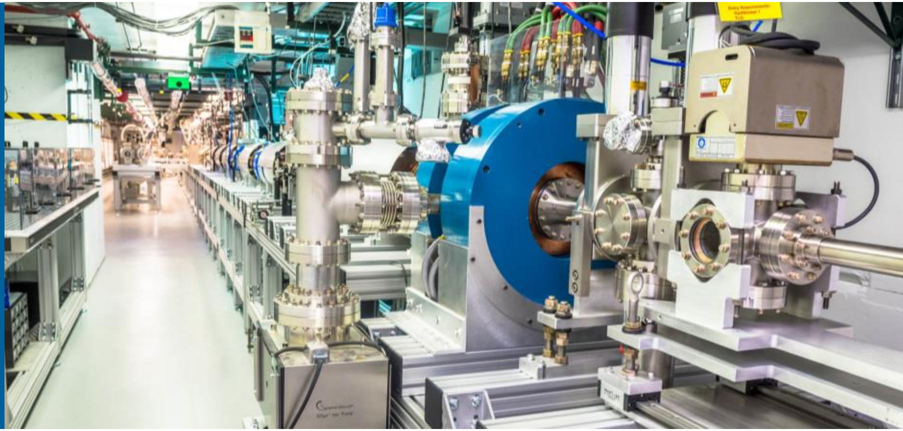
North American Particle Accelerator Conference (NAPAC22)

Design, Fabrication, & Cold Test of a Metamaterial Wakefield Accelerating Structure



Dillon Merenich[1], Xueying Lu[1,2], Scott Doran[2], John Power[2]

[1]Northern Illinois University (NIU)
[2]Argonne National Laboratory (ANL)

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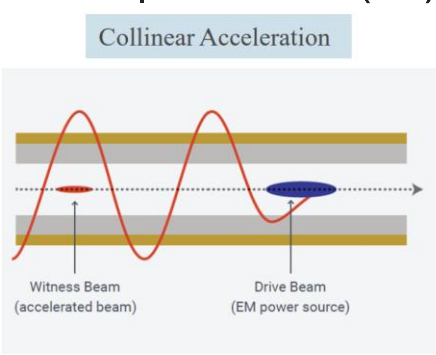
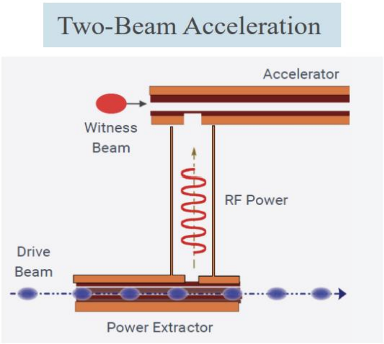
Overview

- Introduction
  - Structure-based wakefield acceleration (SWFA)
  - Metamaterial (MTM) structures for SWFA
- Design of an MTM accelerating structure
- Structure fabrication
- Cold test
- Future work
  - High-gradient breakdown tests for future two-beam acceleration
- Conclusions

Structure-Based Wakefield Acceleration (SWFA)

- Structure-based wakefield acceleration
  - Acceleration of a **witness beam** using wakefield excited by a **drive beam**
  - Two schemes:
    - Collinear wakefield acceleration (CWA)
    - Two-beam acceleration (TBA)
- Short-pulse SWFA → Higher gradients
  - RF breakdown rate (BDR) ∝ $E^{30}t_p^5$
    - Short RF pulses ~O(ns) → lower BDR

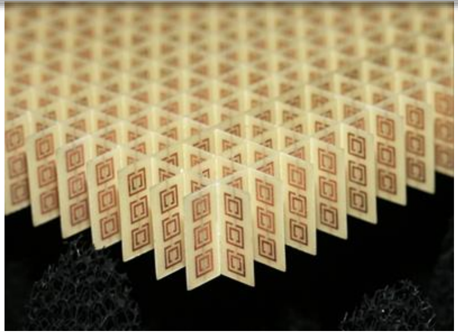




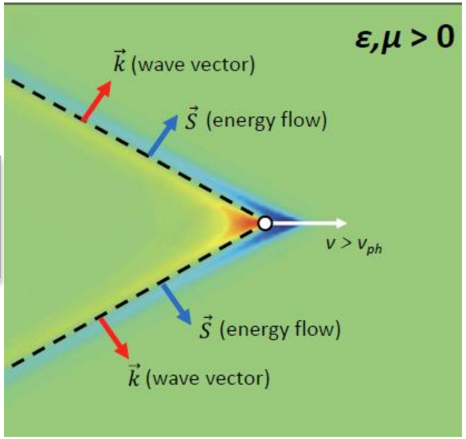
Metamaterial (MTM)

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

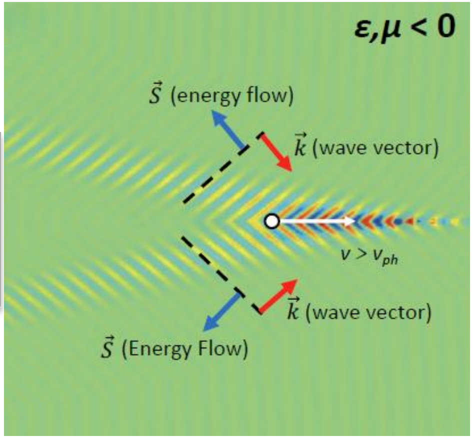
Metamaterial with split ring resonators on PC Boards



Cherenkov Radiation



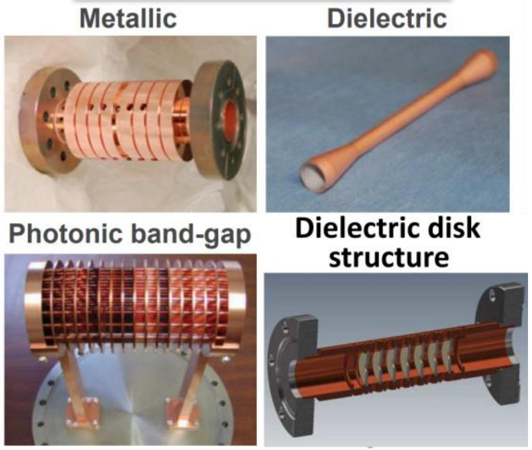
Reverse Cherenkov Radiation



MTM Advantages for SWFA

- SWFA with ~*O*(ns) pulse length has special requirements for wakefield structures
  - High gradient at transient state (short pulse) vs. at steady state (with long pulses)
  - Tradeoff between shunt impedance and group velocity
- Advanced structures are needed
- Metamaterial structures are promising from:
  - Strong beam-wave interaction due to the subwavelength feature
  - Large parameter space for optimization

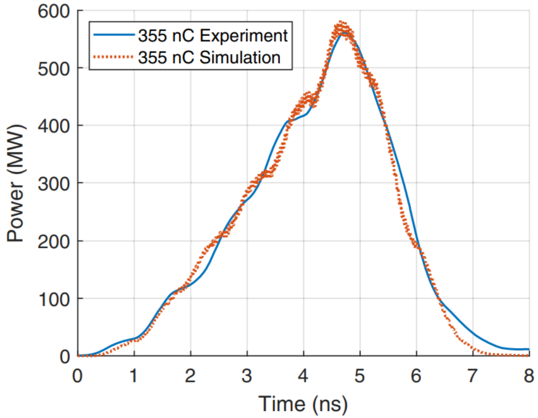
Other advanced structures studied at AWA

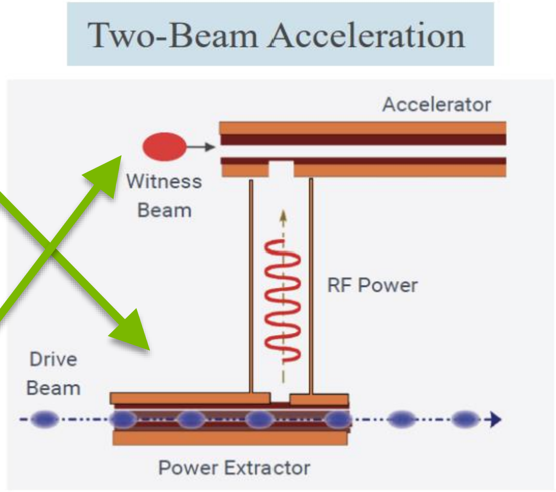


This Work vs. Previous Work on MTM Structures

- Previous work: Series of MTM X-band power extractor experiments
  - **Highest power: 565 MW** peak power extracted from the AWA drive beam

565 MW peak power measured at 11.7 GHz

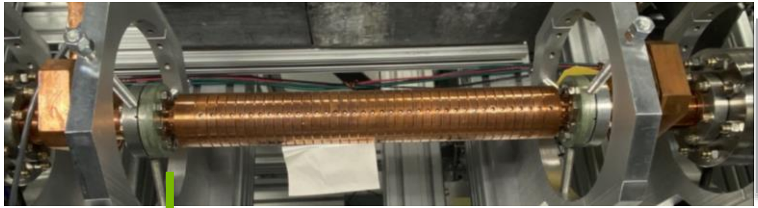




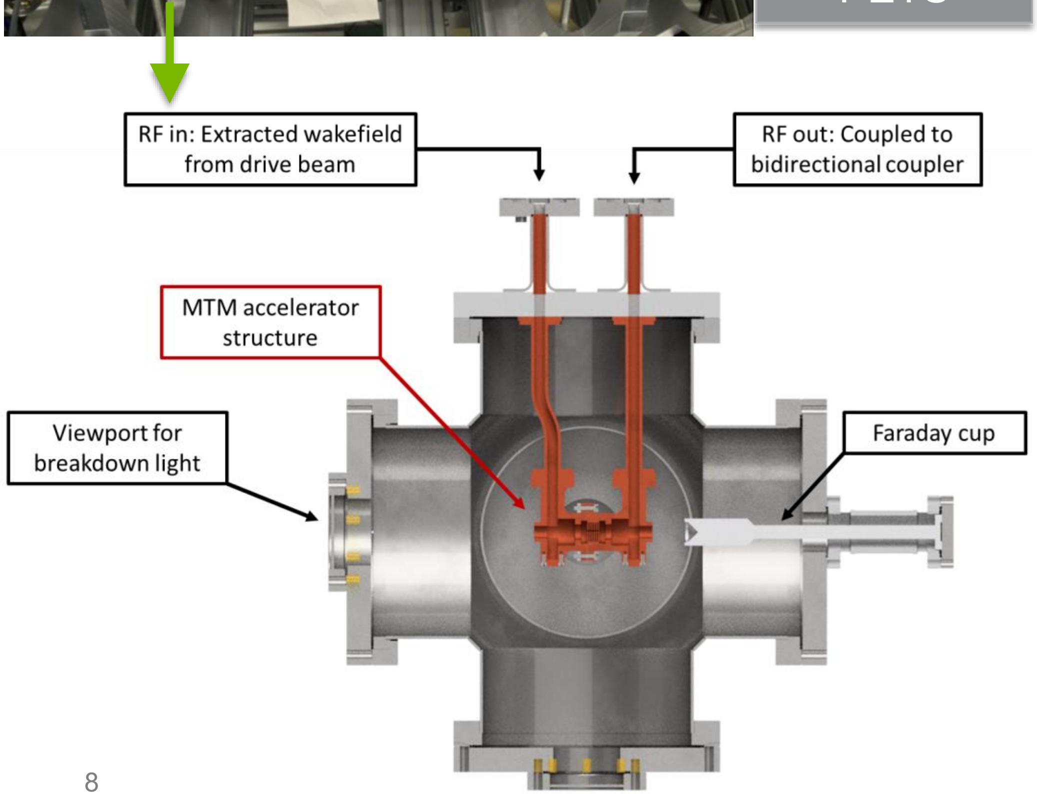
- This work: First demonstration of an MTM accelerating structure

Experimental Setup

- Phase I high-power test of the MTM accelerating structure
  - RF in: Up to 500 MW of peak power extracted from a ~500 nC 8-bunch train by a metallic disk-loaded PETS
- High-gradient operation of the MTM accelerating structure

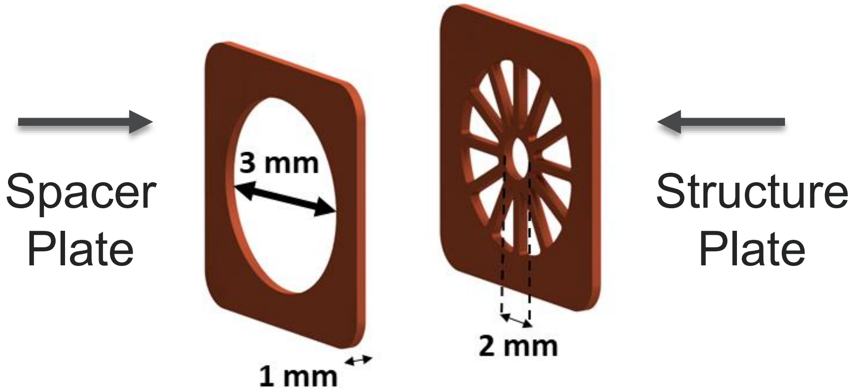


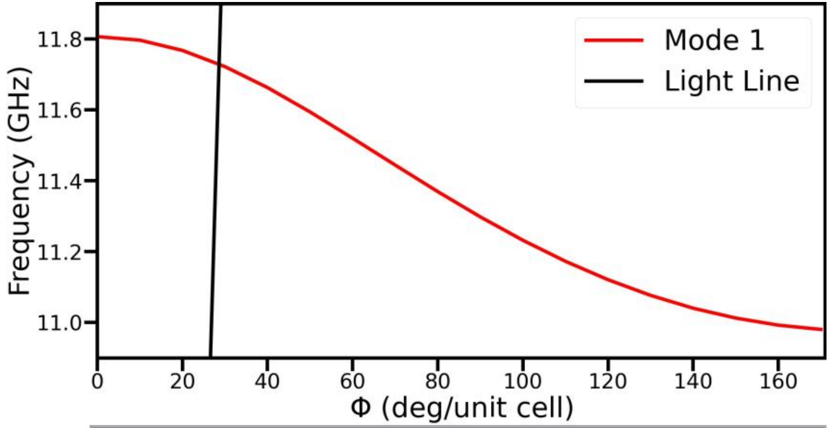
Metallic disk-loaded PETS



Unit Cell Design

- "Wagon wheel" MTM unit cell designed at 11.7 GHz
  – Cell period = 2 mm << RF wavelength
- Fundamental TM_{01}-like mode with a negative group velocity
- Tradeoff between high gradient at the steady state & short fill time required by ns-long input pulses

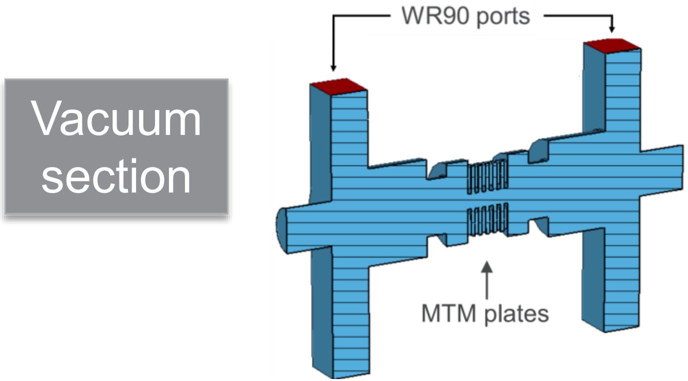


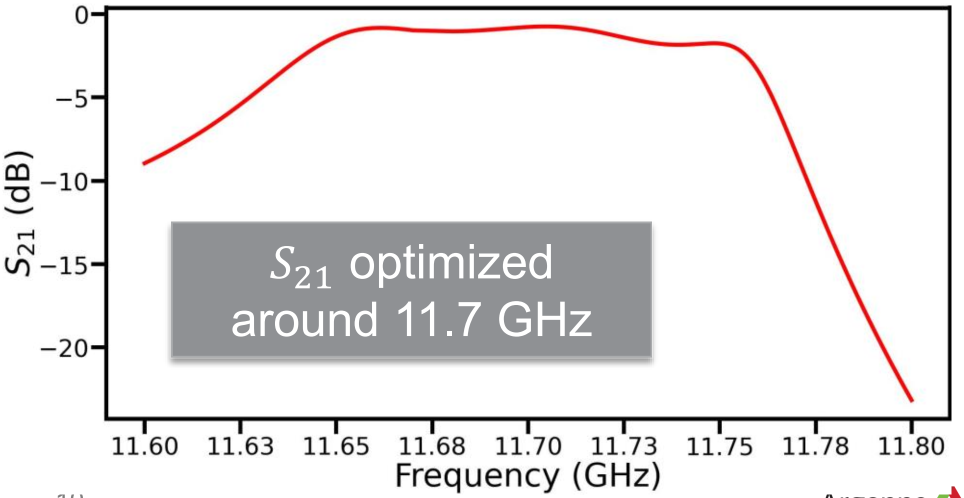


Dispersion curve

Full Structure Design: Frequency Response

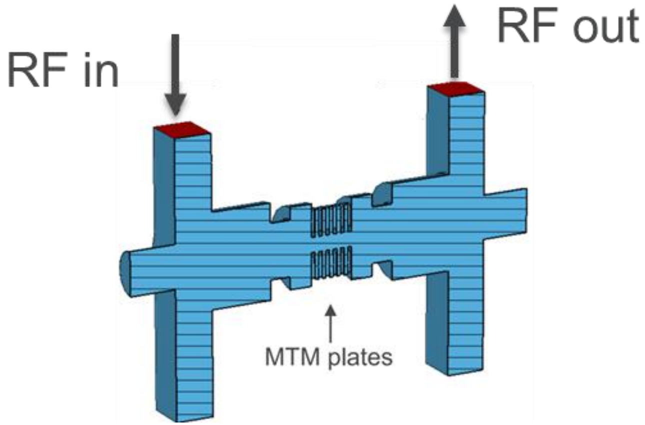
- 6 unit-cell w/ couplers
  - Signal transmission optimized around 11.7 GHz
- Short input pulse → decent bandwidth required while achieving a high gradient



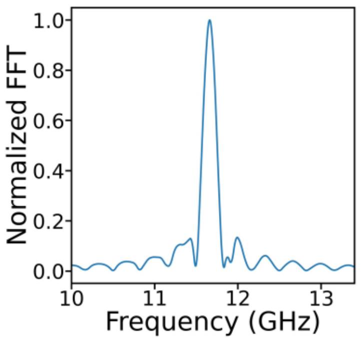


Full Structure Design: Time Response

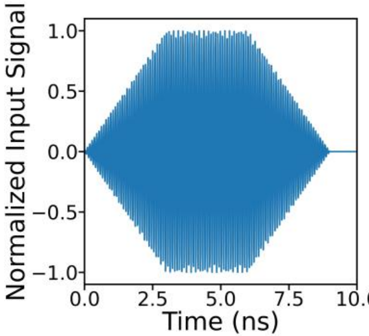
- Input pulse from disk-loaded, metallic PETS
- High gradient over 300 MV/m achieved with 500 MW peak power



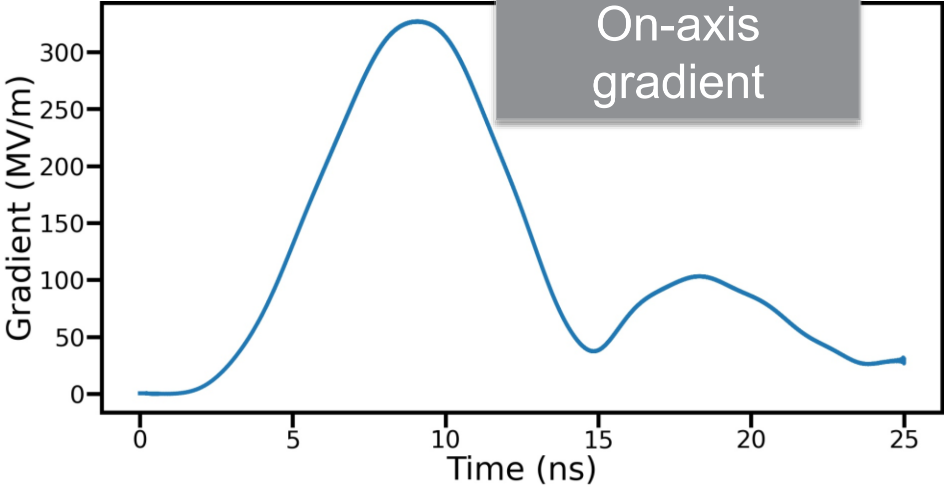
Input voltage FFT



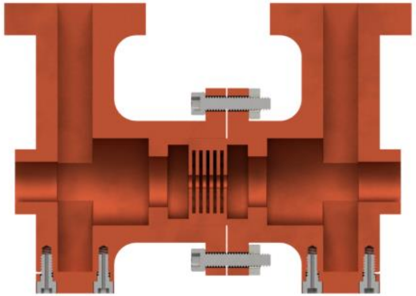
Input voltage pulse

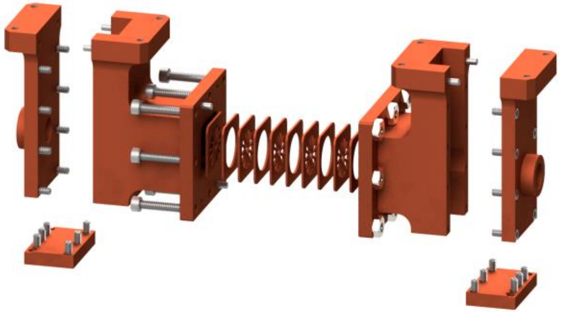


On-axis gradient



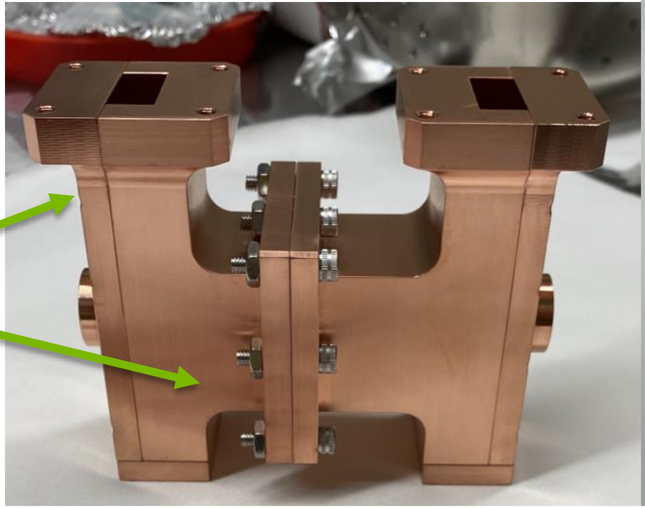
Mechanical Design and Structure Fabrication

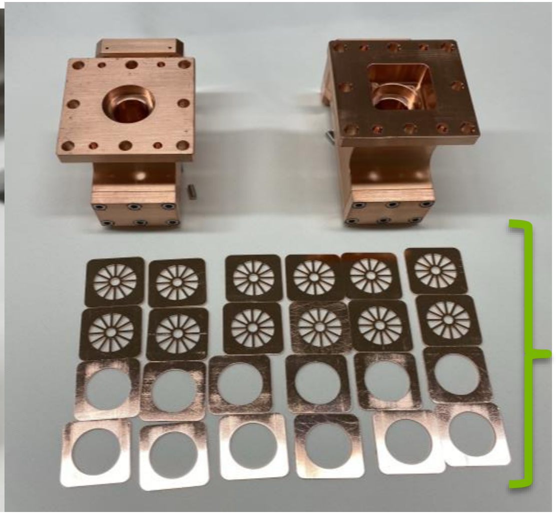




Brazeless structure

- 6 unit cells
- No tuning required

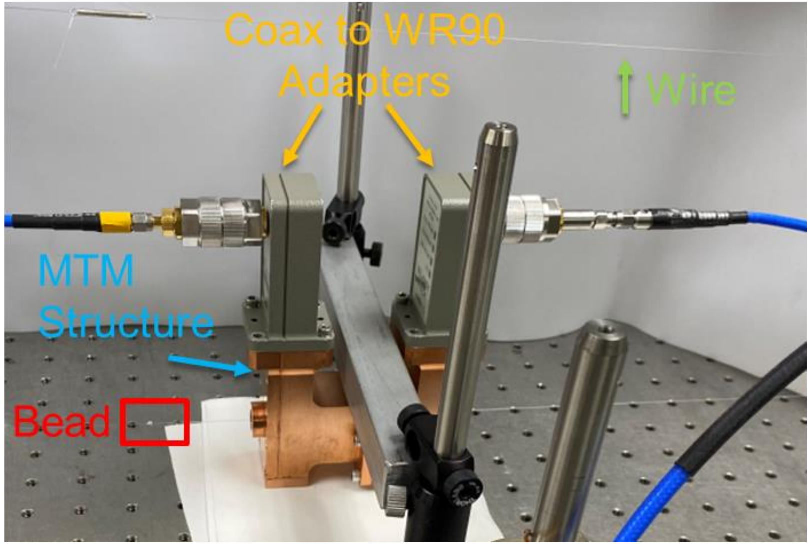




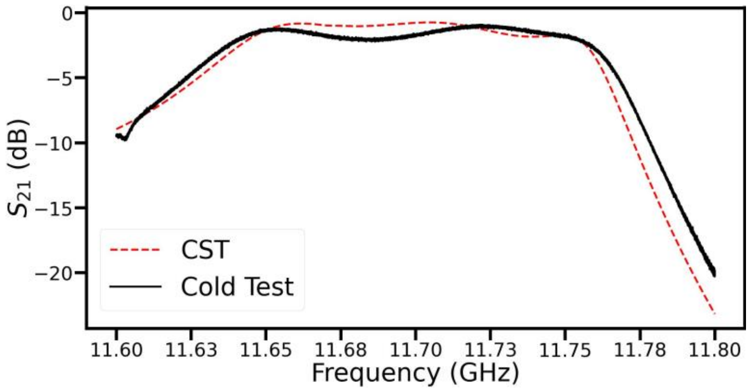
MTM plates electropolished

Cold Test

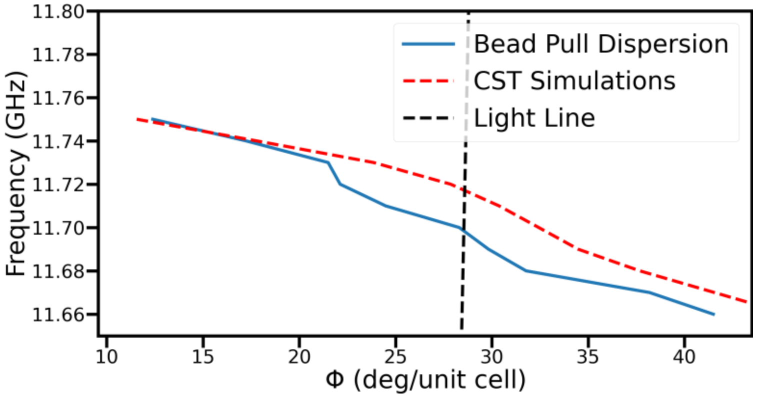
- Good agreement between cold test and simulation
  - S parameters
  - Dispersion relation from bead pull measurement



S_{21} from Cold Test

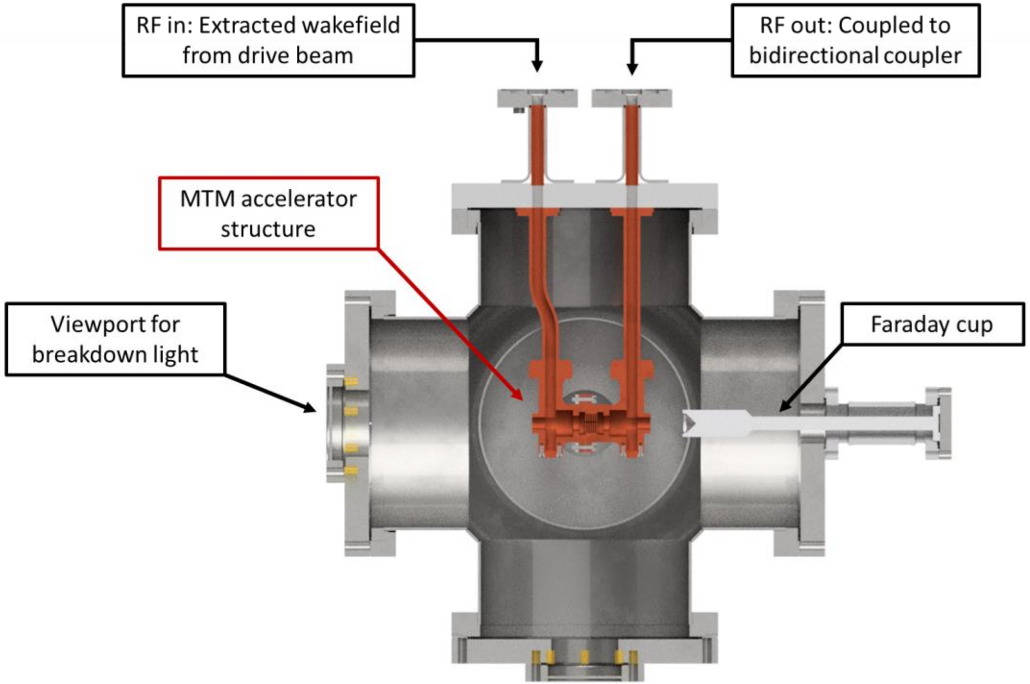


Dispersion Curve from Cold Test



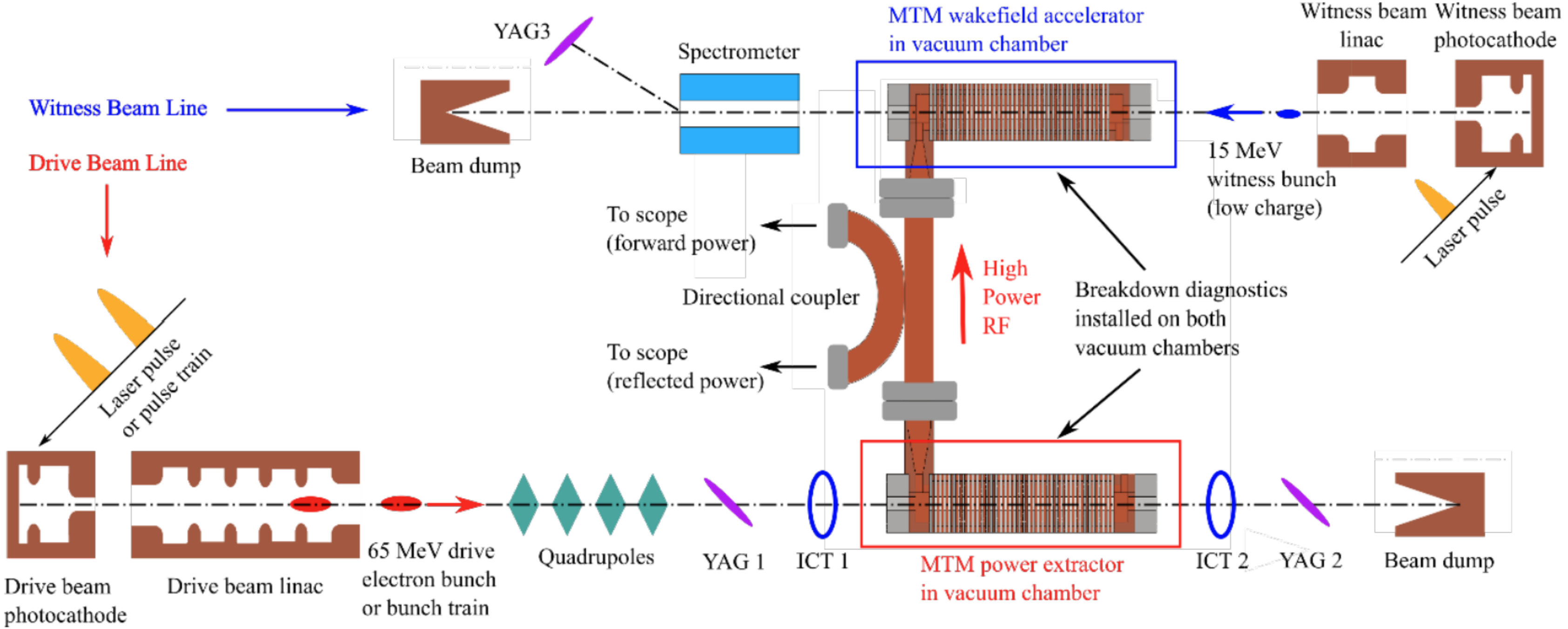
Phase I: Breakdown Test

- Phase I high-power test of the MTM accelerating structure
  - Breakdown diagnostics at high gradients



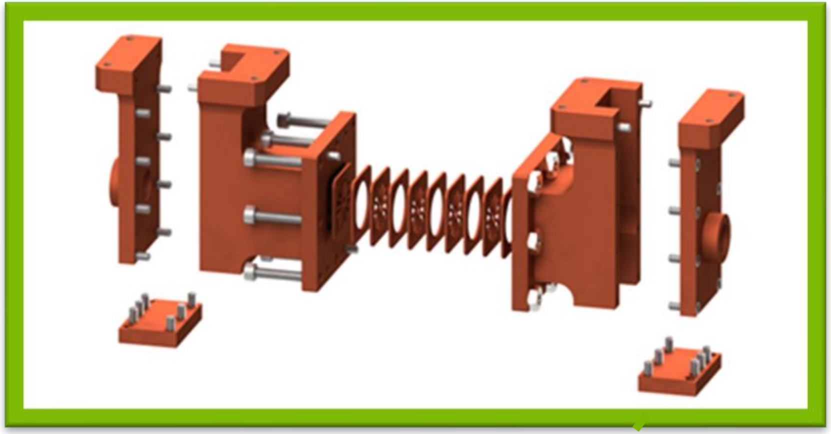
Future: MTMs for Two-Beam Acceleration at AWA

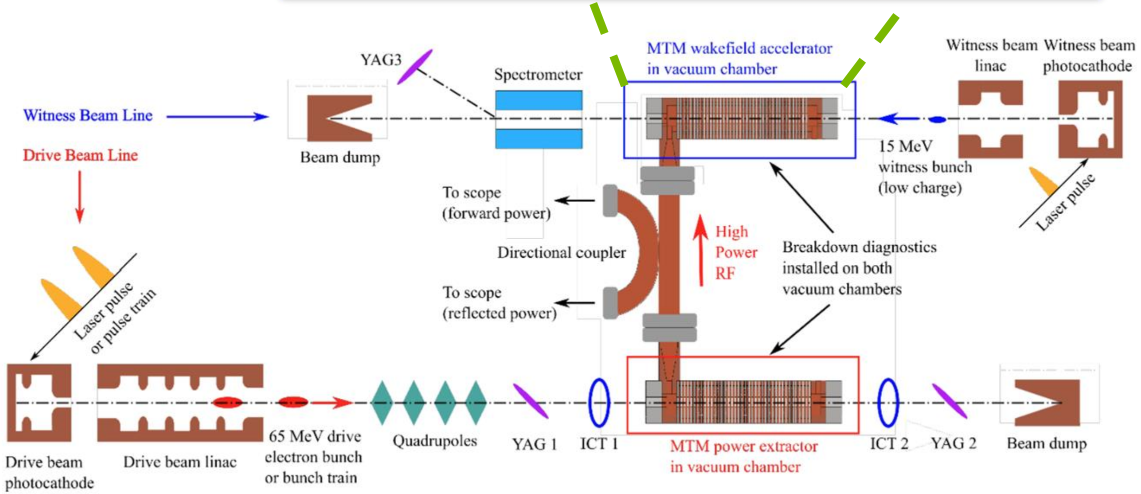
Two MTM structures → One power extracting structure & One accelerator structure



Conclusions

- MTMs show promise as structures for short RF pulse SWFA
  - Mitigate limitations in conventional structures
- An 11.7 GHz MTM accelerating structure designed
  - Expected gradient > 300 MV/m with 500 MW, 3 ns input pulses extracted from a wakefield power extractor
- Structure fabrication and cold test completed
  - Cold test results show good agreement with simulations
- Future
  - High gradient test with breakdown diagnostics at AWA (this year)
  - MTM-based two-beam acceleration demonstration



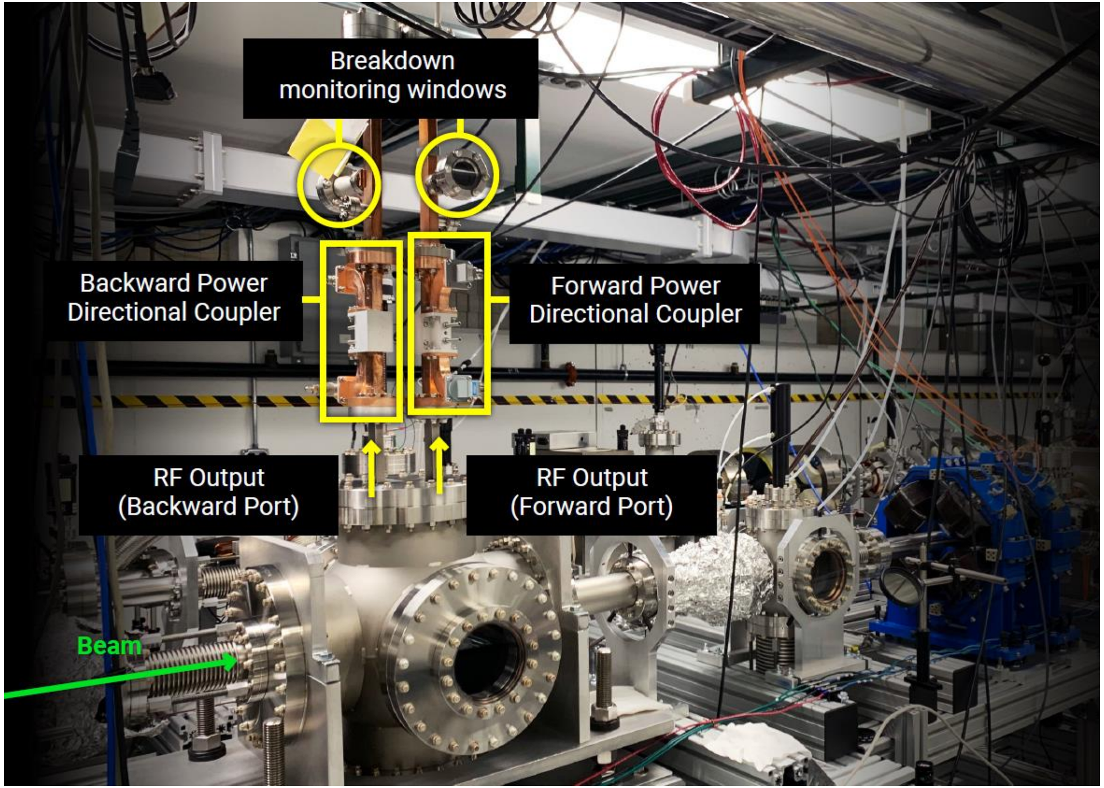


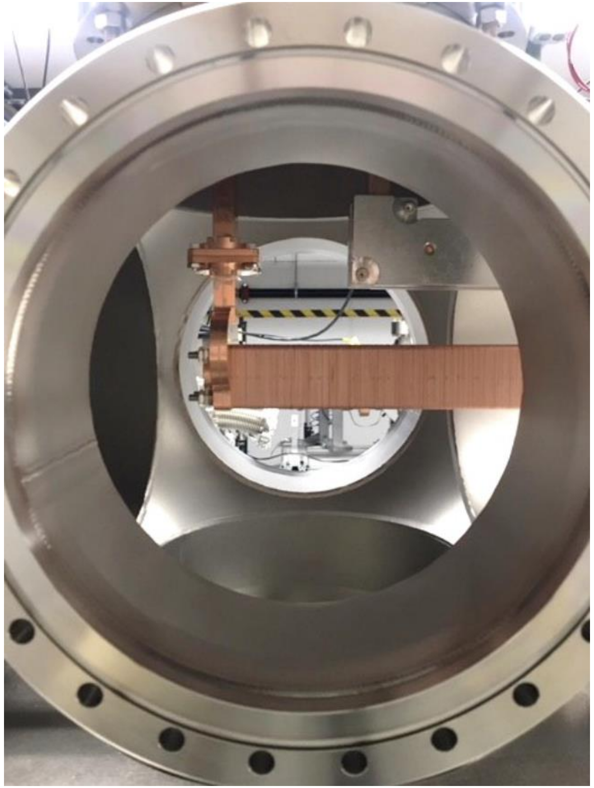
YAG3
Spectrometer
MTM wakefield accelerator
in vacuum chamber
Witness beam
linac
Witness beam
photocathode
Witness Beam Line
Drive Beam Line
Beam dump
15 MeV
witness bunch
(low charge)
Laser pulse
To scope
(forward power)
Directional coupler
High
Power
RF
Breakdown diagnostics
installed on both
vacuum chambers
To scope
(reflected power)
Laser pulse
or pulse train
Drive beam
photocathode
Drive beam linac
65 MeV drive
electron bunch
or bunch train
Quadrupoles
YAG 1
ICT 1
MTM power extractor
in vacuum chamber
ICT 2
YAG 2
Beam dump

Questions?

BACKUP

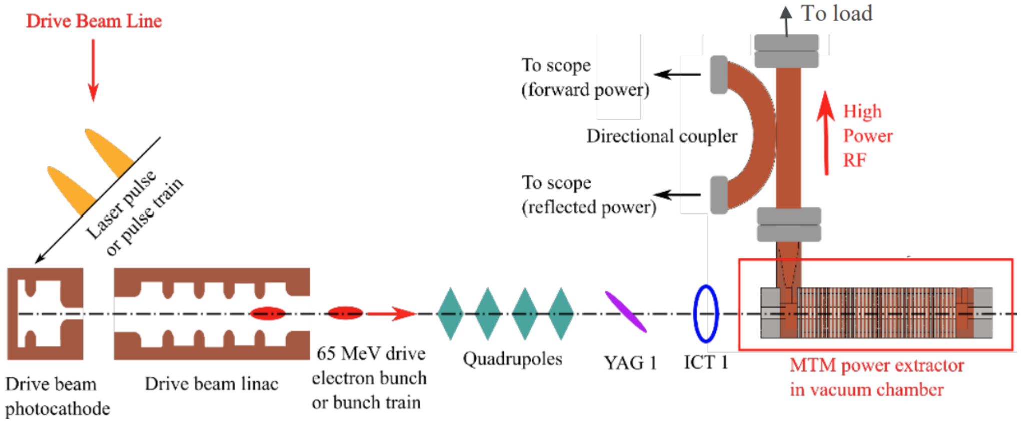
MTM Power Extractors



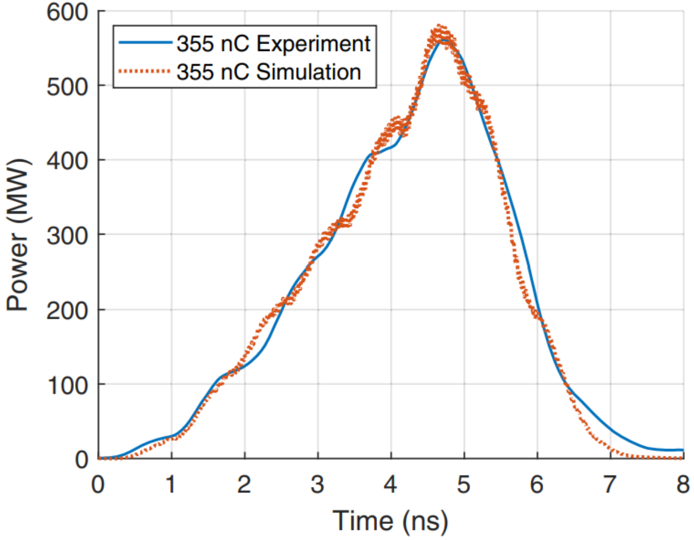


Highest Power Extracted in SWFA

- Series of MTM X-band power extractor experiments starting from 2018
  - Drive beam: 65 MeV, a train of 8 bunches, total charge 355 nC
  - **Highest power: 565 MW** peak power at 11.7 GHz (2021 experiments)



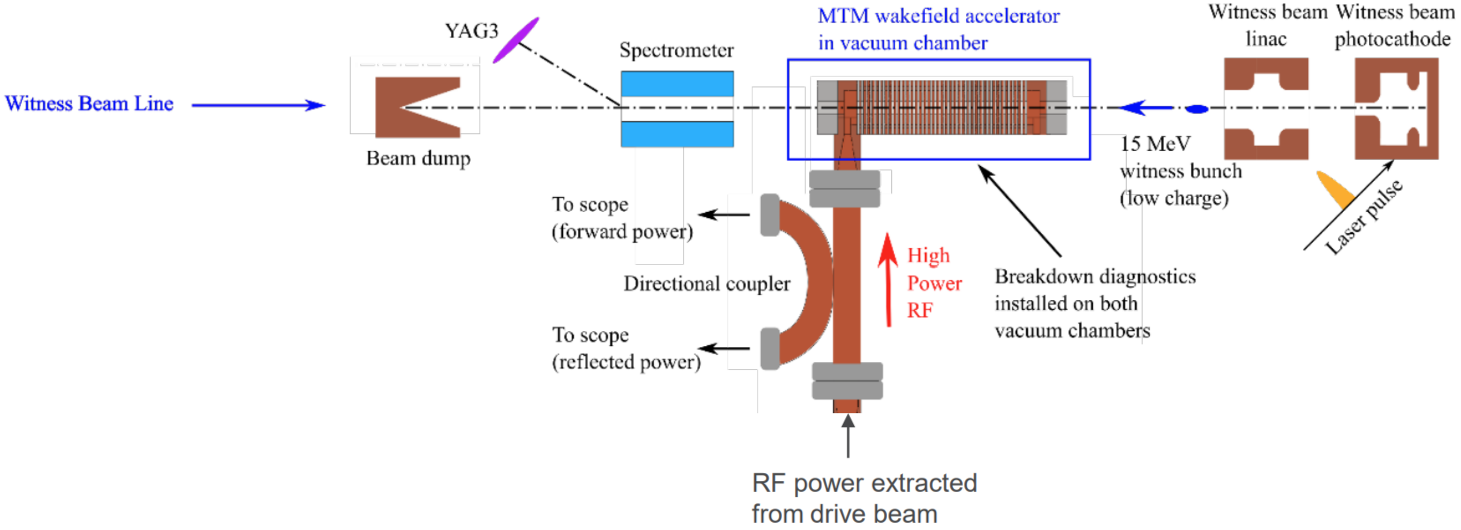
565 MW peak power measured

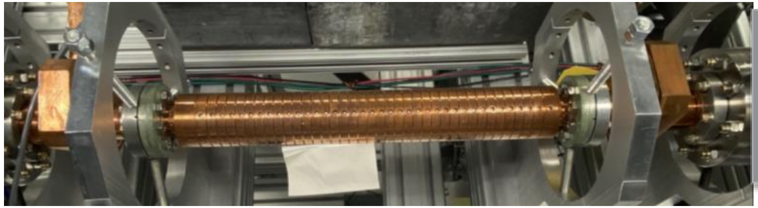


J. Picard, et al., PRAB **25**, 051301 (2022)

MTM Accelerating Structure

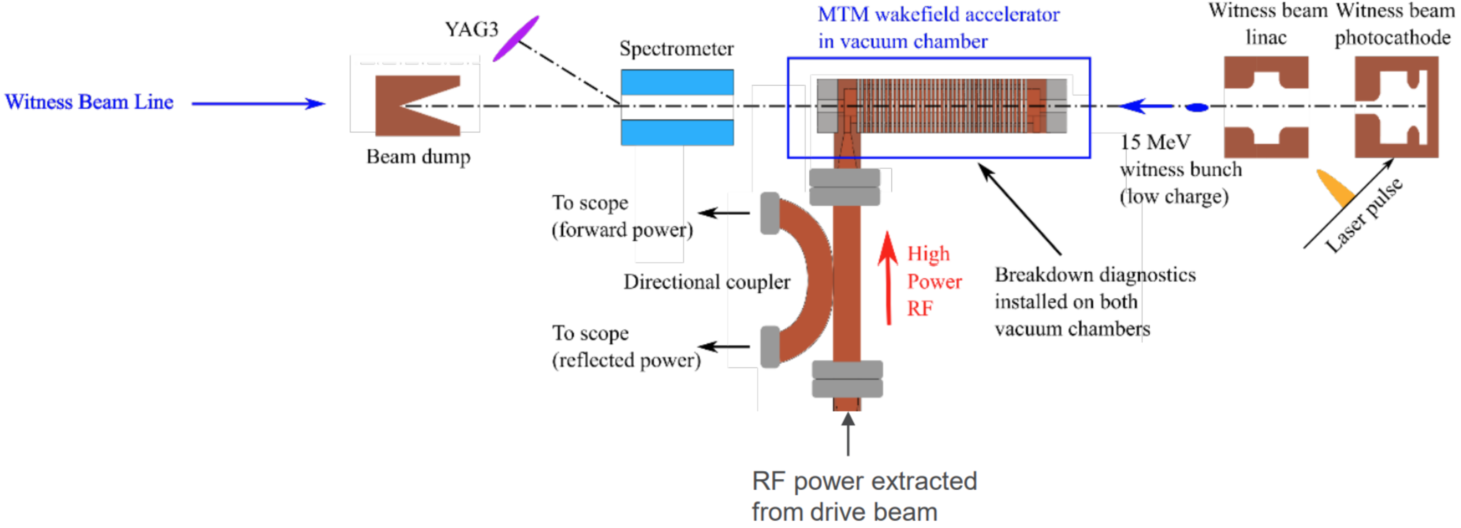
- Design based on output from X-band metallic disk-loaded PETS
  - 500 MW of peak power extracted from a ~500 nC 8-bunch train





Metallic disk-loaded PETS

MTM Accelerating Structure



Future Experiment

- Phase I high-power test of the MTM accelerating structure
  - Breakdown diagnostics at high gradients
  - No witness beam in structure in the coming Phase I experiment
- Longer-term future experiment:
  - Full demonstration: MTM-based TBA