GARD RF ROADMAP UPDATE - NCRF MEETING

# SHORT-PULSE NCRF FOR ULTRA-HIGH GRADIENTS

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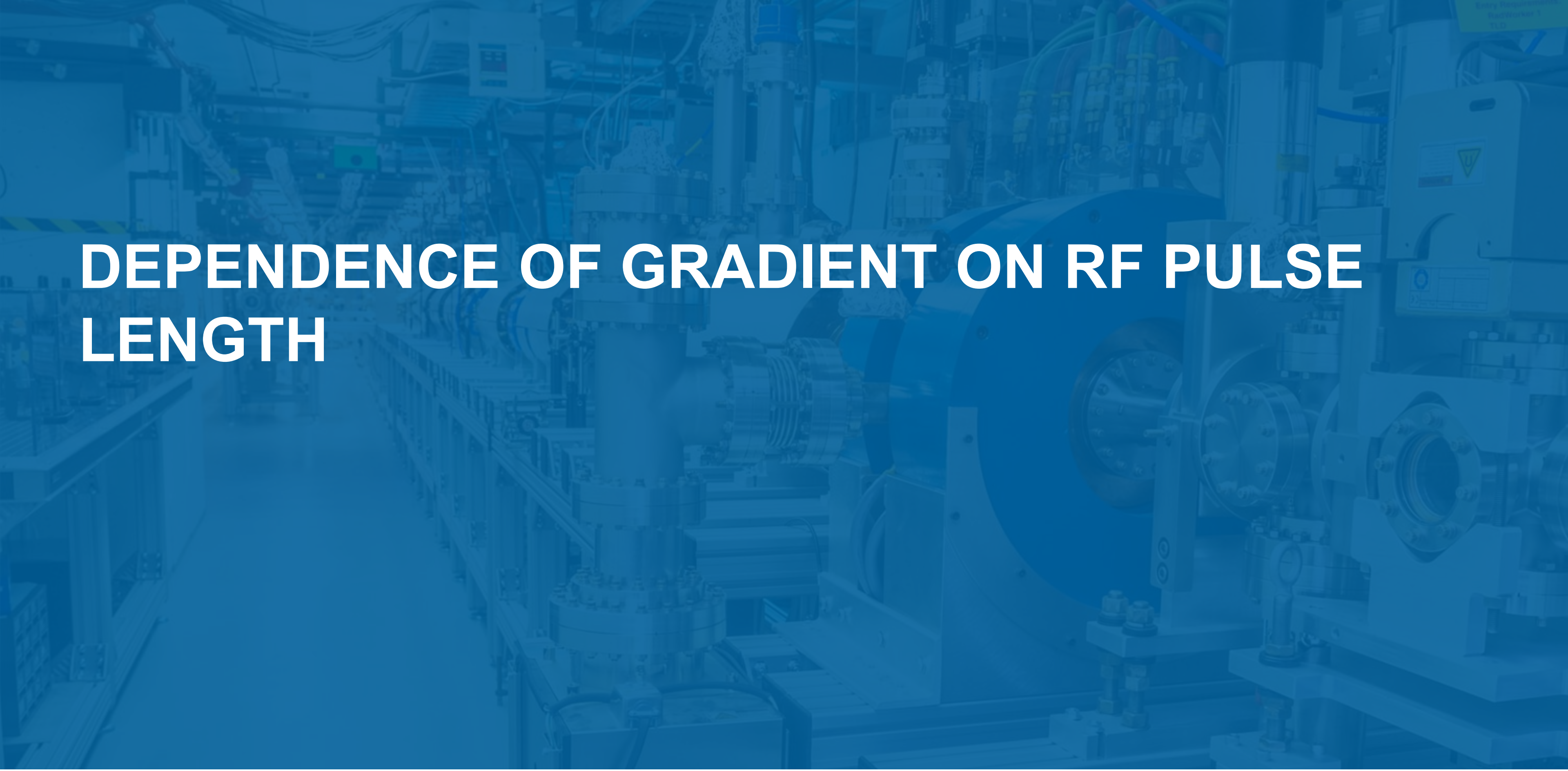
1/20/2026

# OUTLINE

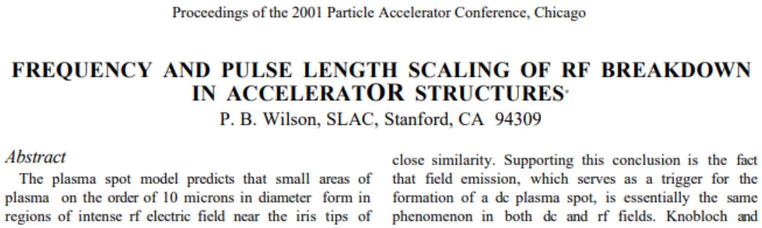
- Dependence of Gradient on RF pulse length
  - Scaling law?
  - Observation from CLIC 30GHz era
  - Discovery of BIAR (breakdown insensitive accelerator regime) at AWA
- Make a short RF pulse case for >500MeV/m gradient
- Challenges and R&D work



# DEPENDENCE OF GRADIENT ON RF PULSE LENGTH

# RELEVANT HISTORY OF STUDYING RF BREAKDOWNS DEPENDENCES ON RF PULSE LENGTH

## Theoretical model



Proceedings of the 2001 Particle Accelerator Conference, Chicago

### FREQUENCY AND PULSE LENGTH SCALING OF RF BREAKDOWN IN ACCELERATOR STRUCTURES

P. B. Wilson, SLAC, Stanford, CA 94309

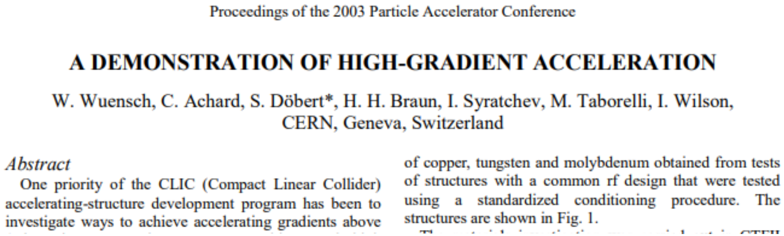
*Abstract*

The plasma spot model predicts that small areas of plasma on the order of 10 microns in diameter form in regions of intense rf electric field near the iris tips of

close similarity. Supporting this conclusion is the fact that field emission, which serves as a trigger for the formation of a dc plasma spot, is essentially the same phenomenon in both dc and rf fields. Knobloch and

There is no simple scaling ($\sim\omega^n$ or $\sim T_P^{-m}$) for breakdown gradient as a function of frequency or pulse length.

## Experimental efforts



Proceedings of the 2003 Particle Accelerator Conference

### A DEMONSTRATION OF HIGH-GRADIENT ACCELERATION

W. Wuensch, C. Achard, S. Döbert*, H. H. Braun, I. Syratchev, M. Taborelli, I. Wilson, CERN, Geneva, Switzerland

*Abstract*

One priority of the CLIC (Compact Linear Collider) accelerating-structure development program has been to investigate ways to achieve accelerating gradients above

of copper, tungsten and molybdenum obtained from tests of structures with a common rf design that were tested using a standardized conditioning procedure. The structures are shown in Fig. 1.

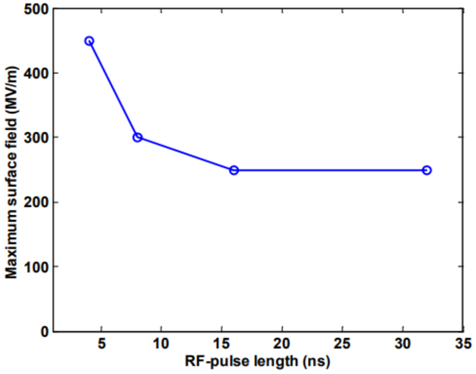


Figure 5: Pulse length dependence of the copper structure.

# EMPIRICAL SCALING LAW

- Empirical formula summarized from decade of high gradient accelerator research (x+$k_a$ bands)

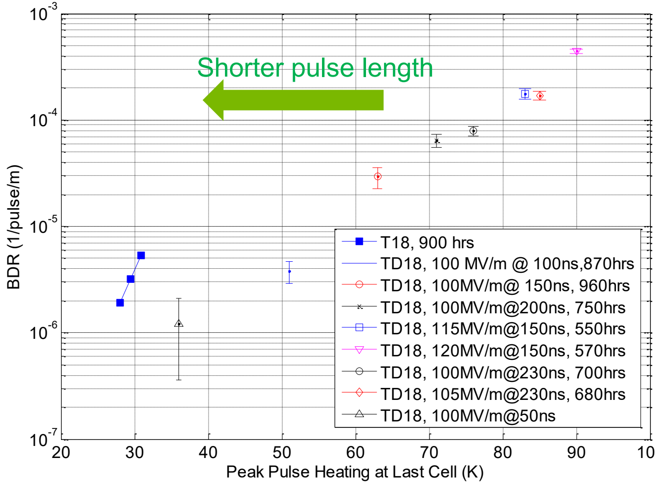
$$BDR \propto E^{30}\tau^{5}$$

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

| **Freq.** | **Pulse length (ns)** | **Max. Grad. (MV/m)** |
|---|---|---|
| S-band at FERMI 2.0 | 700 | 28 |
| C-band in Japan | 300 | 50 |
| X-band at CERN | 180 | 120 |

## SLAC Breakdown and pulse heating study 2010

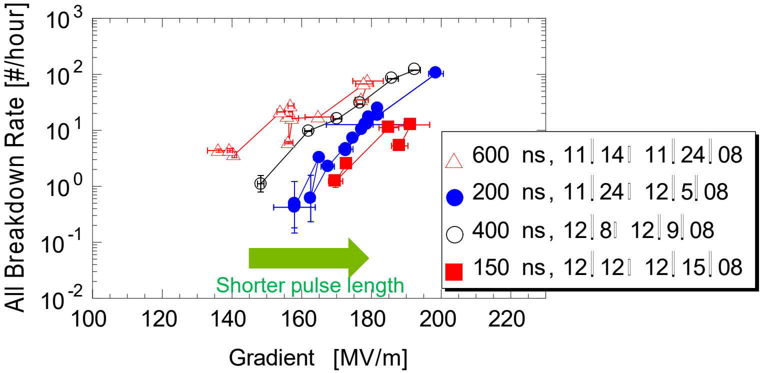
(from F. Wang, AAC10 presentation)



110 MV/m

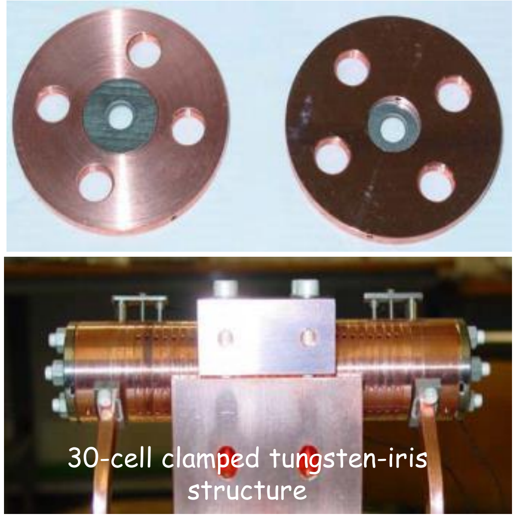
## SLAC Breakdown study 2008

(from V.A. Dolgashev, AAC10 presentation)

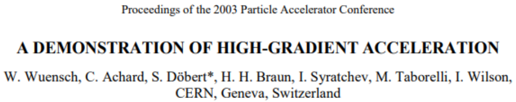


# OBSERVATION FROM CLIC 30GHZ ERA

- A 30-cell structure with Mo irises and low $E_S/E_A$ largely exceeded the CLIC accelerating field requirements without any damage
- 190 MV/m accelerating gradient in first cell - tested with beam ! (but only 16 ns pulse length)



30-cell clamped tungsten-iris structure



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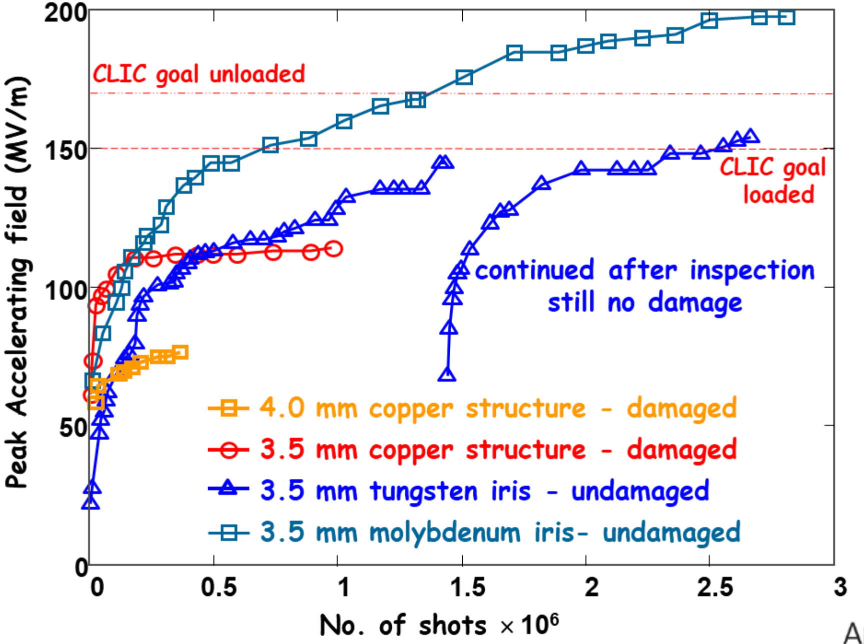
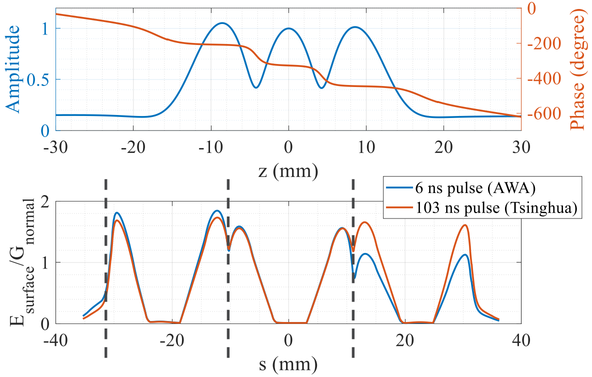


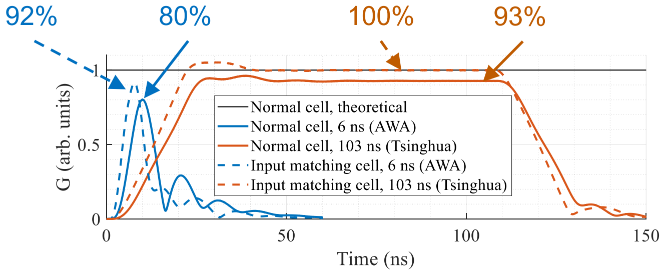
# DISCOVERY OF BIAR (BREAKDOWN INSENSITIVE ACCELERATOR REGIME) AT AWA-I

## 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 | 1.4x10⁴ Ω/m |
| Group velocity | 0.0114c |

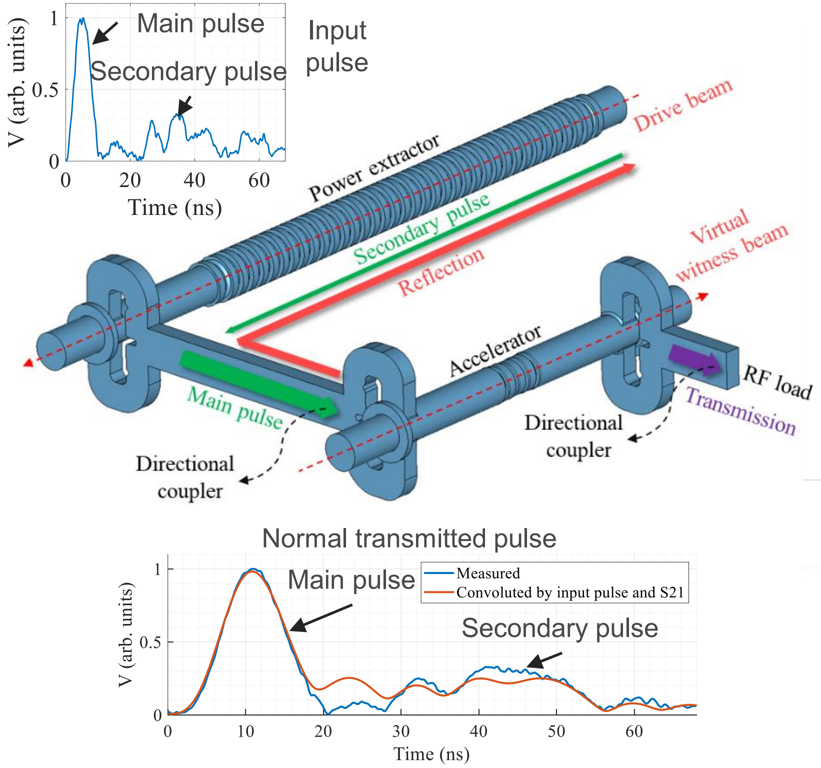




- The input matching cell has higher gradient and surface field than the normal cell

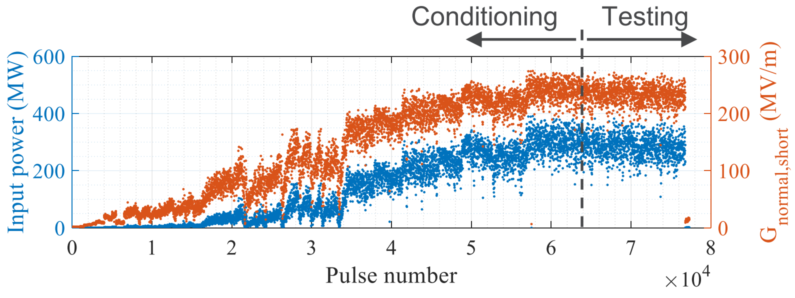
# DISCOVERY OF BIAR AT AWA-II

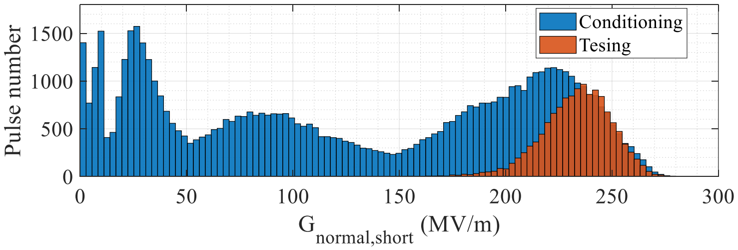
## Experimental setup



## RF conditioning

- 7.7x$10^4$ pulses accumulated at 2 Hz repetition

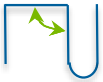




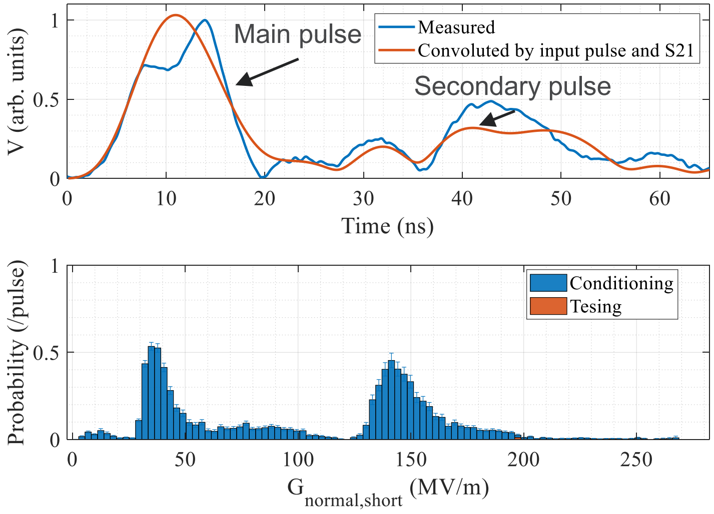
# DISCOVERY OF BIAR AT AWA-III

## BD type I

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

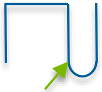


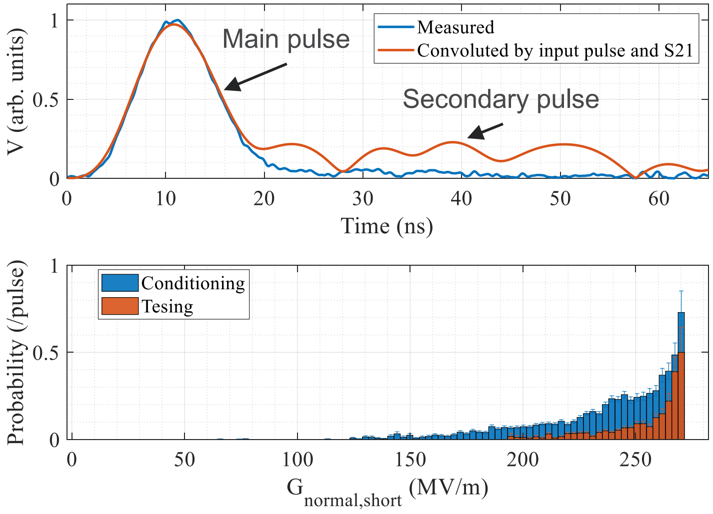
H. Xu et al., PRAB 22, 021002 (2019)



## BD type II

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

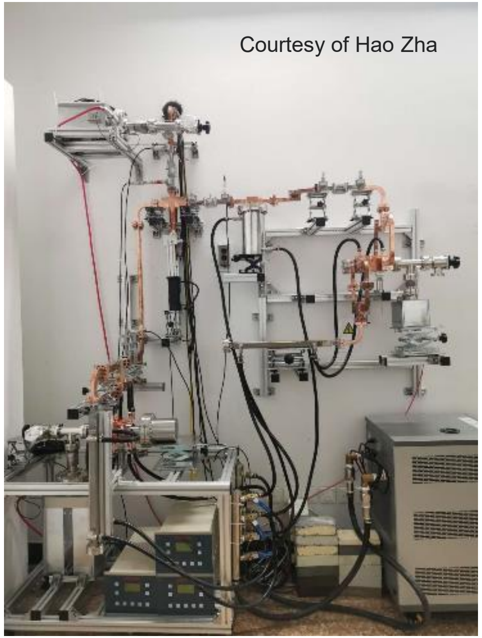




# LONG-PULSE HIGH-POWER TEST AT TSINGHUA

## Experimental setup

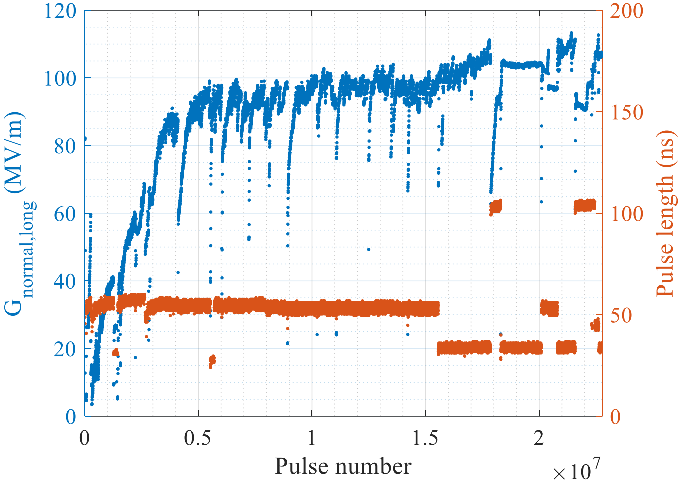
- Driven by klystron with pulse compressor



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

## RF conditioning

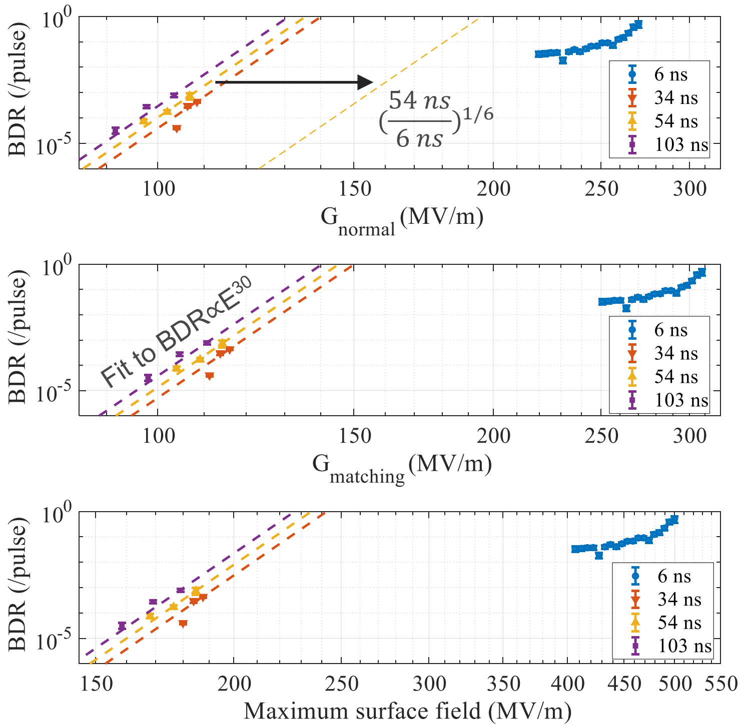
- $2.3\mathrm{x}10^7$ pulses accumulated at 40 Hz repetition



# RESULTS DISCUSSION (I)

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

## Comparison of short and long pulse results



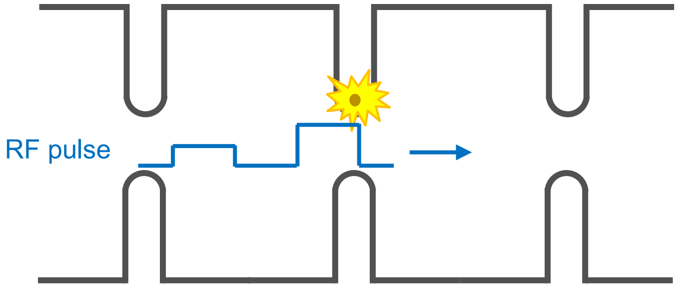
- Accelerating gradient of the normal cell and the input matching cell reaches 270 MV/m and 310 MV/m
- Surface field of the input matching cell reaches 500 MV/m
- Gradient improved at least twofold using short pulse (limited conditioning period, only secondary pulse taken into consideration)
- BDR vs.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

- New physics of RF breakdown in short-pulse regime

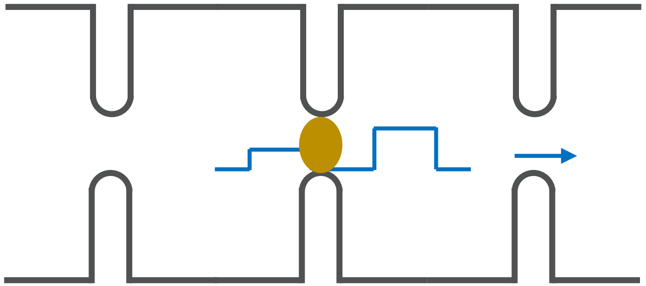
# RESULTS DISCUSSION (II)

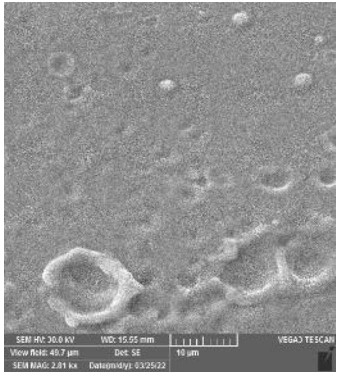
## Breakdown Insensitive Acceleration Regime (BIAR)

0 ns
RF causes BD and plasma generation

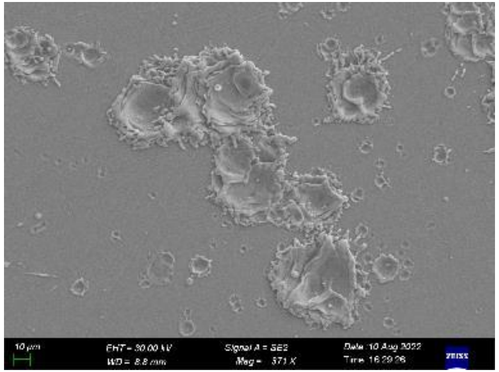


after ~10 ns
Plasma expansion to block RF transmission





ANL: ϕ10-20 µm

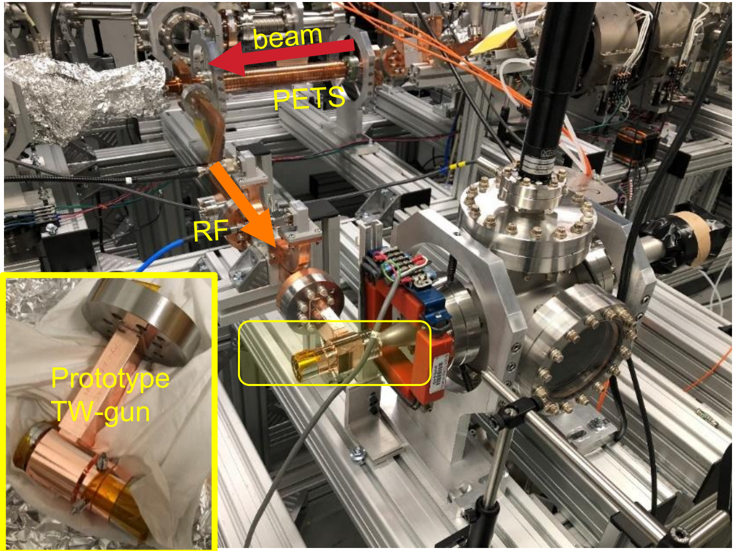


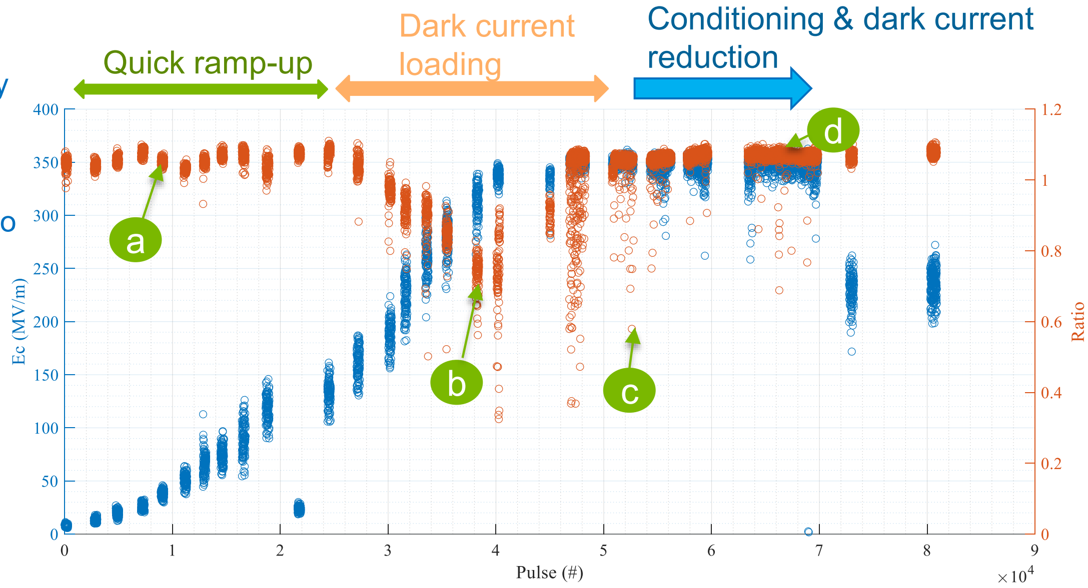
Tsinghua: ϕ30-100 µm

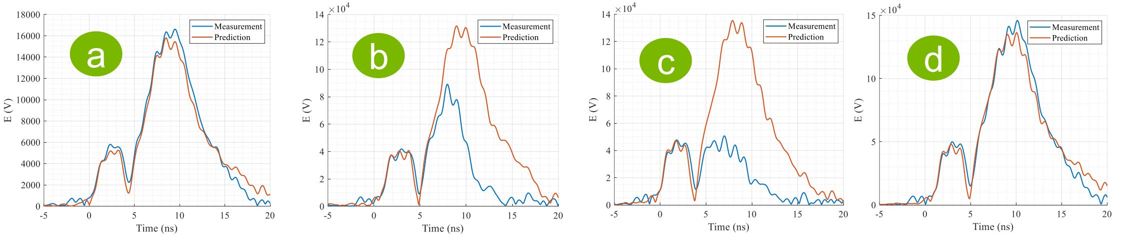
- Transmitted RF pulse and accelerated beam not influenced by RF breakdown
- Reduced structure damage due to limited energy available for breakdown avalanche

# ANOTHER EXAMPLE: SHORT PULSE RF PHOTOGUN

- 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

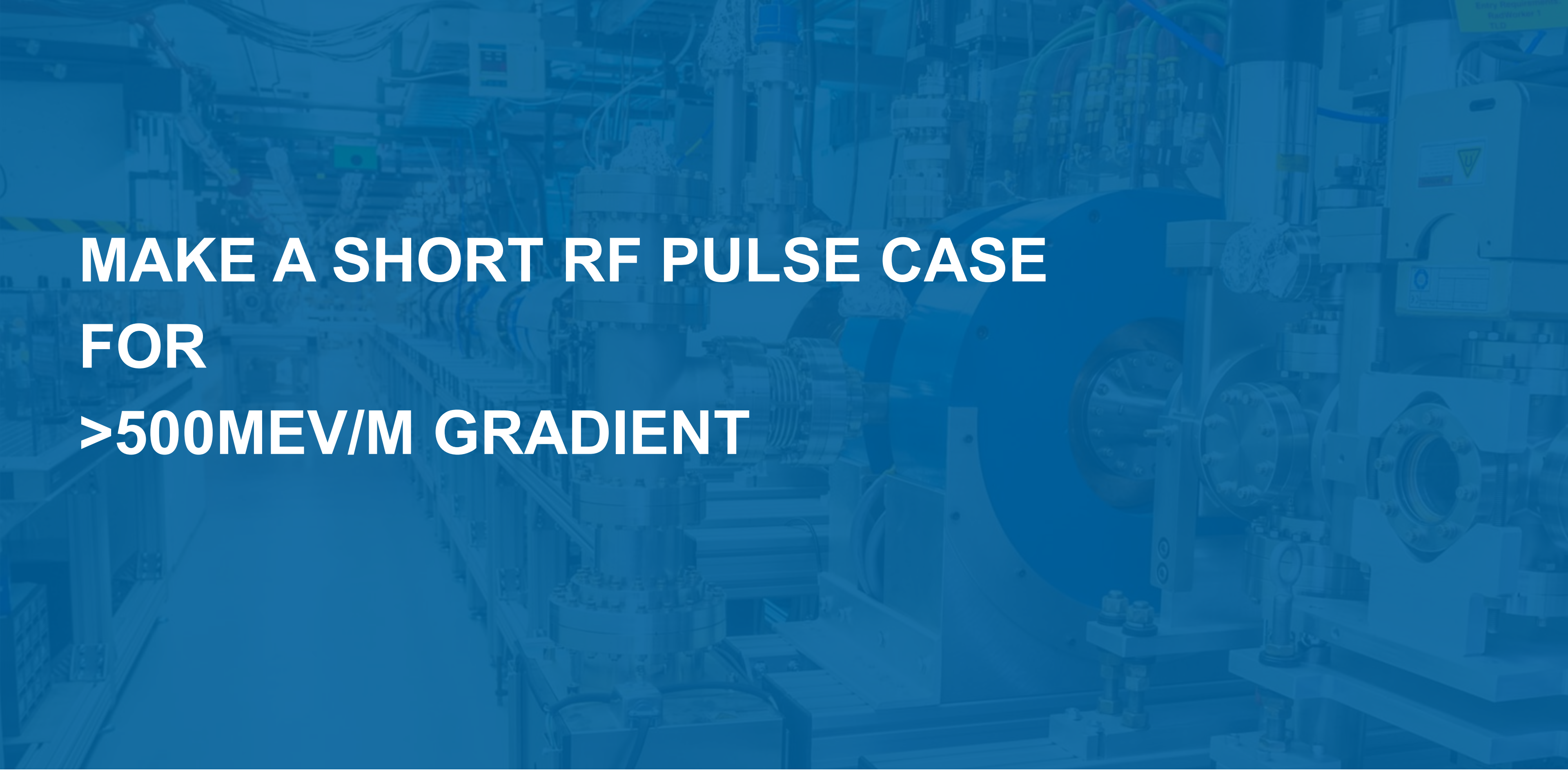






**Reflection signal from bi-directional coupler**

Euclid, SBIR Grant #DE-SC0018709, 2020



# MAKE A SHORT RF PULSE CASE FOR >500MEV/M GRADIENT

# What’s a creditable route for SWFA to achieve 500MeV/m of geographical gradient?

**AWA is currently developing an X-band accelerator operating in the short pulse regime.**

| Parameters | Designed Values |
|---|---|
| Freq. | 11.7 GHz |
| Filling time | 6 ns |
| Structure length | 25 cm |
| Input Power | 320 MW |
| Gradient | 170 MV/m |

$$\frac{R}{Q} = \frac{(E_a L_{cell})^2}{\omega U} \qquad U = \frac{P}{V_g}$$

Simply scale this structure to 11.7*3=35.1GHz, then R/Q is the same, Vg is the same, then 300MW will build up ~500 MV/m. If double the power from PETS to 600MW, the gradient will be ~700 MV/m. If the fill factor is 0.7, the geographical gradient will be ~500MeV/m.

*But, the beam aperture will be <1.5mm. (ref. CLIC 30GHz has aperture 2.4mm~3.2mm.)*

# On the power source side

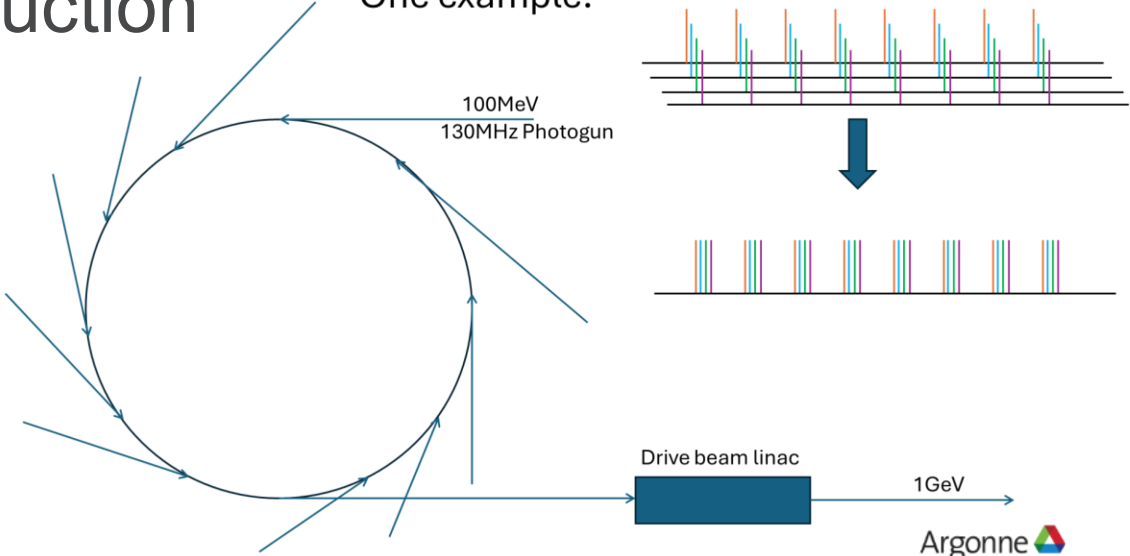
| | **AWA X-band PETS in operation** | **Scale 3 X frequency** | | |
|---|---|---|---|---|
| **PETS basics** | Metallic<br>ID=17.6 mm \| L=30 cm | Metallic<br>ID=5.9 mm \| L=30 cm | | |
| **PETS freq.** | 11.7 GHz | 35.1 GHz | | |
| **Power** | ~400 MW | ~600 MW | | |
| **Pulse length** | ~9 ns (full) | ~15 ns (full) | | |
| **$\sigma_z$ \| F(ω)** | 1 mm \| 0.94 | 0.5 mm \| 0.93 | | |
| **Qb** | 50 nC | 9 nC | 3 nC | 1 nC |
| **Bunch spacing** | 796 ps | 256 ps | 85 ps | 28 ps |

# CHALLENGES AND R&D WORK

# ACCELERATORS SUBJECT TO STUDY TAILED TO SHORT PULSE REGIME

- Main accelerating structure (WF, BD)
- Power extractor (WF)
- Drive beam production

One example:



# 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* |

# REMARKS

- CLIC 30GHz era left abundant data and many unanswered questions, which is worth revisiting them.
- Experiments in short pulse regime exhibits some unique performance which is worth exploring.
- Challenges on wakefield damping are tremendous, but it may work perfectly for the single bunch or light beam loading applications.

# THANKS FOR YOUR ATTENTION!