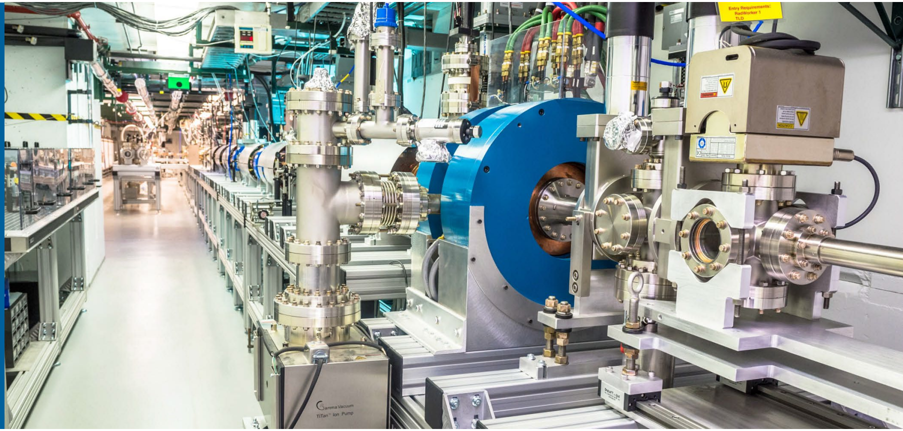
International Workshop on Breakdown Science and High Gradient Technology (HG2022)

May 17, 2022, Virtual

Metamaterial Structures for High-Gradient Wakefield Acceleration



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Northern Illinois University (NIU)
& Argonne National Laboratory (ANL)

On behalf of:
MIT/AWA/NIU teams

Acknowledgements

- Julian Picard
- Ivan Mastovsky
- Michael Shapiro
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- Charles Whiteford
- Eric Wisniewski
- Chunguang Jing (Euclid)

- Brendan Leung
- Dillon Merenich

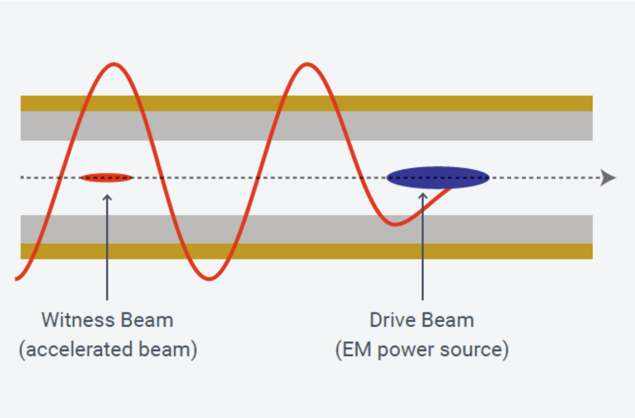
Outline

- Motivation & Introduction
  - Needs for advanced structures for structure-based wakefield acceleration (SWFA)
  - Advantages of metamaterial (MTM) structures for SWFA
- Experimental Studies at AWA
  - MTM power extractors
  - MTM accelerators for two-beam acceleration
- Ongoing/Future Work
  - Modular MTM designs for near-term demonstrators
  - MTM structures at sub-terahertz frequencies
- Conclusions

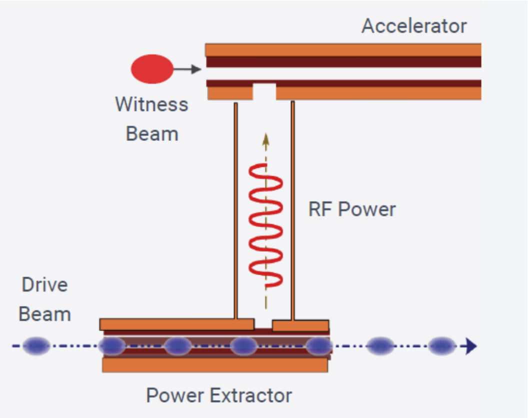
Structure-Based Wakefield Acceleration (SWFA)

- Structure-Based Wakefield Acceleration (SWFA):
  - Extract wakefield from a “drive” beam to accelerate a “witness” beam
- SWFA requires different structure optimization from short RF pulses
  - SWFA at AWA : a few ns pulse length
  - Klystron-driven linacs: ~100 ns to ~μs

Collinear Acceleration

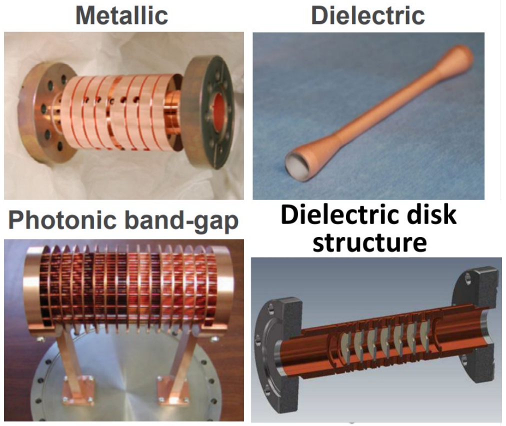


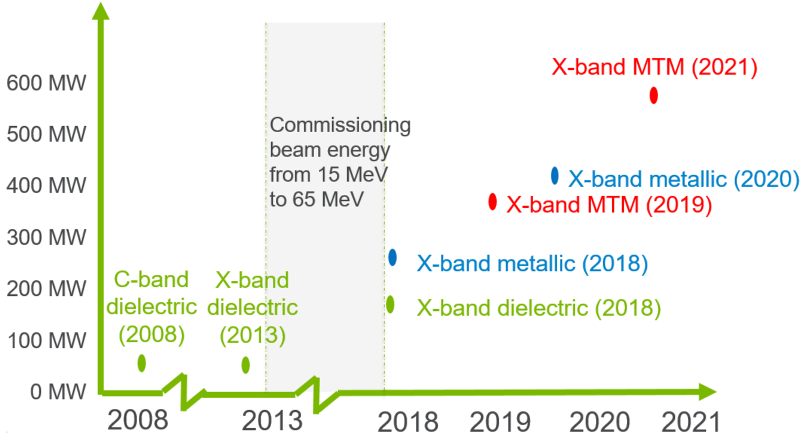
Two-Beam Acceleration



Needs for Advanced Wakefield Structures

- Short-pulse operation:
  - Possibly lower breakdown rate BDR $\propto E^{30} t_p^5$
  - Challenging RF design requirements
- Advanced structures for high-gradient SWFA
  - Steady process on advanced structures in recent years at AWA



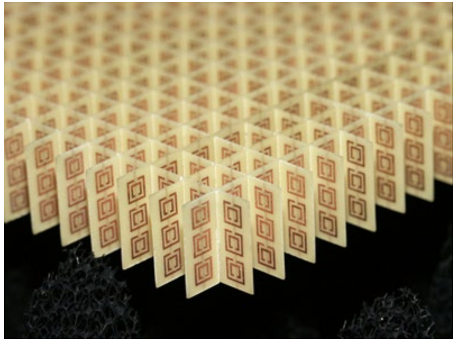


X. Lu, et al., “Advanced RF Structures for Wakefield Acceleration and High-Gradient Research”, Whitepaper submitted to Snowmass 2021

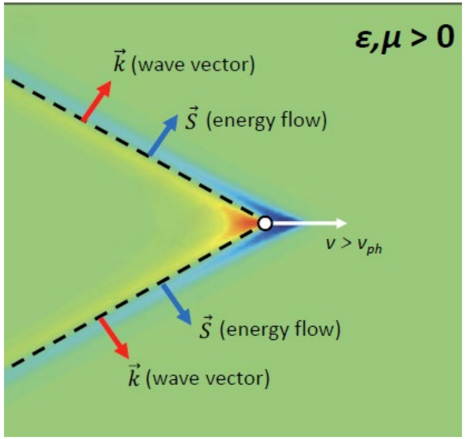
Metamaterials (MTMs)

- An artificial material with a subwavelength unit cells
- Unit cell designs could lead to exotic EM properties
- Double-negative MTMs: $\varepsilon,\, \mu < 0$

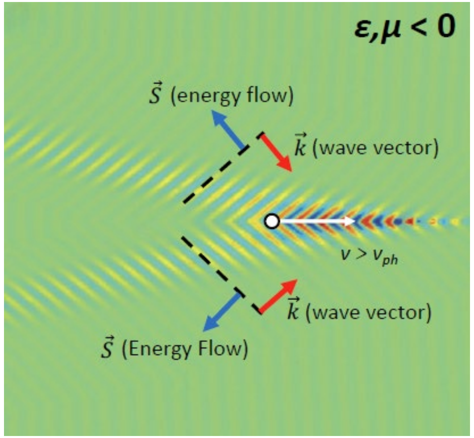
Metamaterial with split ring resonators on PC Boards



Cherenkov Radiation



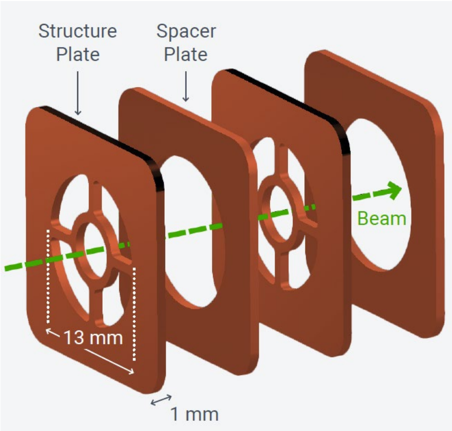
Reverse Cherenkov Radiation



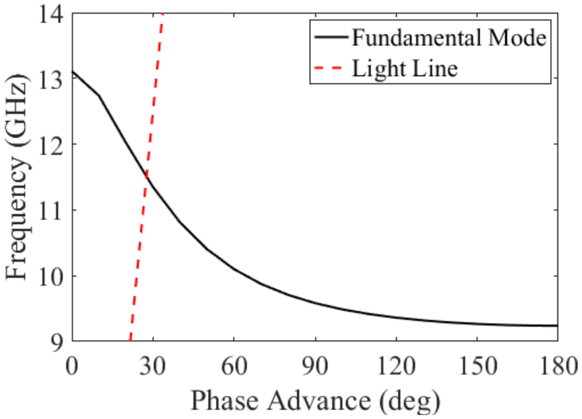
MTM Structures for SWFA

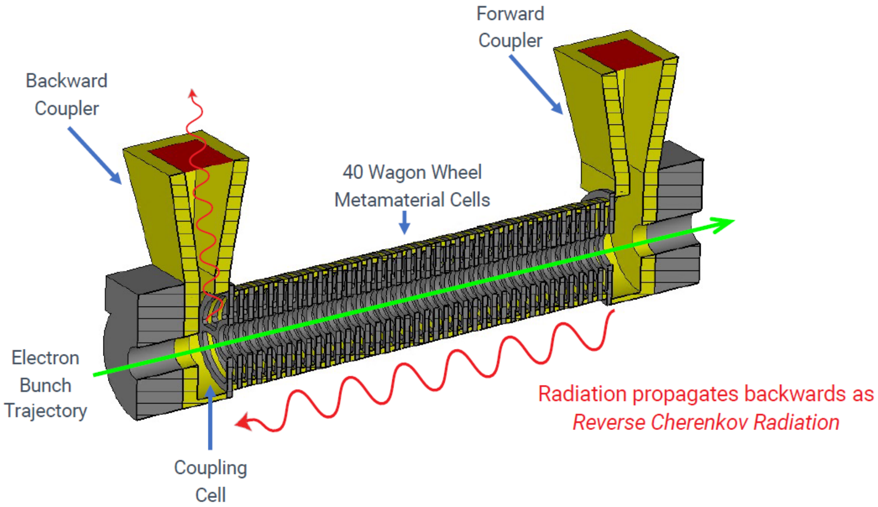
- "Wagon wheel" MTM structure
  - Periodic subwavelength structure
    - 2 mm period vs. 26 mm free-space wavelength
  - Negative group velocity
    - Negative slope of dispersion
  - Fundamental TM-like mode

Wagon wheel MTM structure



Dispersion curve





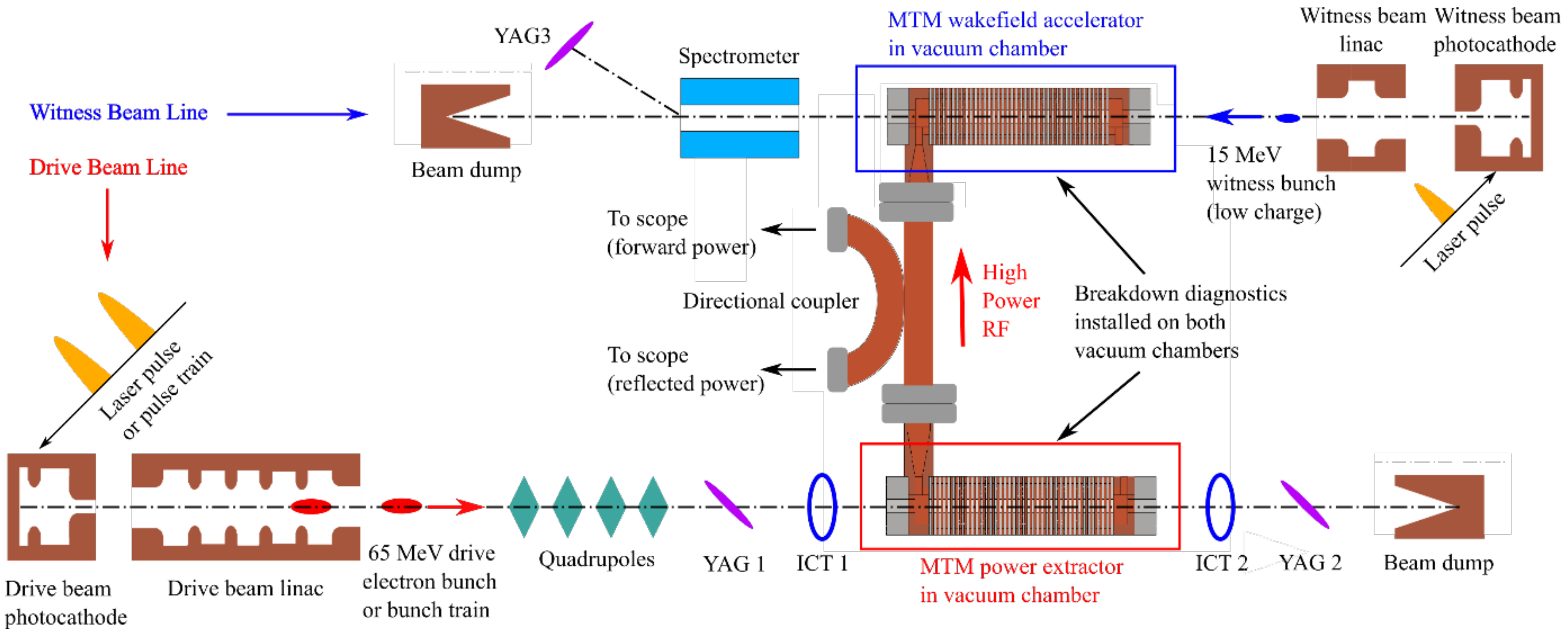
MTM Structures Fulfill SWFA Requirements

- 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
- These requirements are challenging for conventional structures
  - General rule: beam aperture ↓, r/Q ↑, v_g ↓
- Reversing group velocity sign fulfills SWFA requirements

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

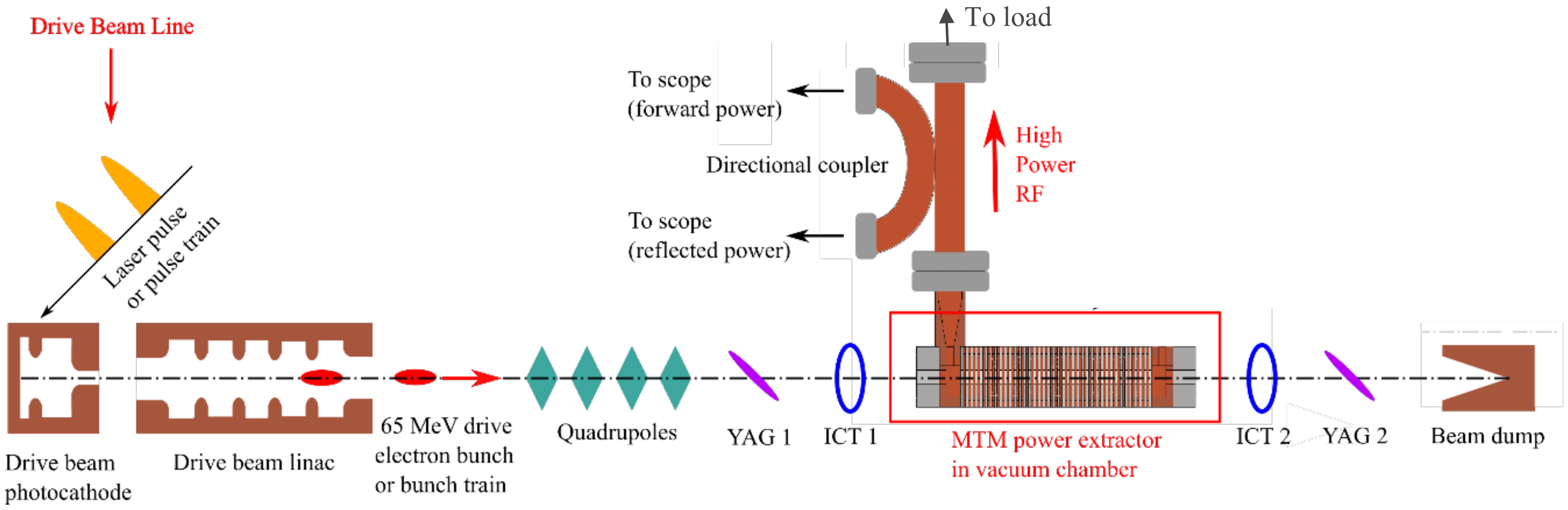
Goal: MTM-Based Two-Beam Acceleration

One MTM power extractor on drive beamline + One MTM accelerator on witness beamline

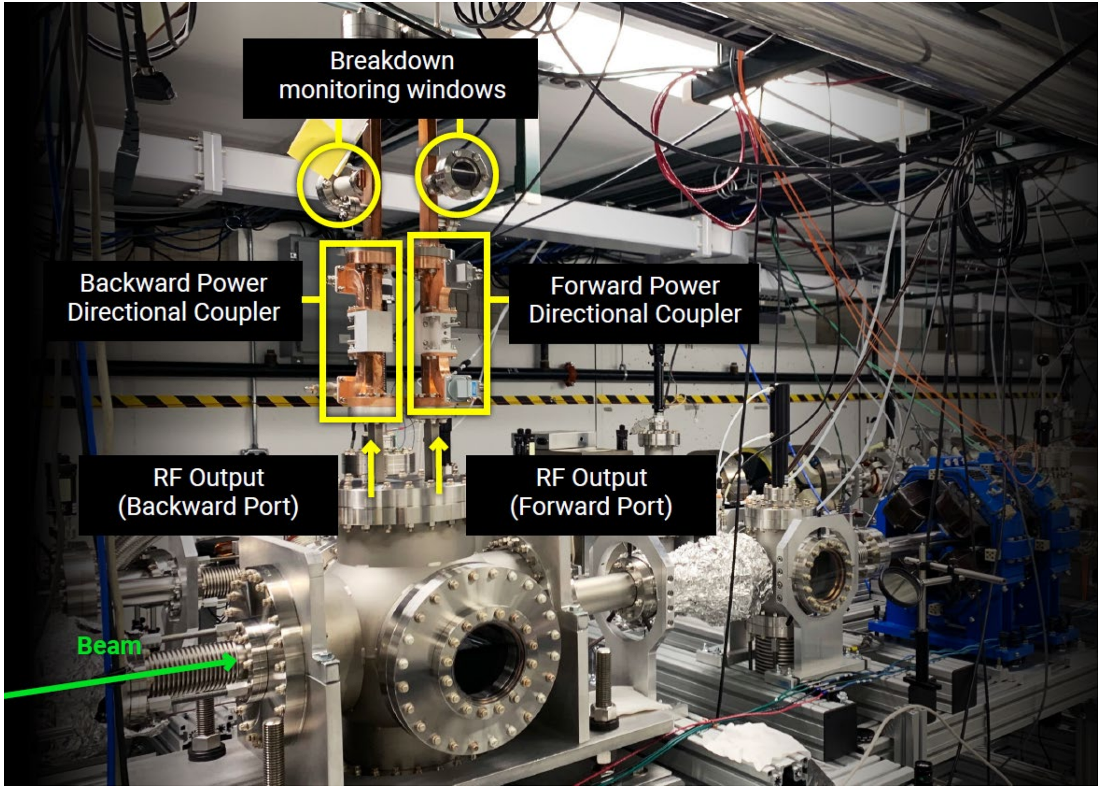


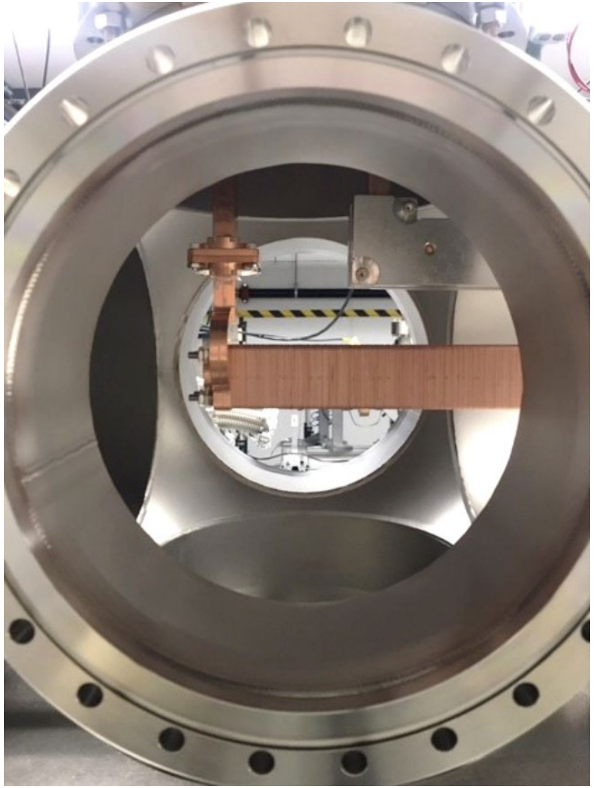
Goal: MTM-Based Two-Beam Acceleration

One MTM power extractor on drive beamline



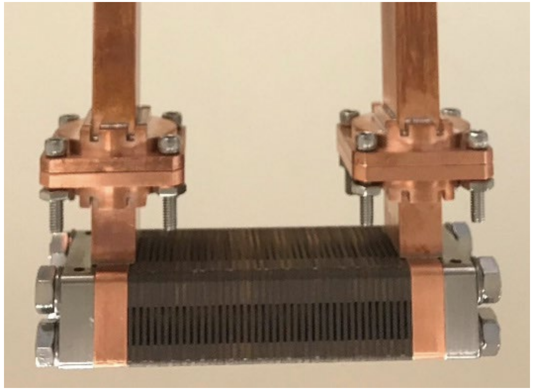
Experimental Setup for MTM Power Extractors





Series of Experiments on MTM Power Extractors

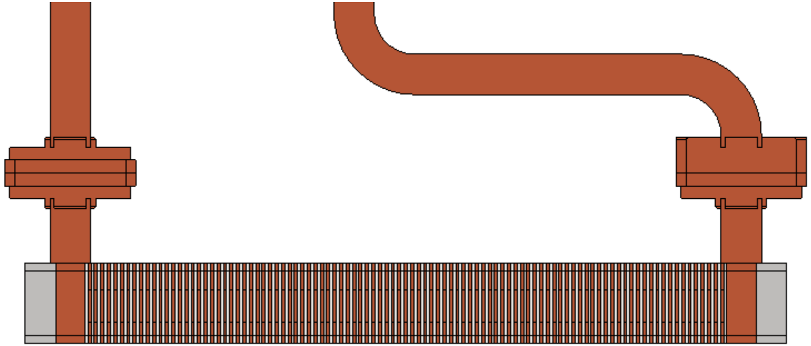
- Stage 1 (Experiment in 2018)



40-cell MTM structure
80 MW peak power at 11.4 GHz from 2 bunches

X. Lu, *et al., Physical Review Letters*, **122**, 014801 (2019)

- Stage 2 (Experiment in 2019)



100-cell MTM structure
380 MW peak power at 11.7 GHz from 8 bunches

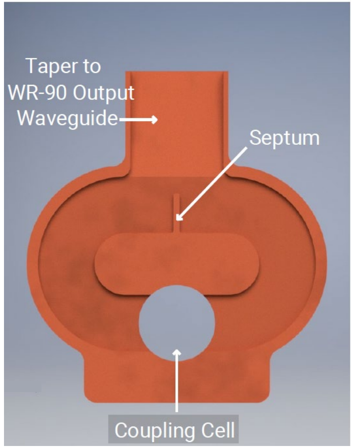
X. Lu, *et al., Applied Physics Letters*, **116**, 264102 (2020)

Stage-3 Experiment (2021)

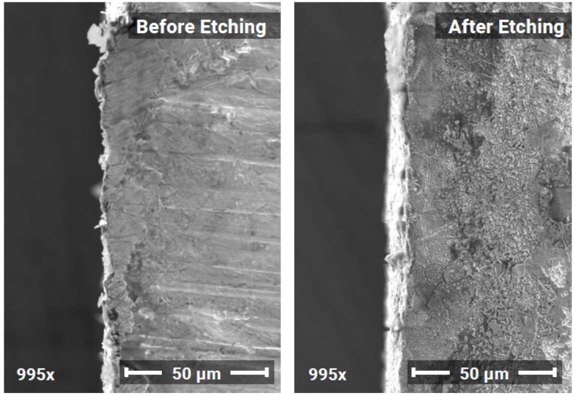
Thesis work of
Julian Picard
(graduated from MIT)

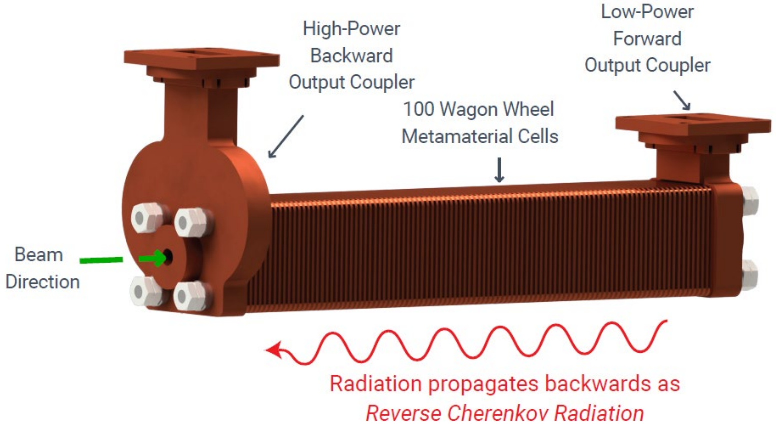
- Two beam tests at AWA: Feb.- Mar. & Sep.- Oct. 2021
- Significant improvements in Stage-3 design:
  - All-copper construction
  - Symmetric output coupler design
  - Treatment of plates to mitigate breakdown risk

Symmetric Coupler Design



SEM Images before & after treatment



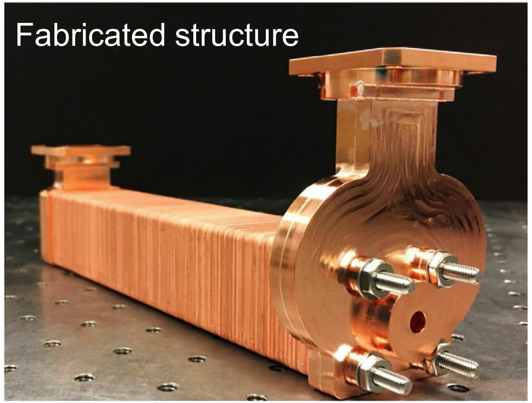


All-Copper Construction

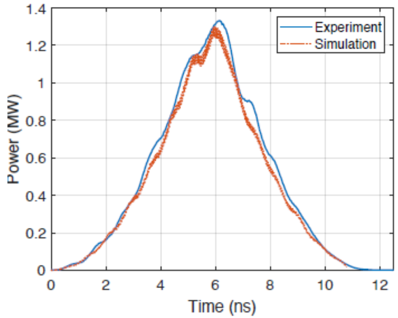
Thesis work of
Julian Picard

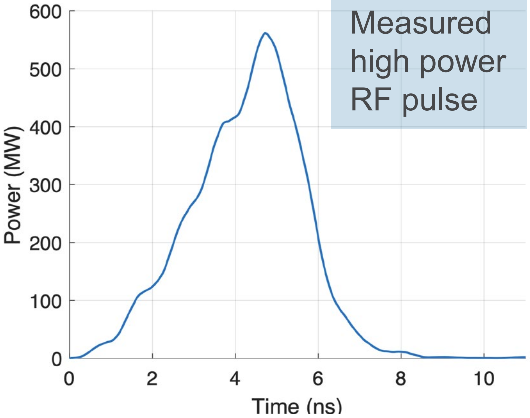
Highest Power Generated: 565 MW at 11.7 GHz

- 565 MW from Stage-3 MTM power extractor tested in 2021
  - Highest power generated by a structure-based power extractor
  - Generated from a 355 nC train of eight bunches
  - Peak on-axis gradient of 135 MV/m
  - No breakdowns detected despite estimated surface fields >1 GV/m



Low-charge (8 bunches, 12 nC total) for validation of power measurement



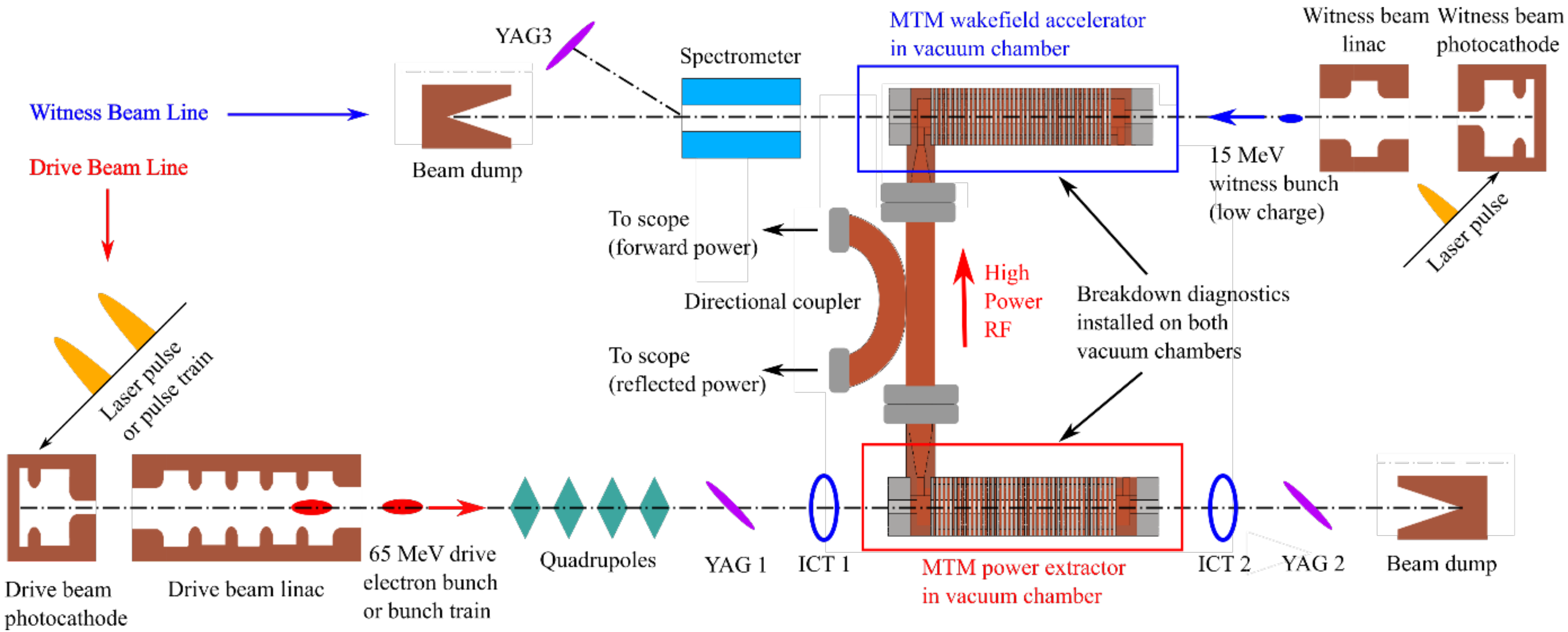


Measured high power RF pulse

J. Picard, *et al.*, "Generation of 565 MW of X -band power using a metamaterial power extractor for structure-based wakefield acceleration", *Physical Review Accelerators and Beams*, **25**, 051301 (2022)

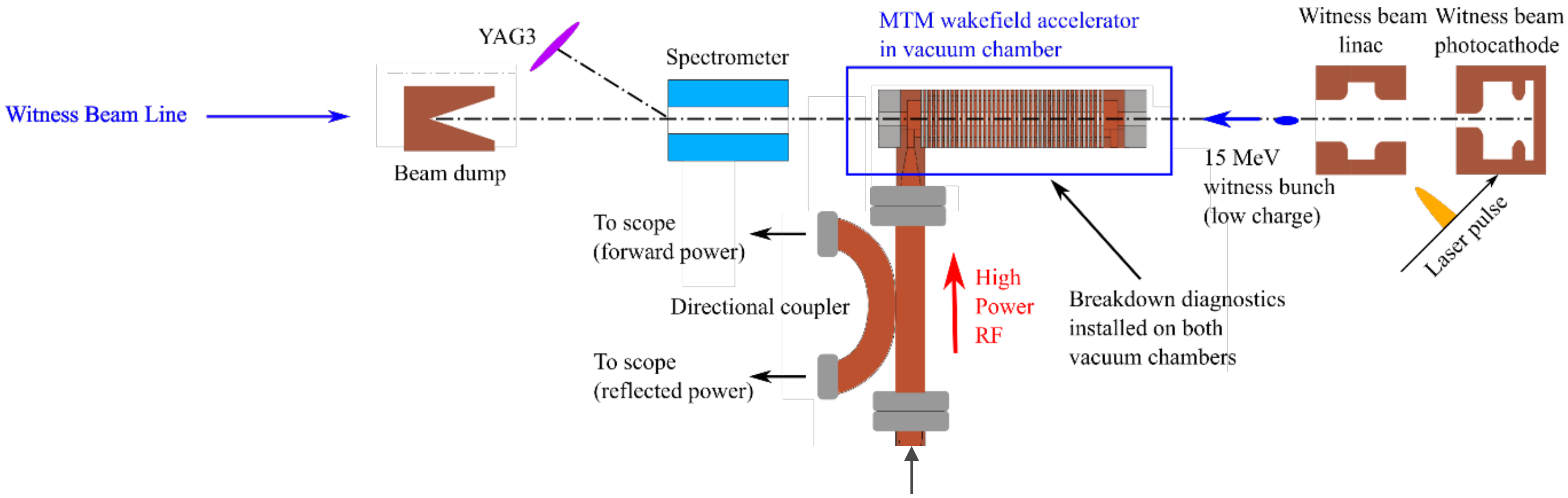
Goal: MTM-Based Two-Beam Acceleration

One MTM power extractor on drive beamline + One MTM accelerator on witness beamline



Goal: MTM-Based Two-Beam Acceleration

One MTM accelerator on witness beamline



RF power extracted
from drive beam

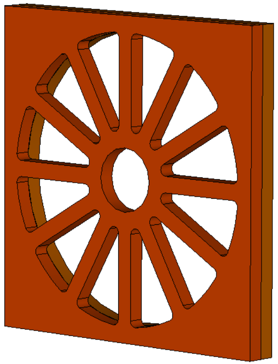
MTM Accelerator Design

NIU student
Dillon Merenich

- Phased demonstration:
  - Stage-1: RF breakdown test on an MTM accelerator (no witness beam)
  - Stage-2: Complete two-beam acceleration
- MTM accelerator design
  - First prototype: 6-cell MTM accelerator driven by a metallic disk-loaded power extractor

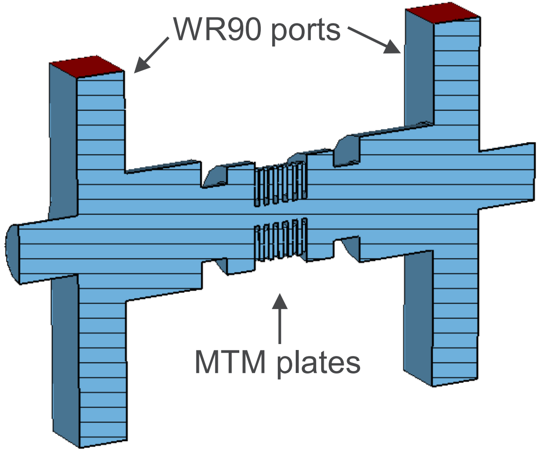
Unit Cell

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



Full Structure (Vacuum Part)

~300 MV/m peak gradient from 500 MW peak, 3 ns flattop pulse extracted from the drive beam

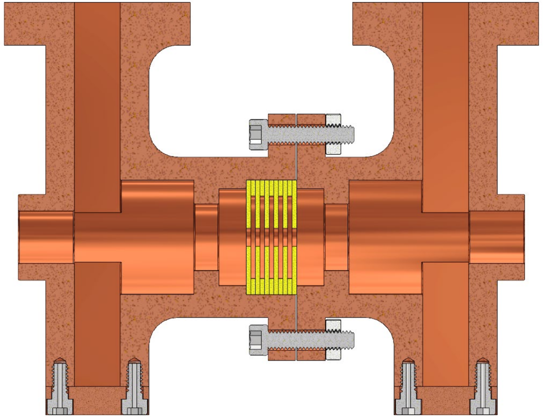


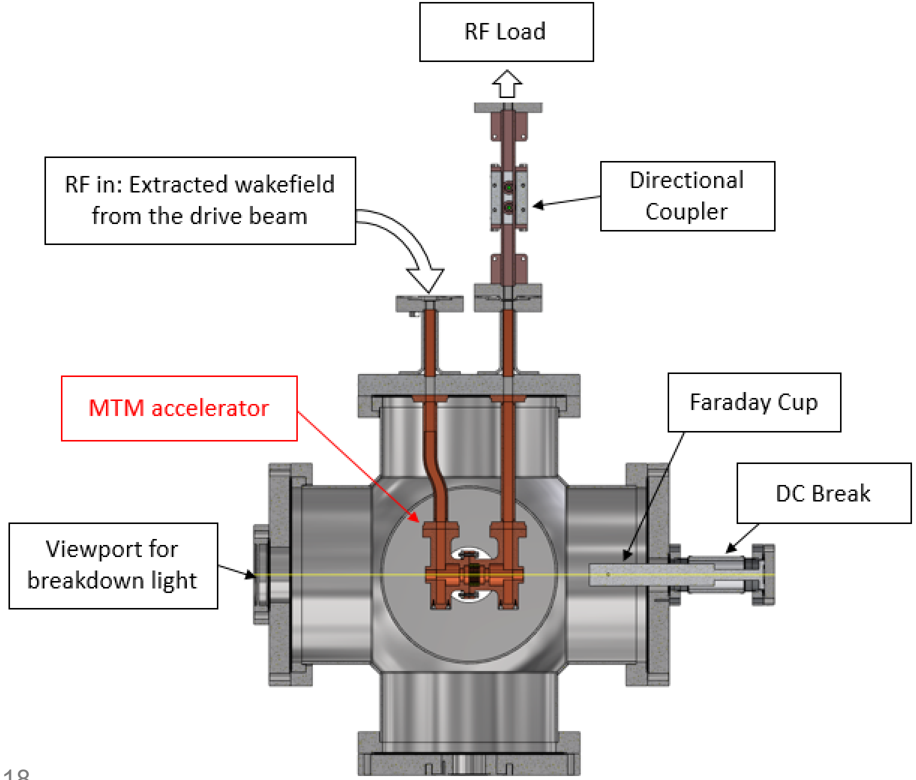
NIU student
Dillon Merenich

MTM Accelerator Breakdown Test

- Structure under fabrication
- Experiment scheduled for June 2022

Mechanical Drawing



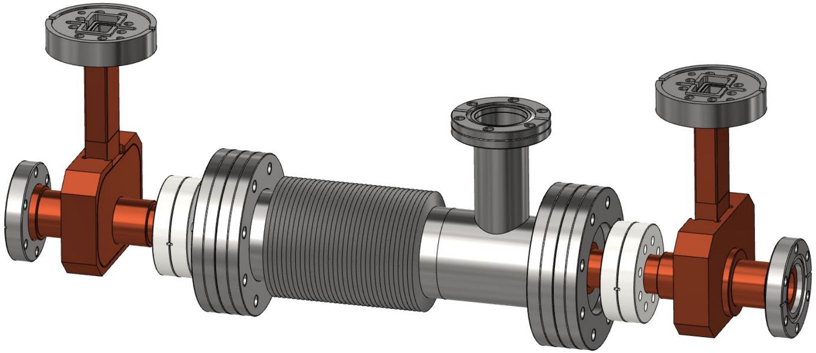


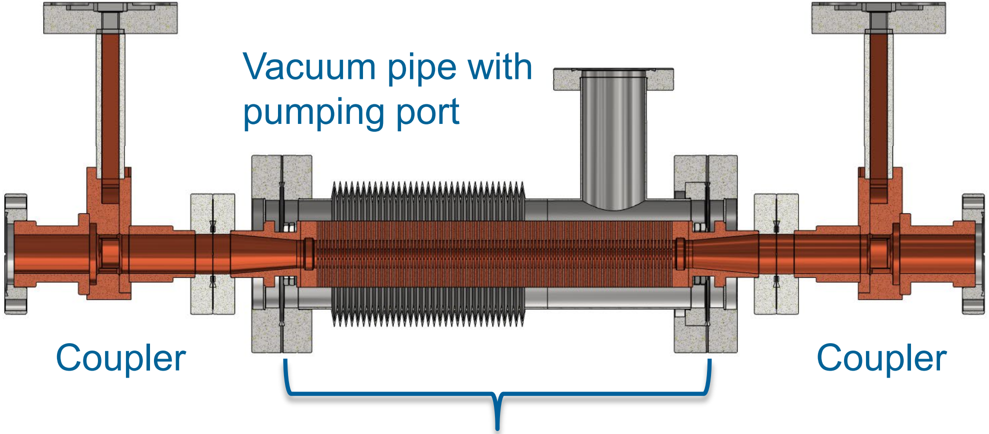
Modular Design for Future Demonstration

Courtesy of Scott Doran (AWA)

- Compact and cost-effective SWFA modules
  - All-metal brazeless (clamped) structure
  - Reusable mode launchers and vacuum chambers

- Nearer-term applications:
  - Compact X-ray FEL
  - Staging demonstration



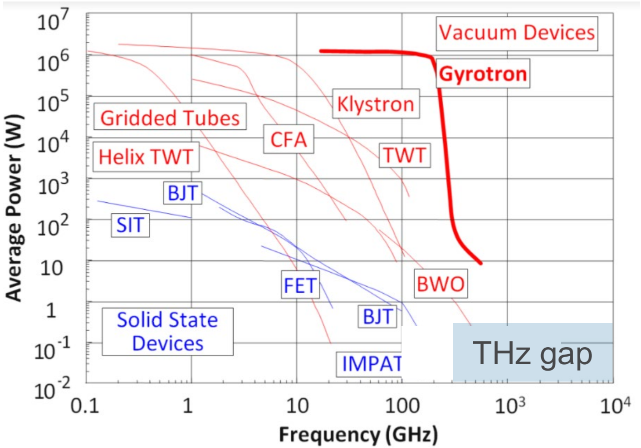


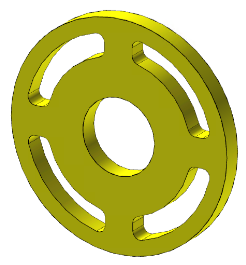
NIU student
Brendan Leung

Sub-Terahertz MTM Structures

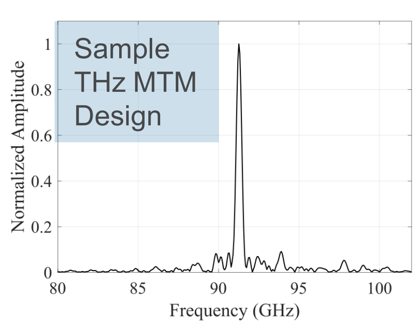
- Motivation
  - Potential higher gradient for more efficient SWFA
  - Lack of high-power radiation sources in the THz gap

- Current Status
  - In the process of fabricating sample structures (e.g. W-band corrugated waveguides) for characterization of fabrication technologies





Beam aperture 1 mm



Conclusions

- SWFA with ~ns long RF pulses is a promising candidate for AAC-based colliders
- R&D on advanced structures for SWFA is much needed and has made significant progress in recent years
- Metamaterial structures can fulfill the special requirements of short-pulse SWFA
  - As power extractors
    - Highest power, 565 MW, generated by a structure-based power extractor
  - As accelerators for two-beam acceleration
- Advantages of metamaterials for SWFA:
  - Rugged structure with high group velocity and high beam-wave interaction
  - Large degree of flexibility for optimization in parameter-space
  - Compact and cost-effective modules from the clamped design

- Work supported by US DOE HEP
  - MIT: DE-SC0011556
  - NIU: DE-SC0021928
  - AWA: DE-AC02-06CH11357

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