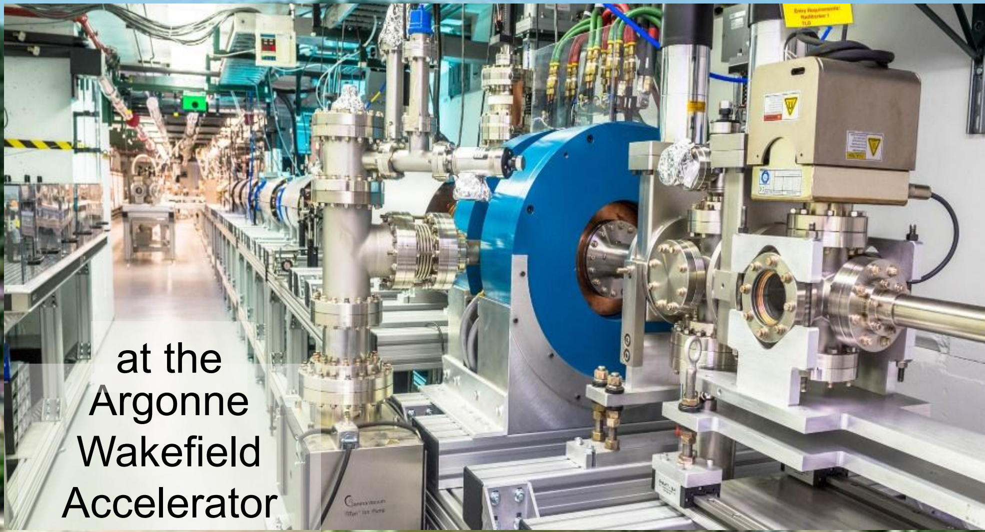
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY 75 1946–2021

EAAC2025

PROGRESS TOWARD HIGH-GRADIENT STRUCTURE WAKEFIELD ACCELERATORS



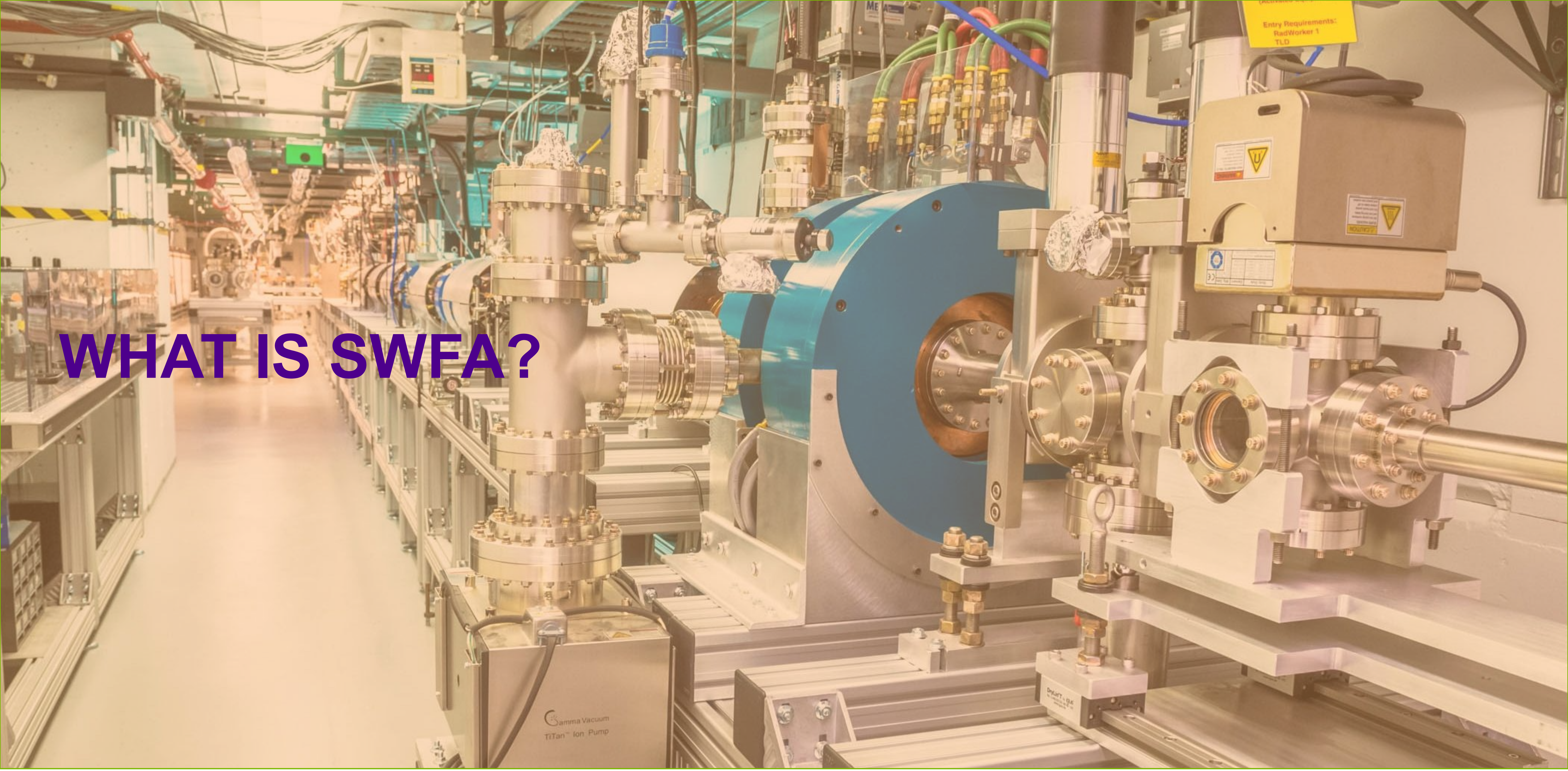
Sept 24, 2025

Argonne National Laboratory
jp@anl.gov
https://www.anl.gov/awa
JOHN POWER for the Argonne Wakefield Accelerator collaboration

Outline

- What is Structure Wakefield Acceleration?
- Motivation: SWFA-based applications
- The Argonne Wakefield Accelerator (AWA) Facility
- Progress: SWFA recent milestones
- Roadmap: keeping the progress going

WHAT IS SWFA?


Entry Requirements:
RadWorker 1
TLD
Gamma Vacuum
TiTan™ Ion Pump

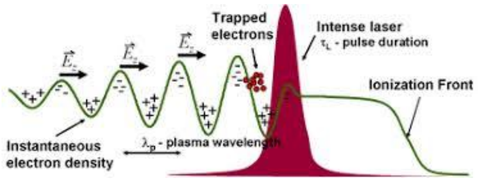
Where does Structure Wakefield Acceleration fit in?

The 4 Advanced Accelerations Concepts

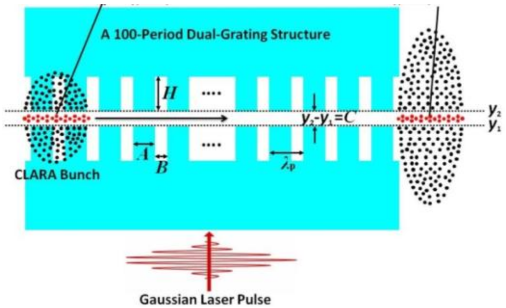
Energy Source

Laser pulse

LWFA
(Laser WF Accelerator)

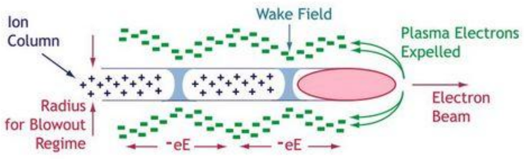


DLA
(Dielectric Laser Accelerator)

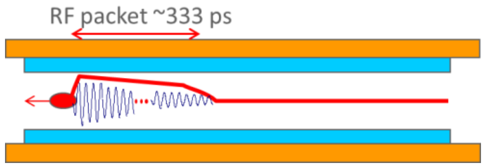


Particle beam

PWFA
(Plasma WF Accelerator)



SWFA
(Structure WF Accelerator)

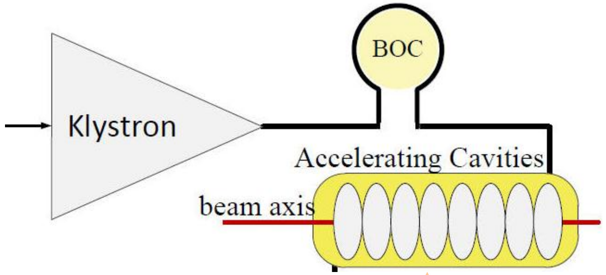


Plasma

Medium

Structure

RF Driven Structure



Medium (structure)

Energy source (Drive beam)

OVERLAP 1

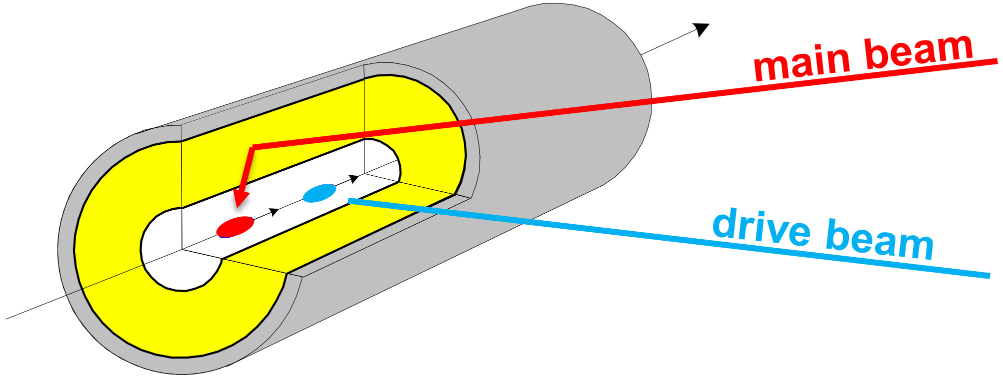
OVERLAP 2

Structure Wakefield Acceleration (SFWA)

Beam-Structure Interaction (Drive beam + Main beam)

COLLINEAR WAKEFIELD ACCELERATION (CWA)

PWFA-like



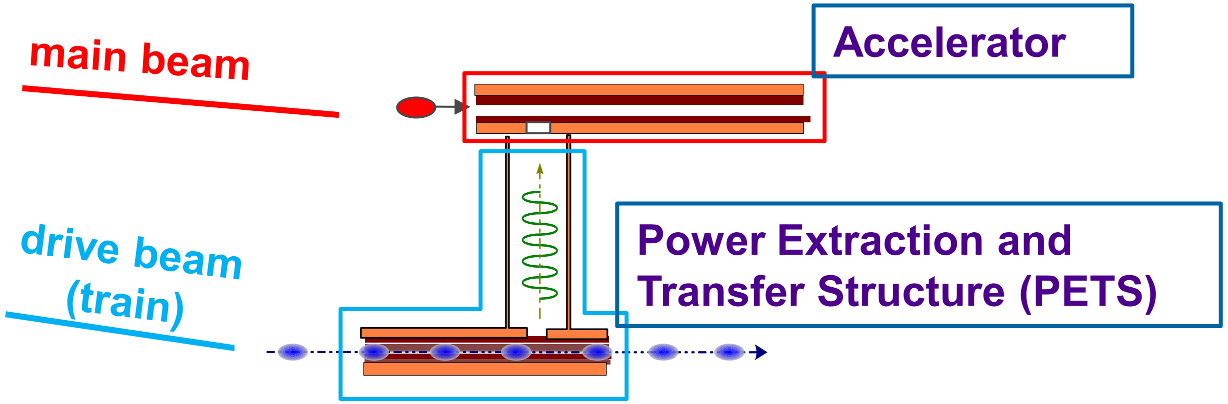
- **A. Zholents** et al, "A high repetition rate millimeter wavelength accelerator for an X-ray free-electron laser", **2025 JINST 20 P01023**

Application: Light Source

Application: High Energy Physics

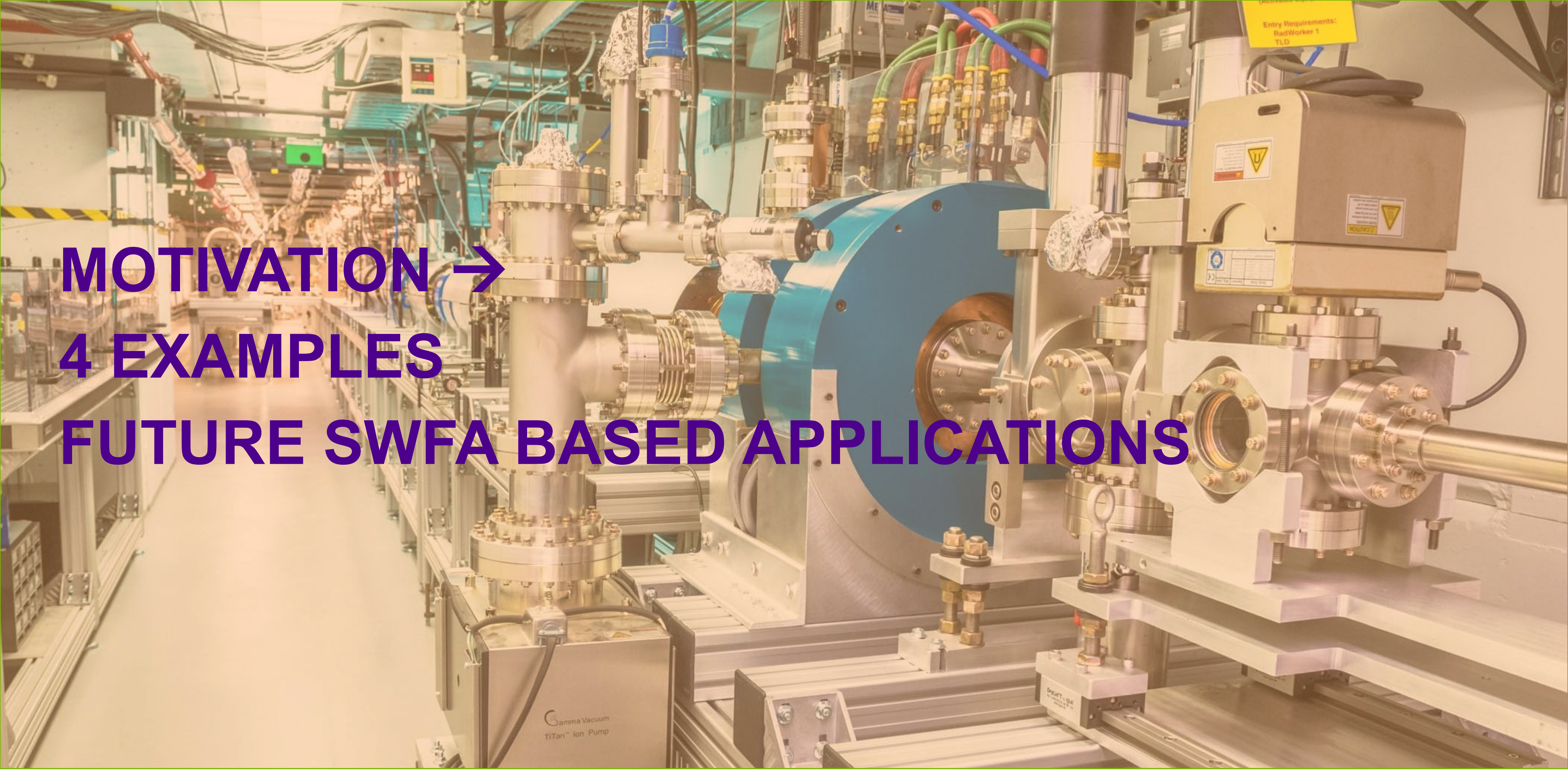
TWO BEAM ACCELERATION (TBA) – like CLIC

Klystron-like



- **W. Gai, J.G. Power, and C. Jing**, "Short-pulse dielectric two-beam acceleration", J. Plasma Phys., vol. 78, 339–345.
- **G. Ha**, et al., "" Status of the experimental demonstration of GW power generation from THz-TBA", WEP083, NAPAC2025 (2025)
- **R. Margraf-O'Neal** et al., "Simulated performance of a compact water-window FEL driven by a structure wakefield accelerator", LINAC2024, **THPB005**

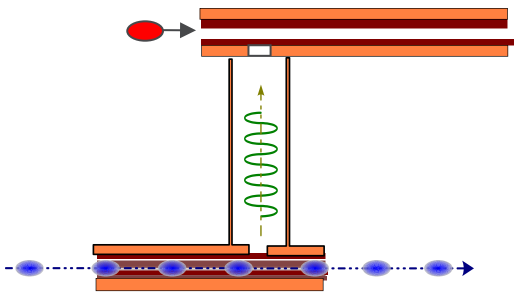
M. Rosing and W. Gai, Phys. Rev. D Vol 42, No. 5 (1990)



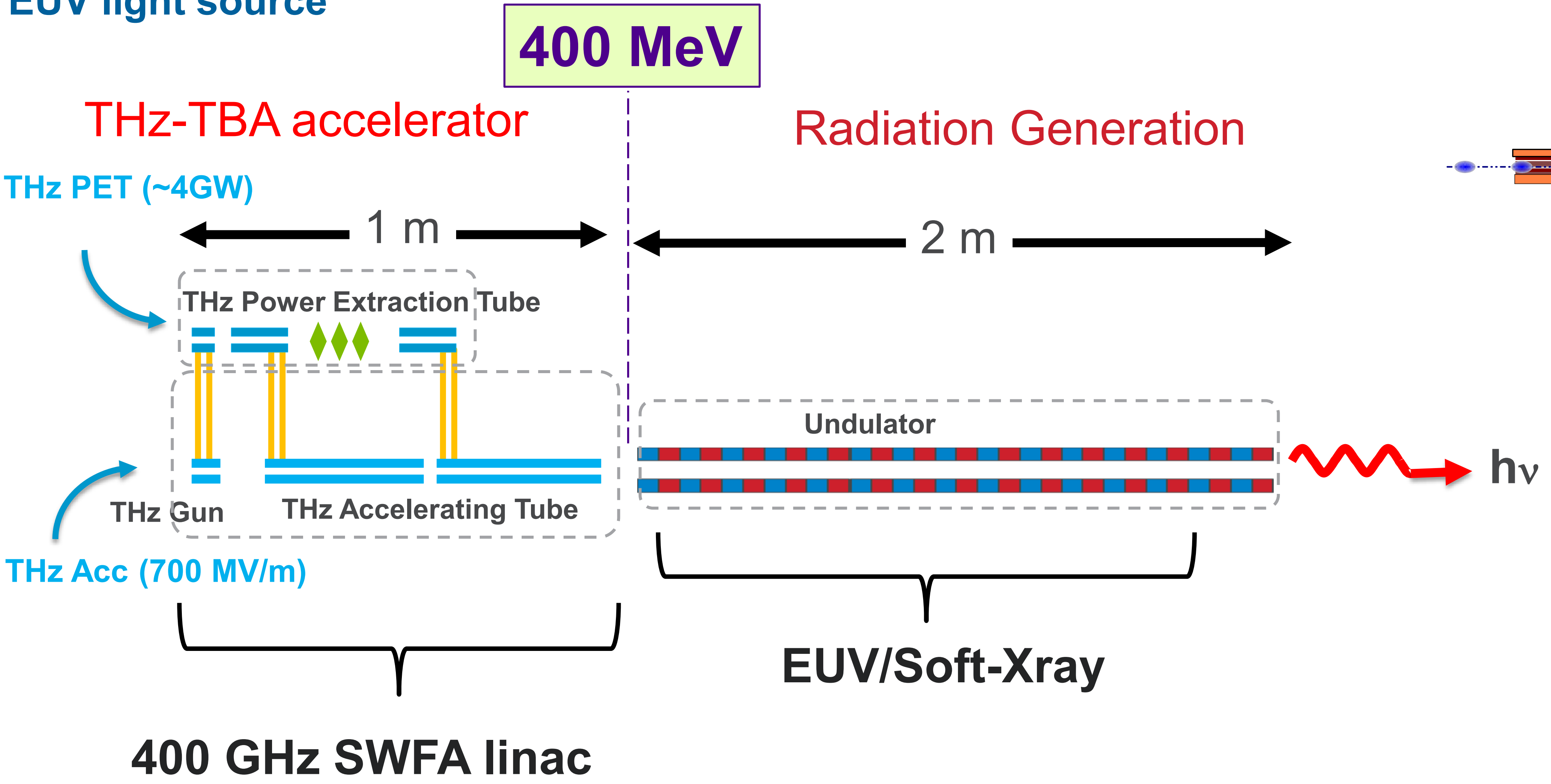
MOTIVATION →
4 EXAMPLES
FUTURE SWFA BASED APPLICATIONS

STRUCTURE WAKEFIELD ACCELERATION: TBA

Two Beam Acceleration



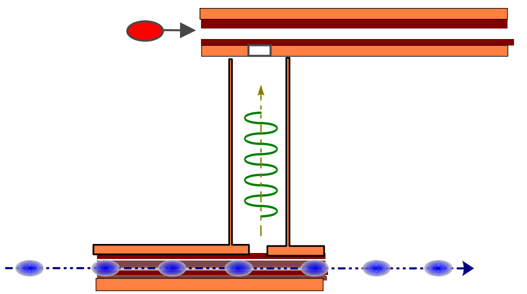
EUV light source

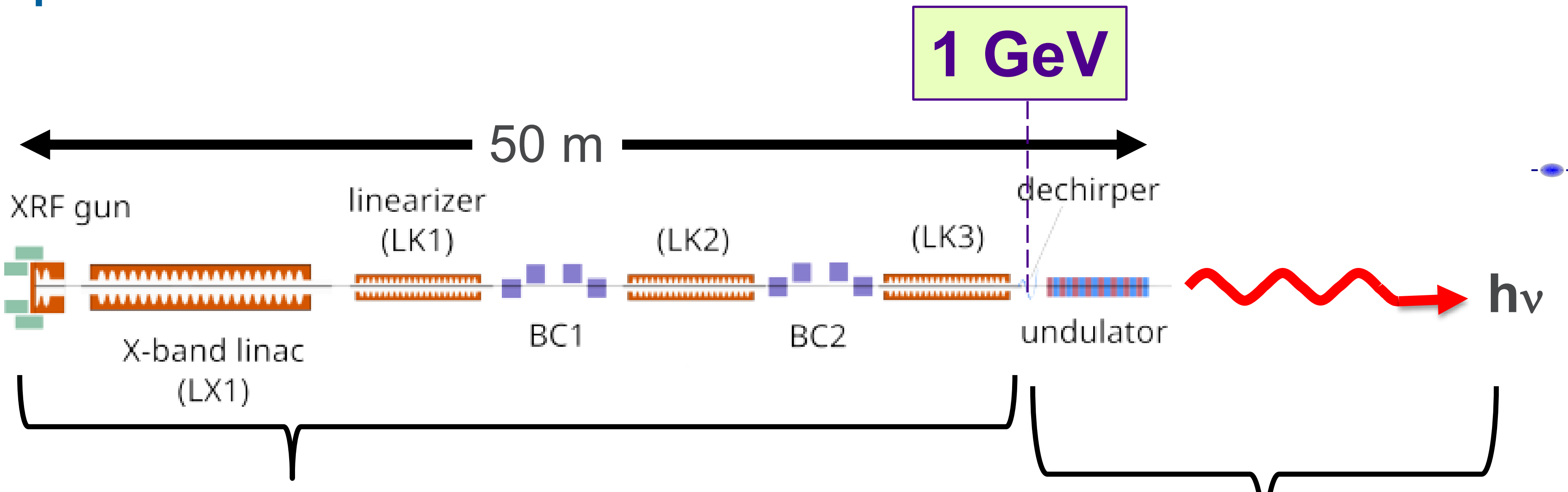


G. Ha, et al., TUPL057, IPAC2023 (2023)

STRUCTURE WAKEFIELD ACCELERATION: TBA

Compact water-window FEL





SWFA X-band and K-band linac

– 1 GeV, high brightness

to drive an FEL

– water-window regime [2,4] nm
– Energy/pulse [100, 300] μJ
– Short [10's of fs]
– High-power (GW-scale)

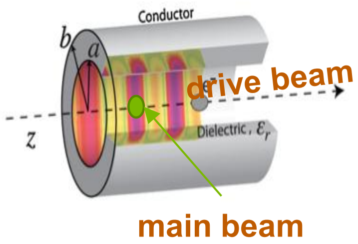
P. Piot, "Design of a Water-Window Free-Electron Laser Using the Two-Beam Acceleration Scheme", **THURS. 16:40 - 17:00, Bonaparte 2 (Hotel Hermitage)**

R. Margraf-O'Neal et al., "Simulated performance of a compact water-window FEL driven by a structure wakefield accelerator", in Proc. LINAC2024, Chicago, IL, USA, Aug. 2024, pp. 637-640. doi:10.18429/JACoW-LINAC2024-THPB005

STRUCTURE WAKEFIELD ACCELERATION: CWA

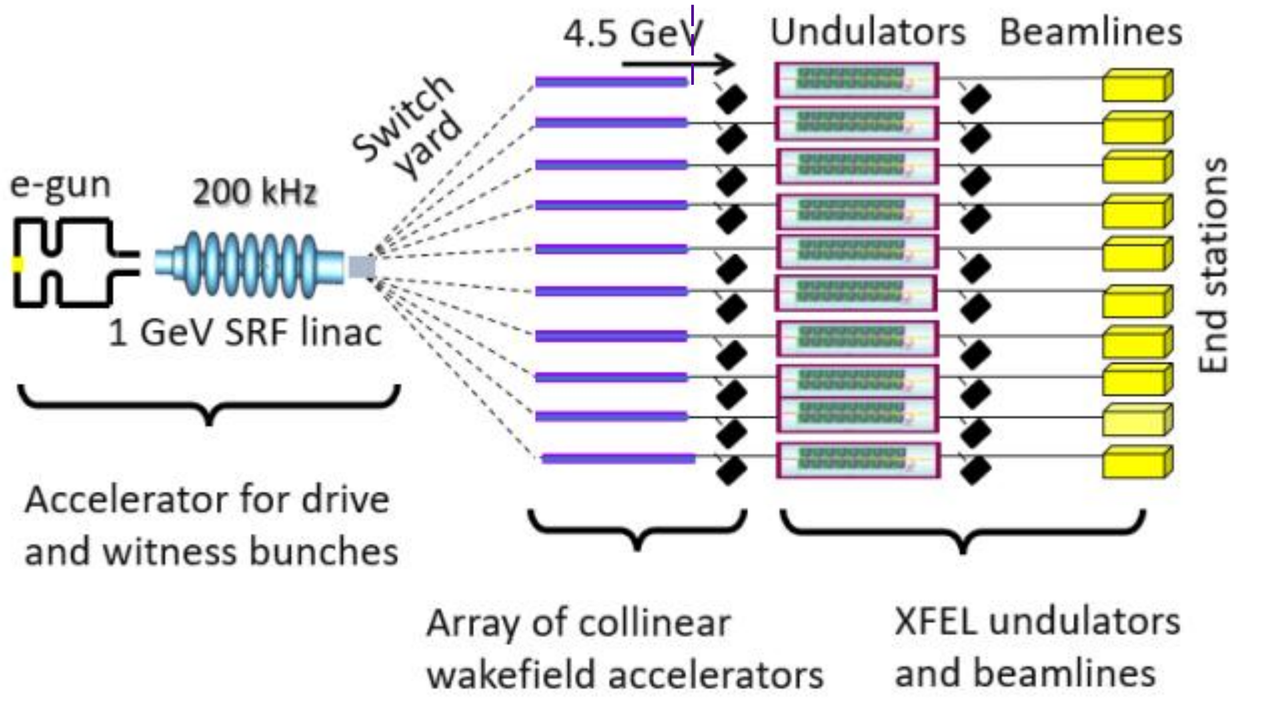
High repetition rate multi-user X-ray FEL facility

Collinear Wakefield Acceleration



4.5 GeV

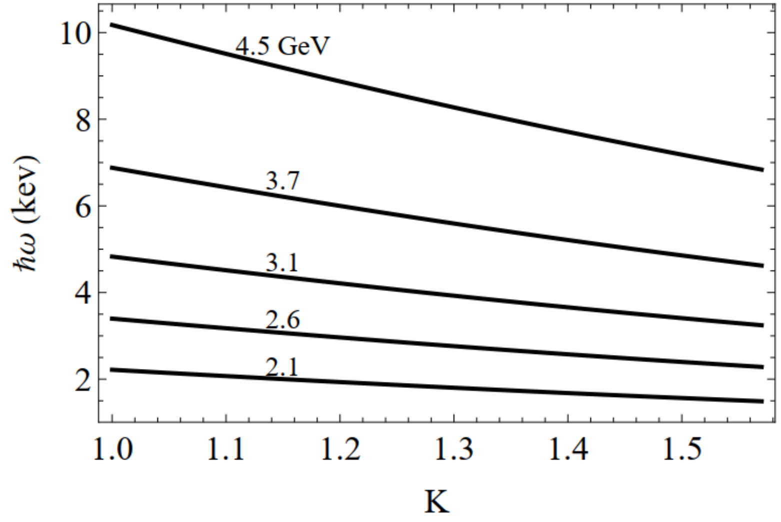
A-STAR



A. Zholents et al, "A high repetition rate millimeter wavelength accelerator for an X-ray free-electron laser",
2025 *JINST* 20 P01023

10 Beamlines

- Independently tunable
- Repetition rate of up to 20 kHz
- X-ray spectrum:1.5 keV to 10.2 keV

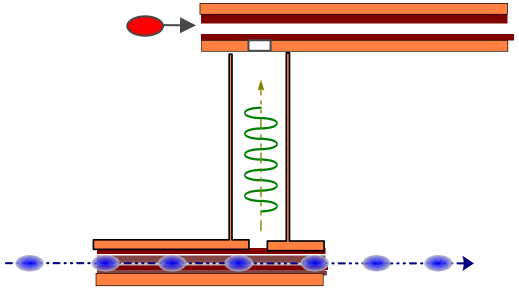


Photon energy $\hbar\omega$ versus undulator parameter K calculated for an undulator with a period of 12.6 mm and different beam energies shown above the lines.

STRUCTURE WAKEFIELD ACCELERATION: TBA

Linear Collider

Two Beam Acceleration



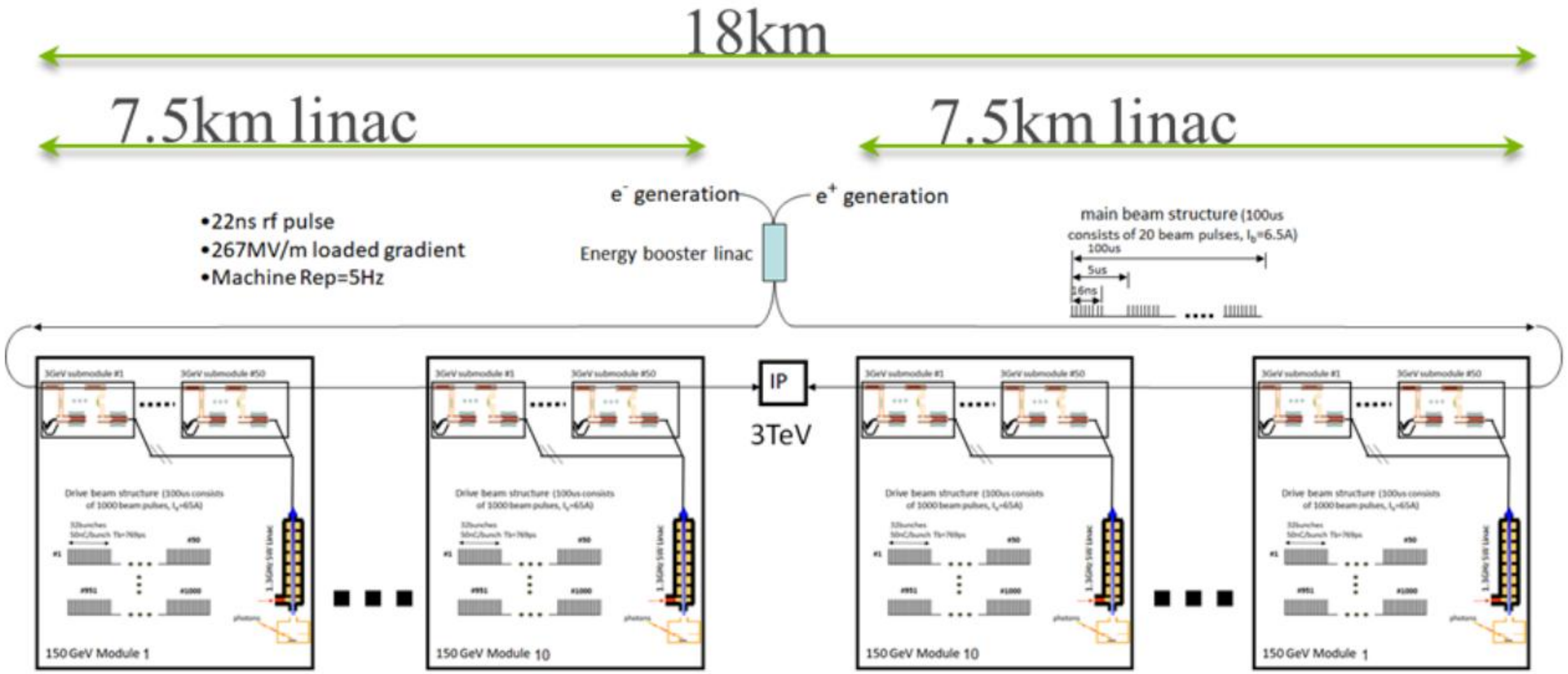
- **2013 P5.** 3 TeV Linear Collider concept.
  - High Power ~1 GW
  - 320 MV/m unloaded gradient
  - 267 MV/m loaded gradient
  - 200 MeV/m real estate gradient

- **2023 P5.** 10 TeV Linear Collider concept.
  - 500 MeV/m real estate gradient

?

1.5 TeV (x2)

ARGONNE FLEXIBLE LINEAR COLLIDER



W. Gai, J.G. Power, and C. Jing, *J. Plasma Phys.*, vol. 78, 339–345.

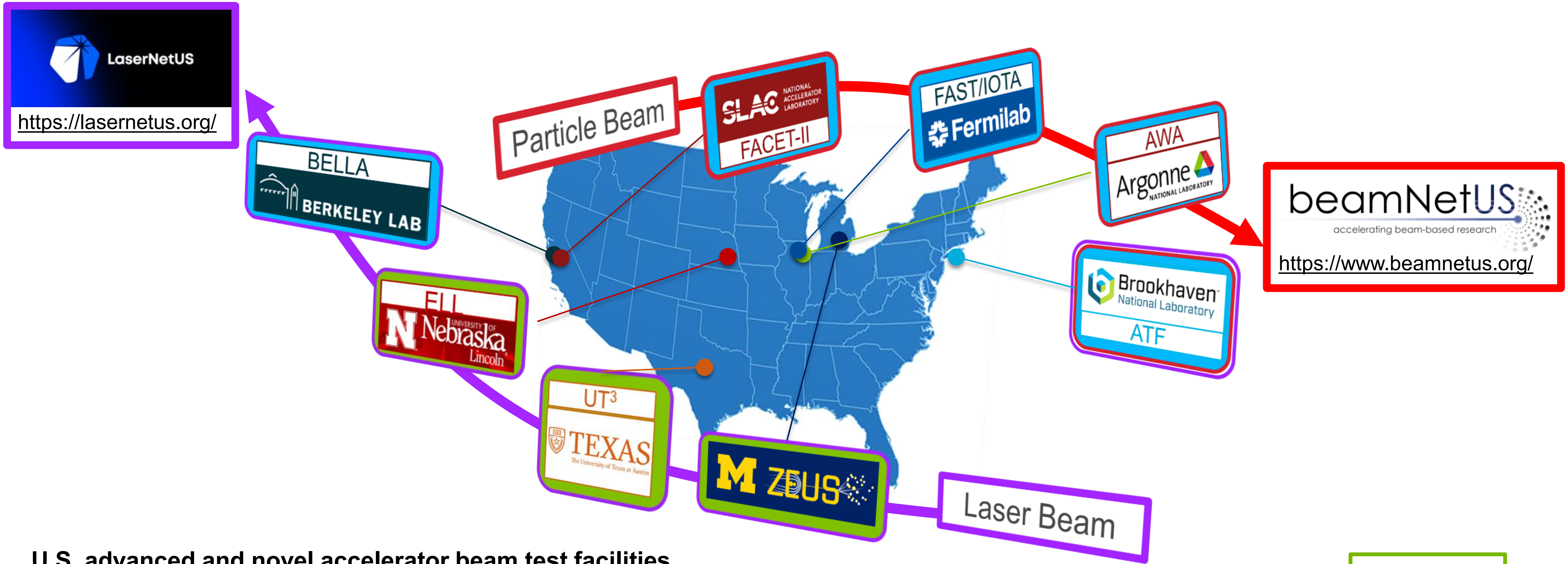
Modular design
(easily staged)

e^+ e^- 267 MeV/m of loaded gradient
(200 MeV/m effective gradient)

THE AWA FACILITY

NETWORK OF AMERICAN BEAM TEST FACILITIES

Experimental demonstration of emerging accelerator science



U.S. advanced and novel accelerator beam test facilities
[C. Clarke et al 2022 JINST 17 T05009, https://iopscience.iop.org/article/10.1088/1748-0221/17/05/T05009]

U.S. DEPARTMENT OF ENERGY | Office of Science

National Laboratories **Universities**

NSF

The Argonne Wakefield Accelerator (AWA) Facility

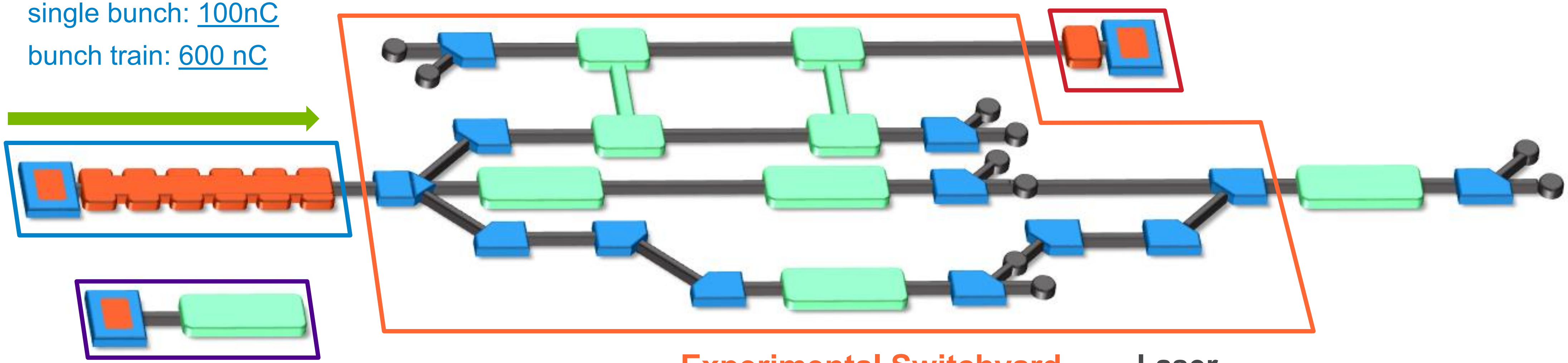
Beam Test Facility to enable novel acceleration

Witness RF photoinjector (15 MeV)

- Provides two-beam capability
- Bright beams for low-energy experiments

Drive RF Photoinjector (65 MeV)

- single bunch: 100nC
- bunch train: 600 nC



Argonne Cathode Test Stand (2-4 MeV)

- Cathode research and diagnostics
- Physics of high-gradient breakdown

Experimental Switchyard

- Highly reconfigurable
- 6D phase space manipulation

Laser

Photoinjector laser

- 100 mJ (800nm), 10 mJ (262nm),
- 300 fs – 6 ps (UV)
- temporal shaping

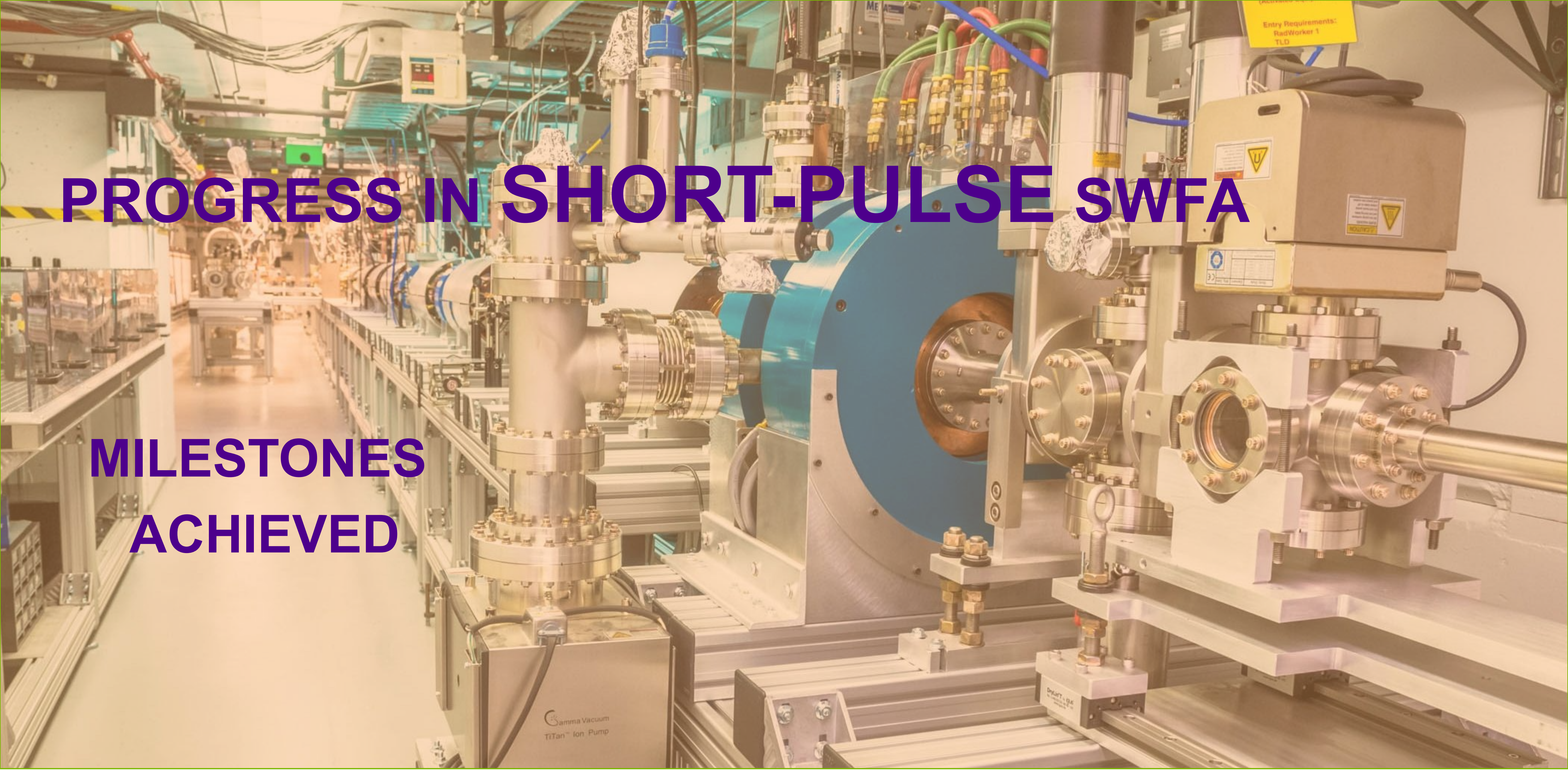
Diagnostic laser

- 81.25 MHz (1550 nm)

https://www.anl.gov/awa

PROGRESS IN SHORT-PULSE SWFA

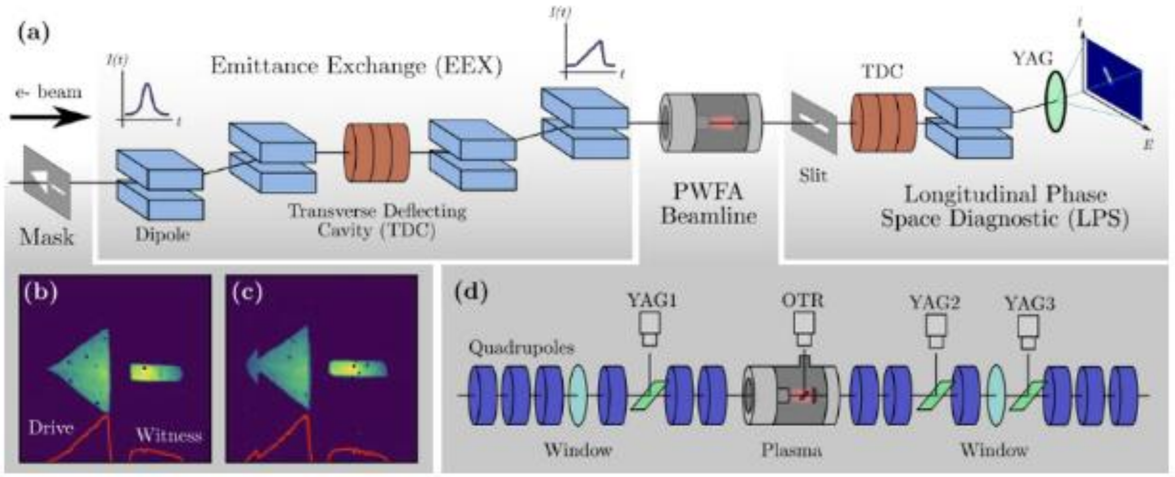
MILESTONES ACHIEVED



MILESTONE: CWA

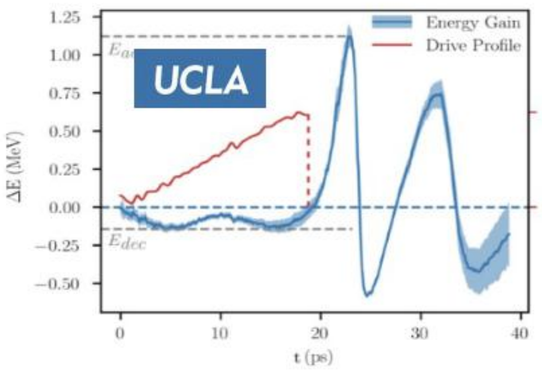
demonstration of >5 transformer ratios

- The transformer ratio relates to efficiency $R = \frac{E_{acc}}{E_{dec}}$
- To achieve *R*>2 → bunch shaping
- Shaping with an emittance-exchange (EEX) beamline
- Two experiments demonstrated R>2:
  - PWFA using a plasma R~7
  - SWFA using a structure R~6



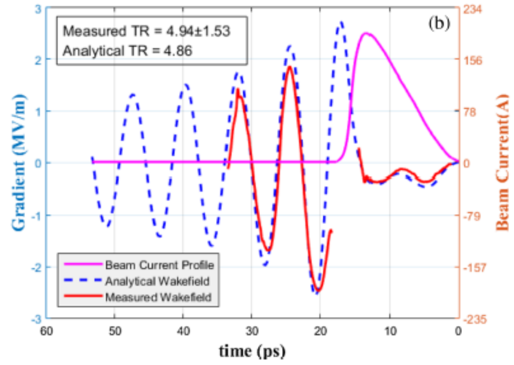
High R with shaped beams

PWFA



R. Roussel *et al. PRL (2020*]

SWFA

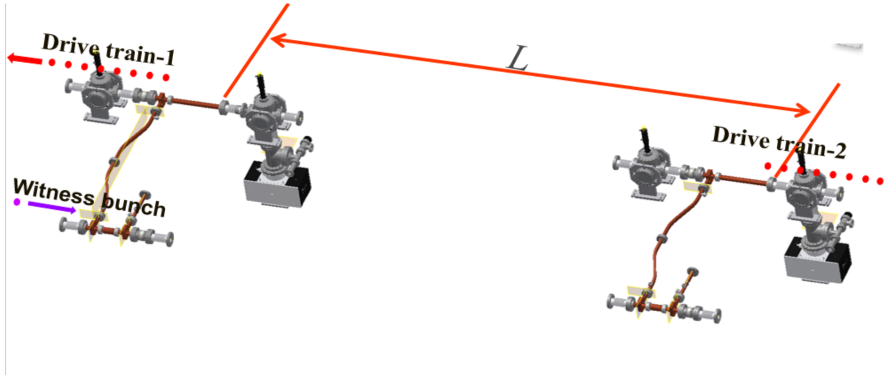


Q. Gao, *et al, PRL* (2018)

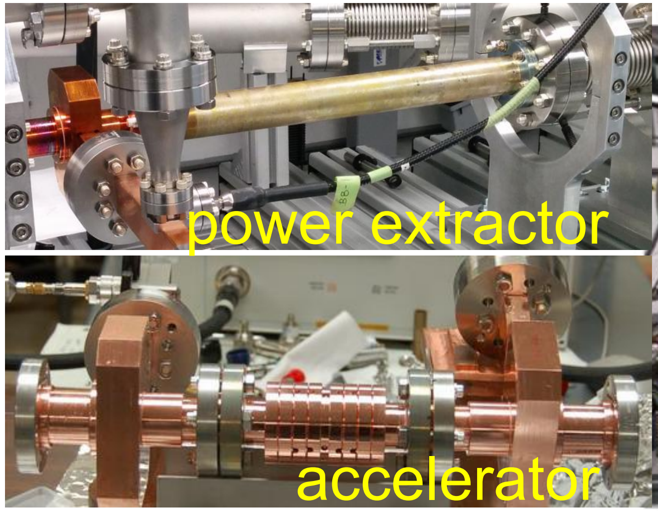
MILESTONE: TBA

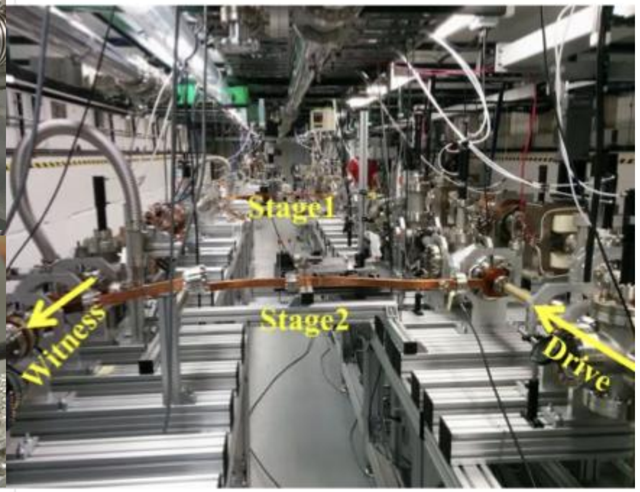
Staging of acceleration

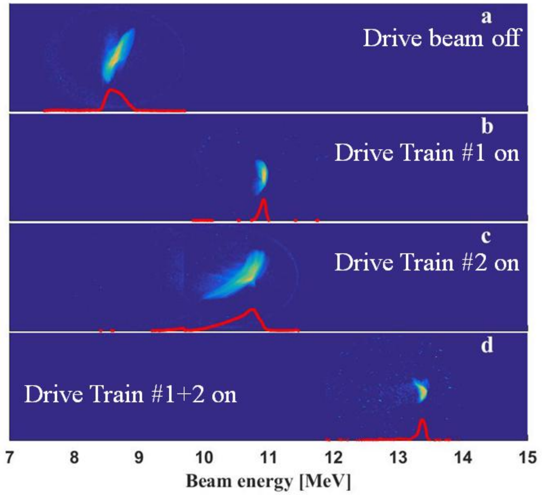
- Demonstration (simplified) two-stage SWFA
- Scalable to any number of accelerating module



X-band 11.7 GHz structures

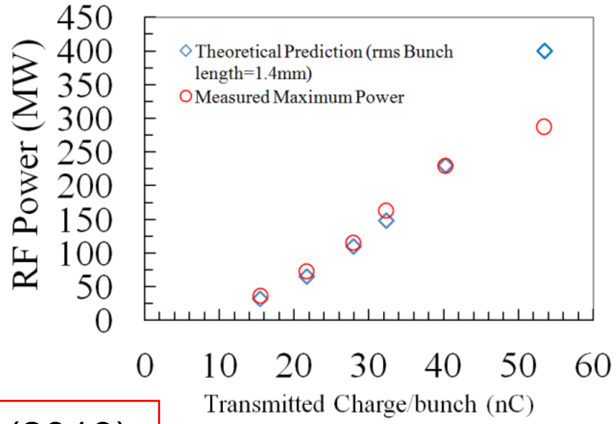






70 MeV/m
acceleration in each stage

300 MW, 150 MeV/m
acceleration single stage



C. Jing, *et al*, *Nucl. Instrum. Meth. A.*, 898, 72-76 (2018)

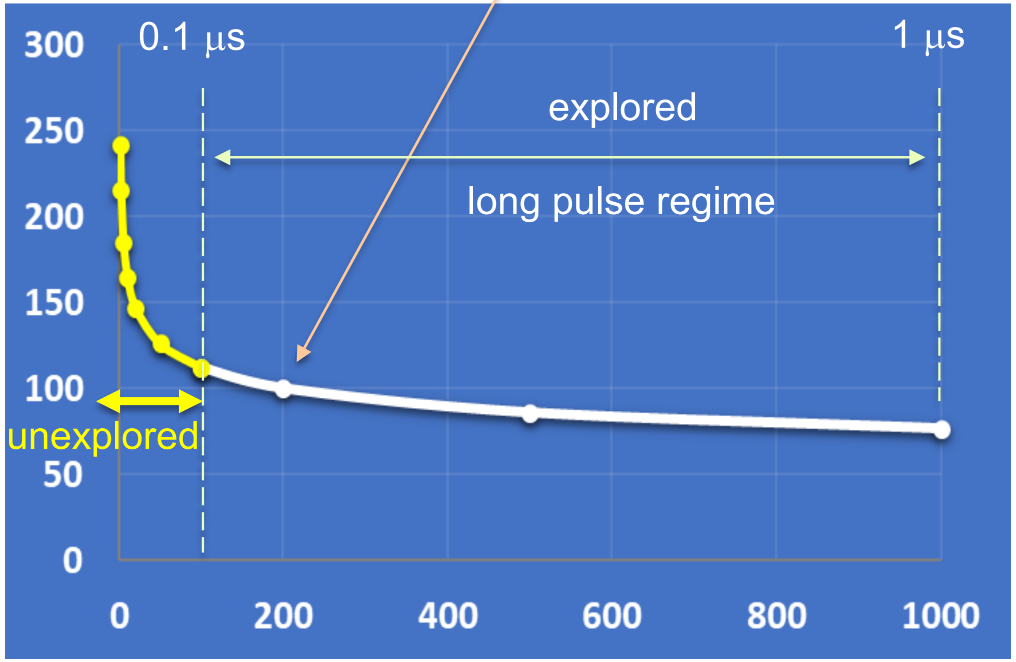
Why Short Pulse RF? (Part I): TBA

3e−7 breakdowns/pulse/m, 100 MV/m, 200ns

Motivation #1:
the CLIC scaling law

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

BreakDown Rate — Accelerating field — RF pulse length



S. Doebert et al.,PAC’05
A. Grudiev, S. Calatroni, and W. Wuensch, Phys. Rev. ST Accel. Beams 12,102001 (2009)
W. Wuensch, et al., “*A demonstration of high-gradient acceleration*”, PAC’03
***W. L. Millar**, et al, “*High-Power Test of Two Prototype X-Band Accelerating Structures Based on SwissFEL Fabrication Technology*, IEEE Tran. NS, 70, 1, (2023),1-19.

Short Pulse Regime

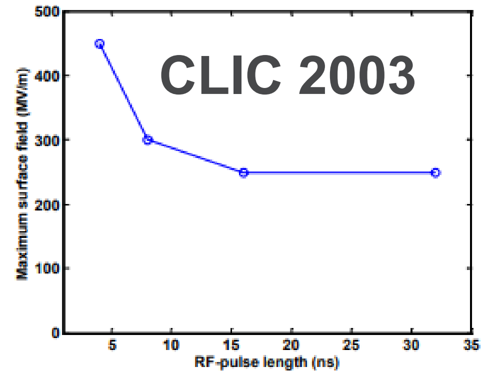
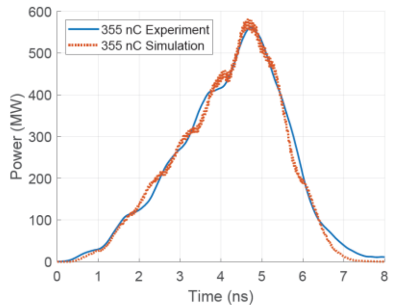


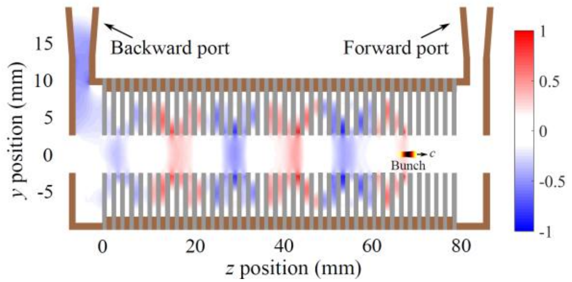
Figure 5: Pulse length dependence of the copper structure.

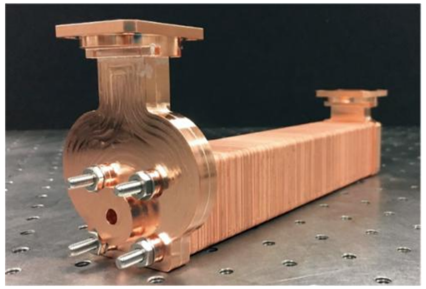
MILESTONE: TBA

High Power RF

MTM X-band PETS (565 MW)



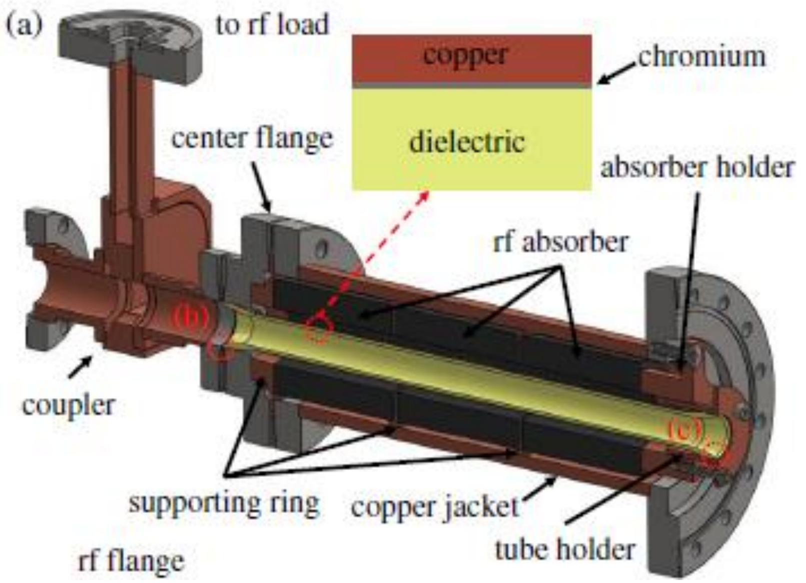




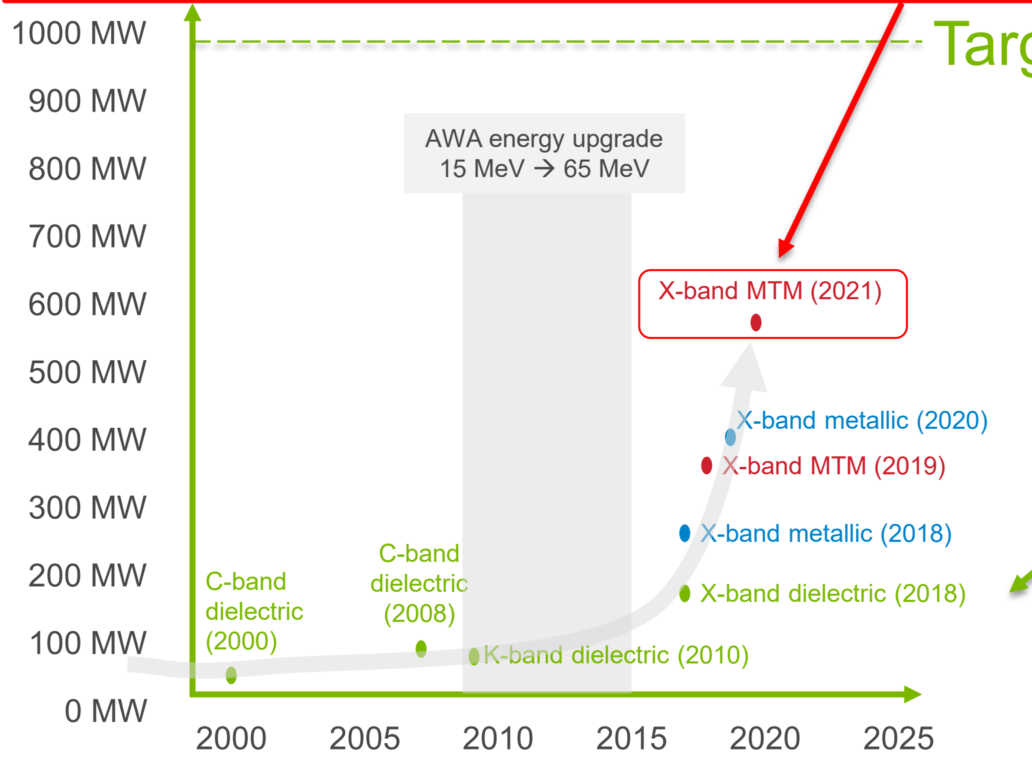
Highest peak power as 565 MW from a train of eight bunches with a total charge of 355 nC

J. Picard et al., PRAB 25, 051301 (2022)

Dielectric X-band PETS (200 MW)

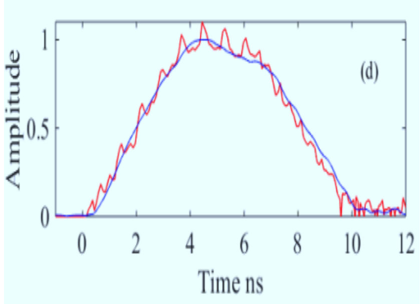


DOI: 10.1103/PhysRevAccelBeams.23.011301



Target: GW

Metallic X-band PETS (400 MW)

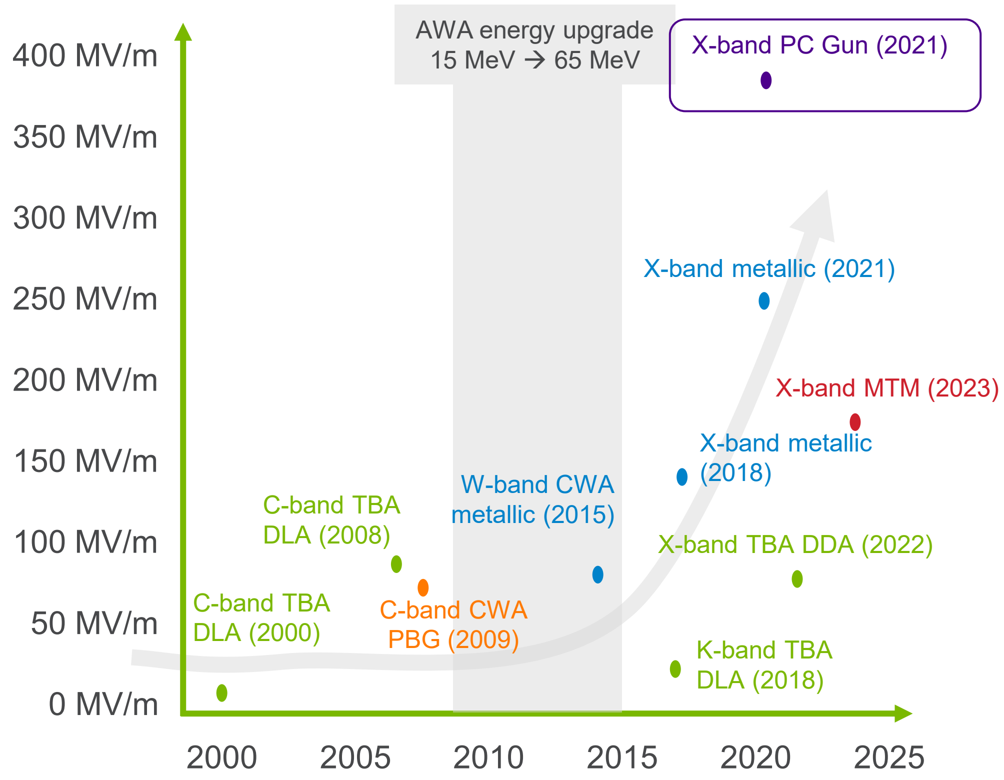


J. Shao *et. al.*,
https://accelconf.web.cern.ch/ipac2019/papers/MOPRB069.pdf

MILESTONE: TBA

High fields

Evolution of peak field in structures over the last two decades at AWA

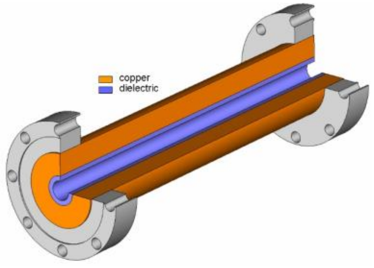


Demonstrated accelerating fields:

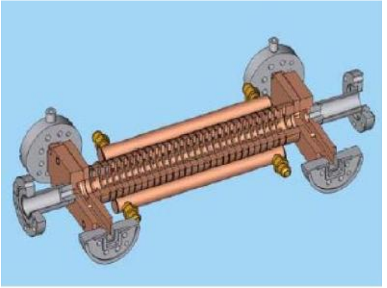
- ~300 MV/m in accelerating structures (~500 MV/m surface field)
- ~400 MV/m in RF gun (~600 MV/m surface field)

Novel accelerating structures

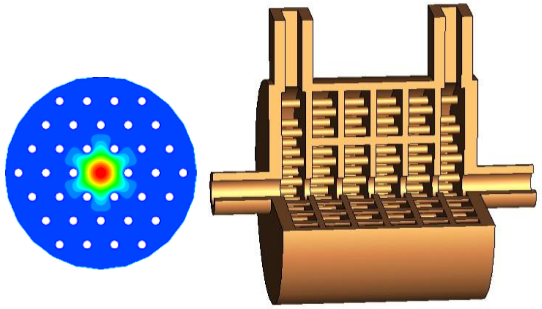
Dielectric



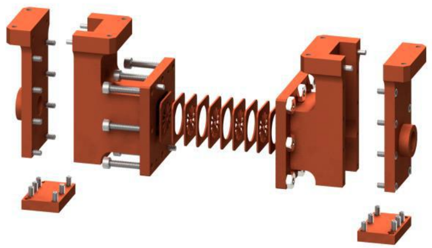
Iris loaded



Photonic Band Gap



Metamaterial



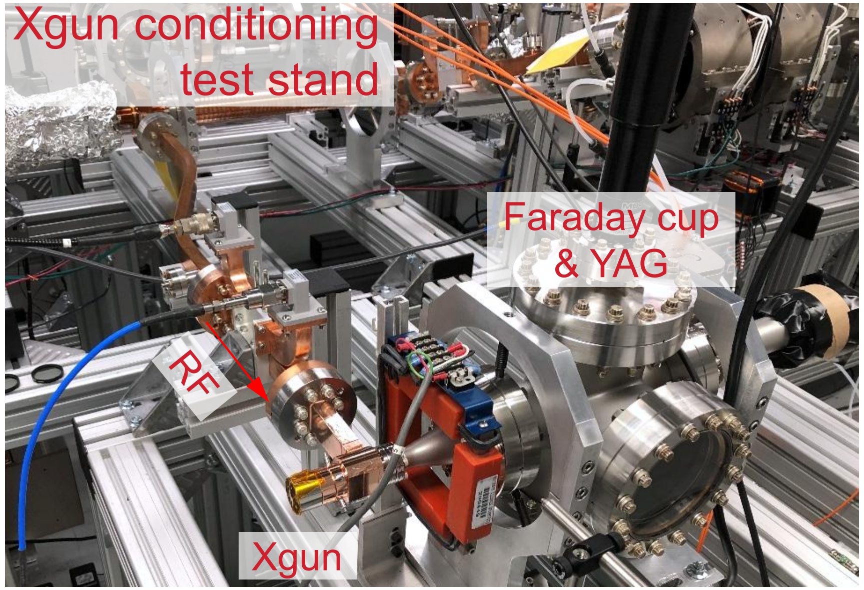
Current work includes

- Design and testing of new structures
- Fundamental studies on high fields

MILESTONE: TBA

Photoemission from a high-field RF gun

HIGH-GRADIENT & LOW DARK CURRENT

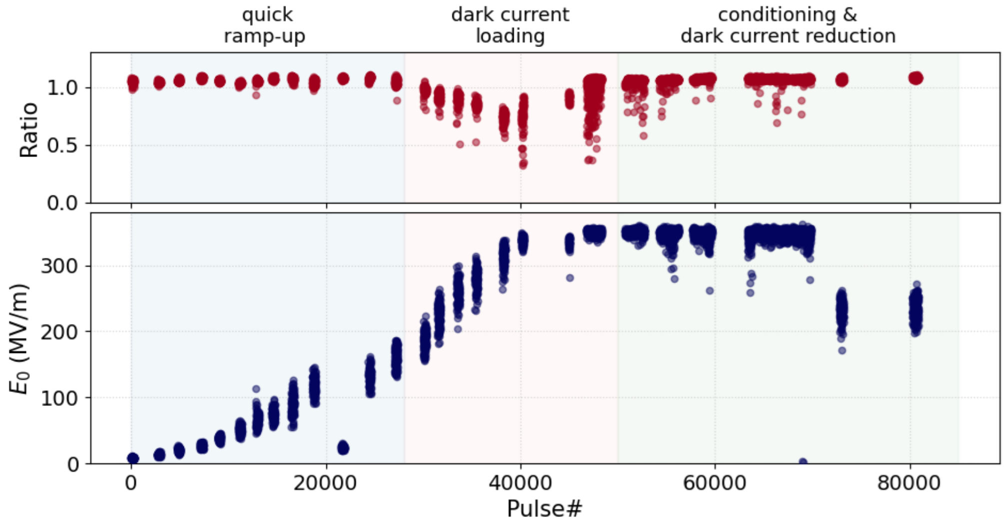


Gun milestones

- 0.4 GV/m on photocathode, 0.6 GV/m surface
- BDR ~4e-6 (estimated)
- Ultra low dark current (<1pC per RF pulse)

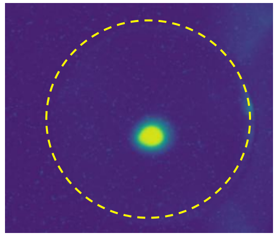
J. Shao et. al., 10.1103/PhysRevLett.115.264802

Fast RF conditioning (70,000 pulses)



FIRST BEAM FROM PHOTOCATHODE GUN

~3 MeV
387 MV/m
(confirmed)



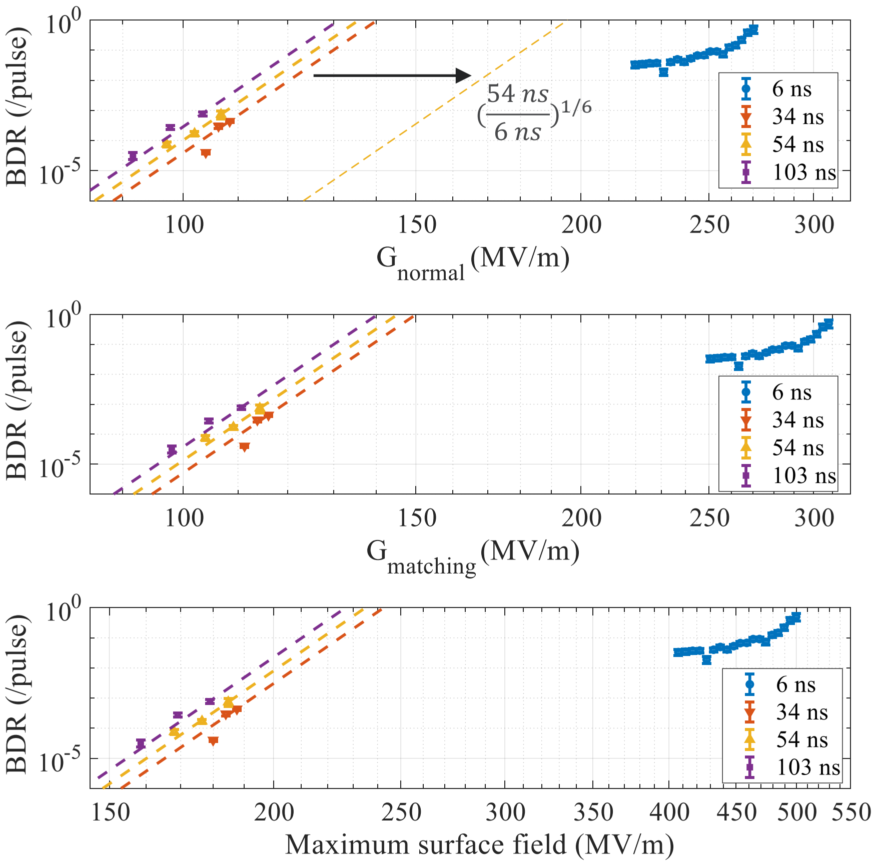
~6 MeV
Boosted
with linac

W.H.Tan *et. al.*, Phys. Rev. Accel. Beams 25, 083402, August 2022 (2022)

Why Short Pulse RF? (Part II)

Motivation #2:
beyond the CLIC scaling law (<15ns)

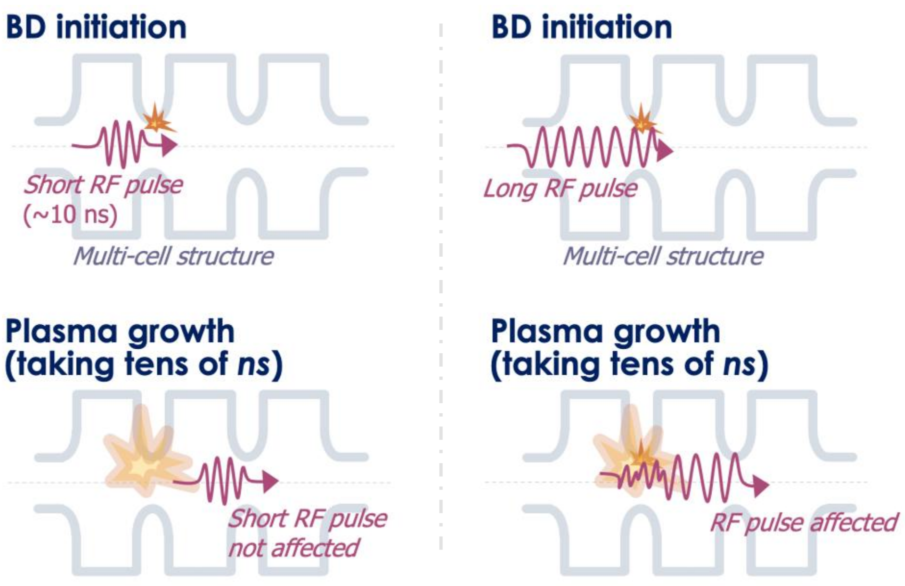
$$E_a \tau_p^{1/6} = Const.$$



BDR vs. pulse length doesn't follow the CLIC empirical scaling law in the short-pulse regime **(τ ~<15 ns)**

Breakdown insensitive acc. regime (hypothesis): **(BIAR)**

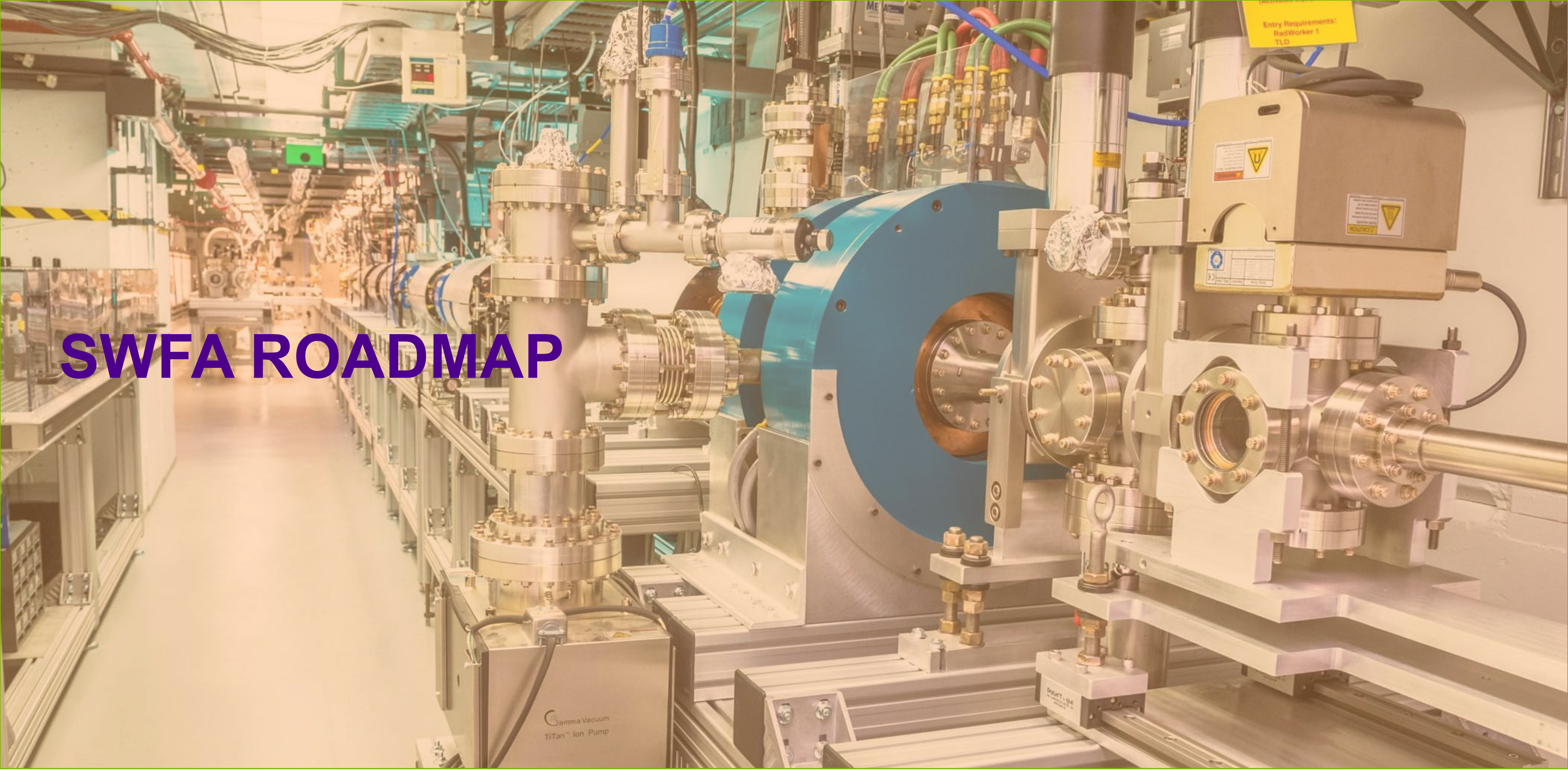
Short Pulse vs. Long Pulse



- If BD initiates plasma, the short RF pulse may transmit through the structure and remain largely unaffected [1, 2]

[1] J. Shao et al., IPAC2022, doi: 10.18429/JACOW-IPAC2022-FROXSP2.
[2] D. Merenich et al., Phys. Rev. Accel. Beams, vol. 27, no. 4, p. 041301, Apr. 2024

SWFA ROADMAP



SWFA ROADMAP

How do we get from HERE to a linear collider?

Fundamental R&D

Demonstrated 2025
- Simplified staging
- >5 transformer ratio
- 0.4 GV/m field
- BIAR regime
-

Technology Demonstrators

Integration (2026-2030)
- 100 MeV high brightness injector
- 500 MeV demonstrator

Applications

Applications (>2030)
- 1 GeV WW-FEL
- 5 GeV Multiuser XFEL
- 10 GeV Hard X-ray FEL
- 380 GeV High Factory
- 10 TeV linear collider

MOVING FORWARD: Fundamental R&D

PI: Xueying Lu (NIU/ANL)

Dark current, multipactor, and breakdown in the short-pulse regime

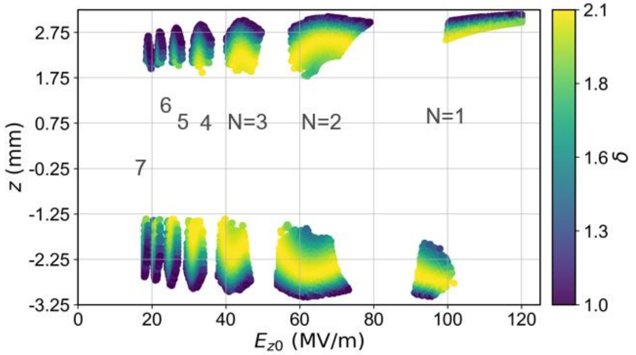
Example: MTM studies

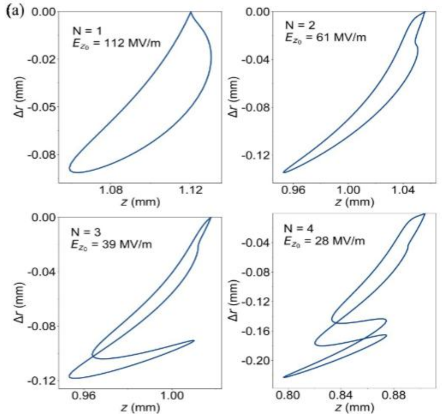
Dark current / mutlipactor

Analytical

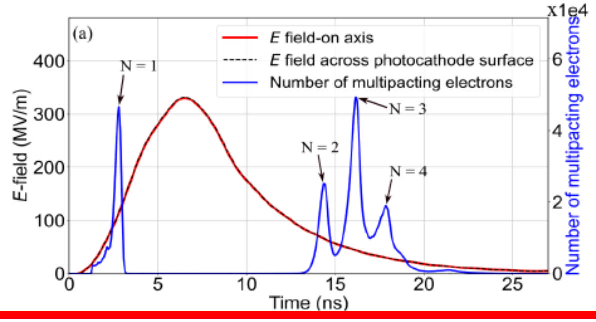
Simulations

Secondary electron yield
δ at various gradients



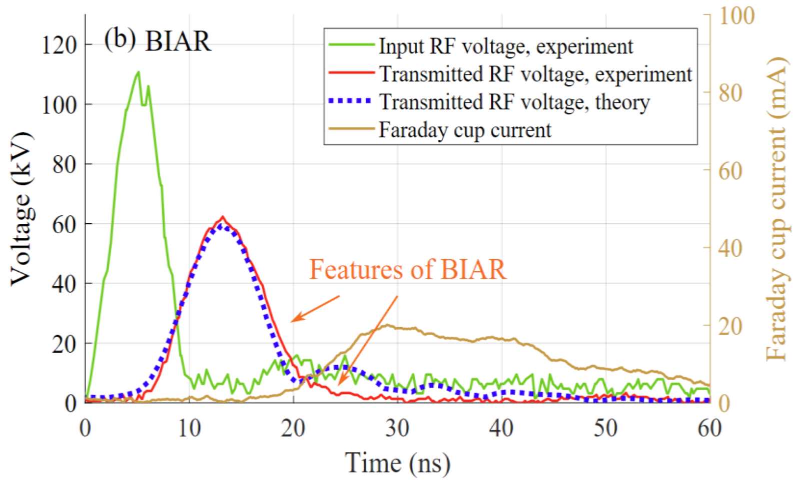


Multipacting resonances



Number of multipacting electrons

Breakdown Insensitive Acceleration Regime (BIAR)



BIAR breakdown

- Primary pulse not interrupted
- Secondary pulse not present

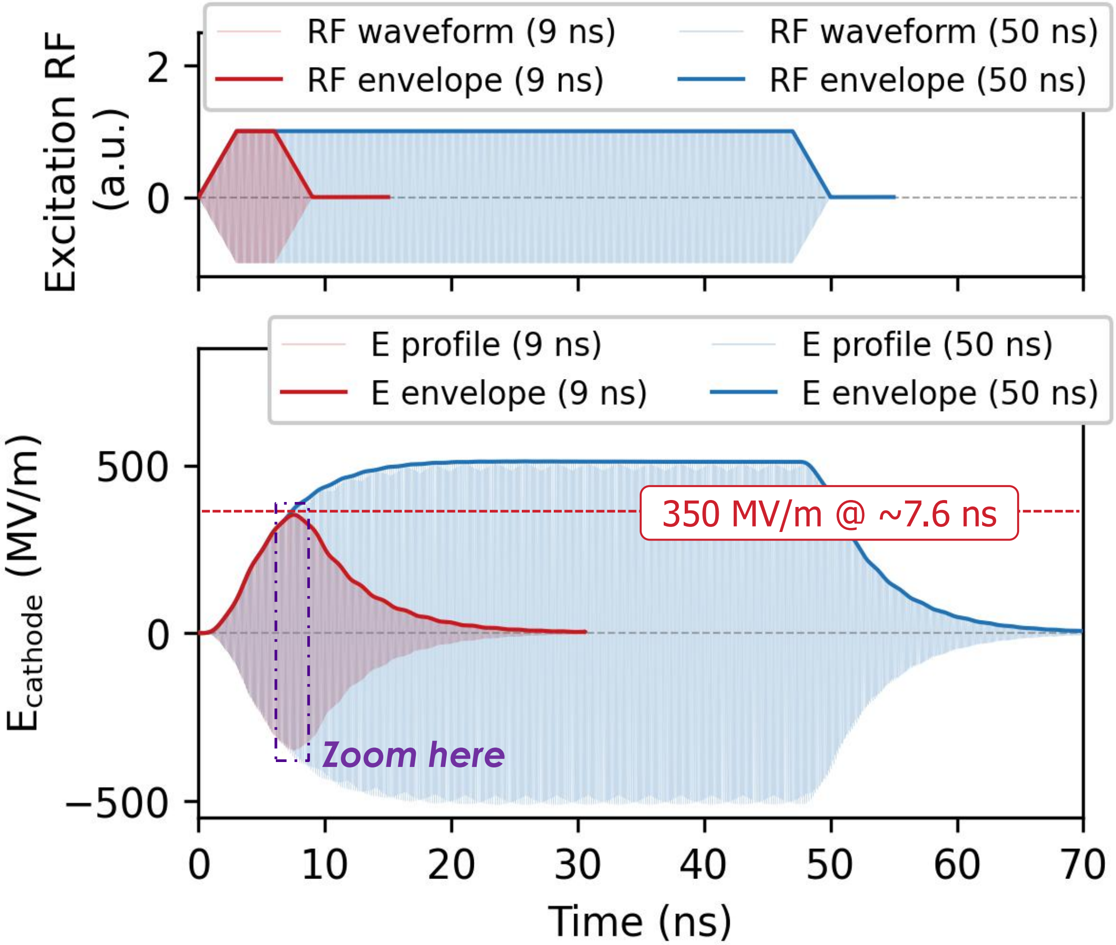
Northern Illinois Center for Accelerator and Detector Development

D. Merenich et al., Phys. Rev. Accel. Beams, vol. 27, no. 4, p. 041301, Apr. 2024

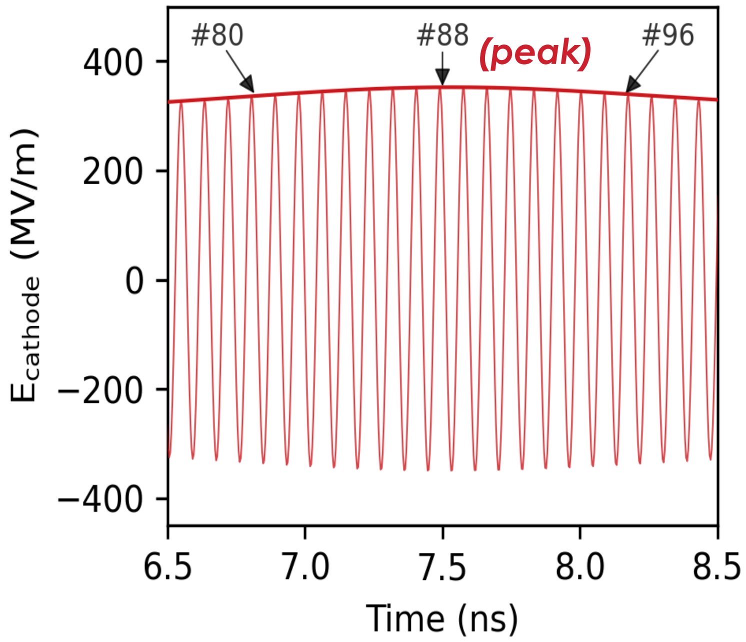
MOVING FORWARD: Fundamental R&D

PI: Gongxiaohui Chen

Beam dynamics in the Transient Regime in the short-pulse regime



Zoom-in around the mostly filled region



- If driven by 9 ns pulse, Xgun is under-filled and staying in the transient state during the full RF duration.
- E-field on cathode is changing cycle by cycle.
- Broad high-gradient operational window.

G. Chen, et al.,: arXiv:2503.09575. doi: 10.48550/arXiv.2503.09575.

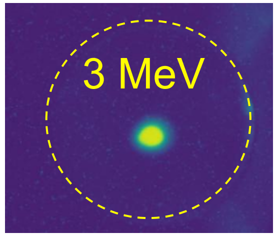
MOVING FORWARD: Technology Demonstrators

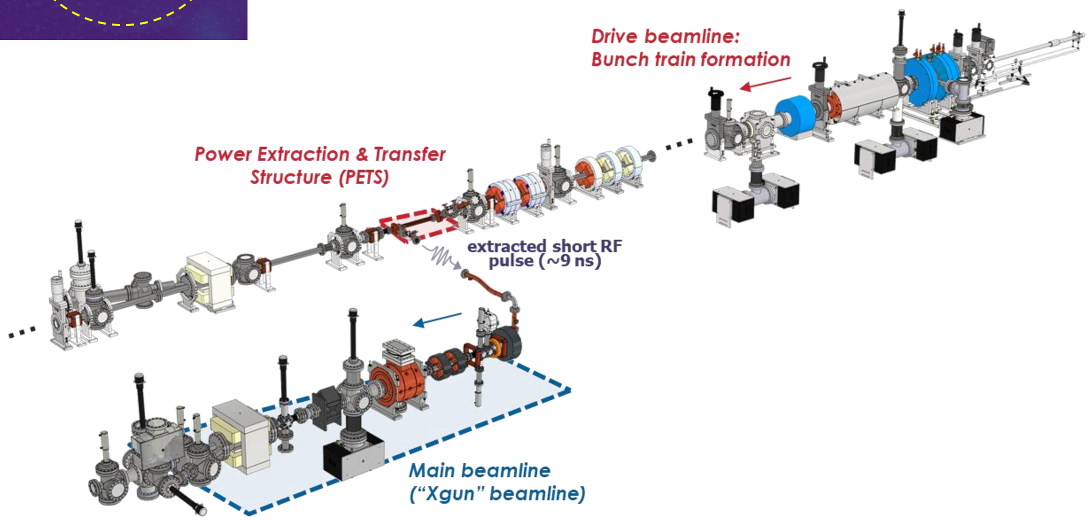
PI: Gongxiaohui Chen

Injector: 100-MeV, 100 pC, 100 nm (Near term ~5 years)

Gun milestones demonstrated

- 0.4 GV/m on photocathode, 0.6 GV/m surface
- BDR ~4e-6 (estimated)
- Ultra low dark current (<1pC per RF pulse)

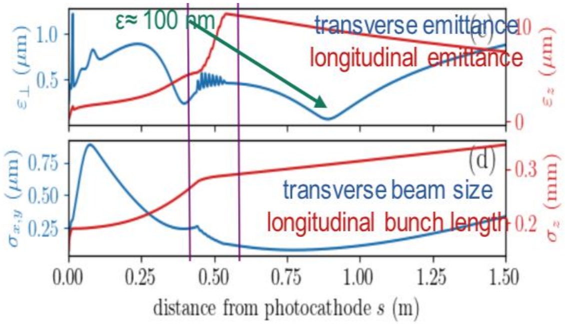




2025-27

Acceleration to 10 MeV

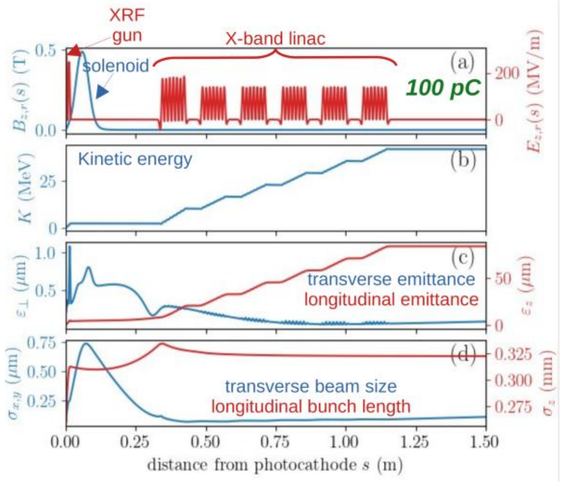
- new Xgun design with removable cathode stalk
- Add booster linac
- Local emittance compensation
- Beam characterization
- Design of "shovel-ready" 100 MeV injector



2028-31

Acceleration to 100 MeV

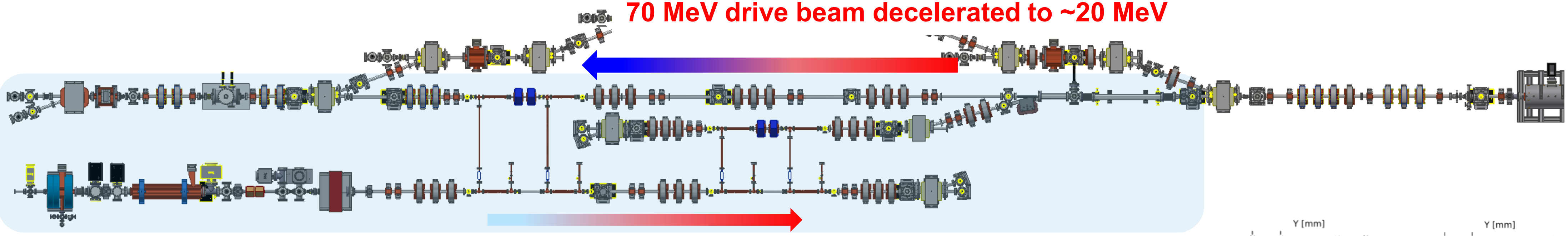
- Add staging to 100 MeV
- Characterize bright electron beam

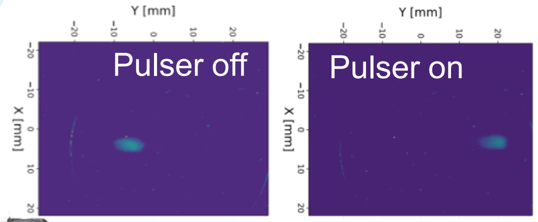


MOVING FORWARD: Technology Demonstrators

0.5 GeV demonstrator

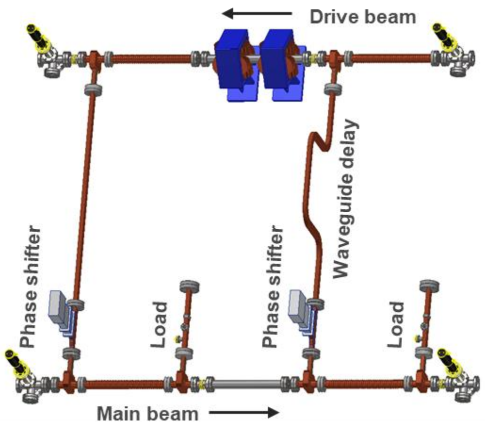
- **Demonstrate key technologies of SWFA based linear collider**
- **Fits into AWA's existing bunker**

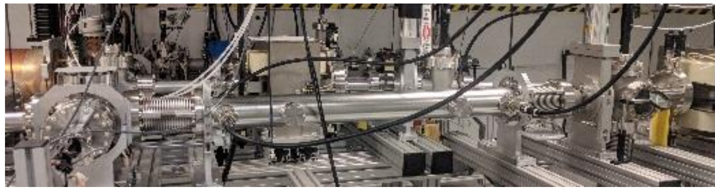




Critical Technology Elements

1. GW power level
2. 300MV/m gradient
3. Full staging (drive beam distribution)
4. Fast kicker

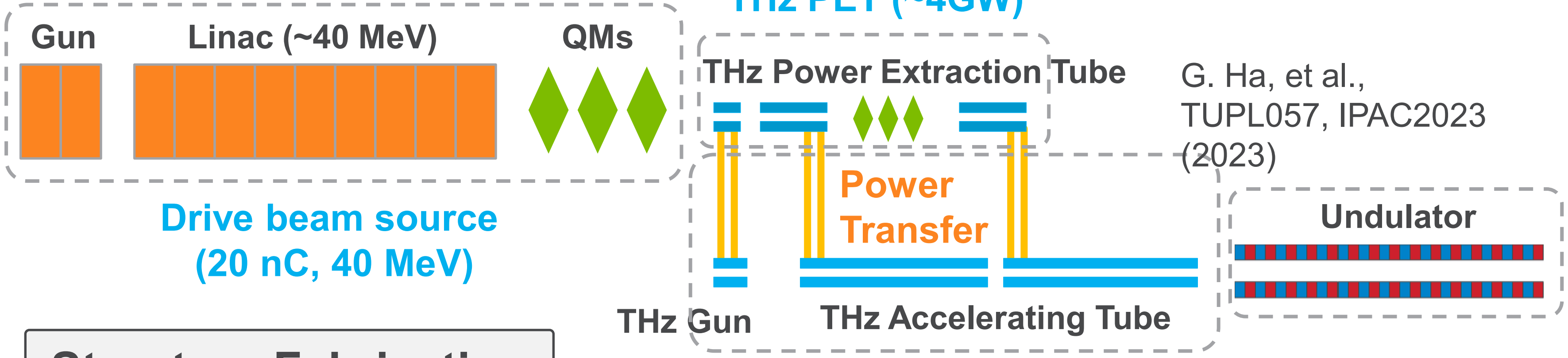




MOVING FORWARD: Applications

Light Source: 400 MeV EUV light source

THz PET (~4GW)



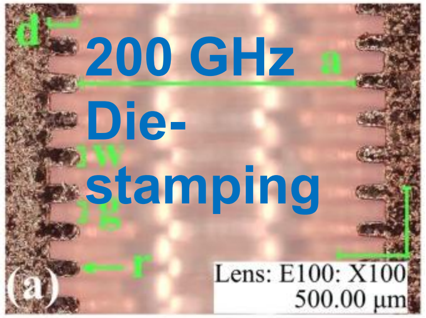
Drive beam source
(20 nC, 40 MeV)

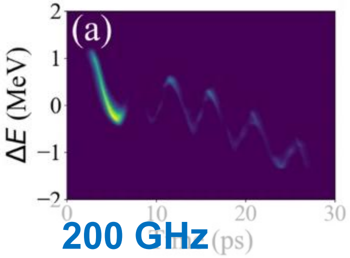
THz Acc (700 MV/m)

G. Ha, et al., TUPL057, IPAC2023 (2023)

Led by an International collaboration

Structure Fabrication

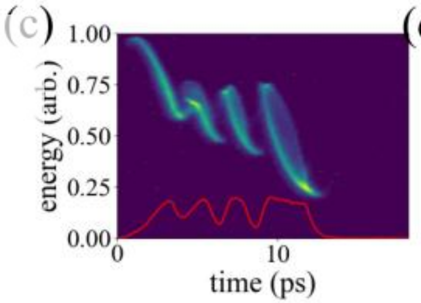


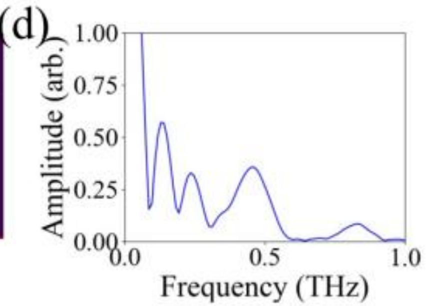


200 GHz
~10 MV/m/nC

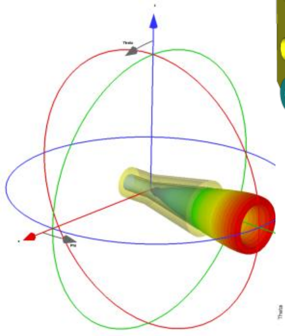
H. Kong, et al., Scientific Reports 13, 3207 (2023)

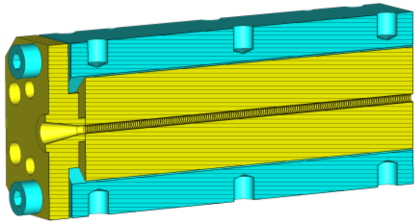
Preparation toward GW Power Generation

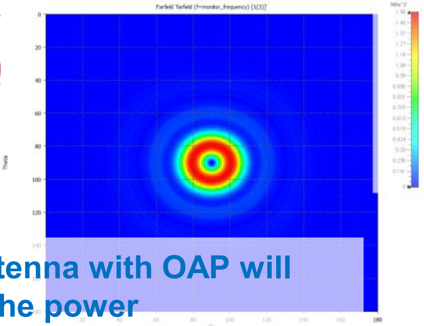




400 GHz Compatible drive bunch train (1 nC/bunch)
Later will be 16 bunches







Horn antenna with OAP will extract the power

G. Ha, et al., WEP083, NAPAC2025 (2025)

MOVING FORWARD: Applications

Light Source: 1 GeV WW-FEL

Brightness from the injector

$B_{5d} \sim 3\times10^{14}$ A/m^2

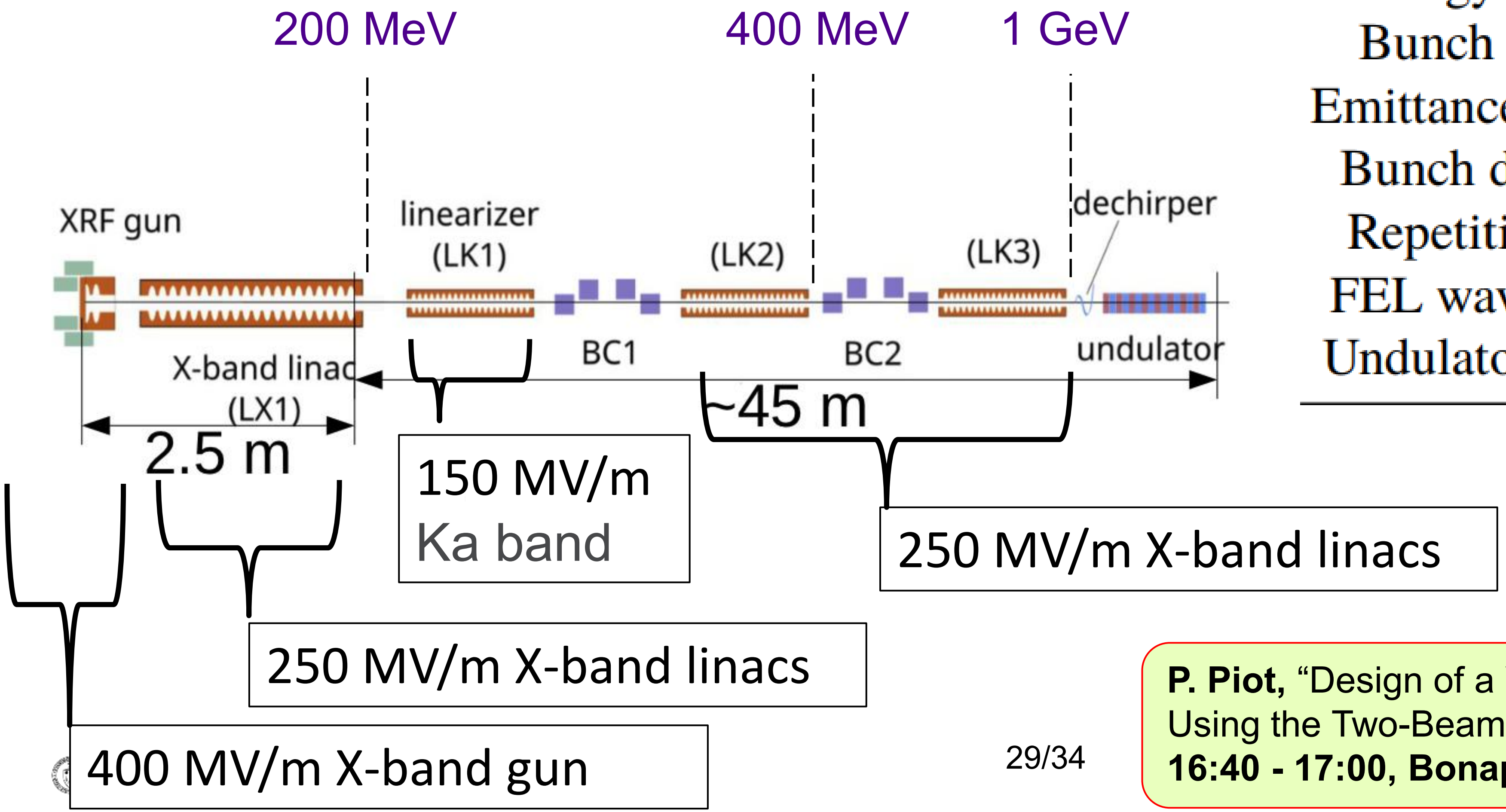


Table 2: Simulation Parameters

Energy	ε	1	GeV
Energy Spread	σ_ε	0.5	MeV
Bunch charge	Q	100	pC
Emittance (Norm)	$\epsilon_\perp$	50-150	nm
Bunch duration	τ	15-40	fs
Repetition rate	f_{rep}	≤ 120	Hz
FEL wavelength	λ	2.3-4.4	nm
Undulator period	λ_u	10	mm

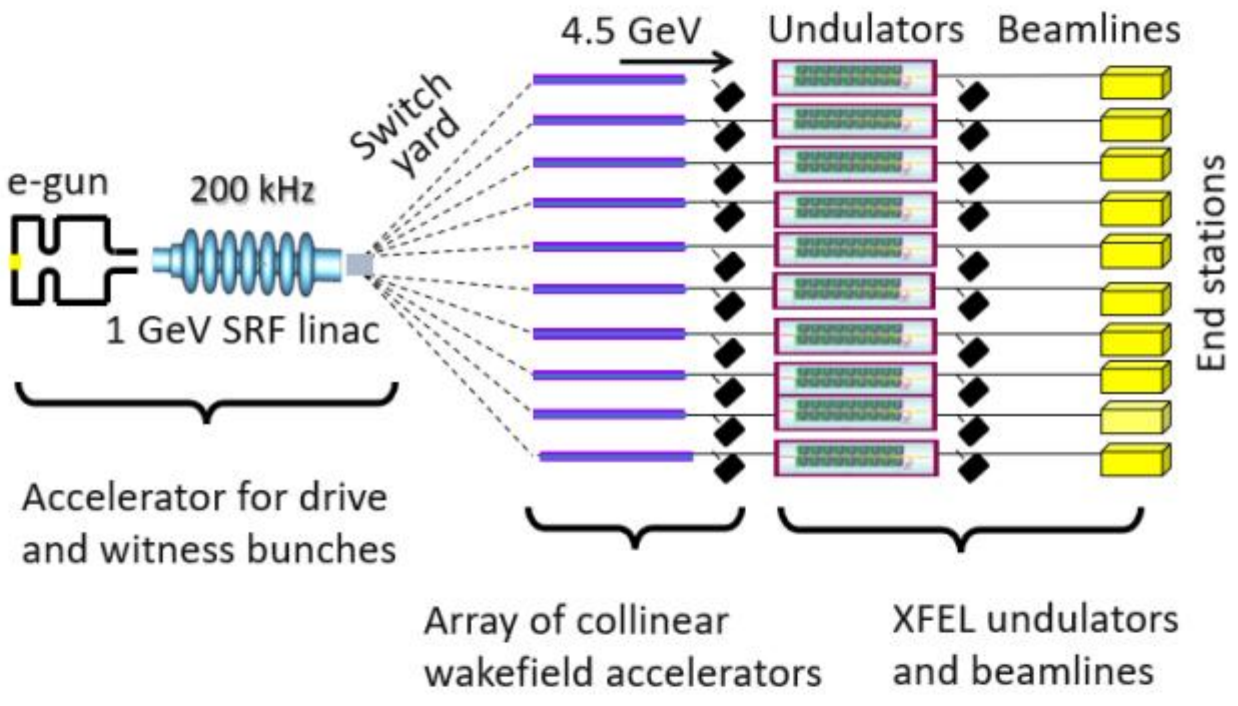
P. Piot, “Design of a Water-Window Free-Electron Laser Using the Two-Beam Acceleration Scheme”, **THURS. 16:40 - 17:00, Bonaparte 2 (Hotel Hermitage)**

MOVING FORWARD: Applications

PI: Branko Popovic

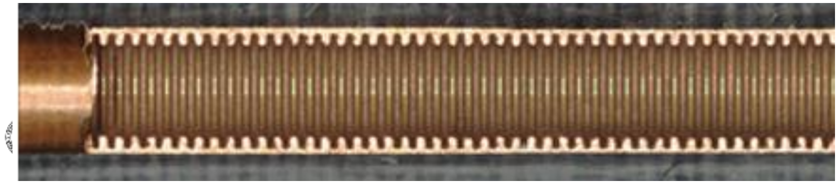
A CWA-based High repetition rate multi-user X-ray FEL facility

A-STAR

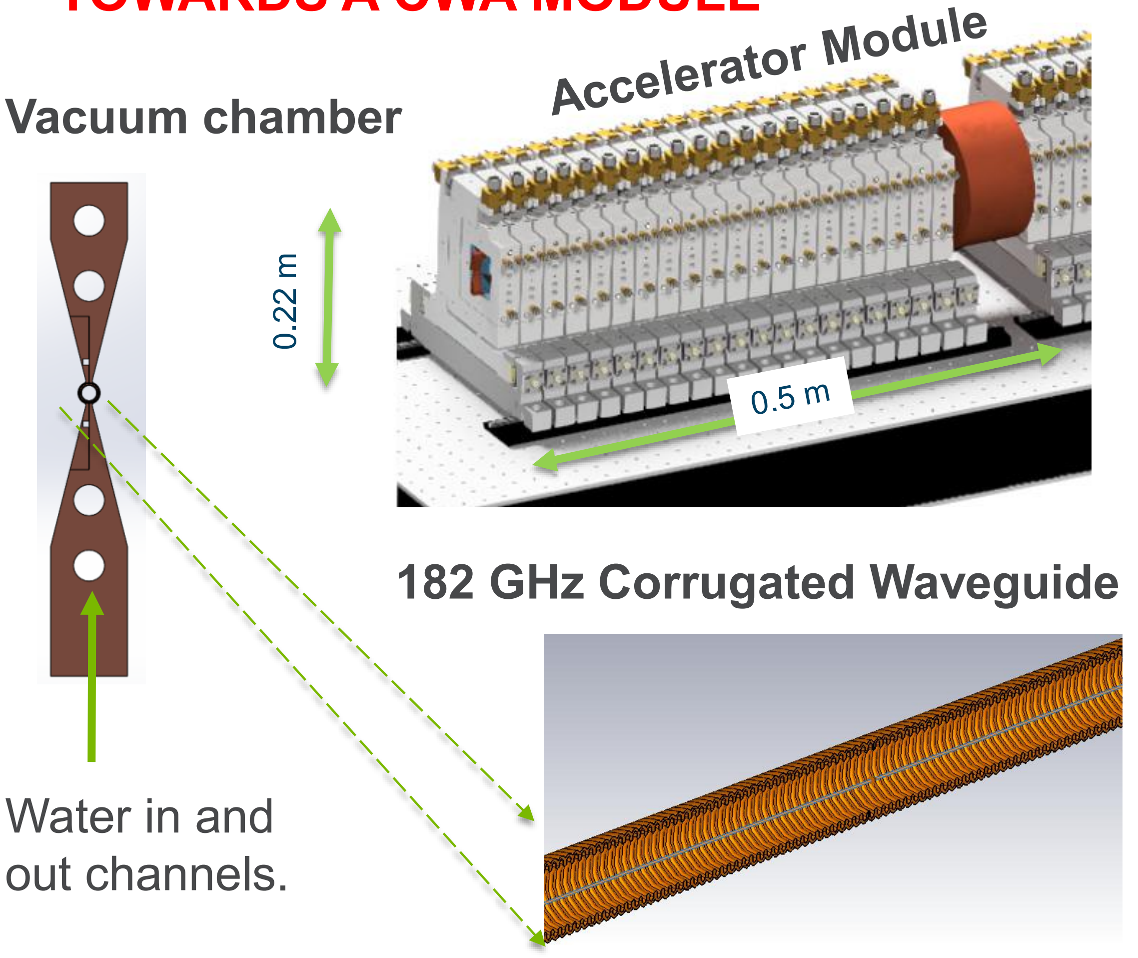


Demonstrated

- Fabricated 182 GHz CWA
- Measured beam wakes



NEXT GOAL: CONTINUE MOVING TOWARDS A CWA MODULE



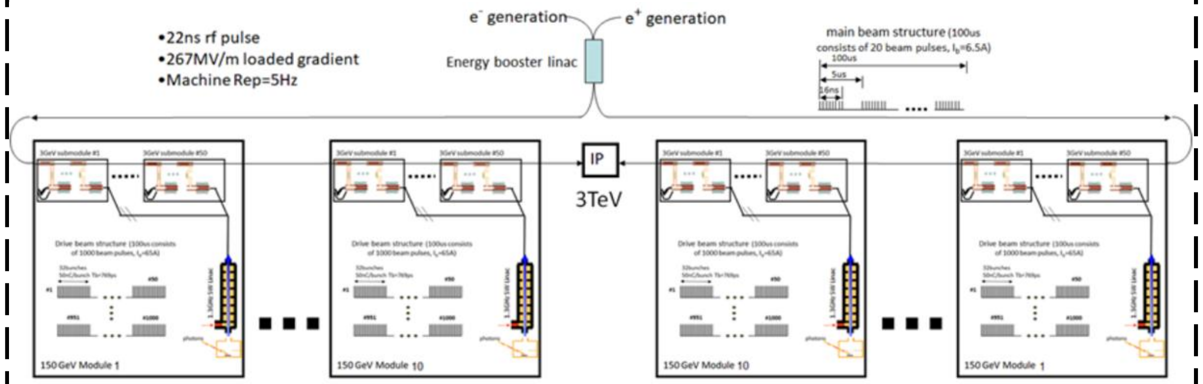
MOVING FORWARD: Applications

linear colliders

Strawman Design (2013)

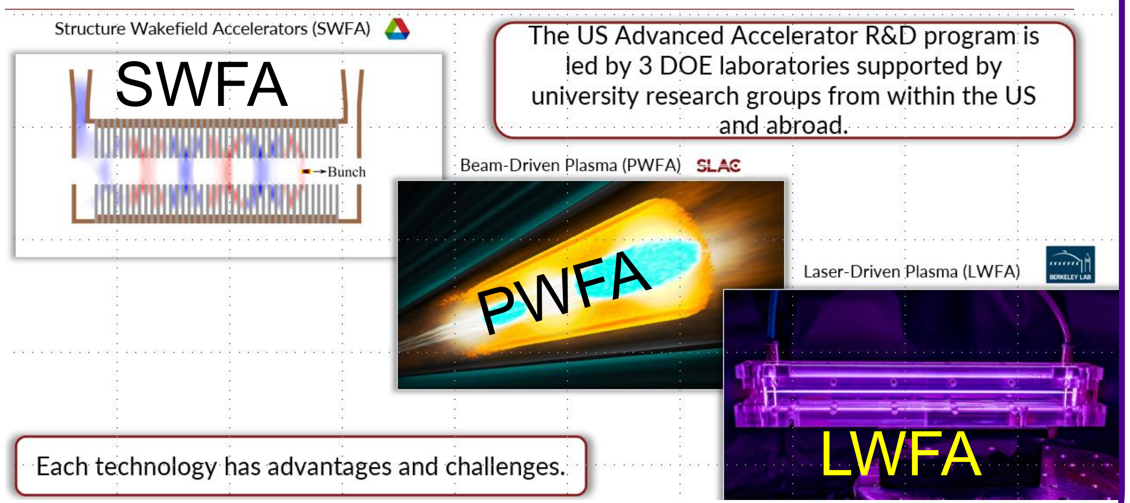
18 km

3 TeV $e^+ e^-$ linear collider



- **320 MV/m unloaded gradient**
- **267 MV/m loaded gradient**
- **200 MeV/m real estate gradient**

10 TeV Wakefield Collider Design Study



S. Gessner et al., “Design Initiative for a 10 TeV pCM Wakefield Collider”, https://arxiv.org/abs/2503.20214

How can SWFA contribute?

1. All SWFA
2. Hybrid SWFA-PWFA
3. Injector for L/PWFA

MOVING FORWARD: Applications

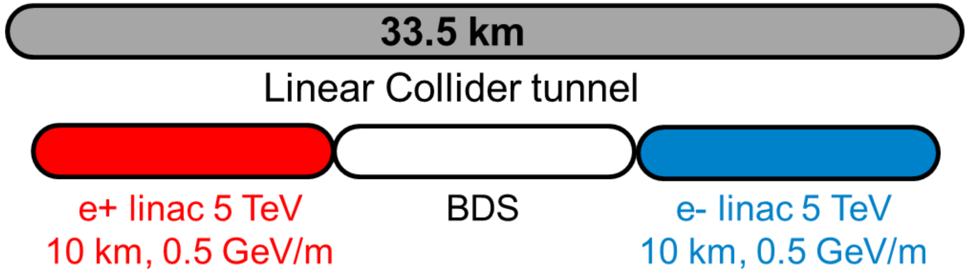
SWFA $e^+ e^-$ linear collider options

A Linear Collider Vision for the Future of Particle Physics (CERN)
https://arxiv.org/abs/2503.19983

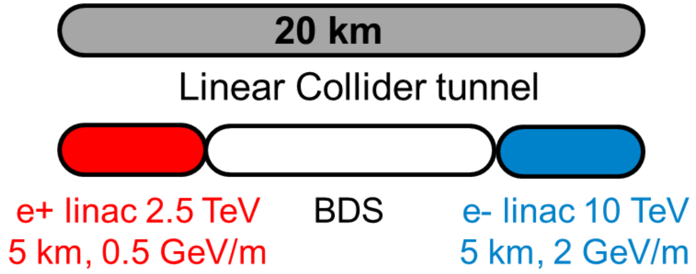
Global Collider Roadmap

1. **ILC (Japan)**: 250 GeV – 1 TeV (SRF, 31.5 MeV/m).
2. **CLIC (CERN)**: up to 3 TeV (NCRF, ~100 MeV/m).
3. **Plasma/Structure-Wakefield Colliders**: long-term R&D for 10 TeV+.

1. Fully SWFA-Based Linear Collider.



2. Hybrid SWFA – L/PWFA Linear Collider.



3. SWFA-Based Injector into Plasma (L/PWFA) Linear Collider. (Bubble 30/100 μm ↔ Frequency 3-10 THz)

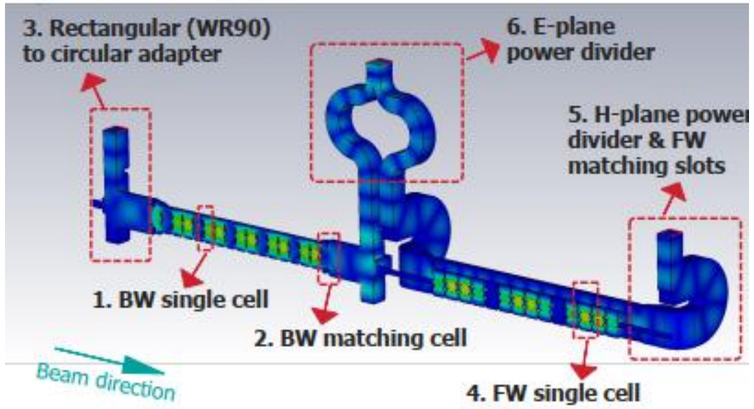
X. Lu et al., "RF acceleration with short pulses: Breaking the high-gradient barrier," in Proc. 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, 2025, doi: 10.18429/JACoW-IPAC2025-MOYD3.

MOVING FORWARD: Applications

Can SWFA achieve 500MeV/m of geographical gradient?

180 MV/m

Developing **X-band short-pulse structure**



Structure Parameters	Designed Values
Freq.	11.7 GHz
Filling time	6 ns
Structure length	30 cm
Input Power	600 MW
Gradient	180 MV/m

Scale x3

535 MV/m

Ka-band structure

$$\frac{R}{Q} = \frac{(E_a L)^2}{\omega U} \qquad U = \frac{P}{V_g}$$

1. f = 11.7*3 = 35.1 GHz
2. Scale (R/Q and Vg are the same)
3. Given P=1.2GW. then gradient=764 MV/m.
4. Given fill factor is 0.7, then **geographical gradient will be 535MeV/m.**

Challenge: Small aperture. (ref. CLIC 30GHz has aperture 2.4mm~3.2mm.)

Ka-band PETS **1200 MW**

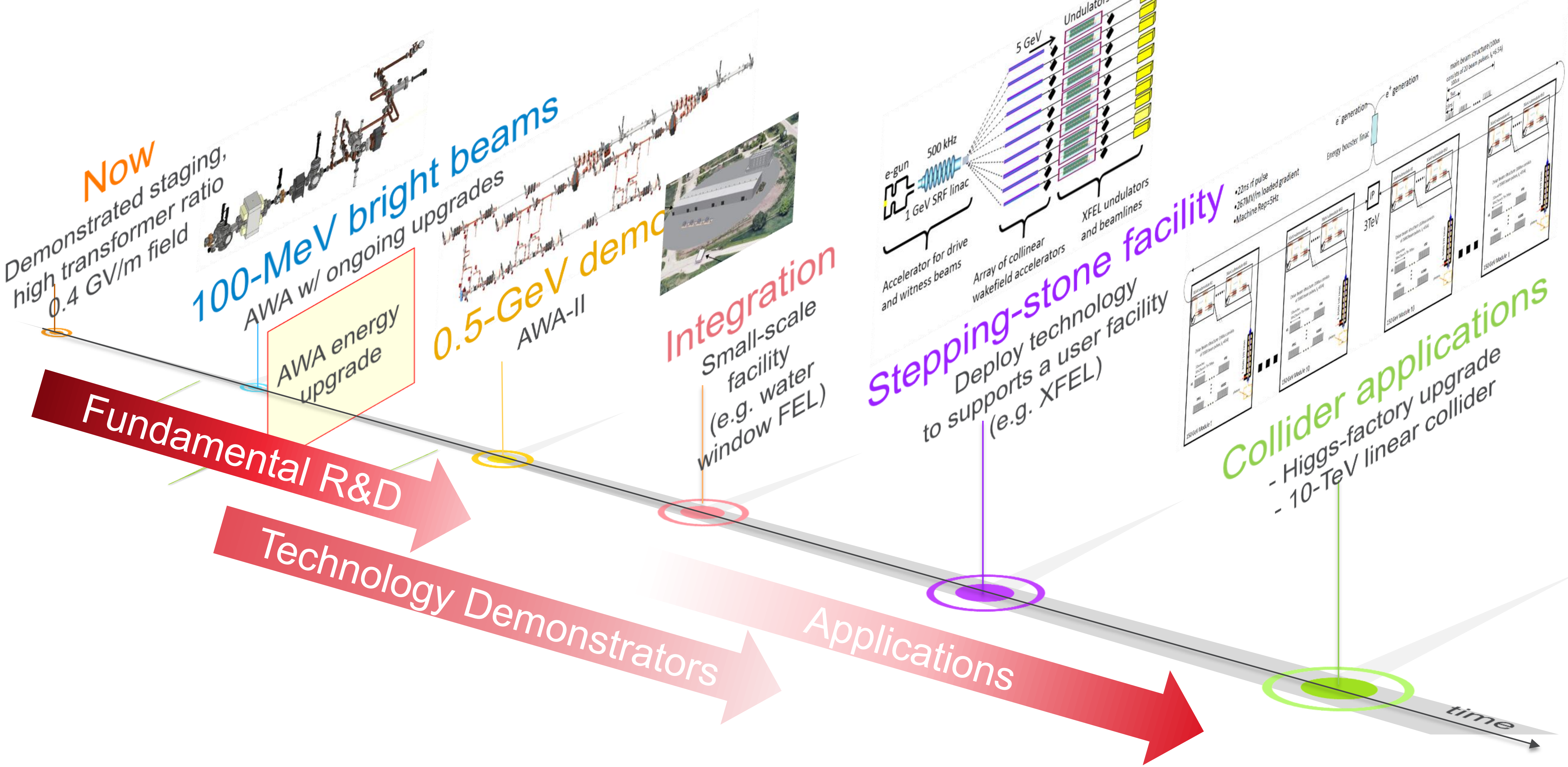
$$P = \frac{1}{4}\frac{\omega}{v_g}\frac{r}{Q}L^2 I^2 F^2 \left(\frac{1-e^{-\alpha L}}{\alpha L}\right)^2$$

Scale 11.7*3=35.1GHz, If P=1.2GW, then Q=16.7nC/bunch (assuming F~1). **Challenge:** Small aperture only 17.6mm/3=5.9mm.

G. Andonian, "Higher order modes in accelerating structures for flat beams", **WED., 12:00 - 12:30,**

B. Higuera-Gonzalez, Proposal to control BBU instability in SWFA by using adjustable rectangular dielectric waveguides. **TUES., 17:00 - 17:20, Bonaparte 2 (Hotel Hermitage)**

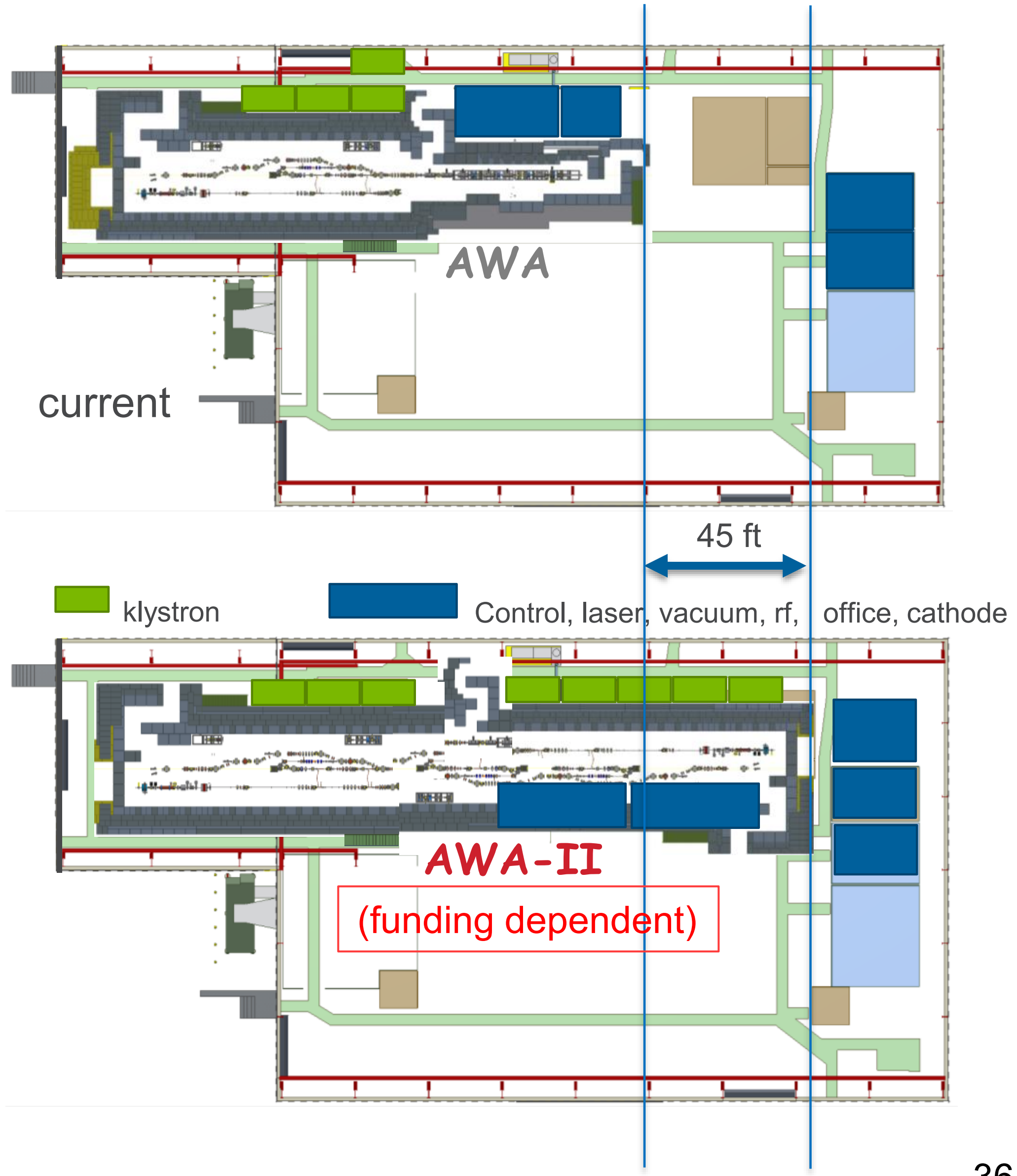
SWFA SUMMARY



EXTRAS

MOVING FORWARD

Upgrade to AWA-II



(funding dependent)

FY21-26

>FY26

UPGRADE PATH

AWA: Ongoing upgrades

Quality upgrades

- Brightness. Emittance improvement by RF symmetrized gun (AWA) & RF symmetrized cavities (LBNL)
- Stability. New RF synchronization system (LBNL BACI), RF Station stability project (APS RF group)

Capabilities upgrades

- Extended Bunch shaping. (SLM based Laser shaping, TDC shaping, EEX multi-leaf Collimator, etc.)
- Machine Learning. For machine control, virtual diagnostics and physics (EPICS upgrade w/ APS Controls group)

AWA-II: High energy version of AWA

- Drive beam 65 MeV → ~150 MeV
- Tighter focus for acceleration research
  - **High-quality ~1 GeV TBA demonstrator (roadmap)**
  - **Allows SWFA to enter GV/m regime**
  - **High beam density needed for PWFA**
- Increase the size the experimental switchyard