ALEGRO Workshop 2024, Lisbon, 19-22 March

Northern Illinois University

Argonne NATIONAL LABORATORY

ADVANCES IN STRUCTURE WAKEFIELD ACCELERATOR R&D FOR INTEGRATION IN A LINEAR COLLIDER

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Tuesday, March 19th, 2024

Some of the materials was originally produced by
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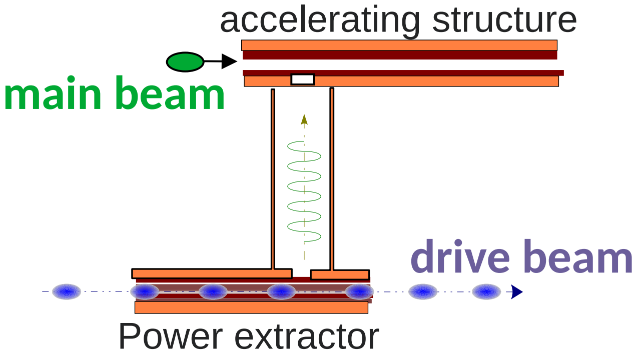
APPROACHES FOR ACCELERATION

Two-Beam Acceleration (TBA) versus Collinear Wakefield Acc. (CWA)

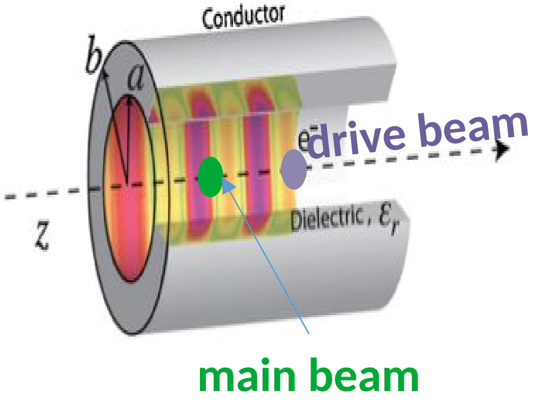
TBA

- “drive” beam excites wakefield in power extractor → powerful (GW) short (ns) pulses
- “main” beam is accelerated in a collocated accelerating structure



CWA

- “drive” beam excites wakefield in structure → high-field wakes
- “main” beam is accelerated co-linearly in the *same* structure



DB: drive bunch
MB: main bunch

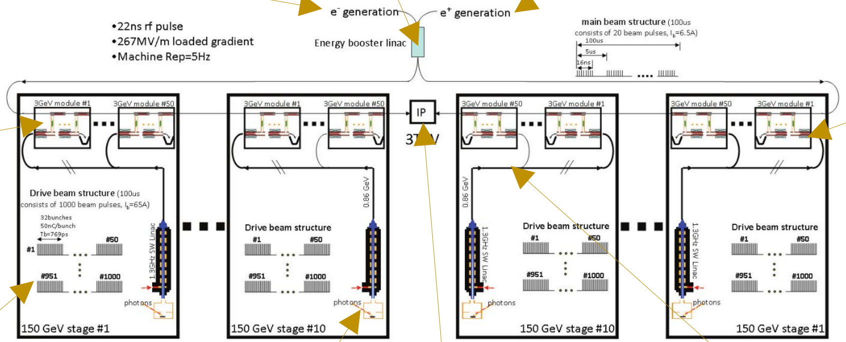
INTRODUCTION

SWFA-based linear collider building blocks

injector optimization: injection energy, compression

high-quality electron MB: sources + MB cooling

high-quality positron MB: sources + MB cooling



staging of acceleration: # stages, MB phase-space preservation, DB merging/extraction

RF structures: design + beam/ wave interaction

DB tailoring: to improve transformer ratio

DB generation: high charge trains of e- bunches

IP & BDS: nm-size beams beam-beam effects

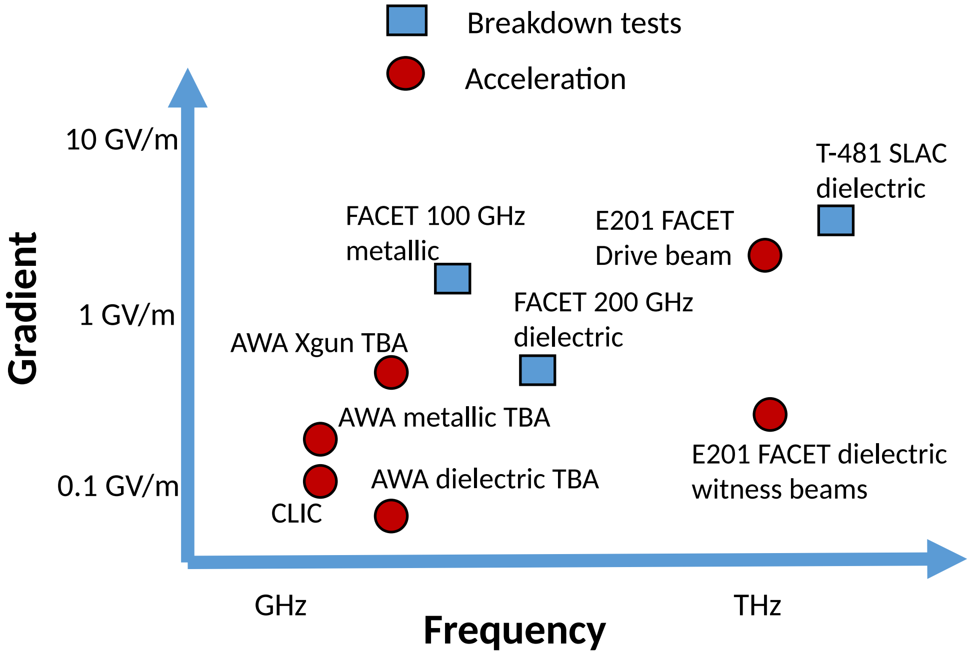
DB dynamics: mitigating collective effects

ATTAINING HIGH GRADIENTS IN STRUCTURES

Limiting effects & pathway to high fields

- RF breakdowns limits reliability of collider, damages structure **mitigation**: short RF pulses, cryogenic cooling, new structure designs

- Field emission produces excess electrons that load the wake and/or can be trapped and accelerated **mitigation**: short RF pulses, new structure designs



TBA: POWER GENERATION

Principle

- Drive bunch excites wake
- Pulse duration is related to group velocity of the mode and length of the structure *L*

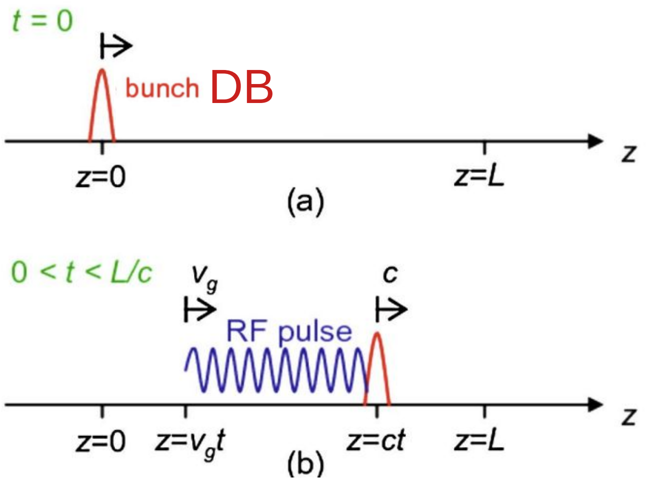
$$\tau \simeq \frac{L}{v_g}\left(1-\frac{v_g}{c}\right)$$

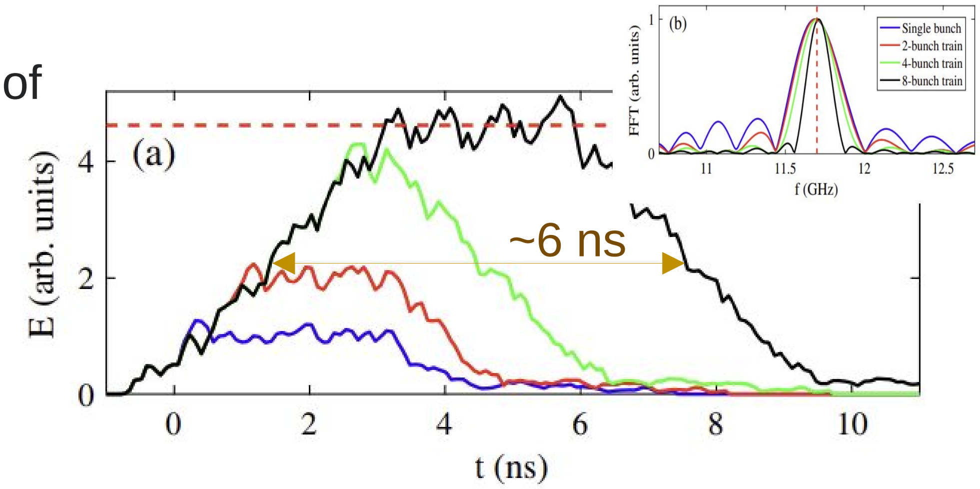
group velocity

- Train of bunch → "coherent stacking of the RF pulses from each bunch

Advantages

- Short-pulse excitation → high power
- Can operate at any frequencies

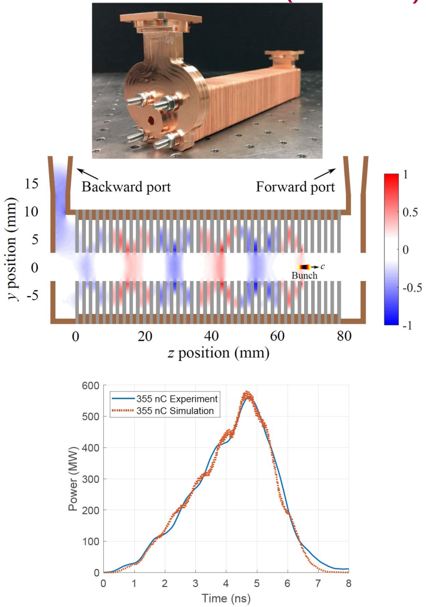




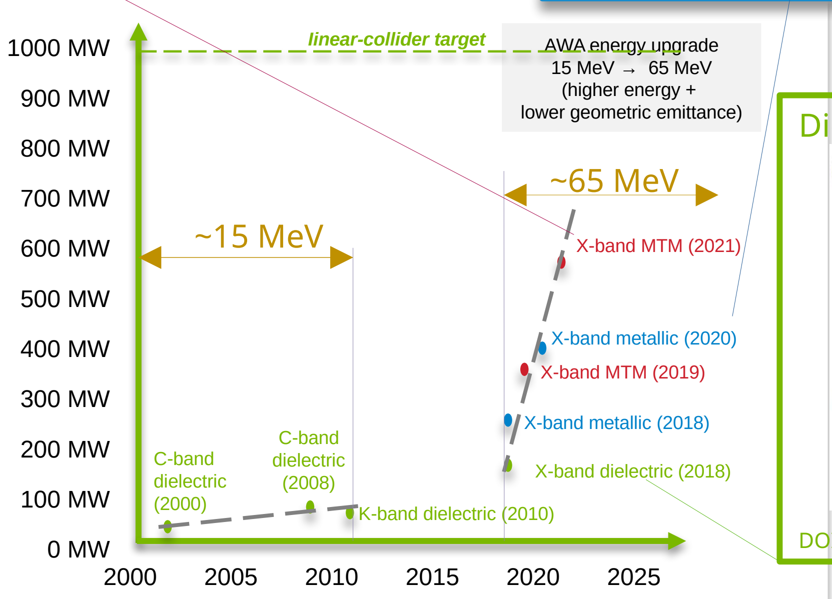
TBA: POWER GENERATION

State of the art: ~0.6 GW peak power

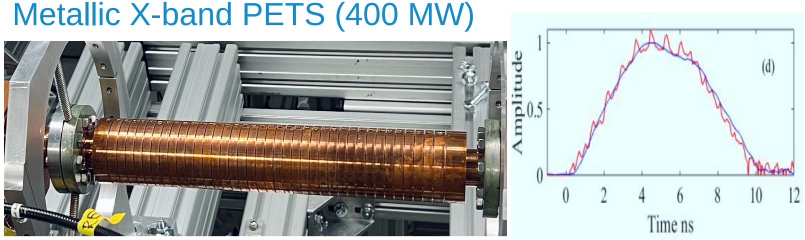
MTM X-band PETS (565 MW)



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

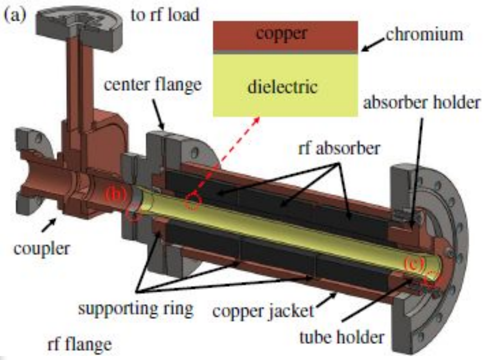


Metallic X-band PETS (400 MW)



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

Dielectric X-band PETS (200 MW)



DOI: 10.1103/PhysRevAccelBeams.23.011301

PATH TO GV/M FIELDS IN STRUCTURES

Short high-peak-power RF pulses

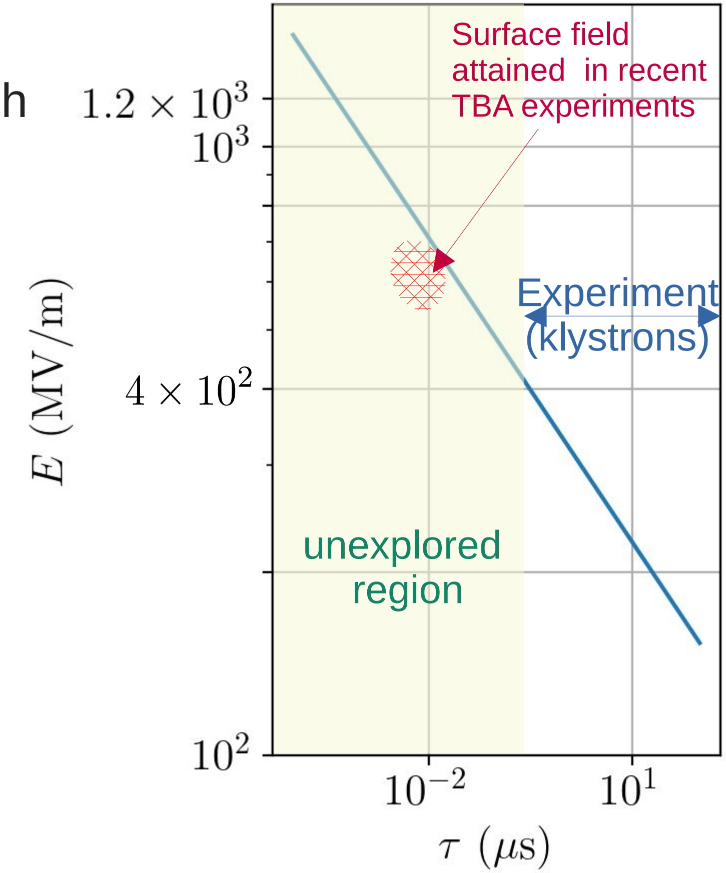
- Breakdown is a major limitation to attaining high electric fields in structures
- Fitting of experimental data* (CERN) on breakdown suggest a scaling

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

RF pulse duration (τ)

accelerating field (E)

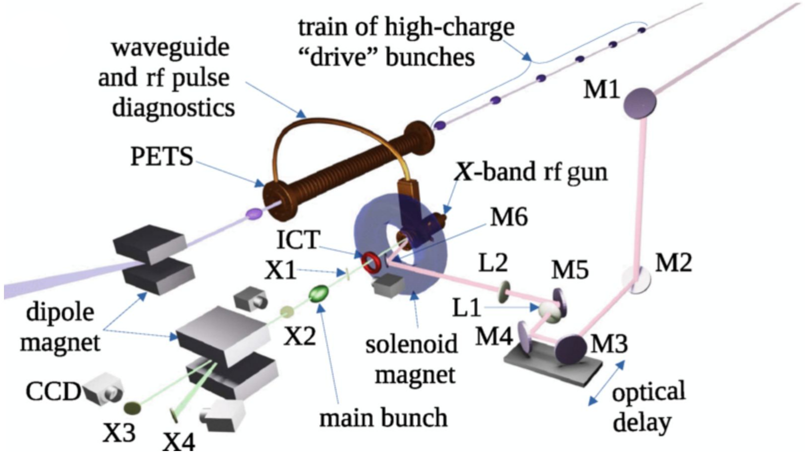
- So far pulse duration was limited by minimum RF pulse duration available from klystrons
- RF-pulse duration produced via wakefield can be much shorter (~few ns at X-band freq.)

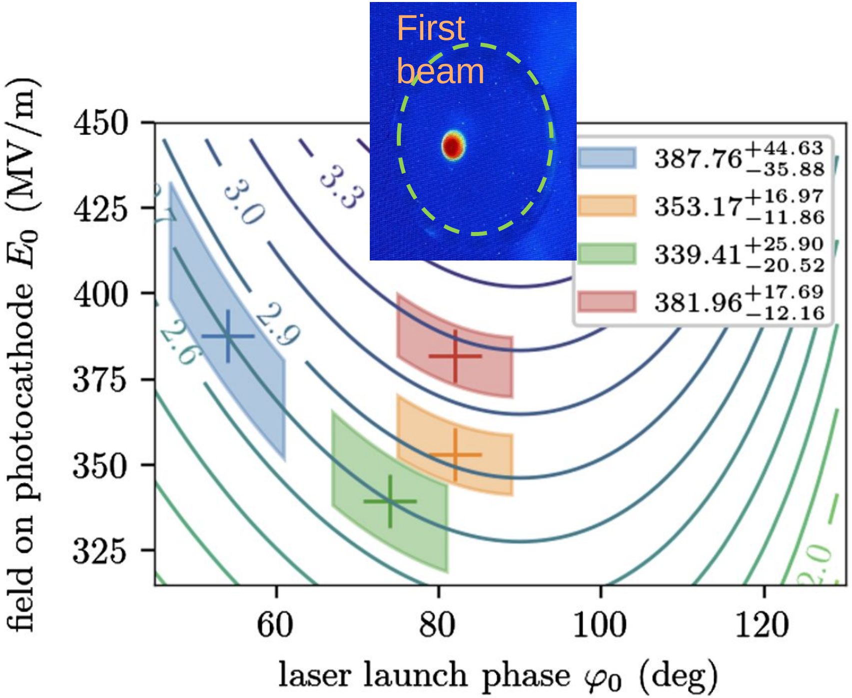


*A. Grudiev, et al. PRAB 10.1103/PhysRevSTAB.12.102001 (2009)

TBA-BASED ELECTRON SOURCE DEMO

Increasing brightness with higher photocathode fields





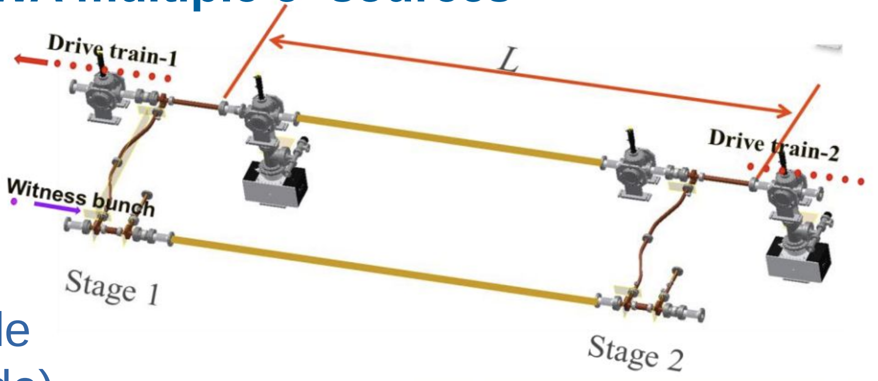
W.H. Tan, et al. PRAB 10.1103/PhysRevAccelBeams.25.083402 (2022)

- PETS driven by 8 bunches (E=60 MeV, Q~350 nC)
- Surface fields of ~0.4 GV/m on cathode (beam-based and RF measurements)

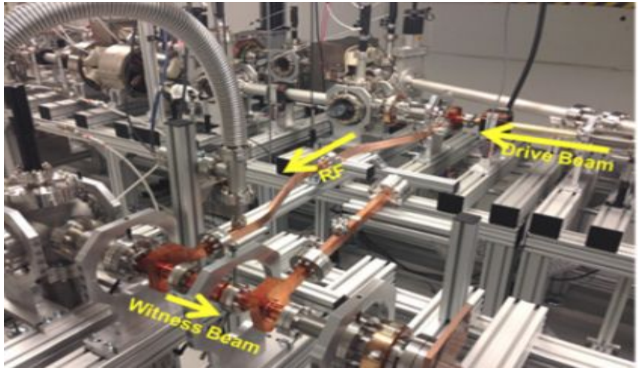
TBA: STAGING

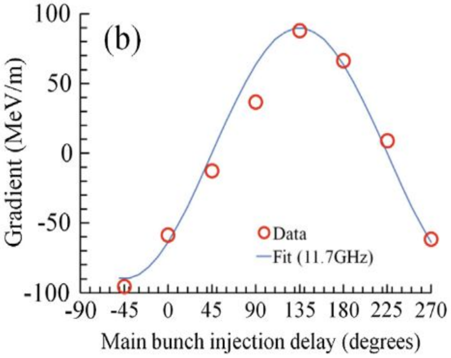
Integrated experiment capitalizing on AWA multiple e- sources

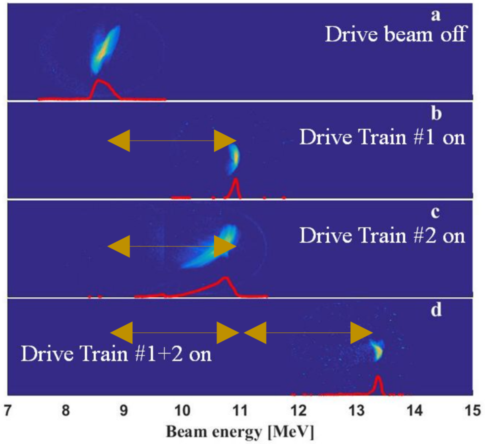
- Staging of a TBA SWFA accelerator demonstrated (2 stages)
- 100 MeV/m average gradient attained with iris-loaded GHz structure
- Scaling toward a 500-MeV demo (possible at AWA would benefit from energy upgrade)



[Jing et al., NIMA 898, 72 (2018)]







DRIVE BEAMS NEEDS FOR CWA

DB properties directly impact the field topology in CWA

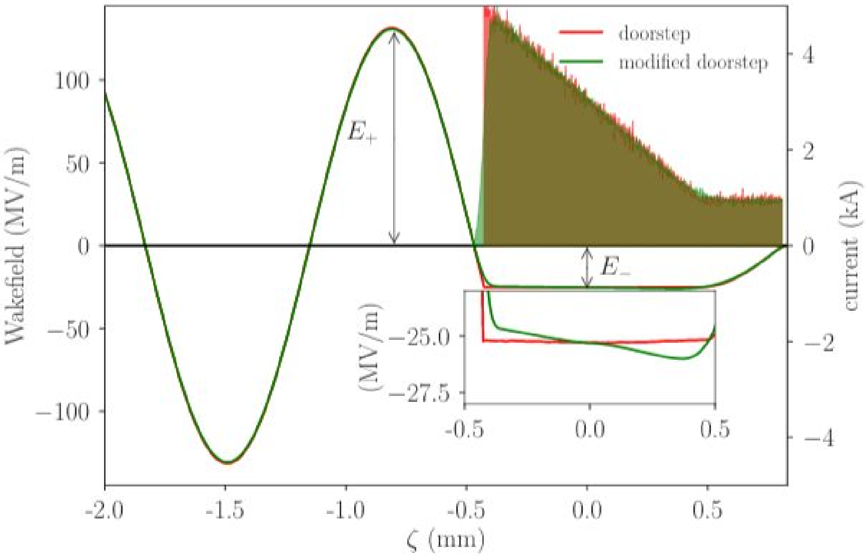
- Scaling of wakefield peak amplitude in SWFA

$$\hat{E}_z \sim \frac{Q}{a^2} \tau_\perp [Q(x,y)] b_{||} [\lambda, Q(z)]$$

longitudinal form factor

structure aperture

transverse suppression factor (SWS geom. & beam distrib.)



- Exciting large E-field amplitudes requires high charge, low emittance, short DBs
- Improving transfer of energy from drive to witness beam demands
  - low-emittance (eff. interaction length),
  - Shaped temporal distribution (transformer ratio)

$$\mathcal{R} \equiv \frac{E_+}{E_-}$$

CWA: RECENT WORK ON EFFICIENCY

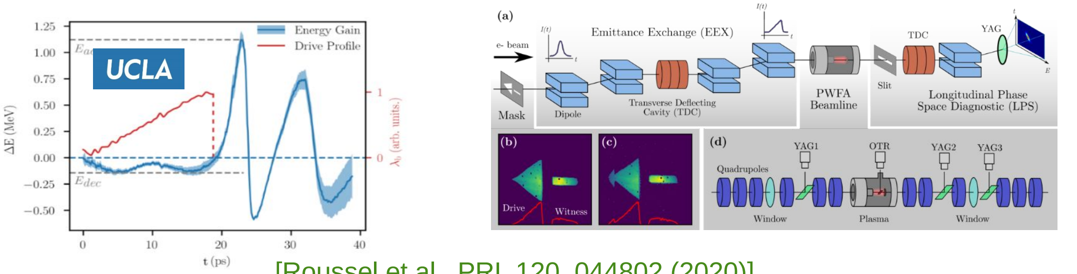
Improving transformer ratio

- Enhanced transformer ratio (TR) demonstrated using shaped beam via EEX.

- **Current research focus:** *Demonstrate high TR with high accelerating field*
  - Improve shaping capabilities (e.g. shorter pulses)

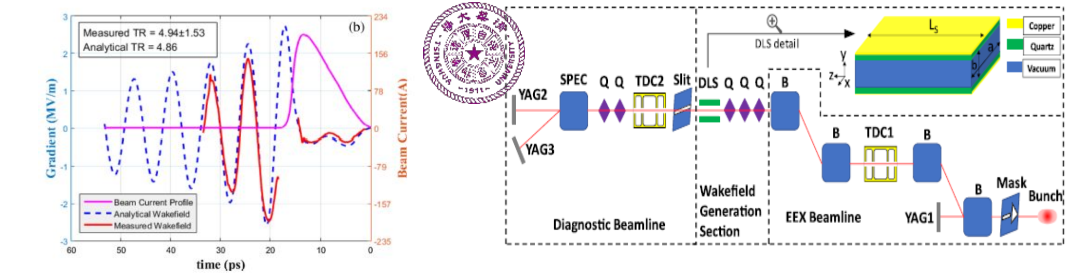
- **Synergistic with PWFA**

PWFA



[Roussel et al., PRL 120, 044802 (2020)]

SWFA



[Gao et al., PRL 124, 114801 (2018)]

CWA: TRANSVERSE STABILITY

Improving beam stability

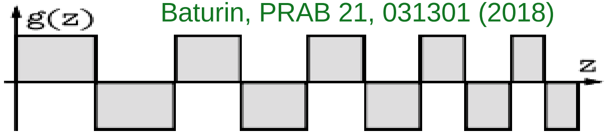
- Embed structure in quadrupole wiggler with adaptive focusing; length of quadrupole magnet scales as

$$L = L_0\sqrt{1-\alpha z}$$

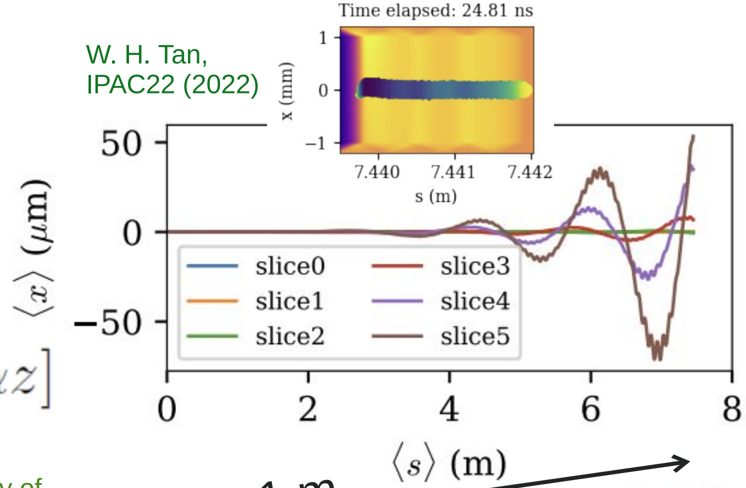
with the DB deceleration $\gamma(s,z) = \gamma_0\left[1-\alpha z\right]$

- Prepare a DB distribution to dynamically chirp the beam during deceleration and insure it remains constant
→ modified Bane's distribution
- Experimental tests on these mitigation techniques planned at AWA

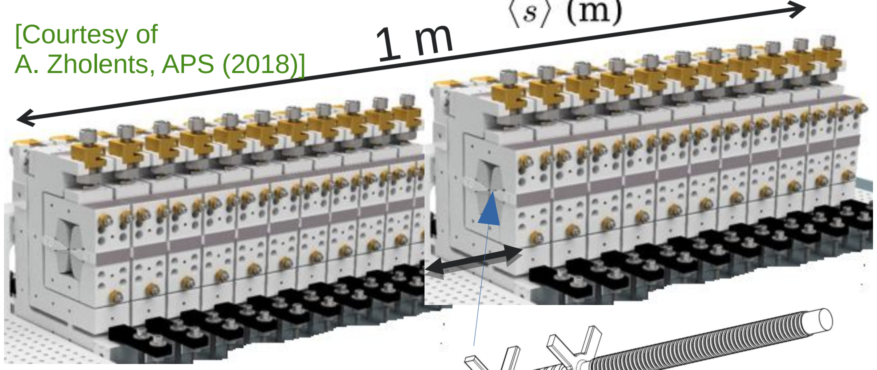
Baturin, PRAB 21, 031301 (2018)

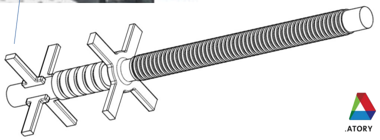


W. H. Tan, IPAC22 (2022)



[Courtesy of A. Zholents, APS (2018)]





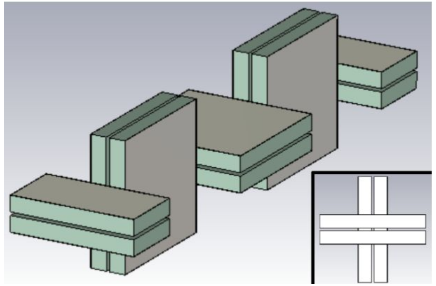
[Courtesy of A. Siy, UW Madison]
[G. Waldschmidt et al. IPAC18 (2018)]

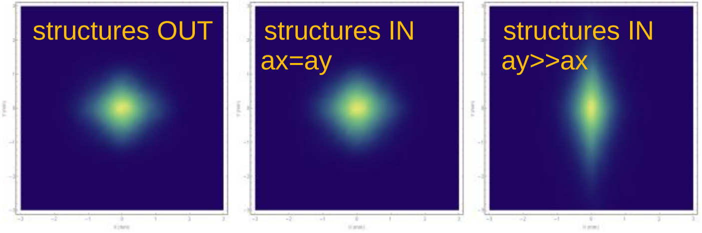
TRANSVERSE STABILITY

Mitigation and new observations…

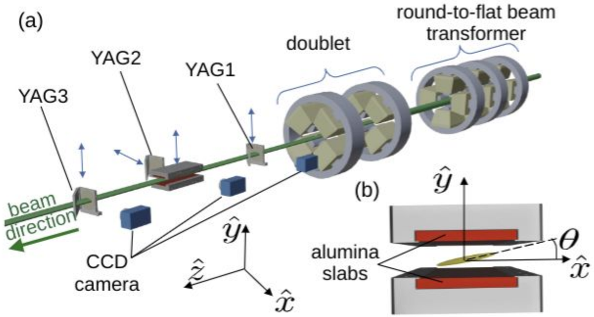
- Acceleration in alternating slab structures for beam control
- Preliminary experiment performed and confirm simulations

W. Lynn, et al.
NAPAC22 (2022)



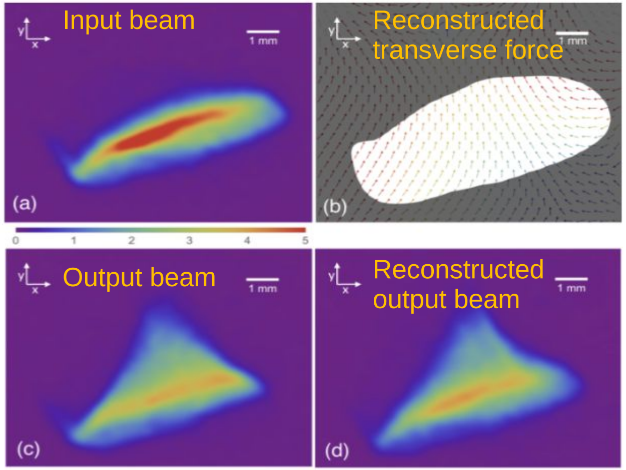


- Observation of skew-wakefield in slab structure (driven by tilted flat beams)



W. Lynn, et al.
PRL (in press, 2024)

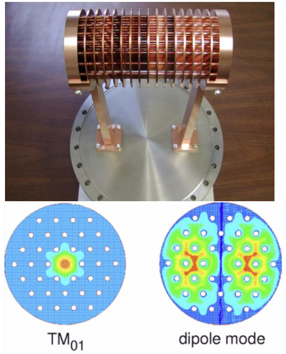
N. Majernik, et al.
PRAB 2023

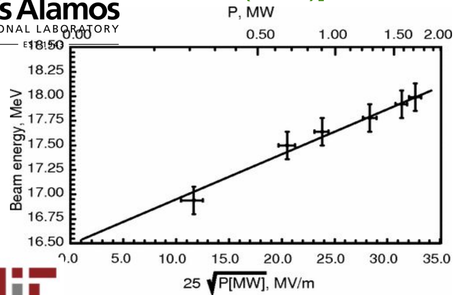


ADVANCED STRUCTURES

Exotic structures

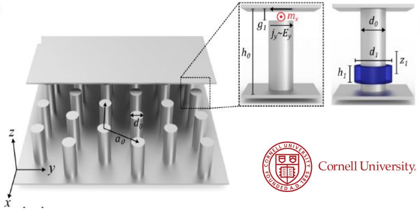
[Simakov, et al., PRL 116, 064801 (2016)]

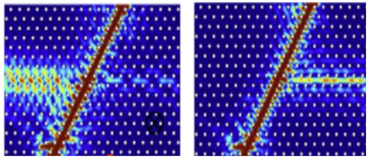


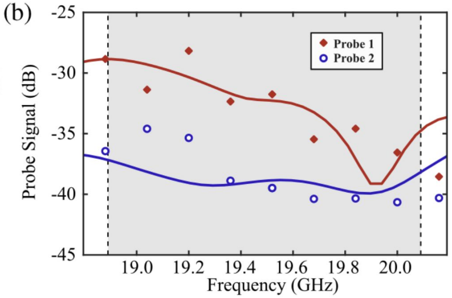


Photonic band gap

[Yu, et al., PRL 123, 057402 (2019)]

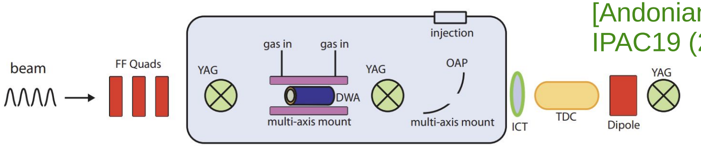


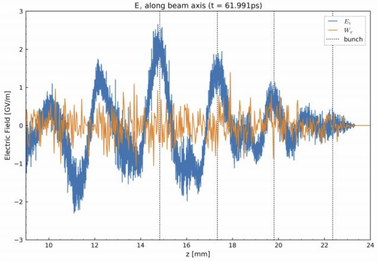


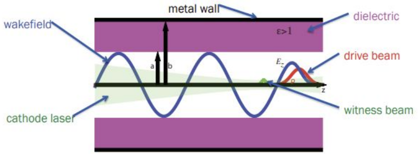


Photonic topological Xtals

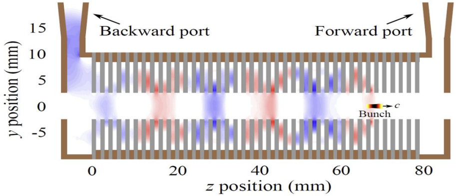
[Andonian et al., IPAC19 (2019)]

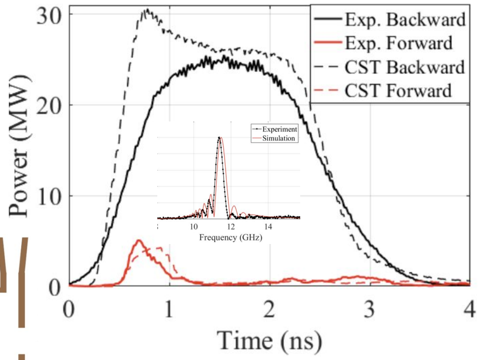






DWFA Trojan-horse





Meta-material

[Lu, et al., PRL 122, 014801 (2019)]

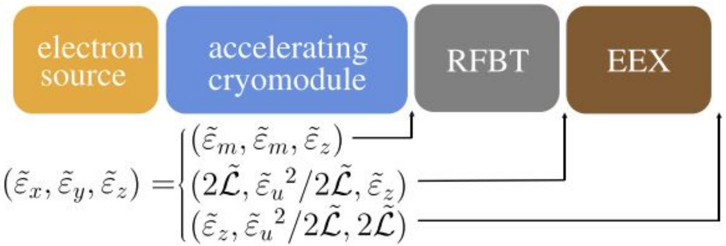
BRIGHT FLAT E- BEAMS W/O COOLING

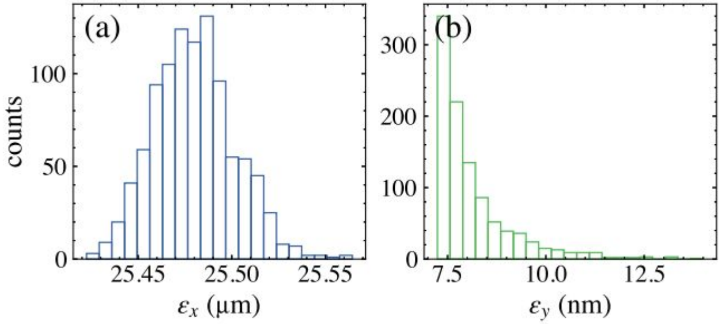
Removing damping ring from LC design

- State of the RF gun produce 6D brightness larger than required to reach emittance at IP
- Cascaded cross-plane phase-space manipulation can redistribute emittance of a bright beam to be consistent with requirement for linear collider

	ILC	CLIC	rf gun
Reference	[7]	[8]	[5]
Charge Q (nC)	3.2	0.83	2
Energy E_b (GeV)	250	380	24×10^{-3}
ε_x (μm)	10	0.9	1.3
ε_y (nm)	35	20	1.3×10^{3}
σ_z (mm)	0.3	0.07	2.31
σ_δ (%)	0.19	0.35	~0.1
ε_z (m)	0.27	0.18	$\sim 1.1 \times 10^{-4}$
$\mathcal{B}_6$ (pC μm^{-3})	3.4×10^{-2}	0.25	~11

T. Xu, et al., PRAB (2023)

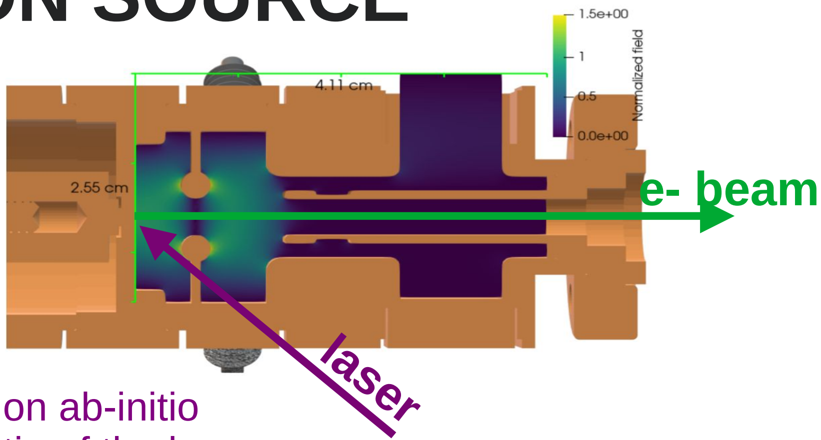




- Application to e+ remains challenging

HIGH-FIELD PHOTOEMISSION SOURCE

Producing brighter electron beams



- Bright electron beam generation relies on RF photoinjector
- Beam brightness scales as

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

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

field experienced at emission → E_0

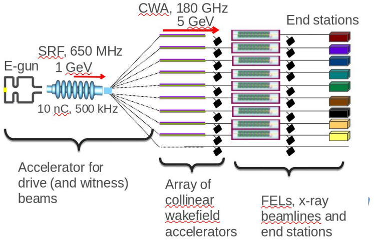
depends on ab-initio aspect ratio of the beam → ν

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

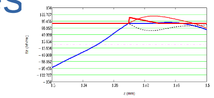
- *Ideally*, high field is favorable to higher brightness; however chemical and physical topology of photocathodes sets a limit on the brightness
- The TBA XRF gun discussed earlier could be an option for bright-beam generation in an advanced collider

CONCLUDING REMARKS (I)

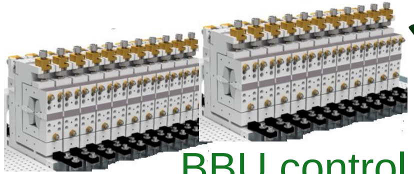
Multi-user soft X-ray free-electron laser combining SRF with CWA or **NC with TBA**



Improve efficiency
Beam dynamics of main bunch
develop new structures

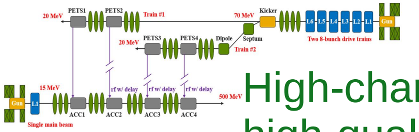


AWA energy doubler

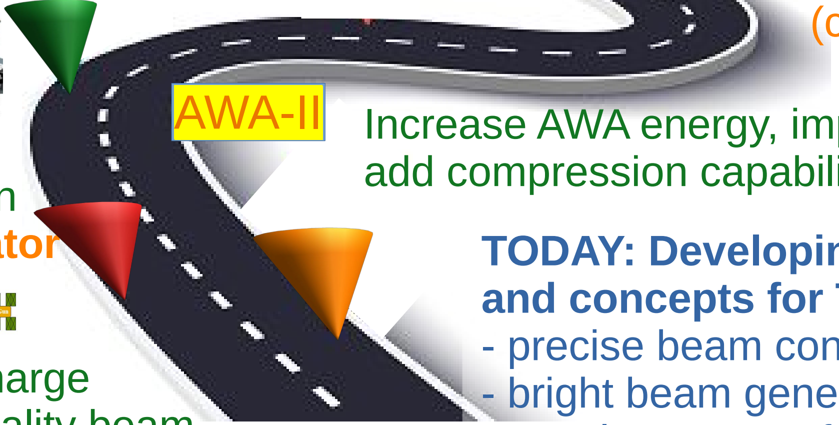


BBU control
compression

500-MeV demonstrator

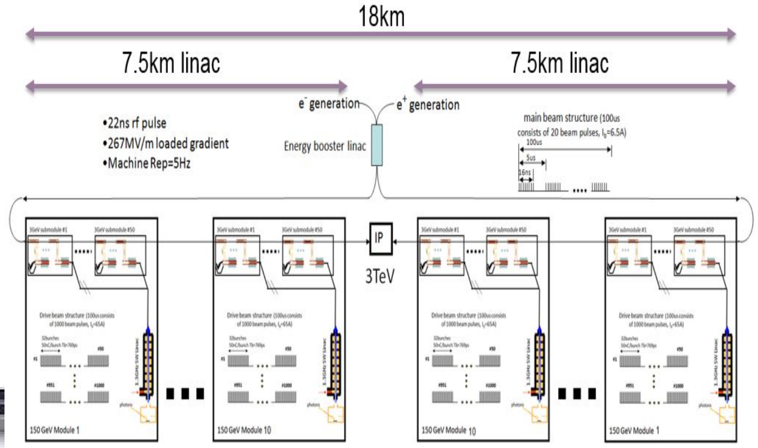


High-charge
high-quality beam



AWA-II

Increase AWA energy, improve brightness,
add compression capability (THz structures)



TeV-class e+/e- linear collider
(currently TBA scheme)

TODAY: Developing enabling technologies and concepts for TBA and CWA:
- precise beam control (TR, BBU supp., efficiency)
- bright beam generation
- novel structures for power extraction
high-gradient acceleration

CONCLUDING REMARKS (II)

- Significant progress has been made on operating RF structure with surface field close to GV/m within the last 4 years
- Short (< 10-ns) RF-pulses naturally produced in two-beam accelerators (TBA) are critical to GW peak-power generation at X-band frequencies
- Concept for a 10-TeV collider still lacking (so far only a straw man design for a 3 TeV TBA based on the CLIC design)

- About collaboration:
  - There are many common topics between PWFA and CWA-SWFA (especially related to drive beam generation and dynamic)

QUESTIONS