Research activities at SLAC on Normal Conducting RF Accelerators

KEK – Accelerator Seminar

Mamdouh Nasr

P. Borchard, G. Bowden, V. Dolgashev, C. Limborg, Z. Li, E. Nanni, M. Othman, S. Tantawi, B. Weatherford, P. Welander

Technology and Innovation Directorate, SLAC

Sept 19 , 2018

Outline

- Advances in Accelerator Science: Discovering the Basic Physics of Breakdown in High Gradient Normal Conducting RF Structures
- Evolution in Manufacturing Techniques with Increased Flexibility and Improved Cost-Capability
- Distributed Coupling Accelerator Structures: A new Paradigm in High Gradient Linacs
- State of the art solutions for enhanced accelerating performance
  - New Geometric-Optimization Approaches
  - Multi-Frequency Accelerator Structures
  - Cryogenic Operation for Copper Structures
- mm-Wave/THz Acceleration

Core Areas of Research for RF Accelerator Technology

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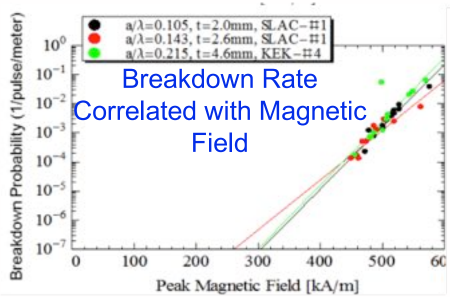
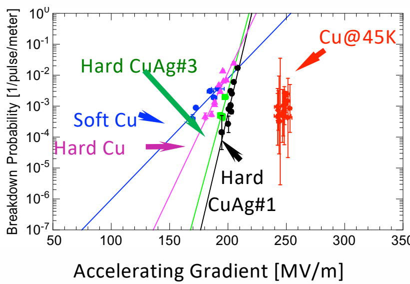
Physics of Breakdowns



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

Discovery of magnetic field's role in breakdowns triggered new research directions for high gradient linear accelerators.

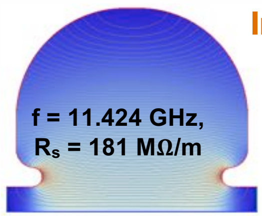
Material Science



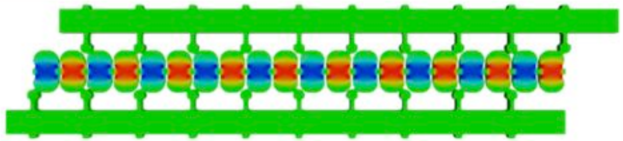
Investigate Materials to Improve the Performance of High Gradient Accelerating Structures

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

Innovative Electrodynamics



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



Geometry of Accelerating Structures Optimized Accounting for Our New Understanding of the Physics of Breakdown

Manufacturing Engineering

- 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

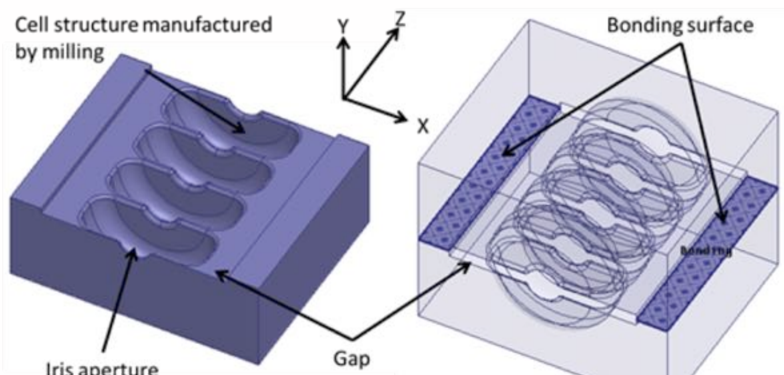
Manufacturing Techniques that are Compatible with Superior Materials and Unique Geometries

New linac architecture has to allow for the use of single-cell optimized geometries and compatible with manufacturing techniques that don't require brazing or diffusion bonding

Novel Fabrication Methods for Accelerating Structures are Compatible with Hard Metals and Cost Effective

SLAC

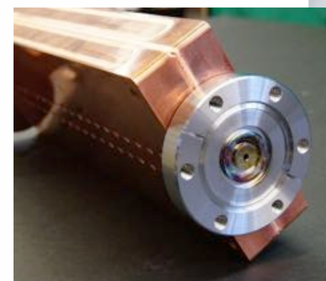
- Novel manufacturing technique: milling structure out of two halves instead of machining and then brazing single cells
- Novel geometry: open structure – no RF currents through the joint
- Consistent with manufacturing structures out of **hard copper alloys**
- Demonstrating next generation of welded structures

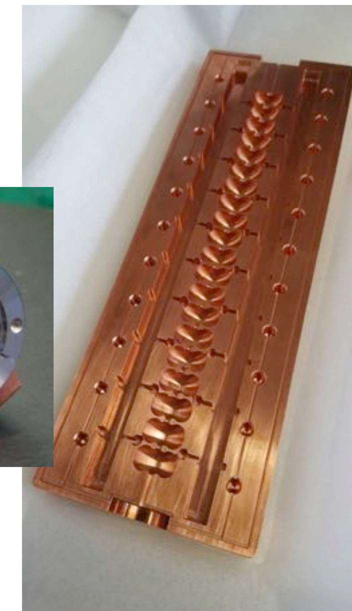


Solid Model

Two halves bonded together

V. Dolgashev





Demonstrated with Standing and Traveling Wave Structure

S. Tantawi, P. Borchard, Z. Li

Developing new manufacturing techniques to implement advanced materials in practical accelerating structures and reduce costs

Novel Fabrication Methods for Accelerating Structures are Compatible with Hard Metals and Cost Effective

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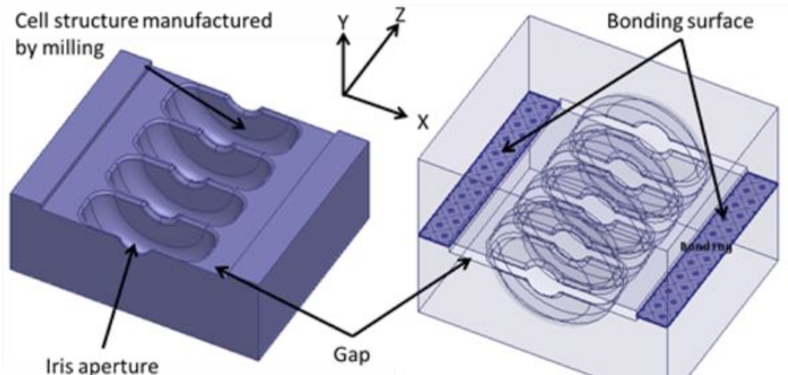

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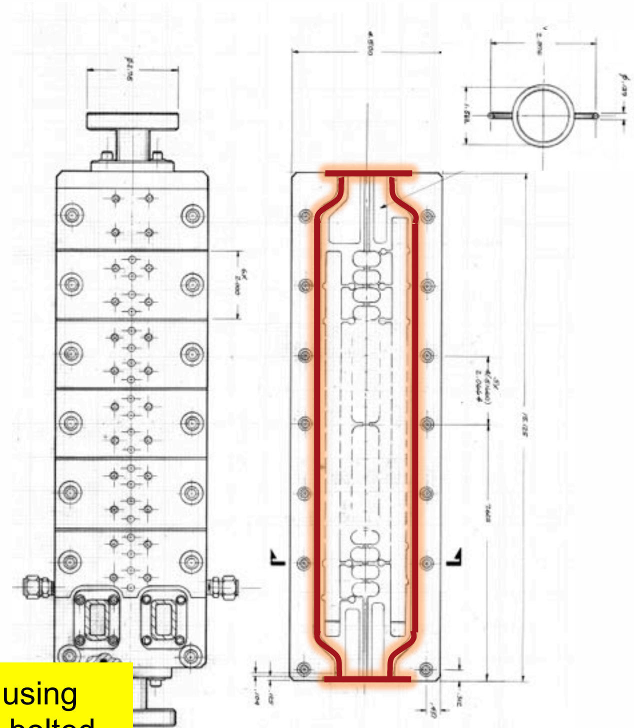


New architecture using special gasket and bolted halves for our experiment

G. Bowden, M. Nasr, Z. Li, S. Tantawi

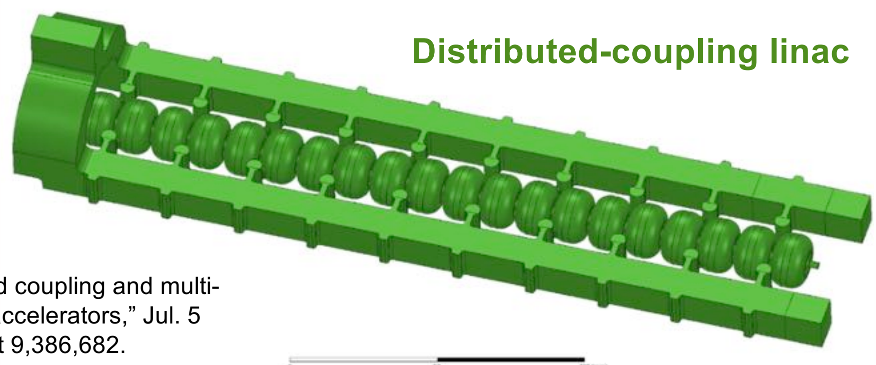
Developing new manufacturing techniques to implement advanced materials in practical accelerating structures and reduce costs

Distributed coupling Linacs provides a new technology that enables much flexible cell-design optimization and pushes the limitation of Linacs performance.

- Geometry of accelerating structures should be optimized minimize peak magnetic field on the surface even if that happens, to some limited extent, on the expanse of electric field levels at the surface.

- The existing linac designs, however, requires careful consideration of the coupling between adjacent cells which limits the ability of designers to optimize the cell shape.

- The distributed coupling linac overcomes the limitations of cell-to-cell coupling imposed on the shape by providing a new topology that allow feeding each accelerator cell independently using a periodic feeding network.

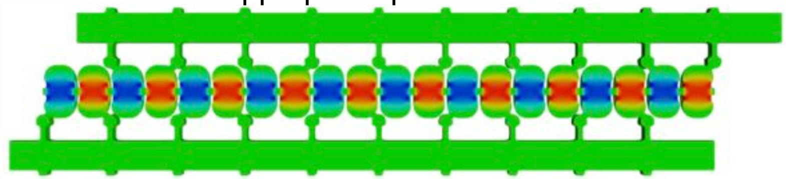


Tantawi et al. “Distributed coupling and multi-frequency microwave accelerators,” Jul. 5 2016, US Patent 9,386,682.

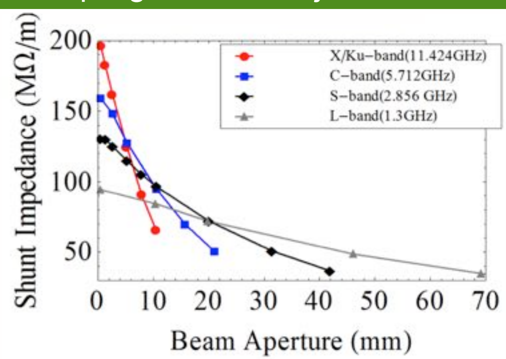
Distributed coupling linac allow for the use of single-cell optimized geometries and is compatible with manufacturing from two parts

Distributed Coupling Accelerator Structures:
A new Paradigm in High Gradient Linacs

Carefully designed to provide equal power distribution and appropriate phase to each cell

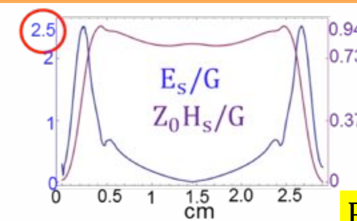


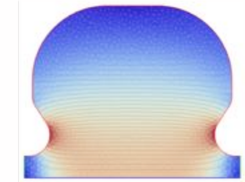
Cavities can be optimized without the constraint usually applied from the coupling between adjacent cavities.



New Scaling Laws Determine the Best Performance for Accelerating Structures

Designed to minimize surface magnetic field

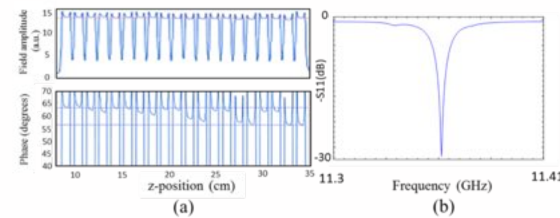


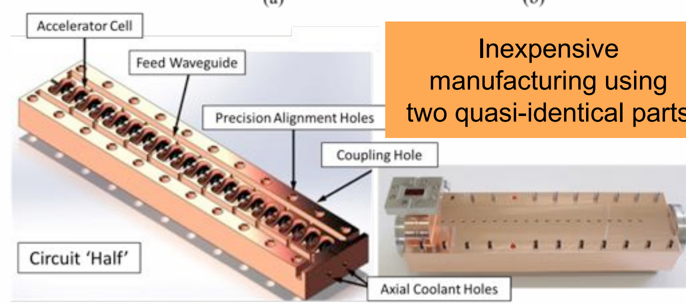


π-mode, Xband, 20 cells Linac

$R_{shunt} = 155\ \mathrm{M\Omega/m}$

Easy tuning and single frequency rather than 20

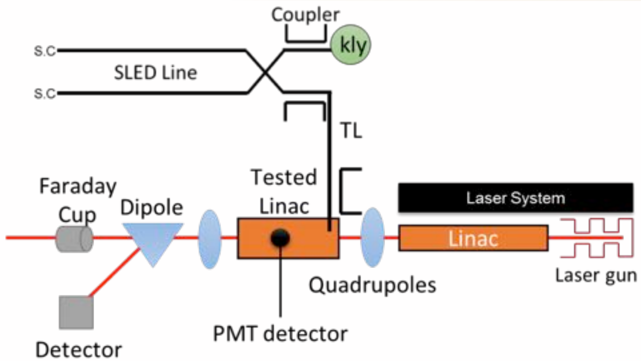


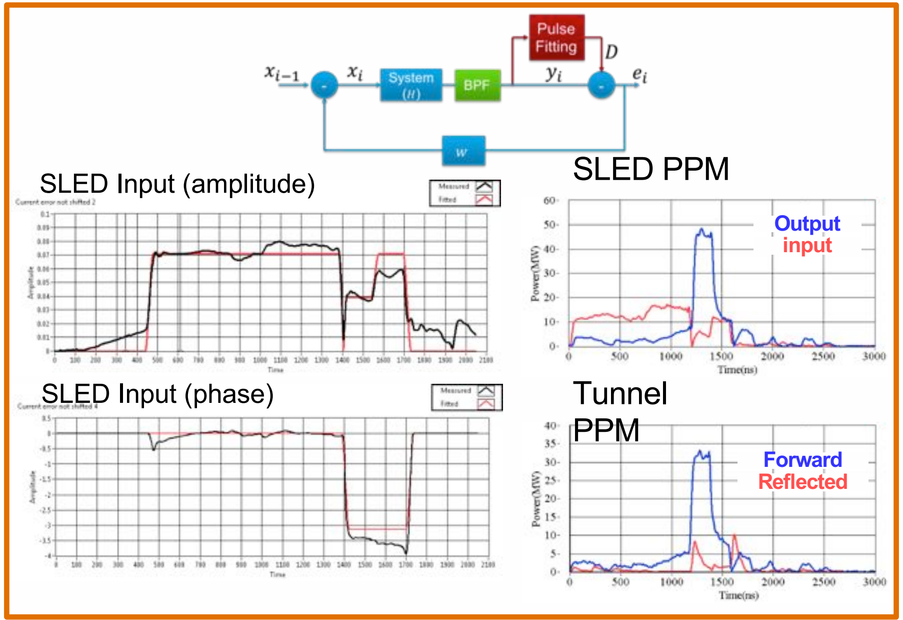


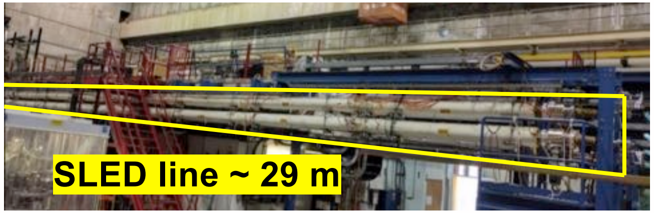
Inexpensive manufacturing using two quasi-identical parts

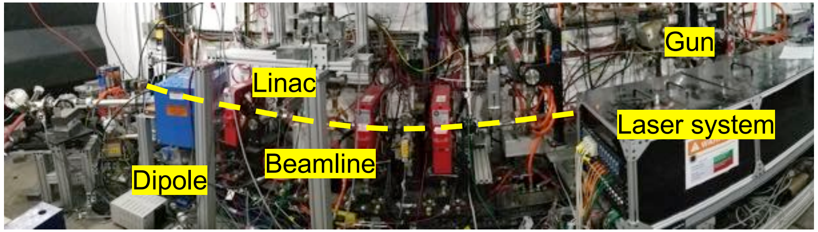
Scalable technology with enhanced shunt impedance capable of reaching high duty factors

Experimental setup and software development for processing and testing of the distributed coupling linac







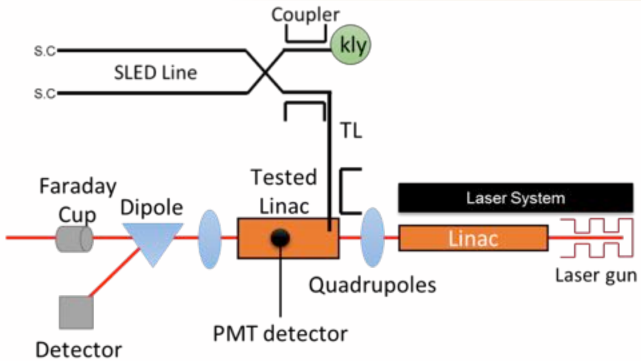


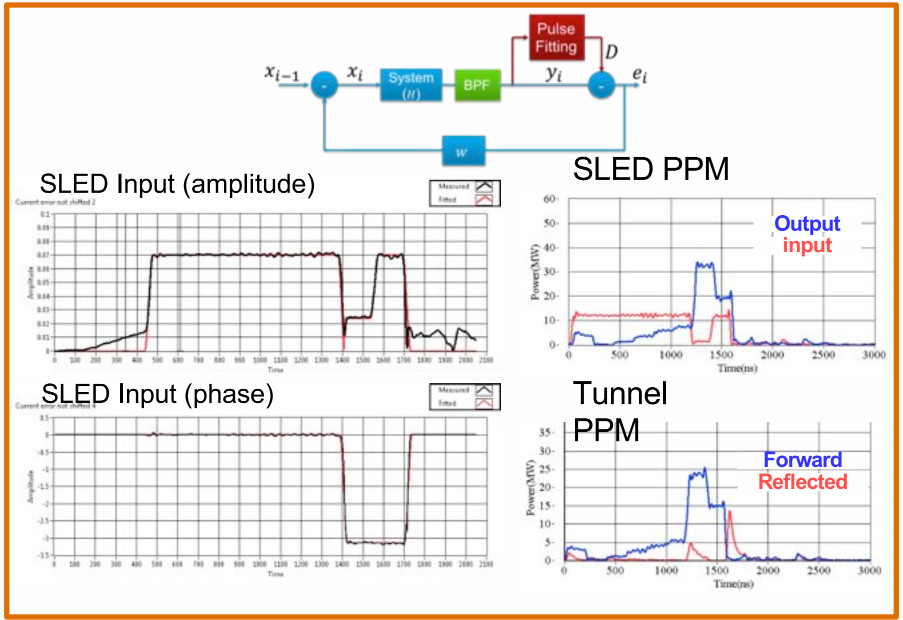
Developments of Processing Software

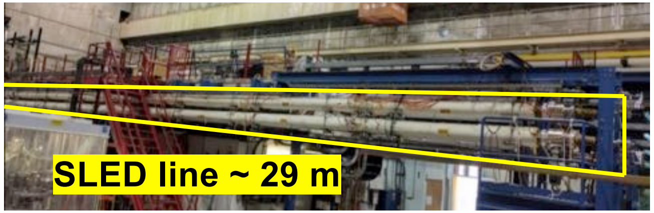
- Demodulation
- Pulse Correction
- Cavity model fitting
- Resonance Adjustments
- Processing Code
- SLED Tuning
- Gradient Calculation

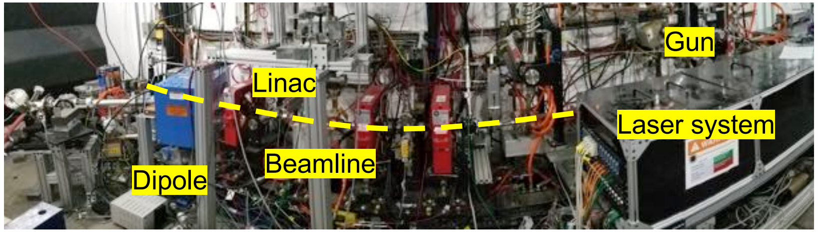
M. Nasr, S. Tantawi

Experimental setup and software development for processing and testing of the distributed coupling linac









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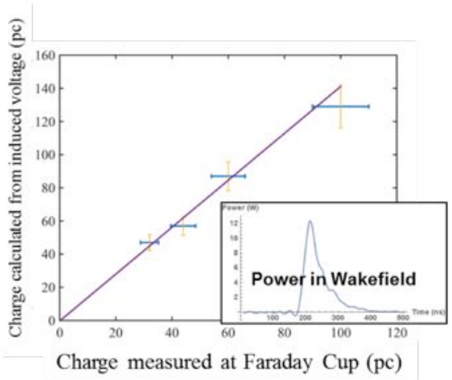
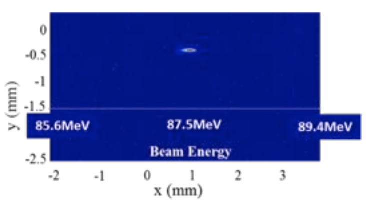
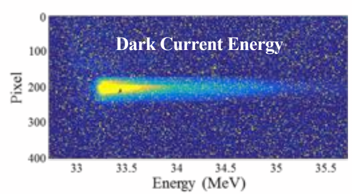
Verification of accelerating parameters and study of breakdown mechanism in the structure

Verification using beam energy, dark current, and charge measurements





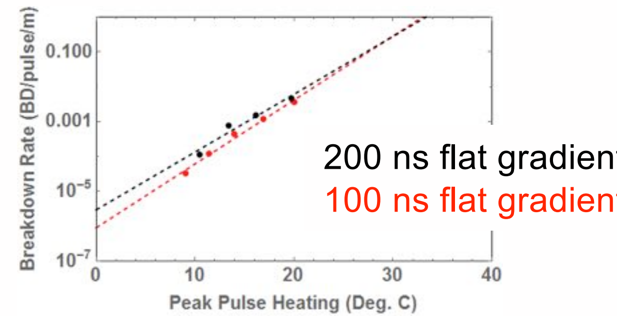
Gradient=100 MV/m



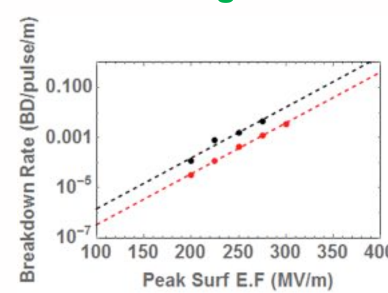
Gradient=140 MV/m

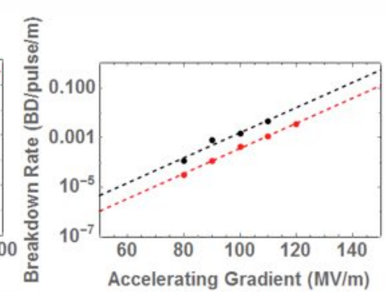
Results agree with the designed shunt impedance and predicted quality factor

Breakdown measurements at 100 ns and 200 ns flat gradient.



Pulse heating lines matches for both pulses





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SLAC

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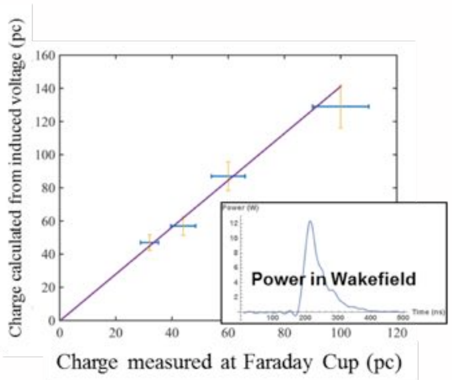

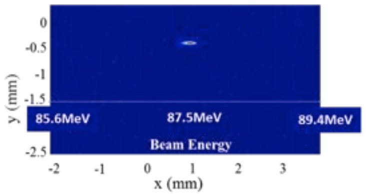

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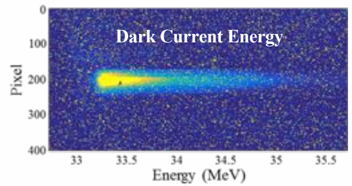

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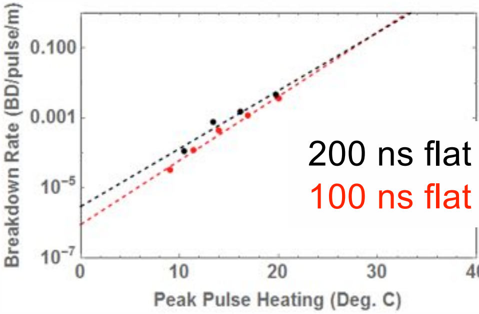

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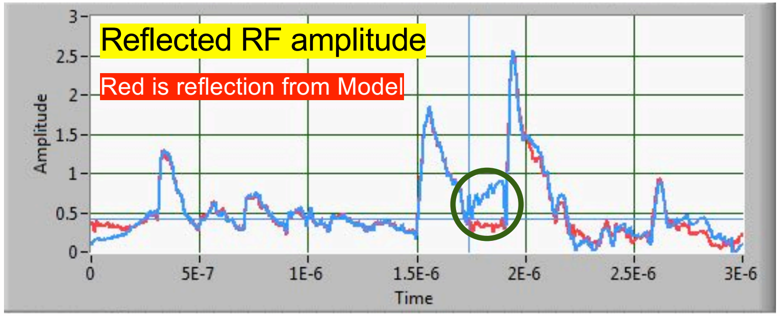


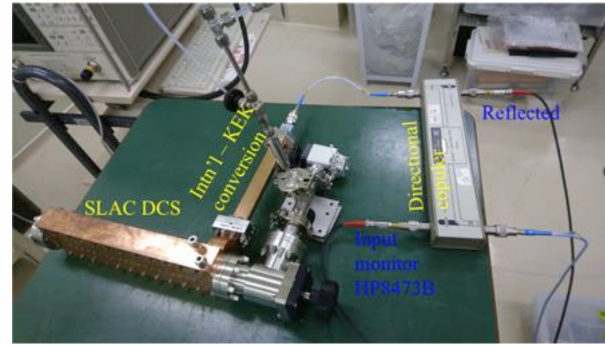
At breakdowns the input power reflects back rather than getting absorbed

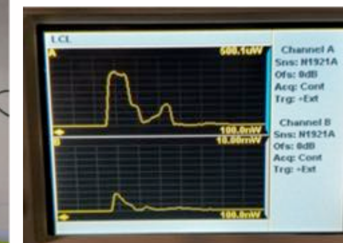
M. Nasr, B. Weatherford, C. Limborg, S. Tantawi

Next distributed-coupling linac testing at KEK (Nextef A)

Electrical Discharge Machining (EDM)

US-Japan collaboration



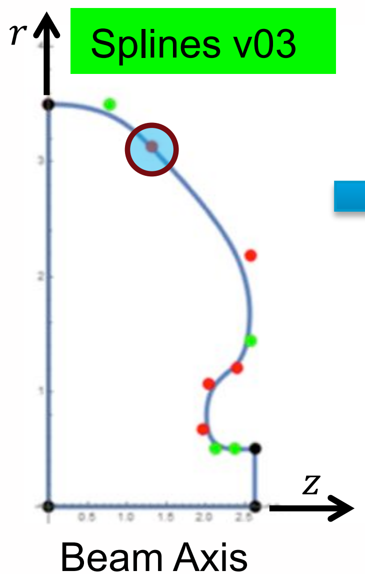


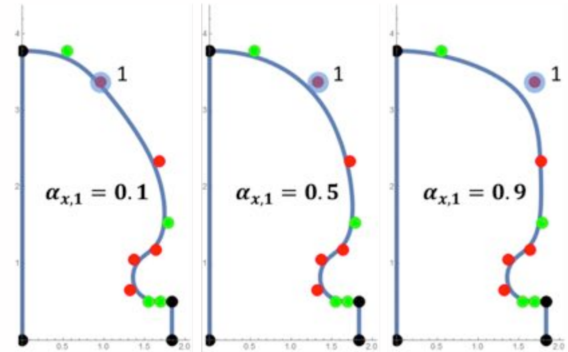
- Structure cold tested at SLAC and KEK
- Installation is completed at KEK (Nextef A)
- Initial measurements at low power level are performed
- Applying pulse correction algorithm to the new setup

T. Abe, T. Higo, M. Nasr, B. Weatherford, et al

New geometric-optimization approaches that minimizes both electric and magnetic fields on cavities' surface

The cavity curvature is defined with a set of control points with variable positions to control splines which describes the cavity shape.





M. Nasr et al. New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance, IPAC'18

Our first design, using circular shapes, had the drawback of high electric field levels on the surface

$$\frac{\mathrm{Peak}[\mathrm{E_{surf}}]}{\mathrm{Gradient}} = 2.5 \rightarrow \mathrm{R_s} = 155\mathrm{M\Omega/m}$$

Can we do better?

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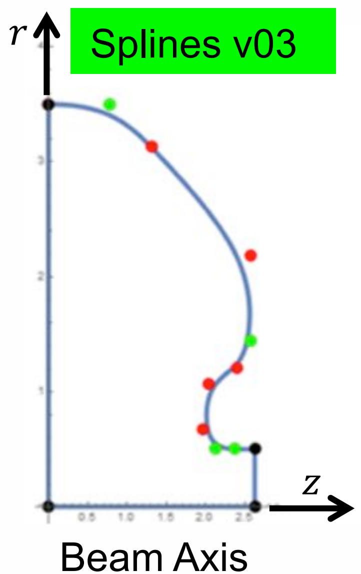
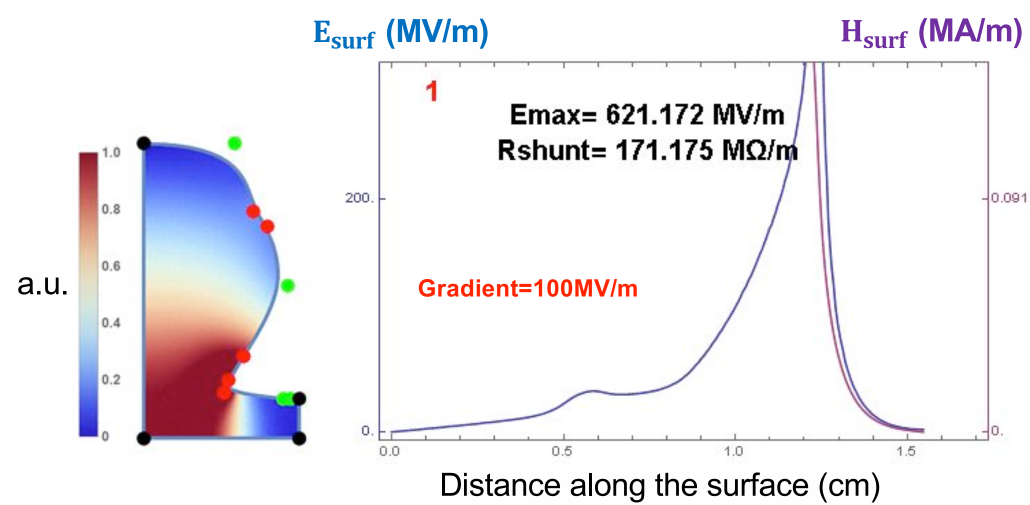


Evolution of an optimization example

X-band, 11.424 GHz, iris diameter 0.1λ



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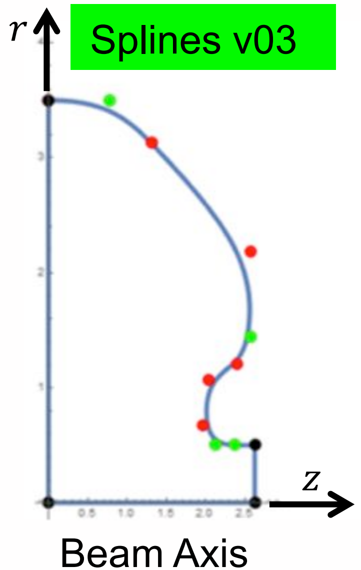

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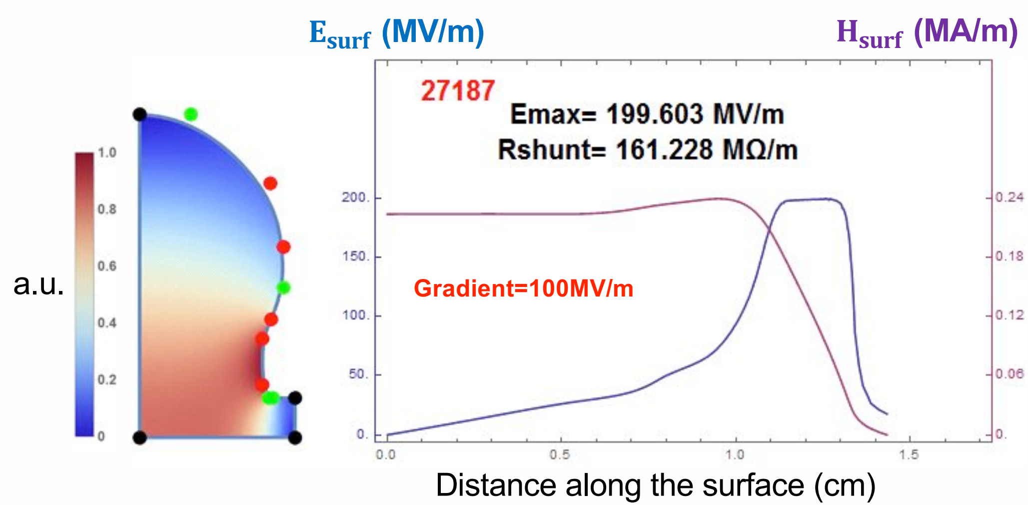


Peak surface field to gradient ratio reduction from 2.5 to 2 with even higher shunt impedance

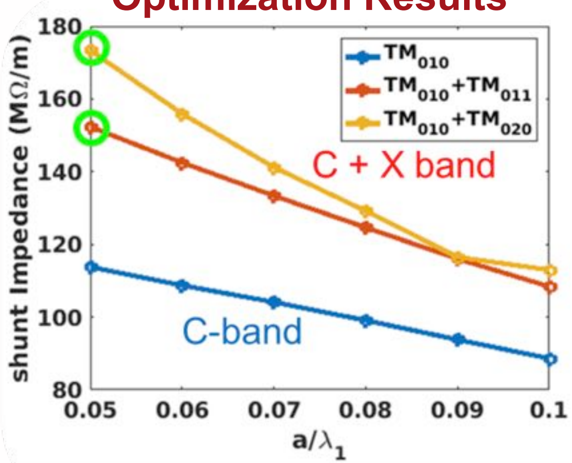
Having every cell fed individually by a manifold naturally inspires the use of another manifold with another mode feeding the same cavity

Power ∝ (gradient)²

Performance of cavity improves when powered with two different RF modes

- **Efficiency:** Linear superposition of fields by adding power in the two modes.
- **Gradient:** doubling the accelerating gradient without doubling surface fields; ~ 300 MV/m gradient at room temp

Optimization Results



Previous designs were strict to harmonically related frequencies which is not optimal.

Our design is free from this constraint, and instead operate at the common sub-harmonic of the used frequencies.

Using distributed feeding network that feeds every cell independently for each mode.

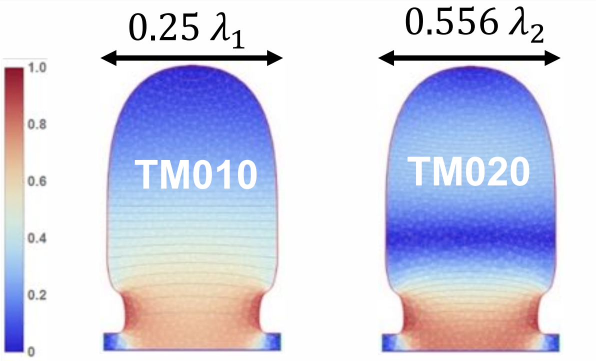
- **Optimized designs shows that harmonic frequencies are not the optimal choice**
- **Up to 60% increase of the shunt impedance for same surface fields**

M. Nasr et al. A Novel Dual-Mode Dual-Frequency Linac Design, IPAC’17

S+C bands dual-frequency design is optimized for low surface fields, maximized shunt impedance, and high common sub-harmonic frequency

SLAC

The design was optimized to maximize the common sub-harmonic for multi-bunch operation



2.856 GHz
102 MΩ/m

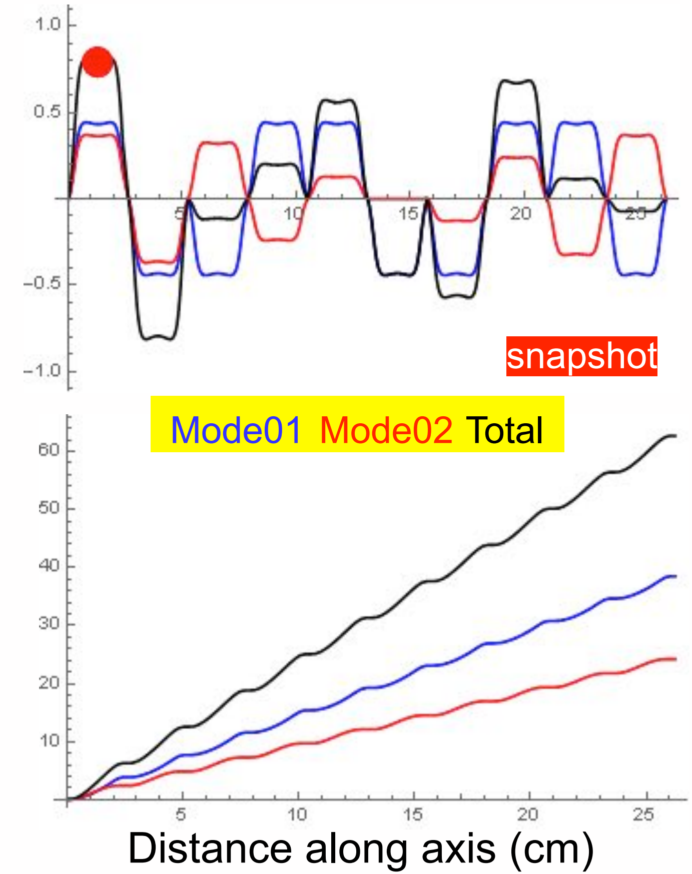
6.34667 GHz
60 MΩ/m

$\mathrm{R_{s,tot}} = 162\ \mathrm{M}\Omega/m$

f_{common}	Φ_1	Φ_2	$P_{in,2}/P_{in,1}$
317.33 MHz	90°	200°	0.6

Allow for multi-bunch operation with bunch spacing as low as ~3ns

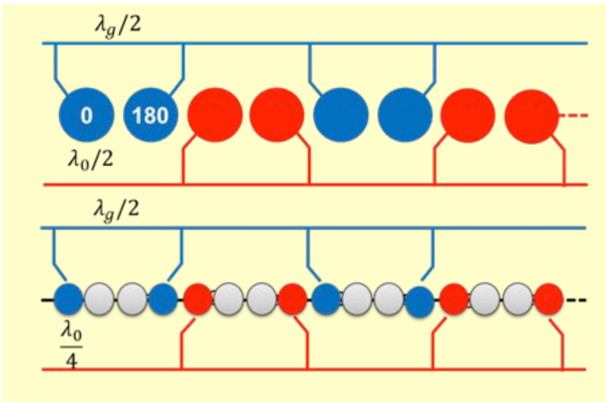
Axial fields along 10 accelerating cells



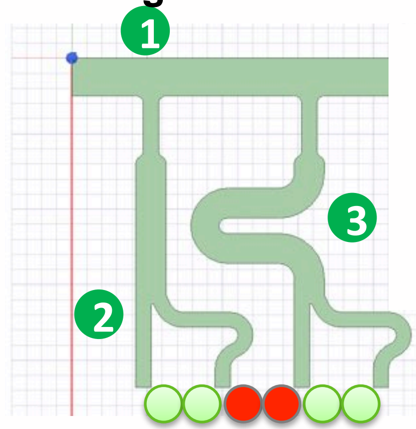
M. Nasr et al. The Design and Construction of A Novel Dual-mode Dual-frequency Linac Design, IPAC'18

Feeding the power to the 1st mode: 90Deg phase advance is challenging due to the short cells width of $\lambda_0/4$

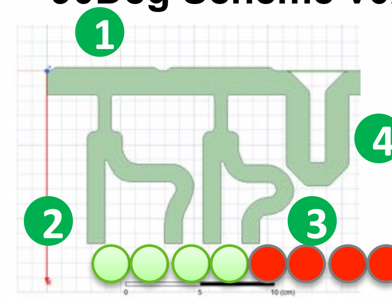
180Deg Scheme



90Deg Scheme v01

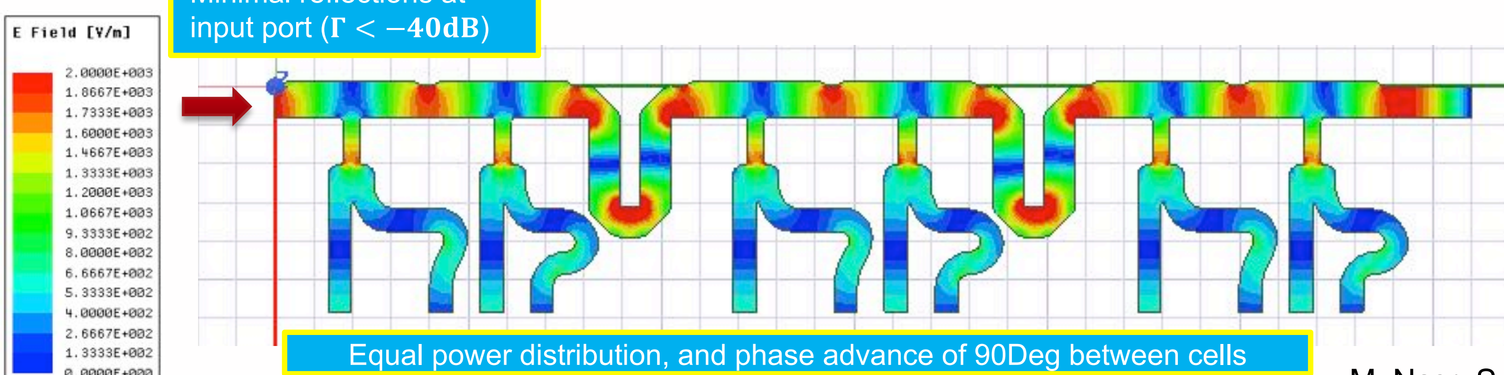


90Deg Scheme v02



Comparison to-scale

Minimal reflections at input port ($\Gamma < -40\mathrm{dB}$)



Equal power distribution, and phase advance of 90Deg between cells

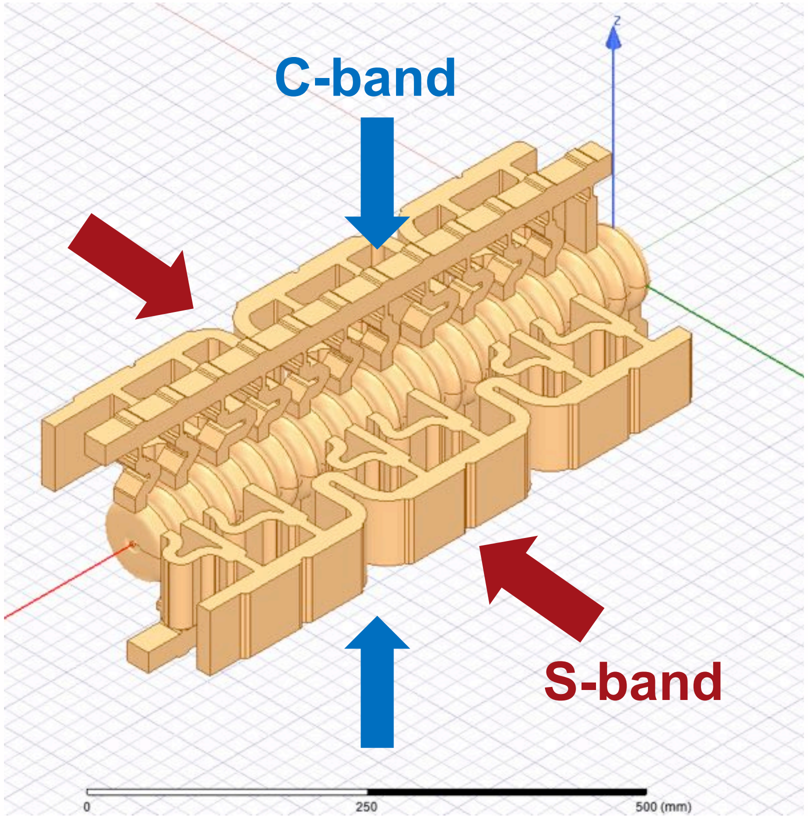
M. Nasr, S. Tantawi

State of the art dual-mode linac design operating at S+C bands simultaneously

Allow for much higher gradient with low input power

Fields don't add temporally or spatially to the surface

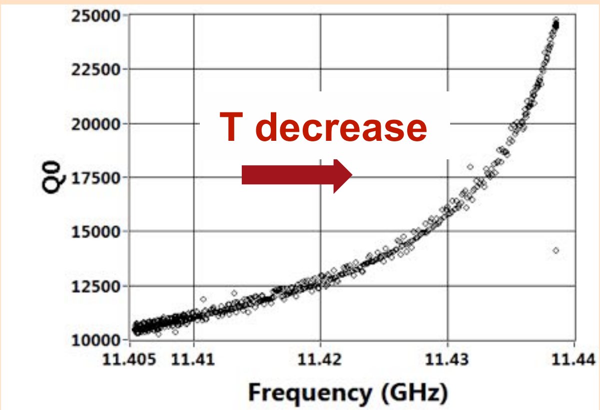
f_{res1}(GHz)	2.856
f_{res2}(GHz)	6.34667
f_{common}(MHz)	317.33
ϕ_1	90Deg
ϕ_2	200Deg
$R_{shunt,tot}(\mathrm{M}\Omega/m)$	161
$\frac{P_{in,2}}{P_{in,1}}$	0.6



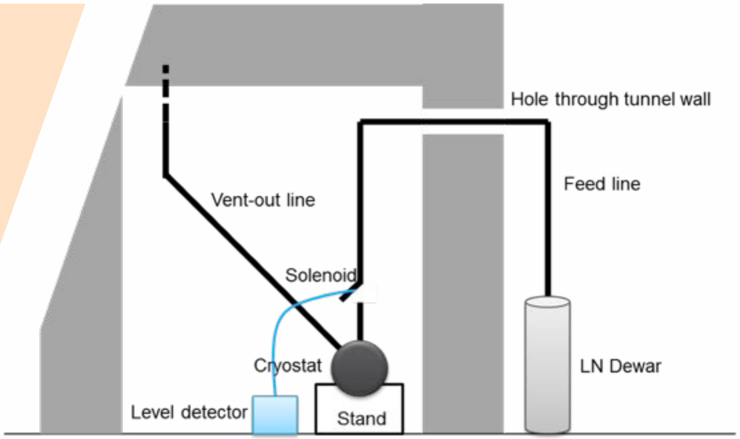
M. Nasr, S. Tantawi

Cryogenic-Copper Accelerating Structures: New Frontier for Beam Brightness, Efficiency and Cost-Capability

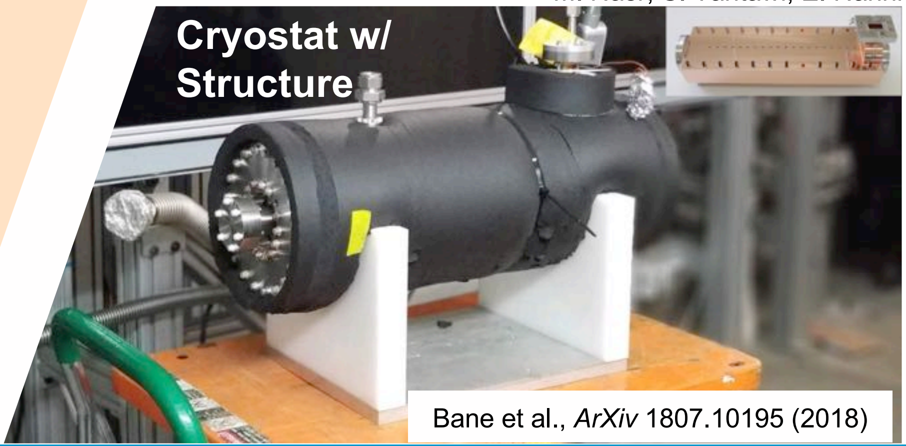
- Increased conductivity and hardness enables higher gradients
- Dramatic reduction in cost of system including cryogenics at 77K
- 2.5X less power establishing gradient allows for heavy beam loading even at high gradient – improving system efficiency



Increase in Q_0 by a factor of 2.5



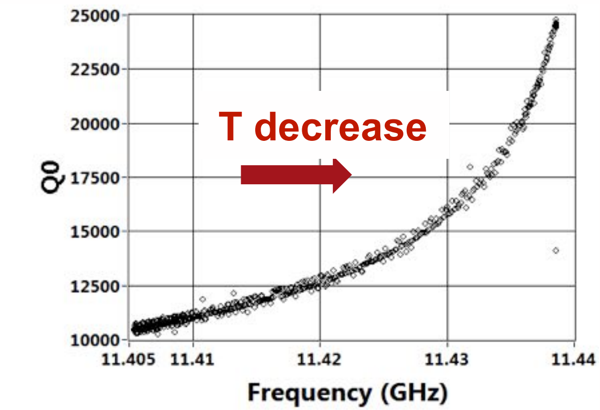
M. Nasr, S. Tantawi, E. Nanni et al.



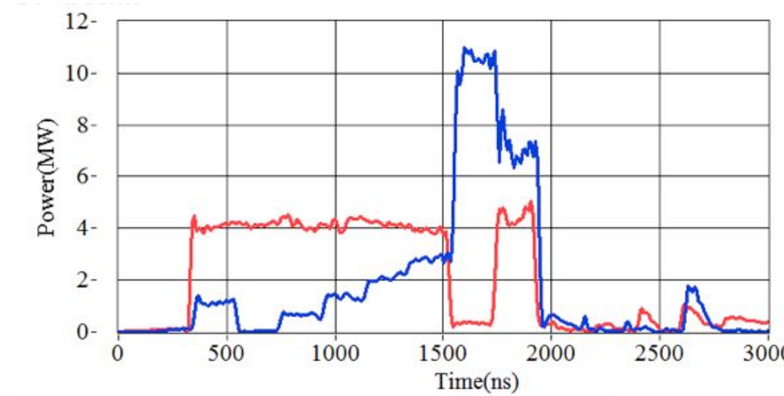
Bane et al., *ArXiv* 1807.10195 (2018)

Impact of novel structures and temperatures → order of magnitude increased performance

Peak power measurements



$f_{res} = 11.43855$ GHz
Temp $= -183.3$°C

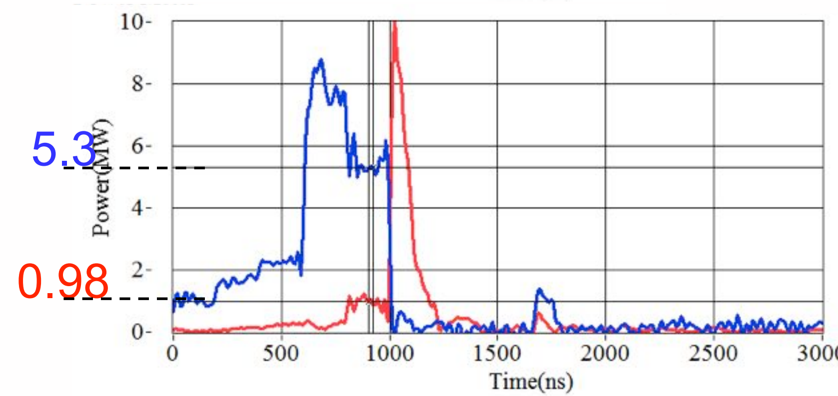


From cold-test:

$$\Gamma = \left|\frac{1-\beta}{1+\beta}\right| = 0.4286$$

From measurement:

$$\Gamma = \sqrt{\frac{P_{ref}}{P_{in}}} = 0.43$$



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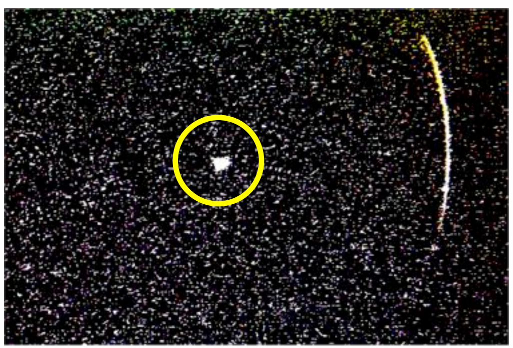
Gradient simulation and dark current measurements

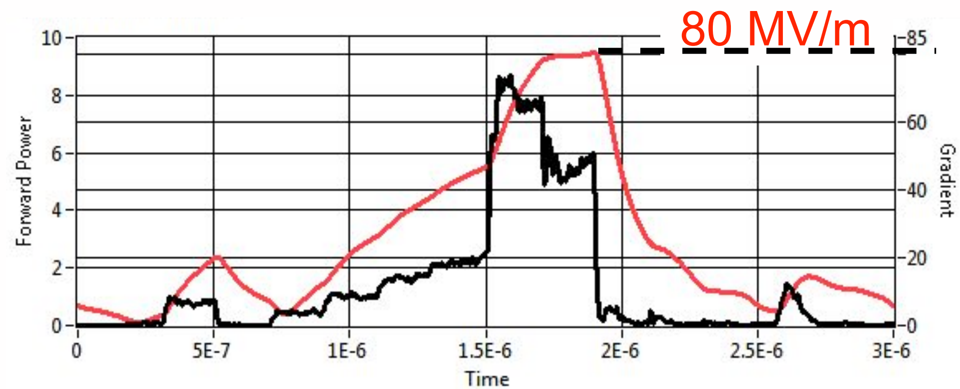
Simulated parameters

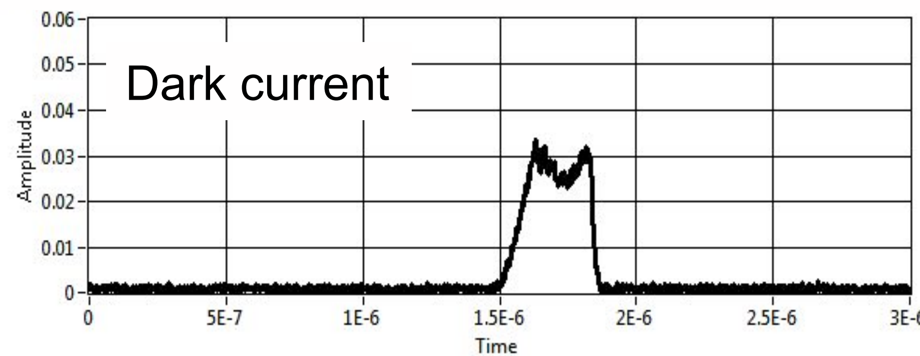
$$\frac{1-\beta}{1+\beta} = -0.4286$$

$$Q_{tot} = 7142$$



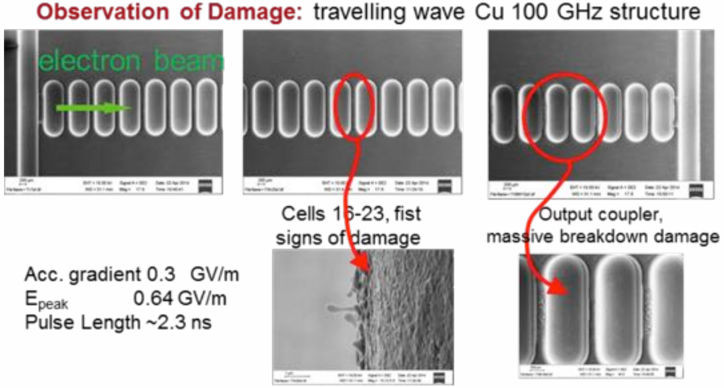
Energy gain=19 MeV
Gradient=72.4 MV/m

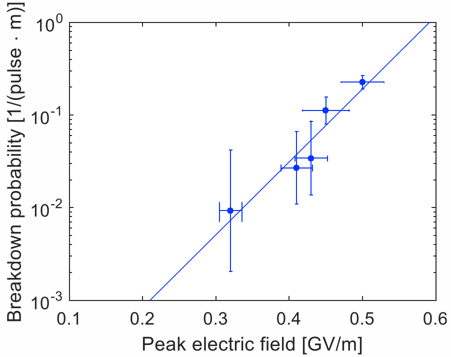




mm-Wave/THz Acceleration

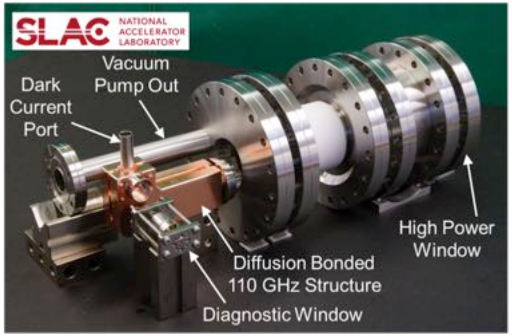
First Measurement of Breakdown Statistics in High-Gradient Beam-Driven Accelerator





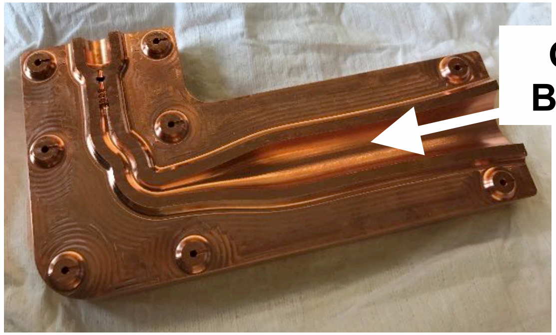
Breakdown rate measurements: travelling wave Cu-Ag 100 GHz structure (Nov 2015)

What is the Real Scaling in Frequency for Breakdown Physics?



- Demonstrate realizable mm-wave accelerating structure at 110 GHz
- Power with stand-alone RF source – Experimental test underway at MIT with 1 MW gyrotron oscillator
- Direct comparison w/ X-band breakdown studies

E. Nanni et al., IRMMW '18



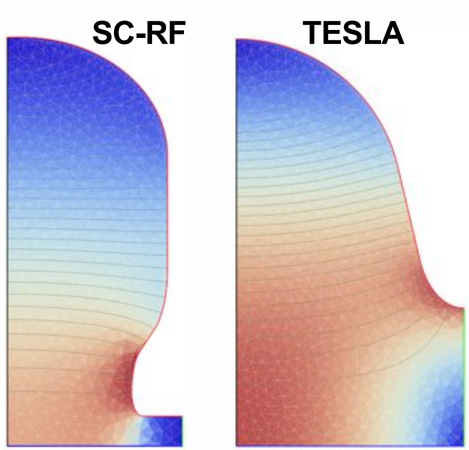
M. Dal Forno, et al., *Physical Review Accelerators and Beams* 19.1 (2016): 011301.
M. Dal Forno, et al., *Physical Review Accelerators and Beams* 19.5 (2016): 051302.

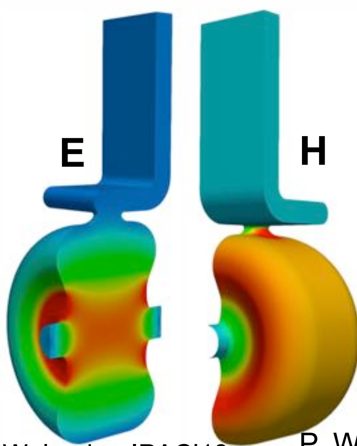
Transformation of SRF Accelerator Technology with Distributed Coupling Topology Investigation

f = 1.3 GHz	SC-PF	TESLA
a (cm) (aperture radius)	0.66	3.5
Q_0	0.8e10	1.0e10
R_{sh} (Ω/m)	2.4e13	9.8e12
E_{pk}/E_{acc}	2.05	1.98
H_{pk}/E_{acc} (mT/(MV/m))	**2.41**	**4.17**
R_{sh}/Q_0 (Ω/m)	3047	983
P_{loss}/E_{acc}^2 (mW/m/(MV/m)^2)	**41.1**	**101.7**

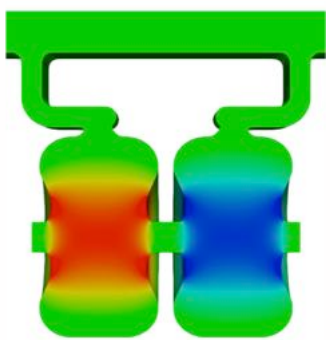
- Developing SRF parallel-feed accelerator structure under LDRD funding (thru FY19) for testing of bulk-Nb prototype
- ~2X lower peak H-field, 2.5X less dynamic thermal load

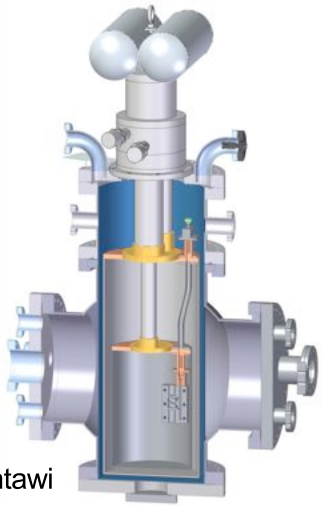
- Long-term: leverage structures expertise and cryogenic high-power testing system to advance SRF accelerators





P. Welandar, IPAC'18





P. Welander, M. Nasr, Z. Li, S. Tantawi

Conclusion

- Novel Fabrication Methods for Accelerating Structures are Compatible with Hard Metals and Cost Effective
- Distributed coupling Linacs provides a new technology that enables much flexible cell-design optimization and pushes the limitation of Linacs performance.
- An X-band SW distributed feeding Linac is being tested at NLCTA to push the structure to ultra-high gradient.
- New geometries, that reduces the peak electric field while maintaining low levels of magnetic field, have been developed for next generations of distributed coupling linacs.
- Novel dual-mode dual-frequency designs where the frequencies are not constrained to be harmonically related will provide lower surface fields and lower power requirements compared to single-mode optimized designs.
- Cryogenic-Copper Accelerating Structures has the promise for new frontier for beam brightness, efficiency and cost-capability

Questions!