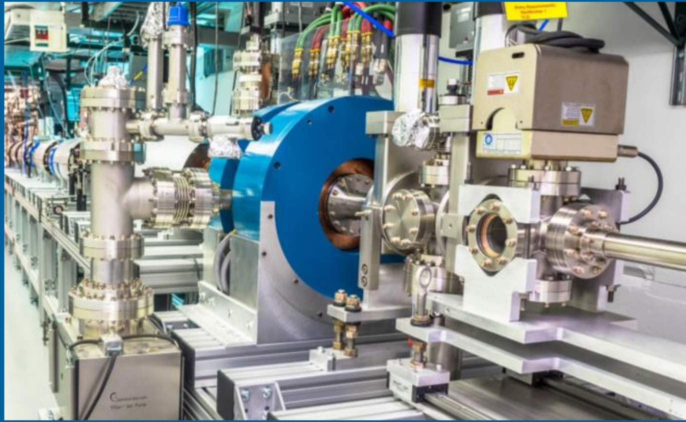
Argonne NATIONAL LABORATORY

nicadd Northern Illinois Center for Accelerator and Detector Development NIU

euclid TECHLABS

Physics and Applications of High Brightness Beam
San Sebastian, Spain - June 19-23, 2023

Advances in sub-GV/m X-band Photocathode Gun at the Argonne Wakefield Accelerator Facility



JOHN POWER

ON BEHALF OF
AWA, EUCLID, and NIU

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

https://www.anl.gov/awa

MY GOAL TODAY…

*is to help you understand the **sub-GV/m injector program** at the Argonne Wakefield Accelerator.*

- **Why?** → A high brightness electron source
- **What approach?** → short-pulse & two-beam acceleration
- **Where?** → Argonne Wakefield Accelerator Facility
- **Details?** → Progress so far on Xgun
- **Plans?** → Next steps

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TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

short-pulse and TBA

4D beam brightness

High Gradient R&D

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

Cathode R&D

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]

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

TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

short-pulse and TBA

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

High Gradient R&D

R&D: cryo, hard metals, geometry, **short-pulse**, …

HG2023 workshop (https://agenda.infn.it/event/34253/)

Do guns benefit from high gradient?

- High gradient helps with space charge but may amplify surface imperfections.

Cathode R&D

Materials, surface characteristics, laser properties, …

P3 2021 workshop (https://conf.slac.stanford.edu/photocathode-physics-photoinjectors-2021/)
EWPAA 2022 workshop (https://agenda.infn.it/event/29956/)

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short-pulse and TBA

High Gradient R&D

R&D: cryo, hard metals, geometry, **short-pulse**, …

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

Limits to high gradient operation:

1. RF Breakdown ← main problem
2. Field emission/dark current (unwanted beam loading and ionizing radiation can blind beam diagnostics, etc.)
3. Excessive conditioning time

TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

short-pulse and TBA

4D beam brightness

High Gradient R&D

R&D: cryo, hard metals, geometry, **short-pulse**, …

HG2023 workshop (https://agenda.infn.it/event/34253/)

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

State of the art high gradient limits

Structure (most understood):

- X-band, 100<*pulse length*<1000 ns, Normal conducting at room temp, OFE Copper BDR = 1e−6 m^{-1}

RF Breakdown guidelines

- Gradient: E_{surf} < 250 MV/m,
- Pulse heating: ΔT < 50 ^{0}C,
- Power: abs(Sc) < 5 MW/mm^2
- Stored Energy: U < 1 J

Simakov, Dolgashev, Tantawi, "Advances in high gradient normal conducting accelerator structures, NIMA, Volume 907, 2018, https://doi.org/10.1016/j.nima.2018.02.085

TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

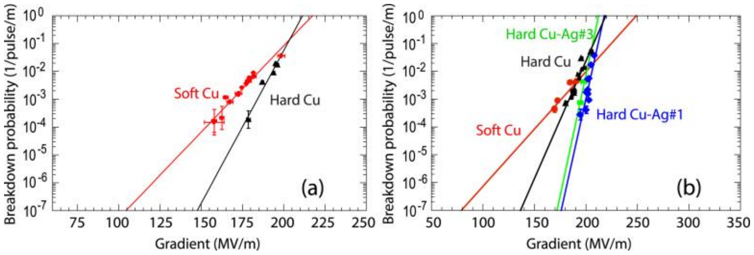
short-pulse and TBA

High Gradient R&D

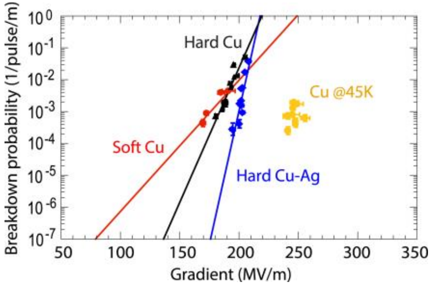
$$B \propto \frac{E^{\alpha}}{MTE}$$

R&D

3 promising paths to higher gradients



1 Material: **Hard** bi-metallic alloy (SLAC: Cu:Ag 0.8% Ag)



2 Temperature: **cryogenic** temp (SLAC/UCLA/LANL: cold copper)

TWO PATHS TO HIGH BRIGHTNESS e- SOURCES

short-pulse and TBA

High Gradient R&D

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

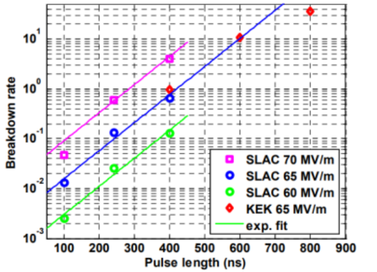
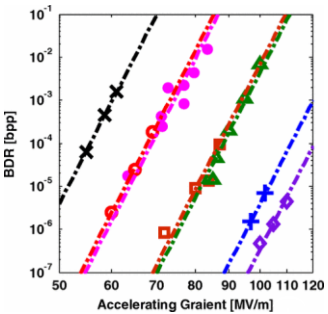


Figure 4: Pulse length dependence of the breakdown rate.



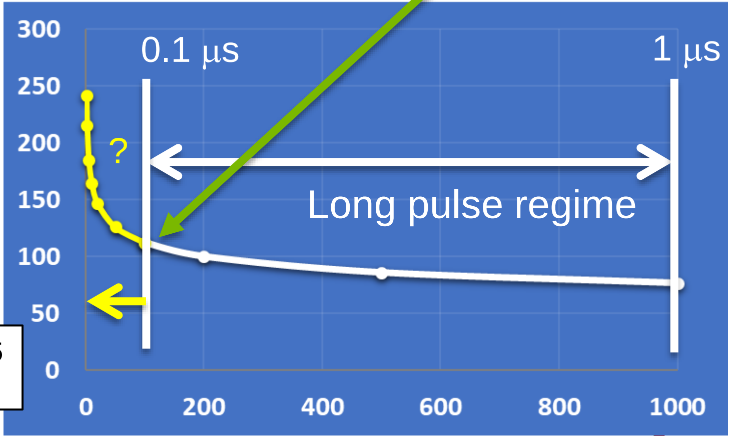
R&D

3 promising paths to higher gradients

Scaling Law

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

3e−7/m, 100 MV/m, 200ns



3 Pulse length < 100 nsec
Tsinghua: Short ~50 nsec
AWA/Euclid/NIU: Ultrashort =9 nsec

New physics?
Empirical scaling law, underlying mechanism may change

H. H. Braun, et al., “*High-power testing of 30 ghz accelerating Structures at CTF II*”, CLIC Note 475
W. Wuensch, et al., “*A demonstration of high-gradient acceleration*”, PAC’03

KLYSTRON-BASED XFEL

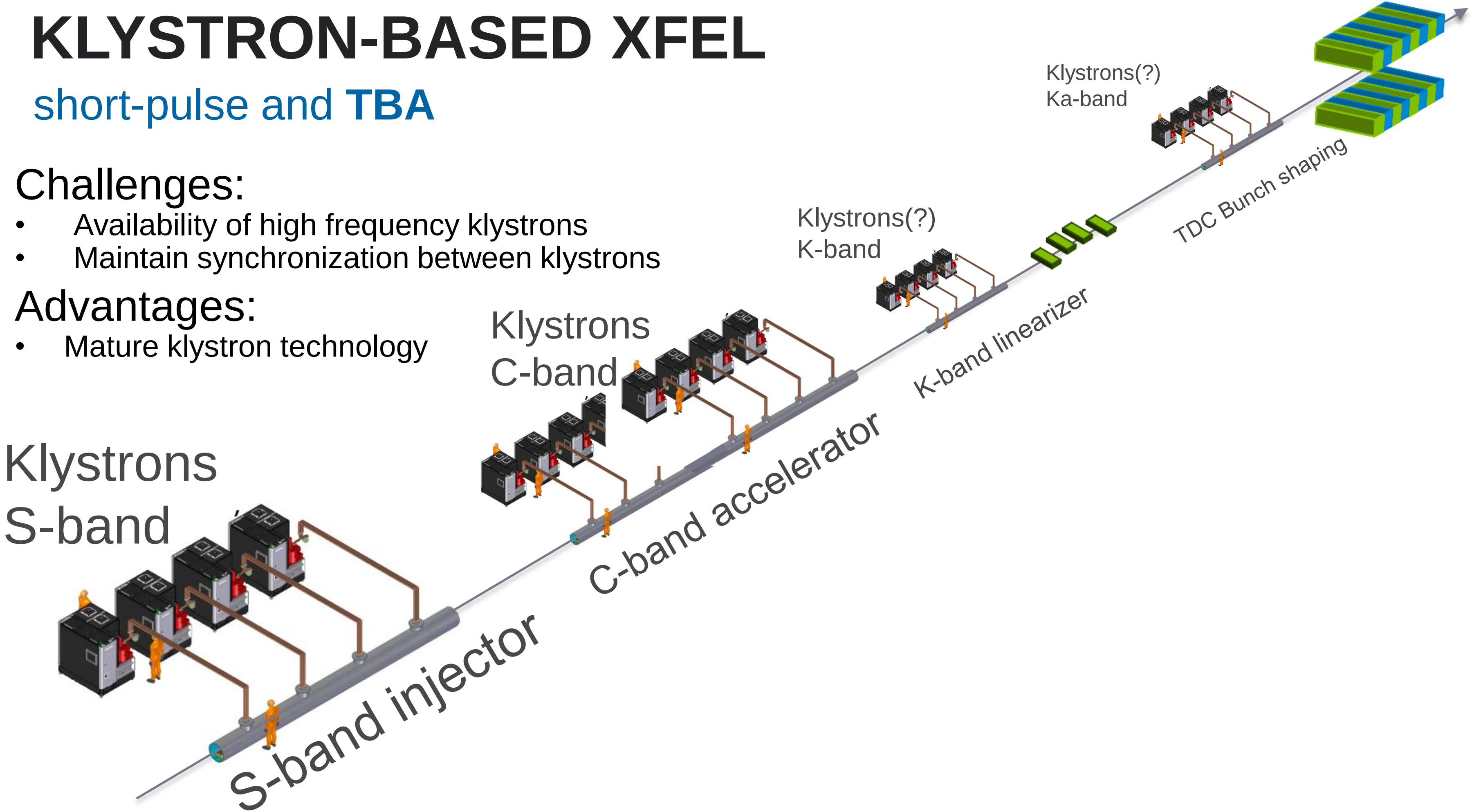
short-pulse and **TBA**

Challenges:

- Availability of high frequency klystrons
- Maintain synchronization between klystrons

Advantages:

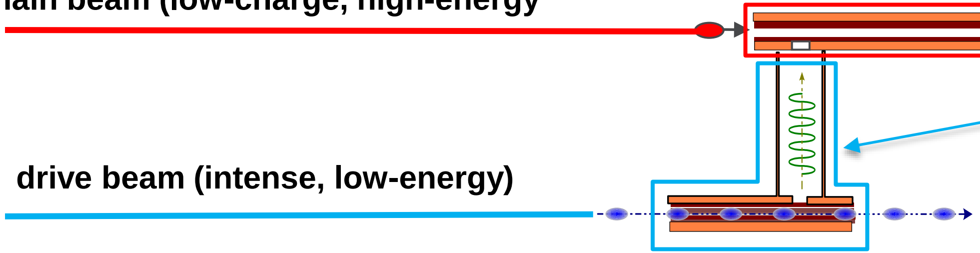
- Mature klystron technology



Electron beam-driven structure wakefield acceleration (SWFA)

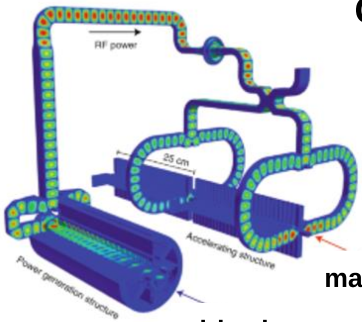
Two Beam Acceleration (TBA)

Argonne NATIONAL LABORATORY



1. **D.B. Hopkins, A.M. Sessler, J.S. Wurtele**, NIMA: (1984) https://doi.org/10.1016/0168-9002(84)90004-4.
2. **CLIC CDR**: https://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
3. **W. Gai, C. Jing, J.G. Power**, *JPP* **78**, 339-345 (2012)

CLIC



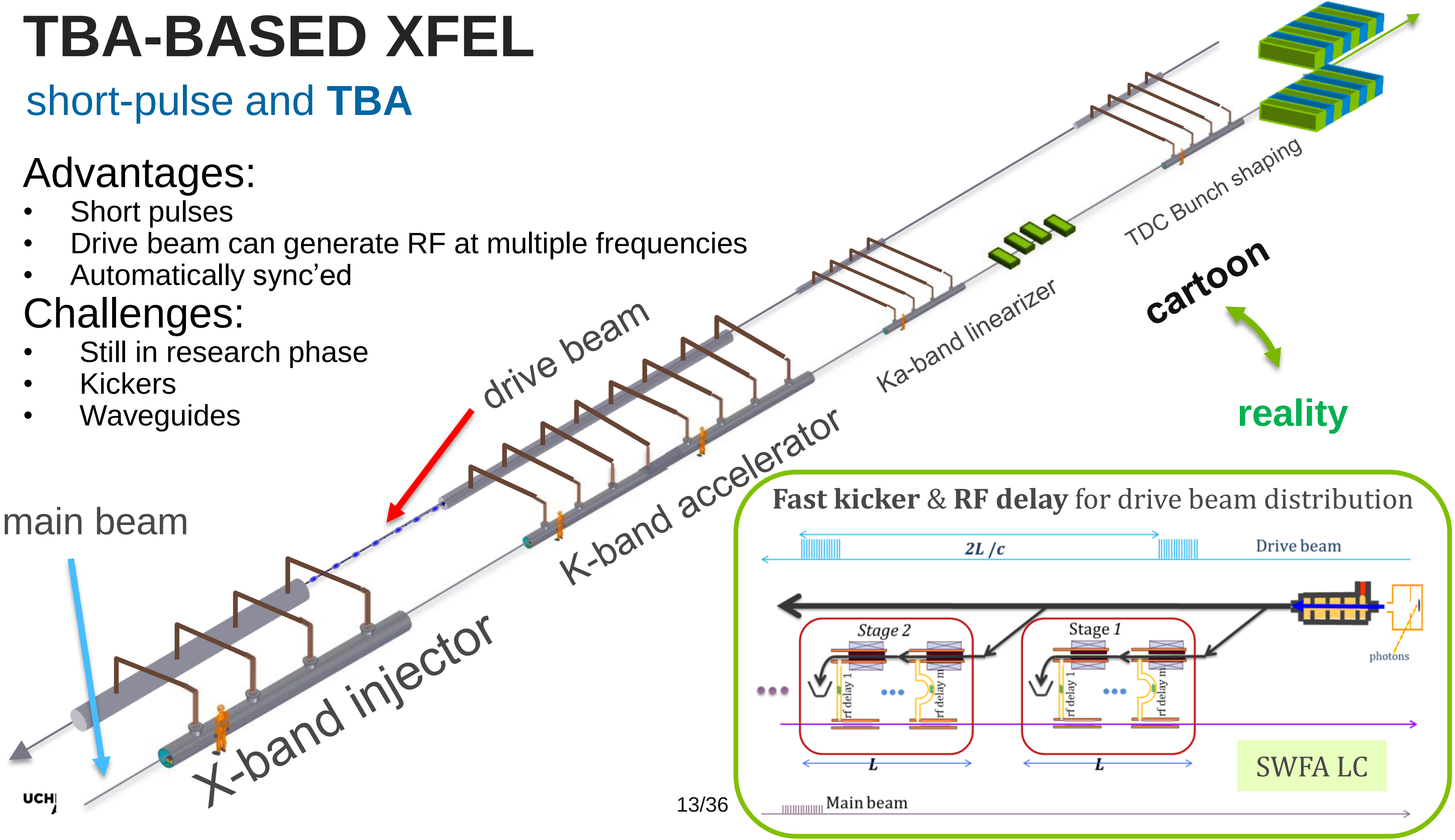
Sicking, E., Ström, R. From precision physics to the energy frontier with the Compact Linear Collider. *Nat. Phys.* **16**, 386–392 (2020). https://doi.org/10.1038/s41567-020-0834-8

TBA-BASED XFEL

short-pulse and **TBA**

Advantages:
- Short pulses
- Drive beam can generate RF at multiple frequencies
- Automatically sync'ed

Challenges:
- Still in research phase
- Kickers
- Waveguides



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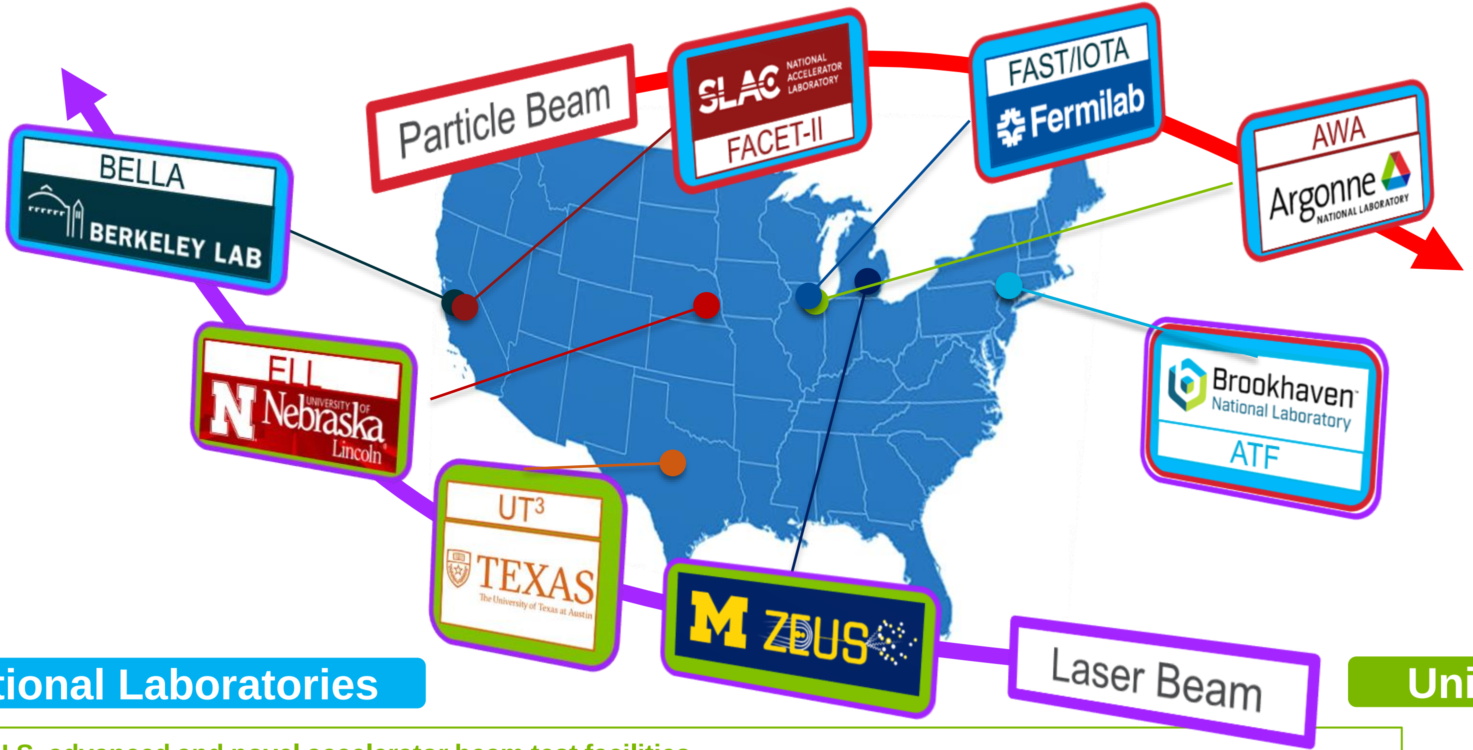
USA BEAM TEST FACILITIES

Demonstrating the viability of emerging accelerator science ultimately relies on experimental validation.



National Laboratories

Universities

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]

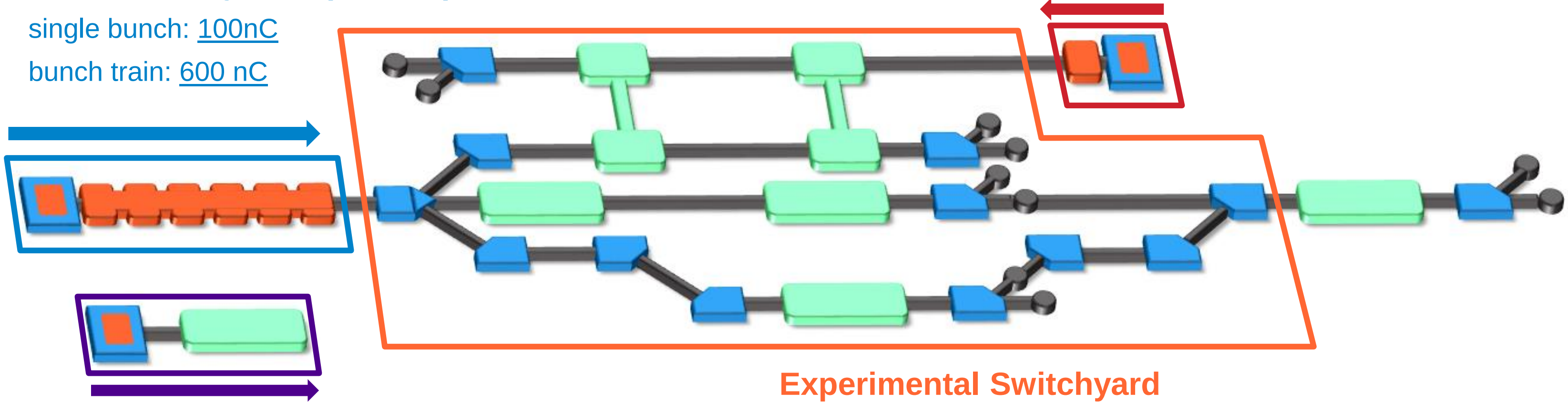
THE AWA FACILITY

https://www.anl.gov/awa

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



Experimental Switchyard
- Highly reconfigurable
- 6D phase space manipulation

Argonne Cathode Test Stand (2-4 MeV)
- Cathode research and diagnostics
- Physics of high-gradient breakdown

Laser
- <100 mJ (IR), 10 mJ (UV),
- >300 fs (nominal)
- temporal shaping

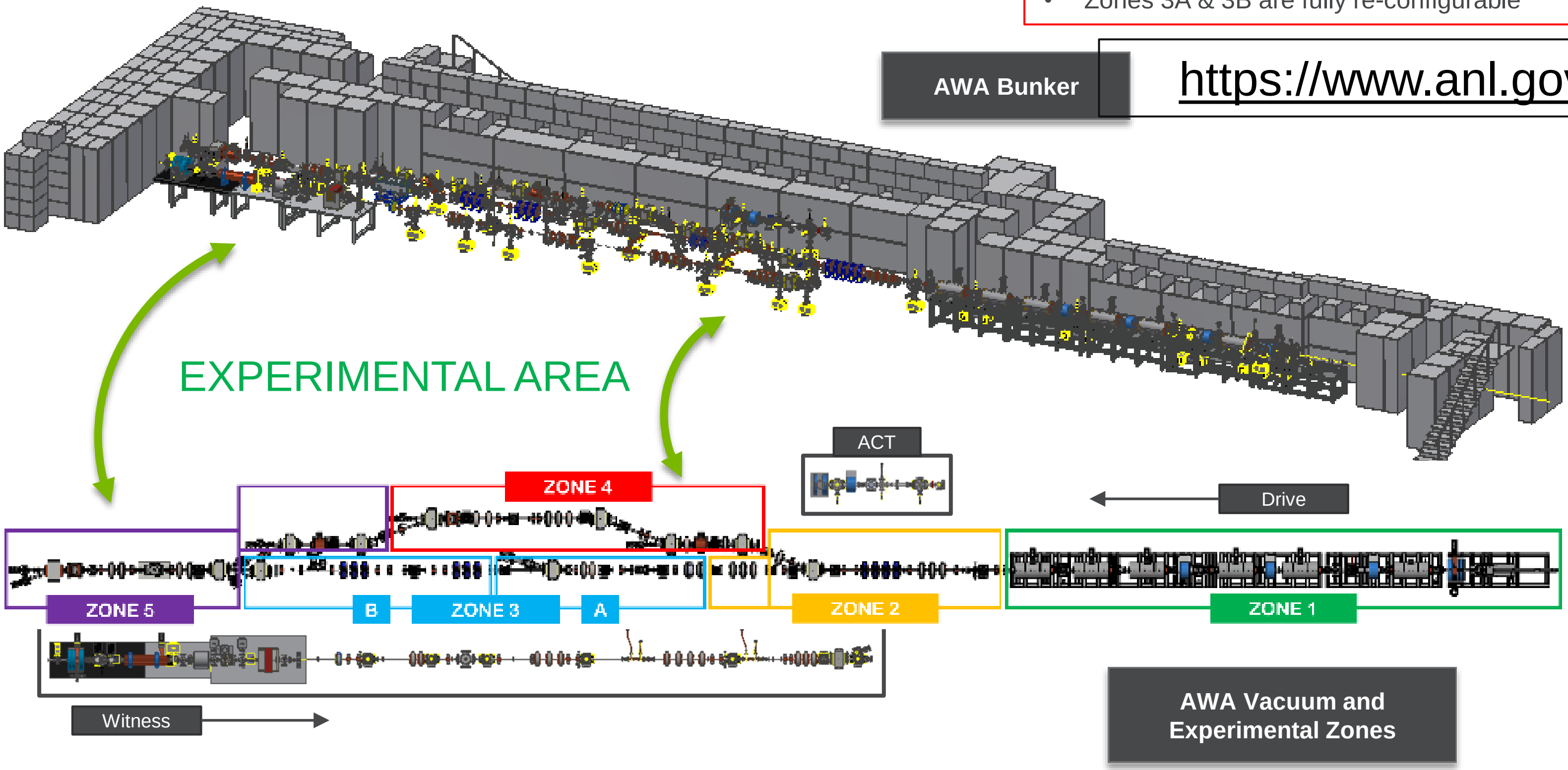
THE ARGONNE WAKEFIELD ACCELERATOR

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



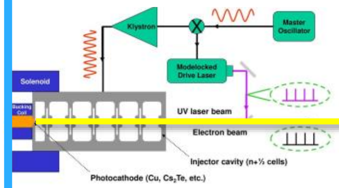
THE ARGONNE WAKEFIELD ACCELERATOR

https://www.anl.gov/awa

AWA SCIENCE: themes

THEME 3
Beam Production

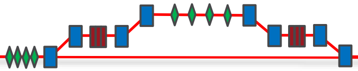
e.g. RF Photoinjector



- Electron sources
  - High-brightness
  - High-intensity

THEME 2
Beam Manipulation

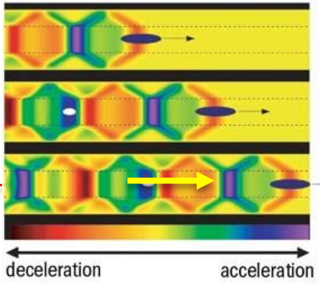
e.g. Double Emittance Exchange



- Beam shaping & control.
- Beam Diagnostics.

THEME 1
Advanced Accelerator

e.g. SWFA



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

APPLICATION

Thurs, 15:45-16:05, Seongyeol Kim. Update on Electron Beam Manipulation at the Argonne Wakefield Accelerator Facility.

Tues, 16:00-16:20, Juan Pablo Gonzalez-Aguilera. Detailed Phase Space Reconstruction from a Limited Number of Beam Measurements Using Neural Networks and Differentiable Simulations.

Tues, 16:00-16:20, Walter Lynn. Transverse stability in an alternating gradient planar-symmetric dielectric wakefield structure.

Tuesday Posters, Emily Frame.

1. Parametric study of high-charge bunch generation in an L-band photoinjector
2. A high-field X-band photoinjector for low-emittance electron-beam generation
3. Opportunities for Bright-Beam Generation at the Argonne Wakefield Accelerator

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is to help you understand the **sub-GV/m injector** program at the Argonne Wakefield Accelerator.

- **What?** → A high brightness electron source based on a **short-pulse** and **TBA** injector
- Why? → It's high-gradient AND simple & synch'ed
- Where? → Argonne Wakefield Accelerator Facility
- **Details?** → Progress so far on Xgun
- Next? → Plans

Xgun EXPERIMENTAL PROGRAM

Brief overview over last 2 ½ years

[-] Xgun design

[1] RF conditioning: Xgun

[-] RF conditioning: Fgun, (clamped gun, breakdown limited)

[2] First beam measurements: Xgun

[3] RF conditioning: Power splitter/Phase Shifter

[4] Second beam measurement: Xgun and clamped linac

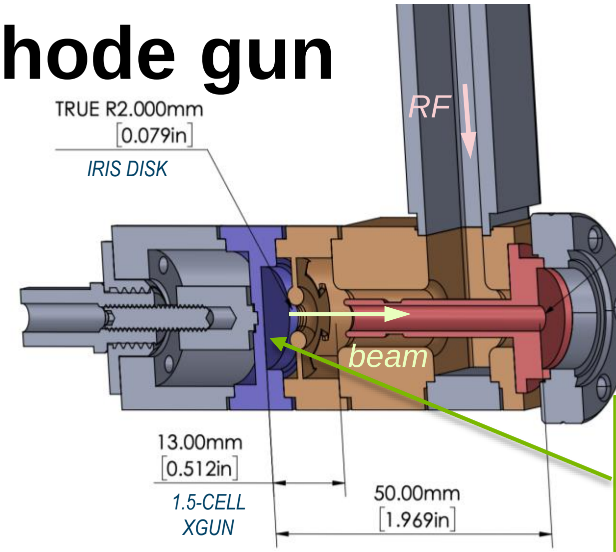
[5] RF conditioning II: Xgun

[-] (future work) Third beam measurement: Bgun

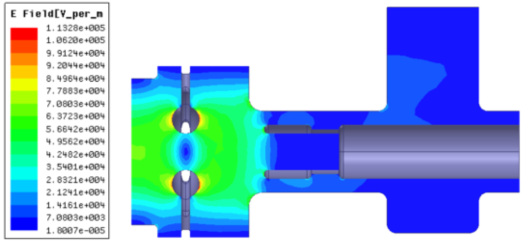
Xgun: 1.5 cell RF photocathode gun

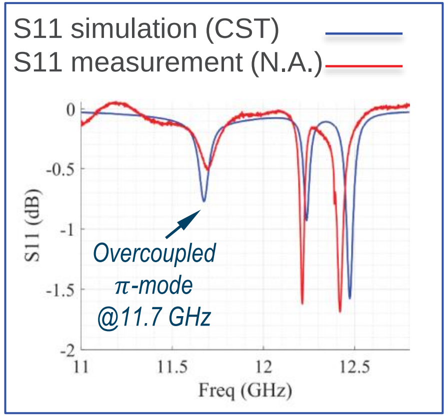
RF Design

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



Cathode is the Cu backwall



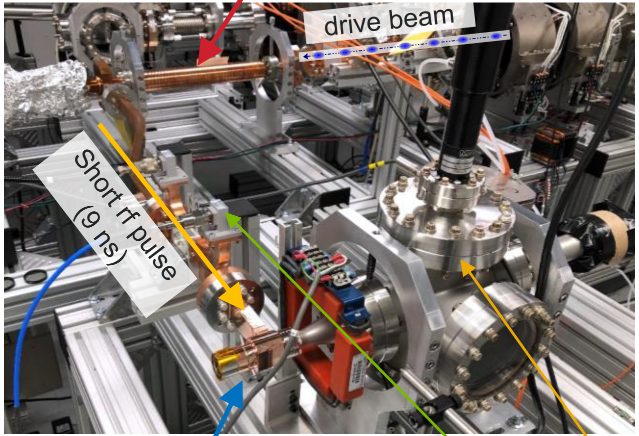


S. Kuzikov et al., (IPAC21)
An X-band Ultra-high Gradient Photoinjector
https://accelconf.web.cern.ch/ipac2021/papers/wepab163.pdf

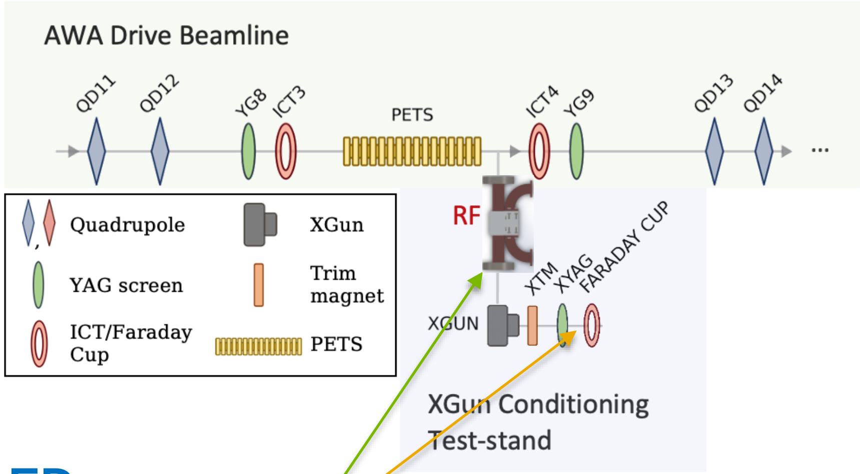
EXPERIMENT #1: high-power rf conditioning

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

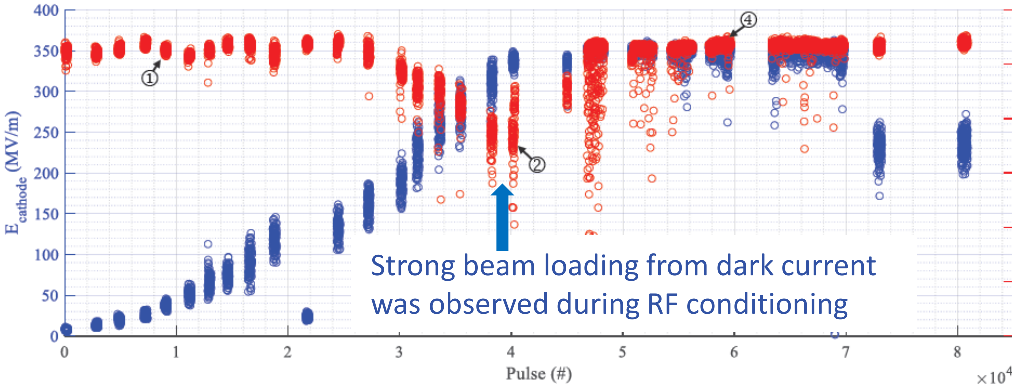
[2] J. Shao, et al., (IPAC 21)
High-power test of a highly over-coupled X-band rf Gun driven by short rf pulses
https://accelconf.web.cern.ch/ipac2021/papers/thpab331.pdf

EXPERIMENT #1: high-power rf conditioning

Xgun only

Experimental results (Dec, 2020: 1 week run)

RF conditioning history of the Xgun



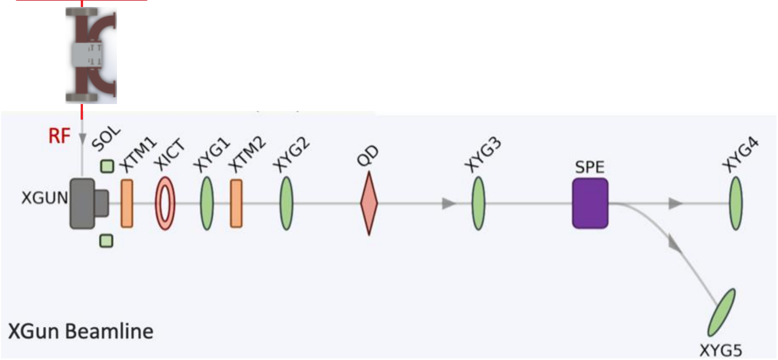
1. $E_{cathode}$ **350 MV/m** (inferred from measured P=180MW)
2. Low Breakdown Rate
3. RF conditioned fast (~70k pulse)
4. No detectable dark current (<1pC)

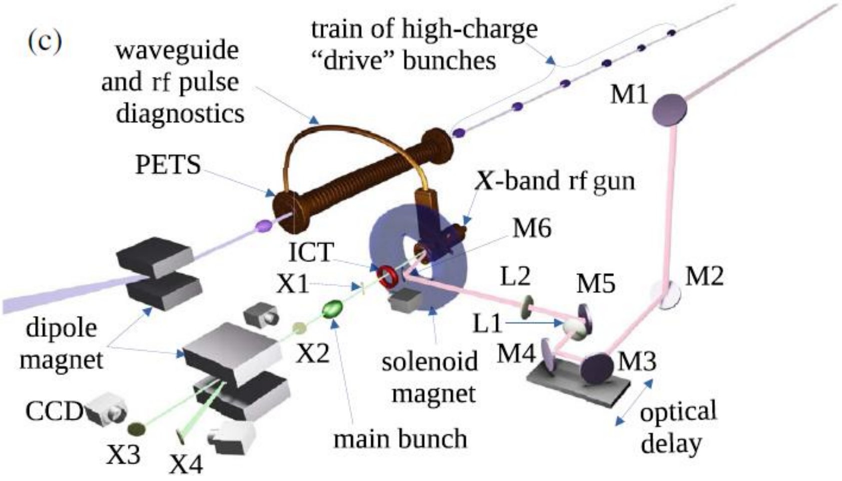
J. Shao, et al., (IPAC 21)
High-power test of a highly over-coupled X-band rf Gun driven by short rf pulses
https://accelconf.web.cern.ch/ipac2021/papers/thpab331.pdf

EXPERIMENT #2: first beam measurements

Xgun only

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





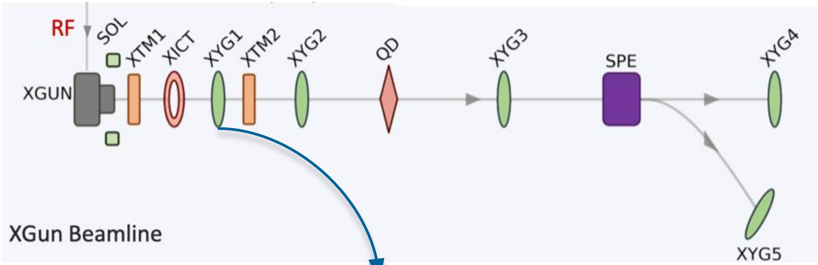
Additions to Exp't #1

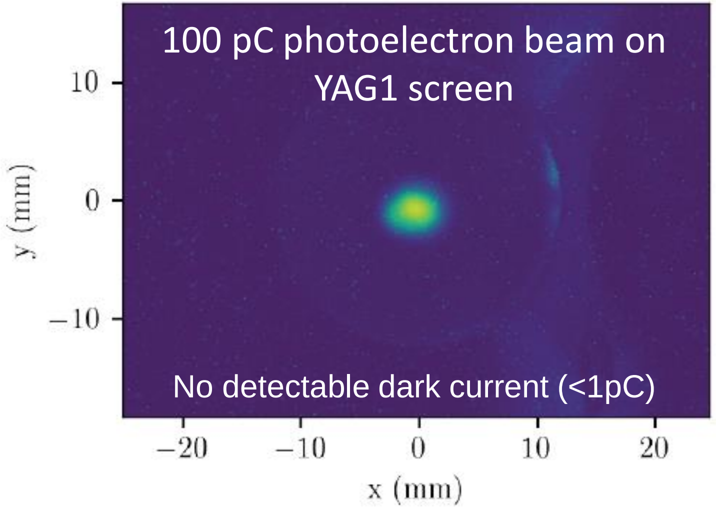
1. Installed a complete beamline w/ spectrometer installed for energy measurements
2. Added UV laser injection for e- beam generation

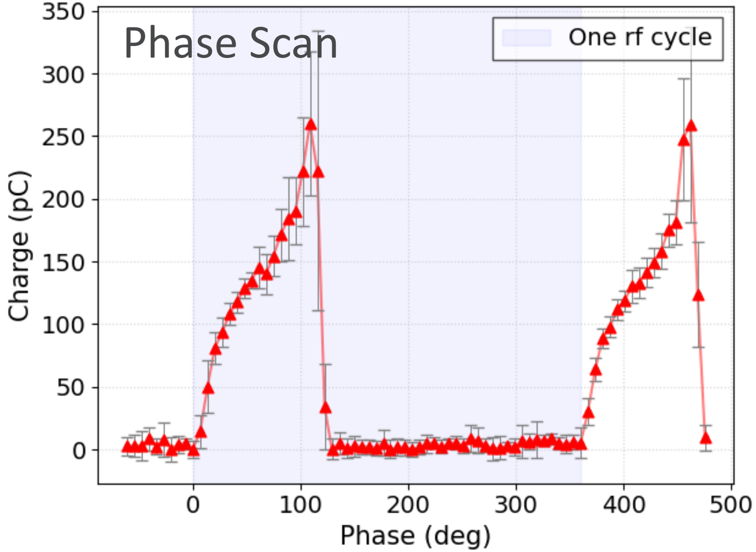
W.H.Tan et. al., PRAB 2022
Demonstration of sub-GV=m accelerating field in a photoemission electron gun powered by nanosecond X-band radio-frequency pulses
Phys. Rev. Accel. Beams 25, 083402, August 2022 (2022)

EXPERIMENT #2: first beam measurements

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





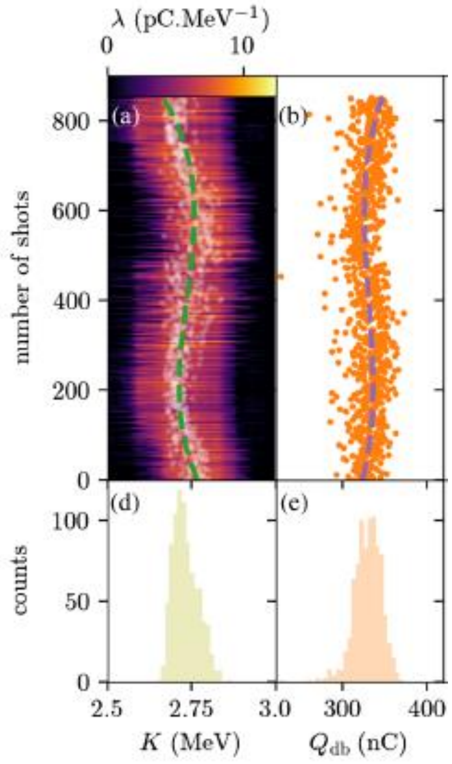


- Xgun phase scan @**340 MV/m**
- Evidence of strong Schottky effect

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}

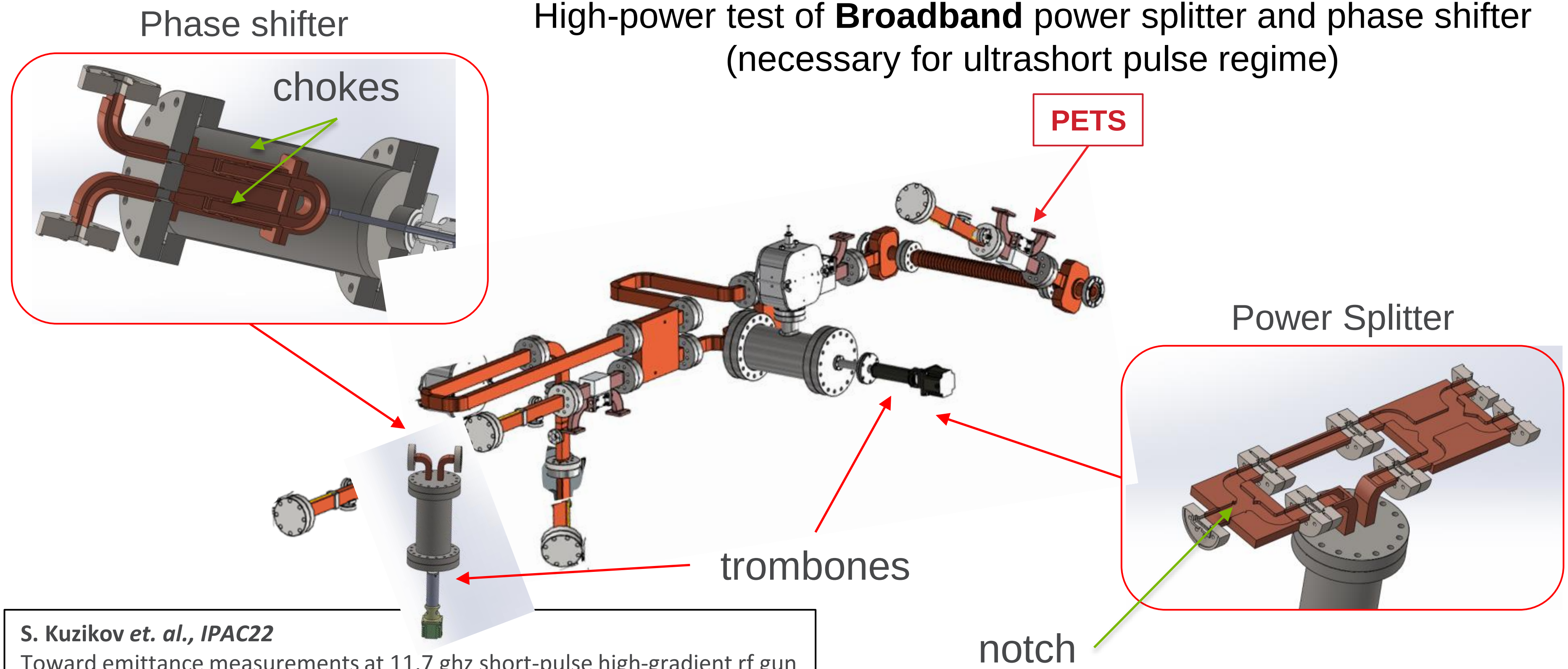
Low dark current

- No detectable dark current (<1pC)

EXPERIMENT #3:Power splitter and phase shifter test

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

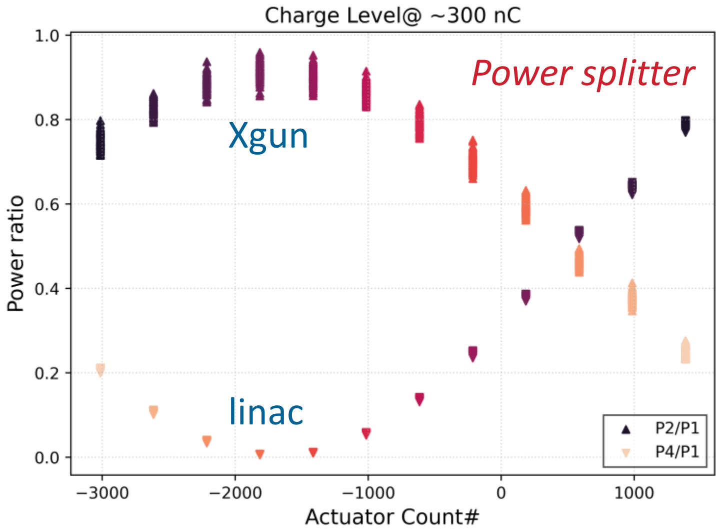
High-power test of **Broadband** power splitter and phase shifter (necessary for ultrashort pulse regime)

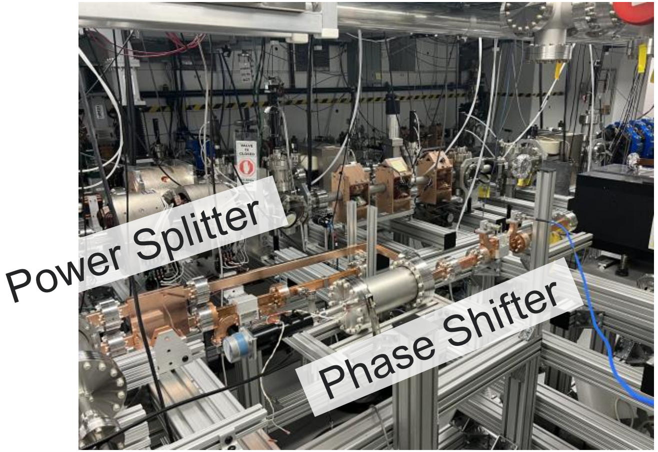


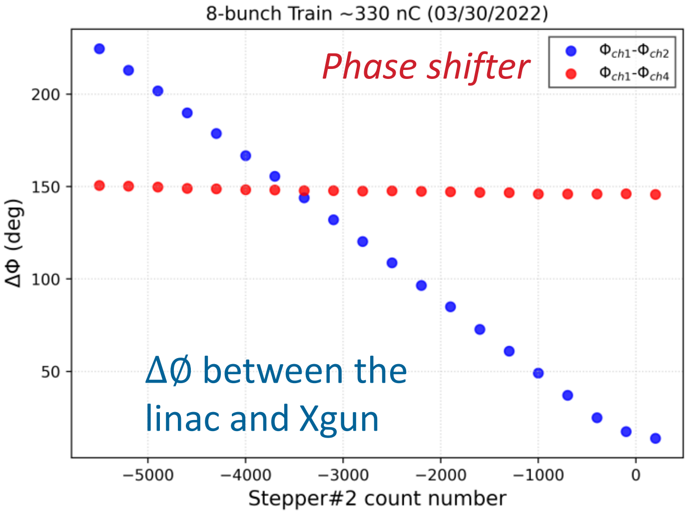
S. Kuzikov *et. al., IPAC22*
Toward emittance measurements at 11.7 ghz short-pulse high-gradient rf gun
https://accelconf.web.cern.ch/ipac2022/papers/MOPOMS013.pdf

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

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

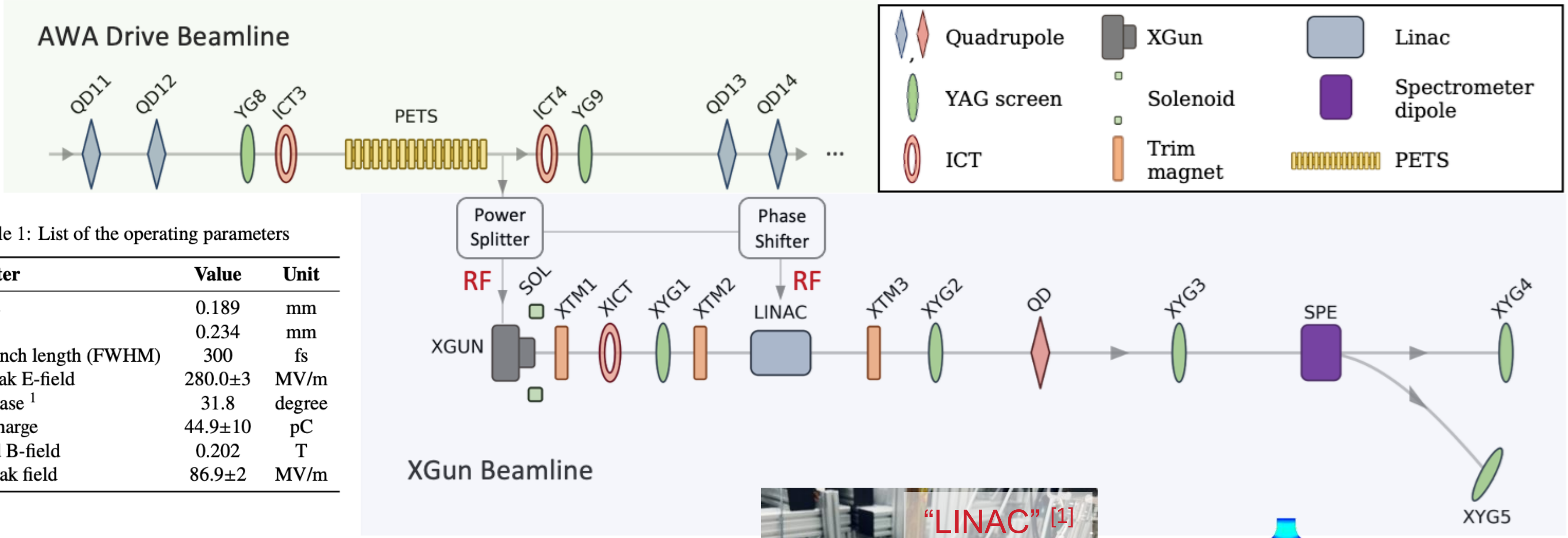
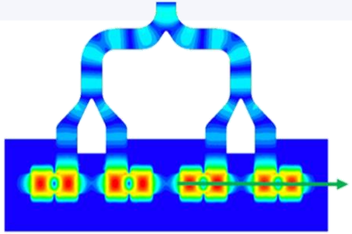


Table 1: List of the operating parameters

Parameter	Value	Unit
Laser σ_x	0.189	mm
Laser σ_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

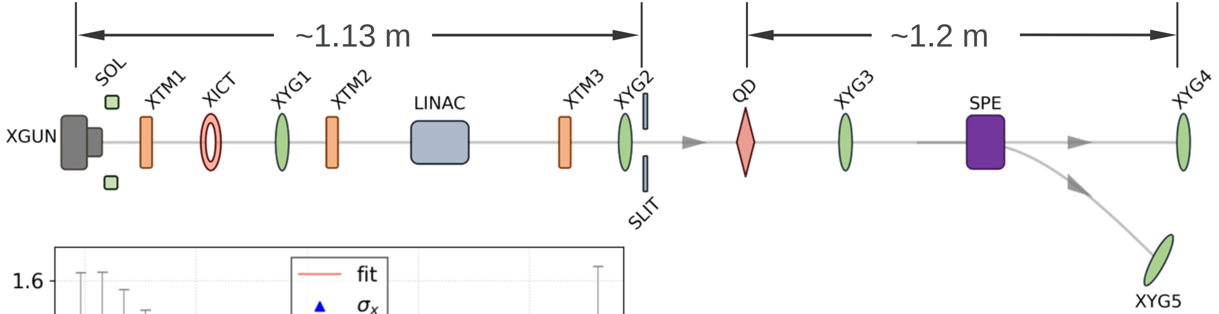


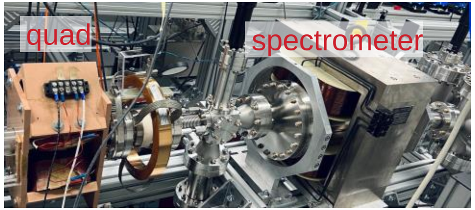
G. Chen *et. al., NAPACC22*
Emittance measurements and simulations from an x-band short-pulse ultra-high gradient photoinjector
https://epaper.kek.jp/napac2022/papers/moze3.pdf

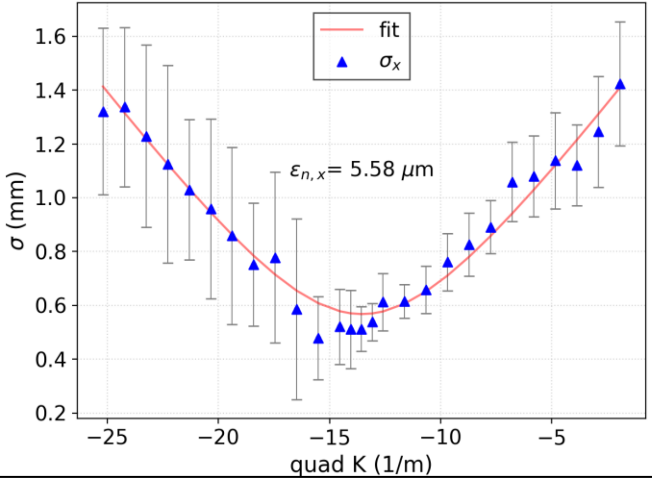
EXPERIMENT #4: second beam measurements

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 ε high? And what next?

Issues in the 1st ε 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.)*

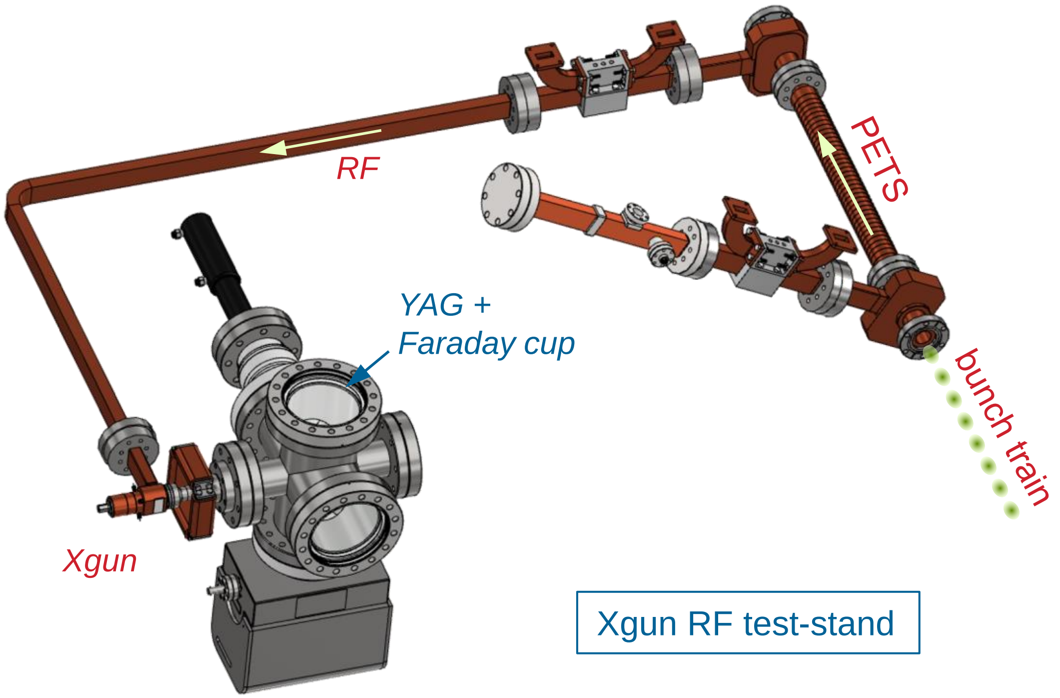
Conclusion: pause program to understand breakdown

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)

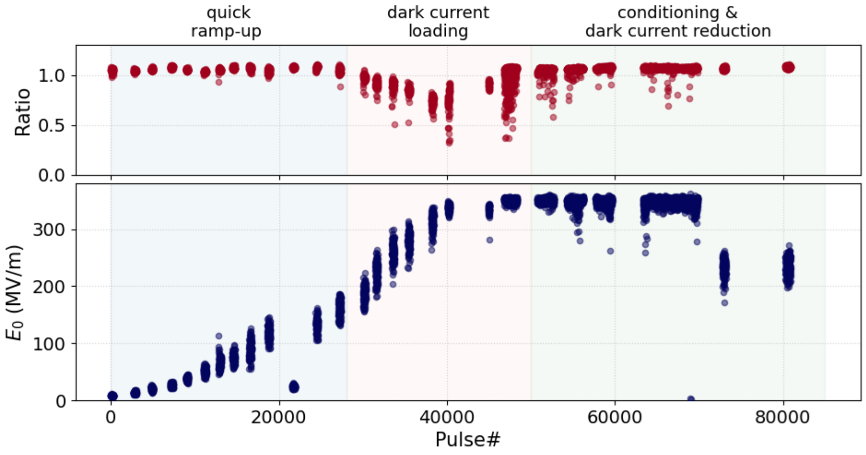
Xgun alone
- without linac
- without phase shifter
- without power splitter



EXPERIMENT #5: Second high-power rf conditioning

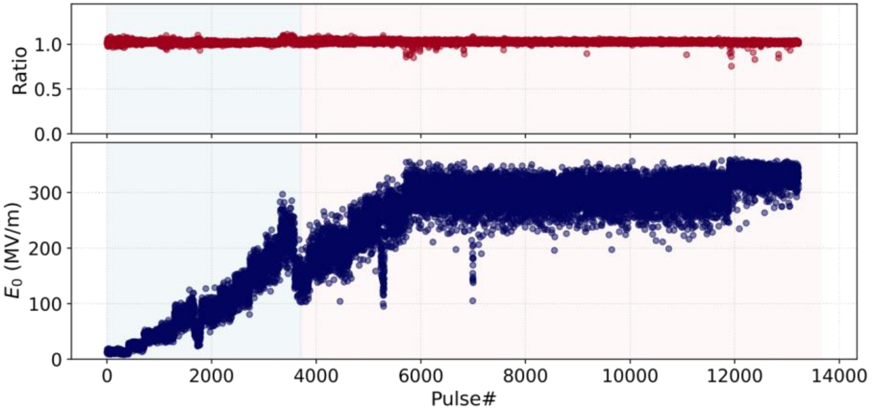
Result: Xgun has no damage, immediately back to ~350MV/m

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

MY GOAL TODAY…

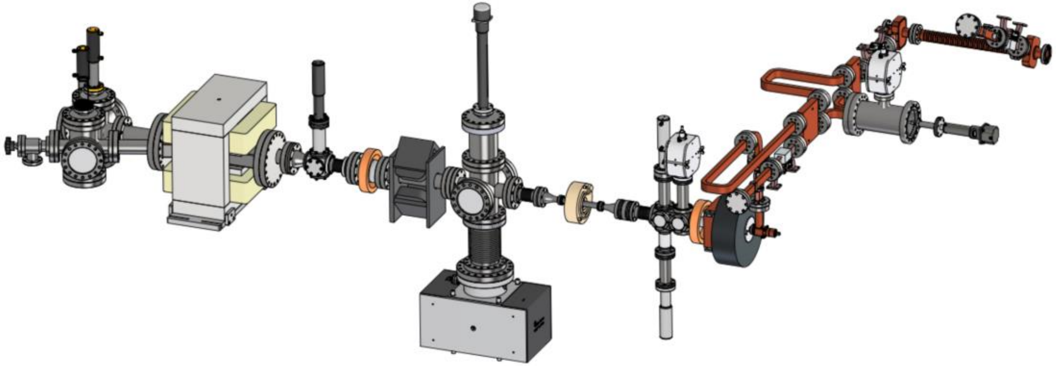
*is to help you understand the **sub-GV/m injector program** at the Argonne Wakefield Accelerator.*

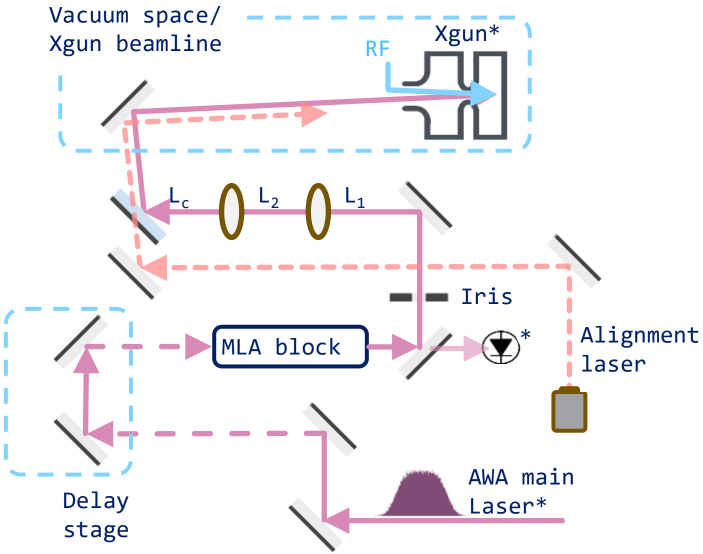
- **Why?** → A high brightness electron source
- **What approach?** → short-pulse & two-beam acceleration
- **Where?** → Argonne Wakefield Accelerator Facility
- **Details?** → Progress so far on Xgun
- **Plans?** → Next steps

EXPERIMENT #5: Third beam measurements

Setup: 4-week run (July 2023)

Installed June 2023





GOALS for this RUN:

- Schottky studies at different gradients up 50 – 350 MV/m.
- Fundamentals of photoemission (Copper cathode):
  - QE measurements
  - Thermal emittance measurements

SUMMARY AND FUTURE DIRECTIONS

SUB-GV/M XGUN: A HIGH BRIGHTNESS INJECTOR

PROGRESS SO FAR

- **RF milestones**
  - high gradient (~400 MV/m)
  - Low BDR (<1e-5)
  - low dark current (<1pC)
- **Beam milestones**
  - Beam energy measurements confirm gradient
  - First beam generated w/ Xgun confirm low dark current
  - First beam measurements made (re-purposed linac, solenoid, etc.),

NEXT STEP (JULY 2023)

- **Physics: emission studies in the high gradient regime**
  - Schottky Scan: QE dependence
  - Schottky Scan: intrinsic thermal emittance
  - Do cathodes benefit from high gradient?

INTO THE FUTURE

- New Xgun (removable back wall, optimized solenoid, etc), Extend beamline (new linac) Targeting: 10 MeV and 100nm@100pC, … 100 MeV injector … Applications … UED … XFEL ... LC …

BIG THANKS TO 1OUR TEAM!

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AWA Collaborator Program