Advanced High Gradient High Efficiency RF Technology

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgment

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Outline

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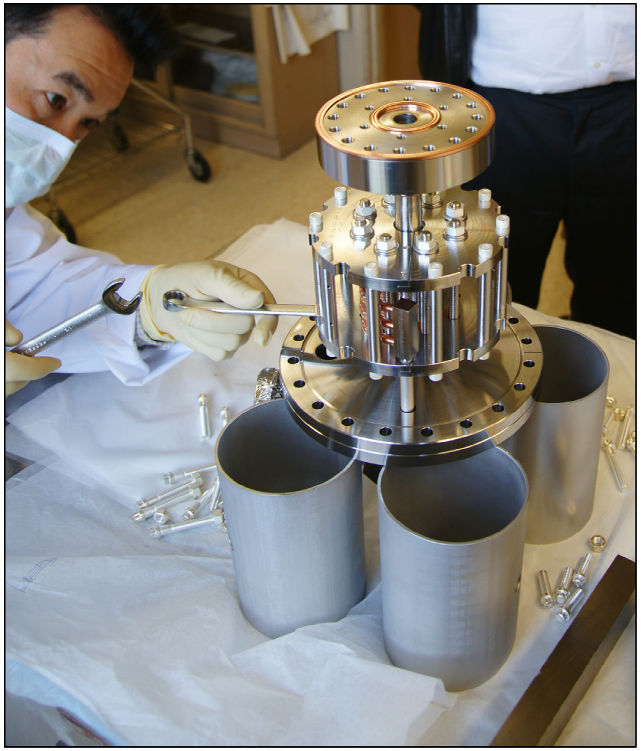
- History of High Gradient (HG) Research
- Basic physics research on the RF breakdown phenomena
- Application to modern accelerator structure designs
- Applications of modern accelerator technology to Medical Linacs: a paradigm shift
- Summary



Clamped structure for testing without brazing

Core Areas of Research for the Advancement of RF Accelerator Technology

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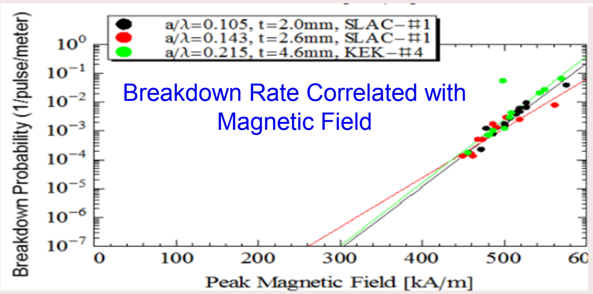
Physics of Breakdown

Discovery of Magnetic Field's Role in Breakdown Triggered New Research Initiative

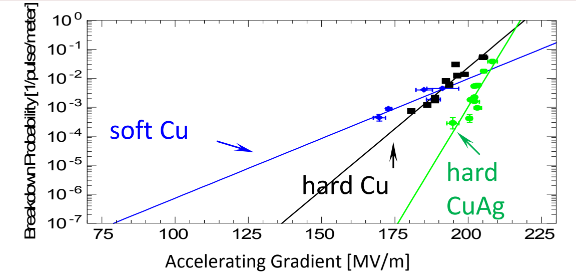
- Achieved through studies of surface electric and magnetic fields, processing techniques, surface finish



Materials Science

Investigate Materials to Improve the Performance of High Gradient Accelerating Structures

- Enhanced performance with increasing material strength
- Low temperature operation also increases the strength of materials



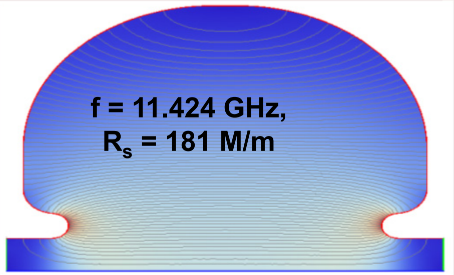
Innovative Electrodynamics

Geometry of Accelerating Structures Optimized Accounting for:

1. ***Our New Understanding of the Physics of Breakdown (magnetic fields, materials etc.)***

AND

2. ***The Beam Parameters Required for a Specific Application***

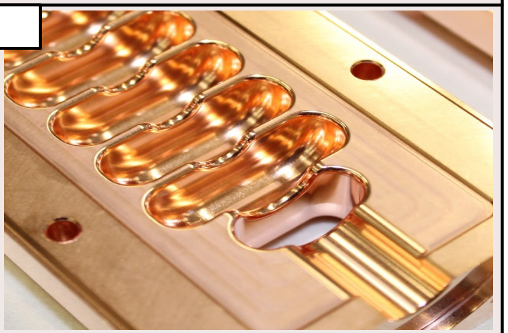


Geometry optimizations for accelerator structures based on reduction of the magnetic surface field

Manufacturing Engineering

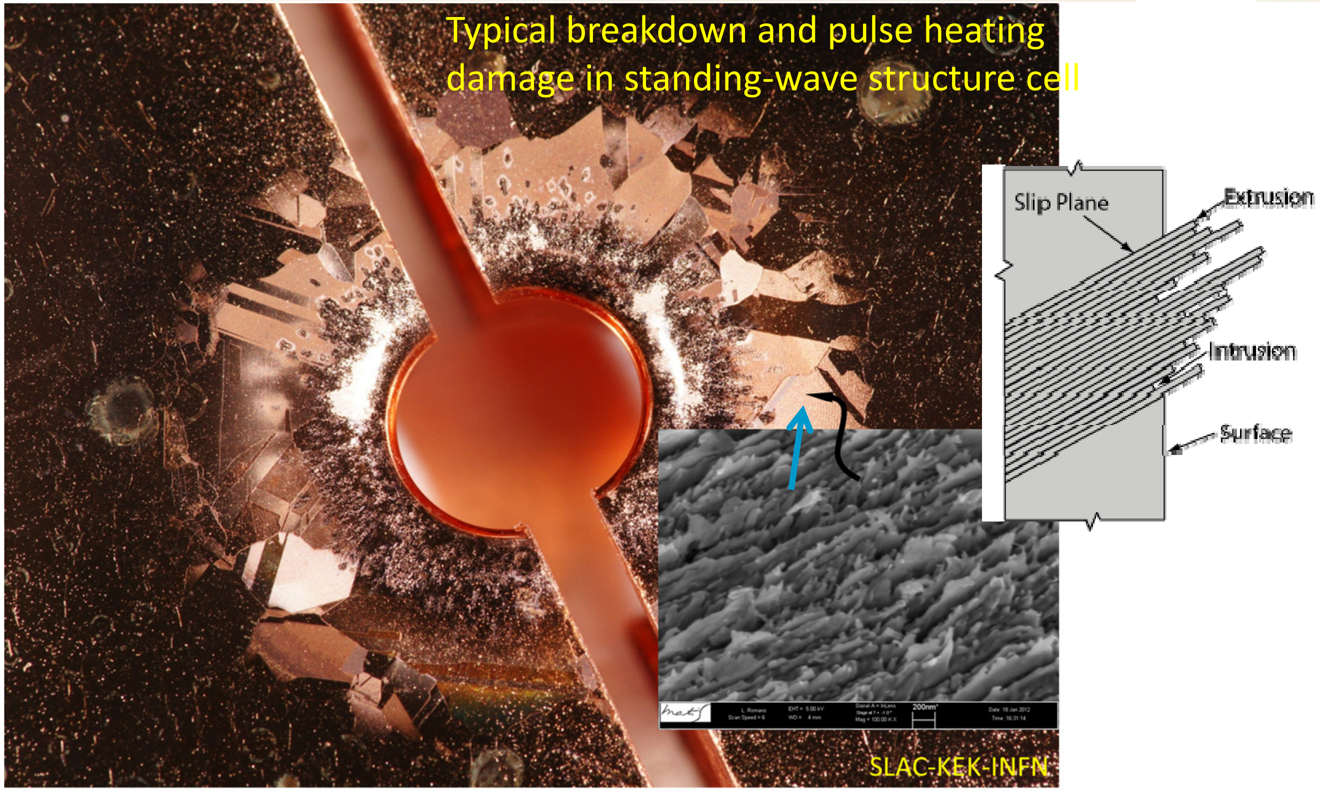
Manufacturing Techniques that are Compatible with Superior Materials and Unique Geometries

- Low temperature assembly with clamped structures and welding
- Split-block machining for increased flexibility in fabricating advanced structures and reducing cost



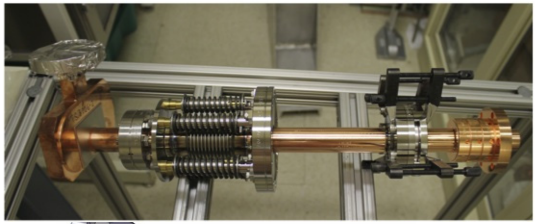
Novel split-block assembly for novel gap accelerator

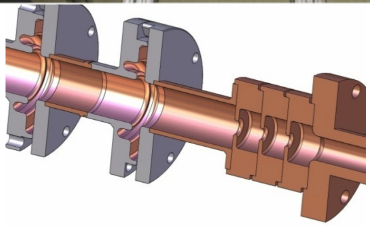
More than 60 different structures have been tested to date, each takes about a month to test and collect statistics.

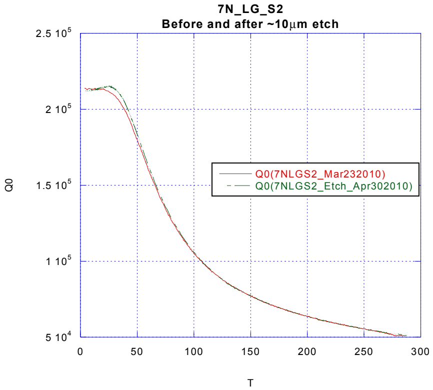


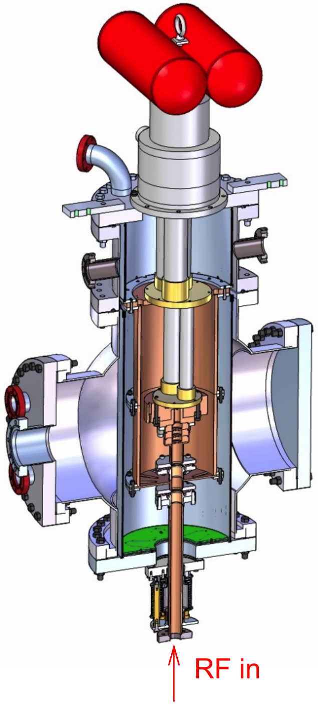
Accelerator Structures at Cryogenic Temperatures

- We made detailed measurements for copper conductivity at 11.424 GHz. Because of the anomalous skin effect this data was not available.
- Conductivity increases (by a factor of 17.6 at 25K), enough to reduce cyclic stresses.
- The yield strength of copper improves.
- The experiment is currently running



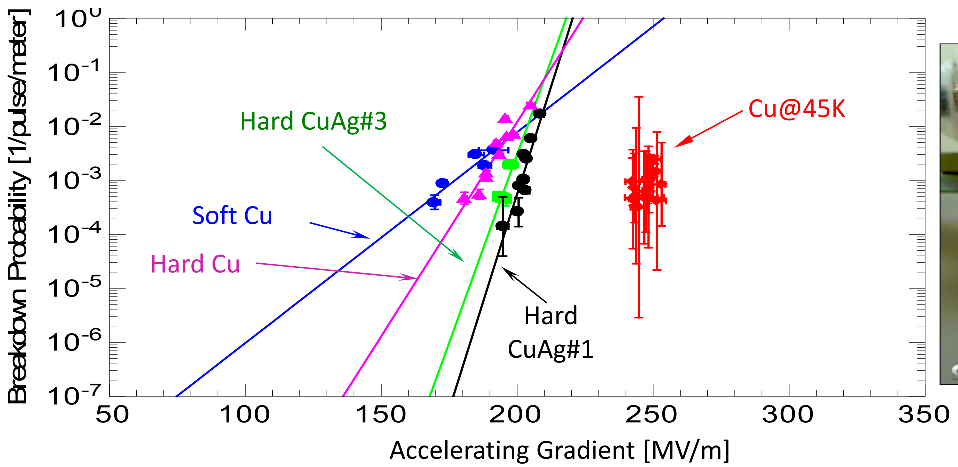


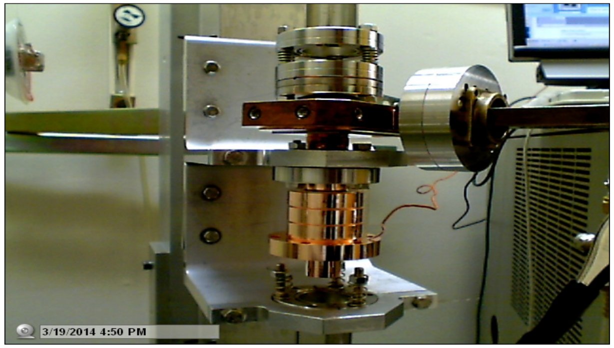




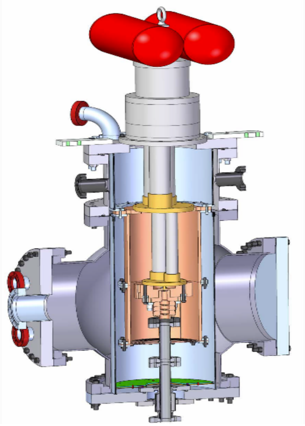
Understanding the Physics of Breakdown at High Gradients has Established the Limits Normal-Conducting Copper Structures

- Material properties determine the performance of accelerating structures at high gradient
- Dislocations caused by stress from fields form protrusions
- Reduced in higher strength materials and at lower temperatures





Bead Pull Test

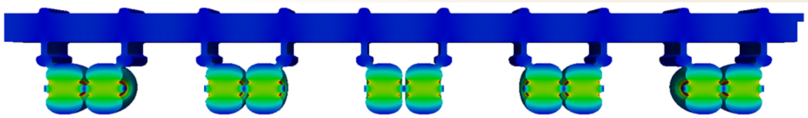


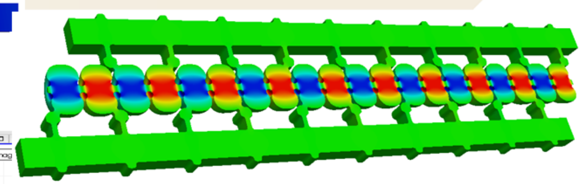
Cryostat assembly

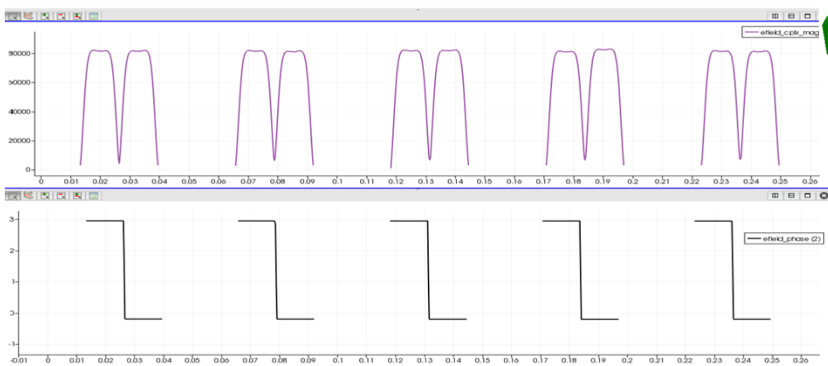
- Controlling material properties for accelerating structures has produced dramatic improvements in the achievable accelerating gradient

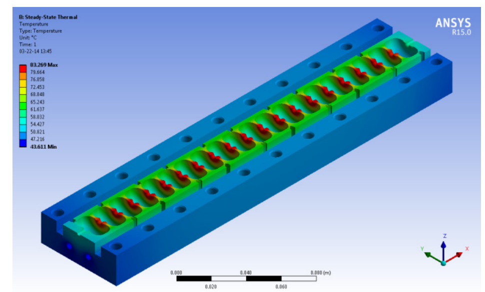
V. Dolgashev, S. Tantawi

Novel Distributed Coupling to Each Accelerator Cell Enables *Doubling* RF to Beam Efficiency and Ultra-High-Gradient Operation.



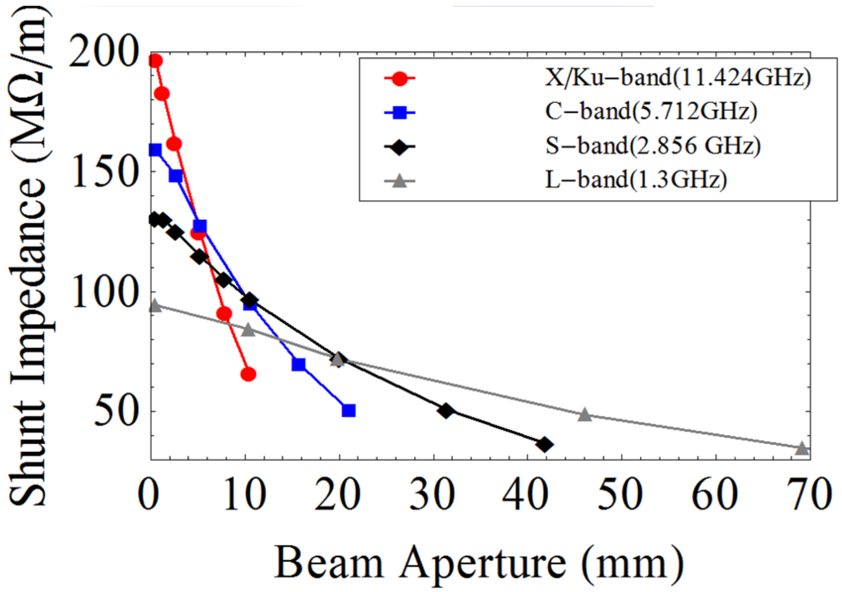






- Optimize individual cell shape for maximum gradient and shunt impedance without cell-to-cell coupling constraint
- Requires only 66 MW/m for 100 MV/m gradient compared to 200 MW/m for a typical X-band structure
- **Inexpensive to manufacture**
- Patent filed by Stanford
- **First 150 MV/m accelerator structure of this class is now under testing at high power**

highly optimized standingwave structure with distributed feeding allow for new possibilities



With the enhanced shunt impedance, it is quite possible to have a very light weight 1 MeV Accelerator powered by a solid state drivers as a replacement for Ir192

Novel Distributed Coupling to Each Accelerator Cell Enables *Doubling* RF to Beam Efficiency and Ultra-High-Gradient Operation

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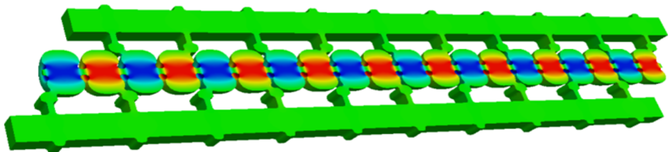
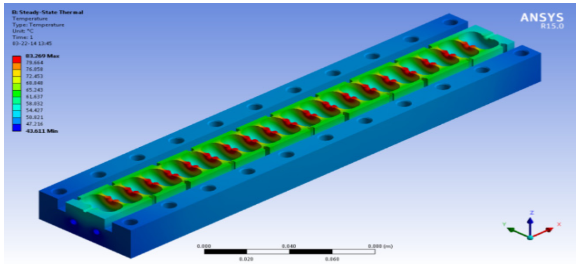
- Structure is much more efficient, easy to build and tune
- Successful High-Gradient Demonstration: 300 ns pulses @ 120 MeV/m with no observable breakdown after ~50 hours

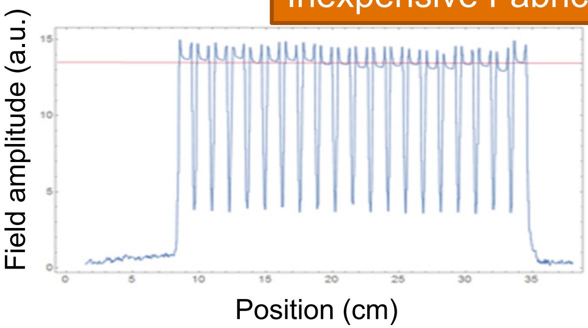


Distributed Coupling to Each Cell

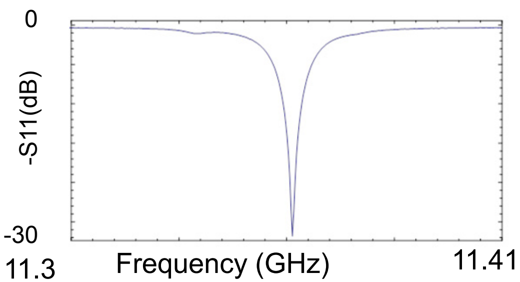
Inexpensive Fabrication Demonstrated



Solid-Model of Split-Block Assembly



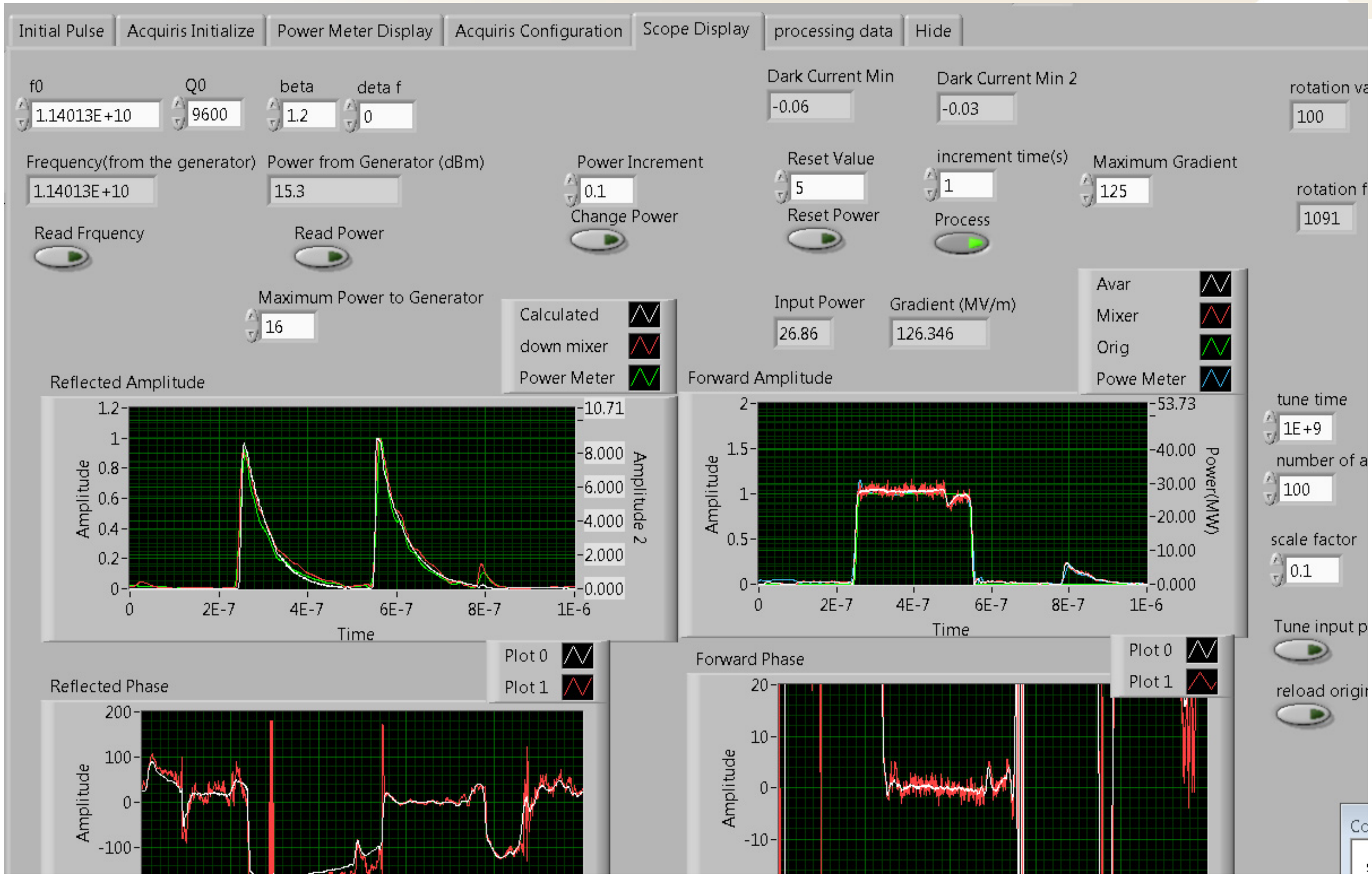
Easy Tuning



Single frequency rather than the traditional 20 resonances

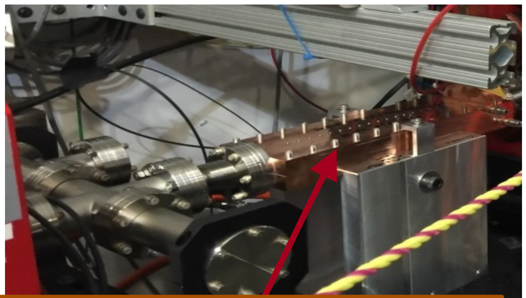
- Only possible through modern virtual prototyping using high power computing

S. Tantawi, P. Borchard, Z. Li



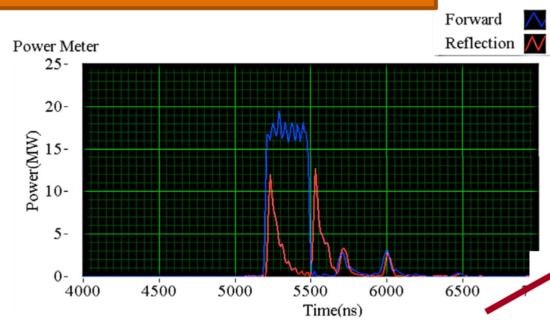
Initial Pulse
Acquiris Initialize
Power Meter Display
Acquiris Configuration
Scope Display
processing data
Hide
f0
1.14013E+10
Q0
9600
beta
1.2
deta f
0
Dark Current Min
-0.06
Dark Current Min 2
-0.03
Frequency(from the generator)
1.14013E+10
Power from Generator (dBm)
15.3
Power Increment
0.1
Change Power
Reset Value
5
Reset Power
increment time(s)
1
Process
Maximum Gradient
125
Read Frquency
Read Power
Maximum Power to Generator
16
Calculated
down mixer
Power Meter
Input Power
26.86
Gradient (MV/m)
126.346
Avar
Mixer
Orig
Powe Meter
Reflected Amplitude
Amplitude
Amplitude 2
Time
Forward Amplitude
Power(MW)
tune time
1E+9
100
scale factor
0.1
Plot 0
Plot 1
Reflected Phase
Forward Phase

Split Structure Accelerates Beam and Operates at High Gradient Demonstrating the Predicted Shunt Impedance

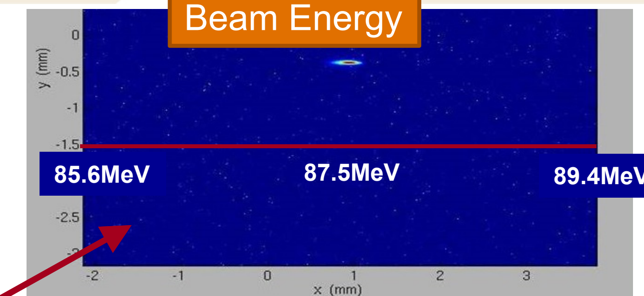


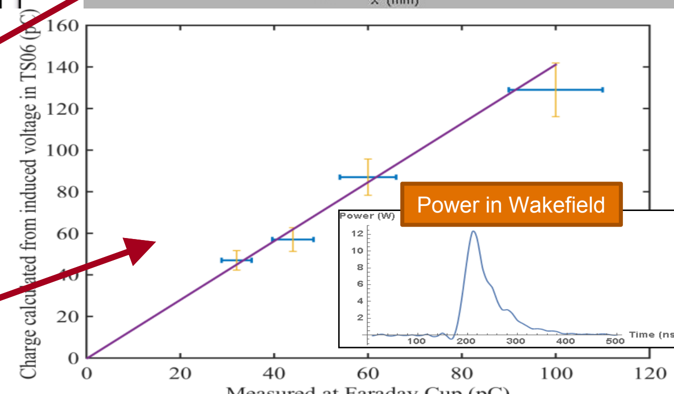
26 cm structure installed at XTA

Forward and Reflected Power



Beam Energy





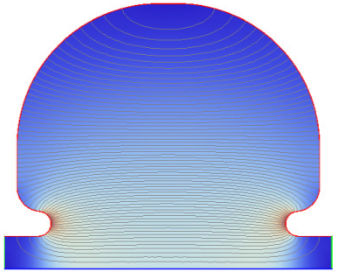
Measured Charge with Faraday Cup and Calculated from Induced Wakefield

- Confirmation of gradient by measuring 32 MeV energy gain
- Operating with ~122 MeV/m gradient with 32 MW of input power and 300 ns pulse length
- Additional confirmation of RF performance by measuring wakefield power to determine charge

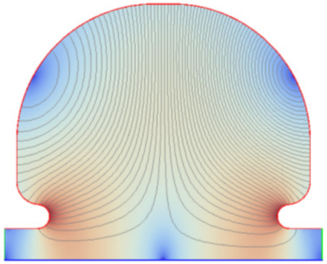
- The structure is being processed at XTA to go beyond 135 MeV/m

S. Tantawi, C. Limborg, A. Cahill, M. Nasr

Multi-Frequency Acceleration Has Potential to Impact Efficiency and Gradient of Both *Normal and Superconducting* Structures



f=11.424 GHz, Rs=181 MΩ/m



f=18.309 GHz, Rs=63 MΩ/m

- Cavity accelerates with two different RF modes
- **Efficiency:** Typically gradient ~ (power)$^{1/2}$. Double gradient by adding power in the two modes.
- **Gradient:** doubling the accelerating gradient without doubling surface fields; ~ 300 MV/m gradient at room temp
- Potential for > 70 MV/m superconducting accelerators
- Potential reduction of accelerator cryogenic load by 2x
- Opens door for many future applications related to hadrons and e+/e- facilities.

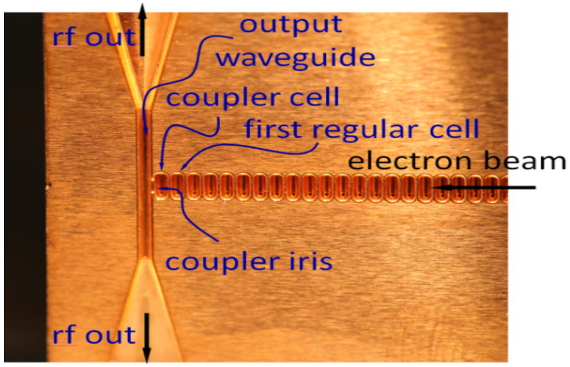
2016-2017 R&D plan
- *Need to jump start research R&D on Nb derivative films*
- *Need to create theoretical design and realistic simulation for the two mode system*

Beyond 2017
- *Implement a two frequency system in normal conducting structures and then move to superconducting structures*

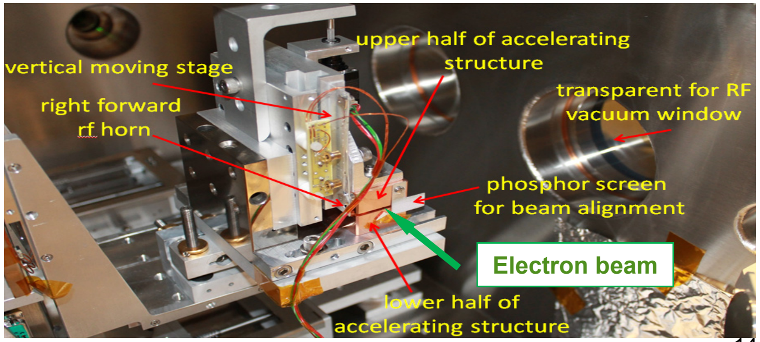
mm-Wave Metallic Accelerator Holds the Potential for High-Gradient Accelerators

- mm-wave metallic accelerators have increased shunt impedance and RF efficiency
- Need to determine statistical properties of RF breakdown in metal structures at mm-wave frequencies
  - Investigate structure geometry, accelerating gradient, pulse length and materials (Cu, SS, Cu-Ag).
- FACET beam available to produce high-gradient wakefields

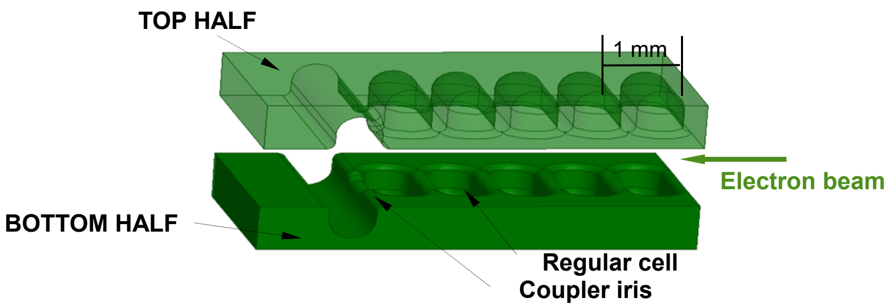
Picture of the 100 GHz copper accelerating structure



Experimental setup with copper accelerating structure – FACET E204



Solid model of the 100 GHz accelerating structure



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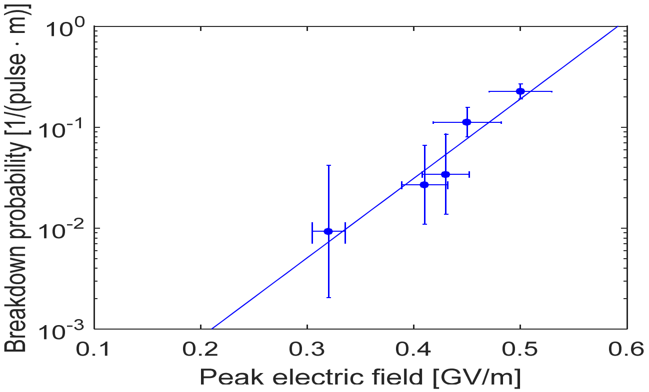
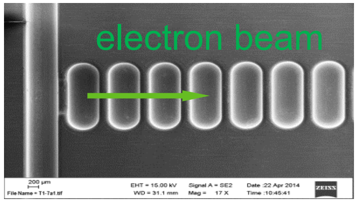
First Measurement of Breakdown Statistics in High-Gradient Beam-Driven Accelerator

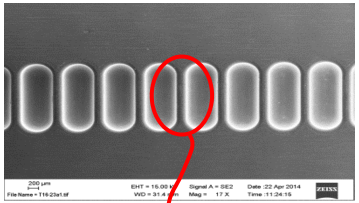
Breakdown rate measurements: travelling wave Cu-Ag 100 GHz structure (Nov 2015)



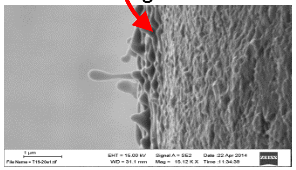
Observation of Damage: travelling wave Cu 100 GHz structure

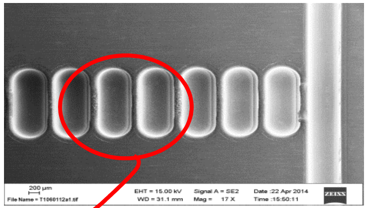


Input coupler, cells 1-7, no damage

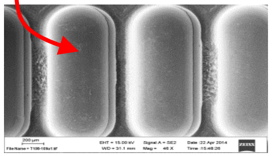


Cells 16-23, fist signs of damage



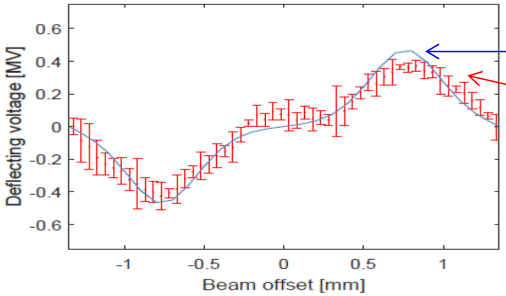


Output coupler, massive breakdown damage



Acc. gradient 0.3 GV/m
E_{peak} 0.64 GV/m
Pulse Length ~2.3 ns

Wakefields, accelerating and deflecting voltage calculations and measurements:



Simulations of deflecting voltage (blue)

Measurement of beam Deflection in a horizontal scan (red)

130 GHz Copper Travelling wave structure (Mar 2015)

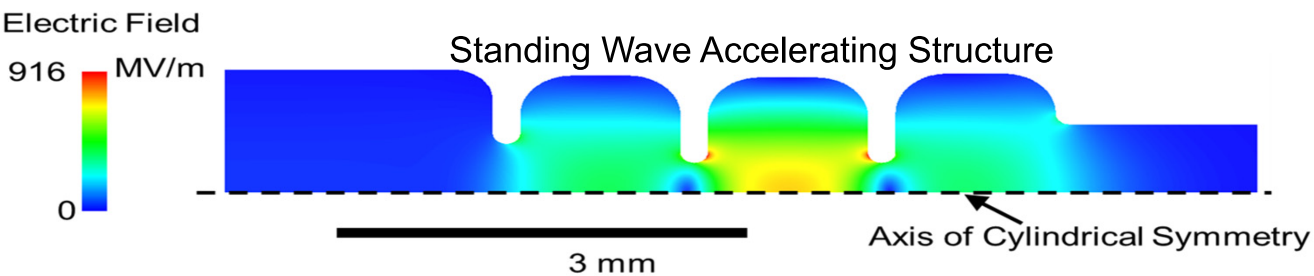
- FACET-E204 Tests: finished experiments at 100 GHz and 235 GHz with data analysis in progress
- We hypothesize drive beam significantly impacts breakdown rate

M. Dal Forno, et al., *Physical Review Accelerators and Beams* 19.1 (2016): 011301.
M. Dal Forno, et al., *Physical Review Accelerators and Beams* 19.5 (2016): 051302.

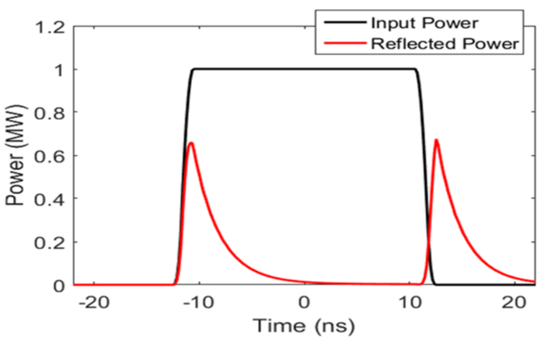
V. Dolgashev, M. Dal Forno

What is the Real Scaling in Frequency for Breakdown Physics?

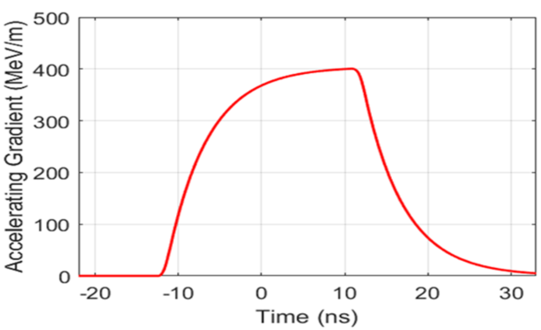
- Demonstrate realizable mm-wave accelerating structure
- Power with stand-alone RF source (gyrotron @ MIT)
- Direct comparison with breakdown studies at x-band



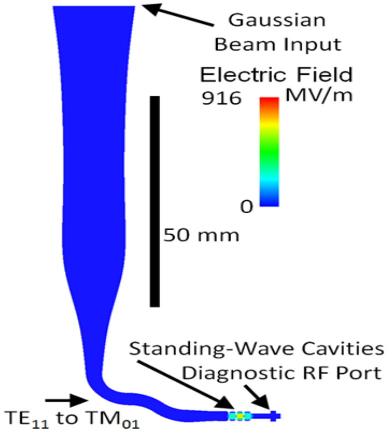
110 GHz Gyrotron Pulse



Accelerating Gradient



Full RF Structure



E. Nanni, V. Dolgashev, J. Neilson

Next Step: The 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 regiem

- 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 Wakefied accelerators

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

Millimeter
Wave
P ~ 10 ps

New Code for simulating and optimizing rf sources

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The state of the art for simulating RF sources are not adequate:

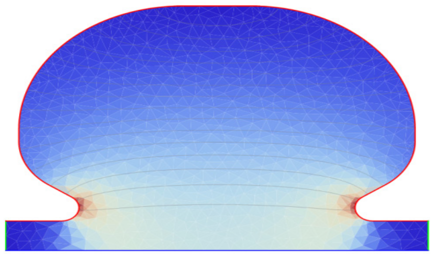
- RF sources operate in an awkward regime, relativity can not be neglected, and particles are not highly relativistic
- Space charge plays an important role but image charges (boundaries) can not be neglected.
- Full PIC codes Takes days to simulate simple structures and not suitable fro design and optimization

New code philosophy:

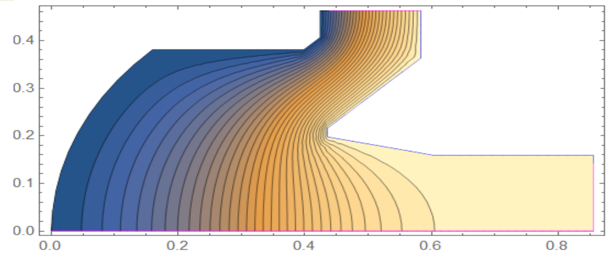
- Traditional E&M formulations starts with deferential equations based on Maxwell equation *driven for a particular gauge*.
    - Requires vector basis functions
    - Does not handle space charge appropriately
- *We start from the Lagrangian formulations of Maxwell equations without a presumption of the gauge.*
    - Simplify the basis functions; all nodal basis
    - Rigorously calculates space charge forces in a precise and natural formulation
- In collaboration with ACD we will do 2D codes first and then move to 3D codes

A new code will allow for fast rapid design and optimizations of RF sources

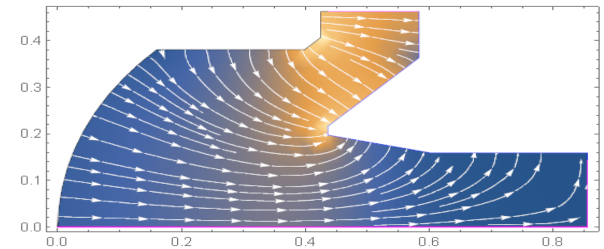
Code development philosophy takes into account platforms, current and future user interfaces



RF solver



Static potential



Fields derived from static potential without loss of order

- To really make a fast optimization code we are writing out ***own mashers***, which in principle takes advantage of the multiprocessor plat forms.
- From the very beginning we are thinking about the user interfaces and how we will disseminate this code.

> - Faster than standard meshers
> - Provide better data bases suited for the problem at hand

Reducing the cost of RF power is necessary to realize high gradient accelerator operation.

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- The prohibitively high cost of traditional RF sources are derived from both:
  - High capital cost
    - Sources are complicated to build
    - High voltage power supplies (~300 kV)
  - High operating cost
    - Limited by efficiency (~50%) at high power

Reducing the cost of accelerators requires reimagining the topology of the RF source.

New embodiments of the RF source must be developed to achieve lower cost.

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- **Simplifying the RF system to reduce capitol cost.**
  - Standardized modular design to scale to higher power
    - Exploit manufacturing and engineering advantages
  - Utilize integrated low voltage electron beams (~60 KV)
    - Reduce size, weight, and cost of modulator
- **Breaking the mold of linear beam to enhance efficiency and reduce operating cost.**
  - Exploit multi-dimensional geometries and power combining techniques.
    - Target higher efficiency, low space charge, regimes of operation
    - Eliminate solenoidal focusing

Three active devices are in development to realize these cost reduction concepts.

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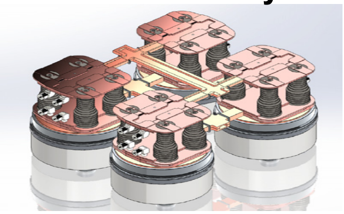
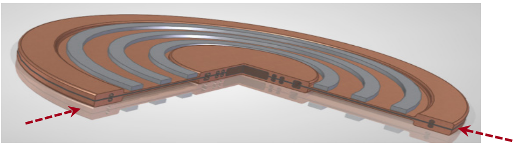
- **Modular-Array Multi-Beam Klystron**
  - Redefining the landscape of multi-beam architectures.
    - Simplified, low part count, klystrinos
    - Phase locked Floquet power extraction network
- **Radial Klystron**
  - Exploiting a novel geometry to mitigate space charge effects.
    - Low space charge radially propagating beam
- **Deflected Beam Amplifier**
  - State-of-the-art power extraction that enables high efficiency X-band operation.
    - Complete beam-wave synchronism with multi-stage output structure.

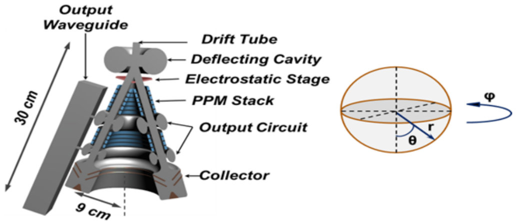
Multi-beam klystron



Radial klystron

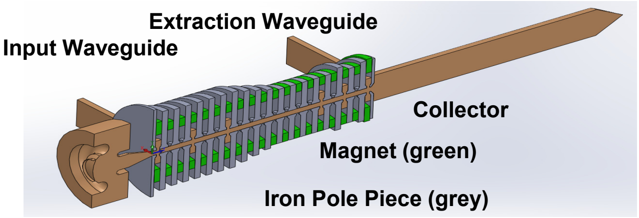


Deflected beam amplifier

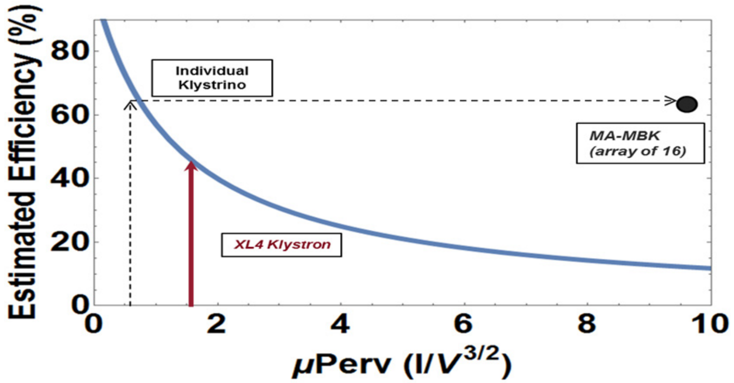


MA-MBK takes advantage of low space charge system to attain high efficiency.

- **Modular klystrinos allow for high shunt impedance cavities**
  - Maintain small drift tube radius
- **Low loss Floquet power combiner to reach high total power**



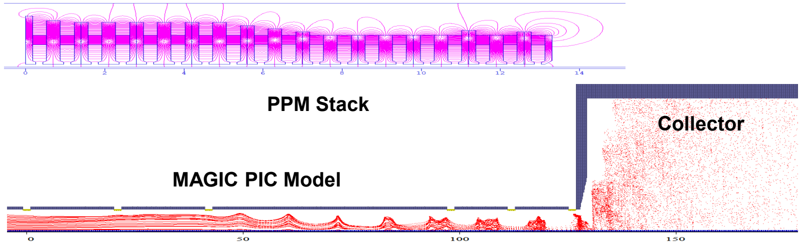
Parameter	Near Term Goal
Beam Voltage (kV)	60
Frequency (GHz)	11.424
Output Power (MW)	5
Beamlets	16
Efficiency (%)	60+

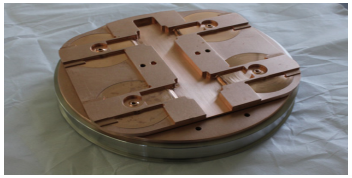


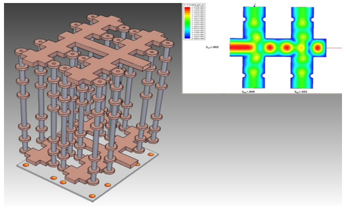
The MA-MBK is not restricted to the geometric limitations of a classic MBK

The modular design of the MA-MBK affords many advantages.

- **Low space-charge beamlets ease focusing requirements**
  - **Permanent magnet focusing**
- **Low loss power combining network defies classical scaling**
  - **Coherent summation of independently operating klystrinos**
    - No RF communication or feedback between sources
  - **Scalable phased array**
    - 100 % coherent combining of 2 x 2 MBK klystrinos
    - Expandable in 4 x 4 (16 klystrino grids)







Prototypes of the MA-MBK have been designed/fabricated and are in testing phase.

A. Jensen, S.Tantawi

The Radial Beam Klystron (RBK) exploits low space charge geometry to improve cavity efficiency.

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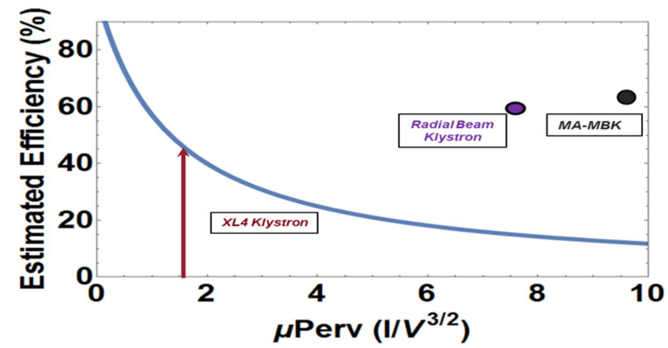
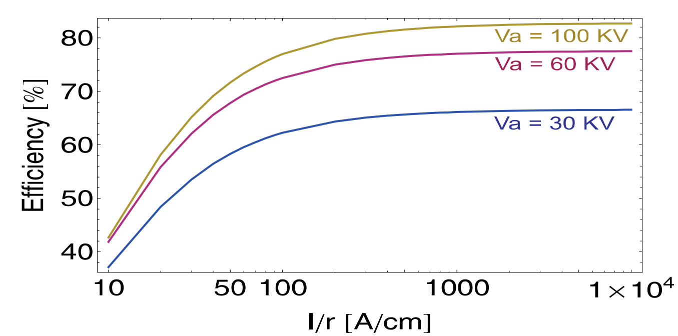
- **Radially converging electron beam**
  - Continuous rather than discrete power combining
  - Extremely low current density
    - Minimal focusing required



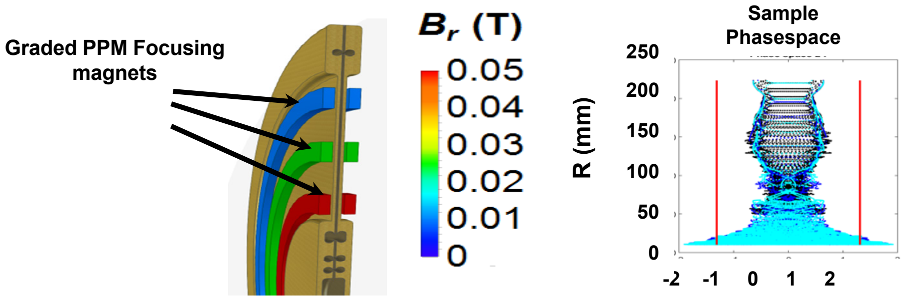
Parameter	Near Term Goal
Beam Voltage (kV)	30
Beam Current (A)	40
Frequency (GHz)	11.424
Output Power (MW)	0.72
Beams	1
Efficiency (%)	60+



The RBK provides a, naturally stable, high current beam transport structure.

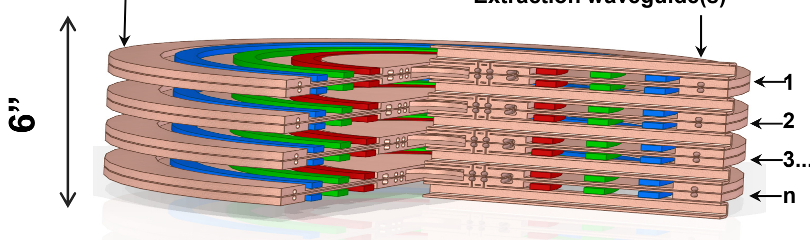
The "pancake" like shape of the MA-MBK is advantageous high current beams.

- **The MA-MBK is a naturally stable device**
  - **Permanent magnet focusing**
    - 3 Concentric magnets in co-planar sets
    - 0.05 T peak on axis field
      - **Order of magnitude less axial field than typical RF device**



On-axis radial magnetic field

- **Low profile configuration ideal for compact high power arrays**
  - **Compact stackable systems**
    - Less than 2 cm axial profile



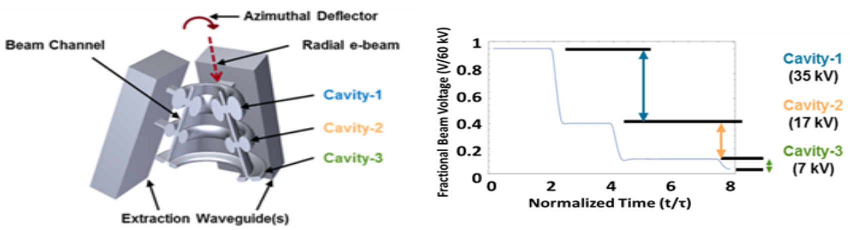
Output combined using similar technology as MBK

Design of the beam transport and RF circuit for the RBK are completed and fabrication is set to begin.

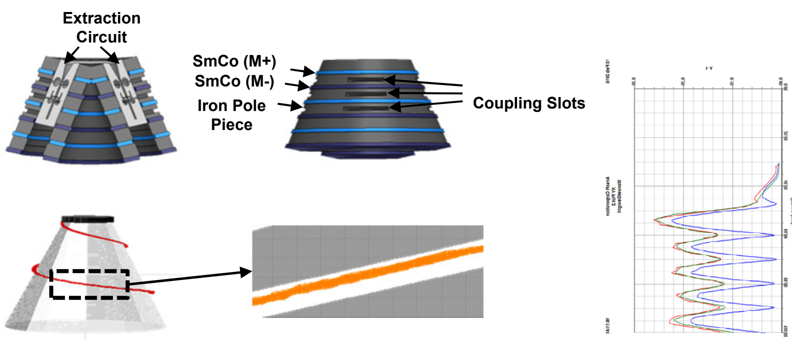
The DBA is an evolved form of deflected beam technology that offers low operating cost.

- **Implements a state of the art, multi-decoupled-cell output network**
  - Minimized potential for RF breakdown
    - Peak voltage of 35 kV in output cavities
- **Current density in the extraction network is low**
  - Radial spread of beam reduces space charge
    - Up to 25 A Beam can be focused with PPM system

Cavity voltage is tuned for optimal overall efficiency



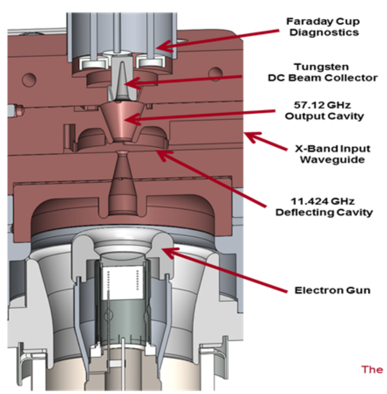
Beam is confined with commercial SmCo magnets



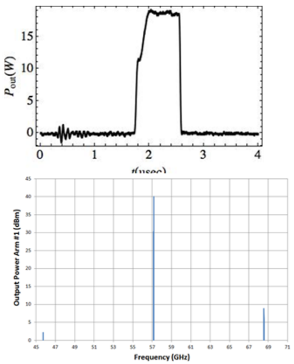
Low beam voltage and low cavity voltage allow for higher frequency operation.

The Deflecting Beam Amplifier combines high electronic efficiency with high frequency operation.

- **Phase synchronous deflected beam interaction**
  - Electron beam continuously interacts with decelerating phase of RF
    - **No traditional “bunching” of beam**
  - Builds off of successful demonstration of a 57 GHz deflected beam frequency multiplier
    - **Successful LDRD technology that has advanced to the GARD portfolio**

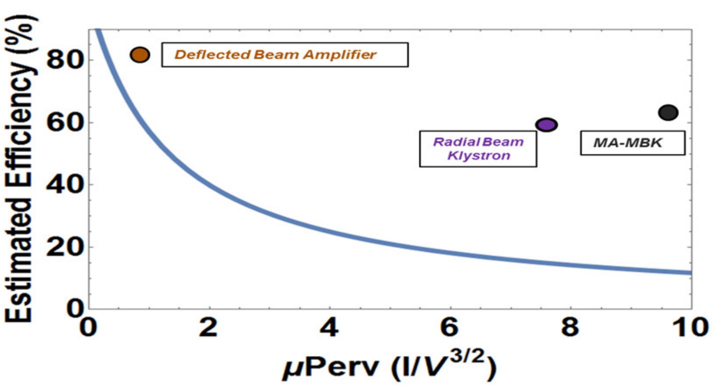


Mechanical Model Cutaway



The 57.15 GHz 5th Harmonic Power is > 30dB Above Adjacent Harmonics

Parameter	Near Term Goal
Beam Voltage (kV)	60
Beam Current (A)	16
Frequency (GHz)	11.424
Output Power (MW)	0.77
Efficiency (%)	80+



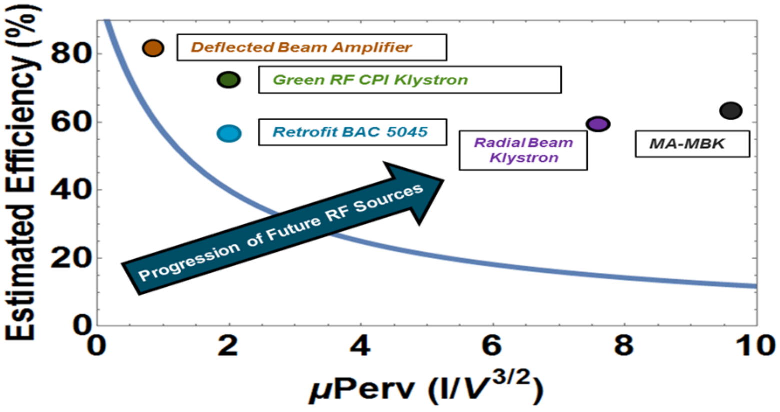
M.Fazio, S.Tantawi, F.Toufexis, A. Vrielink

Redefining the state of the art RF source.

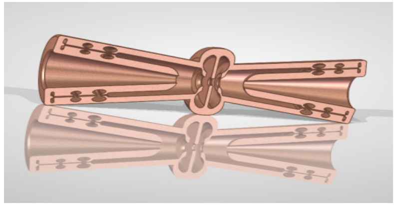
- **Exploration of novel technology to improve efficiency and reduce the cost per Watt of RF power**

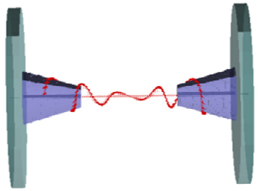
- **2 enhanced efficiency designs:**
  - Retrofit BAC 5045
    - Prototype currently in test
  - Green RF CPI Klystron
    - Full design completed

- **3 novel RF source topologies:**
  - Modular-array Multi-Beam Klystron
    - *Prototype currently in test*
  - RBK *(radial beam klystron)*
    - *Electrical design completed*
  - DBA *(Deflected beam amplifier)*
    - *Exploring advanced concepts*



Exploit symmetry to enhance utility of deflector





Applications

U.S. DEPARTMENT OF ENERGY Office of Science

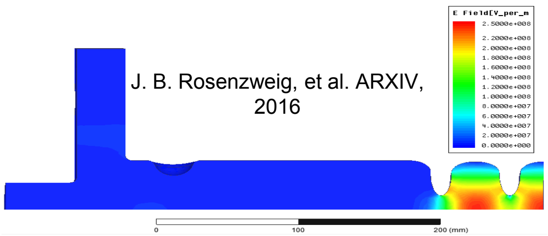
SLAC NATIONAL ACCELERATOR LABORATORY

Broader Impacts Resulting from Advancements in RF Accelerator Technology

SLAC

Cryogenic RF Photoinjector (UCLA/SLAC)

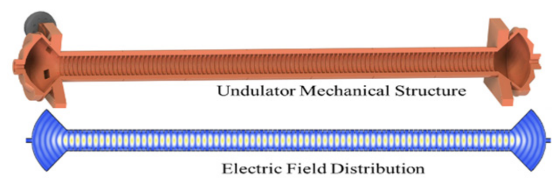
- **Cryogenic Cu with surface fields nearly twice room temperature Cu, rf photo-injectors with 30X increase in peak brightness wrt LCLS gun**



J. B. Rosenzweig, et al. ARXIV, 2016

RF Undulator (NSF)

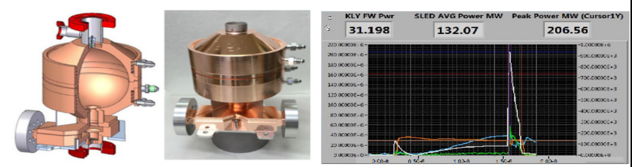
- **Microwave undulators with large aperture, short period and active polarization control**



S. Tantawi, et al. *PRL* (2014)

Pulse Compressors (LCLS/BES)

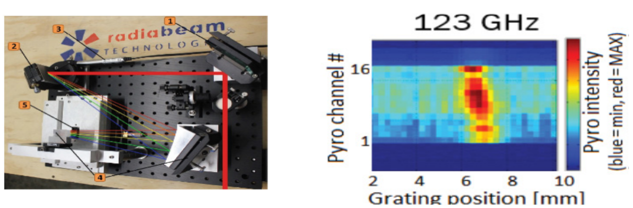
- **Super compact X-Band SLED system, doubles the kick in transverse deflector at LCLS**



J.W. Wang, et al. IPAC 2016

Single Shot THZ Spectrometers (SBIR/HEP)

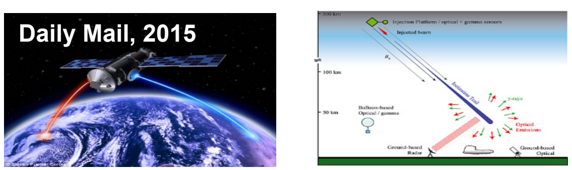
- **SBIR with Radiabeam in support of THz acceleration experiments**



S.V. Kutsaev, et al. IPAC 2016

Accelerators Deployed on Satellites (NSF)

- **Requires extremely efficient and compact accelerator to produce MeV beams**

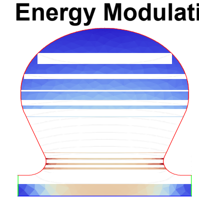


R. A. Marshall, et al. JGR: Space Physics, 2014
E. A. Nanni, et al. SLAC-R-1058, 2016

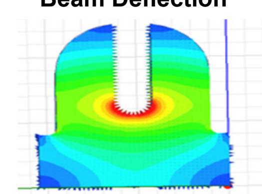
Proton Acceleration (Stanford Med./UCSF/SLAC)

- **Efficient accelerating structures to modulate beam energy and deflect beams for proton radiation therapy**

Energy Modulation



Beam Deflection



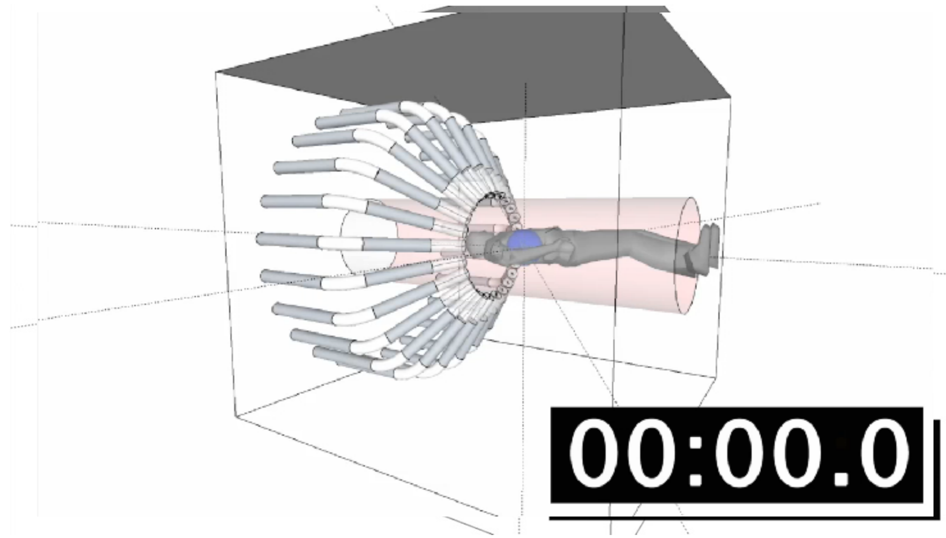
- **Collaborations and Investments have Advanced HEP GARD Mission**

The PHASER solution

Current state-of-the-art

The PHASER solution

Current state-of-the-art



Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER)

The PHASER solution

Ultra-fast ➔ Ultimate precision
Compact, hi throughput ➔ Global access

Current state-of-the-art

Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER)

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Ultra-fast ➔ Ultimate precision
Compact, hi throughput ➔ Global access

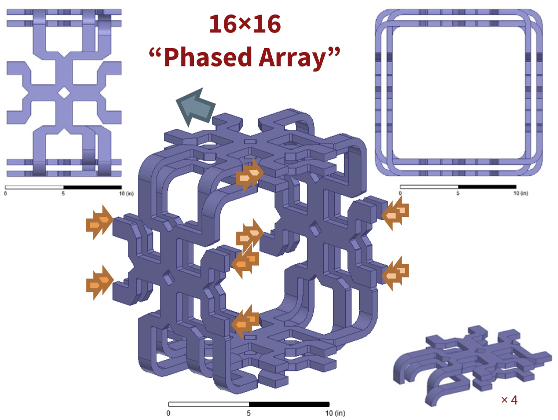
Current state-of-the-a

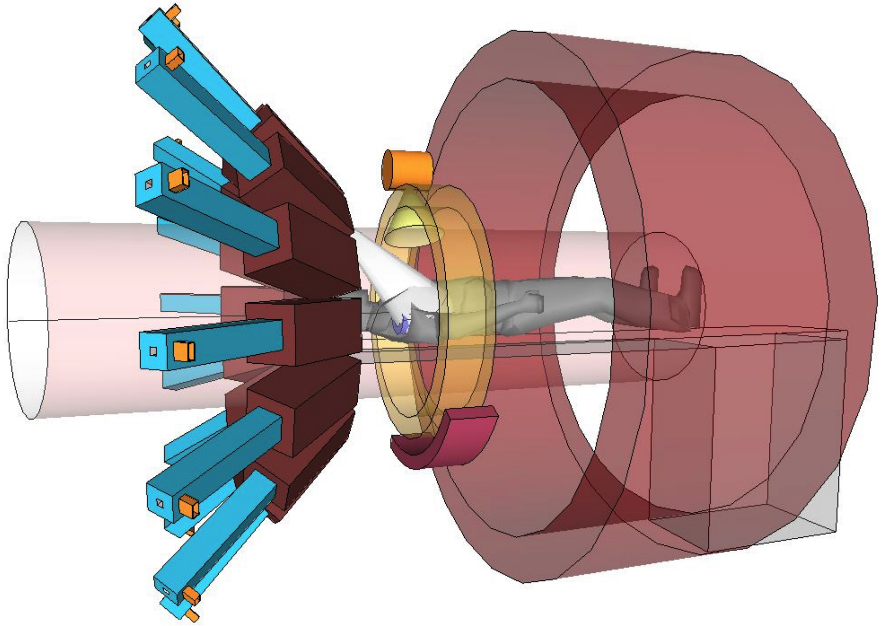
igh-energy Agile Scanning Electronic
diotherapy (PHASER)

Special case – pediatric RT

PHASER technology

PHASER layout





Stanford MEDICINE

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Thank you!

Pluridirectional High-Energy Agile Scanning Electronic Radiotherapy (PHASER)

Conclusions: The impact of this work affects HEP mission by reducing cost, increasing efficiency and achieving high gradients

- Advancements in RF accelerator technology with research in four core areas:
  - **Physics of Breakdown:** Advanced the understanding of the basic physics for breakdown in high gradient acceleration structures, investigating new frequency regime
  - **Materials Science:** Accelerator improvements with superior materials
  - **Innovative Electrodynamics:** Optimized accelerator designs yielded increased performance in both gradient and efficiency
  - **Manufacturing Engineering:** Evolution of manufacturing techniques to enable building exotic structures with reduced cost
- Applications of this work to many other areas providing additional funding and expertise to enhance our efforts