LEDS 2024

BERN SWITZERLAND

# Progress on the Ultrahigh Gradient, Short-pulse X-band Photogun at the Argonne Wakefield Accelerator


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On behalf of
GONGXIAOHUI CHEN
and the AWA facility at Argonne National Laboratory


Sept 17, 2024

# outline

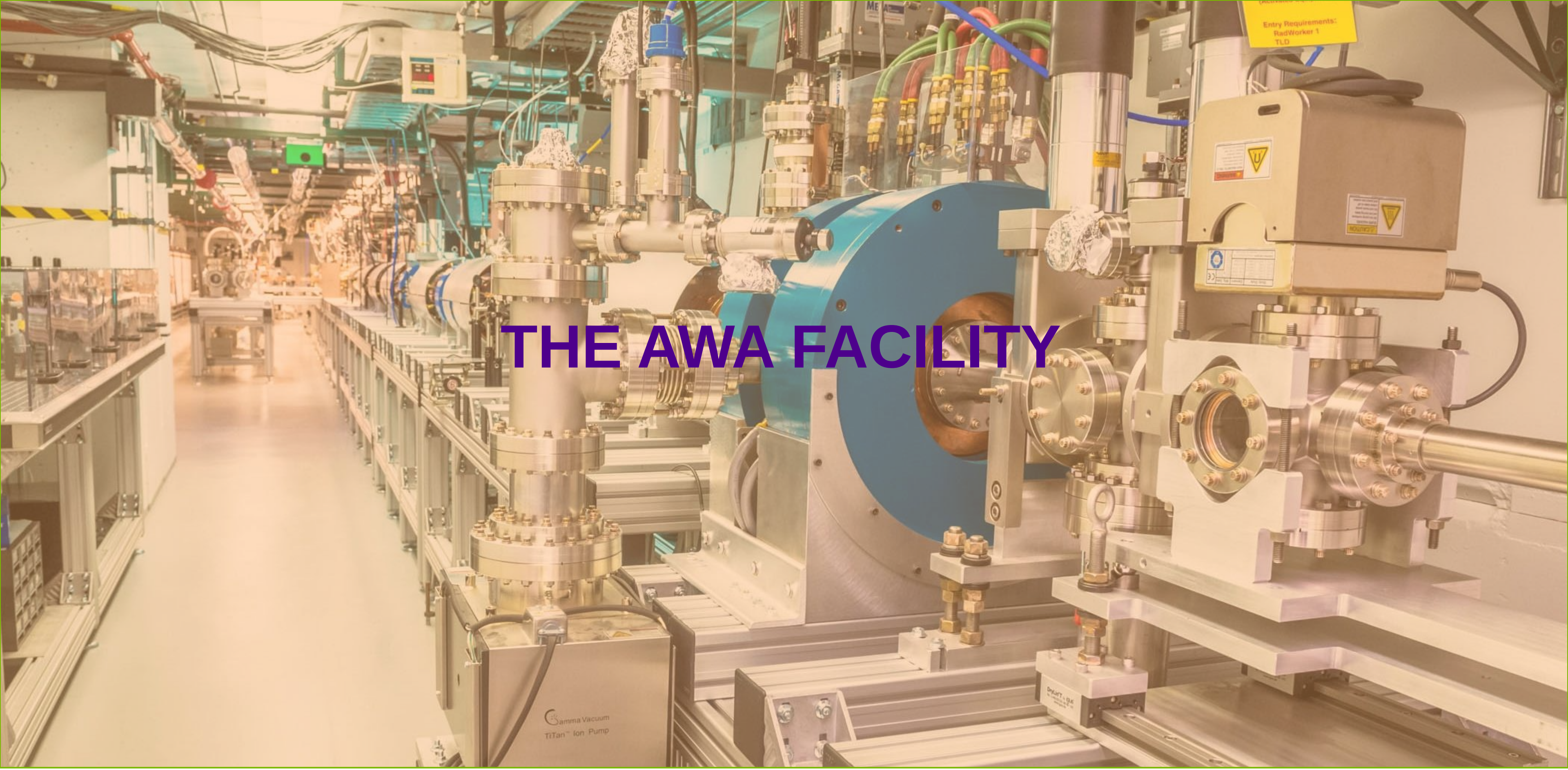
**I am assuming (practically) no one here has heard of the AWA or SWFA.** 🙂

Argonne Wakefield Accelerator (AWA) Facility

Structure Wakefield Acceleration at the AWA Facility

High Gradient X-band Photogun

# THE AWA FACILITY



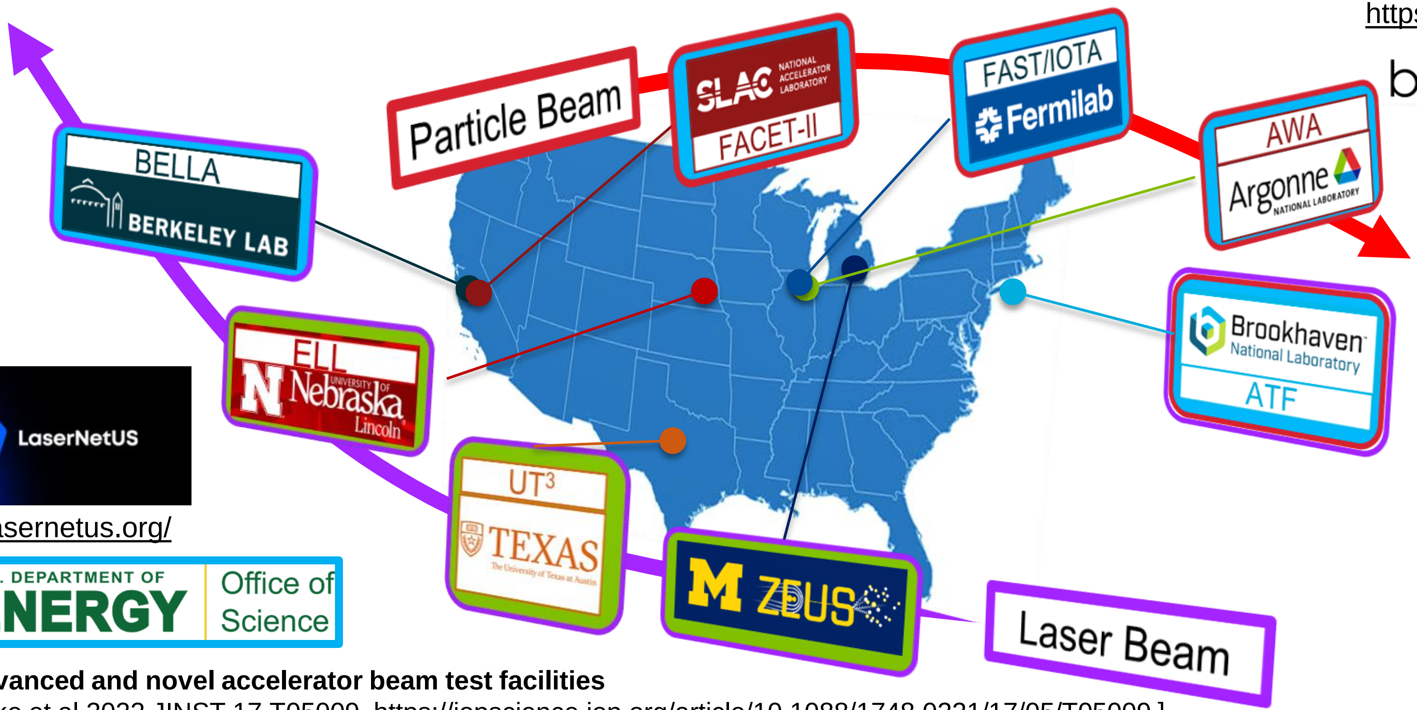
# WHAT IS THE *ADVANCED ACCELERATION CONCEPTS (AAC)* PROGRAM

**AAC ~ Wakefield Acceleration:** Laser Wakefield Acceleration, Plasma Wakefield Acceleration, and Structure Wakefield Acceleration (SWFA).

**Beam Test Facilities:** Demonstrating the viability of emerging accelerator science ultimately relies on experimental validation.

https://www.beamnetus.org/

beamNetUS
accelerating beam-based research




LaserNetUS

https://lasernetus.org/

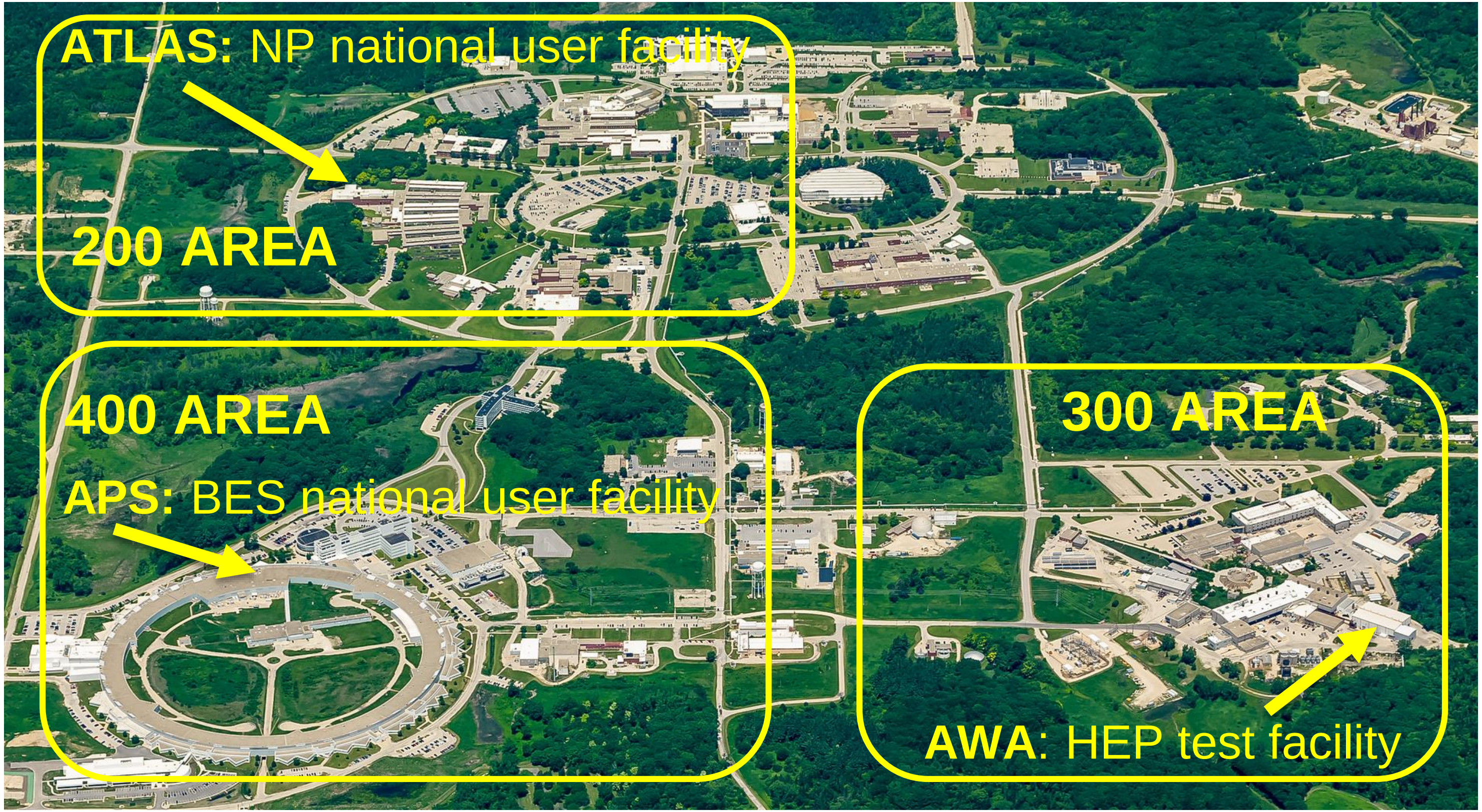
U.S. DEPARTMENT OF ENERGY | Office of Science

**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 ]

NSF

# ARGONNE WAKEFIELD ACCELERATOR (AWA)

## Argonne Campus: 15 minutes west of Chicago



# The Argonne Wakefield Accelerator (AWA) Facility

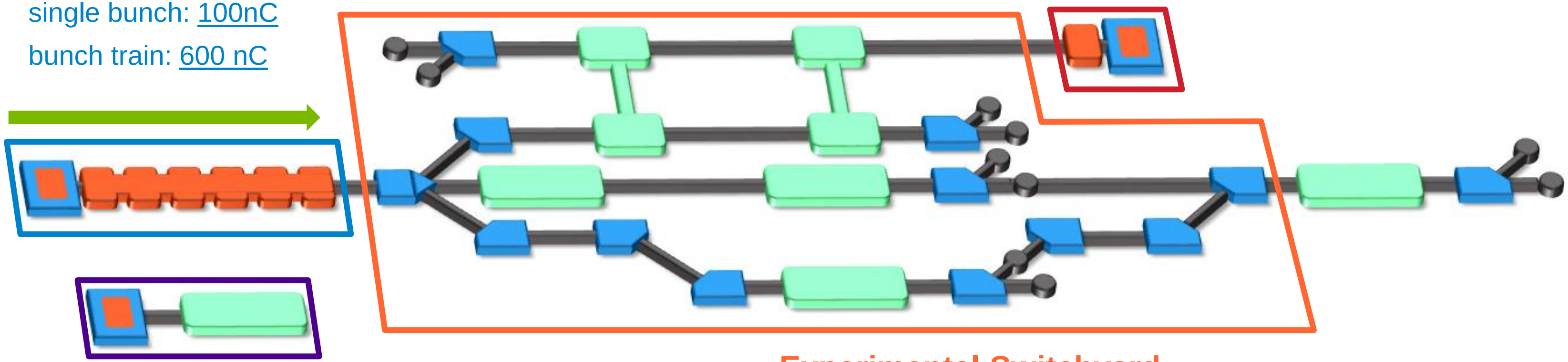
## A Beam Test Facility to enable the development of novel acceleration technology

### 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

- 100 mJ (IR), 10 mJ (UV),
- 300 fs – 6 ps (UV)
- temporal shaping

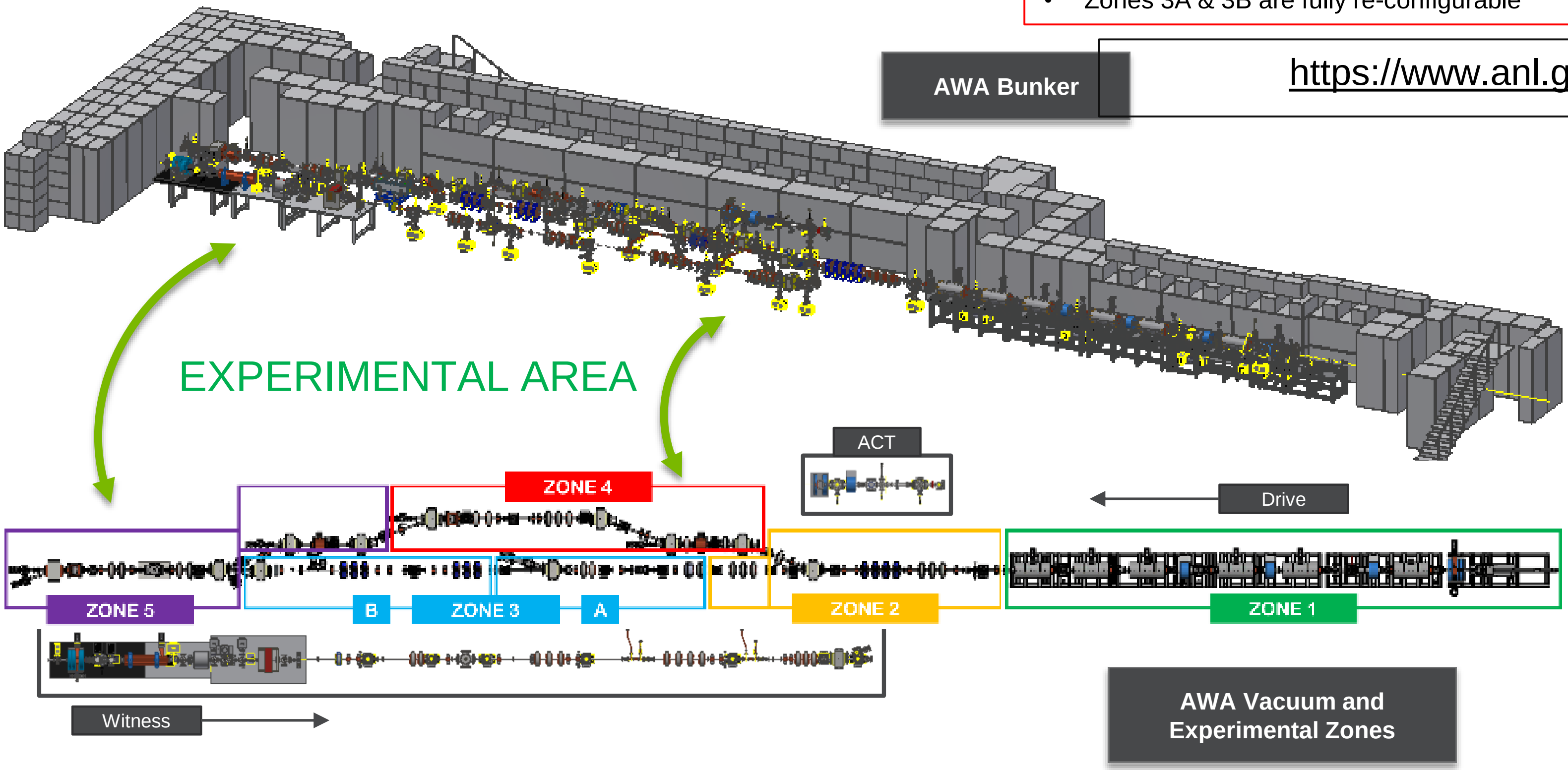
# THE ARGONNE WAKEFIELD ACCELERATOR

## The AWA Facility

**5 Zones**

- Zones 2-5 are experimental areas
- Zones 2, 4, and 5 have ~ 1 m experimental area
- Zones 3A & 3B are fully re-configurable

https://www.anl.gov/awa



# THE THREE AWA RESEARCH THEMES
# TO
# SUPPORT SWFA

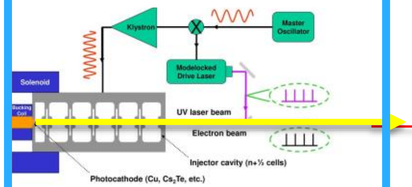
# AWA RESEARCH THEMES

## Timeless research themes

## Applications

### Beam Production

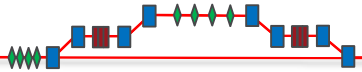
e.g. RF Photoinjector




- Electron sources
  - High-brightness
  - High-intensity

### Beam Manipulation

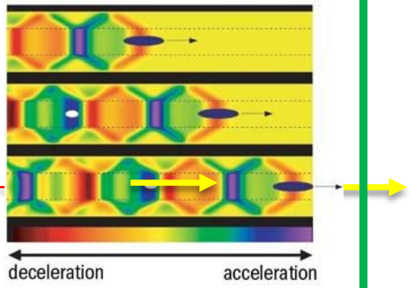
e.g. Double Emittance Exchange



- Beam shaping & control.
- Beam Diagnostics.

### Advanced Accelerator

e.g. SWFA




- SWFA & PWFA
  - High-Gradient
  - High-Efficiency

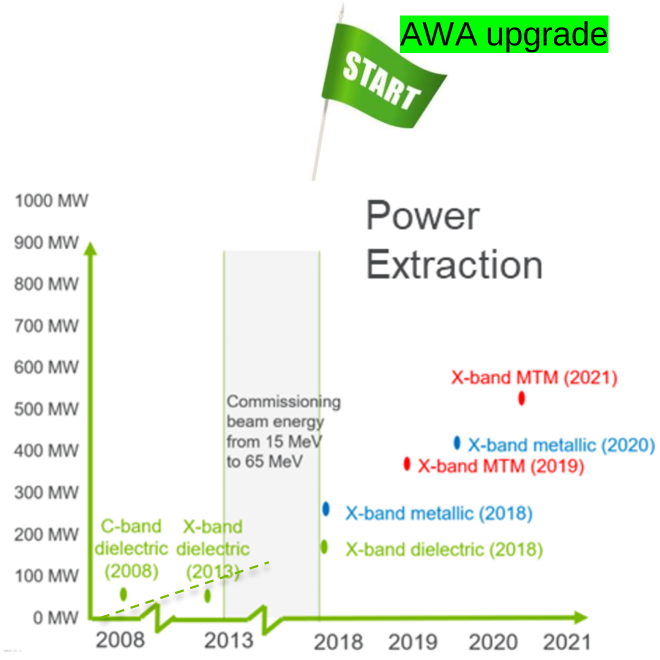
### Applications

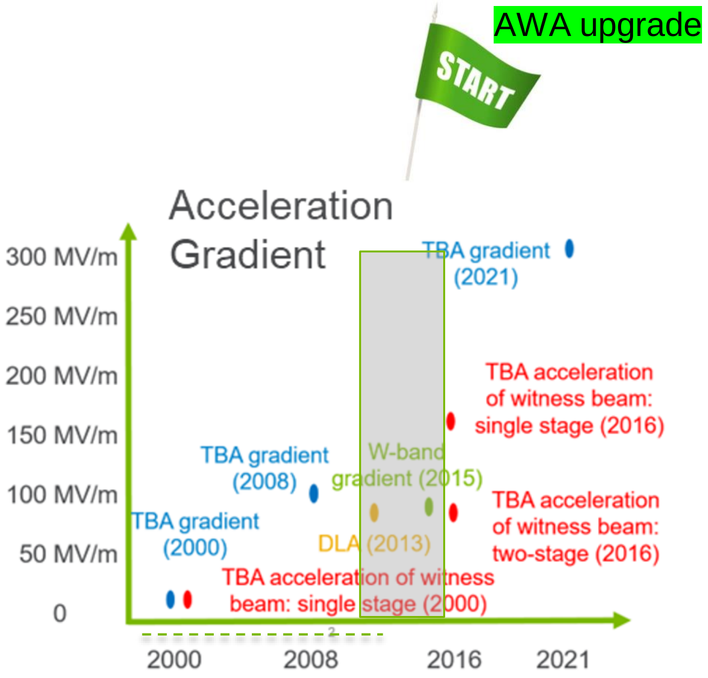
- Linear Collider
- Compact XFEL
- UED
-
-
-
- not exhaustive

# RESEARCH THEME: ADVANCED ACCELERATOR

# HIGH-GRADIENT NORMAL CONDUCTING RF RESEARCH

- Rapid progress with ***short-pulse TBA*** since 2015 upgrade (started 2008)
- AWA-II will enable demonstration of SWFA critical technologies in GeV range



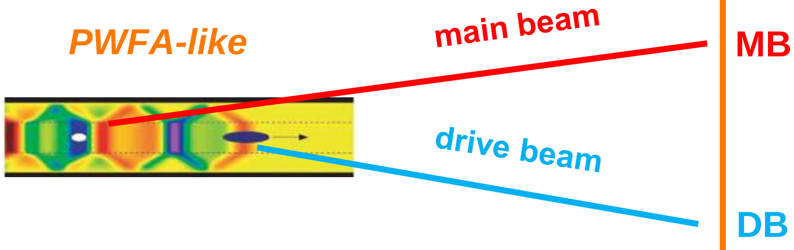



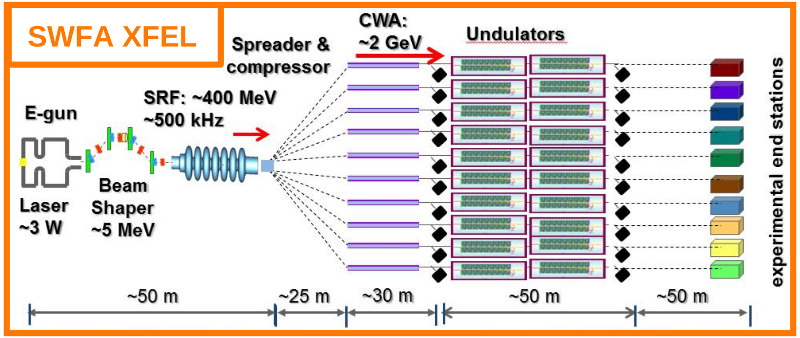
# e-beam Driven Structure Wakefield Acceleration (SFWA)

Advanced Accelerator

## Collinear Wakefield Acceleration (CWA)

*PWFA-like*

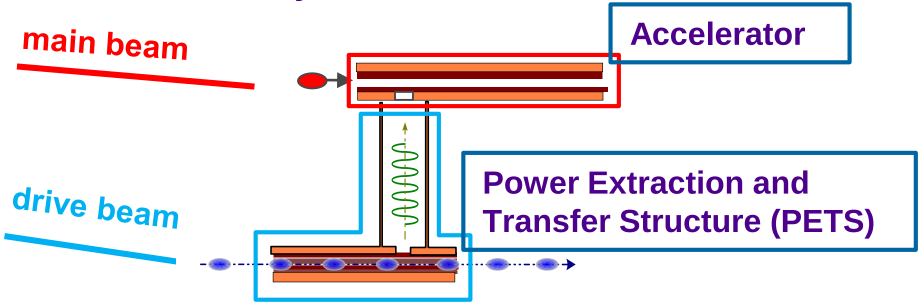


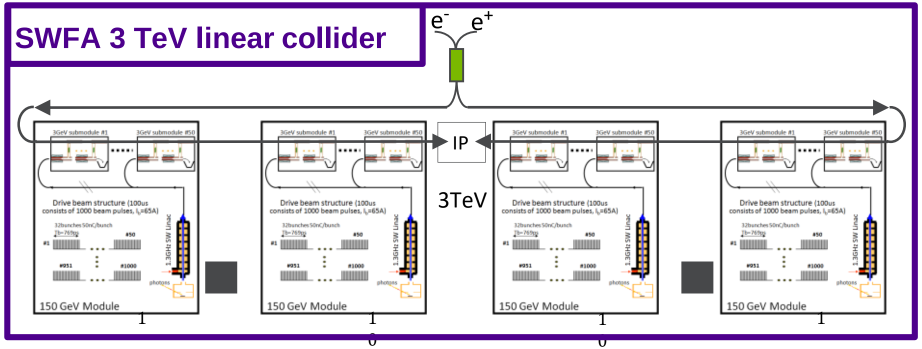




A. Zholents, et al, *NIMA* **829**, 190-193 (2016)
A. Zholents, et al, *Proceedings of IPAC2018*

## Two Beam Acceleration (TBA)

*Klystron-like*



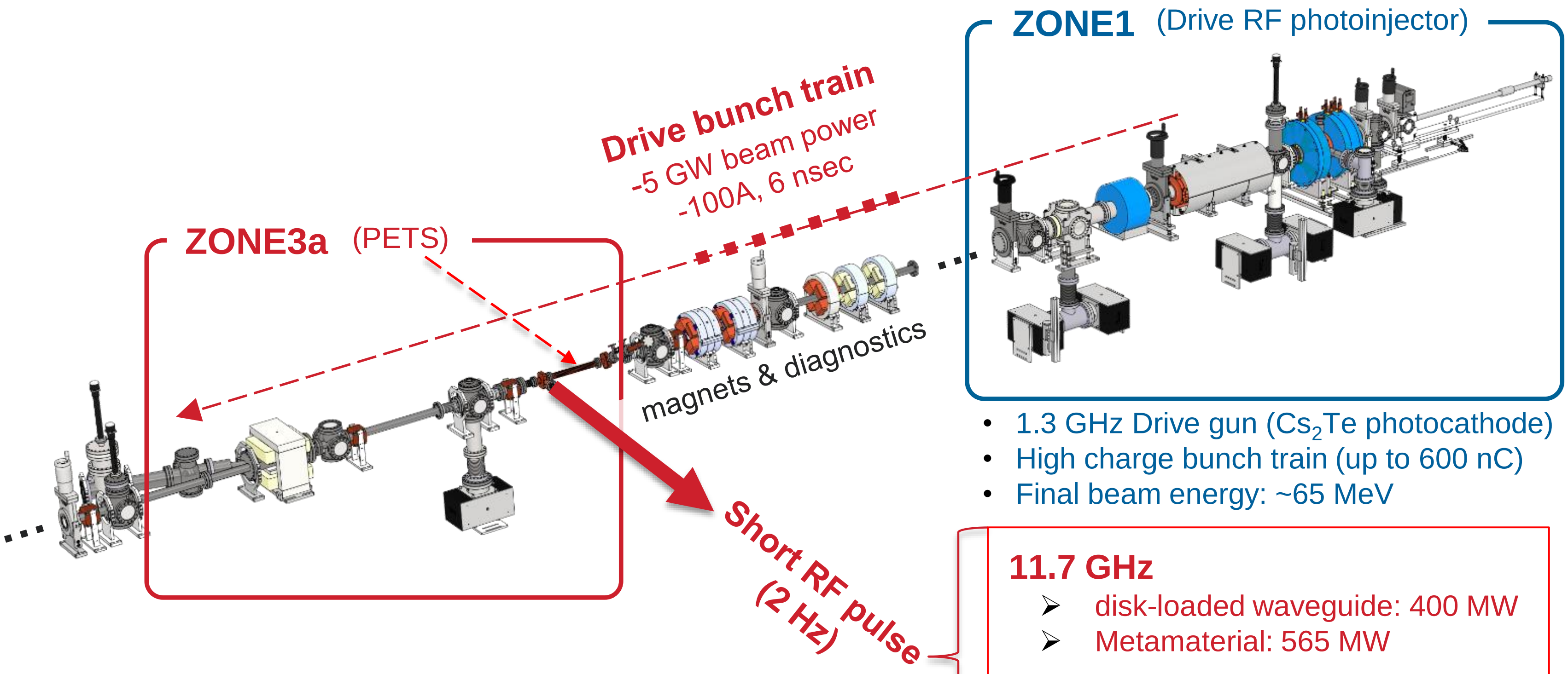




CLIC CDR: https://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
W. Gai, C. Jing, J.G. Power, *JPP* **78**, 339-345 (2012)

# SHORT PULSE RF GENERATION

## TBA drive beam PETS

Advanced Accelerator




- 1.3 GHz Drive gun ($Cs_2Te$ photocathode)
- High charge bunch train (up to 600 nC)
- Final beam energy: ~65 MeV

**11.7 GHz**

- disk-loaded waveguide: 400 MW
- Metamaterial: 565 MW

**26 GHz**

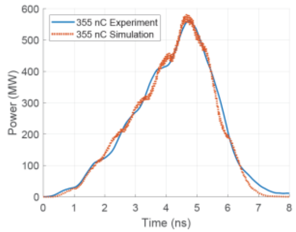
- Dielectric PETS: 80 MW

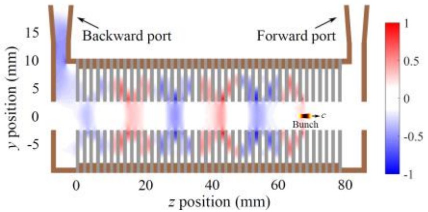
# PETS results at AWA

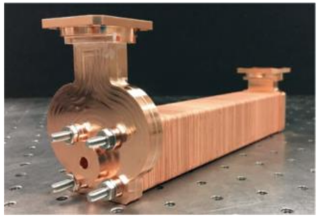
Advanced Accelerator

Argonne NATIONAL LABORATORY

## MTM X-band PETS (565 MW)



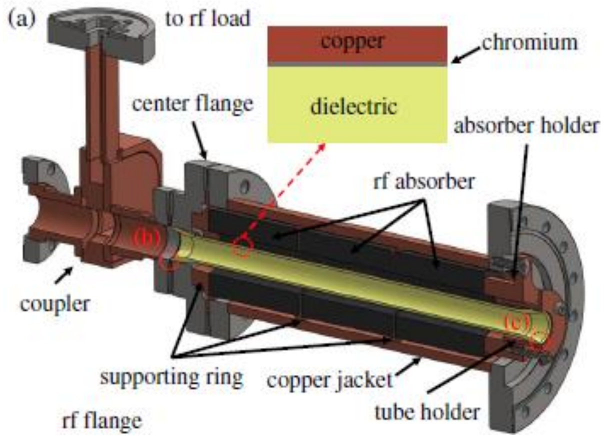



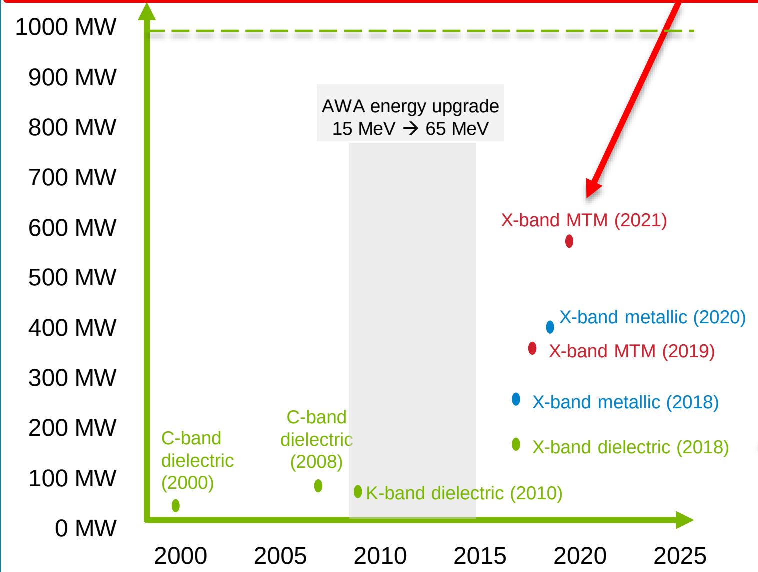
Highest peak power as 565 MW from a train of eight bunches with a total charge of 355 nC

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

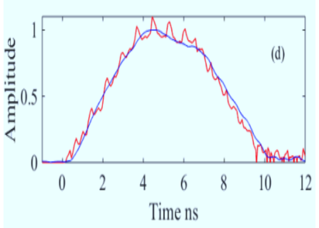
## Dielectric X-band PETS (200 MW)




DOI: 10.1103/PhysRevAccelBeams.23.011301



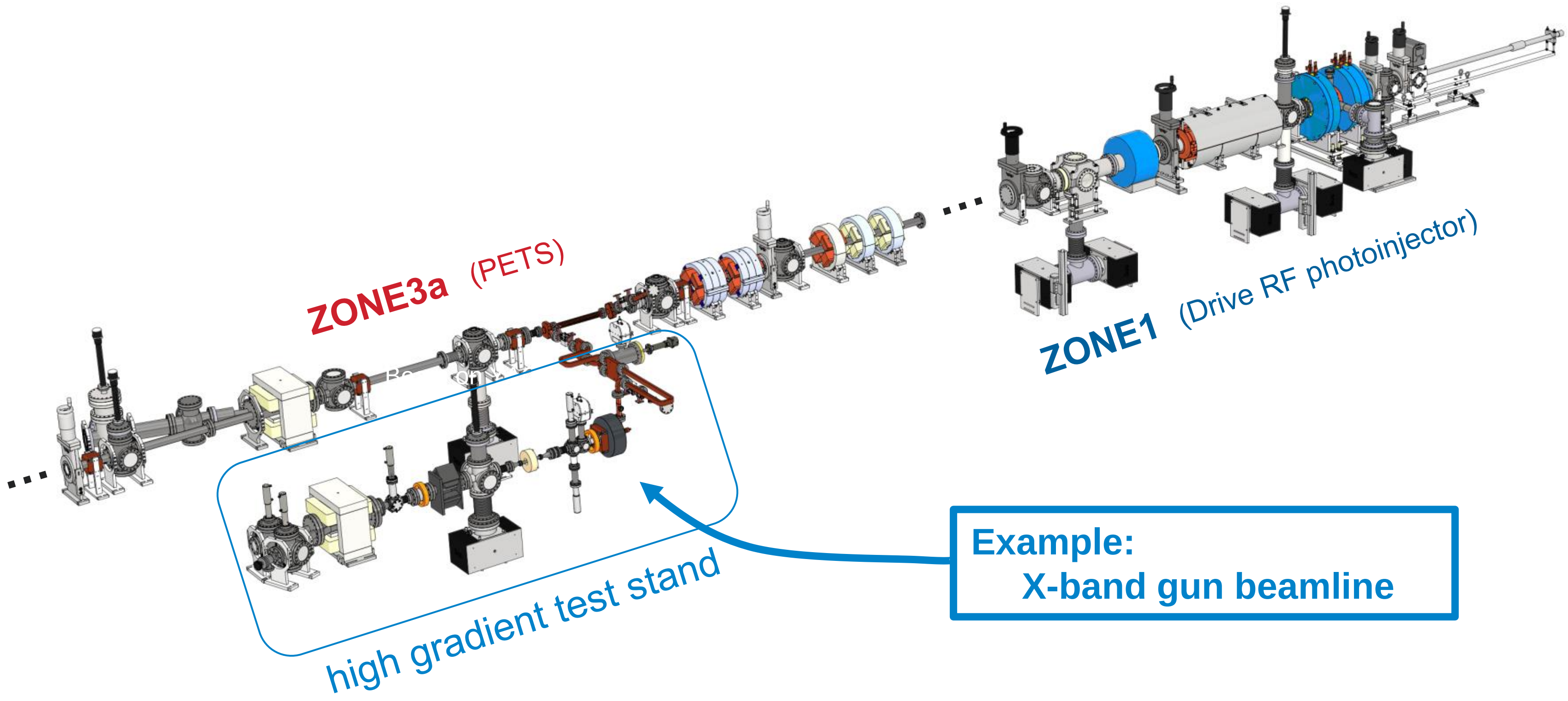

## Metallic X-band PETS (400 MW)



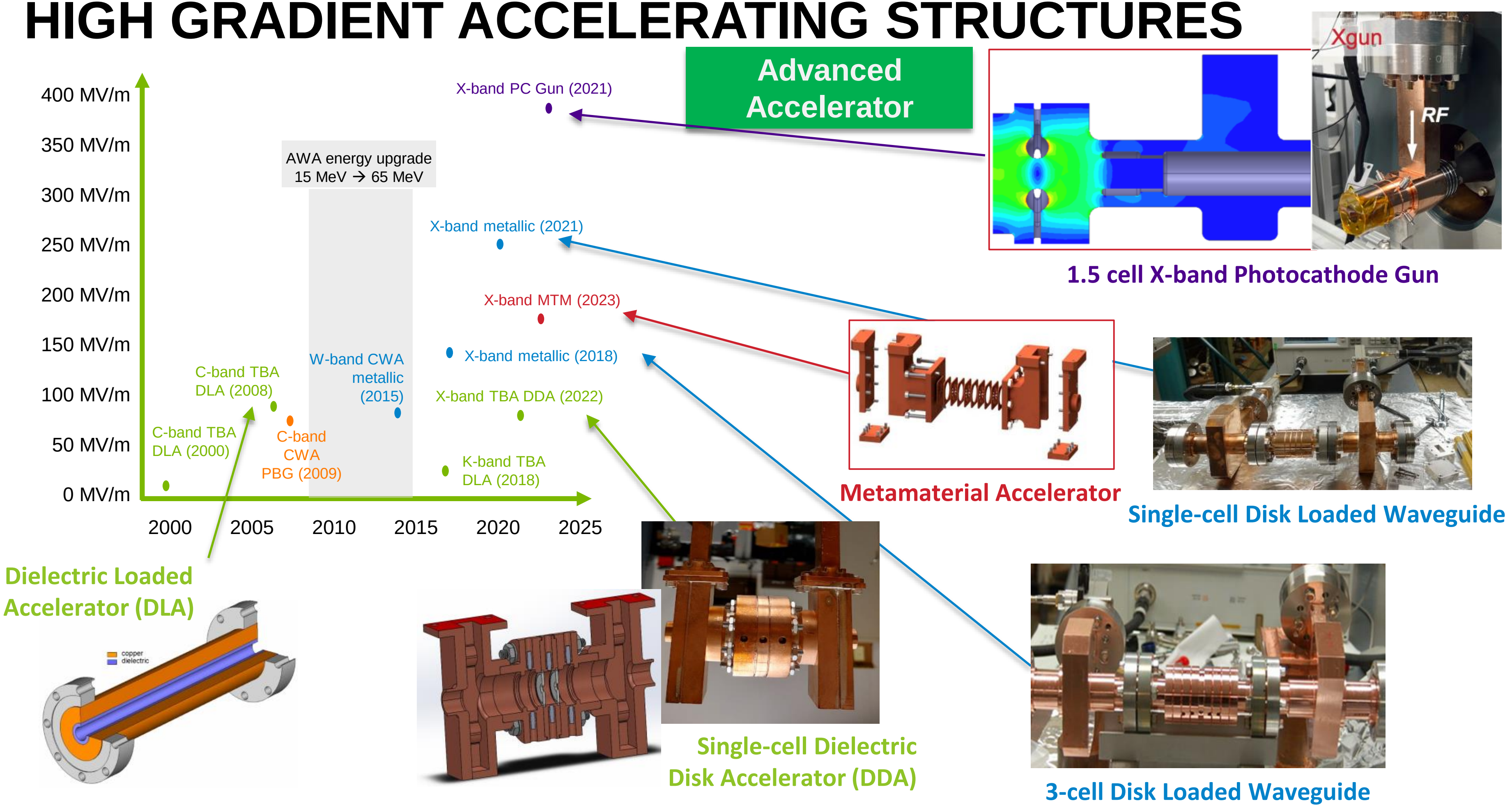

J. Shao *et. al.*, https://accelconf.web.cern.ch/ipac2019/papers/MOPRB069.pdf

# HIGH GRADIENT STRUCTURE TEST STAND

Advanced Accelerator



# HIGH GRADIENT ACCELERATING STRUCTURES

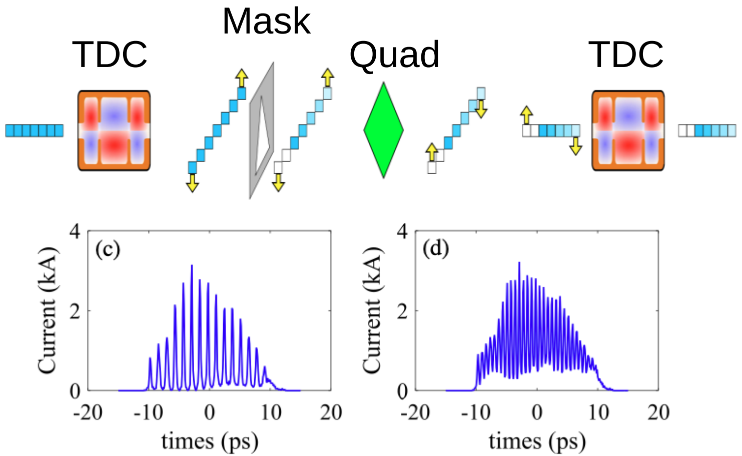


# RESEARCH THEME: BEAM MANIPULATION

# SHAPED ELECTRON BUNCHES

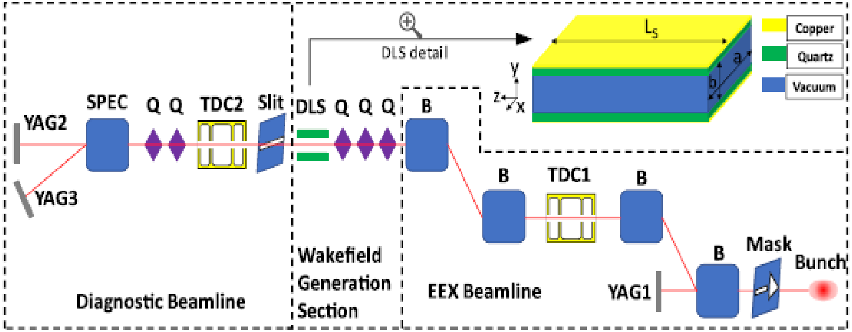
## longitudinal bunch shaping

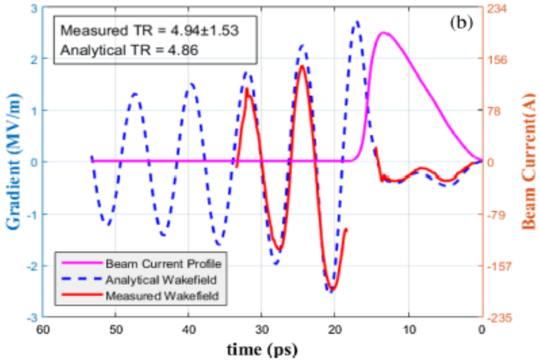
### Deflecting cavity based long bunch shaping




Experimental demonstration planned for 2025.
G. Ha, et al. PRAB (2020)

### Emittance EXchange (EEX) beamline to produce a longitudinally triangular beam profile



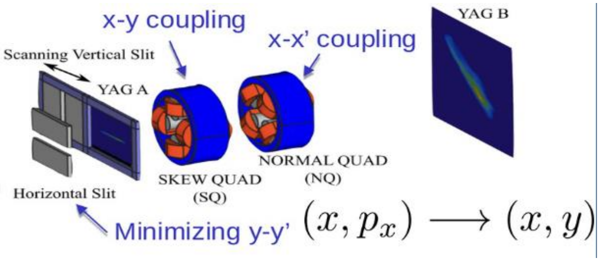



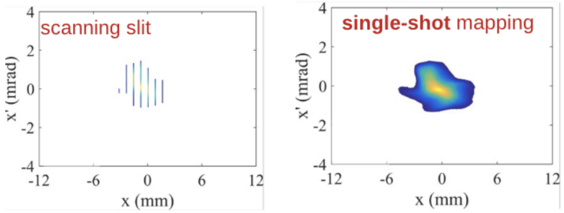

Experimental demonstration of enhanced transformer ratio (TR=4.9) Q. Gao et al., PRL 124, 114801 (2018)

# NOVEL DIAGNOSTICS

**Beam Manipulation**

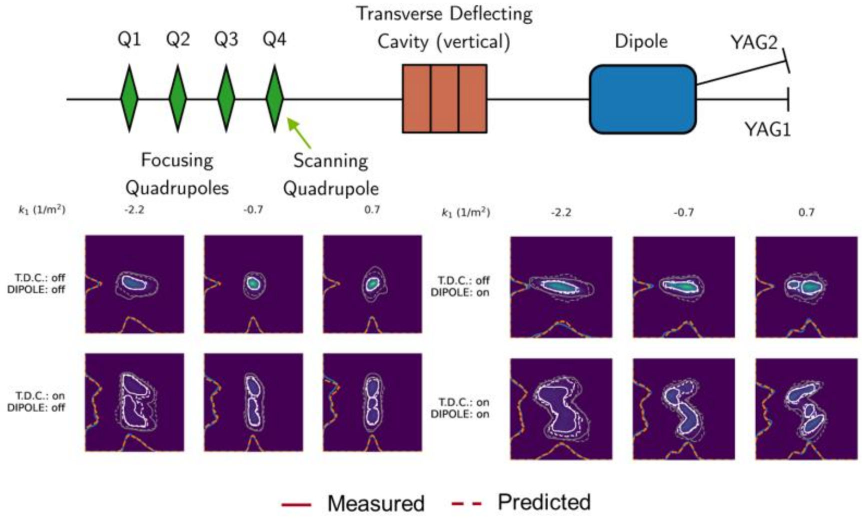
## Single-shot trans. phase space diagnostics

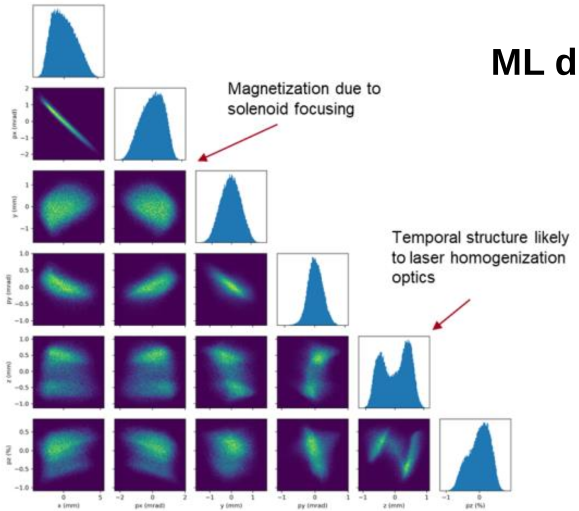



Ha, Gwanghui, et al. "Single-shot measurement of transverse second moments using the projection method." *PRAB* 24.1 (2021): 012802.

## ML diagnostics



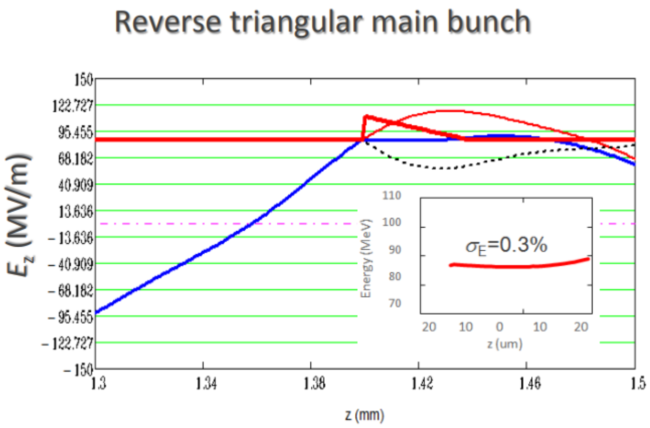

Generative Phase Space Reconstruction (GPSR), 6-dimensional phase space reconstruction of a beam distribution from 20 measurements / ~15 minutes analysis time. Roussel, Ryan, et al. *PRAB* 27.9 (2024): 094601.

# RESEARCH THEME:
# BEAM PRODUCTION

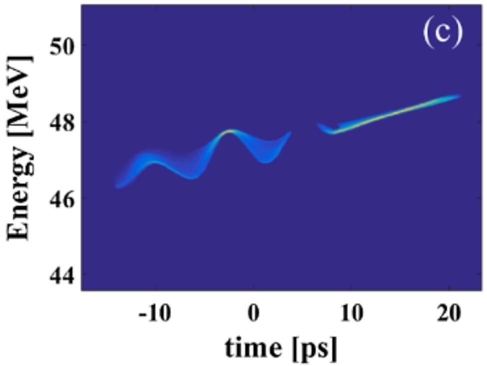
# BRIGHT BEAM GENERATION

## Beams for acceleration and diagnostics

**Main beam**: needed for direct applications (linear colliders and light sources)




**Witness beam**: As a probe to investigate phase-space degradation in CWA and TBA




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

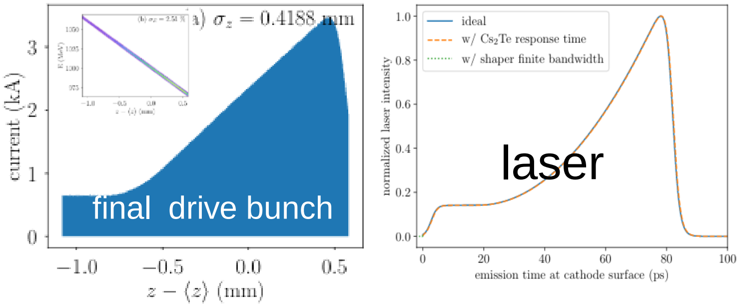
# INTENSE BUNCHES AND BUNCH TRAIN GENERATION

## Drive beams are needed for TBA and CWA

Produce single drive bunch for CWA

- Charge level:
  - 100-nC/Xband
  - 10-nC/sub THz
- pre-shaped bunch for efficient acceleration

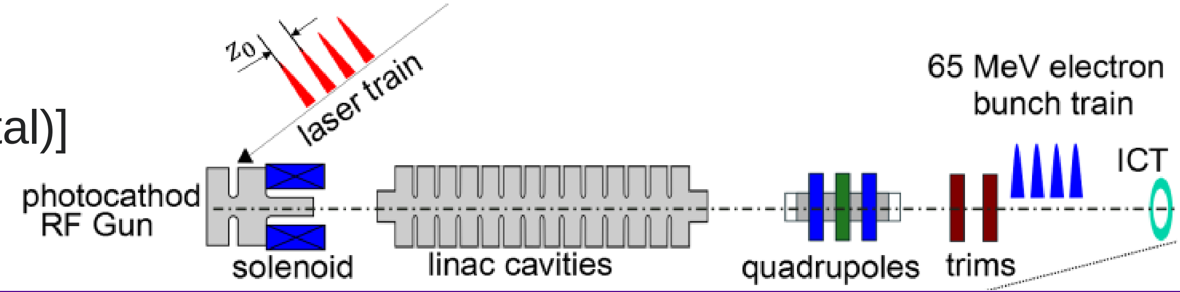
Shaped laser w/ nonlinear e-beam manipulation

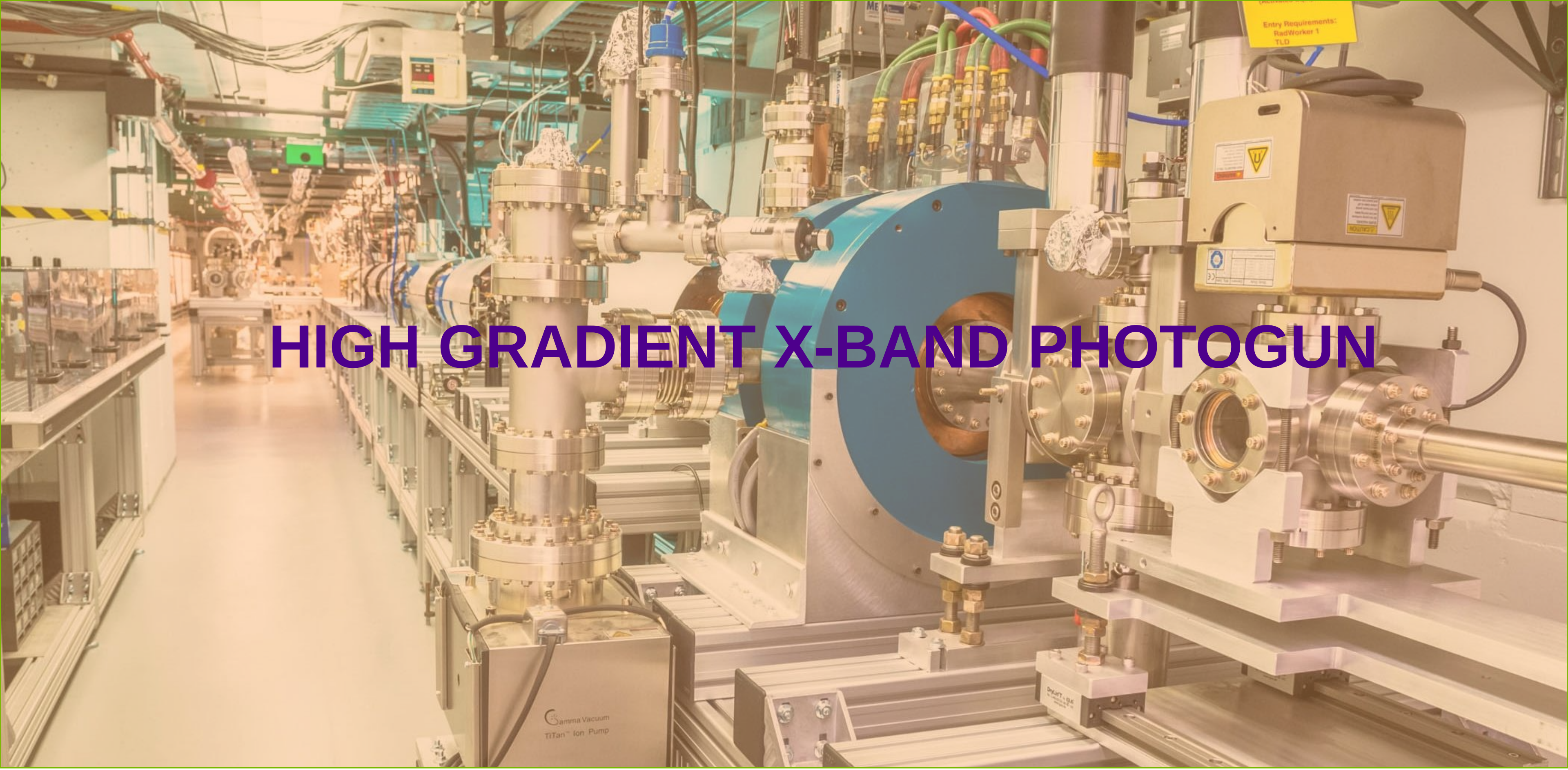



[W. H. Tan, et al. PRAB (2021)]

Produce drive bunch for TBA

- bunch trains w/ ~600 nC (total)]






# HIGH GRADIENT X-BAND PHOTOGUN

# TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

4D beam brightness

$$B \propto \frac{E^{\alpha}}{MTE}$$

High Gradient R&D

**short-pulse** and TBA

field experienced at emission (controlled by applied accelerating field)

*1<α<2* depends on ab-initio long-transverse ratio of the beam

**Mean-T**ransverse **E**nergy [a property of the emitting surface (photocathode) and exciting laser]

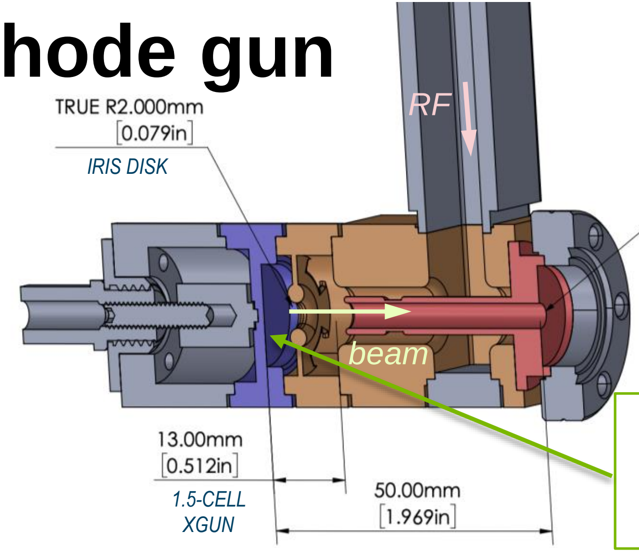
Cathode R&D

**I. V. Bazarov et. al., PRL.** 102, 104801 (2009). https://doi.org/10.1103/PhysRevLett.102.104801
**P. Musumeci, et al., NIMA** 907 (2018) 209–220. https://doi.org/10.1016/j.nima.2018.03.019

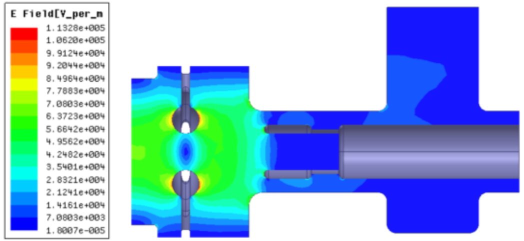
# Xgun: 1.5 cell RF photocathode gun

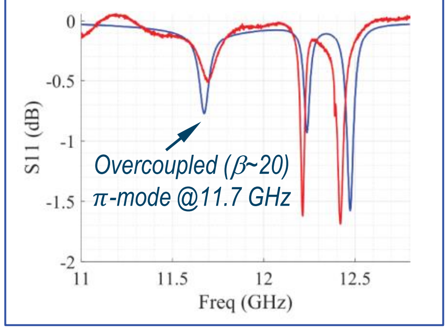
## RF Design

| Parameter | Value |
|---|---|
| Frequency | 11.7 GHz |
| Mode | π |
| t_fill | 5.4 nsec |
| RF pulse length | 9ns<br>(3 ns rise, 3 ns flat, 3 ns, fall) |
| Power | 250 |
| Cathode Field | 470 |




Cathode is the Cu backwall



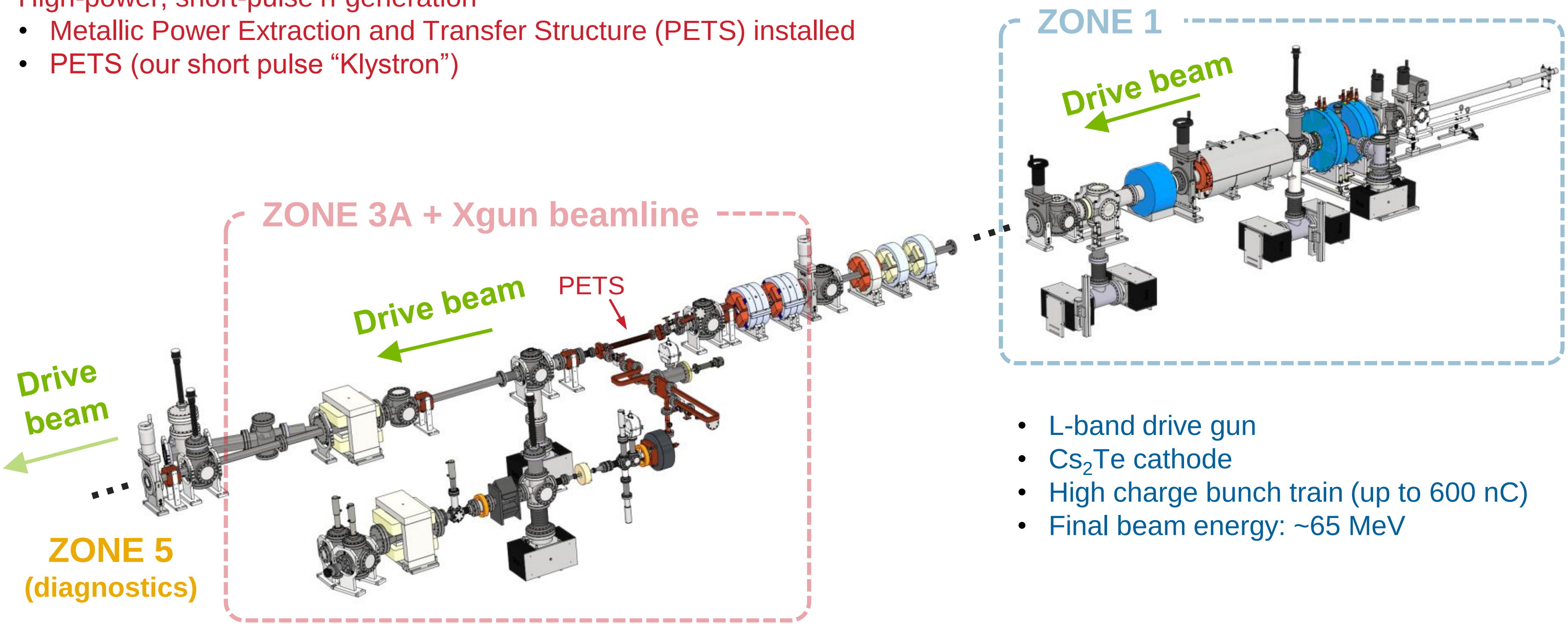



**S. Kuzikov et al., (IPAC21)**
An X-band Ultra-high Gradient Photoinjector
https://accelconf.web.cern.ch/ipac2021/papers/wepab163.pdf

# AWA DRIVE AND XGUN BEAMLINES

High-power, short-pulse rf generation

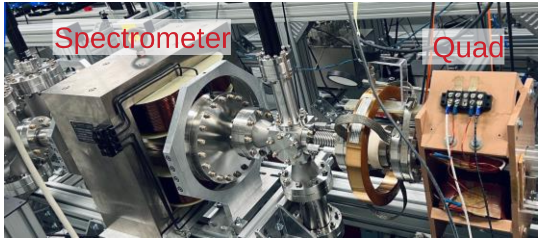
- Metallic Power Extraction and Transfer Structure (PETS) installed
- PETS (our short pulse "Klystron")

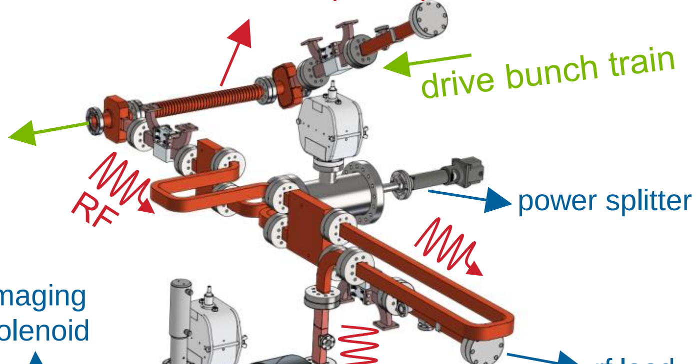


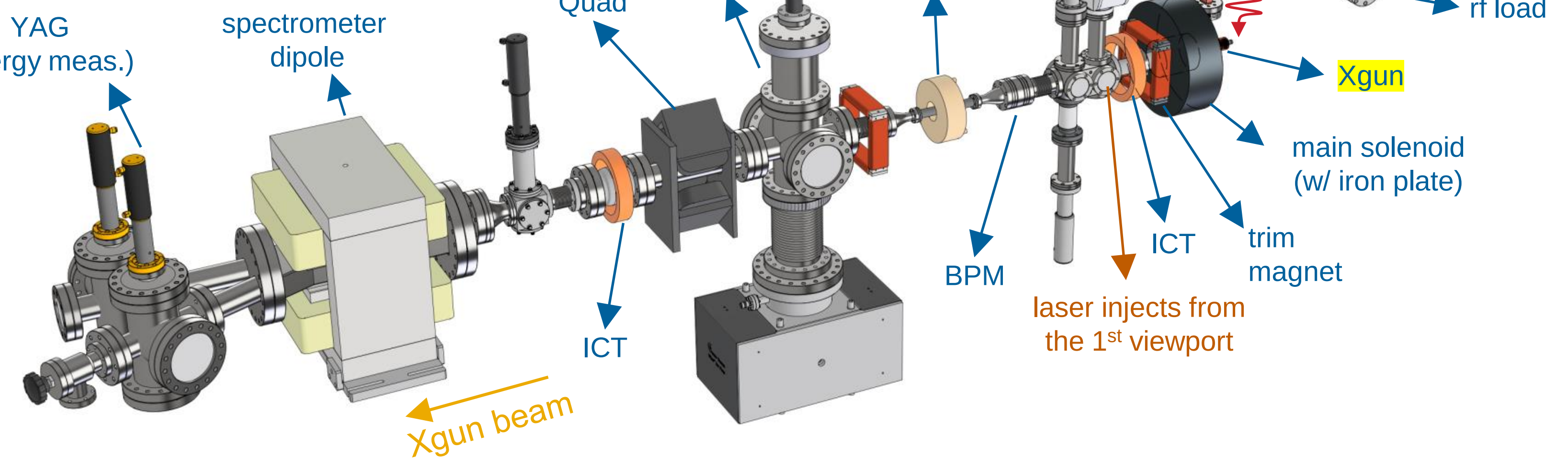

- L-band drive gun
- $Cs_2Te$ cathode
- High charge bunch train (up to 600 nC)
- Final beam energy: ~65 MeV

# XGUN BEAMLINE

## 2023 config. (will upgrade this Fall)





# XGUN TEST HISTORY

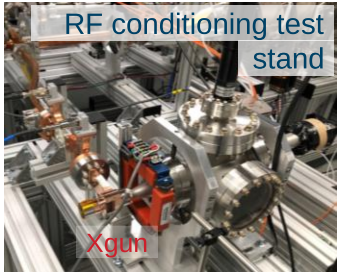
## See “EXTRA” slides for details

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

### pre-2020

**Initial Xgun RF conditioning [1]**

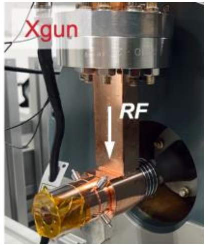
- Achieved 350 MV/m within 70k pulses.
- A dark current loading region observed.
- No observable dark current after conditioning.



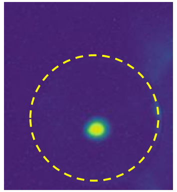

### 2021

**1st beam test [1]**

- High gradient (**388 MV/m**) verified through beam energy measurement.
- Beam energy characterized (~2.7 MeV)
- Low breakdown rate confirmed (>500,000 shots, BDR<$10^{-5}$).




Beam on YAG1



### 2022

**2nd beam test & re-conditioning**

- 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

**3rd beam test (most recent)**

- Study the fundamentals of photoemission (Copper cathode):
- Schottky studies at different gradients.
- QE measurements at different gradients.

***Next section***

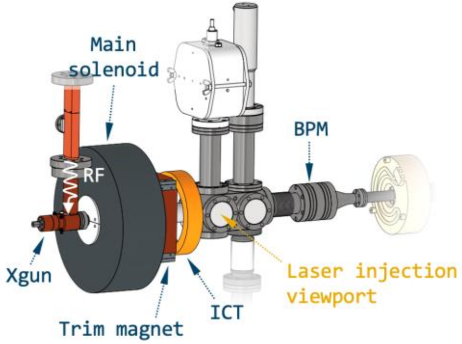
# XGUN PROGRESS

# FUNDAMENTAL PHOTOEMISSION STUDIES

- Schottky scans @ different gradients (60 MV/m to 320 MV/m)
  - Simulation benchmarking
  - Exploring the potential for other emission mechanisms
- Exploring the potential for multipacting

# SCHOTTKY STUDIES

## Benchmarking *Exp. Data* to *ASTRA* simulations




### Simulation setup

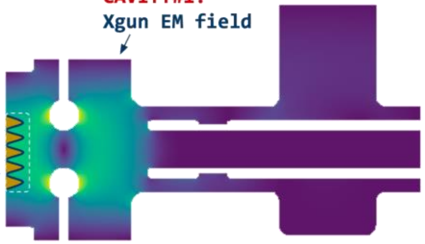
In ASTRA, bunch charge is evaluated as follows,

$$Q = Q_0 + S_1 \cdot \sqrt{E} + S_2 \cdot E$$

where,

$S_1, S_2$: Schottky strength coefficients

$E$: field on the cathode




Possible field ($\boldsymbol{E}$) contributions acting on the cathode:

$$E_{total} = E_0 \cdot sin(\varphi_{rf}) + E_{sc} + E_{roughness}$$

Both included in ASTRA

Modeled separately using a sinusoidal surface [1-2]

where,

$E_0 \cdot sin(\varphi_{rf})$: applied rf field

$E_{sc}$: space charge shielding field

$E_{roughness}$: modeled 3D EM field introduced by surface roughness.

Table 1: List of the simulation parameters in ASTRA

| Parameter | Value |
|---|---|
| Laser $\sigma_{x,y}$ | 0.5 mm |
| Laser pulse length, FWHM | 300 fs |
| Laser energy | 4.73 eV |
| Gradient on cathode | 60 MV/m to 320 MV/m |
| Est. inital bunch charge* | 5.7 pC |
| Est. SRT_Q_Schottky* | 0.003 |
| Est. Q_Schottky* | 0 |
| a** | 0.4 $\mu$m |
| p** | $2\pi/50\ \mu m^{-1}$ |

* Parameters optimized and used in all simulations.
** Parameters in the sinusoidal function for roughness modeling, where z=a·cos(px)

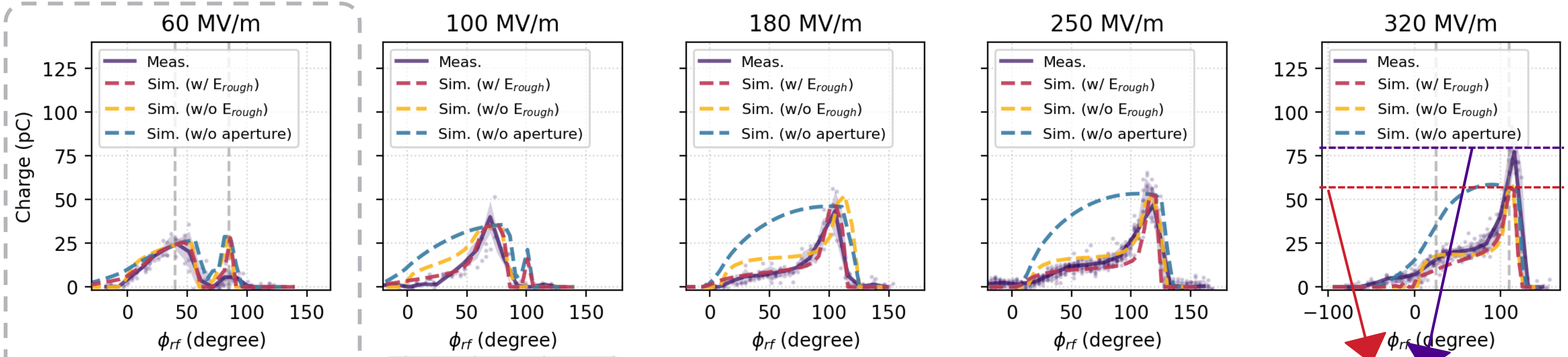

[1] D. J. Bradley, et al., J. Phys. D: Appl. Phys., Vol. 10, (1977).
[2] G. S. Gevorkyan, et al., Phys. Rev. Accel. Beams 21, 093401 (2018).
[3] G. Chen et al., https://accelconf.web.cern.ch/ipac2024/pdf/MOPR76.pdf

# SCHOTTKY STUDIES

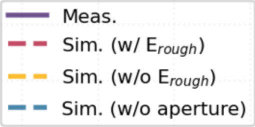
## Simulation benchmarking of exp. data @ 60, 100, 180, 250, 320 MV/m

In ASTRA, bunch charge is evaluated as follows,

$$Q = Q_0 + S_1 \cdot \sqrt{E} + S_2 \cdot E$$



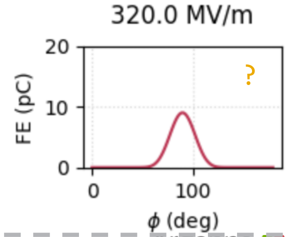

Ref data for simulation param ($S_1$, $S_2$, $Q_0$) optimization




- Peak charge discrepancy only at high gradient.
- Other emission mechanism involved (i.e. photo-assisted field emission)?

**Modified Folwer-Nordheim:**

$$J(E) = a\frac{\beta^2 E^2}{\phi_{eff}}\exp(-b\frac{\phi_{eff}^{3/2}}{\beta E})$$

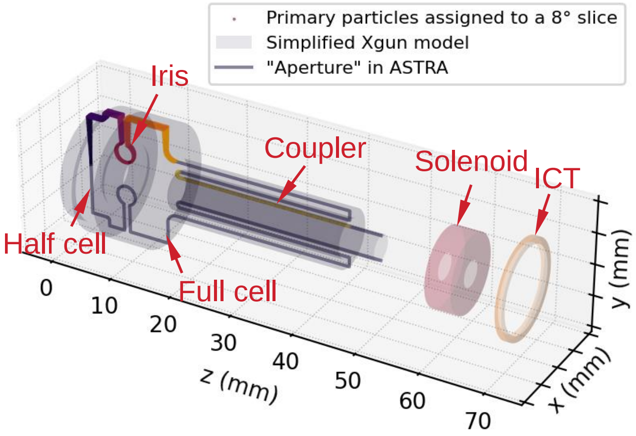



- At all gradients, simulations include the $E_{roughness}$ shows a better agreement with the measurements.
- Revealed a beam clipping issue at the Xgun exit.
- Photo-assisted field emission might happen at high gradient.

# MULTIPACTING SIMULATION

## @ different gradients

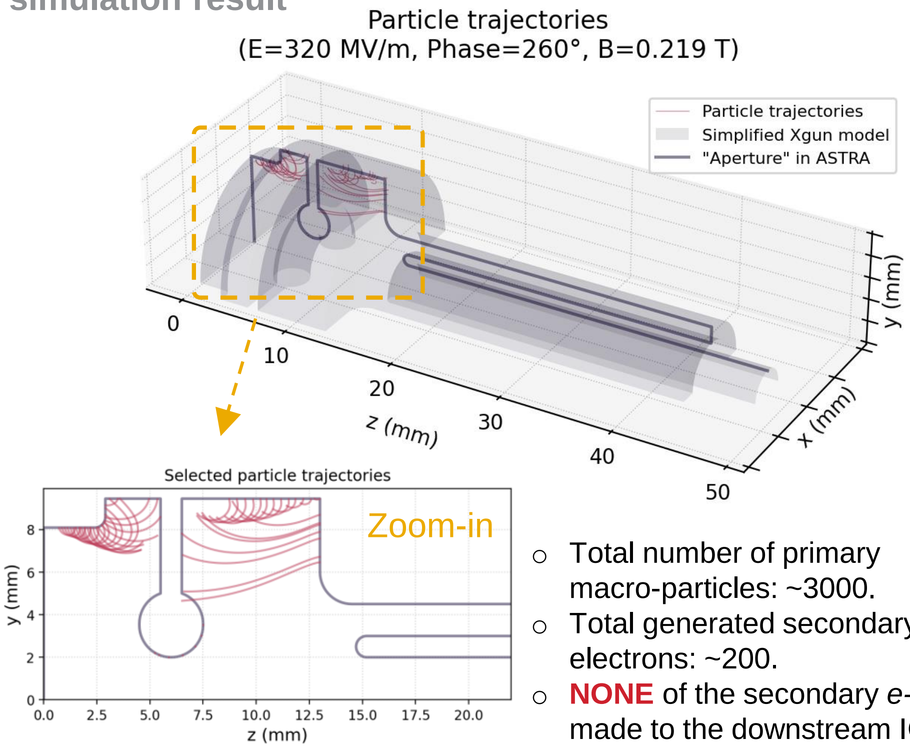
### Simulation setup




**In the simulation:**

- 3D Xgun field map + solenoid field map included.
- Tracking to the downstream ICT.
- Primary particles for MP simulation assigned to an 8 deg slice.
- Cu SEY applied.

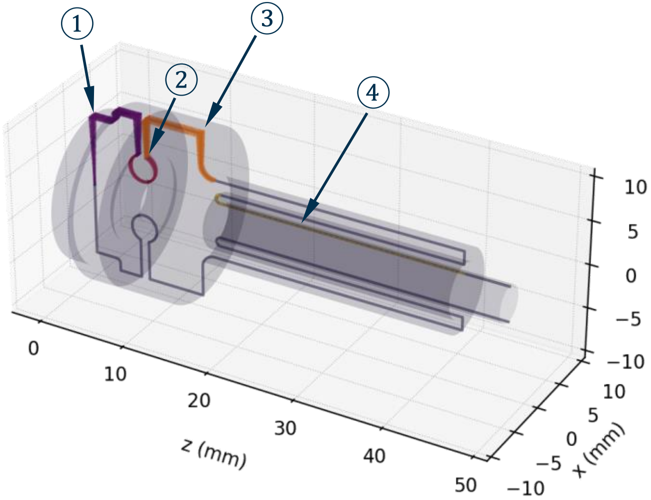
### An example of MP simulation result




- Total number of primary macro-particles: ~3000.
- Total generated secondary electrons: ~200.
- **NONE** of the secondary *e*- made to the downstream ICT.

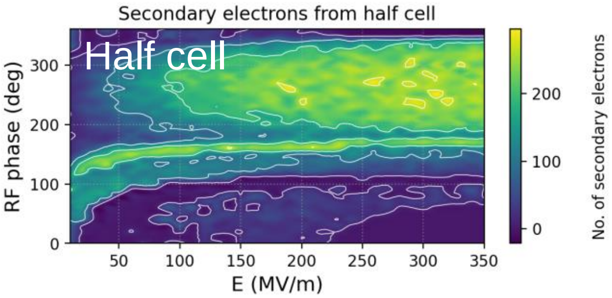
# MULTIPACTING SIMULATION

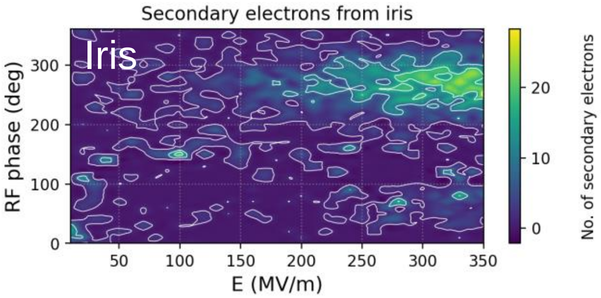
## @ different gradients

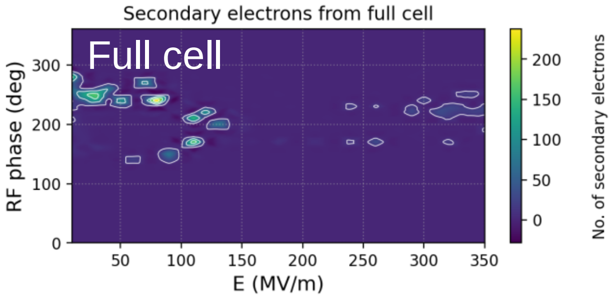



Tracking the MP in different regions separately:

- ① Half cell
- ② Iris
- ③ Full cell
- ④ Coupler (no MP from simulation)




| MP scanning param. | |
|---|---|
| Xgun E | 10 to 350 MV/m |
| Phase | 0 to 360 deg |
| Sol. B* | 0.05 to 0.22 T |
| * Solenoid B for each scan was predicted based on the recorded experimental values | |

- Get an insight on the MP issue which is sensitive to the **gradient**, **rf phase** and **solenoid strength.**
- Nearly **NO** secondary electrons can reach to the downstream ICT.

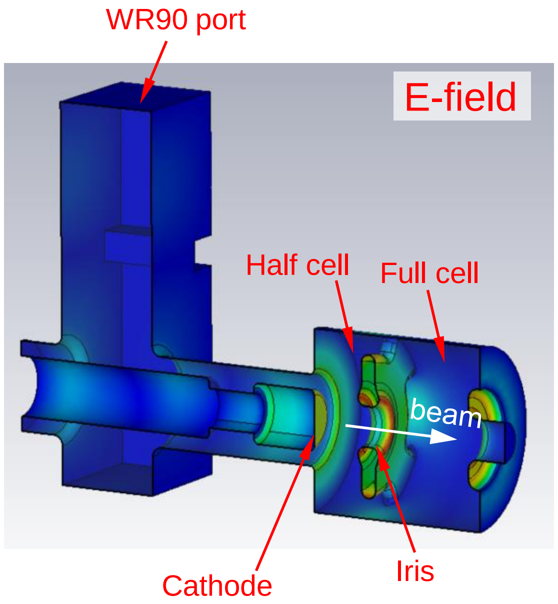
# CONCLUSION

## AWA themes

- Short-pulse TBA (NCRF): High-gradient demonstrated.
  - ~300 MV/m X-band TW accelerating metallic accelerator
  - ~400 MV/m X-band photocathode gun
- Bunch manipulation
  - 6d phase space manipulation
  - Longitudinal bunch shaping and associated diagnostics

## X-band Photogun

- Characterized parameters of Xgun, include:
  - High gradient ~400 MV/m
  - Beam energy 2.7 MeV
  - Good robustness. No noticeable BDs after fully conditioning.
- Fundamental cathode studies have been done:
  - Schottky studies at different gradients have been performed.
  - Benchmarking of experimental data to ASTRA simualtions.
  - Studies on FE and MP issues through simulations underway.
- Future work:
  - New beam test in Fall 2024
  - New designs of the Xgun have been proposed in parallel



# BIG THANKS TO OUR TEAM!

Gongxiaohui Chen (AWA)
Scott Doran (AWA)
Alex Ody (AWA)
Wanming Liu (AWA)
John Power (AWA)
Charles Whiteford (AWA)
Eric Wisniewski (AWA)
Gwanghui Ha (was at AWA, now at NIU)
Jiahang Shao (was at AWA, now at IASF)
Maomao Peng (was at AWA)

Chunguang Jing (Euclid Techlabs / AWA)
Ernie Knight (Euclid Techlabs)
Sergey Kuzikov (Euclid Techlabs)
Ben Freemire (Euclid Techlabs)
Sergey Antipov (Euclid Techlabs, now at PALM Scientific)

Xueying Lu (NIU / AWA)
Philippe Piot (NIU / AWA)
Emily Frame (NIU)
Wei Hou Tan (NIU, now at SLAC)
Sarah Weatherly (IIT)

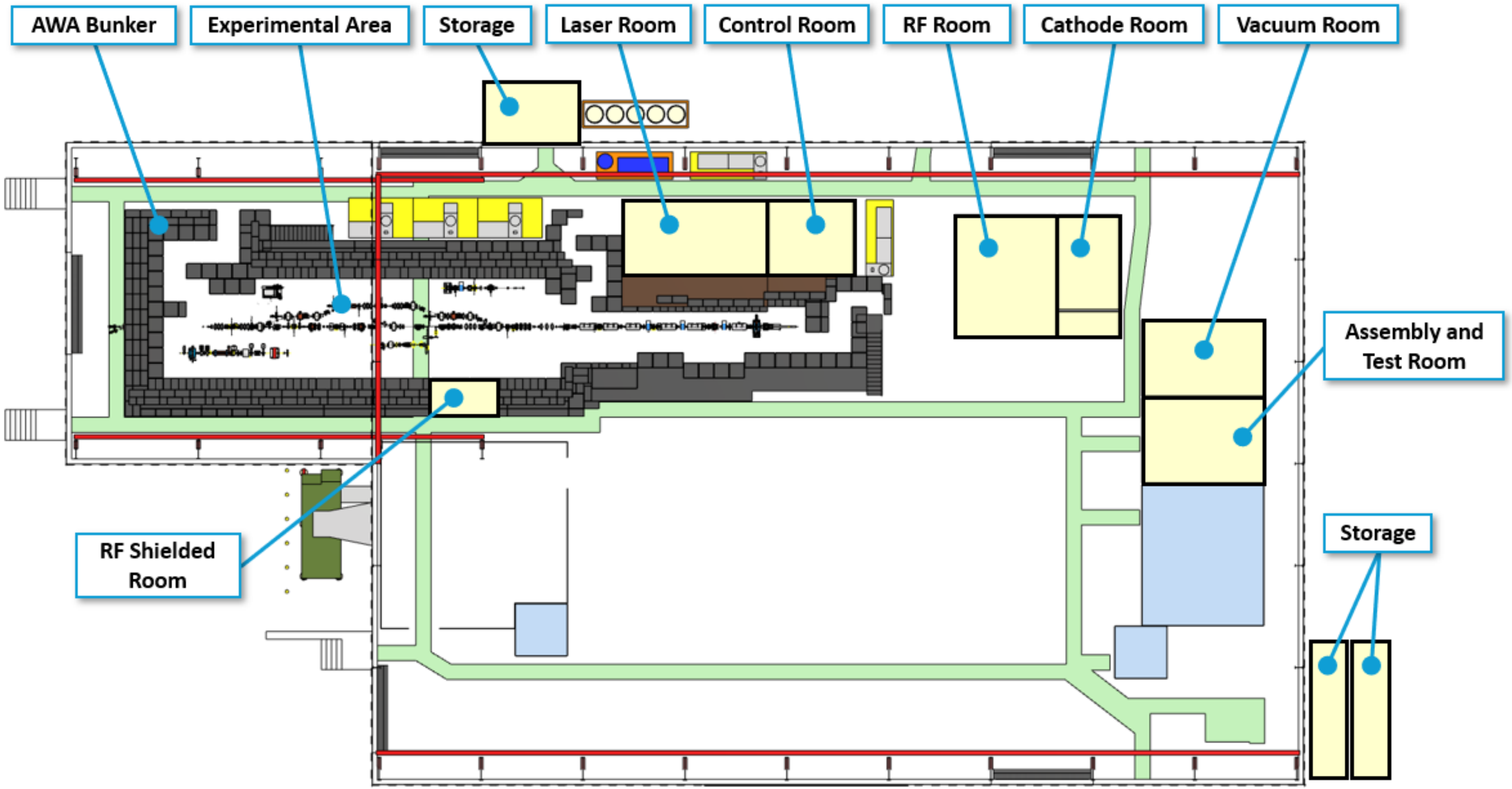
We also thank funding agencies: DoE HEP and SBIR programs and ANL LDRD.

# extras

# The AWA facility

https://www.anl.gov/awa

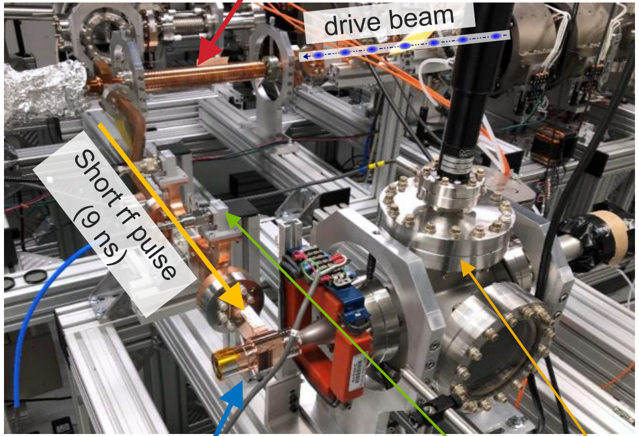
## *65 MeV L-band photoinjector linac, 40 m long bunker, Support areas*



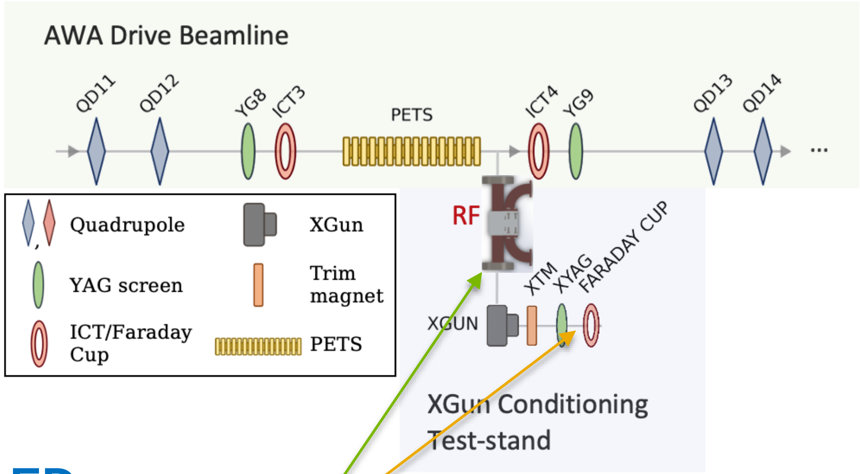
# EXPERIMENT #1: high-power rf conditioning

## Experimental setup at AWA (Dec, 2020: 1 week run)

PETS [1]




Xgun [2]




**INSTALLED DIAGNOSTICS**

YAG screen + Faraday cup

Bi-directional coupler

**[1] M. Peng, et al., (IPAC 19)**
Generation of high power short rf pulses using an X-band metallic power extractor driven by high charge multi-bunch train
https://accelconf.web.cern.ch/ipac2019/papers/MOPRB069.pdf

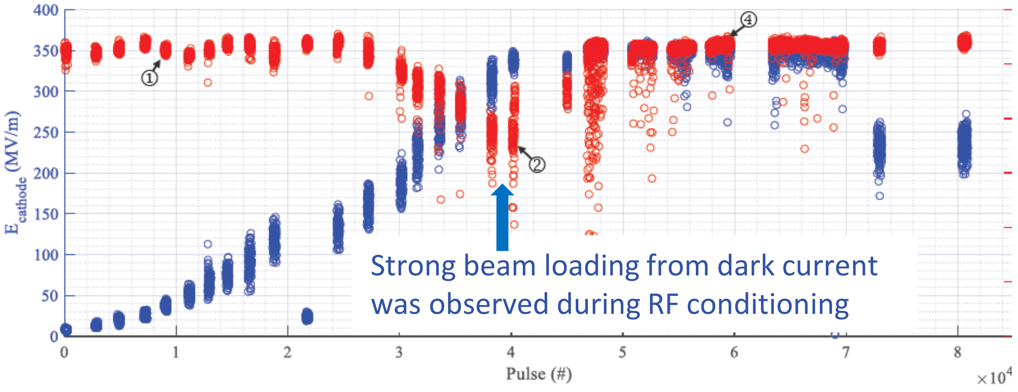
**[2] J. Shao, et al., (IPAC 21)**
High-power test of a highly over-coupled X-band rf Gun driven by short rf pulses
https://accelconf.web.cern.ch/ipac2021/papers/thpab331.pdf

Xgun only

# EXPERIMENT #1: high-power rf conditioning

## Experimental results (Dec, 2020: 1 week run)

### RF conditioning history of the Xgun





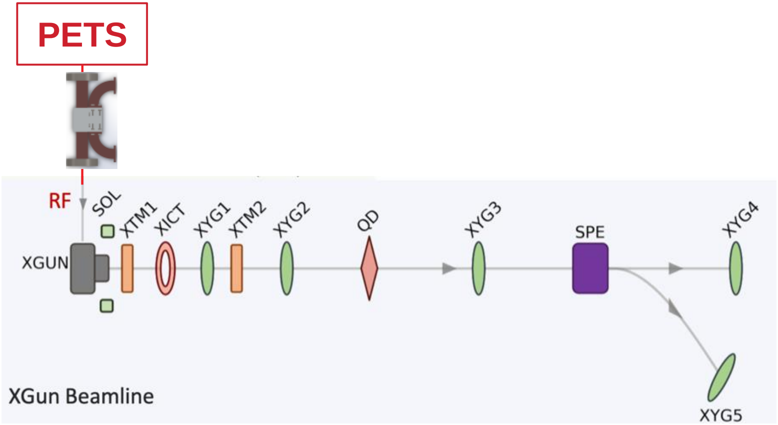
1. $E_{cathode}$ **350 MV/m** (inferred from measured P=250MW)
2. Low Breakdown Rate
3. RF conditioned fast (~70k pulse)
4. No detectable dark current (<1pC)

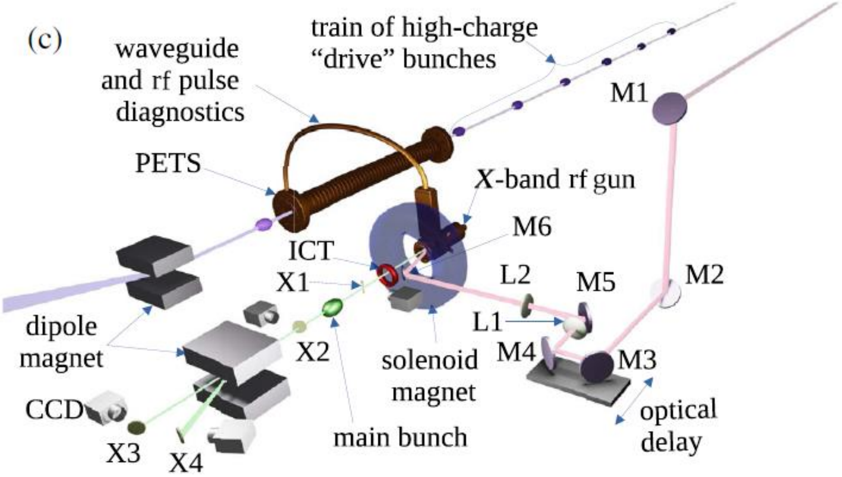
**J. Shao, et al., (IPAC 21)**
High-power test of a highly over-coupled X-band rf Gun driven by short rf pulses
https://accelconf.web.cern.ch/ipac2021/papers/thpab331.pdf

# EXPERIMENT #2: first beam measurements

Xgun only

## Experimental setup at AWA (Nov 2021: 3 week run)




Additions to Exp't #1

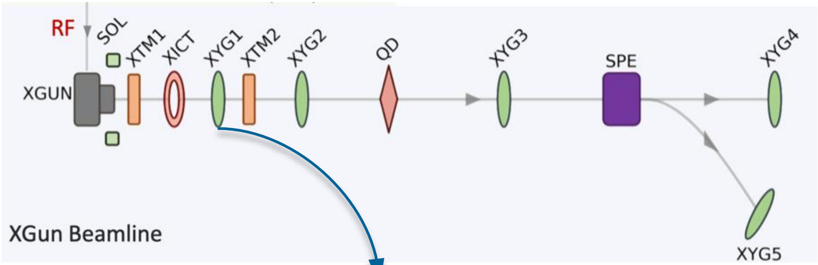
1. Installed a complete beamline w/ spectrometer installed for energy measurements
2. Added UV laser injection for e- beam generation

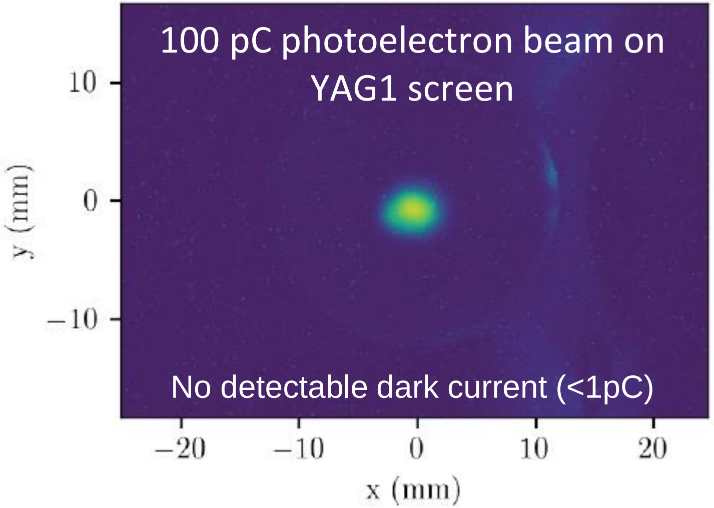
**W.H.Tan et. al., PRAB 2022**
Demonstration of sub-GV=m accelerating field in a photoemission electron gun powered by nanosecond X-band radio-frequency pulses
Phys. Rev. Accel. Beams 25, 083402, August 2022 (2022)

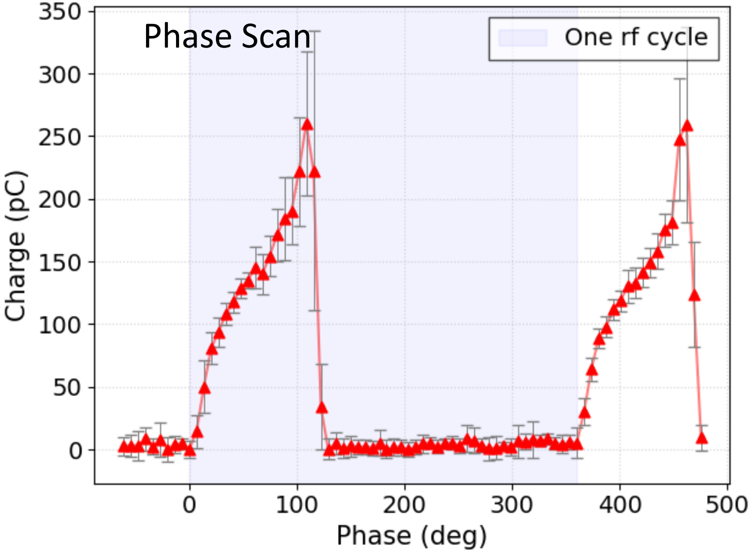
# EXPERIMENT #2: first beam measurements

Xgun only

## Results 1: first electron beam from Xgun (Nov 2021: 3 week run)



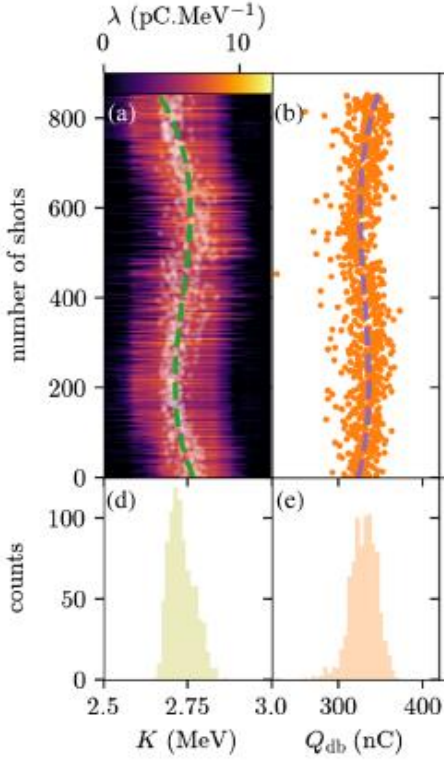




- Xgun phase scan @**340 MV/m**
- Evidence of strong Schottky effect

# EXPERIMENT #2: first beam measurements

Xgun only

## Results 2: energy and gradient (Nov 2021: 3 week run)




**Gradient confirmed**

- Gradient inferred from FR power was beam energy measurement
- Max achieved gradient = 388 MV/m from the beam energy measurement

**Stable beam produced**

- Jitter due to drive beam charge jitter due to laser energy jitter
- Energy fluctuation ~3%, likely due to the drive charge instability due to laser instability

**Low breakdown rate confirmed**

- ~500,000 shots gives a conservative upper limit for the BDR $<10^{-5}$

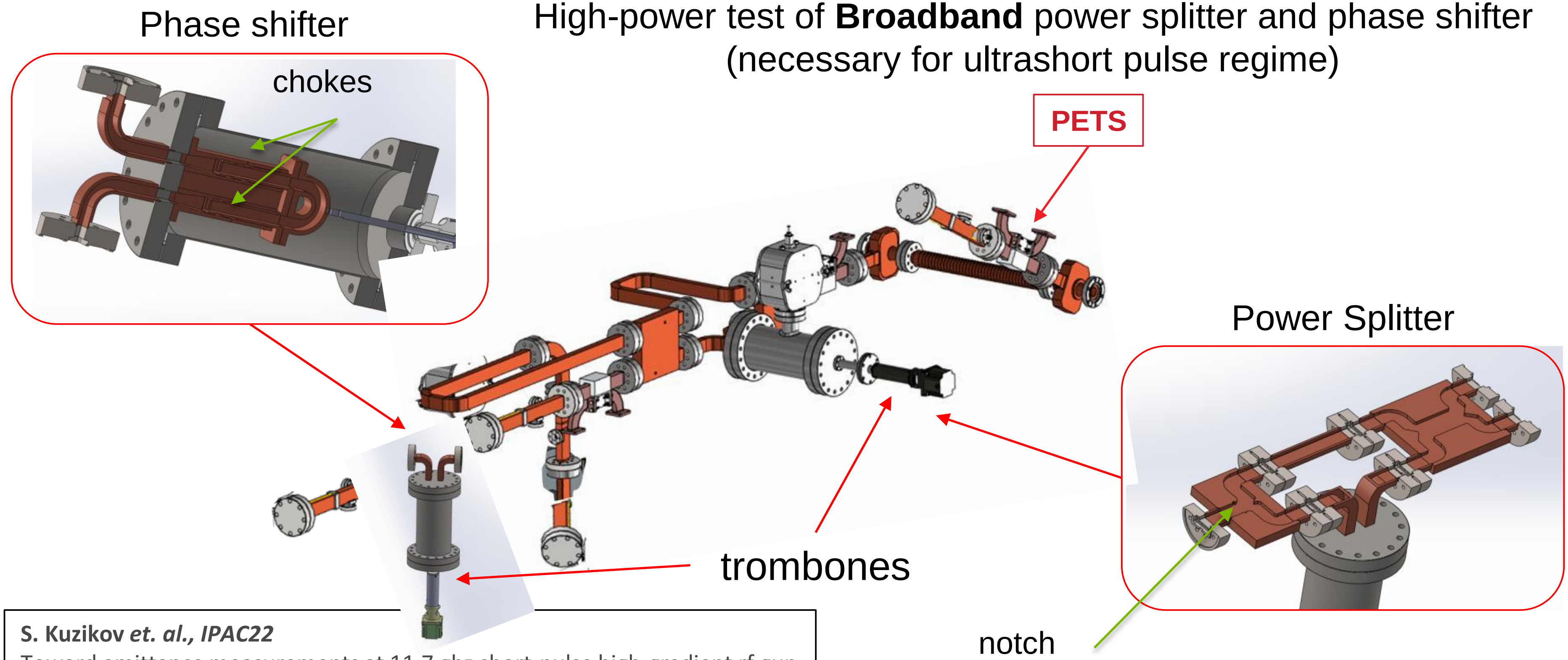
**Low dark current**

- No detectable dark current (<1pC)

# EXPERIMENT #3:Power splitter and phase shifter test

## Setup & design (2-day run, April 2022)

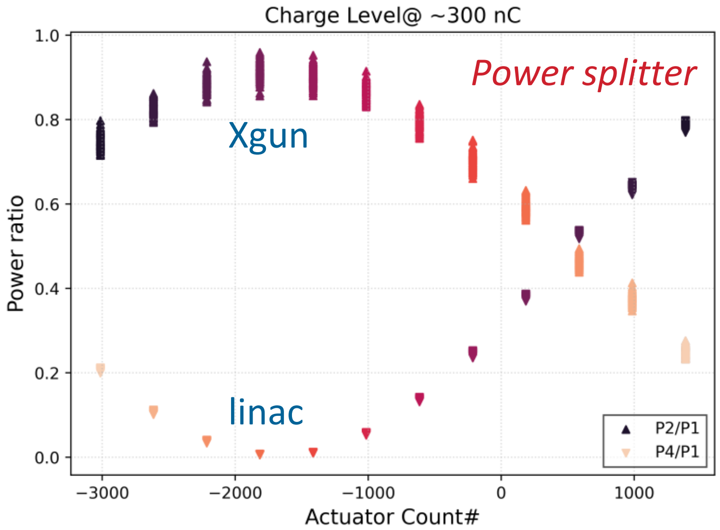
High-power test of **Broadband** power splitter and phase shifter (necessary for ultrashort pulse regime)

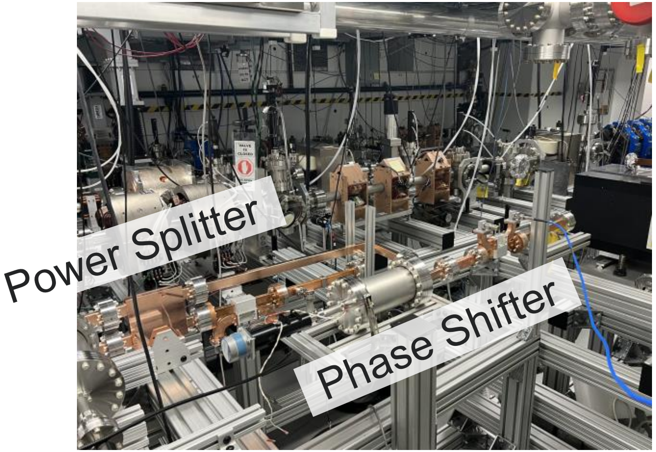


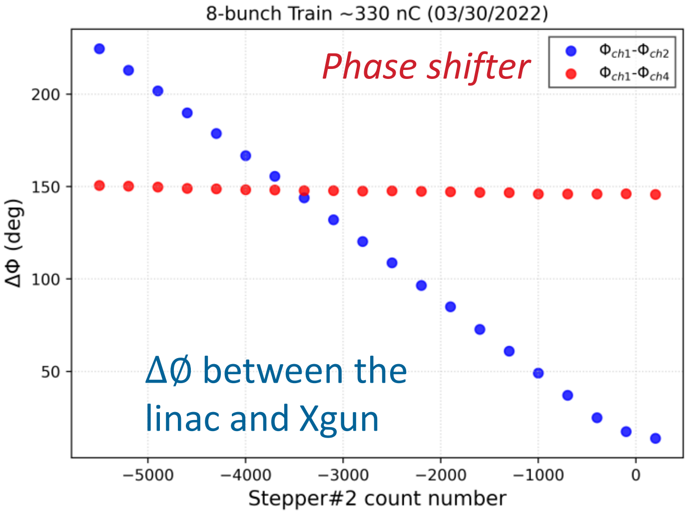

**S. Kuzikov *et. al., IPAC22***
Toward emittance measurements at 11.7 ghz short-pulse high-gradient rf gun
https://accelconf.web.cern.ch/ipac2022/papers/MOPOMS013.pdf

# EXPERIMENT #3: Power splitter and phase shifter test

## Results (2-day run, April 2022)



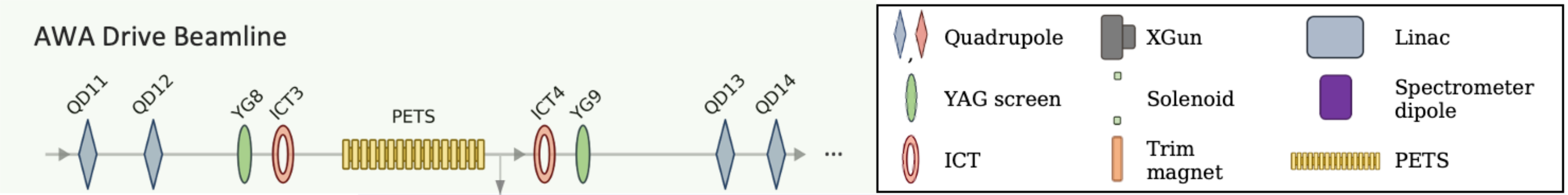




- PETS = 400 MW
- Both components conditioned to >200 MW
- Power splitter (power level): 0-100% power variation
- Phase shifter: >180 deg phase shift

# EXPERIMENT #4: second beam measurements

Xgun, linac, waveguide

## Setup: add a linac and extended the beamline (3-weeks, June 2022)



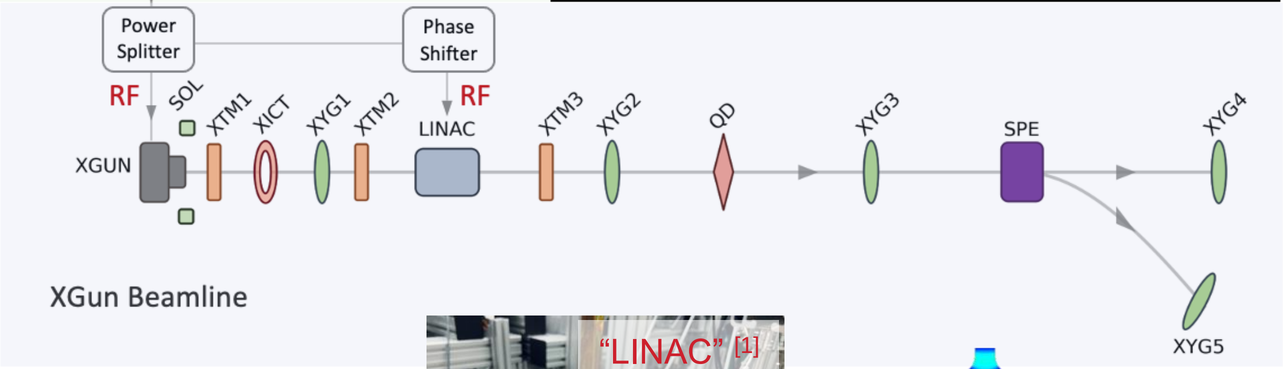
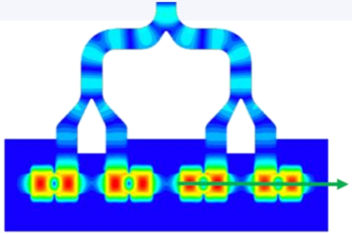




Table 1: List of the operating parameters

| Parameter | Value | Unit |
|---|---|---|
| Laser $\sigma_x$ | 0.189 | mm |
| Laser $\sigma_y$ | 0.234 | mm |
| Laser bunch length (FWHM) | 300 | fs |
| Xgun peak E-field | 280.0±3 | MV/m |
| Xgun phase [1] | 31.8 | degree |
| Bunch charge | 44.9±10 | pC |
| Solenoid B-field | 0.202 | T |
| Linac peak field | 86.9±2 | MV/m |

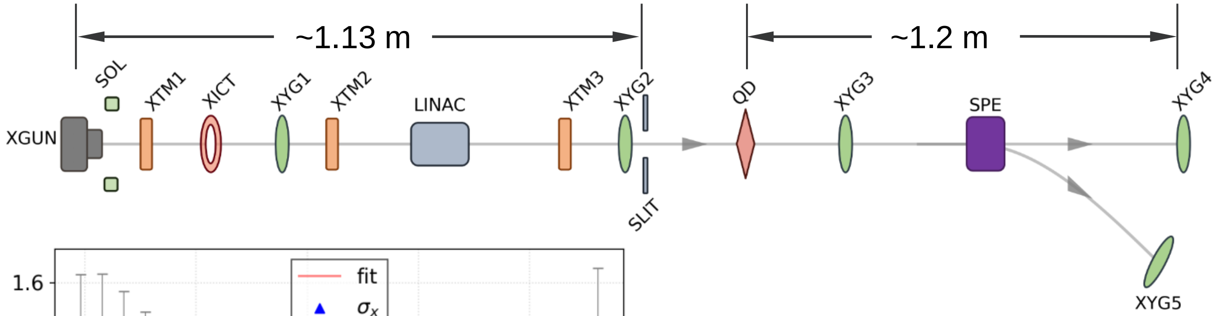



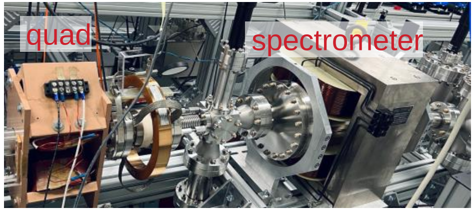
**G. Chen *et. al., NAPACC22***
Emittance measurements and simulations from an x-band short-pulse ultra-high gradient photoinjector
https://epaper.kek.jp/napac2022/papers/moze3.pdf

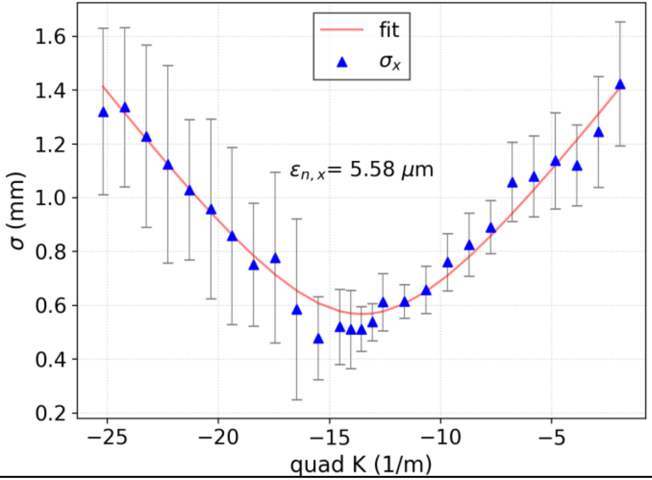
# EXPERIMENT #4: second beam measurements

Xgun, linac, waveguide

## Results: Energy gain with linac demonstrated (i.e. staging!)




- First attempted emittance measurement (beamline not optimized)
  - $\varepsilon_{n,x} = 5.58\ \mu m$
  - $\varepsilon_{n,y} = 11.26\ \mu m$ (due to geometry asymmetry of the linac)
  - Kinetic energy: 5.9 MeV
- Breakdowns observed

?

**G. Chen *et. al.*, *NAPACC22***
Emittance measurements and simulations from an x-band short-pulse ultra-high gradient photoinjector
https://epaper.kek.jp/napac2022/papers/moze3.pdf

# EXPERIMENT #4: second beam measurements

## Results: Why is measured $\varepsilon$ high? And what next?

**Issues in the 1st $\varepsilon$ measurement:**

1. Non-ideal LINAC geometry
   - New LINAC design is proposed
2. Non-ideal solenoid
   - New solenoid design is under review
3. Unknown BDs happened randomly and prevent us reaching to a higher optimized gradient
   - *Has Xgun has been damaged? (We suspect bad vacuum due to clamped linac.)*

**Conclusion:** pause program to understand breakdown

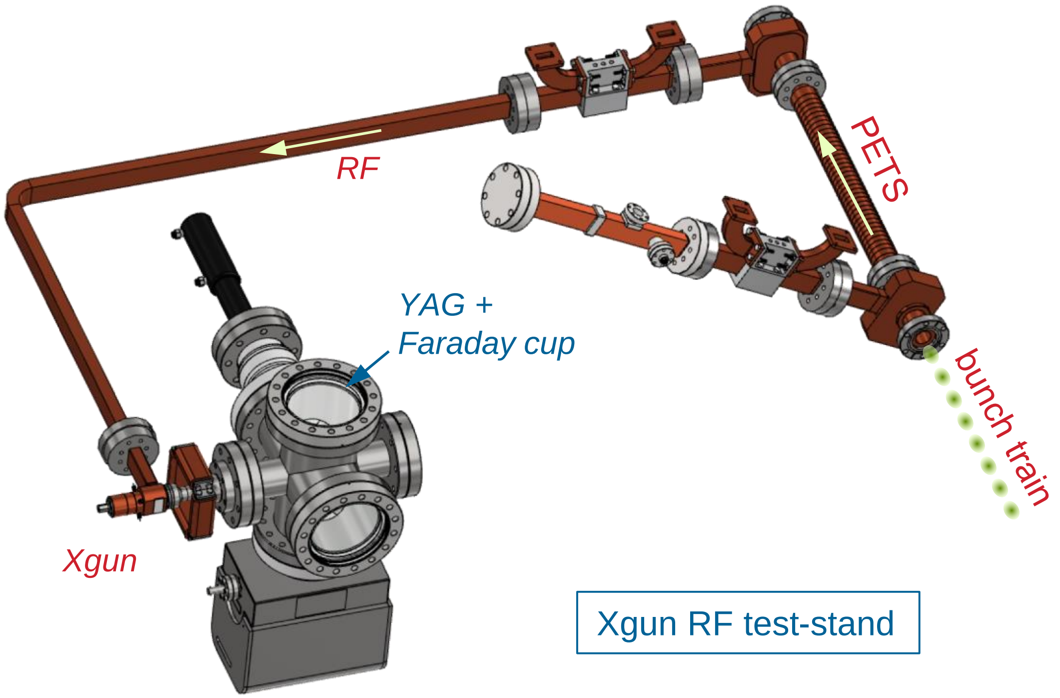
1. Vent the beamline and inspection Xgun
2. Reinstall Xgun without linac and with RF components
3. Add pumping

# EXPERIMENT #5: Second high-power rf conditioning

## Setup at AWA (Oct 2022: 2-day run)

Xgun alone

- without linac
- without phase shifter
- without power splitter

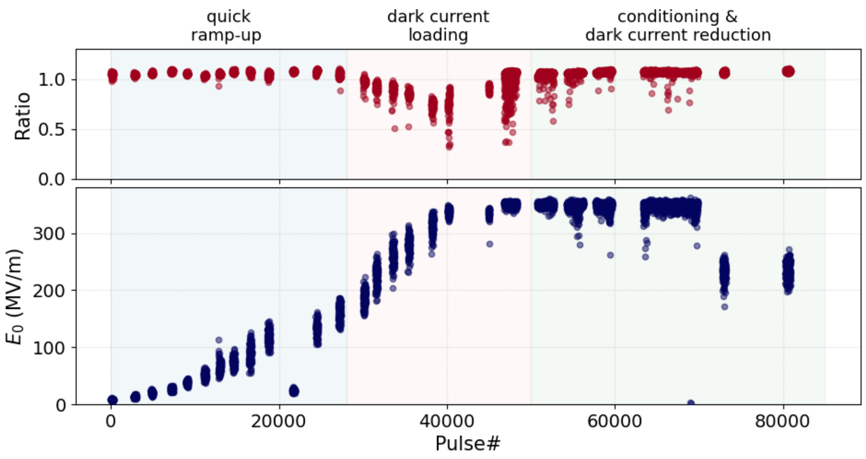



Xgun RF test-stand

# EXPERIMENT #5: Second high-power rf conditioning

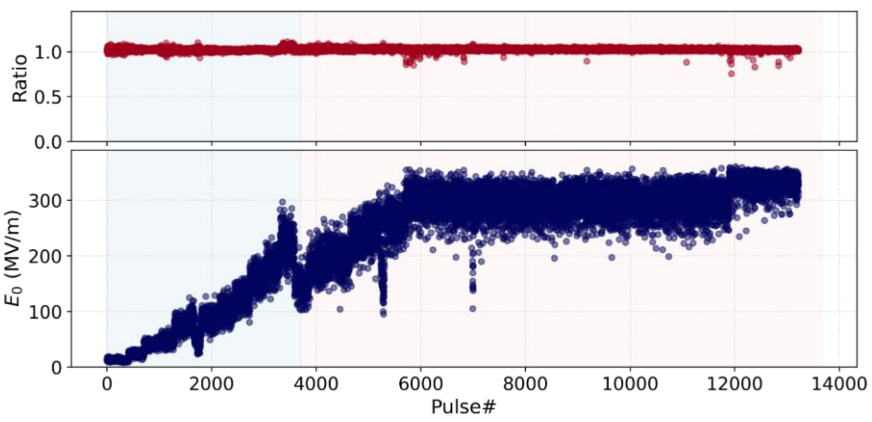
## Result: Xgun has no damage, immediately back to ~350MV/m

### 1st Xgun conditioning (Dec. 2020)




- Conditioning process is quick.
- A dark current loading region observed (~40,000)

### 2nd Xgun conditioning (Oct. 2022)




- The Xgun fully conditioned very smoothly. No damage
- Did not observe dark-current

# NEW XGUN DESIGN

## 1.5 cell gun with removeable cathode

New Xgun is designed by Sergey Kuzikov and Ernie Knight at Euclid TechLabs.