Stanford MEDICINE

SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY Office of Science

Perspectives on Ultra-Compact High Gradient RF Accelerator Technology and its Apllications

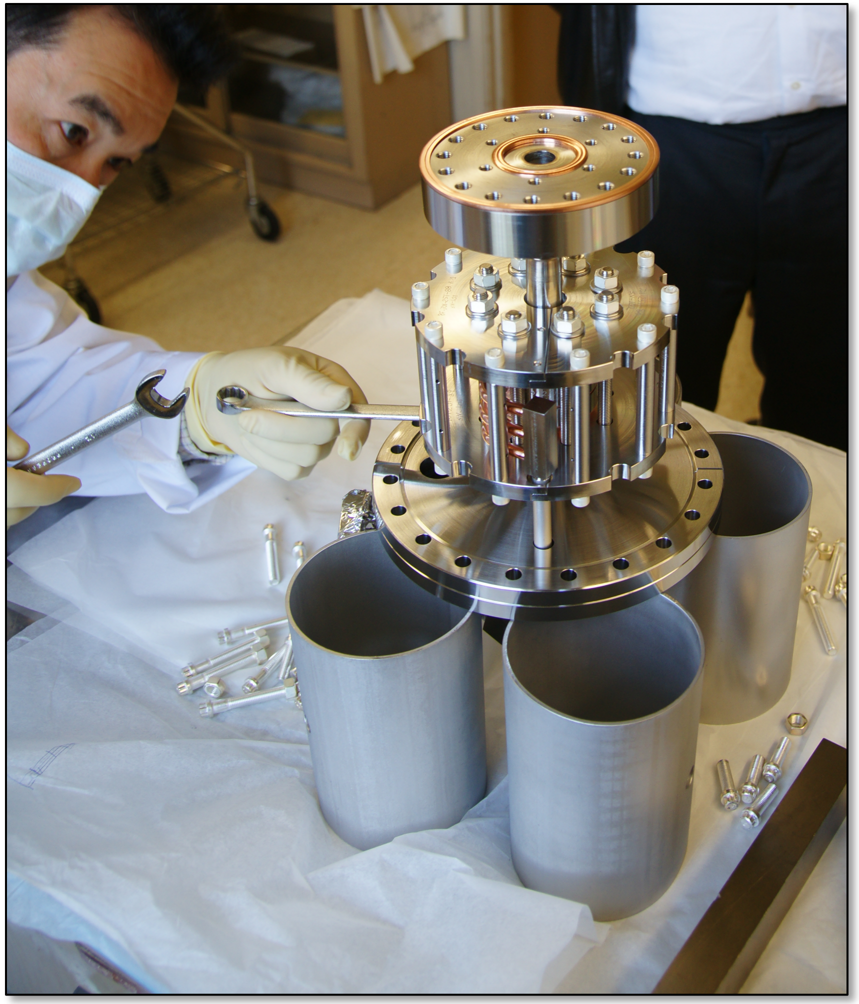
Sami G Tantawi, and collaborators.

STANFORD CANCER INSTITUTE
Stanford University Medical Center
A NATIONAL CANCER INSTITUTE-DESIGNATED CANCER CENTER

PHASER

Outline

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



Clamped structure for testing without brazing

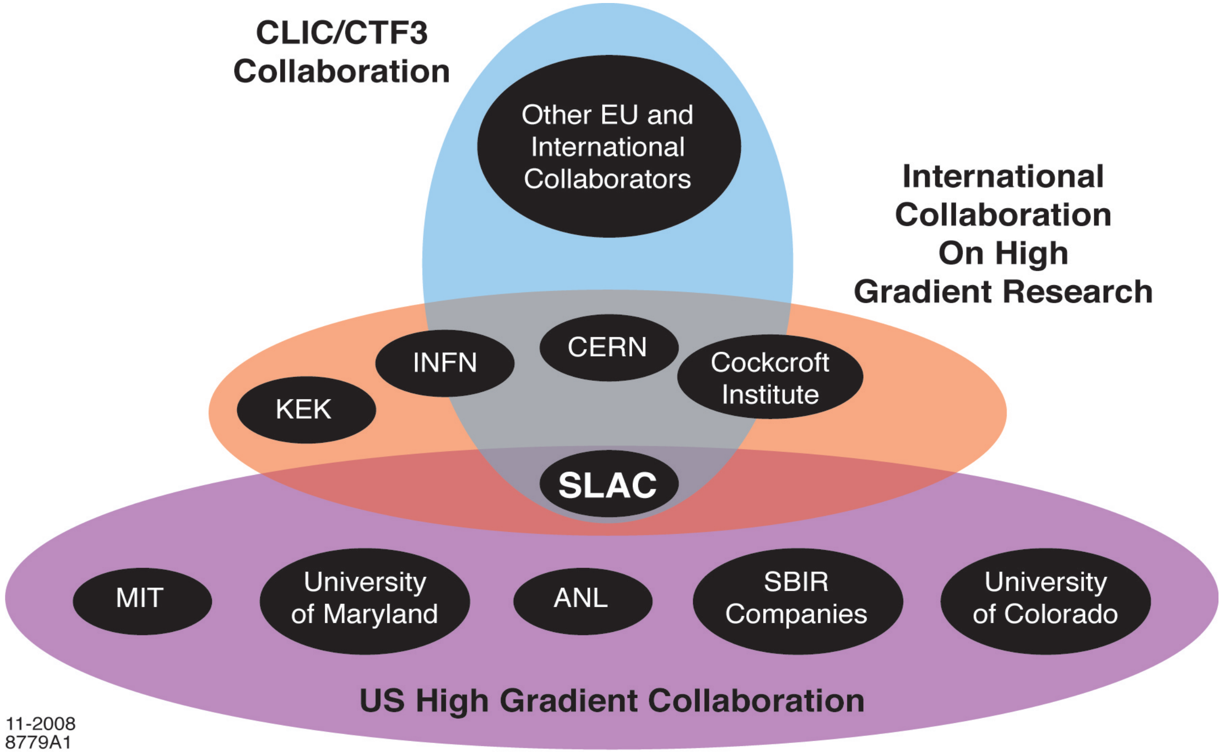
In 2007 a new collaboration have been formed: The US Collaboration on High Gradient Research

SLAC

Governance Structure

- Spokesperson
  - Sami Tantawi, SLAC

- Advisory Council from across 6 institutions
  - *Ron Ruth, SLAC (initiated)*
  - Richard Temkin, MIT
  - Gregory Nusinovich, UMD
  - Wei Gai, ANL
  - Erk Jensen, CERN
  - Toshi Higo, KEK



Motivation Was to Make A Multi-TeV Normal Conducting Accelerator Possible

SLAC

- Multi-TeV linear collider impractical using using low-gradient superconducting technology because of well understood physical limitations on gradient
- When we started (2007) normal conducting technology was 65 MV/m, roughly TWICE the superconducting state of the art
- Practical laser and plasma based acceleration are decades beyond the current horizon
- Multi-TeV energy could be reachable with a breakthrough in normal conducting high gradient technology: no hard limitations are known.

Aspired to understand the limits of normal conducting structures to push to the gradients expected of laser and plasma approaches.

B.C. (Before Collaboration) There Were Conjectures, Voodoo-like Conclusions, and God-Given Scaling Laws…

SLAC

- Surface cleanliness would lead to ultimate gradient
- Ultimate gradient goes as $freq^{1/2}$
- Impedance match (architecture of RF system- source, pulse compressors, cavity, etc) would affect ultimate gradient
- Peak gradient is correlated with peak surface electric field
- Magnetic fields were irrelevant
- Refractory metals would provide the best path
- Dark currents are prime cause for breakdown and suppressing them would improve performance

Attacked these one by one and ALL had misconceptions

A.C. Achieved Its Major 2007 Goals

SLAC

- Extended gradient limit from ~65 MV/m to 175 MV/m – *6x the gradient of superconducting structures*
- Discovered the breakdown mechanisms in normal conducting RF accelerators
- Explored other applications for high gradient technology
- *RF sources, modulators, and RF components, were not included in this effort because this program was not an umbrella to continue the existing pre-2006 status quo*

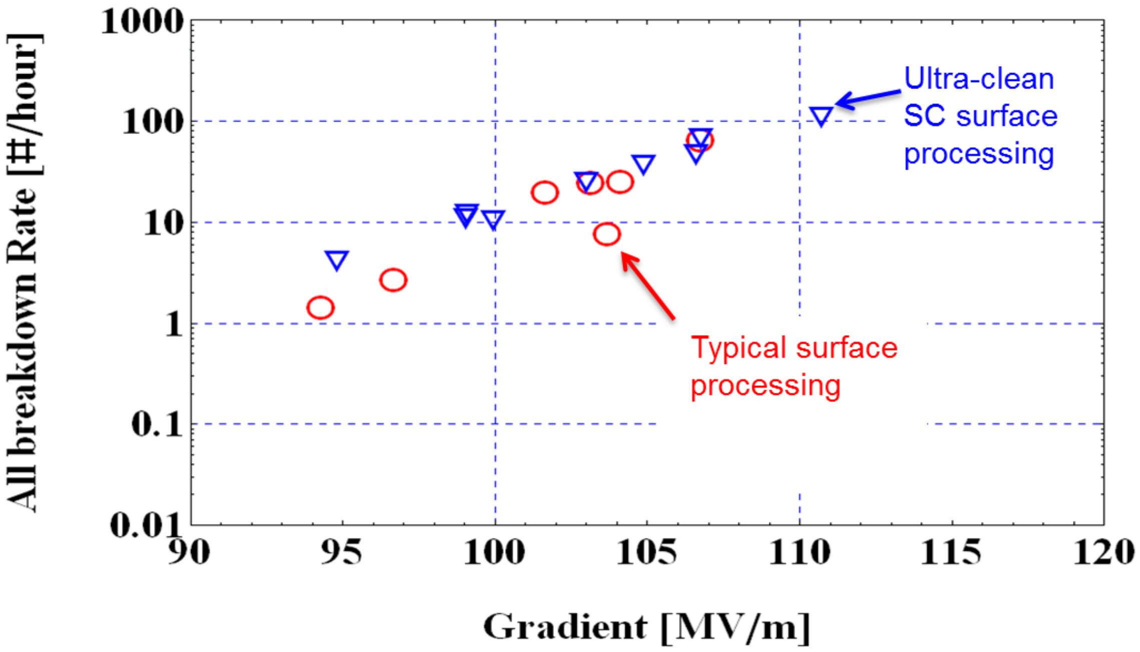
Program has fundamentally changed our understanding and the way we design, build, and test high gradient accelerators.

Program Highlights

- Discovery of magnetic field impact
- Materials
- Comparison of surface processing techniques
- Effect of impedance matching
- High power testing infrastructure
- Spinoffs

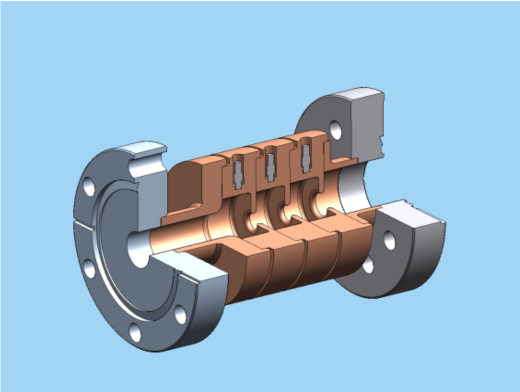
Experiments Proved that Surface Preparation Was Not the Key to Achieving High Gradients

Dr. Yasuo Higashi and Richard Talley assembling Three-C-SW-A5.65-T4.6-Cu-KEK-#2

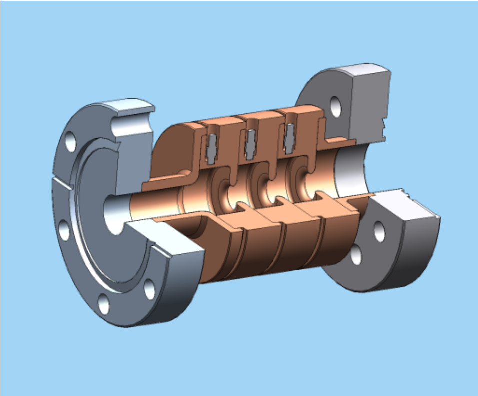


Superconducting processing of surface affected only processing time, not gradient.

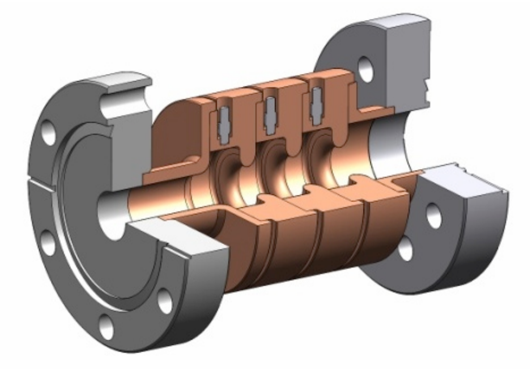
Geometrical Studies: Three Standing-Wave Structures of Different Geometries



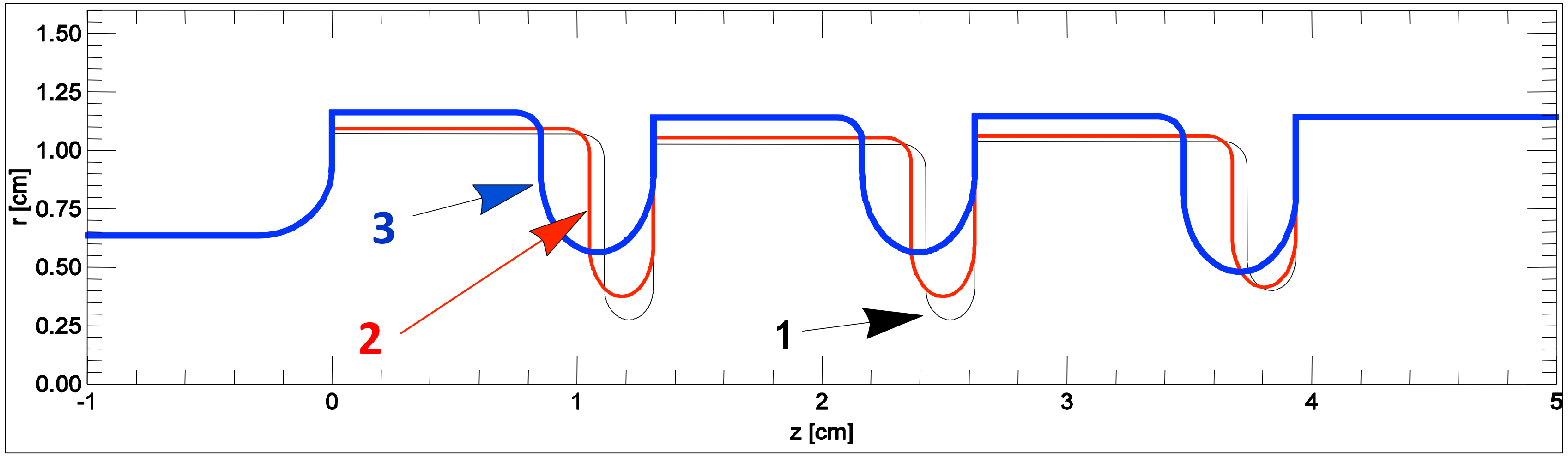
1)1C-SW-A2.75-T2.0-Cu



2) 1C-SW-A3.75-T2.0-Cu

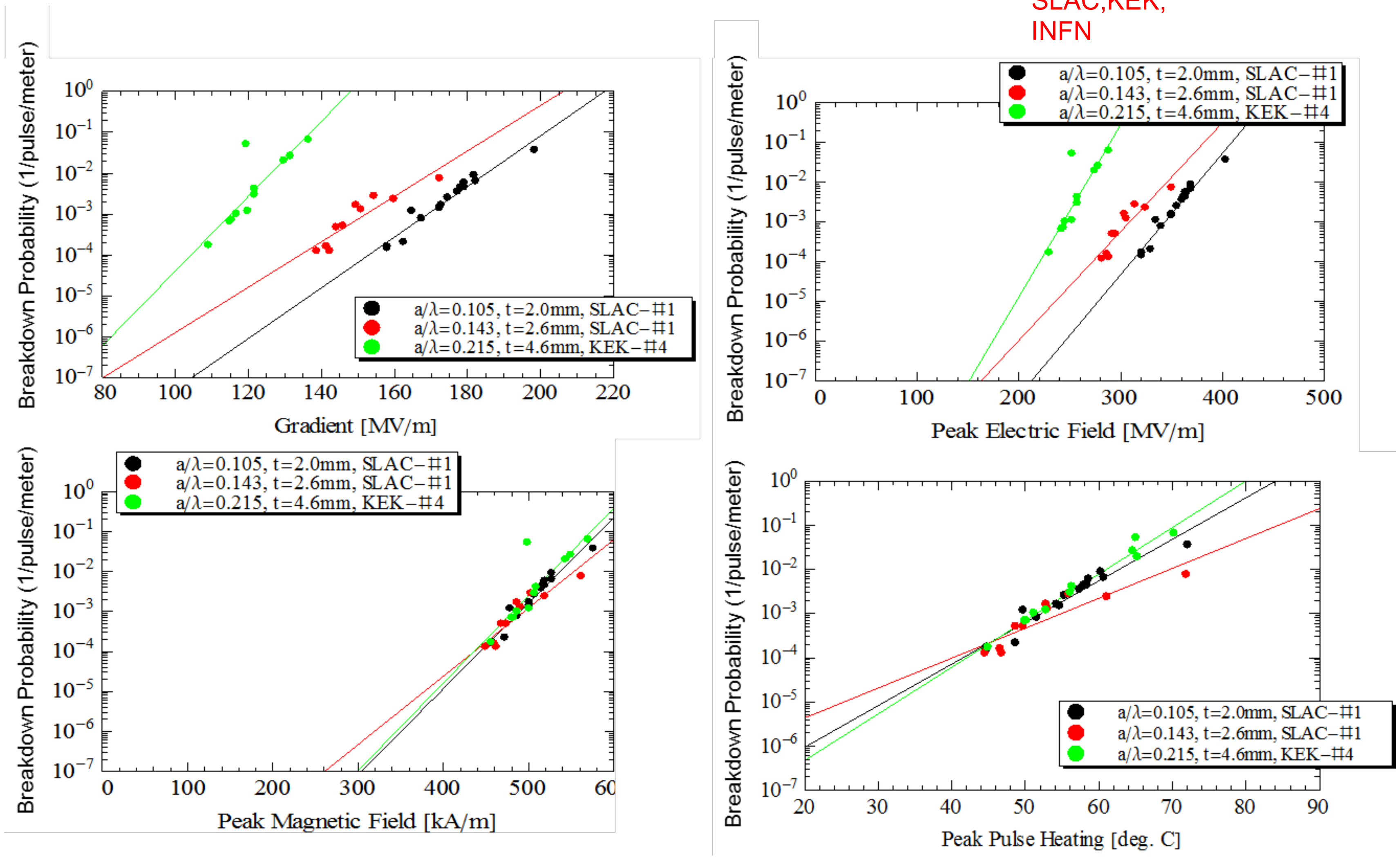


3) 1C-SW-A5.65-T4.6-Cu



Geometrical Studies:
Standing-wave structures with different iris diameters and shapes
a/λ=0.215, a/λ=0.143, and a/λ=0.105

SLAC,KEK, INFN



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

SLAC

- 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
- Applications of new information
  - A new methodology for designing Photonic Band Gap (PBG) structures
  - New understanding of MUON cooling cavity results in operation under strong magnetic fields
  - Improved design of high peak power rf sources

Discovery of magnetic heating effect is already making an impact in design of high power rf structures

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

- 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
- Applications of new information
  - A new methodology for designing Photonic Band Gap (PBG) structures
  - New understanding of MUON cooling cavity results in operation under strong magnetic fields
  - Improved design of high peak power rf sources

Discovery of magnetic heating effect is already making an impact in design of high power rf structures

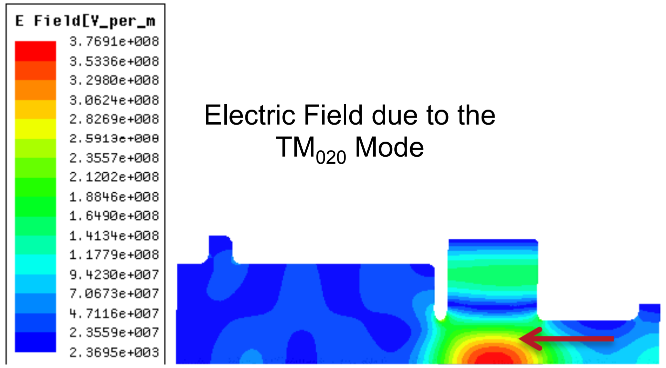
Dual mode Cavity for studying the relative effects of electric and magnetic fields

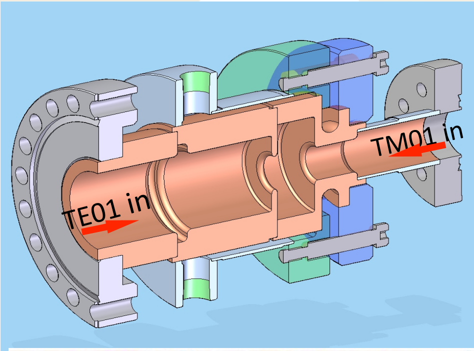
SLAC

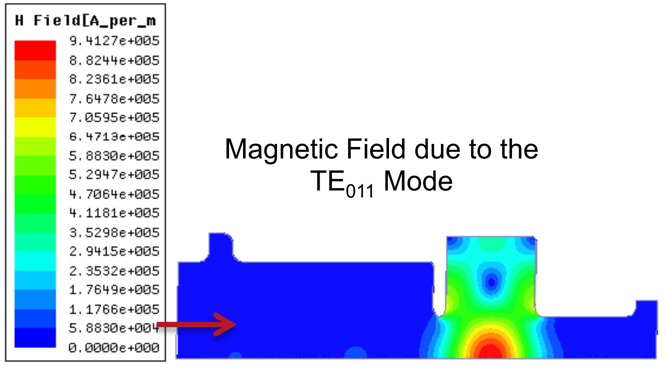
•This experiment began two months ago and we are in the process of collecting statistics.

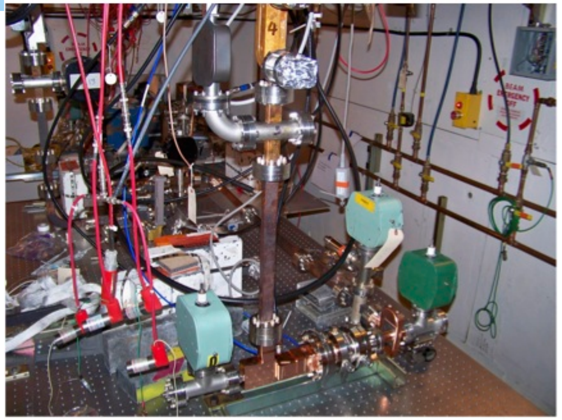
•The experiment is very flexible because it allows us to change the electric and magnetic field timing, ratio and phase

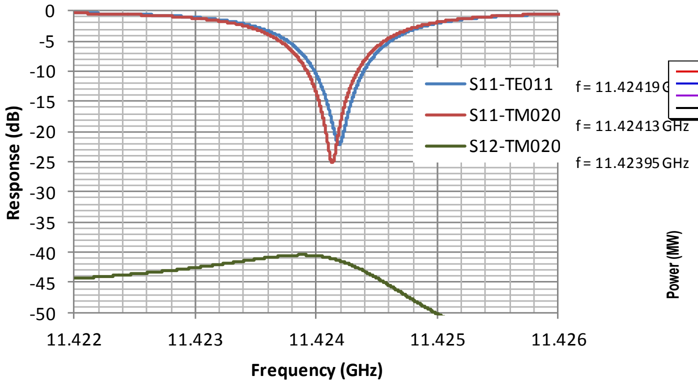
•We are already seeing very interesting results that could have an impact on our understanding of the phenomena

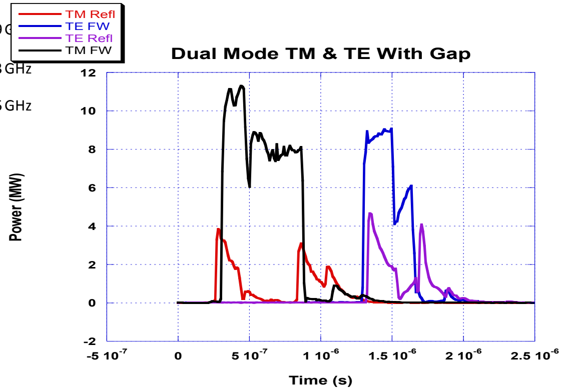










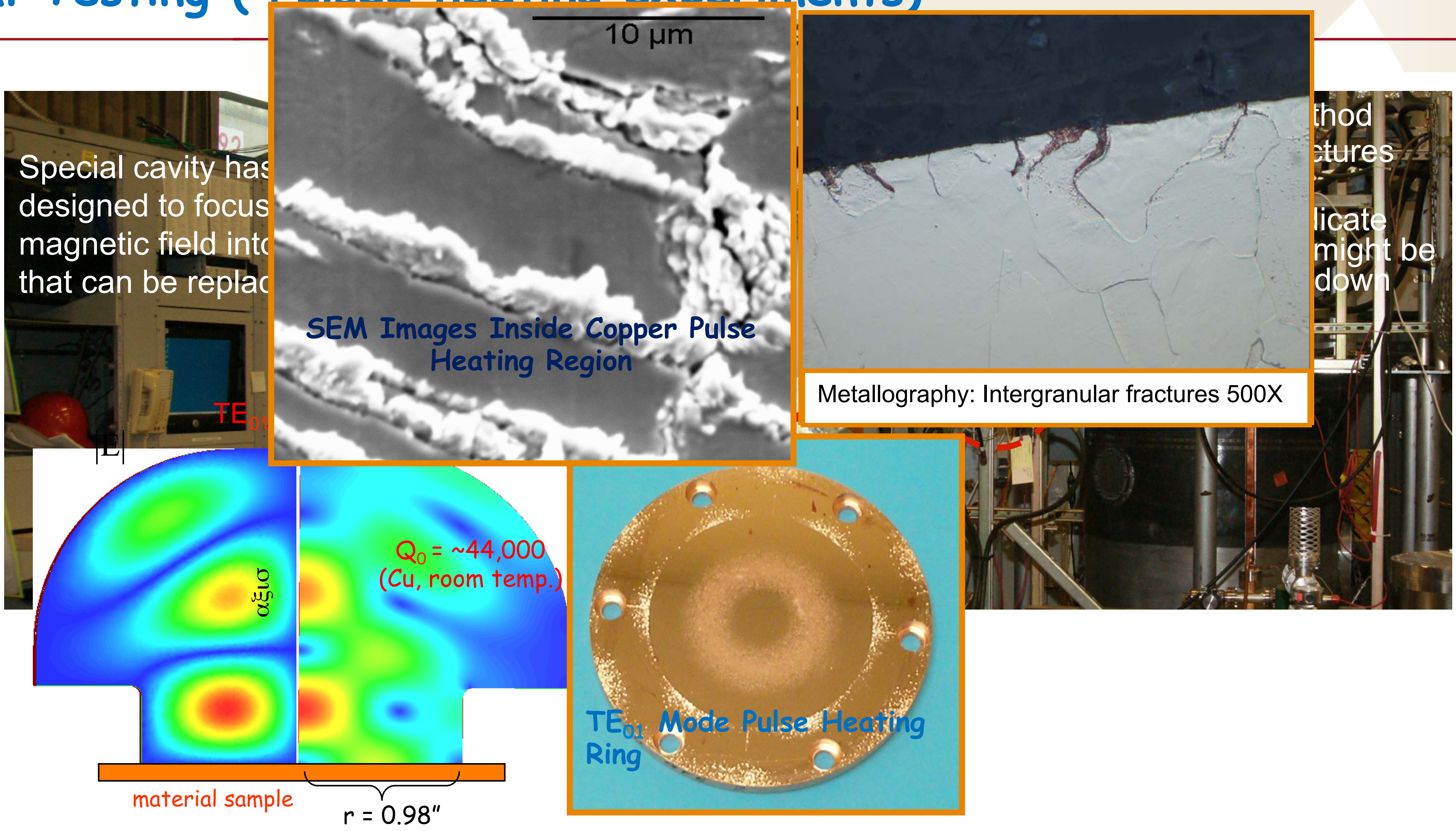


New Discovery of Magnetic Fields Role in Breakdown Triggered a Change in Research Direction

- 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
- Applications of new information
  - A new methodology for designing Photonic Band Gap (PBG) structures
  - New understanding of MUON cooling cavity results in operation under strong magnetic fields
  - Improved design of high peak power rf sources

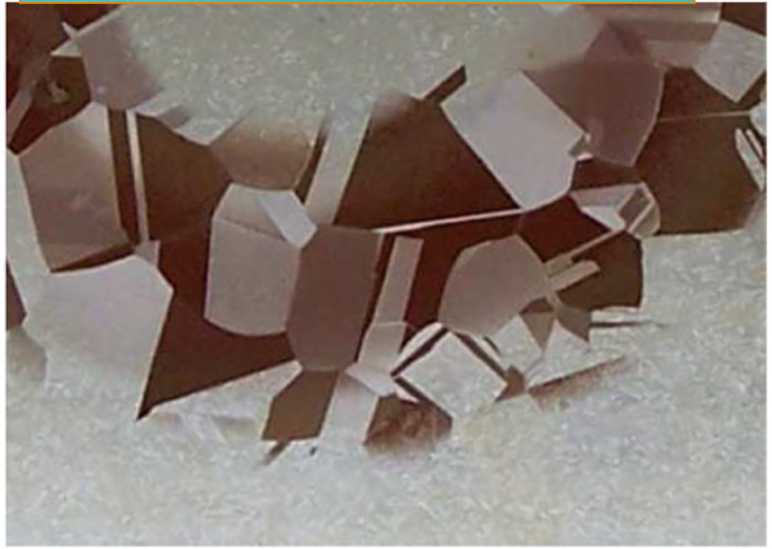
Discovery of magnetic heating effect is already making an impact in design of high power rf structures

Material Testing (Pulsed heating experiments)

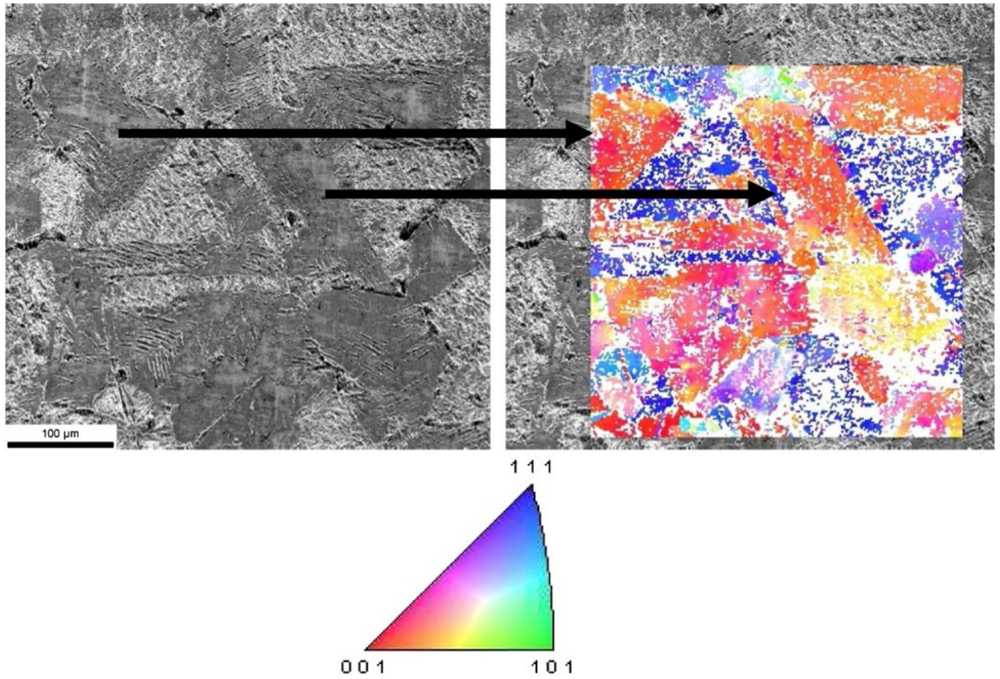


Max Temp rise during pulse = 110°C

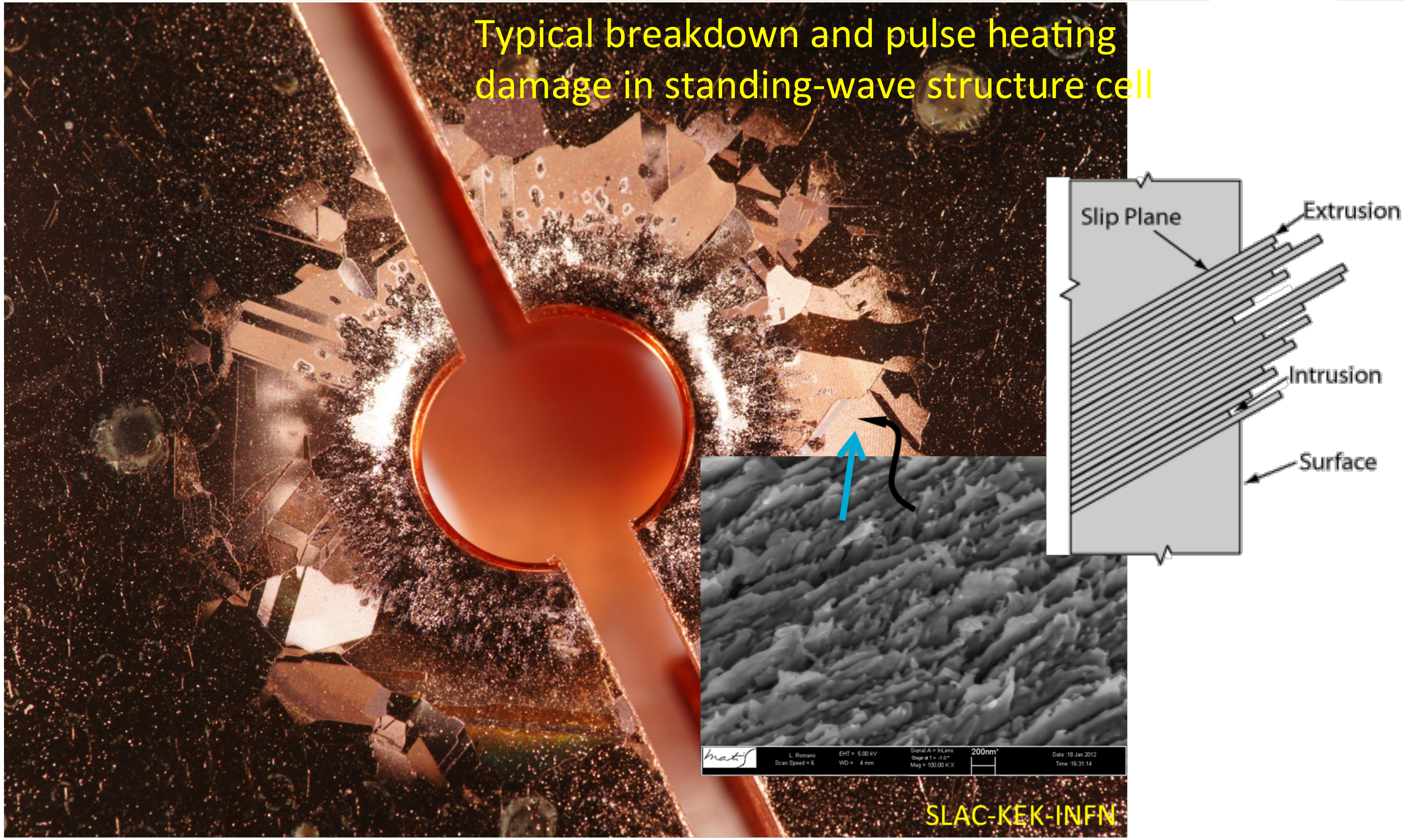
Pulsed heating and crystal orientation



Annealed Copper with large grain shows crystal pattern because damage is different for each crystal orientation



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

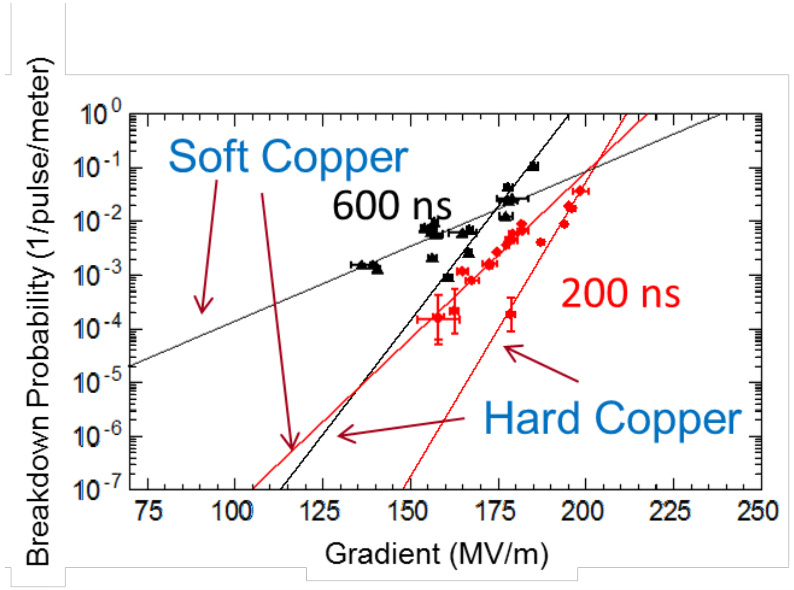


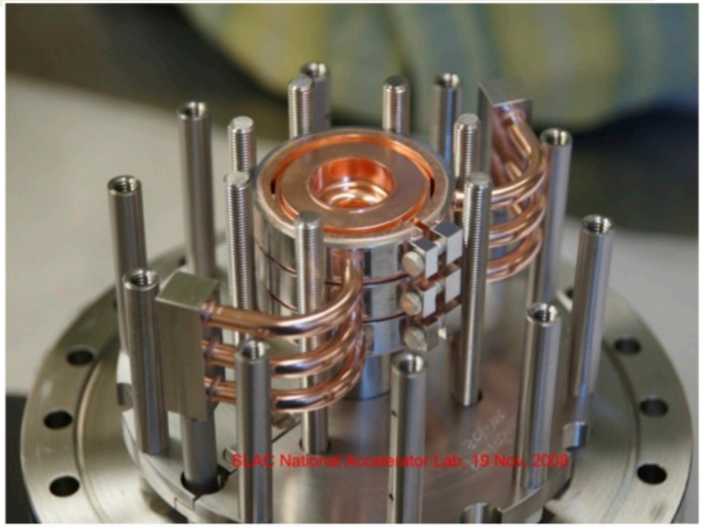
The Conclusion of the HG collaboration and the future: Advanced Ultra-High Frequency Acceleration

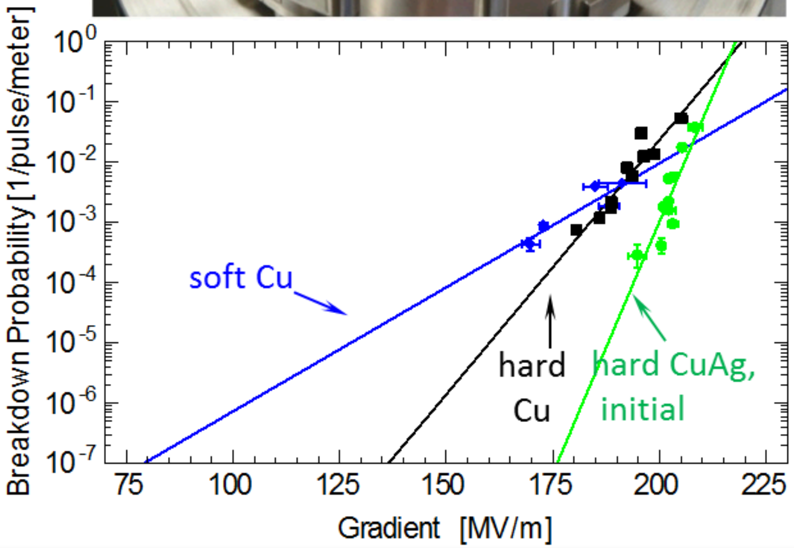
Pulse Heating Samples RF Tested

Hard copper and copper alloys resulted in ultra-high gradients

- We developed an apparatus for testing accelerator structures without brazing
- The results show a great improvement in gradient at very low breakdown rates, Lower than that required by a collider application







Demonstration of 175 MV/m, a major program milestone!

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

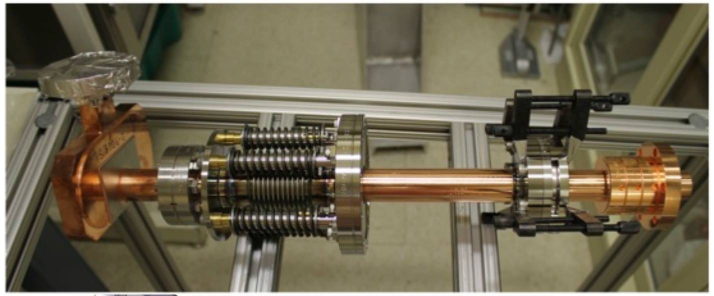
SLAC

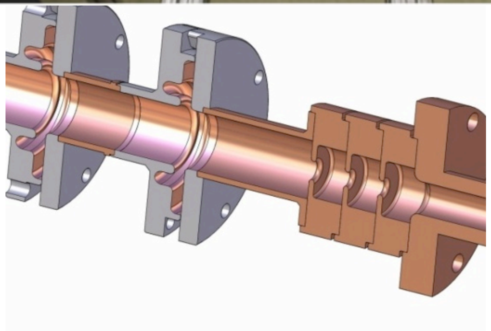
- New research initiated
  - Geometry optimizations for accelerator structures based on reduction of the magnetic surface field
  - Studies of surface magnetic fields and materials
  - Basic Physics studies with mixed E&H dual-mode cavities
  - Low temperature experiments with very high gradient structures
- Applications of new information
  - A new methodology for designing Photonic Band Gap (PBG) structures
  - New understanding of MUON cooling cavity results in operation under strong magnetic fields
  - Improved design of high peak power rf sources

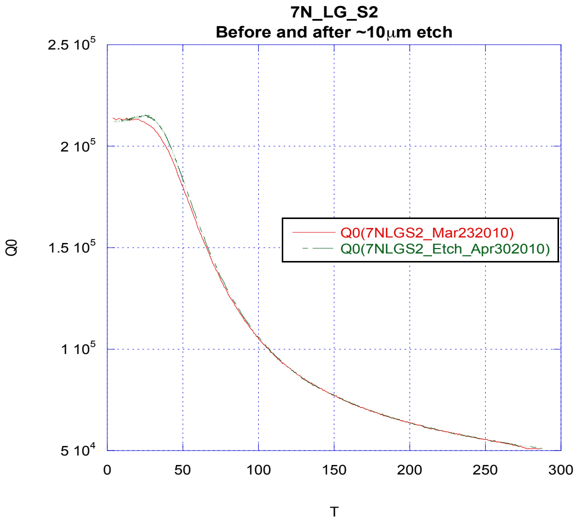
Discovery of magnetic heating effect is already making an impact in design of high power rf structures

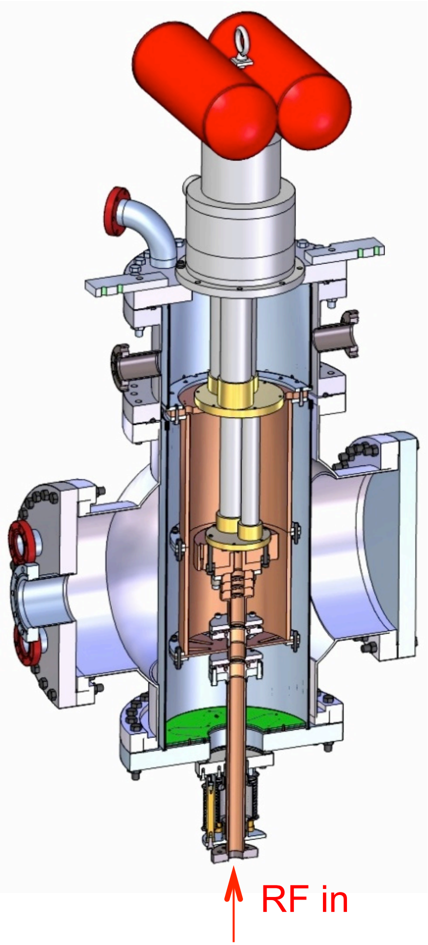
Accelerator Structures at Cryogenic Temperatures

- 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



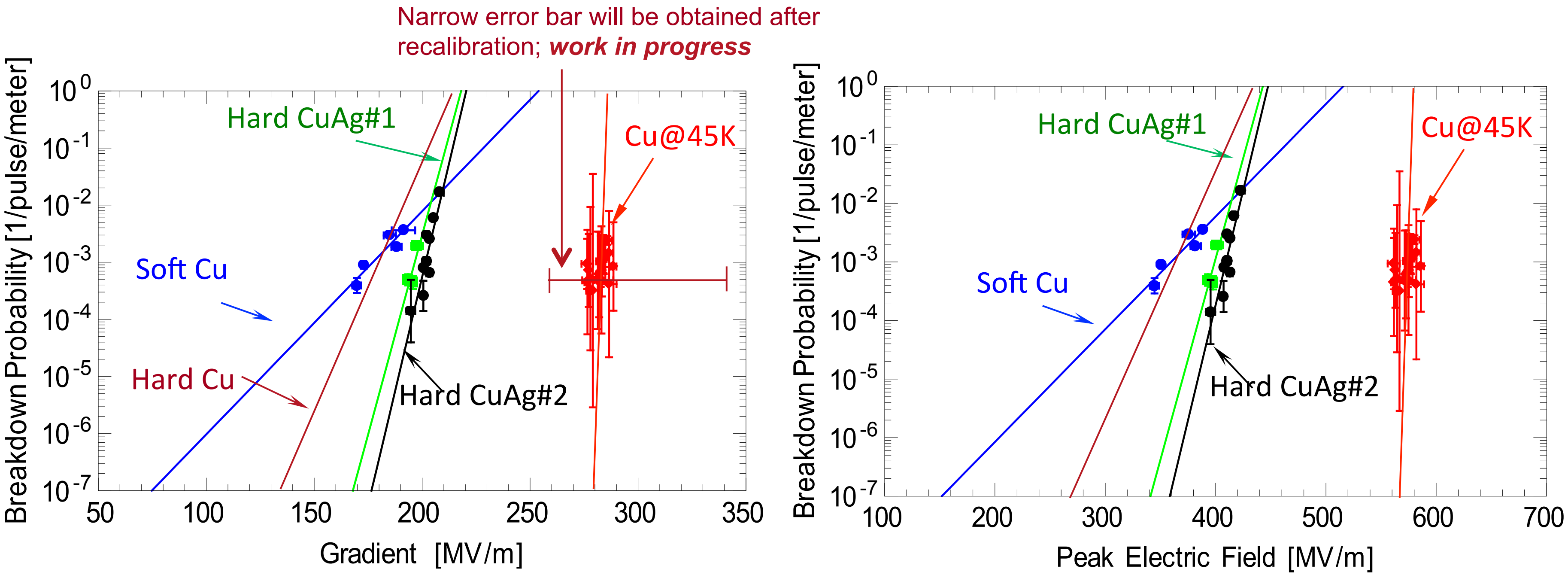






Understanding the Physics of High Gradients has Established the Limits of Normal Conducting Copper Structures

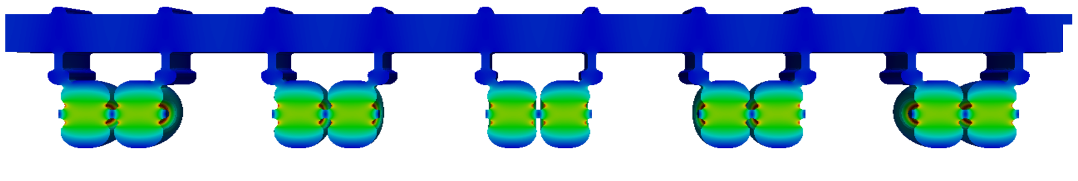
SLAC

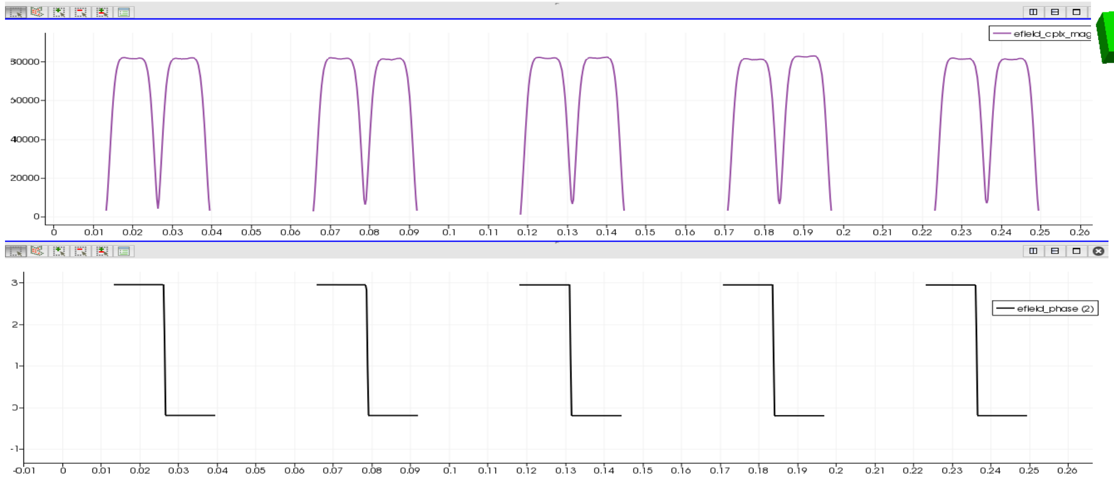


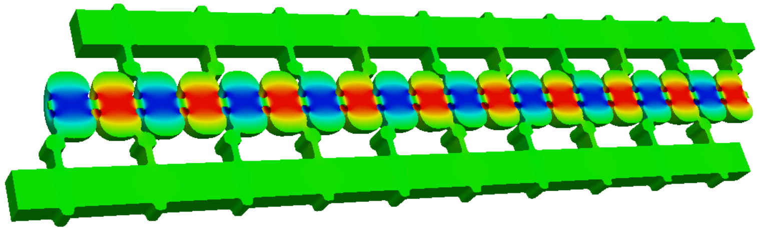
- Basic physics experiments move to testing normal & SC engineered materials
- Cost effective implementation of accelerator structures capable of operating *efficiently* at these gradients.
- Build RF sources that can power these structures to high gradients
- New architectures for future facilities (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.

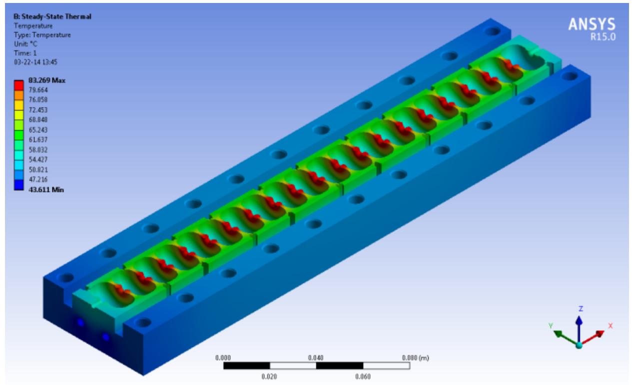
Novel Distributed Coupling to Each Accelerator Cell Enables *Doubling* RF to Beam Efficiency and Ultra-High-Gradient Operation.

SLAC





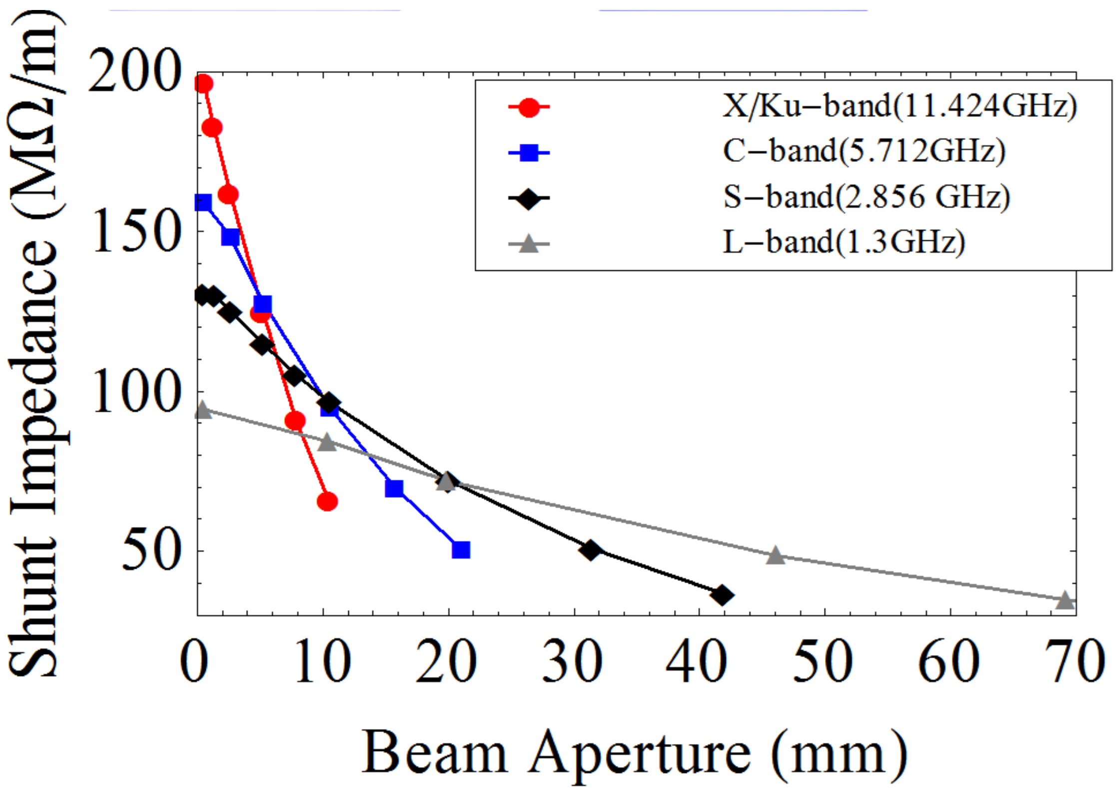




- Optimize individual cell shape for maximum gradient and shunt impedance without cell-to-cell coupling constraint
- Requires only 66 MW/m for 100 MV/m gradient compared to 200 MW/m for a typical X-band structure
- **Inexpensive to manufacture**
- Patent filed by Stanford
- **First 150 MV/m accelerator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

highly optimized standingwave structure with distributed feeding allow for new possibilities

SLAC

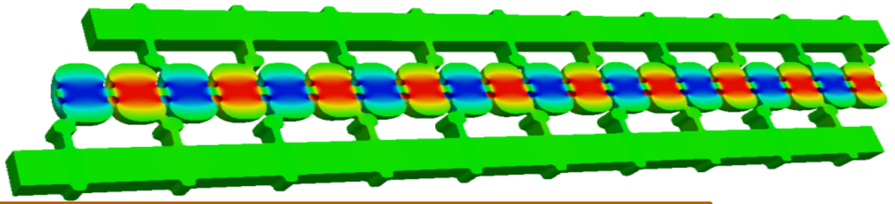


With the enhanced shunt impedance, it is quite possible to have a very light weight 1 MeV Accelerator powered by a solid state drivers as a replacement for Ir192

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

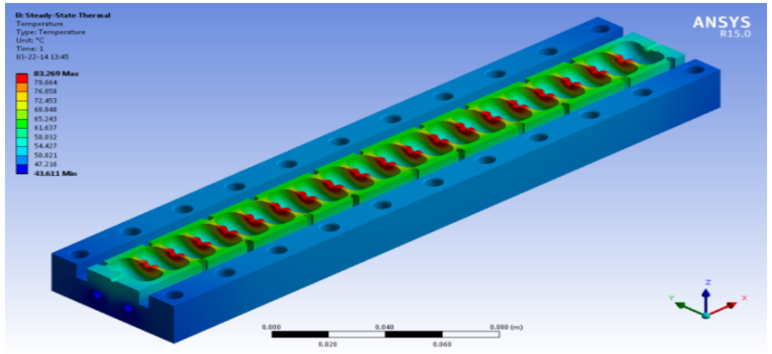
SLAC

- 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

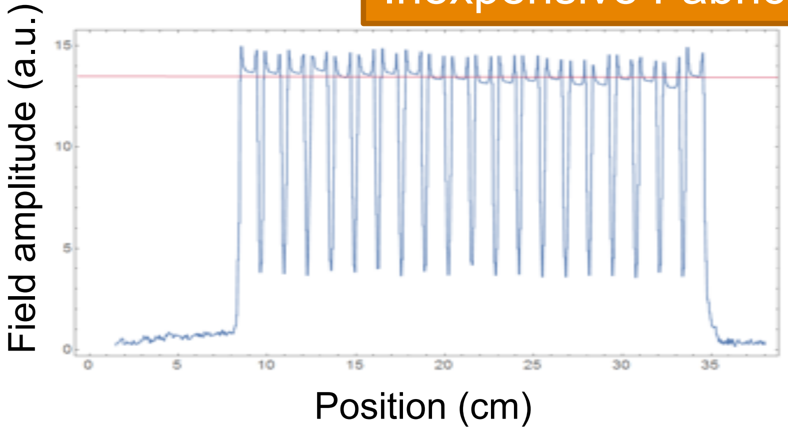


Distributed Coupling to Each Cell

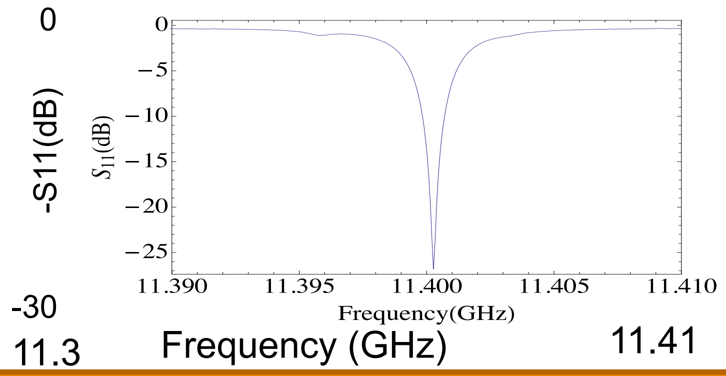
Inexpensive Fabrication Demonstrated



Solid-Model of Split-Block Assembly



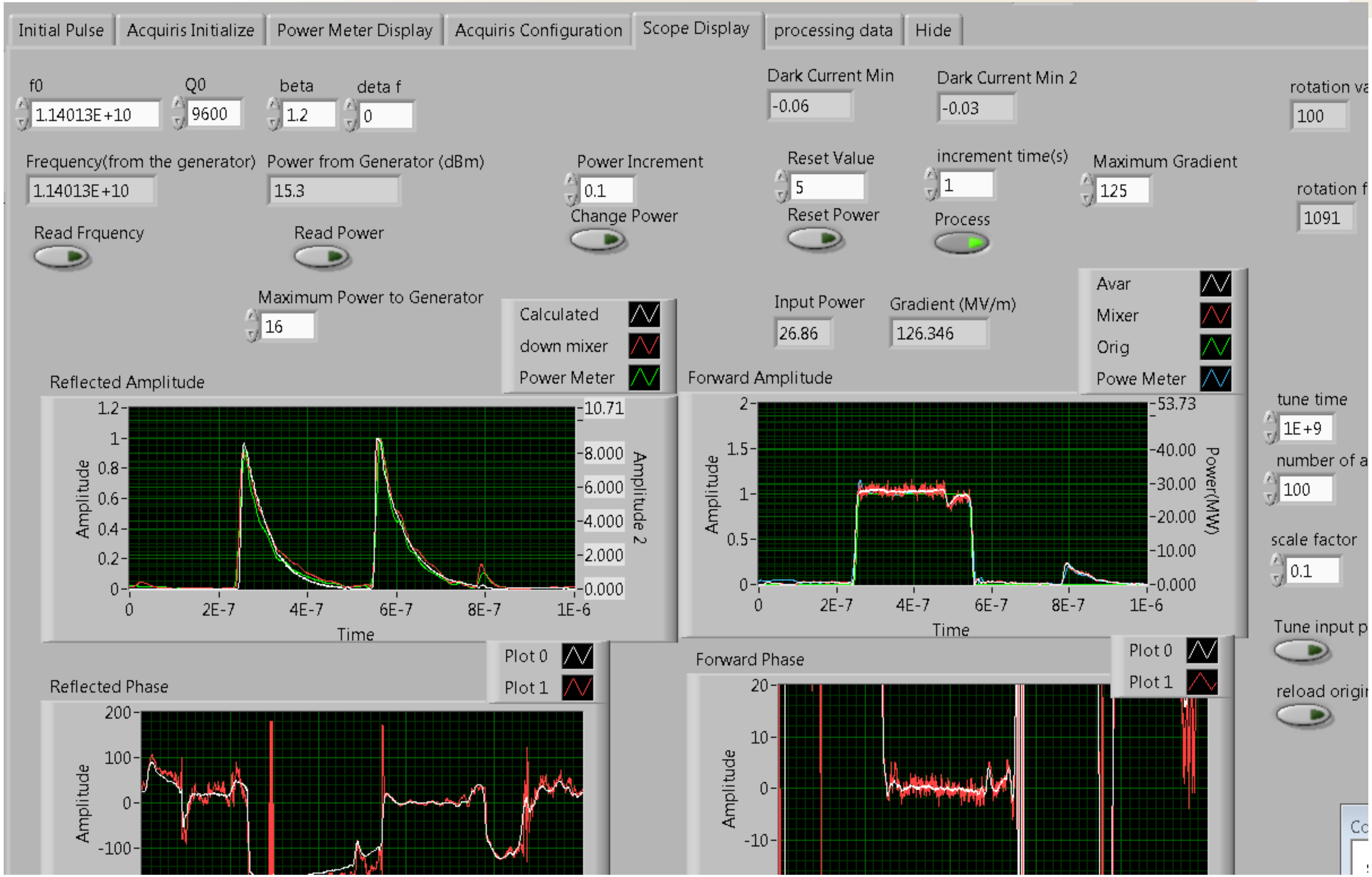
Easy Tuning



Single frequency rather than the traditional 20 resonances

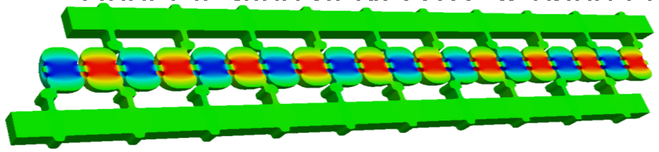
- Only possible through modern virtual prototyping using high power computing

S. Tantawi, P. Borchard, Z. Li

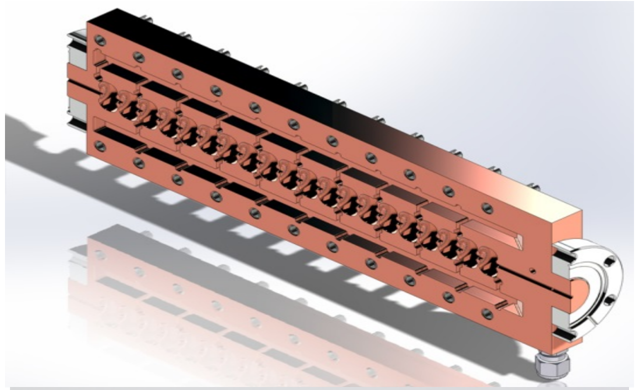

Initial Pulse
Acquiris Initialize
Power Meter Display
Acquiris Configuration
Scope Display
processing data
Hide
f0
1.14013E+10
Q0
9600
beta
1.2
deta f
0
Dark Current Min
-0.06
Dark Current Min 2
-0.03
rotation va
100
Frequency(from the generator)
1.14013E+10
Power from Generator (dBm)
15.3
Power Increment
0.1
Change Power
Reset Value
5
Reset Power
increment time(s)
1
Process
Maximum Gradient
125
rotation f
1091
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
number of a
100
scale factor
0.1
Tune input p
reload origi
Plot 0
Plot 1
Reflected Phase
Forward Phase

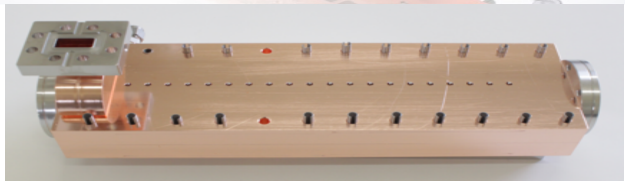
X-band Distributed Feeding Linac

Under testing at NLCTA: X-band (11.4 GHz), π-mode, 20 cells Linac



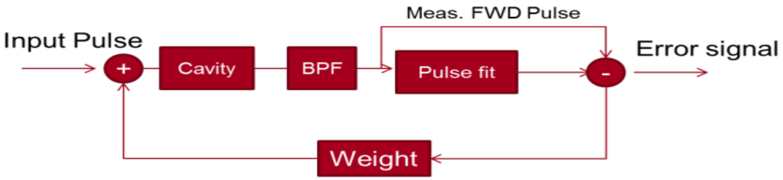
Distributed Coupling to Each Cell

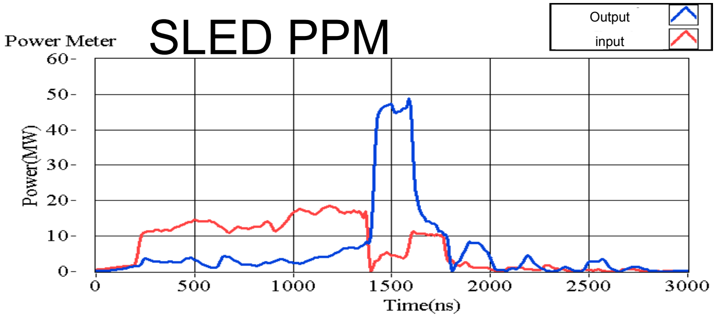


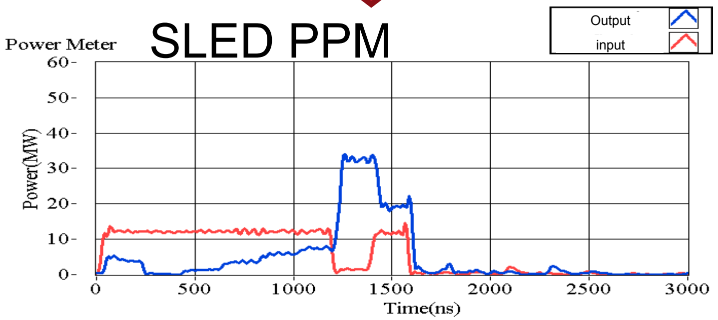


Inexpensive manufacturing using two quasi-identical parts

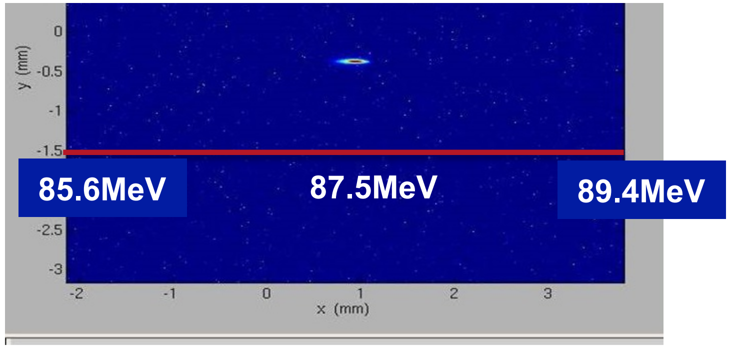
S. Tantawi, P. Borchard, Z. Li





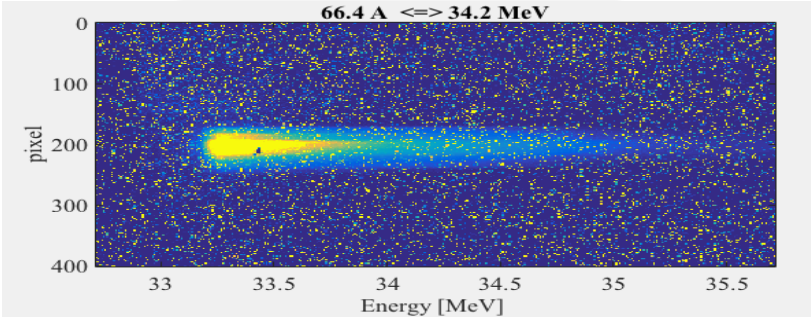


Software Developments: Pulse Correction



Operating with ~100 MeV/m gradient with 16.5 MW of input. Confirmation of gradient by measuring 24 MeV energy gain

Beam Energy



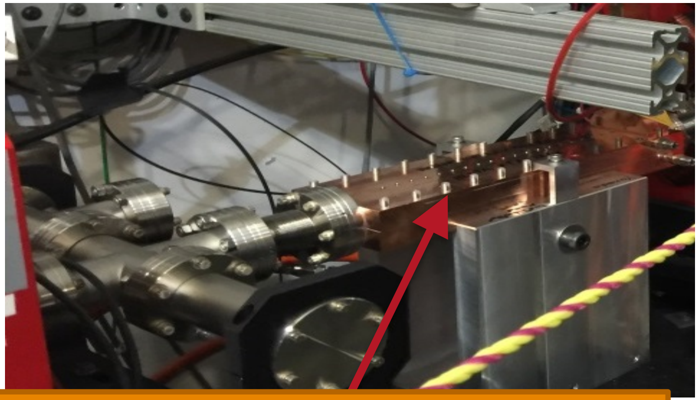
Confirmation was done at ~140 MV/m gradient by measuring 35.7 MeV maximum dark current energy

Measured dark current energy

M. Nasr , C. Limborg, S. Tantawi

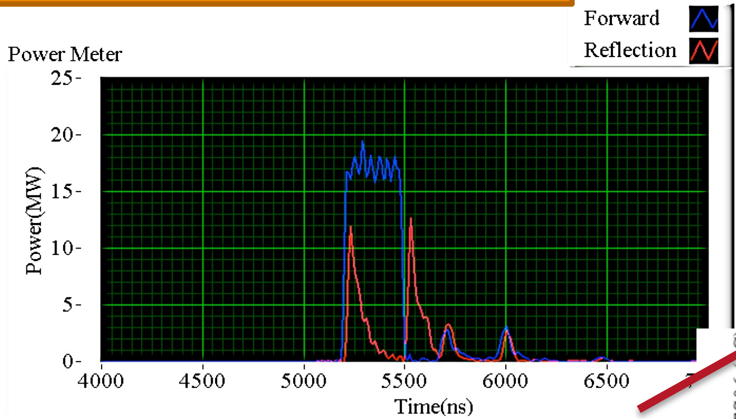
Only possible through modern virtual prototyping using high power computing

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

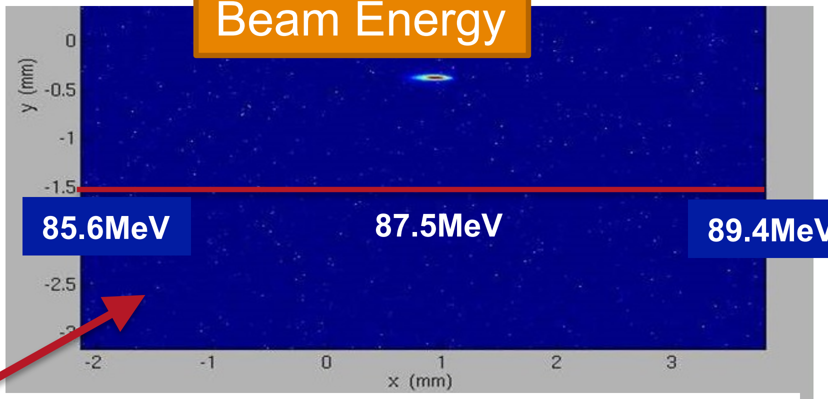


26 cm structure installed at XTA

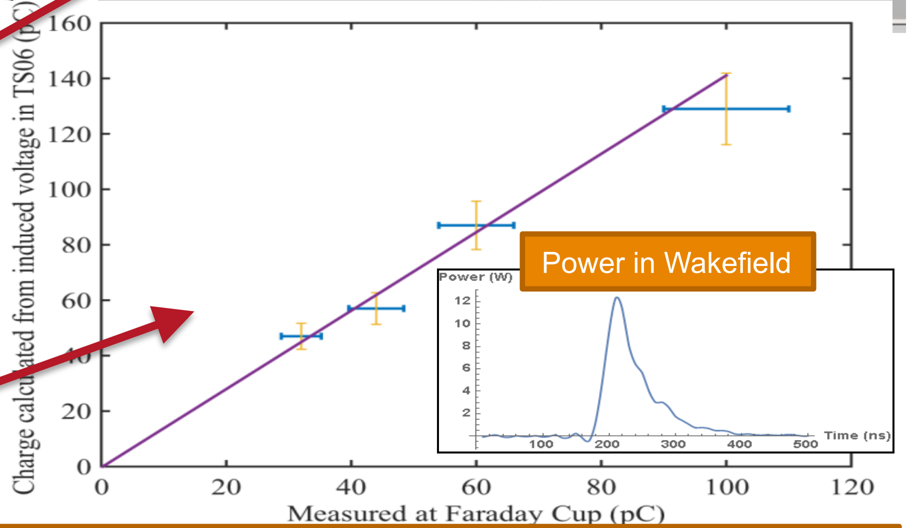
Forward and Reflected Power



Beam Energy



- 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

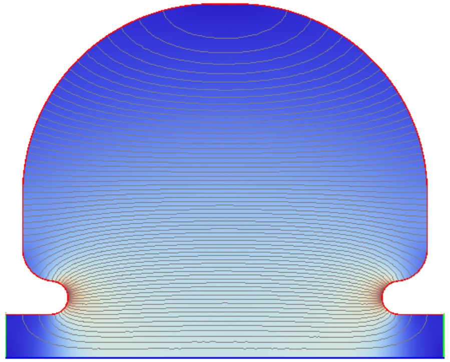


Measured Charge with Faraday Cup and Calculated from Induced Wakefield

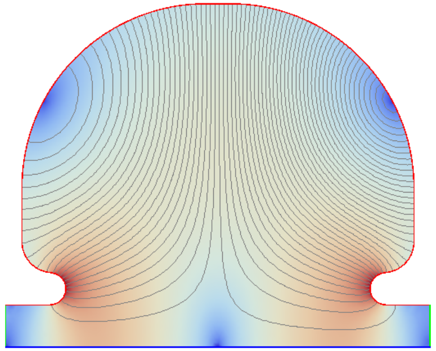
- The structure is being processed at XTA to go beyond 135 MeV/m

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*

A Novel Dual-Mode Dual-Frequency Linac Design

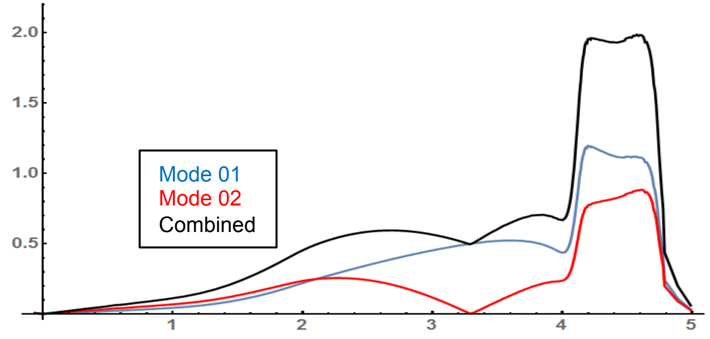
New Design Approach

This technology breaks the quadratic dependence between power and gradient and instead the power of the two modes adds linearly to satisfy the required gradient.

Due to this and the large increase in the total shunt impedance, we will be able to reach a gradient of 200 MV/m

This is made possible using the new invention of a distributed feeding network that feeds every cell independently for each mode.

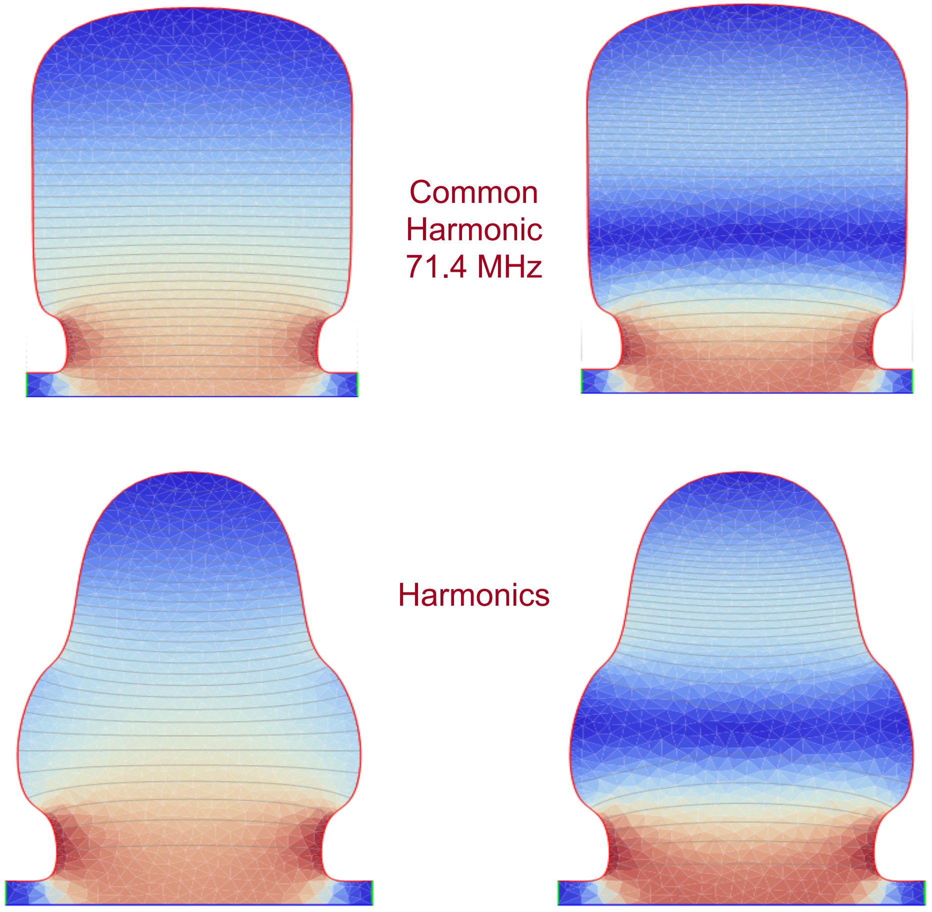
$$\frac{Gradient_2}{Gradient_1} = \frac{R_{s,2}}{R_{s,1}}$$



Sample Design: Adding the second mode → 60% increase in the shunt impedance with same maximum surface field to gradient ratio

Geometries produced by genetic algorithms maximize the performance, large reduction in RMS value and pulse heating

Designs: iris diameter of 5 mm
Surface E.F. to gradient ratio of 2



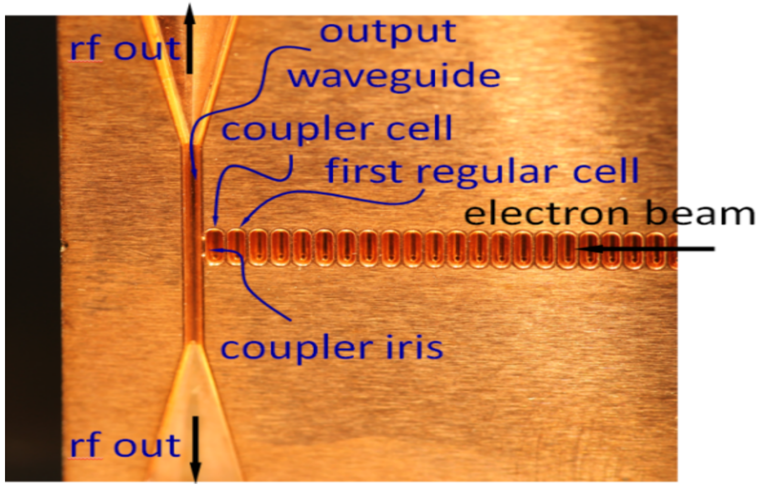
New generic geometries optimized for maximum performance

M. Nasr , S. Tantawi

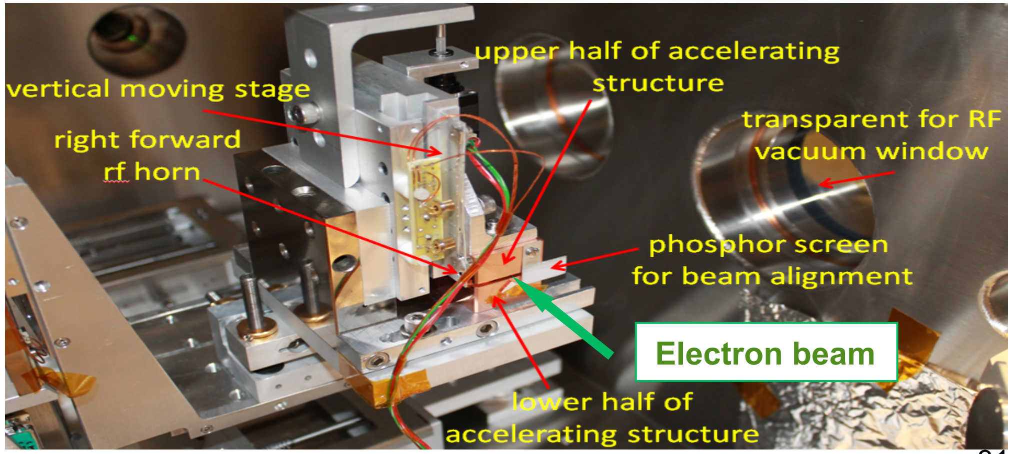
mm-Wave Metallic Accelerator Holds the Potential for High-Gradient Accelerators

- 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

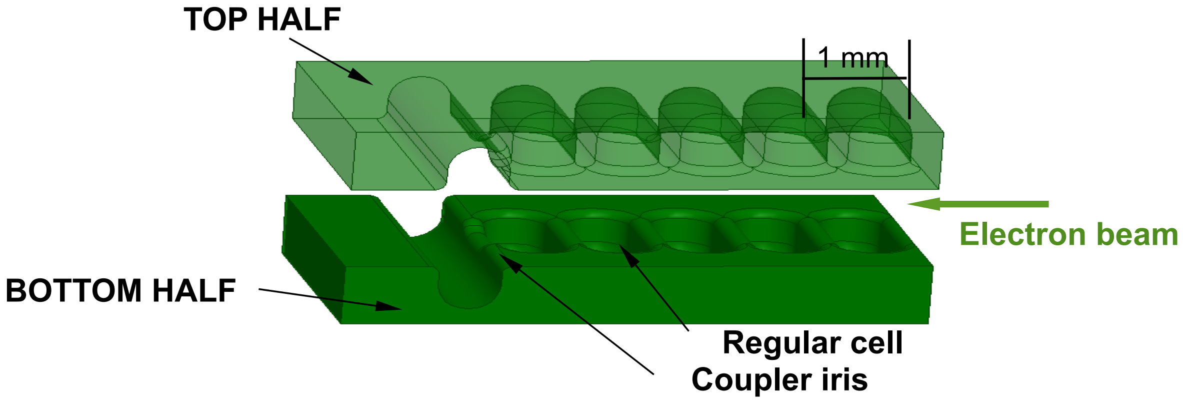
Picture of the 100 GHz copper accelerating structure



Experimental setup with copper accelerating structure – FACET E204



Solid model of the 100 GHz accelerating structure

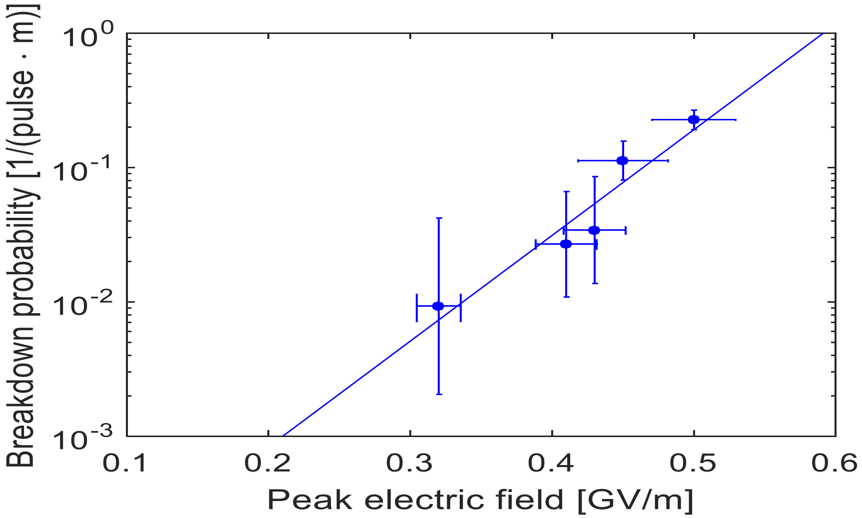


V. Dolgashev, M. Dal Forno

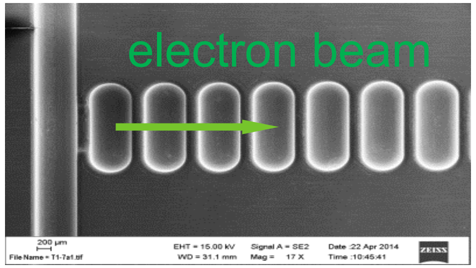
First Measurement of Breakdown Statistics in High-Gradient Beam-Driven Accelerator

SLAC

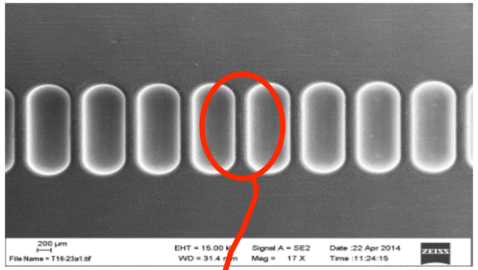
Breakdown rate measurements: travelling wave Cu-Ag 100 GHz structure (Nov 2015)



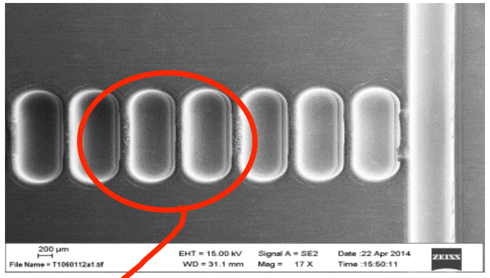
Observation of Damage: travelling wave Cu 100 GHz structure



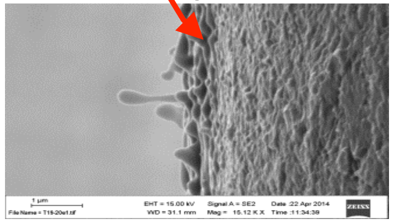
Input coupler, cells 1-7, no damage

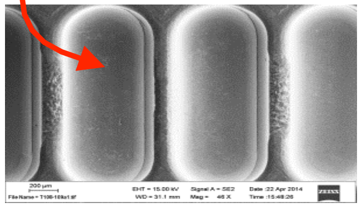


Cells 16-23, fist signs of damage



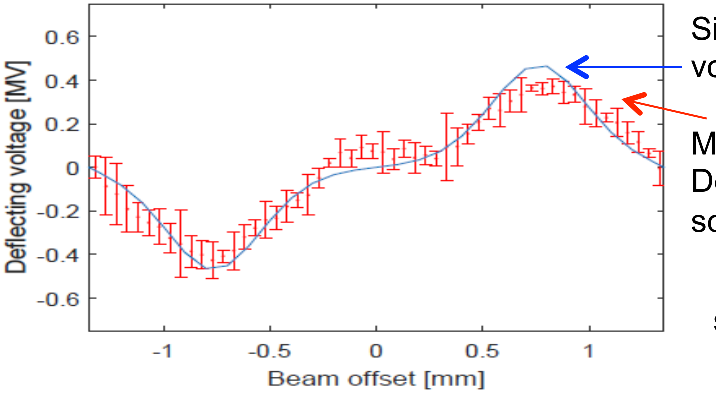
Output coupler, massive breakdown damage





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)

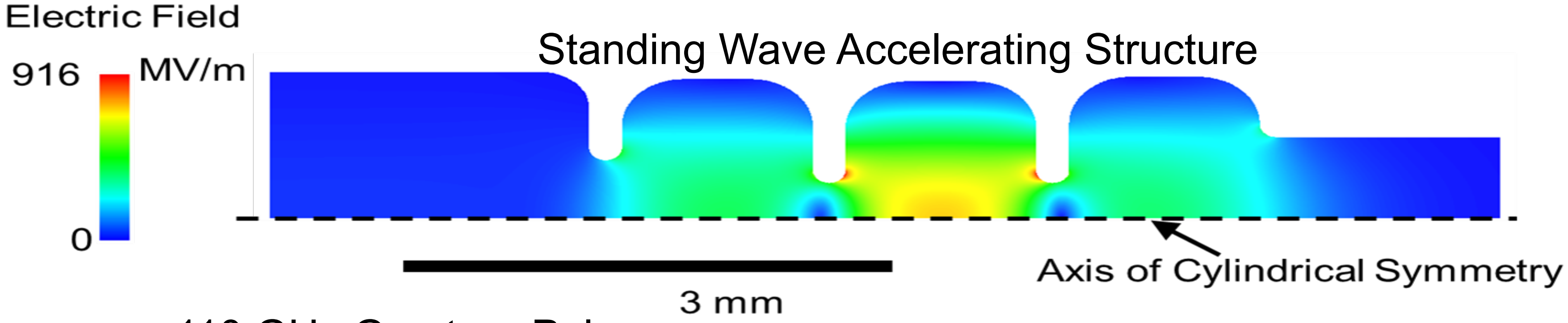
- FACET-E204 Tests: finished experiments at 100 GHz and 235 GHz with data analysis in progress
- We hypothesize drive beam significantly impacts breakdown rate

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.

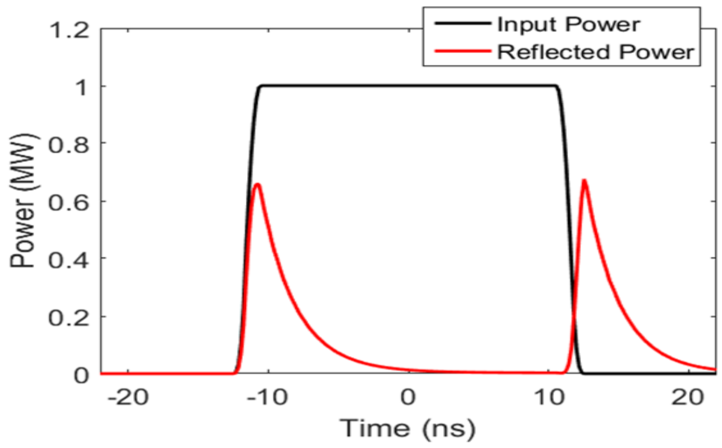
V. Dolgashev, M. Dal Forno

What is the Real Scaling in Frequency for Breakdown Physics?

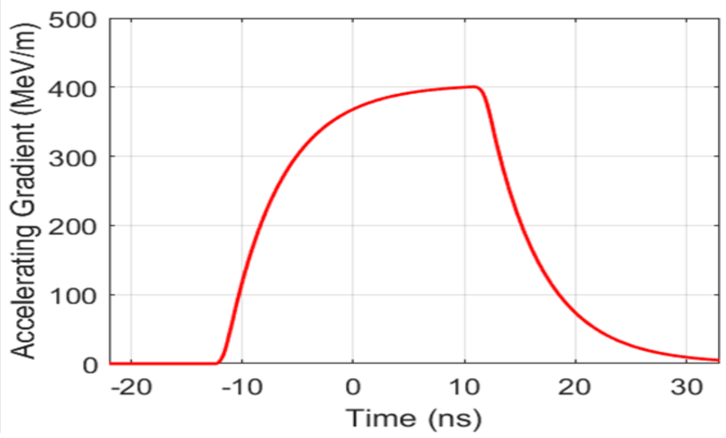
- Demonstrate realizable mm-wave accelerating structure
- Power with stand-alone RF source (gyrotron @ MIT)
- Direct comparison with breakdown studies at x-band



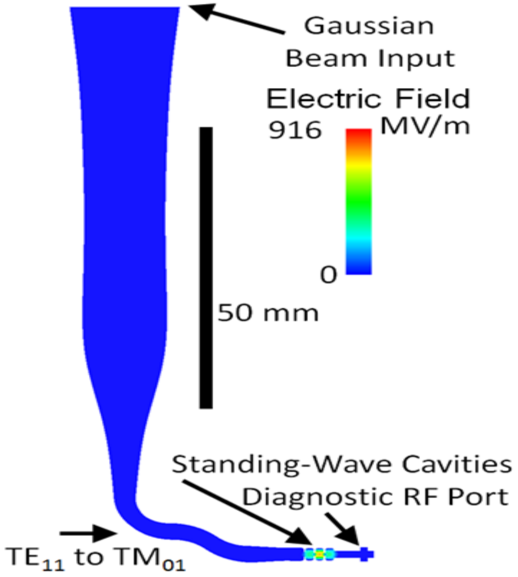
110 GHz Gyrotron Pulse



Accelerating Gradient



Full RF Structure

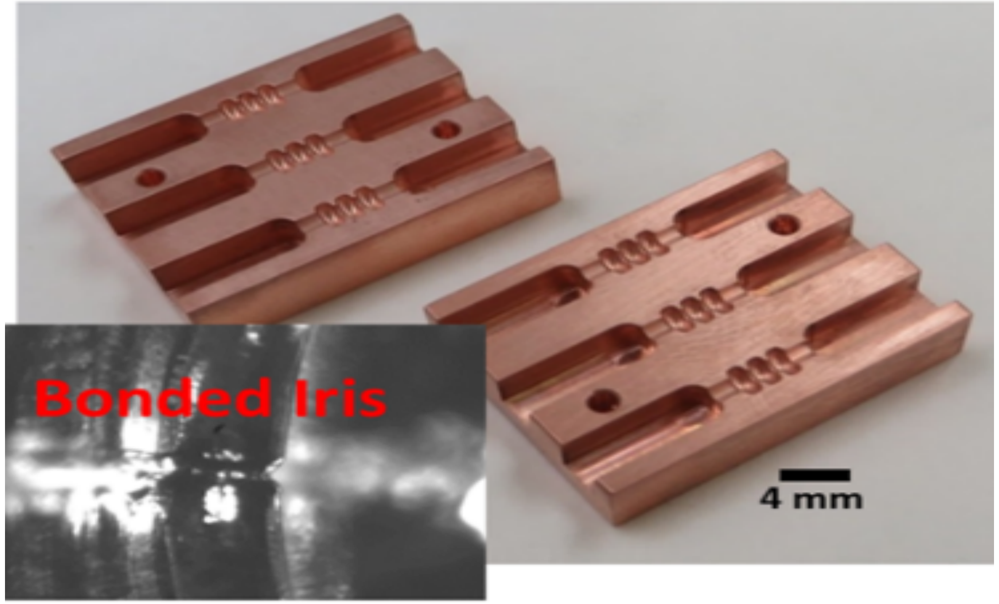


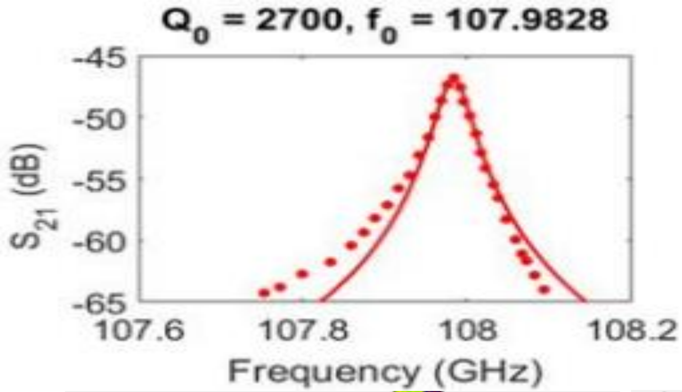
E. Nanni, V. Dolgashev, J. Neilson

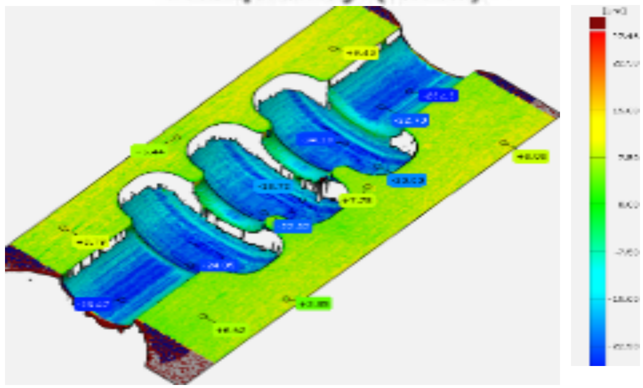
Modern Tools for Fabrication of mm-Wave Standing-Wave Accelerating Structures

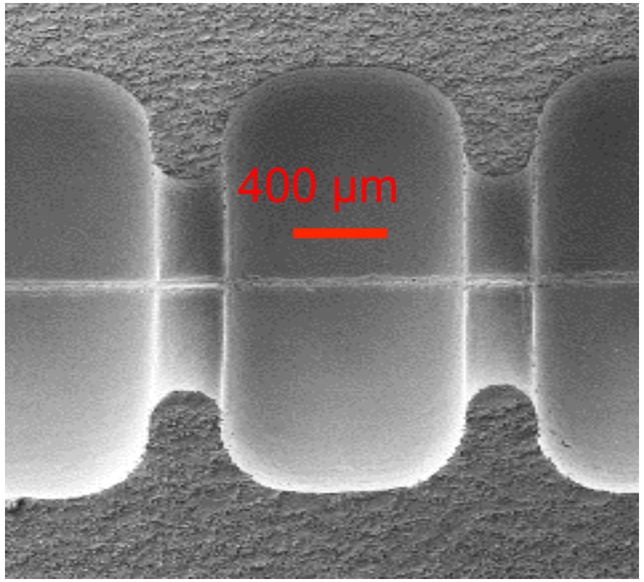
- CNC machining tool provide rapid fabrication of prototype mm-wave accelerating structures
- <50 nm is state-of-the-art positional accuracy
- Unique approaches needed for bonding structures

Standing-Wave Accelerating Structure @ 110 GHz







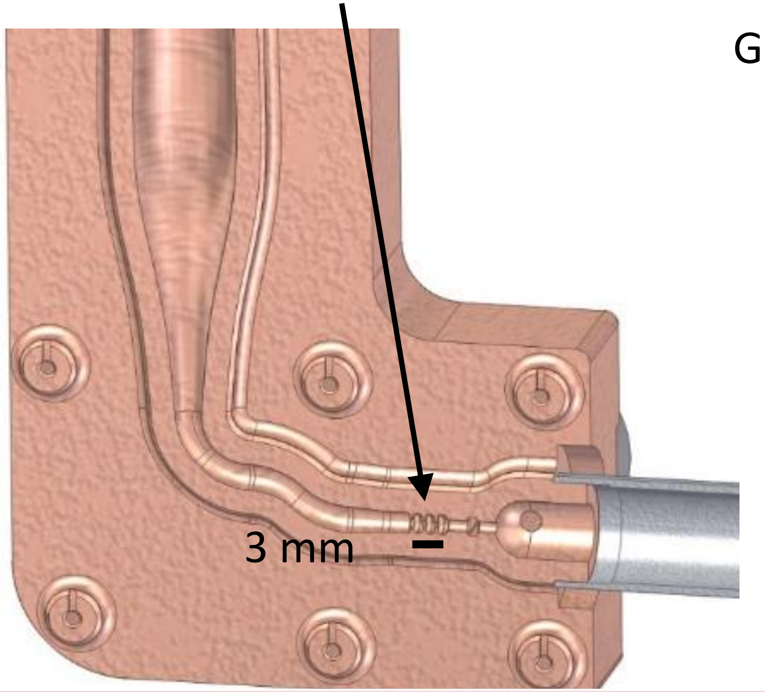


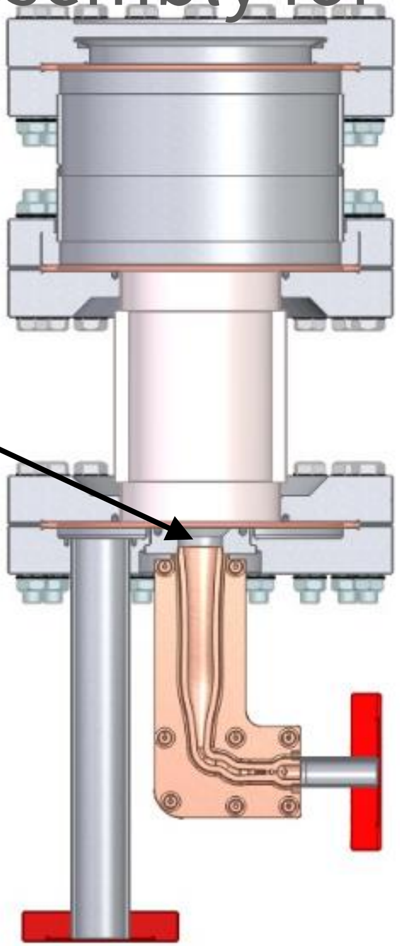
E. Nanni, V. Dolgashev

High-Gradient Structure Test Assembly

- Designed interchangeable test assembly for mm-wave/THz high-gradient structure tests

First structures split-cell with diffusion bond





Future Tests with New Structures Designs, Materials and Different Frequencies

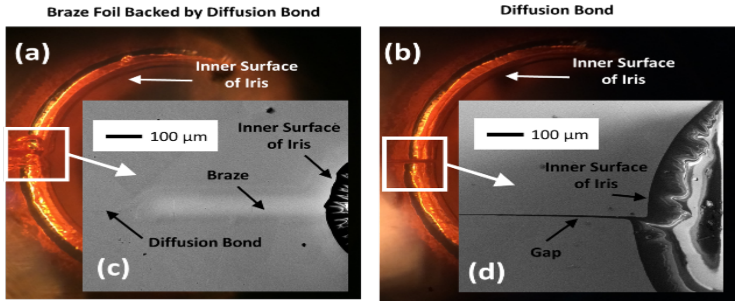
High-Gradient mm-Wave Accelerating Structures

Goal: Demonstrate high-gradient operation in mm-wave/THz frequency range

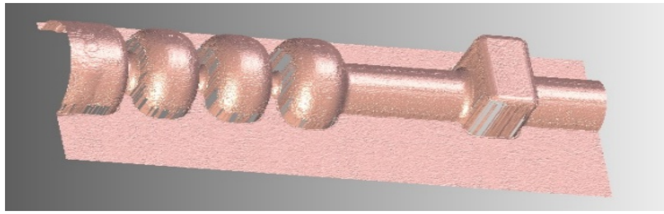
Approaching GeV/m gradients, dramatically reduced power requirements

Developed new fabrication techniques for mm-wave structures

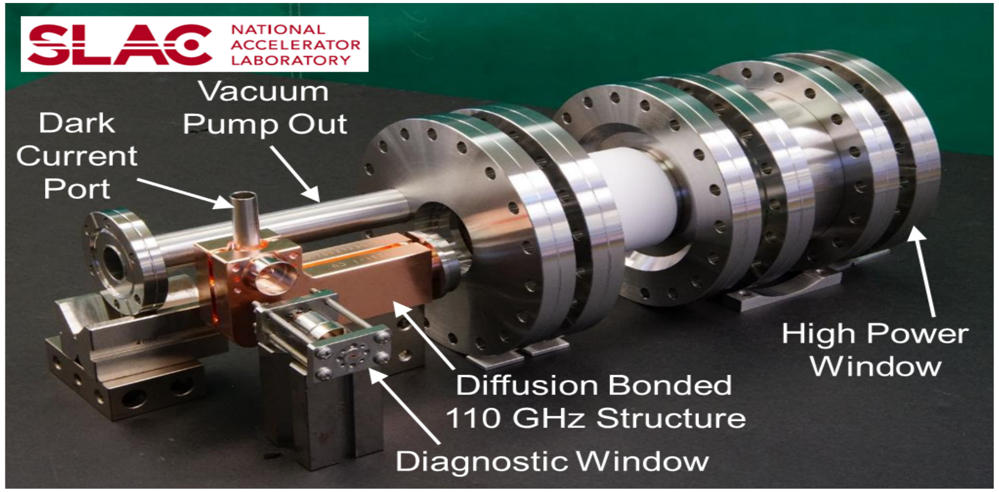
Investigating Bonding Techniques and Impact on Operation



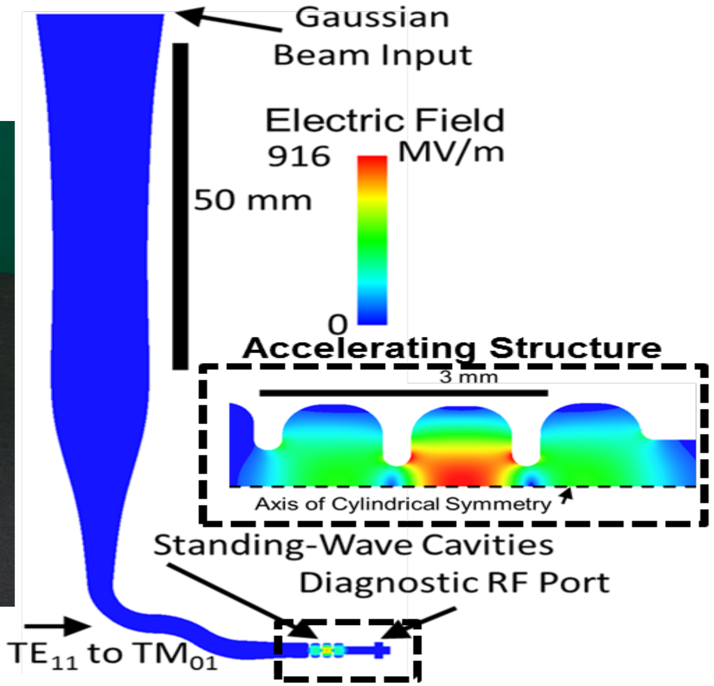
Applying Advanced Metrology for Close Loop Manufacturing



Completed High Power Test Assembly



High-Fields Localized to Test Cavity



Structure Complete → Moving Forward to Test, Target 1 MW Dissipated >400 MeV/m

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

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

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

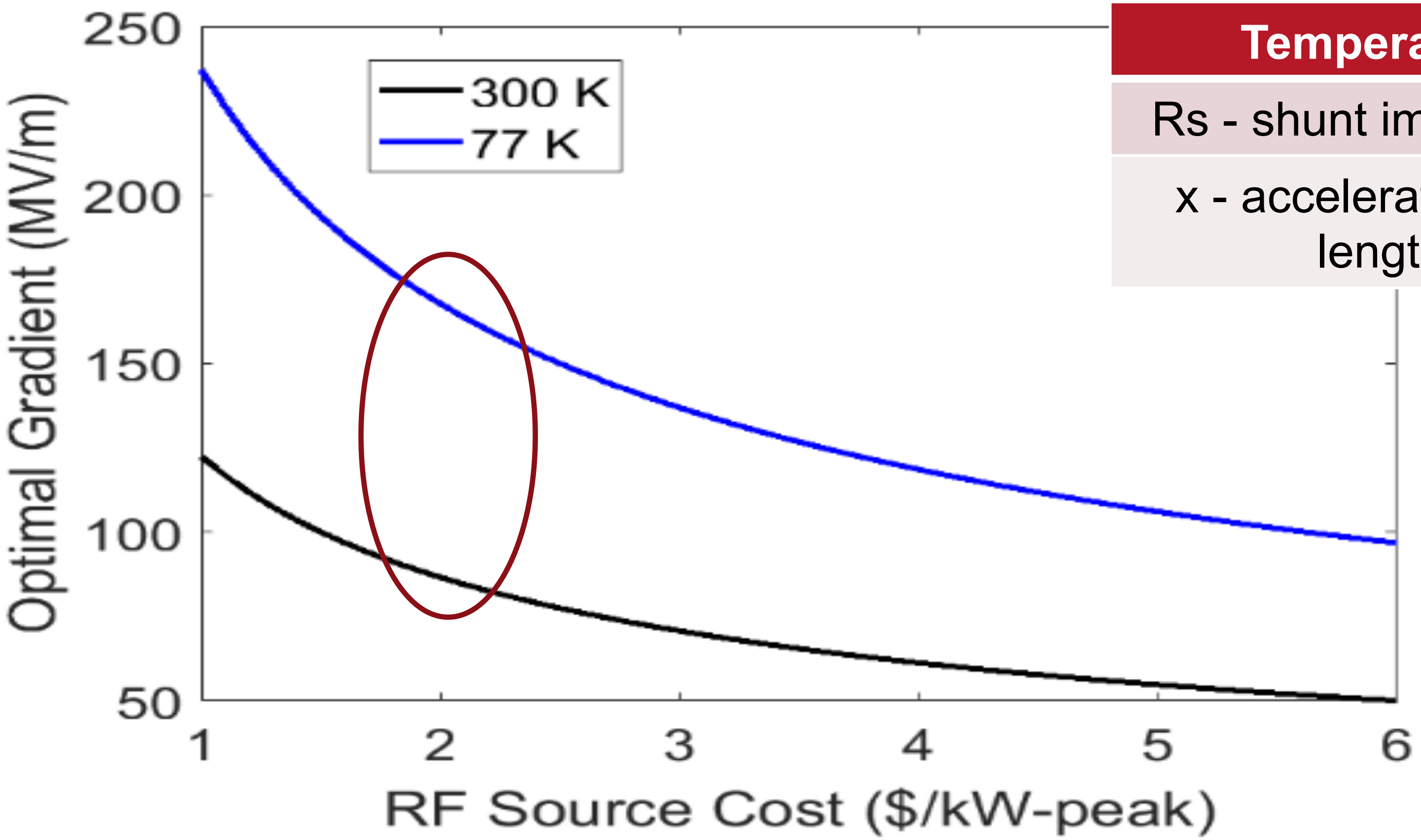
- The prohibitively high cost of traditional RF sources are derived from both:
  - High capital cost
    - Sources are complicated to build
    - High voltage power supplies (~300 kV)
  - High operating cost
    - Limited by efficiency (~50%) at high power

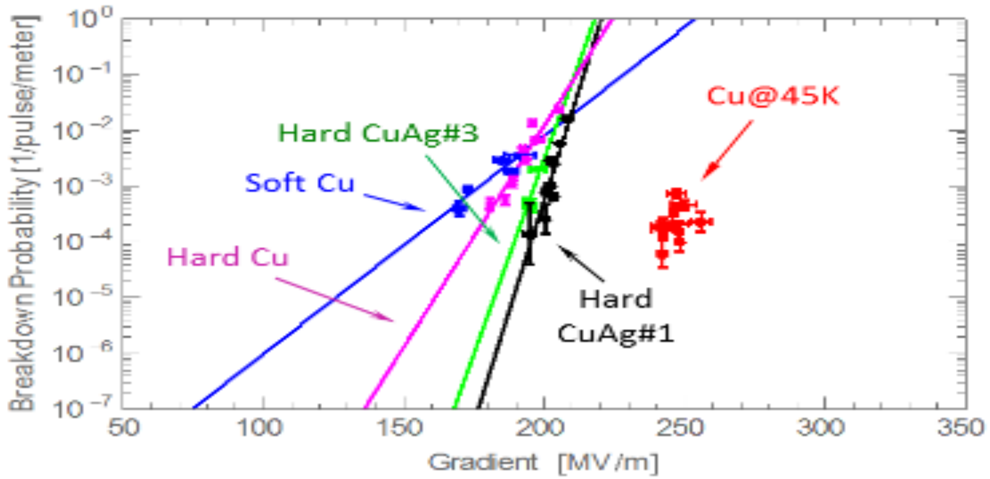
Reducing the cost of accelerators requires reimagining the topology of the RF source.

Operation at High Gradient Requires Low Cost RF Sources and Innovative Accelerator Concepts

- Determine cost optimized gradient from cost model
  - $G=(R_s\ x/y)^{0.5}$
  - y – RF system cost/power ($/kW-peak)

Temperature	300 K	77 K
Rs - shunt impedance	150 MΩ/m	375 MΩ/m
x - accelerator cost/ length	100 k$/m	150 k$/m





New Code for simulating and optimizing rf sources

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

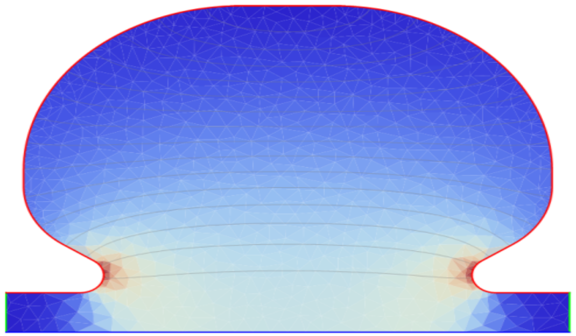
- RF sources operate in an awkward regime, relativity can not be neglected, and particles are not highly relativistic
- Space charge plays an important role but image charges (boundaries) can not be neglected.
- Full PIC codes Takes days to simulate simple structures and not suitable fro design and optimization

New code philosophy:

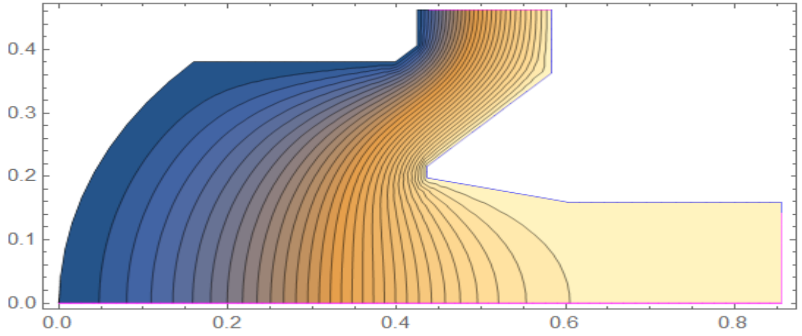
- Traditional E&M formulations starts with deferential equations based on Maxwell equation *driven for a particular gauge*.
  - Requires vector basis functions
  - Does not handle space charge appropriately
- *We start from the Lagrangian formulations of Maxwell equations without a presumption of the 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

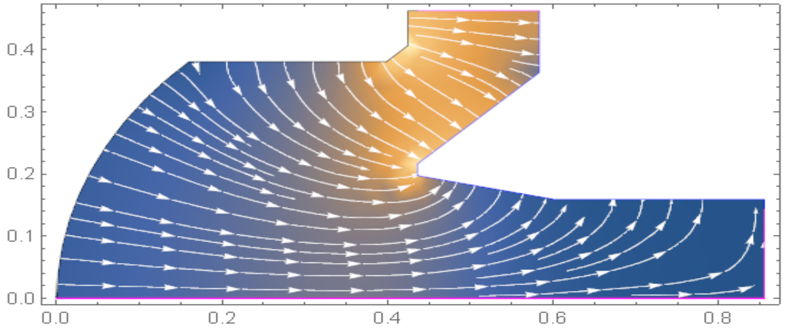
Code development philosophy takes into account platforms, current and future user interfaces



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

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

SLAC

- **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

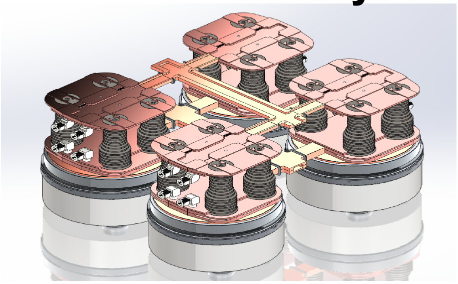
Three active devices are in development to realize these cost reduction concepts.

- **Modular-Array Multi-Beam Klystron**
  - Redefining the landscape of multi-beam architectures.
    - Simplified, low part count, klystrinos
    - Phase locked Floquet power extraction network

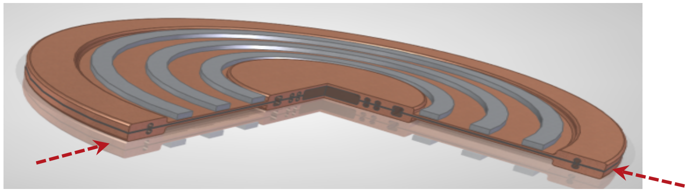
- **Radial Klystron**
  - Exploiting a novel geometry to mitigate space charge effects.
    - Low space charge radially propagating beam

- **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.

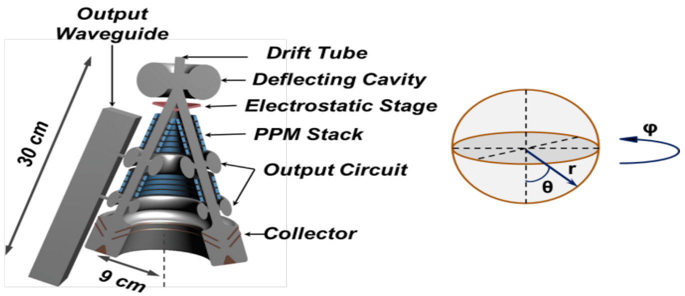
Multi-beam klystron



Radial klystron

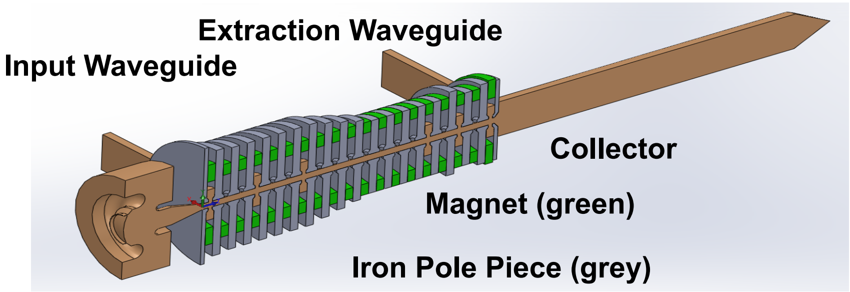


Deflected beam amplifier

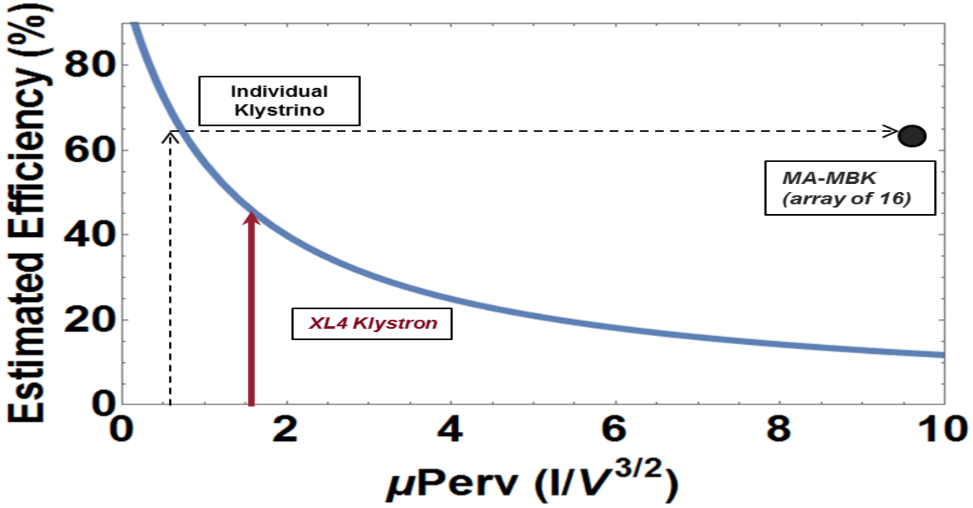


MA-MBK takes advantage of low space charge system to attain high efficiency.

- **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+

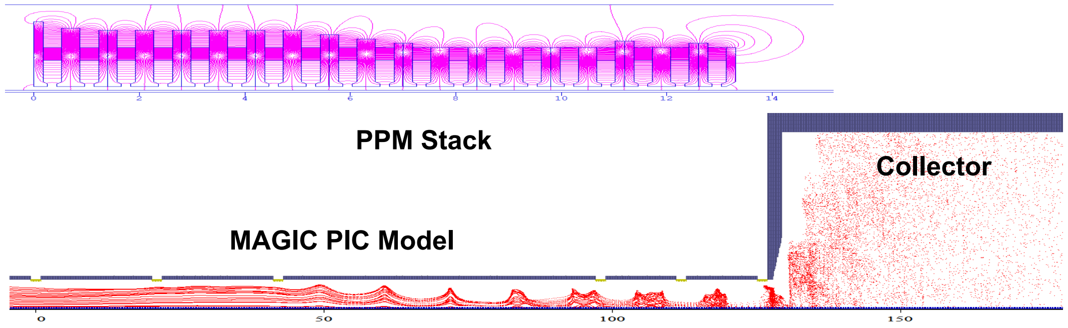


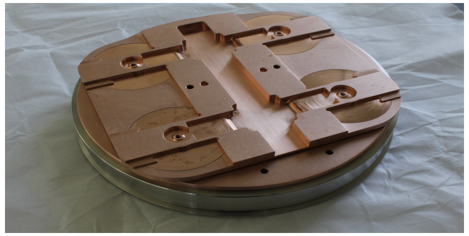
The MA-MBK is not restricted to the geometric limitations of a classic MBK

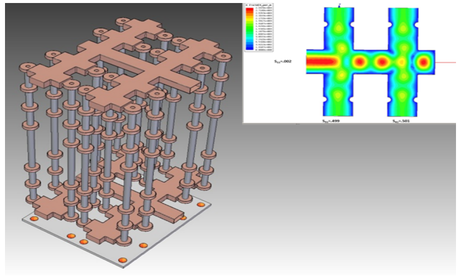
The modular design of the MA-MBK affords many advantages.

SLAC

- **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)





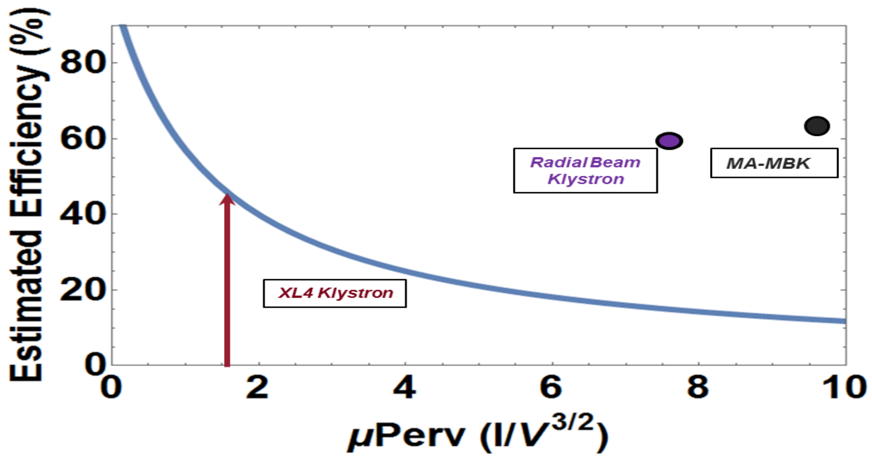


Prototypes of the MA-MBK have been designed/fabricated and are in testing phase.

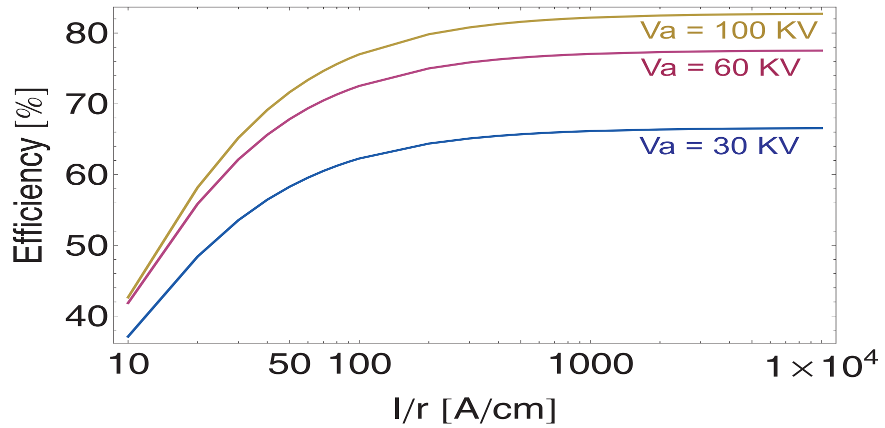
A. Jensen, S.Tantawi

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

- **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+

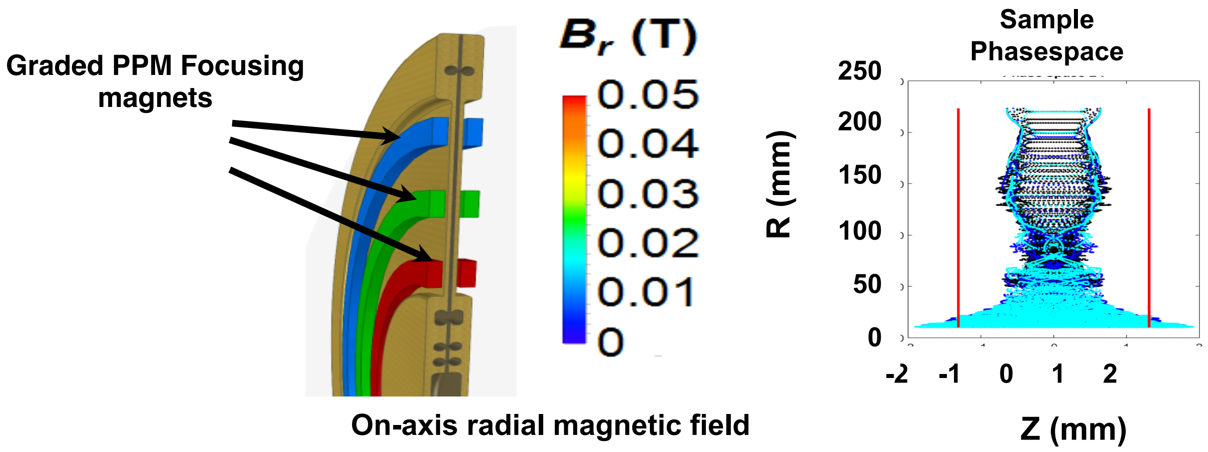


The RBK provides a, naturally stable, high current beam transport structure.

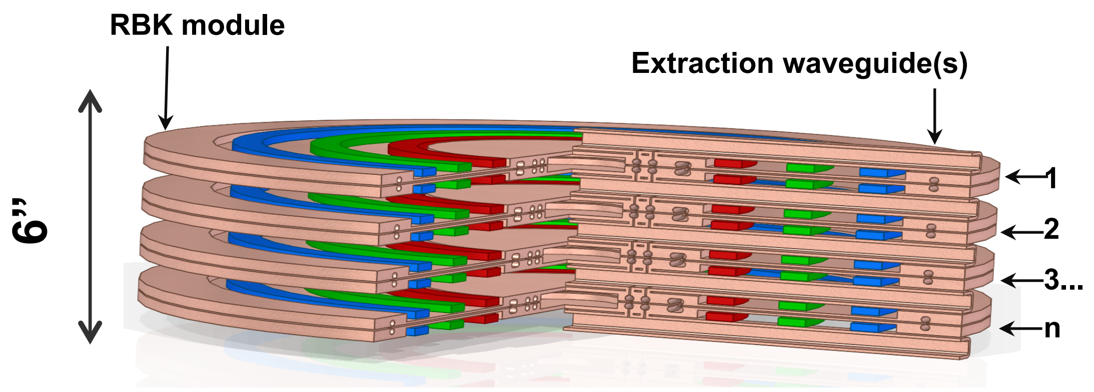
S.Tantawi, M. Dal Forno

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



On-axis radial magnetic field



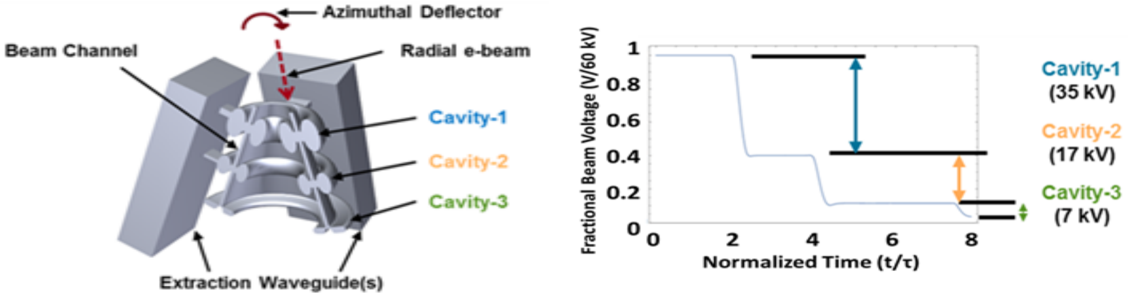
Output combined using similar technology as MBK

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

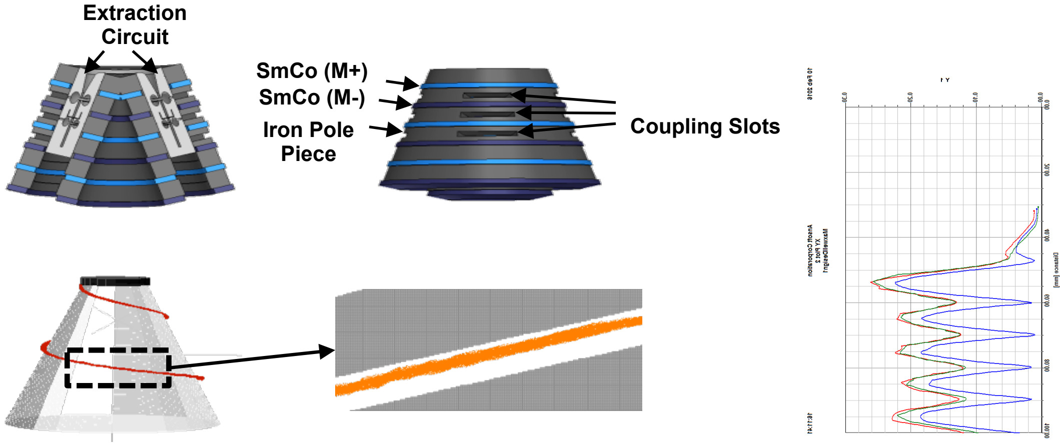
The DBA is an evolved form of deflected beam technology that offers low operating cost.

- **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.

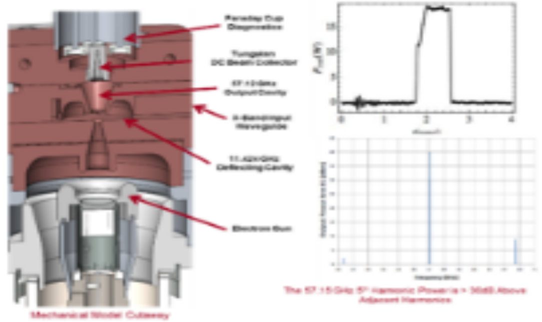
The Deflecting Beam Amplifier combines high electronic efficiency with high frequency operation

- **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**

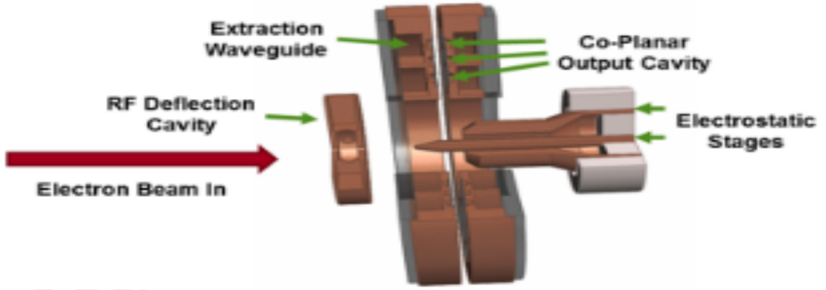
Parameter	Near Term Goal
Beam Voltage (kV)	60
Beam Current (A)	16
Frequency (GHz)	11.424
Output Power (MW)	0.82
Efficiency (%)	85+

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

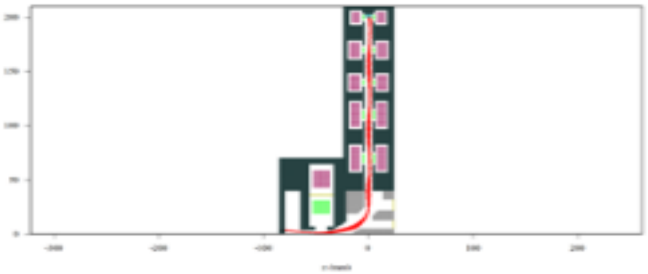
57 GHz Frequency Multiplier (2015)



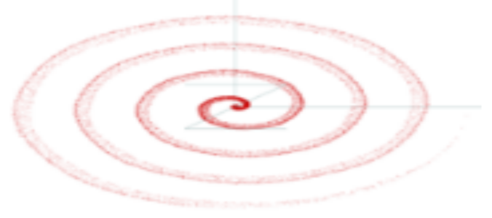
11 GHz High Efficiency Amplifier(2017)



R-Z Plane



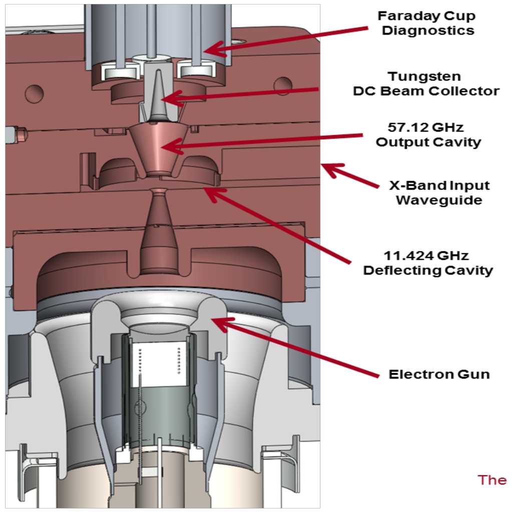
R-θ Plane



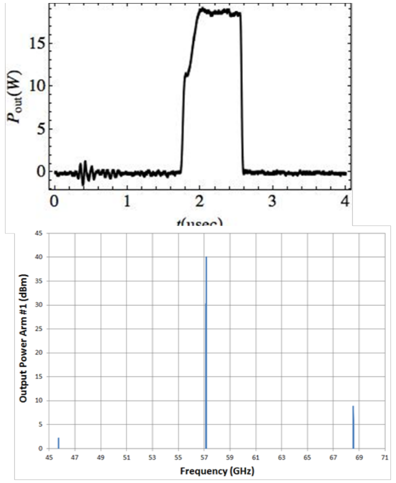
M. Franzi, S. Tantawi, F. Toufexis

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**

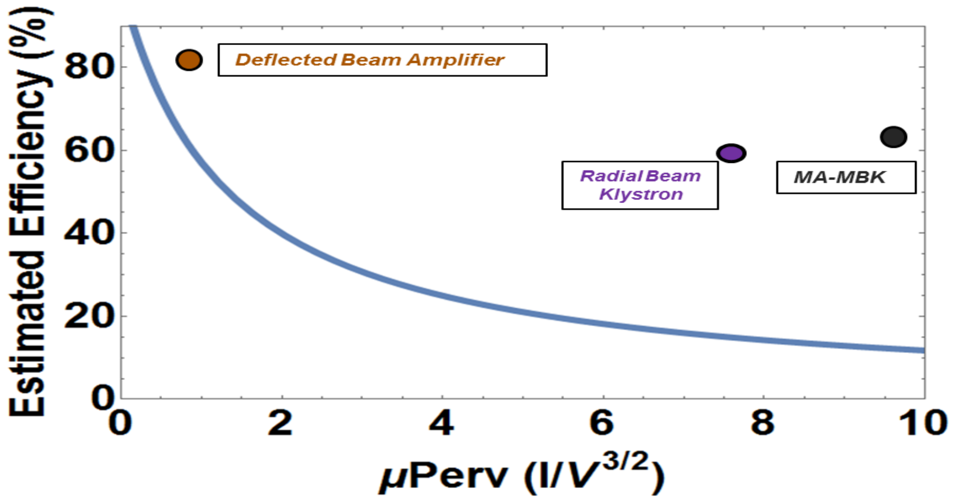


Mechanical Model Cutaway



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

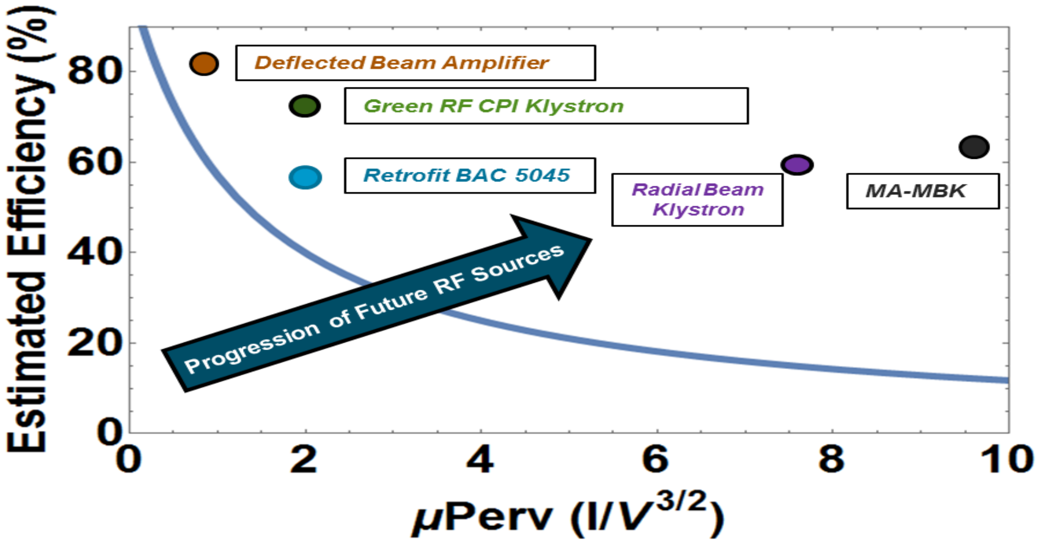
Redefining the state of the art RF source.

SLAC

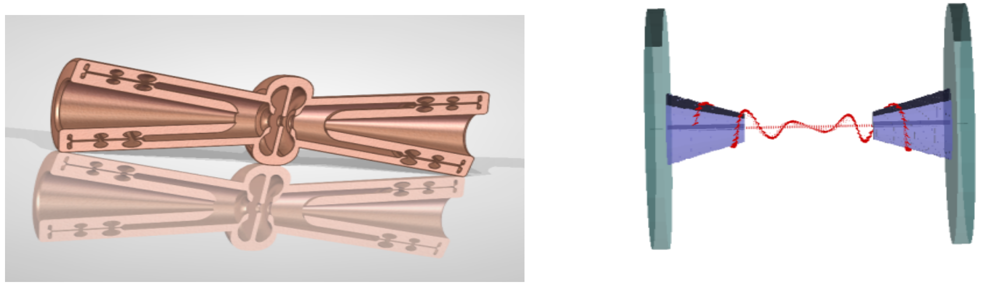
- **Exploration of novel technology to improve efficiency and reduce the cost per Watt of RF power**

- **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



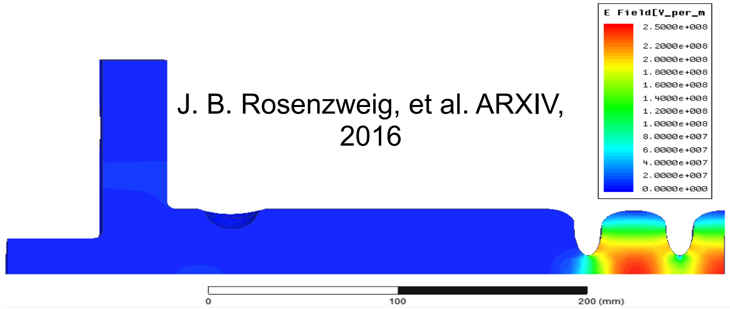
Applications

Broader Impacts Resulting from Advancements in RF Accelerator Technology

SLAC

Cryogenic RF Photoinjector (UCLA/SLAC)

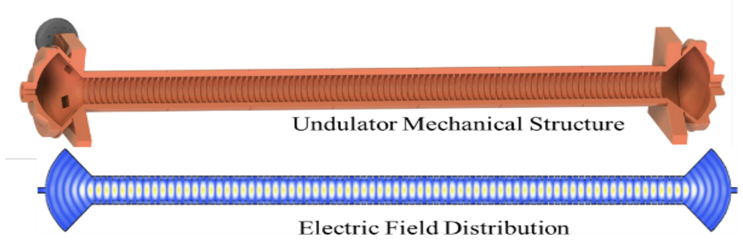
- Cryogenic Cu with surface fields nearly twice room temperature Cu, rf photo-injectors with 30X increase in peak brightness wrt LCLS gun



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

RF Undulator (NSF)

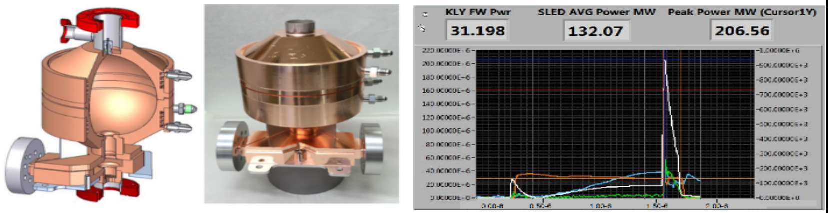
- Microwave undulators with large aperture, short period and active polarization control



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

Pulse Compressors (LCLS/BES)

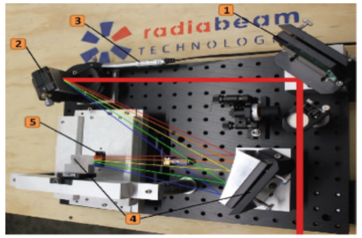
- Super compact X-Band SLED system, doubles the kick in transverse deflector at LCLS

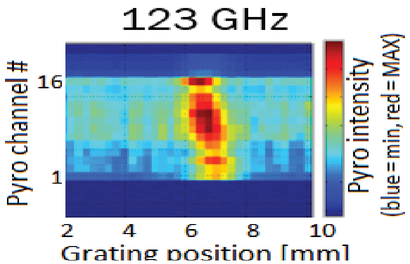


J.W. Wang, et al. IPAC 2016

Single Shot THZ Spectrometers (SBIR/HEP)

- SBIR with Radiabeam in support of THz acceleration experiments

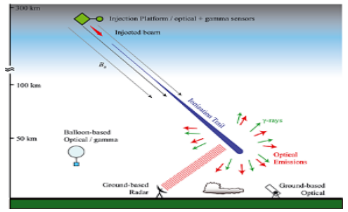




S.V. Kutsaev, et al. IPAC 2016

Accelerators Deployed on Satellites (NSF)

- Requires extremely efficient and compact accelerator to produce MeV beams

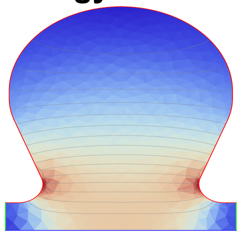


R. A. Marshall, et al. JGR: Space Physics, 2014
E. A. Nanni, et al. SLAC-R-1058, 2016

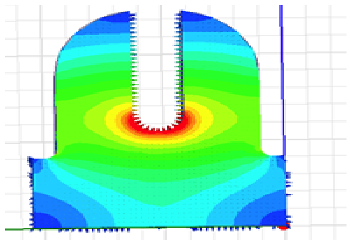
Proton Acceleration (Stanford Med./UCSF/SLAC)

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

Energy Modulation



Beam Deflection



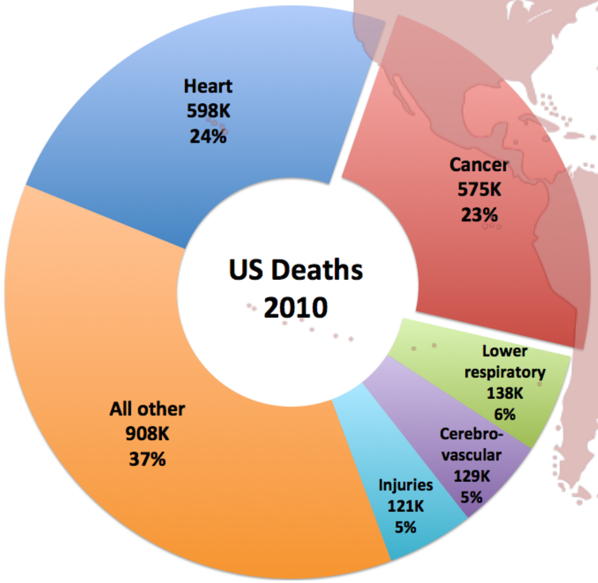
- **Collaborations and Investments have Advanced HEP GARD Mission**

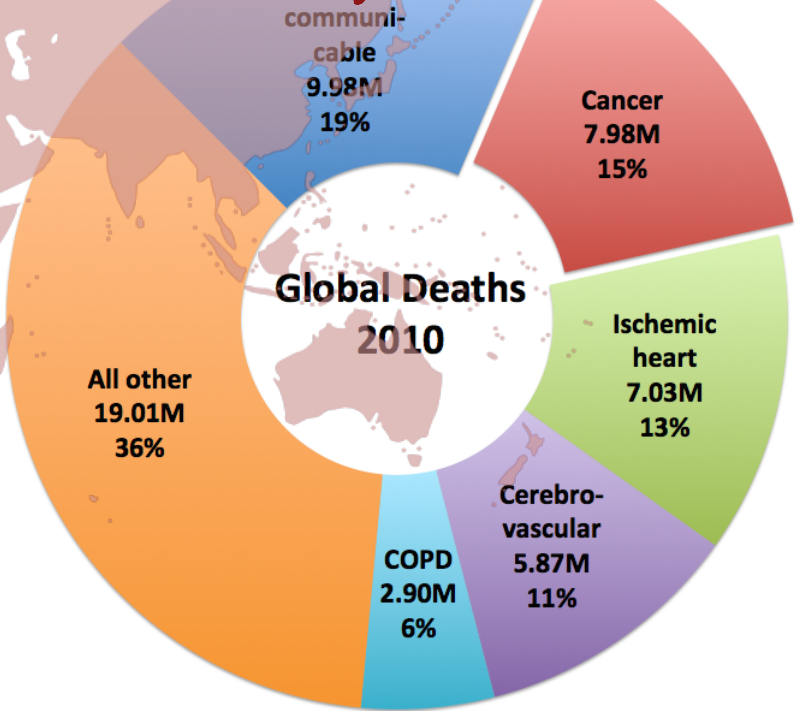
Scope of medical problem

Cancer is the #1 single cause of global deaths

13M cases, 8M deaths yearly & increasing epidemically

Cancer, Cardiac, COPD, Stroke in top 5 causes of death
both in US & worldwide: 24M deaths/yr

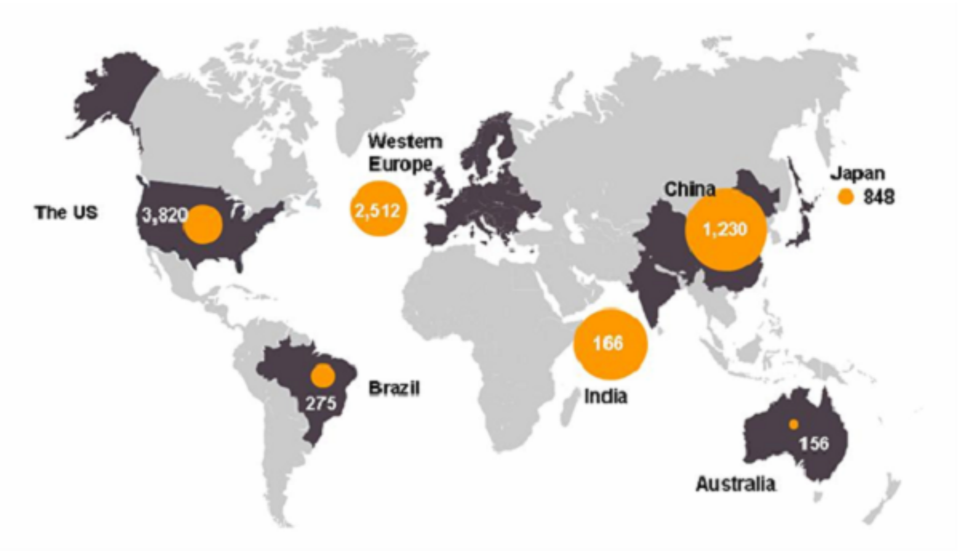




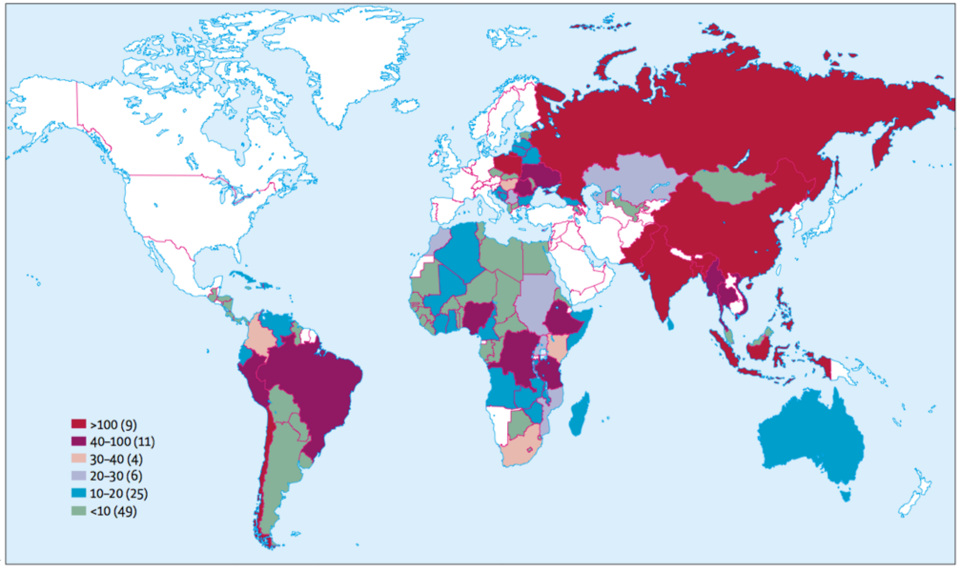
Siegel *CA: Ca J Clin* 2014
Lozano *Lancet* 2012

Importance of radiotherapy (RT)

Cancer: **52-67% of patients benefit from RT**, 52% of those with potential for cure
Cases will increase at least 45% in US & 60% worldwide by 2030 from demographic effects alone



2014 Installed base: ~11K linacs



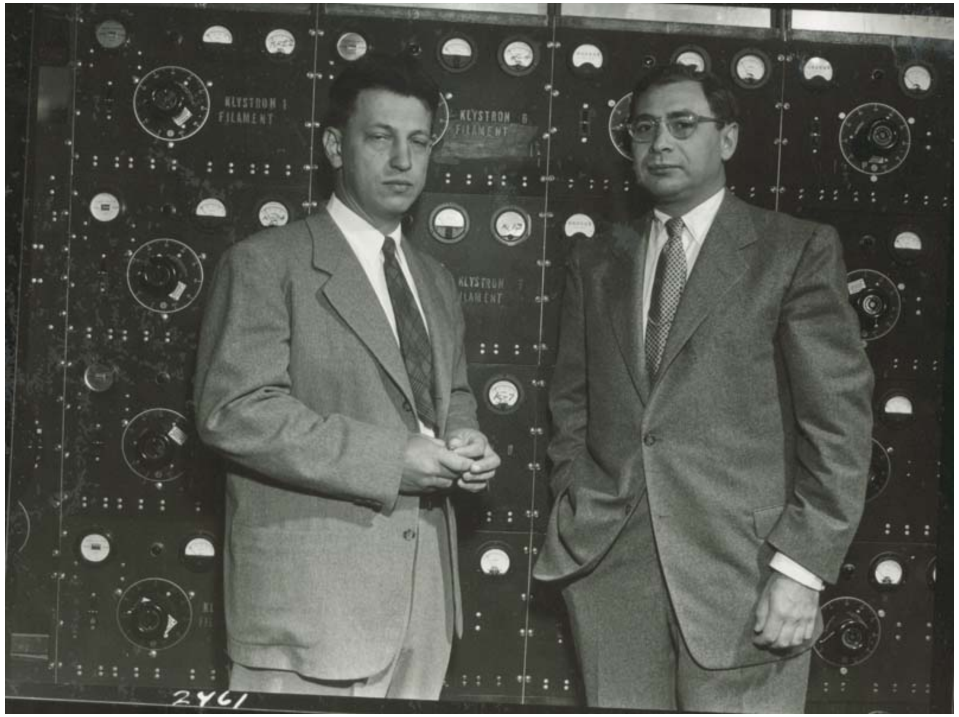
2011 shortfall in LMIC: >6.9K linacs

Barton *Lancet Oncol* 2006; Datta *IJROBP* 2014; Smith *J Clin Oncol* 2009
globocan.iarc.fr; www.rtanswers.org; www-naweb.iaea.org/nahu/dirac
GlobalData 2012 Report: Radiation Therapy Devices – Global Opportunity Assessment and Market Forecast to 2018

B Loo, E Perez – Stanford

Stanford heritage

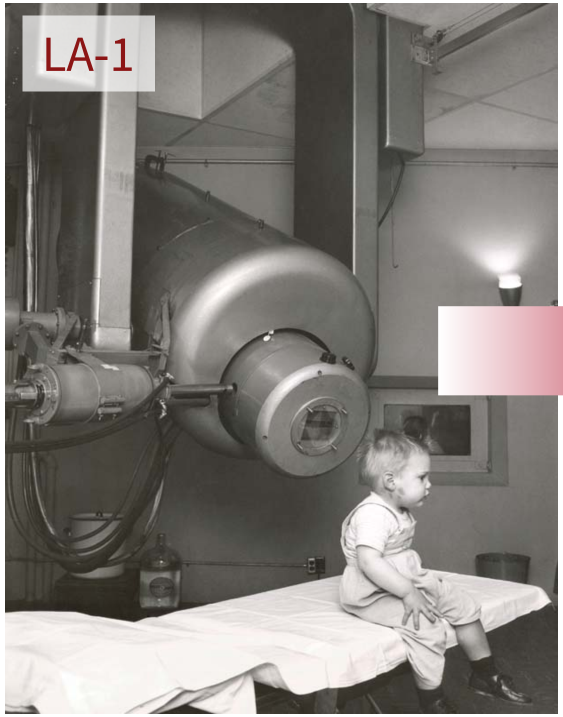
The first medical linear accelerator in the Western Hemisphere (LA-1) was invented at Stanford by Henry Kaplan (Radiology) and Edward Ginzton (Microwave Laboratory)

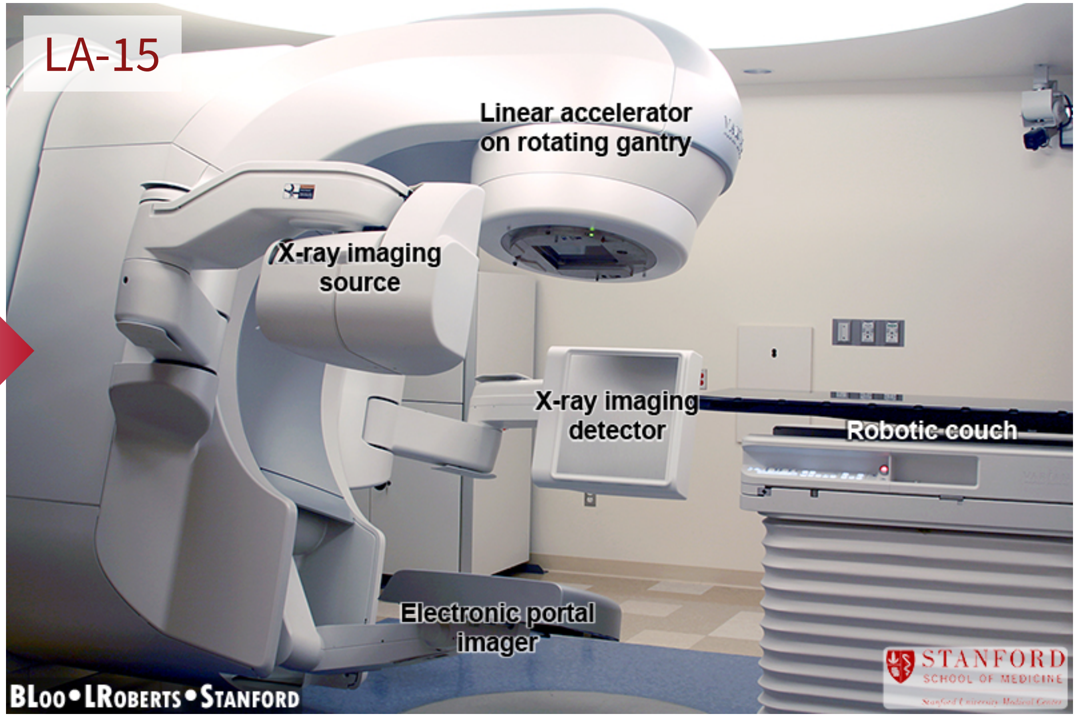


LA-1: the first patient, a child with retinoblastoma, was treated *and cured* in 1956.

Stanford heritage

The first medical linear accelerator in the Western Hemisphere (LA-1) was invented at Stanford by Henry Kaplan (Radiology) and Edward Ginzton (Microwave Laboratory)



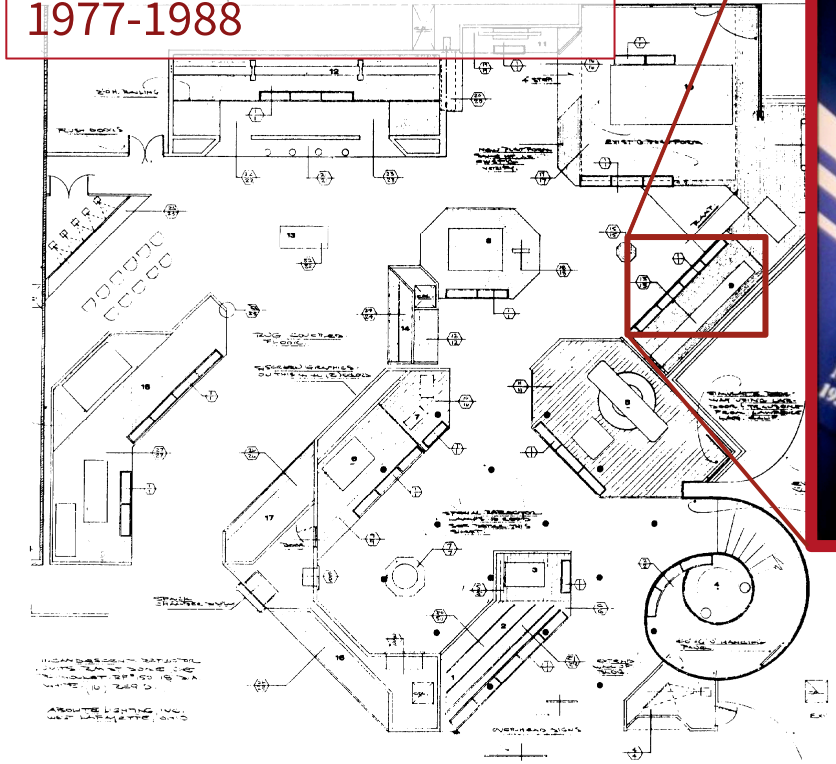


LA-1: the first patient, a child with retinoblastoma, was treated *and cured* in 1956.
Today, millions of patients are treated every year with the same basic technology.

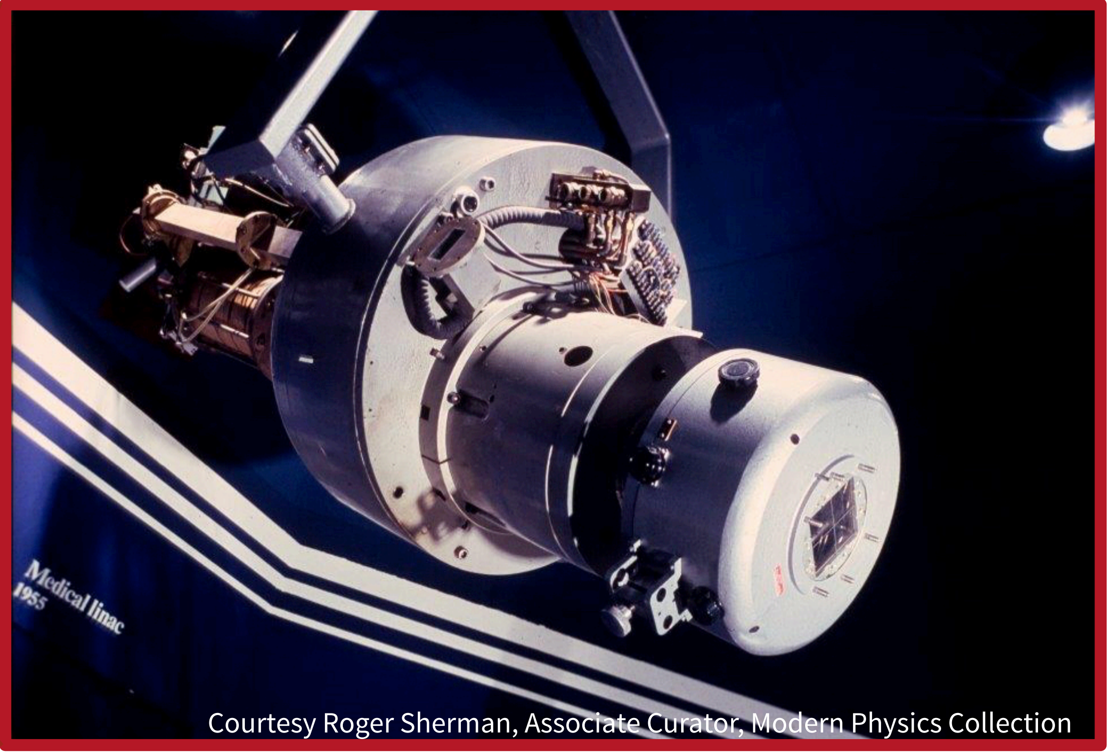
Stanford heritage

LA-1 on display at Smithsonian Institute

“Atom Smashers: 50 Years” at National Museum of American History 1977-1988



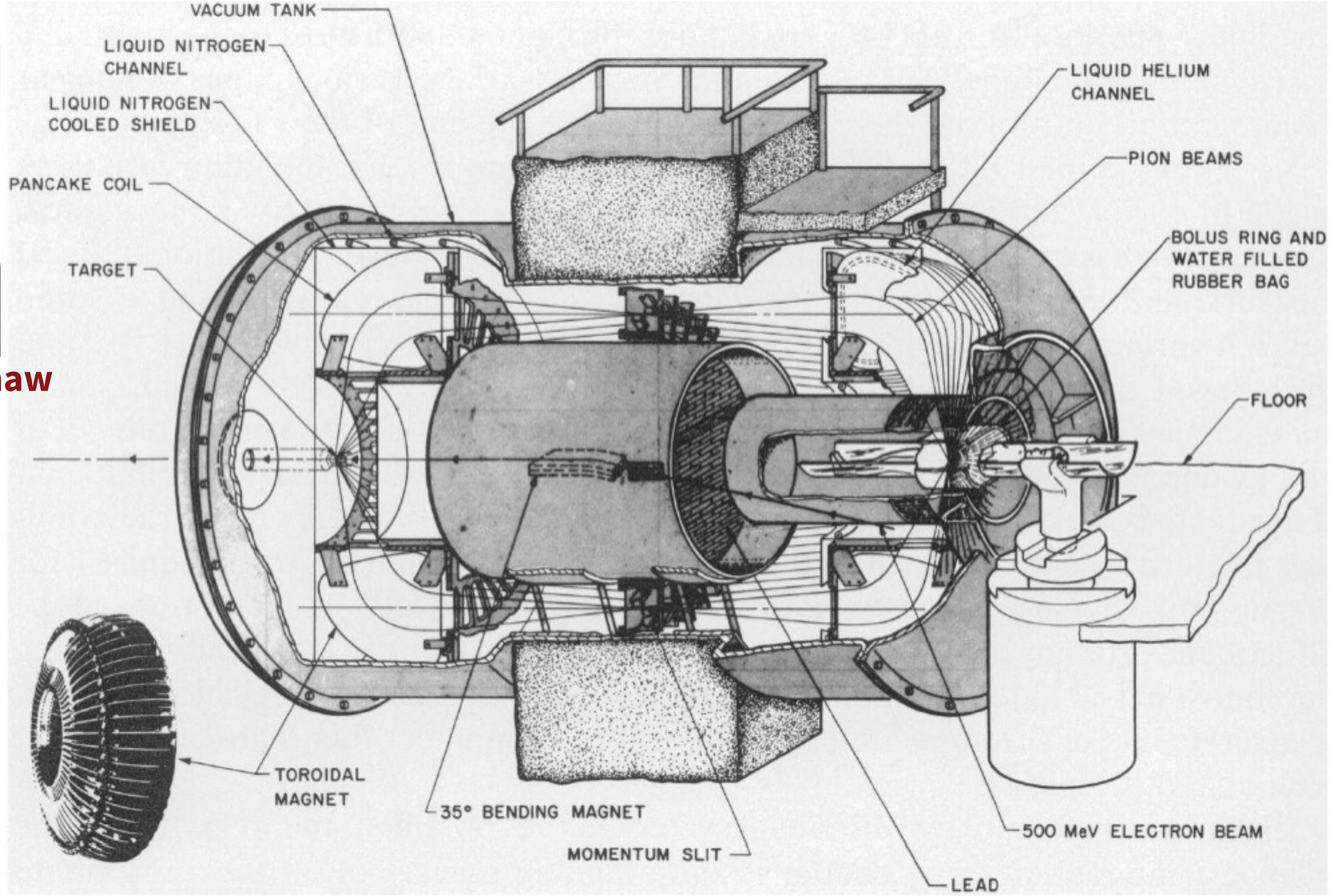
Forman *IEEE Trans Nucl Sci* 1977



Courtesy Roger Sherman, Associate Curator, Modern Physics Collection

Stanford heritage

Dr. Malcolm Bagshaw



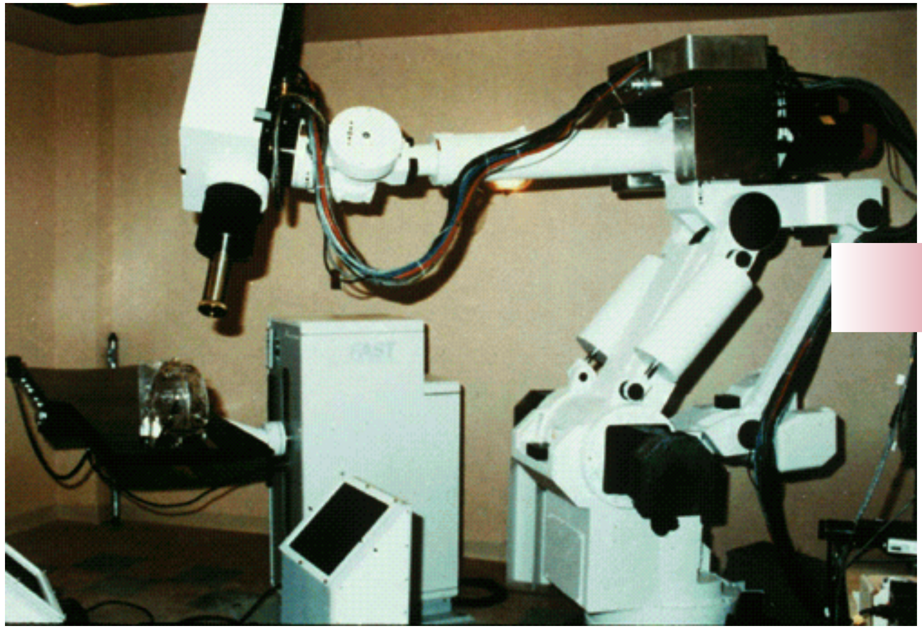
Pistenmaa
Radiology 1977

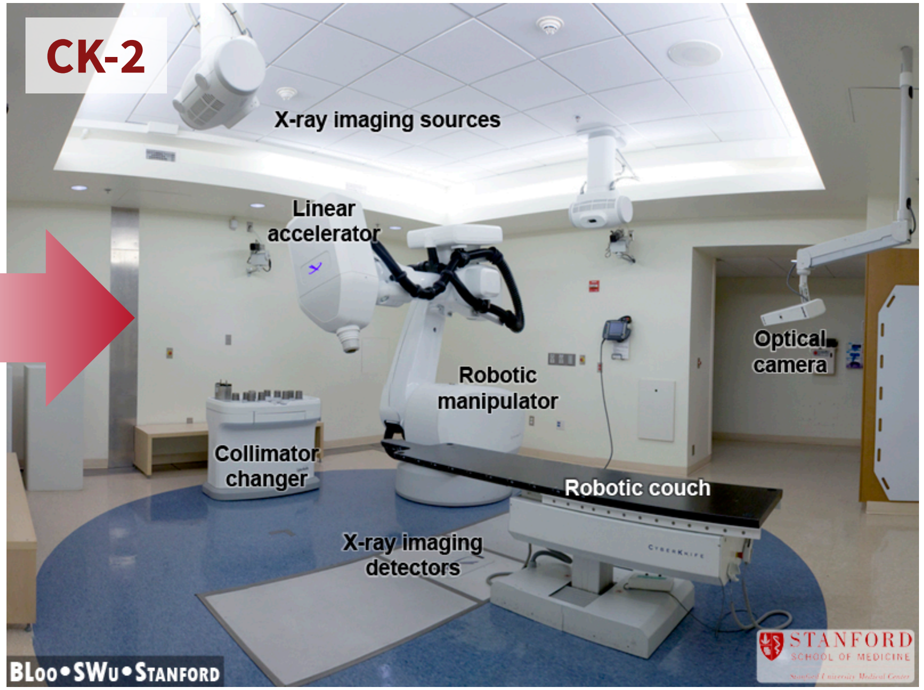
Stanford Medical Pion Generator (SPMG) at HEPL (Mark III) completed in 1974

Stanford heritage

Stanford conducted the **first clinical trials in Western Hemisphere or World** of stereotactic ablative radiotherapy (**SABR**) for:

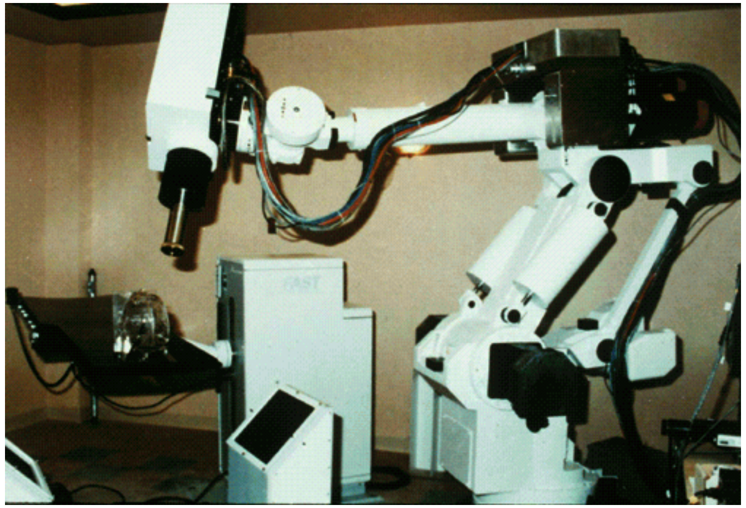
Pancreas, Nasopharynx, Lung, & Prostate cancers



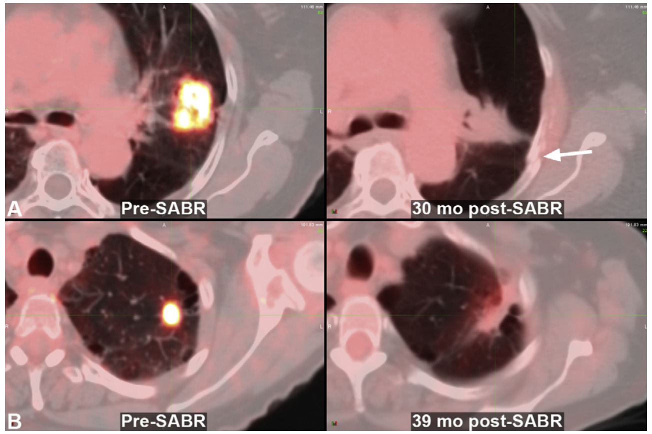


Invented at Stanford: CyberKnife robotic IGRT system, first patient treated in 1994

Pioneering new applications of RT

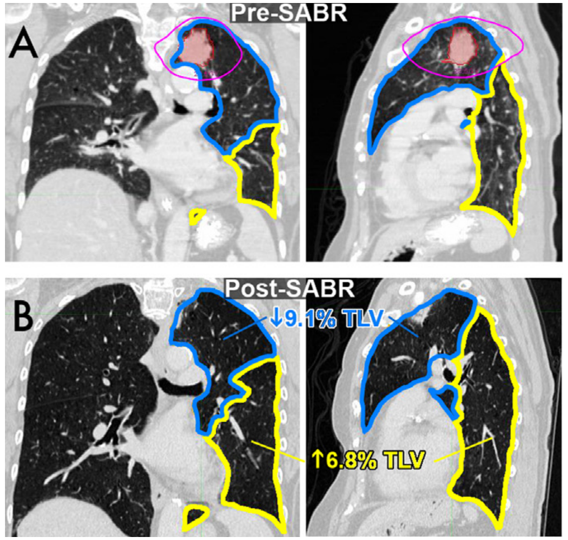


Lung cancer



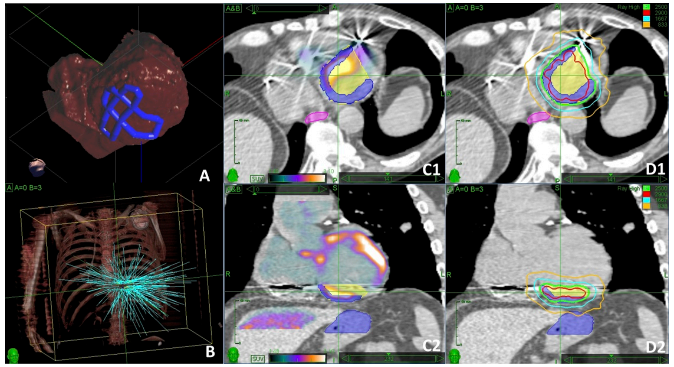
Trakul, Chang *IJROBP* 2012

Emphysema



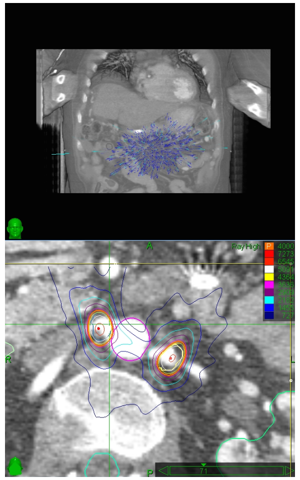
Binkley *IJROBP* 2014

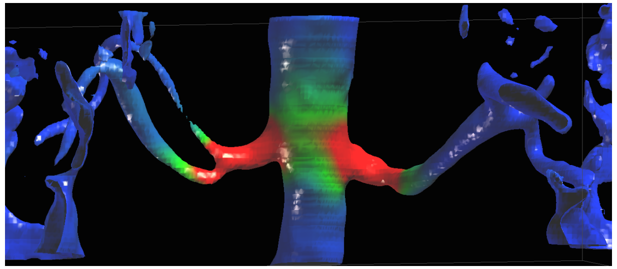
Cardiac arrhythmia



Loo, Soltys *Circ EP* 2015

Hypertension

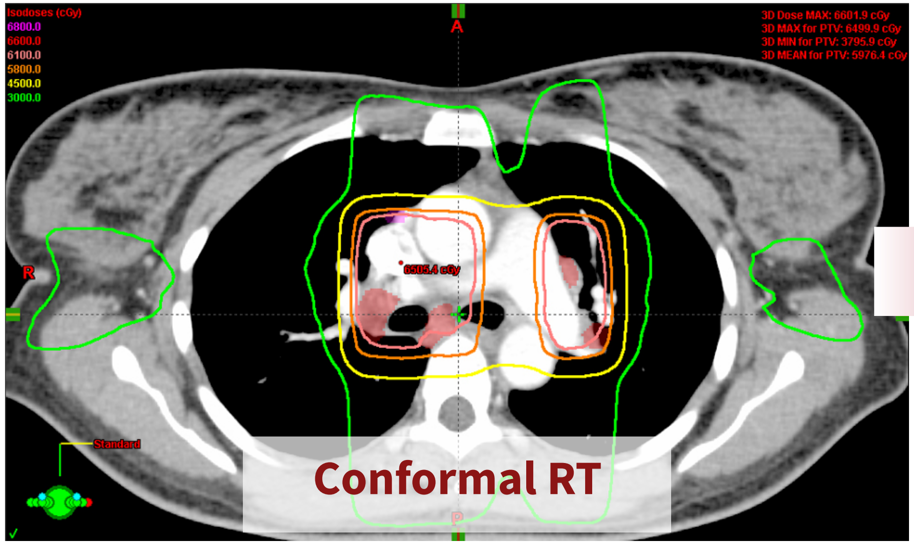


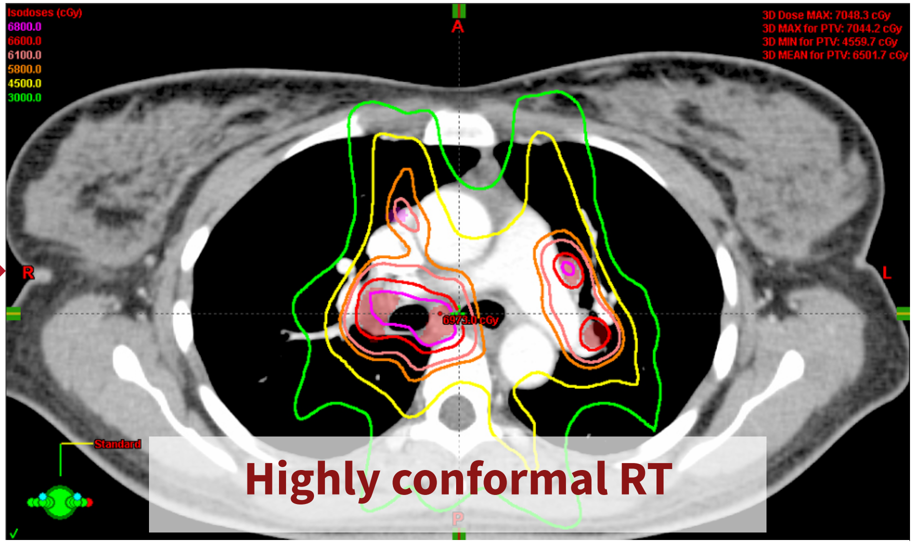


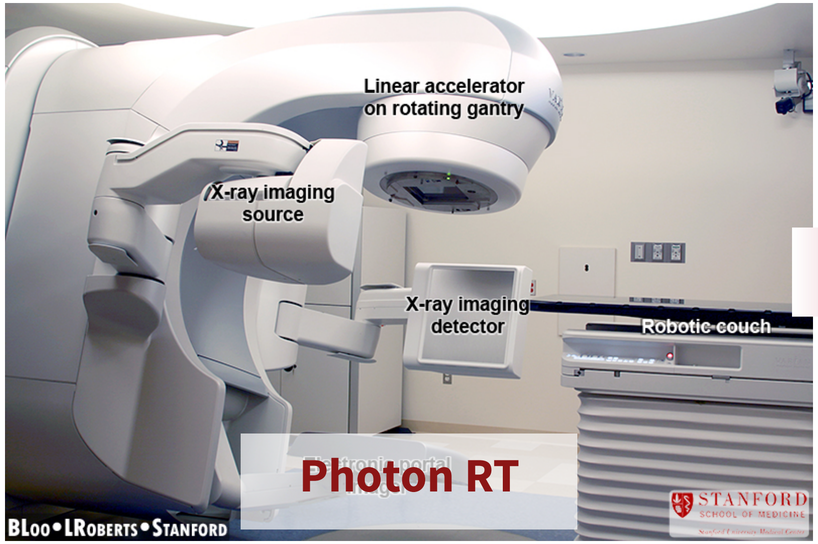
Maxim *AAPM* 2014

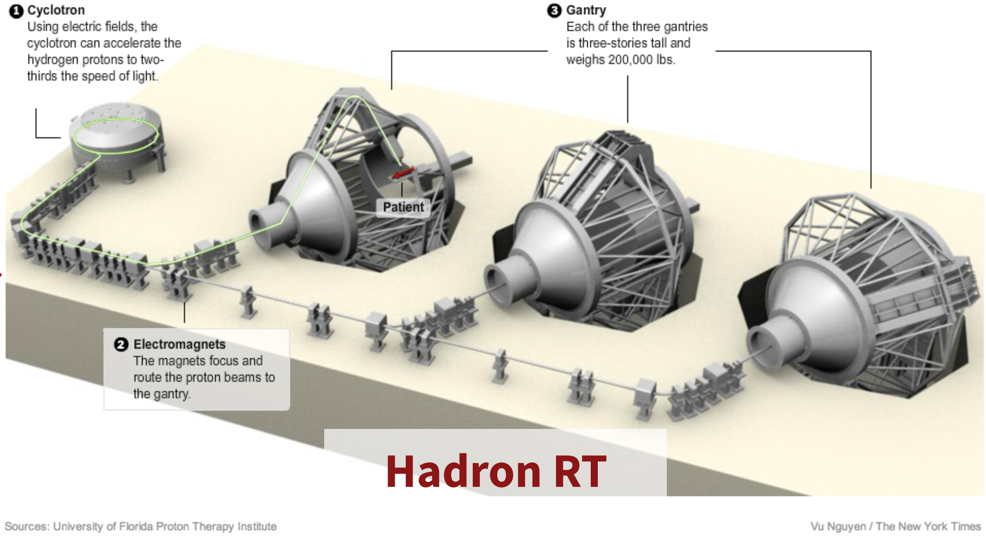
B Loo / Stanford

Push for conformity









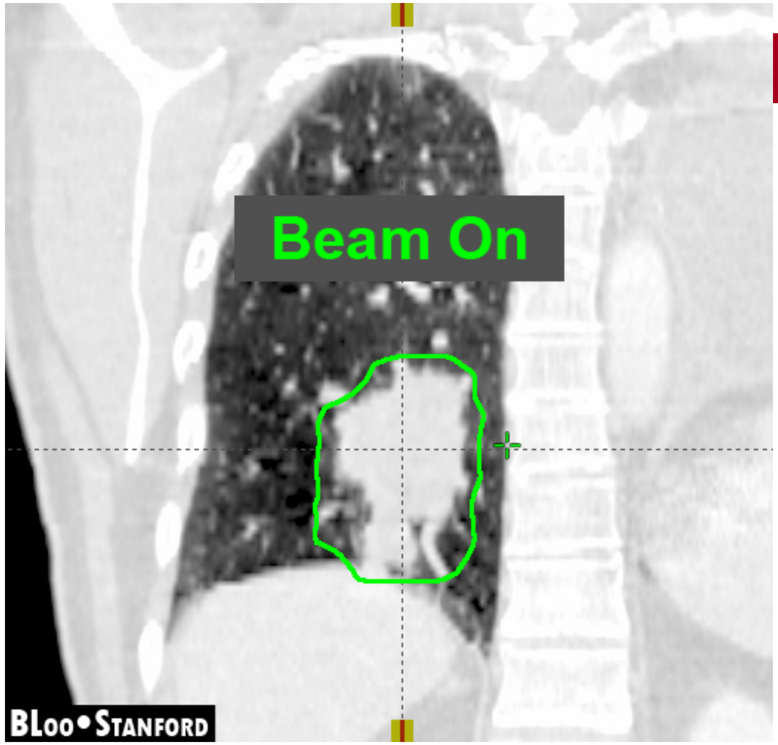
Technical focus of RT in recent history

Push for conformity

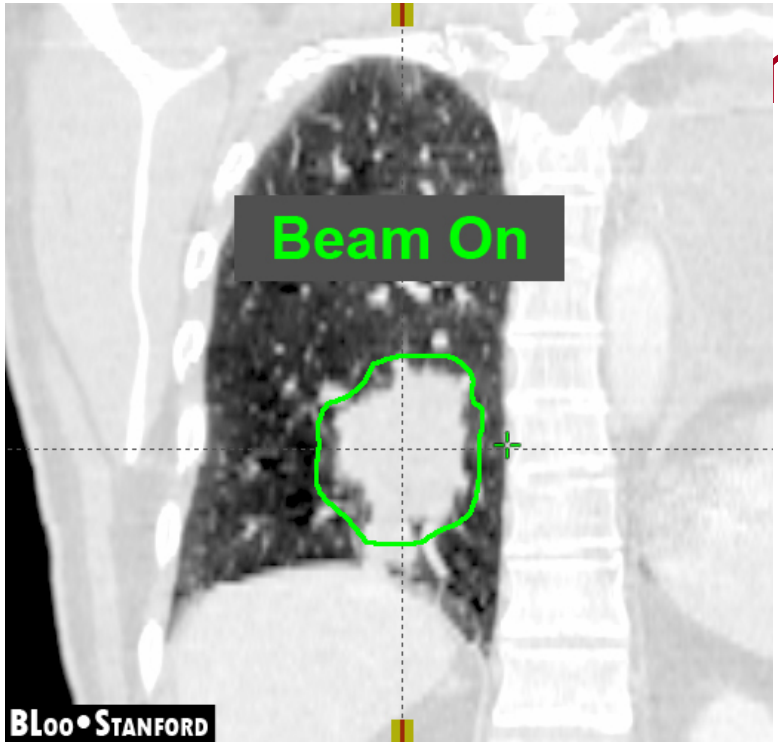
Push for accuracy/precision

- New realizations:
  - Need to define role of RT in “precision medicine”
  - Need for cost-effectiveness/global access

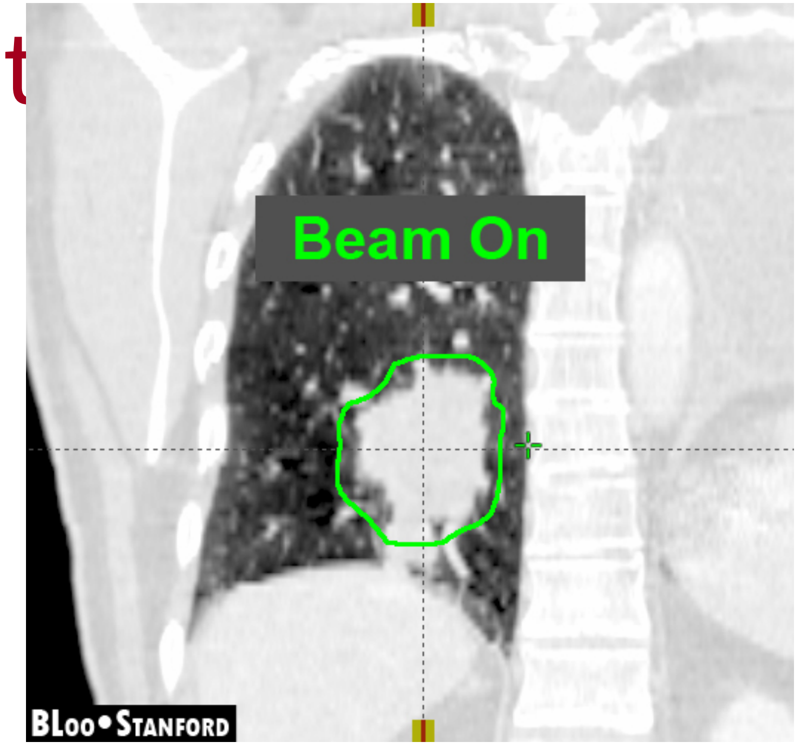
Push for accuracy/precision



Motion inclusive

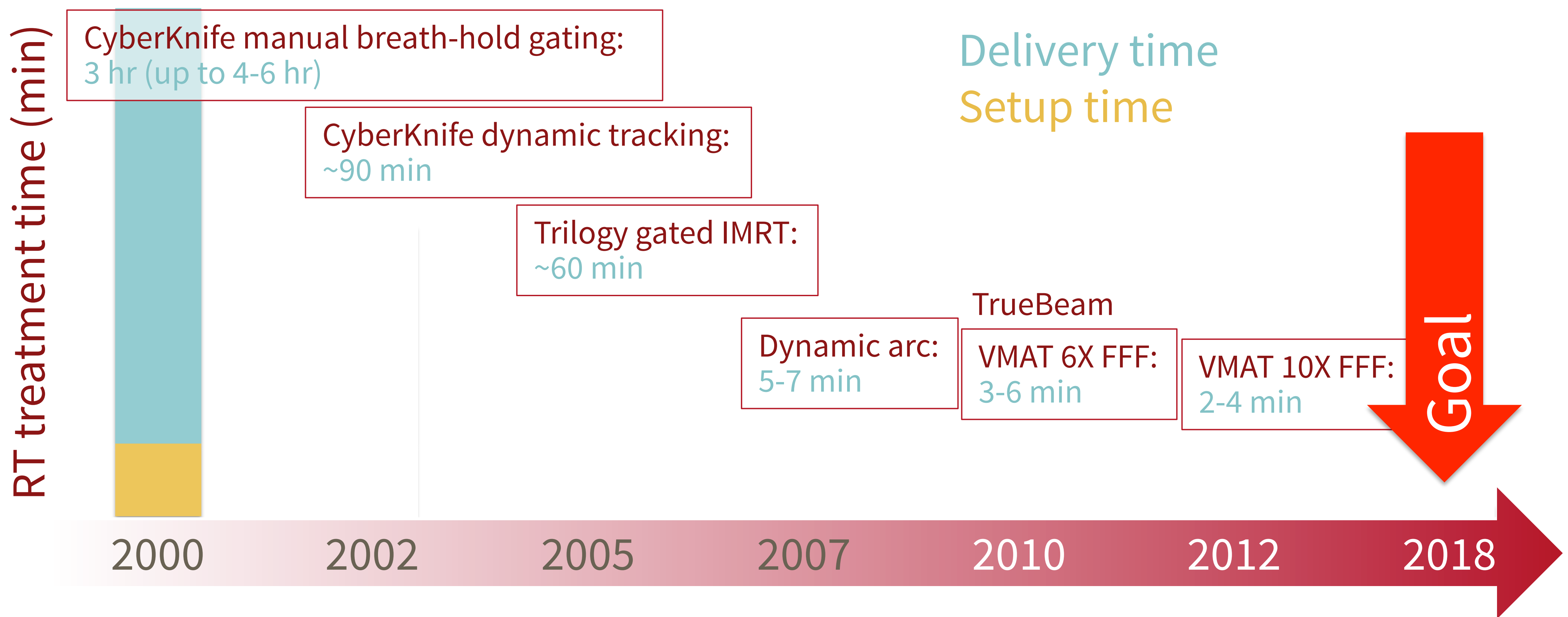


Respiratory gating



Tumor tracking

The Stanford experience – Need for speed



What if RT becomes fast enough to freeze motion?

The Stanford experience – Need for speed

RT treatment time (min)

Delivery time

Setup time

Goal

Solution: Speed

300X faster RT translates to:

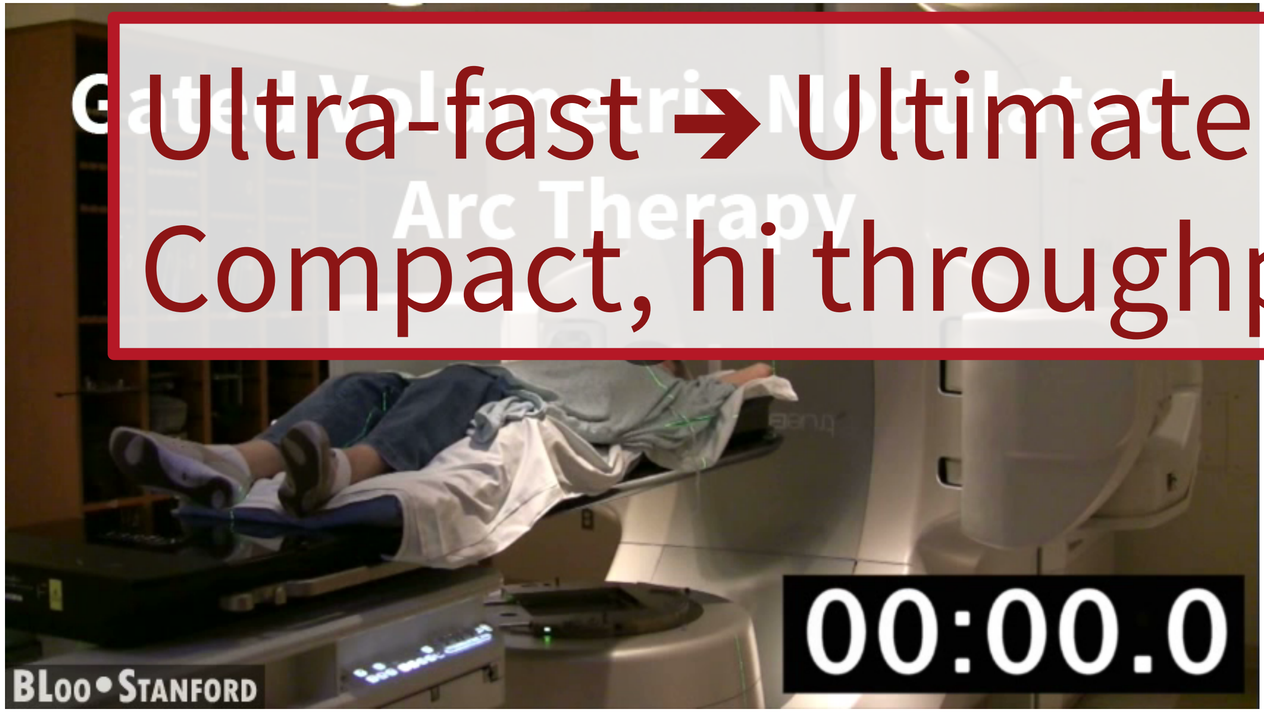
- Ultimate precision
- Higher throughput/cost-effectiveness

What if RT becomes fast enough to freeze motion?

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)

Achieving extreme speed

Requirements:

- 300X beam output
- Eliminate mechanical motion
  - Gantry
  - MLC
- Fast, high-quality volumetric imaging

Constraints:

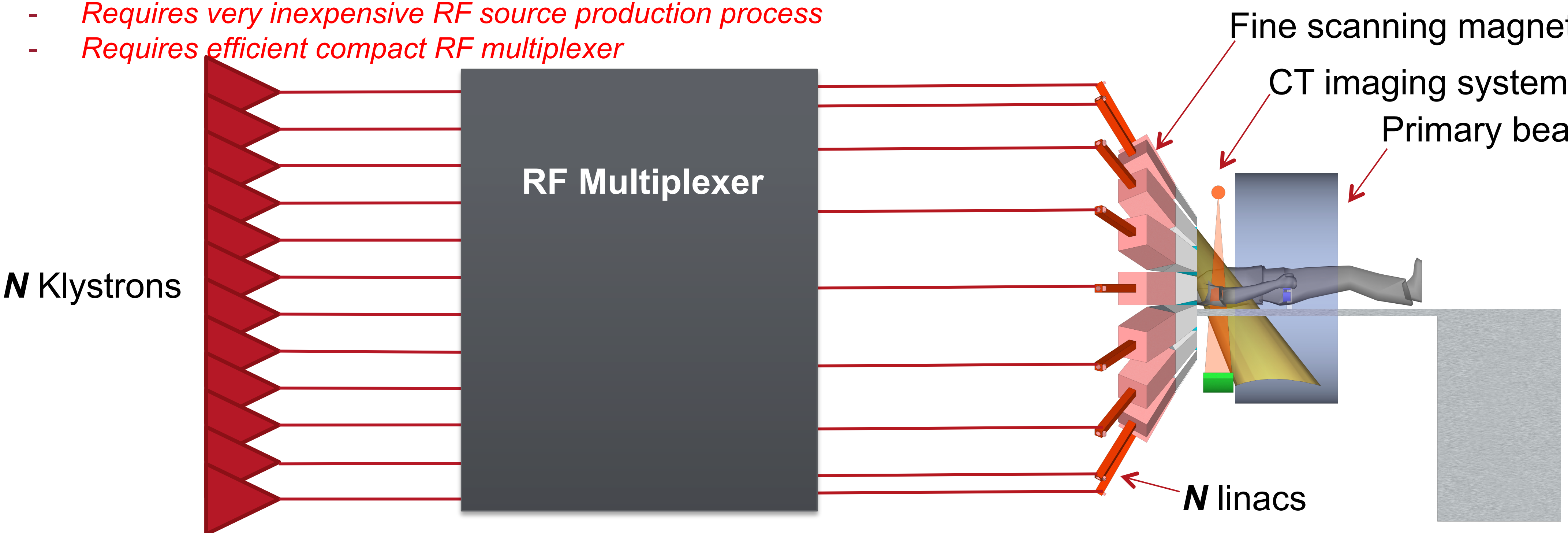
- Compact – fits in existing vaults
- Power efficient
- Economical to manufacture and operate

PHASER team

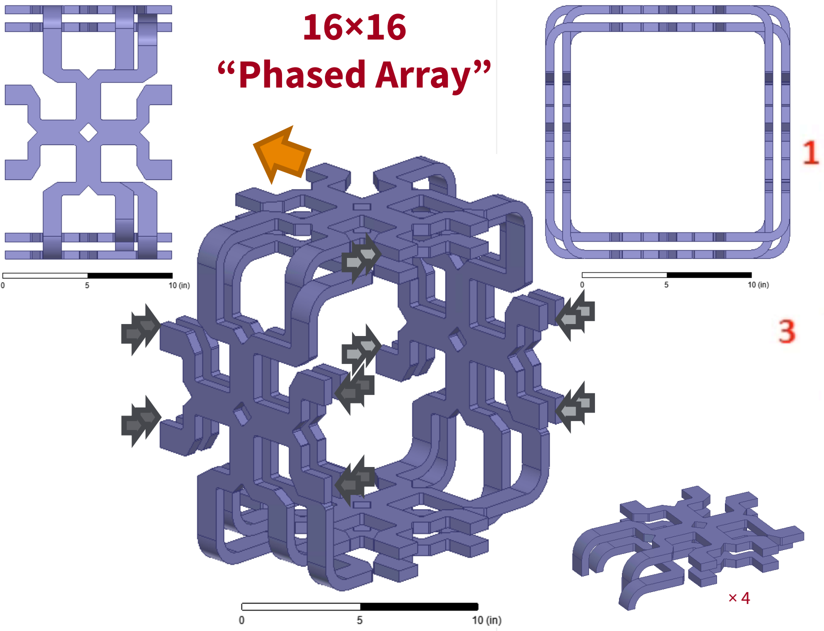

Historic radiation medicine & technology team-up
STANFORD CANCER INSTITUTE
Stanford University Medical Center
A NATIONAL CANCER INSTITUTE-DESIGNATED CANCER CENTER
Stanford School of Medicine – Rad Onc/ Radio
B Loo
P Maxim
R Fahrig
SLAC National Accelerator Lab
S Tantawi
V Bharadwaj
P Borchard
SLAC NATIONAL ACCELERATOR LABORATORY
Junipero Serra Fwy
Sand Hill Rd
Sharon Heights Golf & Country Club
Rosewood Sand Hill
SLAC National Accelerator Laboratory
Starbucks
STANFORD HILLS
Siebel Varsity Golf Training Complex
Stanford Medical Cen
Sharon Hills Park
Whiskey Hill Rd

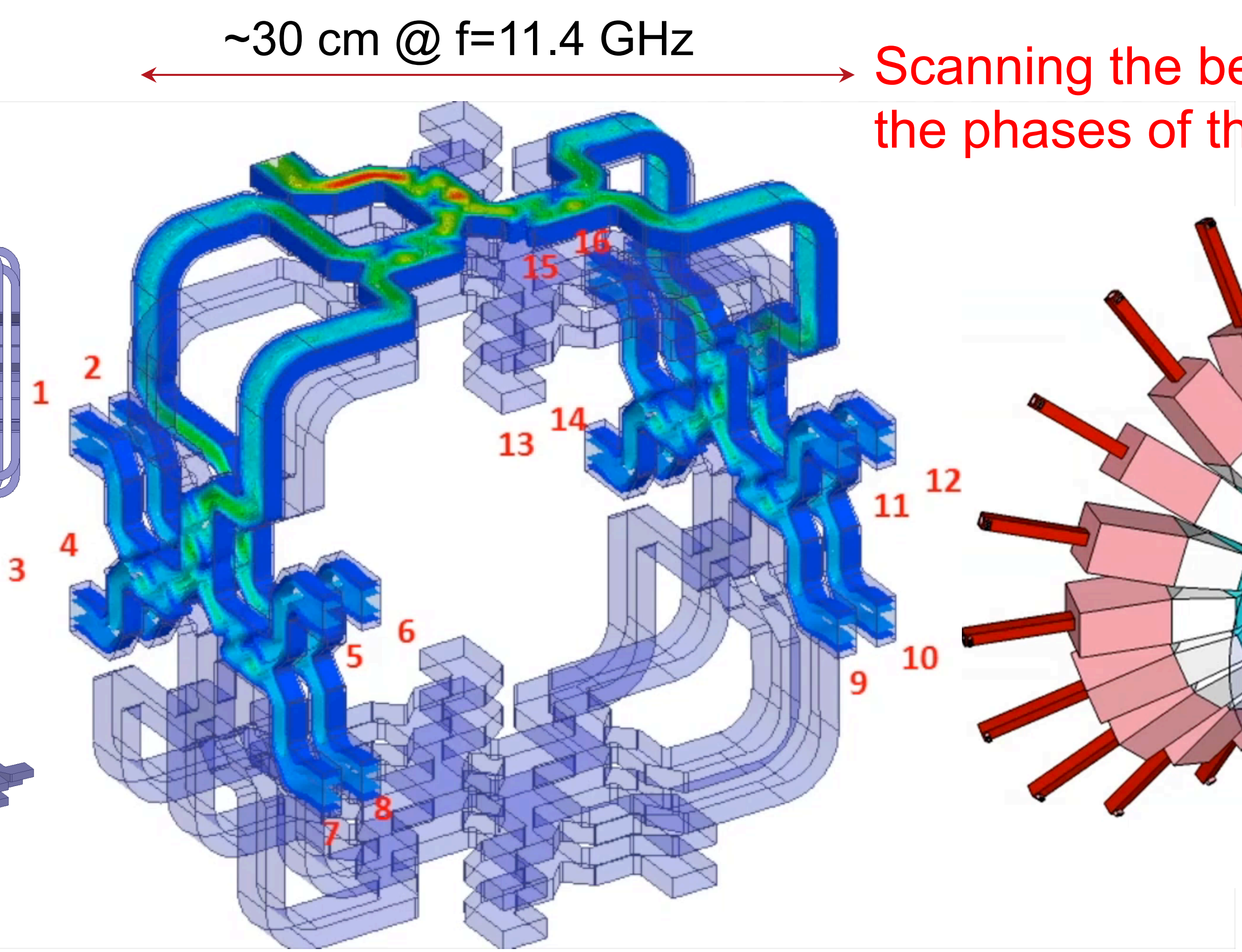
The PHASER System Architecture: Multiple Linacs, Multiple RF sources-multiplexed

- Multiple Linacs (minimum 16 Linacs)
  - Effectively scan the beam around the patient, finer scan from each linac achieve desired resolution
  - Linac are arranged on the surface of a cone to allow for in situ imaging system
  - Distribute the average power for both the linac and target
  - *Requires very inexpensive linac production process*
- Multiple RF sources
  - Needed to deliver the power to each linac
  - If multiplexed, the ***peak*** power from each source can be reduced
    - Reduced power from each source implies reduced modulator voltage, hence less expensive system
    - *Requires very inexpensive RF source production process*
    - *Requires efficient compact RF multiplexer*

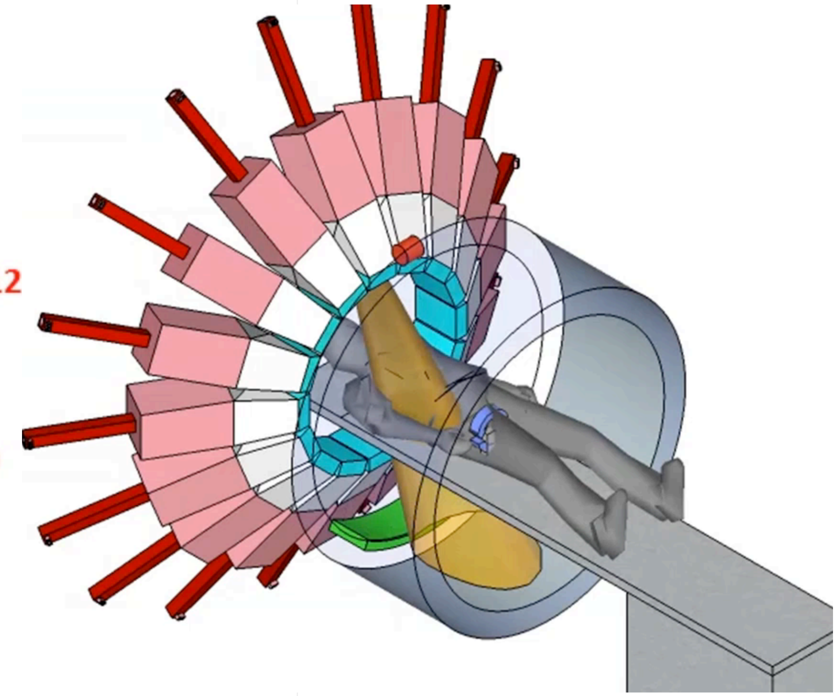


The Multiplexer scans the beam around the patient without any mechanical motion





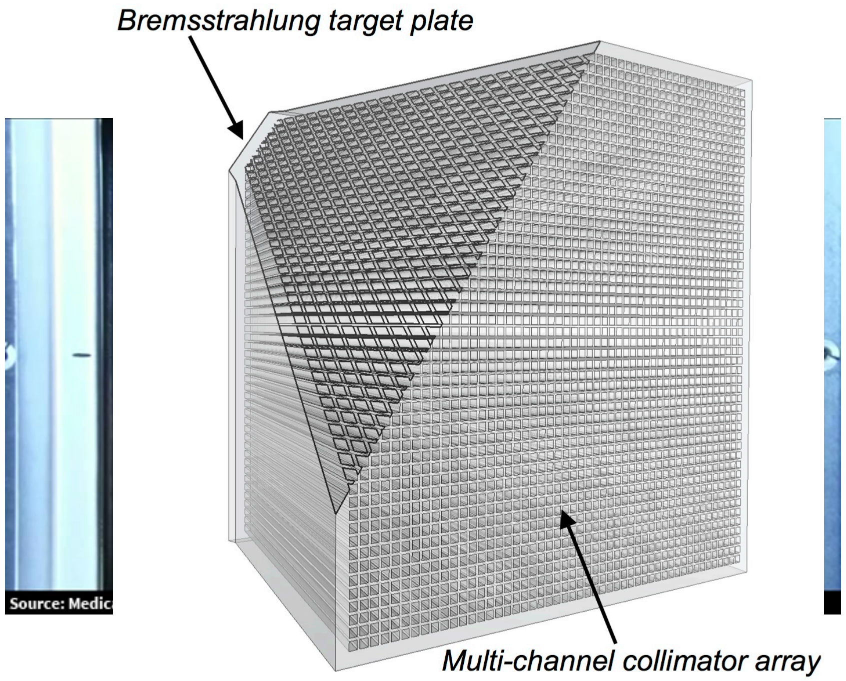
Scanning the beam through scanning the phases of the RF sources



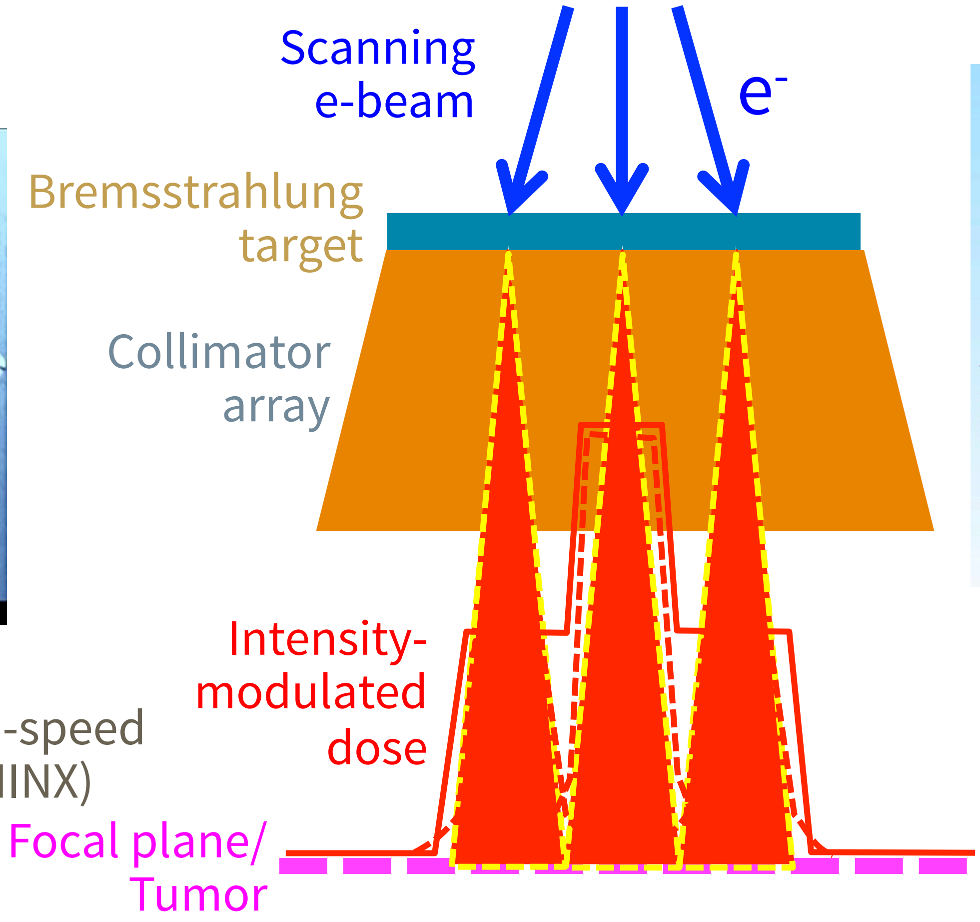
Inputs are numbered from 1-16

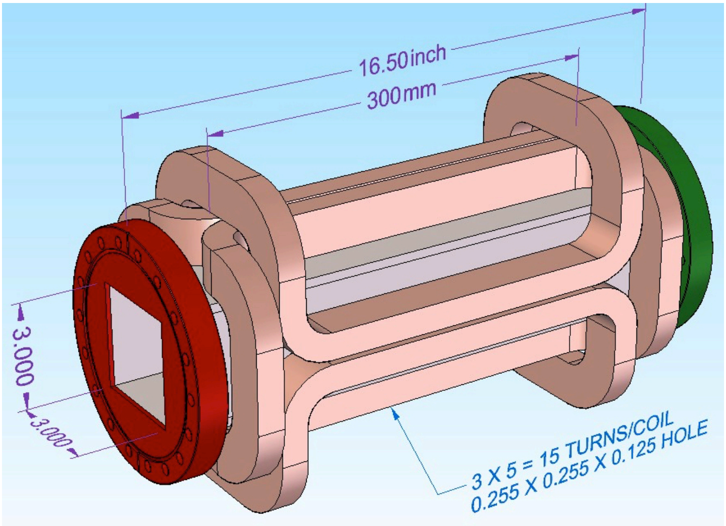
SPHINX – replacement for moving MLC

All-electronic intensity-modulation



Scanning Pencil-array-collimated High-speed Intensity-modulated X-ray source (SPHINX)

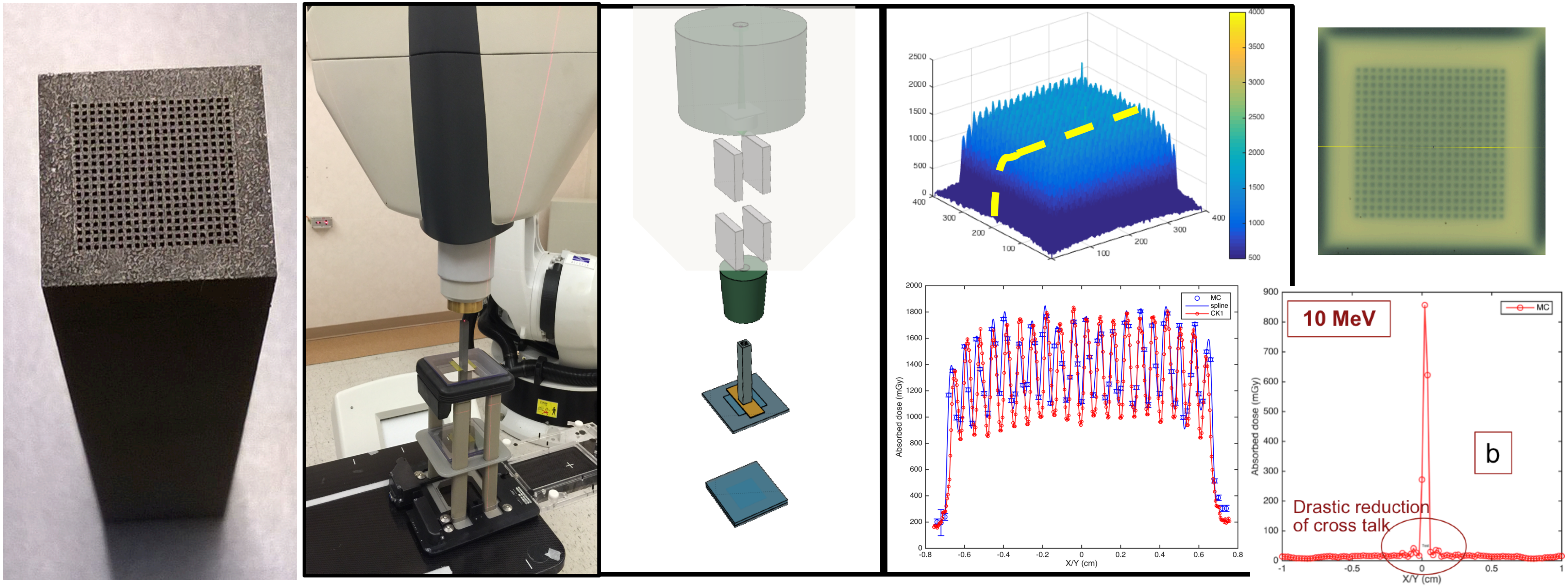




Air-core scanning magnet design

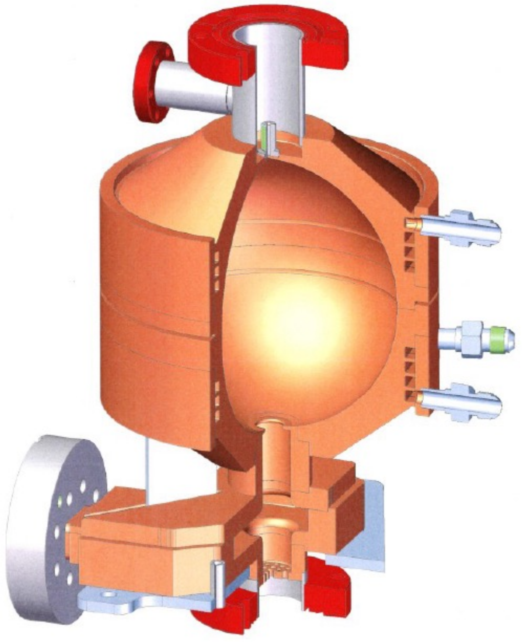
B Loo, L Nicolas – Stanford/SLAC

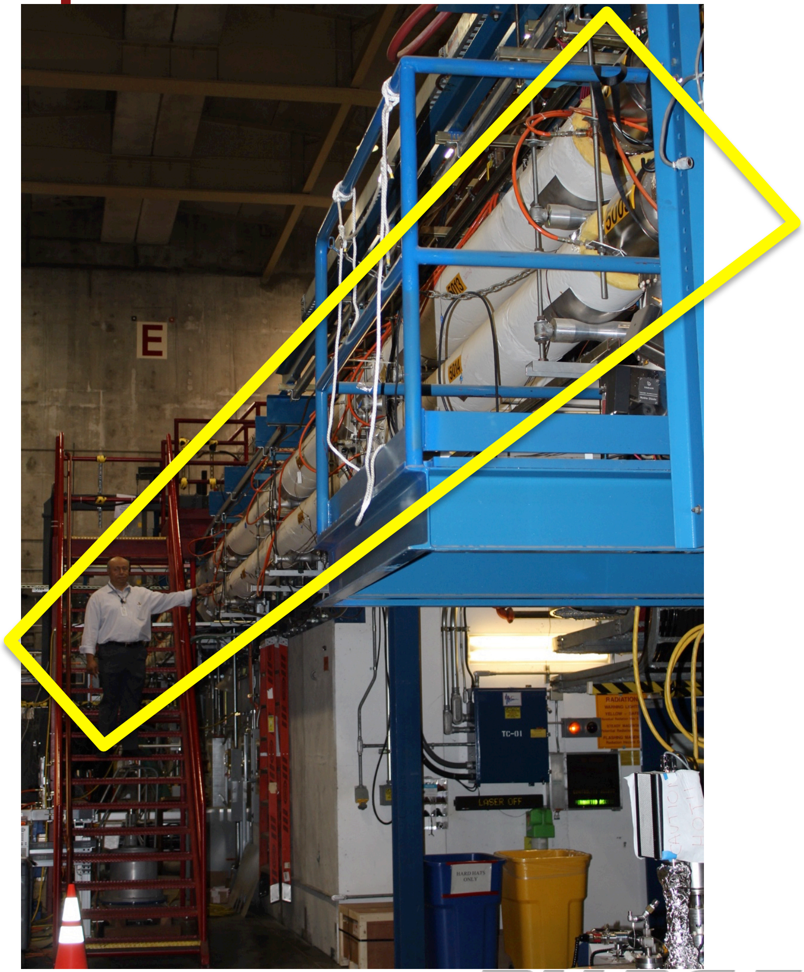
Geometrical accuracy of prototype



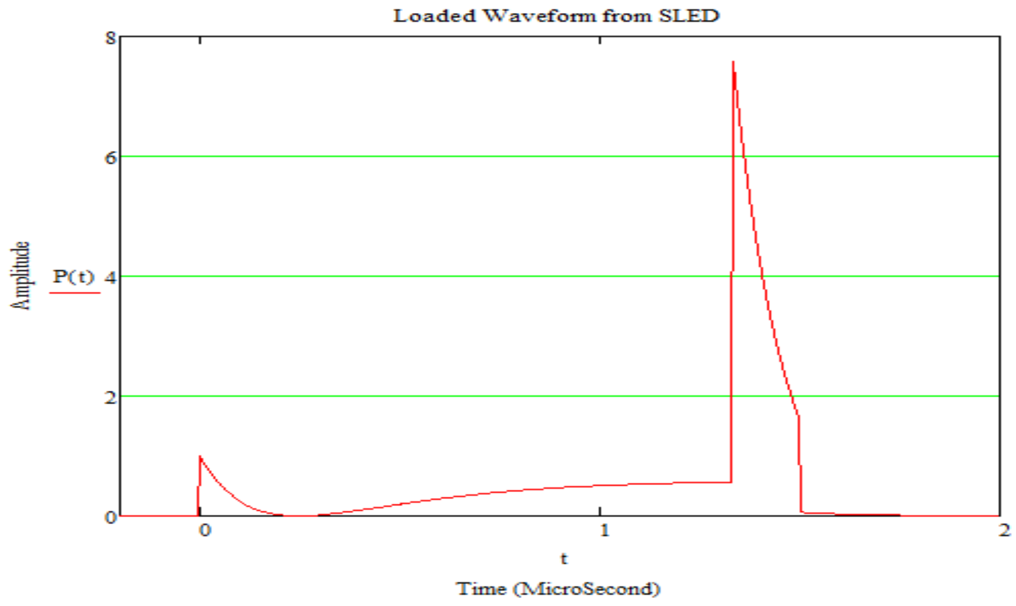
PHASER technology

Prototypes of major components





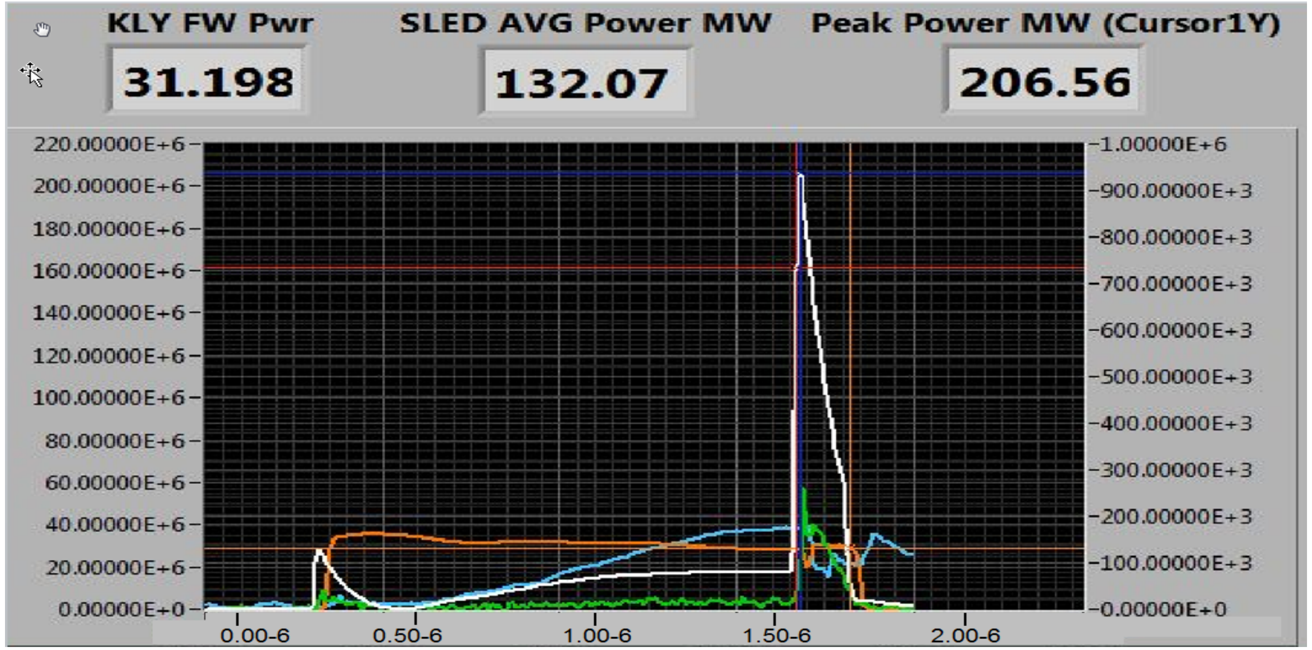
High power calculation and record



Theoretical Calculation

$$\frac{\int_{1.335}^{1.5} P(t)\, dt}{0.165} = 3.925$$

$$P(1.335) = 7.578$$



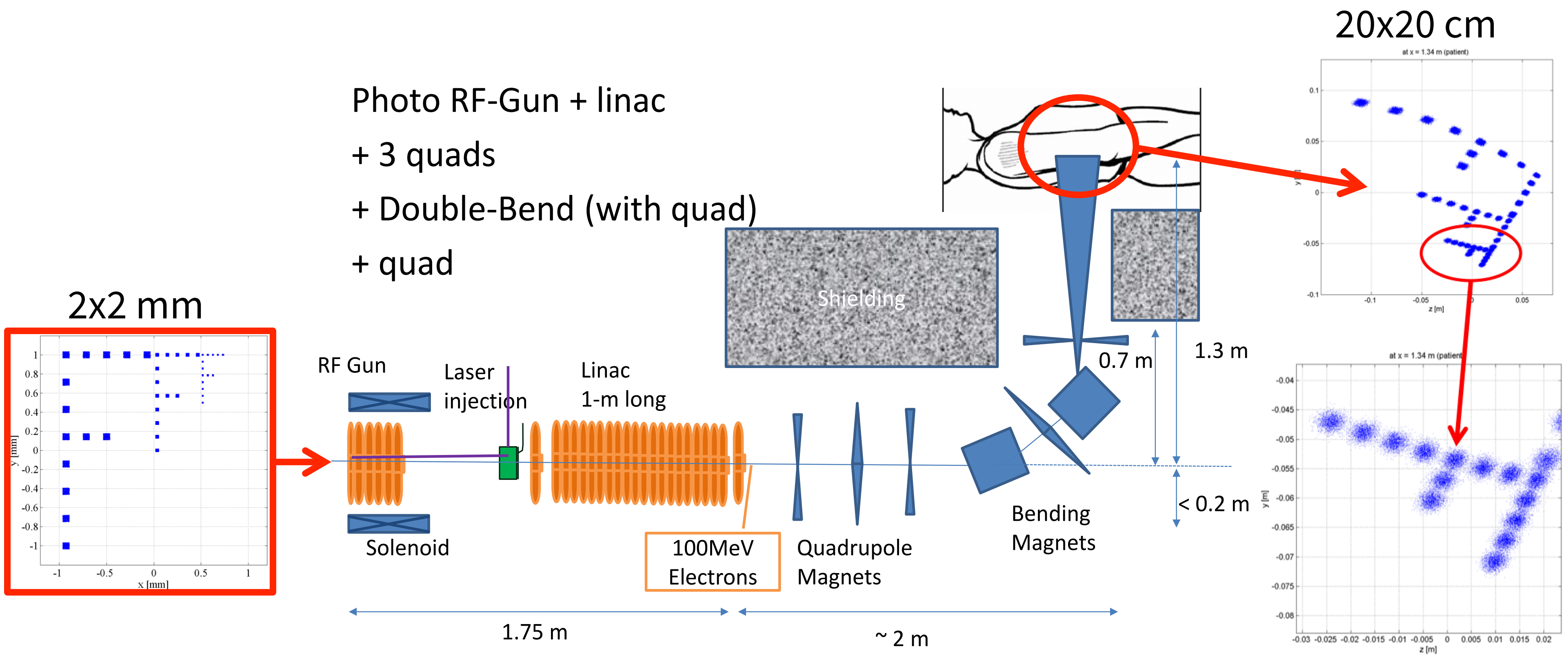
High power test

RF pulse width 1.5 µs, flip phase in last 165 ns
Average klystron output power 31.2 MW
SLEDed average power 132 MW
Peak SLEDed power 206.6 MW

Brown is klystron output, white is SLED output, blue and green are reflected signals with different scale.

Novel VHEE intensity modulation

Unique 100 MeV compact electron beamline optics design to accelerate & project electron "image" from source to patient

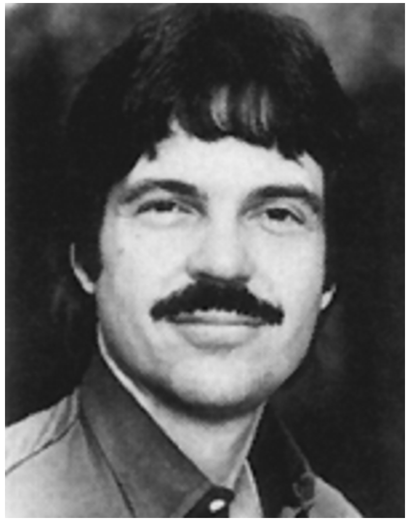


Conclusions

Next generation accelerator and RF power designs provide much higher performance, compactness, and lower cost, and can bring RT to low resource settings

Combined with CT, multi-beamline/RF multiplexer, electronic pencil beam scanning (SPHINX) → ultra-rapid PHASER

- Ultimate motion management/precision
- High clinical efficiency/throughput/cost-effectiveness
- Potential paradigm-shifting biological advantage (FLASH)



The best way to predict the future is to invent it

– Alan Kay at Xerox PARC, 1971

Supported by

Wallace H. Coulter Foundation

Stanford MEDICINE

Weston Havens Foundation

Stanford | Department of Radiation Oncology

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

U.S. DEPARTMENT OF ENERGY
Office of Science

RaySearch Laboratories

U.S. DEPARTMENT OF DEFENSE

BIO-X
STANFORD UNIVERSITY

STANFORD UNIVERSITY
OTL
OFFICE OF TECHNOLOGY LICENSING

AAPM

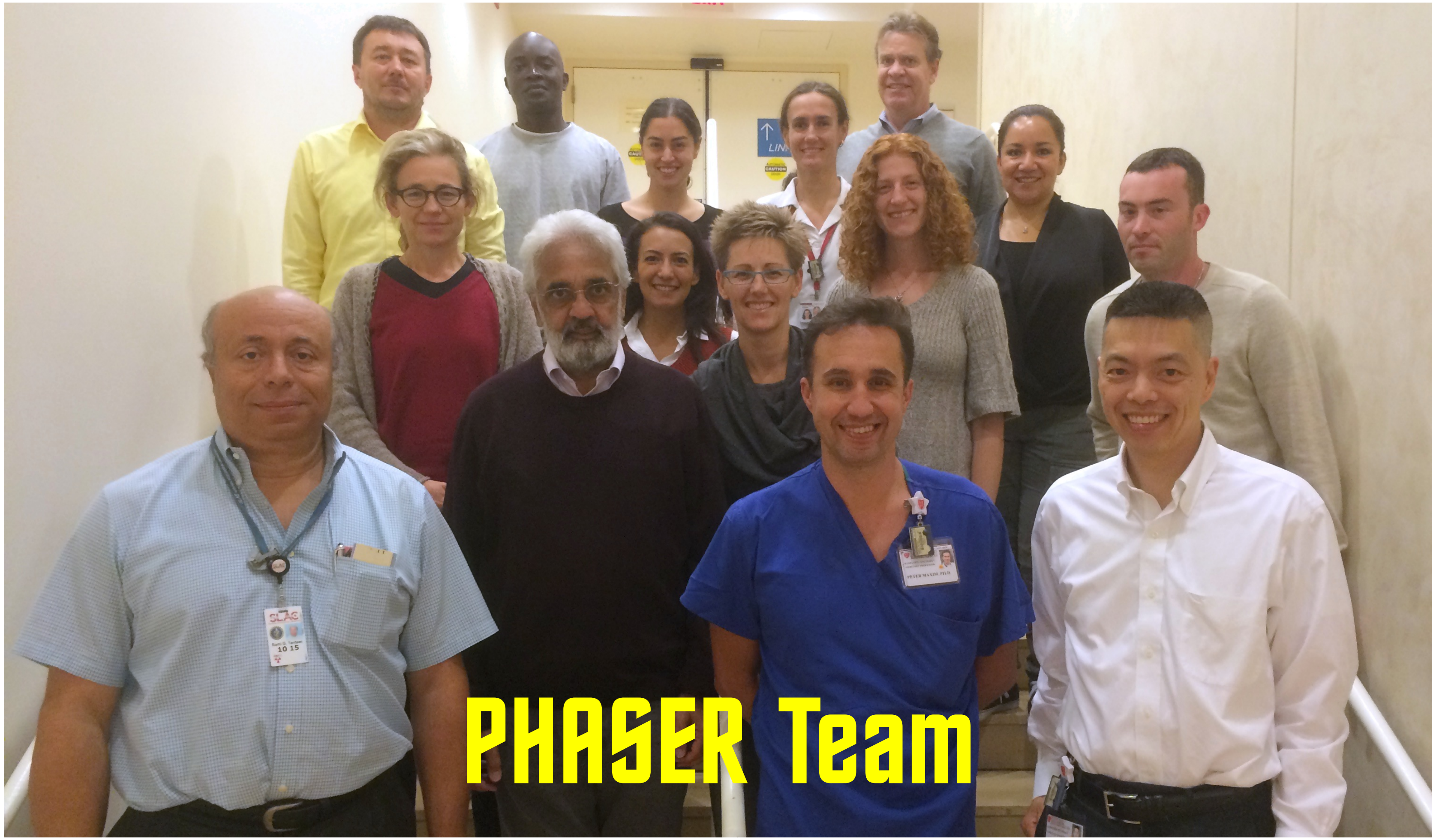
LI KA SHING FOUNDATION
李嘉誠基金會

STANFORD biodesign

BARNCANCER FONDEN

SCIT

Thank you!



Pluridirectional High-Energy Agile Scanning Electronic Radiotherapy (PHASER)