15th Workshop on Breakdown Science and High Gradient Technology (HG2023)

Test of a metamaterial accelerating structure

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Outline

- Breakdown test of an X-band metamaterial (MTM) accelerator structure for short-pulse structure wakefield acceleration (SWFA)
  - Metamaterial structures are good for SWFA applications
  - Short-pulse acceleration is good for breakdown mitigation

- Other ongoing and planned work
  - Sub-terahertz structures for high-gradient high-efficiency acceleration using shaped bunches
  - Beam collective effects in complex electron bunches
  - …

Acknowledgements

- Contributors:
  - NIU graduate students
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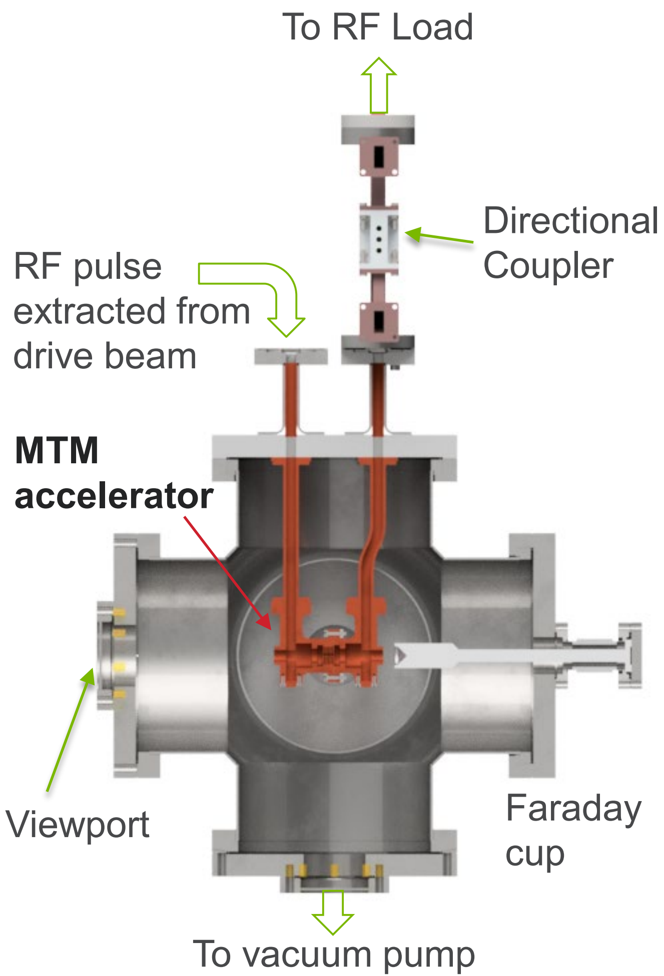


Towards compact accelerators-

- Develop physics understanding of RF breakdown
  - **High-gradient and breakdown science community**
- Explore novel accelerator concepts to mitigate RF breakdown
  - **Advanced Accelerator Concepts (AACs) community**
    - Plasma-based accelerators
    - Laser-based accelerators
    - Accelerators on a chip
    - Terahertz (THz) accelerators
    - Structure wakefield acceleration: short pulse → high gradient

aac24 ADVANCED ACCELERATOR CONCEPTS

A Chicagoland meeting of the global Advanced Accelerator Concepts community

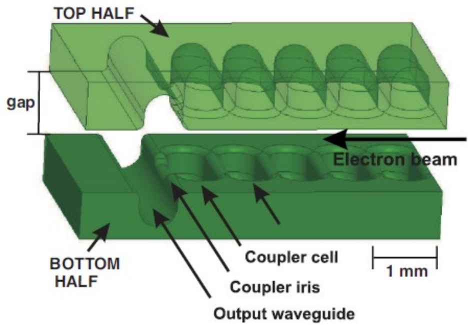
July 21-26, 2024 https://indico.fnal.gov/event/59618/

NIU Naperville campus

Short-pulse acceleration

- Acceleration using $\mathcal{O}$(ns) RF pulses is a promising approach:
  - Suggested by empirical studies
  - and by early evidence:
    - in beam-driven experiments:

Breakdown rate $(\mathrm{BDR}) \propto E^{30}\tau^{5}$

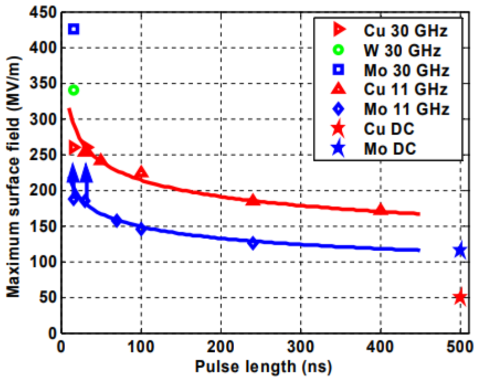


About 300 MV/m gradient excited by FACET beam

- RF pulse length ~1 ns

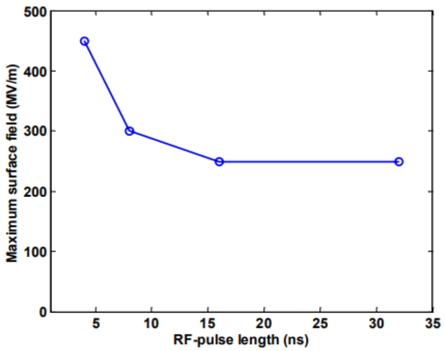
M. Forno *et al.*, PRAB **19**, 011301 (2016)

- and in high-power testing:



@NLCTA, 11.424 GHz

S. Döbert *et al.*, SLAC-PUB-10551 (2004)



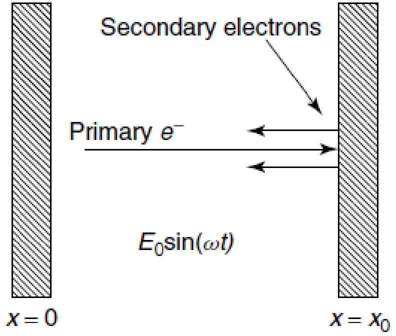
@CTFII, 30 GHz

W. Wuensch *et al.*, Proc. PAC 2003, ROAA011

Mitigation of breakdown risks using short pulses

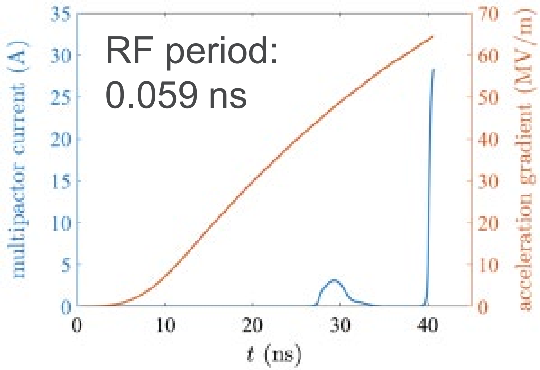
- Common initiators of breakdown may not have time to develop
  - Examples:
    - Pulsed heating
    - Multipactor current takes time to grow

  → Could be mitigated by using short RF pulses



Travel time of electrons
= integer$\cdot\, T_{RF}/2$

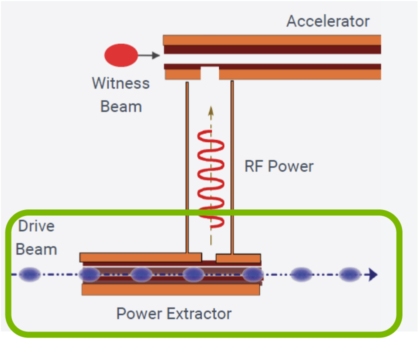
Multipactor current growth in a 17 GHz structure



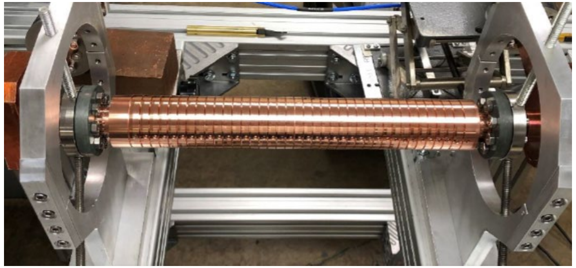
H. Xu, *et al.*, PRAB **22**, 021002 (2019)

& recently reproduced by G. Rijal (NIU)

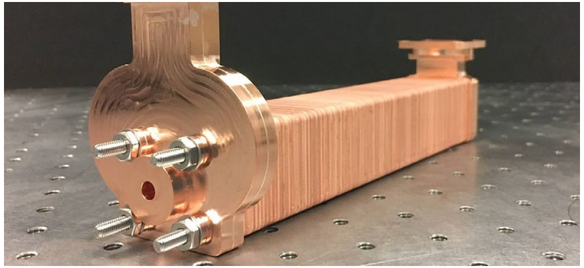
SWFA-based short-pulse RF source



Metallic disk-loaded, 400 MW, 6 ns FWHM

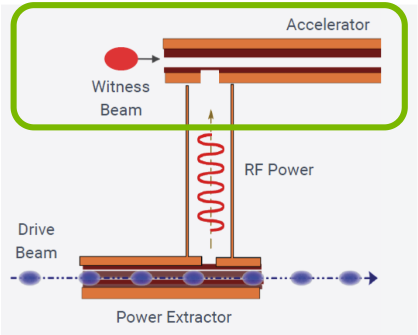


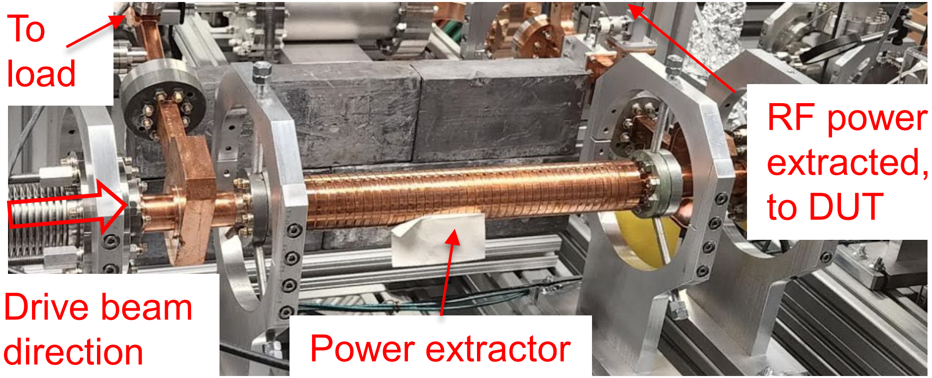
Metamaterial, 565 MW, 6 ns FWHM



- SWFA power extractors as short-pulse RF power sources
- Flexibility in the choice of output frequency
  - Harmonic of the bunch train frequency of 1.3 GHz
  - Power extractor frequencies at AWA :
    - 7.8 GHz, **11.7 GHz** (our X-band frequency), 26 GHz, sub-THz

SWFA-based breakdown test stand





- High-power tests of accelerator structures (without witness beam)
- Powered by an X-band power extractor from the drive beam

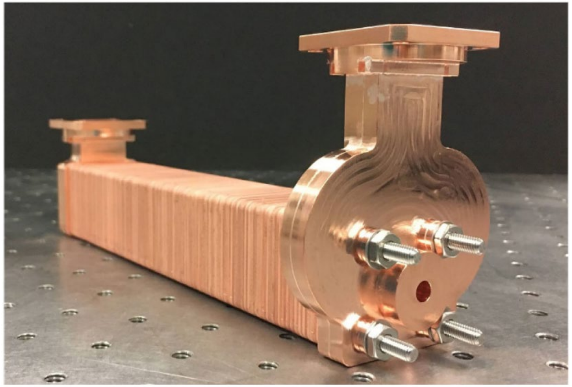
MTM structures fulfill SWFA requirements

- Special requirements for efficient wakefield extraction and acceleration
  - High shunt impedance (r/Q)
  - High group velocity (v_g)
    - For power extractor, $P = q^2 k_L |v_g| \left(\frac{1}{1-v_g/c}\right)^2 \Phi^2$
    - For accelerator, short filling time required for short pulses
- Reversing the group velocity improves performance
  - General rule: beam aperture ↓, r/Q ↑, v_g ↓

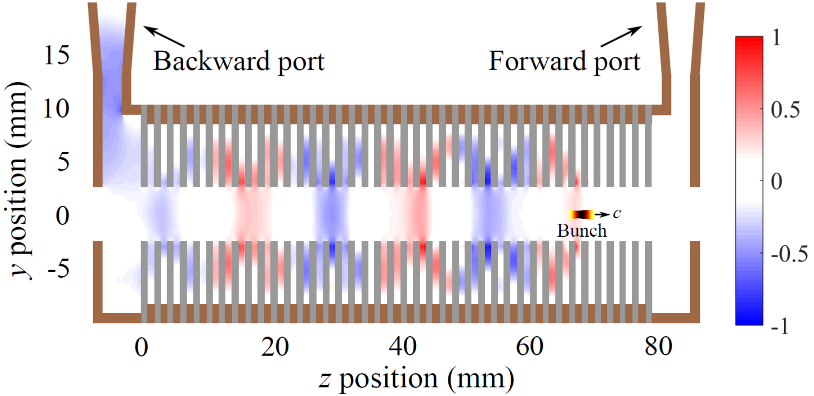
Structure	Beam Aperture (mm)	Group Velocity	r/Q (kΩ/m)
Alumina-loaded tube	6.0	0.106 c	10
Metallic disk-loaded	6.0	0.016 c	16.5
Metallic disk-loaded	17.6	0.22 c	3.9
Photonic bandgap	6.3	0.015 c	14.5
MTM 'wagon wheel'	6.0	-0.158 c	21

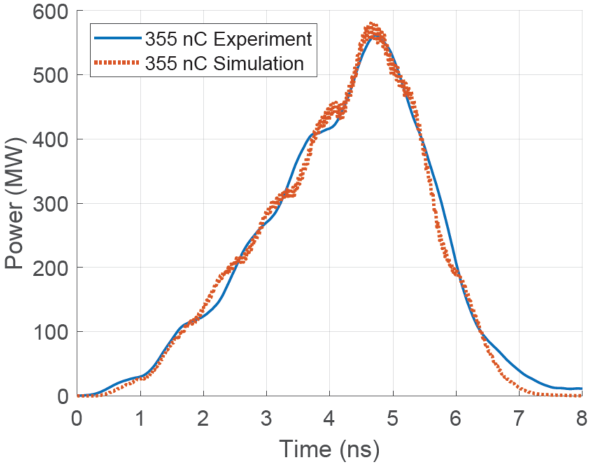
Metamaterial power extractor

- A series of metamaterial power extractors at 11.7 GHz tested at AWA
  - Highest peak power as 565 MW from a train of eight bunches with a total charge of 355 nC



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

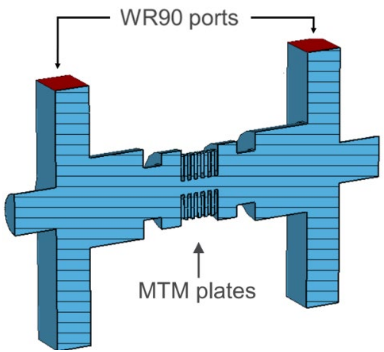


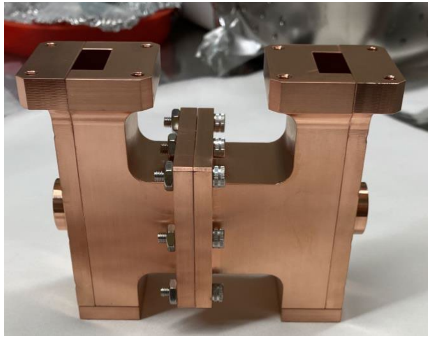


Metamaterial accelerator design

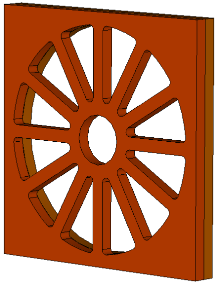
- Efficient structure design to explore gradient limitation
  - Optimized for high transient gradient with 6 ns (FWHM) input RF pulses
  - Negative group velocity in the fundamental TM mode

Full Structure



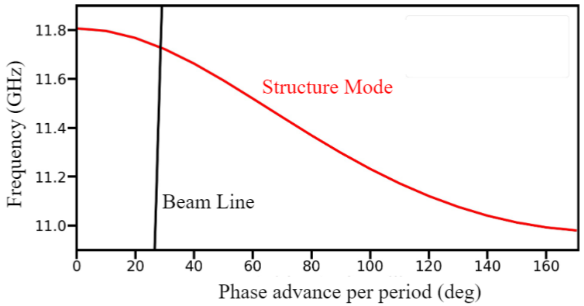


Unit Cell



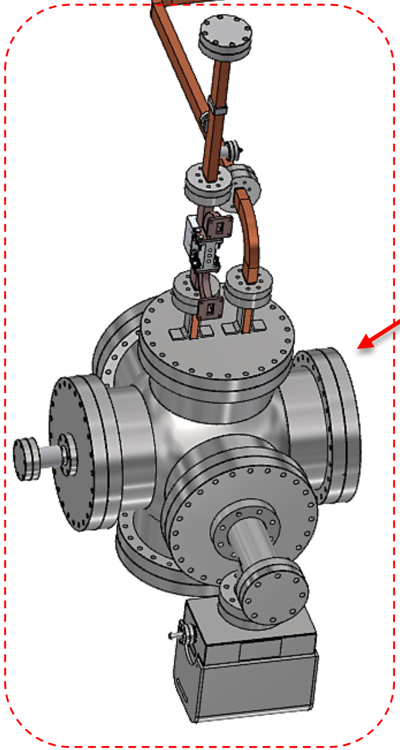
Beam aperture:
4 mm (diameter)
Plate thickness:
1 mm

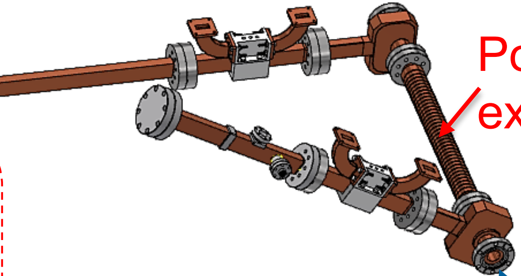
Dispersion curve



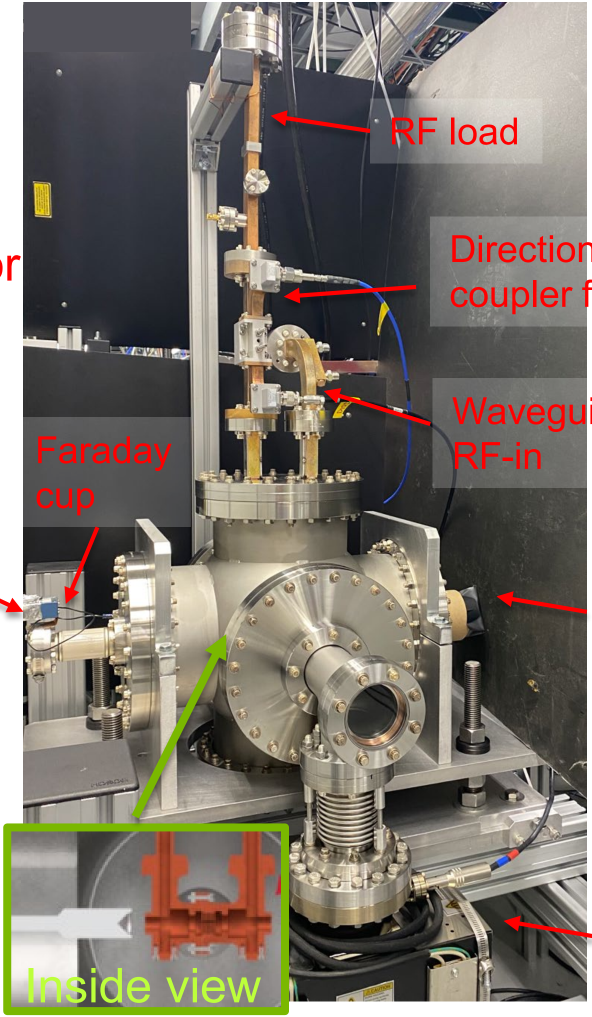
D. Merenich, NIU Master's Thesis: "Design and Cold Test of a Metamaterial Accelerating Structure For Two-beam Acceleration", June 2023

Breakdown test stand





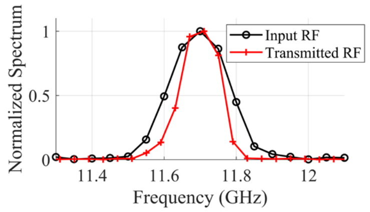
- Vacuum chamber built with breakdown diagnostics
  - Dark electrons (Faraday cup)
  - Light (photodiode and camera)



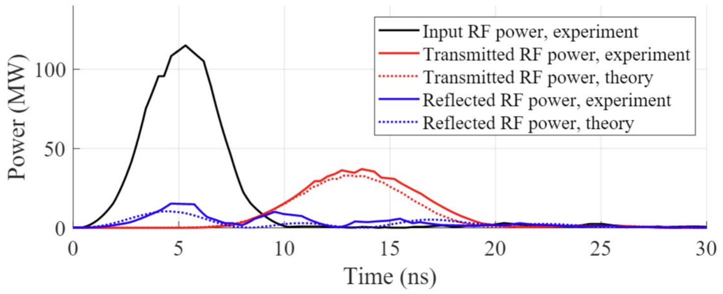
Representative pulse

- Conditioned with over 3×10^5 pulses
- Peak gradient of 190 MV/m with 115 MW of input RF power
- Unconventional time structure due to the short-pulse length
  - Primary pulse + secondary pulse

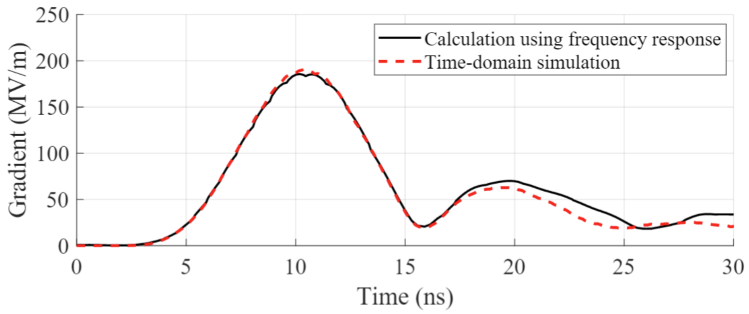
Short pulse → wide band



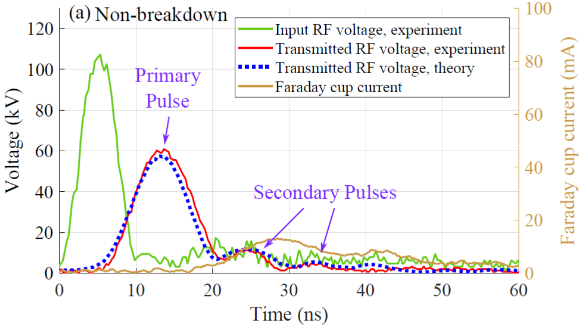
Measured RF traces benchmarked with theory

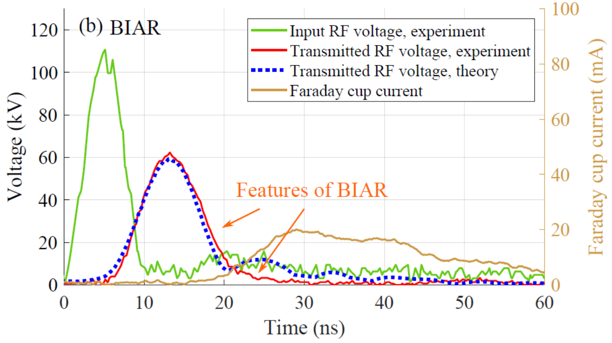


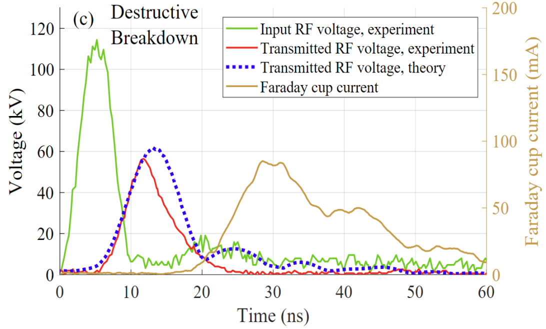
Calculated Gradient



Breakdown insensitive acceleration regime (BIAR)







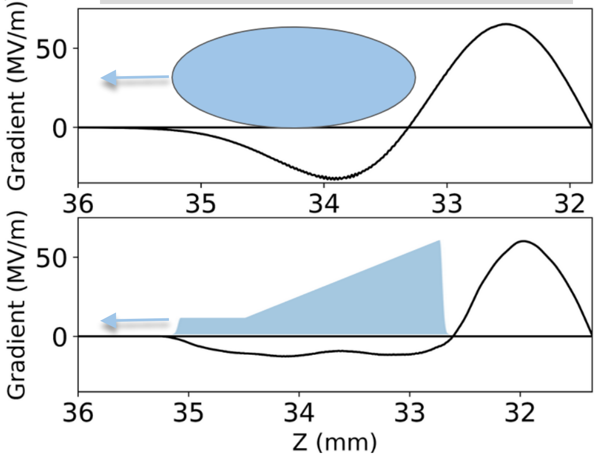
Non-breakdown	BIAR breakdown	Destructive breakdown
Primary pulse present	Primary pulse not interrupted	Primary pulse interrupted
Secondary pulse present	Secondary pulse not present	Secondary pulse not present
Faraday cup signal: Low	Faraday cup signal: Mid	Faraday cup signal: High

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

Sub-THz structures for high-efficiency & high-gradient collinear acceleration

- Integration of wakefield structures + shaped beams
  - Emittance exchange (EEX) beamline at AWA
    - Transverse-to-longitudinal EEX
    - Shaped drive beam
      - Higher "transformer ratio"
      - Longer interaction length
      - Higher efficiency
- Optimization study using masks + EEX
  - Previous bunch shaping study with nonlinear optics (12 sextupole and 12 octupole magnets)
  - Our current plan doesn't require new major hardware or beamline changes at AWA

Particle-in-cell simulations

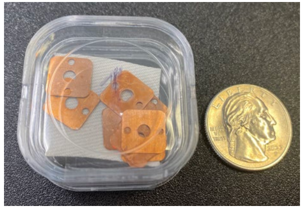


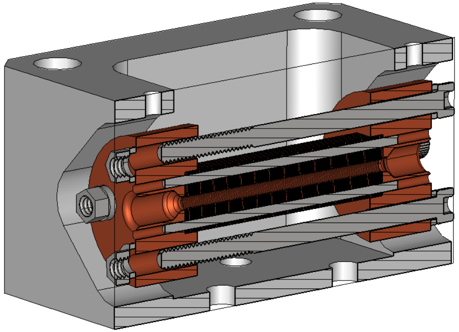
- 110 GHz metallic disk-loaded structure
- Excited by a longitudinally-shaped 10 nC electron bunch, 2.5 mm long

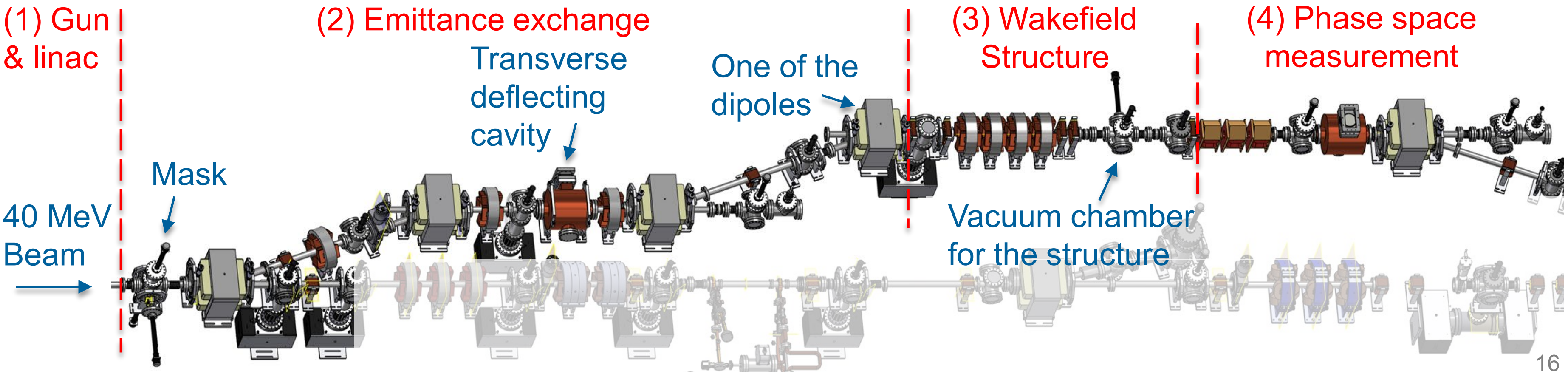
A. Zholents, Proc. IPAC'18, TUPMF010
W. H. Tan, *et al.*, PRAB **24** 051303 (2021)

Experiment preparation

- Structure fabrication
  - Copper plates manufactured by precision laser cutting
  - Complete clamped structure
- EEX Beamline reconfiguration
- First run planned for Nov.-Dec. 2023







Conclusions & Ongoing Work

Efforts towards SWFA-based compact accelerators

- Advanced RF structure development for SWFA
  - X-band metamaterial accelerator experiment, achieving high gradient and demonstrating potential benefits of short-pulse acceleration
    - Breakdown insensitive acceleration regime
  - Sub-THz structure to be tested utilizing shaped electron bunches for high-gradient high-efficiency acceleration
- Other ongoing efforts in synergy
  - RF structures with new topologies (e.g. W-band MTM power extractor)
  - Modeling of dark current in structures with short RF pulses
  - Understanding of coherent synchrotron radiation in complex beams for AAC

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