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Argonne NATIONAL LABORATORY

DEVELOPMENT OF A COMPACT LIGHT SOURCE USING A TWO-BEAM-ACCELERATION TECHNIQUE

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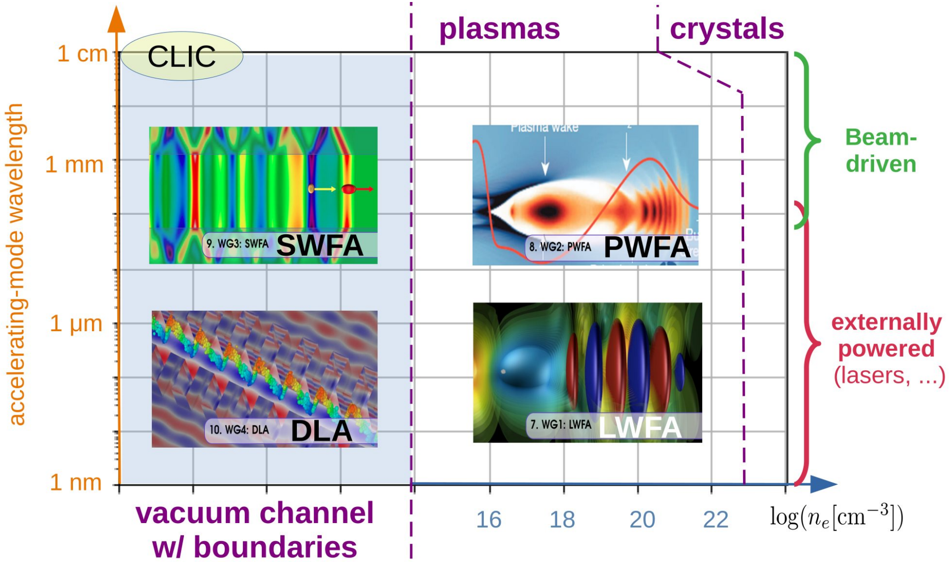
MOTIVATIONS

Y. Cai, P. Piot (Editors) ICFA beam dynamics newsletter **83,** 10.1088/1748-0221/17/05/T05005 (2023).

Developing technologies for future HEP linear colliders

- High-accelerating gradient accelerator offer a path to cheaper, and smaller e+/e- linear colliders
- Many schemes have been proposed e.g. based on plasma or exotic structures
- Our group explore methods for beam-driven acceleration based on **structure wakefield acceleration** (SWFA)

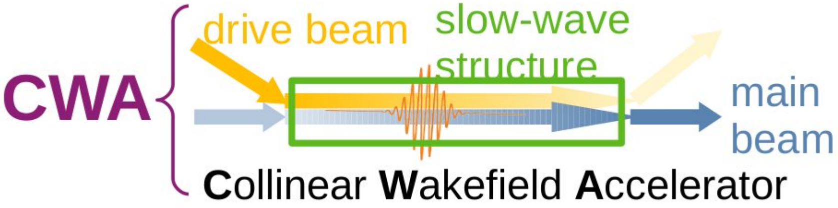


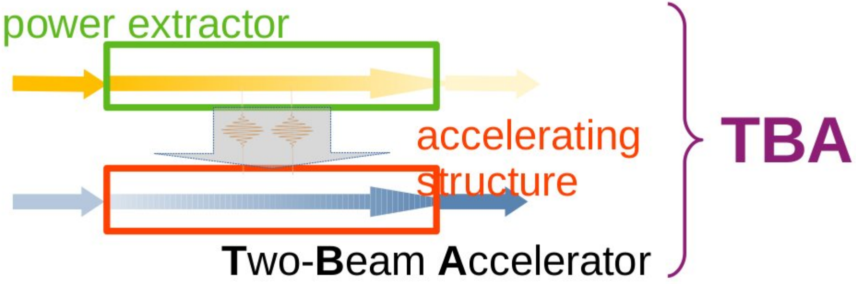
- Examples include: corrugated or dielectric-lined waveguide, metamaterials,…
- SWFA are closer to conventional accelerator and can be configured in two ways

STRUCTURE WAKEFIELD ACCELERATION

CWA versus TBA

- **Collinear wakefield acceleration (CWA)**
  - One beamline for both beam
  - Near-field → scalable to THz frequencies
  - E field ~GV/m demonstrated
- **Two-beam acceleration (TBA)**
  - based on conventional technology
  - High power short pulse generation (~1 GW 10-ns pulses generated)
- **SWFA uses structures so it is ultimately limited by breakdowns**





Y. Cai, P. Piot (Editors) ICFA beam dynamics newsletter **83,** 10.1088/1748-0221/17/05/T05005 (2023).

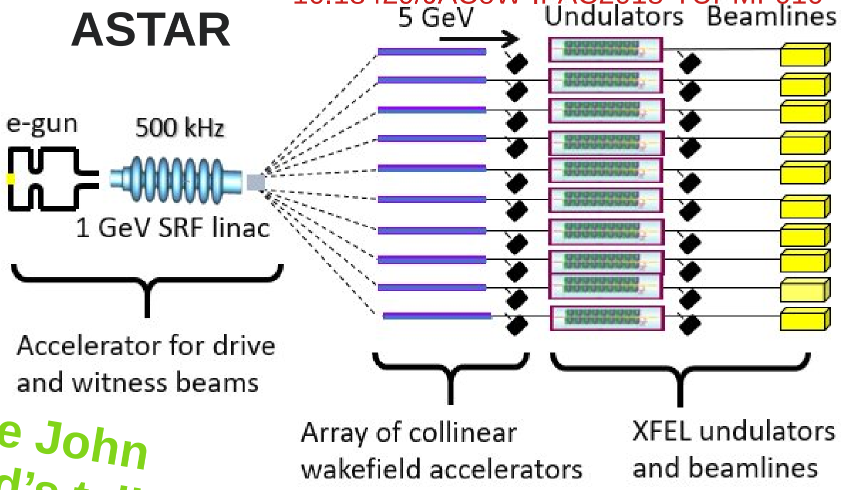
A.A. Zholents, et al., Proc. IPAC18 (2018)
10.18429/JACoW-IPAC2018-TUPMF010

INTRODUCTION

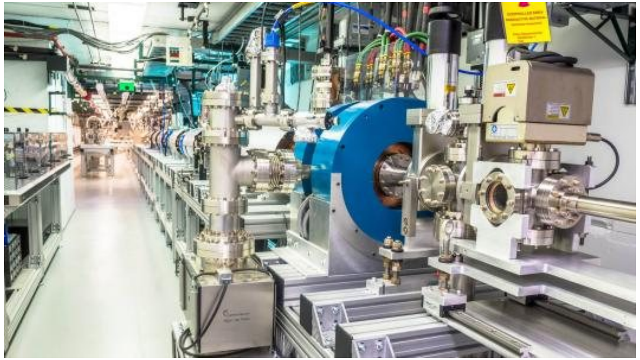
A light source as a stepping stone

- 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)

ASTAR



[See John Byrd's talk]



https://www.anl.gov/awa

- This talk focuses on the TBA option (started Fall2022)
  - Uses conventional technology less risky
  - 500-MeV demo in preparation at the Argonne Wakefield Accelerator (AWA) aligned with facility's research focus on HEP colliders
  - Leverage recent breakthrough on high-field generation in structures

PATH TO GV/M FIELD IN STRUCTURES

Short high-peak-power RF pulse

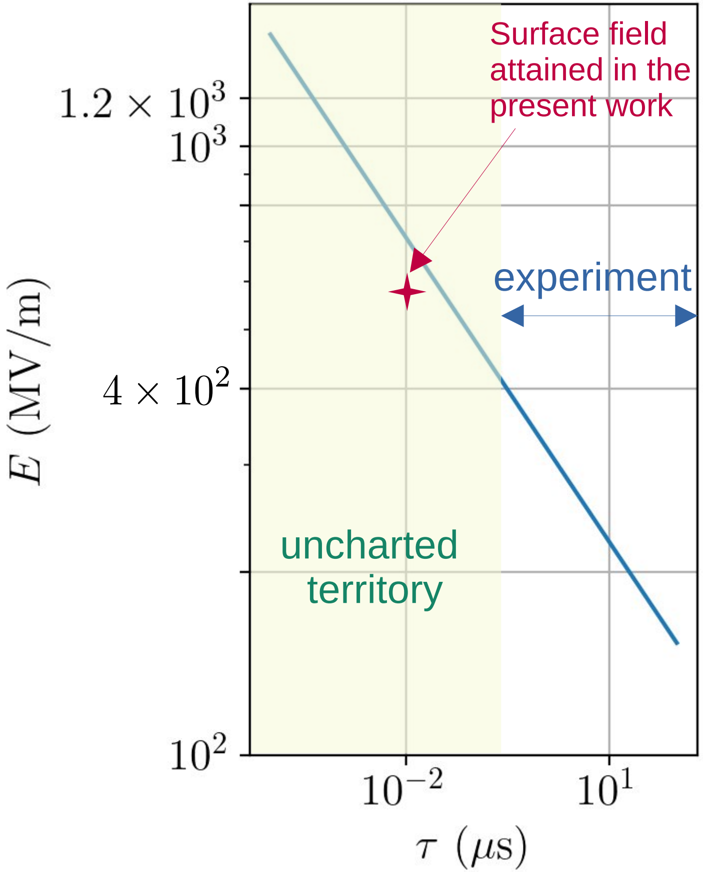
- Breakdown is a major limitation to support high electric field in structure
- Fitting of experimental data* (CERN) on breakdown suggest a scaling

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

RF pulse duration

accelerating field

- So far pulse duration was limited by available RF pulse duration
- RF-pulse duration produced via wakefield can be much shorter…



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

AWA EXPERIMENTAL INFRASTRUCTURE

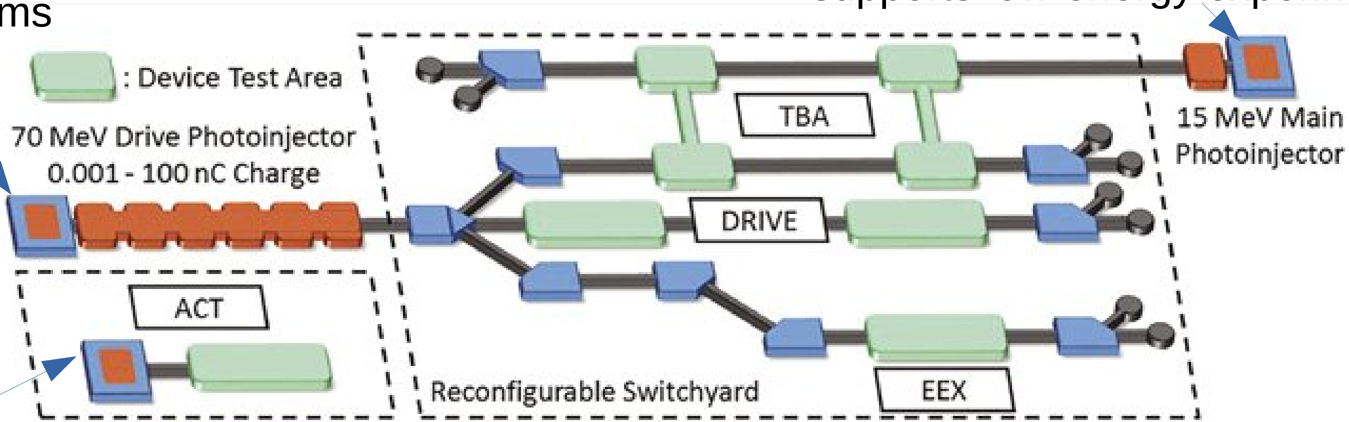
Independent/versatile beamlines and high-power laser

Drive beam:

- backbone accelerator
- <70-MeV bright or high-charge (400 nC) beams

Witness beam:

- ultimately produces bright beam for TBA or CWA applications
- supports low-energy experiments



ACT:

- cathode research
- physics of breakdown
- low-energy diagnostics tests

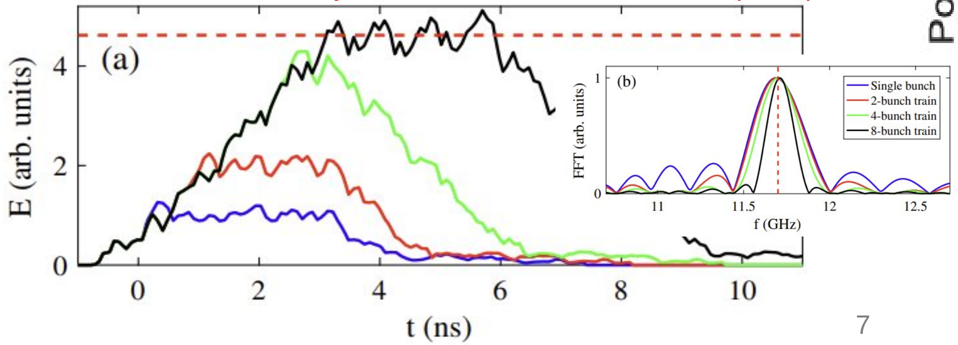
Laser:

- ~100 mJ (IR), 12 mJ (UV),
- 300 fs (nominal)
- temporal shaping

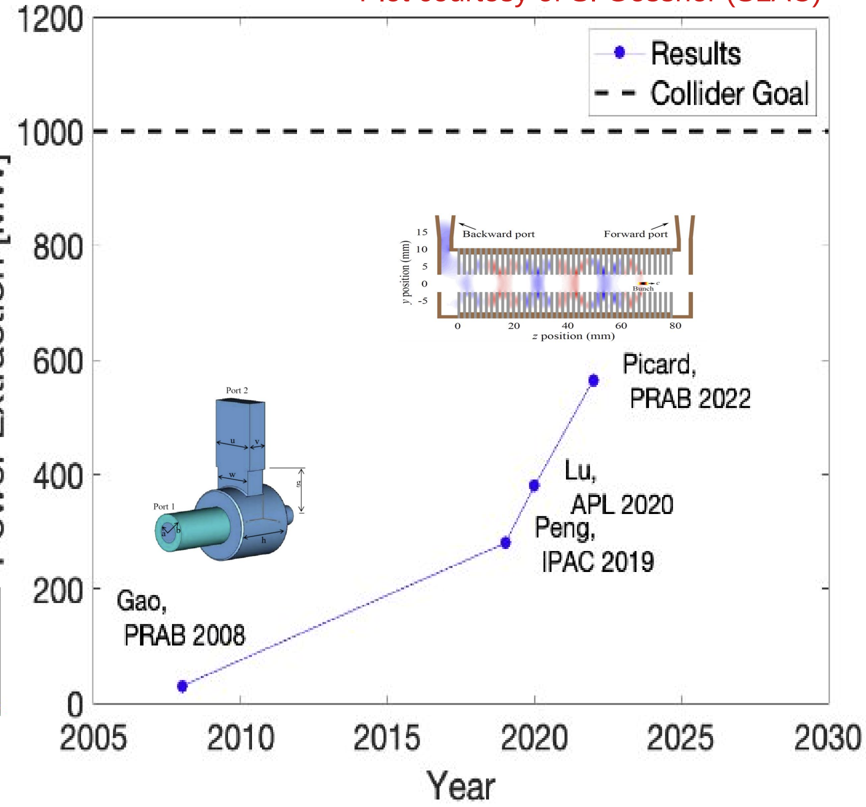
PATH TO GV/M FIELD IN STRUCTURES

Power generation

- Use a relativistic beam into a power extraction and transfer structure (PETS)
- AWA has tested several structures operating at X-band (9x1.3=11.7.GHz)
- We now reliably produce high-peak power (~0.5 GW) short (<3-10 ns) RF pulses J. Shao et al. PRAB 10.1103/PhysRevAccelBeams.23.011301 (2020)

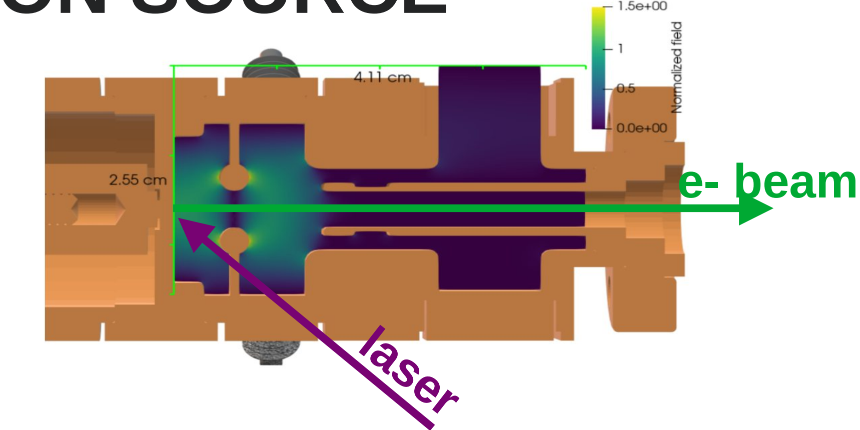


Plot courtesy of S. Gessner (SLAC)



HIGH-FIELD PHOTOEMISSION SOURCE

Producing brighter electron beams



- Conventional approach to producing bright electron beam relies on photo-emission electron source based on RF cavities

- Beam brightness scales as

field experienced at emission (controlled by applied accelerating field)

4D beam brightness (*ideally* invariant)

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

depends on ab-initio aspect ratio of the beam

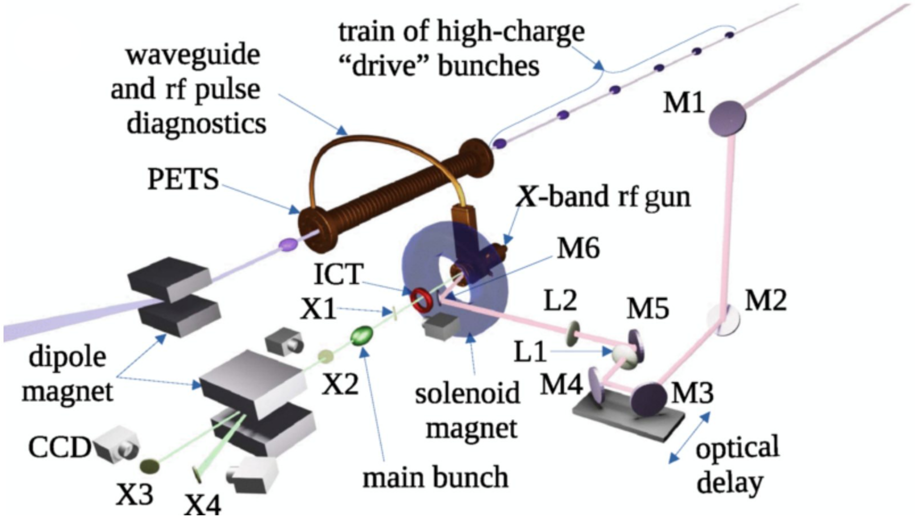
mean-**t**ransverse **e**nergy [a property of the emitting surface (photocathode)]

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

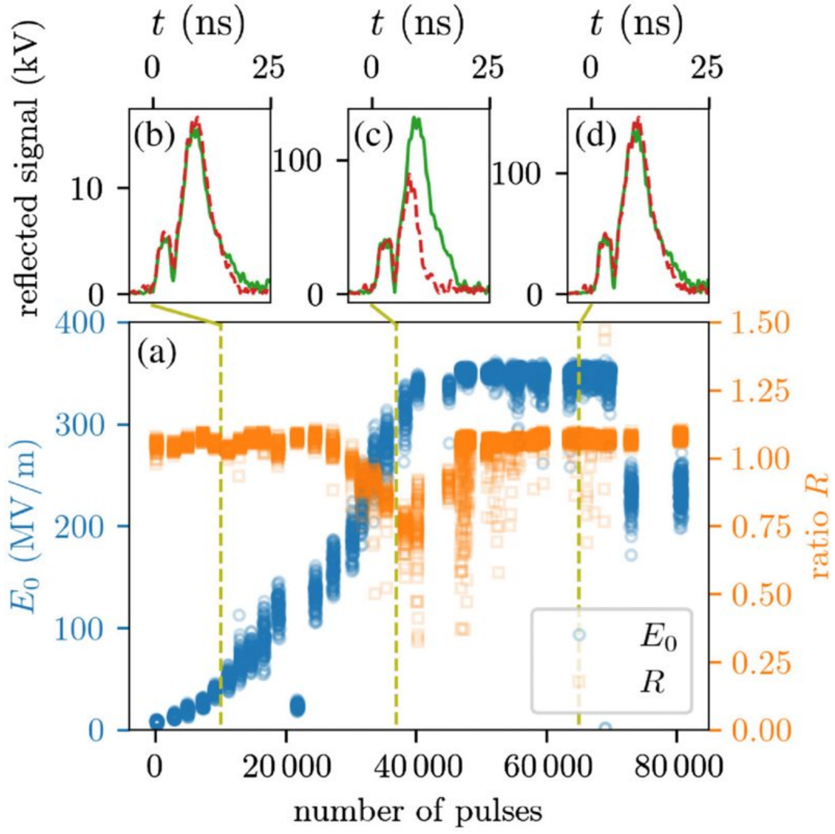
G.S. Gervorkyan, et al. PRAB 10.1103/PhysRevAccelBeams.21.093401 (2018)

ELECTRON SOURCE DEMONSTRATION

Stable operation at high field



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

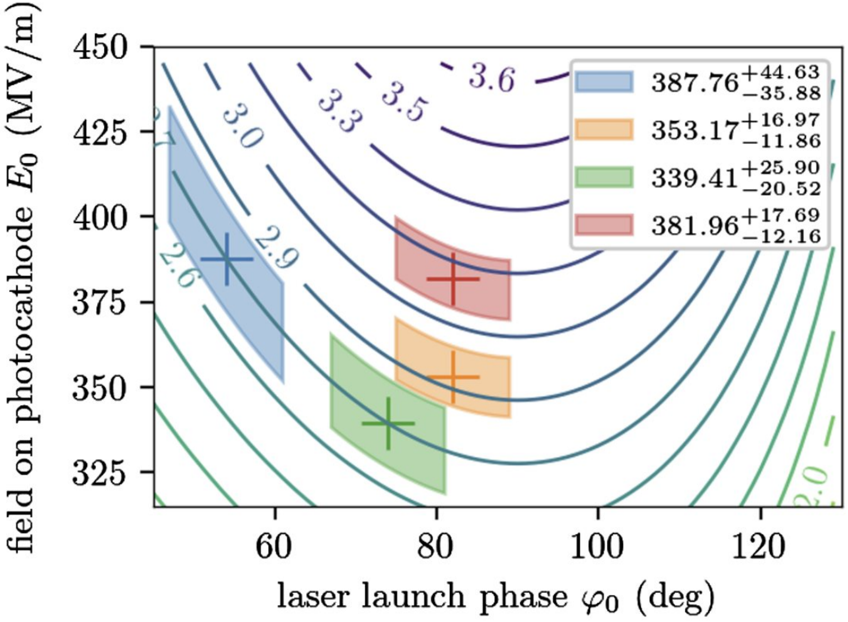


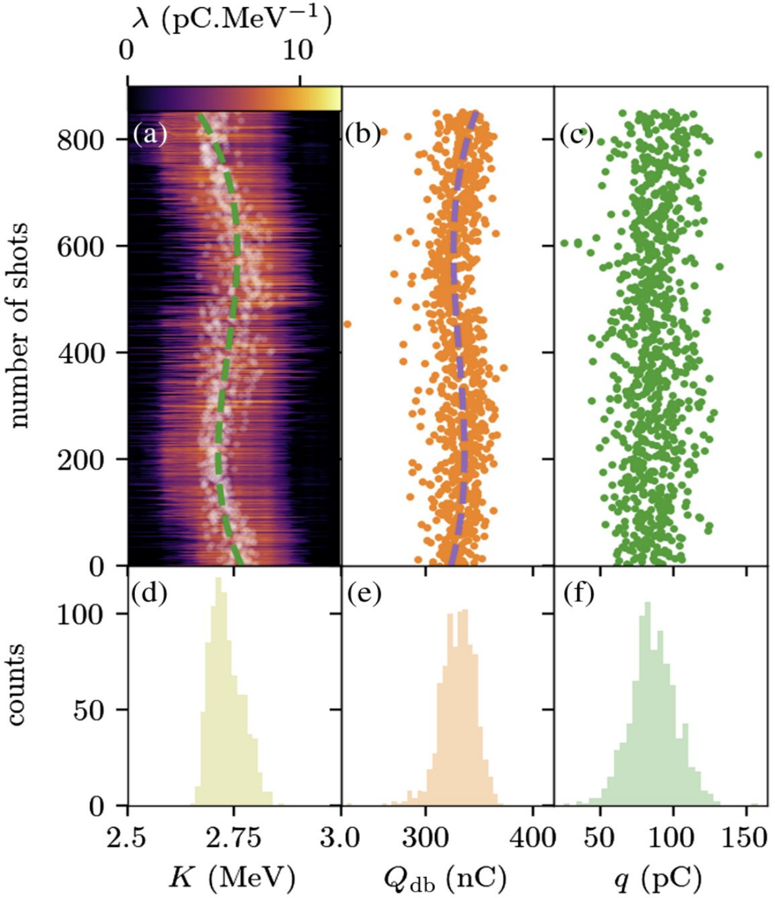
W.H. Tan, et al. PRAB 10.1103/PhysRevAccelBeams.25.083402 (2022)

ELECTRON SOURCE DEMONSTRATION

First electron beam

- Stable beam was produced
- Jitter correlated with drive-beam jitter

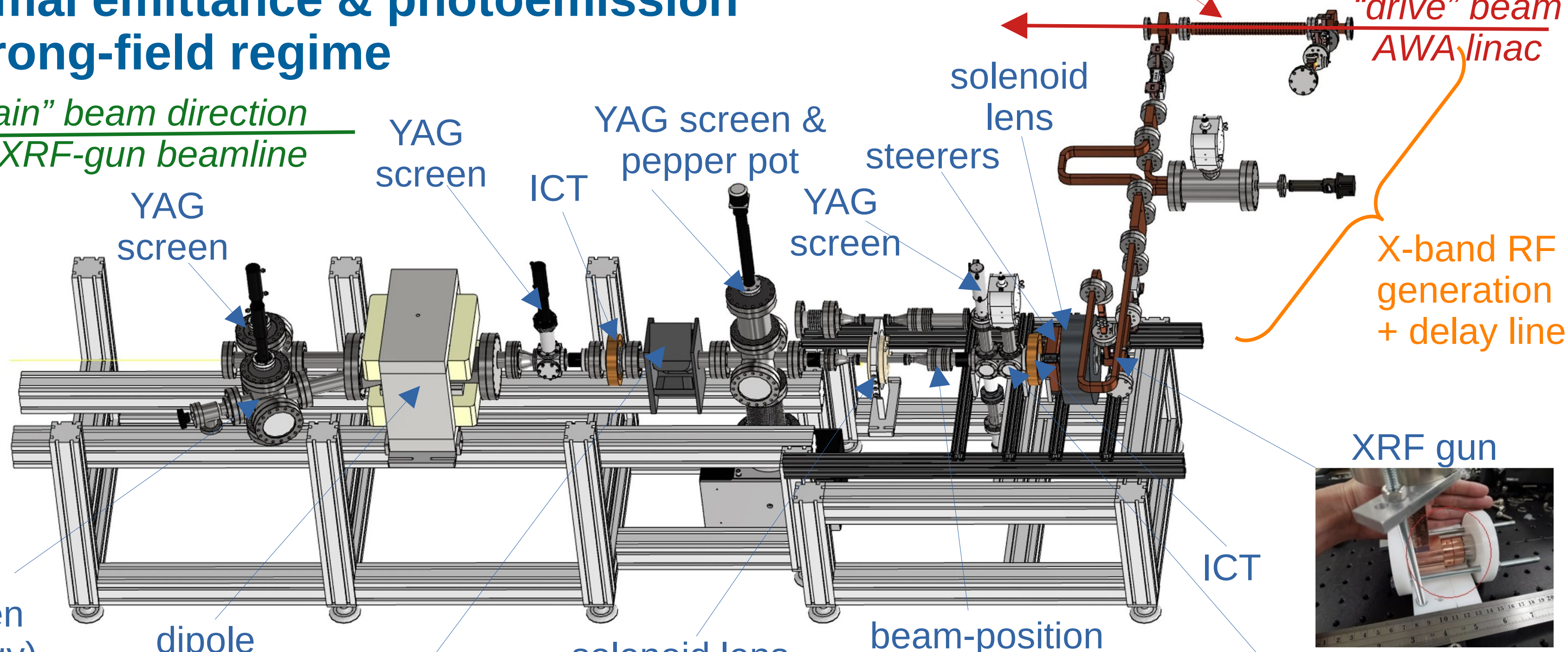




W.H. Tan, et al. PRAB 10.1103/PhysRevAccelBeams.25.083402 (2022)

NEXT-PHASE EXPERIMENT

Thermal emittance & photoemission in strong-field regime



Power Extraction & Transfer Structure (PETS)

"drive" beam AWA linac

"main" beam direction in XRF-gun beamline

X-band RF generation + delay line

YAG screen

YAG screen

ICT

YAG screen & pepper pot

steerers

solenoid lens

YAG screen

XRF gun

YAG screen (energy)

dipole magnet

quadrupole magnet

solenoid lens

beam-position monitor

ICT

photoemission laser injection port

~1 meter

ICT: Integrated Current Transformer
YAG: Yttrium Aluminum Garnet scintillating screen

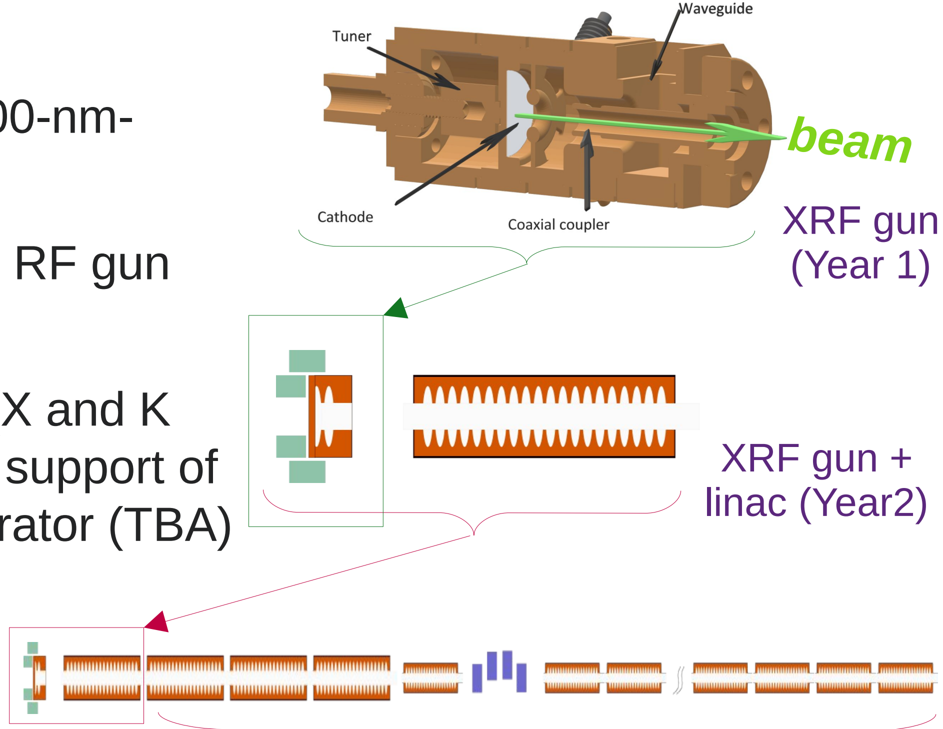
C. Chen, IPAC23 (2023)
10.18429/JACoW-IPAC-23-TUPA064

HIGH-GRADIENT ACCELERATOR

Pathway to a light source & synergies with HEP accelerator R&D

Our approach

- Focus on the production of 100-pC 100-nm-emittance bunches.
- Leverage available hardware: X-band RF gun developed by Euclid Techlabs
- Combine with multi-frequency linacs (X and K bands) under development at AWA in support of a compact 0.5-GeV two-beam-accelerator (TBA) demonstration.



XRF gun (Year 1)

XRF gun + linac (Year2)

0.5 GeV TBA demonstration

Ultimately, the 0.5-GeV TBA could support a full-scale demonstration of a free-electron laser in the E/VUV regime.

BOOSTER LINAC TESTS

Acceleration to ~10 MeV

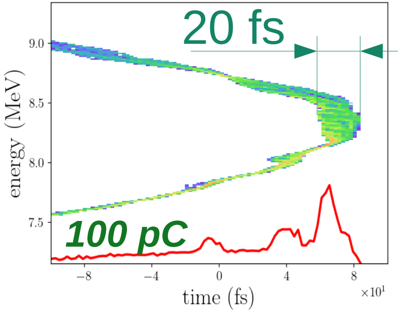
Overarching goals:

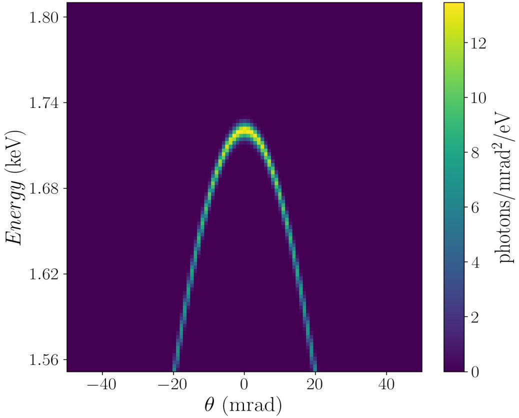
- Accelerate beam from the gun to ~10 MeV.
- Optimize/characterize final beam brightness.
- Explore ultra-short -bunch generation.

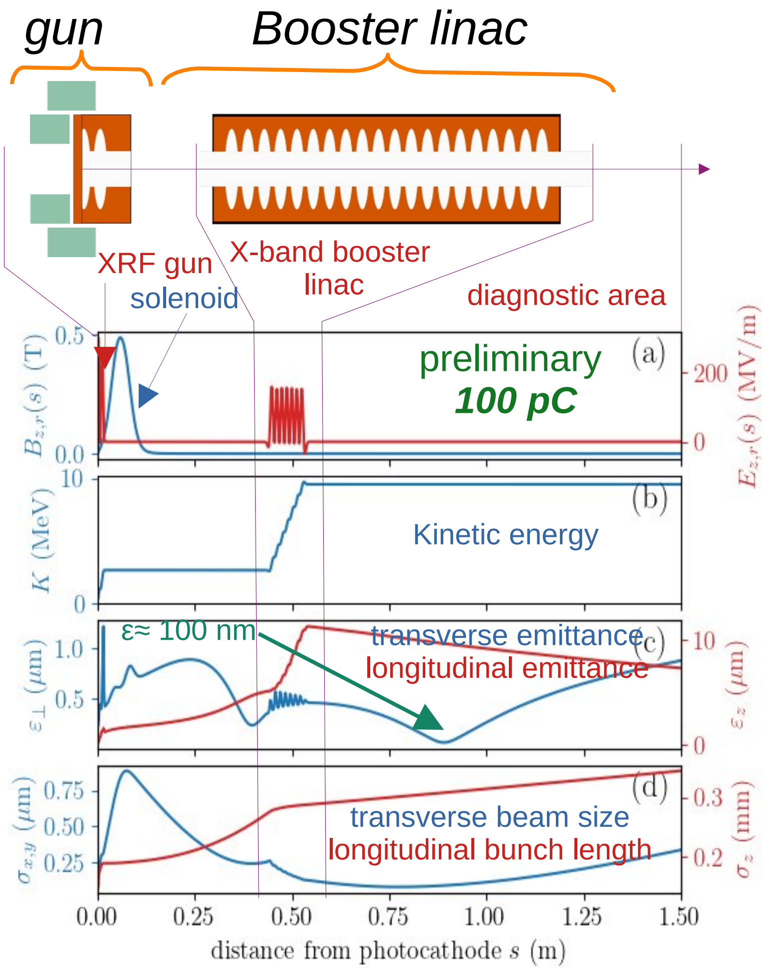
Application:

- Explore X-ray (2keV generation via inverse-Compton Scattering

Velocity-bunching mode: longitudinal phase space

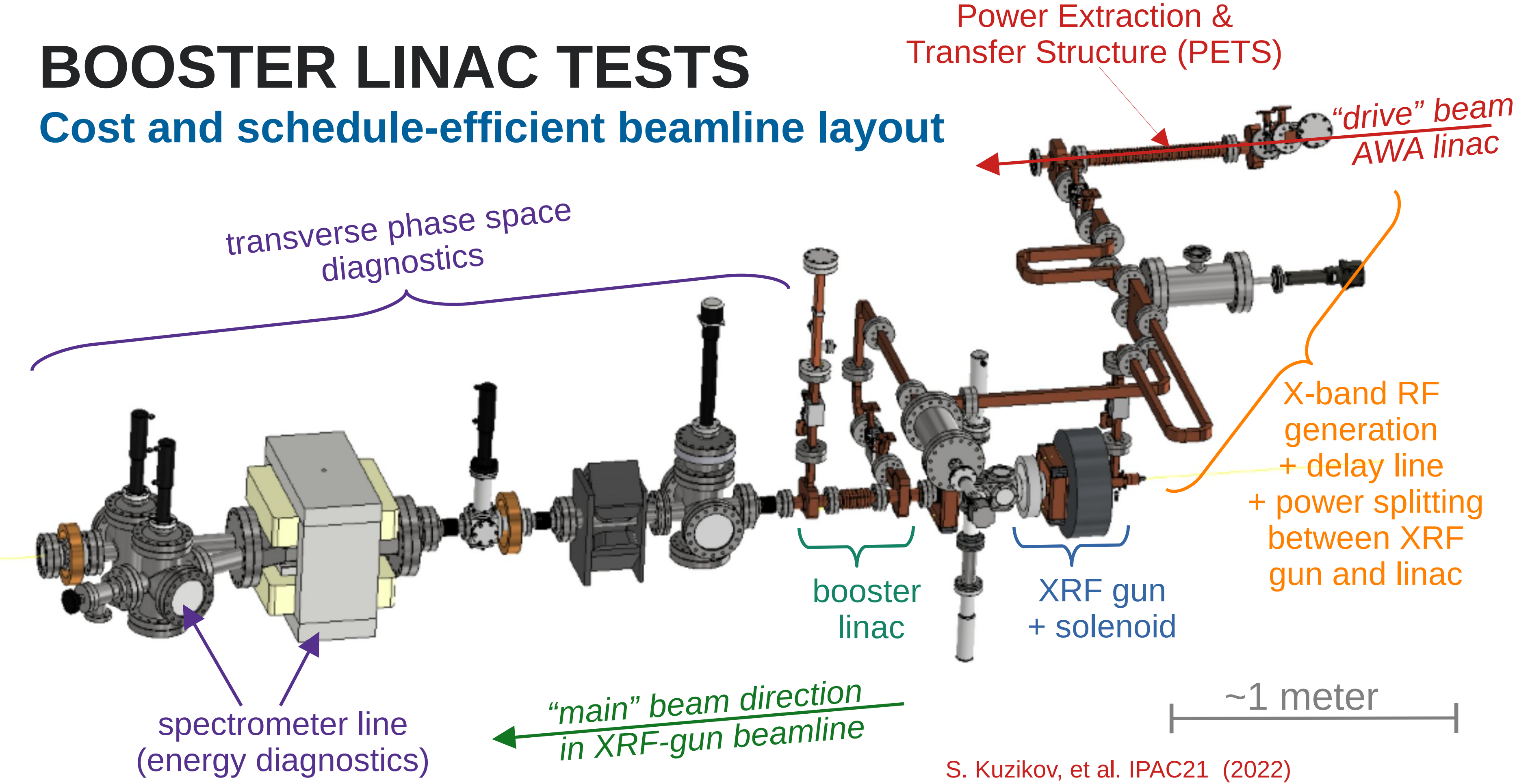






BOOSTER LINAC TESTS

Cost and schedule-efficient beamline layout

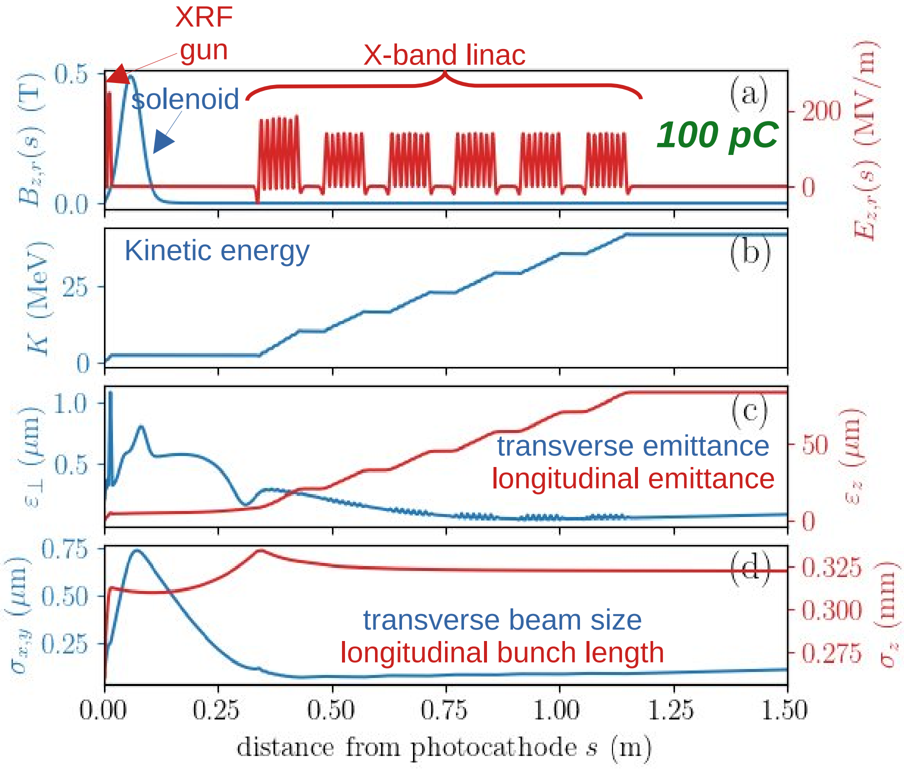


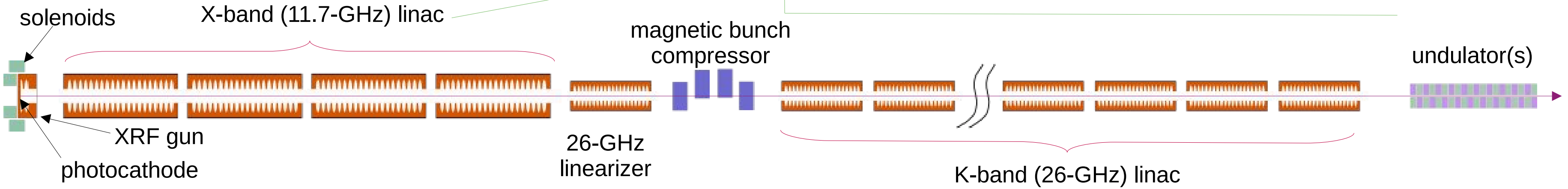
S. Kuzikov, et al. IPAC21 (2022)
10.18429/JACoW-IPAC2021-WEPAB163

INTEGRATED INJECTOR

Emittance compensation

- 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.



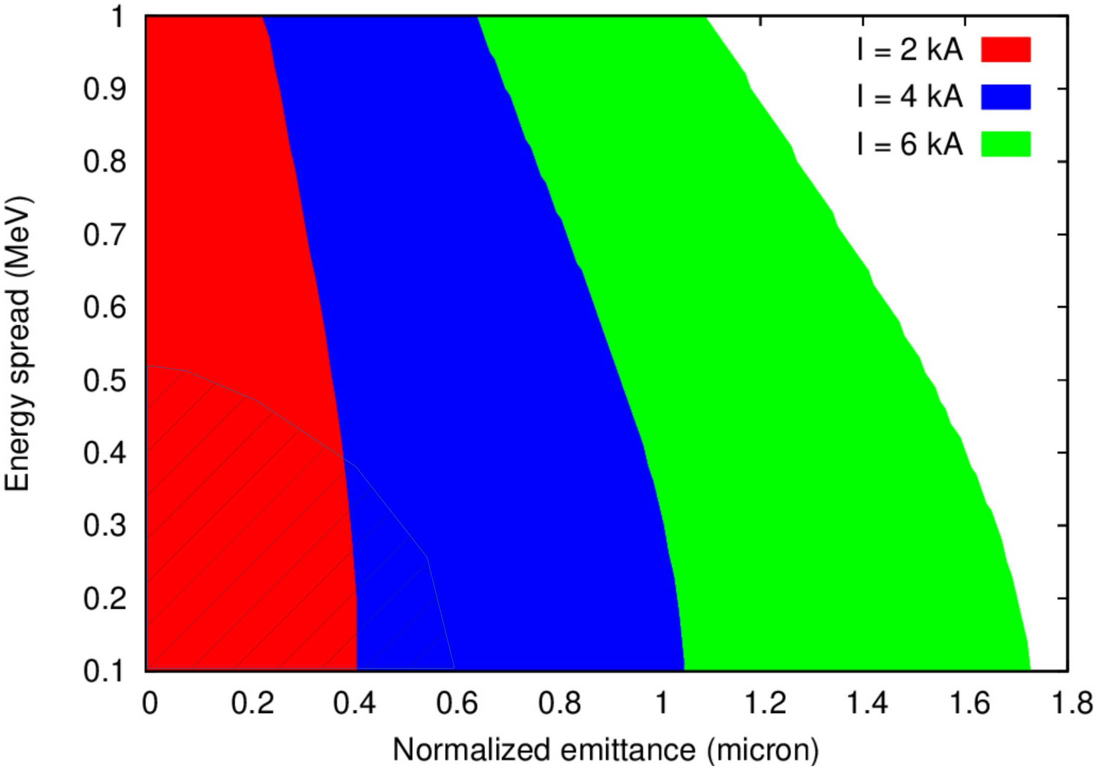


FEL DRIVEN BY THE TBA CONCEPT

V/EUV FEL opportunities

- 1D FEL-gain calculations were performed (Ming-Xie formalism)
- Undulator period is 13 mm and length was constrained to 5 m
- Expected e-beam parameters could support lasing at ~10 nm
- Other possible concepts include a TBA-driven RF undulator (at 26 GHz).

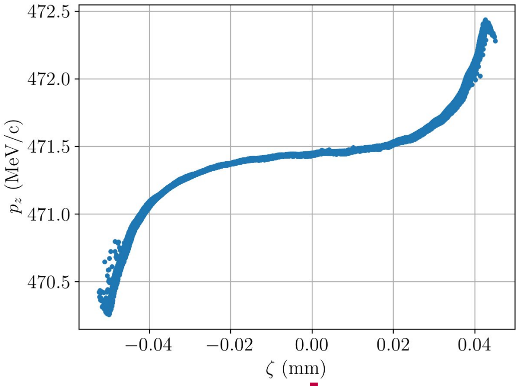
Calculations by R. Lindberg (ANL/APS)

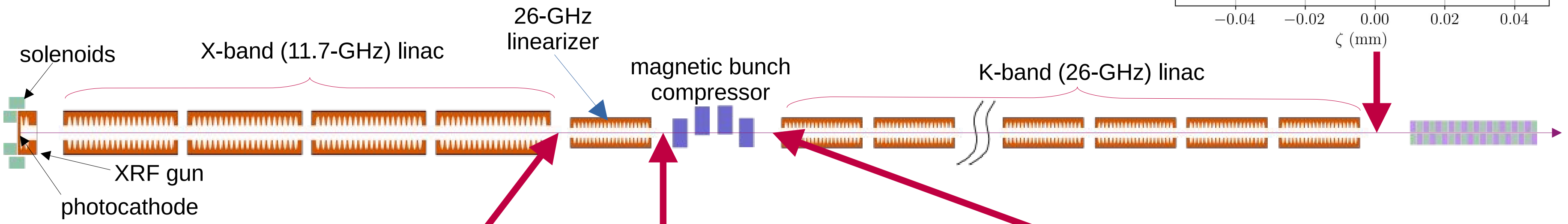


INTEGRATED INJECTOR

Longitudinal dynamics

- Longitudinal-phase-space dynamics preliminary model with a 1D-1V model (no collective effect)





solenoids

X-band (11.7-GHz) linac

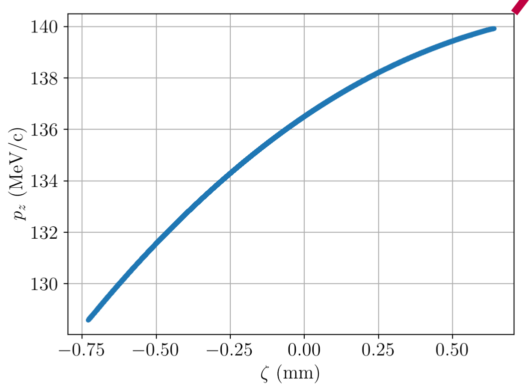
26-GHz linearizer

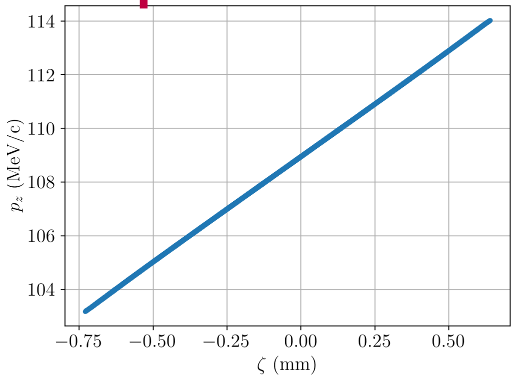
magnetic bunch compressor

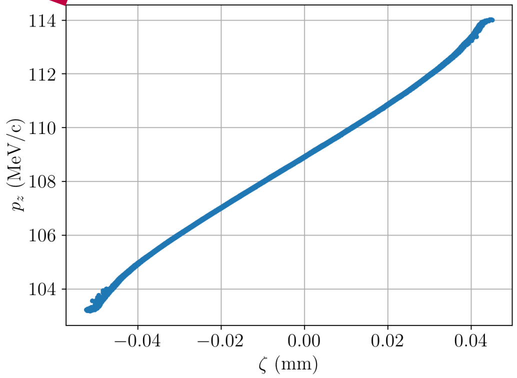
K-band (26-GHz) linac

XRF gun

photocathode

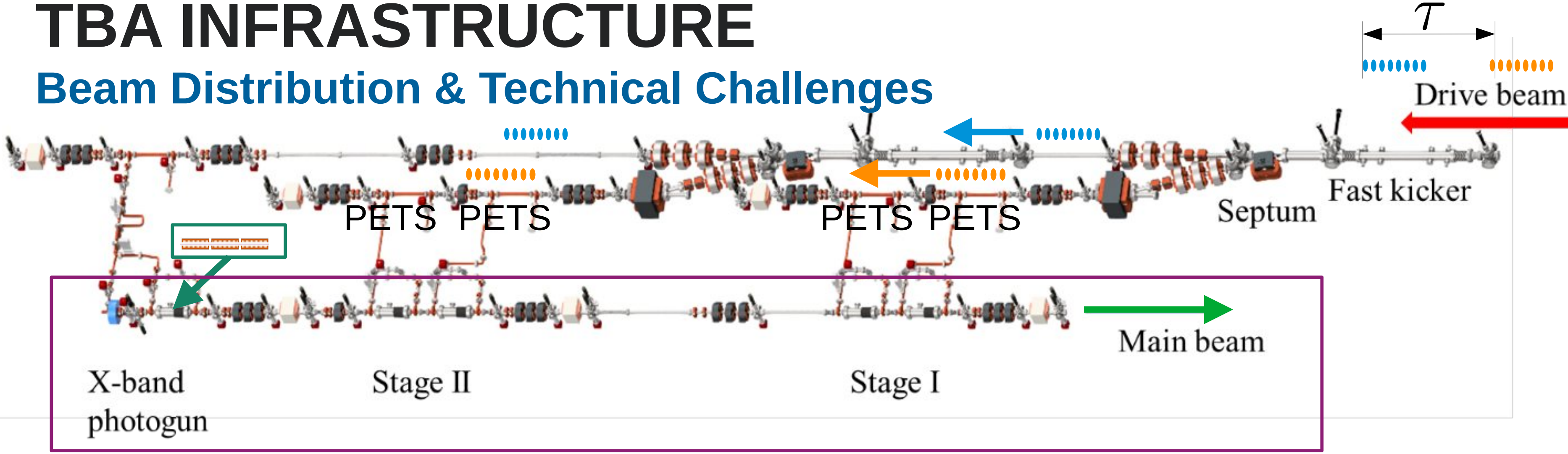






TBA INFRASTRUCTURE

Beam Distribution & Technical Challenges



- Drive beamline distributes two 8-bunch trains into two-parallel lines
  - Demonstrated 2x8 bunches production with variable delay
  - Challenges: transport and distribution of high-charge drive beams, enhancing deceleration in PETS (multiple PETS)
- Production of 500-MeV main beam based on “conventional” design

SUMMARY

- Over the last 2 years 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 AWA. It demonstrated (*i*) 400 MV/m on photocathode, (*ii*) did not produce observable dark current and (*iii*) had no significant breakdown.
- We are now adapting the design of a proposed 500-MeV SWFA-module (linear collider) to leverage the bright e- beam from the gun and support an FEL
- Such an option will give confidence in TBA application to real-word accelerators + provide an option for a post APS-U light-source at Argonne.