2019 North American Particle Accelerator Conference

Experiments with Metamaterial-Based Metallic Accelerating Structures

Xueying Lu
Department of Physics, MIT
Currently at SLAC National Accelerator Laboratory

Julian F. Picard, Michael A. Shapiro, Ivan Mastovsky, Richard J. Temkin
Massachusetts Institute of Technology (MIT)

Manoel Conde, John G. Power, Jiahang Shao, Eric E. Wisniewski,
Maomao Peng, Gwanghui Ha, Jimin Seok, Scott Doran
Argonne National Laboratory (ANL)

Chunguang Jing
Euclid Techlabs LLC

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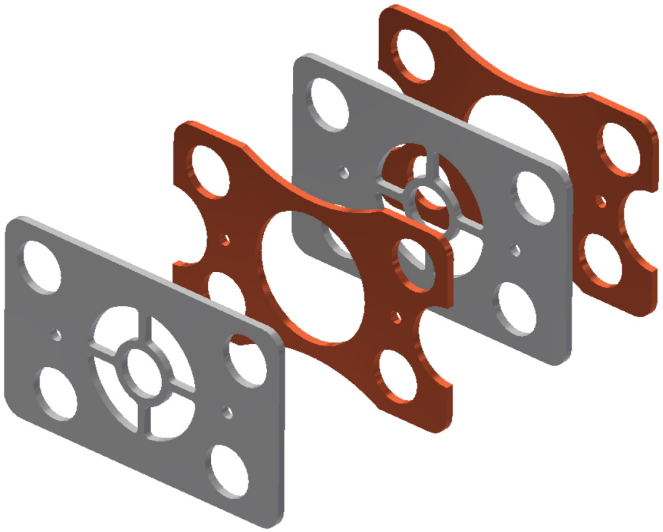
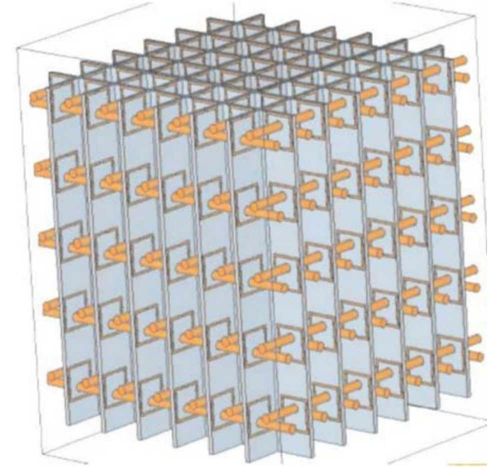
Outline

- Introduction & Motivation
- Experimental Facilities at AWA
- Metamaterial Design and Theory
- Stage I Experiment
- Stage II Experiment
- Conclusions

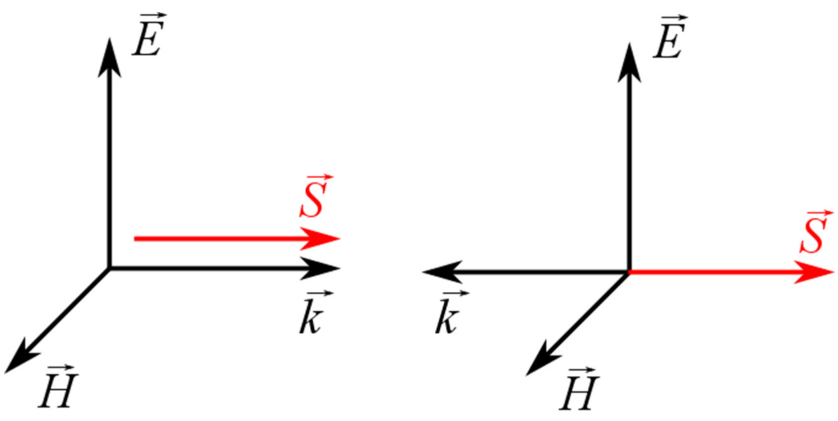


Metamaterials

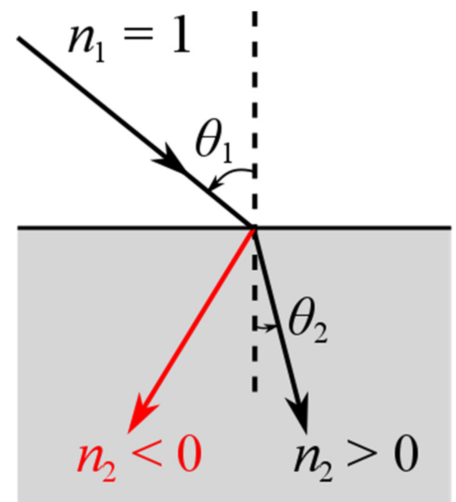
- Metamaterial (MTM):
  - An artificial material with a subwavelength structure
  - Exhibits properties not usually found in natural materials
  - Especially a negative refractive index : simultaneous $\varepsilon, \mu < 0$
- Left-handed materials
  - Negative refraction



Metamaterial with split ring resonators on dielectric boards*

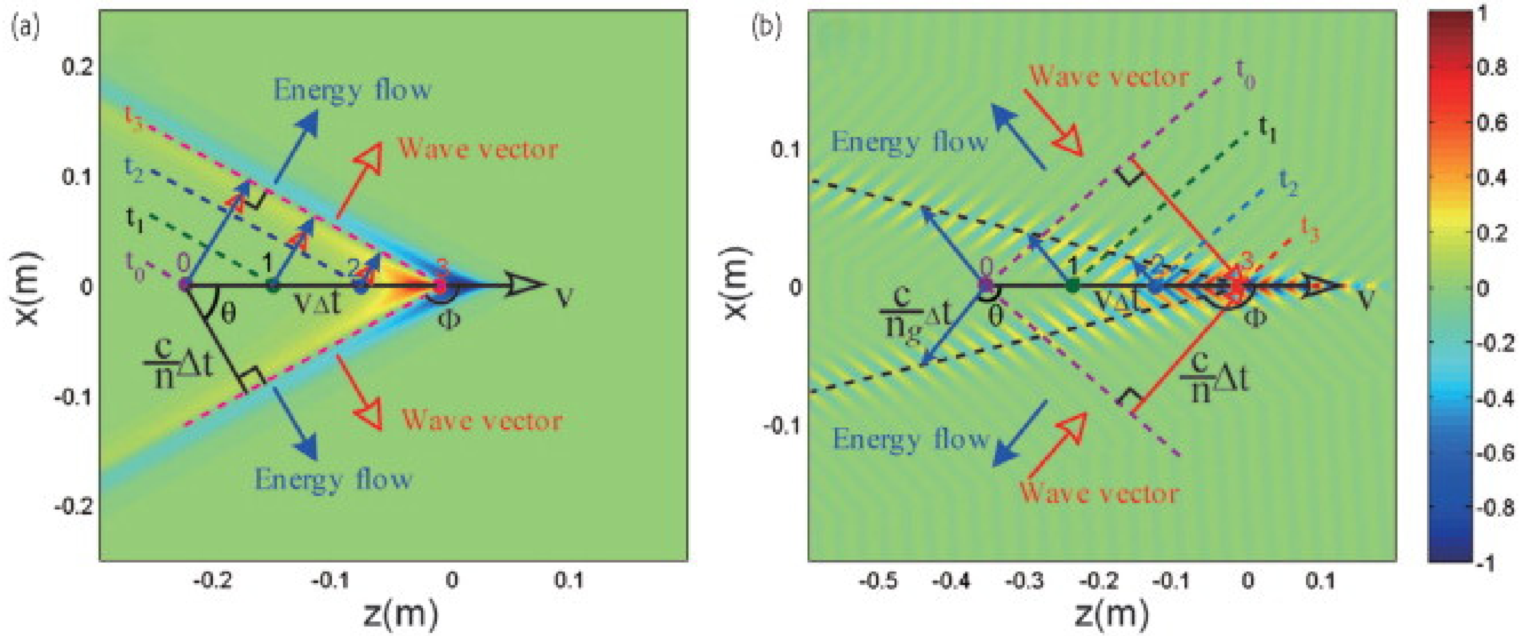


$\varepsilon > 0, \mu > 0$ $\varepsilon < 0, \mu < 0$



* S. Antipov et al., *J. Appl. Phys.* (2008)

Reversed Cherenkov Radiation

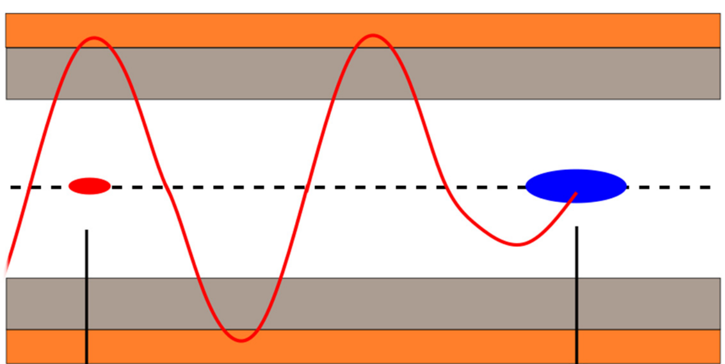


- Cherenkov Radiation
  - Electron velocity exceeds wave phase velocity
  - $\varepsilon, \mu > 0$
  - Wave vector and energy flow **parallel**
- Reversed Cherenkov Radiation
  - $\varepsilon, \mu < 0$
  - Wave vector and energy flow **anti-parallel**

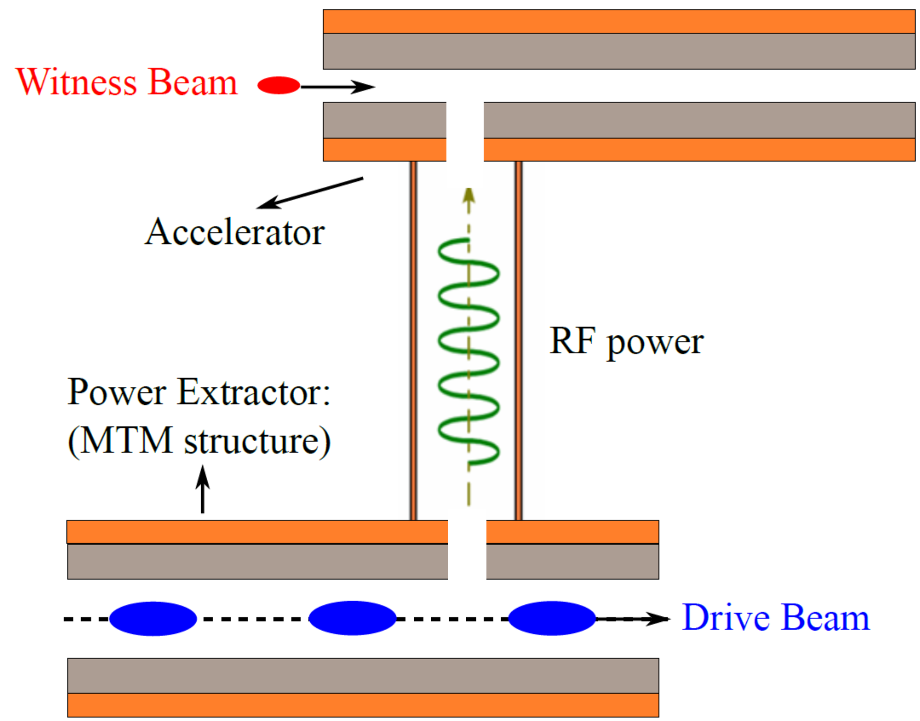
Hongsheng Chen and Min Chen. "Flipping photons backward: reversed Cherenkov radiation." *Materials Today* 14.1-2 (2011).

Structure-Based Wakefield Acceleration

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

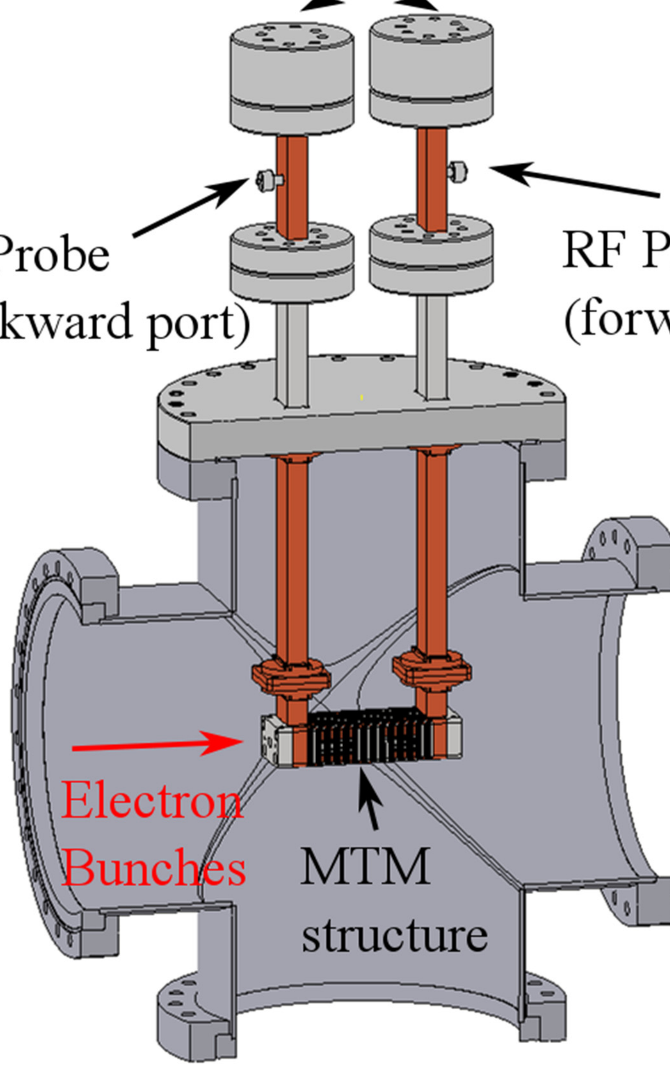


- Two-beam acceleration (TBA):
  - Drive beam generates high power microwaves in a power extractor
  - RF power is transferred from the power extractor to the accelerator
  - Witness beam gets accelerated



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



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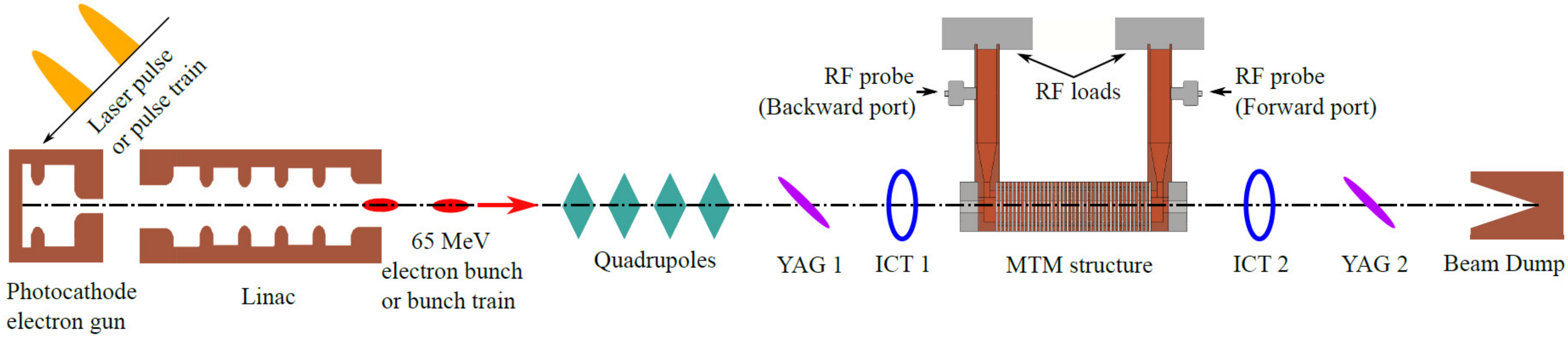
Experimental Setup at AWA



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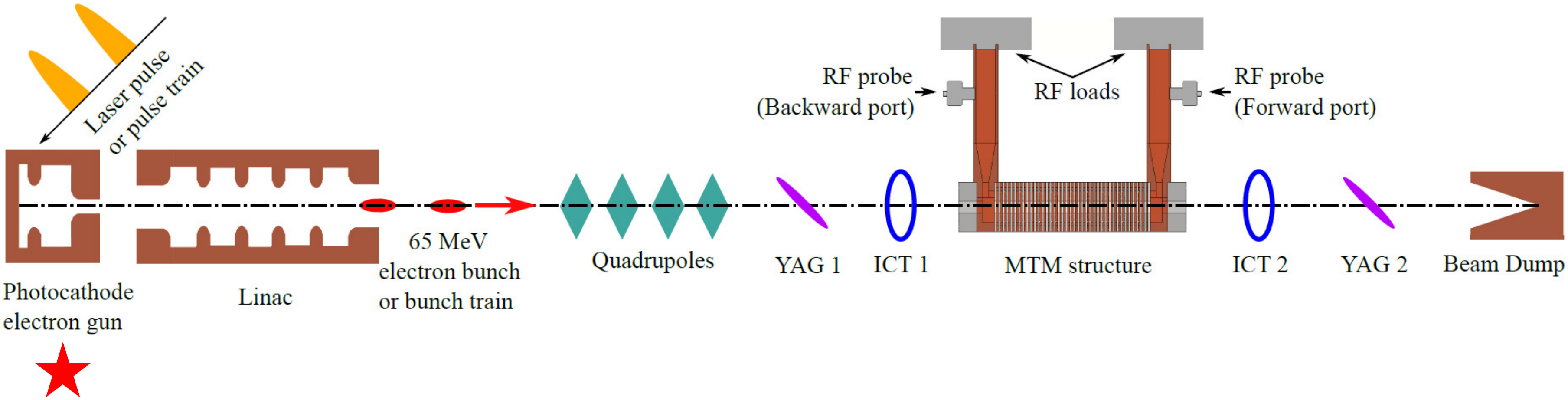
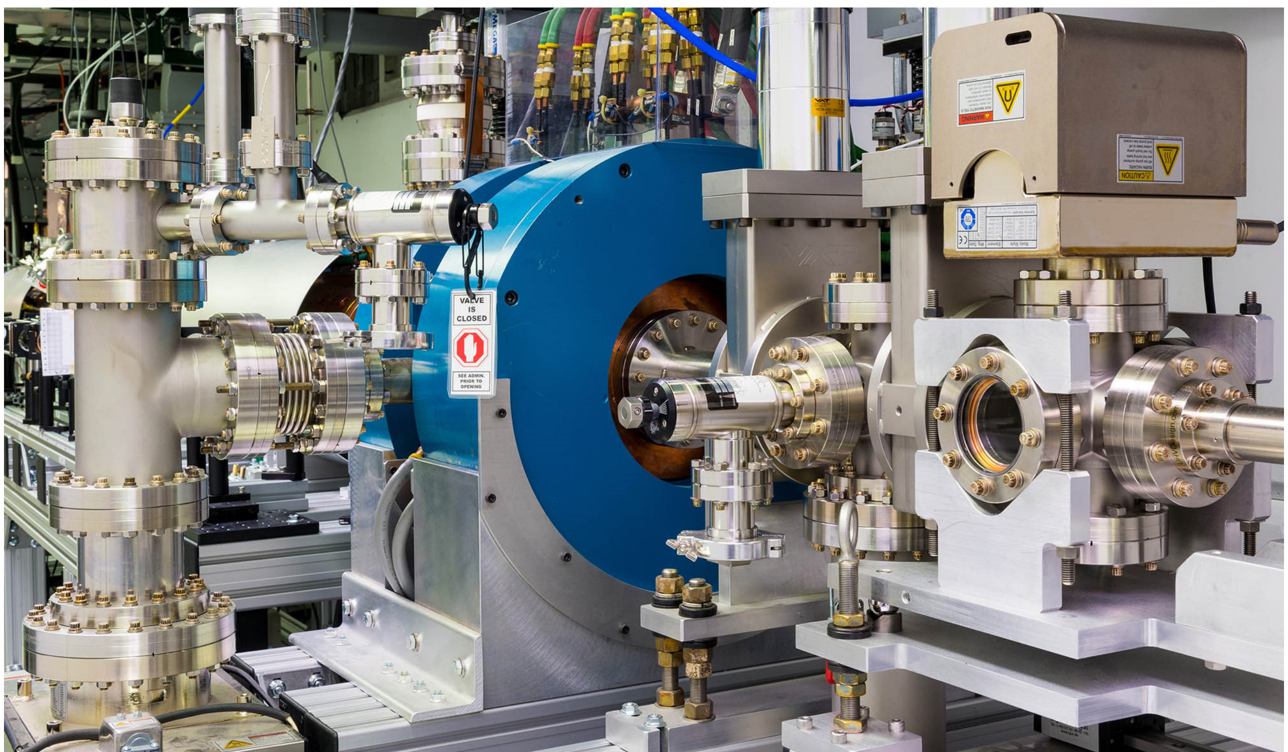
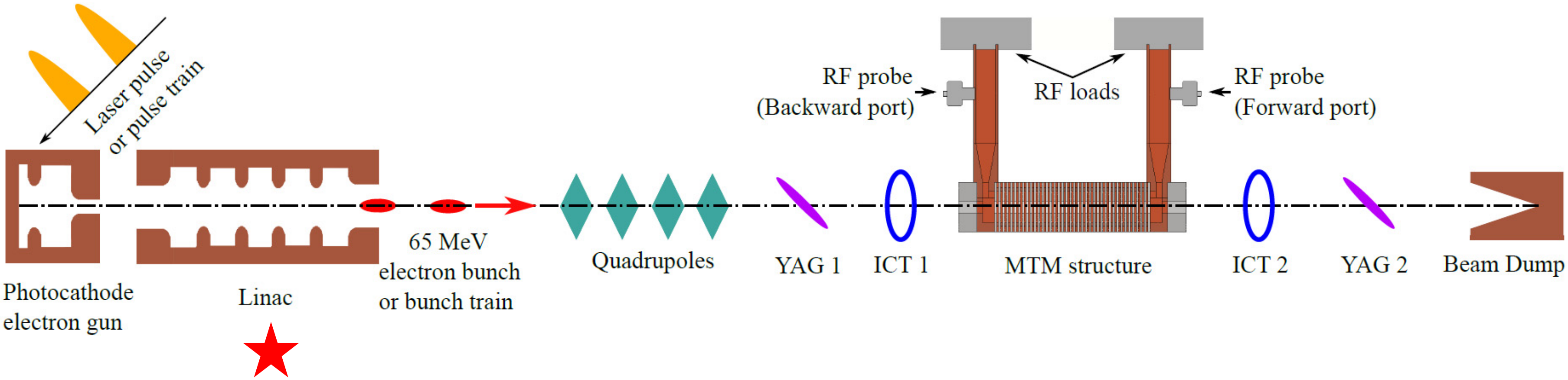


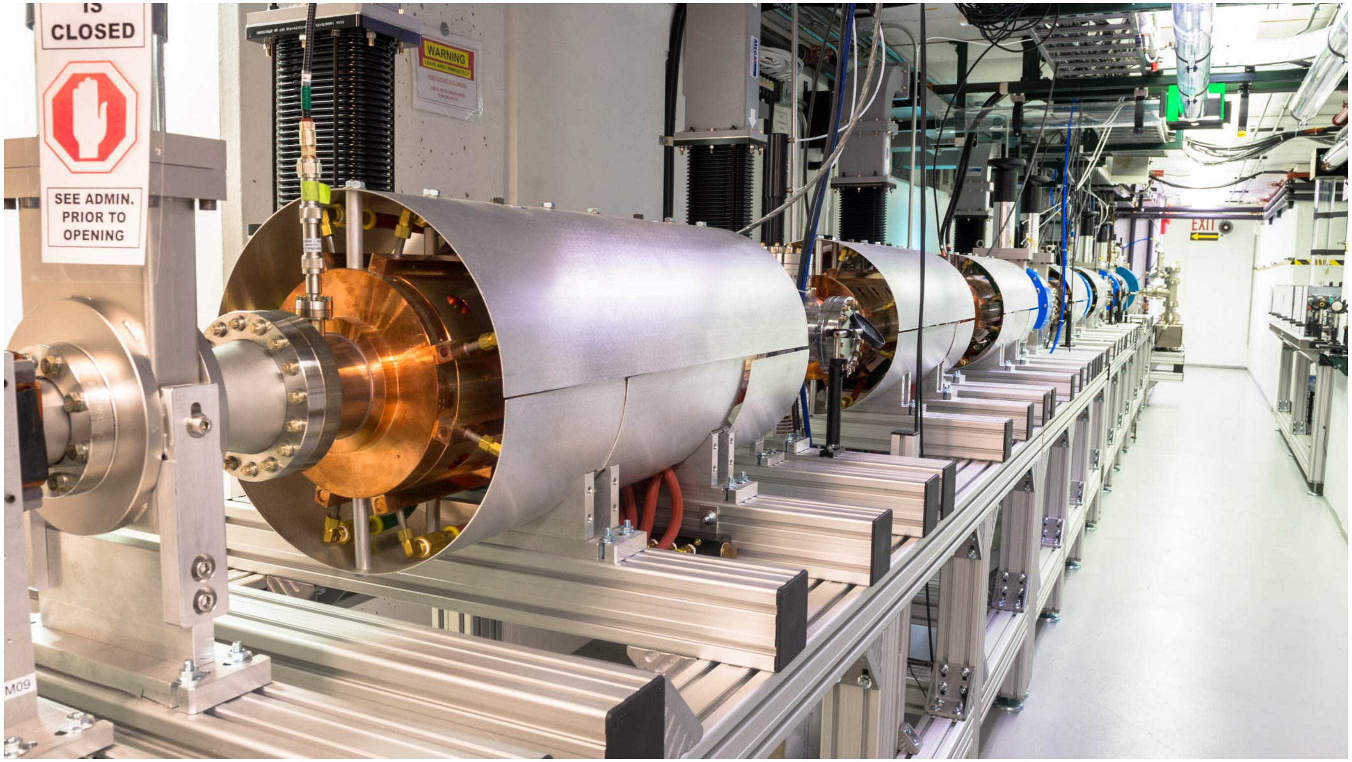


Highest charge photocathode gun

- Bunch trains of up to 32 bunches
- Maximum charge in single bunch: **100 nC**
- Maximum charge in bunch train: **500 nC**

Experimental Setup at AWA

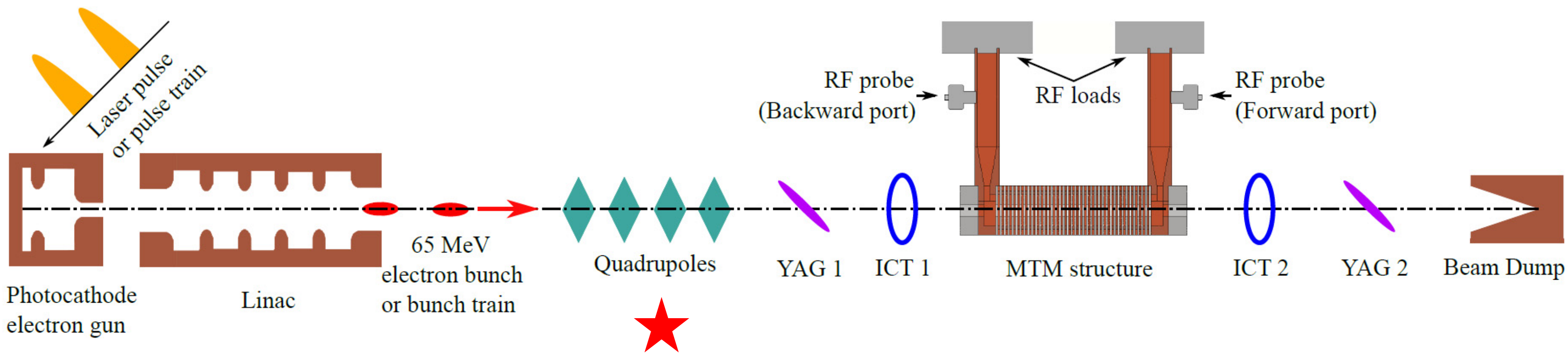




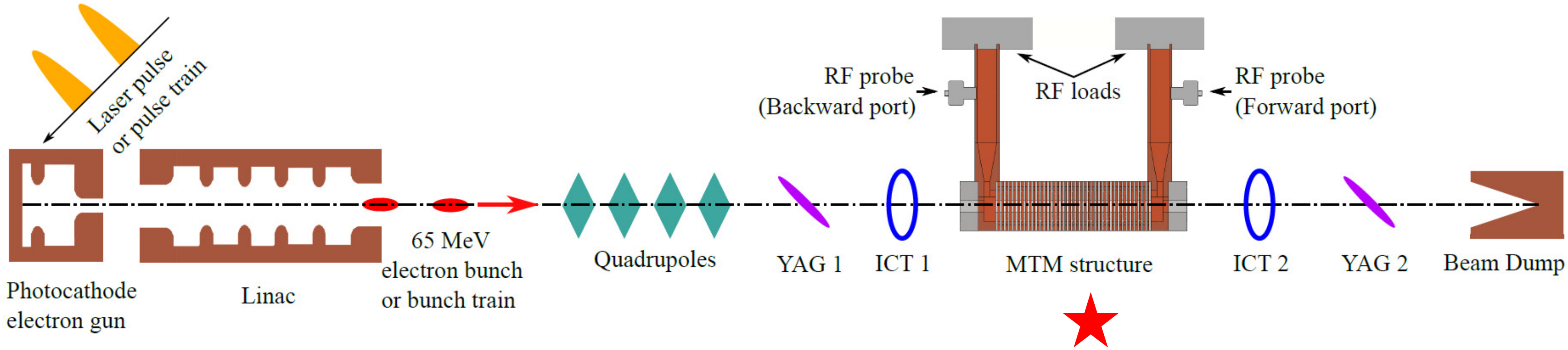
Linac sections

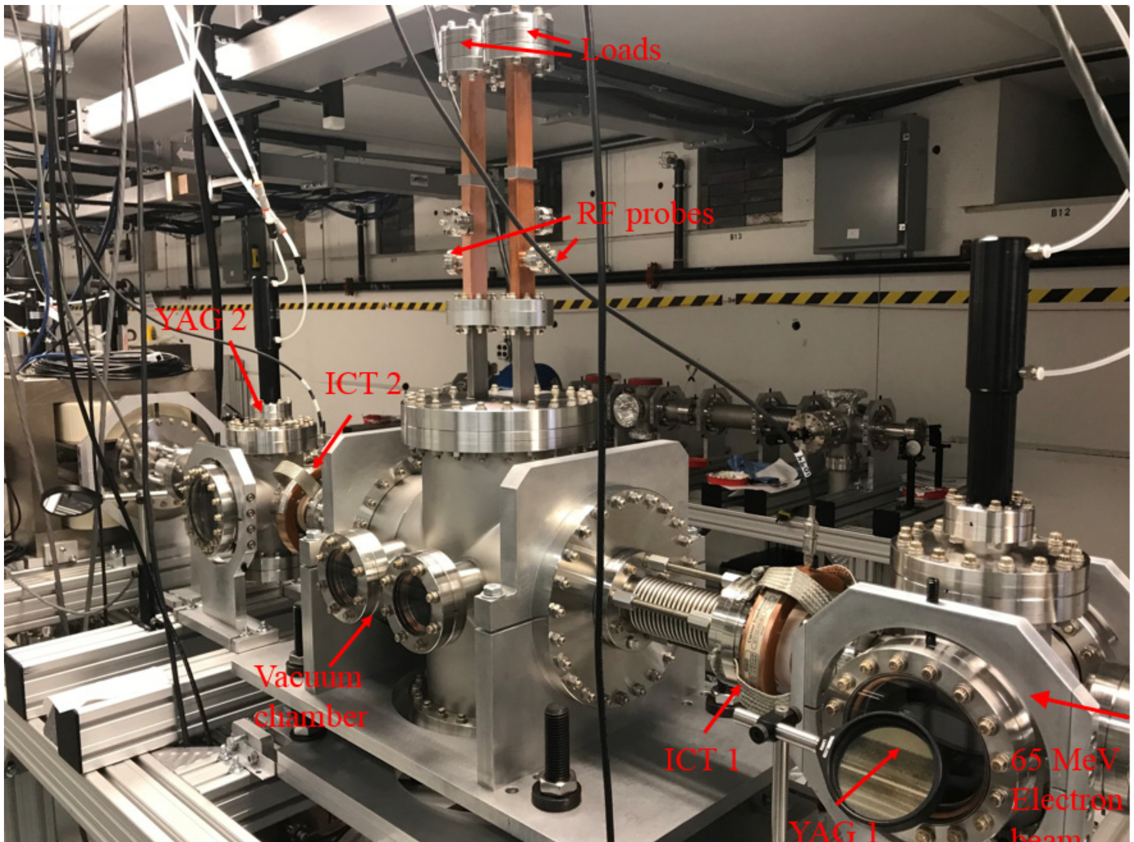
- Frequency: 1.3 GHz
- Final beam energy: 65 MeV

Experimental Setup at AWA



Experimental Setup at AWA





Beam Diagnostics:

- **ICT** (Integrating current transformer): Bunch charge
- **YAG screen:** Bunch transverse size
- **RF probes:** Output microwave

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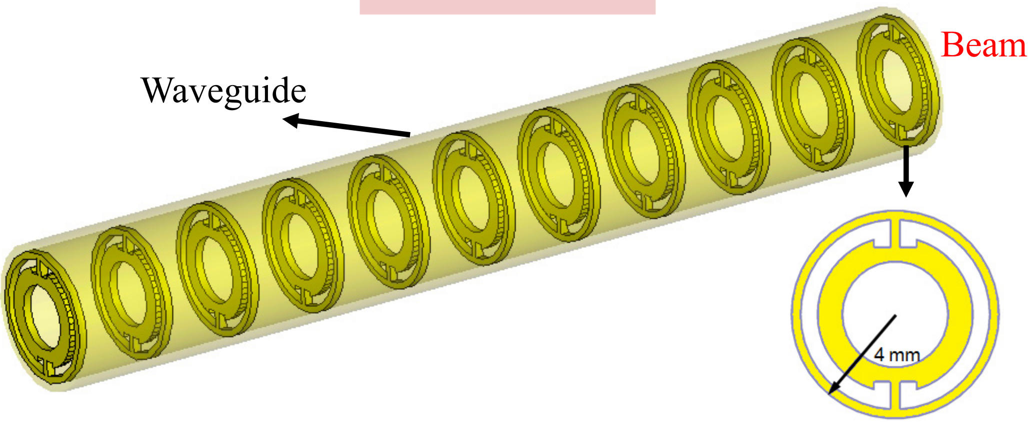
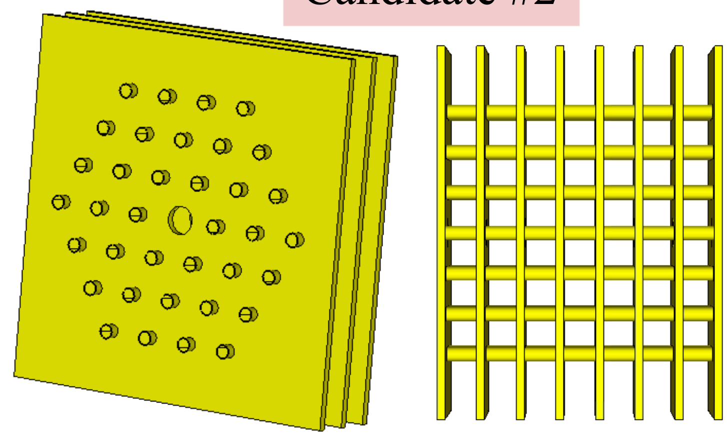
Selection of MTM Design- 1

- Different structures have been compared for wakefield acceleration
  - High shunt impedance for a high extracted power from the drive beam

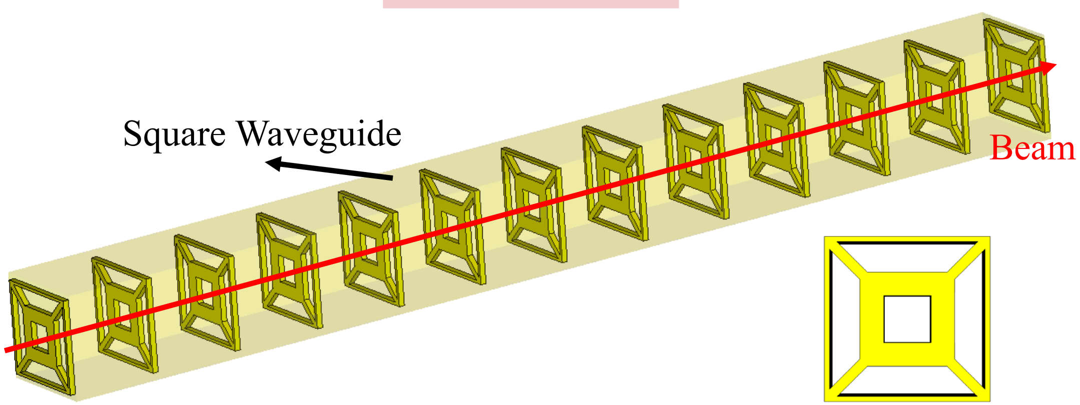
Candidate #1



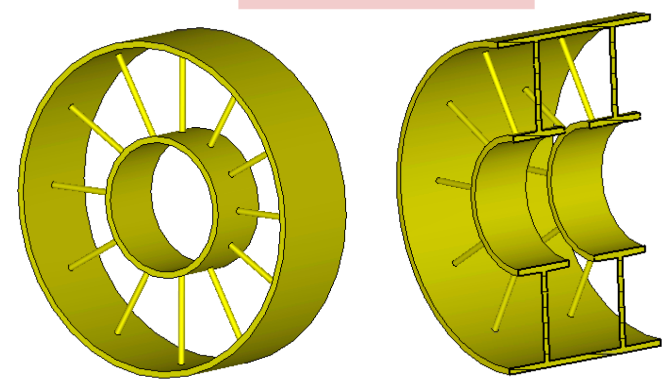
Candidate #2



Candidate #3



Candidate #4

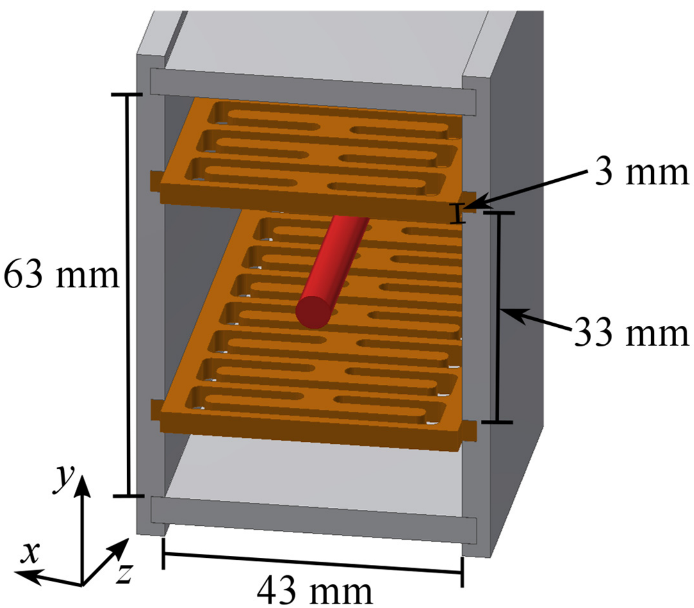


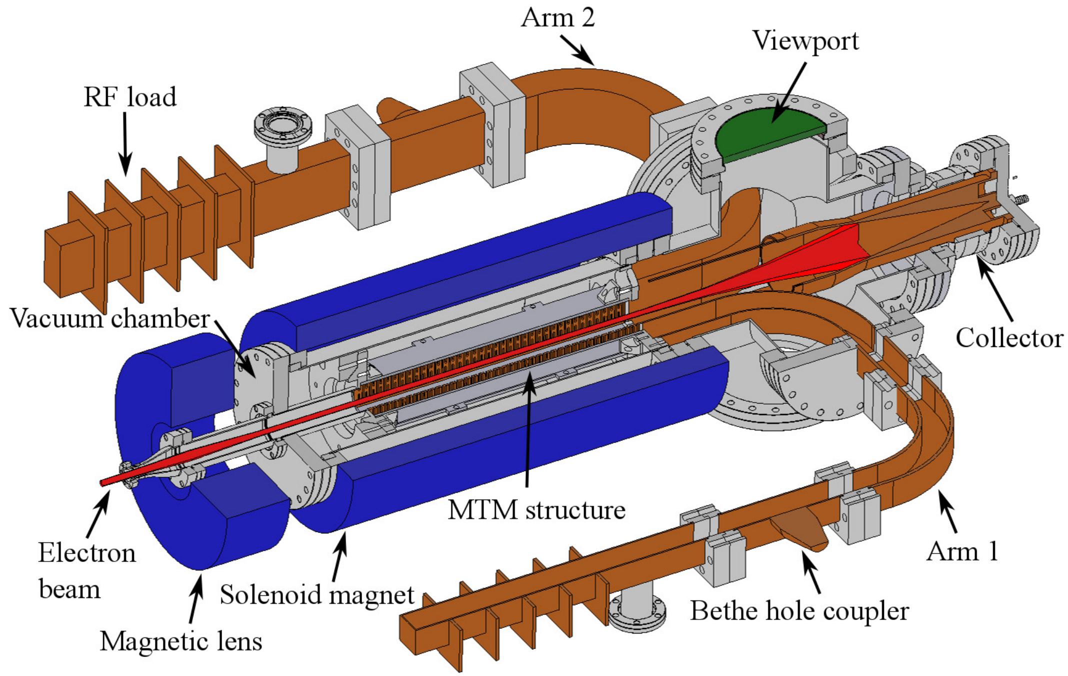
Selection of MTM Design- 2

- Different structures have been compared for wakefield acceleration
  - TM mode as the fundamental mode

S-band MTM Backward Waves Oscillator built at MIT

Lu et al., *Phys. Plasmas* **25**, 023102 (2018)

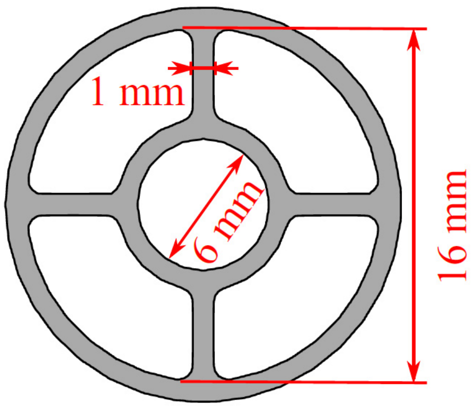


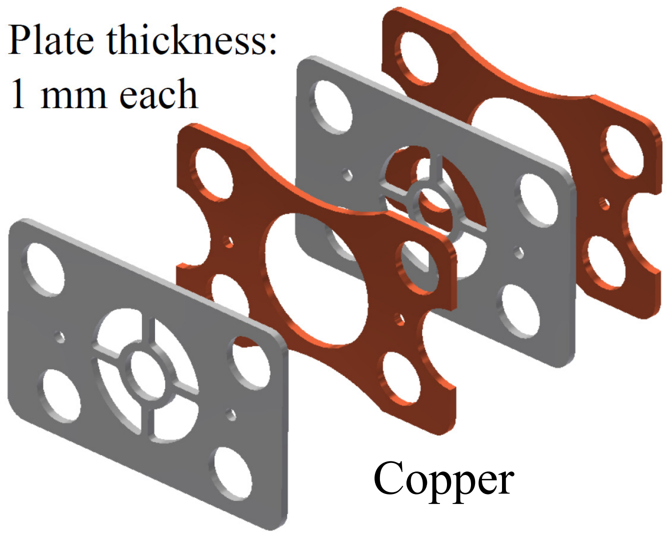


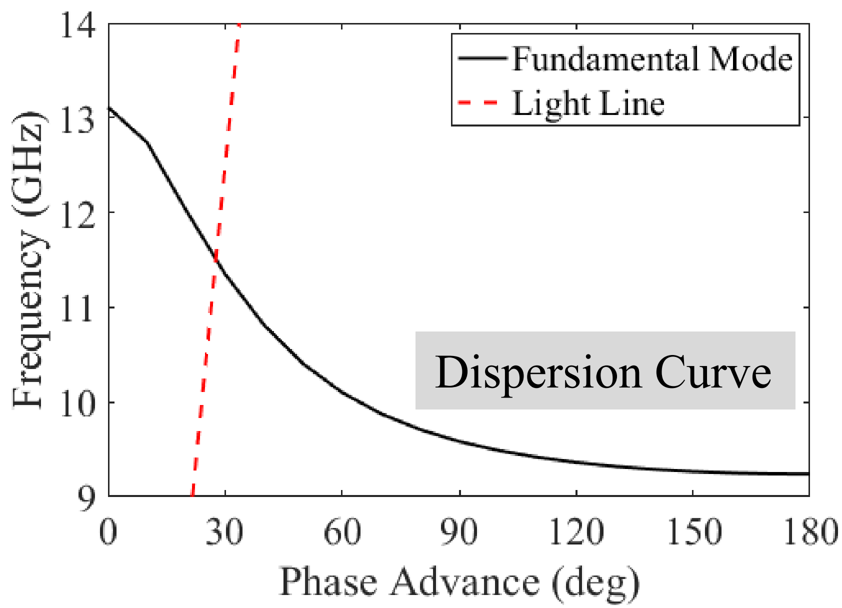
- High power microwave generation by Cherenkov-cyclotron interaction from a hybrid mode with a transverse electric field on axis

Wagon Wheel Structure Unit Cell

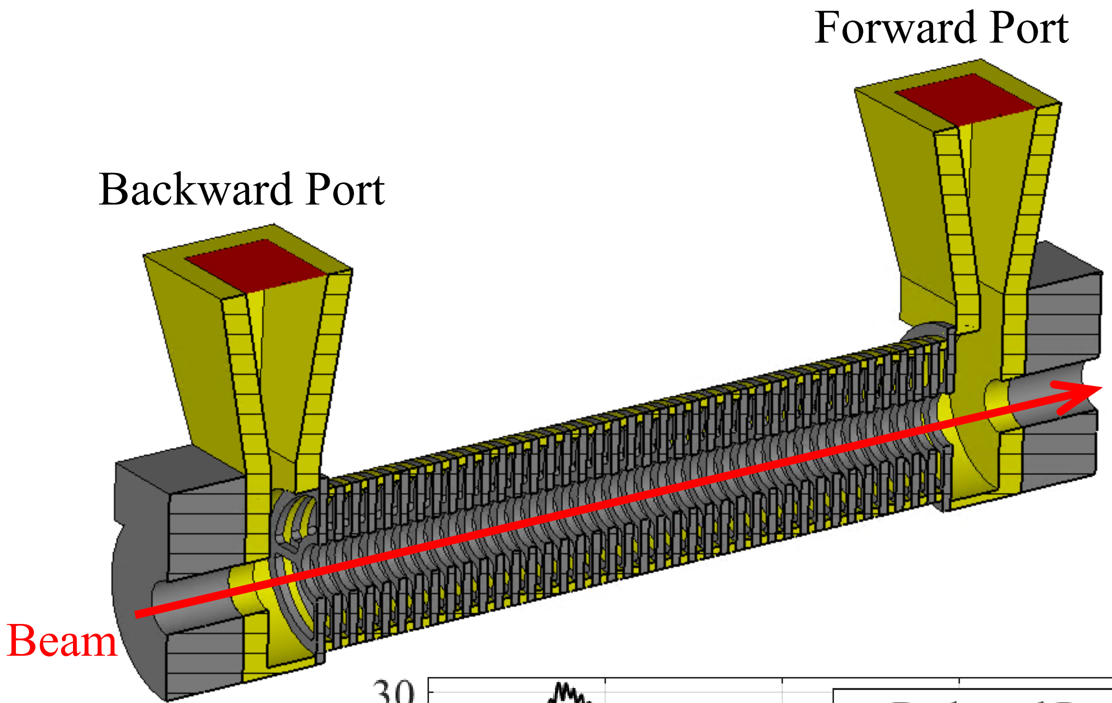
- Wagon wheel structure
  - Periodic subwavelength structure
    - Period: 2 mm
    - Free wavelength at 11.42 GHz: 26 mm
  - Negative group velocity
  - Fundamental mode: TM mode
  - Interaction frequency: 11.42 GHz
    - Cutoff frequency of an empty waveguide: 14.2 GHz

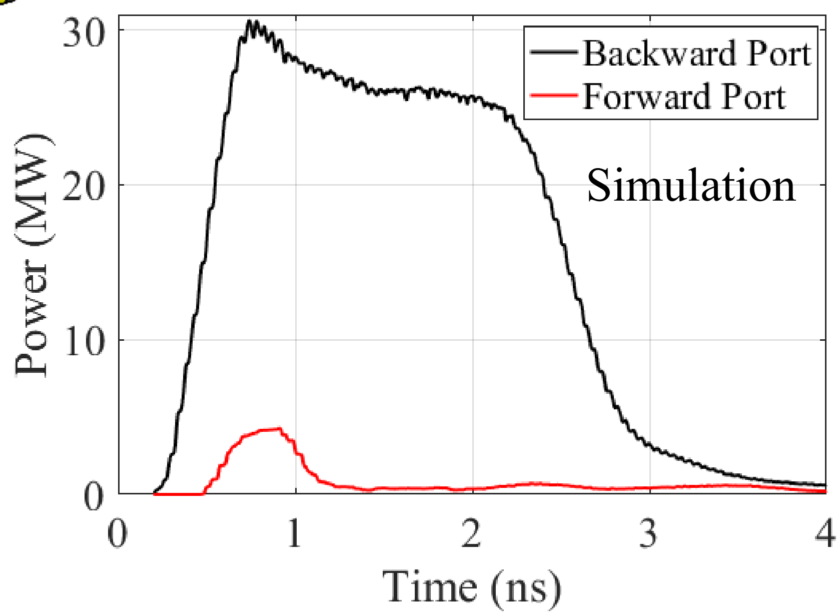






CST Simulation





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

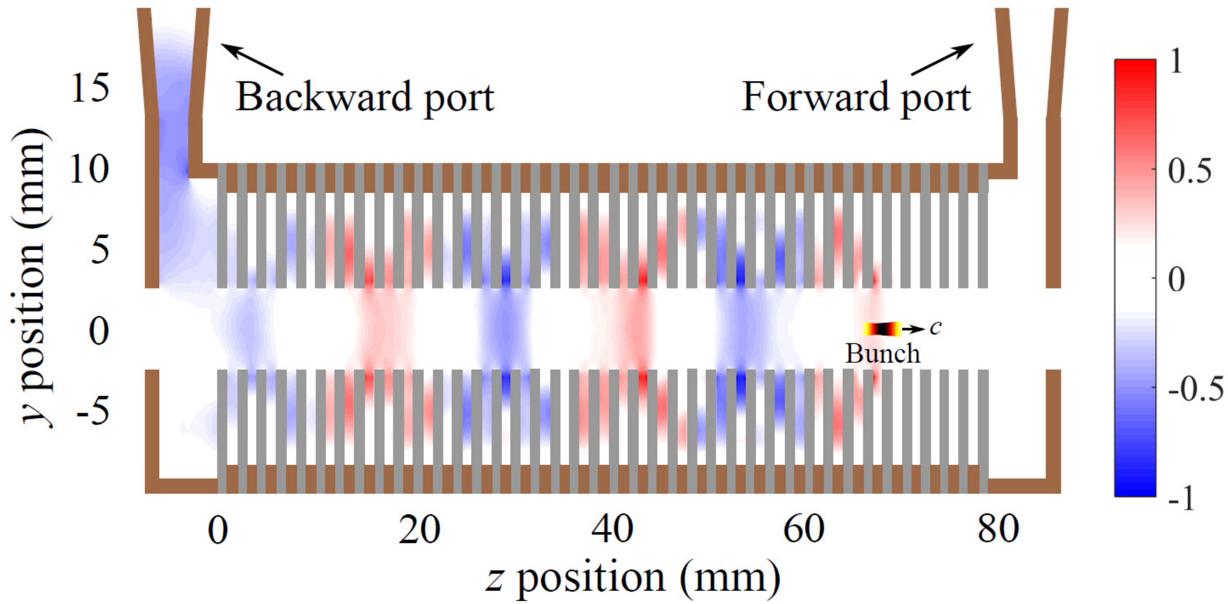
$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c} \right)^2 \Phi^2$$

$= \mathbf{25\ MW}$

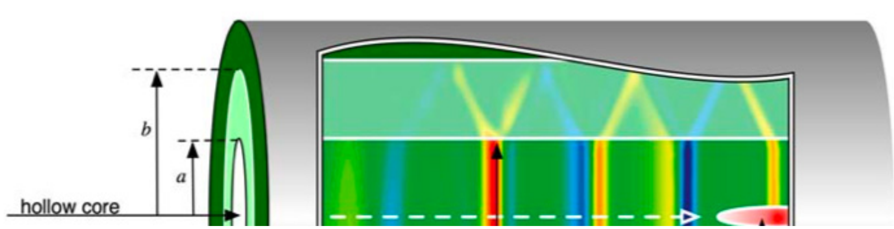
Electric Field Structure

- "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



Advantages of Wagon Wheel Structure

- Rugged all-metal structure
- Enhanced beam-wave interaction
  - Large beam aperture => low shunt impedance, high group velocity
  - Small beam aperture => high shunt impedance, low group velocity
  - MTM with negative group velocity: High group velocity and high shunt impedance at the same time

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

Structure	Beam aperture (mm)	Group velocity	r/Q (kΩ/m)	Output power[1] (MW)
Wagon wheel	6	-0.158 c	21	25
Alumina-loaded tube	6	0.106 c	10	13
Metallic disk-loaded	6	0.016 c	16.5	3

[1] Output power is calculated for a single 45 nC drive bunch.

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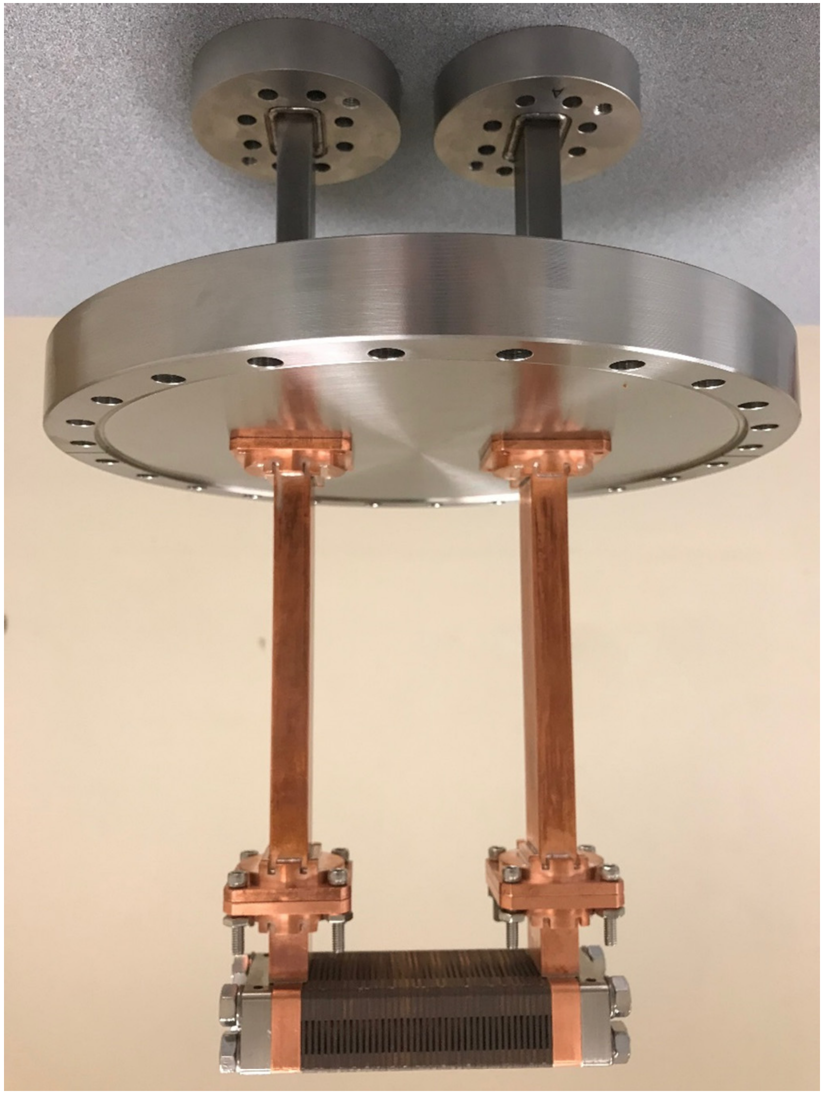
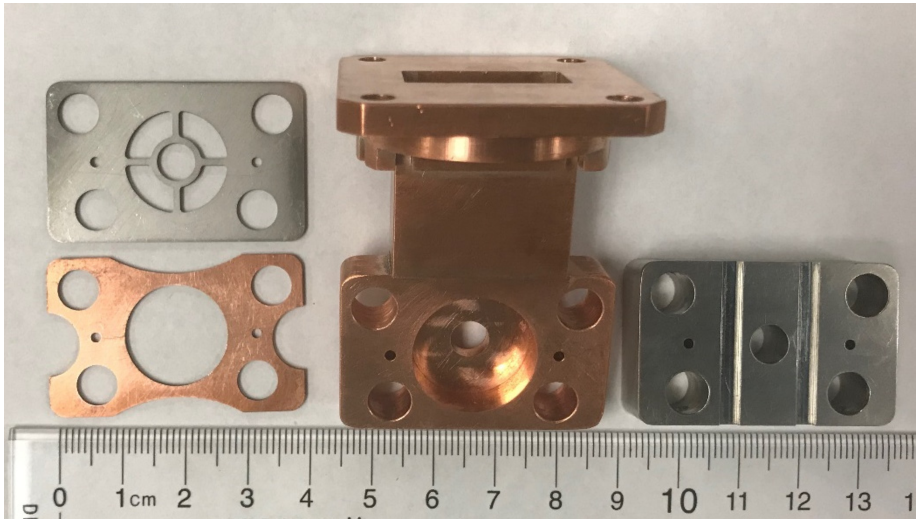
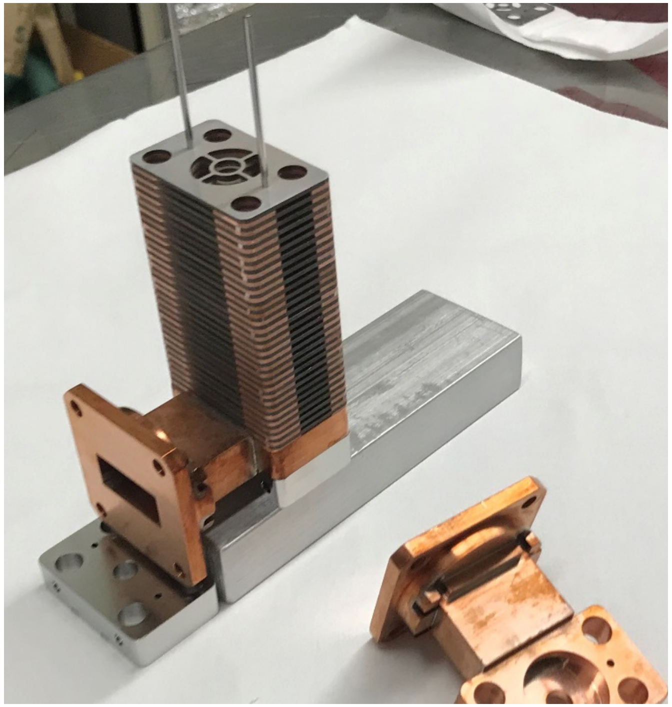
Fabricated Parts at MIT

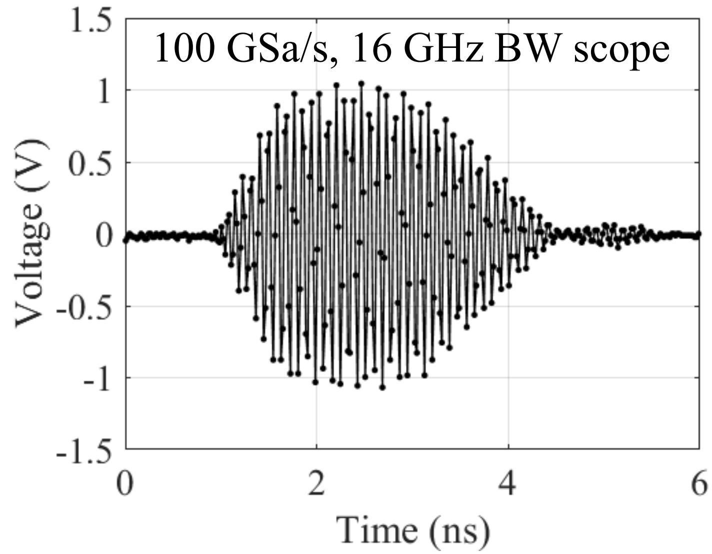


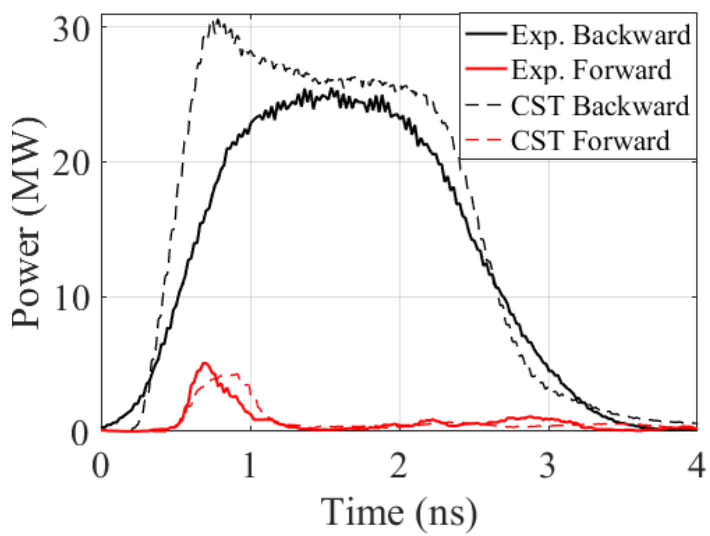


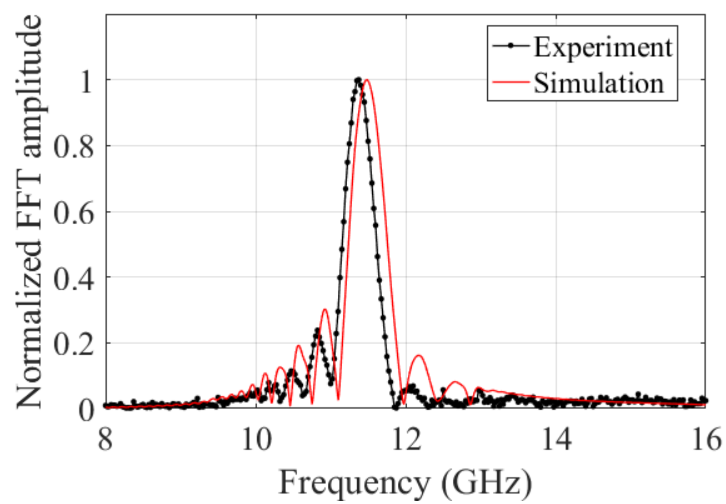


Single Bunch Experiment

- 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

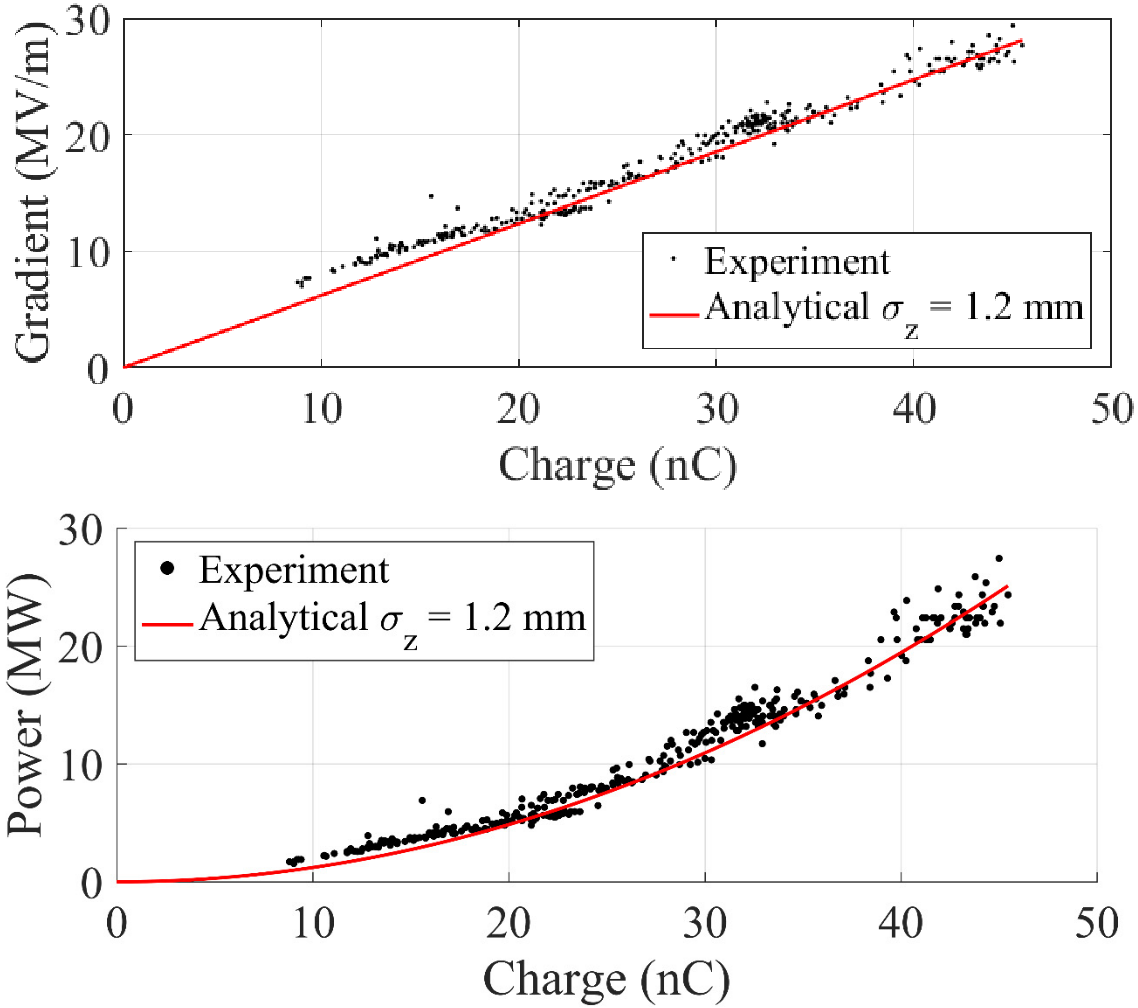






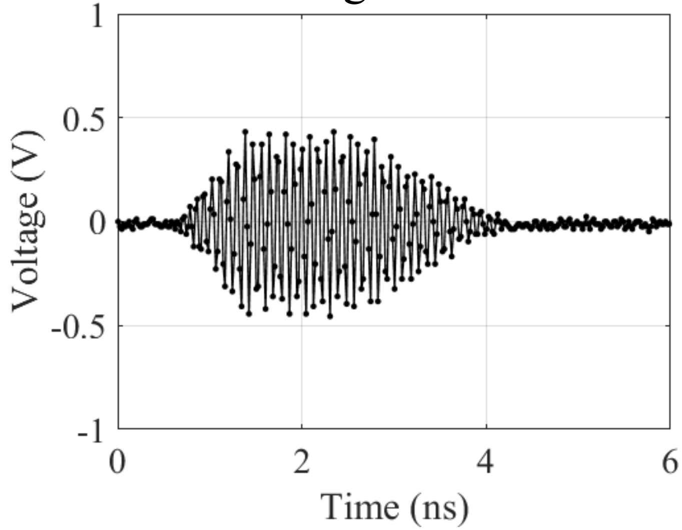
Scaling with Charge

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

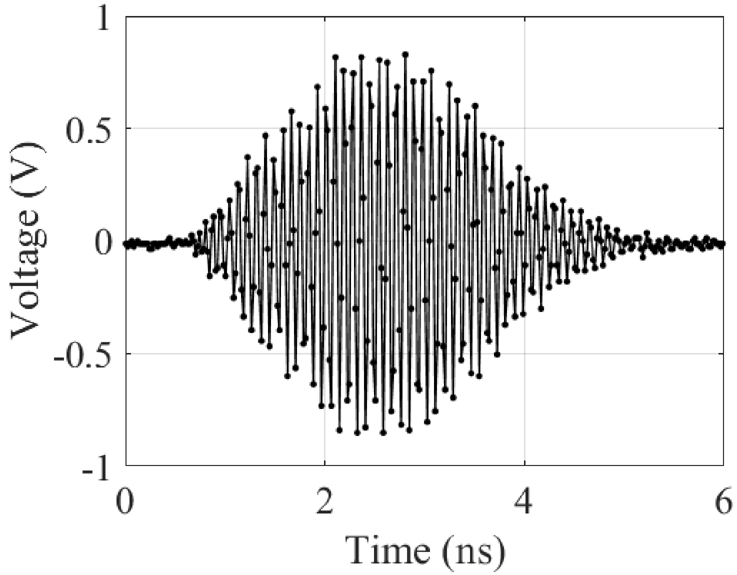


Two-Bunch Experiment

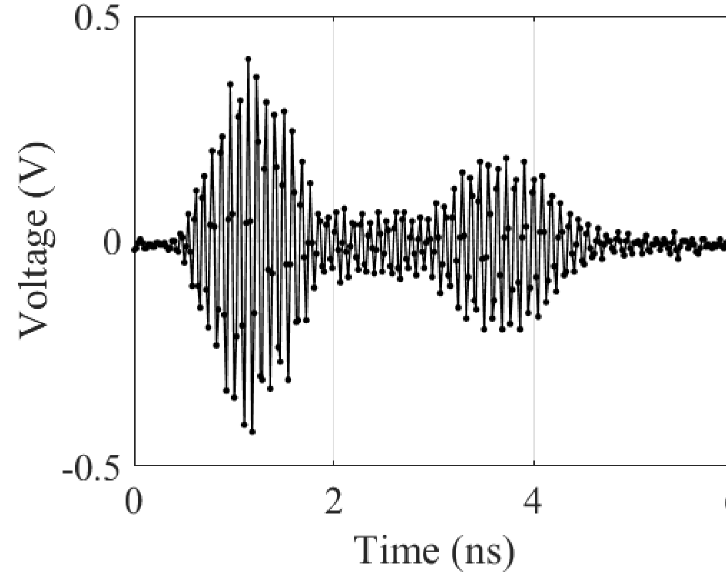
Single bunch



Two bunches with 0 deg phase difference

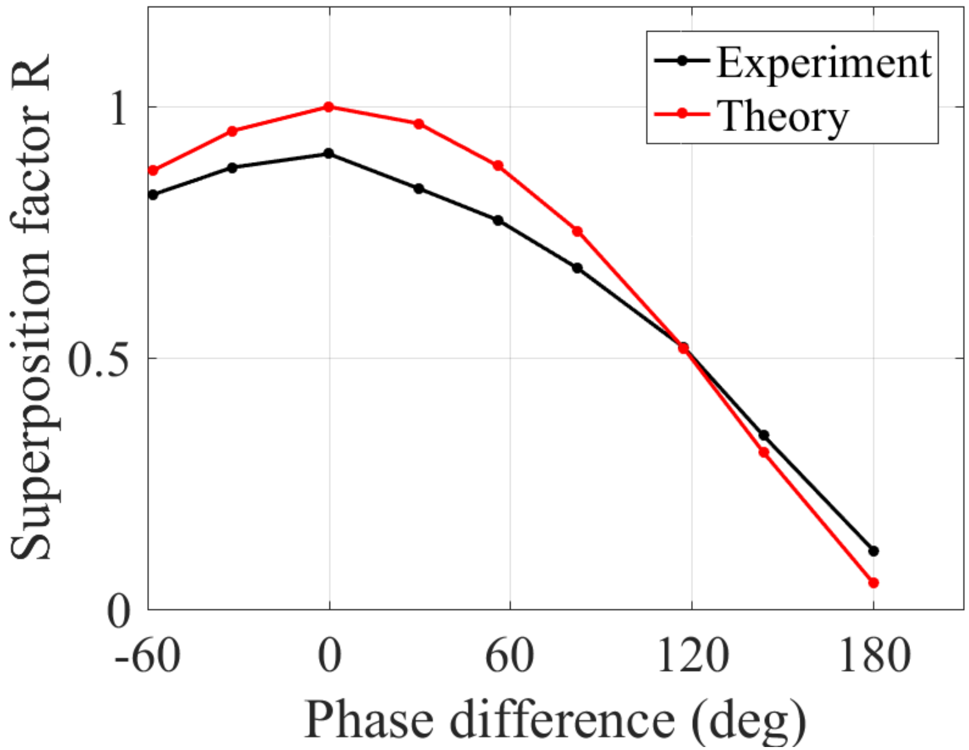


Two bunches with 180 deg phase difference



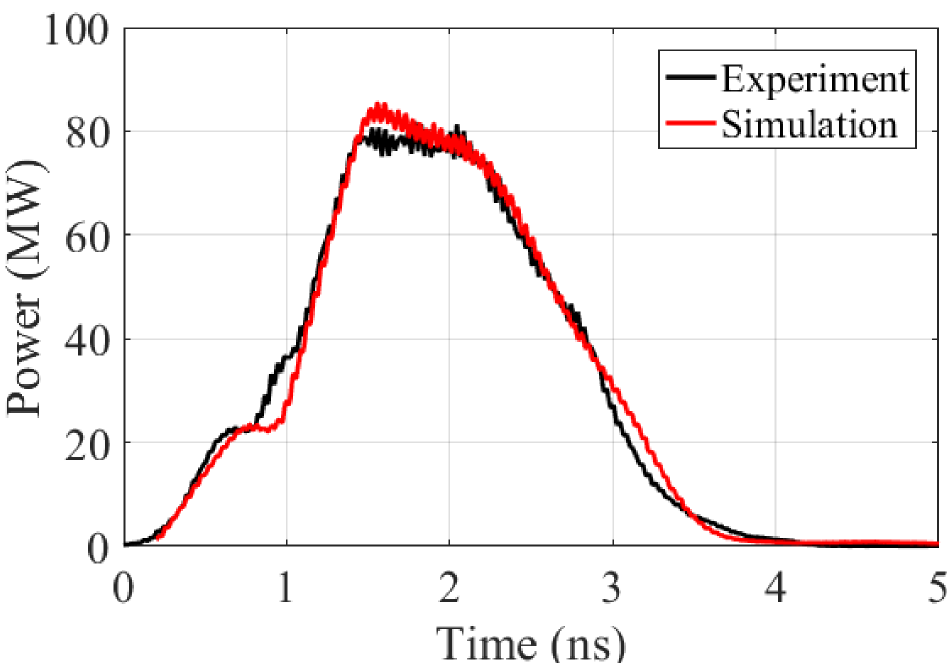
Phase Difference Variation

- Coherent adding/cancelling of two bunches with varied phase difference
  - Phase difference defined for the frequency of 11.4 GHz
- Precise phase control



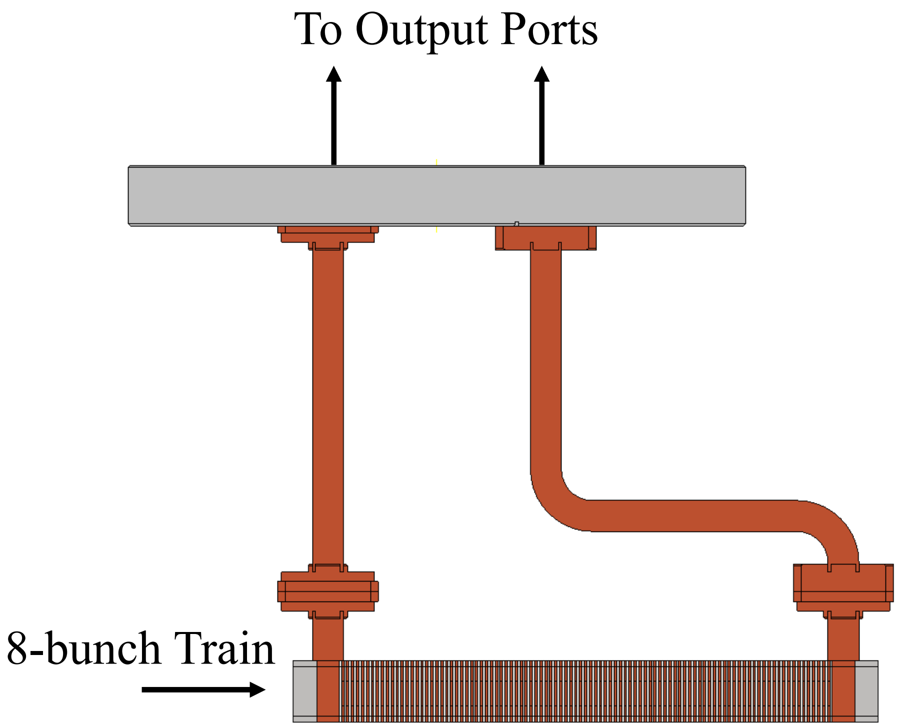
Highest power shot

- Two bunches with a total charge of 85 nC
- **80 MW** extracted RF power
- 50 MV/m decelerating electric field on 2nd bunch



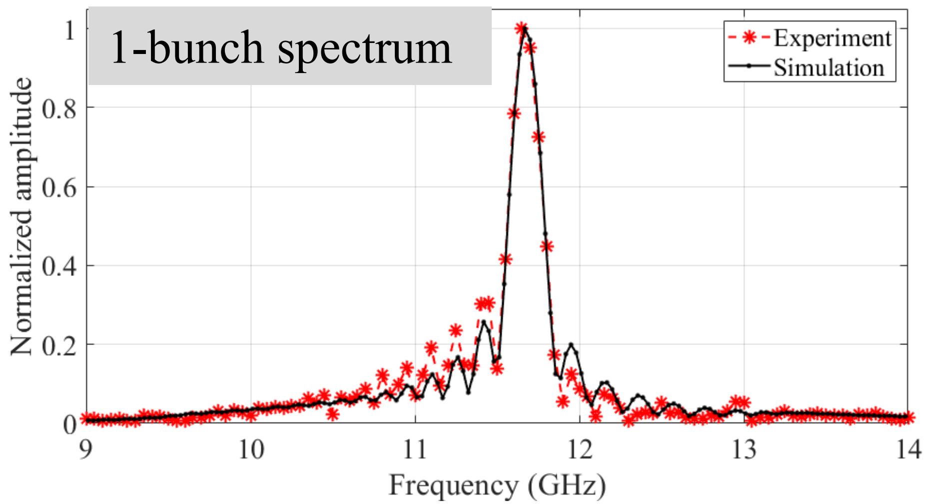
Stage II Experiment: Design

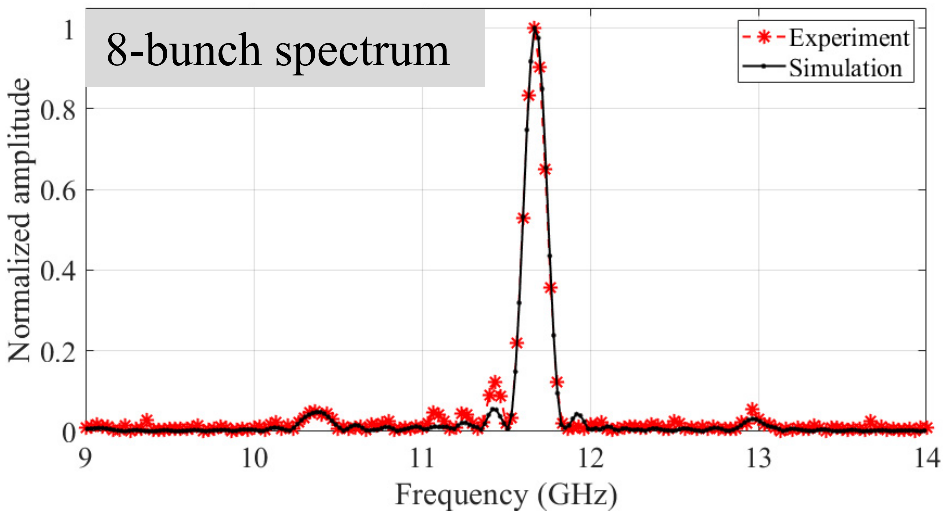
- Design goal: achieve higher RF power / gradient from a train of 8 bunches with a rep rate of 1.3 GHz
- Longer structure: 100-cell structure (20 cm long), 11.7 GHz
- Higher total charge in the 8-bunch train: > 200 nC



Stage II Experiment: Preliminary Results- 1

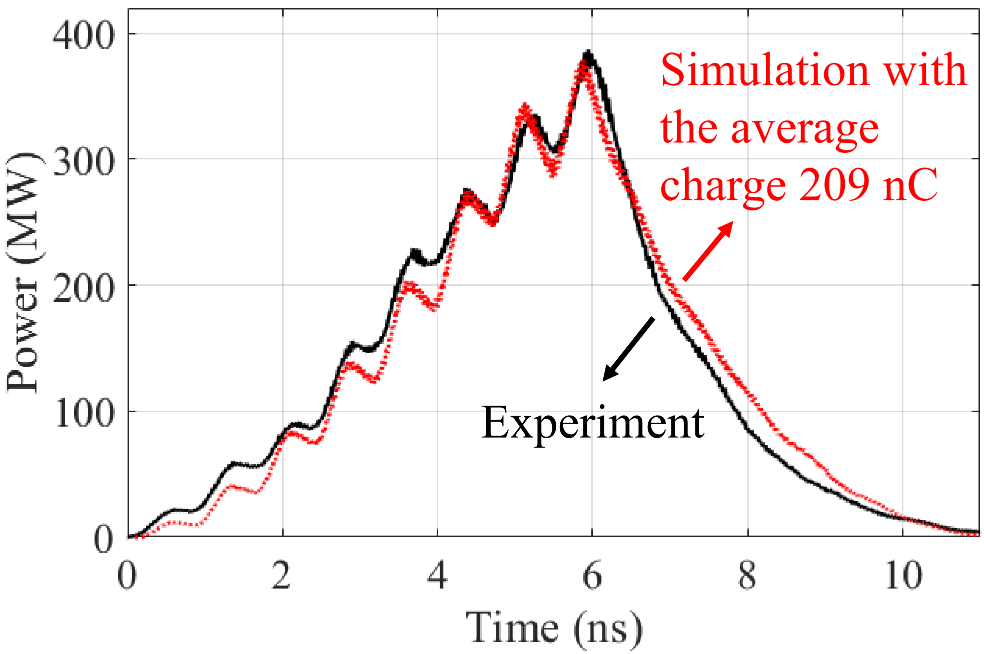
- Frequency spectra agree well with beam simulations





Stage II Experiment: Preliminary Results- 2

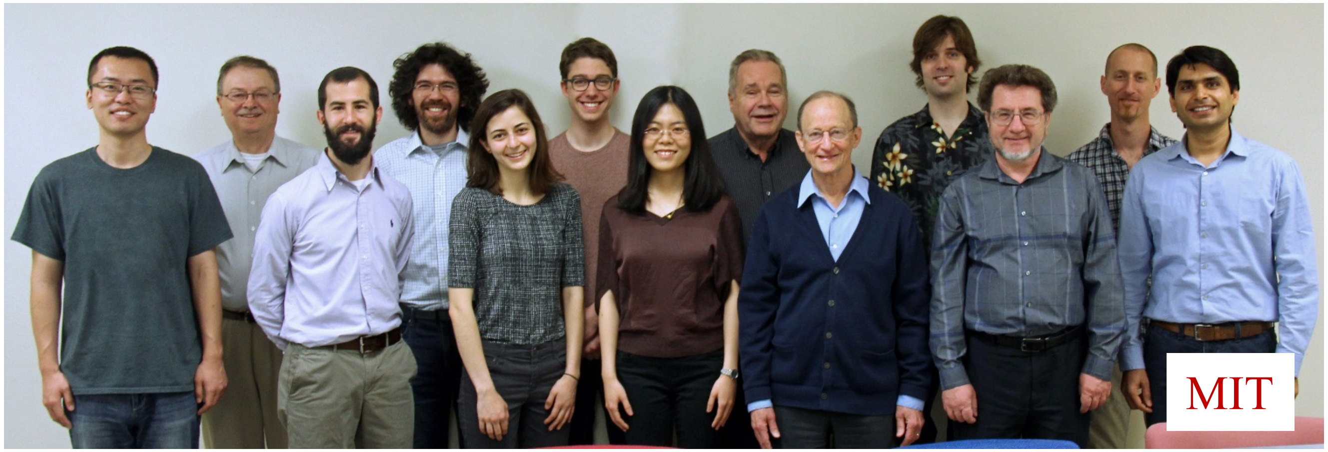
- RF pulse shape agrees well with beam simulations
- Highest power is estimated to be 380 MW peak from 8 bunches with a total charge of 224 nC before the structure, and 194 nC after the structure
  - 110 MV/m gradient at the 8th bunch location

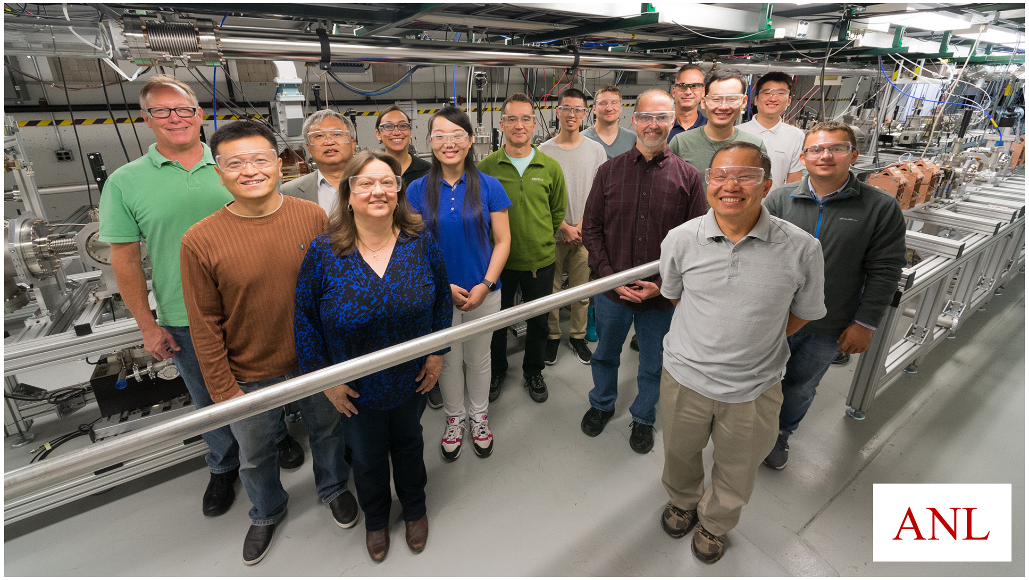


Conclusions

- Two wagon wheel metamaterial structures at X-band have been tested at the Argonne Wakefield Accelerator as power extractors.
- 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.
  - Stage I (40-cell structure): Two bunches, 85 nC, 80 MW, 50 MV/m decelerating gradient, 75 MV/m accelerating gradient
  - Stage II (100-cell structure): Eight bunches with a total charge of 224 nC, estimated peak power of 380 MW
- Wagon wheel structure has its unique advantages for wakefield acceleration
  - Rugged all-metal structure, no dielectrics
  - Enhanced beam-wave interaction

Acknowledgement





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ANL: U.S. Department of Energy, Office of Science under Contract No. DE-AC02-06CH11357.