FOR ACCELERATOR PHYSICS AND ENGINEERING SEMINARS

A NEW REGIME OF HIGH-GRADIENT ACCELERATION: EXPLORING SHORT-PULSE TWO-BEAM ACCELERATION

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On behalf of the AWA facility at
Argonne National Laboratory

Dec. 15, 2023

OUTLINE

- Introduction to SWFA (structure wakefield accelerator)
- Discovery of BIAR (breakdown insensitive accelerator regime)
- Evidence from another high gradient accelerator test
- Short pulse benefit to dielectric accelerators
- The first application: a photogun reaching 400MV/m of gradient on cathode
- Summary

INTRODUCTION TO SWFA (STRUCTURE WAKEFIELD ACCELERATOR)

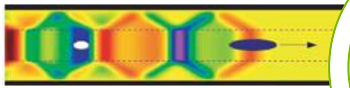
STRUCTURE WAKEFIELD ACCELERATORS

Why SWFA

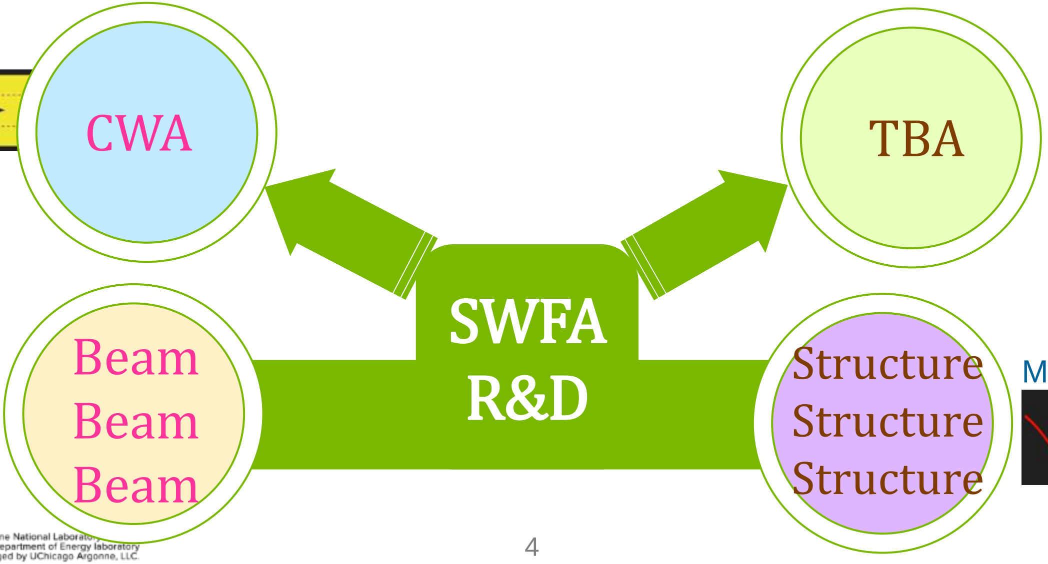
- Structures → undependable of e- and e+
- Empirical scaling law indicates shorter pulse → higher gradient $E_a \tau_p^{1/6} = Const.$
- Wakefield→ shorter pulses

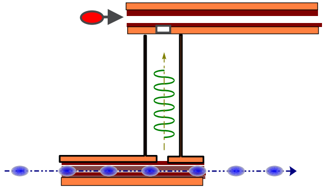
Challenges

- Achieve desirable luminosity (scalable energy, beam power, lower vertical emittance, shorter bunch length, etc)
- How to achieve higher efficiency to reduce the site power



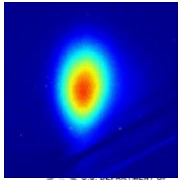
The same channel or multi-channels

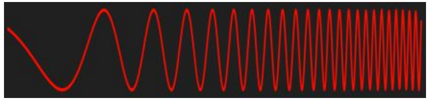




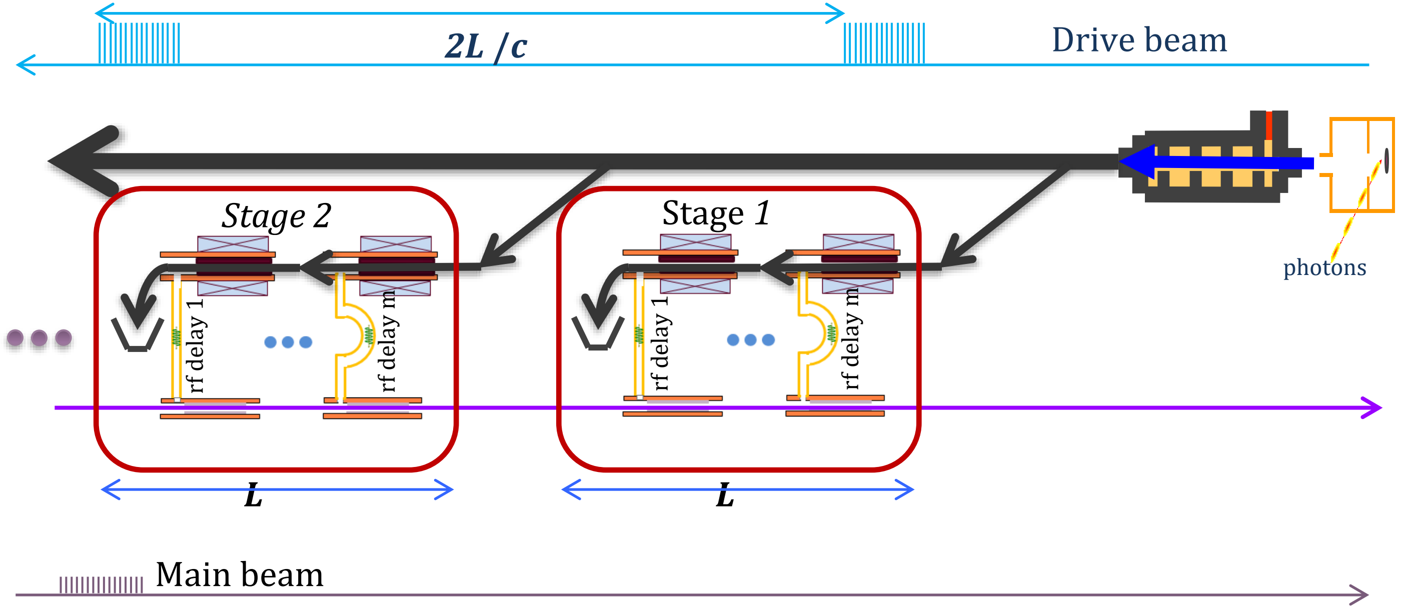
Two independent structures

shaped and intense



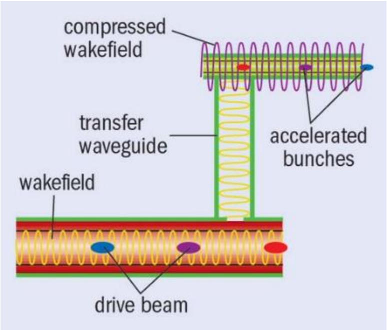


SCALABLE TBA ACCELERATION MODULE

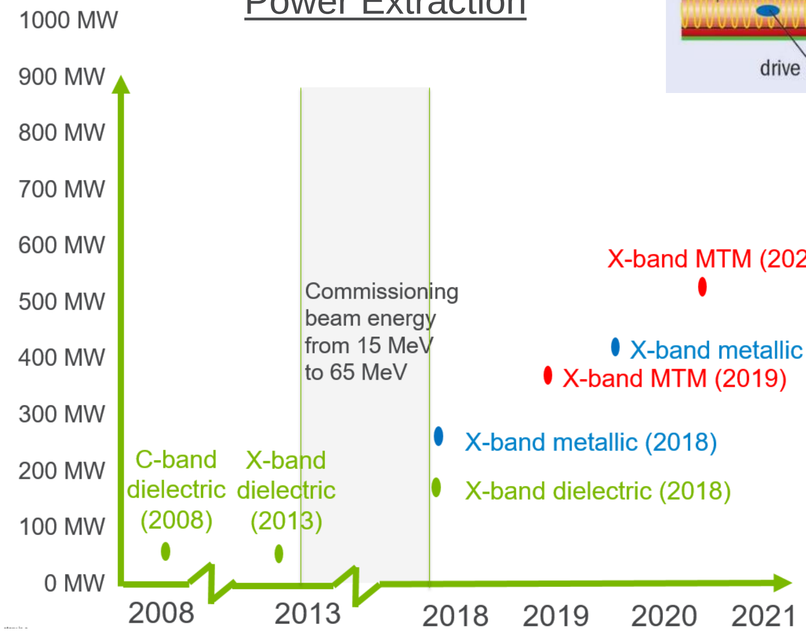


- Fast kicker and RF delay for drive beam distribution

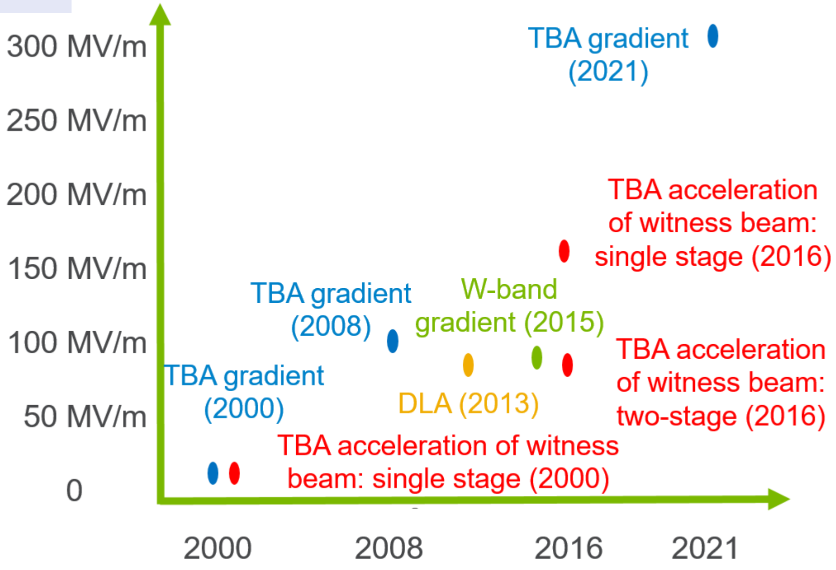
SWFA TBA PROGRESS OVER YEARS



Power Extraction



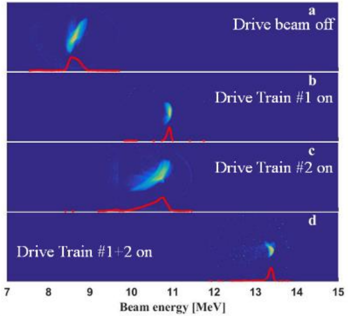
Acceleration Gradient



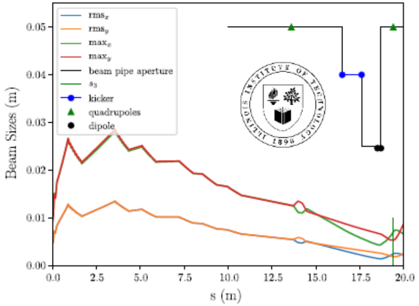
TBA R&D

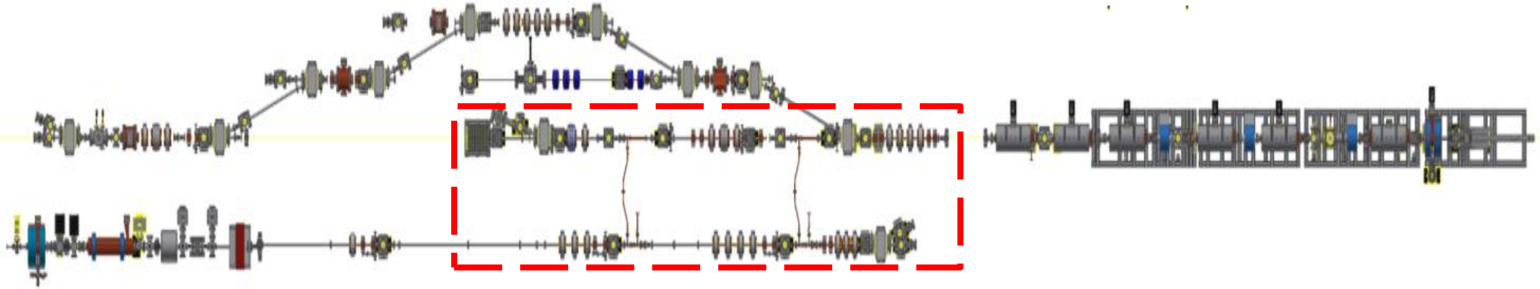
Staging

- Simplified staging demonstrated
- 2 stages, 1 pair of structures per stage
- Main beam energy gain of 5 MeV
- TBA beamline optimization



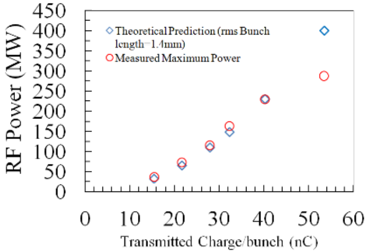
N. Neveu, et al, PRAB 22, 054602 (2019)





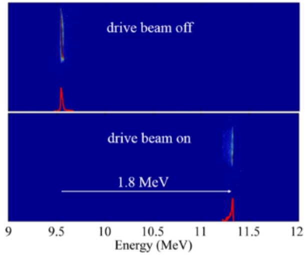
Drive beam power source

- X-band metallic: 300 MW
- K-band dielectric: 55 MW



Main beam acceleration

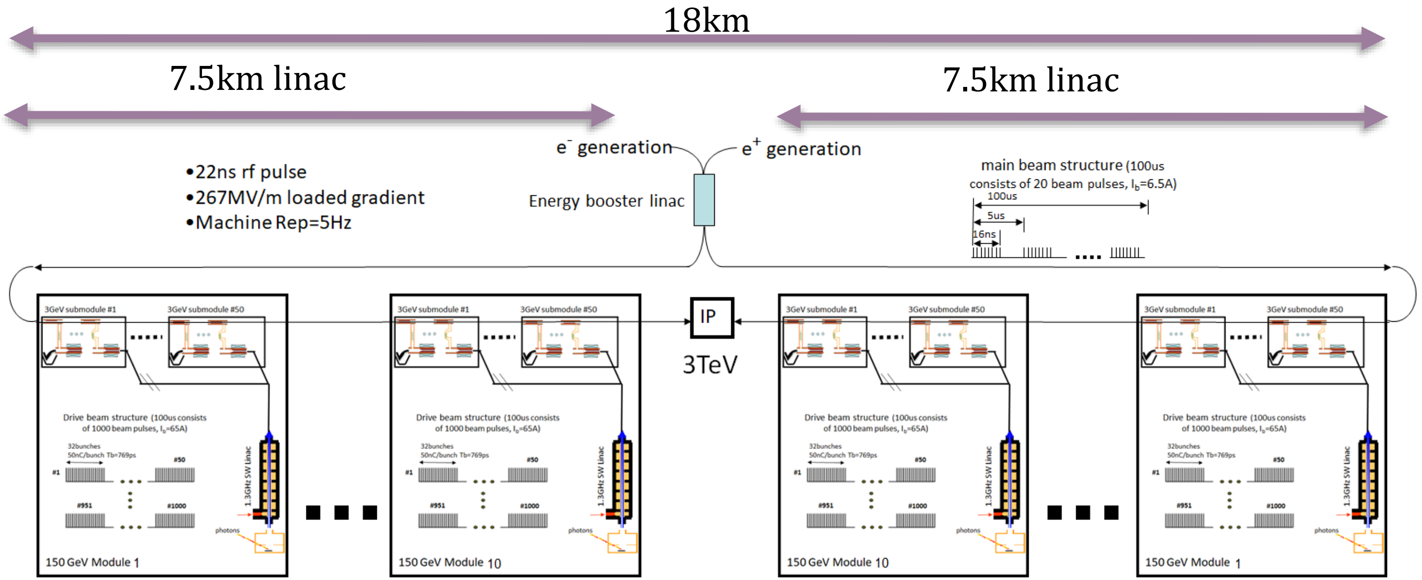
- X-band metallic: 150 MV/m
- K-band dielectric: 28 MV/m



C. Jing, et al, NIMA 898, 72-76 (2018), J. Shao, et al, in Proceedings of IPAC2017

ARGONNE FLEXIBLE LINEAR COLLIDER

3TeV 30MW beam power TBA



❑ **Based on scientifically mature and low cost Dielectric TBA technologies**

- Short rf pulse (**20ns**) for high gradient (**$e^+ e^-$ 200MeV/m of effective gradient**)
- Modular design →easily staged
- Wall plug efficiency (~15%)

DISCOVERY OF BIAR (BREAKDOWN INSENSITIVE ACCELERATION REGIME)

EXPERIMENT 1: X-BAND SINGLE CELL TRAVELLING WAVE ACCELERATING STRUCTURE

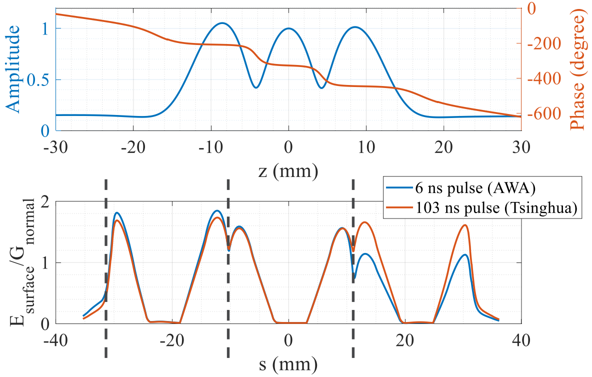
(THANK JIAHANG SHAO FOR SHARING THE SLIDES)

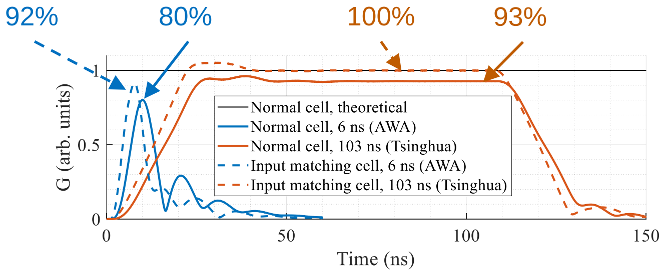
X-BAND SINGLE-CELL TRAVELLING-WAVE STRUCTURE

Single-cell structure

- Optimized for maximum transient gradient

Normal cell properties (11.7 GHz)	
Iris diameter	6.1 mm
Iris thickness	2.9 mm
Phase advance	120 degree
Quality factor	6070
Shunt impedance r/Q	$1.4\text{x}10^4$ Ω/m
Group velocity	0.0114c

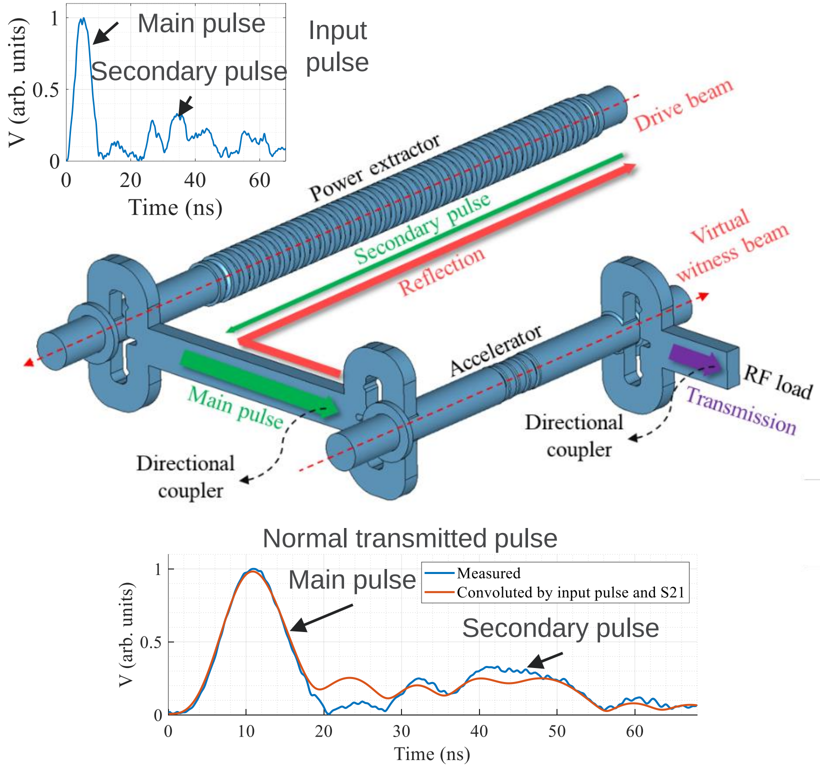




- The input matching cell has higher gradient and surface field than the normal cell

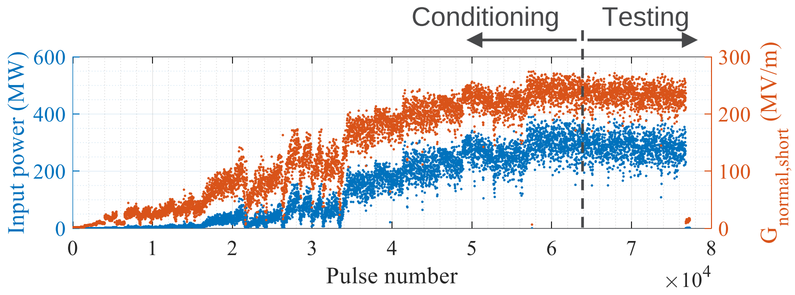
SHORT-PULSE HIGH-POWER TEST AT AWA

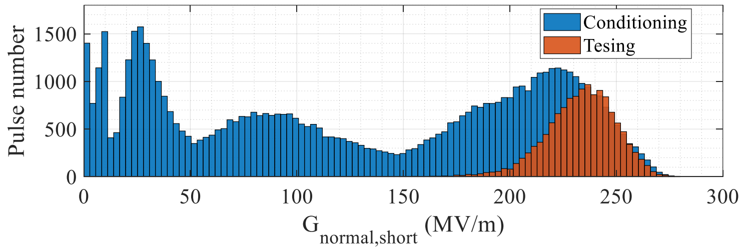
Experimental setup



RF conditioning

- $7.7\text{x}10^4$ pulses accumulated at 2 Hz repetition

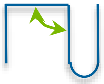




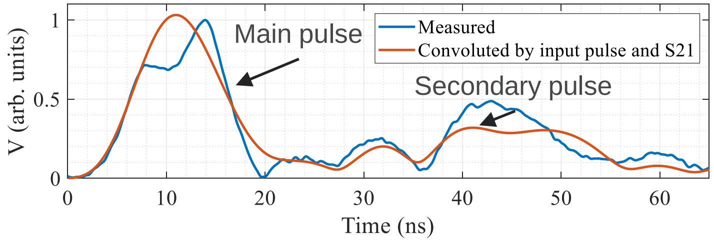
SHORT-PULSE HIGH-POWER TEST AT AWA

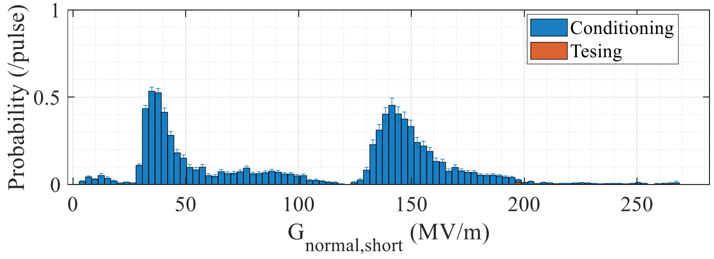
BD type I

- Distorted main pulse
- Disappeared after conditioning
- Likely to be caused by multipacting



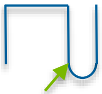
H. Xu et al., PRAB 22, 021002 (2019)

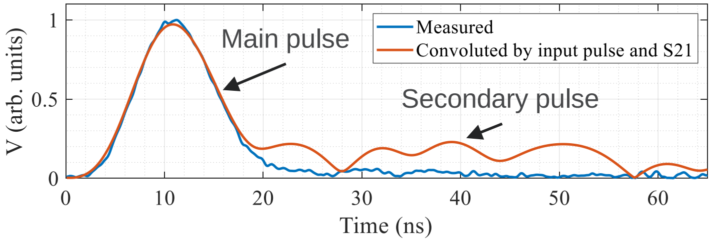


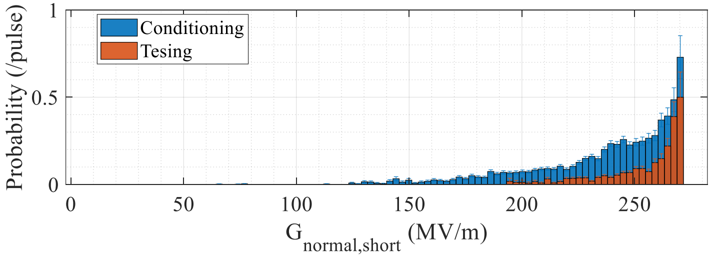


BD type II

- Blocked secondary pulse and normal main pulse
- Probability decreases after conditioning
- Likely to be caused by RF breakdown



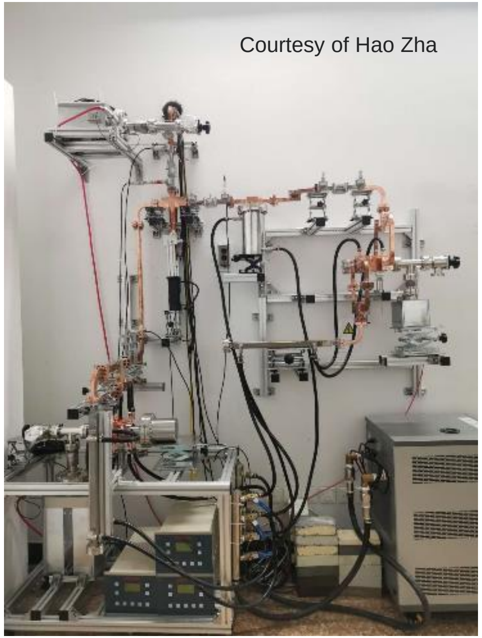




LONG-PULSE HIGH-POWER TEST AT TSINGHUA

Experimental setup

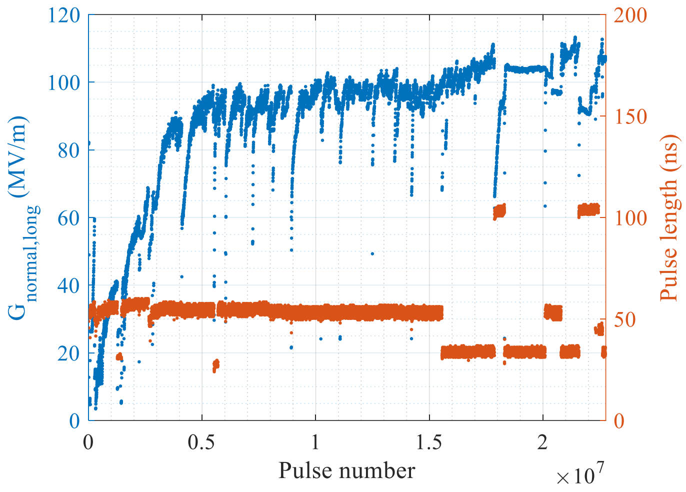
- Driven by klystron with pulse compressor



Y. Jiang et al., IEEE Trans. Microw. Theory Tech., 69, 1586-1593, (2021)

RF conditioning

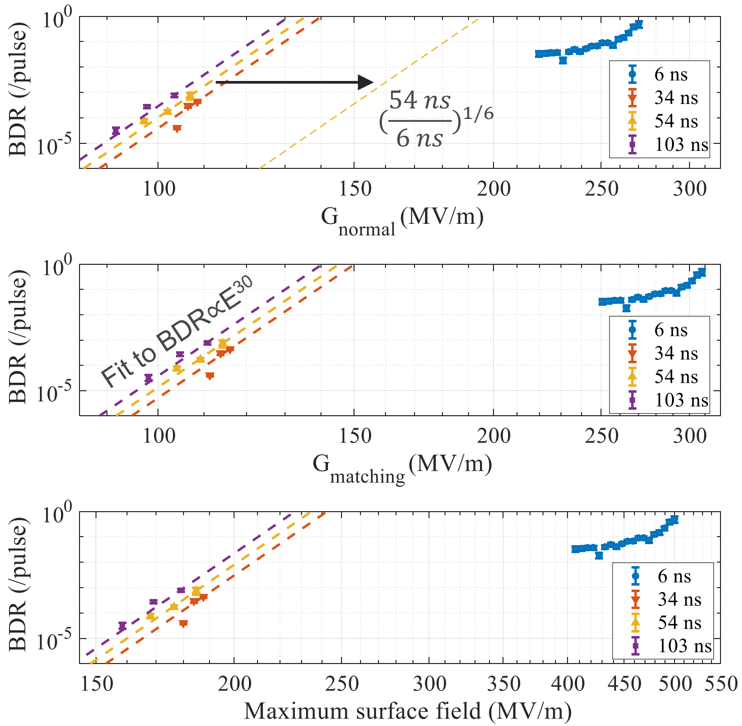
- $2.3\text{x}10^7$ pulses accumulated at 40 Hz repetition



RESULTS DISCUSSION (I)

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

Comparison of short and long pulse results



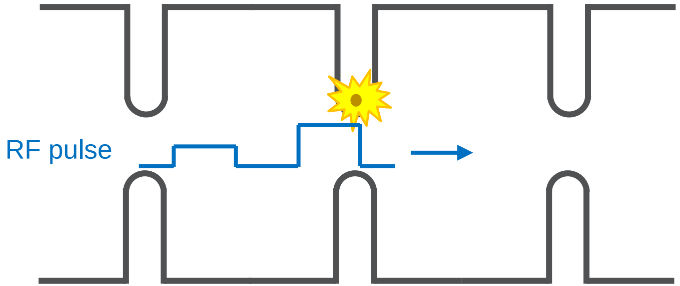
- Accelerating gradient of the normal cell and the input matching cell reaches 270 MV/m and 310 MV/m
- Surface field of the input matching cell reaches 500 MV/m
- Gradient improved at least twofold using short pulse (limited conditioning period, only secondary pulse taken into consideration)
- BDR vs. pulse length doesn't follow the empirical scaling law in short-pulse regime

- New physics of RF breakdown in short-pulse regime

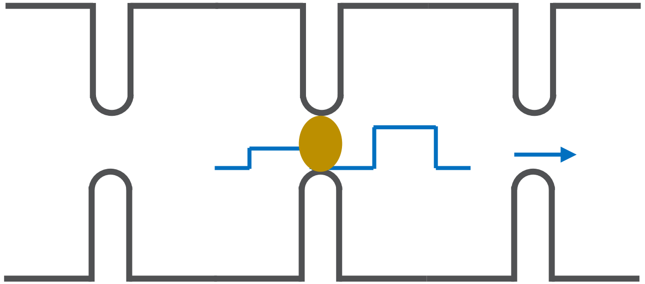
RESULTS DISCUSSION (II)

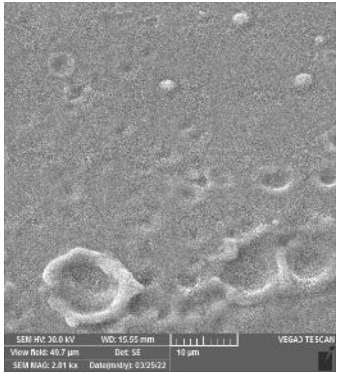
Breakdown Insensitive Acceleration Regime (BIAR)

0 ns
RF causes BD and plasma generation

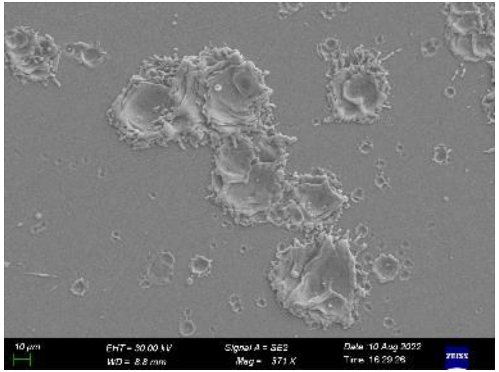


after ~10 ns
Plasma expansion to block RF transmission





ANL: ϕ10-20 μm



Tsinghua: ϕ30-100 μm

- Transmitted RF pulse and accelerated beam not influenced by RF breakdown
- Reduced structure damage due to limited energy available for breakdown avalanche

EVIDENCE FROM THE MOST RECENT HIGH GRADIENT ACCELERATOR TEST

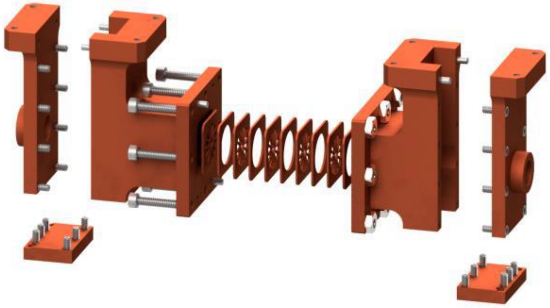
EXPERIMENT 2: X-BAND METAMATERIAL ACCELERATING STRUCTURE

(THANK XUEYING LIU FOR PROVIDING THE SLIDES)

METAMATERIAL ACCELERATOR DESIGN

- Efficient structure design to explore gradient limitation
  - Optimized for high transient gradient with a 6 ns FWHM input pulse
  - Metamaterial structure with a negative group velocity has a higher shunt impedance than structures with the same but positive group velocities

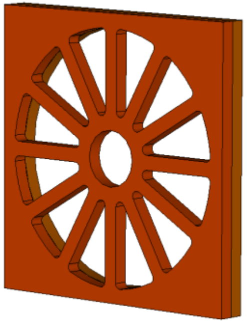
Full Structure



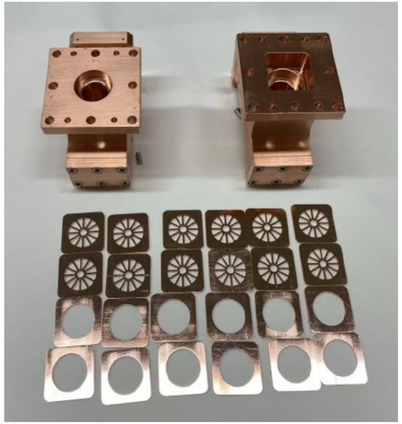
200 MV/m peak gradient from **115 MW** input RF power

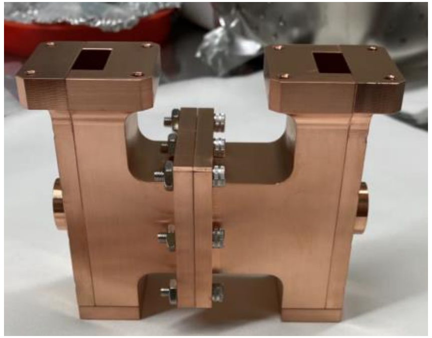
6 ns FWHM pulse extracted from drive beam

Unit Cell

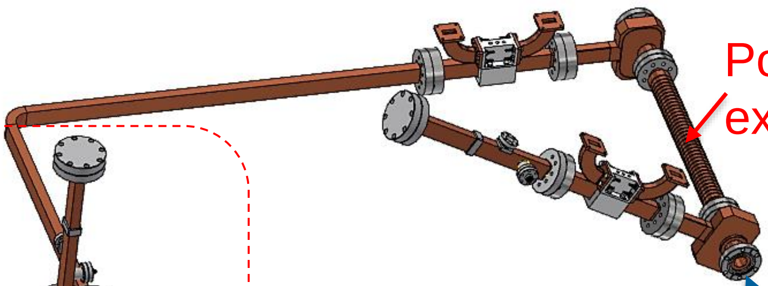


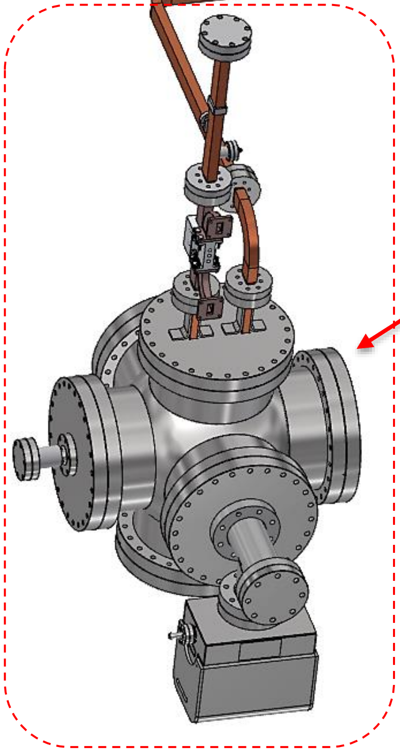
Beam aperture:
4 mm (diameter)
Plate thickness:
1 mm



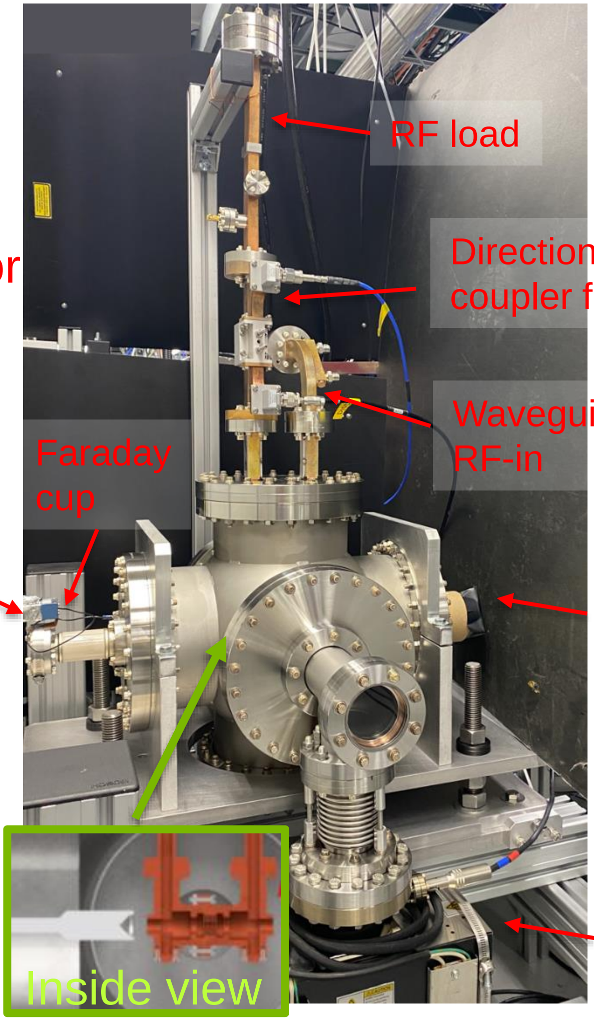


BREAKDOWN TEST STAND



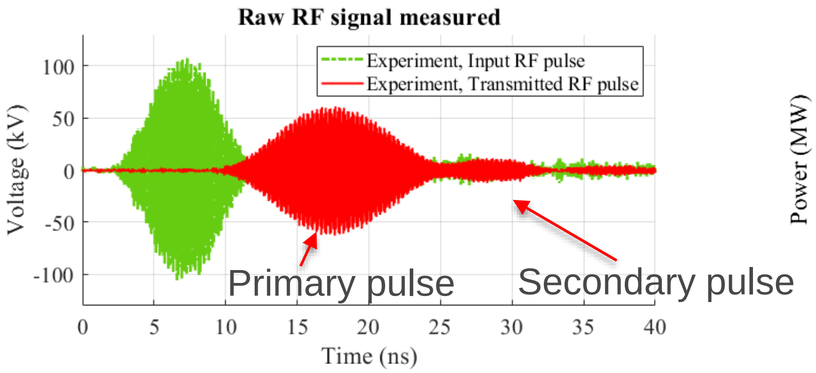


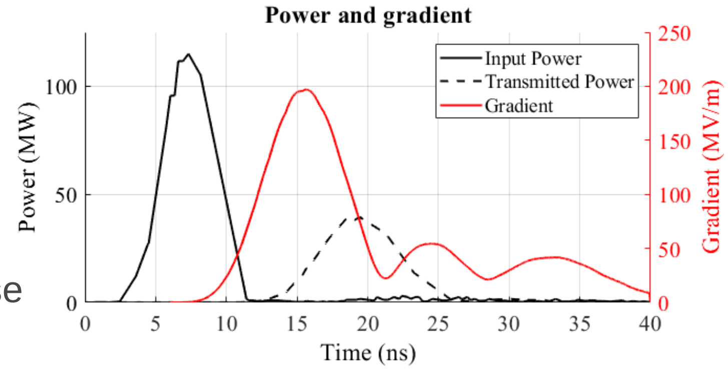
- Vacuum chamber built with breakdown diagnostics
  - Dark electrons (Faraday cup)
  - Light (photodiode and camera)

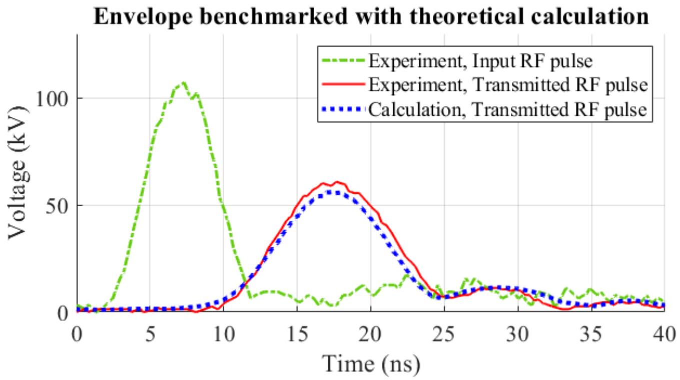


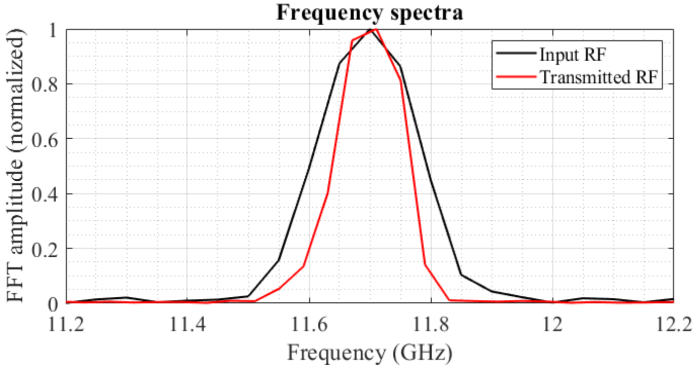
REPRESENTATIVE PULSE

- Measured RF traces agree very well with calculations

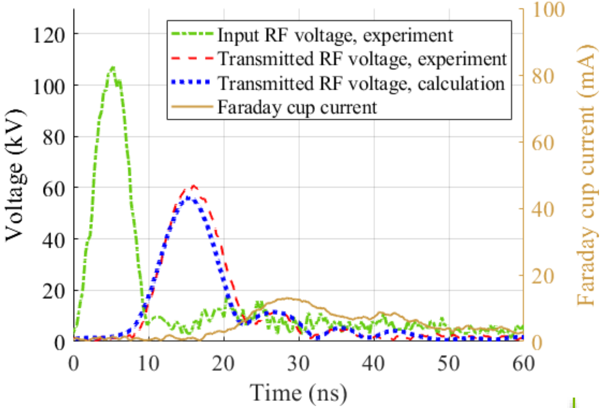


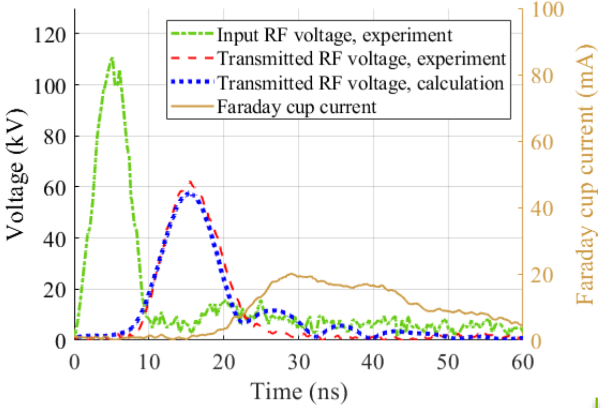


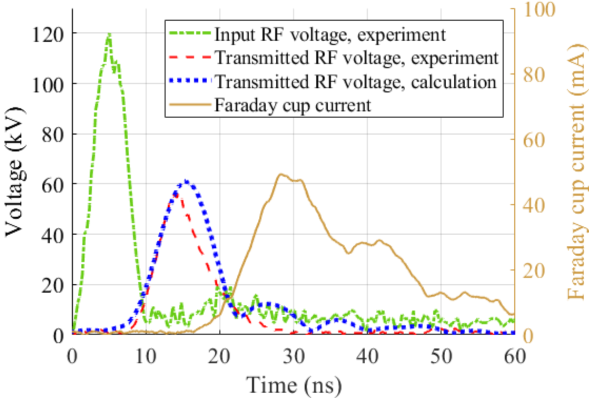




BIAR BREAKDOWN VS. DISRUPTIVE TIVE BREAKDOWN

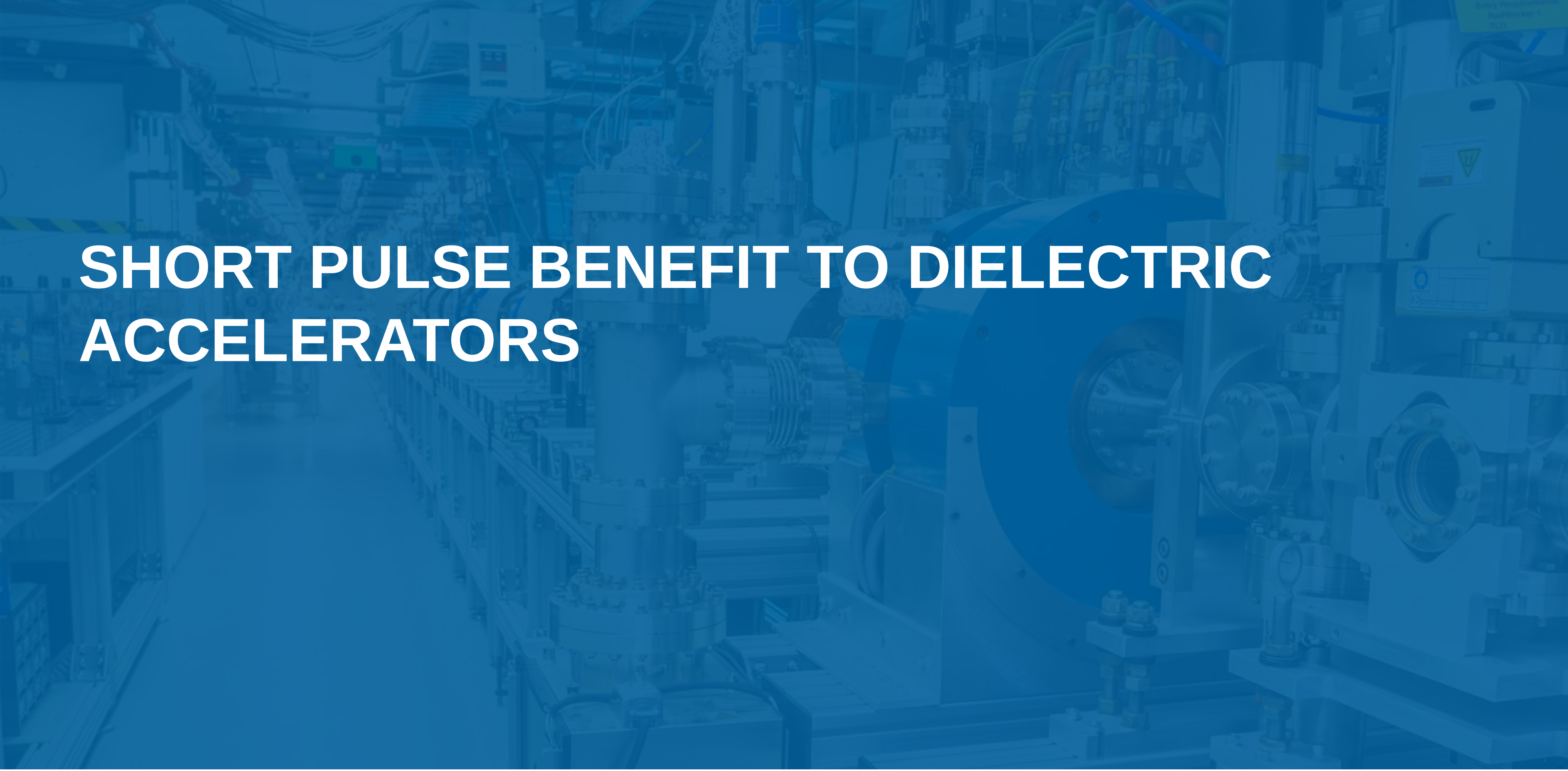






Normal	BIAR breakdown	Disruptive breakdown
Primary pulse present	Primary pulse not interrupted	Primary pulse interrupted
Secondary pulse present	Secondary pulse not present	Secondary pulse not present
Faraday cup signal: Low	Faraday cup signal: Mid	Faraday cup signal: High

No visible light detected in all three cases- possibly a new feature for short-pulse breakdown

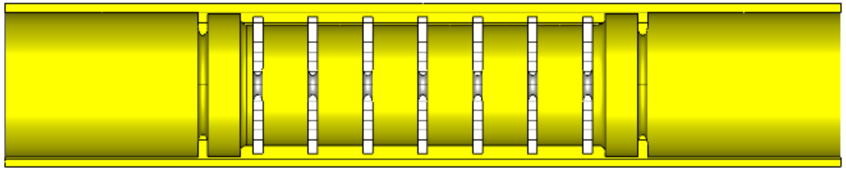


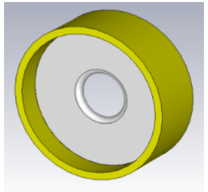
SHORT PULSE BENEFIT TO DIELECTRIC ACCELERATORS

DIELECTRIC DISK ACCELERATORS (DDA)

- Dielectric disk-loaded waveguides introduced in the 1940's-50's
- Modern ceramics with high dielectric constant and low loss provide opportunity to realize high shunt impedance structures
- Higher: group velocity, shunt impedance, Q
- Tuning easier than for DLAs
- Drawback: surface electric field much higher than DLAs, fabrication difficult

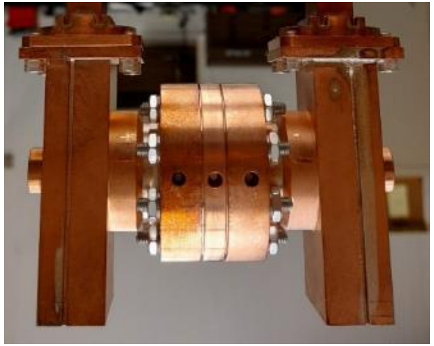
26 GHz Parameter	DDA	DLA	Copper-Disk*
Aperture	3 mm	3 mm	3 mm
Outer Diameter	9.23 mm	4.99 mm	9.27 mm
Thickness	0.5 mm	1 mm (wall)	0.5 mm
Dielectric constant	50	10	N/A
Loss tangent	5e-4	1e-4	N/A
Group velocity	0.16c	0.11c	0.017c
Shunt Impedance	208 MΩ/m	50 MΩ/m	139 MΩ/m
Q	6400	2300	4300
Accel. gradient	363 MV/m	363 MV/m	N/A
Surface gradient	660 MV/m	363 MV/m	N/A

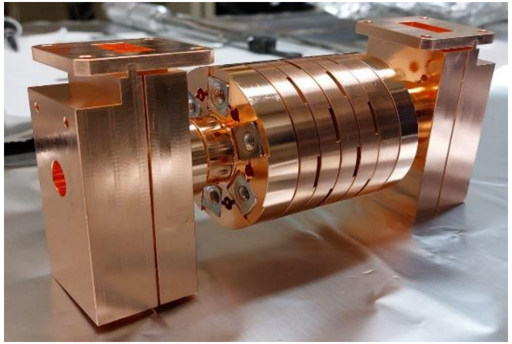


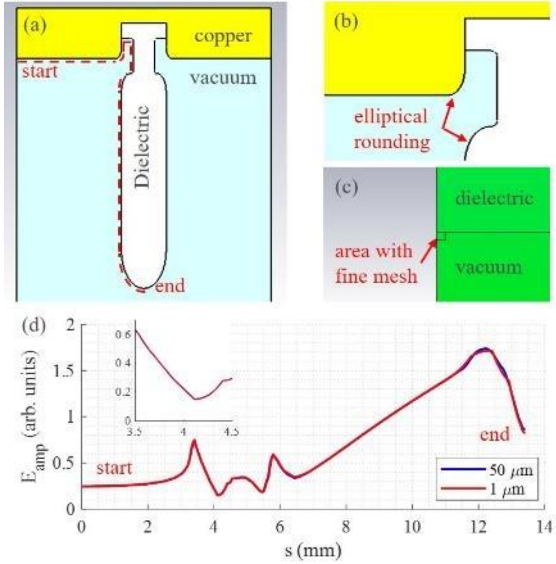


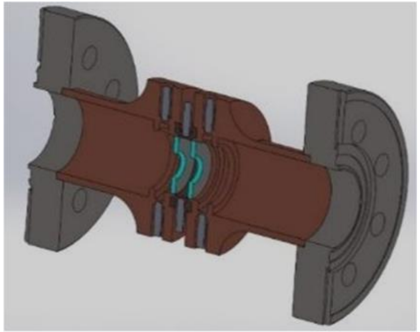
*Constant impedance 2π/3 structure, not suitable for short RF pulse acceleration due to low group velocity

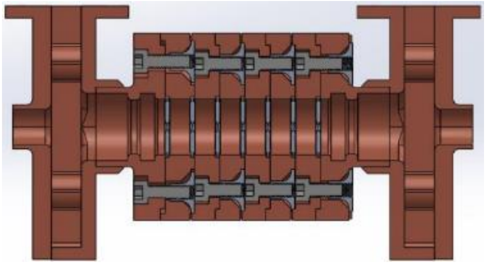
X-BAND DDA DEVELOPMENT

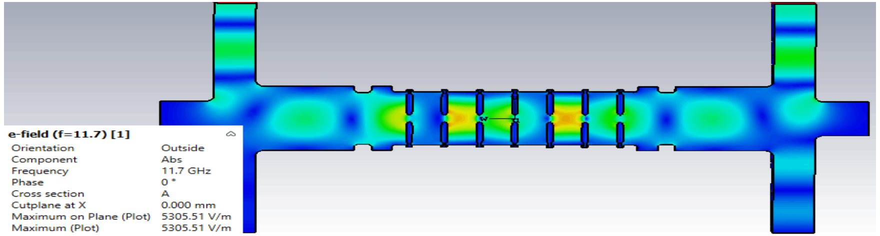




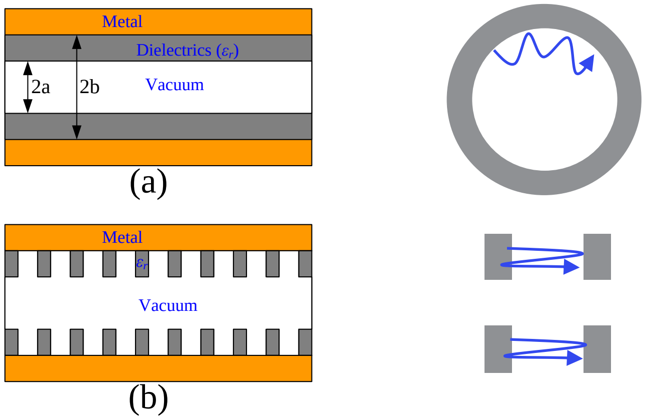






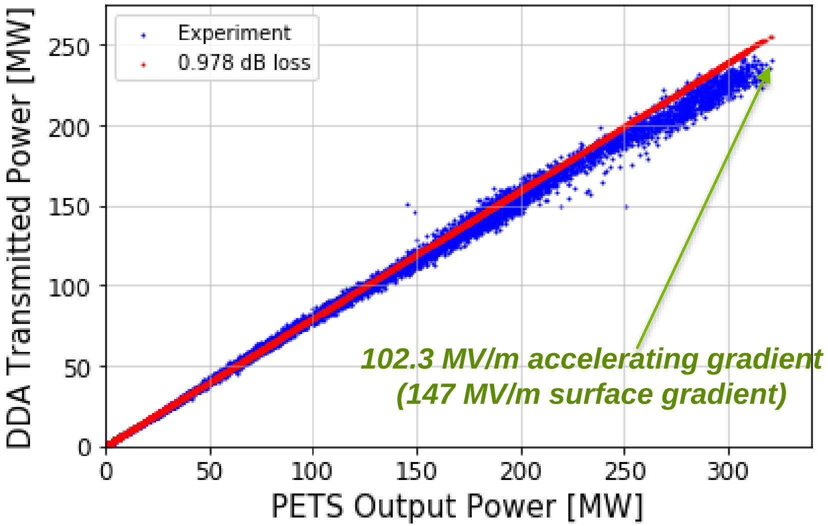


TESTING RESULTS

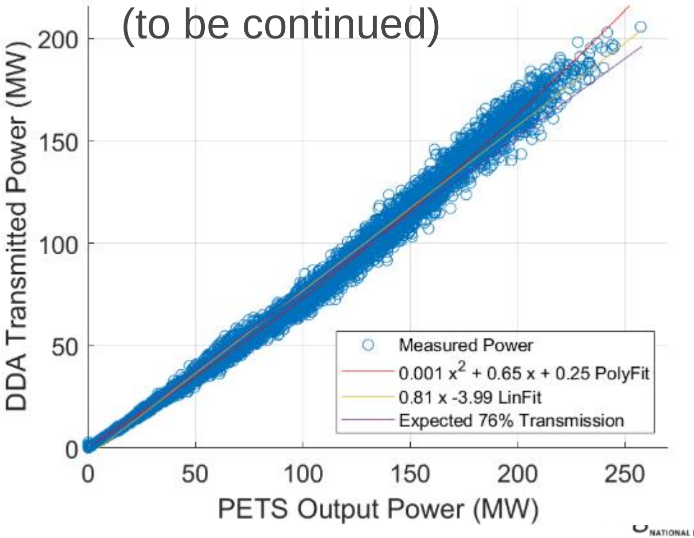


NO multipactor observed in this short pulse regime!

Single cell DDA test@ Dec. 2021



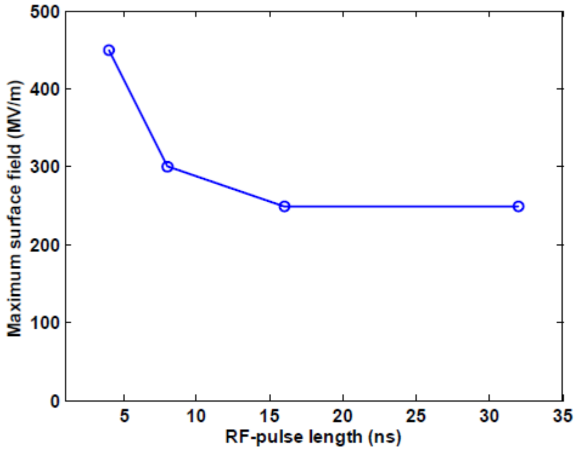
Multicell DDA test@ May 2023 (to be continued)



THE FIRST APPLICATION: A PHOTOGUN REACHING 400MV/M OF GRADIENT ON CATHODE

MOTIVATION

- Early time study in CLIC, 30GHz era



W. Wuensch et al., Proc. PAC03, 495–497, 2003.

- Empirical formula summarized from decade of high gradient accelerator research

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

A. Grudiev *et al.*, *Phys. Rev. ST-AB*, 12, 102001 (2009).

LCLS photogun, the most successful Cu photogun: S-Band, 3~4 us rf pulse, 120MV/m on Cathode

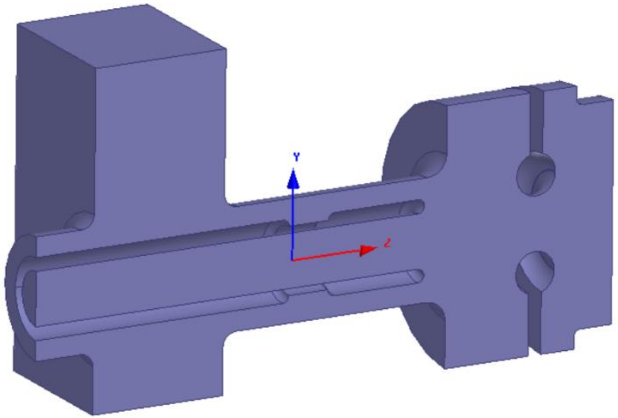
→ ?

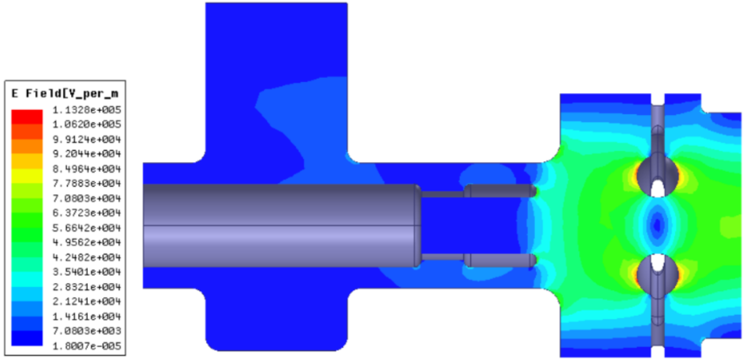
<10ns rf pulse, >300MV/m on Cathode→lower ε_{sc}

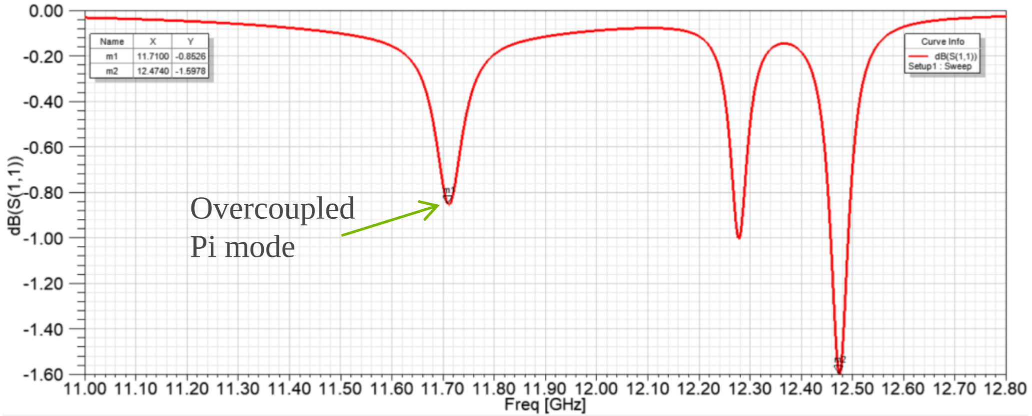
→

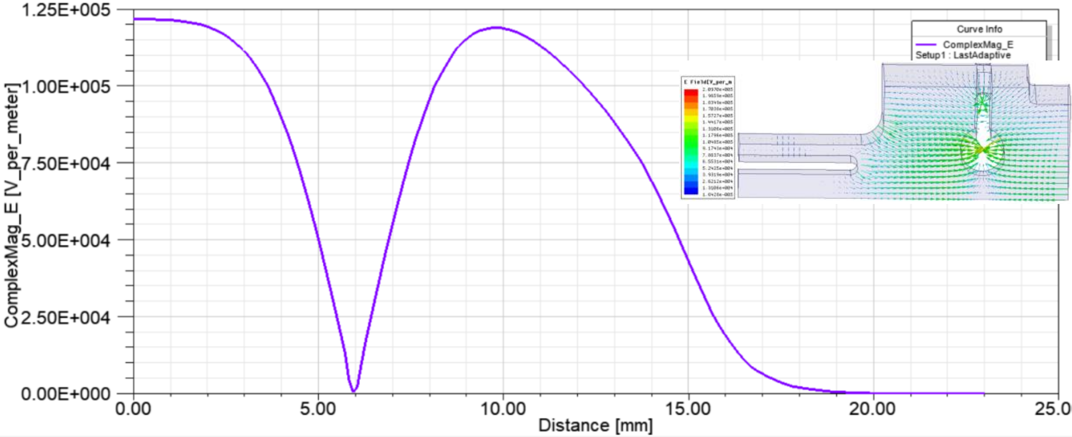
1. More efficient for applications with insignificant beamloading.
2. Less dark current

DESIGN---RF PROPERTIES





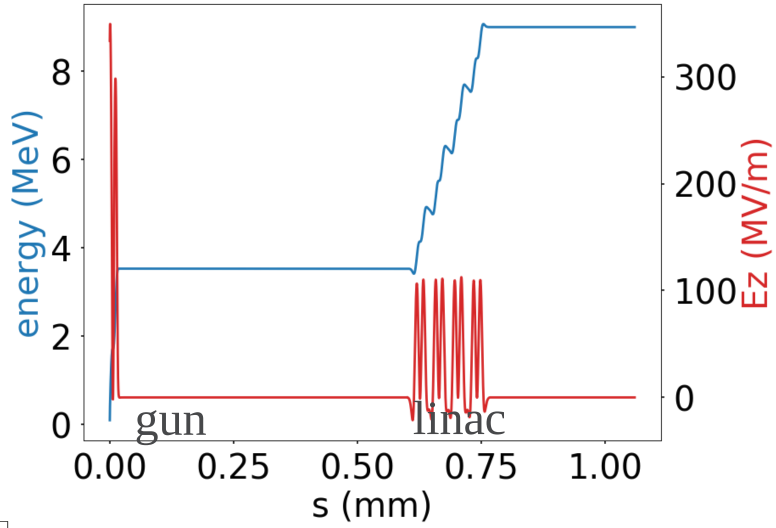


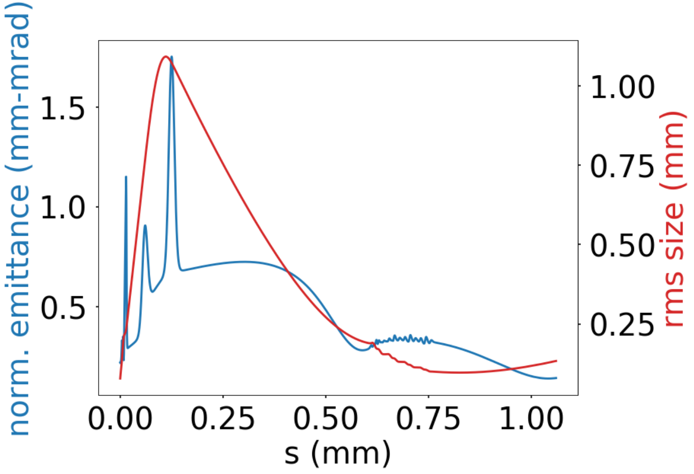


DESIGN---BEAM SIMULATION

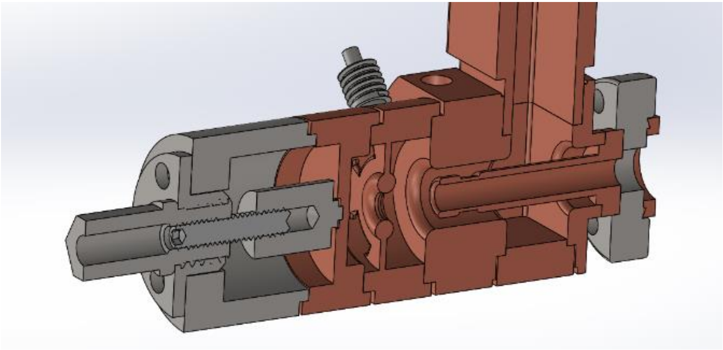
Parameter	Value
Laser spot size on cathode	70 micron
Flat top laser rms length	3.2 ps
Peak field on cathode	350 MV/m
Charge	100 pC
Normalized emittance	0.15 mm-mrad*
RMS bunch length at exit	365 micron
Relative energy spread at exit	0.003
Beam energy at gun exit	3.1 MeV
Beam energy at exit	8.5 MeV

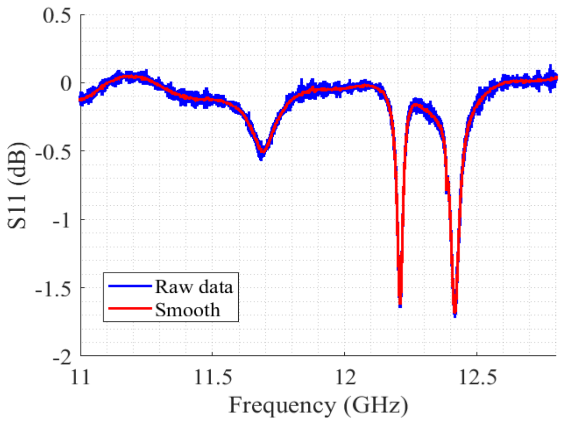
* Optimized with existing components in hand (solenoid, linac, etc).

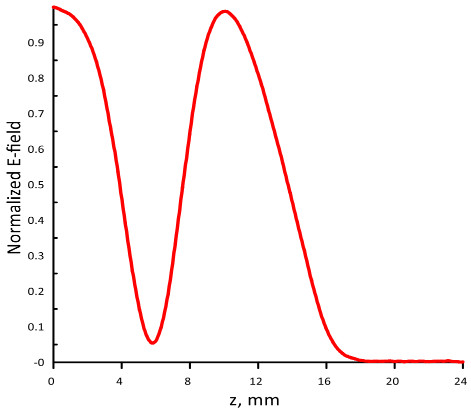




ENGINEERING, FABRICATION, AND BENCH TEST

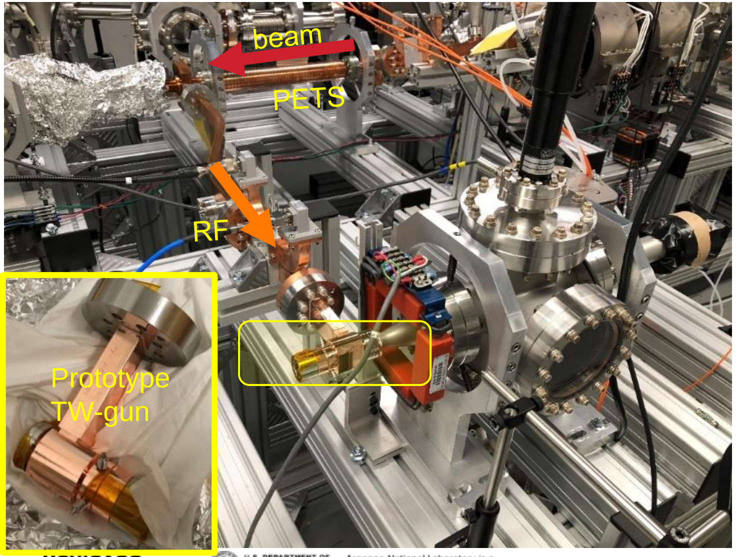


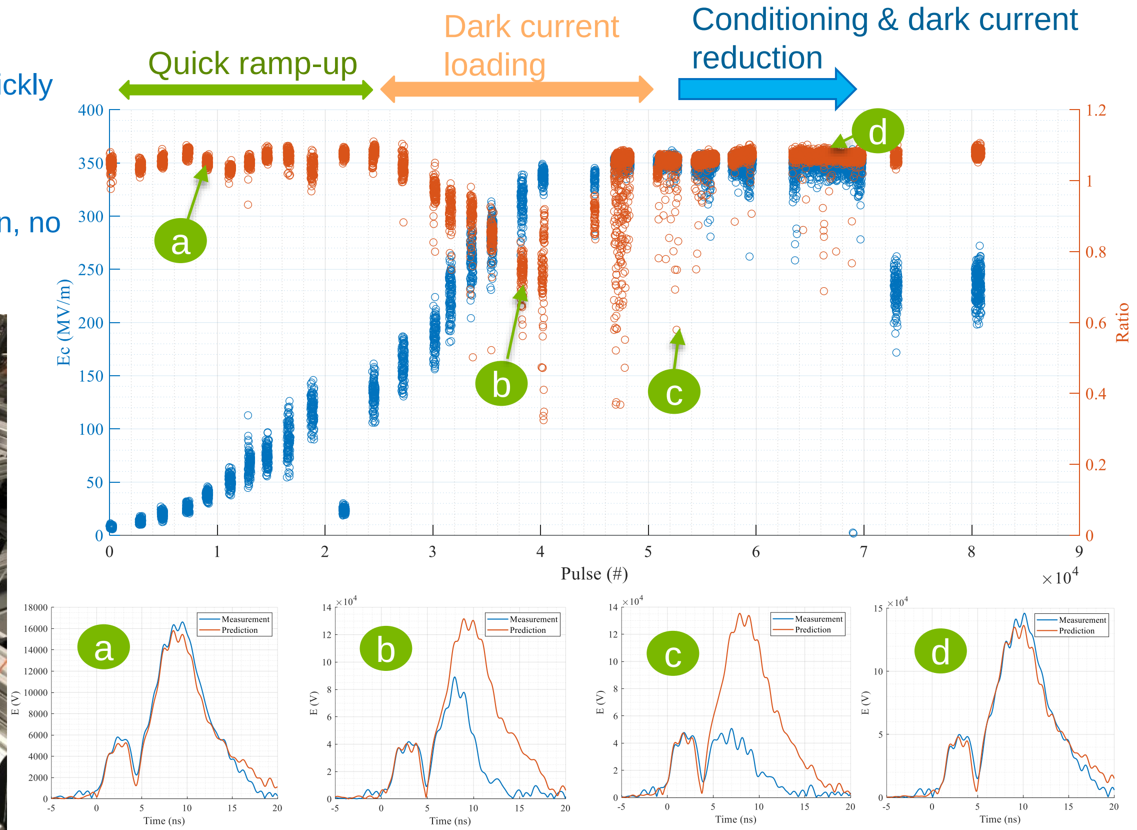




CONDITIONING

- Achieved 350MV/m on cathode
- Observed strong dark current loading regime but quickly conditioned away
- It only took 70k pulses for a full condition
- Back to 200MV/m to 250MV/m region, no breakdown, no measurable dark current



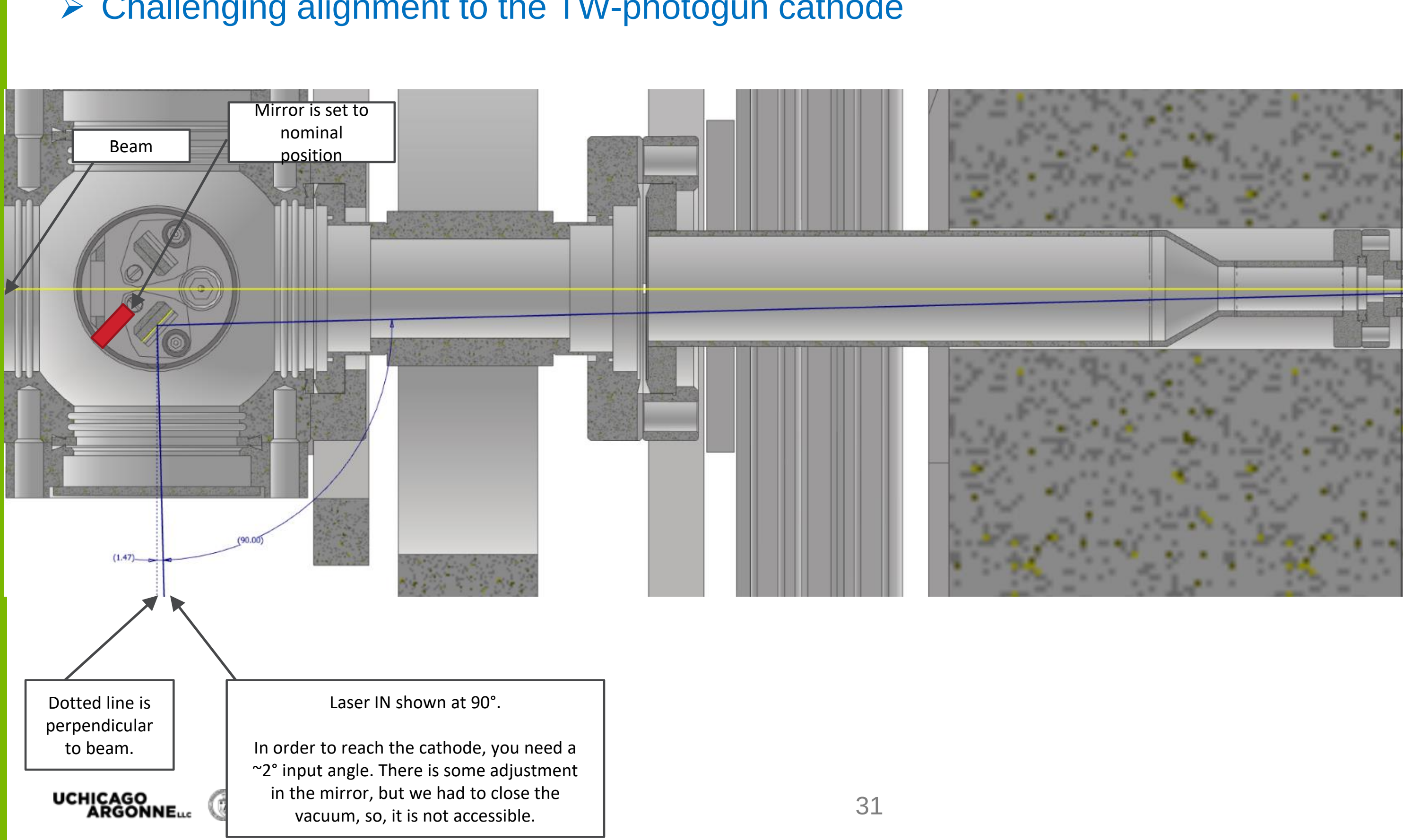


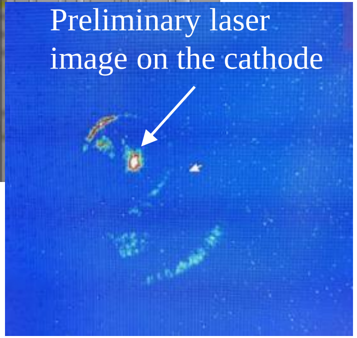
Reflection signal from bi-directional coupler

Euclid, SBIR Grant #DE-SC0018709, 2020

BEAMLINE---LASER ALIGNMENT

- ➢ Challenging alignment to the TW-photogun cathode

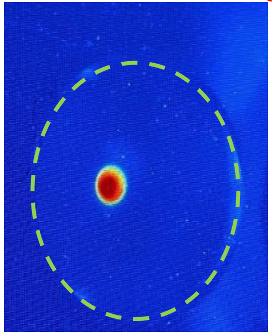


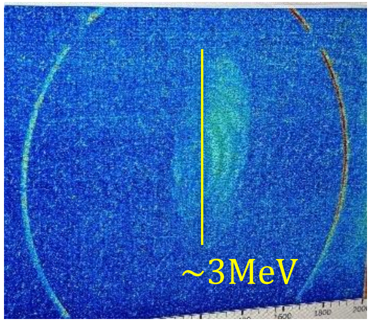


EXPERIMENT--FIRST BEAM! (10/29, 2021)

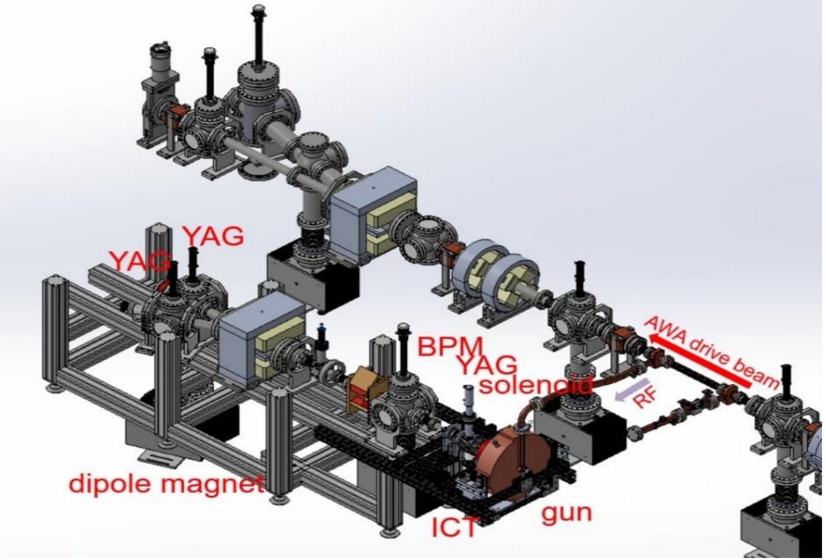
- First beamline was constructed without Linac.
- The goal was to generate the photoelectron beam, measure its charge and energy. Infer the gradient.

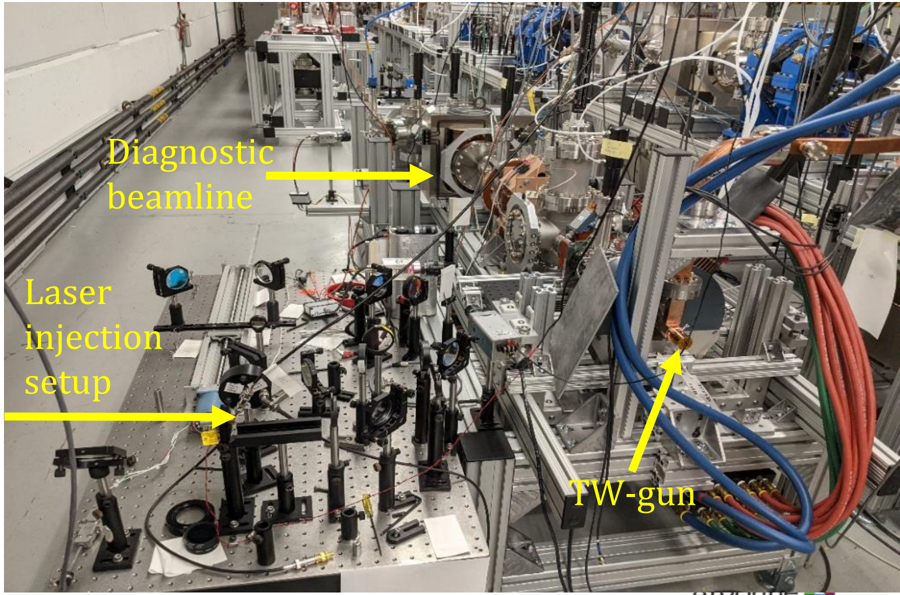
Beam on YAG at exit of gun





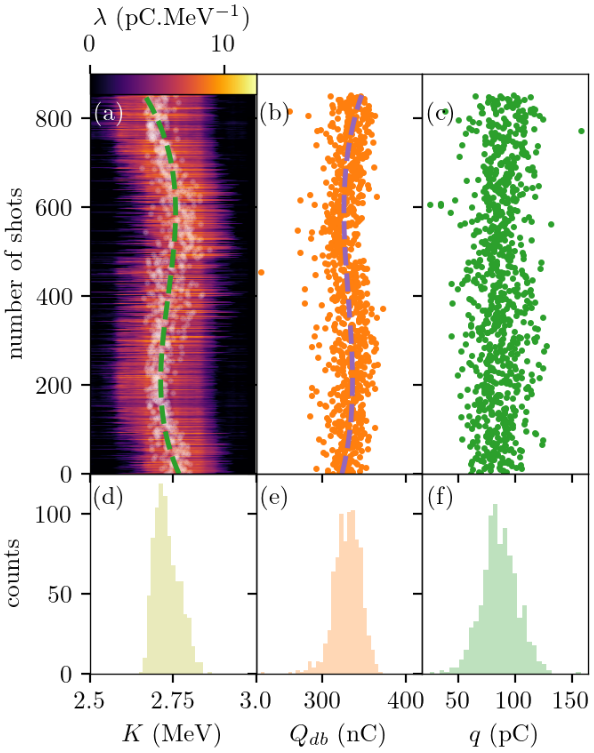
Beam on X4 energy spectrometer

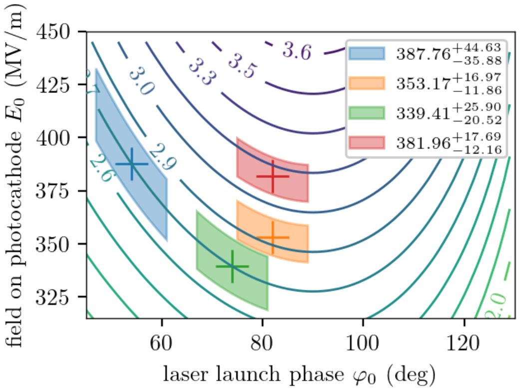


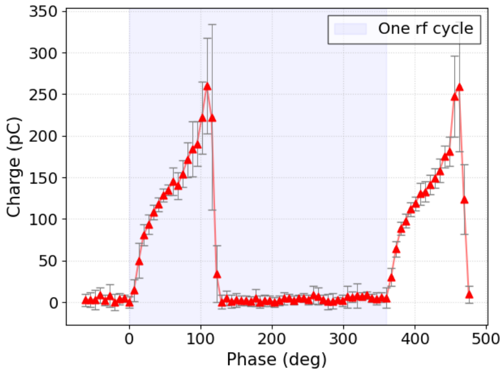


BEAM STATISTICS (GUN ONLY)

"The result of such an analysis confirms that the maximum peak field attained during our experiment was $E_0 = 387.76^{+44.63}_{-35.88}$ MV/m corresponding to a surface field at the iris of $1.55E_0 \simeq 601.03^{+69.18}_{-51.61}$ MV/m."







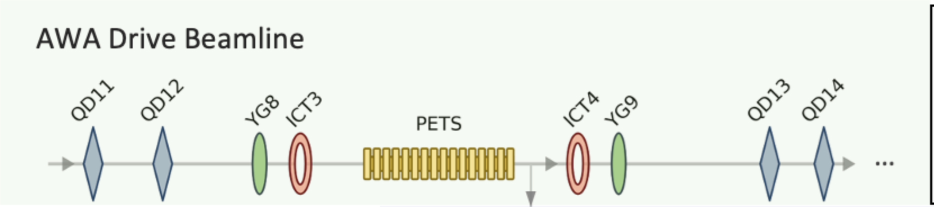
Xgun phase scan @340 MV/m

Experimental Summary

1. 387 MV/m
2. No measurable breakdown
3. No measurable dark current (estimated at 1pC/pulse)

State of the art using CO_2 cleaning →"**0.6 nC within 2 μs**" input RF pulse.
G. Shu et al., "Dark current studies of an L-band normal conducting RF gun," NIMA Vol. 1010, **(2021)**

BEAM MEASUREMENTS W/ A LINAC (JUNE 2022)



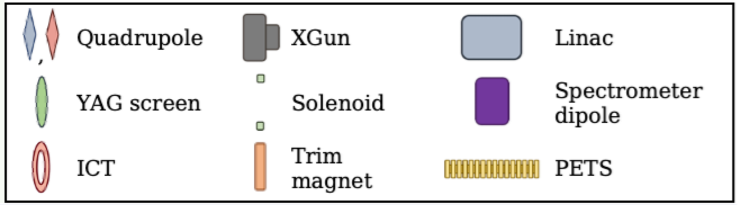
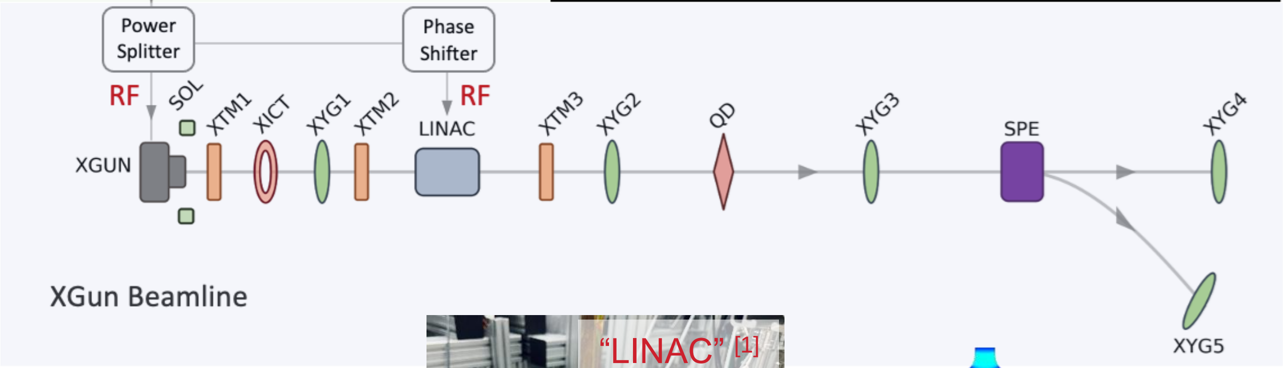
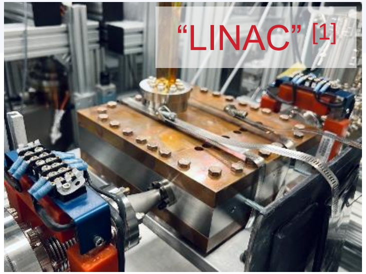
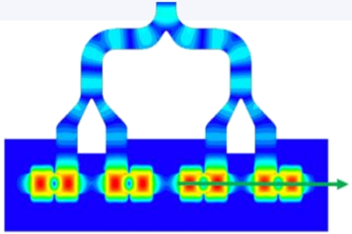


Table 1: List of the operating parameters

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

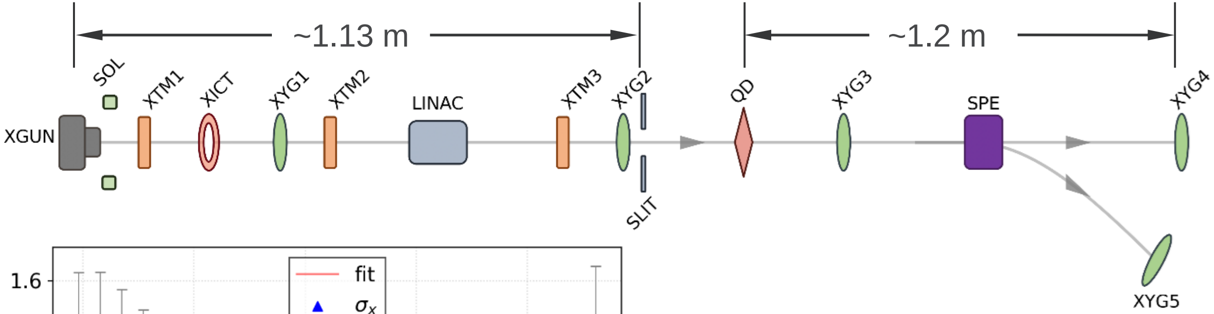


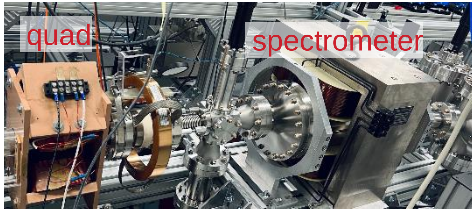


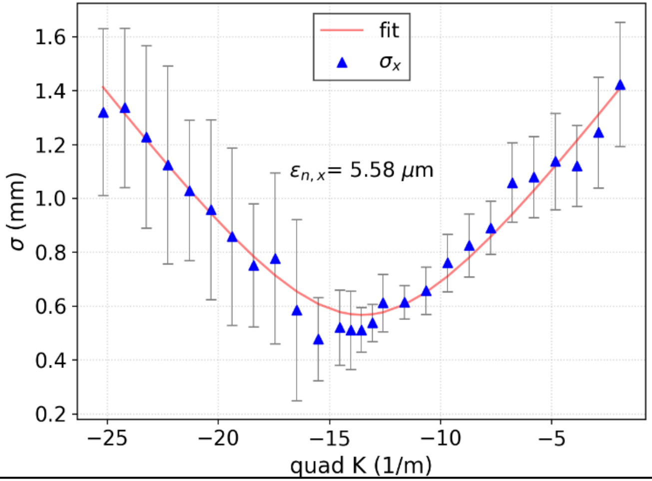


G. Chen *et. al., NAPACC22*
Emittance measurements and simulations from an x-band short-pulse ultra-high gradient photoinjector
https://epaper.kek.jp/napac2022/papers/moze3.pdf

1ST BEAM EMITTANCE MEASUREMENT







- 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

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

Experiment since Aug. 2023:

- Thermal emittance measurement with the patched solenoid.
- Schottky effect study

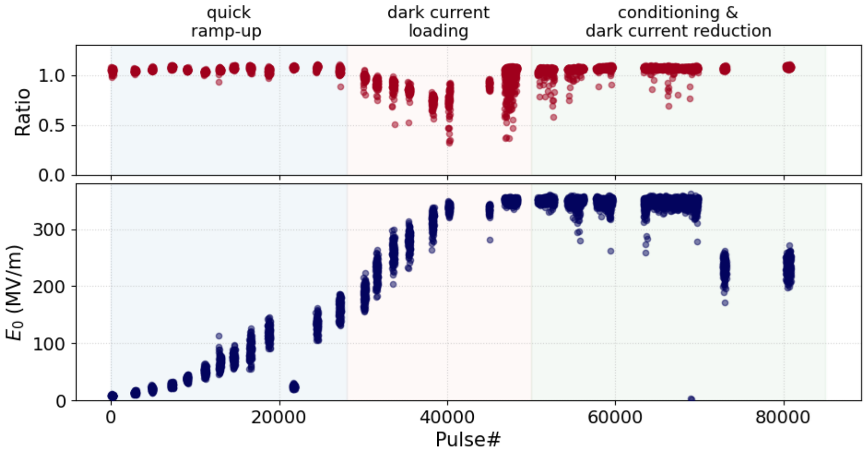
Planned experiment in July-Aug 2024:

- Emittance measurement with a new dedicated solenoid and linac.
- Develop and test a cathode removable X-gun.

ROBUSTNESS OF THE X-GUN IN BIAR

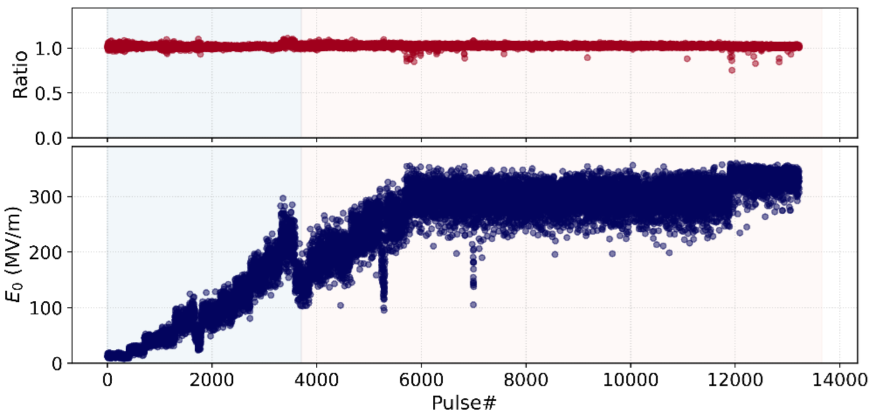
Immediately back to ~350MV/m after exposed to air for months

1st Xgun conditioning (Dec. 2020)



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

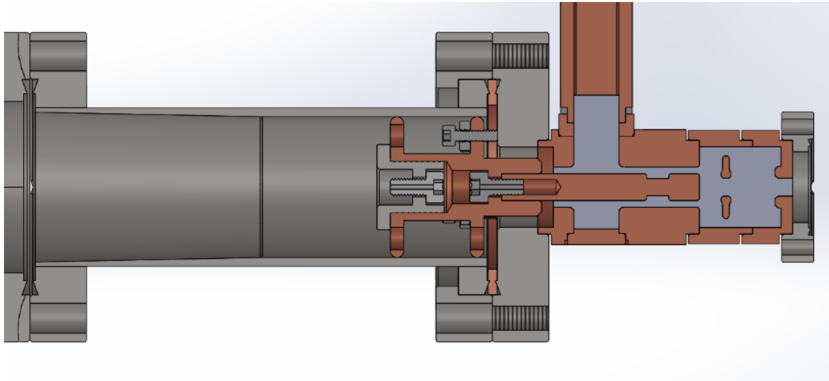
2nd Xgun conditioning (Oct. 2022)

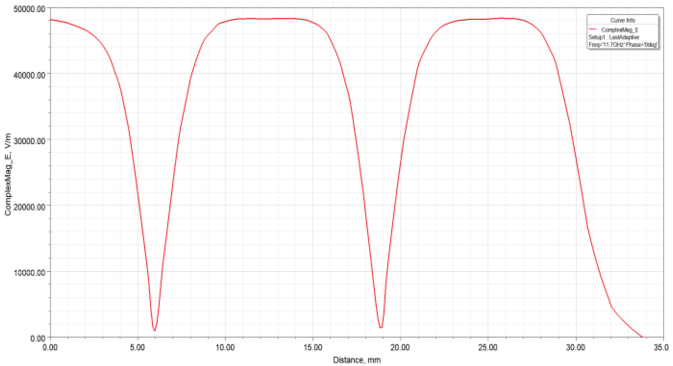


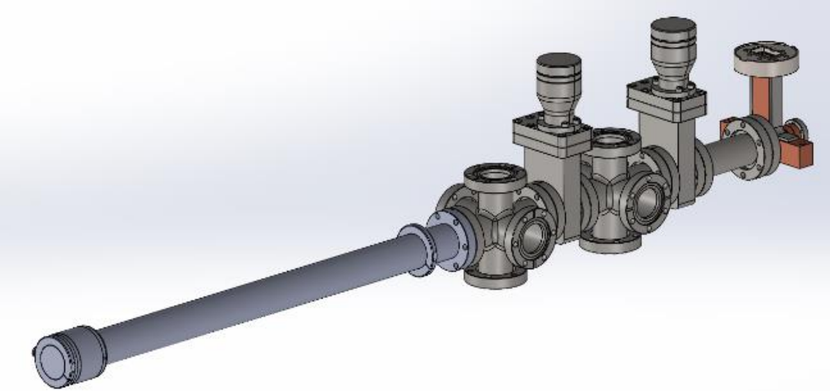
- The Xgun fully conditioned very smoothly. No damage
- Did not observe dark-current

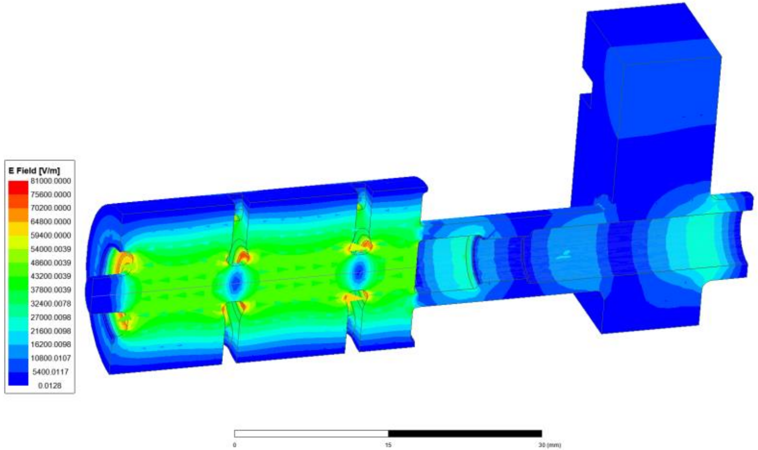
X-GUN WITH CATHODE PLUG

E=371 MV/m for 300 MW.









XFEL IN BIAR?

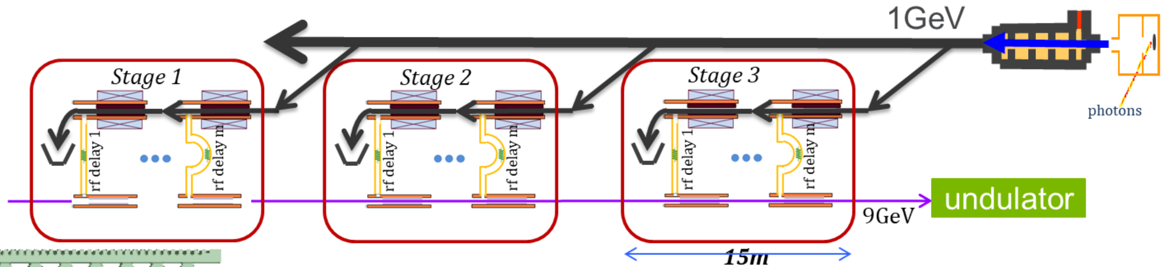
Advantages:

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

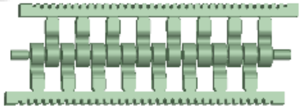
Challenges:

- Still in research phase
- Kickers
- Waveguides

TBA---9GeV Compact FEL in BIAR regime



300MeV/m, 10ns, X-band

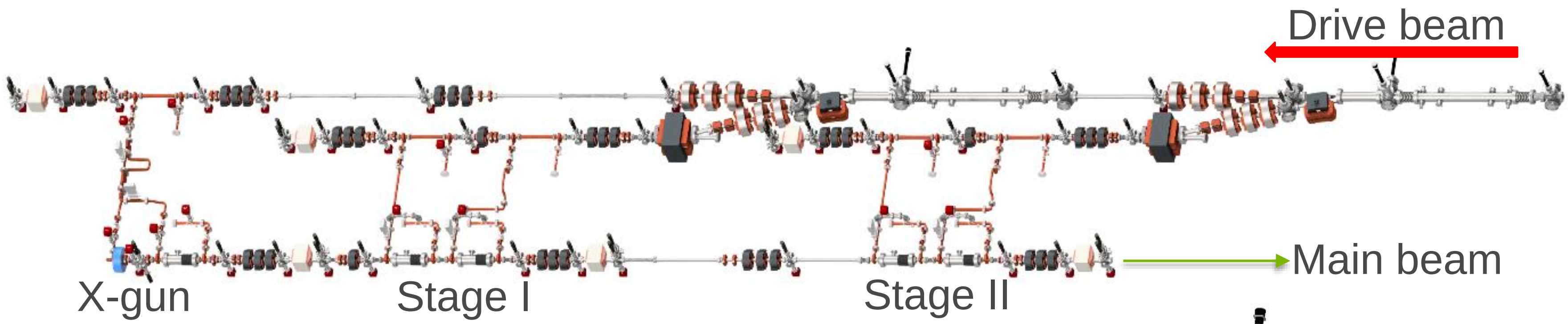


Fast filled accelerator

Yuliang Jiang, et al, PRAB **24**, 112002 (2021)

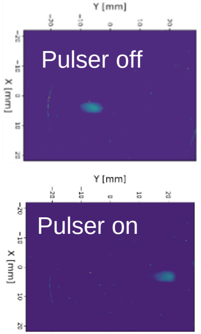
NEAR TERM: 0.5GeV DEMONSTRATOR

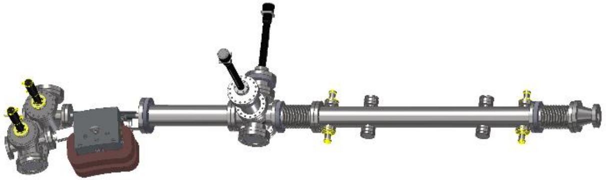
- **Demonstrate key technologies of SWFA based TeV class linear collider**
- **AWA-II**
- **Potential to be converted to a compact ICS gamma source**



CTE:

1. GW level rf power
2. 300MV/m of gradient
3. Drive beam distribution





Fast kicker and septum

SINGLE BUNCH APPLICATIONS

If we use this as a Figure of Merit for an accelerating structure,

Def: **RF usage rate**

	Klystron power	Energy gain	MeV/(MW*Trf[us]) per Str.
S-band standard	50MW, 3us	50MeV in 3m (16.7MeV/m)	0.33
NLC Xband	75MW x 2=150MW, 1.6us, compress to 450MW, 400ns	270MeV in 6.5m (6 structures, total 5.4m structures,83% fill factor, 50MeV/m)	1.5
CLIC-Kly Xband	53MW x 2=106MW, 2us, compress to 170MW x 2=340MW, 334ns	276MeV in 4.6m (80% fill factor, 8 structures, 0.46m ea., 75MeV/m)	2.43
CLIC-TBA Xband	132MW from ea. PETS, 176.5ns	46MeV in 57.5cm (80% fill factor, 2 structures, 23cm ea. , 100MeV/m)	2
Short Pulse X-band-TBA	537MW from ea. DPETS, 22ns	36MeV in 37.5cm (80% fill factor, one structure, 30cm, 120MeV/m)	3
Short pulse X-band Kly	20MW, 1us, compress to 250MW, 10ns	40MeV in 25cm (80% fill factor, one structure, 20cm, 200MeV/m)	16*

PULSE COMPRESSOR FOR BIAR

PRL **110,** 115002 (2013) PHYSICAL REVIEW LETTERS week ending 15 MARCH 2013

Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch

O. A. Ivanov,[1,2] M. A. Lobaev,[1] A. L. Vikharev,[1,2] A. M. Gorbachev,[1,2] V. A. Isaev,[1] J. L. Hirshfield,[2,3] S. H. Gold,[4] and A. K. Kinkead[5]

[1]*Institute of Applied Physics RAS, Nizhny, Novgorod 603600, Russia*
[2]*Omega-P, Inc., New Haven, Connecticut 06510, USA*
[3]*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*
[4]*Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375, USA*
[5]*Icarus Research, Bethesda, Maryland 20814, USA*

(Received 21 November 2012; published 12 March 2013)

A high-power active microwave pulse compressor is described that operates by modulating the quality factor of an energy storage cavity by means of mode conversion controlled by a triggered electron-beam discharge across a switch cavity. This Letter describes the principle of operation, the design of the switch cavity, the configuration used for the tests, and the experimental results. The pulse compressor produced output pulses with 140–165 MW peak power, record peak power gains of 16:1–20:1, and FWHM pulse duration of 16–20 ns at a frequency of 11.43 GHz.

Active Pulse Compressor--- limit by BD of the switch for very high power

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 120401 (2022)

***X*-band two-stage rf pulse compression system with correction cavity chain**

Xiancai Lin, Hao Zha, Jiaru Shi,* Yuliang Jiang, Fangjun Hu, Weihang Gu, Qiang Gao, and Huaibi Chen

Department of Engineering Physics, Tsinghua University, Beijing CN-100084, China and Key Laboratory of Particle and Radiation Imaging, Ministry of Education, Tsinghua University, Beijing CN-100084, China

(Received 19 September 2022; accepted 28 November 2022; published 13 December 2022)

A compact *X*-band two-stage rf pulse compression system has been successfully designed, fabricated, and tested at Tsinghua *X*-band high-power test stand. The pulse compression system consists of a correction cavity chain, a first-stage, and a second-stage storage cavity. The correction cavity chain adopts a new design whose transmission loss and length are reduced by half compared with the old one. A detuning device is applied to the second-stage storage cavity so that the system can work in one-stage or alternatively two-stage compression mode. In the one-stage compression mode, a 150-ns, 70-MW flattop output, with a standard deviation of 1.5% in amplitude and 1° in phase, was generated with a gain factor of 3. In the two-stage compression mode, a first two-stage pulse compression experiment with correction cavities in the *X* band was performed. A peak power of 320 MW was achieved with a gain factor of 9.7 and full-width at half-maximum pulse durations of 53 ns.

Passive Pulse Compressor--- limit by system bandwidth for very short pulse length.

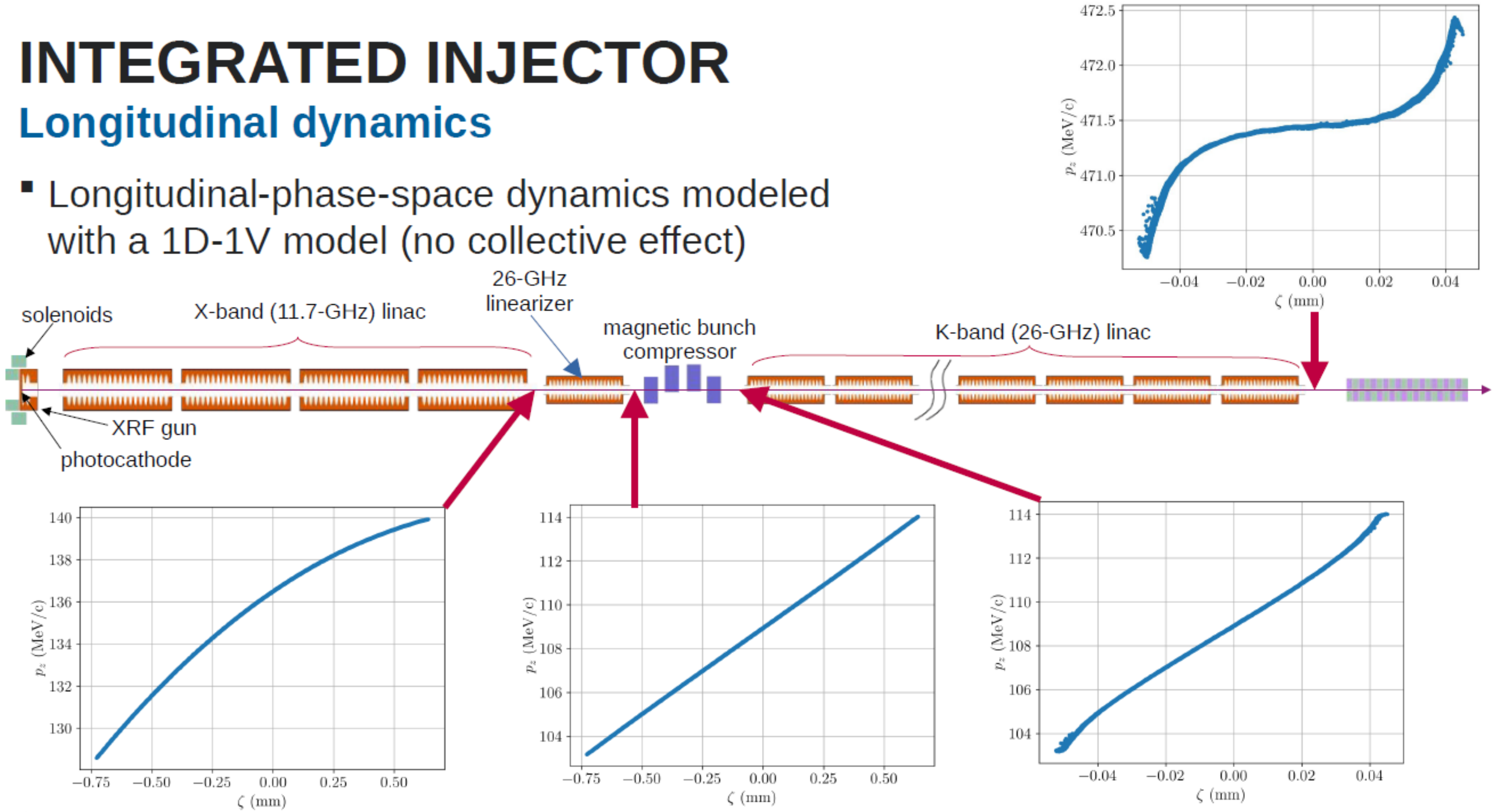
KLYSTRON-BASED XFEL IN BIAR

From P. Piot, Channeling 2023

INTEGRATED INJECTOR

Longitudinal dynamics

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



SUMMARY

- **DISCOVERED NEW ACCELERATION REGIME: BIAR, WHICH HAS BENEFITS OF**
  - high gradient (>300 MV/m)
  - Fast conditioning
  - low dark current (<1pC)
  - No multipactor for DDA

INTO THE FUTURE

- New linac for real beam acceleration in BIAR
- 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 OUR TEAM!

Gongxiaohui Chen (AWA)
Scott Doran (AWA)
Seongyeol Kim (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 program.