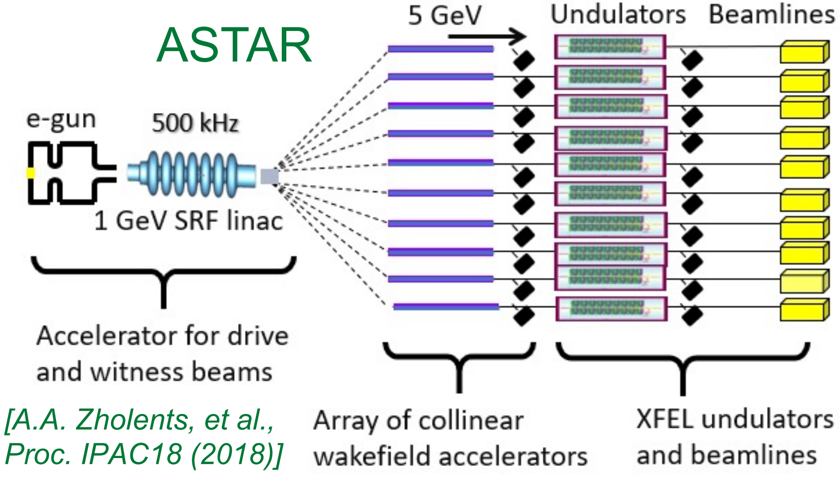


- Drive beam excites wakefield
- Following main bunch experiences accelerating field
- One beamline shared by drive and main bunches (intricate beam dynamics)
- “near-field” interaction
- Share commonalities with other beam-driven methods (e.g. PWFA)

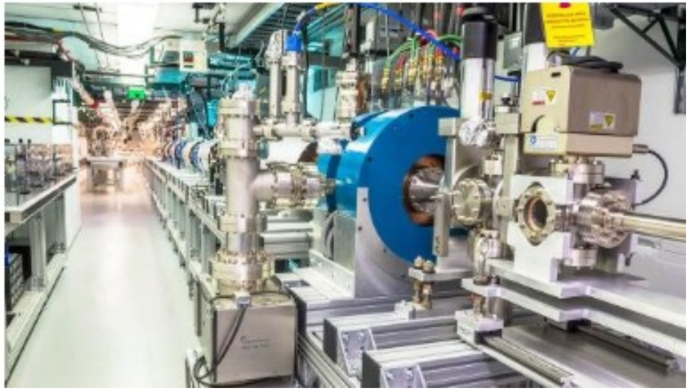
RECENT PROPOSALS

A light source as a stepping stone

- Developing an integrated accelerator for light-source applications is critical to show the viability of the concepts
- Over the last ~5 years ANL has been exploring a CWA options (ASTAR)



[A.A. Zholents, et al., Proc. IPAC18 (2018)]



- This talk focuses on a TBA option (started Fall 2022)
  - Uses conventional technology less risky
  - 500-MeV demo in preparation at AWA aligned with facility's research focus on HEP colliders
  - Leverage recent breakthroughs on high field generation in structures

PATH TO GV/M FIELD IN STRUCTURES W/ TBA

Short high-peak-power RF pulse

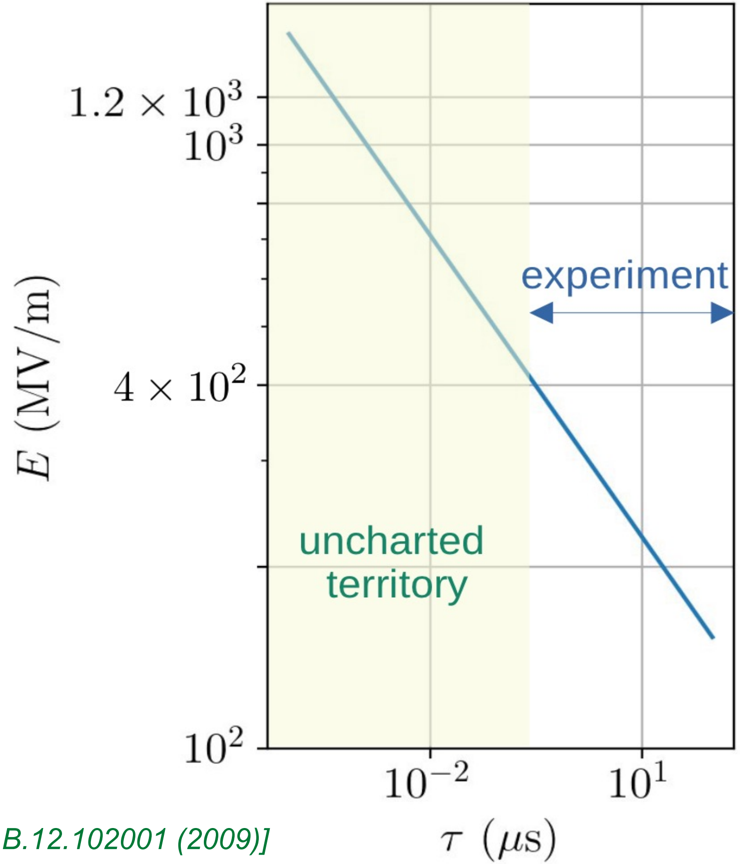
- Breakdown is a major limitation toward producing high electric field in structures
- Phenomenological model based on large data* set suggest a scaling the breakdown rate (BDR)

field

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

RF-pulse duration

- 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



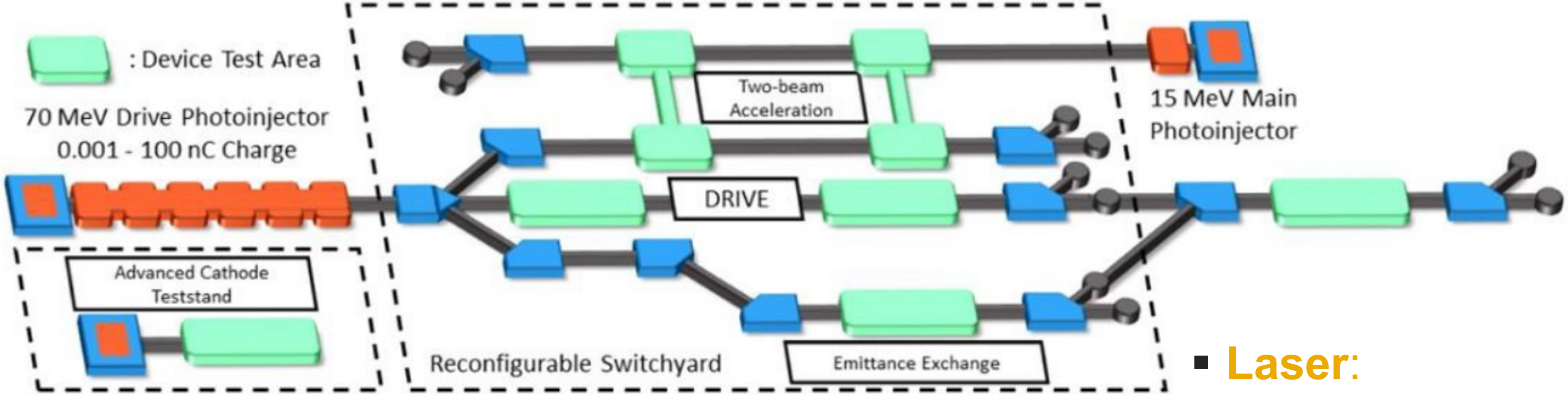
[A. Grudiev, et al. PRAB 10.1103/PhysRevSTAB.12.102001 (2009)]

EXPERIMENTAL FACILITY FOCUSED ON SWFA

The Argonne Wakefield Accelerator

- **Drive beam**:
  - ➢Backbone accelerator
  - ➢~60 MeV, bright or high-charge bunches

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



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

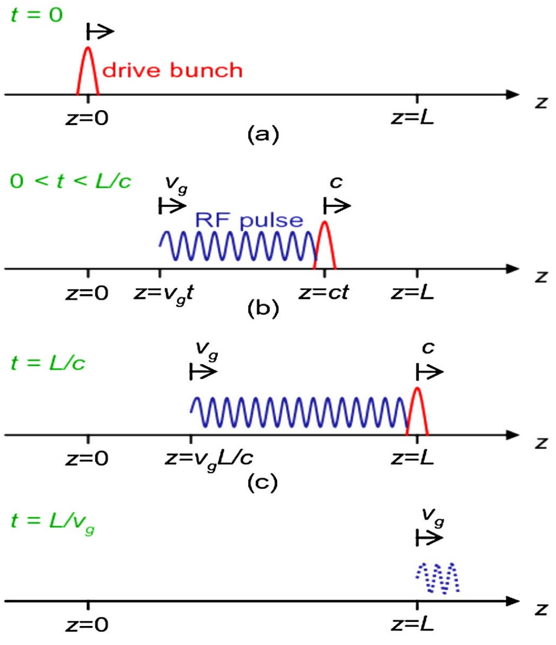
- **Advanced Cathode Teststand (ACT)**:
  - ➢Cathode research (photo- and field-emission)
  - ➢Physics of breakdown
  - ➢Low energy diagnostics

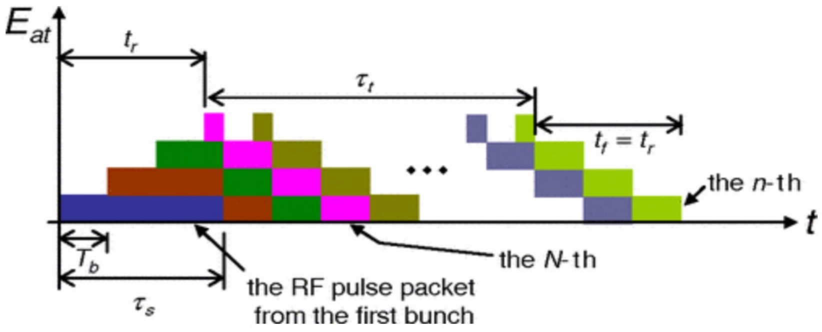
POWER GENERATION

Principle of Coherent Stacking

- **Principle:** E.M. pulse generation from deceleration in a slow-wave structure
  - Use high-charge relativistic bunch
  - Slow-wave structure with broadband couplers

- **Challenge:** High-charge bunch-train generations
  - Formation of sub-μC bunches
  - Transport of high-charge bunches
  - Maximization of interaction length



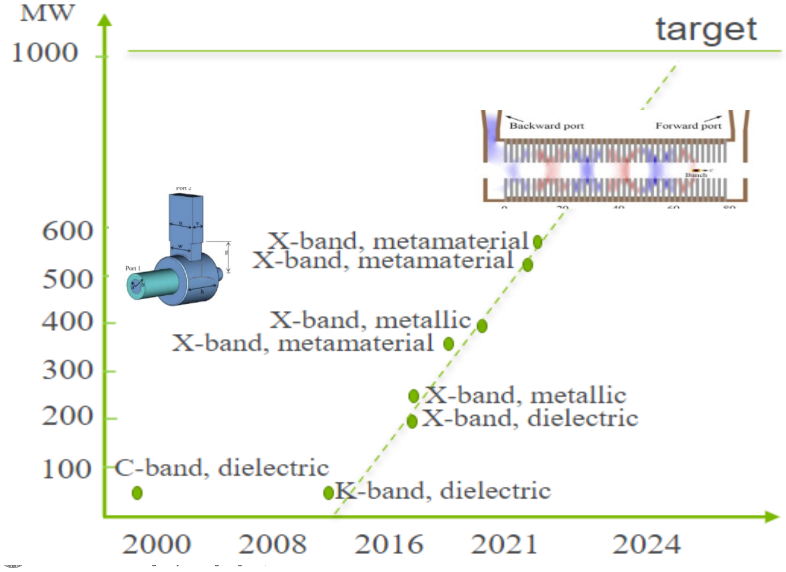


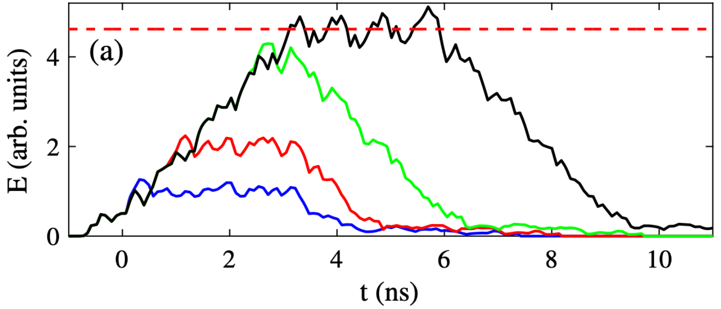
[F. Gao, et al. PRAB 10.1103/PhysRevSTAB.11.041301 (2008)]

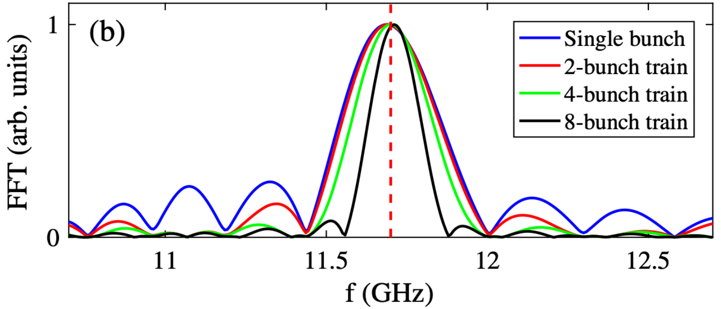
POWER GENERATION

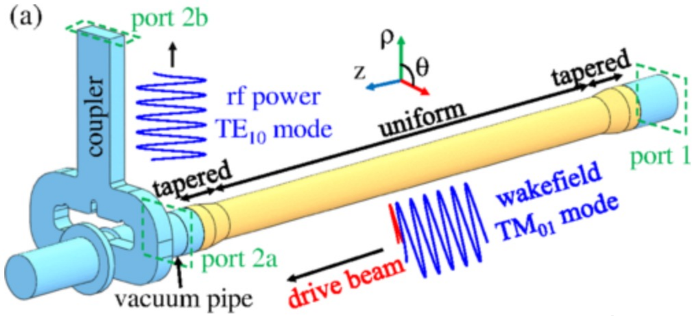
Experimental Results

- **High-peak power:** GW-class pulses at X-band frequencies (11.7 GHz)
- **Short pulse duration:** ~10-ns pulse generated at 11.7 GHz.









[J. Shao et al. PRAB10.1103/PhysRevAccelBeams.23.011301 (2020)]

BRIGHT-BEAM FORMATION

TBA-powered photoinjector

- Conventional approach to producing bright electron beam relies on photo-emission electron source based on RF cavities
- Beam brightness ideally scales as

$$\mathcal{B} \propto \frac{E_0^n}{MTE}$$

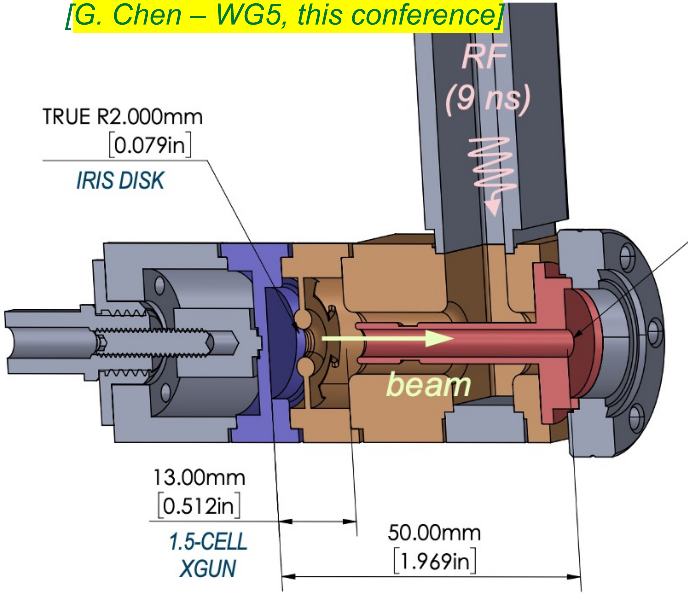
E-field during emission

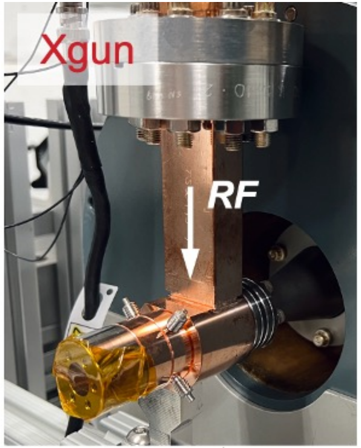
mean transverse energy

- High field is favorable to higher brightness; however chemical and physical topology of photocathodes sets a limit on the brightness*

[G.S. Gervorkyan, et al. PRAB 10.1103/PhysRevAccelBeams.21.093401 (2018)]

[G. Chen – WG5, this conference]

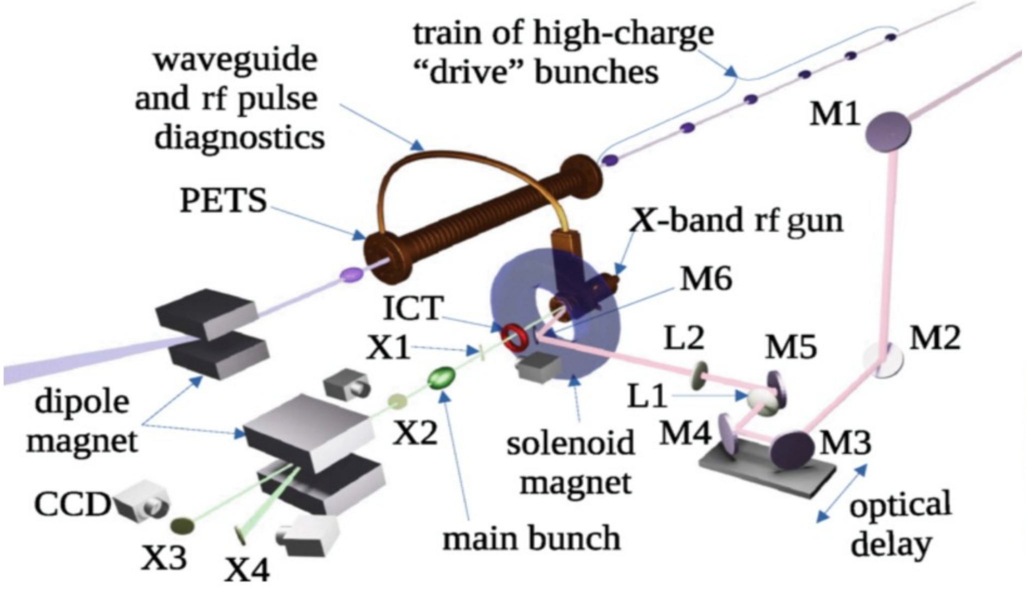


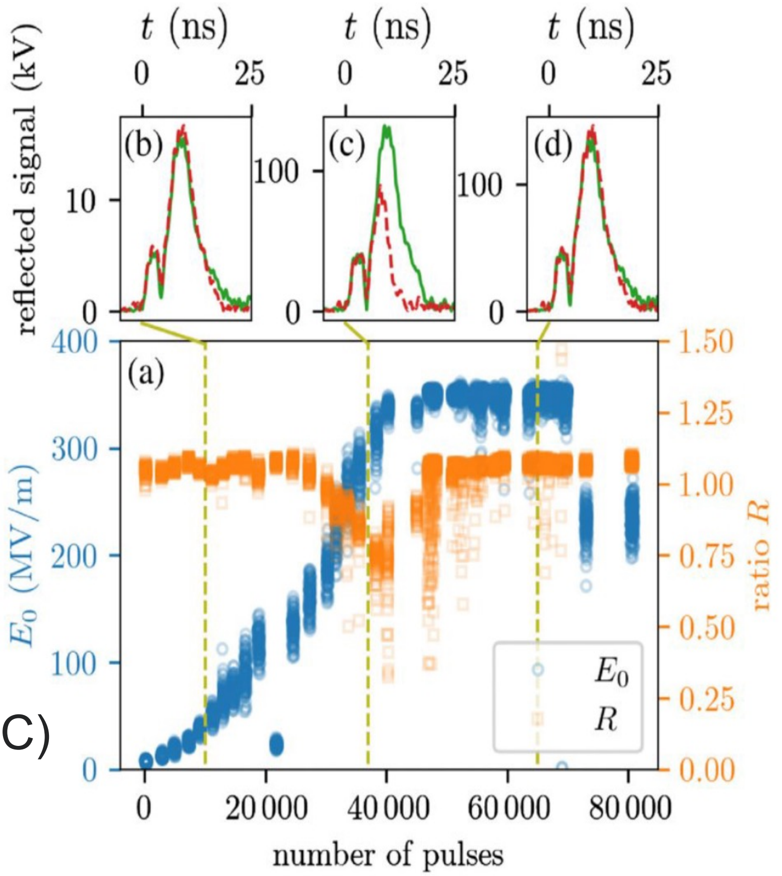


[W.H. Tan, et al. PRAB 10.1103/PhysRevAccelBeams.25.0834 (2022)]

BRIGHT-BEAM FORMATION

Experimental results





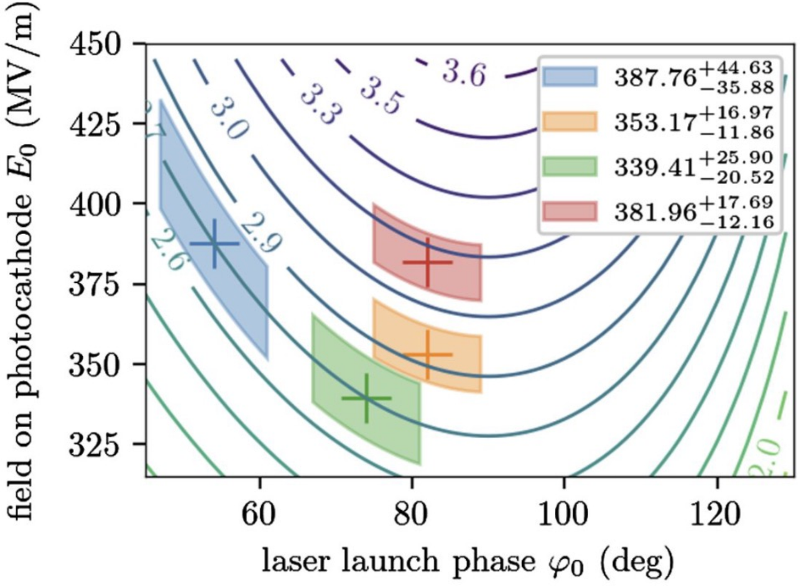
- TBA driven by 8 bunches (E=60 MeV,Q~350 nC)
- Field in excess of 350 MV/m on cathode produced (estimated from RF calibration)

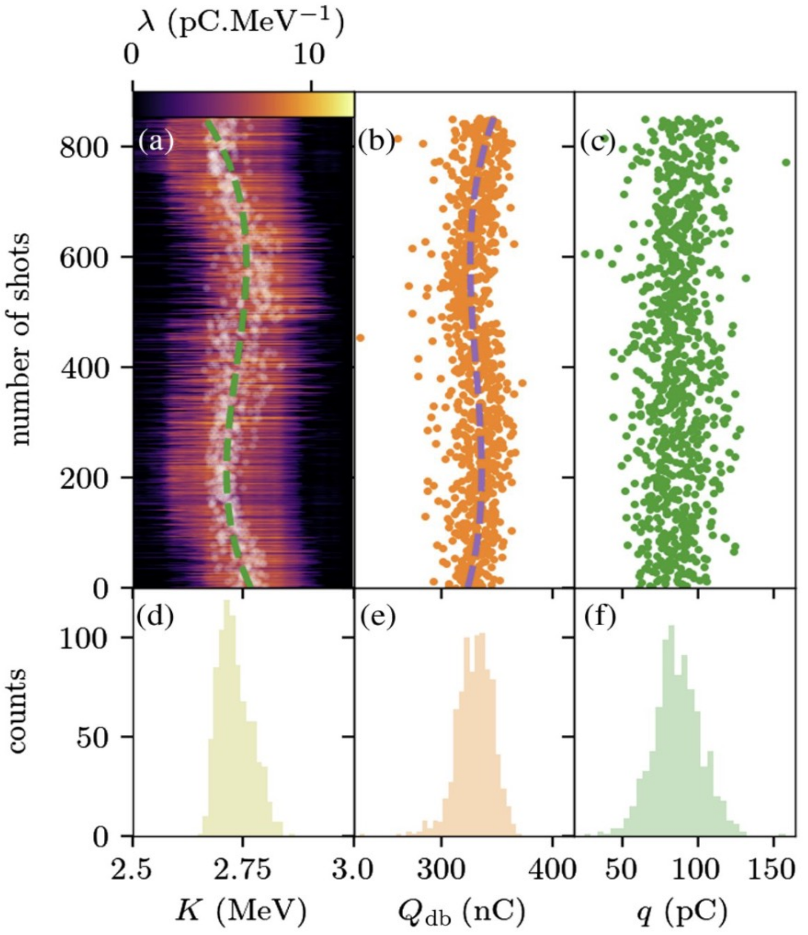
[W.H. Tan, et al. PRAB 10.1103/PhysRevAccelBeams.25.0834 (2022)]

BEAM GENERATION

First electron beams

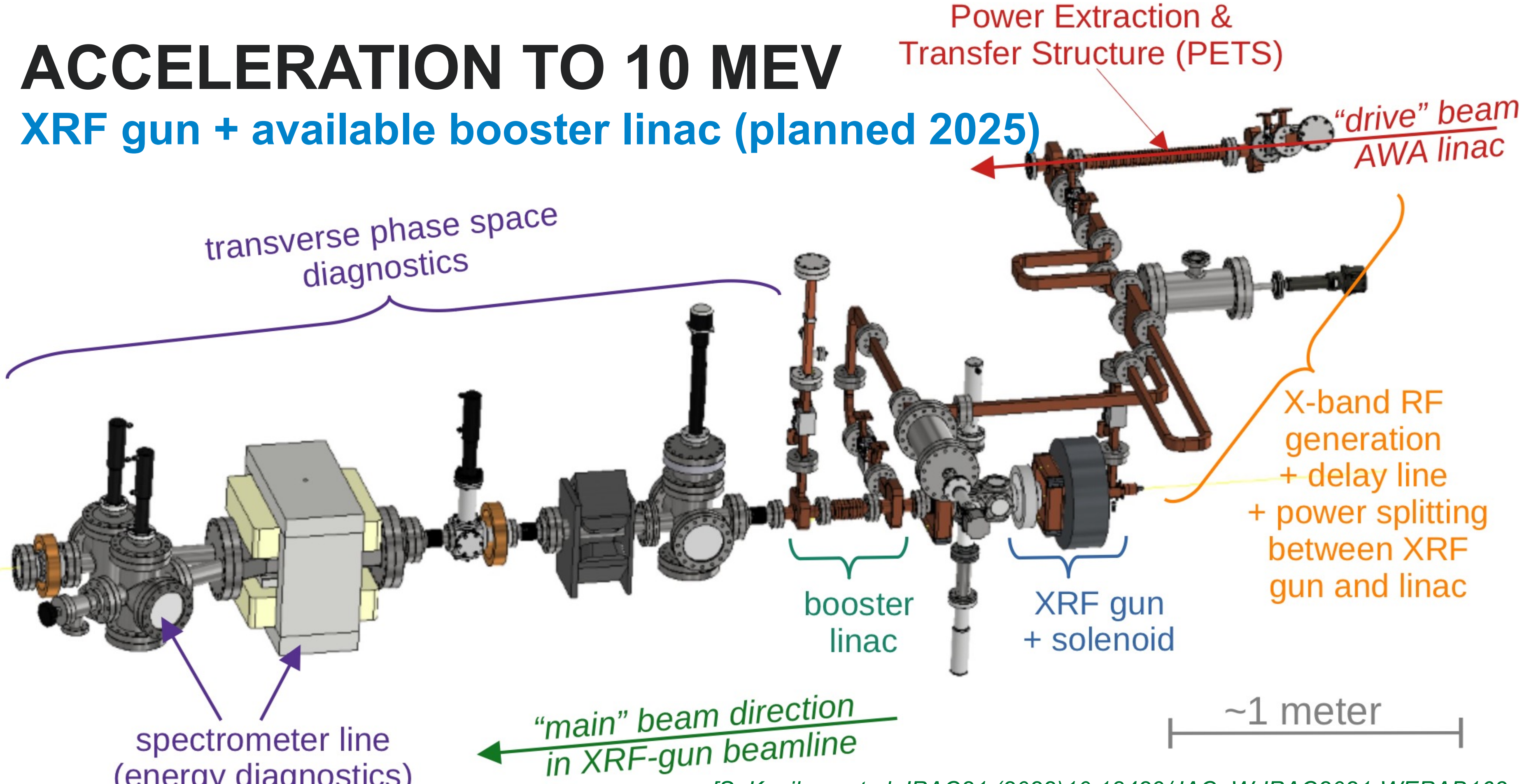
- Stable beam produced in 2022
- Reliable operation over a 3 weeks run
- Jitter correlated with drive beam jitter





ACCELERATION TO 10 MEV

XRF gun + available booster linac (planned 2025)



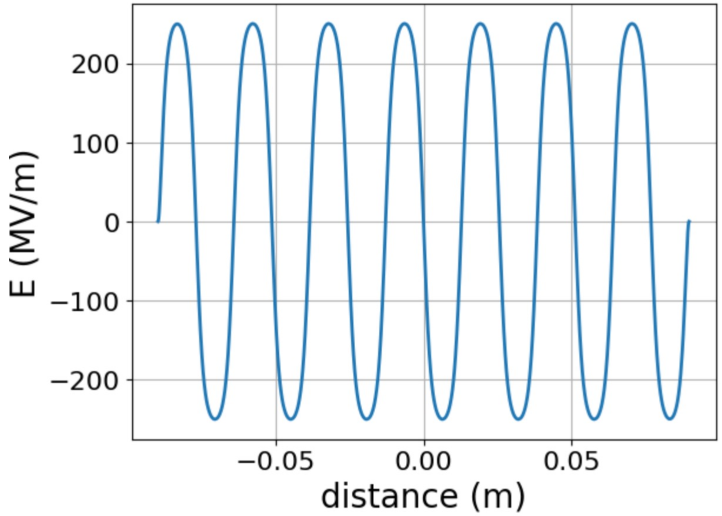
[S. Kuzikov, et al. IPAC21 (2022)10.18429/JACoW-IPAC2021-WEPAB163
G. Chen – WG5, this conference]

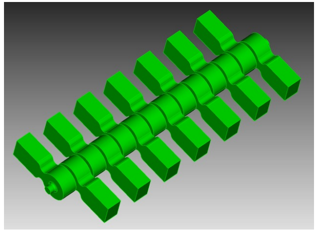
ACCELERATION

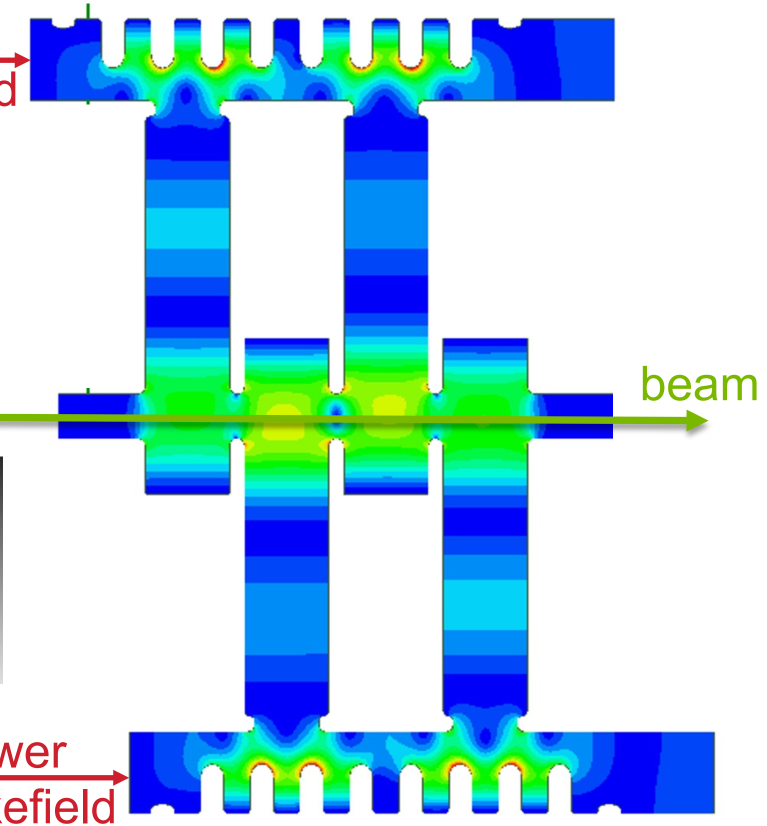
Distributed-coupling linac

[X. Wu, unpublished (2021), original idea by S. Tantawi et al. 10.1103/PhysRevAccelBeams.23.092001*]*

- Optimization of distributed-coupling linac design on going
- Needed for longer interaction length

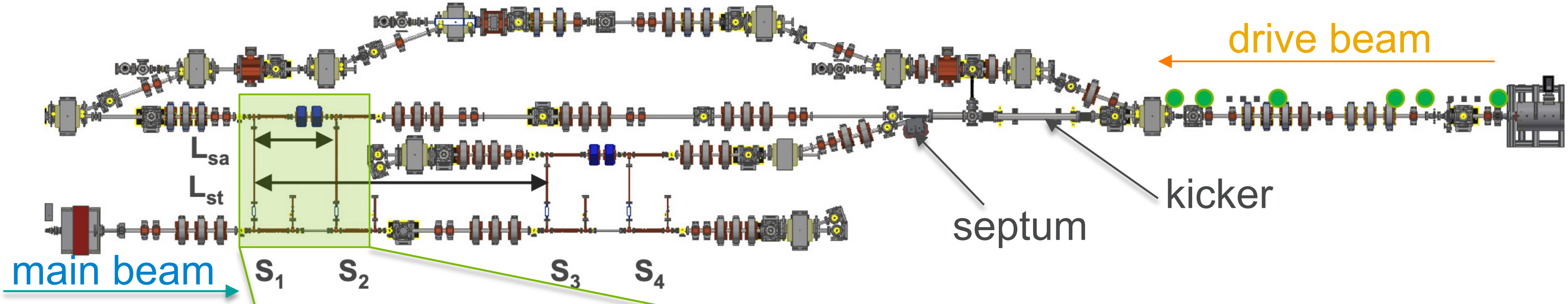


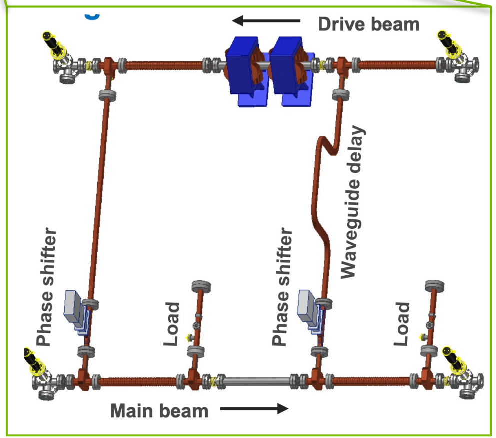




POWER GENERATION/DISTRIBUTION

Drive-beam switchyard and timing control





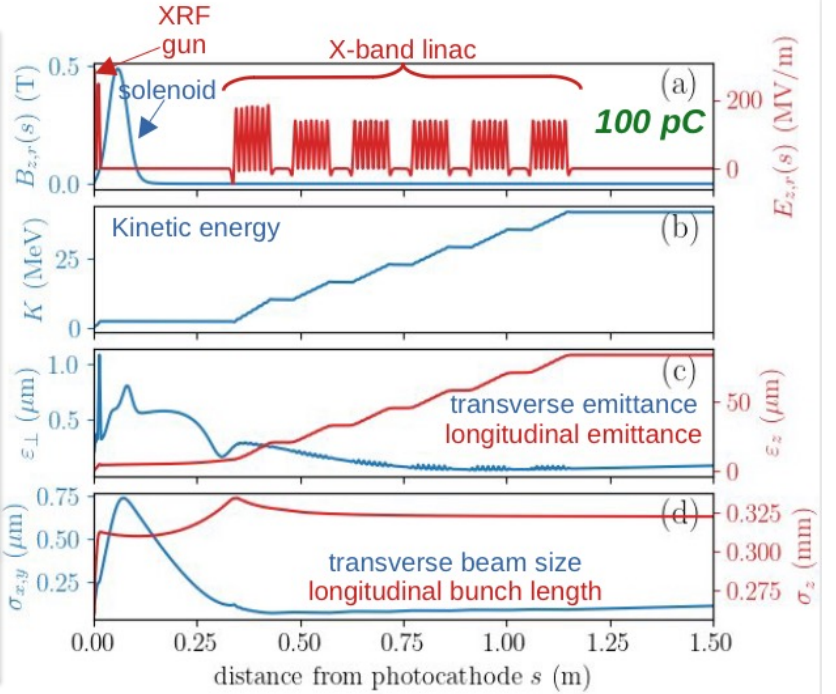
- **Drive-beam switchyard:** kicker + septum magnet to direct bunch trains in parallel beamlines
- **Timing control:** high-power phase shifter and power splitter (all tested) with waveguide delay

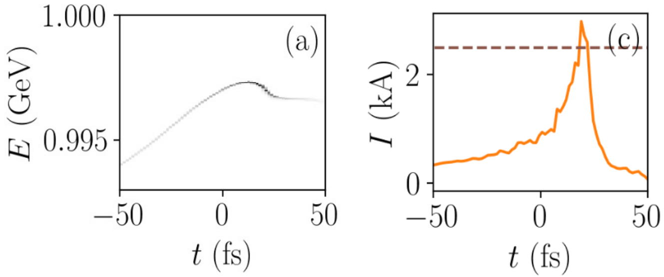
[C. Jing, NIMA 10.1016/j.nima.2018.05.007 *(2018)]*

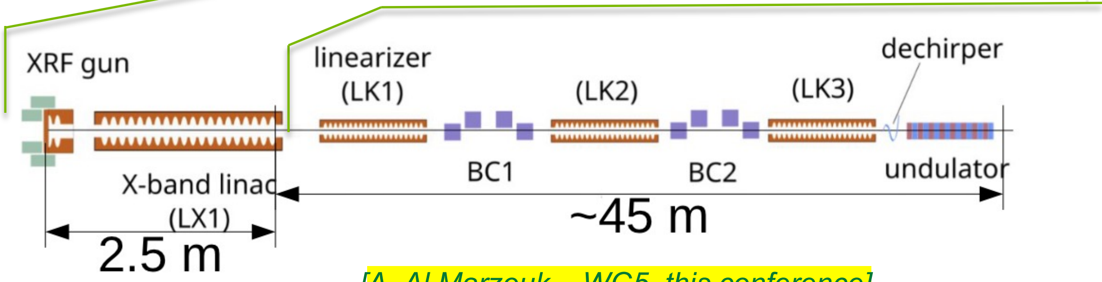
1-GEV LINAC

Compact light source demo at AWA

- Preliminary simulations indicate beam brightness of $\mathcal{B} \simeq 3\times10^{15}$ A/m².
- Similar performance to ultra-compact XFEL proposal (UCLA) or LCLS-II-HE (SLAC) specifications
- Acceleration to 1 GeV could support an FEL window lasing within the water window [2,4] nm





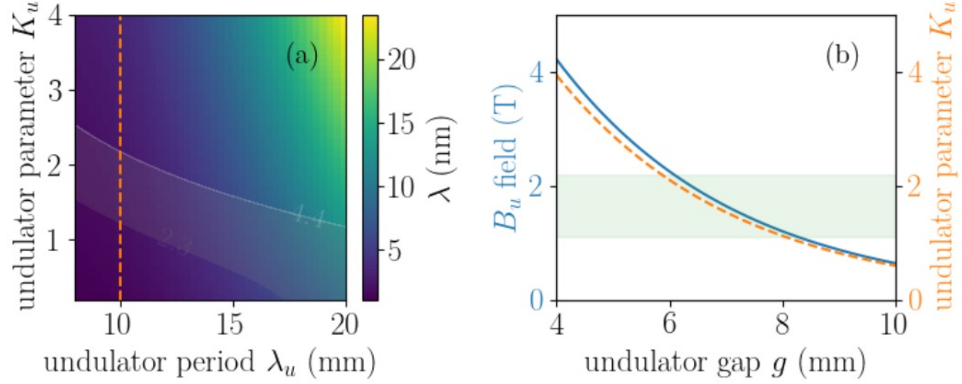


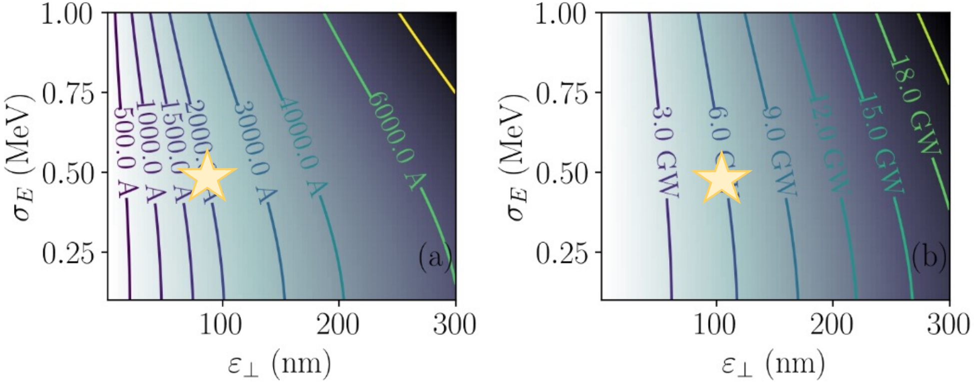
[A. Al Marzouk – WG5, this conference]

FEL DEMO IN THE WATER-WINDOW RANGE

Combining bright beam with short-period undulator

- 1D FEL gain calculations were performed using expected beam parameter
- Use superconducting undulators under development at ANL
- Consider λ_u =10 mm
- Electron-beam parameters enable single-pass lasing in <7 m (saturation) undulators
- Length of 1-GeV accelerator+ undulator magnet is ~50 m
- 3D simulation in progress



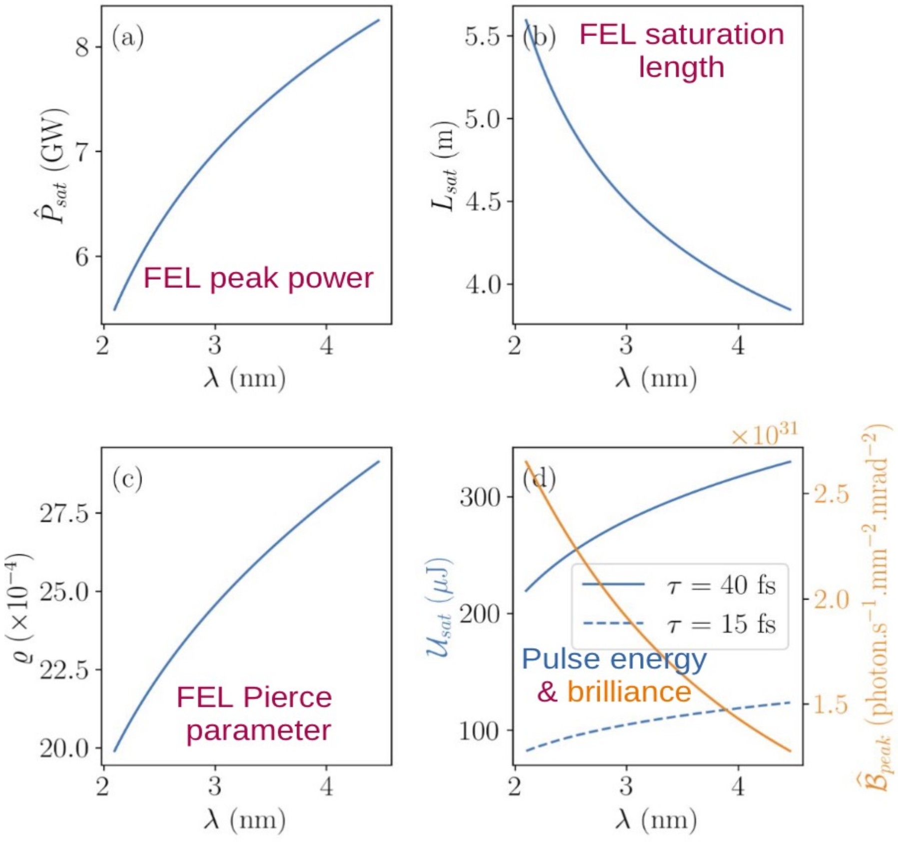


FEL DEMO IN THE WATER-WINDOW RANGE

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 spectral range is <5.5 m

- FEL performances comparable to larger-scale FEL facilities



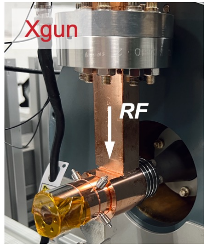
PATH FORWARD

Near term < 5 year 100-MeV bright beam injector

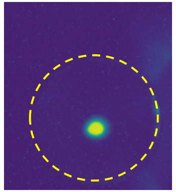
2021-22

1st beam test

- ○ High gradient (**388 MV/m**) verified through beam energy measurement.
- ○ Beam energy characterized (~3% fluctuation).
- ○ Low breakdown rate confirmed (>500,000 shots, BDR<10⁻⁵).



Beam on YAG1



2022-23

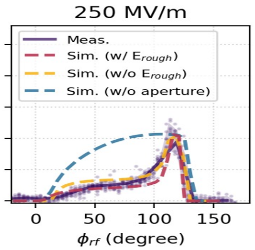
2nd beam test & high-power RF tests

- ○ X-band power splitter and phase shifter conditioned.
- ○ A LINAC added to the Xgun beamline. Beam energy characterized.
- ○ Performed another rf conditioning, very few BD noticed. Good robustness.

2023-24

photoemission in high fields

- ○ Photoemission studies
- ○ QE measurements at different gradients
- ○ Design next-gen XRF gun

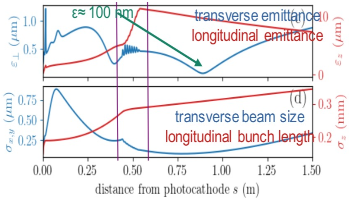


[G. Chen – WG5, this conference]

2024-25

Acceleration to >10 MeV

- ○ Add 3-cell linac
- ○ Local emittance compensation
- ○ Beam characterization
- ○ Design 100 MeV injector



[E. Frame– WG5, this conference]

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
- 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
- Scalability of the concept to soft X-ray regime *should* be straightforward.