Generating 510 MW of X-Band Power for Structure-Based Wakefield Acceleration Using a Metamaterial-based Power Extractor

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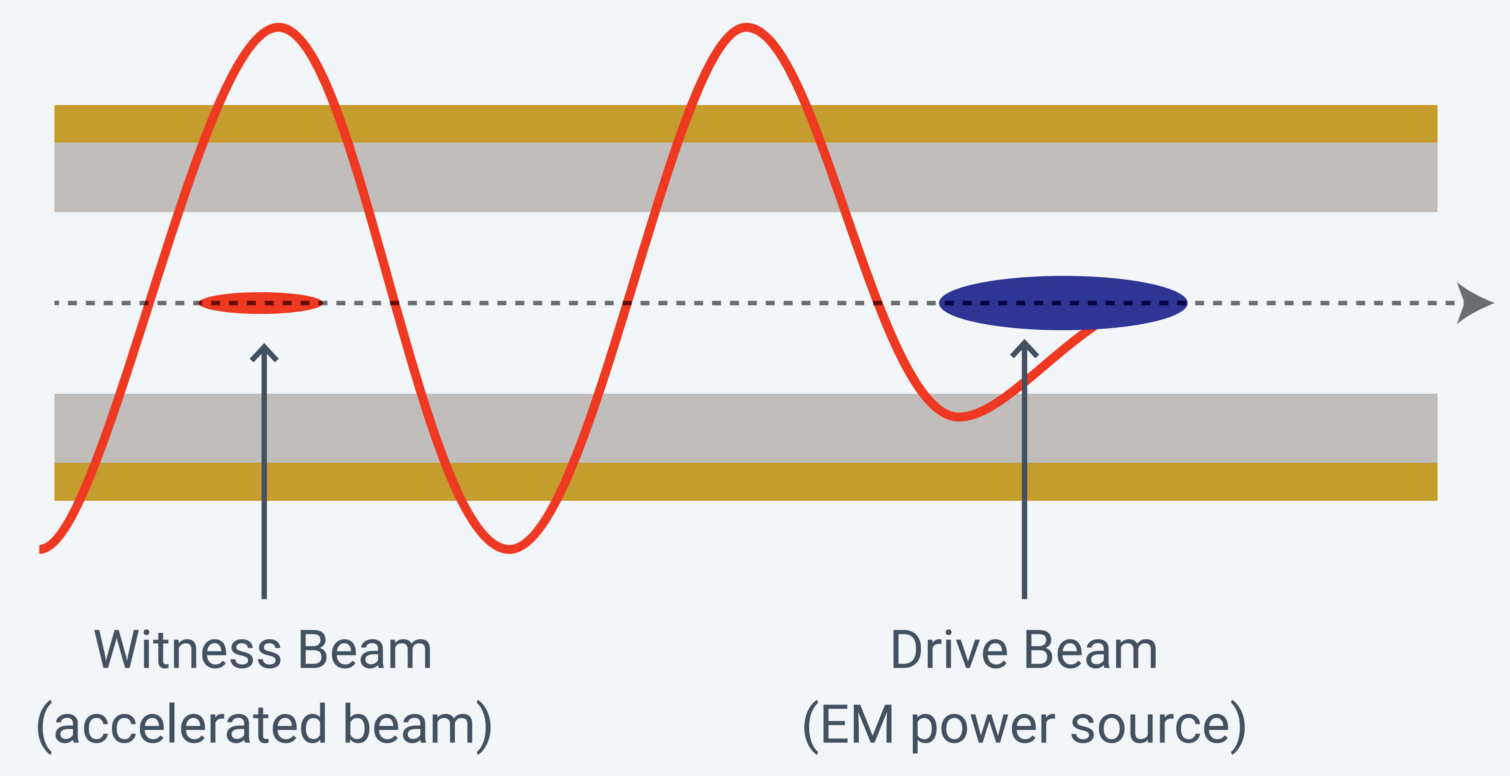
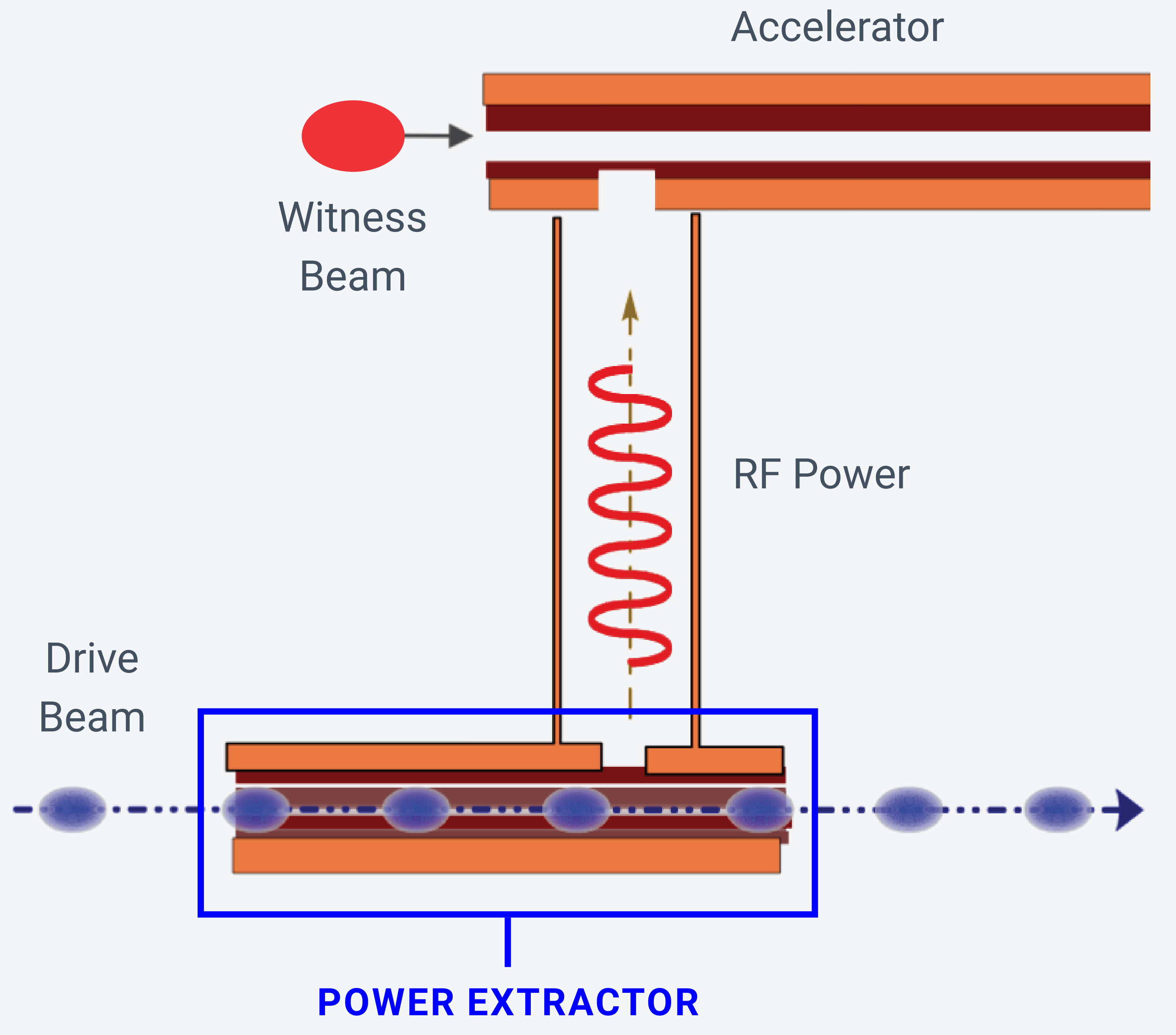
Power Extractors for Wakefield Accelerators

- There are two methods of wakefield acceleration: **Collinear Acceleration** and **Two-Beam Acceleration**.
- Both operate by using the wakefield of a high-charge "drive" beam to accelerate a low-charge "witness" beam.
- In the case of Two-Beam Acceleration, a separate, dedicated, structure is responsible for efficiently extracting power from the drive bunch: a **power extractor**.
- This work focuses on our recent efforts to optimize a power extractor design using metamaterials.



Collinear acceleration scheme



Two-beam acceleration scheme

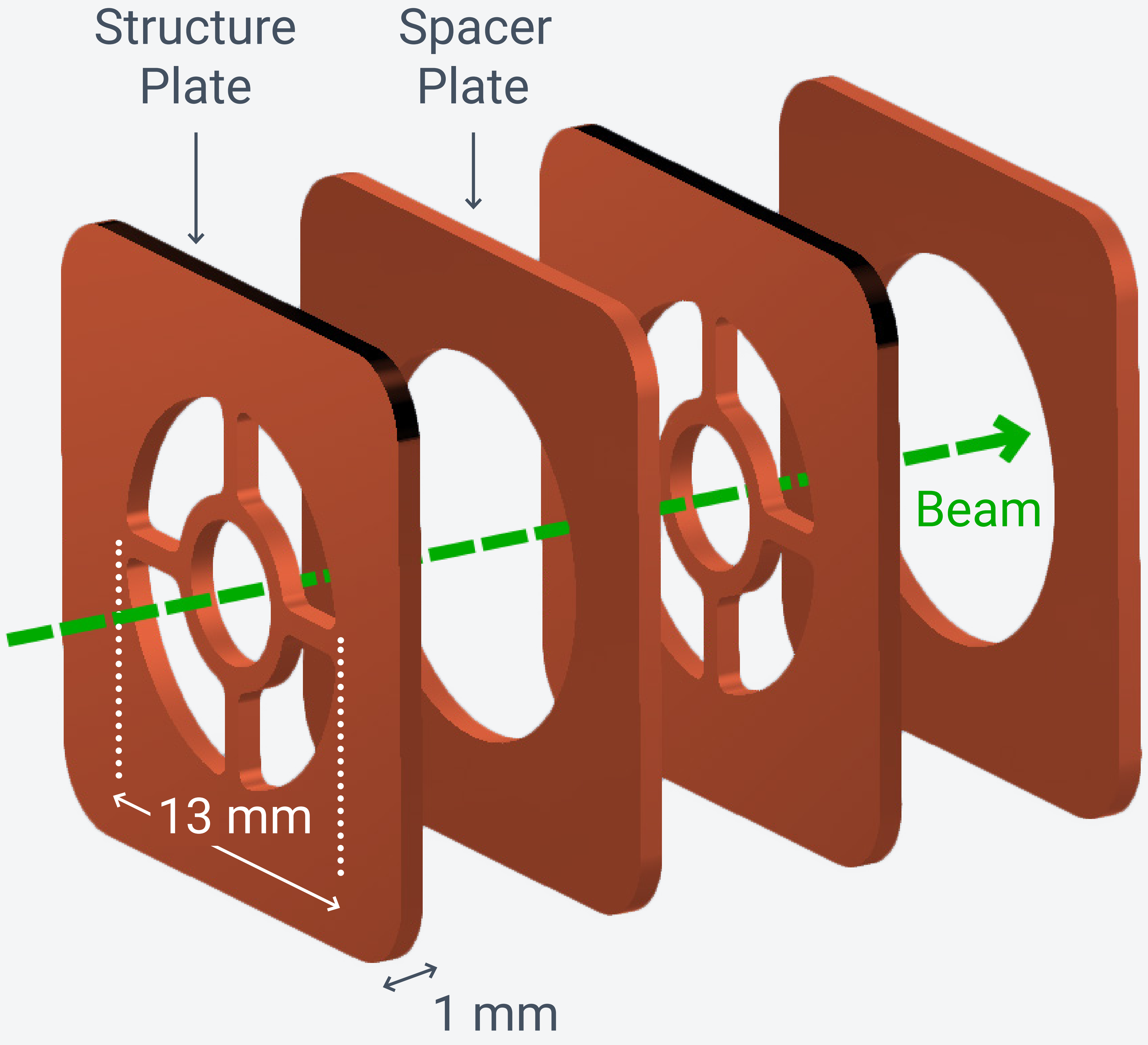
What are Metamaterials?

- Metamaterials are materials constructed from arrays of sub-wavelength components (dimensions << λ), such that light sees a homogeneous medium.
- Unit cells can be tailored such that the macroscopic material exhibits exotic properties not found in nature.
- Some metamaterials, double-negative materials, have a simultaneously $\varepsilon,\mu < 0$. These materials exhibit negative refraction, and charges radiate backwards as *Reverse Cherenkov Radiation*

Classic “split ring” metamaterial

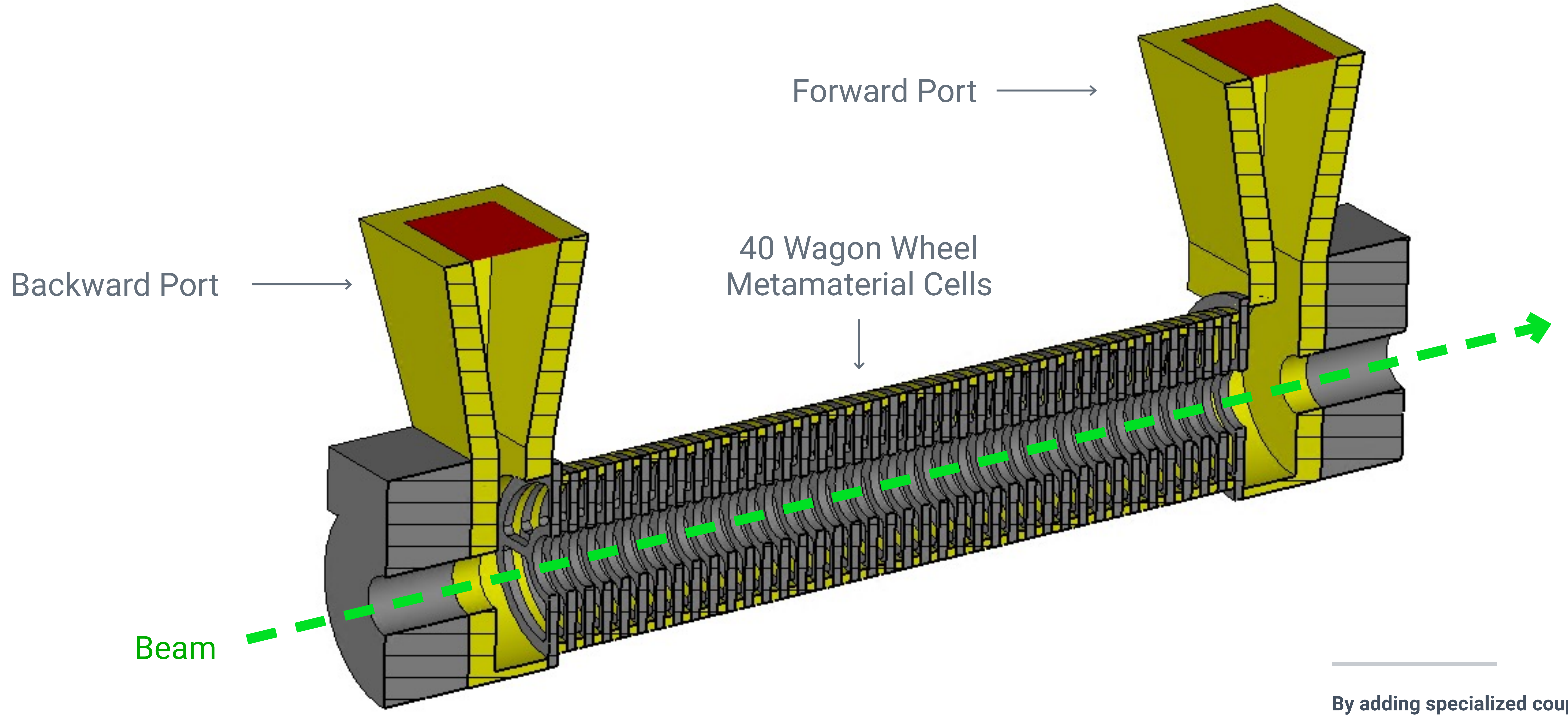
Applying Metamaterials to Power Extractor Design

- By constructing a power extractor from a metamaterial, we can extract energy from a beam via *Reverse Cherenkov Radiation*.
- MIT has created a custom metamaterial, the wagon wheel metamaterial, in which alternating structure and spacer plates produce effective $\varepsilon, \mu < 0$
- Charge passing through the resulting metamaterial radiates in the backward direction with $v_g < 0$ and $v_{ph} > 0$



Exploded view of two "wagon wheel" metamaterial cells

Couplers Enable Power Extraction

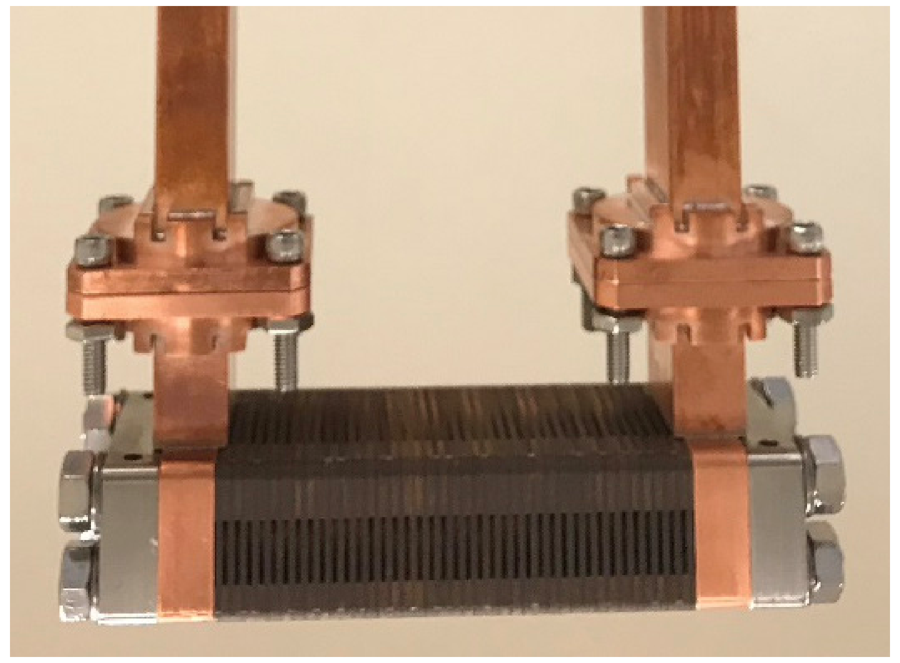


By adding specialized couplers onto each end of the metamaterial cells, the power generated from the electron bunches can be coupled into waveguides.

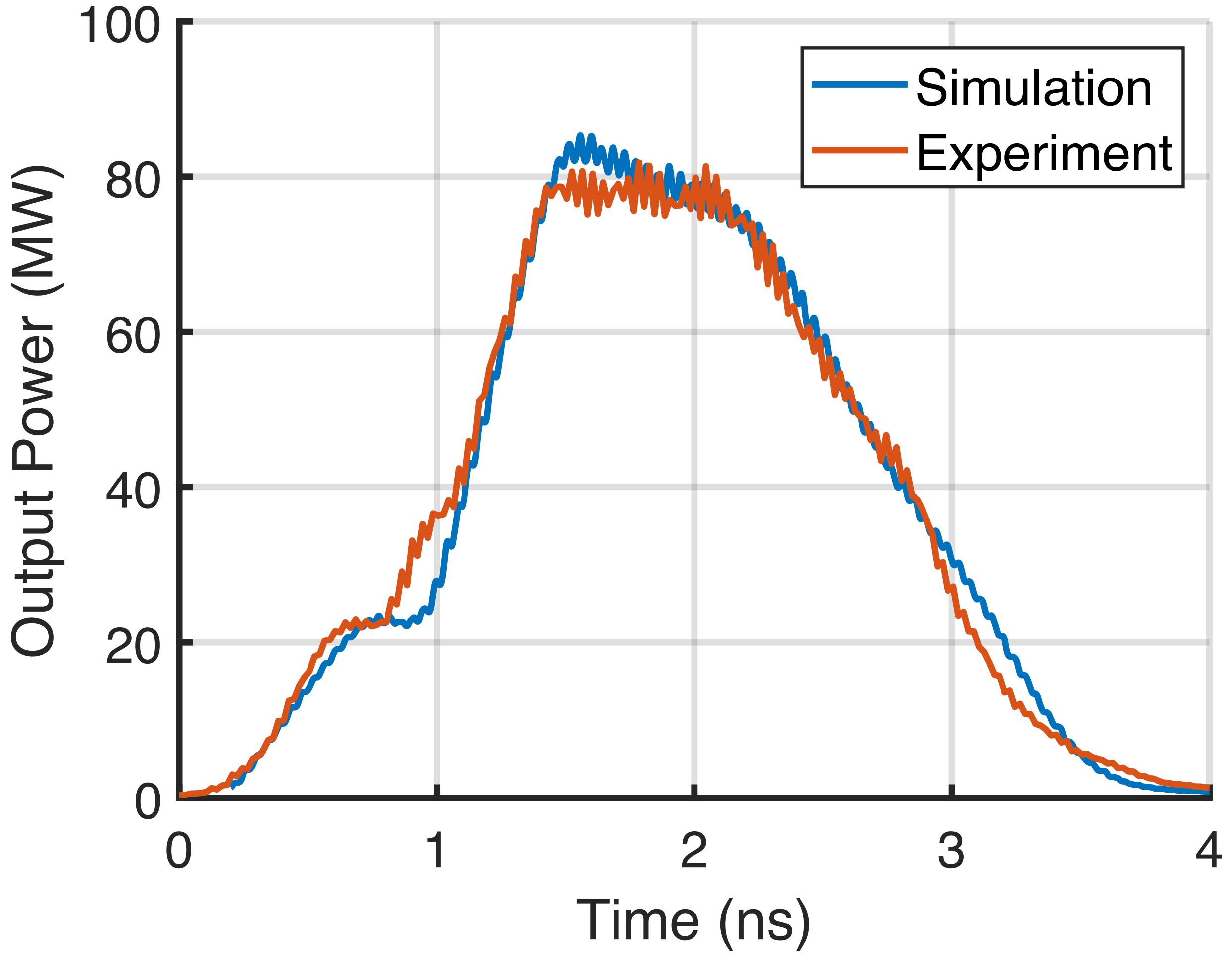
Previous Experimental Results

Two iterations of power extractors based on the wagon wheel metamaterial have been tested with the 65 MeV electron beam at the Argonne Wakefield Accelerator.

STAGE 1 (2018)

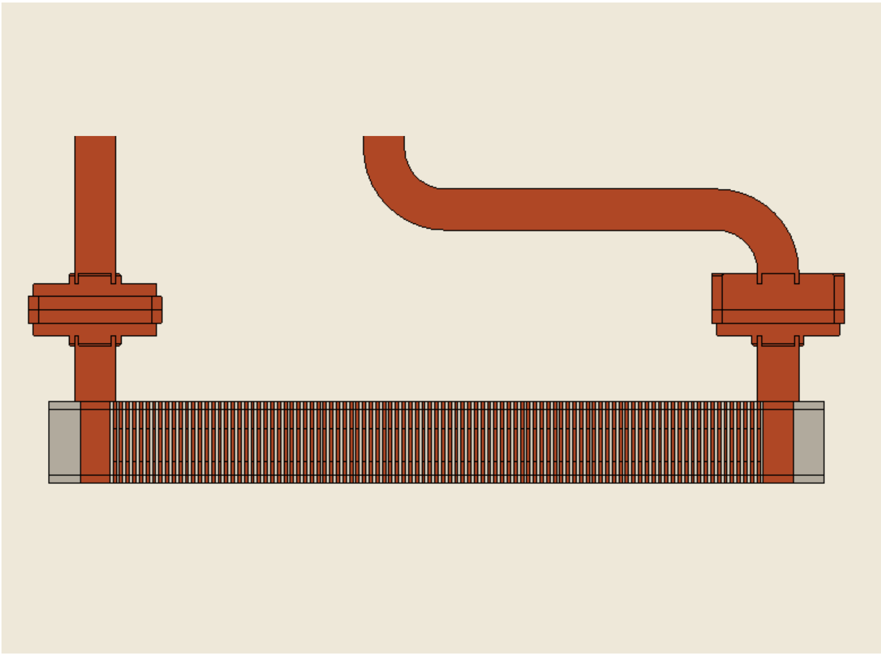


40 metamaterial cells
2 bunches
80 MW output power at 11.4 GHz

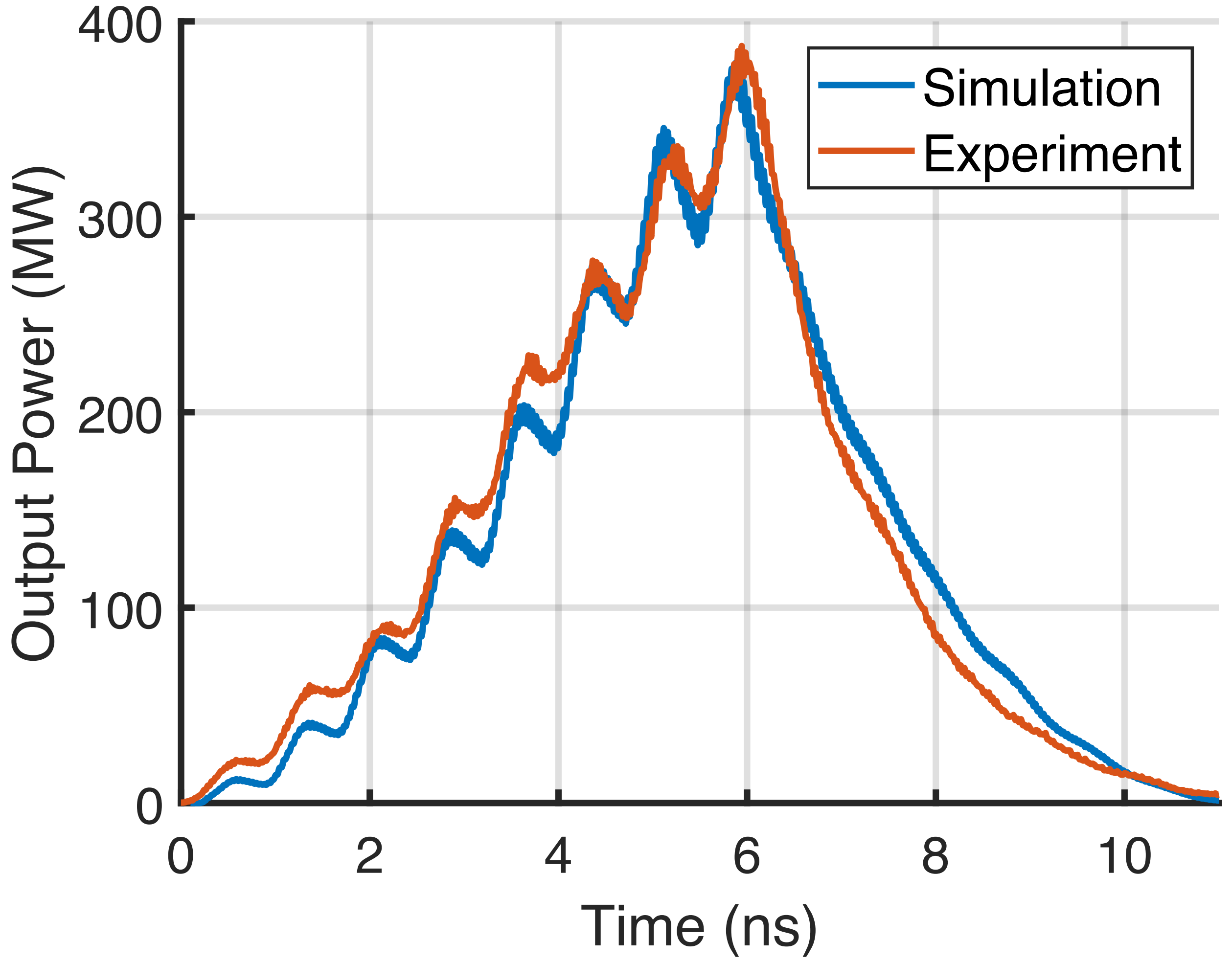


X Lu, J Picard, et al. Physical Review Letters, 122, 014801 (2019)

STAGE 2 (2019)



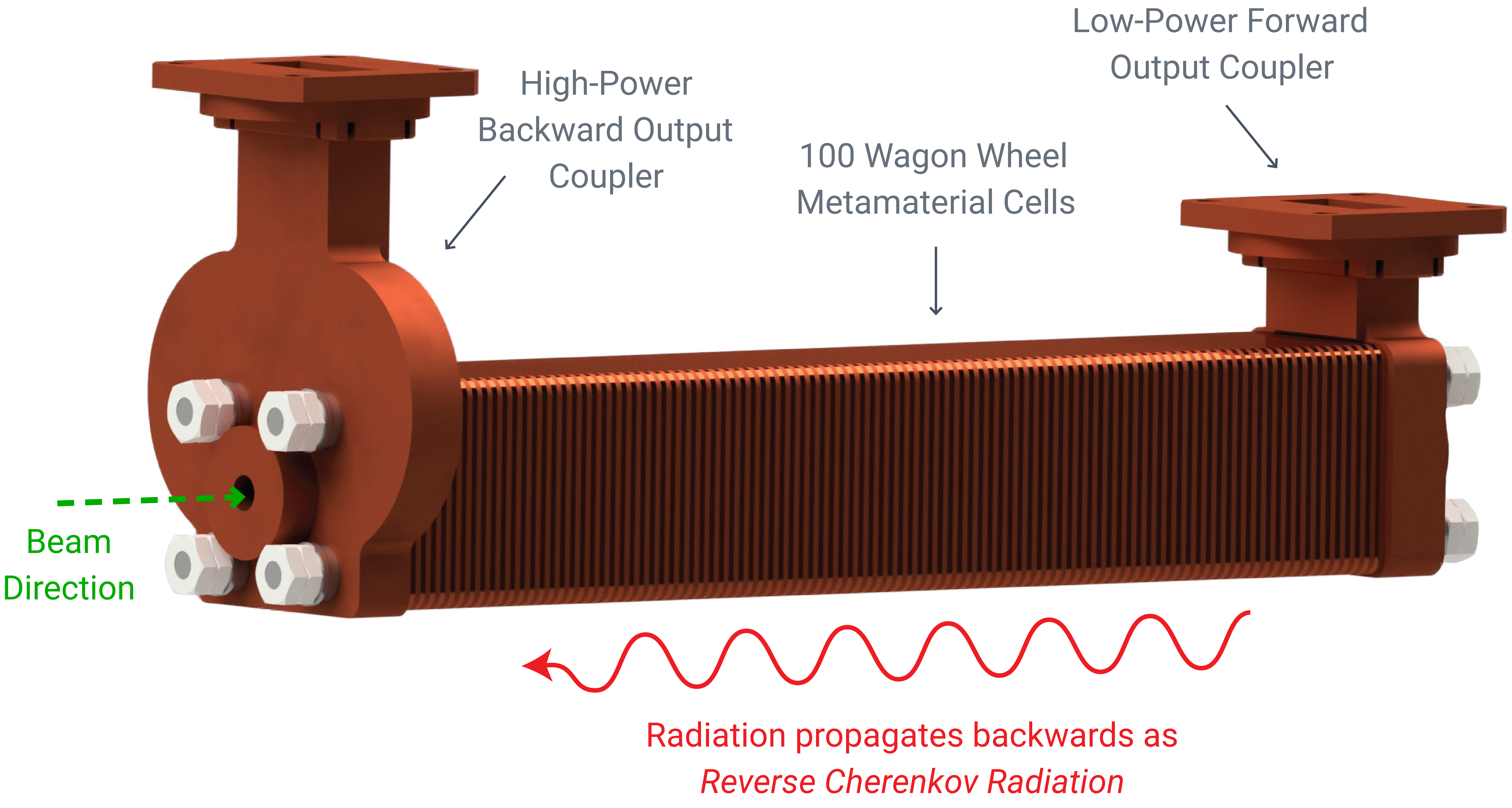
100 metamaterial cells
8 bunches
380 MW output power at 11.7 GHz



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

Stage 3 Experimental Design

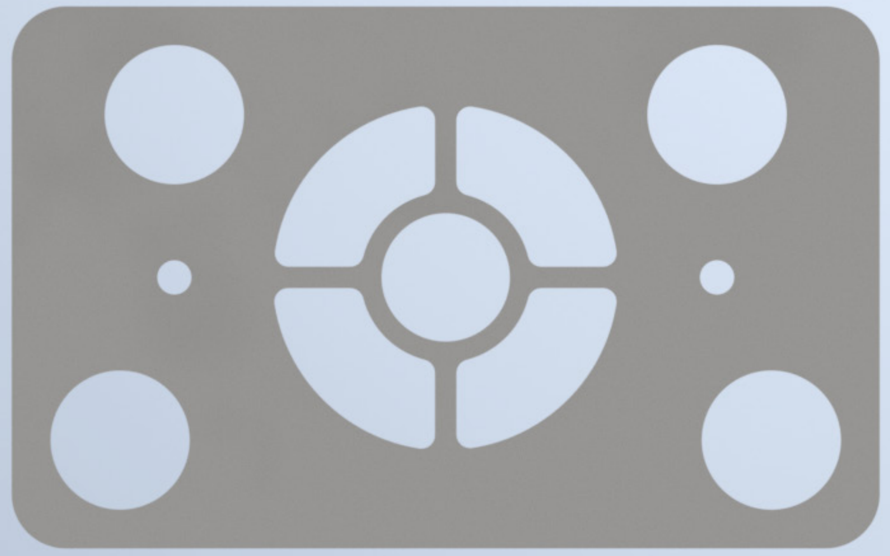
Based on our Stage 1 and 2 experience, we have designed a new structure with improvements to dramatically increase extractor performance.



STAGE 3 DESIGN IMPROVEMENTS

+ All-copper construction
+ Symmetric high-power output coupler design
+ Treatment of plates to mitigate breakdown risk

STAGES 1 & 2

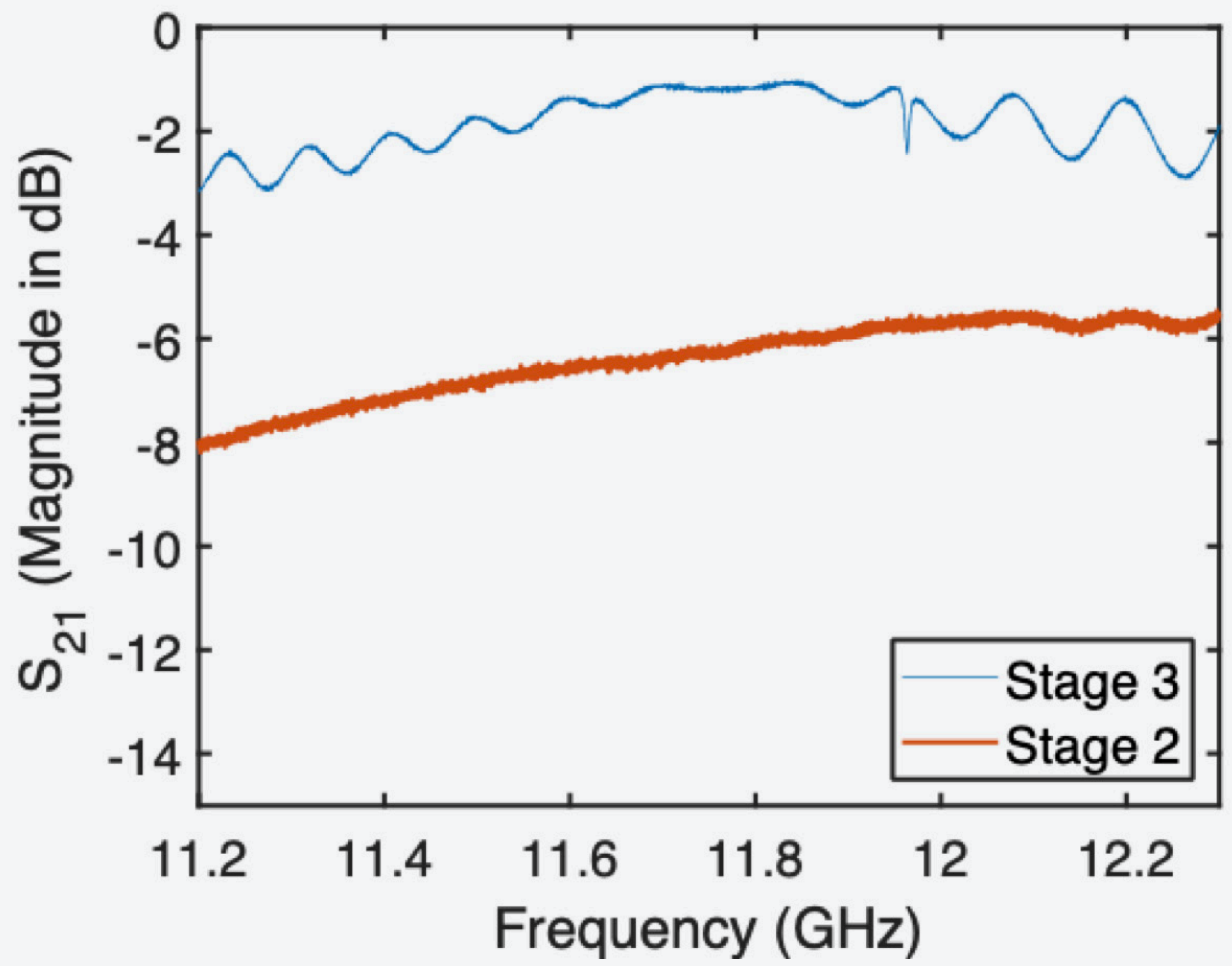


Stainless Steel

STAGE 3

OFHC Copper

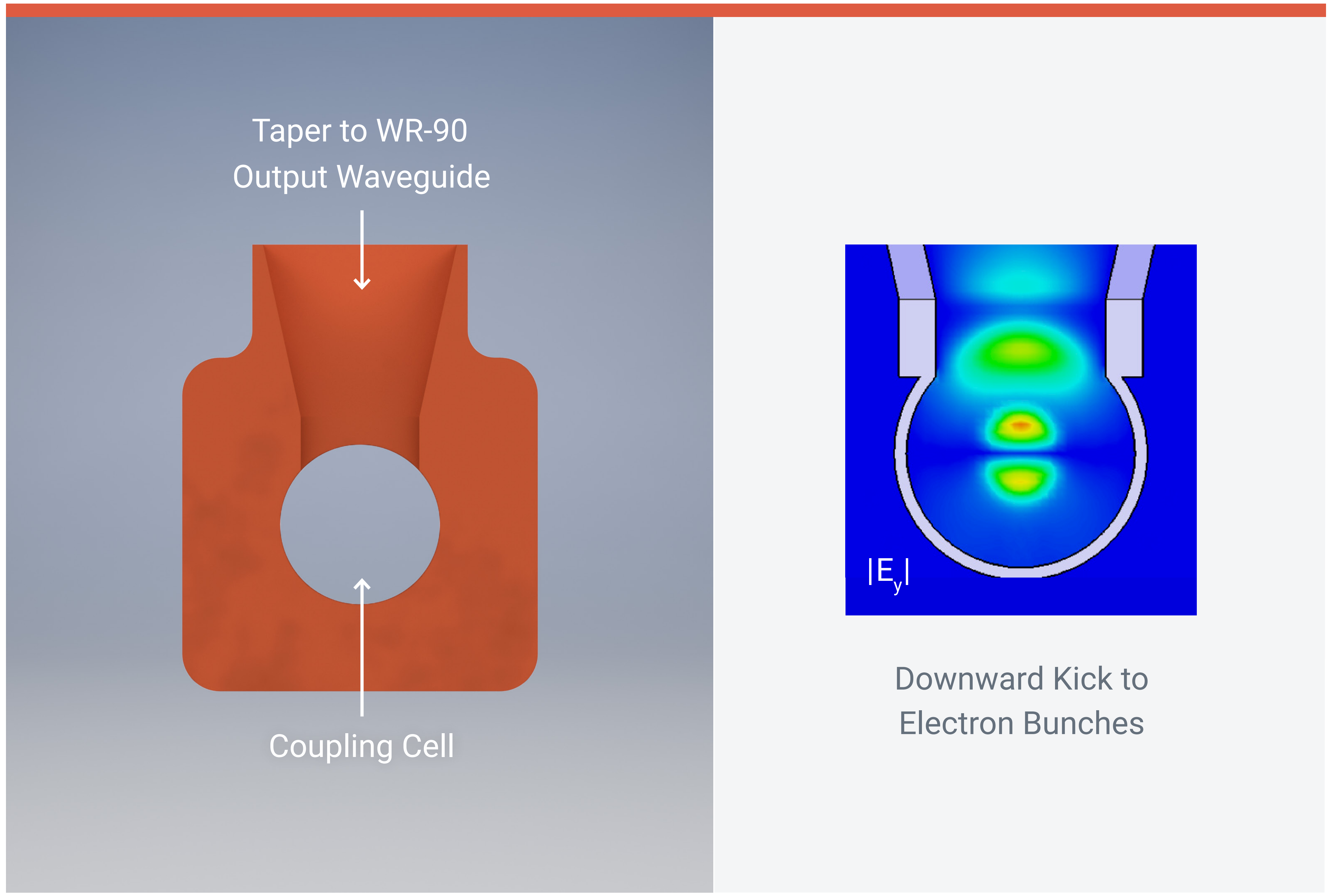
INSERTION LOSS



Stage 3 wagon wheel plates are fabricated from OFHC copper. Stages 1 and 2 used stainless steel plates for structural integrity, but the decreased conductivity drove insertion loss.

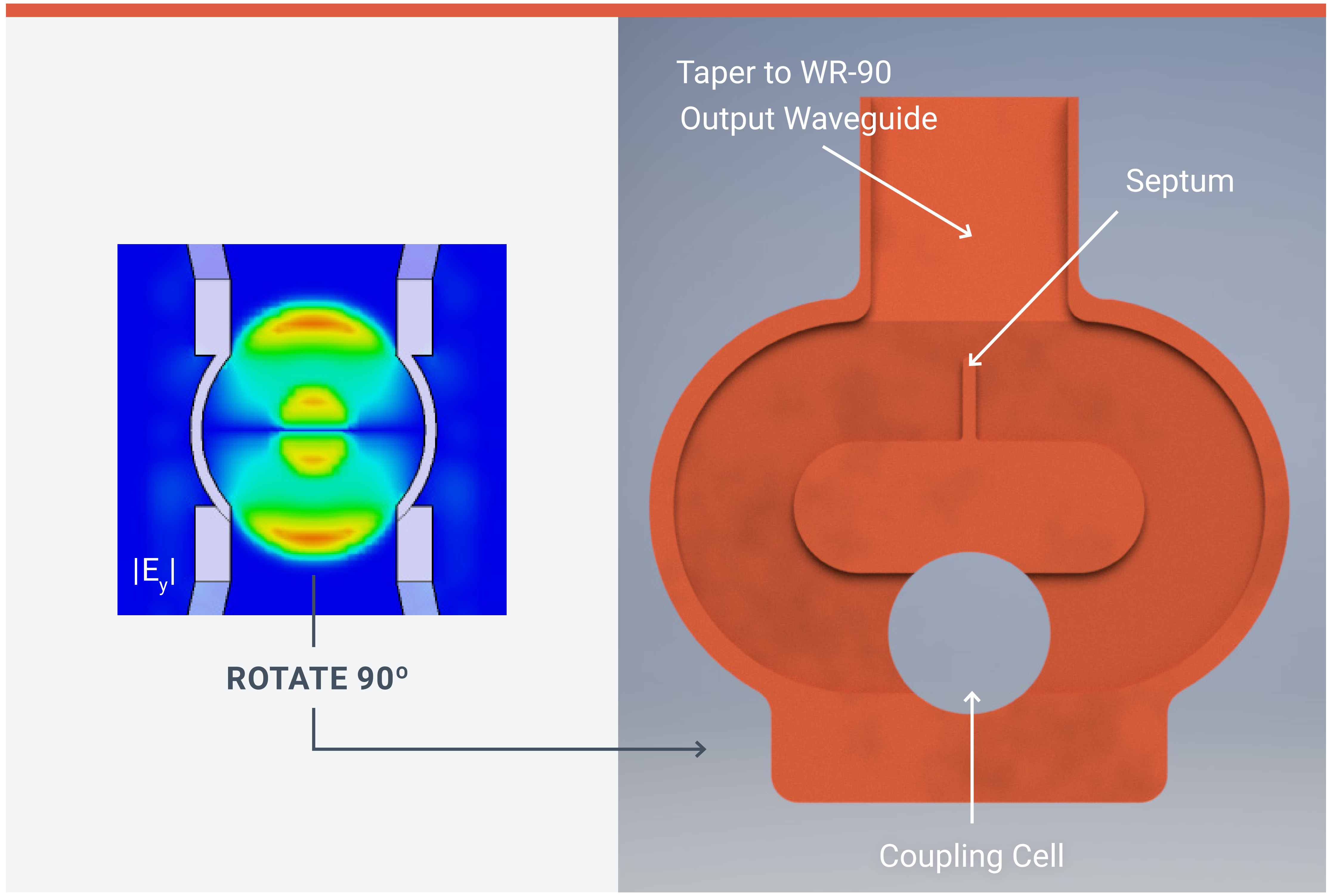
Comparing the Stages 2 and 3 cold test results shows a 5.2 dB increase in S_{21} at the 11.7 GHz design frequency. This reduction in RF loss substantially increases output power.

STAGES 1 & 2



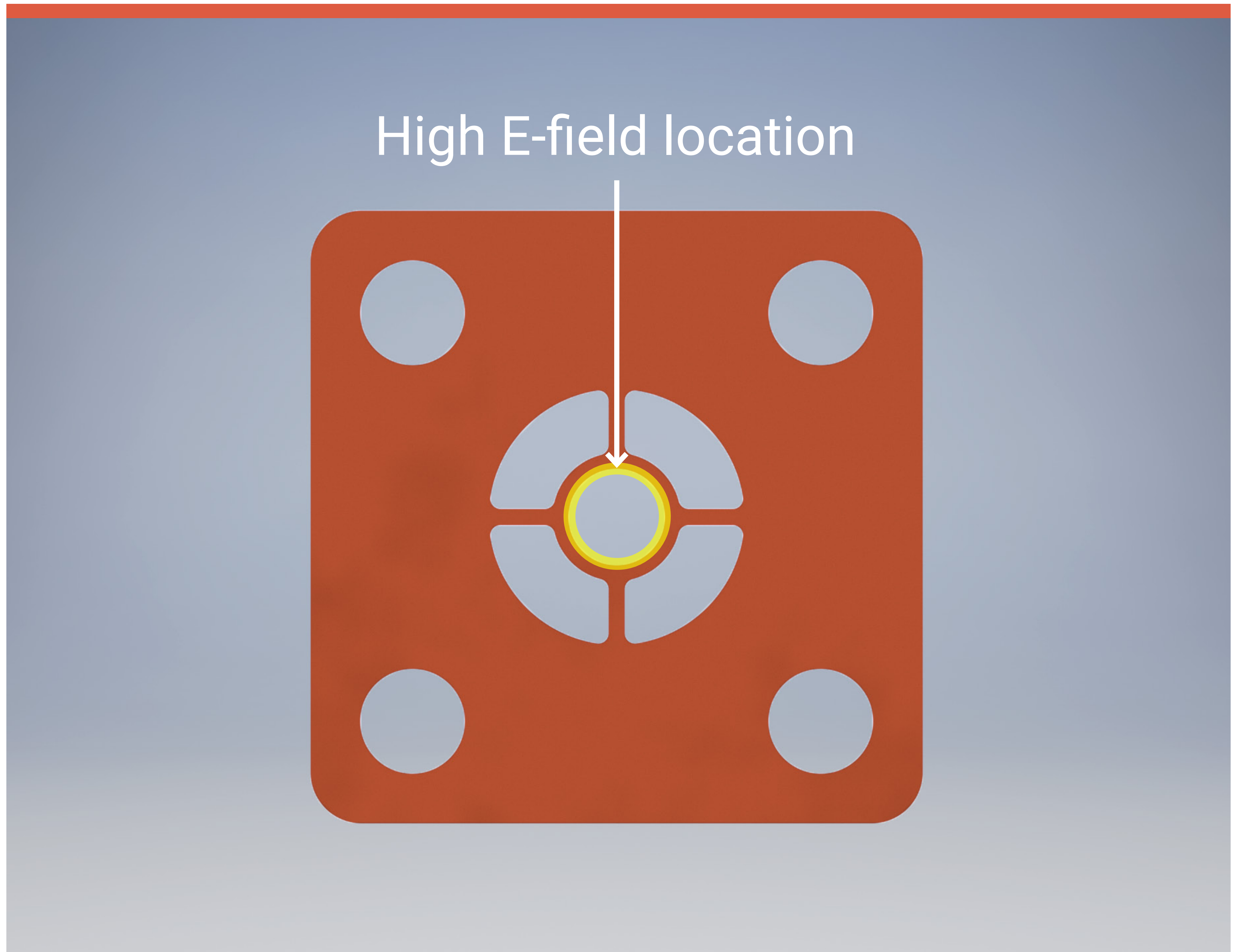
The high-power output coupler in Stages 1 and 2 generated an asymmetric mode in the coupling cell. This introduced a transverse kick to the beam, decreasing efficiency and making transmission harder.

STAGE 3



Stage 3 introduces a fully-symmetric high power combiner. By eliminating the problematic mode, the transverse beam impulse is removed and bunch transmission is improved.

STAGE 3 STRUCTURE PLATE



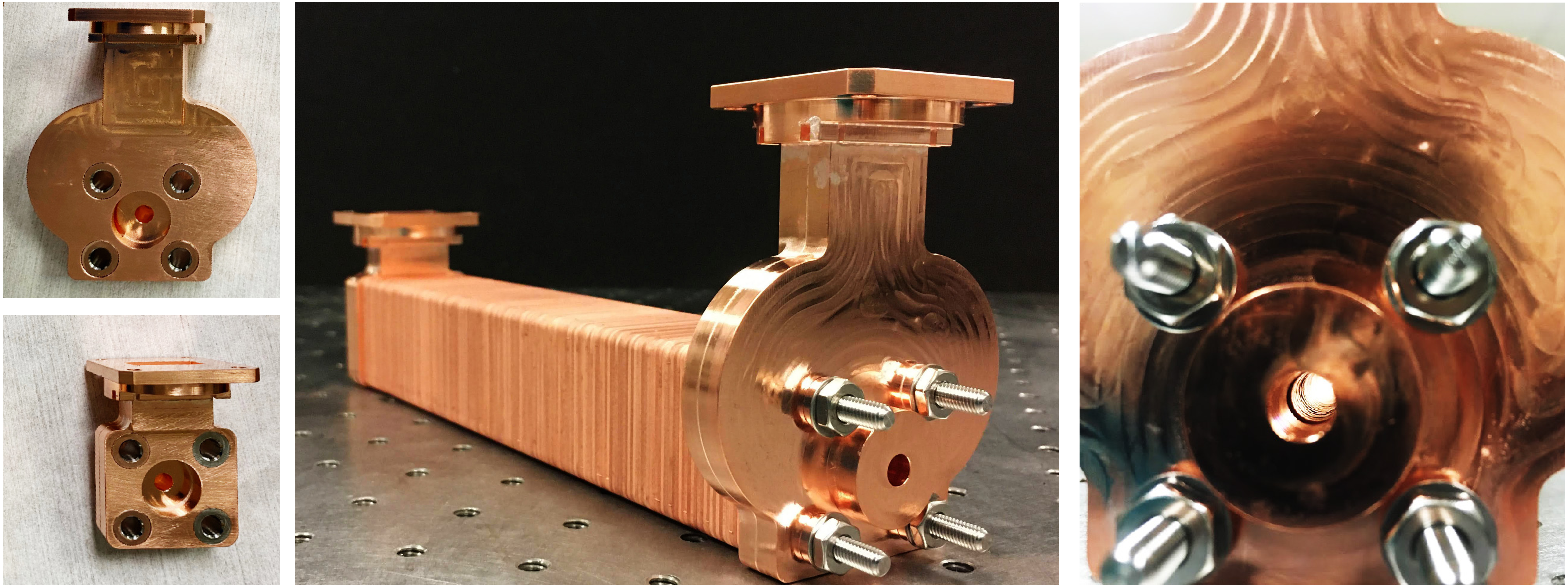
Highest breakdown risk is on internal edges of beam tunnel, exacerbated by edges from EDM cutting process.

BEFORE ETCHING

AFTER ETCHING

All metamaterial plates treated with a dilute acid bath to smooth sharp edges, as can be seen in SEM images

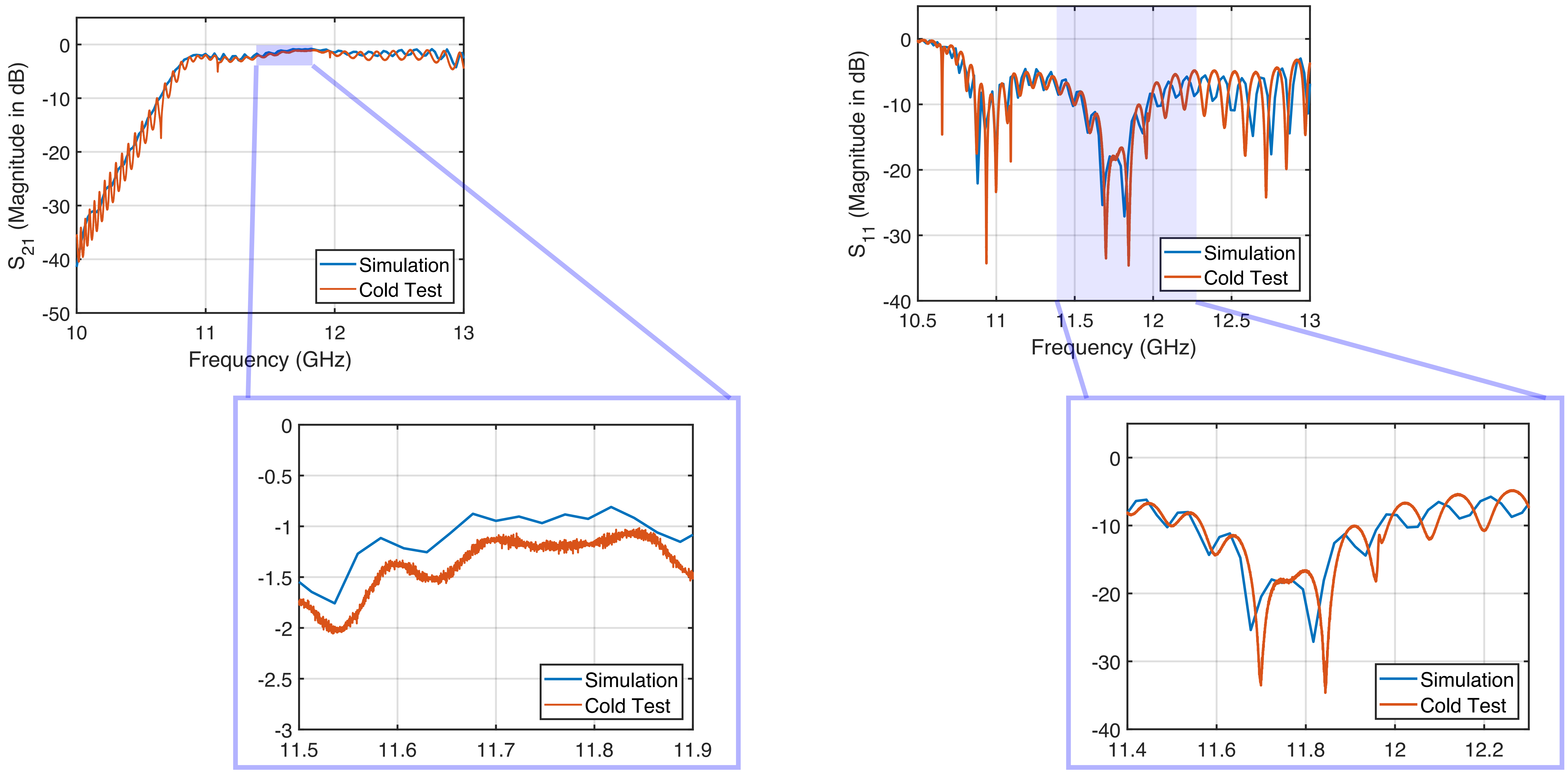
Images of Parts Constructed



Top Left: High power symmetric backward coupler. **Bottom Left:** Low power forward coupler
Middle: Fully assembled structure prior to cold testing. **Right:** Looking down the beam tunnel shows the metamaterial plates.

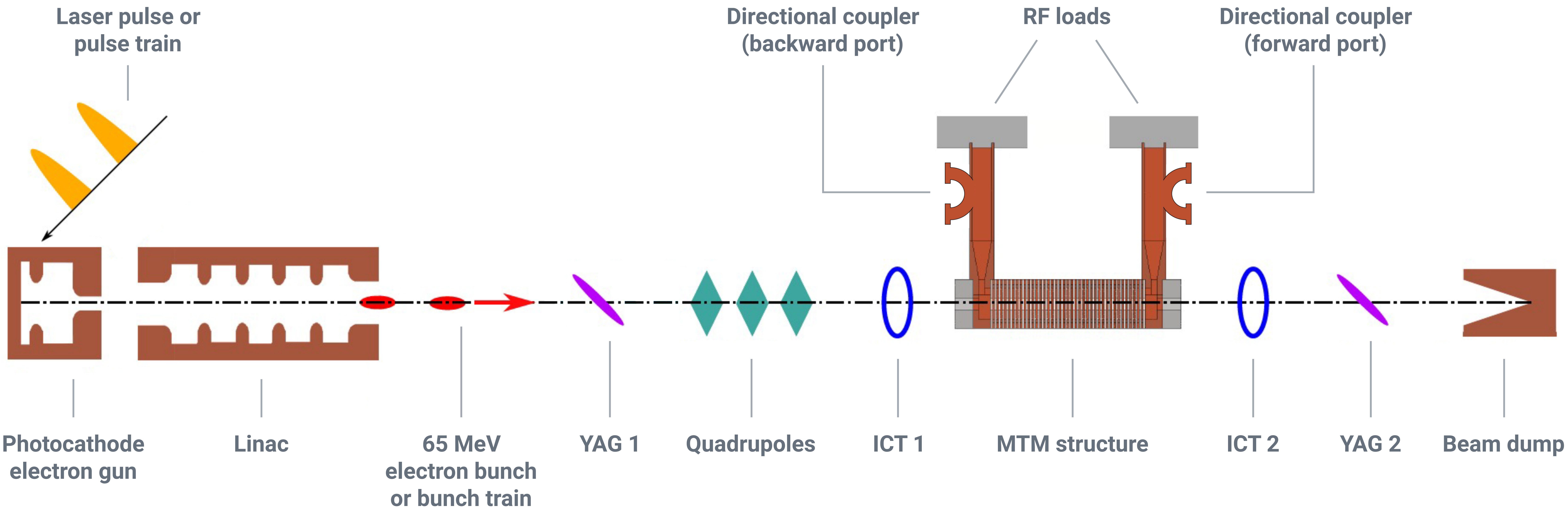
Stage 3 Cold Test Results

Stage 3 cold tests show excellent agreement with simulation.



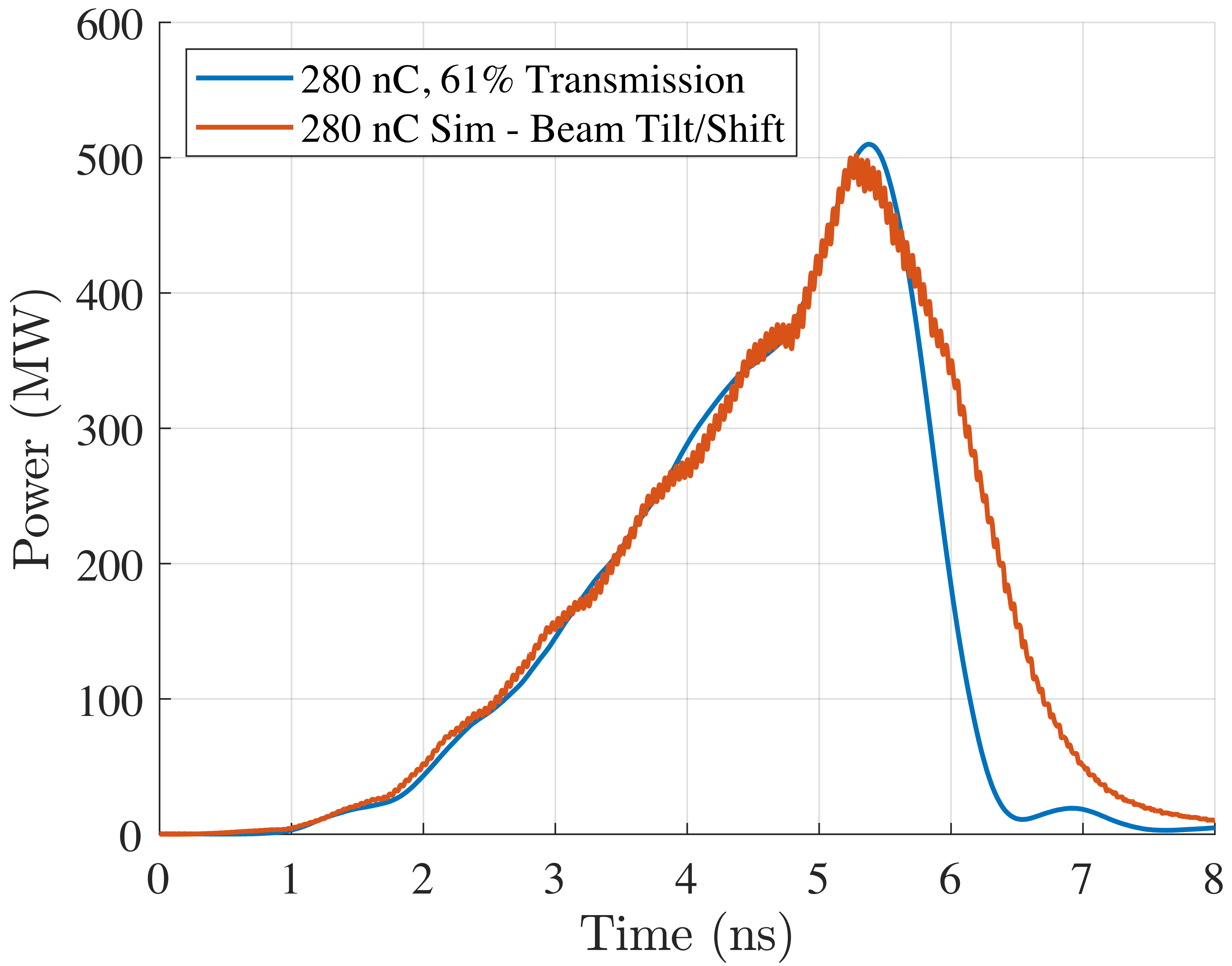
Argonne Wakefield Accelerator Beamline

The Stage 3 experiment has been tested on the beamline at AWA, which has the world's highest-charge photocathode. It is capable of producing up to 64 bunches with a total charge of >400 nC at 65 MeV.



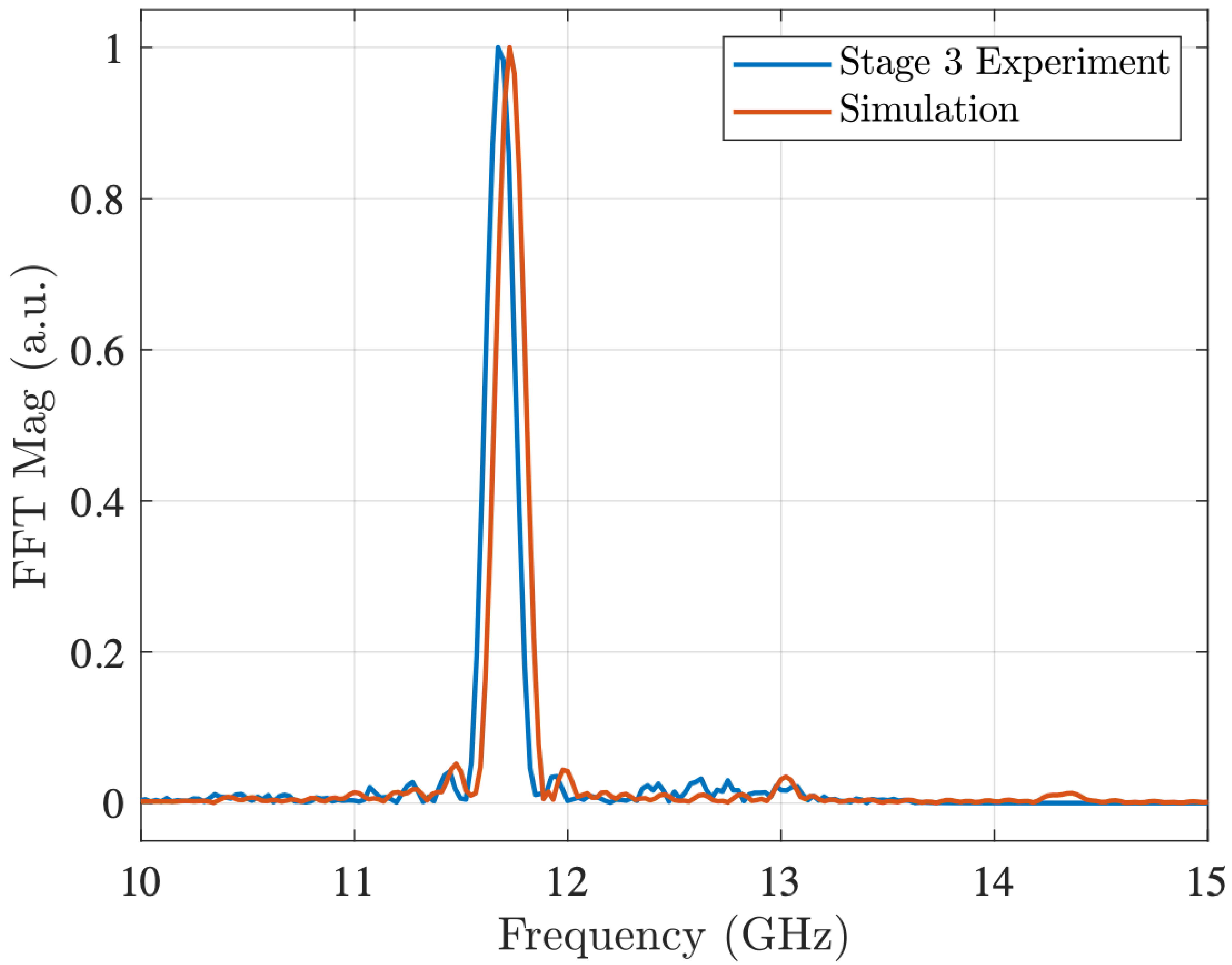
Highest Power Generated: 510 MW

- Highest power generated by a structure-based power extractor at AWA
- Generated from a 280 nC train of eight bunches
- Represents a peak accelerating gradient of >125 MV/m (if applied in collinear scheme)
- Good agreement between simulation and experiment after taking into account the observed position offset in the incoming bunches of electrons



11.675 GHz
Output Frequency

- Very close to design frequency of 11.7 GHz
- Frequency spectrum of 8-bunch pulse shows excellent agreement with simulation and beadpull tests



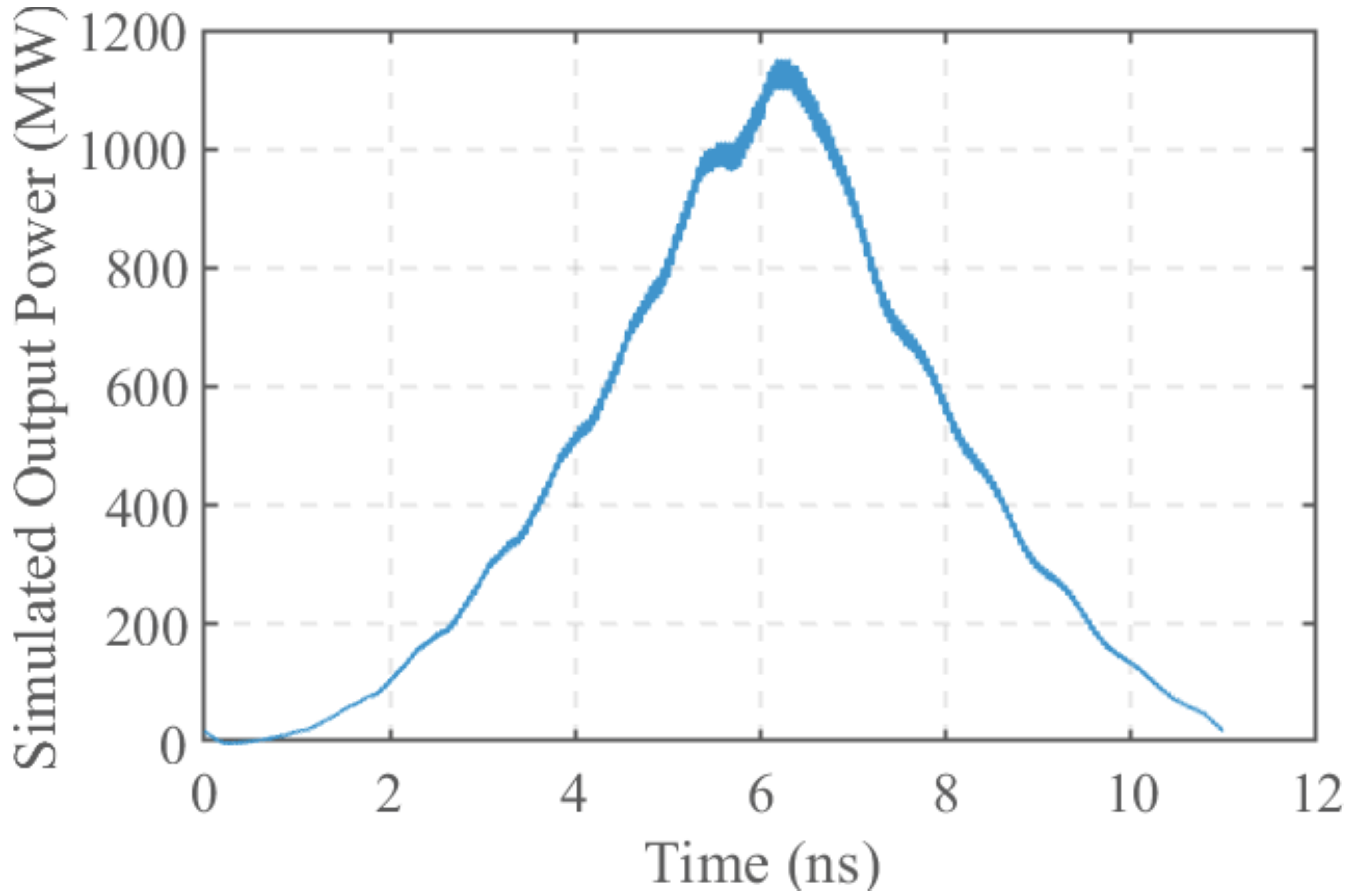
Looking Forward to 1 GW

- Stage 3 power limited by:

  Total available charge (Power $\propto q^2$):
  Maximum 280 nC available during experimental run

  Incident bunch trajectory:
  Transverse wake from 65 MeV Linac generated tilt/shift offset of bunches—observed on YAG screens

- Simulations and Stage 3 experiment data predict that the structure will produce >1 GW of power from 360 nC 8-bunch train (nominal AWA spec) when transverse wakes in Linac is reduced



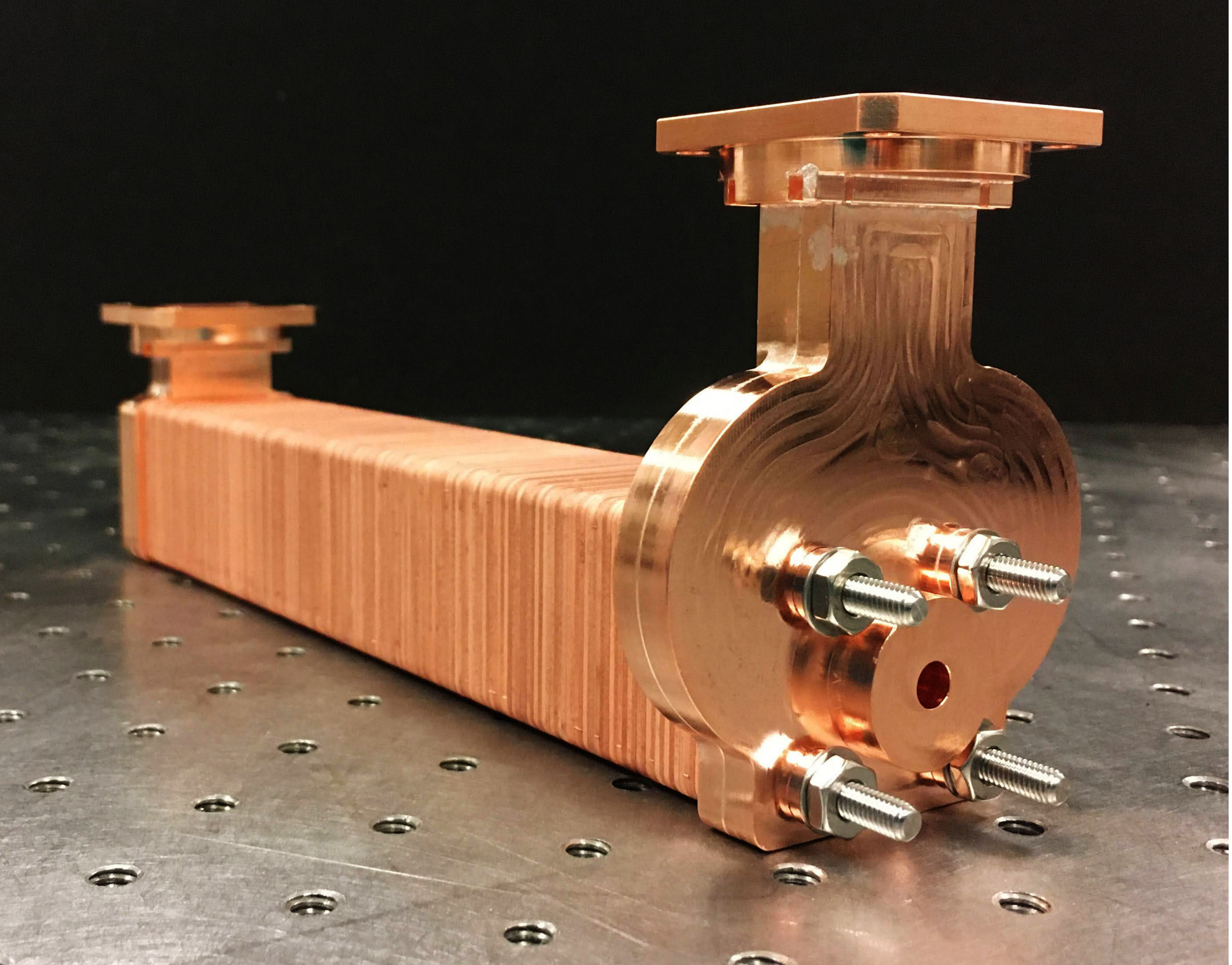
Simulated output pulse from a well-centered 360 nC 8-bunch train

Conclusions

510 MW of output power achieved at 11.675 GHz, a record for SWFA at the Argonne Wakefield Accelerator

Results enabled through the improvements in the Stage 3 design:
- Reduced insertion loss from all-copper construction
- Improved transmission from fully-symmetric output coupler
- Decreased breakdown risk through plate treatment

Metamaterials are a very promising candidate for Structure-Based Wakefield Acceleration, providing a rugged structure with high group velocity, high beam-wave interaction, and a large degree of flexibility in parameter-space.



Thank you

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