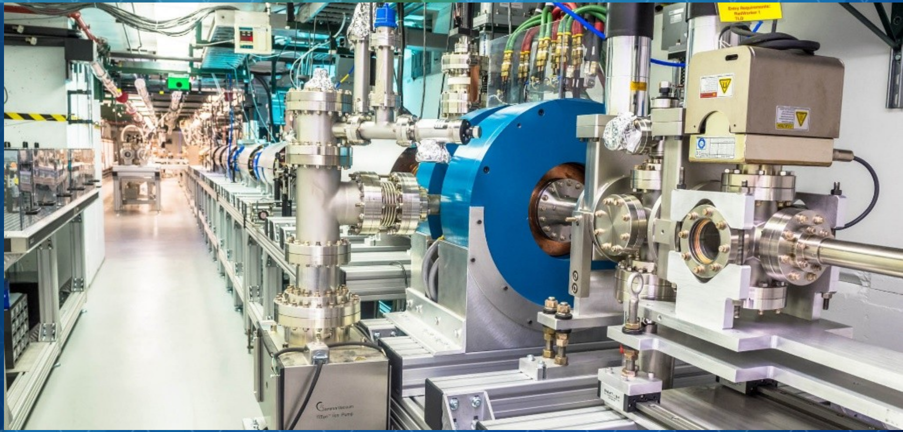
AAC 2024

BREAKDOWN INSENSITIVE ACCELERATION REGIME IN A METAMATERIAL ACCELERATING STRUCTURE



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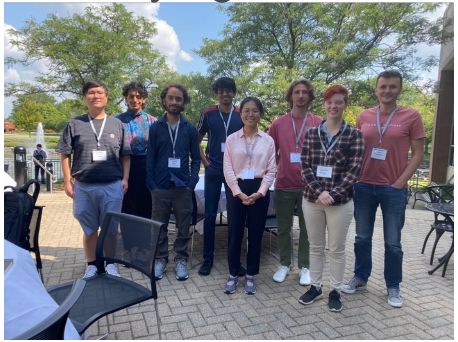

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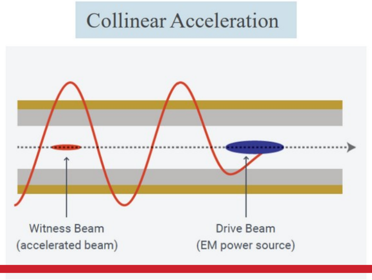
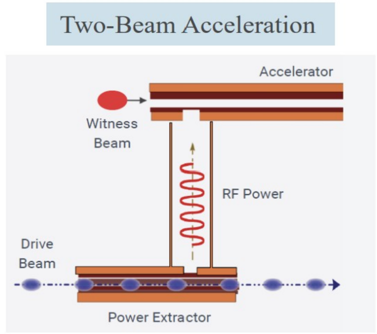
Overview

- Background
  - Structure Wakefield Acceleration (**SWFA**)
  - Metamaterials (**MTMs**) for **SWFA**
- Structure Design
- Experimental Setup
- Experimental Results
  - RF Statistics and the breakdown insensitive acceleration regime (BIAR)
  - Dark Current Assessment
- Future Plans
- Conclusion

Structure Wakefield Acceleration (SWFA)

- Structure-based wakefield acceleration
  - Power is extracted from a **drive** bunch to accelerate a **witness** bunch
  - **Two-beam acceleration** vs collinear acceleration
- Short-pulse extracted → Higher gradients
  - RF breakdown rate (BDR) ~ $E^{30}\ tpulse^{5}$
    - Short (ns) RF pulses → lower BDR





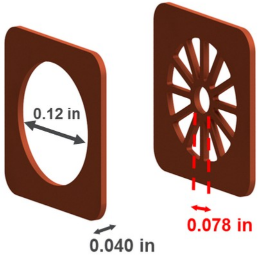
Metamaterials (MTMs) for SWFA

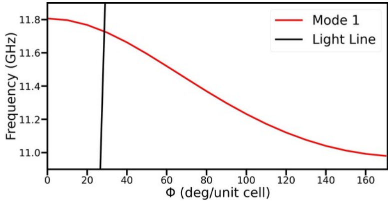
- Metamaterial (MTM)
  - Engineered material with sub-wavelength features that gives rise exotic EM properties
  - Example class: double negative MTMs: $\varepsilon, \mu < 0$
- SWFA requirements:
  - High gradients/shunt impedance (recall our empirical scaling law)
  - Short fill times (high group velocity)
- MTMs with negative group velocities (double negative MTMs):
  - Mitigates group velocity-shunt impedance trade-off
  - Large parameter space → customizeable EM properties

MTM Accelerator Design

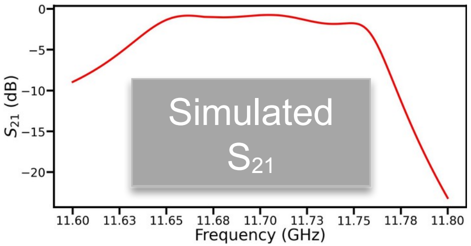
- Unit cell
  - Cell period = 0.04” (2mm) << RF wavelength (11.7GHz)
- Full structure
  - 6 unit cells with WR-90 couplers
  - Short input – large bandwidth pulse

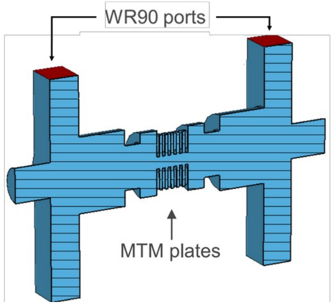
Unit cell and corresponding TM_{01}-like mode dispersion curve



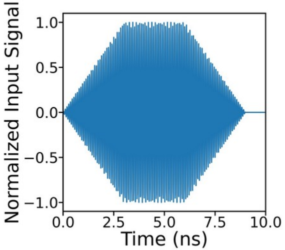


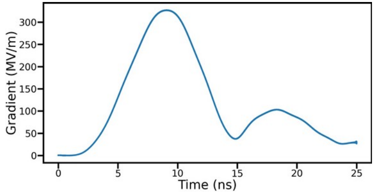
Full structure vacuum



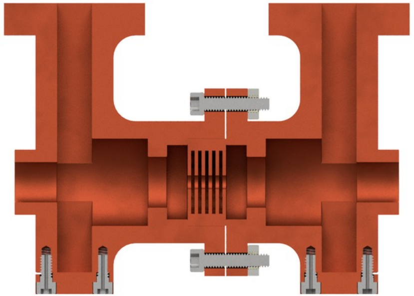


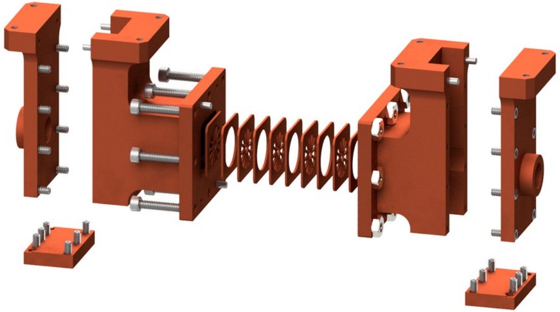
RF input and associated gradient for 200MW peak power

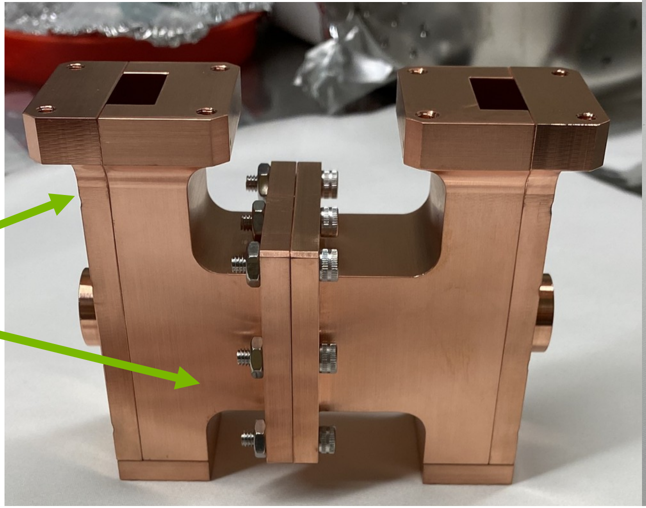


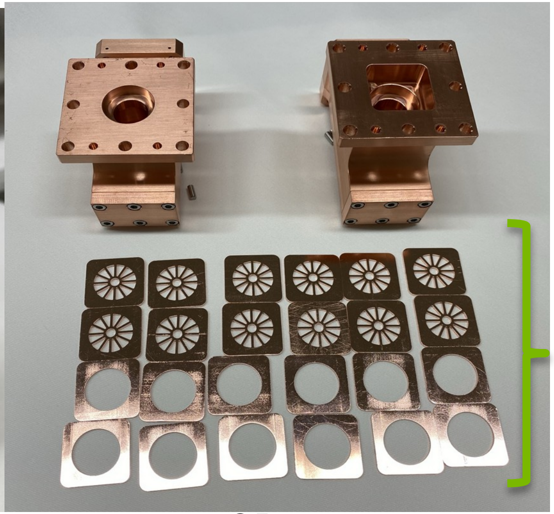


Mechanical Design and Structure Fabrication









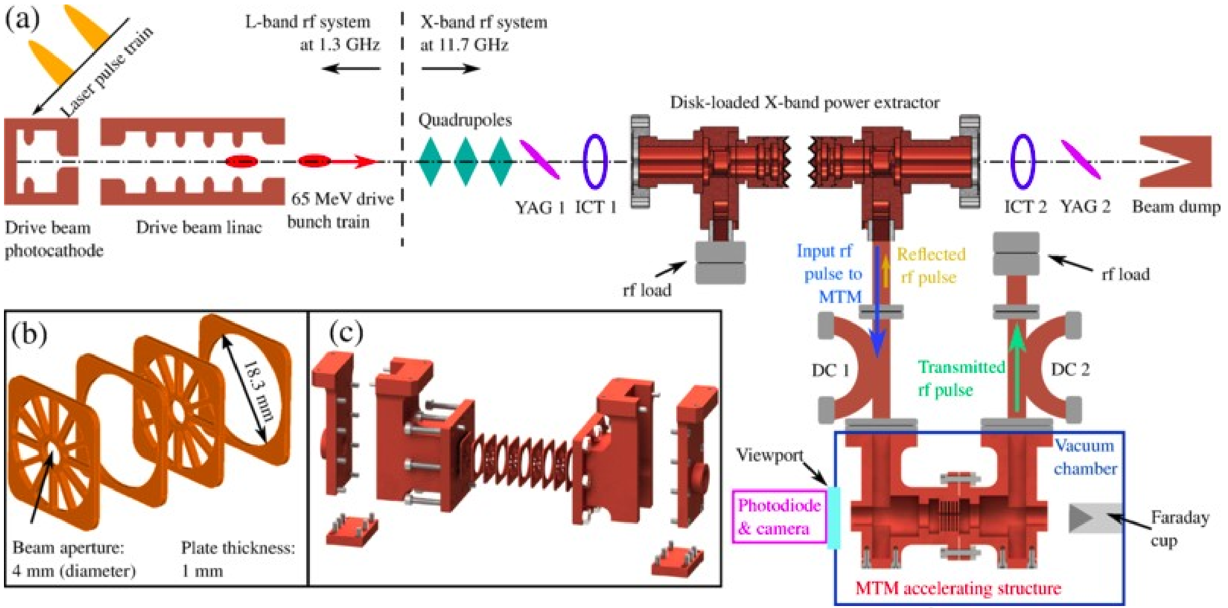
Brazeless structure

- 6 unit cells

MTM plates electropolished

High-power Experiment Setup

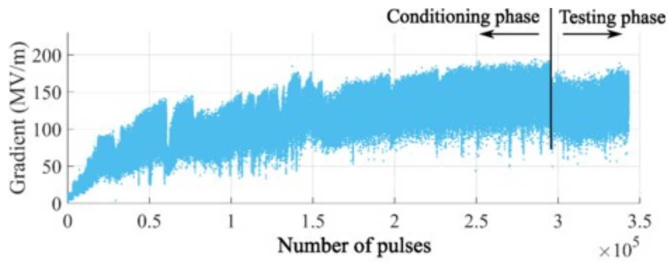
- No witness beam
- Diagnostics: Forward/Reflected RF signals, Faraday cup signal, and photodiode



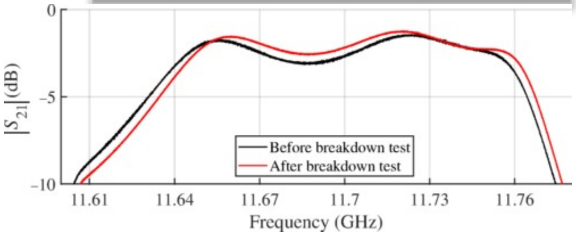
Experimental Results
Histories and Sample RF

- More than 3x10^5 shots
- RF transmission improved over conditioning period
- Diagnostics: RF signal strong agreement with expected

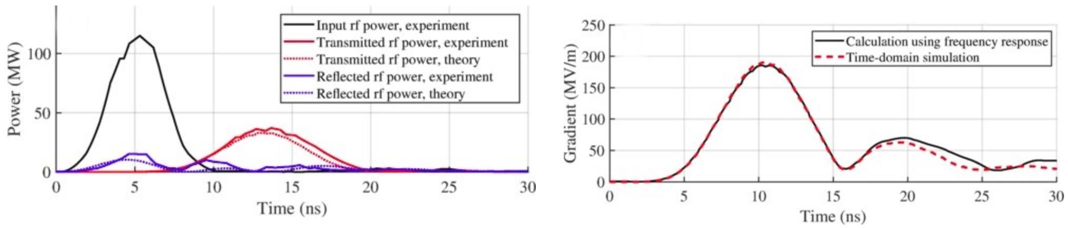
RF histories



Improved transmission



Sample RF diagnostics and theoretical calculations

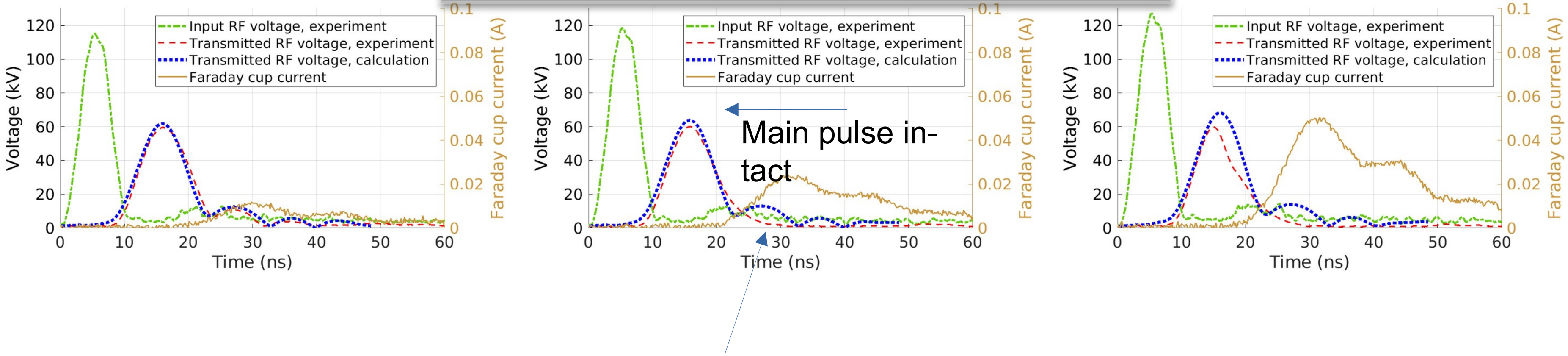


Experimental Results

The Breakdown Insensitive Acceleration Regime (BIAR)

- BIAR associated with lower gradients (events happen in secondary pulses)

RF Sample pulses for non-BD, BIAR, BD events



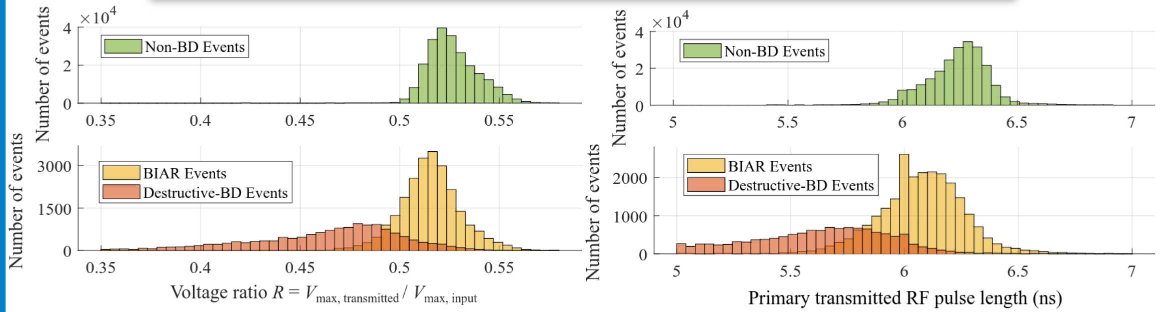
Secondary pulse deformed

Experimental Results

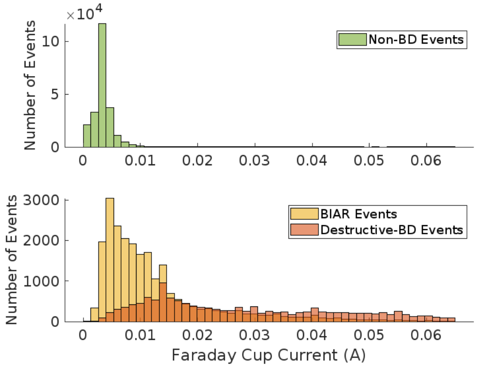
RF Statistics

- Similar RF statistics to non breakdown event
- BIAR dark current behavior differs from breakdown events

RF Binned Statistics

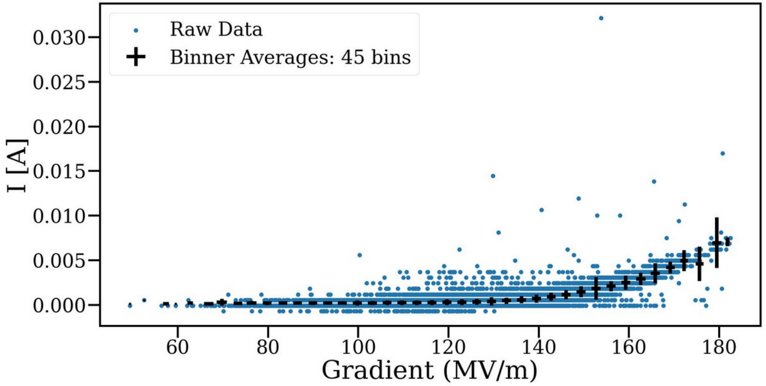


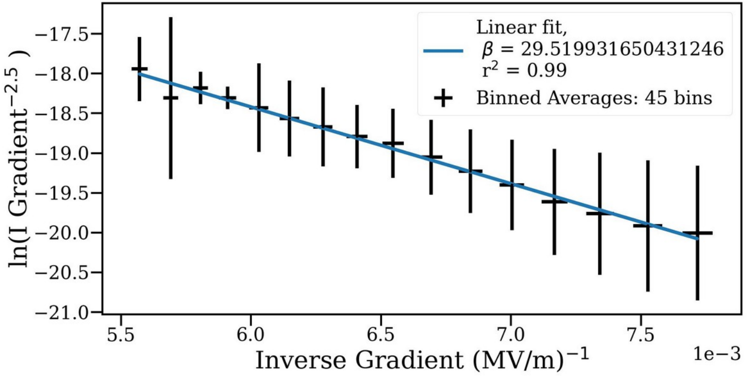
Faraday Cup binned statistics



Dark current for non-breakdown events

- Assumed Fowler-Nordheim emission mechanism
- Data binning required (shot to shot variation)
  - Fitted enhancement factor (FEF) ranging between 28 and 35 depending on number of bins
  - FEF agrees with associated emitter size → similar length scales to damages in post-run imaging)





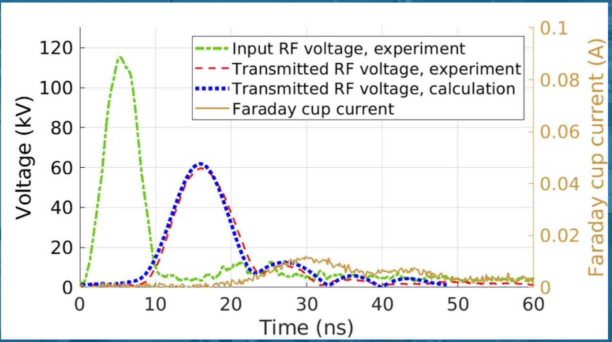
Conclusions

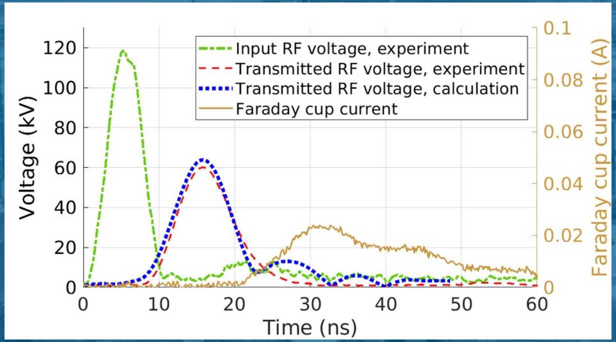
- A high power test using a metamaterial accelerating structure in an SWFA scheme was conducted at Argonne Wakefield Accelerator
- The BIAR was observed where the corresponding RF statistics are similar to the desired non-breakdown case
- BIAR dark currents do not align with breakdown events
- Multipacting associated with lower gradients → could be cause of BIAR secondary pulse deformation
- Short pulse duration may be a contributing factor to BIAR process
  - accelerating gradient has increased rate of change → less time for multipacting too fully develop to full breakdown event

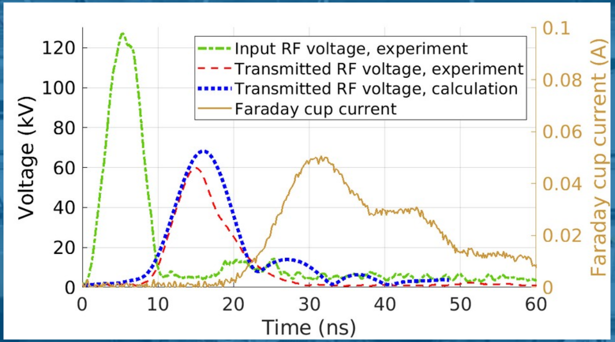
Future Plans

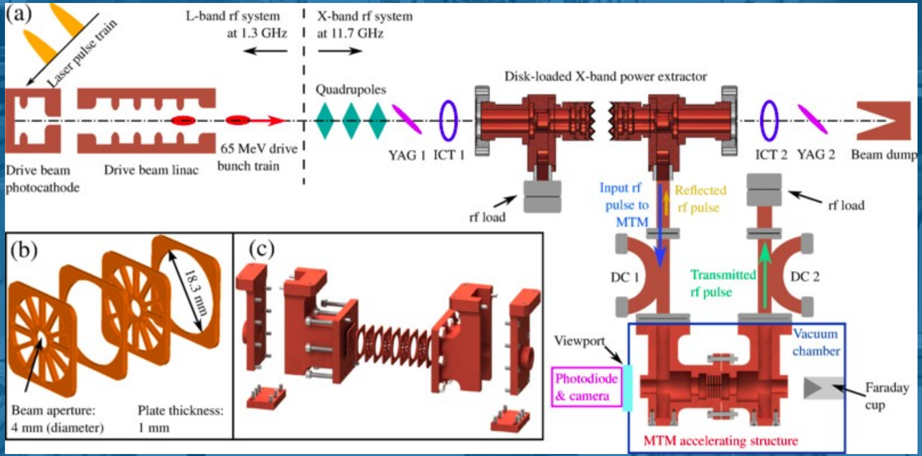
- **Experimental Runs**
- A future experimental run with more complete diagnostics may be useful for understanding BIAR
- Investigate the intended two-bream acceleration using a MTM power extractor to drive the accelerator
- **Modify designs**
- Explore modifications to metamaterial plates to improve figures of merit (group velocity, shunt impedance, etc.)

QUESTIONS?









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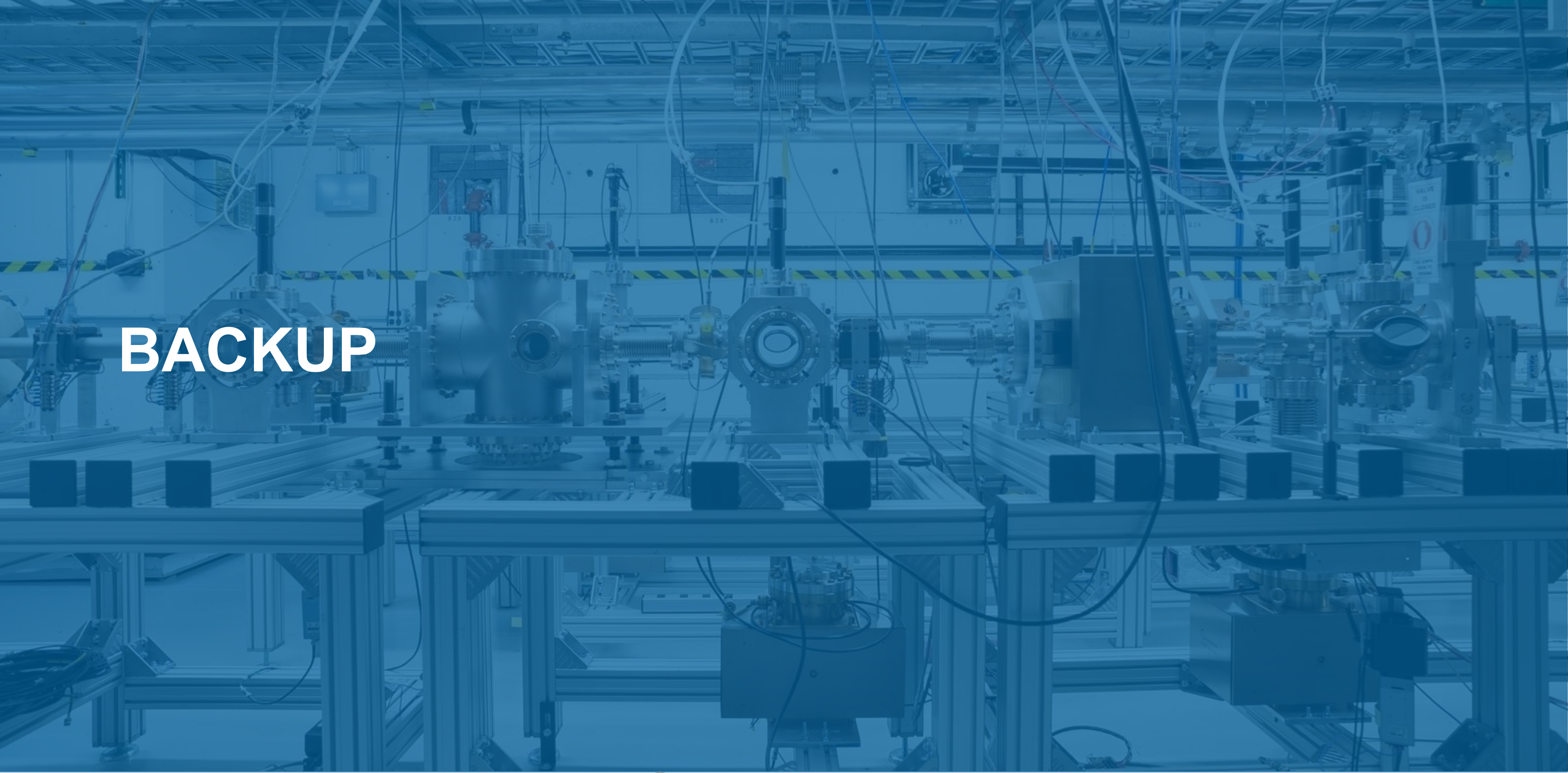
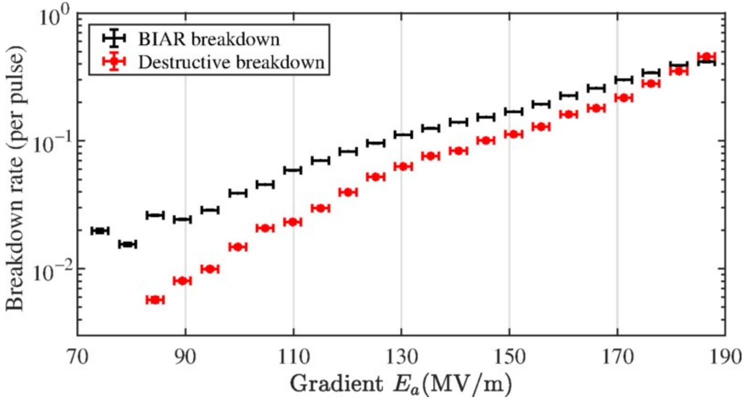
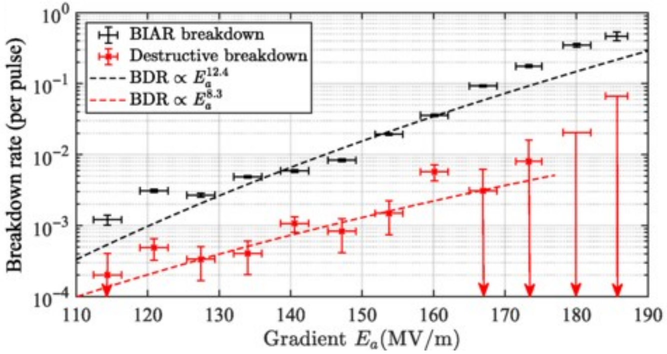
BACKUP

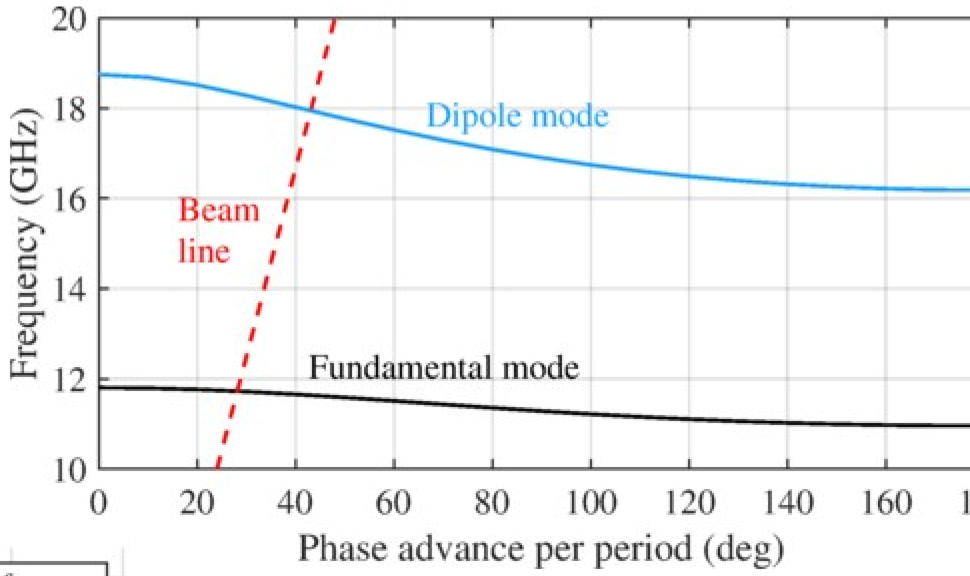


BDRs

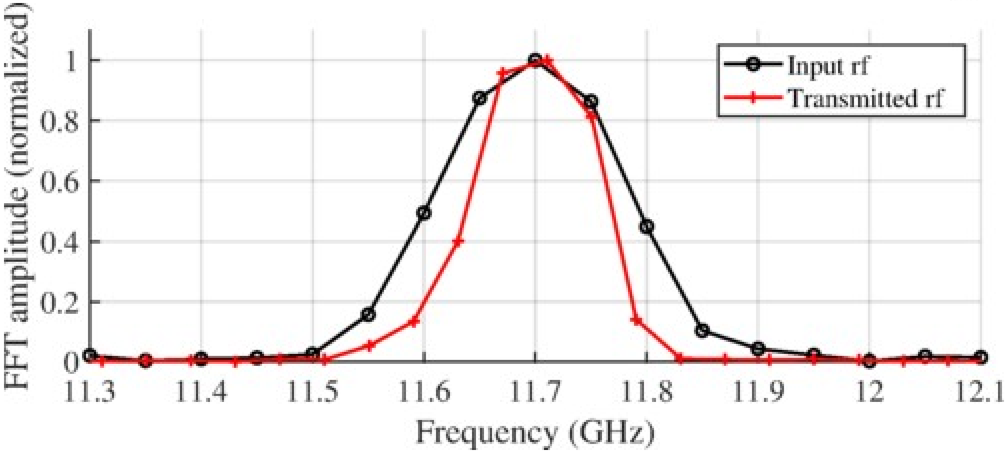

BIAR breakdown
Destructive breakdown
Breakdown rate (per pulse)
Gradient E_a(MV/m)


BIAR breakdown
Destructive breakdown
BDR ∝ $E_a^{12.4}$
BDR ∝ $E_a^{8.3}$
Breakdown rate (per pulse)
Gradient E_a(MV/m)

Design Info



Frequency (GHz)
Phase advance per period (deg)
Dipole mode
Beam line
Fundamental mode



FFT amplitude (normalized)
Frequency (GHz)
Input rf
Transmitted rf