A Metamaterial Structure for Wakefield Acceleration

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A Metamaterial for Next Generation Particle Accelerators

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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

\[ \begin{align*}
\varepsilon > 0, \mu > 0 & \quad & \varepsilon < 0, \mu < 0
\end{align*} \]
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**

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
- Experimental Facilities

- Design and theory
  - Metamaterial Structure Design
  - Theory and Simulation

- Experiment
  - Structure Fabrication
  - Experimental Results

- Conclusions
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

Plate thickness:
1 mm each

Copper
Stainless steel

Dispersion Curve

- Fundamental Mode
- Light Line
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:

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

$$= 25 \text{ MW}$$
“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
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Installed Experiment at AWA

RF loads

Vacuum Chamber

RF probes

65 MeV e− beam

RF Probe (backward port)

RF Probe (forward port)

MTM structure

Electron beam
Outline- ANL WFA Experiment

- Motivation
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- Experiment
  - Structure Fabrication
  - Experimental Results
    - 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

Bunch Train

To Output Ports

CST simulation of output power in the backward port

Power (GW)

Time (ns)
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.
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