Advanced RF Acceleration, X-band and Beyond

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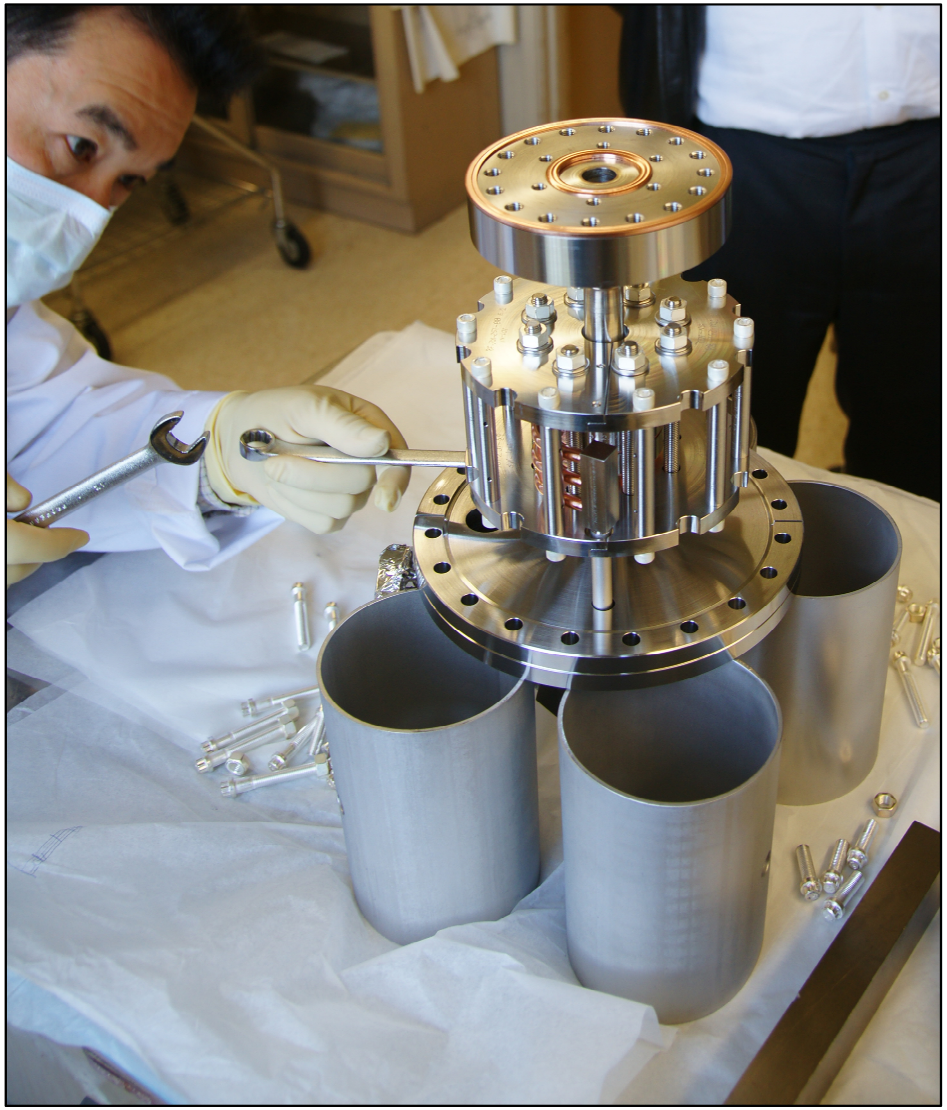
U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Advances for accelerator structures
- Novel Linac Topologies
- Mm-wave accelerators
- New RF sources:
  - Klystrons
  - Novel Multidimensional sources
  - Novel mm-wave/THz CSR-maser
- Summary



Clamped structure for testing without brazing

Our current approach to an efficient cost effective system

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Beam parameters
(***roughly 10 MW CW beam power***)

An Integrated approach that includes:

- Basic physics understanding of the high gradient phenomenon in normal conducting structures
- Novel structure designs that includes both efficient normal and superconducting structures.

Highly efficient RF sources based on:

- Novel transformational ideas
- The development of modern basic physics simulation tools.
- Taking the modulator design into account and demanding a low voltage operation

Modulator:
Intelligent modulators with feedback loops to recover the energy from both the rf source and the accelerator structures

- Efficient Structures operating above 150 MV/m for normal conducting structures; at high frequencies, structures above 1 GV/m
- Efficient superconducting structures with gradients ~ 70 MV/m, with possibilities of operating at temperatures ***higher*** than 1.8 K

The end result we hope: very efficient and consequently low cost systems with a clear path to expansion

Discovery of Role of Magnetic Fields in Breakdown Triggered a Change in Research Direction

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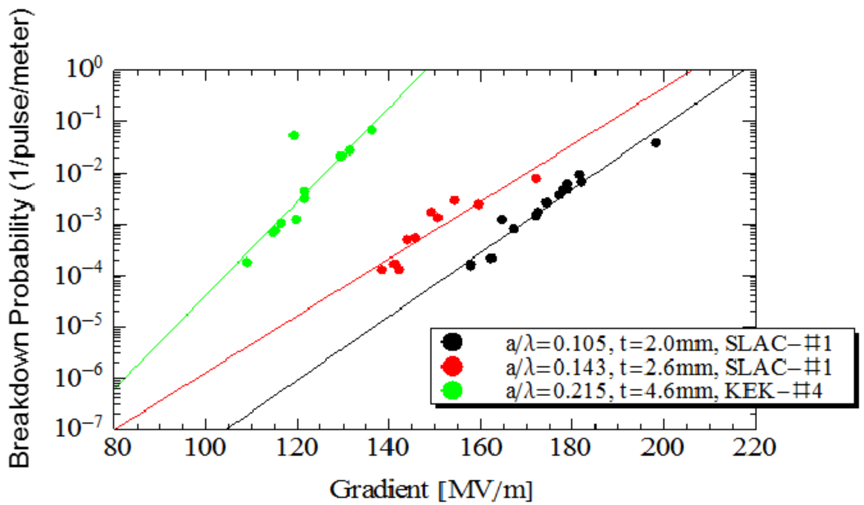
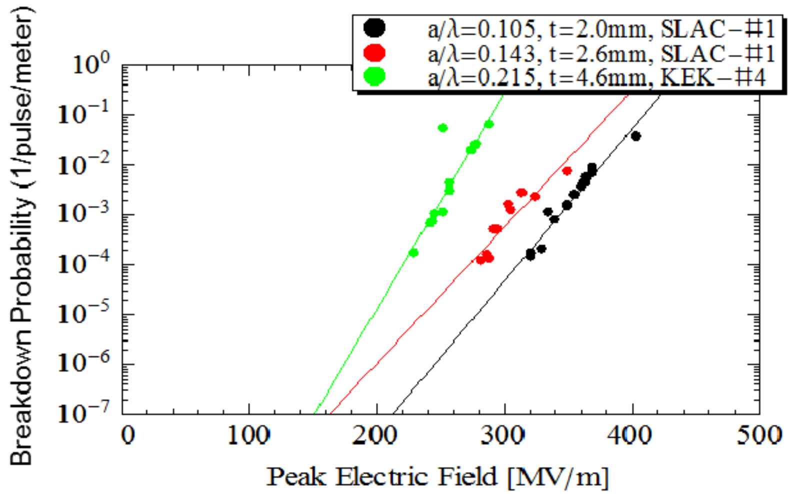
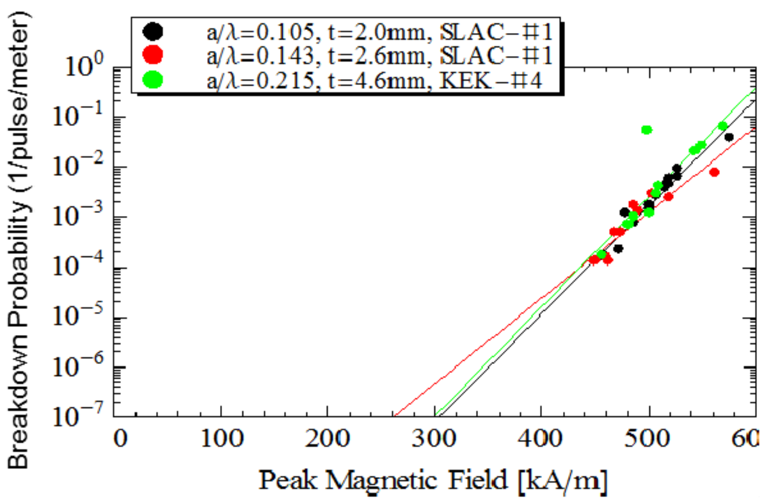
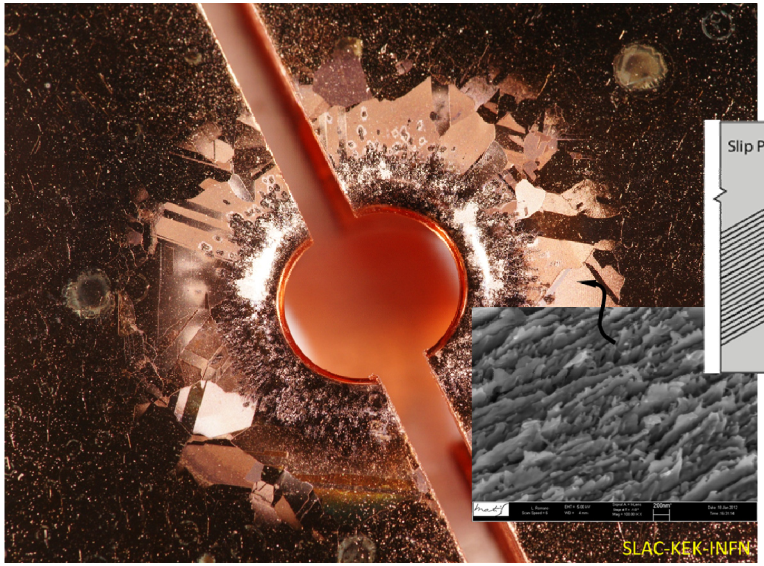
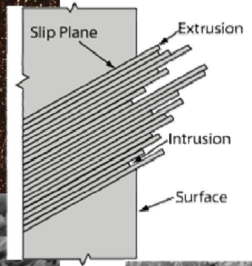
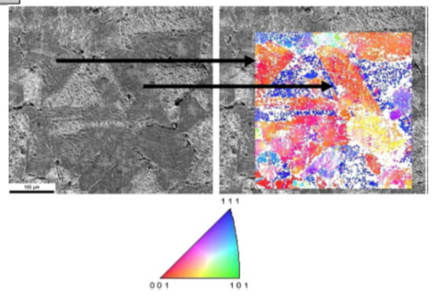






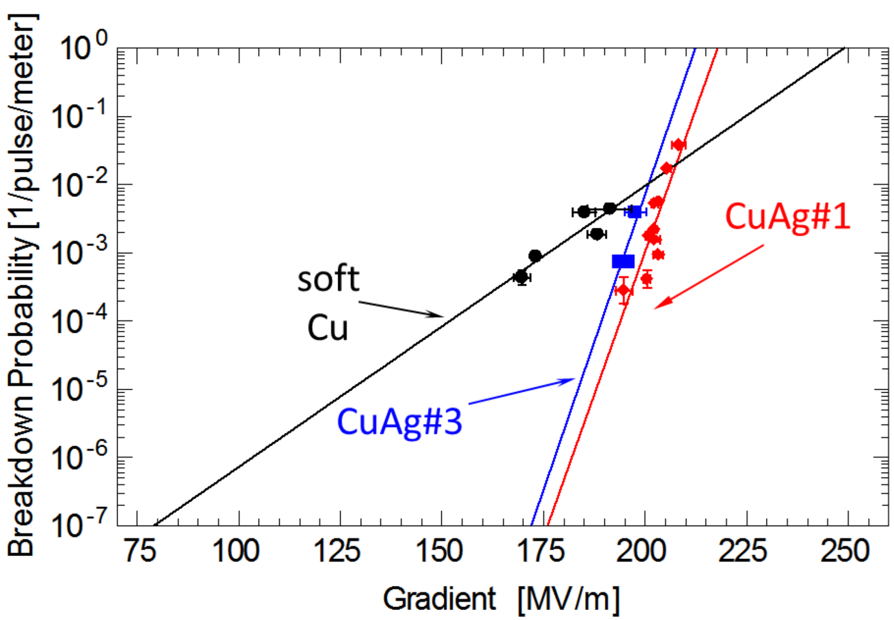


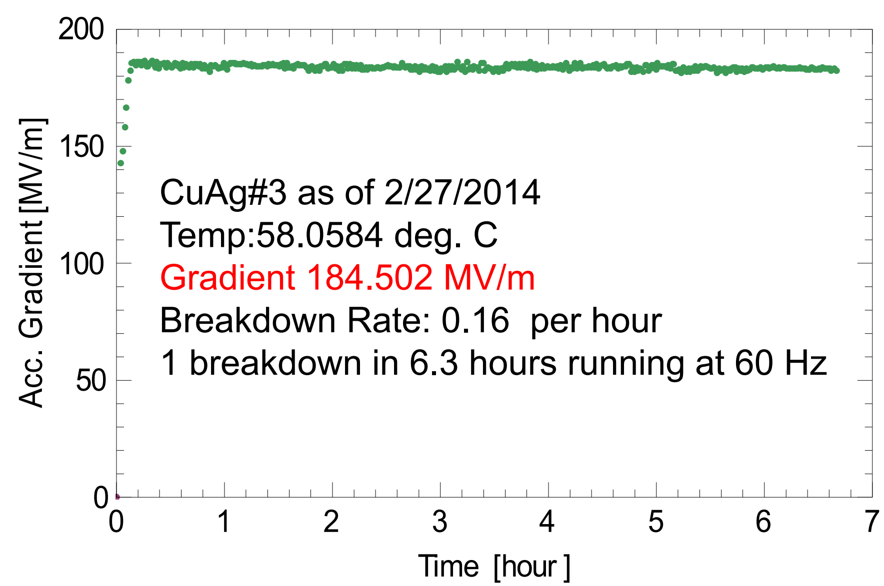




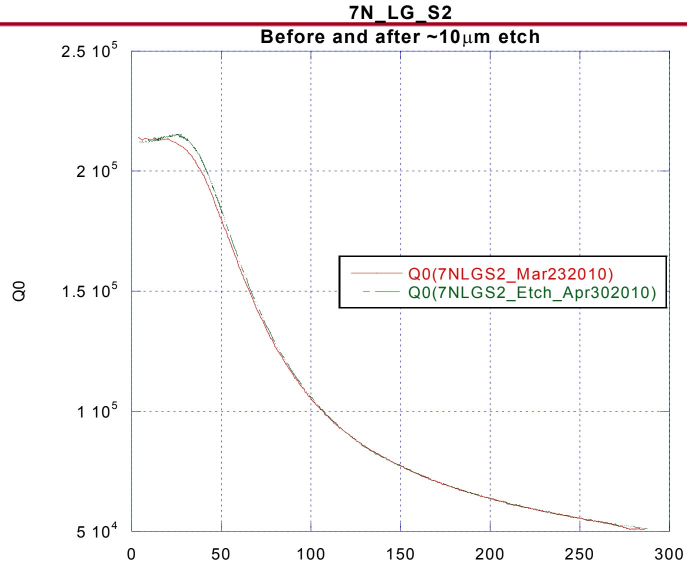
High Gradient Accelerator Structure Materials (Copper Alloys, CuAg)

- Motivation
  - From understanding breakdown phenomena, we predicted better performance with CuAg (0.08% Ag)
- Status
  - First hard CuAg#1 had record performance compared with any other structure tested
  - Testing third structure with great success, verifying the consistency of results
  - Studying the processing time and methodology which appears different than pure Cu

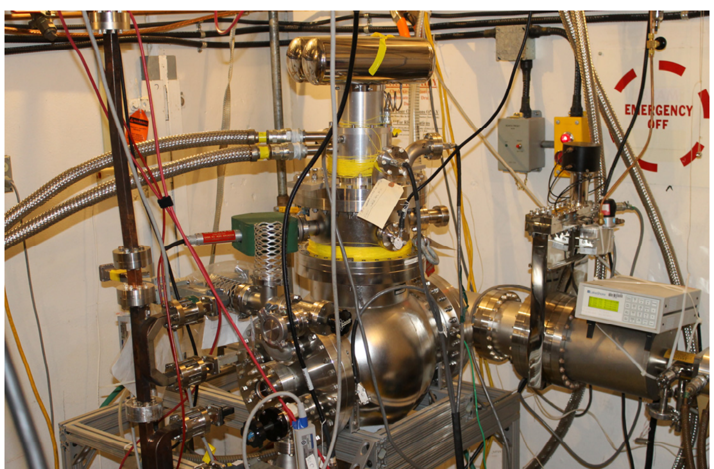


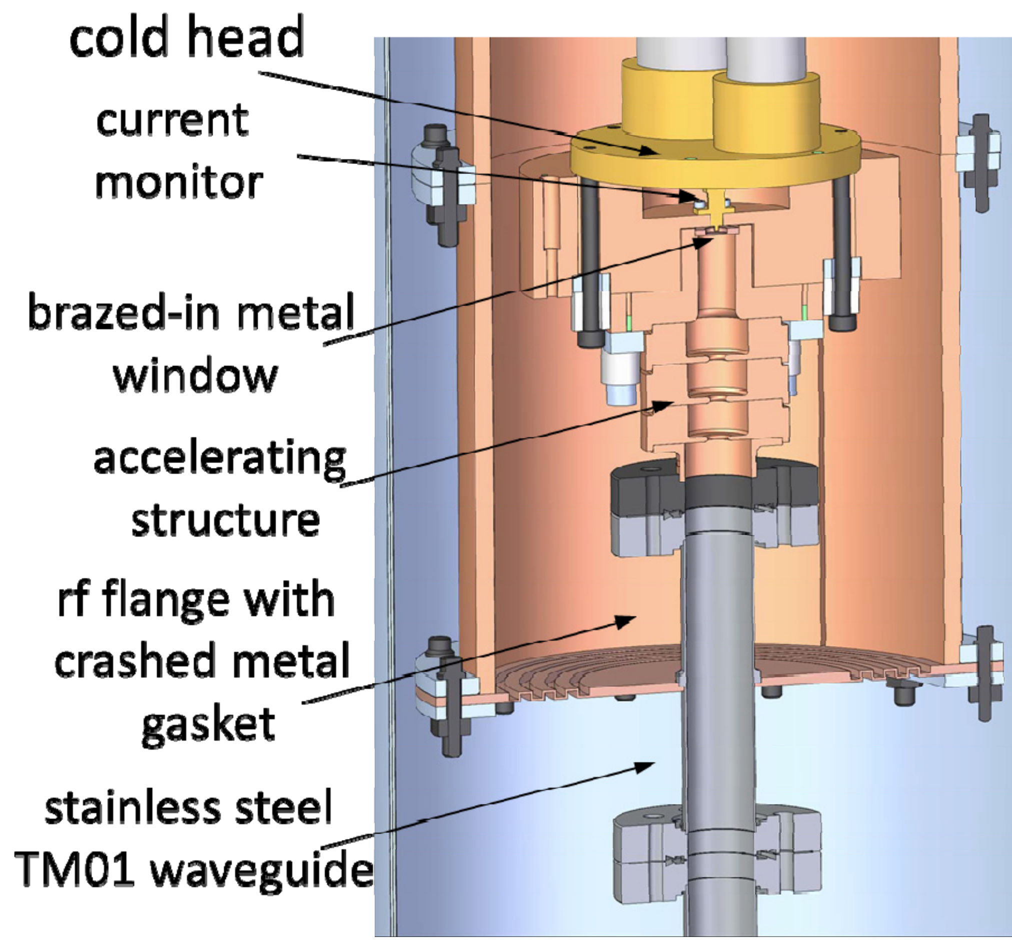


Material properties at cryogenic temperatures improves normal conducting gradient limits



Copper properties at X-band were measured before designing the experiment





Structure is running now at an ***accelerating gradient of 240 MV/m*** @ 45 K

Distributed coupling accelerator structures allow optimization of individual cell shape for peak efficiency

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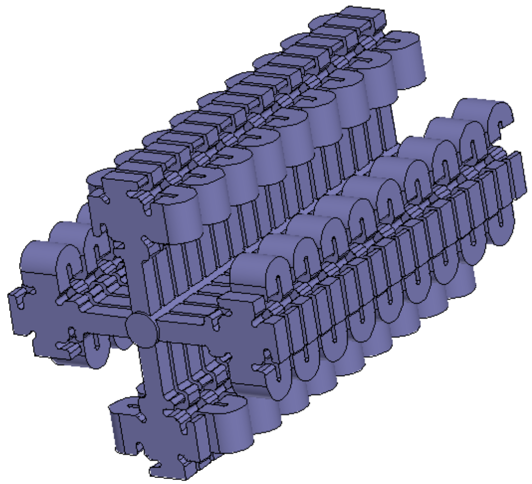
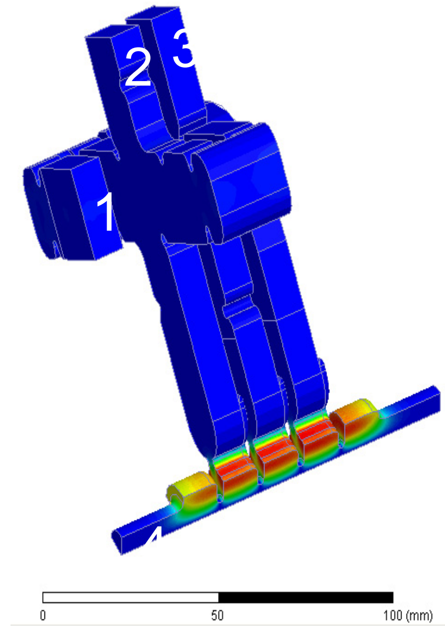
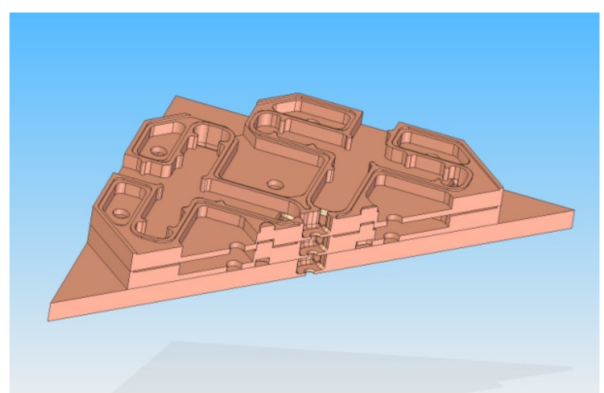
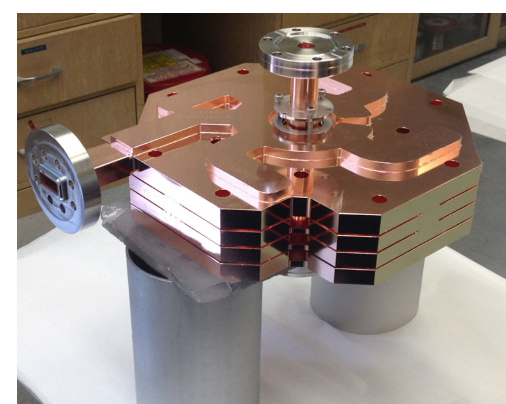
Optimizing the individual cell shape compromises the coupling between cells, hence, we needed to invent a method for distributed coupling

- Structure can be built using brazing and diffusion bonding processes because the directional coupler and the bends are manufactured on the same cell plate
- Most suitable for normal conducting high repetition rate applications
- Interest from some industrial firms to license this technology









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Developed a new type of accelerator structure that is a radical departure from the conventional wisdom, 2x more efficient device.

Shunt Impedance: 155.5 Mohm/m

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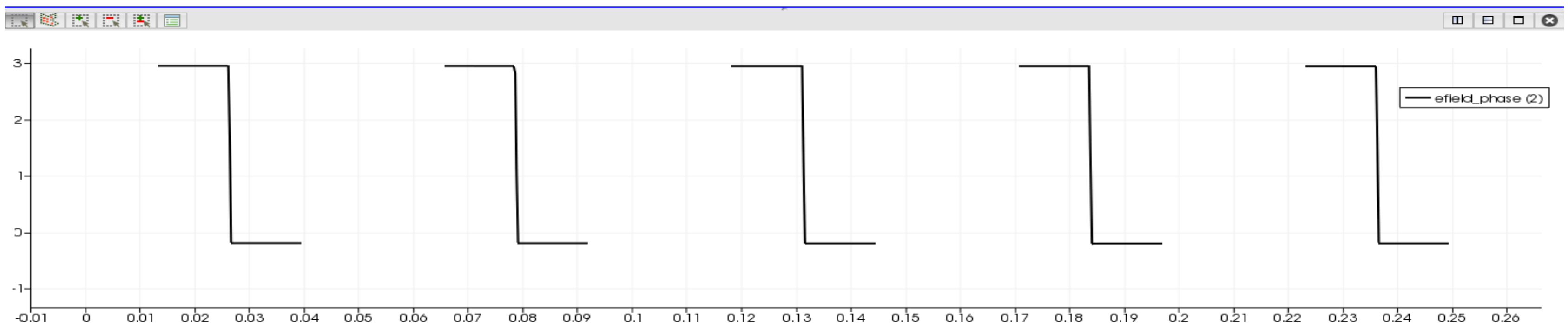
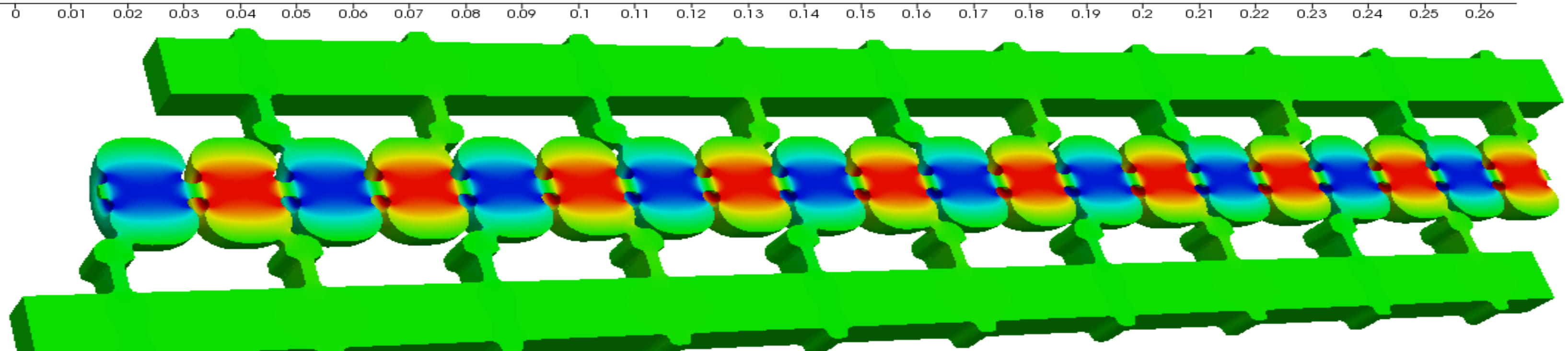
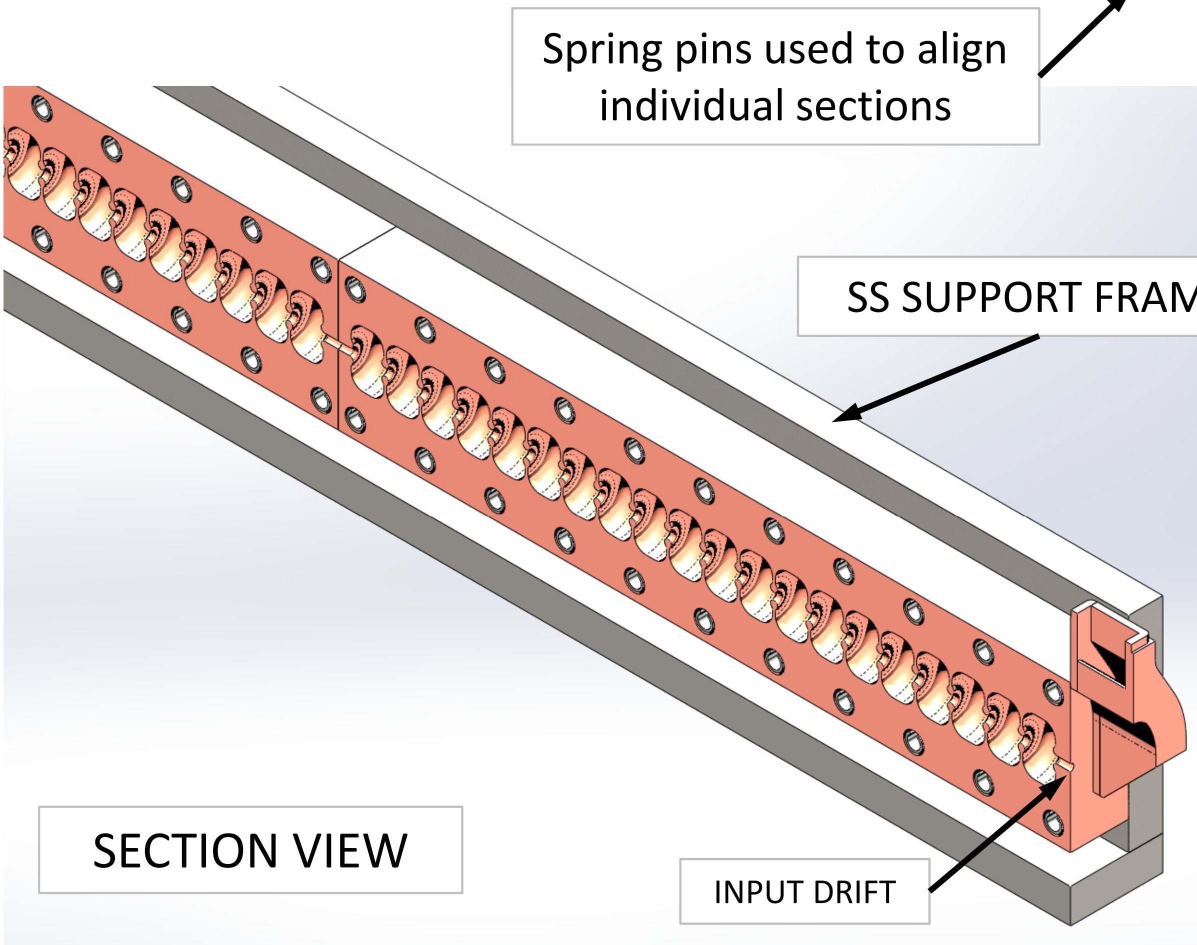


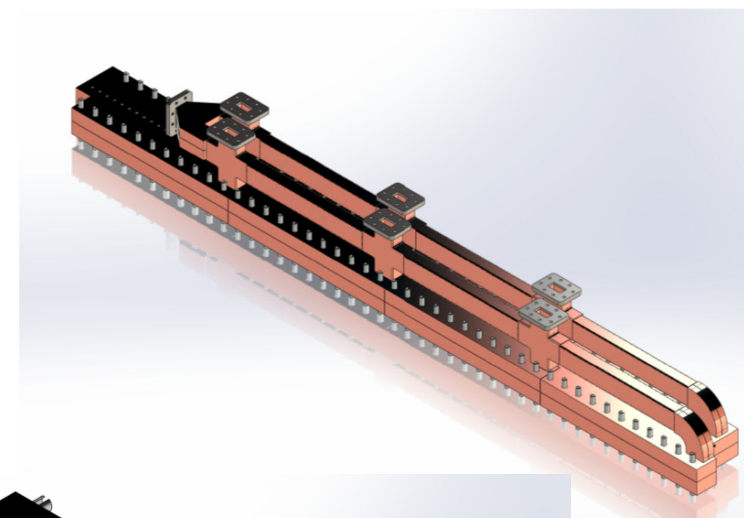


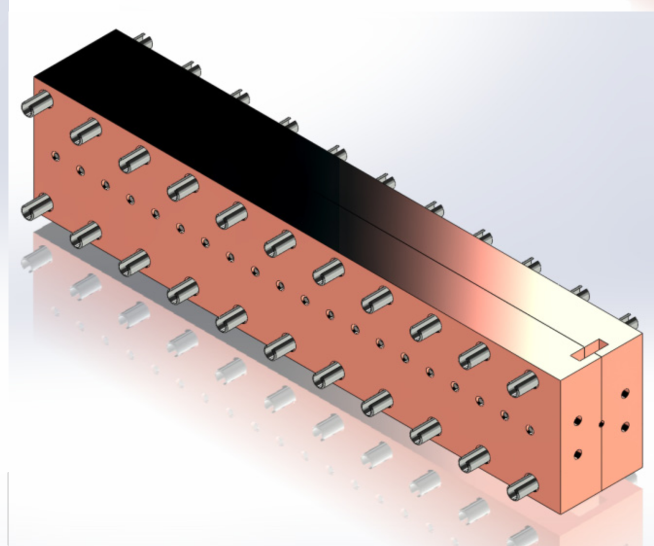
Final Accelerator Assembly Concept for 100 MV/m

Four Sections are Joined Together to make Full Accelerator Structure

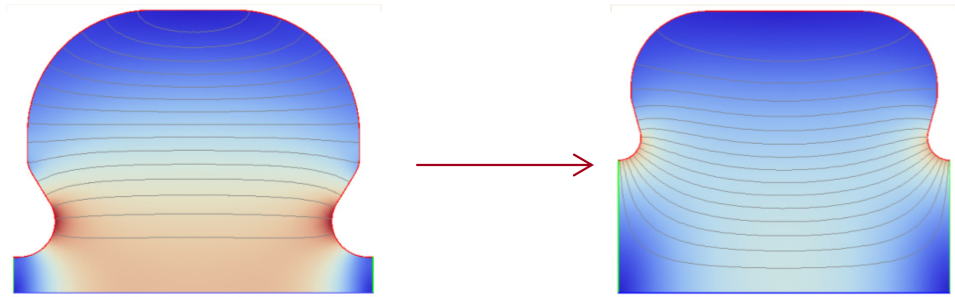
Accelerator Assembly with Four Sections of 20 Cells each (80 Cells Total)

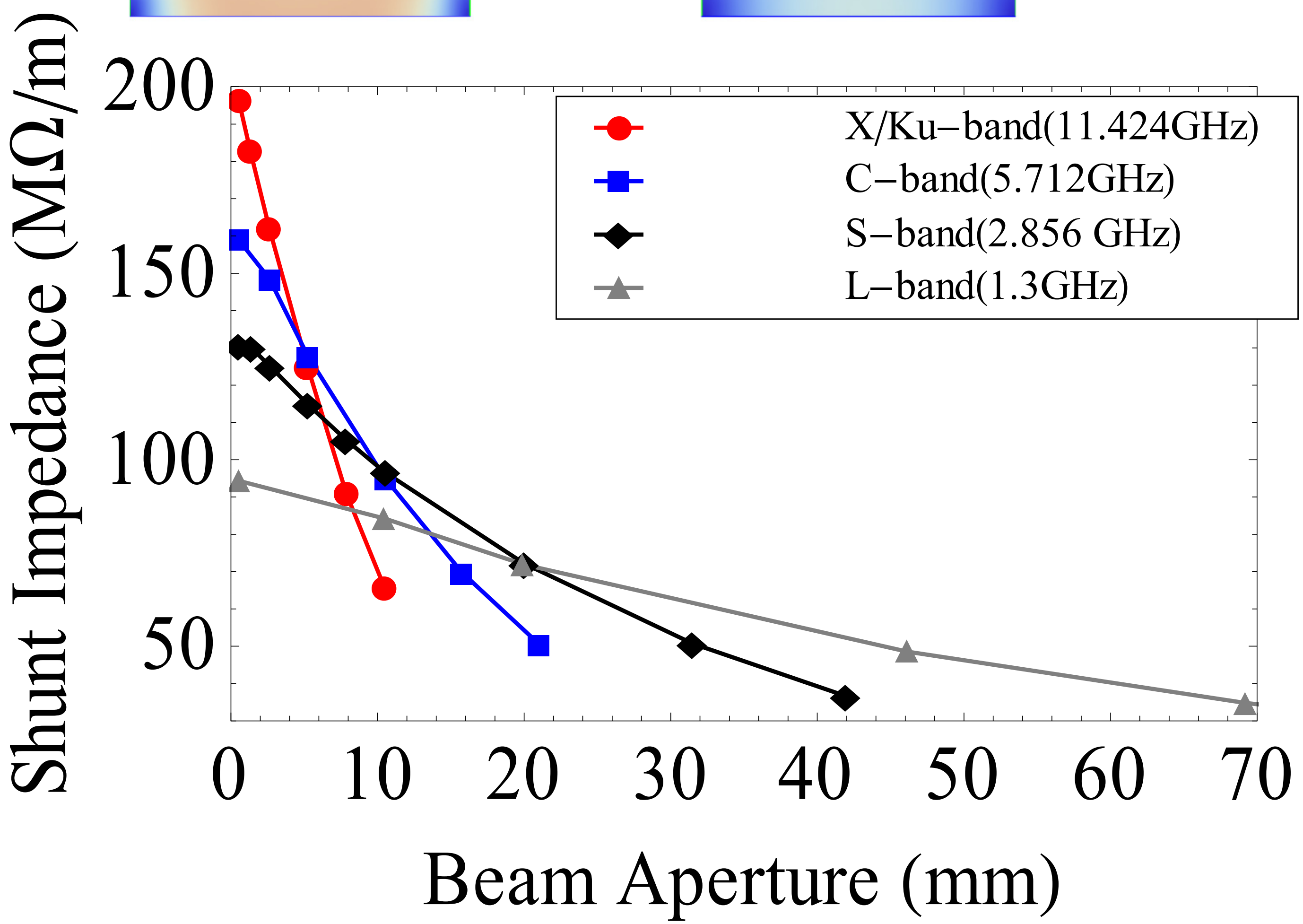






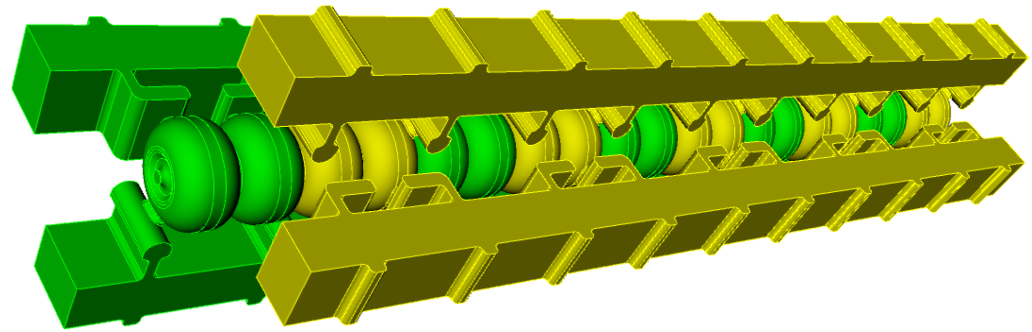
Frequency choice for highly optimized standing wave structure with distributed feeding

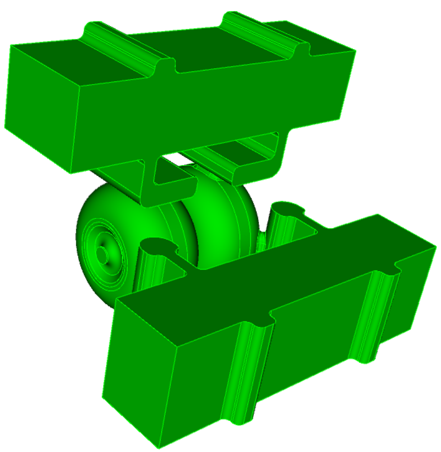


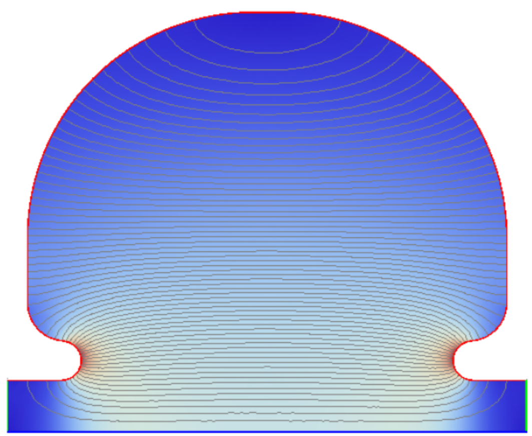


Common sub-harmonic two-frequency acceleration, 3x improvement in efficiency

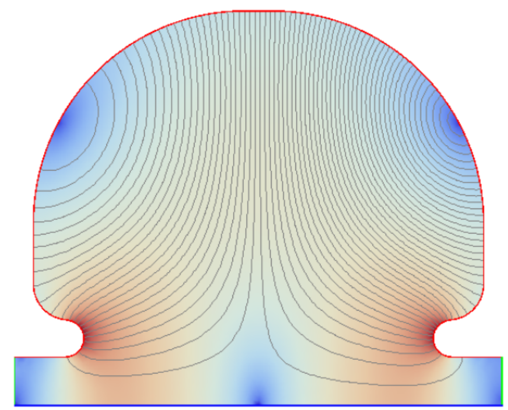
- Two harmonically related frequencies have been suggested before
- But this lowers the efficiency of the structure
- For single bunch operation, one can choose frequencies that simply have a common sub-harmonic.



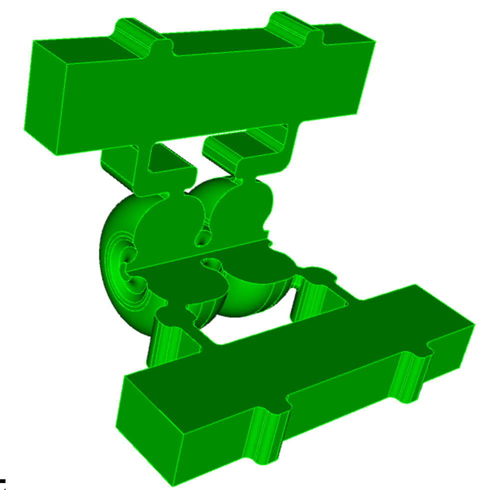




=11.424 GHz
Rs=181 MΩ/m



f=18.309 GHz
Rs=63 MΩ/m



Common sub-harmonic is 300 MHz

Structure has total Shunt Impedance of 244 MΩ/m.
Expect ~300 MV/m gradient at room temperature.

Initial experiments with 100 GHz copper and stainless steel accelerating structures capable of 1 GV/m accelerating gradients

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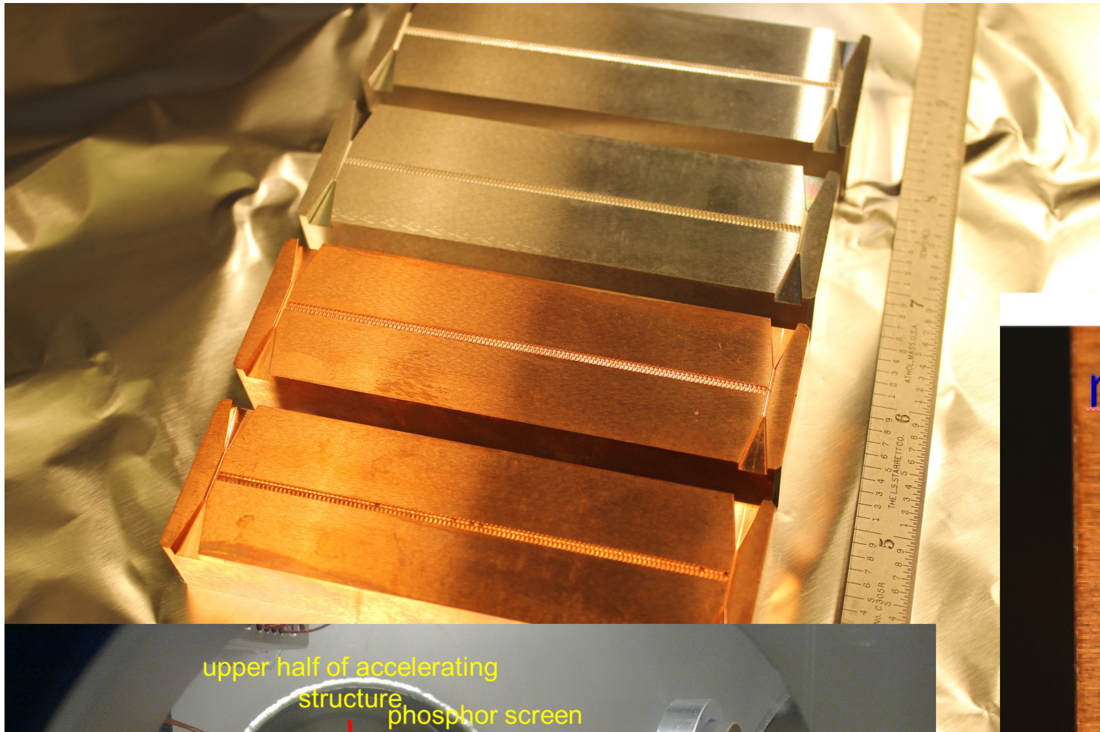

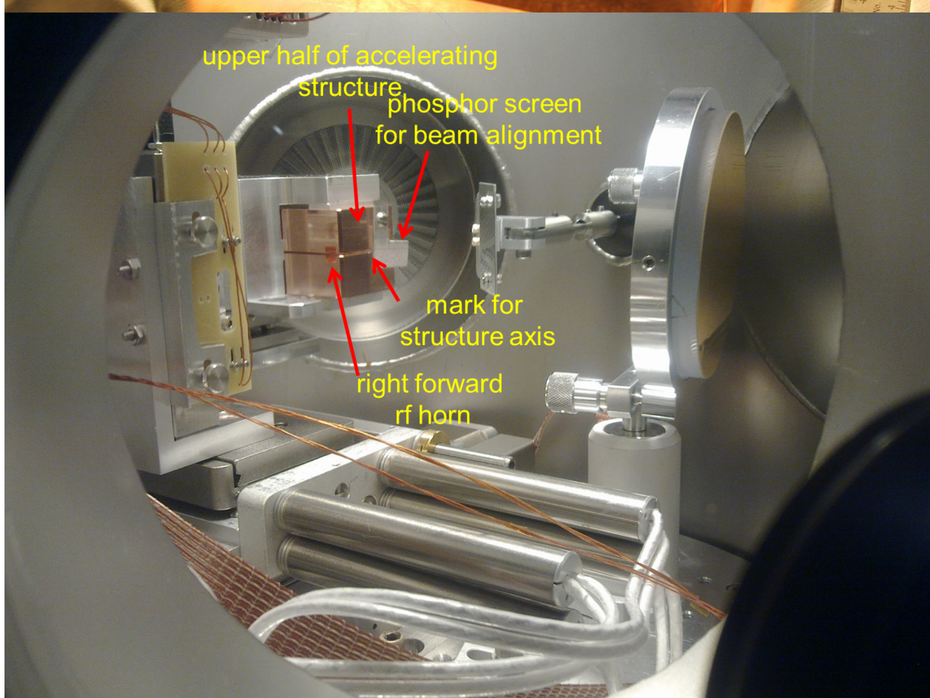

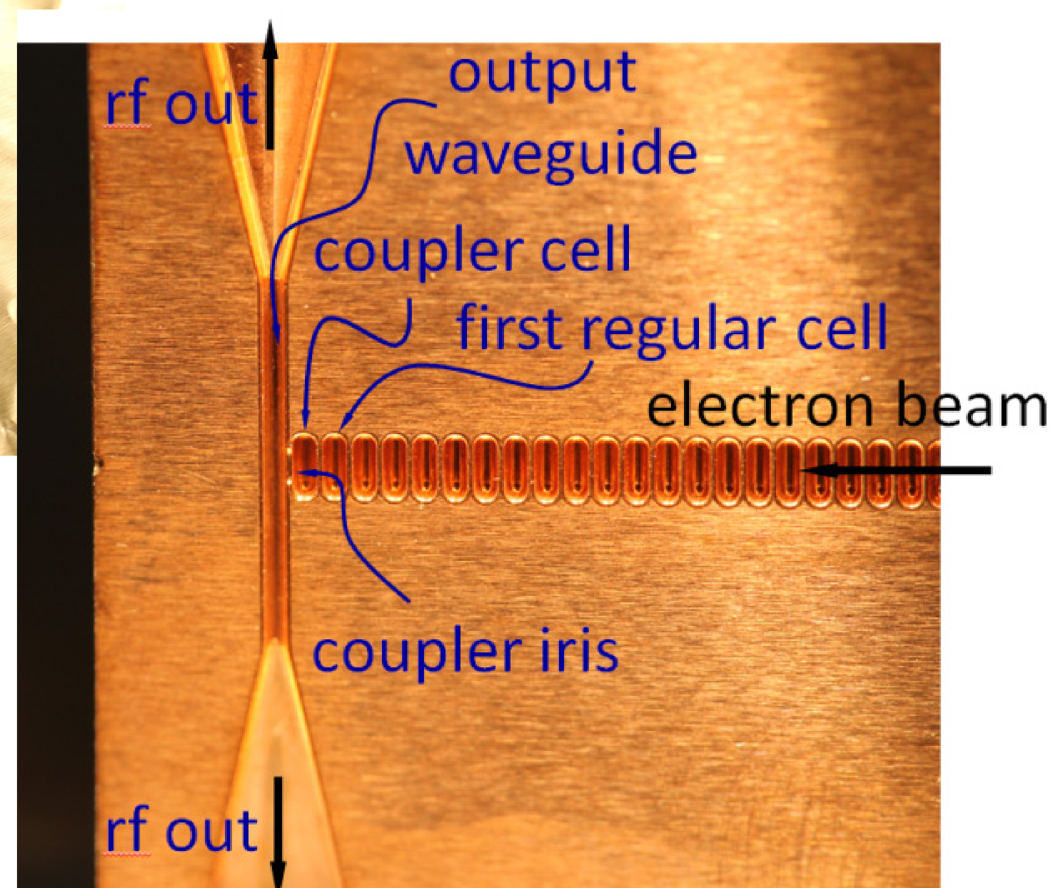

Structure autopsy after being subjected to fields ~5.5 GV/m

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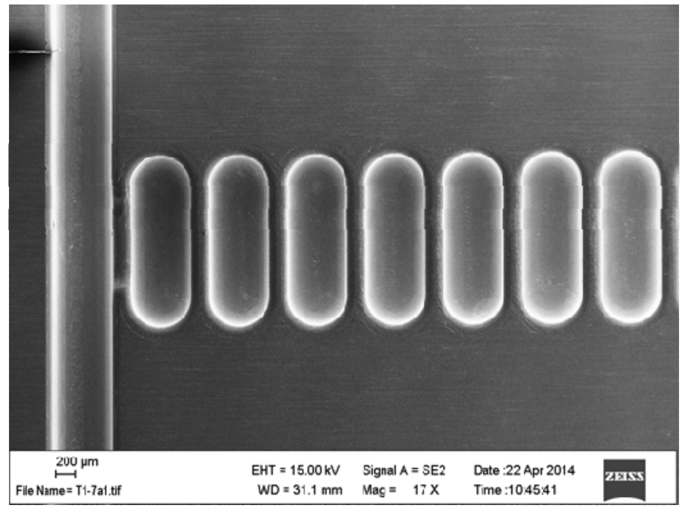
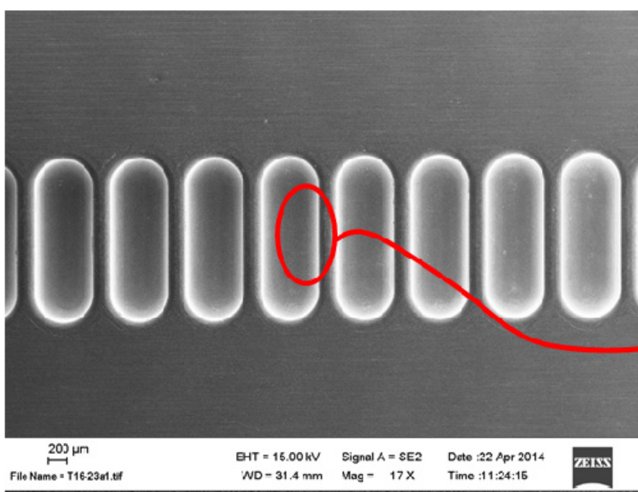
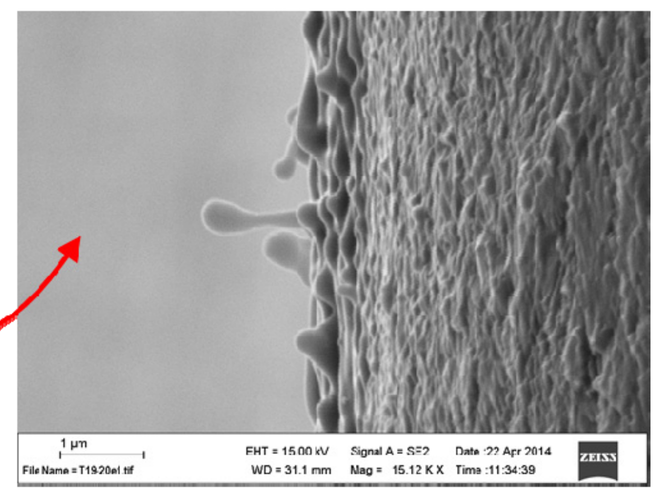
electron beam



Input coupler, cells 1-7, no damage



Cells 16-23, fist signs of damage



Iris 19-20, fist signs of damage

Next Step: Advanced High Frequency Acceleration Program Focuses on Source Efficiency and Frequency Reach

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Basic physics of Microwave Acceleration leads to~
0.2 GV/m
T_f ~100 ns

Applications of HG Research and Technology

- High gradient
- Efficiency
- Build-ability

Higher Gradient requires shorter filling times; i.e., higher frequency
FACET Experiment, 3 ns pulse
1 GV/m @116 GHz

- Sources
- Novel energy recovery & short pulse lengths

Research on GV/m in metallic structures at mm waves to THz regime

- Generate power @ mmW –THz wavelengths

RF source & accelerator science in 0.1 – 1 THz spectral range

1-10 GV/m possible @ mmW-THz

Ultra high gradient accelerators
Novel Wakefield accelerators

High Gradient accelerator structures demonstrated, but RF sources are currently too inefficient, too expensive or unavailable at the higher frequencies. So…

X- Band Multi-Beam Klystron Design Specifications

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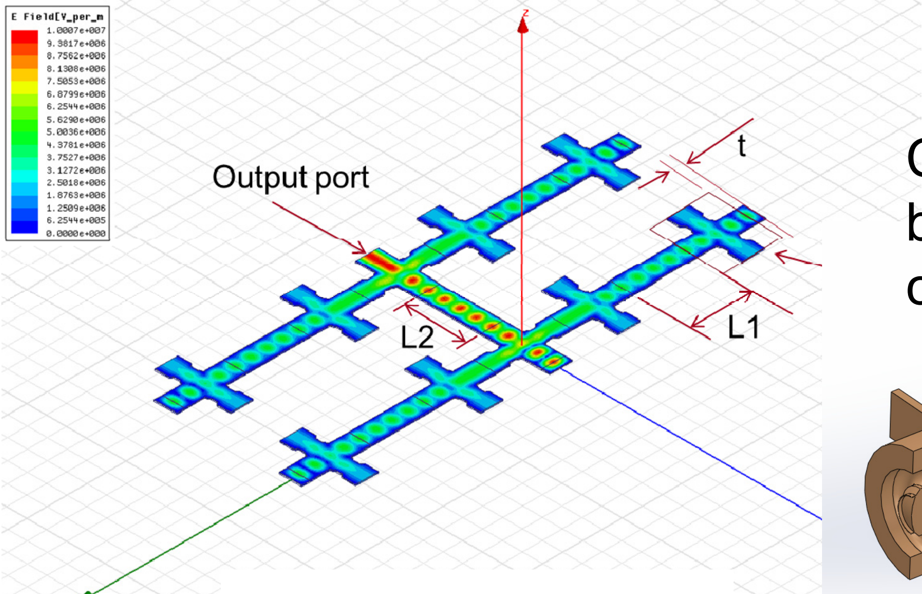
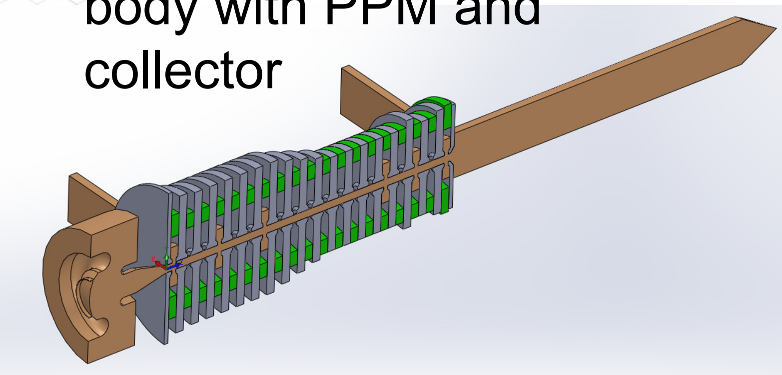
Parameter	Design Goal
Beam Voltage (kV)	60
Frequency (GHz)	11.424
Output Power (kW)	5MW
Beamlets	16
Beam Focusing	Periodic Permanent Magnet (PPM)
Efficiency (%)	60+
Cathode Loading (A/cm^2)	< 10

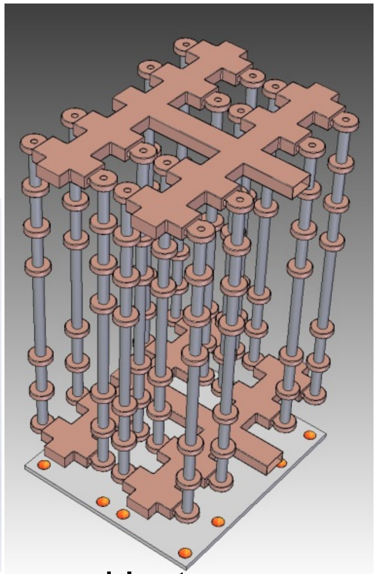
Multi-beam klystron, mechanical design is underway



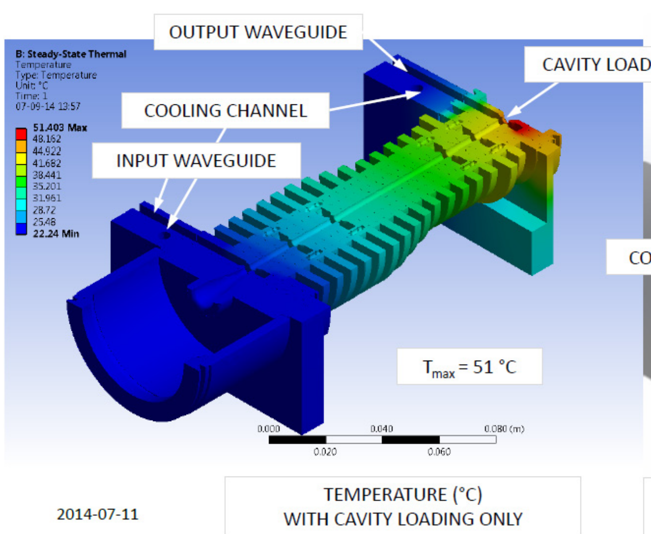
Distribution system

Cut away view of klystron body with PPM and collector

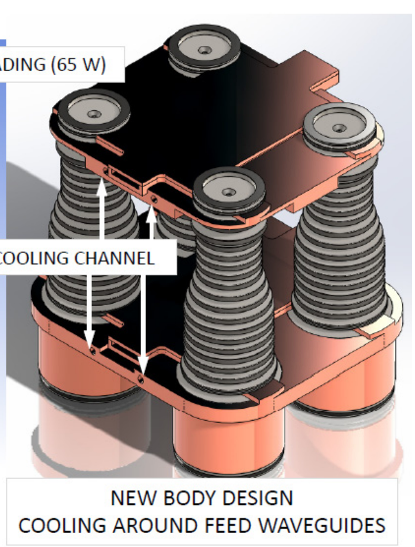




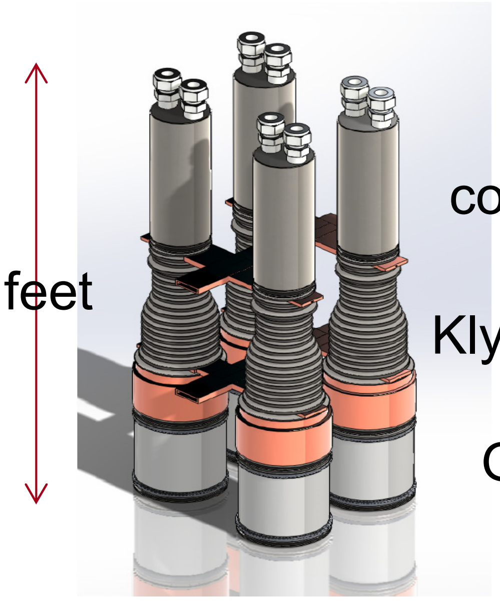
Multi-beam klystron assembly



Thermal analysis



Klystron set body



1.5 feet

collector

Klystron bod

Gun

Multi-dimensional RF sources, radial beam klystron

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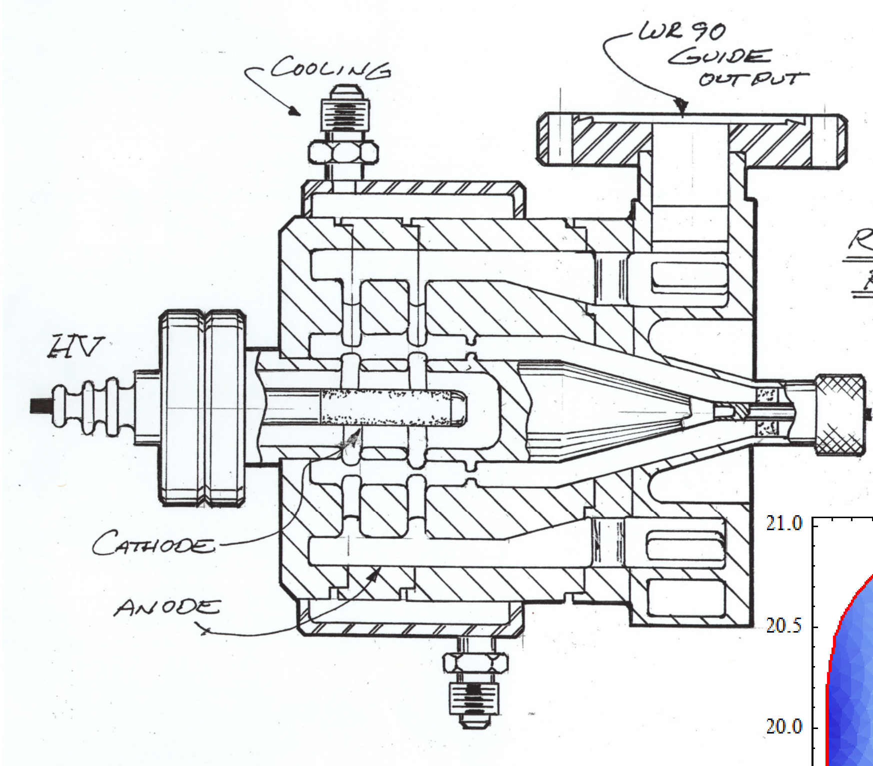

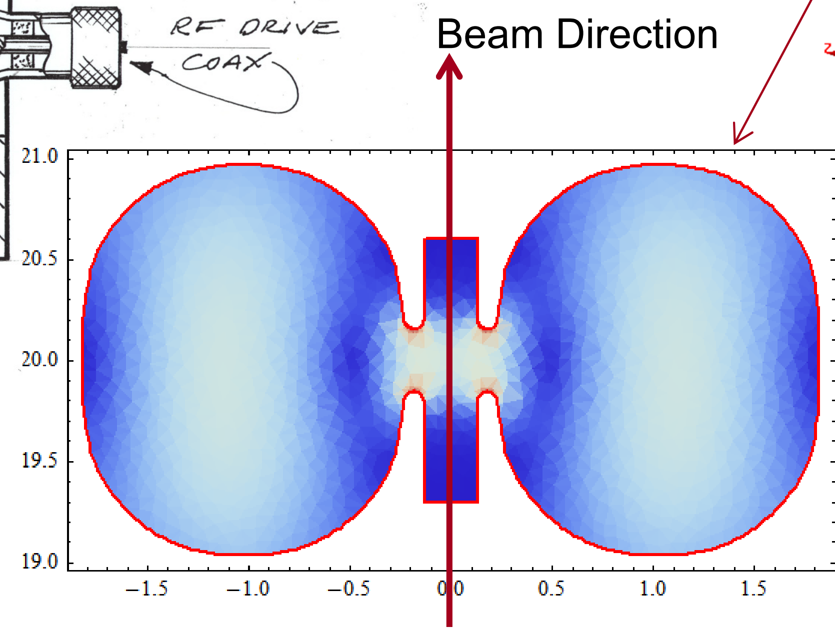

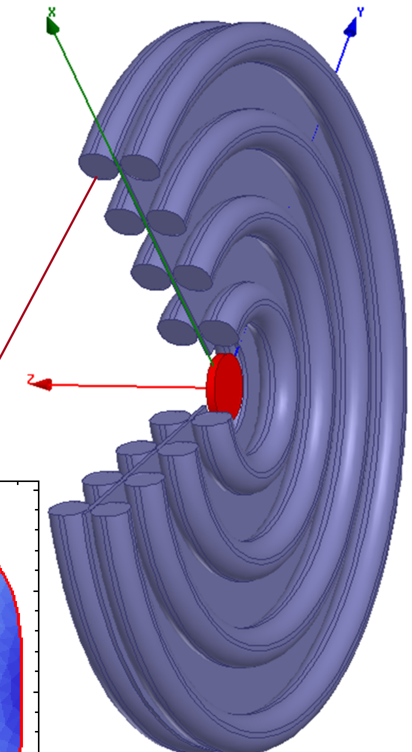

RF cavities, output cavity is at the outer diameter

- Beam naturally expands under space charge forces→magnetic focusing is not required
- The device can have high current and low voltage.
- Developed specialized codes to design and optimize the performance because the device is overmoded and has big dimensions compared to the wavelength. Existing codes cannot do the needed simulations.

(Original Idea by R. Ruth and S. Tantawi)

For mm-wave accelerators, the CSR-Maser concept may provide a viable path to high power up to THz (300 μm)

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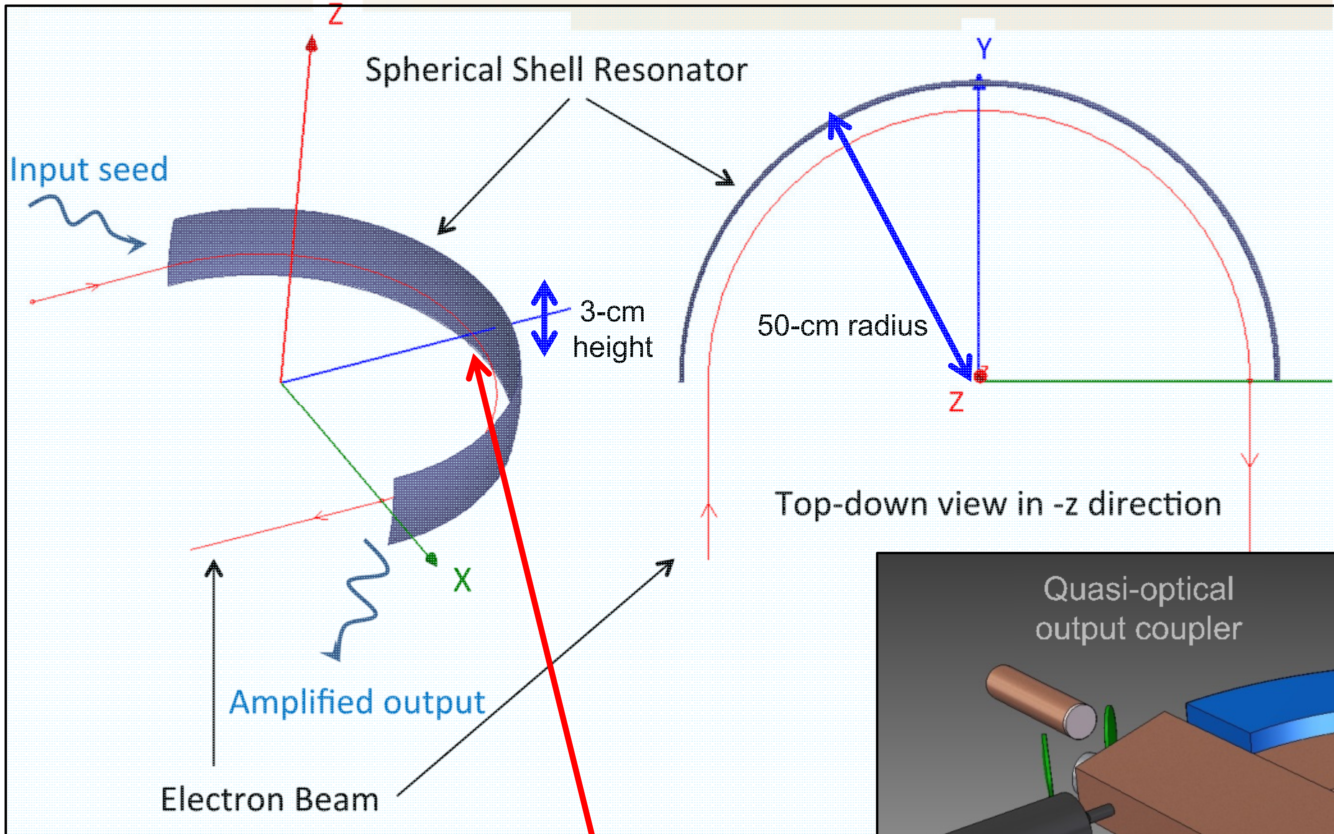
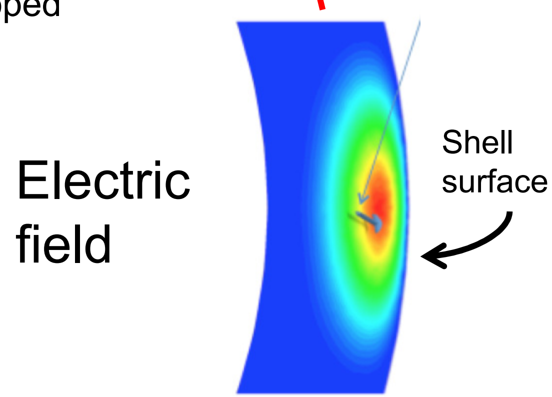
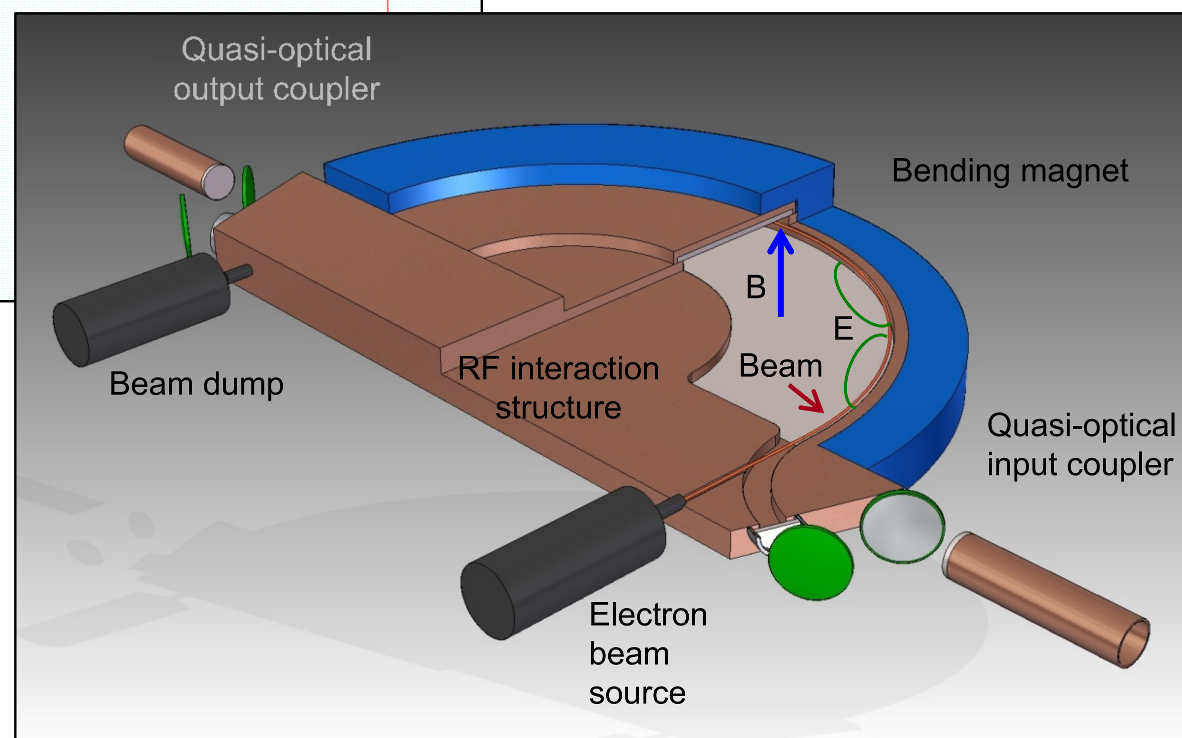


- Bunching with negative mass instability
- 10 MeV beam requires only 700 gauss guiding field
- Can trade off beam voltage, radius, & magnetic field for optimal design

Concept developed by S. Tantawi





Efficiency of 235 GHz structure, simulation results

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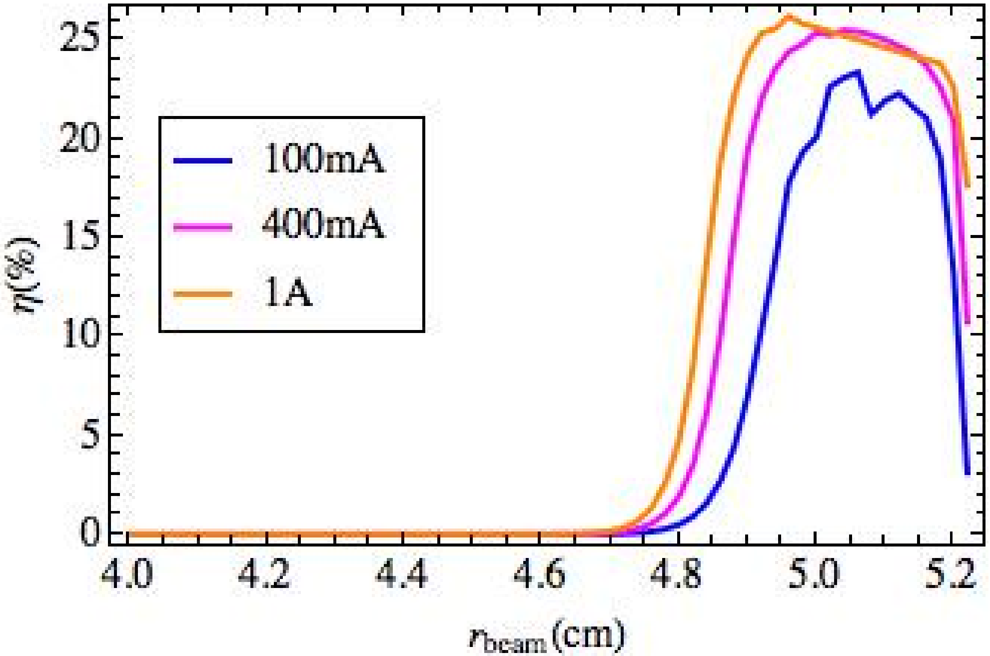
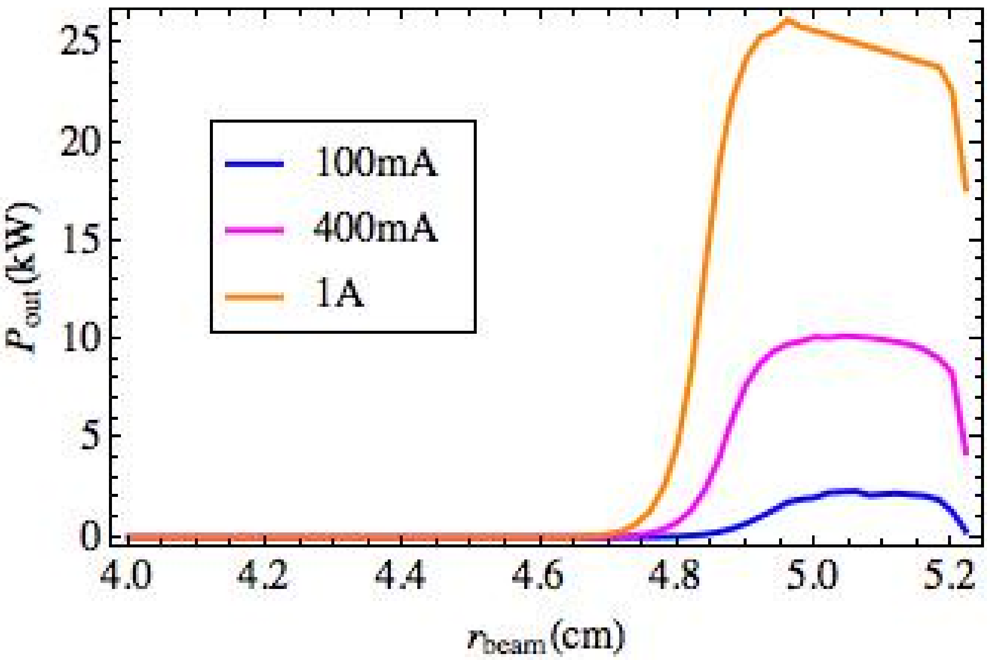




V = 100kV

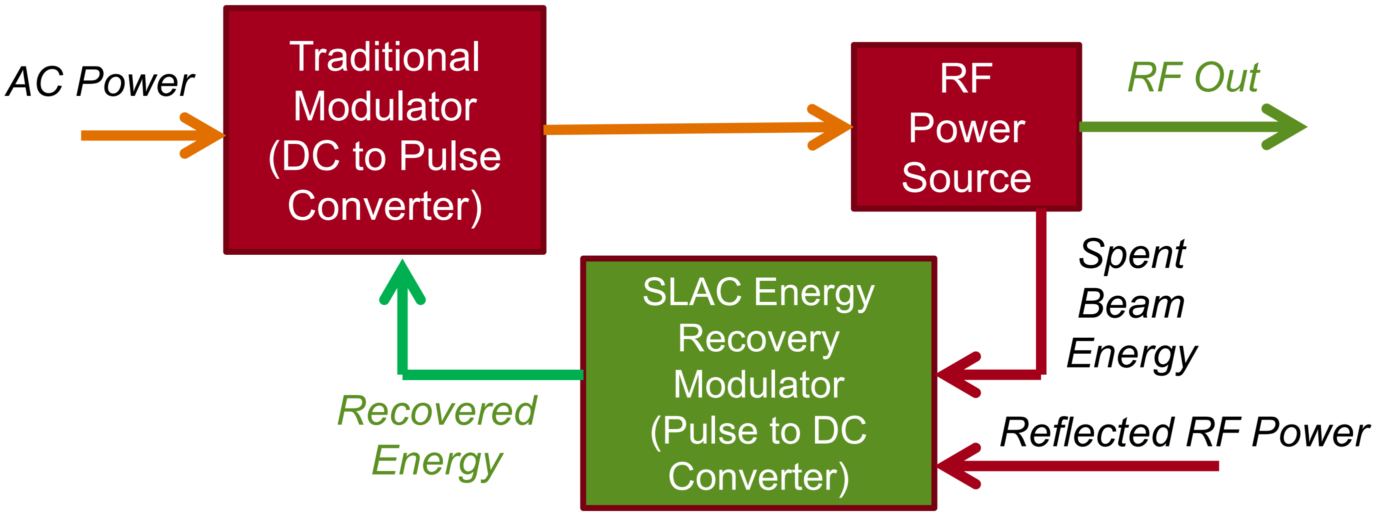
Cavity Radius = 5.24cm

Cavity Height= 1.6cm for -40dB

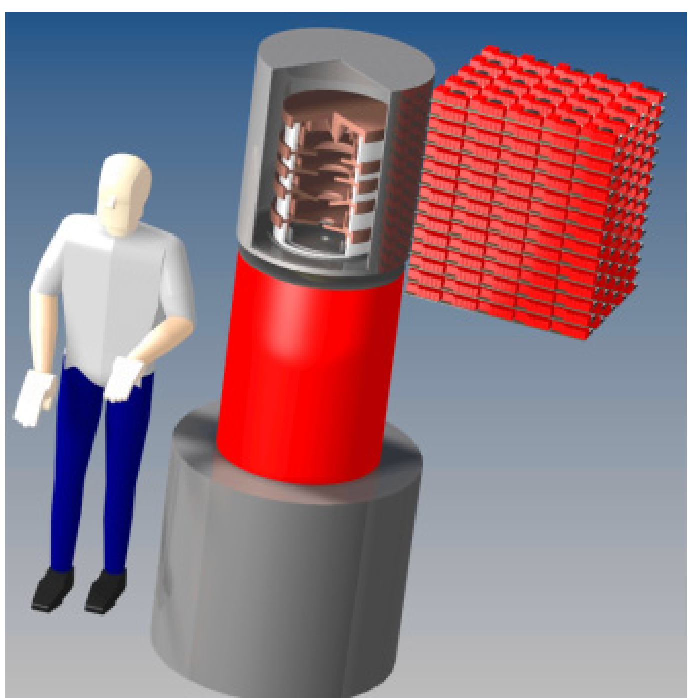
Magnetic Field = 21mT

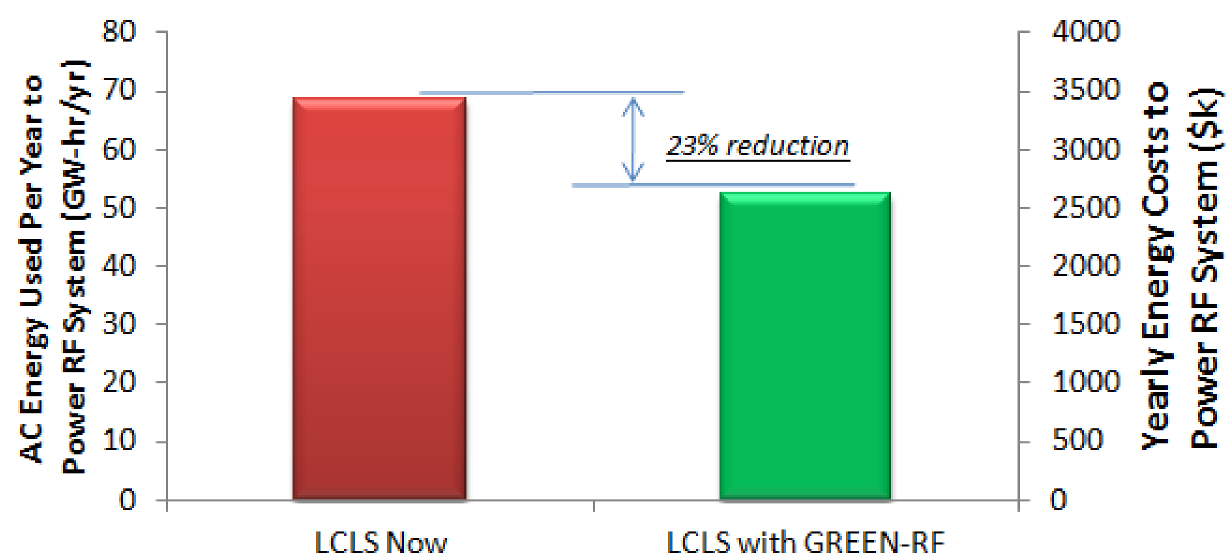
Simulation is done with our new large signal analysis code

Next-Generation Modulator Systems Both *Provide* and *Recover* Energy

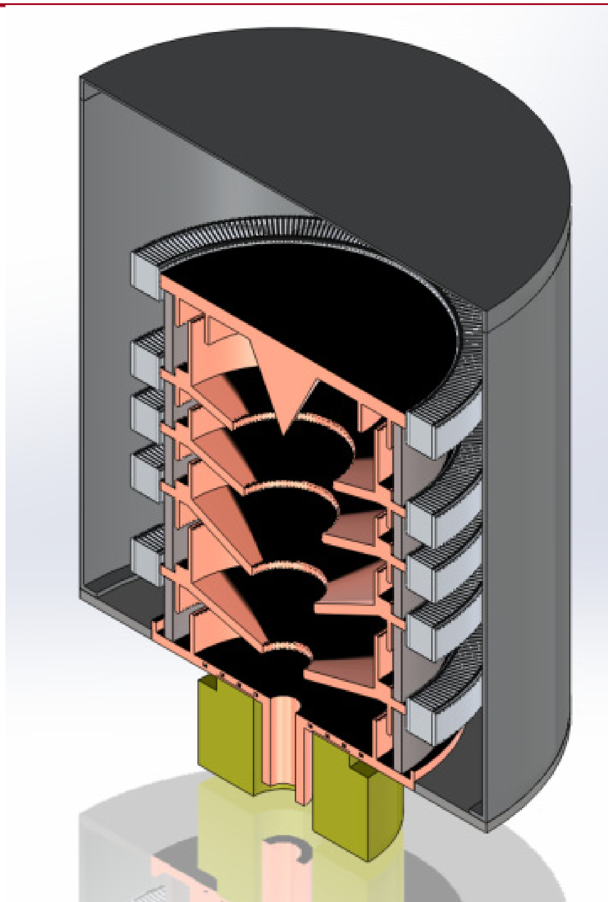


Feed-forward energy recovery modulator technology enables traditionally wasted energy to be utilized on subsequent pulses





Rapid Prototyping and Simulation Possible Due to SLAC HPRF Expertise and Infrastructure



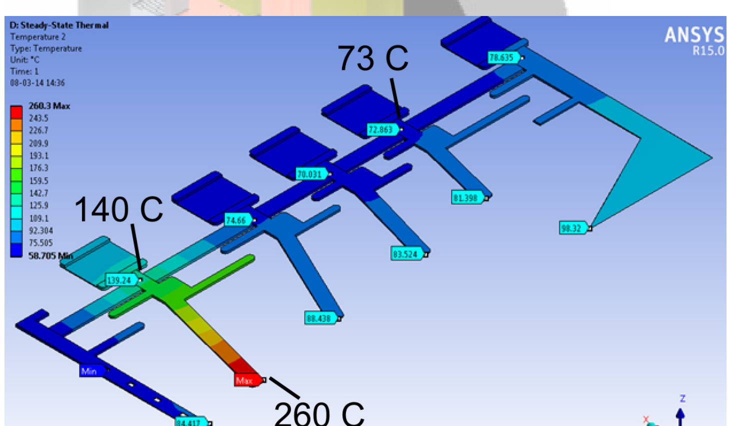
Present

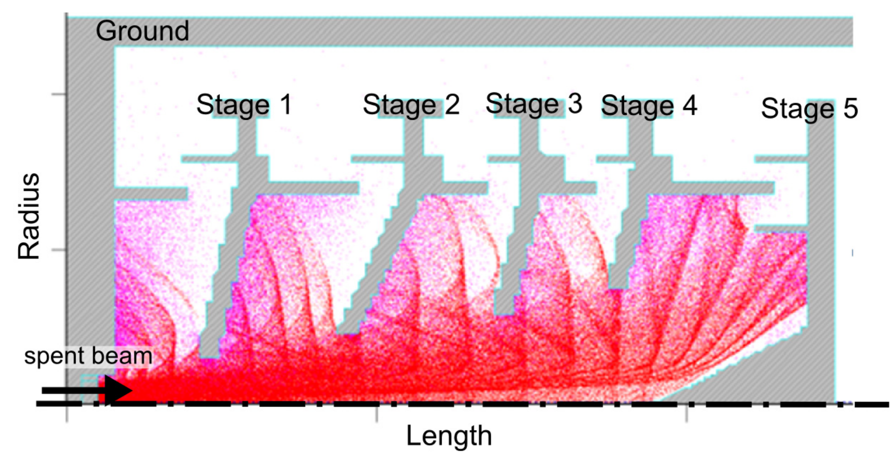
- Simulations show SLAC 5045 klystron <u>efficiency improved from 45% to over 70%</u>
- High peak and average power systems are feasible
- Rise and fall times of pulsed systems are recoverable

Future

- Long-pulse technology research
- Direct RF to DC conversion
- Ultra-compact radiative cooling
- Commercialization through industrial partners

Depressed collector/energy recovery modulator R&D is *complementary* to high-efficiency source R&D





Summary- Solid Foundation for Extending to Higher Frequency and Gradient

- Gradients increased by factor of ~3, from 65 MV/m to > 170 MV/m
- *Very high shunt impedance* can improve RF to beam efficiency
- New Structure Topologies could go beyond 200 MV/m ***efficiently***:
  - ***Pave the way for future high energy colliders***
  - ***Revolutionize proton accelerators***
  - ***Provide an economical driver for plasma wakefield accelerators***
- New RF source designs improve efficiency and lower voltages:
  - Efficient modulators with short rise and fall times
  - Eliminate pulse compression for much higher system efficiency
  - Klystrons with no electromagnets and cost effective depressed collectors
- High efficiency allows NCRF operation beyond 10 KHz
- Many other applications - light sources, medical linacs, ...