SHORT-PULSE WAKEFIELD STRUCTURE R&D FOR HIGH GRADIENT AND HIGH EFFICIENCY ACCELERATION IN FUTURE LARGE-SCALE MACHINES

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Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

AF7 - SUBGROUP RF - MINIWORKSHOP ON CAVITY PERFORMANCE FRONTIER

BACKGROUND

- **High gradient acceleration is critical for future linear colliders**

  Normal conducting at room temperature (long pulse): 150 MV/m, X-band

  Normal conducting at cryogenic temperature (long pulse): 250 MV/m, X-band

- **Short-pulse acceleration is a promising approach to achieve high gradient**

  Experimental observation of BDR dependence on gradient and pulse length

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

  New breakdown physics may exist in short-pulse regime

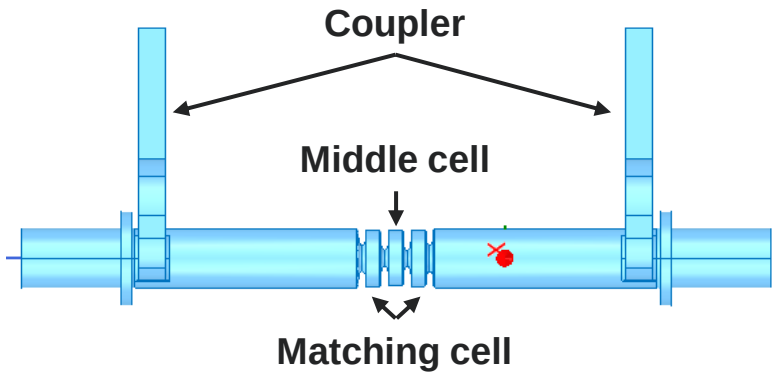
- **Short-pulse acceleration requires special structure R&D**

High gradient (0.3-1 GeV/m) → $E \propto \sqrt{\omega r/Q}$ → **High shunt impedance**

High efficiency (AC-to-RF >30%) → $\eta \propto t_{flat}/t_{pulse}$ → **High group velocity**

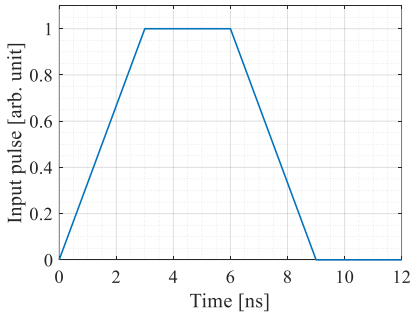
RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

- **Design and optimization**

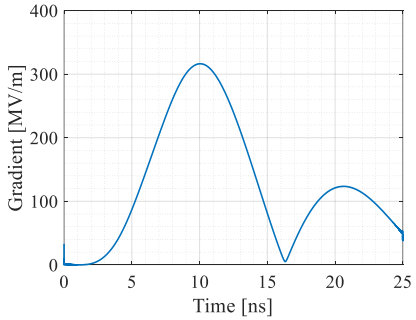


Parameters	Value	Unit
Frequency	11.7001	GHz
2a	6.1	mm
2b	20.914	mm
t	2.9	mm
Cell length	8.5411	mm
Phase advance per cell	$2\pi/3$	
Filling time	2.506	ns
Group velocity	0.0114	c
Gradient @ 500 MW input	389	MV/m
Q	6072.5	
r/Q	14047.9	Ω/m
Es/Ea	1.59	
Hs/Ea	3	mA/V
Sc/Ea^2	0.121	mA/V

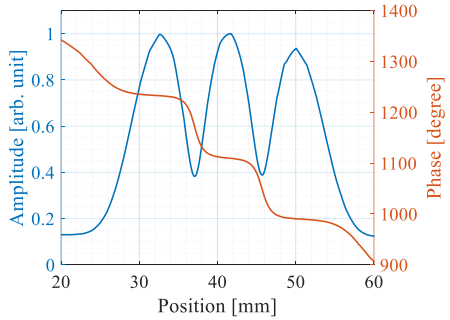
Input pulse



Gradient

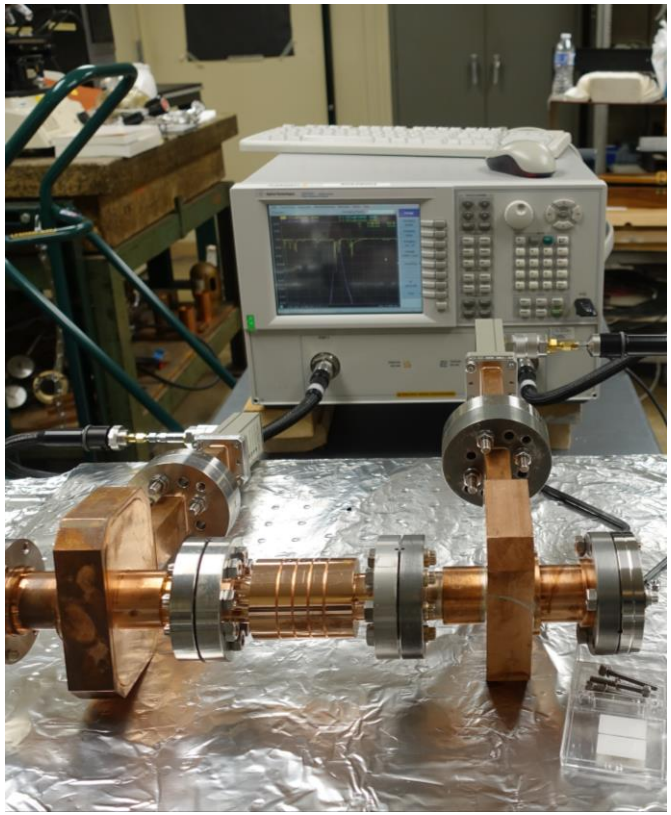


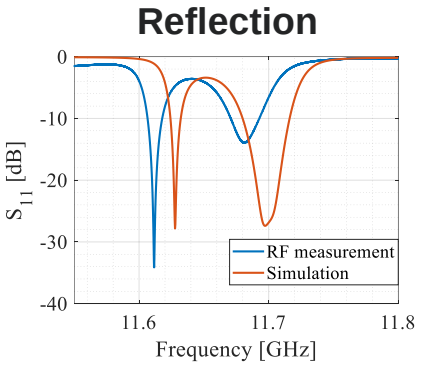
On-axis field distribution

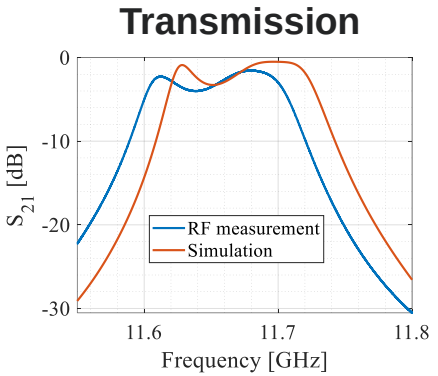


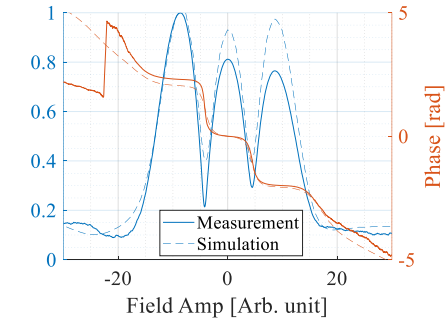
RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

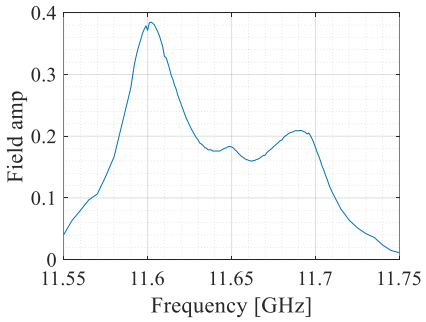
- **Cold test**





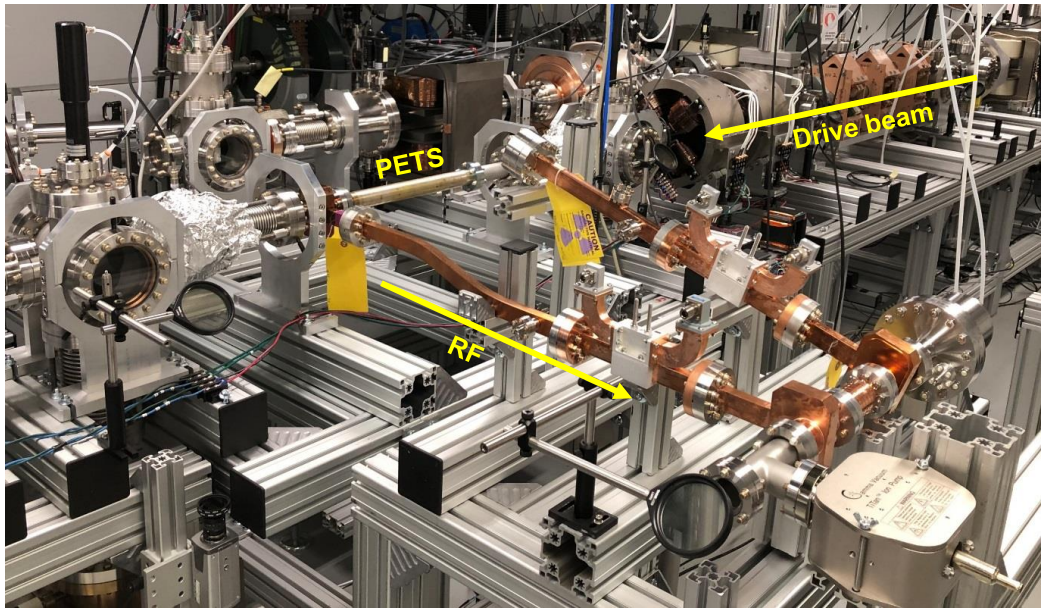






RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

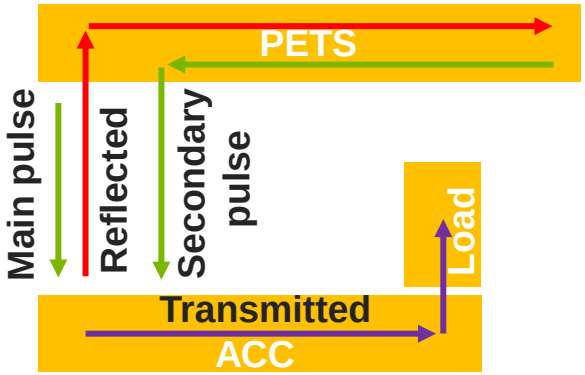
- **High power test**

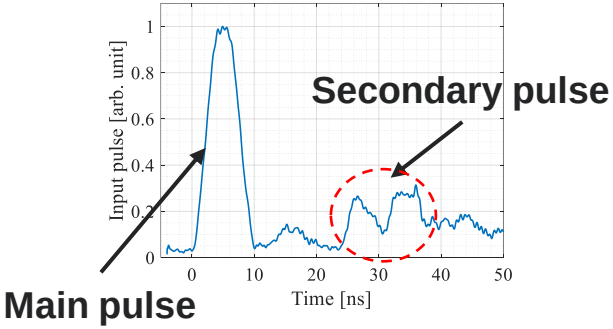


- **400 MW RF power generated from PETS with 450 nC drive beam**
- **~200 MeV/m average gradient in three cells, ~250 MeV/m gradient in the middle cell, ~500 MV/m peak surface field**

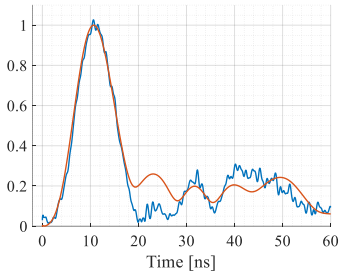
RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

- **Preliminary breakdown study**



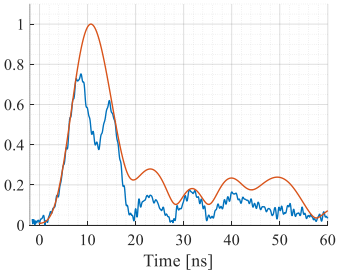


Normal operation:



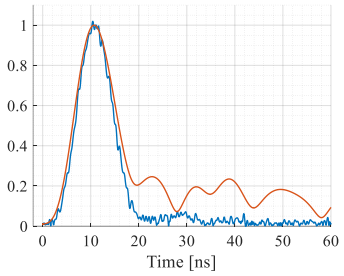
- Good agreement between predication and measurement

Main pulse BD:



- BD within the main pulse
- Very rare

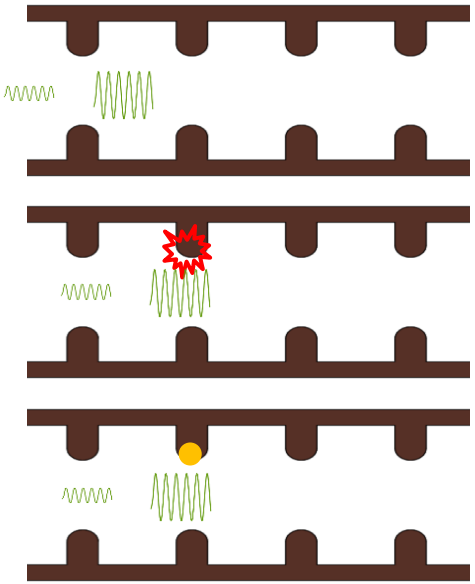
Secondary pulse BD:

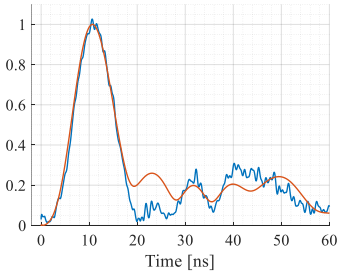
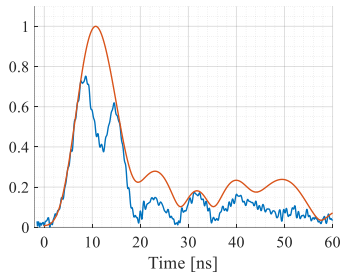
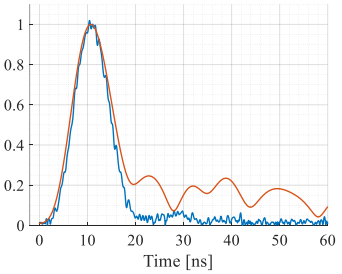


- Only miss the secondary pulse
- 10-20% at high gradient

RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

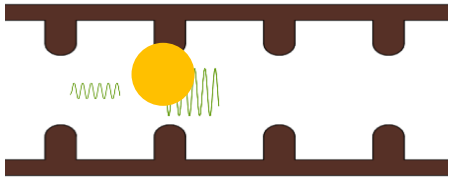
- **Preliminary breakdown study**



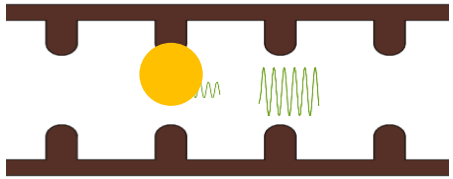
Normal operation:	Main pulse BD:	Secondary pulse BD:
		
- Good agreement between predication and measurement	- BD within the main pulse - Very rare	- Only miss the secondary pulse - 10-20% at high gradient

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

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



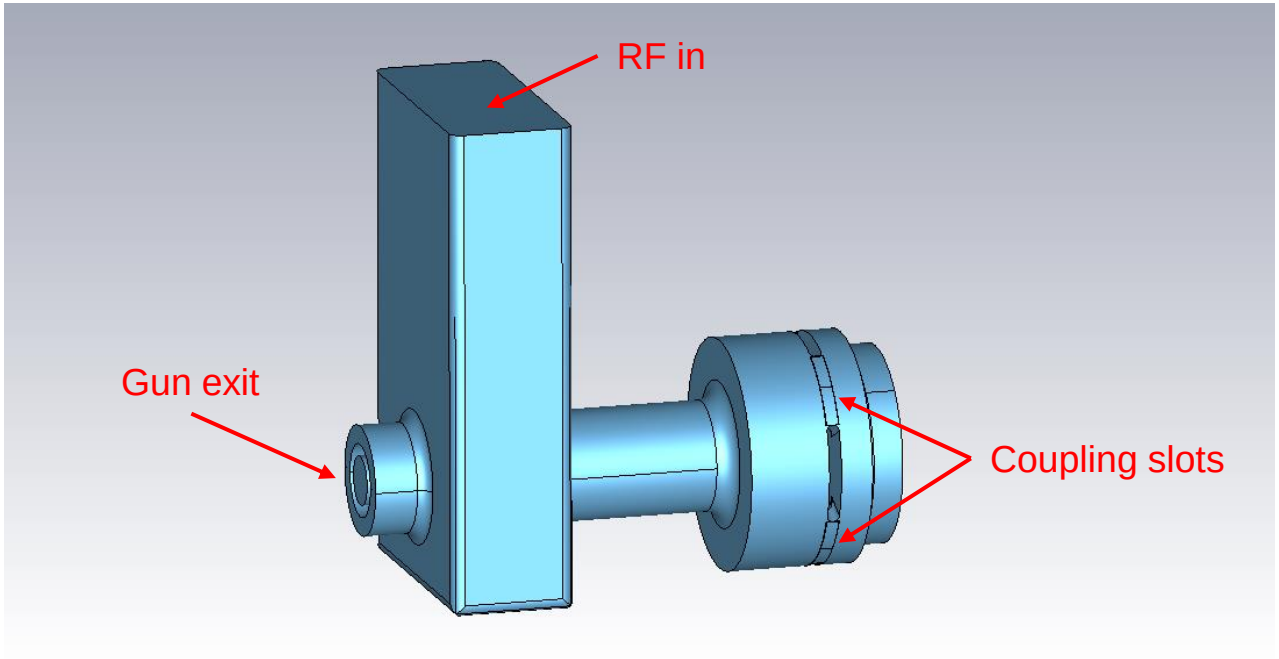
M. Johnson et al, *NIMA* **595**, 568 (2008)



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

RECENT SHORT-PULSE RF BREAKDOWN STUDY AT AWA

- **Over-coupled standing-wave gun**



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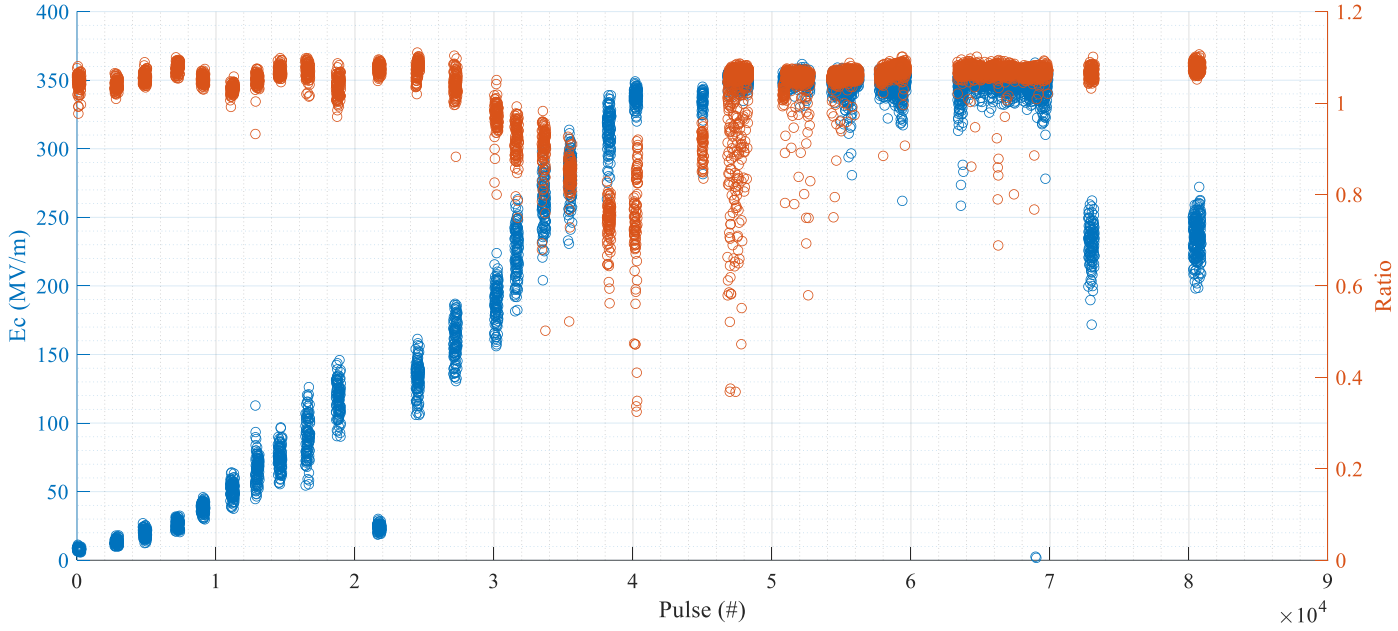
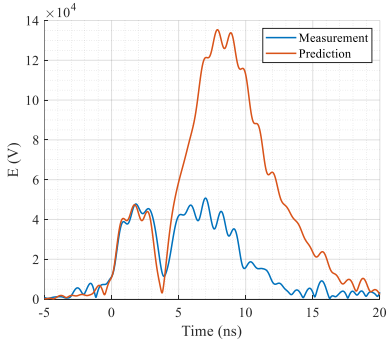
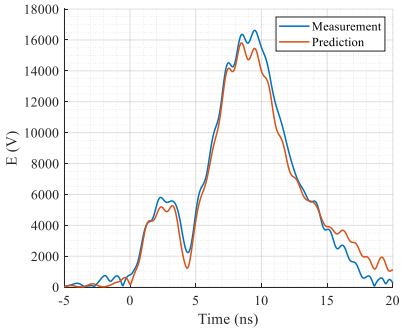


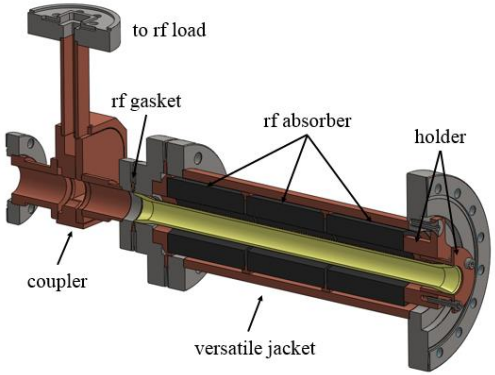




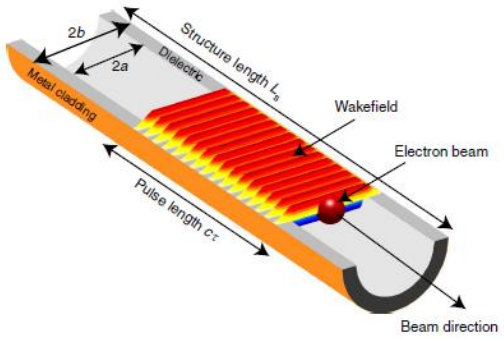
STRUCTURE DEVELOPMENT OF SHORT-PULSE SWFA

- **Dielectric-loaded structure**

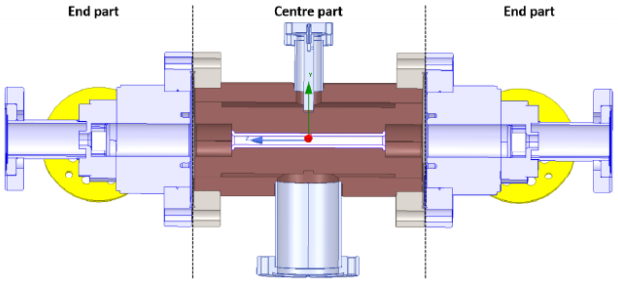
Simple geometry
Low cost
No surface field enhancement
High group velocity but moderate shunt impedance



J. Shao et al, *PRAB* **23**, 011301 (2019)



B.D. O'Shea, et al., *Nature* Comm. **7**, 12763 (2016)

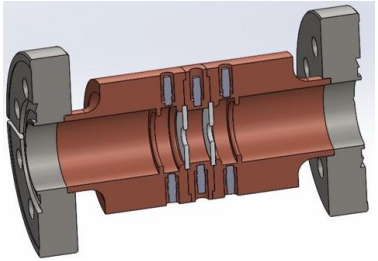


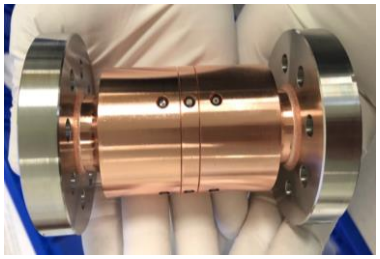
Y. Wei, et al., *arXiv* 2008.09203 (2020)

Collaboration of CERN/Euclid/AWA

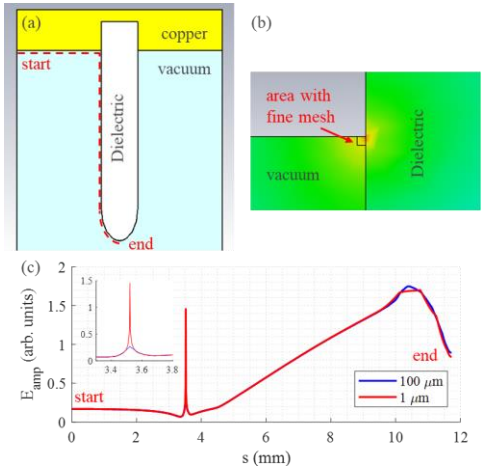
STRUCTURE DEVELOPMENT OF SHORT-PULSE SWFA

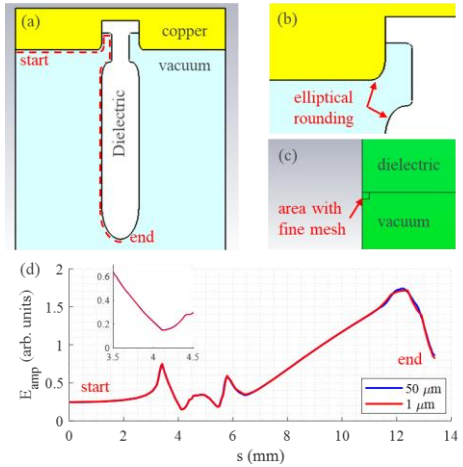
- **Dielectric-disk structure**





	DLA	DDA
Frequency (GHz)	26	26
ID (mm)	3	3
Group velocity	0.11 c	0.16 c
r/Q (kΩ/m)	21.8	32.5
Q	2295	6430
r (MΩ/m)	50.0	208.8
Input power (GW)	1.22	0.96
$\eta_{rf\text{-}beam}$ (%)	~9	~13
E_{max} (MV/m)	365	660

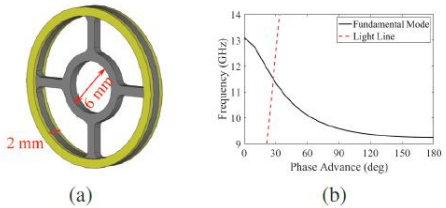


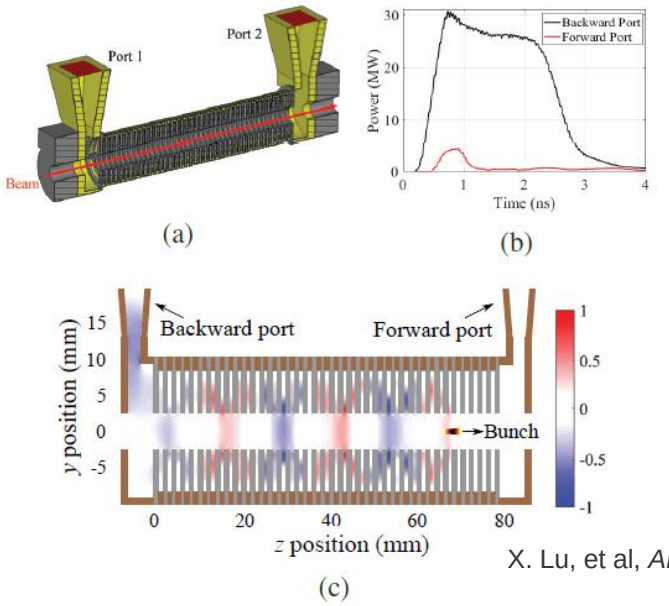


B. Freemire et al. *in preparation*

STRUCTURE DEVELOPMENT OF SHORT-PULSE SWFA

- **Metamaterial structure**

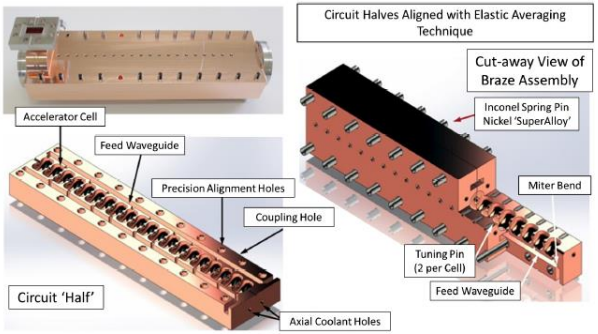




X. Lu, et al, *APL* **116**, 264102 (2016)

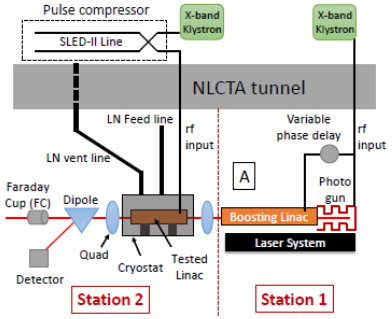
- **Other candidates**

Distributed-coupling



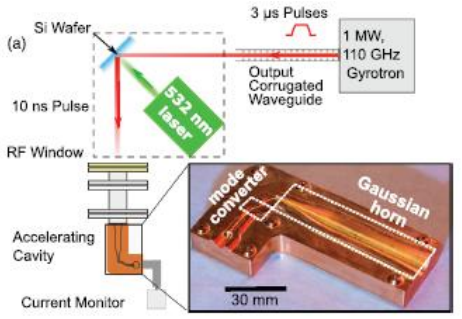
S. Tantawi, et al, *PRAB* **23**, 092001 (2020)

Cryogenic temperature



M. Nasr, et al., *arXiv* 2011.00391 (2020)

mm-wave/THz



M. Othman, et al, *APL* **117**, 073502 (2016)

SUMMARY

- **Short-pulse structure wakefield acceleration is a promising approach to reach high gradient**

- **Systemic study is needed to explore gradient limitation as well as to understand the breakdown physics in this regime**

- **Short-pulse acceleration needs advanced structure R&D for high efficiency and high gradient acceleration**

- **Strengthen collaboration in the SWFA community and the high gradient community**