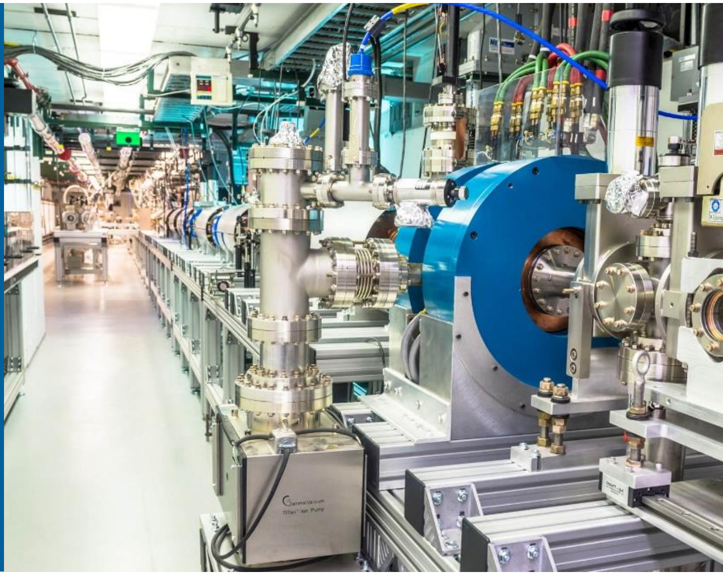
International Workshop on Breakdown Science and High Gradient Technology (HG2022)

Tsinghua University

Argonne NATIONAL LABORATORY

DEMONSTRATION OF GRADIENT ABOVE 300 MV/m IN SHORT-PULSE REGIME USING AN X-BAND SINGLE-CELL STRUCTURE



JIAHANG SHAO

On behalf of collaboration between Argonne National Laboratory and Tsinghua University

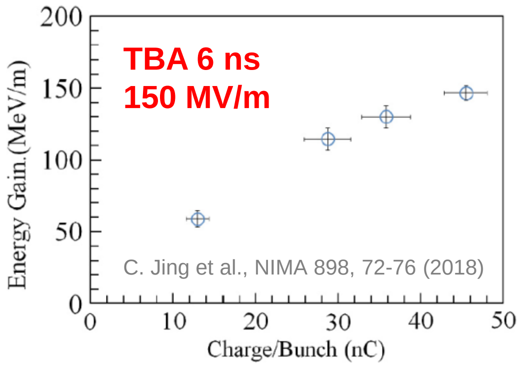
OUTLINE

- Background and motivation
- X-band travelling-wave single-cell structure design
- Short-pulse test at Argonne
- Long-pulse test at Tsinghua
- Discussion
- Summary and future study

BACKGROUND AND MOTIVATION

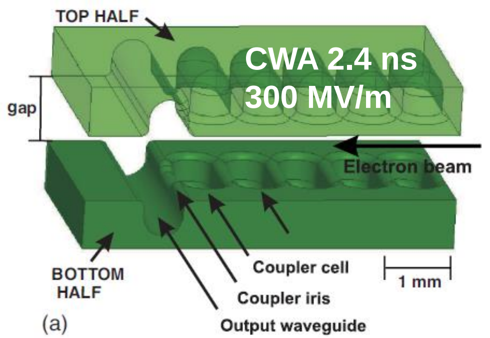
- **High gradient acceleration is critical for future linear collider and compact linac-based facilities**
  - Accelerating gradient usually limited to ~150 MV/m and ~120 MV/m in single-cell and multi-cell structures (room temperature, X-band)
- **Short-pulse acceleration is a promising approach to improve gradient**
  - $BDR \propto E^{30}\tau^{5}$ A. Grudiev et al., PRSTAB 12, 102001 (2009)

X-band 3-cell metallic structure



C. Jing et al., NIMA 898, 72-76 (2018)

mm-wave two-half metallic structure

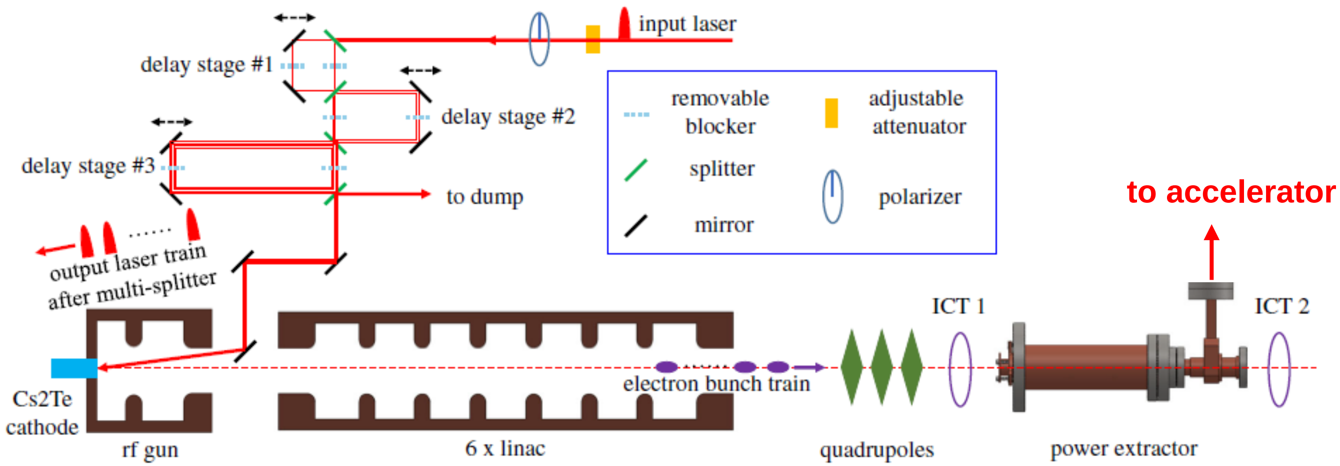


M. Forno et al., PRAB 19, 011301 (2016)

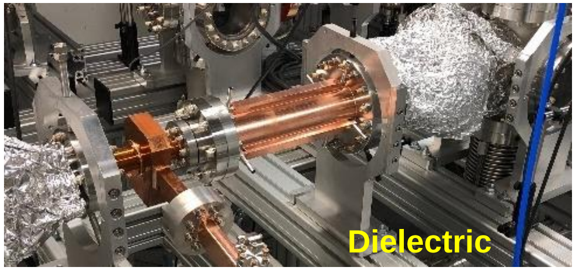
- **Direct comparison of achievable gradient in short pulse (<20 ns) and long pulse is yet to be performed**
  - Potentially lead to breakthrough in understanding breakdown physics and developing acceleration regime

SINGLE-CELL STRUCTURE DESIGN

- **High power short pulse generation at AWA**
  - Critical for breakdown research and wakefield acceleration

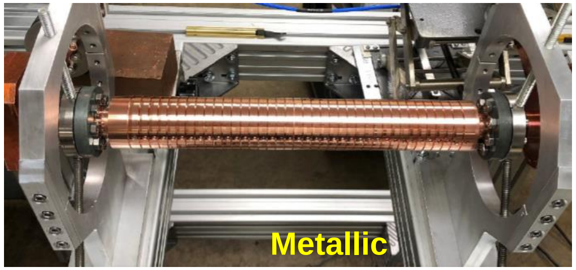


6 ns FWHM, 3 ns flat-top, 200 MW



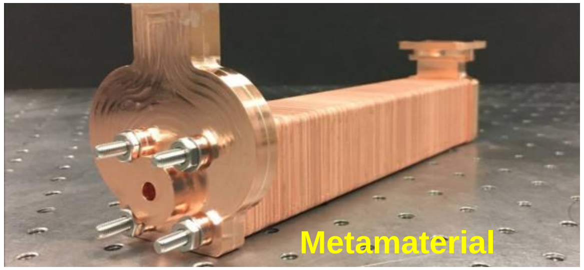
J. Shao et al., PRAB 23, 011301 (2020)

6 ns FWHM, 3 ns flat-top, 400 MW



C. Jing et al., NIMA 898, 72-76 (2018)

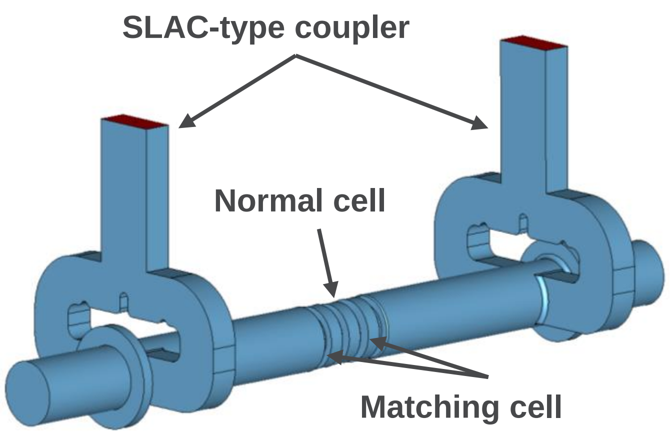
6 ns FWHM, no flat-top, 565 MW

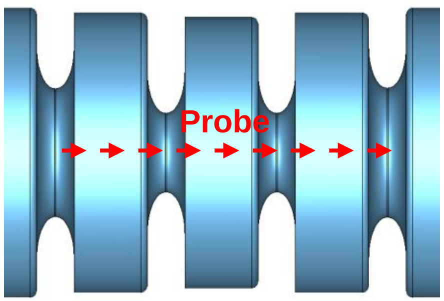


J. Picard et al., PRAB 25, 051301 (2022)

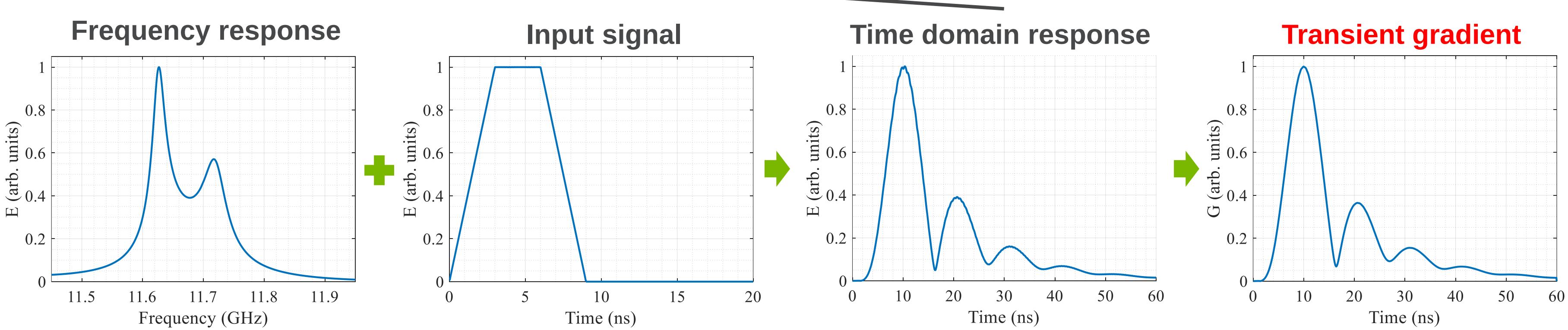
SINGLE-CELL STRUCTURE DESIGN

- **Travelling-wave single-cell accelerating structure**





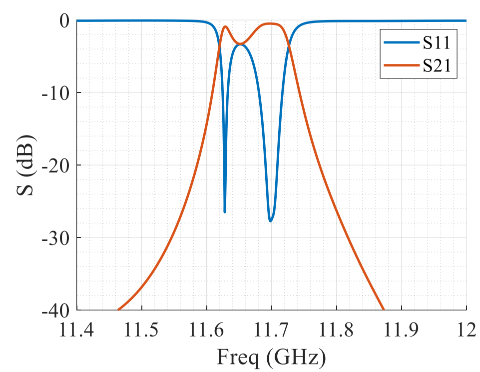
- **Transient acceleration gradient in short-pulse regime**
  - $G(t_0) = [\int_0^L E(z,t)dz]/L,\ t = t_0 + z/c$

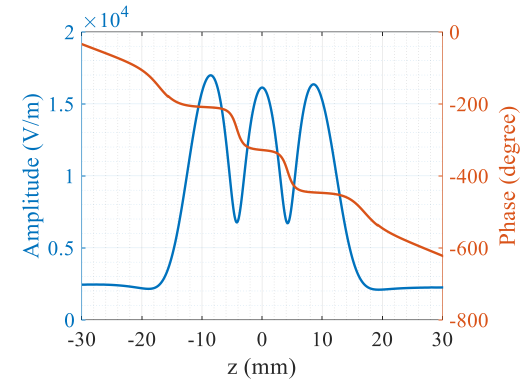


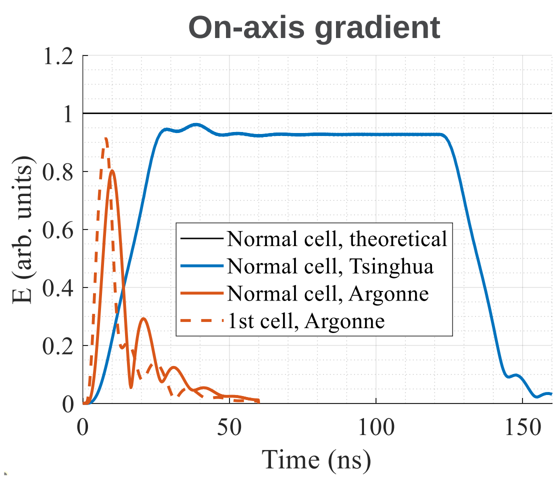
SINGLE-CELL STRUCTURE DESIGN

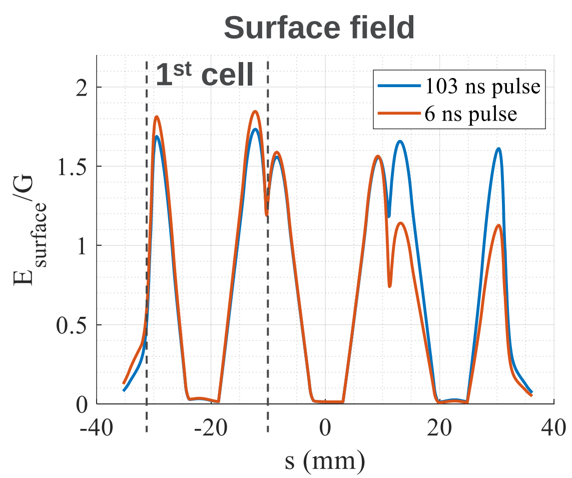
- **Accelerating structure optimized to maximize the transient gradient**

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	1.4×10^4 Ω/m
Group velocity	0.0114c







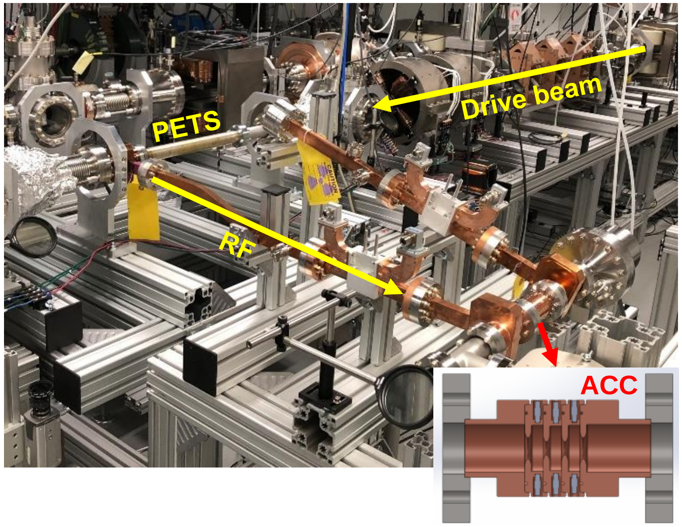


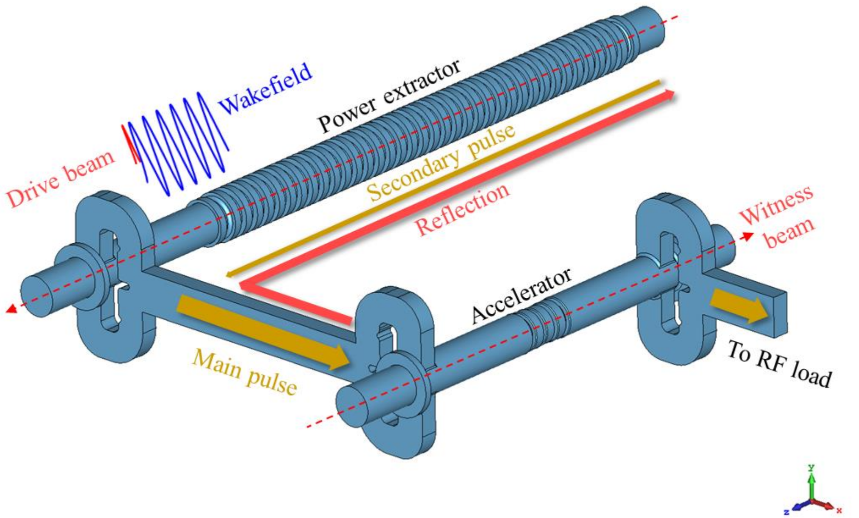
- **Normal cell steady gradient is 93% of theory**
- **Normal cell peak transient gradient is 80% of theory**
- **1st cell peak transient gradient is 14% higher than normal cell**

- **1st cell steady surface field is 73% higher than normal cell steady gradient**
- **1st cell peak transient surface field is 85% higher than normal cell peak transient gradient**

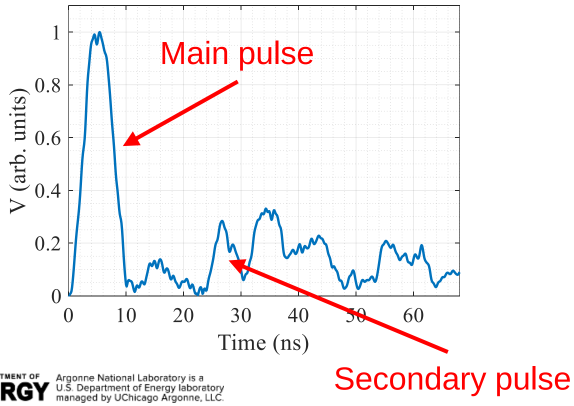
EXPERIMENT AT ARGONNE

- **PETS driven by high-charge 8-bunch train**
  - Dual input pulses formed due to structure reflection

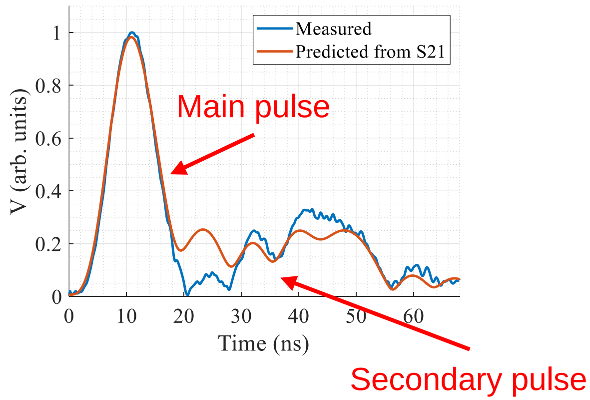




Input pulse

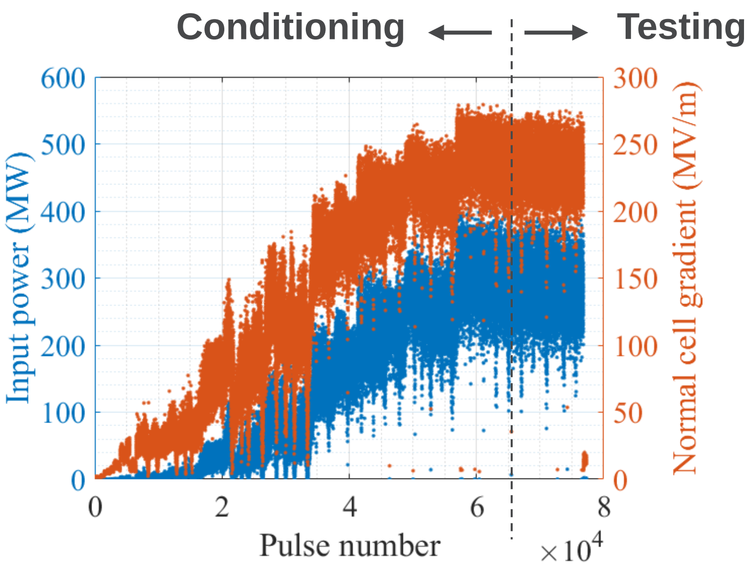


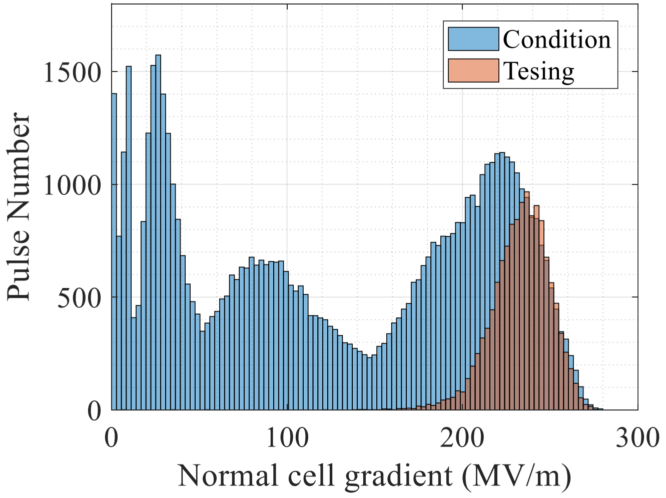
Transmitted pulse



EXPERIMENT AT ARGONNE

- **Conditioning history**
  - Beamline ran at 2 Hz, ~7.7×10^4 pulses recorded
  - RF conditioning: rising power, 6.4×10^4 pulses
  - Testing: after reaching the maximum power, 1.3×10^4 pulses
  - The power is further divided for BDR calculation (gradients above 270 MV/m are dropped due to insufficient data points)



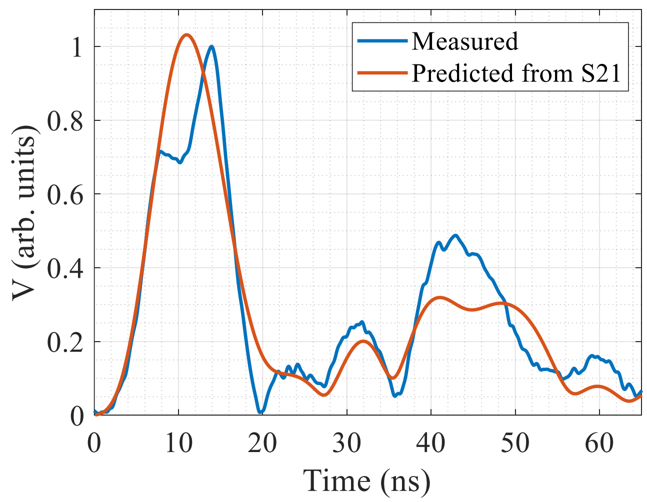


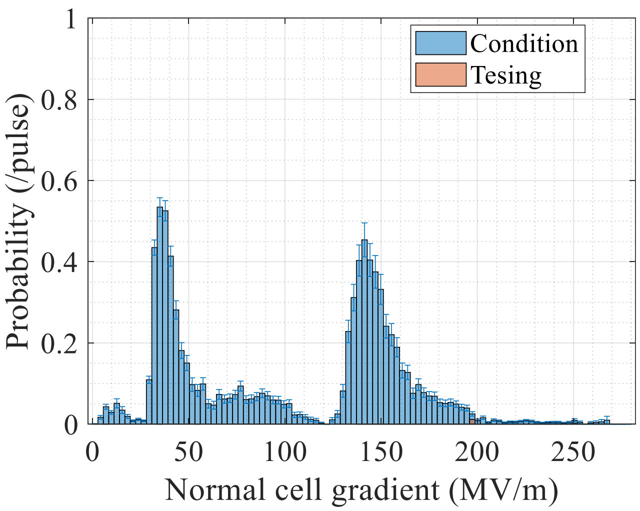
Peak transient

EXPERIMENT AT ARGONNE

- **Abnormal pulses – Type I**
  - The transmitted main pulse is distorted
  - Distribution has two bands, likely to be caused by multipacting
  - Disappeared after RF conditioning, not considered in BDR calculation

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

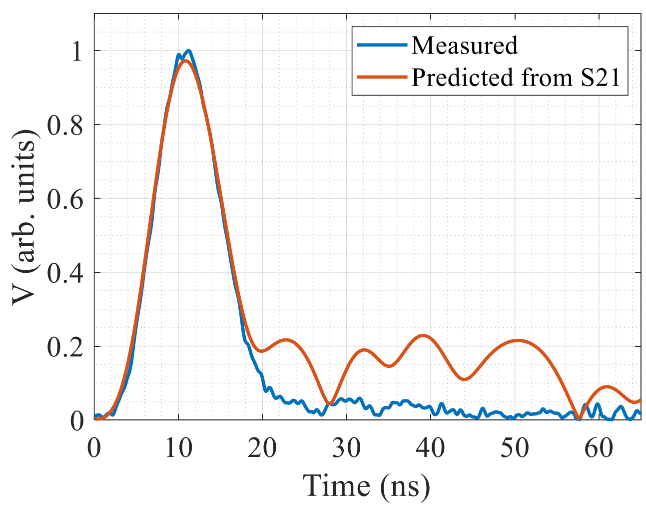


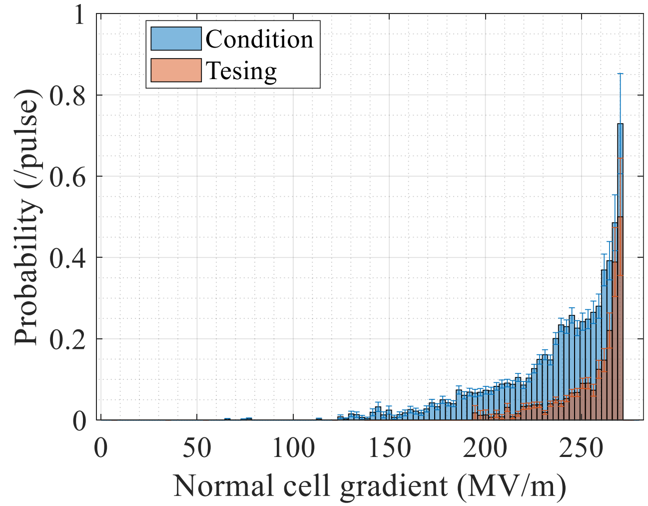


Peak transient

EXPERIMENT AT ARGONNE

- **Abnormal pulses – Type II**
  - The transmitted main pulse agrees well with prediction from S21, but the secondary pulse disappears
  - Probability exponentially depends on gradient, likely to be caused by RF breakdown
  - Probability drops after RF conditioning



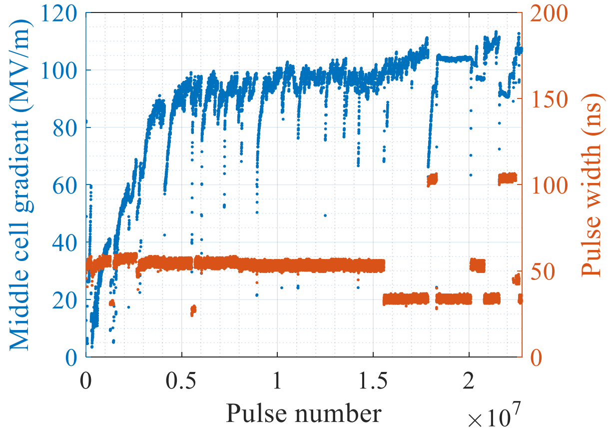


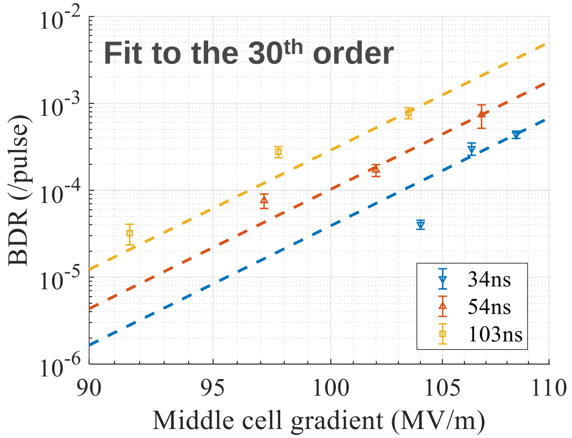
Peak transient

EXPERIMENT AT TSINGHUA

- **Conditioning history**
  - Powered by klystron and pulse compressor
  - Ran at 40 Hz max., accumulated ~2.3x10^7 pulses

Courtesy of Hao Zha

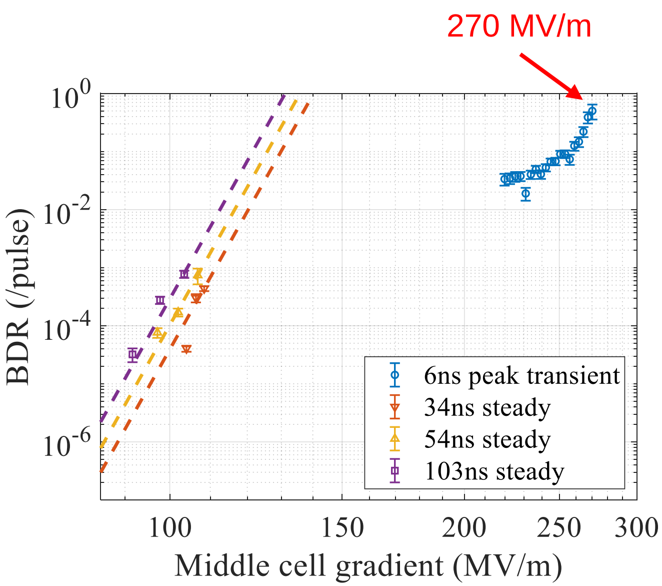


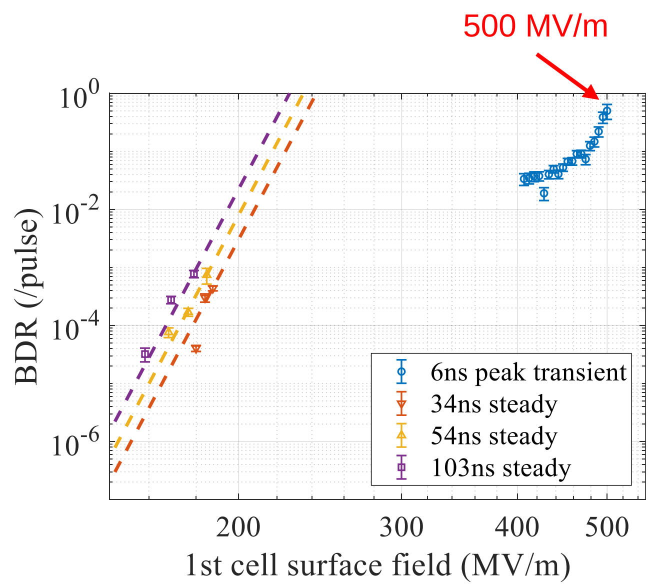


Steady

EXPERIMENT AT TSINGHUA

- **Direct comparison between short and long RF pulses**
  - Take abnormal pulse – Type II for comparison
  - Short-pulse gradient doubles the long-pulses ones at given BDR

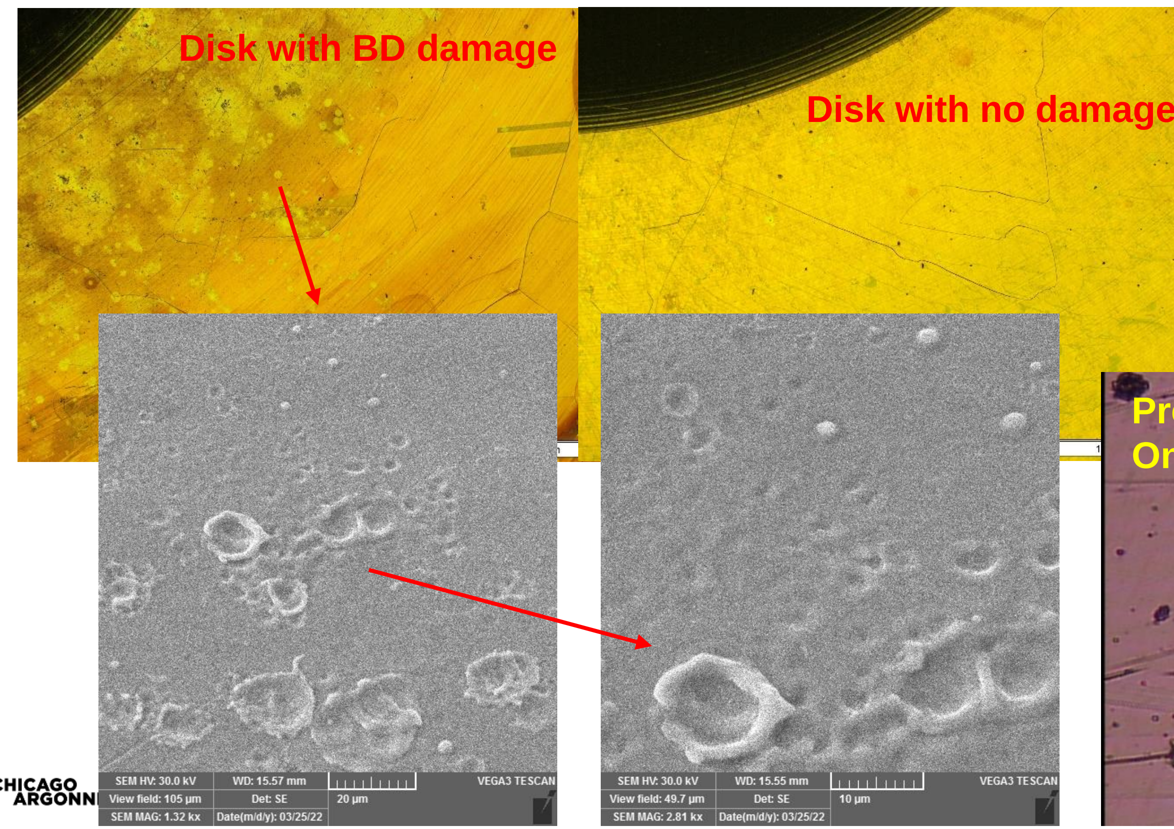




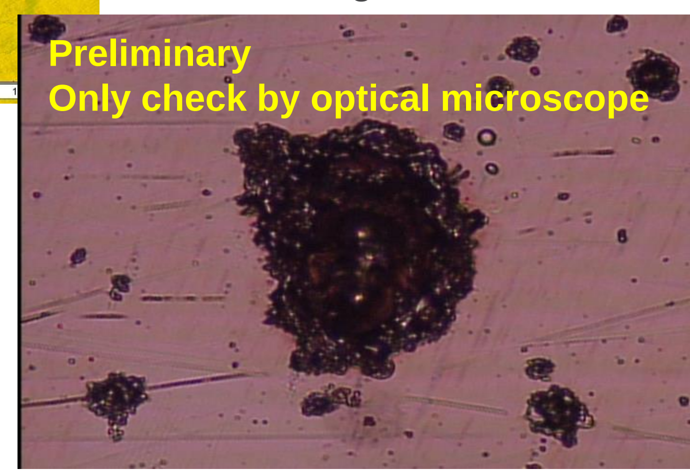
DISCUSSION

- **Surface inspection**
  - BDs in both structures are mainly located on the irises of the first cell, consistent with the peak surface field location
  - BD sizes are ϕ10-20 μm in short-pulse test (up to 500 MV/m surface field), ϕ30-100 μm in long-pulse test (lower than 200 MV/m surface field)

ANL

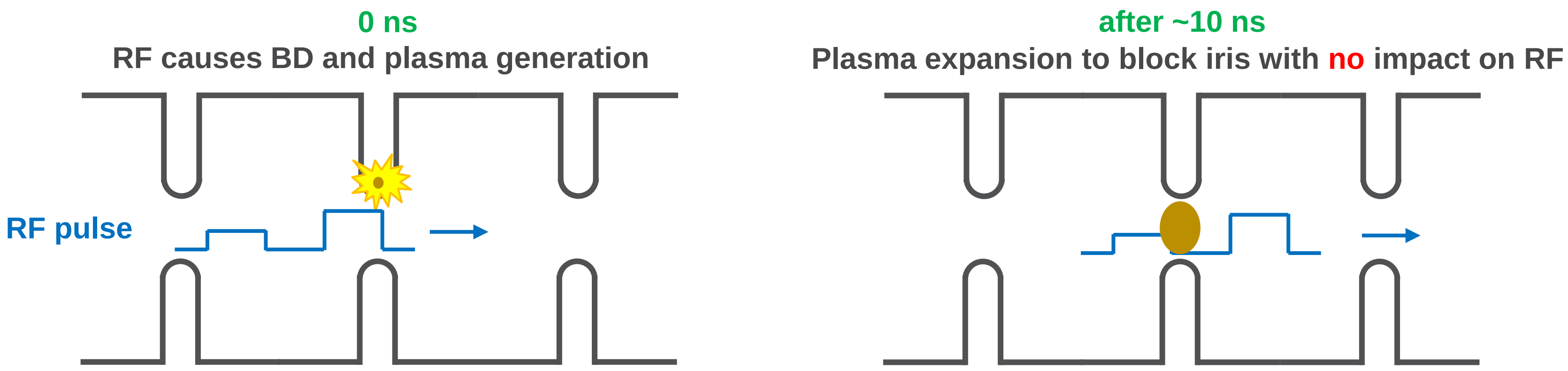


Tsinghua



DISCUSSION

- **Possible physics of higher gradient and smaller BD spots in short-pulse regime**
  - RF period is shorter than the BD-indued plasma expansion time
  - Lower overall stored energy in the structure that is available for BD avalanche process



- **Breakdown insensitive acceleration regime (BIAR)**

SUMMARY AND FUTURE STUDY

- **First direct comparison of achievable gradient in short and long pulse TBA scheme**
  - Short-pulse gradient doubles the long-pulse one:
    - **270 MV/m and 300 MV/m** accelerating gradient in the normal cell and the first cell
    - **500 MV/m** surface gradient in the first cell
  - With short pulses, the main pulse shape remains intact at high field and structure surface shows less damage

- **Future directions**
  - Systematically investigate the dependence of BDR on pulse length and iris size in short-pulse regime
  - Expand high gradient study into multi-cell structures: DDA, parallel-coupled, …

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