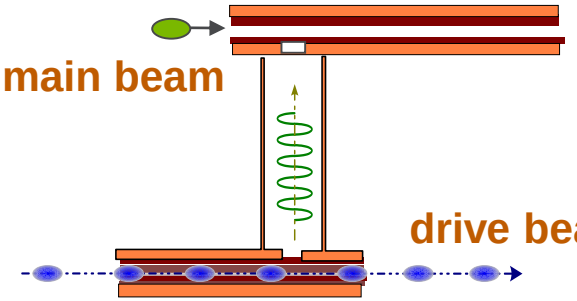
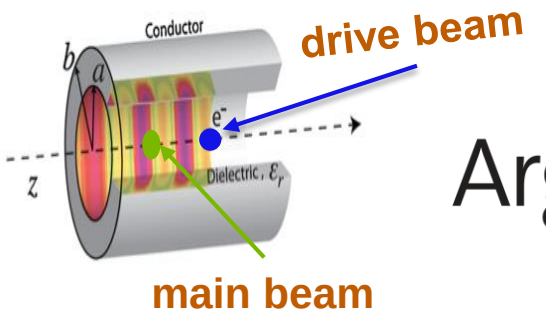



Two-Beam Acceleration (TBA)

**STRUCTURE WAKEFIELD ACCELERATION**

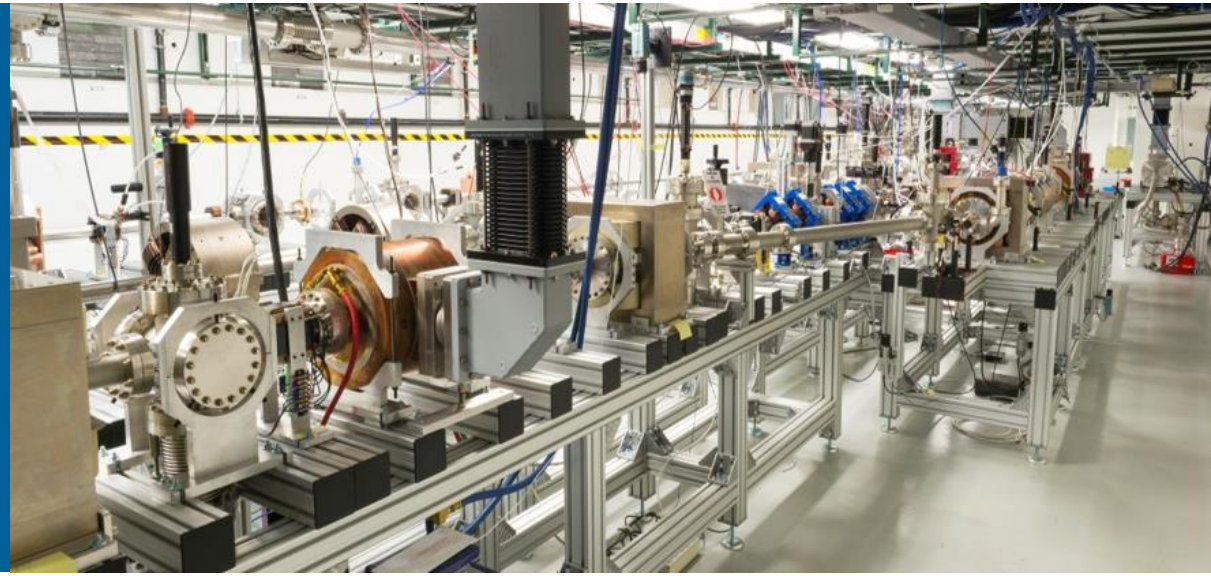



Colinear Wakefield Acceleration (CWA)

Argonne NATIONAL LABORATORY

# HIGH GRADIENT RESEARCH ACTIVITIES AT AWA

***the short-pulse regime***



**JOHN POWER FOR AWA**

https://www.anl.gov/awa

International Workshop on Breakdown Science and High Gradient Technology (HG2021) 19-21 April 2021

# WHY LISTEN TO THIS TALK? (i.e. motivation)

**A personnel perspective and a VERY INCOMPLETE HISTORY of our field:**
**Slow and steady progress on *THE QUEST FOR HIGH GRADIENT***

## Workhorse (~10 MV/m, 1950's to 1990's)

- **The SLAC Blue Book, 1968** (Richard B. Neal, Gregory Loew, Doug Dupen, Harry Hoag, Pief Panofsky)
- **Linear Accelerators,1970** (P. Lapostolle and A. Septier)
- **Kilpatrick Limit** (Theory); Juwen Wang & Greg Loew (SLAC, Expt)

## Near term R&D (~100 MV/m, 1990's to present)

- **NLC, JLC, CLIC,** (SLAC, KEK, CERN)

**PULSE LENGTH DEPENDENCE**
(CLIC, SLAC, KEK)

## Long term R&D (~GV/m??, ~2005 to the present)

- **The Age of Exploration**

**THEORY**
P. Wilson, F. Djurabekova, Y.Ashkenazy, etc

**MATERIAL**
- Dielectric (AWA/Euclid)
- Metallic (Hard/Soft Copper (SLAC), Refractory Metals (CLIC), …)

**NOVEL**
PBG, Metamaterial (MIT, SLAC, AWA, LANL)

**GEOMETRY**
cylindrical, planar

**TEMPERATURE**
Room Temp, Cold (77 K)m Cryo (<77K)
SLAC/UCLA Top Gun

**FREQUENCY**
MHz, GHz,THz
(MIT/SLAC/Radiabeam)

# BREAKDOWN RATE (BDR)

In order to limit luminosity loss due to this effect to less than 1%, BDR < 3e−7 for CLIC at 3 TeV at 100 MV/m

S. Doebert et al.,PAC'05
https://accelconf.web.cern.ch/p05/PAPERS/ROAC004.PDF

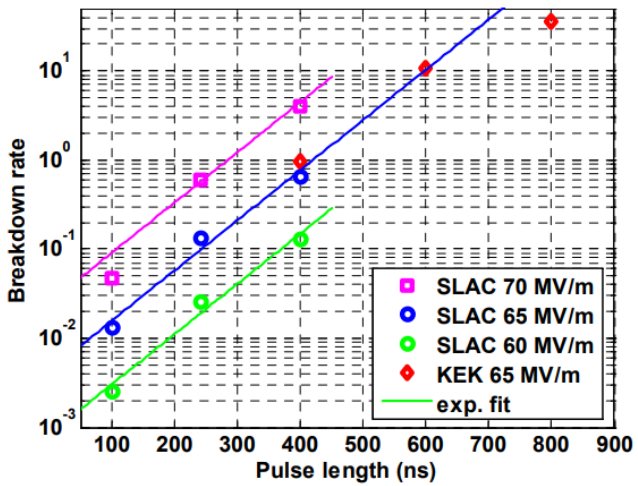
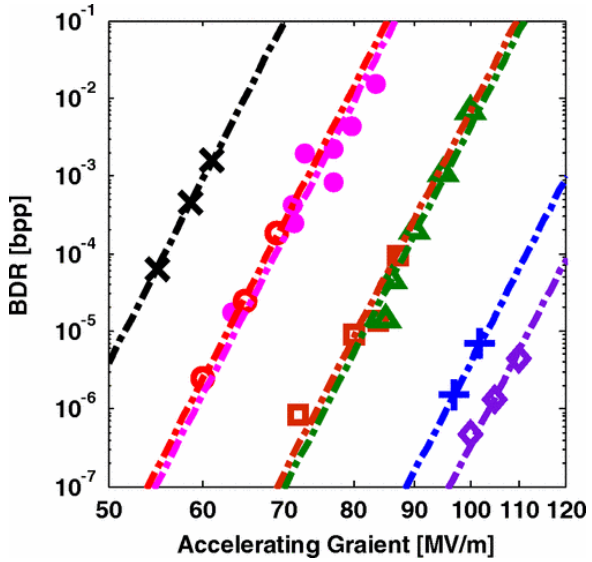


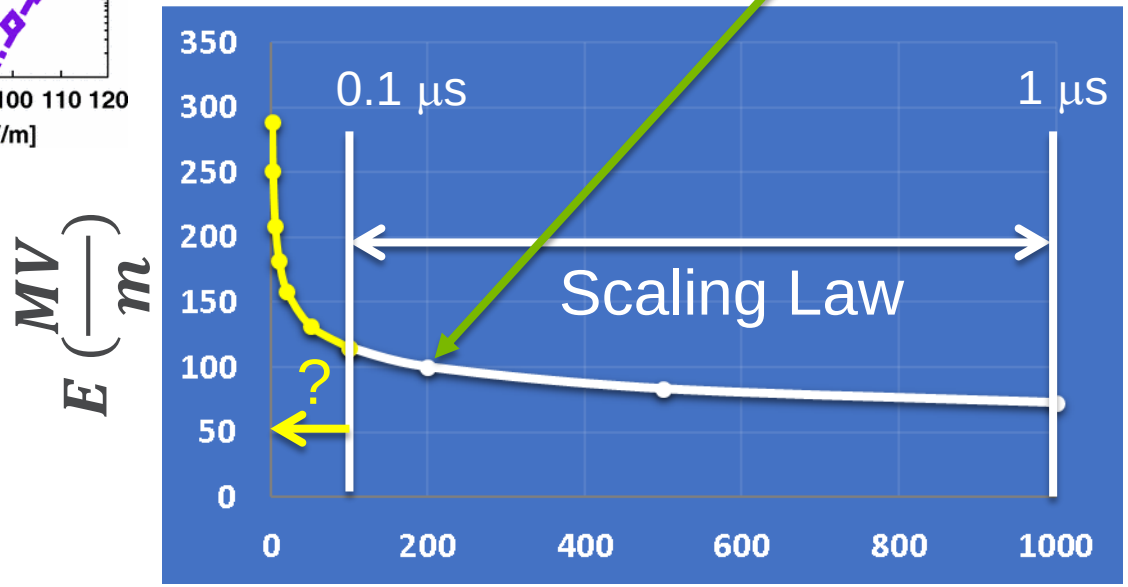

Figure 4: Pulse length dependence of the breakdown rate.

A. Grudiev, S. Calatroni, and W. Wuensch
Phys. Rev. ST Accel. Beams 12,102001 (2009)




$$BDR \propto E^{30}\tau^{6}$$

**3e−7, 100 MV/m, 200ns**




## SHORT-PULSE REGIME

- **New physics:** Scaling law is a power-law approximation of exponential, underlying mechanism may change
- **Applications:** Challenges to operate in the short-pulse regime: efficiency, broadband couplers,, stability, etc.

# HIGH-GRADIENT *STRUCTURE WAKEFIELD ACCELERATION* AT THE AWA FACILITY

**OUTLINE**

- **SWFA**
- **AWA Facility**
- **Recent R&D Highlights**
  - Exploring breakdown physics in the short-pulse regime
  - Applications in the short-pulse regime
- **Summary**

# INTRODUCTION TO SWFA

- Two Beam Acceleration – TBA
- Collinear Wakefield Acceleration - CWA

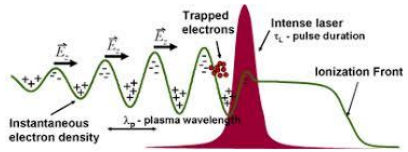
# STRUCTURE WAKEFIELD ACCELERATION (SWFA) – CONTEXT

## Advanced Acceleration Concepts

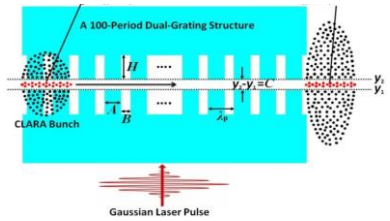
Energy Source

Laser pulse

**LWFA**
(Laser WF Accelerator)

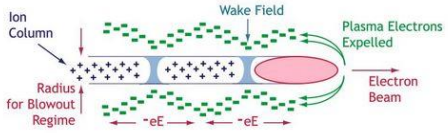



**DLA**
(Dielectric Laser Accelerator)

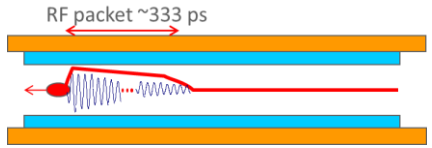



Beam driven

**PWFA**
(Plasma WF Accelerator)




**SWFA**
**(Structure WF Accelerator)**



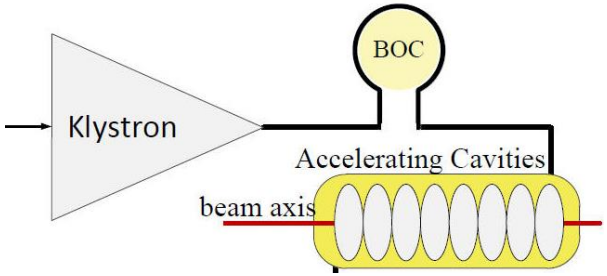

Plasma

**Structure**

**Medium**

## Externally Driven RF Acceleration Structures

RF Driven




**Structure**

**Note:** there are many overlaps between beam-driven and RF structures.

# SWFA OVERVIEW

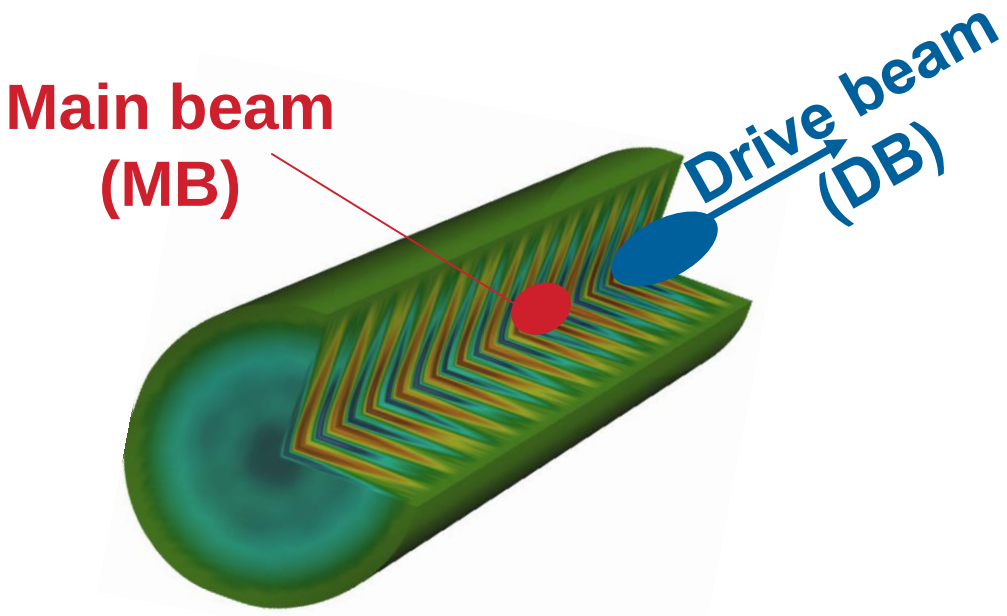
## KEY ≡ Beams & Structures

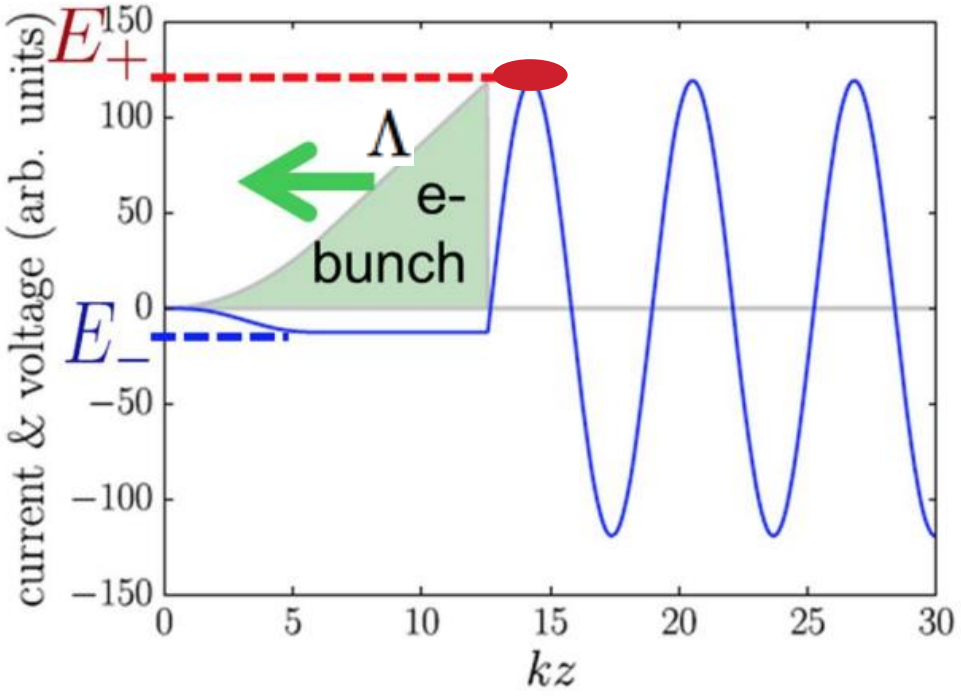
- **Drive bunch** excites EM wave in a slow-wave structure
- Wakefield is used to accelerate properly delayed trailing **main bunch**

$$E_z(\zeta) = \int_{-\infty}^{\zeta} \Lambda(\zeta - \zeta') \sum_{n,m} w_n^{(m)} \cos(k_n^{(m)} \zeta') d\zeta'$$

Drive Bunch distribution

Structure Modes

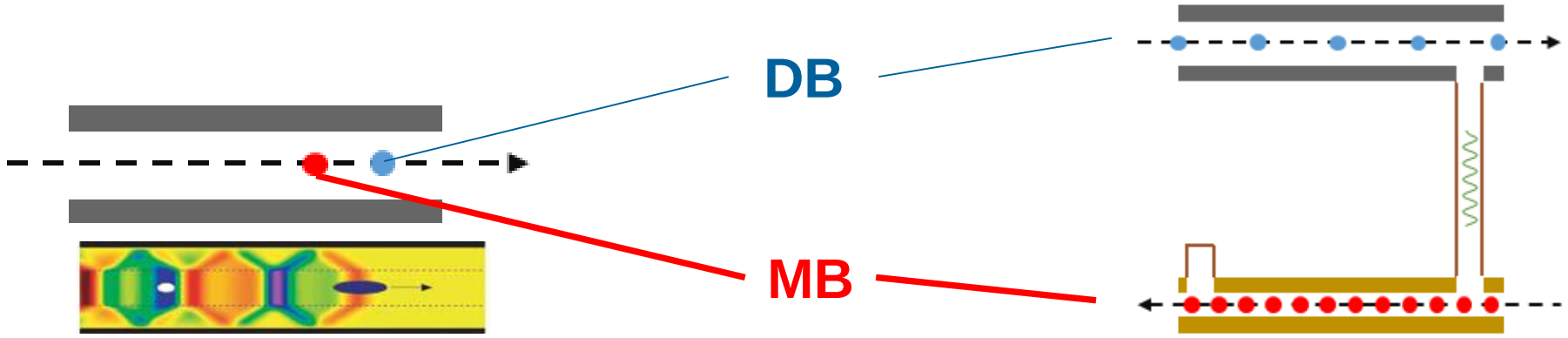


# ELECTRON BEAM DRIVEN SFWA

## Collinear Wakefield Acceleration

## Two Beam Acceleration




*PWFA-like*

**CWA uses single beamline**

- **Pros**
  - **Cheaper? One beamline, One structure, No couplers**
- **Cons**
  - **Challenges associated with combined beam dynamics of drive and witness bunches.**

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

*RF driven -like*

**TBA uses two parallel beamlines**

- **Pros**
  - **Decoupled drive/main beam optics design**
  - **Two different structures allow simultaneous high gradient and high efficiency acceleration**
- **Cons**
  - **Cost?**

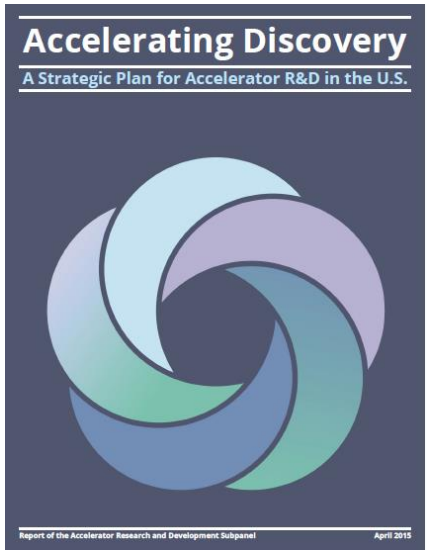
CLIC CDR: https://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
W. Gai, C. Jing, J.G. Power, *JPP* **78**, 339-345 (2012)

# *THE ARGONNE WAKEFIELD ACCELERATOR*

# TEST FACILITY

# AWA/SWFA PARTICIPATION IN GLOBAL ACCELERATOR R&D

**2015**: General Accelerator R&D in U.S.

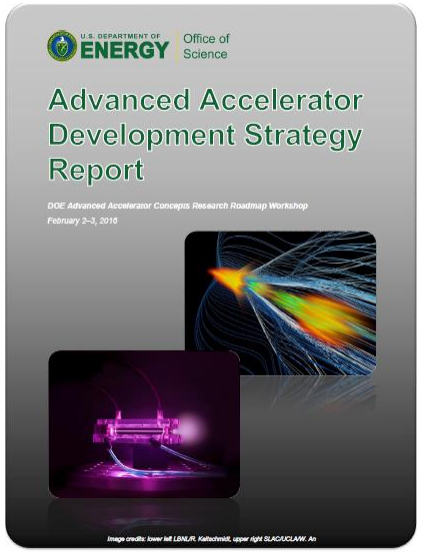



-- AWA facility at ANL has been built to demonstrate the **two-beam concept** and key technologies of wakefield generation by high-charge beams

-- at 200 MV/m to 400 MV/m gradients in the frequency range of 20 GHz to 60 GHz.

https://science.osti.gov/-/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf?la=en&hash=06D02916CED66F6C5B48CF8FA649A32AFA0547C8

**2016**: Advanced Accelerator Concepts Roadmap in U.S.

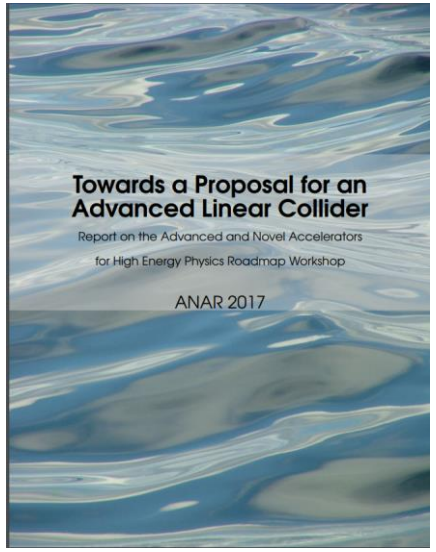



-- AWA facility was transformed into a flexible, state-of-the-art LC testbed.

-- **DOE Target:** LC operating at gradient of 300 MeV/m and powered by gigawatt-scale, short RF pulse (20 ns)

https://www.osti.gov/biblio/1358081

**2017**: ANAR Workshop: Application of AAC to Global HEP

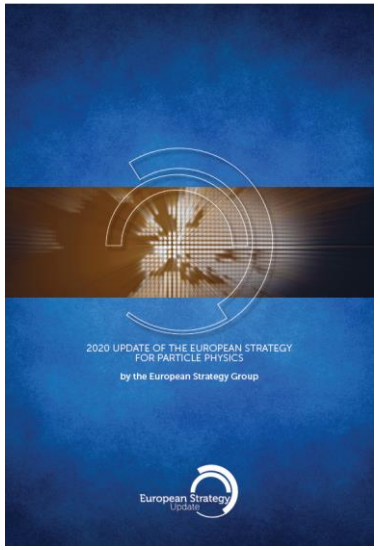



-- SWFA's have primarily focused on GHz-scale TBA configuration

-- More recently, structures utilizing different materials, geometries, and higher frequencies

https://arxiv.org/pdf/1901.10370.pdf

**2020**: The European Strategy Group. (for particle physics.)




-- Plasma wakefield acceleration and other high-gradient accelerating structures,

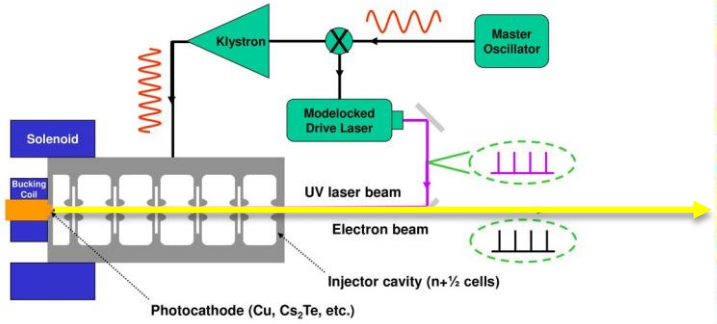
-- The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.

https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

# AWA R&D PROGRAM

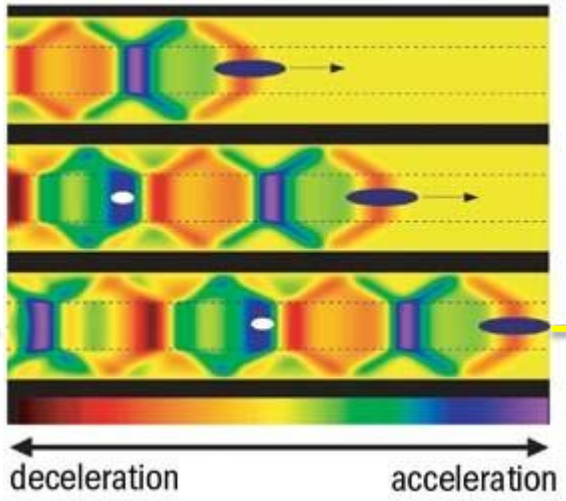
Electron Source → Advanced Accelerator Concept → Beam Physics → APPLICATION

RF Photoinjector




High brightness electron source, novel cathodes

SWFA




High-gradient & high-efficiency SWFA & PWFA acceleration

Double Emittance Exchange

Beam manipulation
Beam Diagnostics

# THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

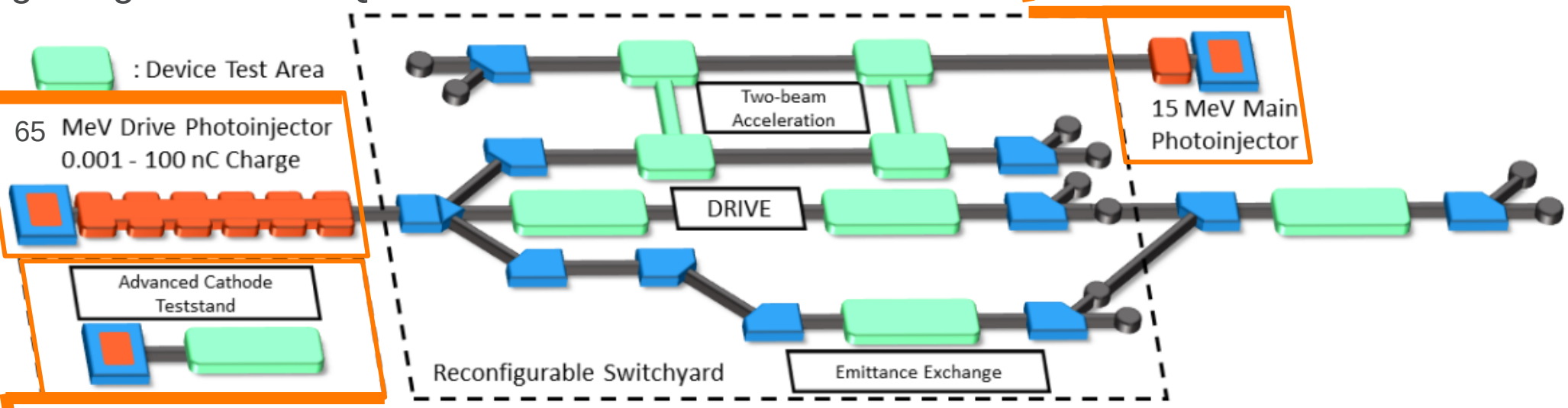
## 3x 1300 MHz RF photocathode guns

### DRIVE

- 65-MeV Drive photoinjector ($Cs_2Te$) linac
  - World's highest-charge (e.g. 100 nC) photoinjector
  - High brightness low-Q beams

### WITNESS

- 15 MeV photoinjector linac
  - Produces bright beam acceleration
  - Supports low-energy experiments



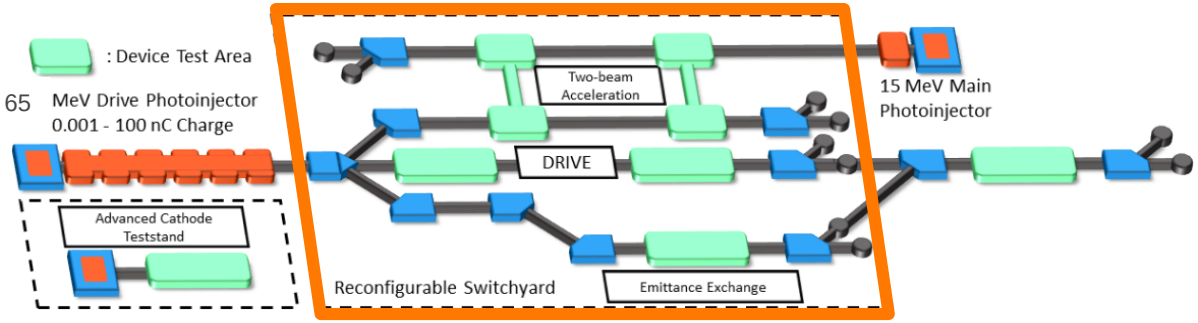

### ACT

- 1-5 MeV RF gun
  - dedicated Argonne Cathode Test stand (photocathode and field emission research)
    - physics of breakdown & diagnostics tests

# THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

## Experimental Switchyard

### THE AWA FACILITY




**Experimental Switchyard**

## UNIQUE FACILITY CAPABILITIES

**World's Highest Charge Photoinjector**

- 0.1-100nC single bunch
- 8 x 75 nC (600 nC) bunch trains (= 42 J)
- 25 kAmp directly out of gun

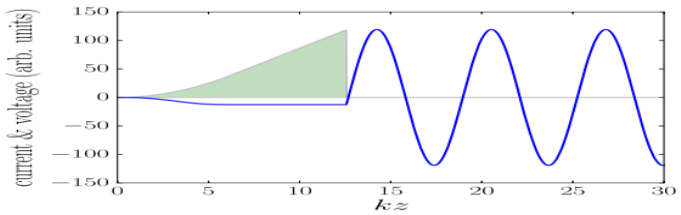
**Independent Drive and Witness Beamlines**

**Dedicated Cathode Test Stand**

**Reconfigurable Switchyard (4 Zones)**

**6D phase space manipulation**

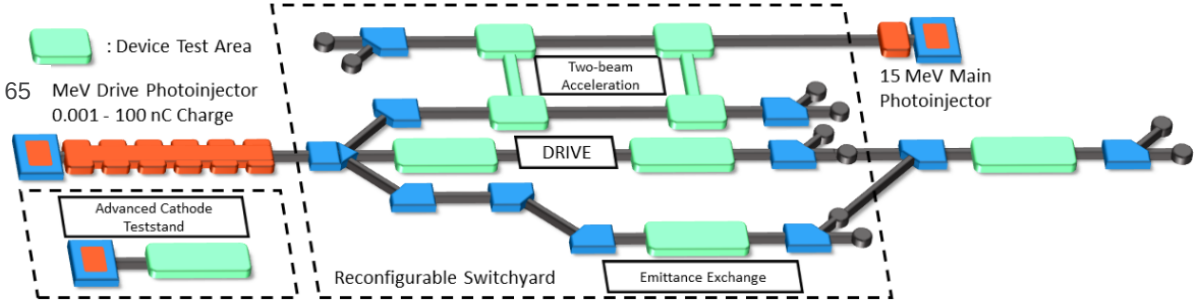
- World's only EEX beamline + Flat-beam transformer
- Arbitrarily shaped longitudinal profile available




- Single-shot LPS and TPS diagnostics

# THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

## THE AWA FACILITY




## RESEARCH AREAS

### Beam-driven wakefield acceleration

- Structure Wakefield Acceleration (SWFA)
  - Collinear Wakefield Acceleration (CWA)
  - Two-Beam Acceleration (TBA)
- Plasma Wakefield Acceleration (PWFA)

### Accelerator and Beam Physics

- 6D phase space manipulation
- Electron cooling
- Novel diagnostics (Single-shot, AI/ML Virtual, etc.)

### RF Acceleration Technology

- 100's MV/m NCRF short-pulse structures
- 100's MW NCRF short-pulse power source

### Electron sources

- Photo and field emission. High brightness beams.

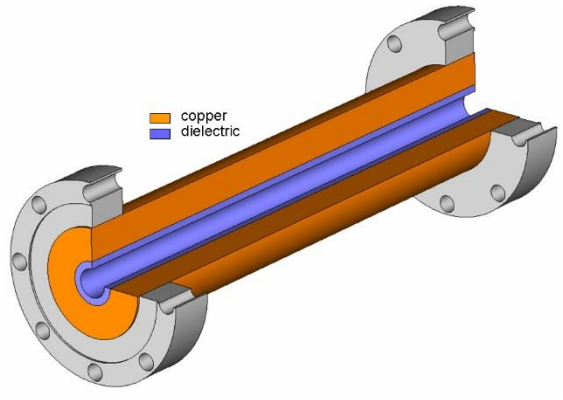
### Machine Learning

- ML for machine control, virtual diagnostics and physics

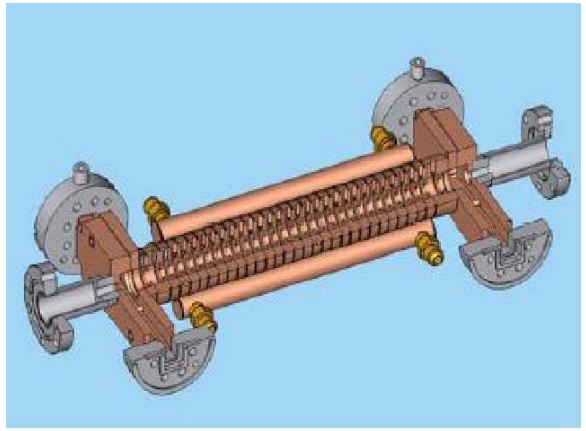
# THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

## Structure Development

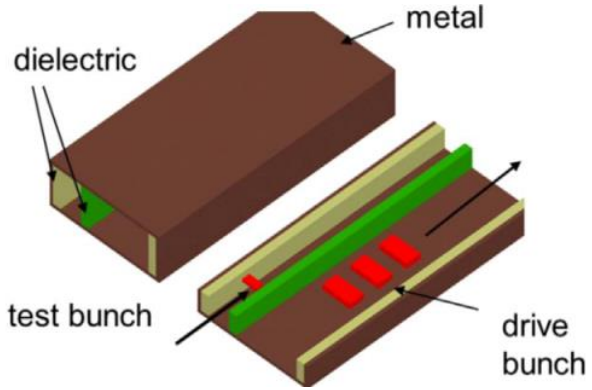
### Dielectric loaded structures



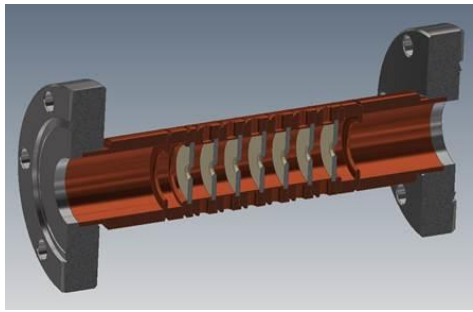

### Iris loaded structures



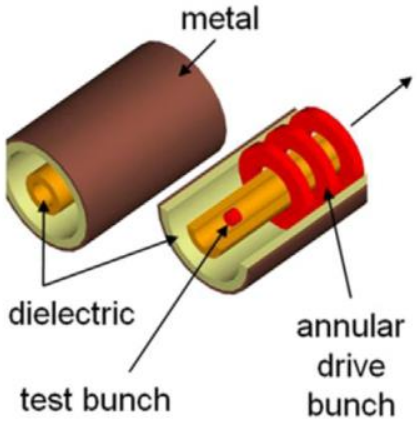
### 2-channel rectangular dielectric



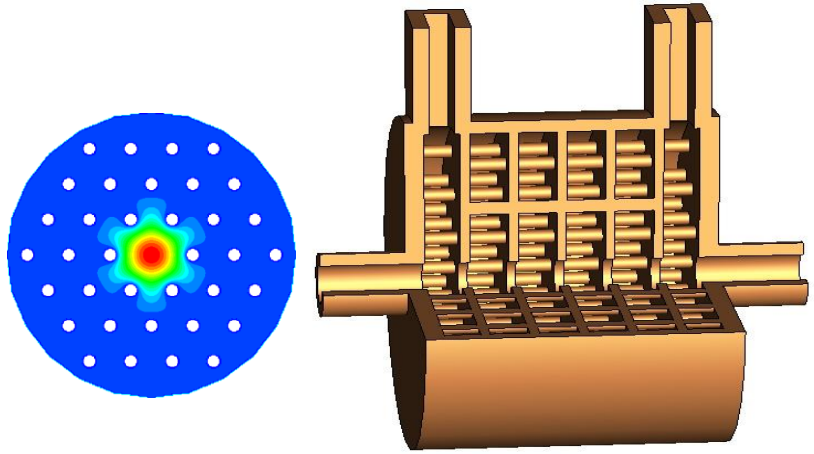

### Dielectric disk accelerator



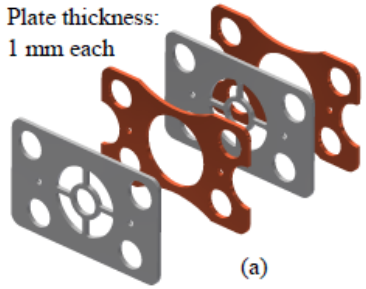
### Coaxial dielectric



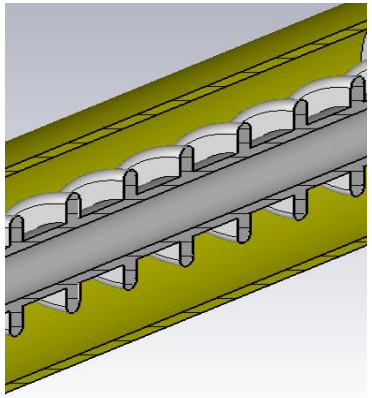

### Photonic band gap structures



### Meta/left-handed structures



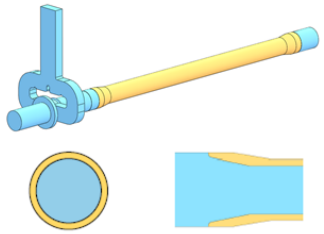

### Cryogenic Dielectric Corrugated accelerator



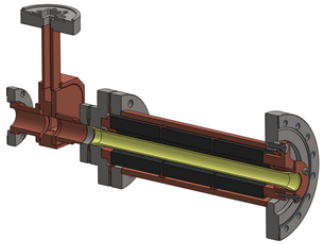
# THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

## RF Structure R&D: Design-to-beam test available

**Physics design**

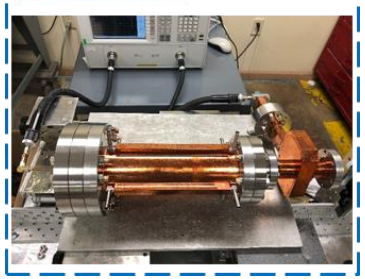


**Mechanical design**

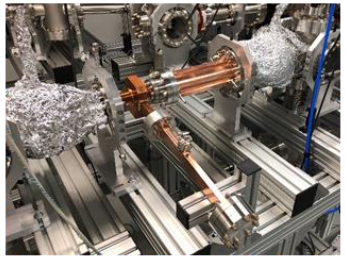


**Fabrication***

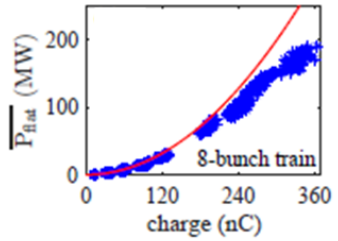
**Bench test**



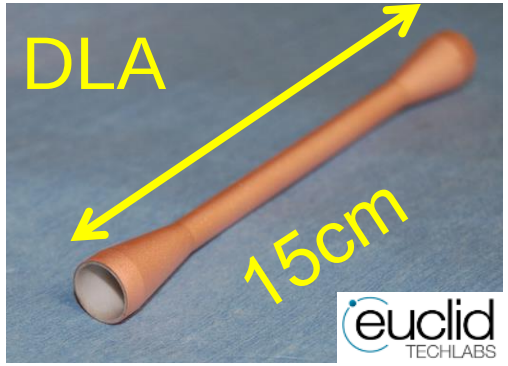
**High power test**

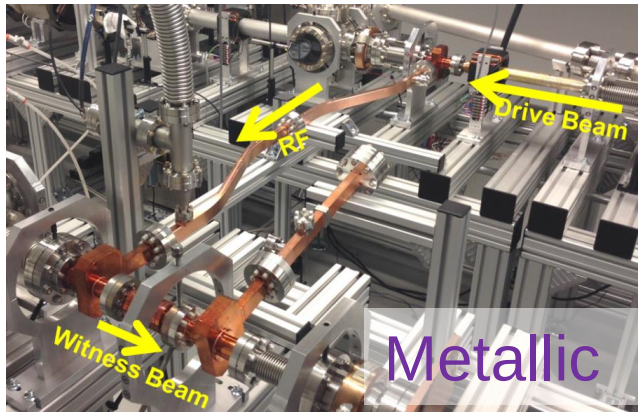


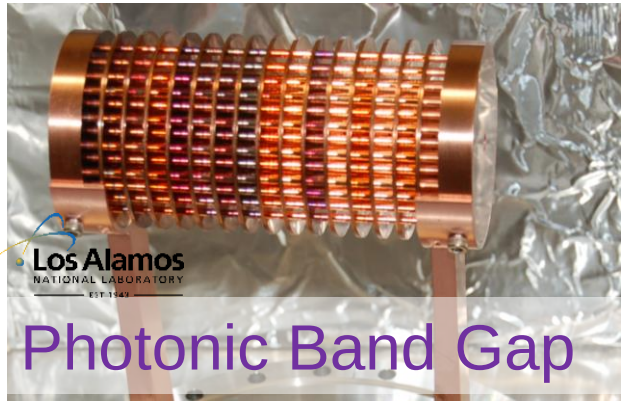
**Data analysis**

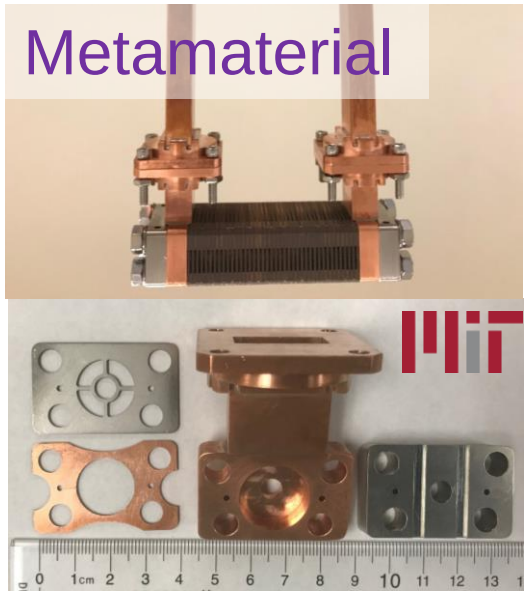



## Examples



← all preliminary results →

# *HIGH-GRADIENT SWFA*

# RECENT PROGRESS IN THE *SHORT-PULSE REGIME*

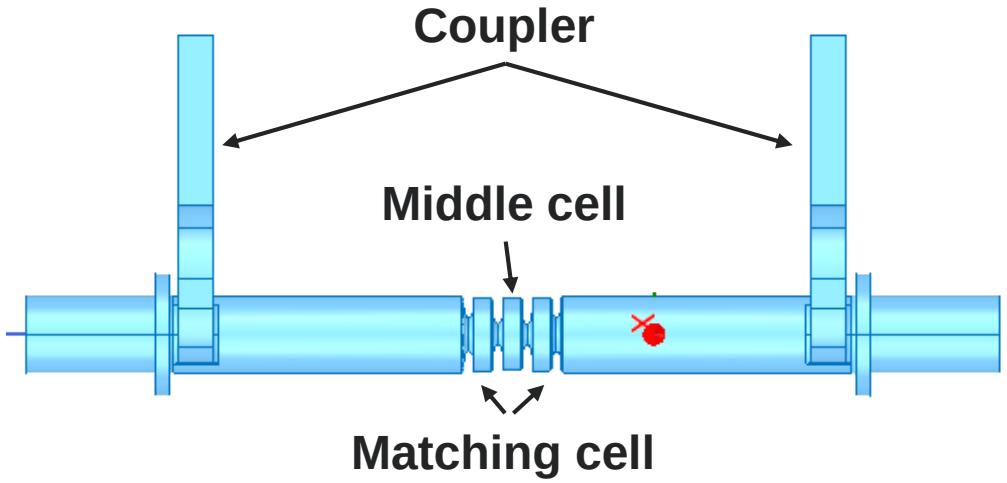
1. Breakdown Insensitive regime
2. 400 MV/m & low-dark current RF TW photocathode gun
3. 500 MW PETS

# 1. BREAKDOWN INSENSITIVE HIGH GRADIENT REGIME

IN THE ***SHORT-PULSE REGIME***

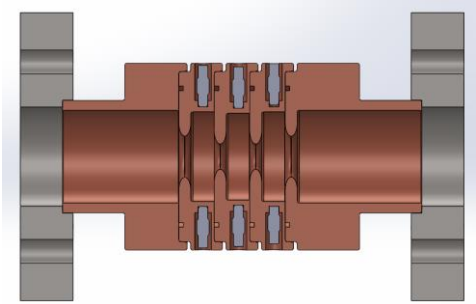
# BREAKDOWN INSENSITIVE HIGH-GRADIENT REGIME
## in the short-pulse regime

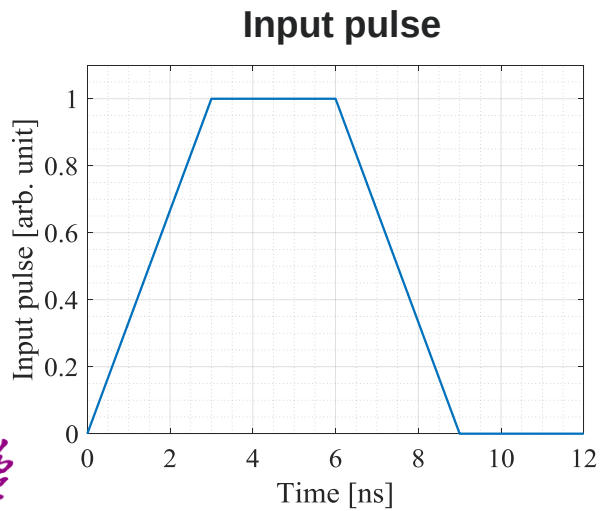
### Design and optimization

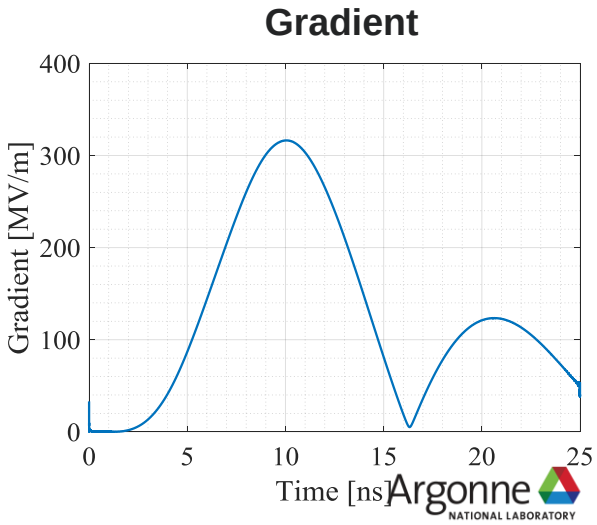



| Parameters | Value | Unit |
|---|---|---|
| Frequency | 11.7001 | GHz |
| 2a | 6.1 | mm |
| 2b | 20.914 | mm |
| t | 2.9 | mm |
| Cell length | 8.5411 | mm |
| Phase advance per cell | $2\pi/3$ | |
| Filling time | 2.506 | ns |
| Group velocity | 0.0114 | c |
| Gradient @ 500 MW input | 389 | MV/m |
| Q | 6072.5 | |
| r/Q | 14047.9 | $\Omega/m$ |
| Es/Ea | 1.59 | |
| Hs/Ea | 3 | mA/V |
| $Sc/Ea^2$ | 0.121 | mA/V |

### Mechanical design

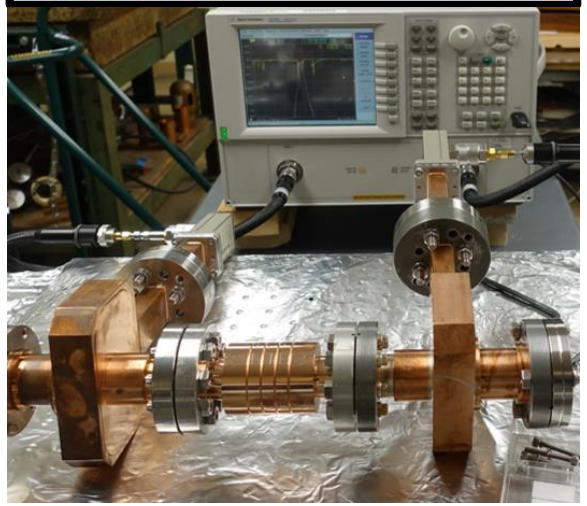




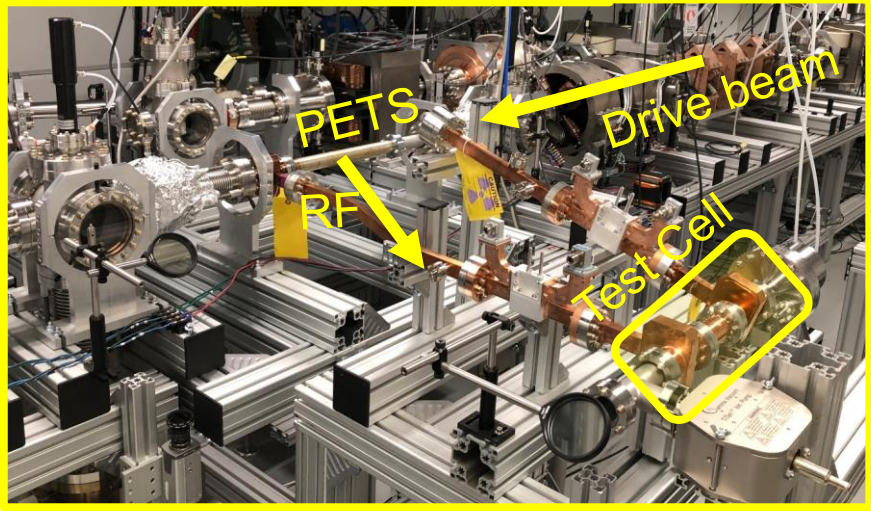



# BREAKDOWN INSENSITIVE HIGH-GRADIENT REGIME
## in the short-pulse regime

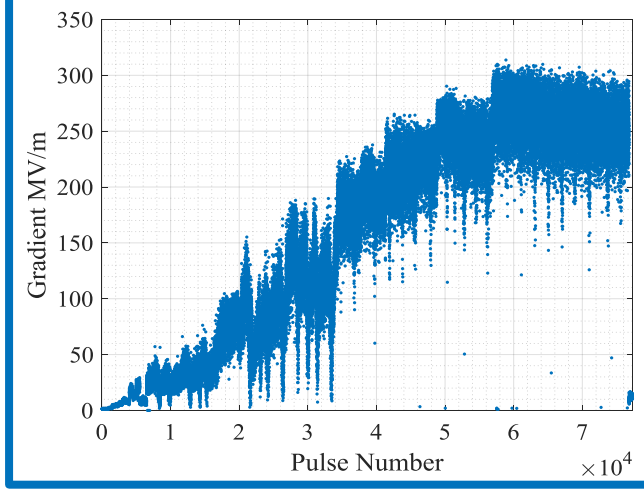
### Cold test



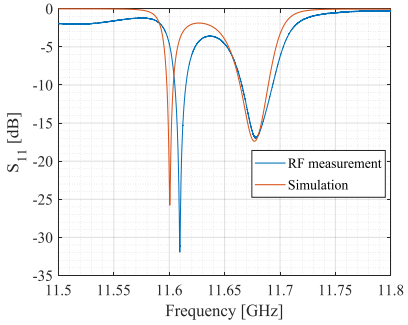
### High power test setup



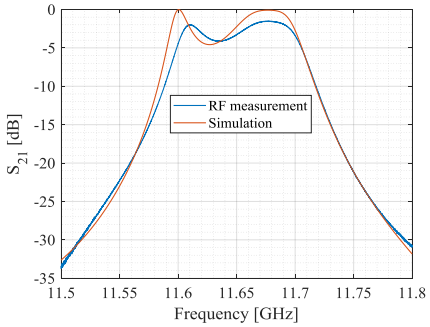

### Conditioning history




**Reflection**




**Transmission**

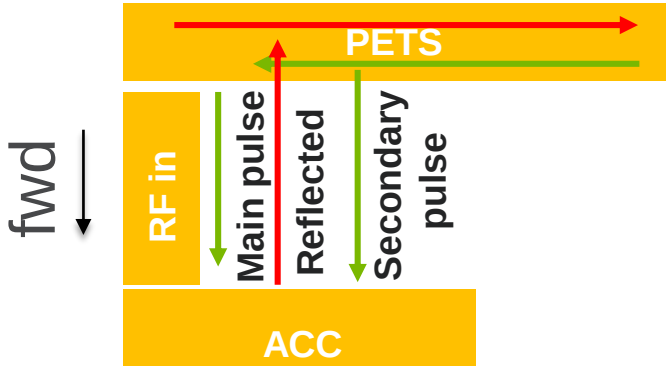



- 400 MW RF power generated from PETS with 450 nC drive beam
- 300 MeV/m gradient in the middle cell, ~500 MV/m peak surface field

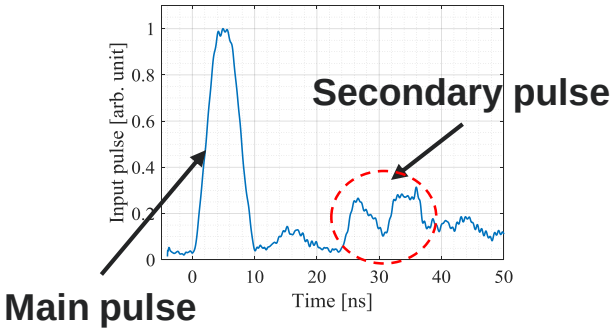
# BREAKDOWN INSENSITIVE HIGH GRADIENT REGIME
## in the short-pulse regime

### data analysis of RF traces

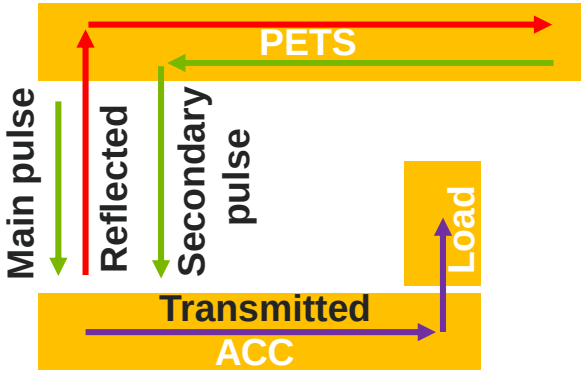
**1. Typical input pulse**

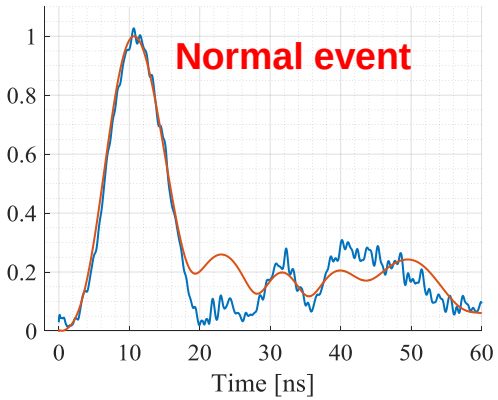


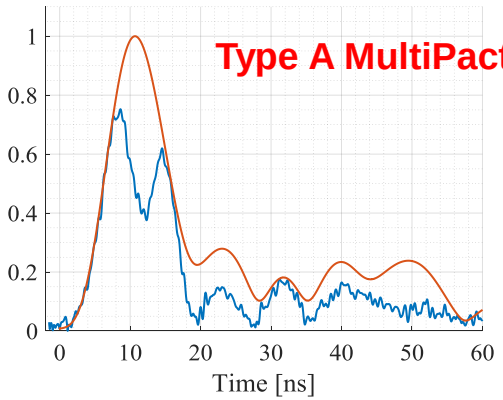

**Typical input pulse (fwd)**

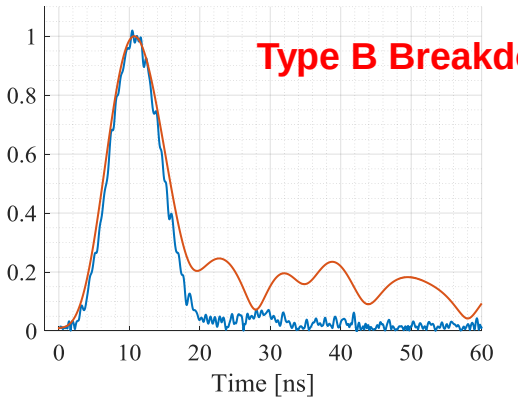



**2. 3 types of transmitted pulses**



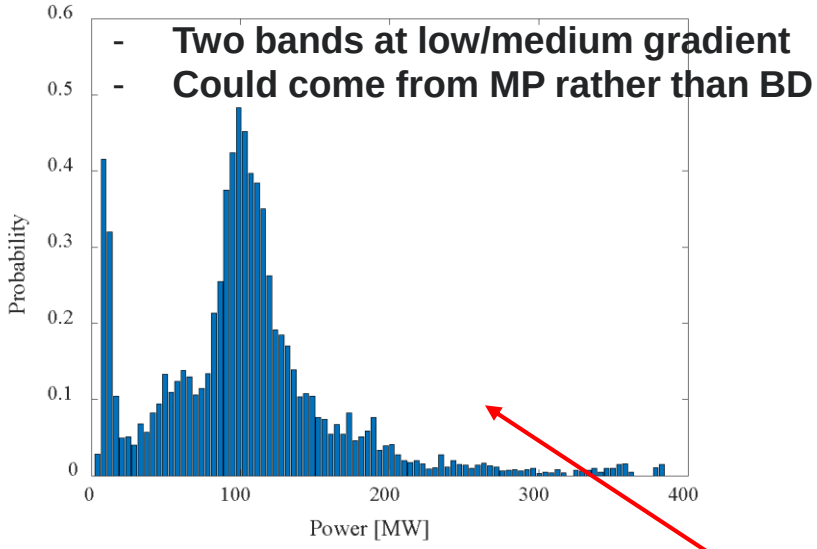



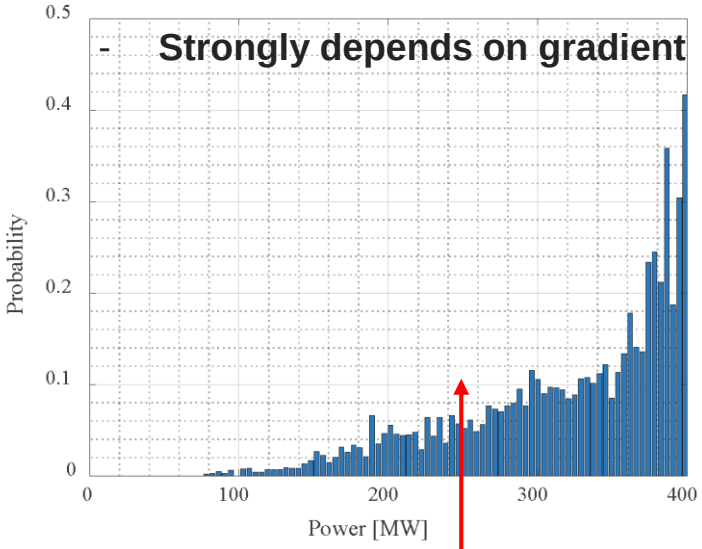



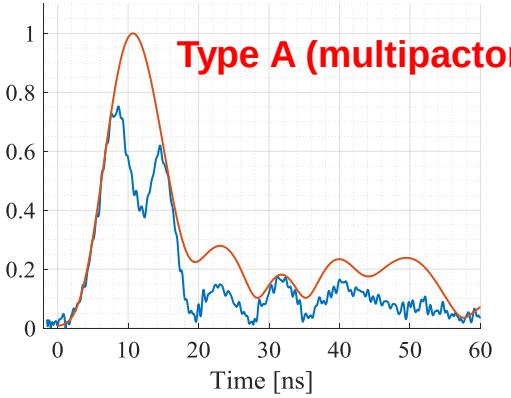



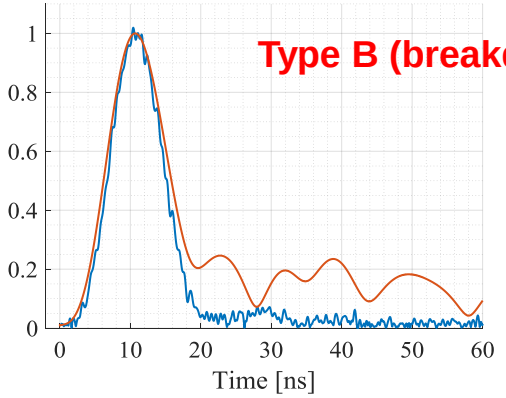
# BREAKDOWN INSENSITIVE HIGH GRADIENT REGIME
## in the short-pulse regime

### Statistics of Type A and B pulses



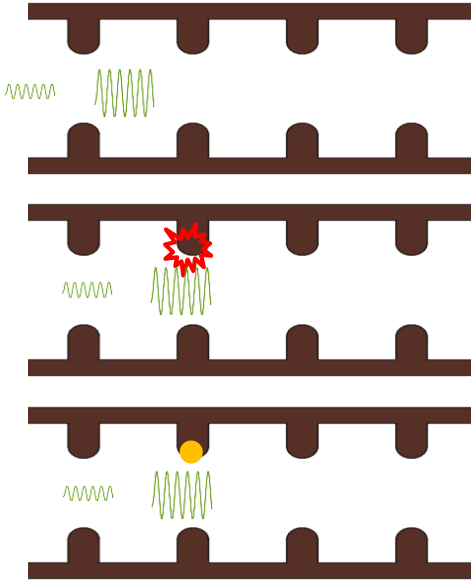



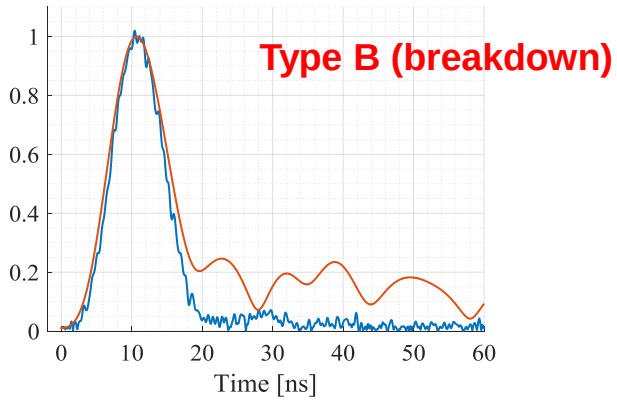




**Note:** strange type of BD event, no collapse of RF pulse. **What is the explanation?**

# BREAKDOWN INSENSITIVE HIGH GRADIENT REGIME
## in the short-pulse regime

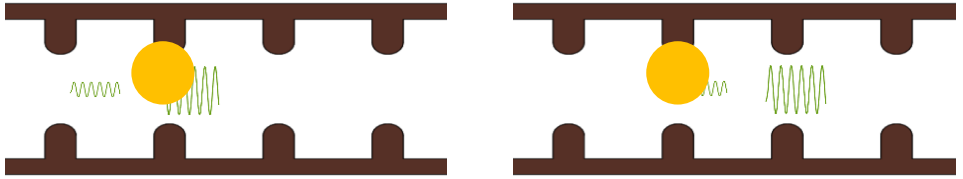
Why is the main pulse not impacted by breakdown?






**Ion speed in cold plasma explosion: $10^{4\text{-}5}$ m/s**

**Time to move 1 mm: at the order of 10 ns**



V. Ziemann, *NIMA* **575**, 539 (2007)

M. Johnson et al, *NIMA* **595**, 568 (2008)

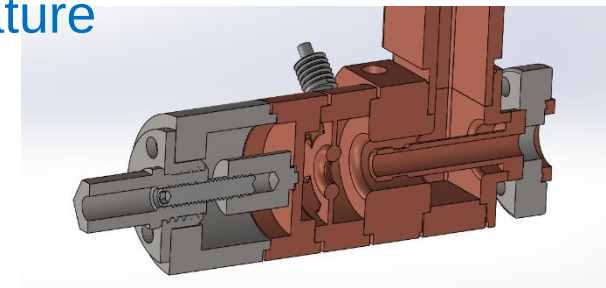
Can we accelerate in this regime?

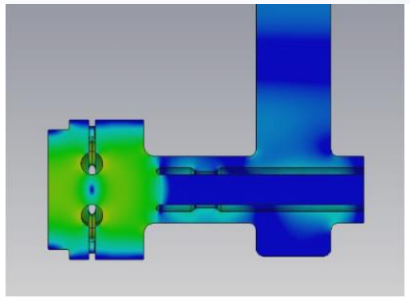
# 2. HIGH-GRADIENT & LOW-DARK CURRENT TRAVELING WAVE PHOTOCATHODE GUN

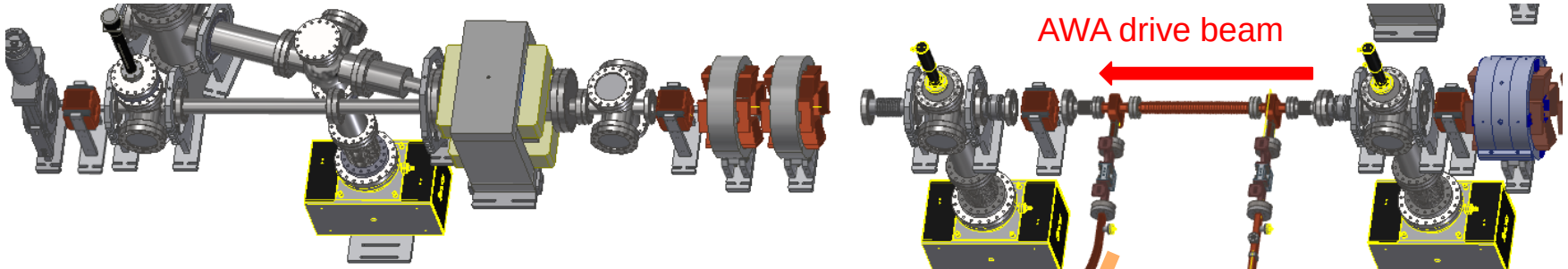
IN THE ***SHORT-PULSE REGIME***

# 2. TRAVELING WAVE PHOTOCATHODE GUN
## in the short-pulse regime

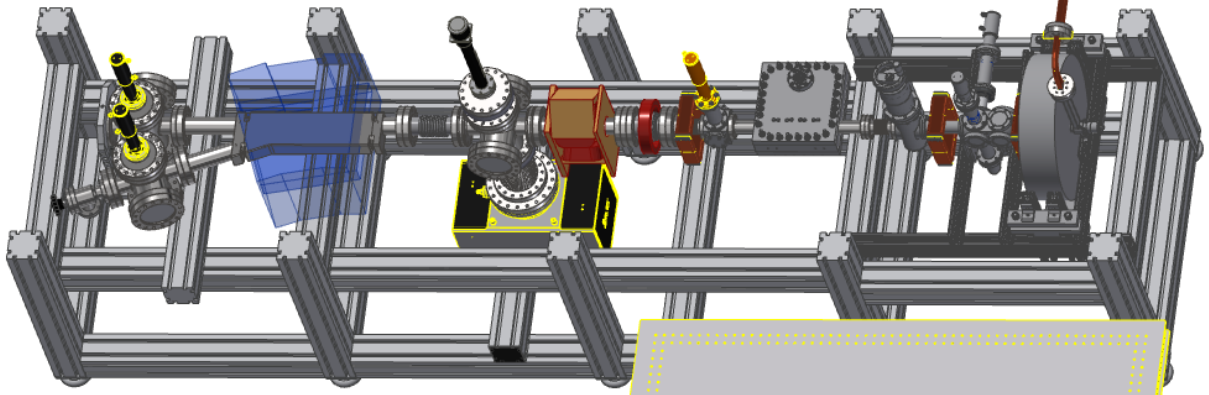
- Ultrashort RF pulse→ unprecedented 400MV/m of gradient at room temperature
- <200nm emittance at 100pC
- Ultrashort RF pulse→ unprecedented low dark current



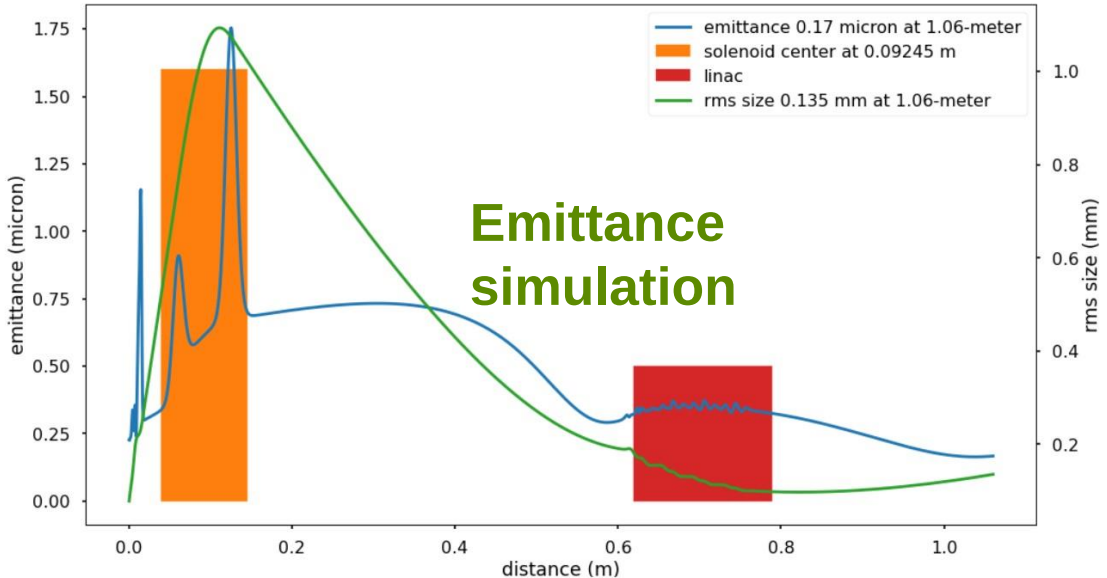





**Part of the beamline layout**



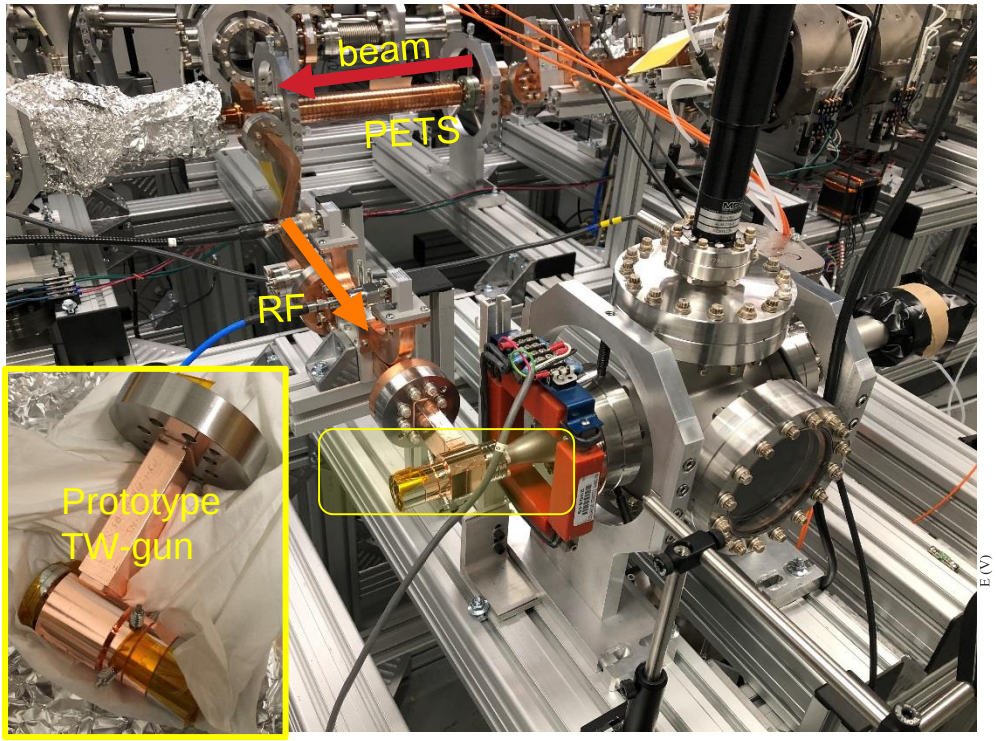
For laser optics

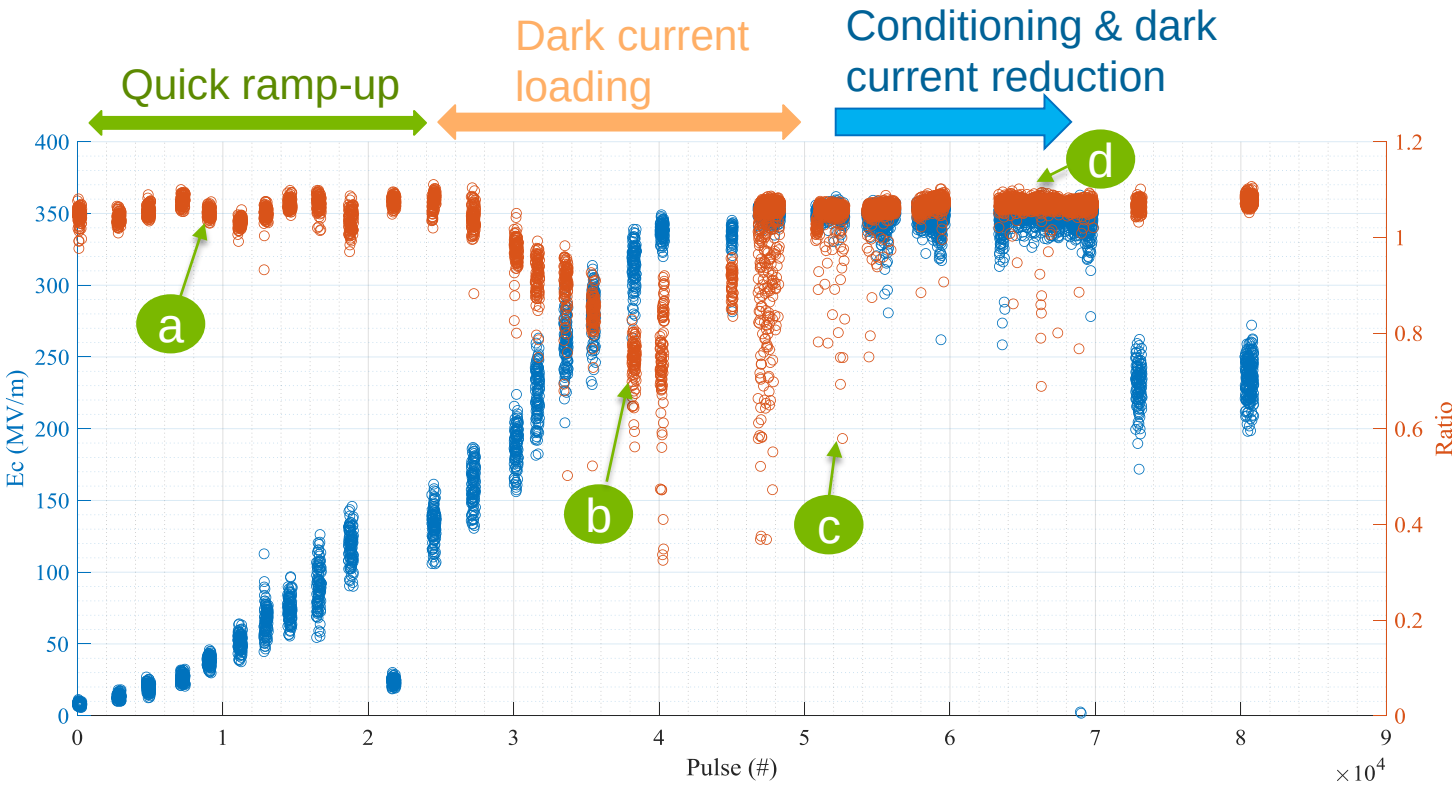


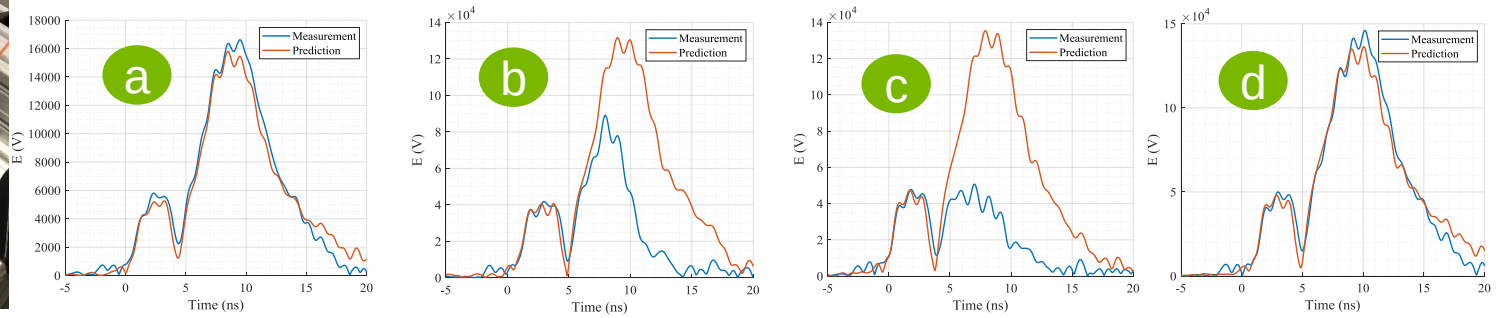

**Emittance simulation**

# BREAKDOWN TEST OF A PROTYPE GUN AT AWA (2020)

- 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**

# 3. 500 MW METAMATERIAL POWER EXTRACTOR

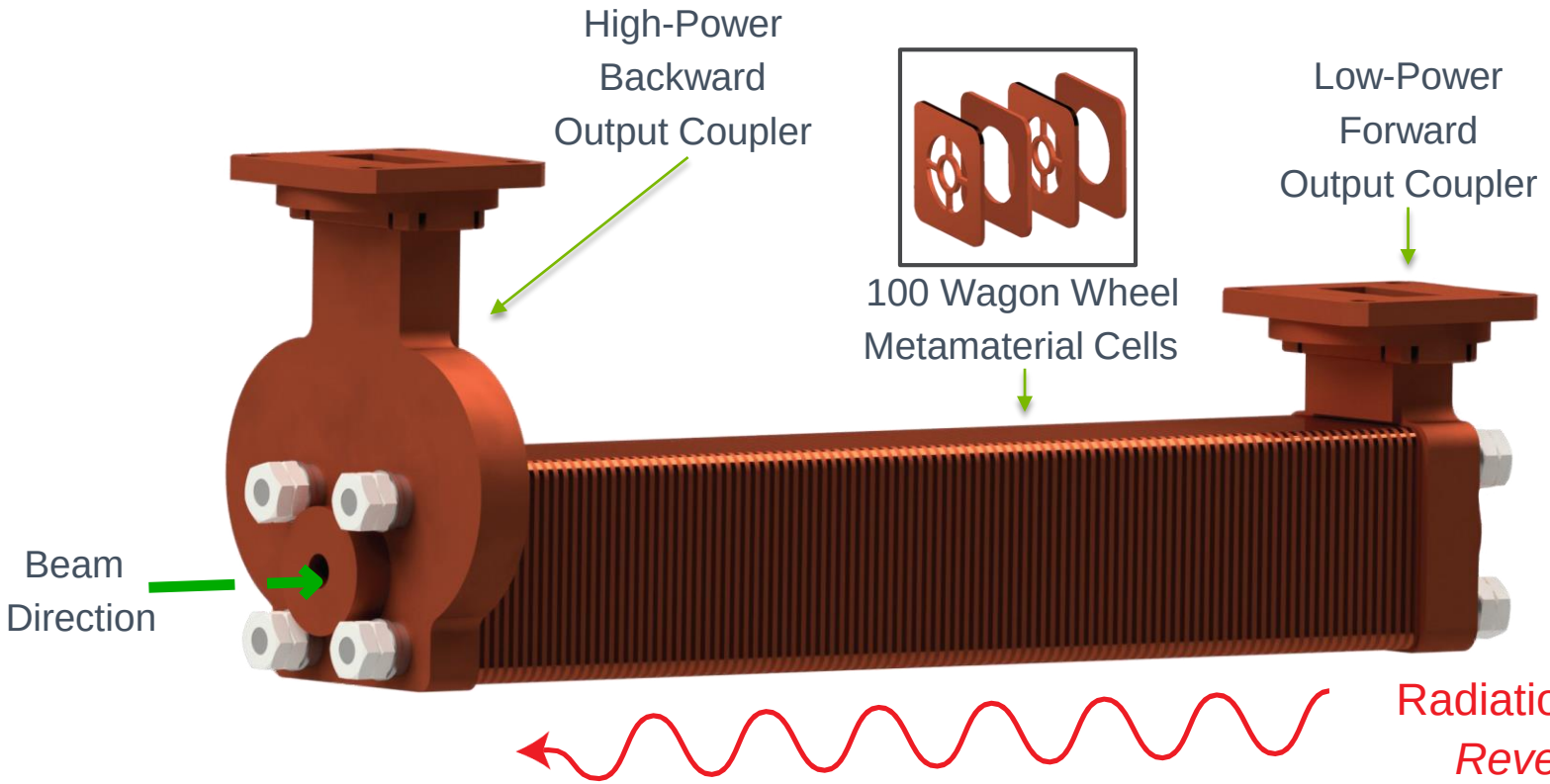
IN THE ***SHORT-PULSE REGIME***

# 3. METAMATERIAL POWER EXTRACTOR
## in the short-pulse regime

**MTM Generation 3: Experimental Design Improvements**

- All-copper construction (Generation 2 used stainless)
- Symmetric high-power output coupler design
- Treatment of plates to mitigate breakdown risk

See Talk by Julian Picard on Wednesday.

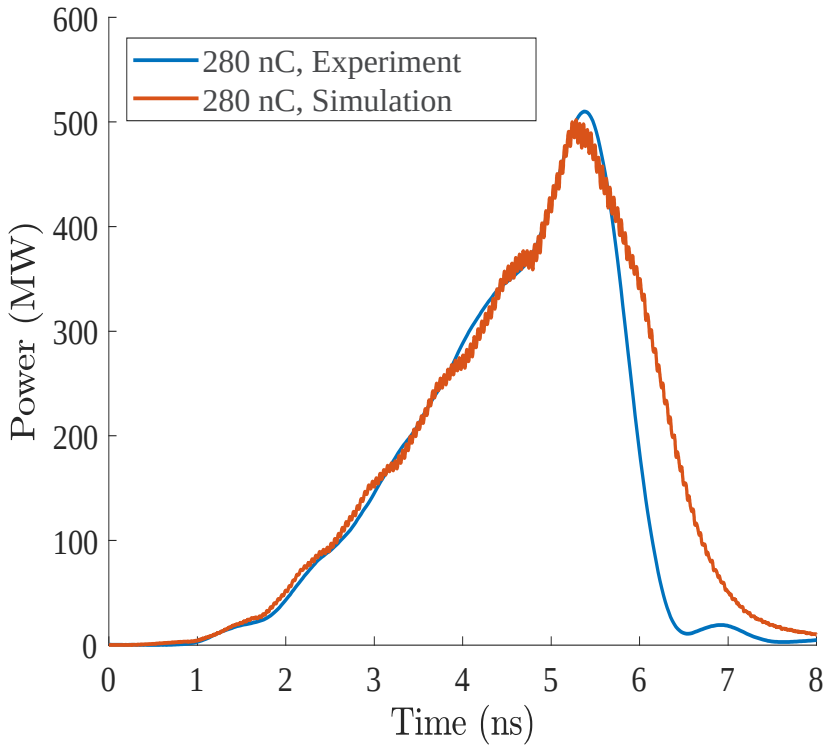


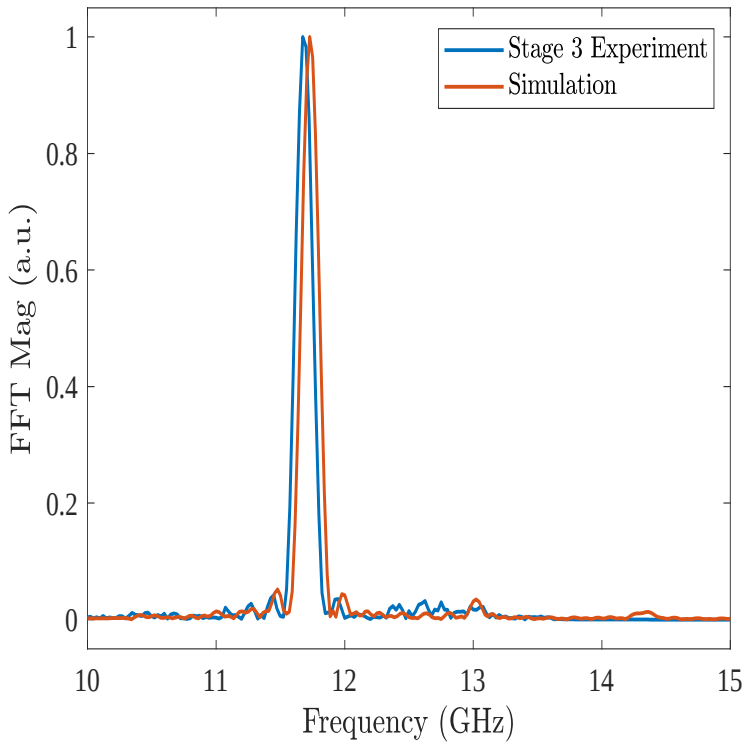

Radiation propagates backwards as *Reverse Cherenkov Radiation*

# METAMATERIAL POWER EXTRACTOR

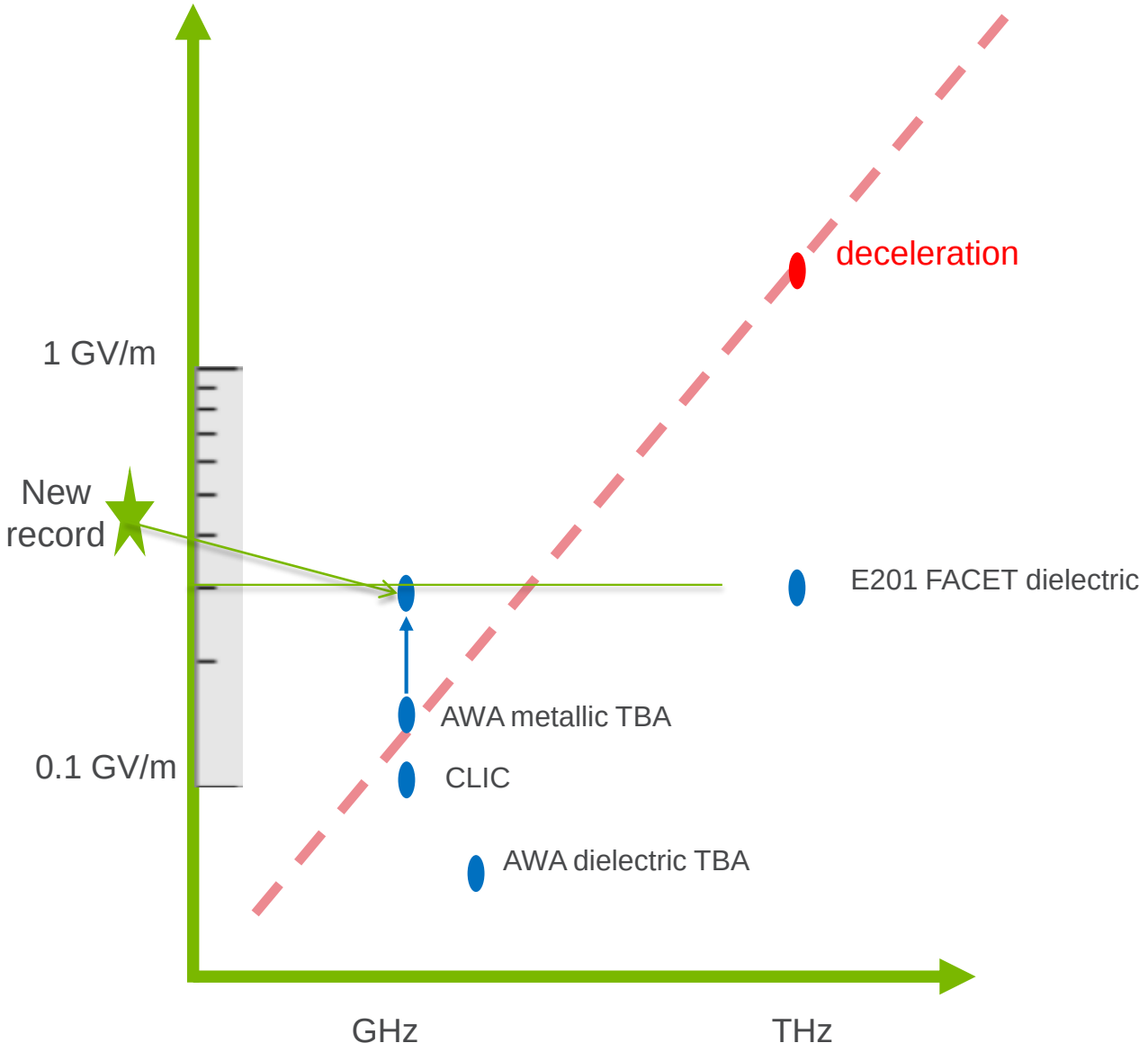
## Stage 3 Experimental Results

- 510 MW achieved at the design frequency of 11.7 GHz from an eight bunch train with 280 nC total charge with no breakdowns observed

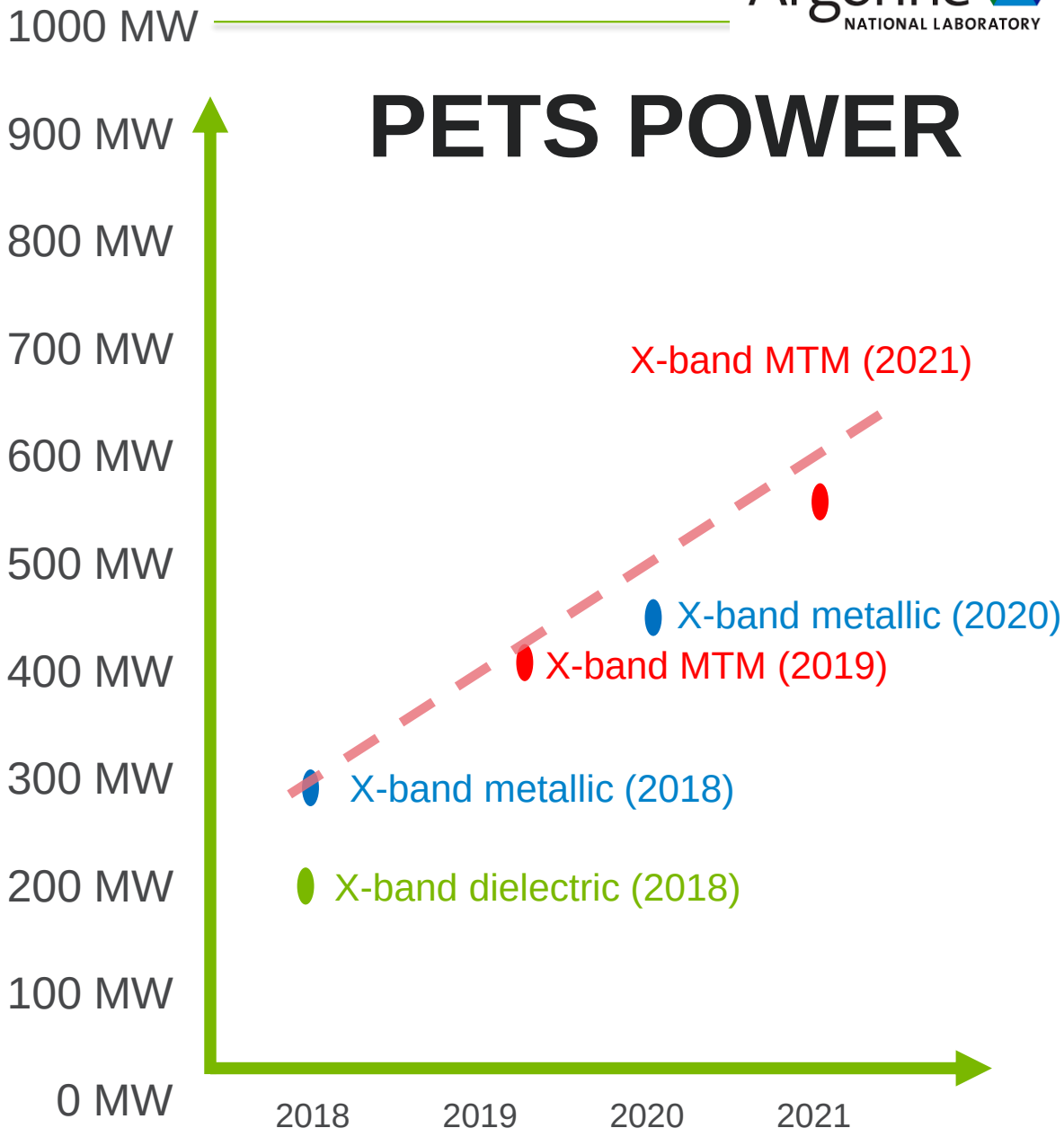


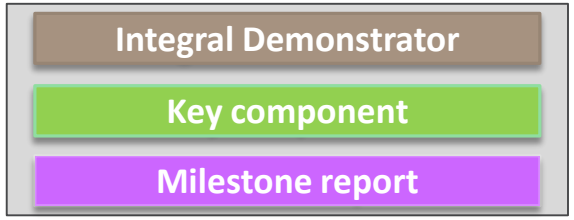
# ACCELERATION

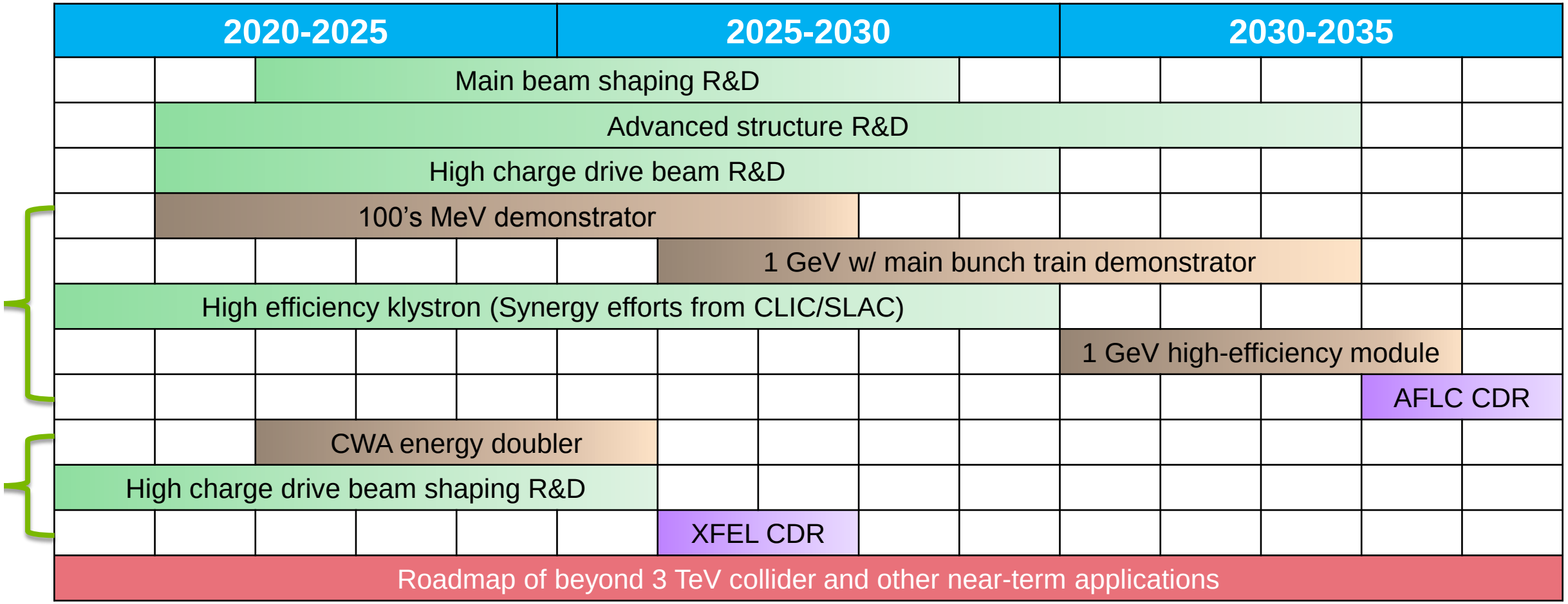



# PETS POWER



# SWFA 15-YEAR ROADMAP




**AWA-II facility upgrade**

* Depending on the available drive beam energy

# SUMMARY

**Strengthen collaboration between SWFA and HG Community**

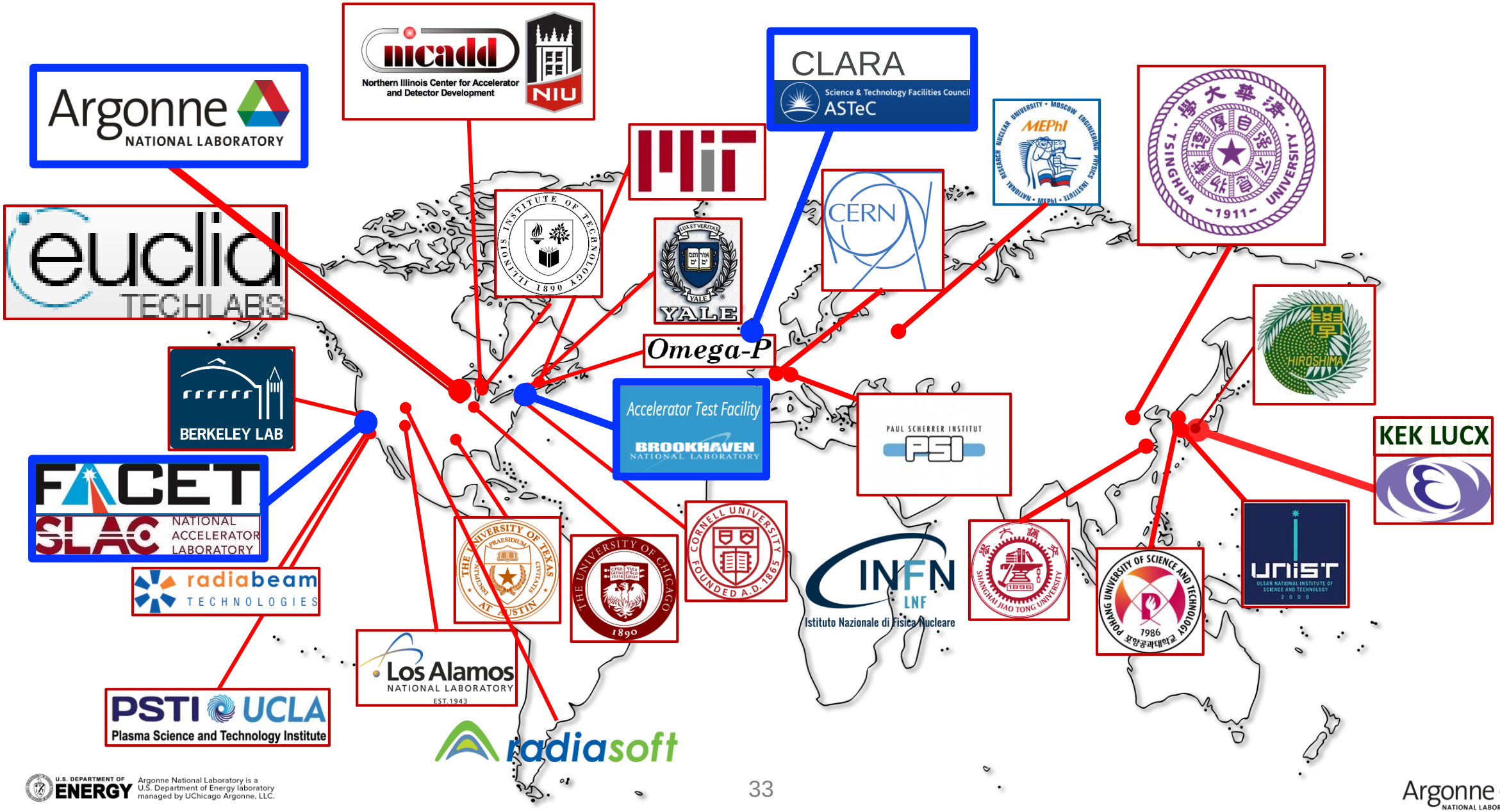
**Short-pulse regime**

- Exploring breakdown physics on short time scales (1-100ns)
- Applications
  - breakdown insensitive high-gradient regime
  - 400 MV/m X-band TW photocathode gun
  - 500 MW metamaterial power extractor

**Many AWA activities not included today.**

- Dielectric disk accelerator (Yelong Wei, CLIC, Tuesday)
- Brazeless structures (C. Jing, Euclid,Tuesday)
- Participation in Snowmass

# THANKS TO SWFA GLOBAL COMMUNITY



# OPEN POSITIONS AT AWA

## INPIRES

**Argonne Wakefield Accelerator Group: RF Physicist/Engineer position in Accelerator Physics** (Advanced Accelerating Structure Focus) available at levels:

- **Postdoc**: https://inspirehep.net/jobs/1851387
- **Staff** (junior scientist (RD2) to scientist (RD3)): https://inspirehep.net/jobs/1851101 levels.