DOE GARD RF Roadmap Update

NCRF Meeting

Engineered Electromagnetic Materials for High-Gradient Structures

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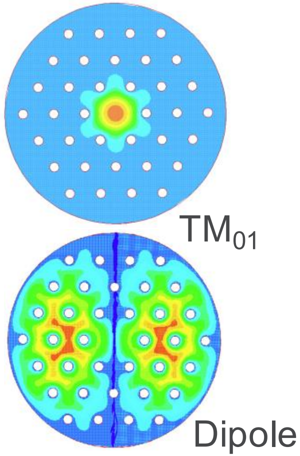
01/20/2026

"Engineered Electromagnetic Materials" in this talk

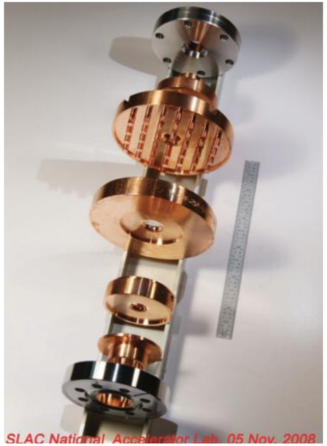
- This talk focuses on **advanced NCRF accelerating structures** using **engineered electromagnetic materials** in the **microwave** range, including but not limited to:
  - Metamaterial structures
  - Photonic crystals, including photonic bandgap structures
  - ...
- This talk does **<u>NOT</u>** cover the following highly active and relevant areas:
  - Application of these advanced structures as **SRF** accelerating structures
  - Application of these advanced structures as interaction circuits in **high-power microwave (HPM)** sources
    - Demonstrations in gyrotrons, traveling-wave tubes (TWTs), klystrons, extended-interaction klystrons (EIKs), backward-wave oscillators (BWOs), ...
  - **Optical** wavelength and laser applications
  - Engineered **surfaces**, such as metasurfaces or metafilms
    - Vital for many applications including communication, microscopy/imaging, sensing/detection, optical computing and others
  - **Multi-functional** or multiphysics designs for simultaneous control of electromagnetic waves and other physical regimes (e.g., thermal management, acoustic, ...)
- *Apologies for incompleteness!*

Representative examples of engineered electromagnetic materials for NCRF accelerator applications

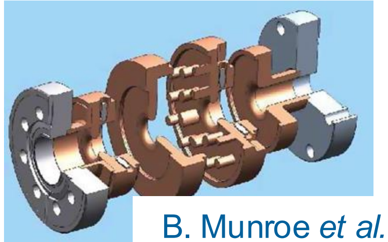
Photonic bandgap structures



E. Simakov *et al.*

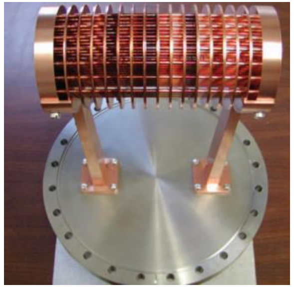


R. Marsh *et al.*



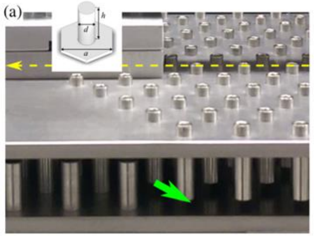
B. Munroe *et al.*

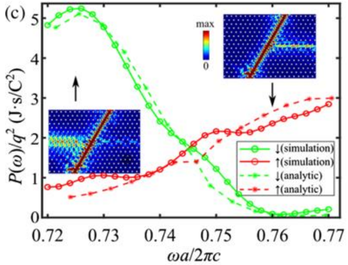
J. Zhang *et al.*



E. Simakov *et al.*

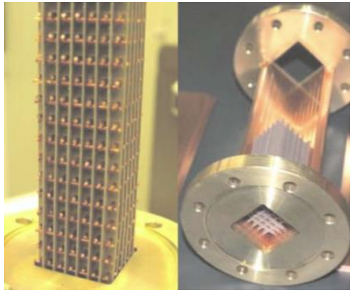
Photonic topological crystals



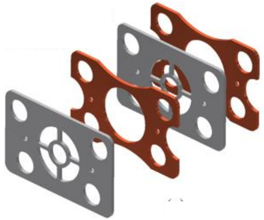


Y. Yu *et al.*

Metamaterial structures



S. Antipov *et al.*

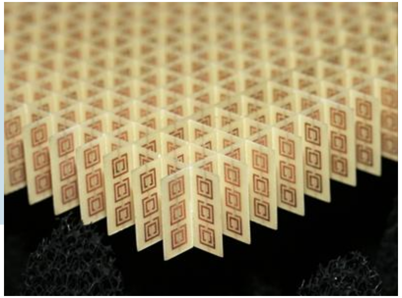


X. Lu, J. Picard, *et al.*

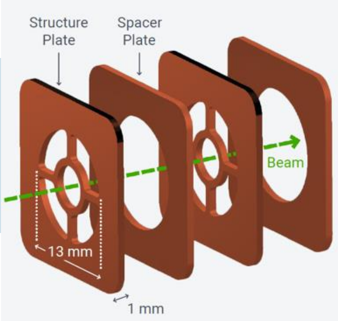
Metamaterials (MTMs)

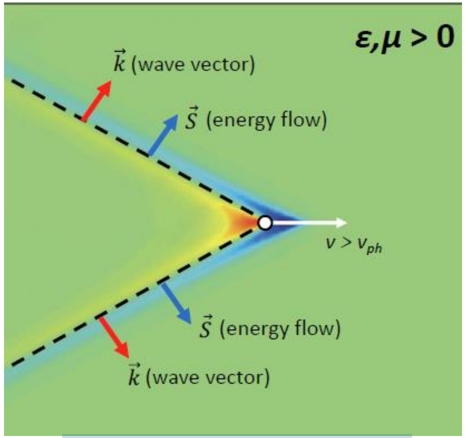
- An artificial material with a subwavelength unit cells
- Unit cell designs could lead to exotic EM properties
  - **Double-negative** MTMs: $\varepsilon,\ \mu < 0$
  - **Reversed Cherenkov radiation**
- "**Wagon wheel**" MTM structures
  - Subwavelength periodic structures
  - Rugged structure with high group velocity and high shunt impedance
  - Large degree of flexibility for optimization in parameter-space
  - Compact and cost-effective modules from the clamped design

Metamaterial with split ring resonators on PC Boards

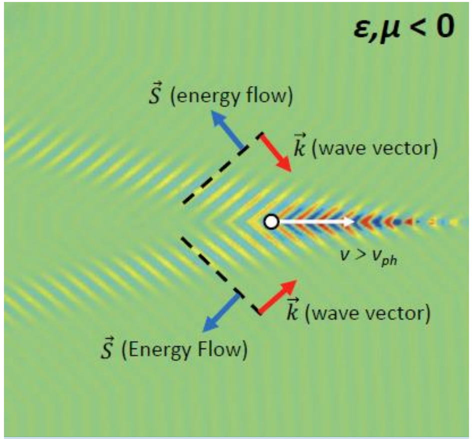


Wagon wheel MTM structure





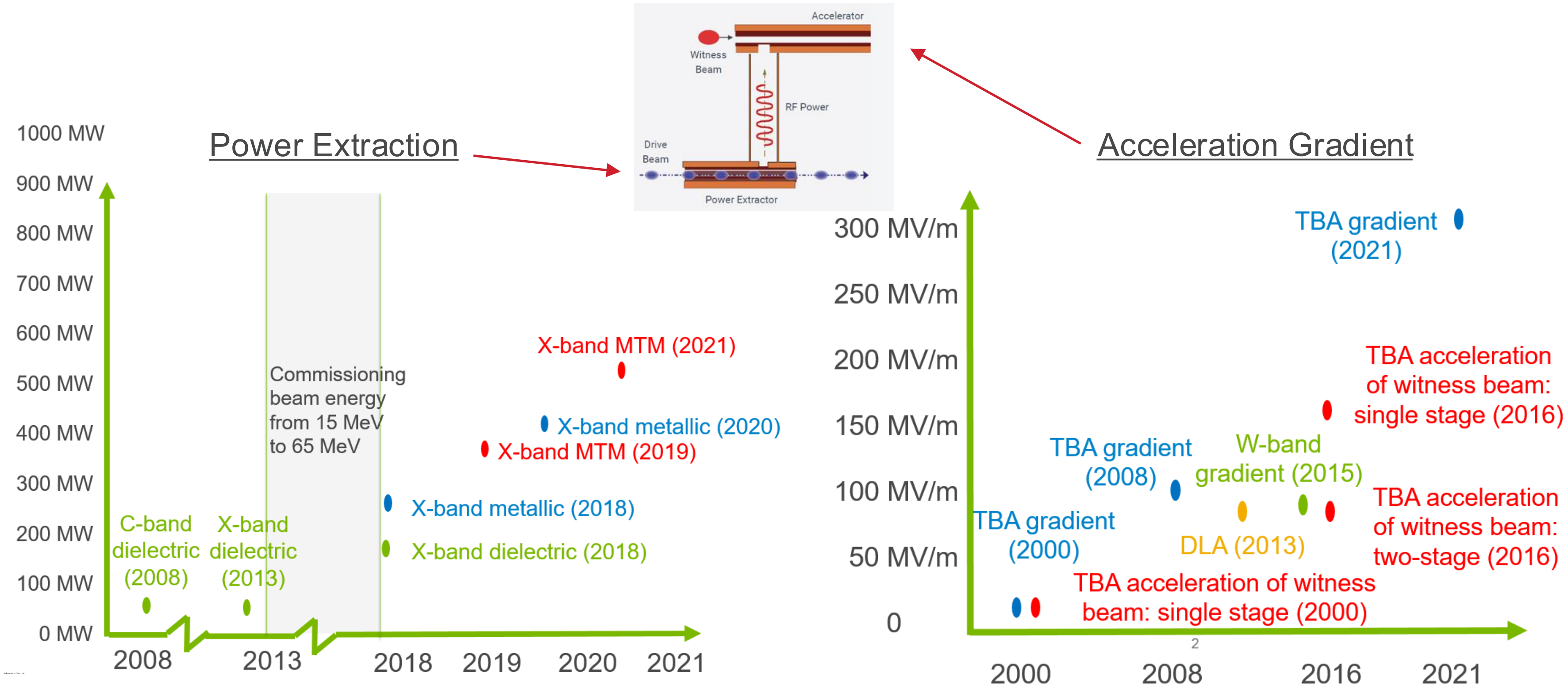
Cherenkov Radiation



Reverse Cherenkov Radiation

Application of MTM structures in Structure Wakefield Acceleration (SWFA)

Specifically, Two-Beam Acceleration (TBA)



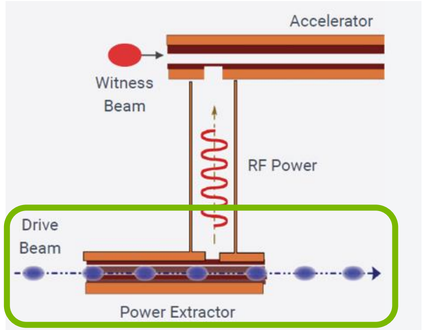
MTM structures fulfill SWFA requirements

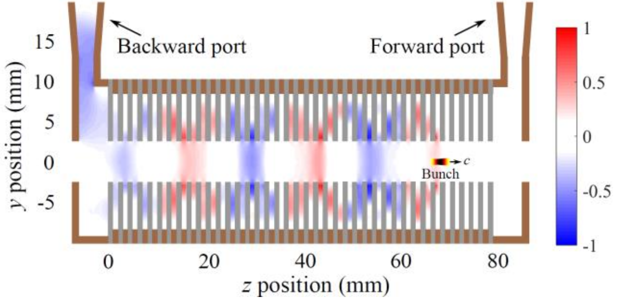
- Special requirements for efficient wakefield extraction and acceleration
  - High shunt impedance (r/Q)
  - High group velocity (v_g)
    - For power extractor, $P = q^2 k_L |v_g| \left(\frac{1}{1-v_g/c}\right)^2 \Phi^2$
    - For accelerator, short filling time required for short pulses
- Reversing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

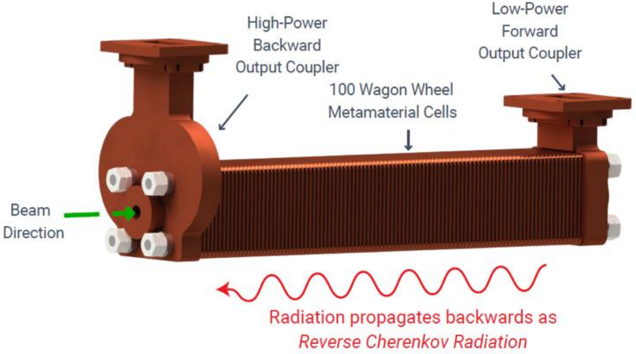
Structure	Beam Aperture (mm)	Group Velocity	r/Q (kΩ/m)
Alumina-loaded tube	6.0	0.106 c	10
Metallic disk-loaded	6.0	0.016 c	16.5
Metallic disk-loaded	17.6	0.22 c	3.9
Photonic bandgap	6.3	0.015 c	14.5
MTM ‘wagon wheel’	6.0	-0.158 c	21

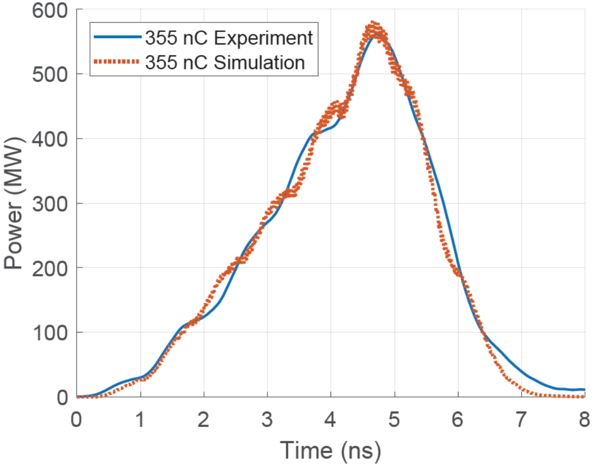
Highest power generated in SWFA extractors

- **565 MW** from an X-band MTM power extractor
  - Generated from a 355 nC train of **eight bunches**
  - Coherent addition of reversed Cherenkov radiation





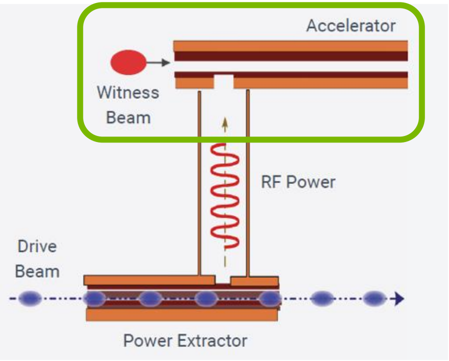




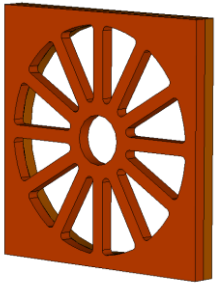
J. Picard *et al.*, PRAB **25**, 051301 (2022)

MTM accelerator design for two-beam acceleration

- Wagon wheel structure optimized for high transient gradient with a 6 ns FWHM input pulse available at AWA
- MTM structure with a negative group velocity has a **higher shunt impedance** than structures with the **same but positive** group velocities



Unit Cell

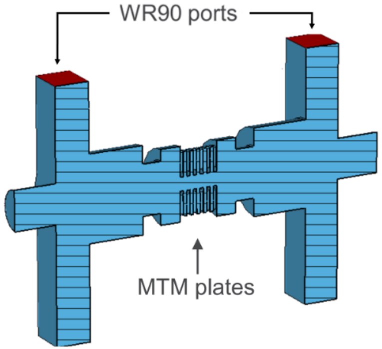


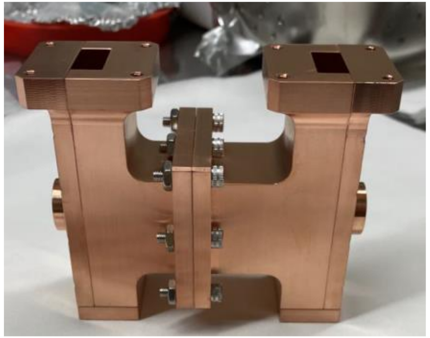
Subwavelength period

Beam aperture:
4 mm (diameter)

Plate thickness:
1 mm

Full Structure (vacuum)

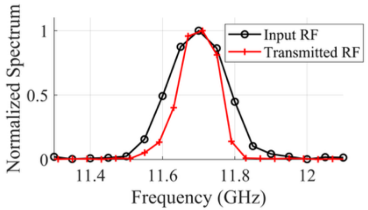


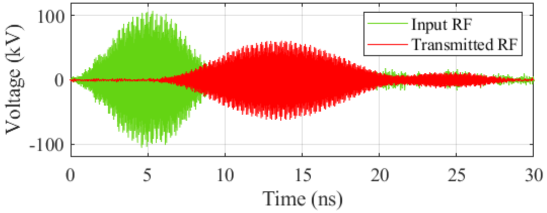


D. Merenich *et al*., PRAB **27**, 041301 (2024).

Representative pulse

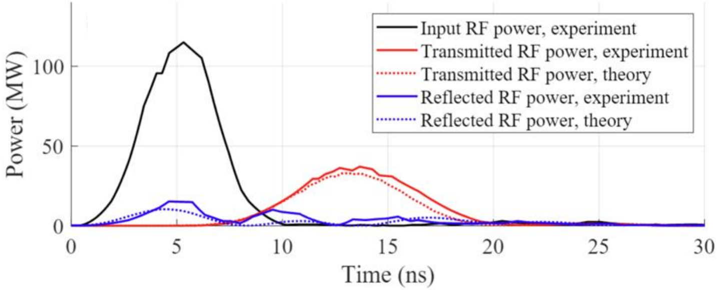
- Conditioned with over 3×10^5 pulses
- Peak gradient of 190 MV/m with 115 MW of input RF power
- Unconventional time structure due to the short-pulse length
  - Primary pulse + secondary pulse



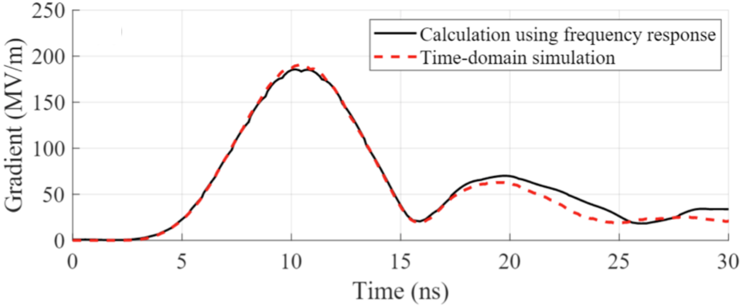


Raw measurement

Measured RF traces benchmarked with theory

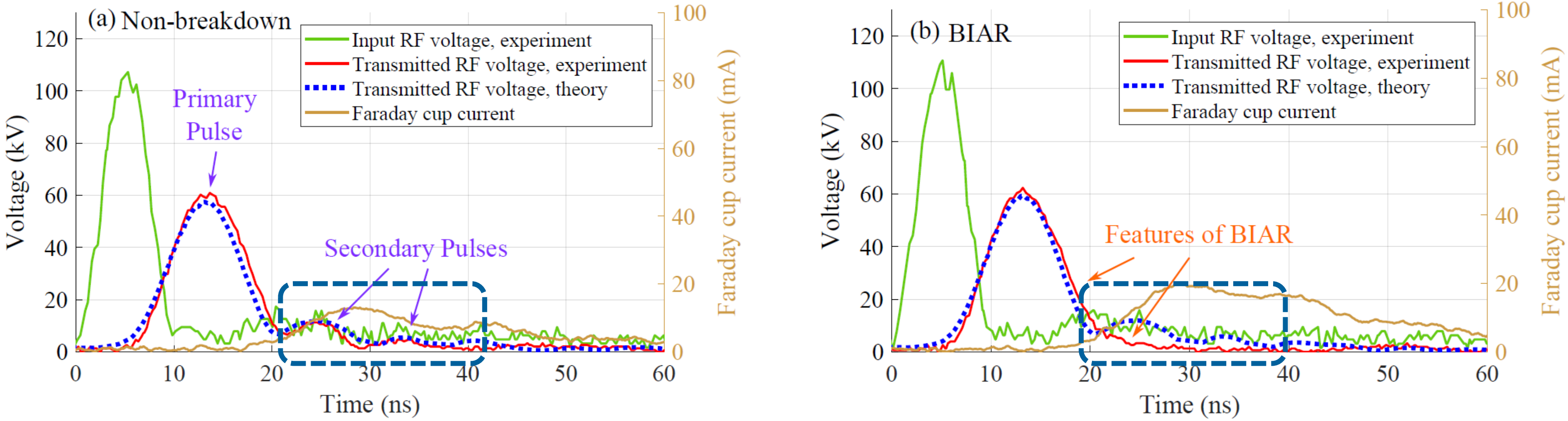


Calculated Gradient



Breakdown Insensitive Acceleration Regime (BIAR)

- An observation suggesting the benefits of short-pulse acceleration
  - “Primary” pulse (useful for acceleration) not interrupted
  - RF breakdown in “secondary” pulses
- *To be demonstrated*: beam acceleration during a BIAR breakdown event



Current areas of investigation on BIAR

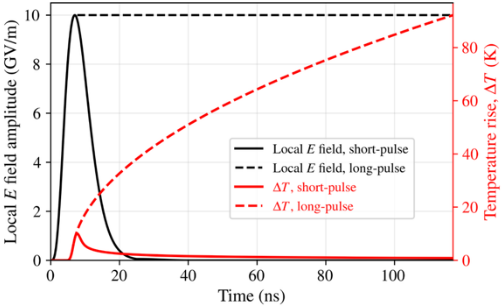
- Understanding gradient limits stemming from RF breakdown is **highly relevant** to the design and implementation of engineered electromagnetic materials.
- **BIAR** could enable higher gradients, as shown in a series of exp., though challenges remain.
  - Little empirical data and modeling in this parameter space
  - Experimental demonstrations still required to understand the impact on beam quality
  - Maturation of the technology for large-scale HEP applications (a “stepping-stone” facility with less stringent requirements would help bridge the current R&D gap)
- Breakdown physics in the short-pulse regime is a valuable research topic for the community.
  - Complementary to existing testing data to help populate a **comprehensive breakdown library**
  - Enabling better use of accelerators with shorter RF pulses
  - Possibility of **decoupling breakdown-related processes** on various time scales to enhance physics understanding across different scenarios
- Ongoing R&D efforts on this topic:
  - **Beam dynamics studies** in the transient regime ← G. Chen *et al.*, arXiv:2503.09575 (2025).
  - Further experimental campaigns planned at AWA to characterize **beam quality**
  - Testing of **new structures** designed for short-pulse acceleration
  - Development of a targeted setup to initiate BIAR breakdown physics studies: **theory and sims. of dark current** in a pillbox-like cavity to compare long- and short-pulse operation

G. Rijal *et al.*, PRAB **28**, 111301 (2025).

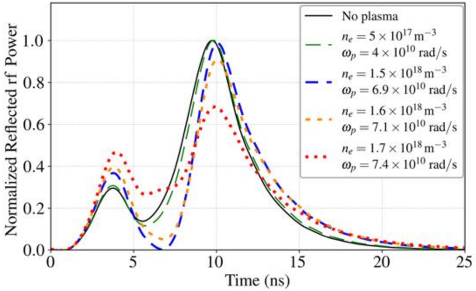
Possible mechanisms of breakdown mitigation

- Limited pulse duration and rapid temporal variation of the EM fields restrict the time windows for breakdown-related processes to develop.
  - Field emission, pulsed heating, multipacting, plasma formation, ...
- Further development of detailed RF/plasma modeling tools is required for better characterization.

Field emission: comparison of temperature rise from field-emission-induced Joule heating

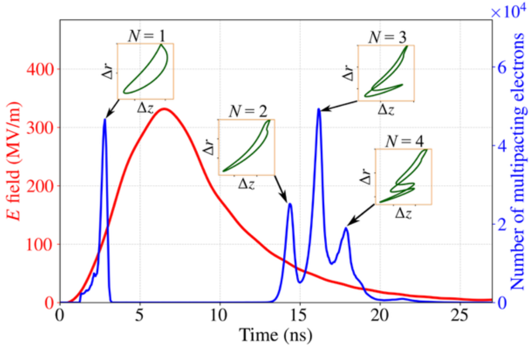


Electron cloud: with various electron densities; ion motion negligible in the timeframe

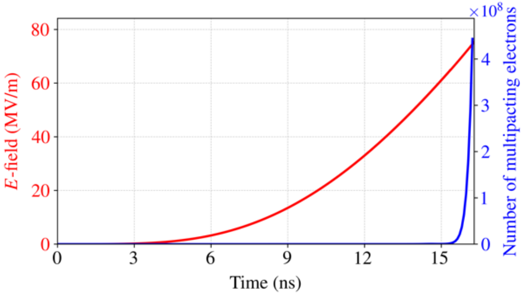


Multipacting: Comparison of electron #

Short-pulse



Long-pulse



Topics of interest in NCRF structures for HEP relevant to this talk (personal view)

- **Advanced NCRF structure development:**
  - **High-gradient accelerating structures:** design and optimization of structures with low surface E/H field to gradient ratio satisfying minimum acceptable beam aperture requirement across applications
  - **Novel structure topologies and/or coupling schemes:** to meet constraints, e.g., short filling time, tight space in cryomodules or magnets, power coupling between enclosed cavities in muon ionization cooling channel, heavy beam loading, ...
  - **Cavities for beam diagnostics, control and other RF components:** beam position monitor cavities, transverse deflecting cavities, RF kickers, RF windows, power couplers, RF loads, ...
  - **Collective effects:** wakefield suppression, HOM damping and detuning, mitigation of beam instabilities, ...
  - ...
- **Fundamental physics:** RF breakdown mechanisms and gradient limits
  - **Dedicated test stands:** development of specialized and synergistic facilities (DC, RF, cryogenic, with B-field, various frequency bands, various pulse lengths using SWFA or pulse compressors, ...) to probe fundamental limits and experimentally evaluate mitigation strategies
  - **Modeling across scales:** coupled multiphysics modeling (RF, plasma, thermal, ...) on various scales to understand breakdown initiation, evolution and scaling behavior
  - **RF breakdown under unconventional conditions:** short RF pulses, strong magnetic field, cryogenic operation, ...
  - ...

Enabling technologies: reasons for optimism ☺

- Major advances in key technologies transforming the design, fabrication and operation of NCRF structures, including engineered electromagnetic materials
  - **High-fidelity simulation tools** leveraging increased computing resources to simulate complex structures
  - **Advanced machining** (e.g. precision machining, additive manufacturing, microfabrication, cost-effective technologies, ...) to achieve tighter tolerances and enable novel geometries
  - **New materials** and surface treatment approaches for NCRF cavities
  - **Cryogenics**
  - **AI/ML**, with a few examples below:
    - Optimizing RF structures for various applications, e.g. using reduced order models for efficient RF system design, intelligent forward/inverse design, and on-demand customization
    - Prediction of beam instabilities in NCRF accelerators (e.g. beam breakup instability in structure wakefield accelerators), integrated with advances in beam diagnostics/control enabled by AI/ML
    - ...
  - ...

Summary

- R&D on **advanced NCRF structures** is an active field of research and is essential for the development of future HEP accelerators.
- **Engineered electromagnetic materials** are excellent examples to showcase recent progress in advanced NCRF structure R&D.
  - As an example, metamaterial structures have been demonstrated for high-gradient structures, specifically as both power extractors and accelerators for two-beam acceleration.
- Understanding of **RF breakdown** and development of advanced NCRF structures go hand in hand.
  - Characterizing RF breakdown under unconventional regimes, including **short RF pulses**, can help populate a comprehensive breakdown library; more detailed modeling and exhaustive experimental characterization are the immediate next steps.
- Pipelines have been developed for **workforce development** in this area through DOE-funded traineeships, SCGSR programs, national lab outreach programs and others.
  - Recruitment and retention of early-career researchers are still critical to maintain US leadership, and after all, the more, the merrier.

Acknowledgements

- Salih Colmekci (NIU)
- Gongxiaohui Chen (ANL)
- Scott Doran (ANL)
- Ryan Farrell (NIU)
- Thomas Harless (NIU)
- Josh Hlavenka (ANL)
- Chunguang Jing (Euclid/ANL)
- Brendan Leung (NIU)
- Wanming Liu (ANL)
- Rachel Margraf-O’Neal (ANL)
- Dillon Merenich (NIU)
- Calcifer Phillips (NIU)
- Julian Picard (MIT graduate)
- Omkar Ramachandran (NIU)
- Gaurab Rijal (NIU)
- Michael Shapiro (NIU)
- Richard Temkin (MIT)
- Philippe Piot (ANL)
- John Power (ANL)
- Charles Whiteford (ANL)
- Eric Wisniewski (ANL)

- Contributions from many other colleagues in the community; apologies for any omissions.
- Much of the work presented here has been supported by DOE HEP GARD across multiple institutions.

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