mm-Wave Structure Development for High Gradient Acceleration

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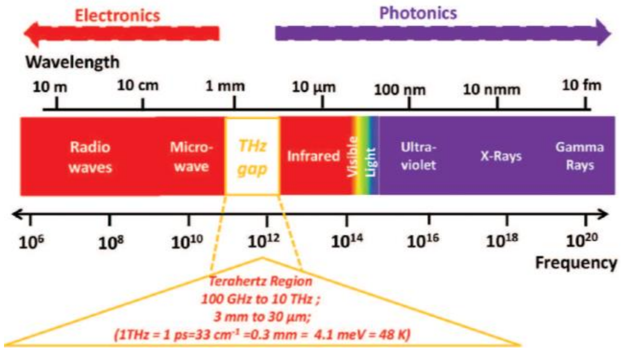
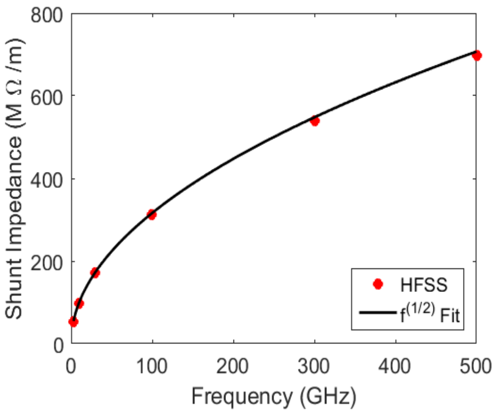
Outline

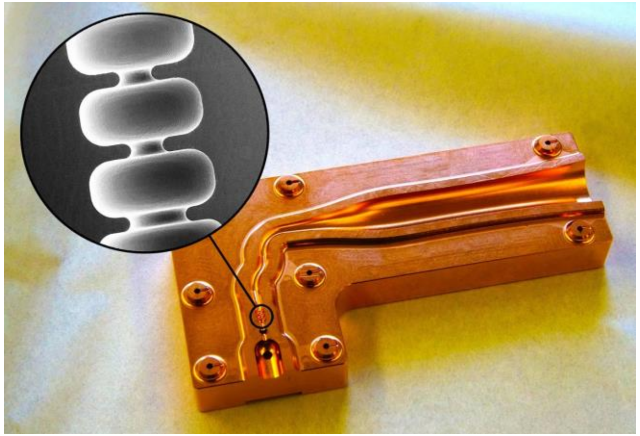
I. Motivation
II. Fabrication and cold test
III. Tuning techniques
IV. Distributed coupling design

THz and mm-Wave Accelerators

- Can sustain higher gradients due to higher breakdown thresholds
- Reduced fill times result in decreased pulsed heating and allow for higher repetition rates
- Increased shunt impedance and RF efficiency
- Ultra compact structures







Othman et al., *Appl. Phys Lett*. 117(7) 073502 (2020).

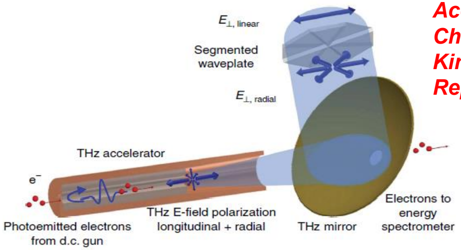
Breakdown threshold

$E_s \sim \tau^{-1/4} f^{1/2}$

Recent developments in THz and mm-Wave Accelerators

Field is now a very active area of research:

- First demonstration of THz driven electron acceleration in 2015
- Beam driven structures tested at nanosecond timescale have achieved peak surface fields of up to 1.5 GV/m
- Many approaches under development

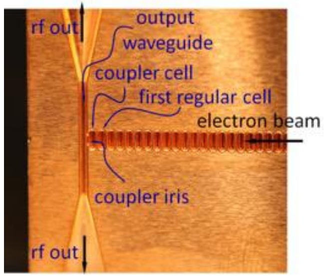


Accelerating gradient ~ 10MV/m
Charge 25 fC
Kinetic energy ~ 50 keV
Rep. rate ~ kHz

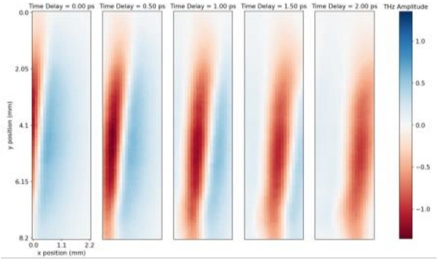
E. A. Nanni, et al. *Nature communications* 6 (2015): 8486.

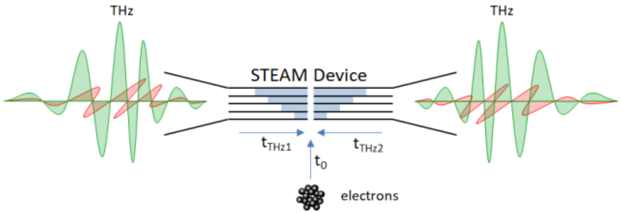
M. Dal Forno, *PRAB* 19.5 (2016): 051302.

Accelerating gradient ~ 50 MV/m
Surface fields ~ 500 MV/m
Pulse length ~ 100 ps
Drive bunch 4 GeV, ~ nC;
Witness Bunch ~ pC



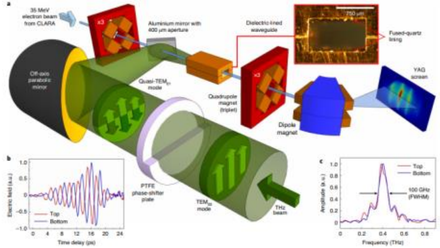
Poster: A.E. Gabriel, 06/13, 1400 – 1600





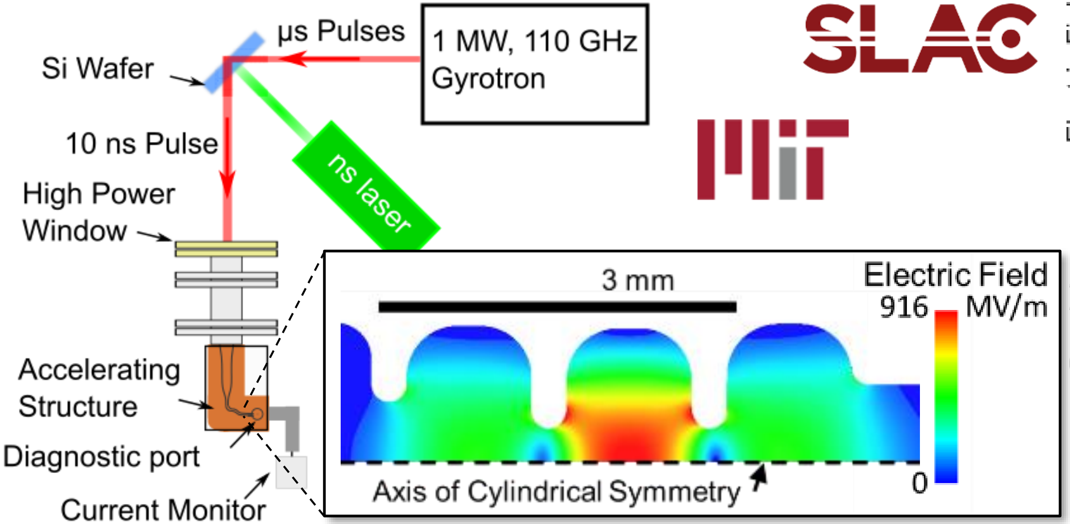
D. Zhang, et al. *Nature Photonics* (2018): 1.

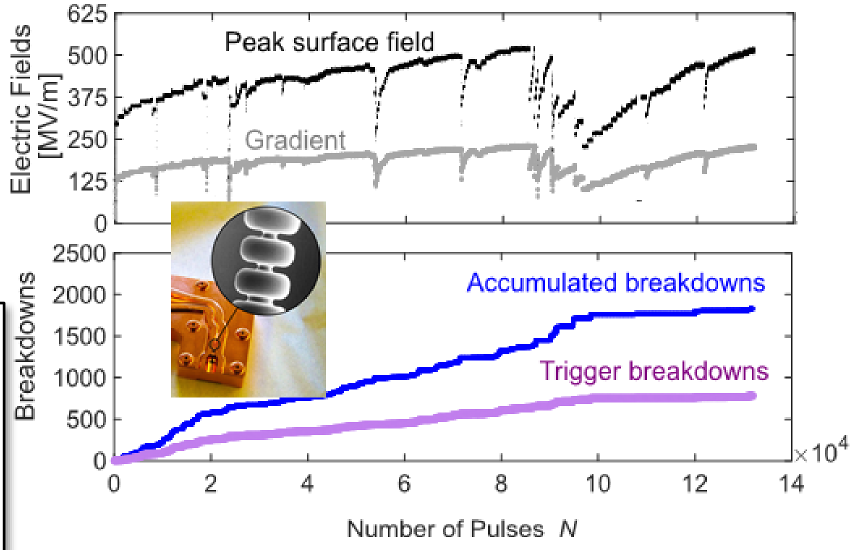
Hibberd, M. T., et al. *Nature Photonics* 14.12 (2020): 755-759.



High power testing of externally driven W-band structure

- Previous work utilized split-block accelerator fabrication at mm-wave scale
- Achieved gradient up to 225 MV/m for 600 kW, 10 ns pulses in central cell
- Demonstrated efficient coupling with quasi-optical transport and adiabatic horn with mode converter

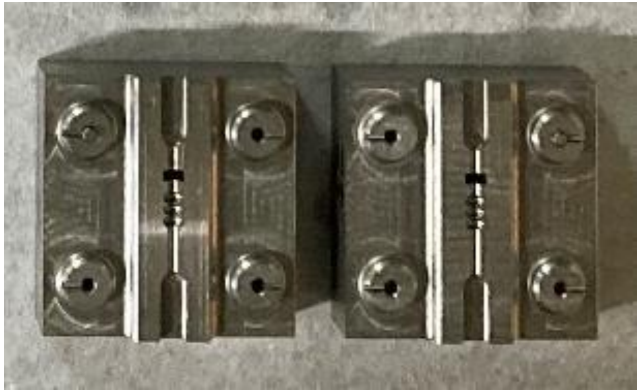


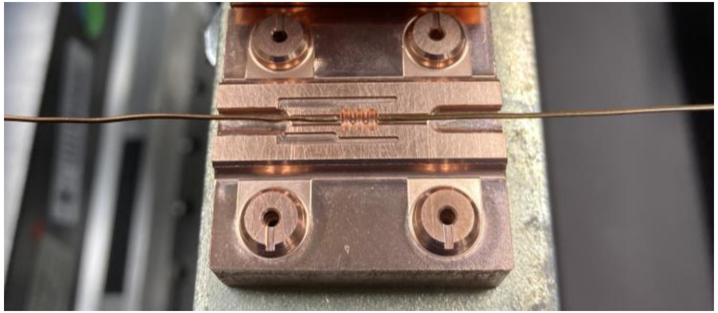


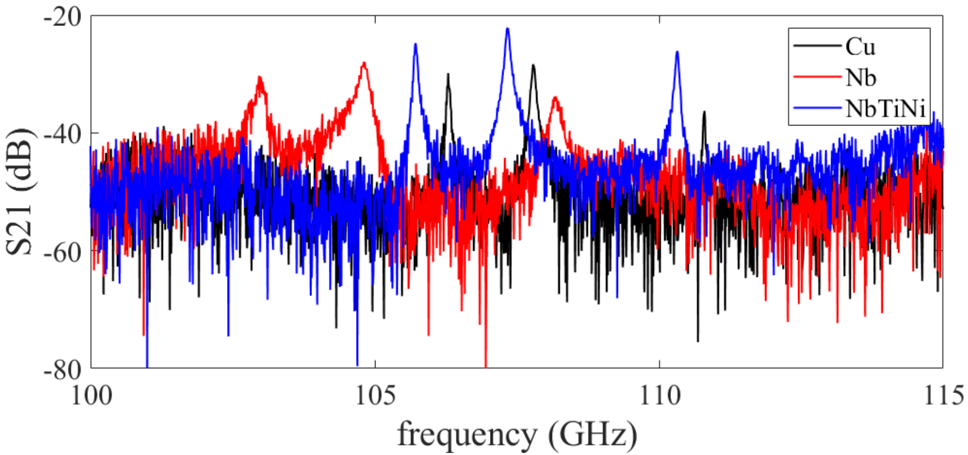
Appl. Phys Lett. 117(7) 073502 (2020).

Fabrication of mm-wave cavities

- Using same 3-cell standing wave π-mode structure design
- Frequency tuning initially accomplished with shims
- Cavities fabricated in copper, niobium, and copper plated with NbTiNi
- Cold test performed using network analyzer with coaxial probes







Development of targeted tuning technique

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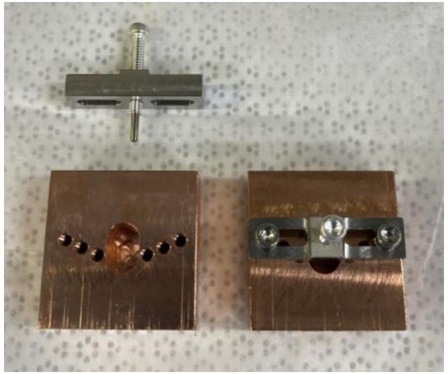
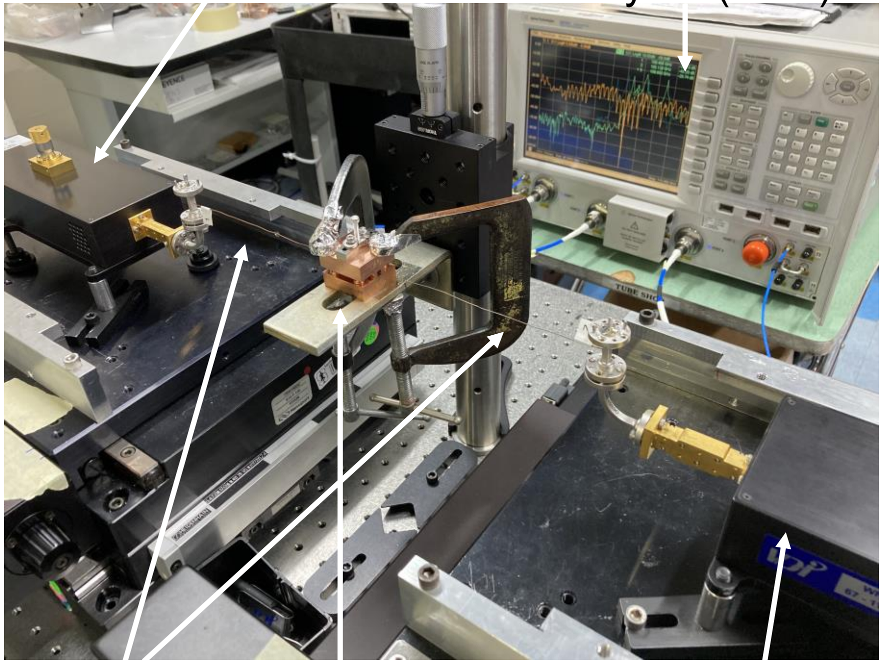
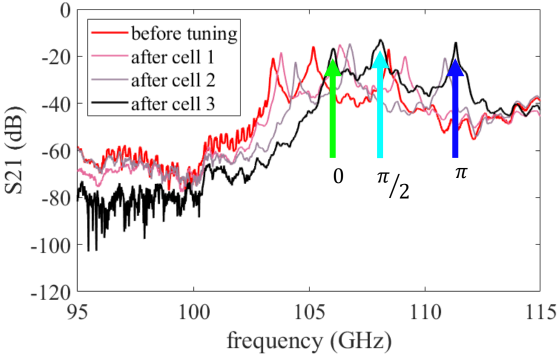
- Cell period (~1.6 mm) is too small for conventional approach with tuning pins brazed onto each cavity wall
- Slot was machined into structure halves leaving only a 1 mm wall thickness
- Demountable tuning pin was fabricated with alignment holes for each cavity position

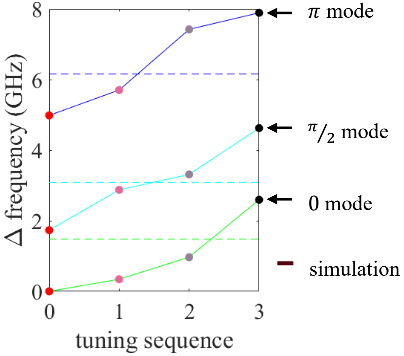


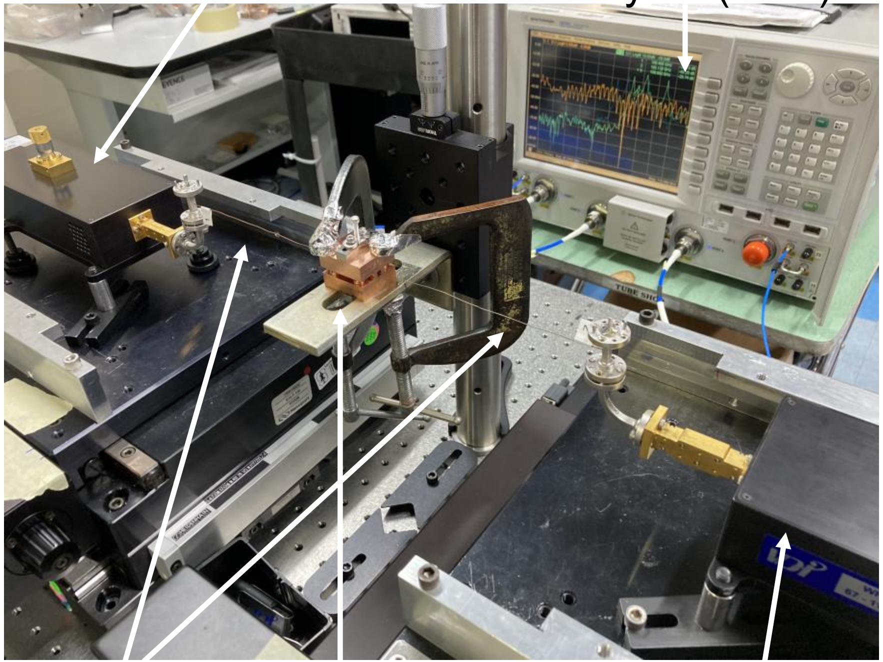


Tuning measurements

- Cells were tuned in sequence
- Active monitoring with VNA
- Observed up to 3 GHz shift in resonant frequencies
- Pushed cavities to the point of deformation to find maximum range

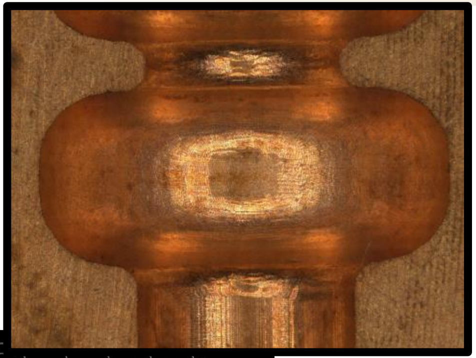


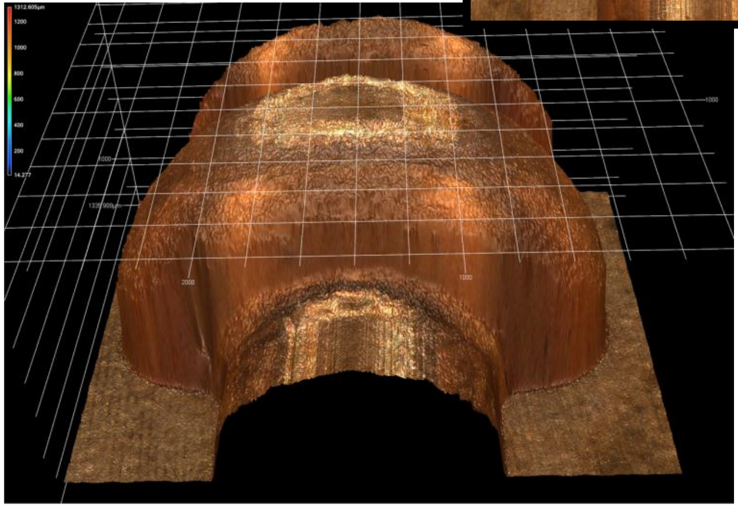




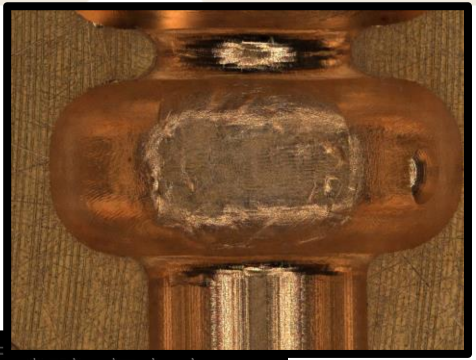
3D microscope images of deformed cavity

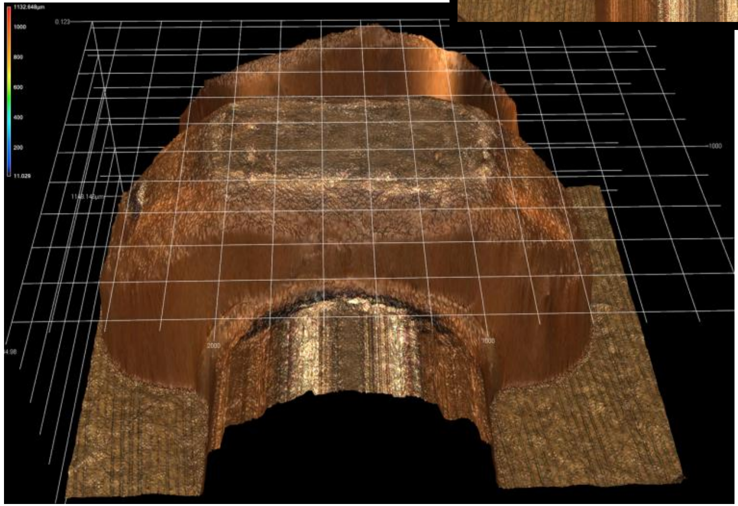
Without tuning





After tuning

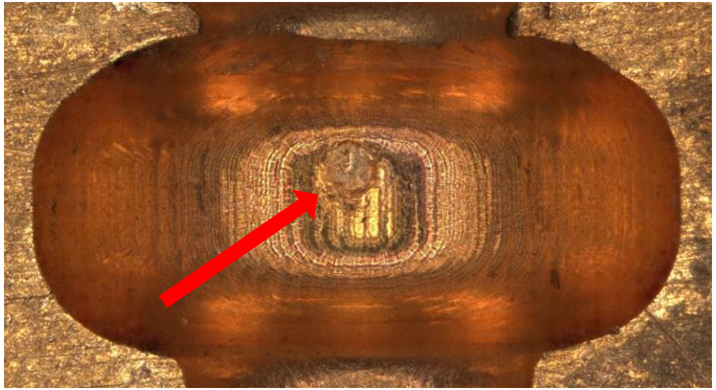




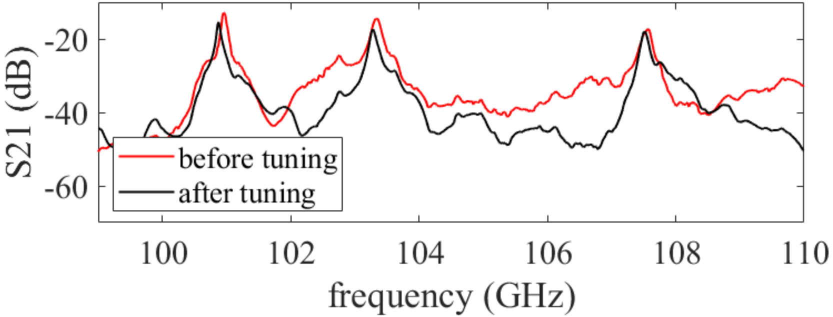
Tuning down in frequency

- Techniques under investigation:
  - Shimming
  - Temperature control
  - Brazed tuning pin on structure wall
  - Pressing on wall from inside
- Challenges:
  - Tuning while disassembled, not compatible with tuning after brazing
  - Reproducibility/reversibility
  - Understanding RF properties – effect on surface
  - Tuning range

Initial Test of Pressing on Wall

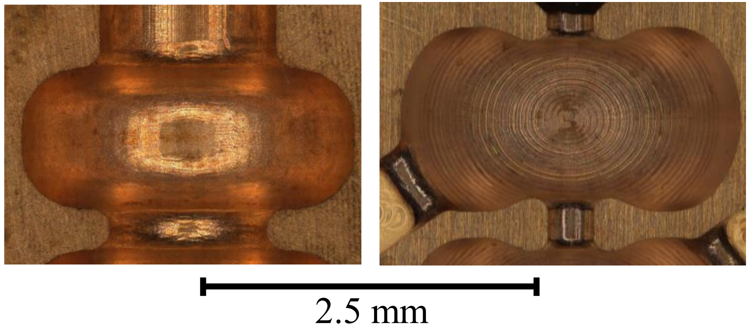


Observed average shift of 47 MHz



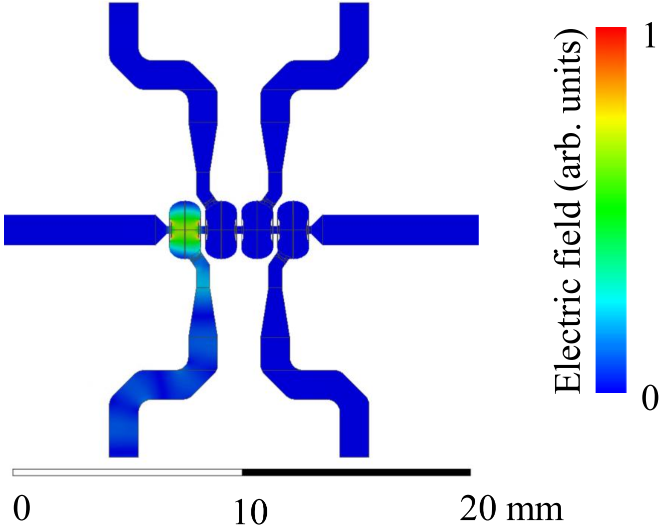
High shunt impedance cavity design

- Cavity optimization with re-entrant nose-cones increases the shunt impedance to ~440 MΩ/m
- Need to transition from power coupling on-axis to side-coupled cells



4-cell prototype design modeled in HFSS

- Developed to test fabrication of side-coupled cavities with re-entrant nose cone
- Waveguide routing to each cell individually
- Power distribution manifold in subsequent design
- Greatly reduced coupling between cells compared to original design



Cold-tests of 4-cell side-coupled prototype

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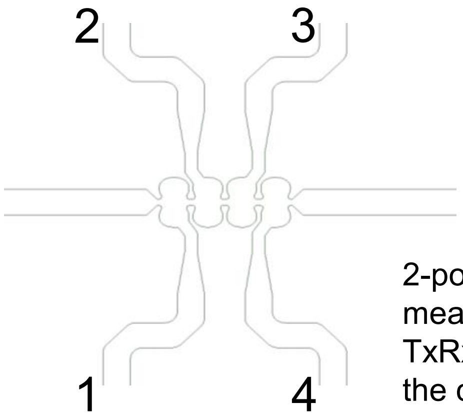
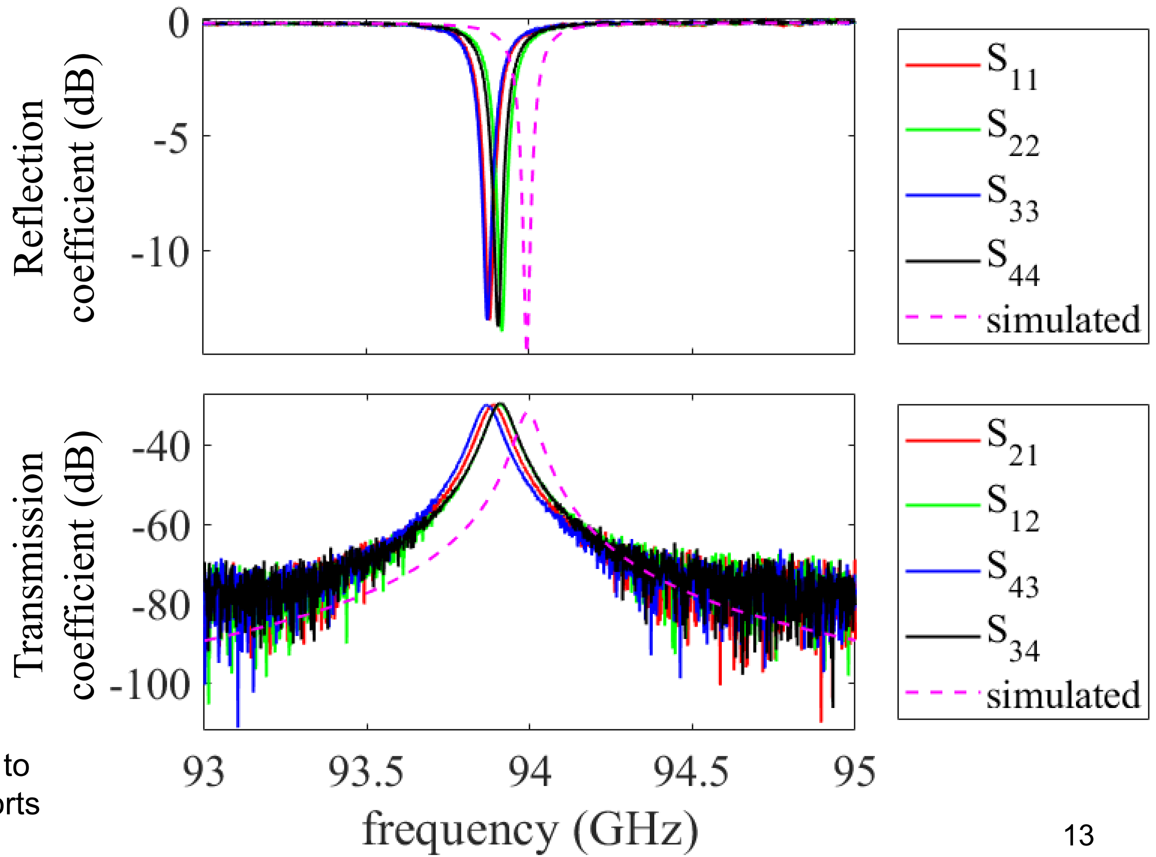
The spread in resonant frequency between the 4 cells is 46 MHz, reaching a maximum of 122 MHz away from the design frequency of 93.99 GHz.

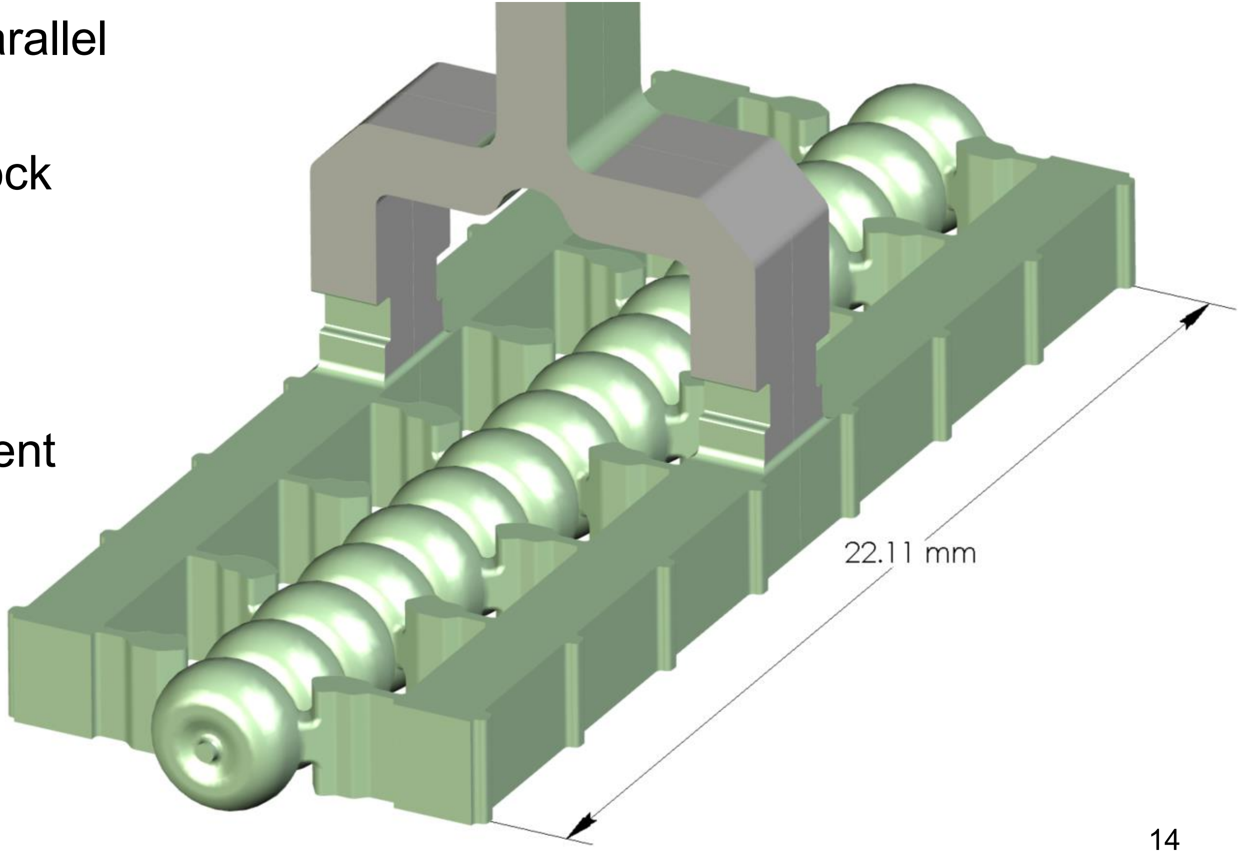


2-port VNA measurements with TxRx and Rx moved to the corresponding ports



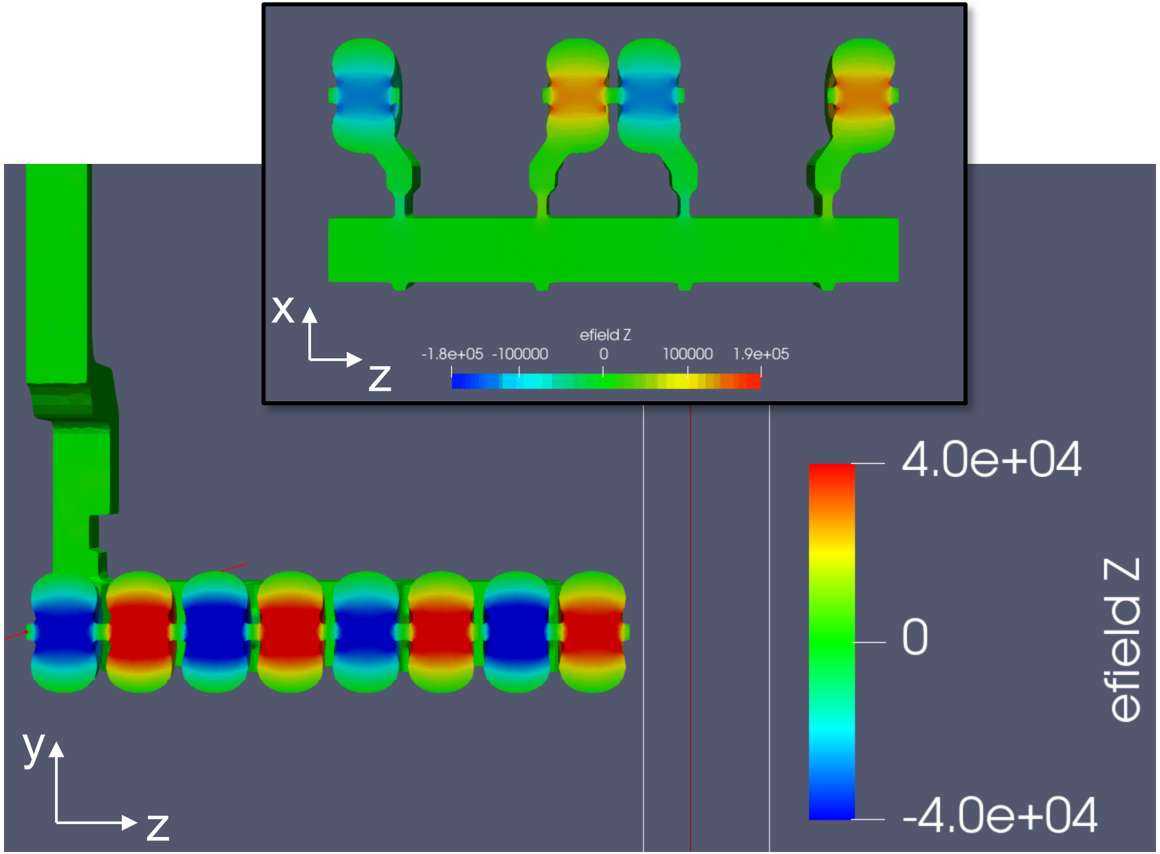
Extended linac with power distribution

- 16-cell design fed by parallel manifolds
- Will fabricate in split-block configuration
- 1 MW case:
  - ~ 3 MeV gain
  - ~136 MeV/m gradient



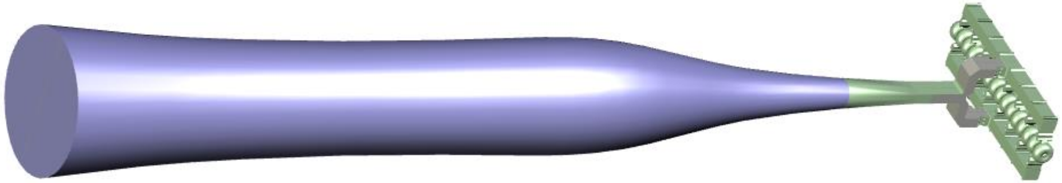
Modeling the distributed coupling linac

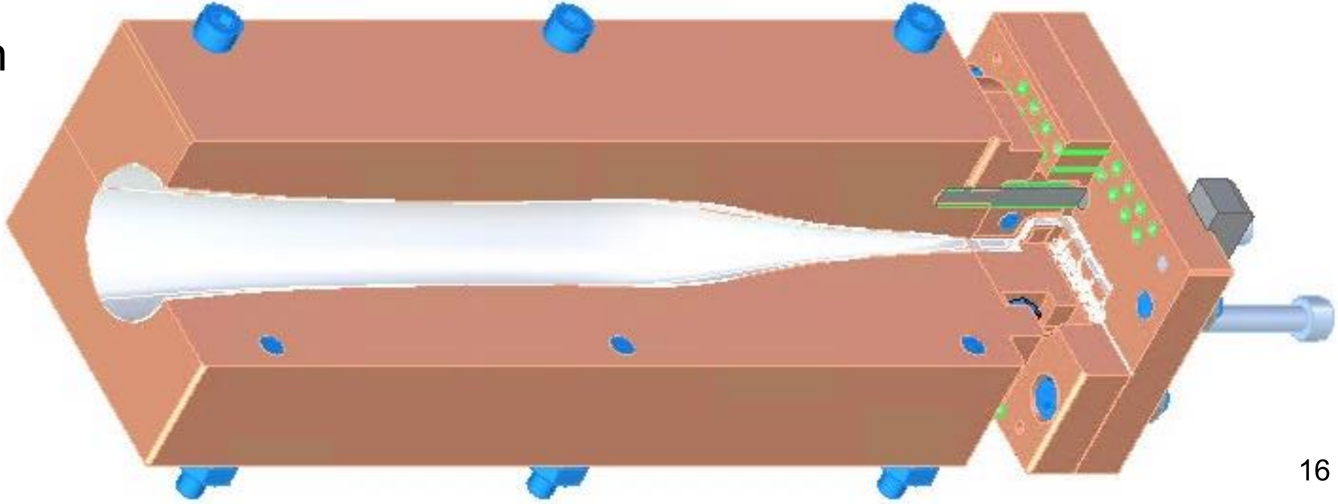
Simulations of the distributed coupling manifold first modeled in ANSYS-HFSS then optimized using SLAC's parallel electromagnetic code suite ACE3P



Quasi-optical coupling horn with mm-wave linac

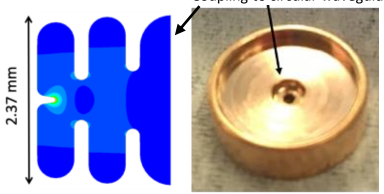
- Horn couples into WR-10 waveguide before routing through a y-split to parallel distribution manifolds
- During cold test can utilize 2 tuning pins per cell



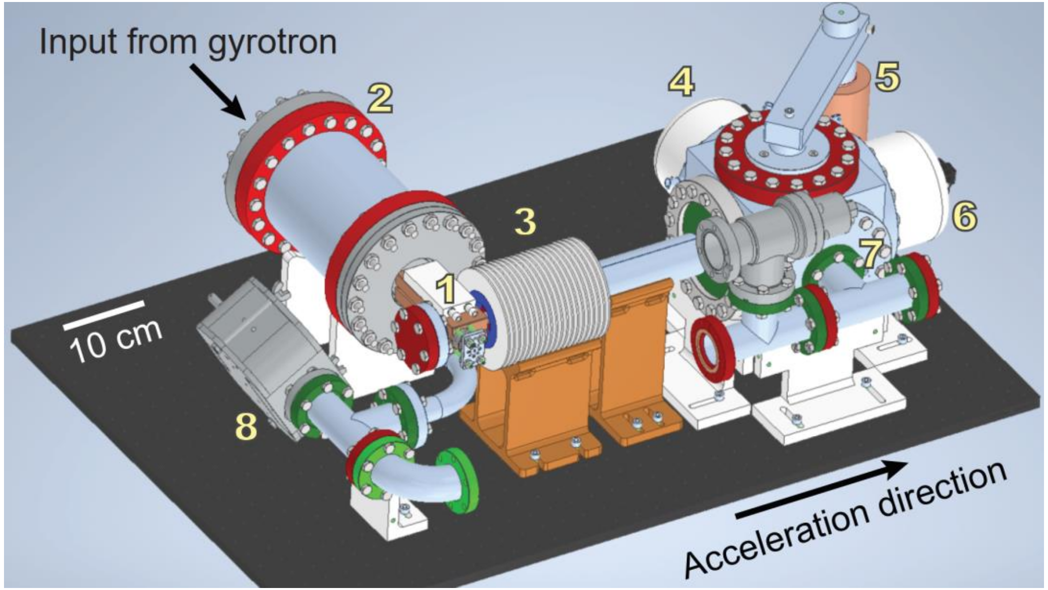


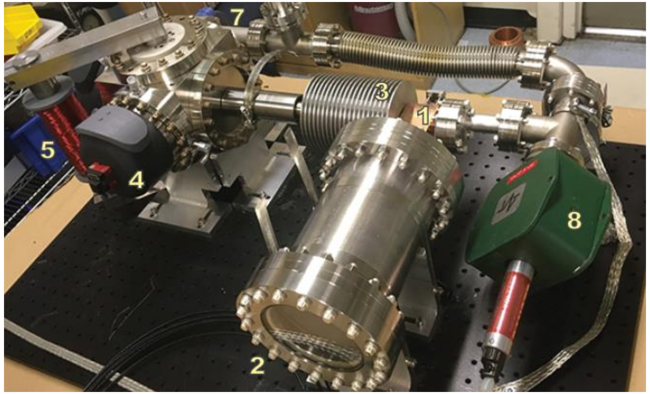
Outlook: High Power Test

- Partnered with MIT to test 110 GHz field emission gun
- Collaborating with AFRL to test mm-wave structures at 94 GHz with active pulse compression



S. Lewis, E. Nanni, J. Merrick





THz gun high power experimental setup. (1) gun assembly, (2) high power input window, (3) solenoid, (4) energy spectrometer microchannel plate detector, (5) bending dipole, (6) on-axis microchannel plate detector, (7) Faraday cup, and (8) ion pump. The acceleration and THz input directions are shown.

Summary

- Mm-wave structures offer a path to ultra-compact high-gradient accelerators
- The research presented here adapts conventional accelerator techniques for the mm-wave regime
  - Cavity tuning
  - Distributed power coupling
- These elements will be combined for high power testing of an extended mm-wave linac