High Gradient RF Acceleration at SLAC

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International Workshop on Breakdown Science and High Gradient Technology (HG2015)
16-19 June 2015, Tsinghua University, Beijing , China

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Advances in Basic Physics of High Gradient normal conducting RF structures.
- Novel Accelerator structures
  - Distributed Coupling accelerator structures
  - Multi-frequency accelerator structures
- mm-Wave/THz acceleration
- Novel RF source developments
  - Distributed coupling multi-beam klystrons
  - Multi-dimensional klystrons
- Superconducting accelerator structures

Advanced RF Acceleration

Discovery of Magnetic Fields Role in Breakdown triggered New research initiated

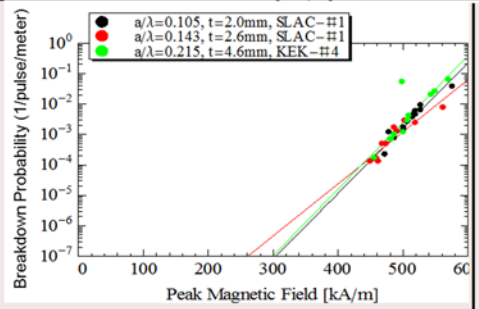
Geometry optimizations for accelerator structures based on reduction of the magnetic surface field

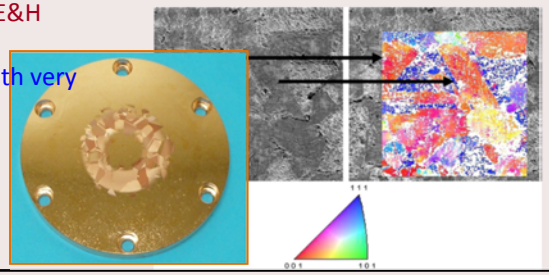
Studies of surface magnetic fields and materials

Basic Physics studies with mixed E&H dual-mode cavities

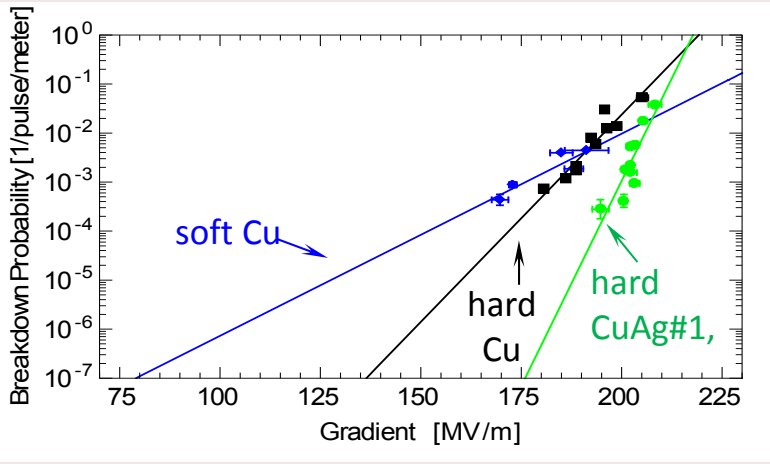
Low temperature experiments with very high gradient structures

Different Crystal orientations respond differently to magnetic field induced pulsed heating

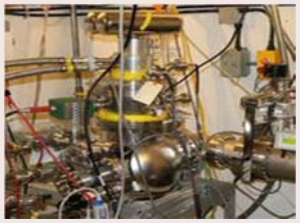


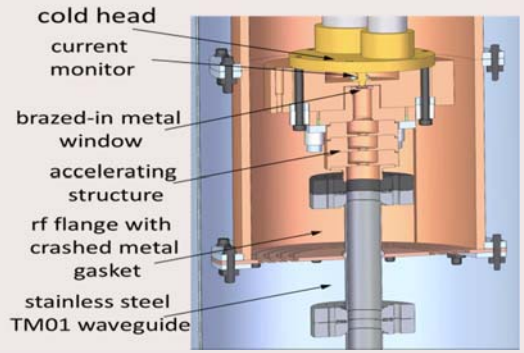


Based on our understanding of the breakdown phenomena we predict an enhanced performance of CuAg (0.08% Ag)



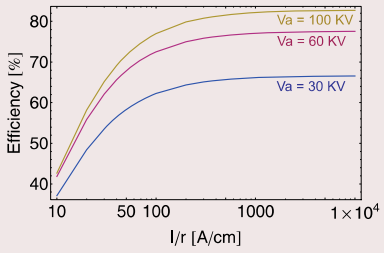
Recent results of the cryo-cooled normal conducting structure

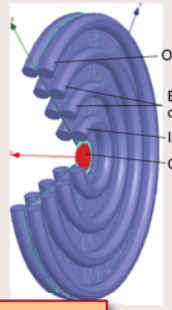


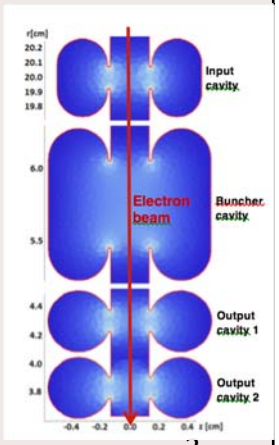


Structure is running now at an ***accelerating gradient of about 250 MV/m*** with a breakdown rate ~ 10^{-6} /pulse/meter.

Paradigm shift in RF source developments: Multi-dimensional RF sources



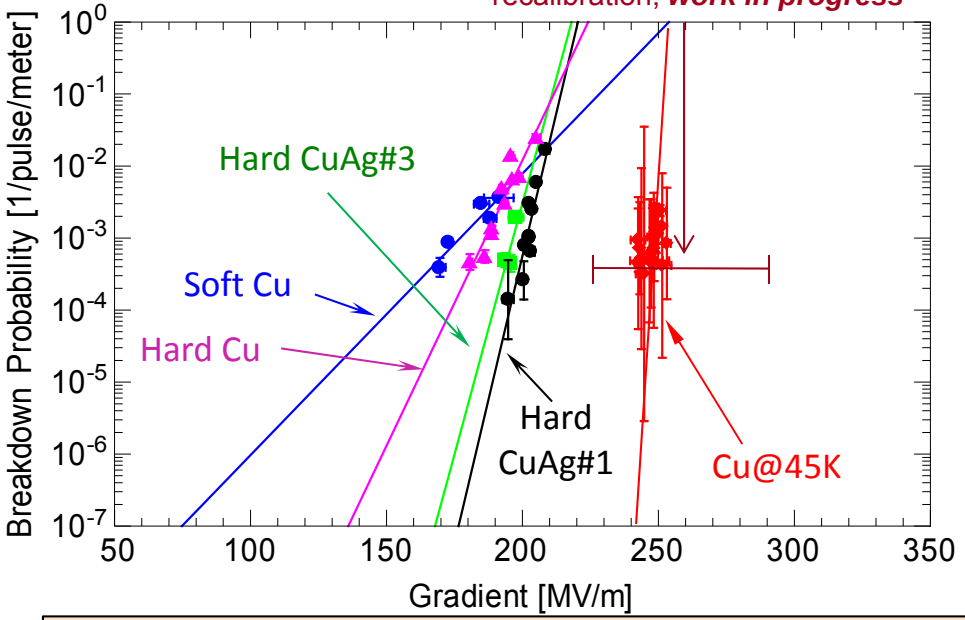


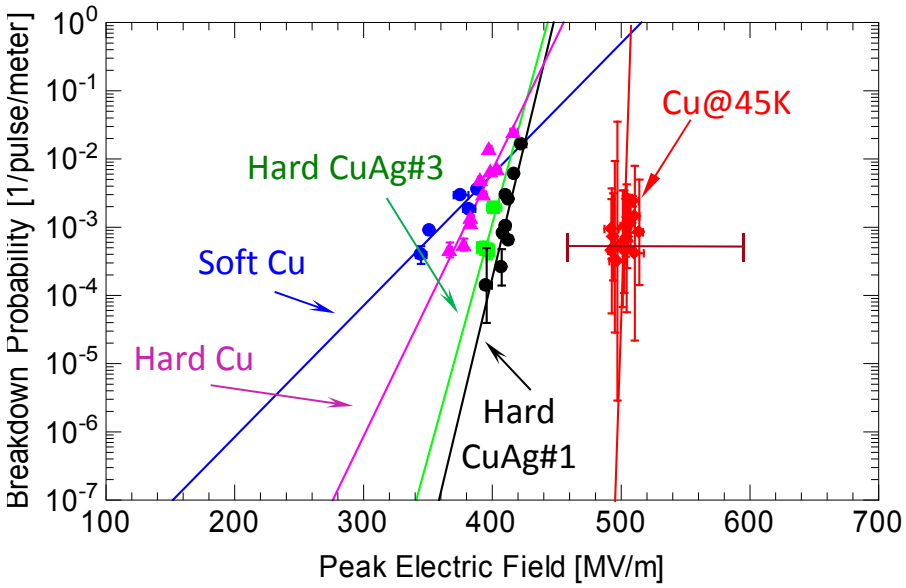


- Ultra-high efficiency
- Compact
- No solenoids
- Low voltage and high power

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

Narrow error bar will be obtained after recalibration; ***work in progress***

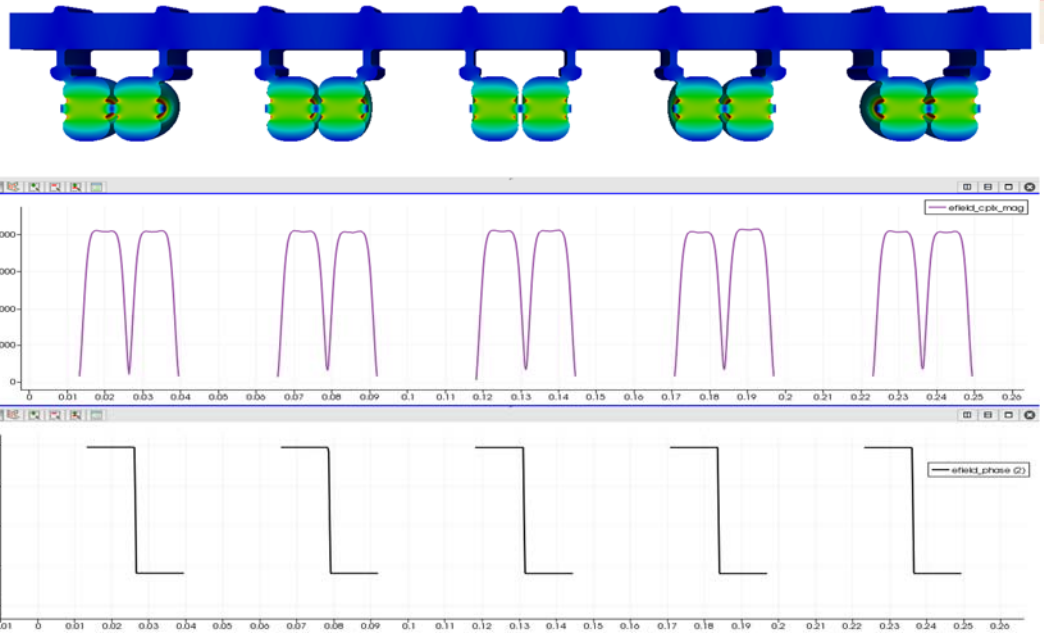


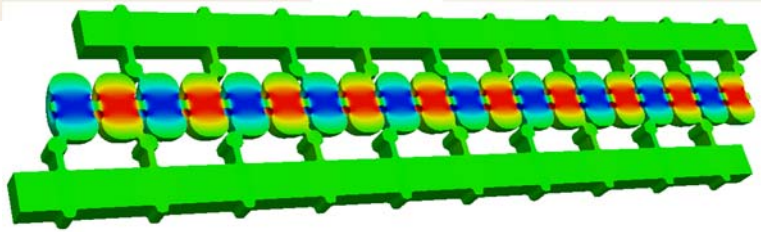


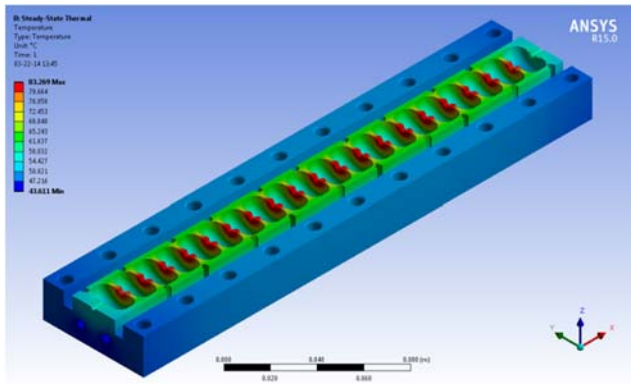
- Basic physics experiments move to testing normal conducting & SC engineered materials (2016-2017).
- Cost effective implementation of accelerator structures capable of operating *efficiently* at these gradients (basic development 2016-2017, and then growing effort to 2020)
- Build RF sources that can power these structures to high gradients (basic development 2016-2017, and then growing effort to 2020)
- New architectures for future facilities (colliders, light sources, etc.) will emerge when efficient RF systems to power linacs operating at these gradients become available
- Immediately, this technology will lead to RF guns with unprecedented brightness.

See talk V.A. Dolgashev, Preliminary results of high power tests of normal conducting cryo cavity, HG2015, Tuesday, June 16th, 2015

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

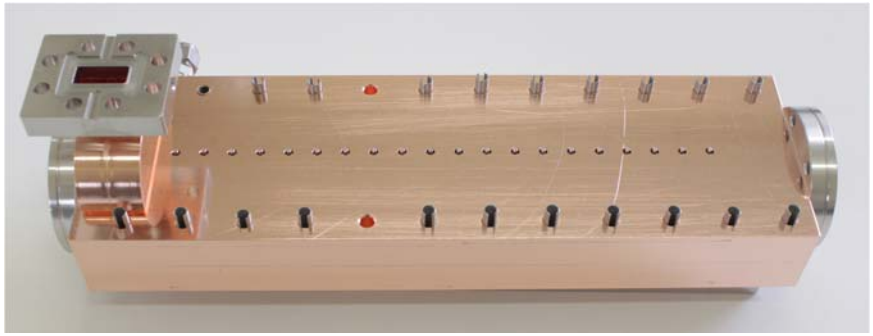


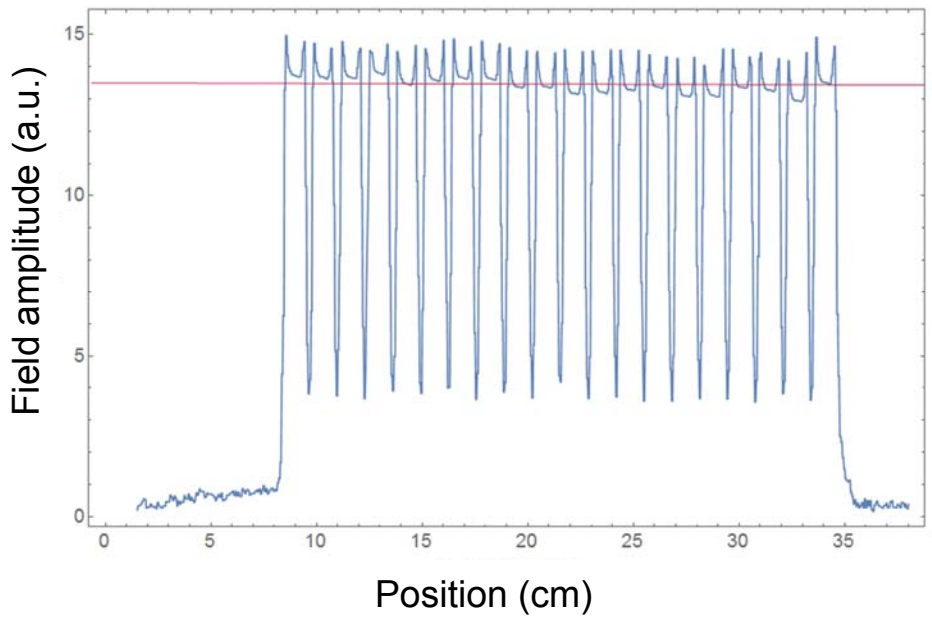


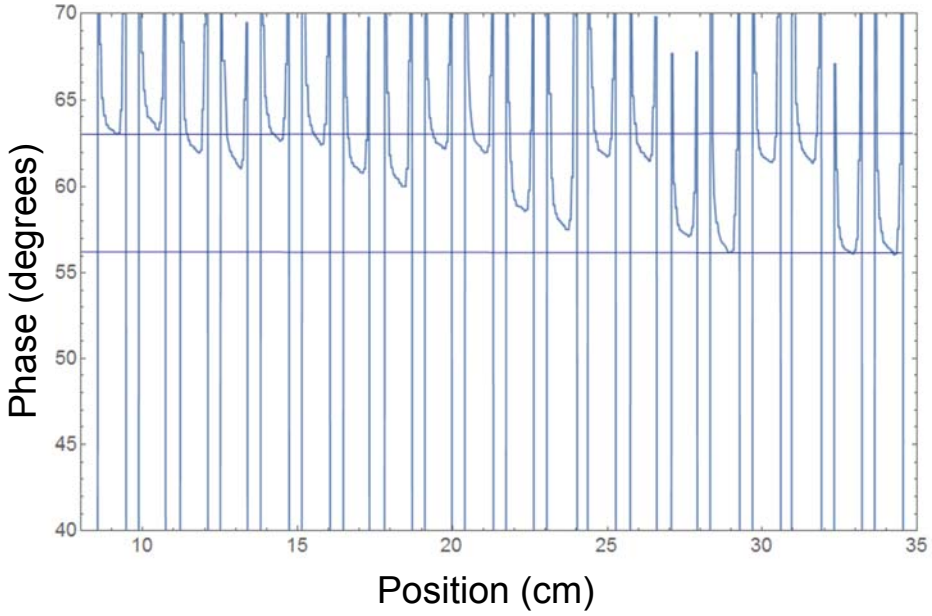


- Optimize individual cell shape for maximum gradient and shunt impedance without cell-to-cell coupling constraint
- Requires only 66 MW/m for 100 MV/m gradient compared to 200 MW/m for a typical X-band structure
- Inexpensive to manufacture
- Patent filed by Stanford
- 2015- First 150 MV/m accelerator structure of this class is now under test at high power
- 2016-2017
  - Combine the structures into one monolithic super structure
  - Understand the Wakefield properties
  - Construct structures with engineered materials (alloys)
- Beyond 2017
  - Incorporate into an energy recovery system.
  - Fold into a realistic modular design for a future TeV collider

First cold test of the new structure

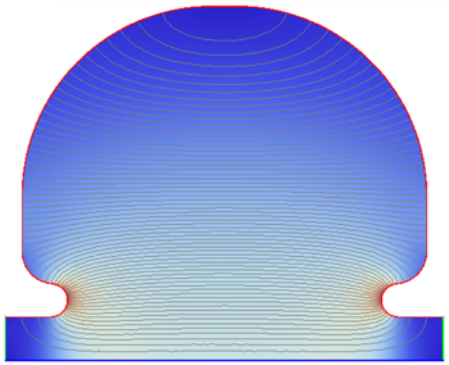




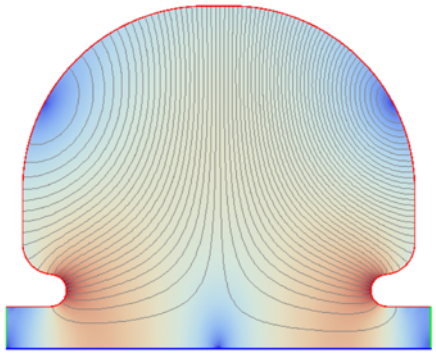


- First 150 MV/m accelerator structure class is under test at high power
- Funded by grants to the Stanford School of Medicine and SLAC

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

Structure has total Shunt Impedance is 244 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*

Approach to revolutionize conventional SC accelerator technology: superconducting thin film coatings that enable novel topologies for highly efficient accelerator structures

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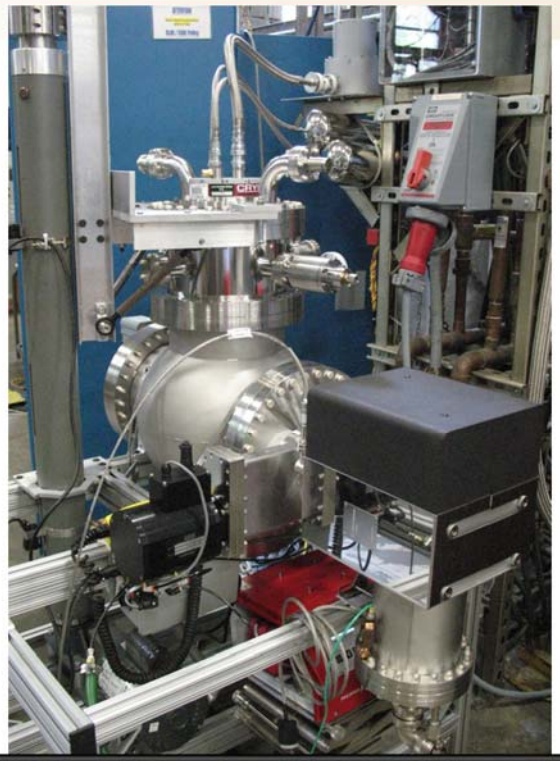
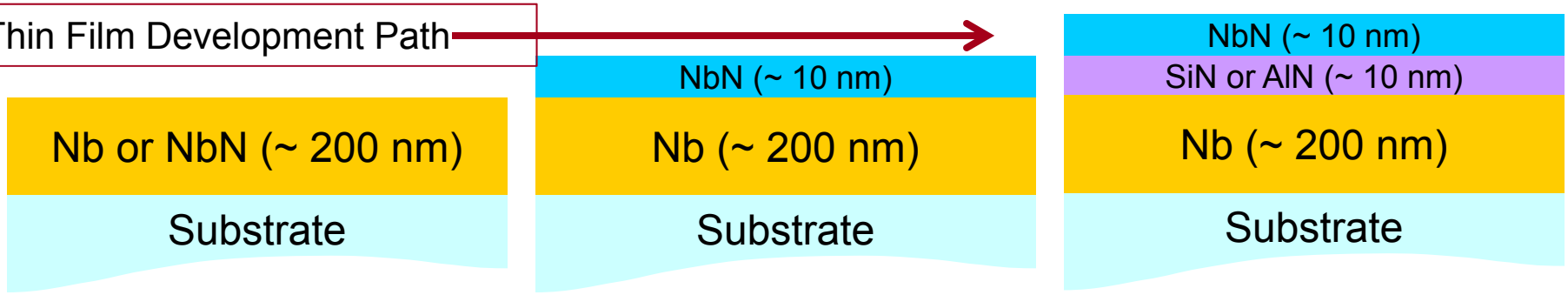


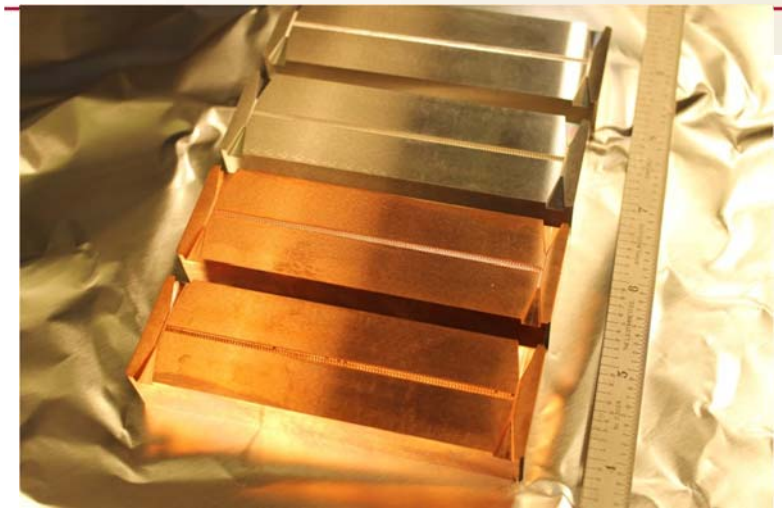
Dedicated Cryostat for Cavity Testing

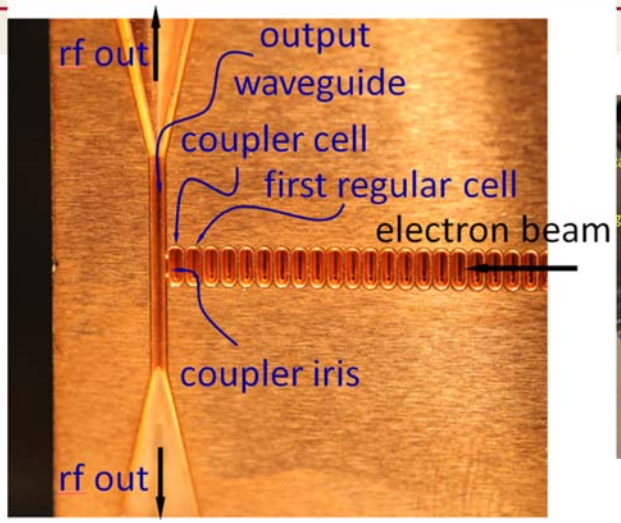
- *We need to jump start research development with Nb derivative films*
- Potential for > 70 MV/m superconducting accelerators
- Potential for reduction of accelerator cryogenic loads by a factor of 2.
- Will open the door for many future applications related to hadrons and e+/e- facilities.

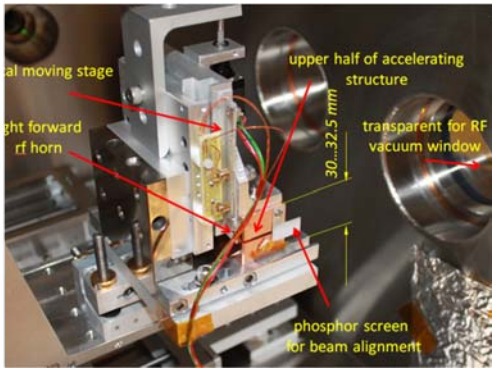
Thin Film Development Path →

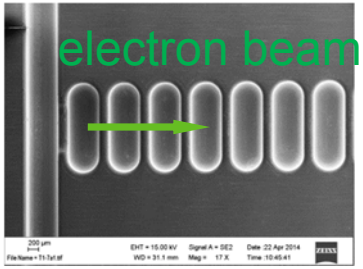


100 GHz Open Accelerating Structure Experiments Show Possibility of ~ 0.5 - 1 GeV/m Accelerators

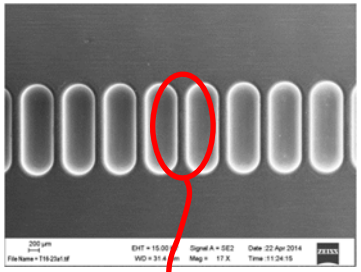




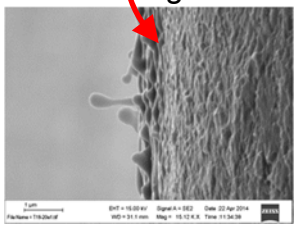


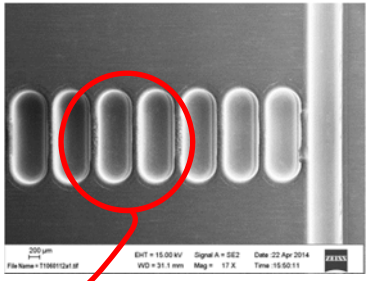


Input coupler, cells 1-7, no damage

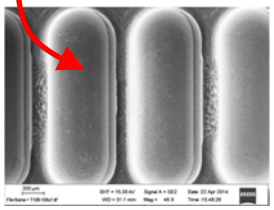


Cells 16-23, fist signs of damage





Output coupler, massive breakdown damage



Acc. gradient 0.3 GV/m
Epeak 0.64 GV/m
Pulse Length ~2.3 ns

2015-2017 R&D plan

- FACET Tests: we finished set of experiments both 100 GHz and 235 GHz and now work on understanding the data

Beyond 2017:

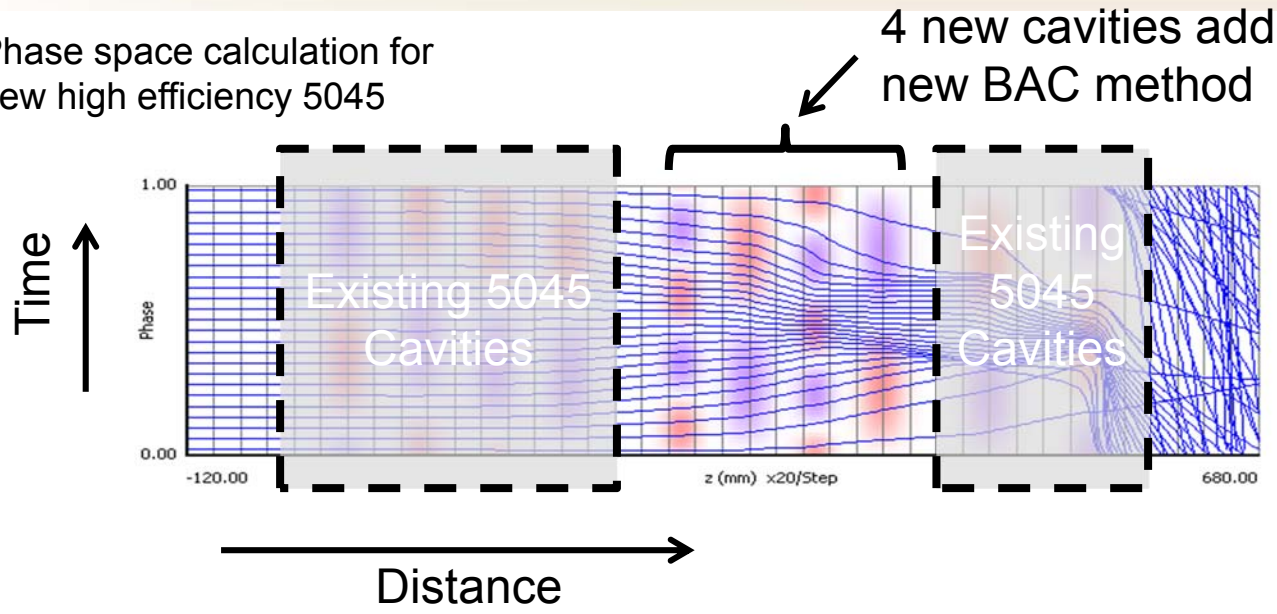
- Implement a full system at frequencies > 100 GHz powered by stand alone rf source.

See talk V.A. Dolgashev, Breakdown tests of 100 GHz accelerating structures, HG2015, Tuesday, June 16th, 2015

Advanced High Efficiency RF Sources:

New High Efficiency 5045 Klystron Design Could Reduce the SLAC Linac Power Consumption by a Factor of 2

Phase space calculation for new high efficiency 5045



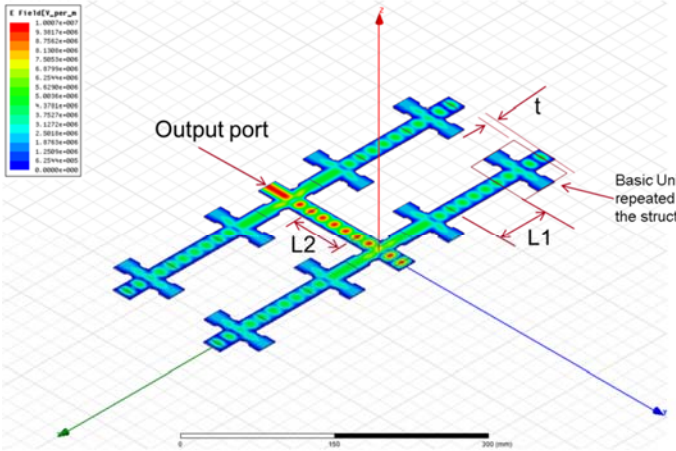
SLAC 5045
65MW S-band tube

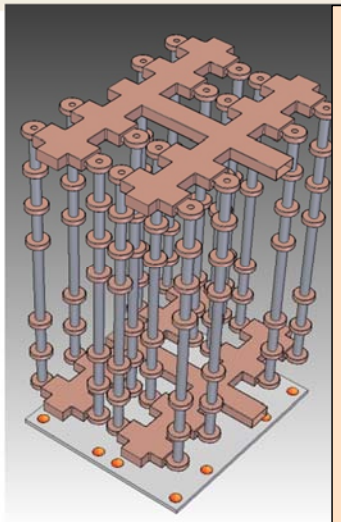
- GARD funded advances that enabled high efficiency electrical design
- New cavity design based on Bunch-Align-Collect* method & pulsed depressed collector yields 80% efficiency (an increase of 50%)
- "Plug-compatible" with existing 5045
- Opens path toward practical and efficient multi-frequency sources (Provisional patent field)

- 1st test this winter & 1st demonstration of RF source suitable for future facilities
- 2016 – Migrate to BES funding.

* Syratchev, I., *"Prospects for High Efficiency Klystrons,"* Efficient RF Sources Workshop, June 2014.

Distribution Structure and mechanical design





Most compact possible configuration:

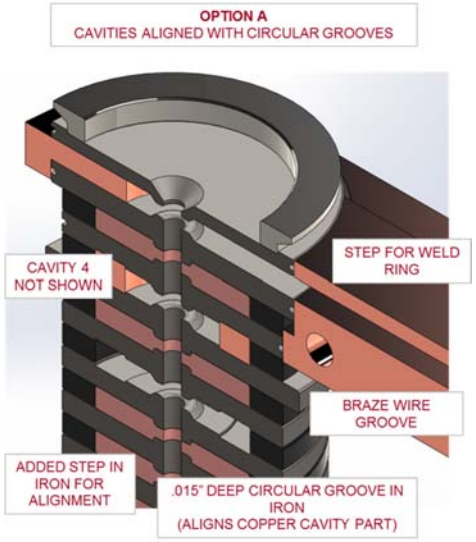
The number of beams is (2N)2; where N is the division ratio for single splitter

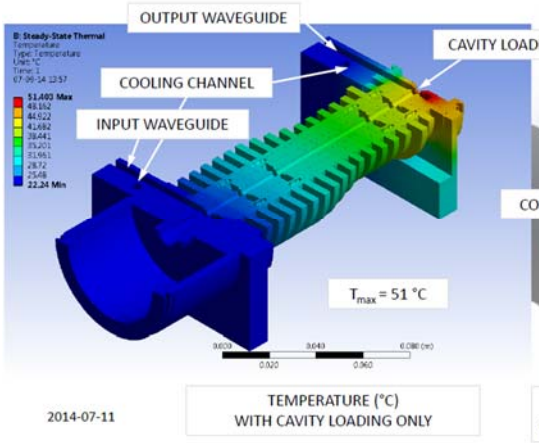
No electromagnets, focusing is done with Permanent Periodic Magnets (PPM)

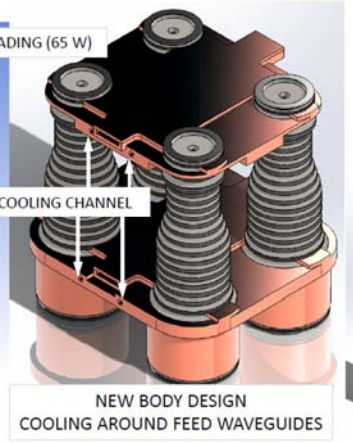
Low voltage:
simplified gun structure and
no oil;
efficient inexpensive modulator; and
the possibility of using gridded cathodes

2016-2017 R&D

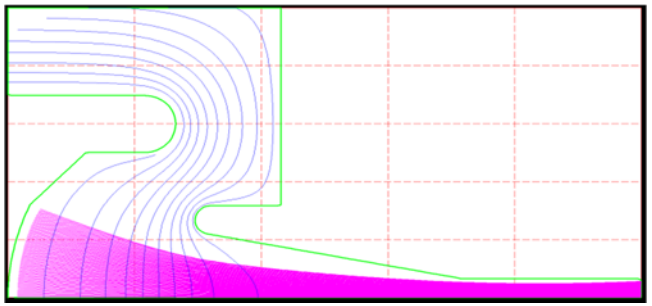
- Implement proof of principle experiments
- Integrate with advanced modulator concepts



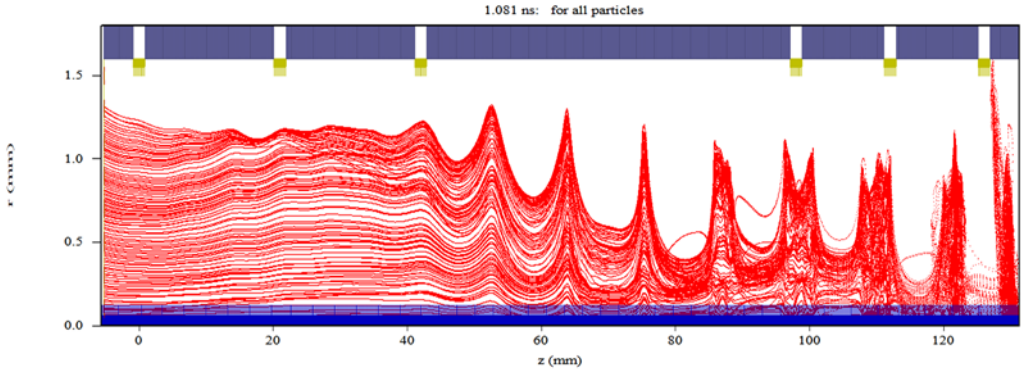




X-Band MBK Simulation



Pierce Electron Gun
(simulated using EGUN)



PPM Beam Transport with RF
(simulated using MAGIC2D)

Preliminary design and simulation of the gun and ppm stack have been completed.

Preliminary RF simulations predict 65% efficiency. The next steps are to optimize the design, incorporate cavities into the PIC simulation, and to begin the mechanical design.

X- Band Multi-Beam Klystron
Design Specifications

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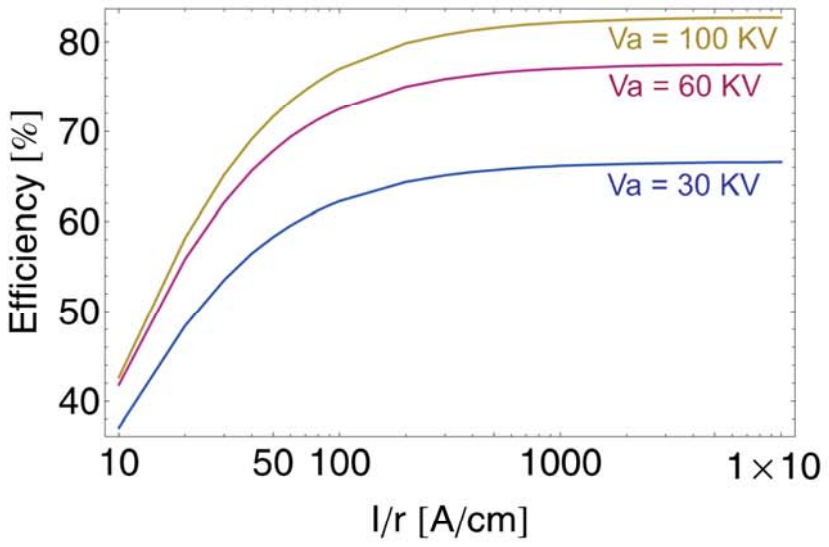
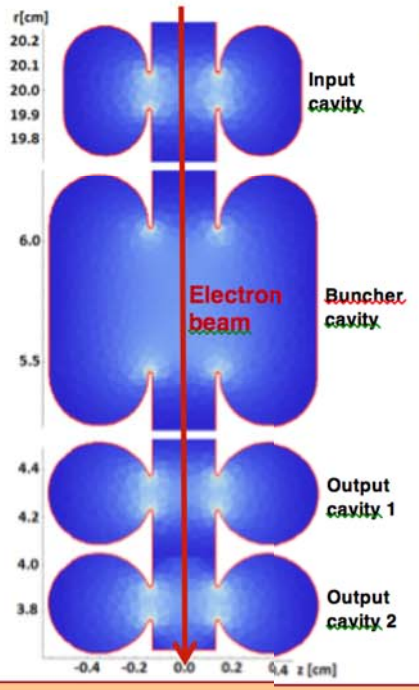
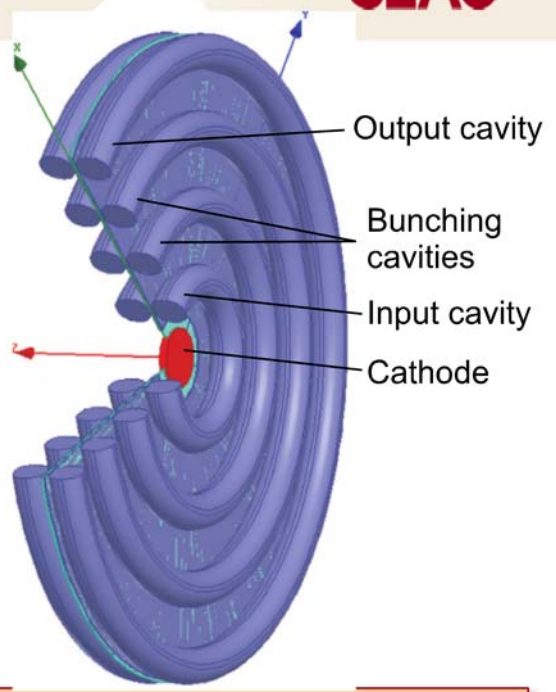
Parameter	Design Goal
Beam Voltage	60 kV
Frequency	11.424 GHz
Output Power	5 MW
Beamlets	16
Beam Focusing	Periodic Permanent Magnet (PPM)
Efficiency	> 60 %
Cathode Loading	< 10 A/cm^2

Multi-dimensional RF sources (Original Idea by R. Ruth and S. Tantawi)







- Ultra-high efficiency
- Compact
- No solenoids
- Low voltage and high power

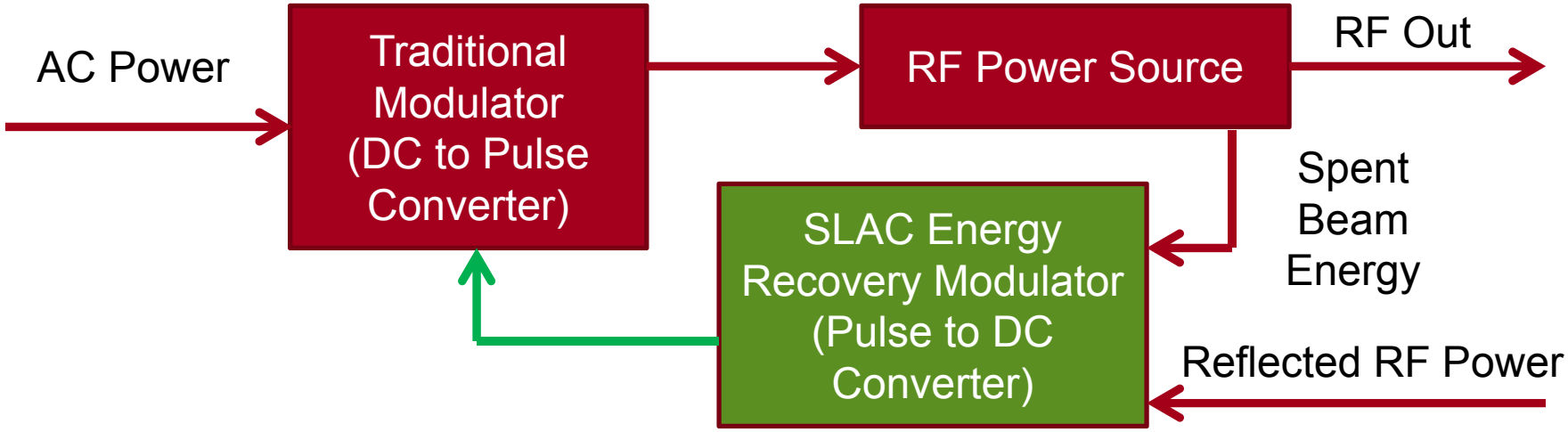
2016-2017 R&D

- Implement proof of principle experiments for both concepts.
- Integrate with accelerator structure
- Integrate with advanced modulator concepts

Beyond 2017

- Optimize the mechanical and structure design for manufacturability and reduced cost.
- Integrate into a TeV class collider design.

Need to Consider the Total System Efficiency : Next-Gen Modulator Systems *Provide* and *Recover* Energy



- Feed-forward energy recovery modulator enables traditionally wasted energy to be utilized on subsequent pulses
  - SLAC firsts: Inverse Marx Modulator, Inverse Blumlein Generator

- Taking advantage of low-perveance klystron beams, ultra-high efficiency depressed collectors are used to recover energy

Next-generation modulator development completes holistic approach to RF system design

Conclusion

SLAC

- We are pushing the limits of High Gradient structures; it is now possible to think of an accelerator system operating at ~ 300 MV/m.
- We are building the foundations for a paradigm shift for rf sources; compact, high efficiency, and low voltage.
- With new accelerator structure architecture it is possible to envision a new class of both normal conducting and superconducting Linac with extremely high RF to beam efficiency.
- We are looking at the rf system as a single unit from wall plug to beam, and we are optimizing this systems with multiple feed back loop for energy recovery.
- New ideas for multi-frequency structures and mm-wave/THz structure paves the future for new class of accelerators operating at ultra-high gradients.