CLIC Workshop 2019

A Metamaterial Structure for Wakefield Acceleration

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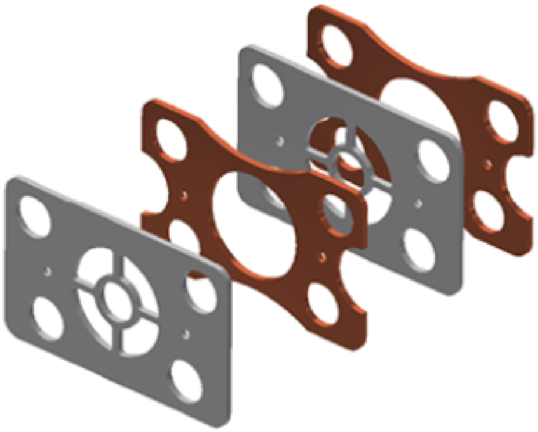
Recent Publication

PHYSICAL REVIEW LETTERS **122,** 014801 (2019)

Editors' Suggestion | Featured in Physics

Generation of High-Power, Reversed-Cherenkov Wakefield Radiation in a Metamaterial Structure

Physics VIEWPOINT



A Metamaterial for Next Generation Particle Accelerators

Published 7 January 2019

An experiment reveals the potential of custom-engineered metamaterials to yield higher accelerating gradients than current particle accelerator technology allows.

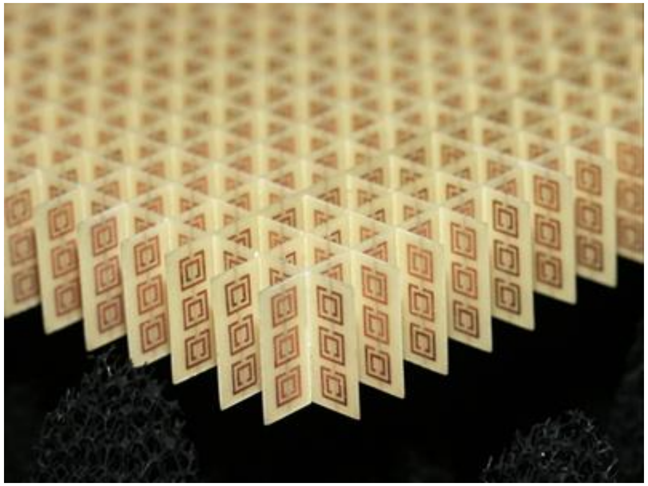
See more in *Physics*

Outline

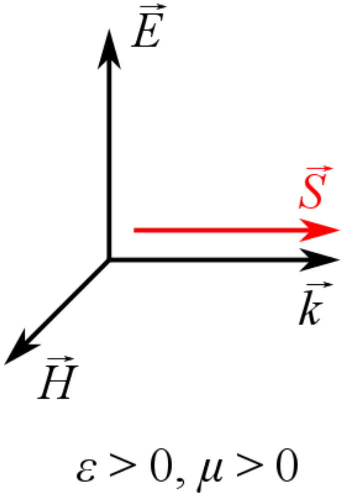
- Introduction & Motivation
- Experimental Facilities
- Design and theory
  - Metamaterial Structure Design
  - Theory and Simulation
- Experiment
  - Structure Fabrication
  - Experimental Results
- Conclusions

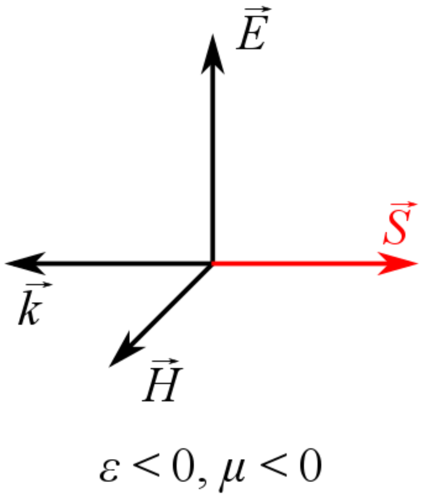
Metamaterials

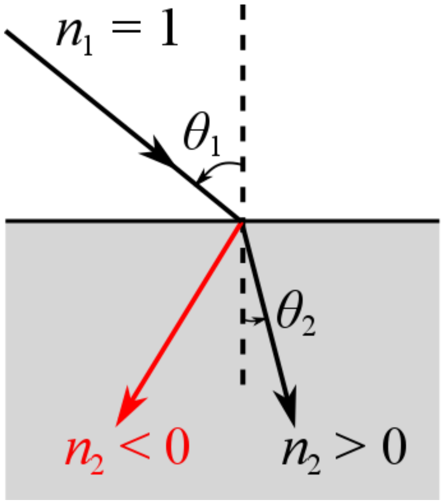
- Metamaterial (MTM):
  - An artificial material with a subwavelength structure
  - Exhibits properties not usually found in natural materials
  - Especially a negative refractive index : simultaneous $\varepsilon, \mu < 0$
- Left-handed materials
  - Negative refraction



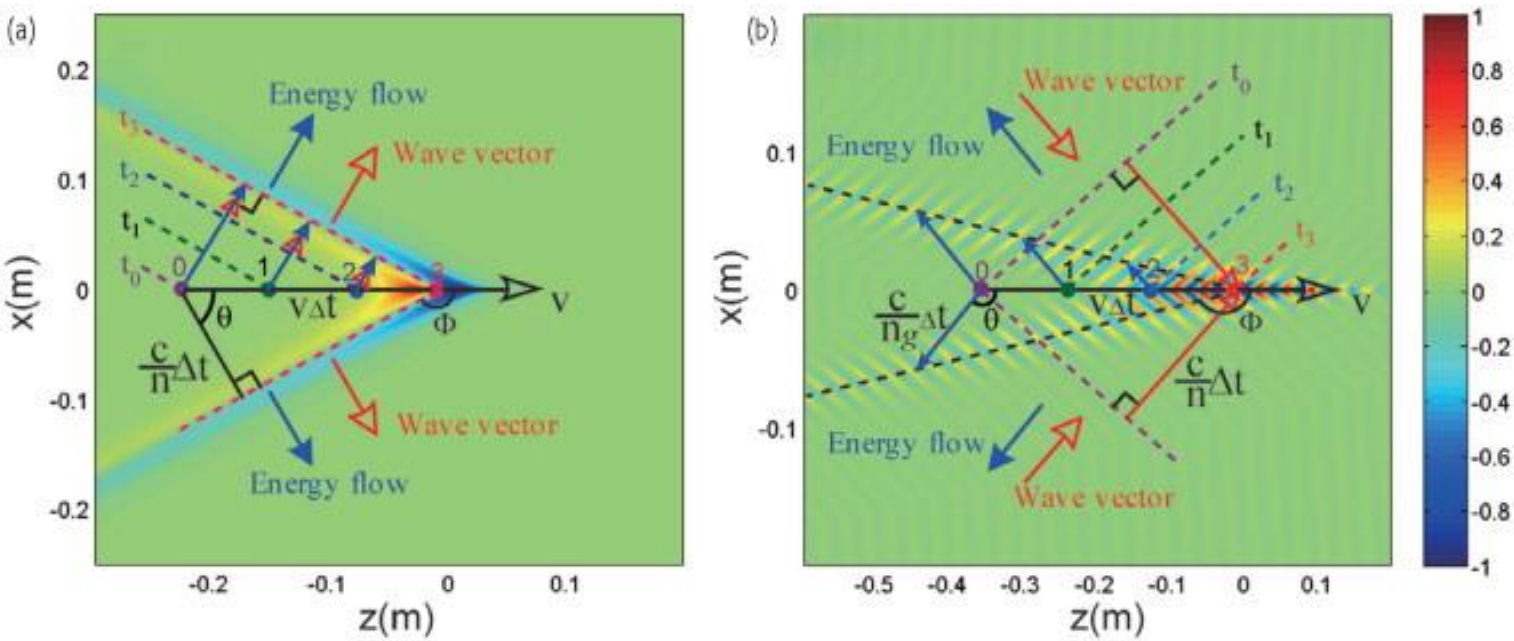
Metamaterial with Split Ring Resonators on PC Boards







Reversed Cherenkov Radiation



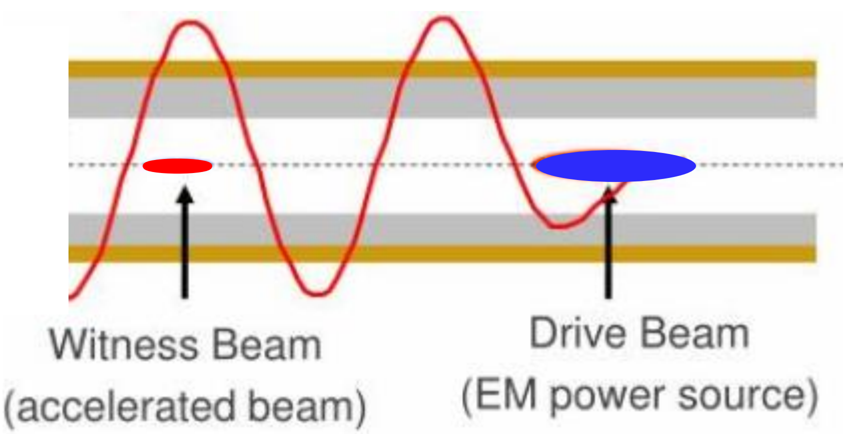
- Cherenkov Radiation
  - Electron velocity exceeds wave phase velocity
  - $\varepsilon, \mu > 0$
  - Wave vector and energy flow **parallel**
- Reversed Cherenkov Radiation
  - $\varepsilon, \mu < 0$
  - Wave vector and energy flow **anti-parallel**

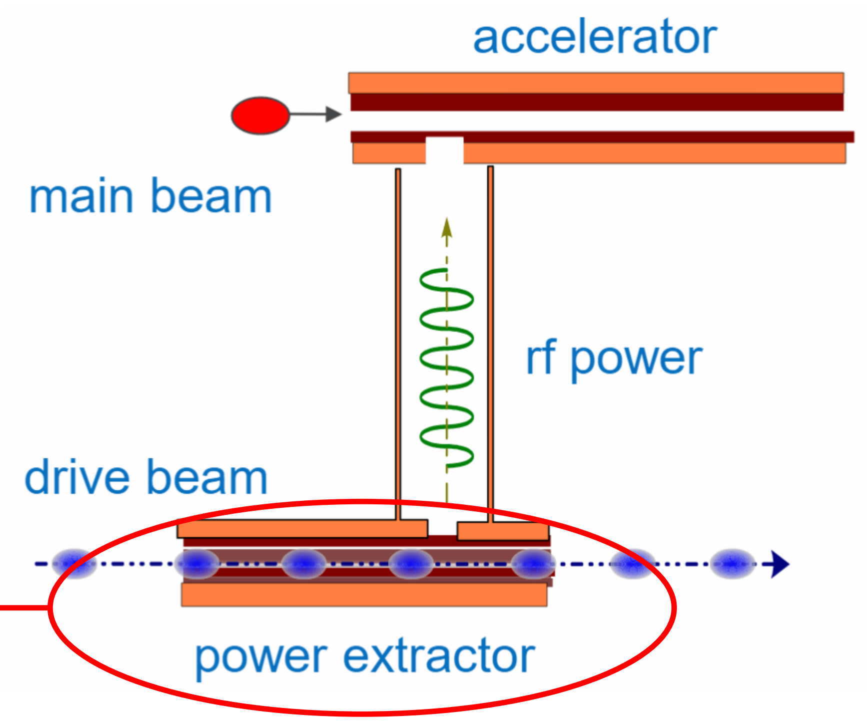
Hongsheng Chen and Min Chen. "Flipping photons backward: reversed Cherenkov radiation." *Materials Today* 14.1-2 (2011).

Structure-Based Wakefield Acceleration

- Collinear acceleration:
  - Drive beam generates high power microwaves in a structure
  - Witness beam gets accelerated after the drive beam

- Two-beam acceleration (TBA):
  - Drive beam generates high power microwaves in a power extractor
  - RF power is transferred from the power extractor to the accelerator
  - Main beam gets accelerated

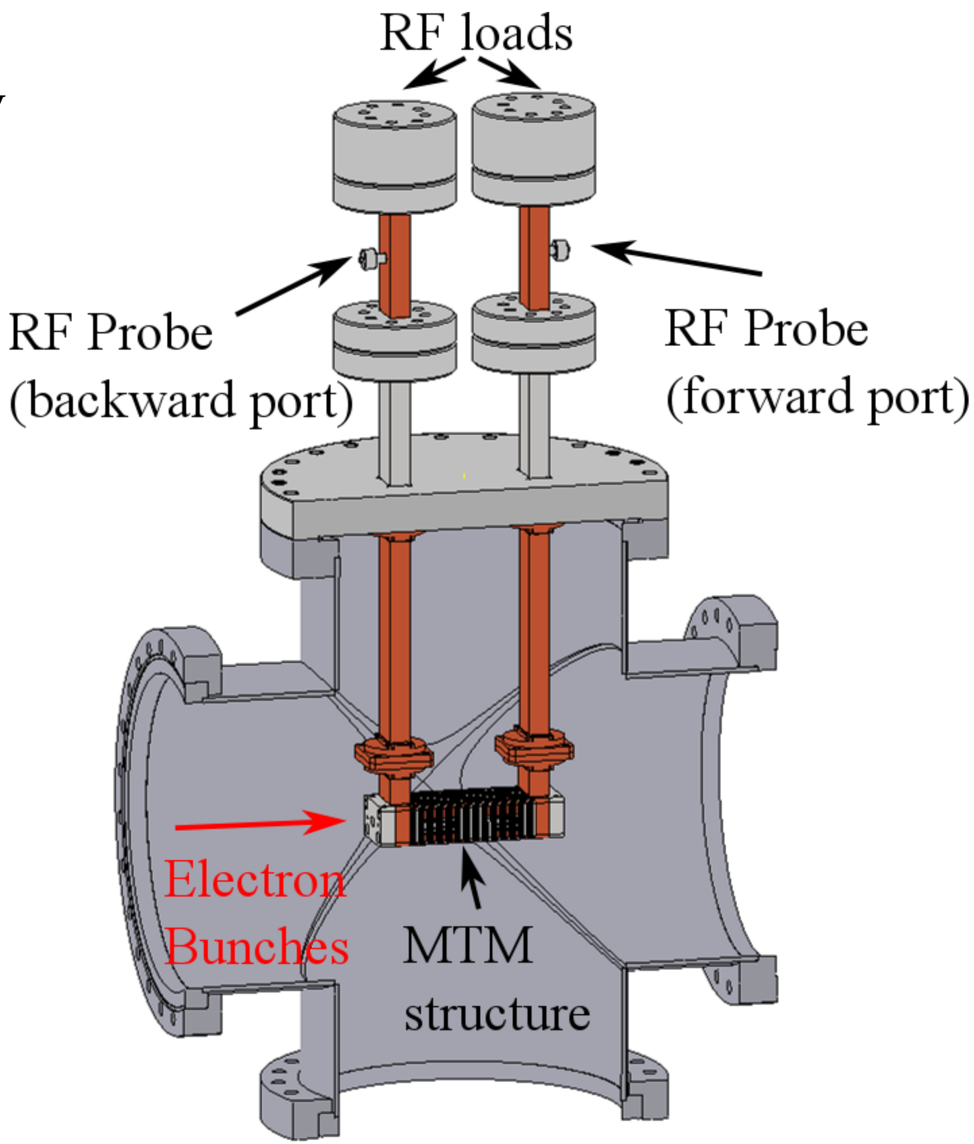




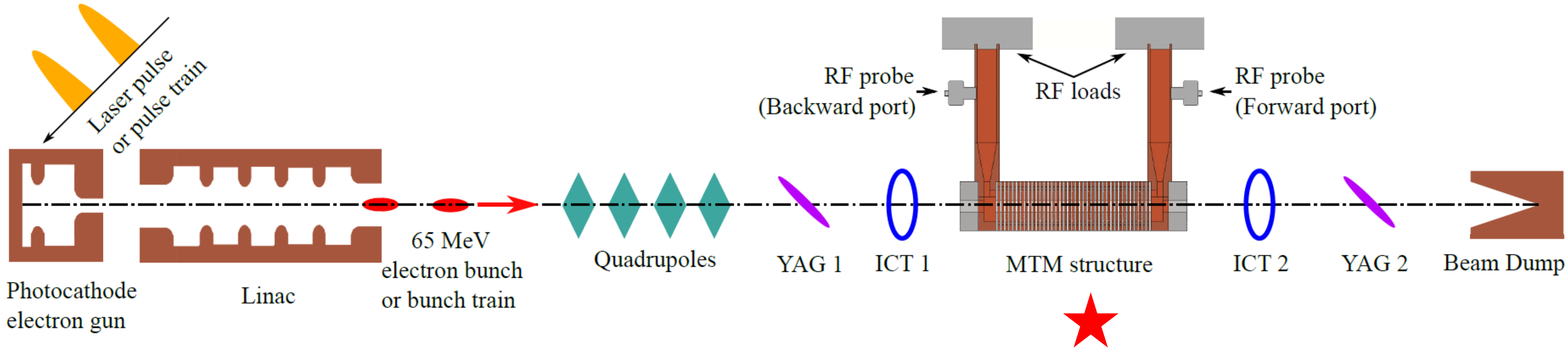
This experiment:
A Power Extractor

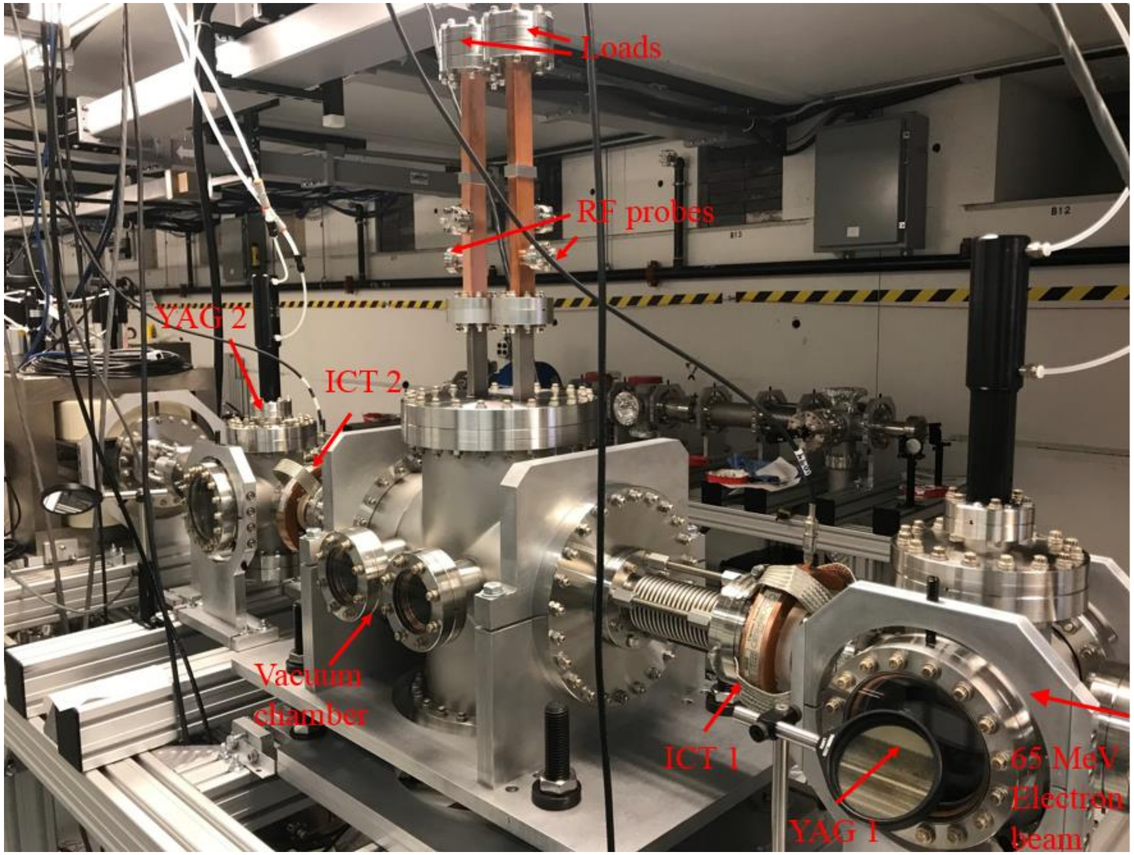
Motivation

- Science:
  - Verify reversed Cherenkov radiation in a metamaterial structure from a direct measurement
- Application:
  - High power microwave generation for wakefield acceleration in both collinear and two-beam acceleration regimes
  - All-metal structure to survive high RF power



Experimental Setup at AWA





Diagnostics:

ICT (Integrating current transformer): Bunch charge

YAG screen: Bunch transverse size

RF probes: Output microwave

Outline- ANL WFA Experiment

- Motivation
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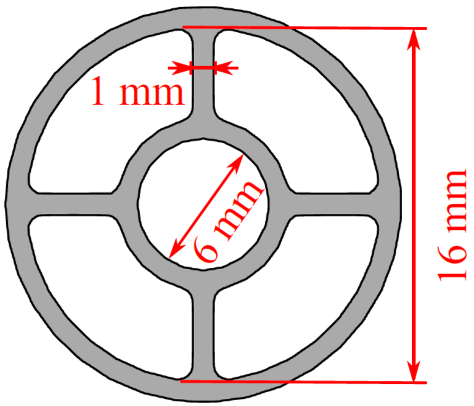
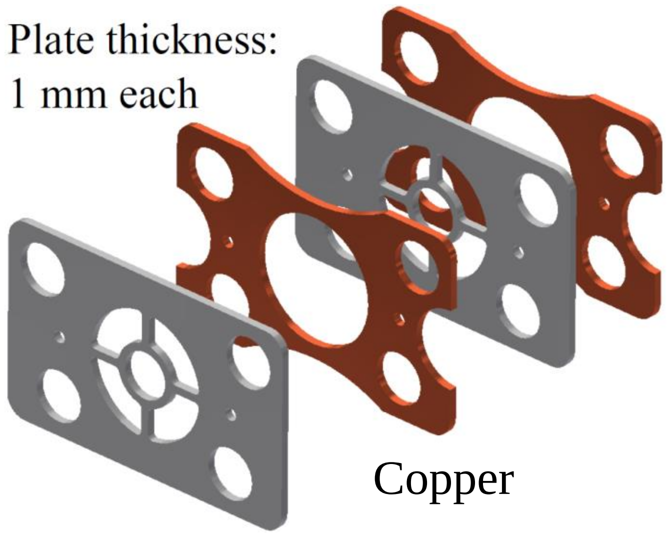
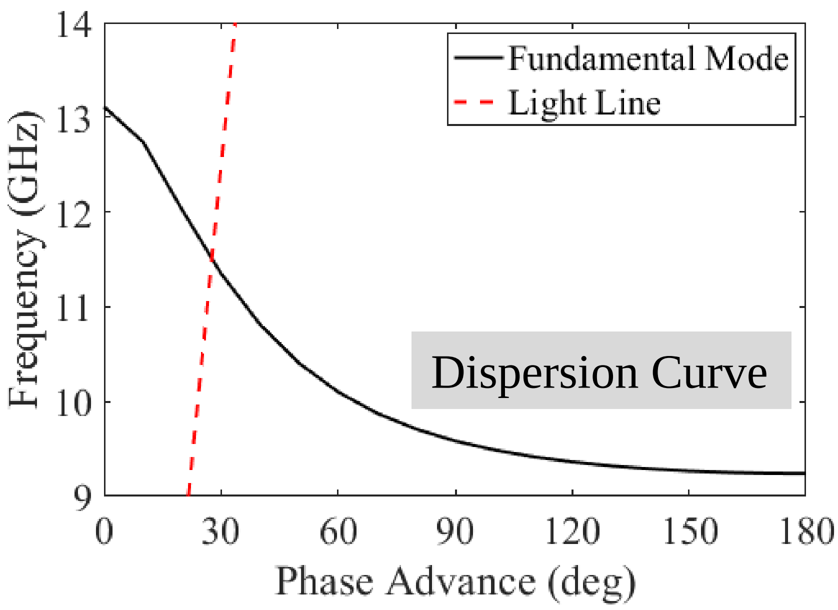
Wagon Wheel Structure Unit Cell

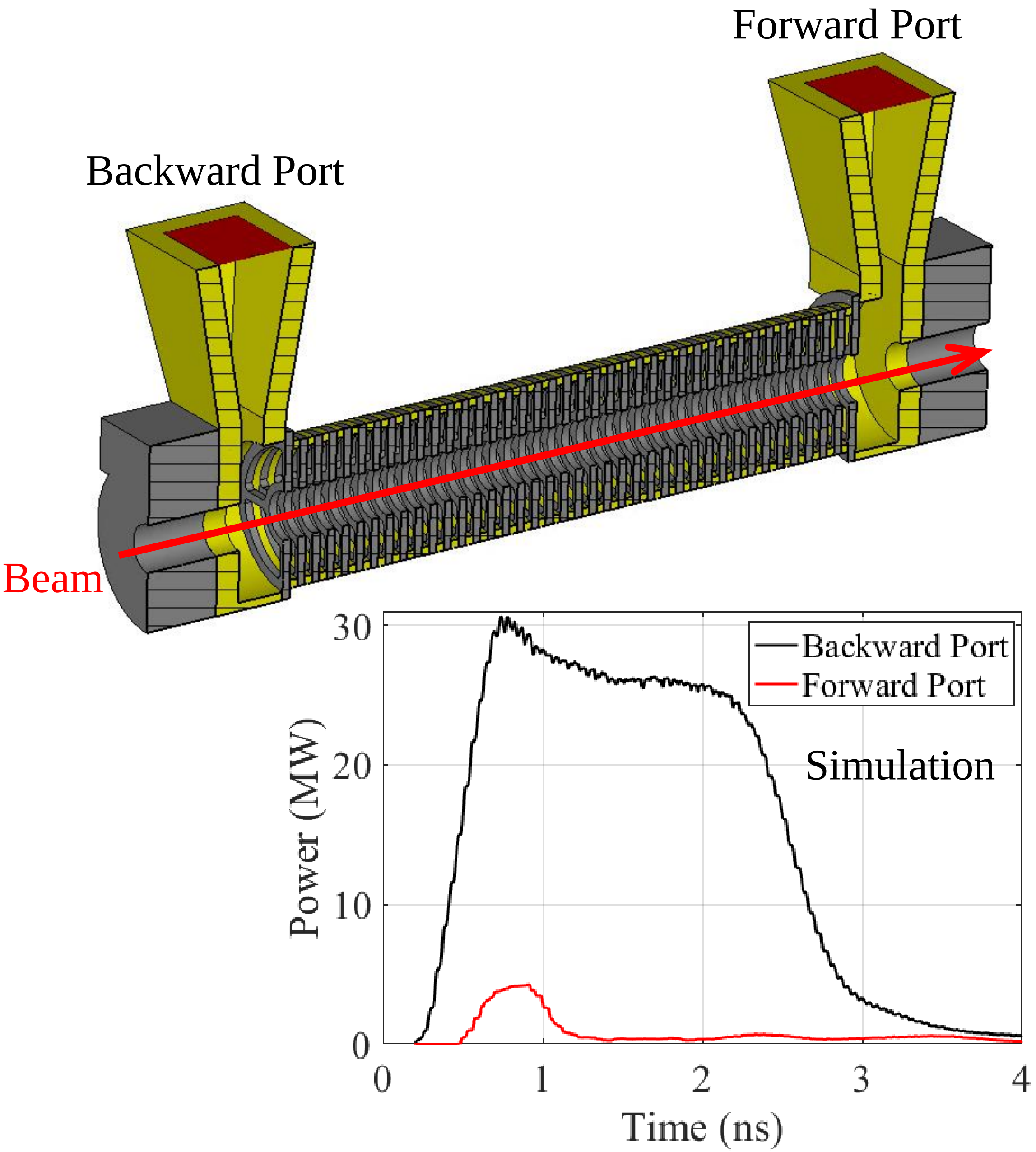
- Wagon wheel structure
  - Periodic subwavelength structure
    - Period: 2 mm
    - Free wavelength at 11.42 GHz: 26 mm
  - Negative group velocity
  - Fundamental mode: TM mode
  - Interaction frequency: 11.42 GHz
    - Cutoff frequency of an empty waveguide: 14.2 GHz







CST Simulation



- CST Wakefield solver, single bunch
  - 45 nC, σ_z = 1.2 mm
- **26 MW** steady state in the backward port
- Much lower power in the forward port
  - Reversed Cherenkov radiation
- Analytical theory:

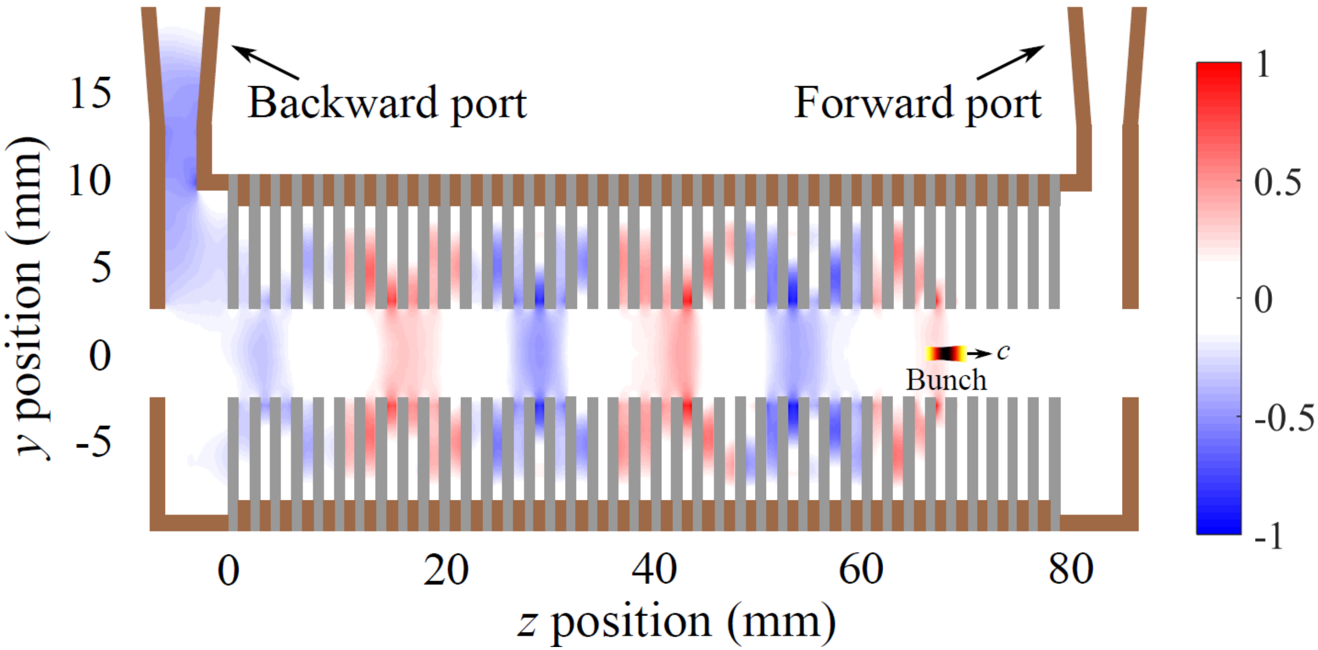
$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c} \right)^2 \Phi^2$$

= 25 MW

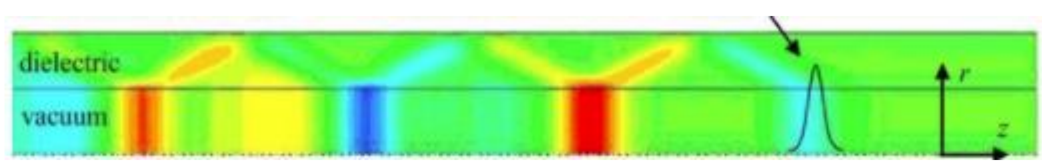
Electric Field Structure

- "Artificial dielectric" structure with all metal
  - Similar "bouncing feature" of the electric field in the wagon wheel structure and a dielectric tube
  - Very easy to tune the effective dielectric constant with the huge parameter space in the metamaterial design

Wagon Wheel



Dielectric tube



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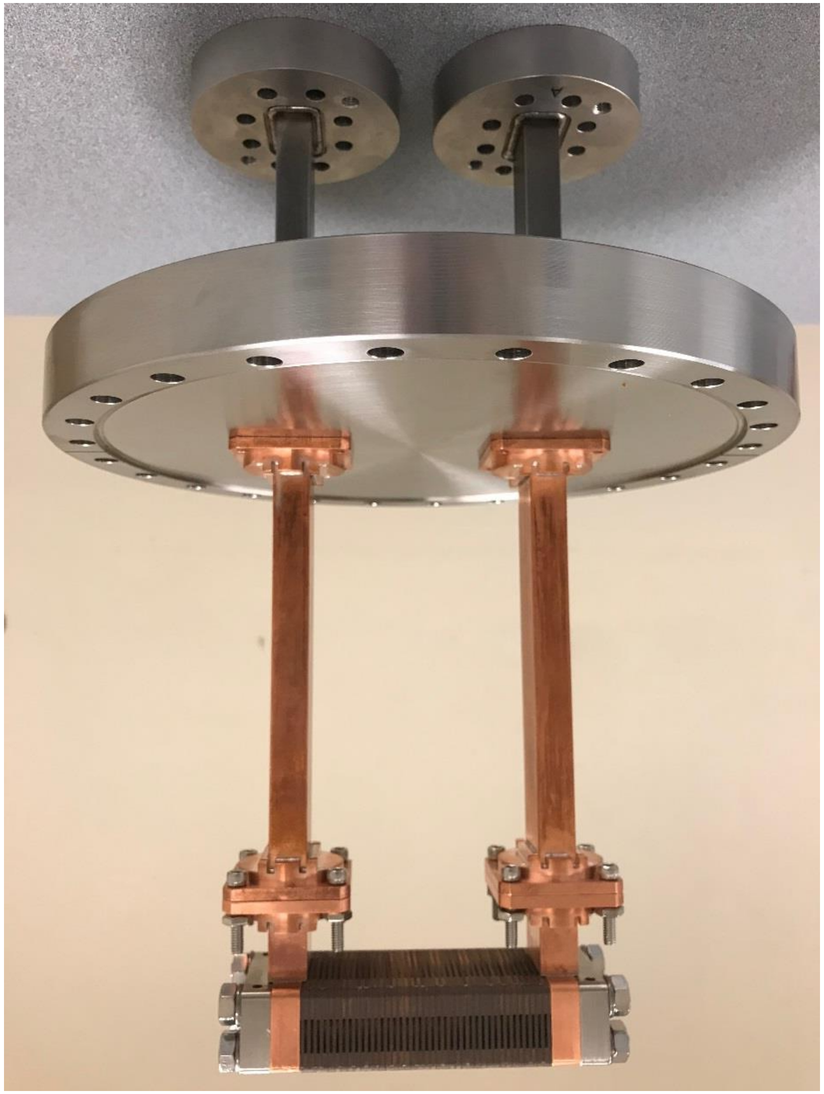
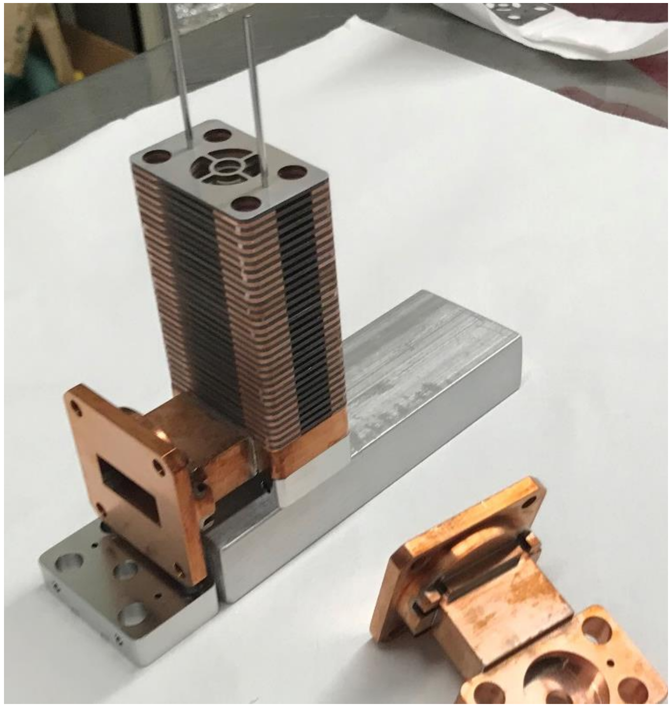
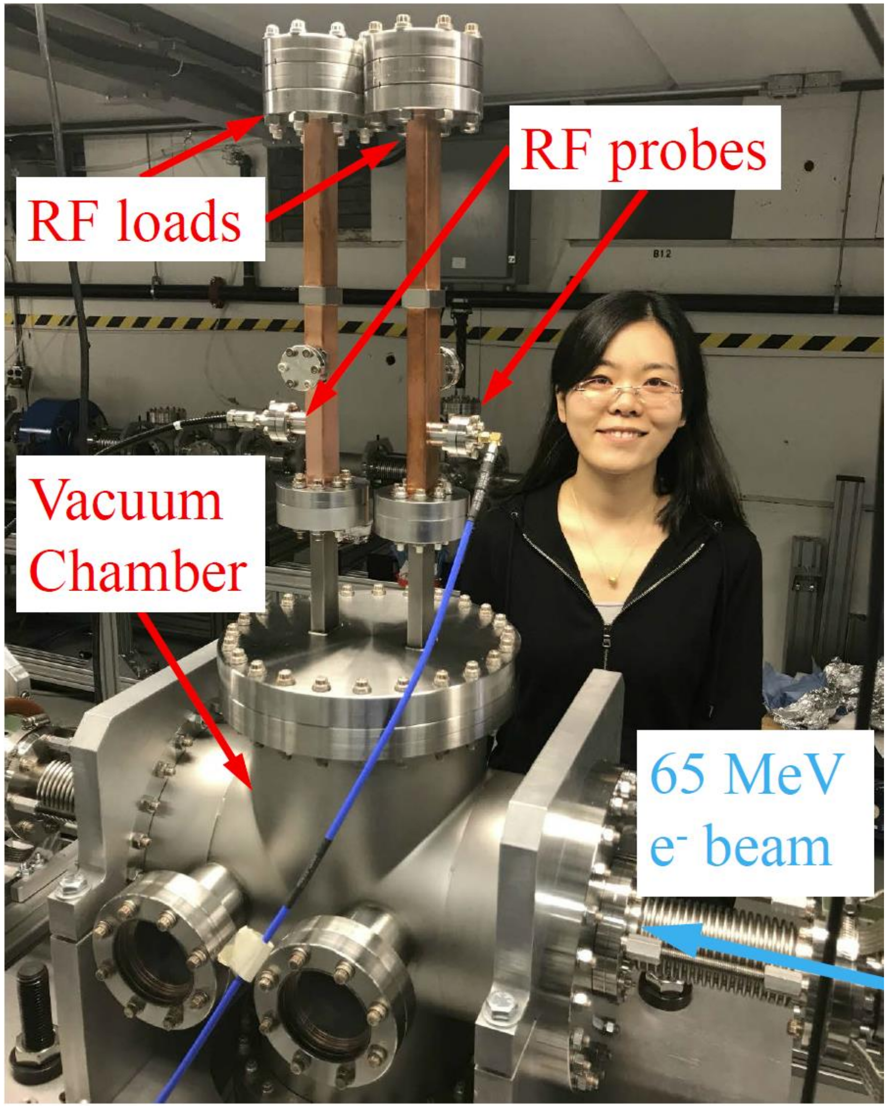
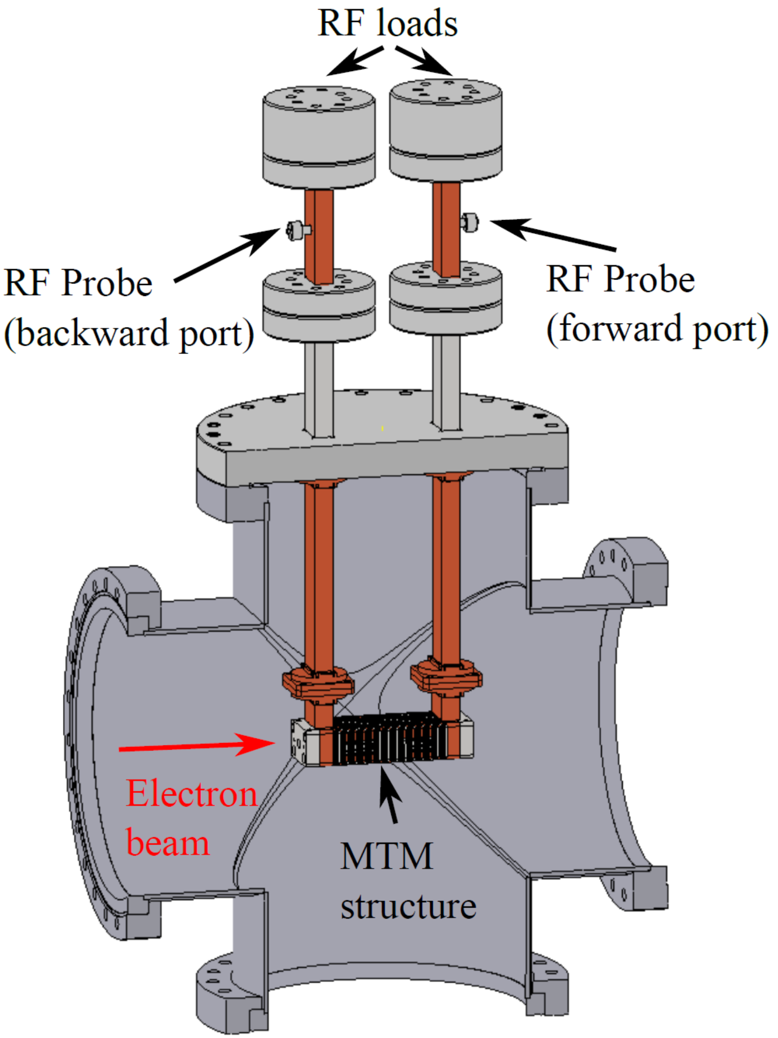
Fabricated Parts at MIT





Installed Experiment at AWA





Outline- ANL WFA Experiment

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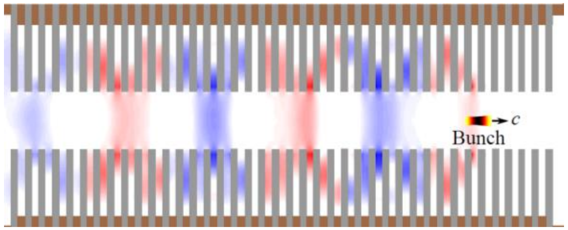
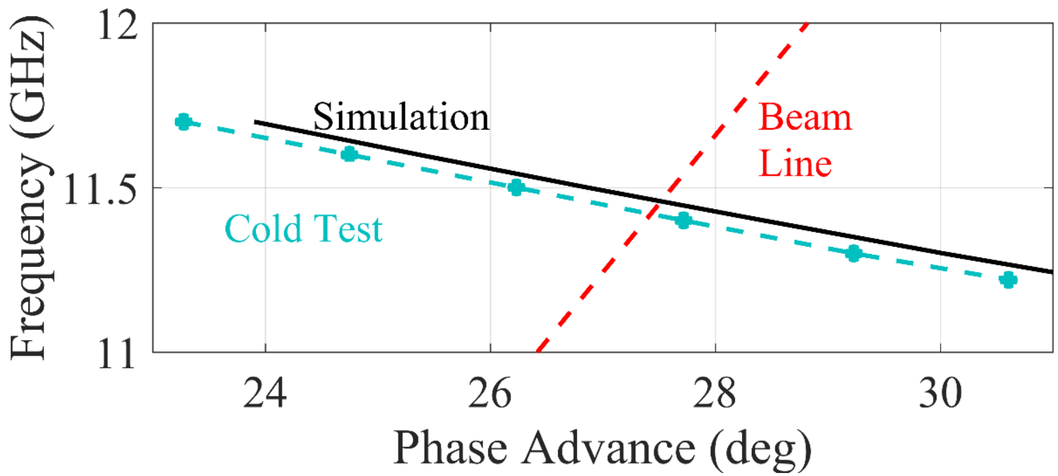
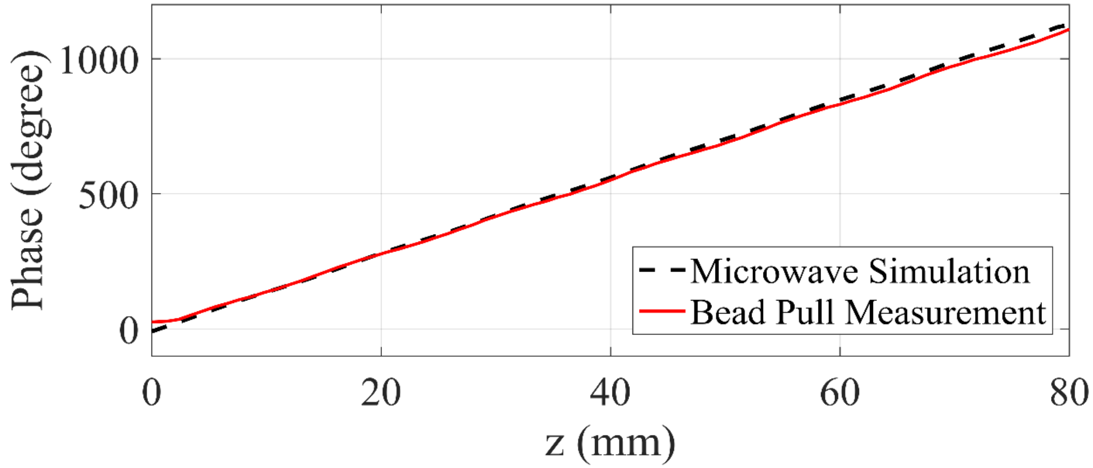
    - Cold Test
    - Single Bunch High Power Test
    - Two-bunch High Power Test
- Conclusions

Bead Pull Measurement

- Dispersion agrees very well with simulation
- Constant phase velocity
  - From the subwavelength feature

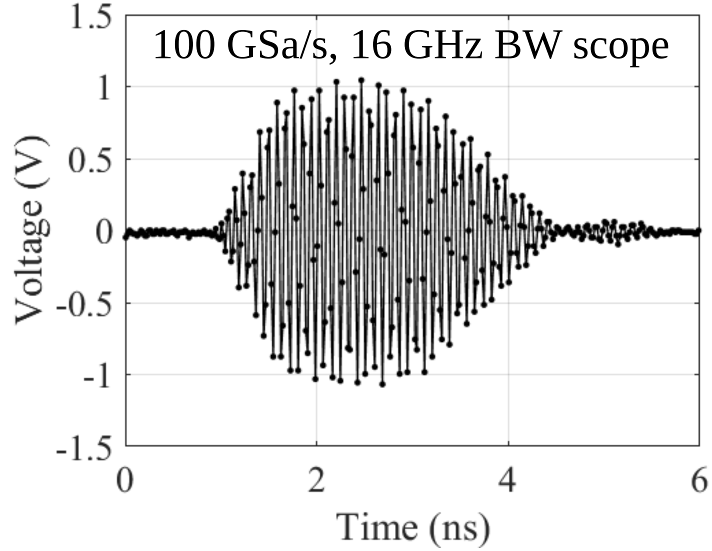


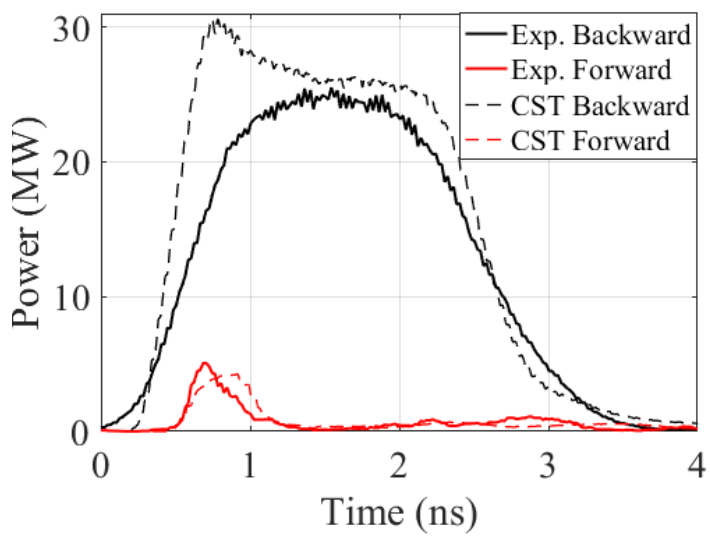


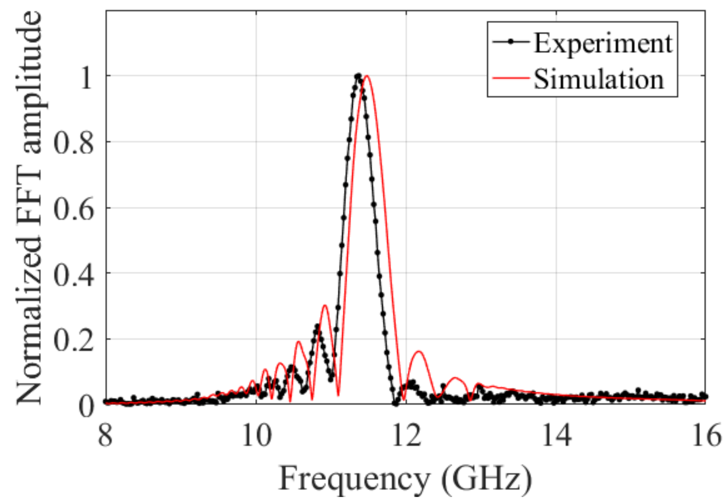


Single Bunch Experiment

- High RF power from a single 45 nC bunch
  - Experiment: 25 MW
  - Simulation: 26 MW (steady state)
  - Analytical theory: 25 MW
- Reversed Cherenkov radiation verified
  - Coherent radiation at 11.4 GHz
  - Backward port has much more power

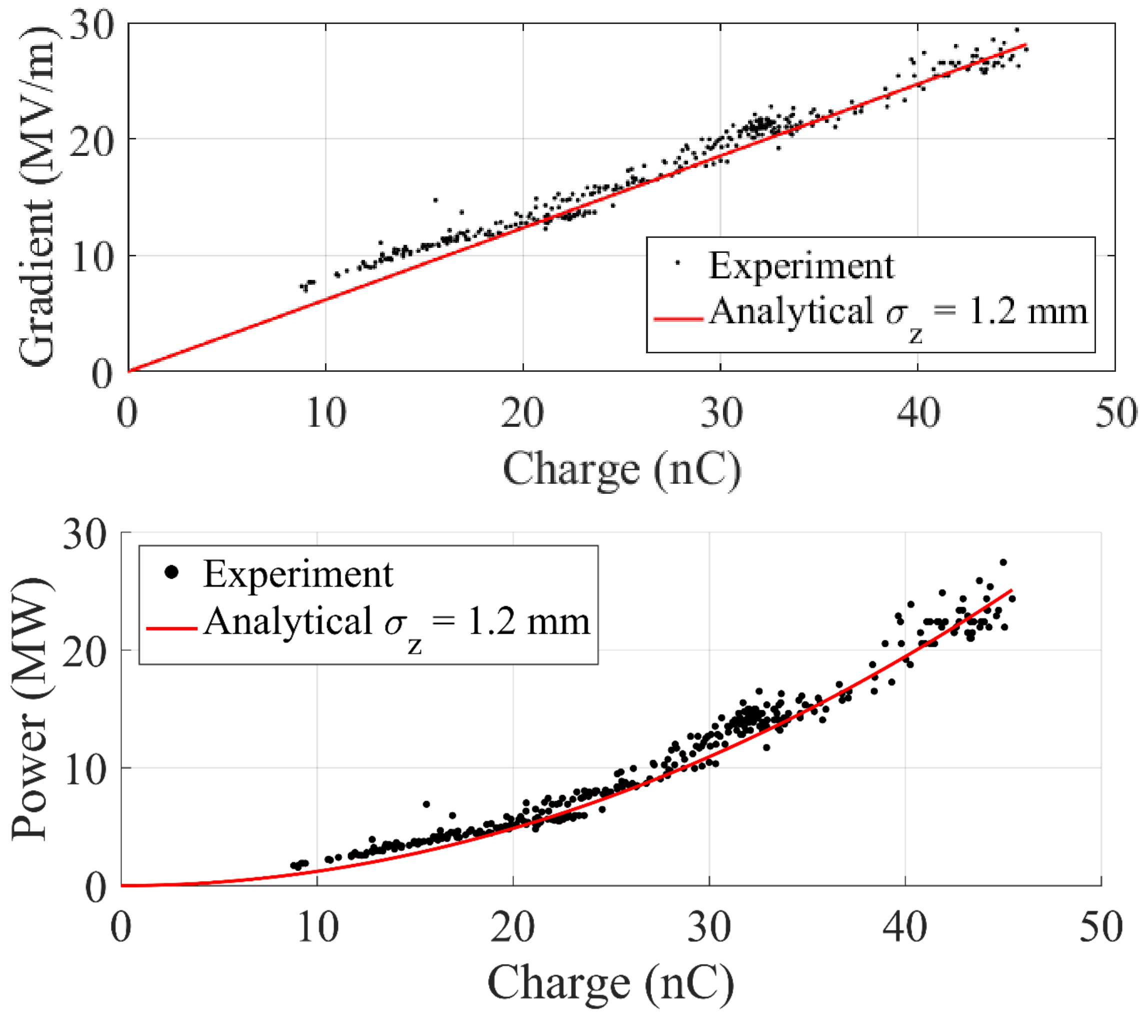






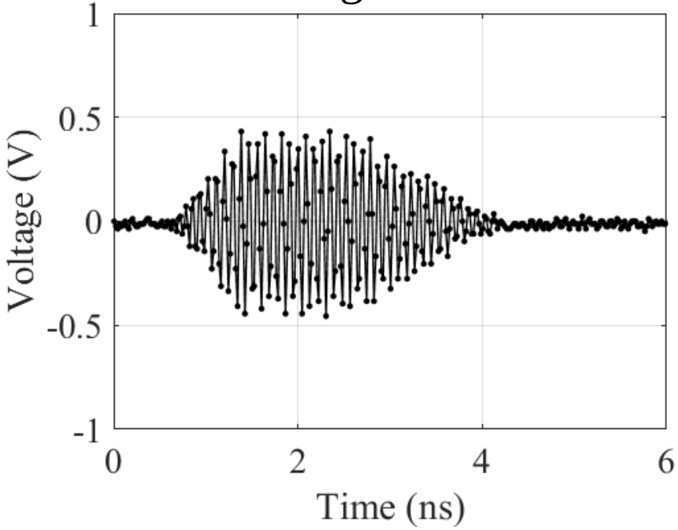
Scaling with Charge

- Good linear scaling of gradient vs. charge, good agreement with theory
  - No breakdown events

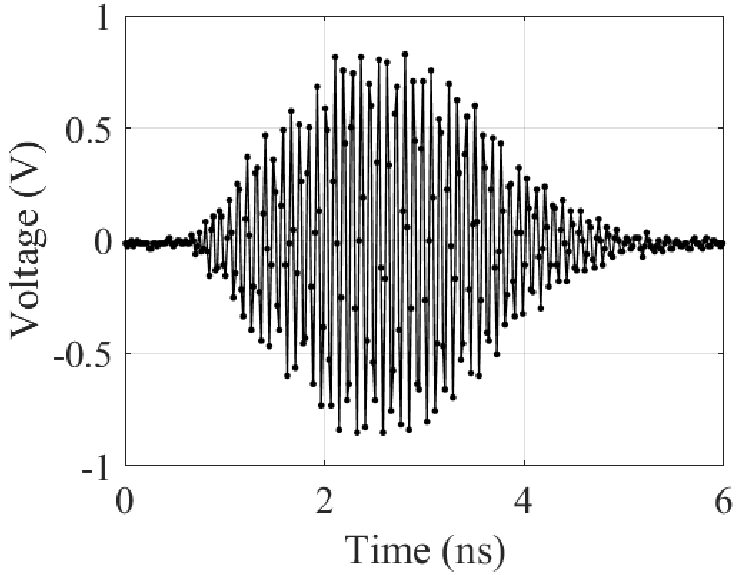


Two-Bunch Experiment

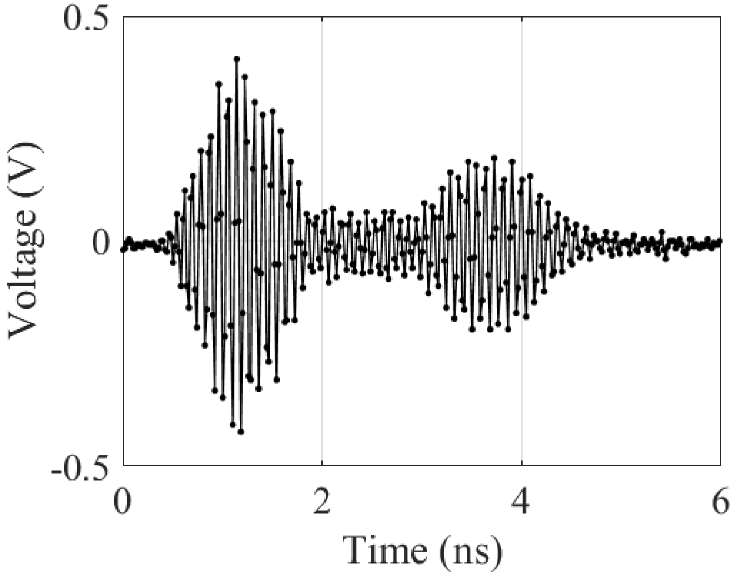
Single bunch



Two bunches with 0 deg phase difference

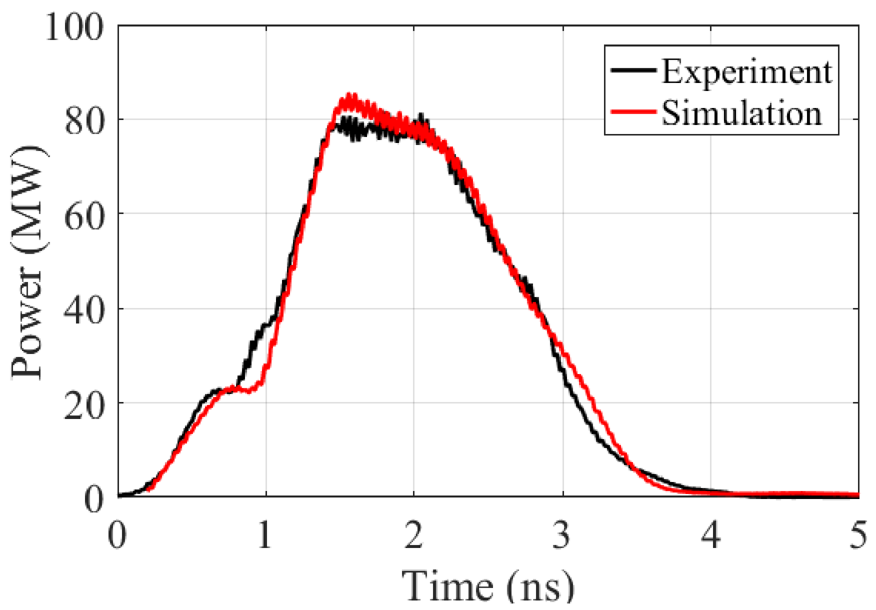


Two bunches with 180 deg phase difference



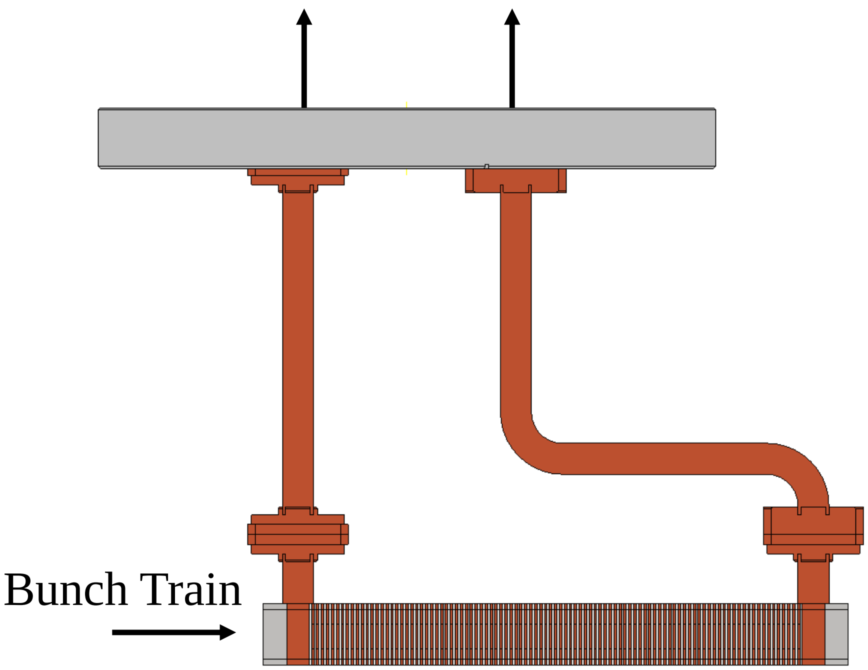
Highest power shot

- Two bunches with a total charge of 85 nC
- **80 MW** extracted RF power
- 50 MV/m decelerating electric field
  - 75 MV/m available accelerating gradient for a possible witness bunch
- ~130 MV/m maximum surface field

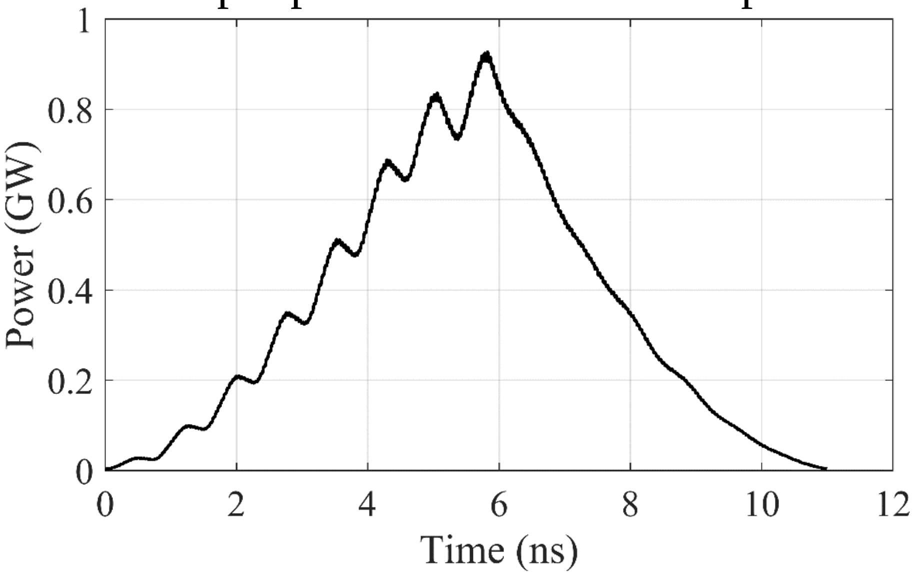


Next Experiment: Longer Structure, GW-level

- 100-cell structure (20 cm long), 8 bunches, 40 nC/bunch
  - 0.9 GW peak power
  - 170 MV/m decelerating gradient
  - 250 MV/m available accelerating gradient for a witness bunch



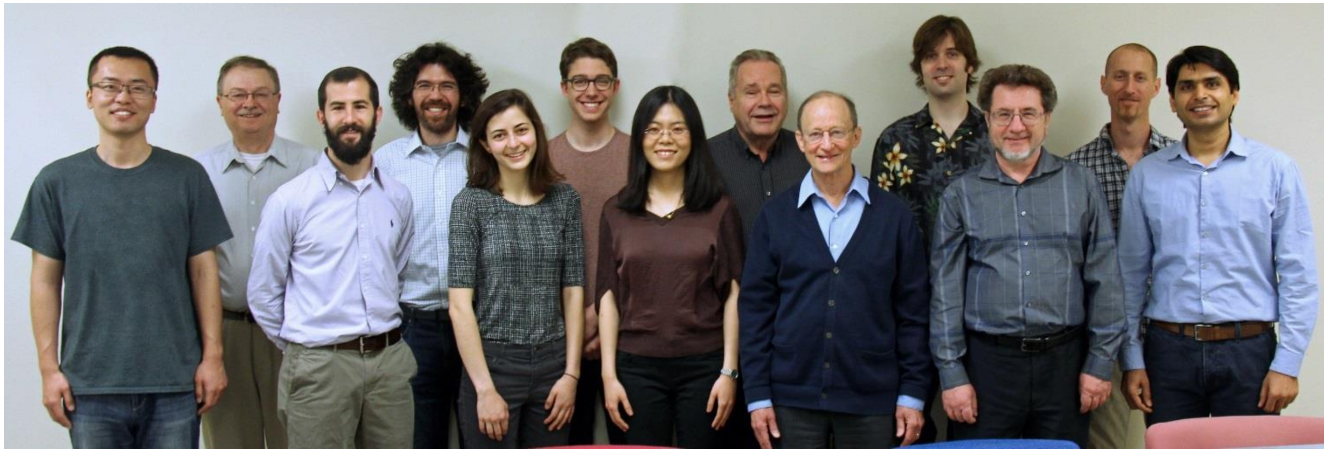
CST simulation of
output power in the backward port

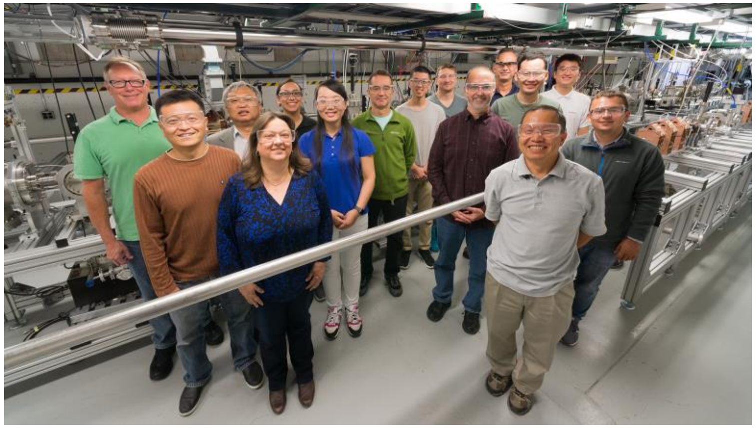


Conclusions

- A wagon wheel metamaterial structure at 11.4 GHz has been tested at the Argonne Wakefield Accelerator as a power extractor.
- Reversed Cherenkov radiation has been verified in a metamaterial structure with a negative group velocity
- High microwave power was generated, in agreement with analytical theory and CST simulations.
  - Single bunch, 45 nC, 25 MW, 28 MV/m decelerating gradient, 43 MV/m accelerating gradient
  - Two bunches, 85 nC, 80 MW, 50 MV/m decelerating gradient, 75 MV/m accelerating gradient
- Wagon wheel structure has its unique advantages for wakefield acceleration
  - Rugged all-metal structure, no dielectrics
  - Large parameter space for optimization and precise control of electromagnetic properties.

Acknowledgement





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