Distributed Coupling Linacs from Room to Cryogenic Temperature

Jefferson Lab, Accelerator Seminar

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford | ENGINEERING
Electrical Engineering

Outline

- **Physics of breakdown**
  in high gradient normal conducting structures

- **The distributed-coupling technology**
  New geometric optimization capabilities

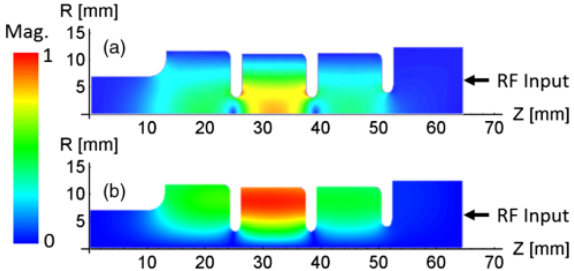
- **Superconducting distributed-coupling linacs**
  Reduced surface fields and power loss

Understanding the physics of breakdowns triggered new research directions for high gradient linear accelerators

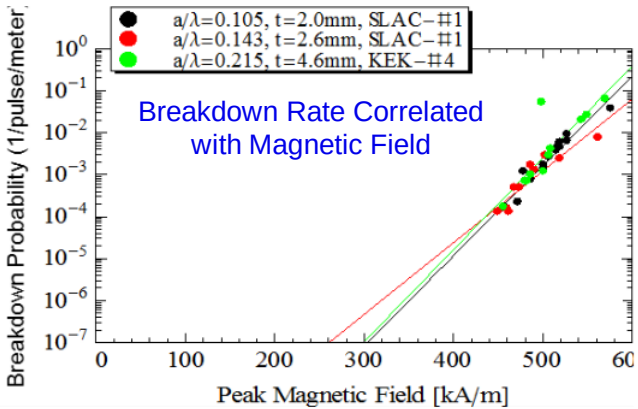
Experimental studies for understanding the physics of breakdowns have led to many discoveries

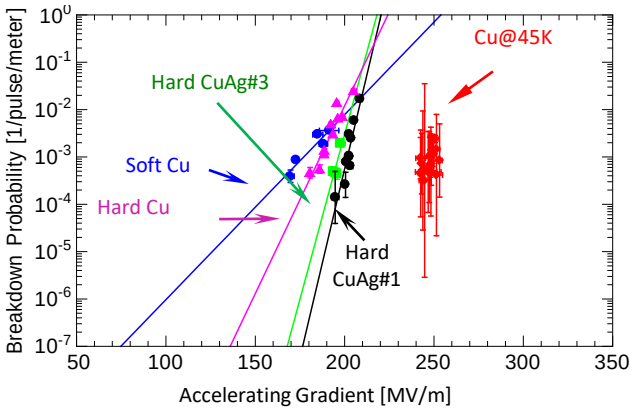
- **Magnetic field**'s role in breakdowns through pulsed heating
- Reduced breakdown rates with increased **material strength** (hard materials and low temperature operation)

Single-cell testing



Full scale structures are long, complex, and expensive





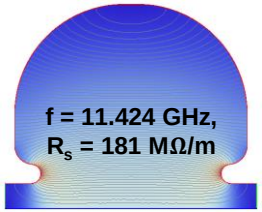
Valery Dolgashev et al., "Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures," Applied Physics Letters, Volume 97, Issue 17, pp 171501 - 171501-3, October 2010.
Alex Cahill et al., "High gradient experiments with X-band cryogenic copper accelerating cavities" Phys. Rev. Accel. Beams 21, 102002 – Published 23 October 2018.

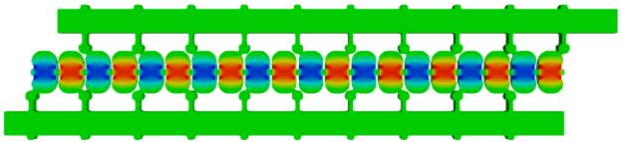
Understanding the physics of breakdowns triggered new research directions for high gradient linear accelerators

Pushing the limitations of high gradient acceleration

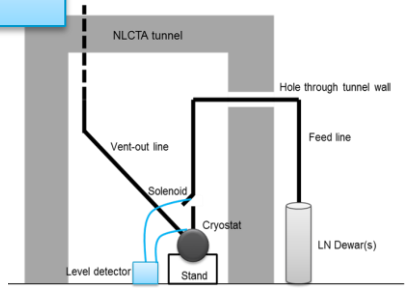
Novel Manufacturing Techniques

New Optimized Geometries of Accelerating Structures





Cryogenic Operation of NC Structures

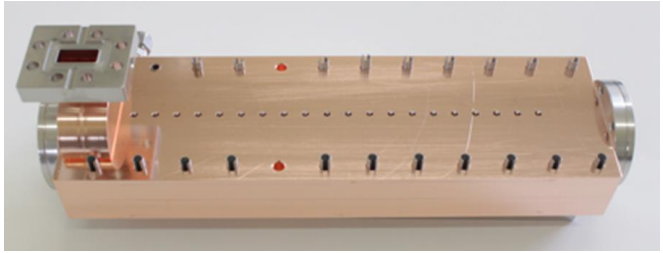


Novel Manufacturing Techniques

Novel fabrication methods are compatible with hard metals and reduced cost

- Milling structure out of two halves instead of machining and then brazing single cells
- No RF currents through the joint
- Consistent with manufacturing structures out of **hard copper alloys**

Demonstrated with Standing and Traveling Wave Structure



S. Tantawi, P. Borchard, Z. Li
V. Dolgashev

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

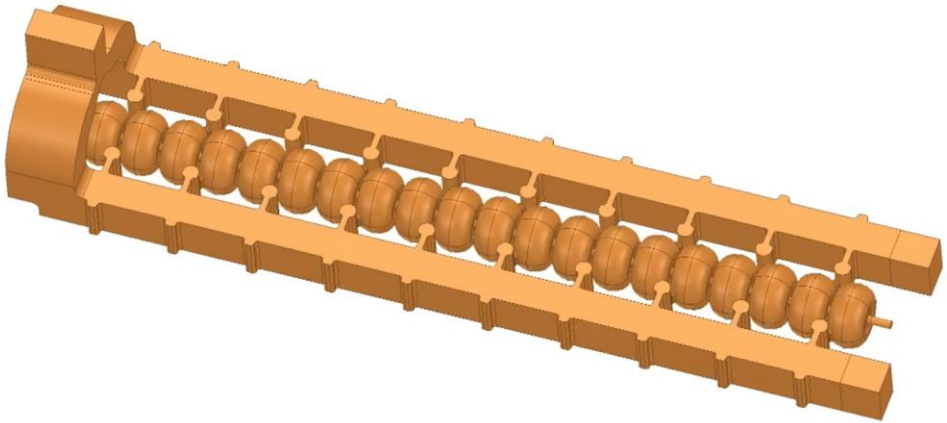
Optimized Geometries
using
Distributed-Coupling Topology

Distributed coupling Linacs provides a new technology that enables much flexible cell-design optimization

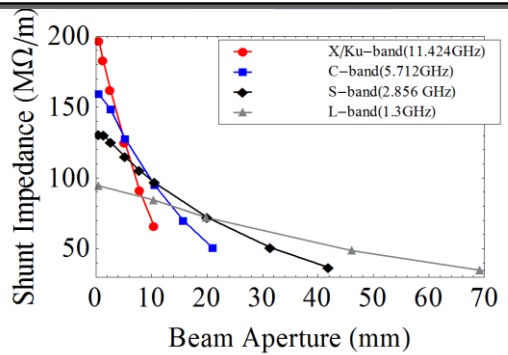
The existing linac designs requires careful consideration of the coupling between cells which limits the ability of designers to optimize the cell shape.

Distributed coupling Linacs provides a new technology that enables much flexible cell-design optimization

The distributed coupling linac overcomes these limitations by providing a new topology that allows feeding each accelerator cell independently using a periodic feeding network.



Distributed-coupling linac

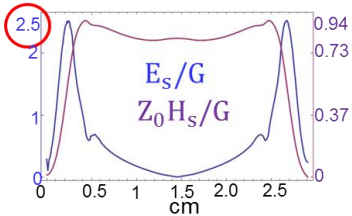


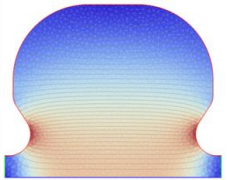
New Scaling Laws Determine the Best Performance for Accelerating Structures

Designed to minimize surface magnetic field

π-mode, Xband, 20 cells Linac

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





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

S. Tantawi, M. Nasr, Z. Li, C. Limborg and P. Borchard, “Distributed coupling accelerator structures: a new paradigm for high gradient linacs,” arXiv preprint arXiv:1811.09925, 2018

Distributed coupling Linacs provides a new technology that enables much flexible cell-design optimization

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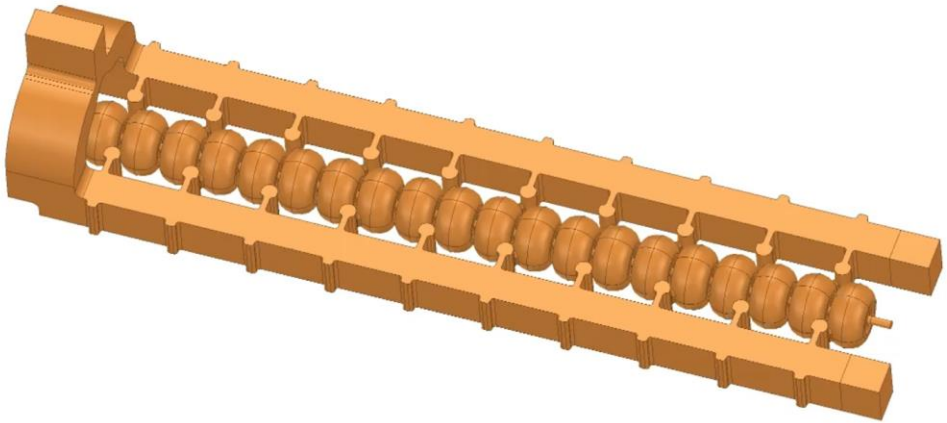
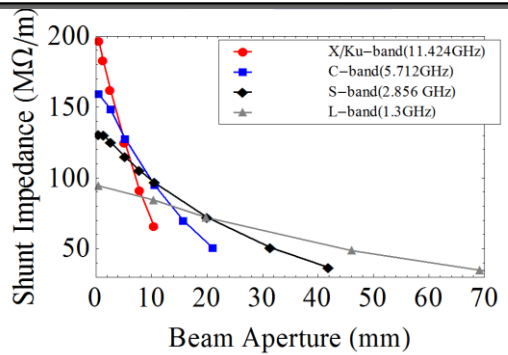
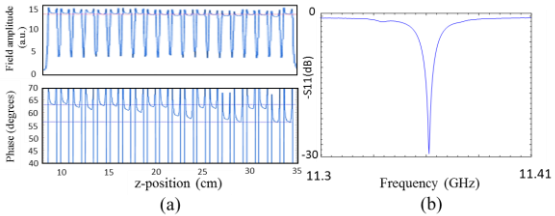


Distributed-coupling linac



New Scaling Laws Determine the Best Performance for Accelerating Structures

Easy tuning and single frequency rather than 20



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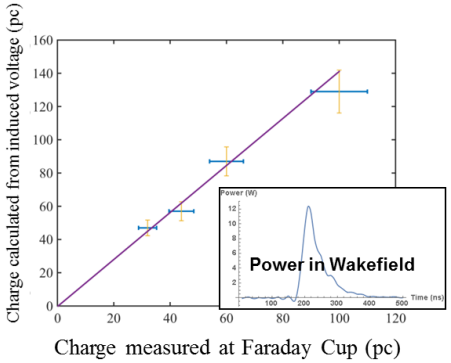
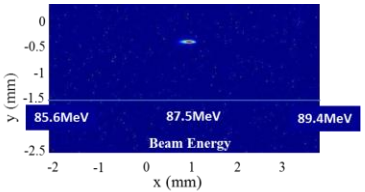
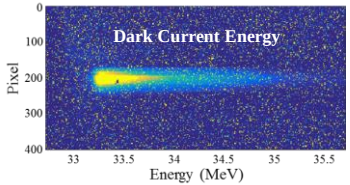
Verification of accelerating parameters and study of breakdown mechanism in the first distributed-coupling linac

Verification using beam energy, dark current, and charge measurements



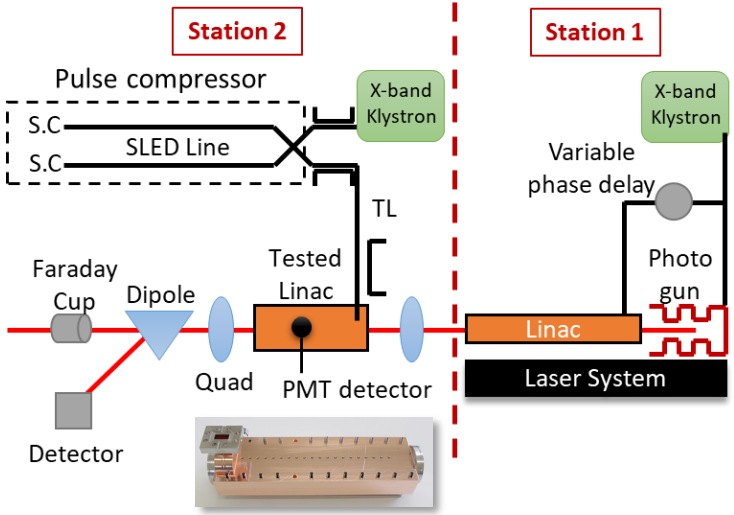


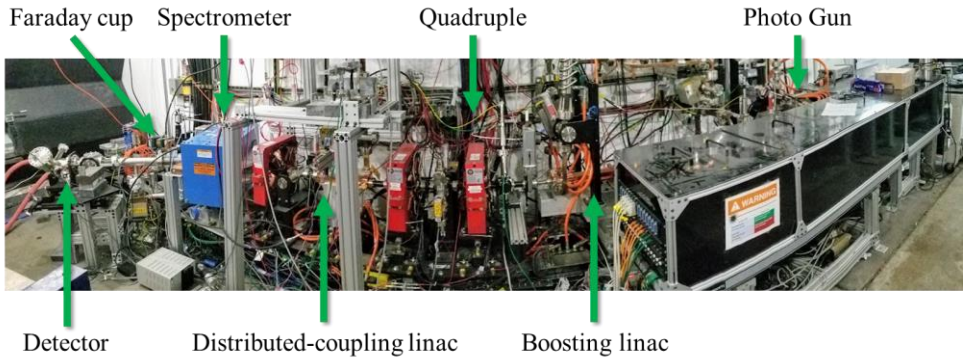
Gradient=100 MV/m



Gradient=140 MV/m

Results agree with the designed shunt impedance and predicted quality factor





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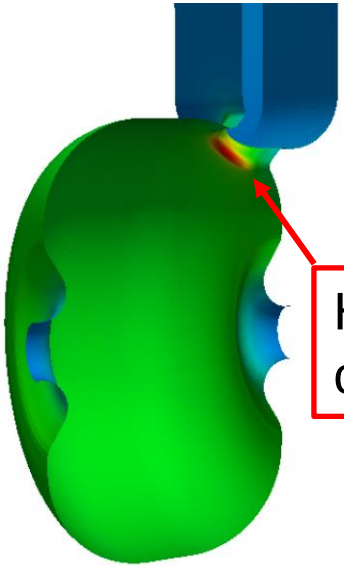
Verification of accelerating parameters and study of breakdown mechanism in the first distributed-coupling linac

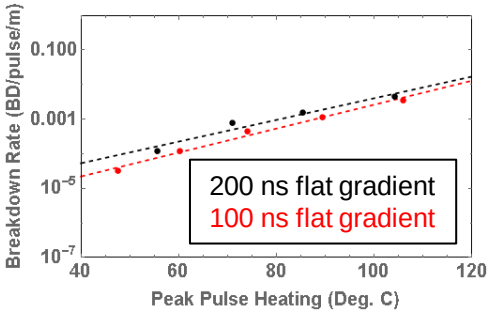
$$\text{Peak } E_s/\text{Gradient} = 2.5$$



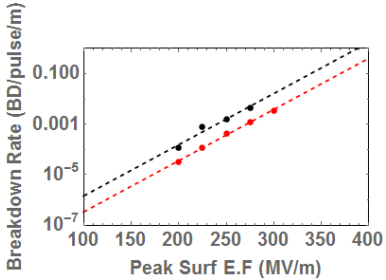
H field enhancement at coupler iris: ×2.28

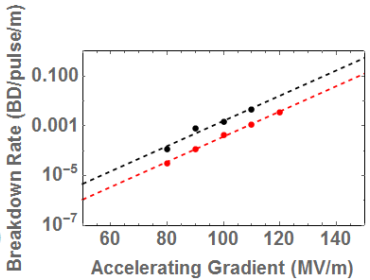
H Field

Breakdown measurements at 100 ns and 200 ns flat gradient.



Pulse heating lines matches for both pulses





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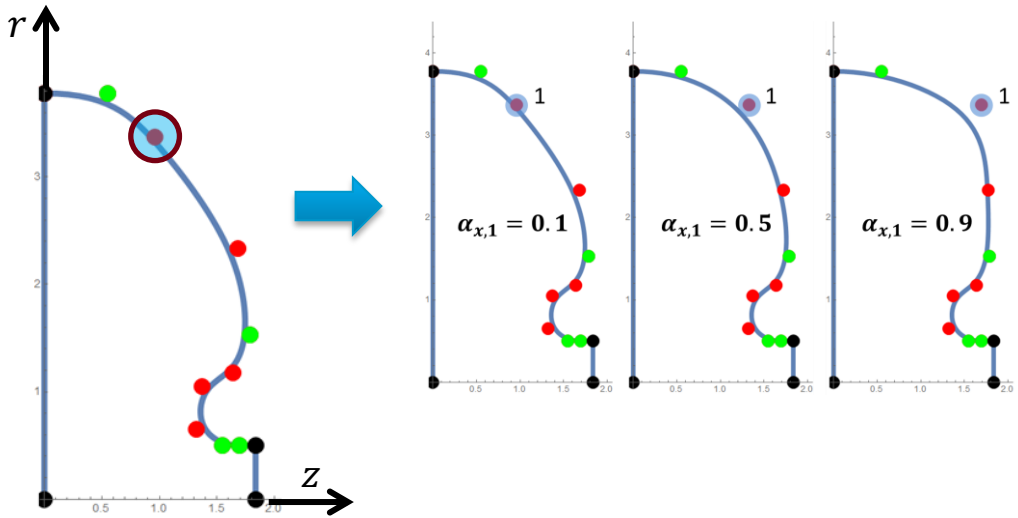
Next-Generation Distributed-Coupling Linac

Next-generation distributed coupling linac:
New geometric-optimization approaches and optimized ports

New geometric-optimization approaches

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



Beam Axis

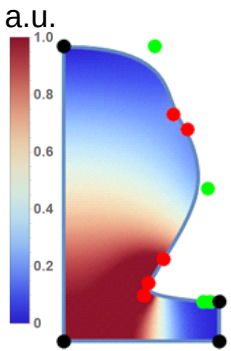
M. Nasr et al. New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance, IPAC'18

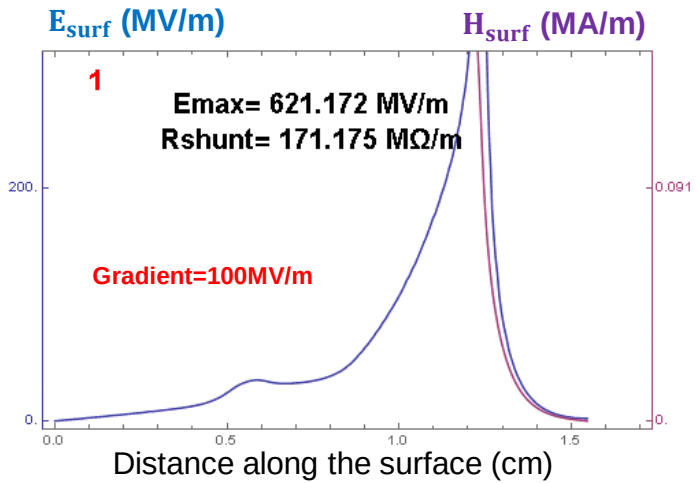
Next-generation distributed coupling linac:
New geometric-optimization approaches and optimized ports

New geometric-optimization approaches

X-band, 11.424 GHz, iris diameter 0.1λ

Starting shape





Target: Maximize shunt impedance with peak surface E-field to gradient ratio of 2

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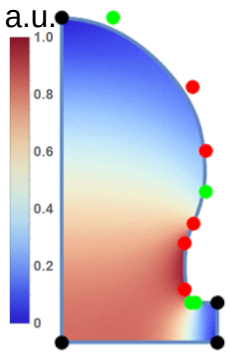
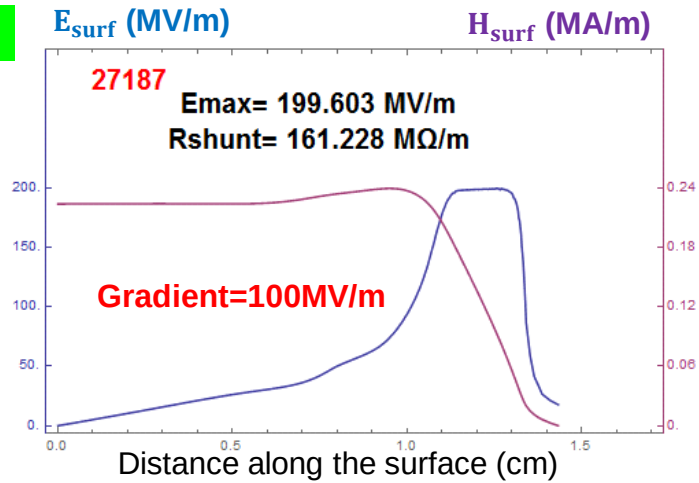
Next-generation distributed coupling linac:
New geometric-optimization approaches and optimized ports

New geometric-optimization approaches

X-band, 11.424 GHz, iris diameter 0.1λ

Optimized shape





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

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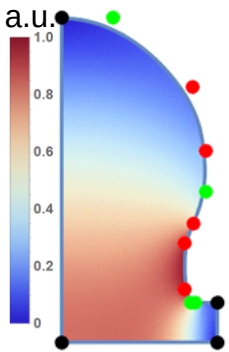
Next-generation distributed coupling linac:
New geometric-optimization approaches and optimized ports

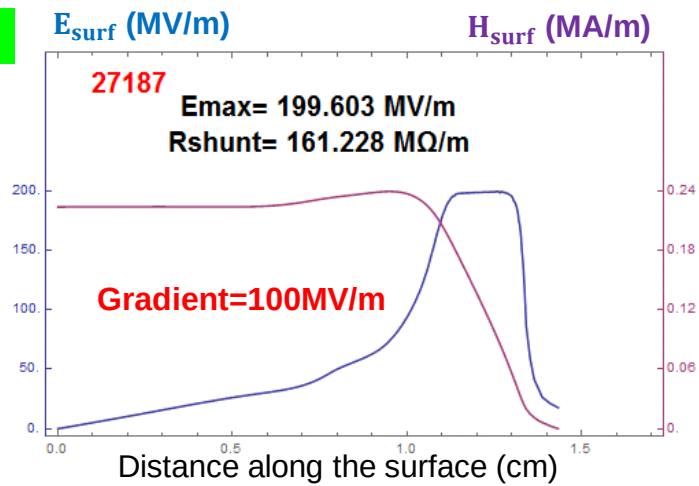
SLAC

New geometric-optimization approaches

X-band, 11.424 GHz, iris diameter 0.1λ

Optimized shape





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

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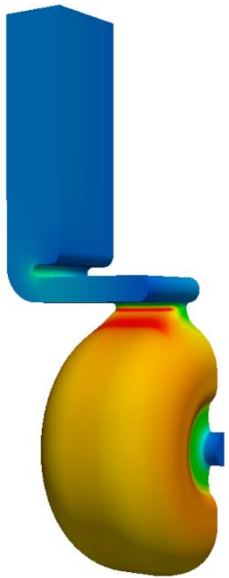
Optimized coupling ports



H Field

Reducing magnetic field enhancement to from x2.3 to x1.17

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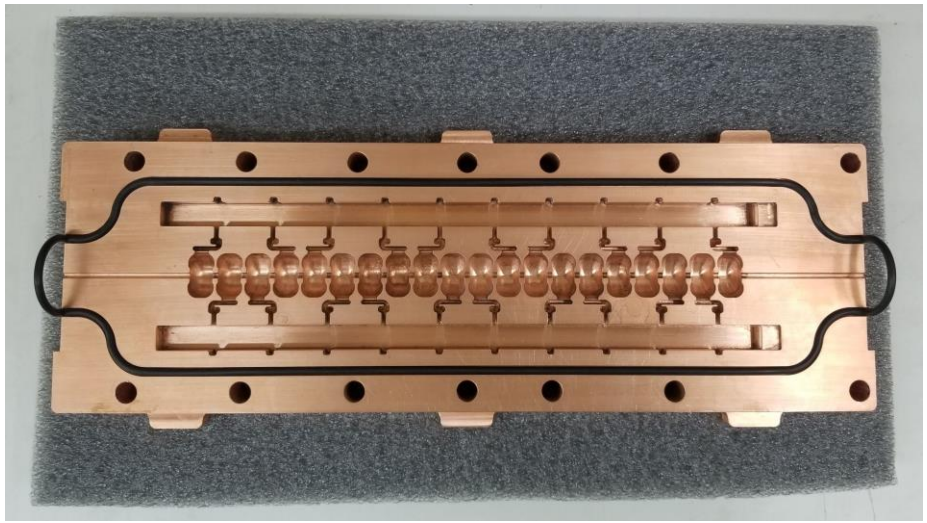
Next-generation distributed coupling linac:
New geometric-optimization approaches and optimized ports

SLAC

New geometric-optimization approaches



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

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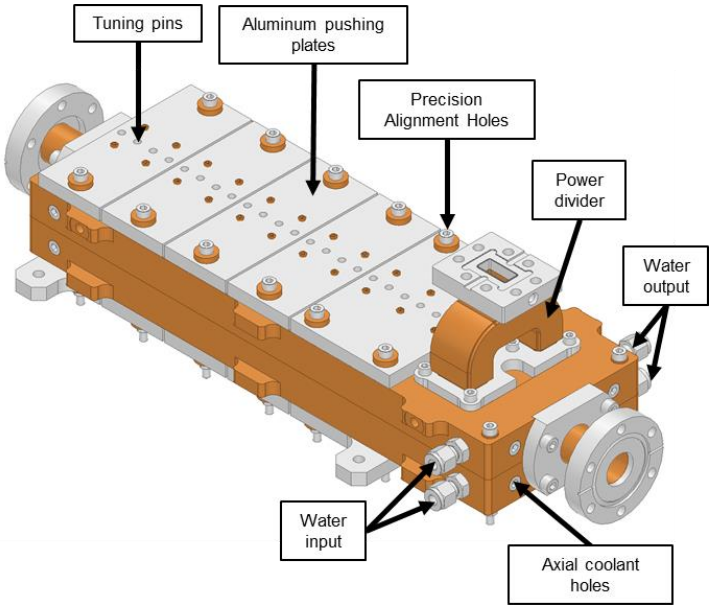
Optimized coupling ports



Reducing magnetic field enhancement to from ×2.3 to ×1.17

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Dual-Mode Dual-Frequency Linac

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

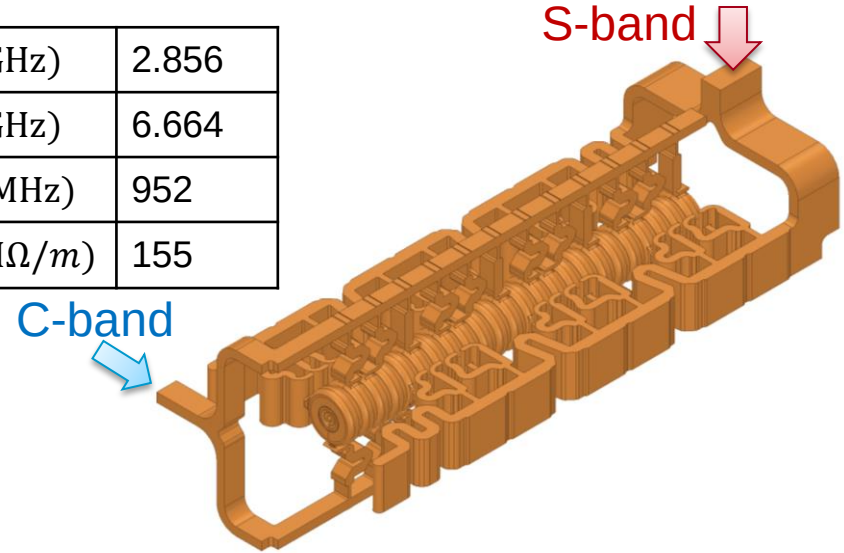
Power ∝ (gradient)²

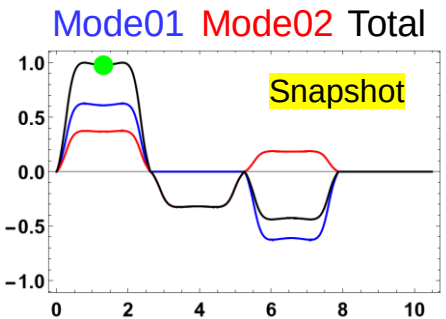
Performance of cavity improves when powered with two different RF modes

- **Efficiency:** Linear superposition of fields by adding power in the two modes.
- **Gradient:** doubling the accelerating gradient without doubling surface fields

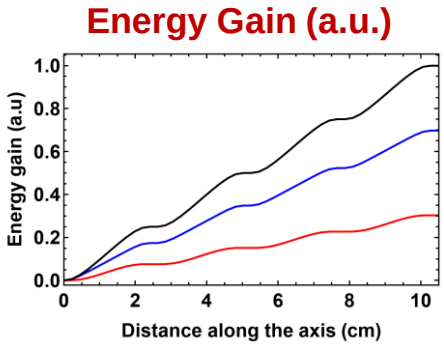
Optimum designs require non-harmonic operation; instead, we design for frequencies that are not necessarily harmonically related, but rather have a common sub-harmonic.

f_{res1}(GHz)	2.856
f_{res2}(GHz)	6.664
f_{comm}(MHz)	952
R_{shunt}(MΩ/m)	155





Axial fields along 4 cells



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

M. Nasr et al. "The Design and Construction of a Novel Dual-Mode Dual-Frequency Linac Design", IPAC'18

M. Nasr, and S. Tantawi

Cryogenic Operation
of
Normal Conducting Structures

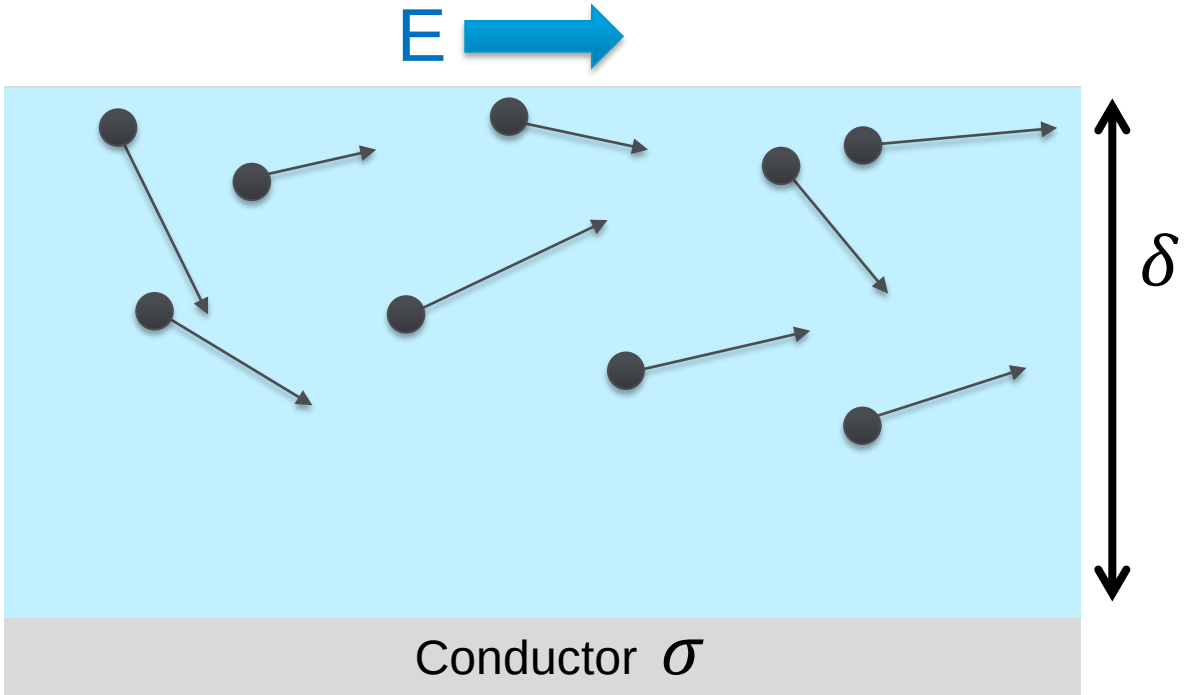
Cryogenic operation of NC accelerating structures

- **Increase conductivity**
  - **Low losses** allows for heavy beam loading
  - **Enhanced shunt impedance** increases efficiency

- **Increase material strength** **reduces breakdown rates**

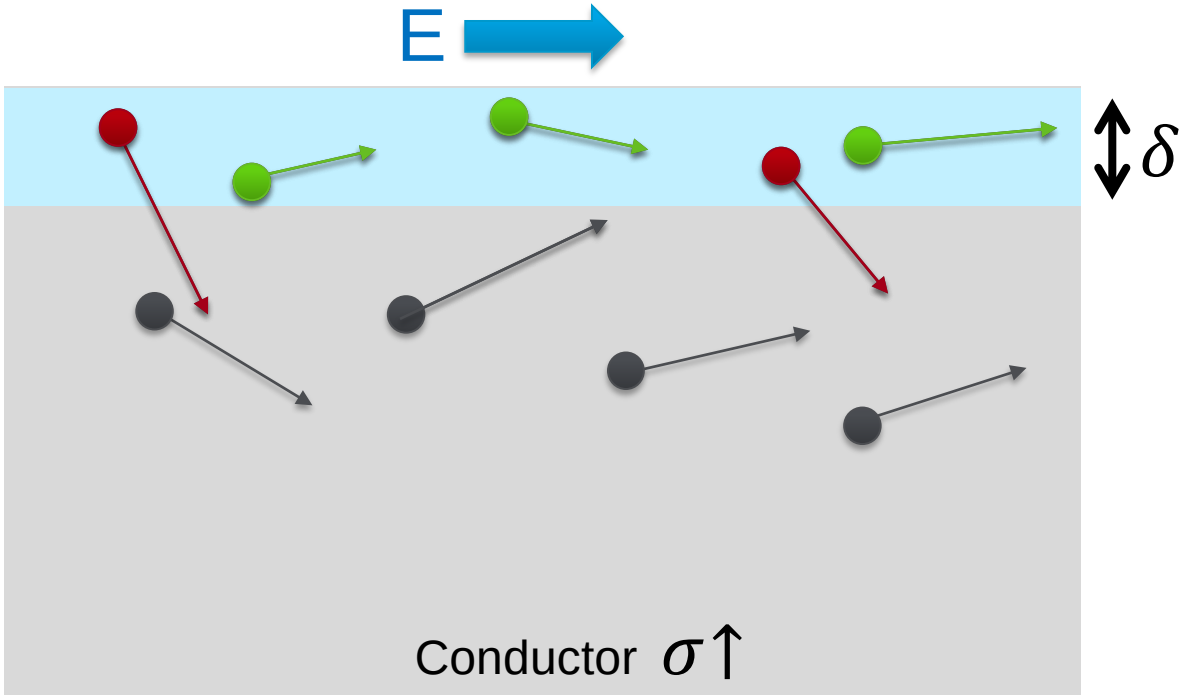
The theory of Anomalous skin effect in metals

At high temperatures and low frequencies, the mean free path of the electrons in a good conductor is much smaller than the classical skin depth.



The theory of Anomalous skin effect in metals

At low temperatures and high frequencies, the mean free path of the electrons in a good conductor becomes greater than the classical skin depth.



Cryogenic operation of normal conducting materials

The theory of Anomalous skin effect in metals

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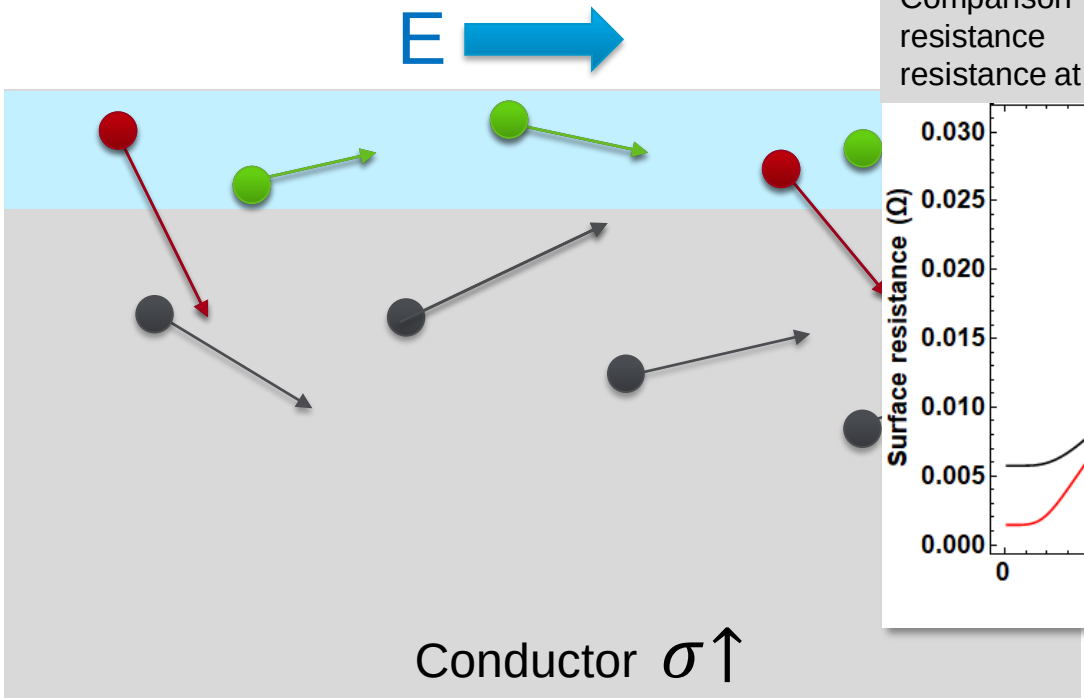
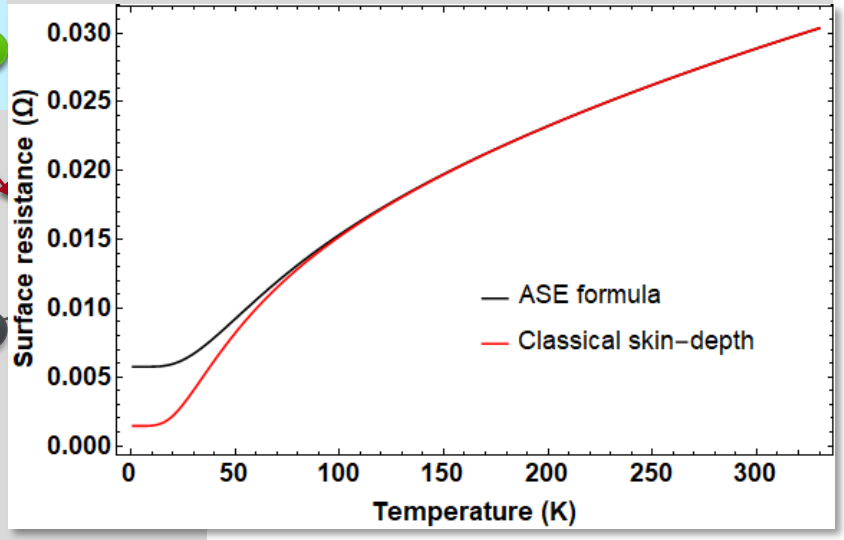
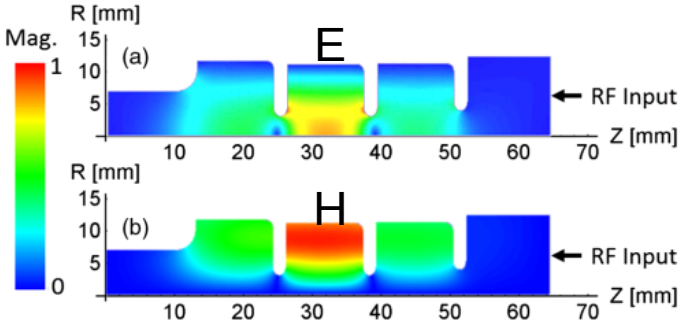


Comparison of the normal skin effect surface resistance and anomalous skin effect surface resistance at 11.424 GHz in RRR=400 copper

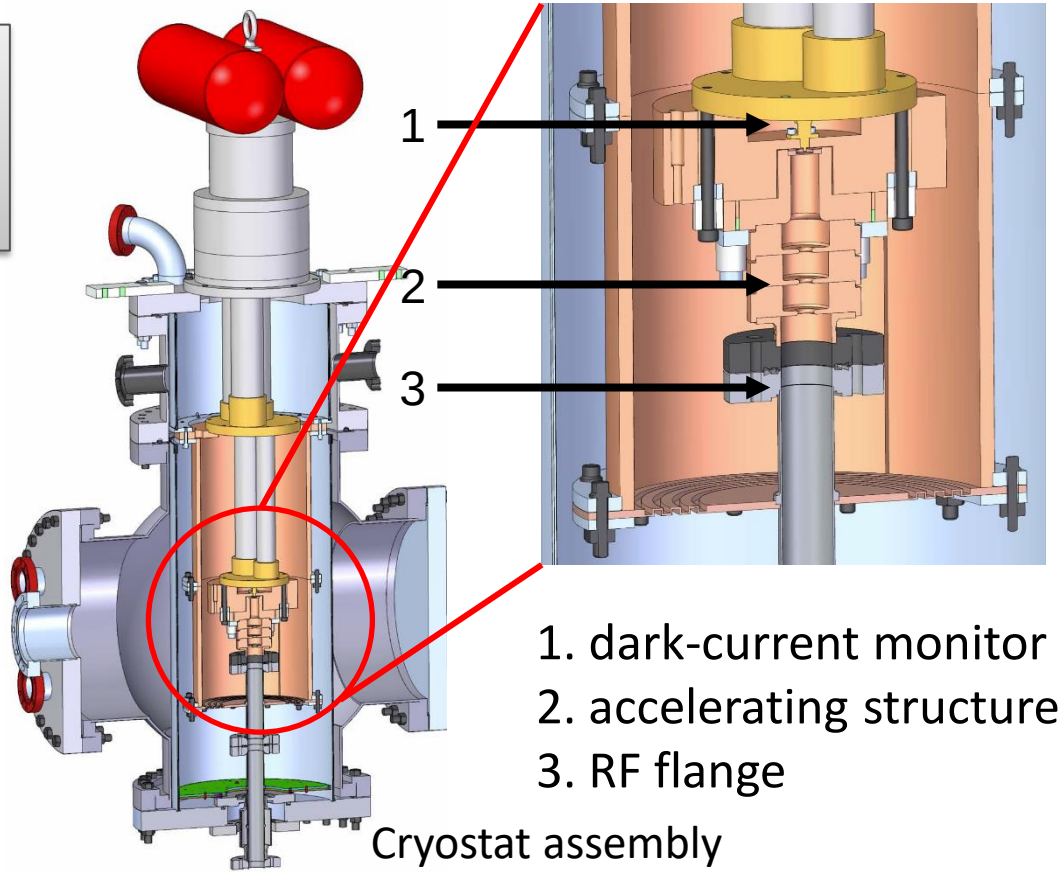


High-power testing of single-cell structure at cryogenic temperature of 45k

Studying the operation and performance of NC accelerating structure at cryogenic temperature with single-cell accelerator high-power testing at 45K



The single-cell fields profile



1. dark-current monitor
2. accelerating structure
3. RF flange

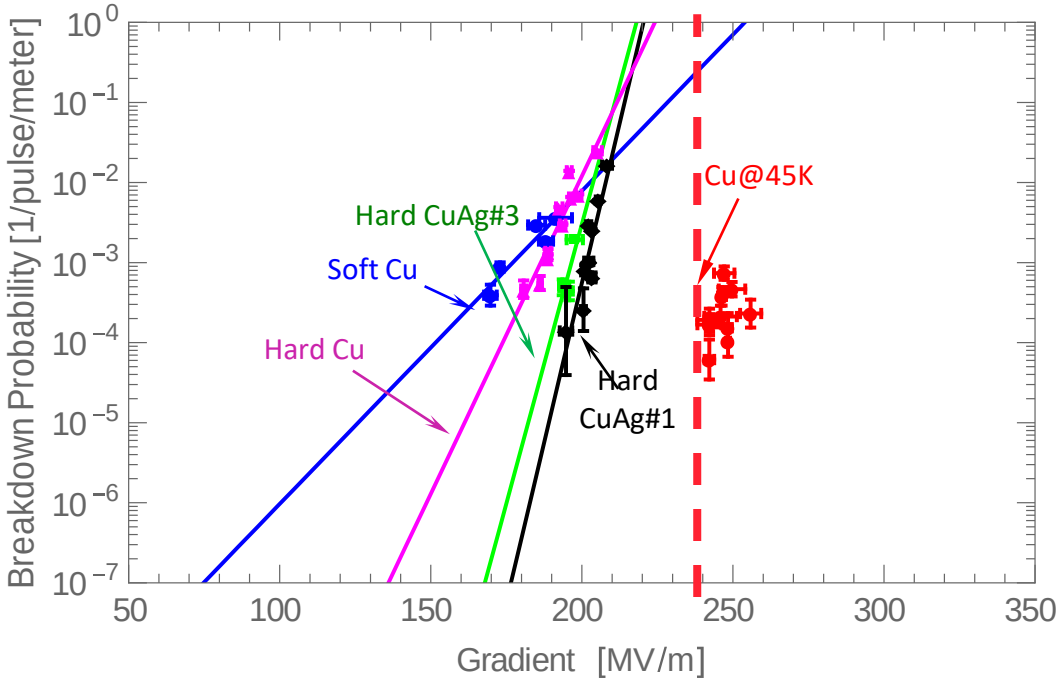
Cryostat assembly

A. Cahill *et al.*, "High gradient experiments with X-band cryogenic copper accelerating cavities," PRAB, 21, 2018

Breakdown Rate Results for *first breakdowns*

Breakdown rate *vs.* gradient for first rf breakdowns,

1C-A2.75-T2.0 structures, shaped RF pulse with 150 ns flat part



Threshold

A. Cahill *et al.*, "High gradient experiments with X-band cryogenic copper accelerating cavities," PRAB, 21, 2018

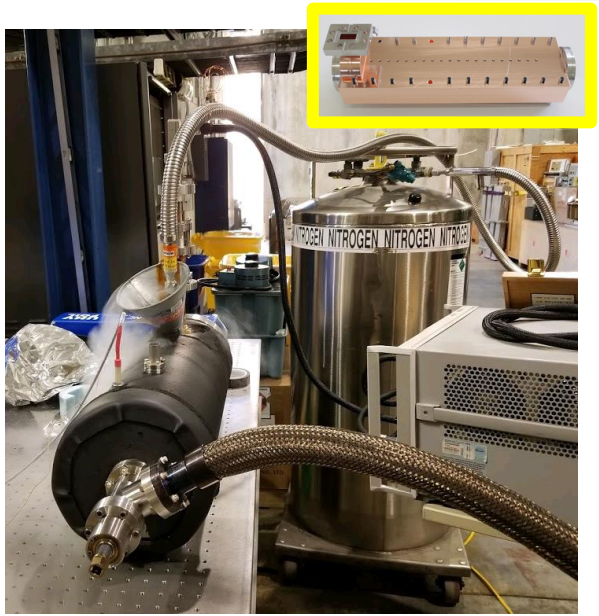
Full practical accelerator testing at cryogenic temperature

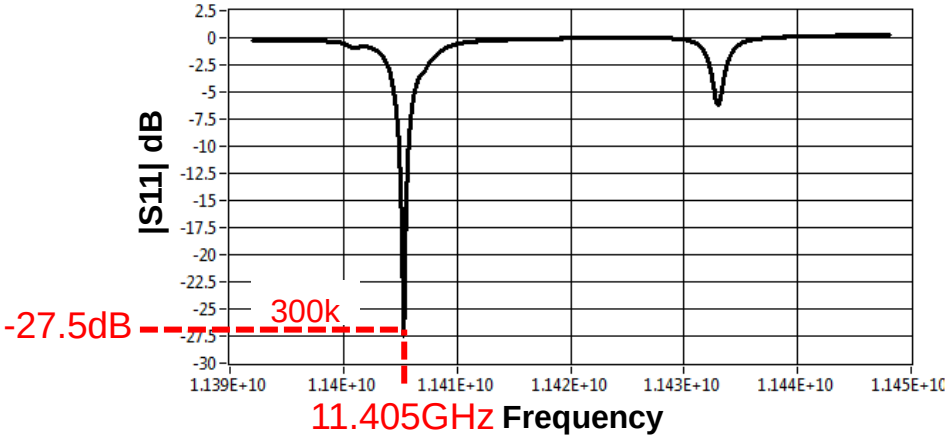
- **Distributed-coupling technology**
  with flexible optimization and exceptional Rs

- **Cryogenic operation**
  for increased Rs and reduced breakdown rates

- **Dramatic reduction in cost**
  using cryogenics at 77K

Cold cold-test of the distributed-coupling structure (Xband, 20 cells Linac) at LN cryogenic temperature (77k)





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

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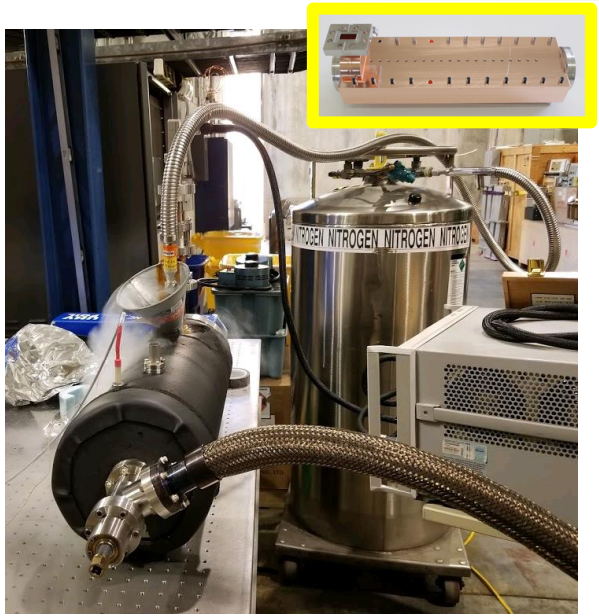

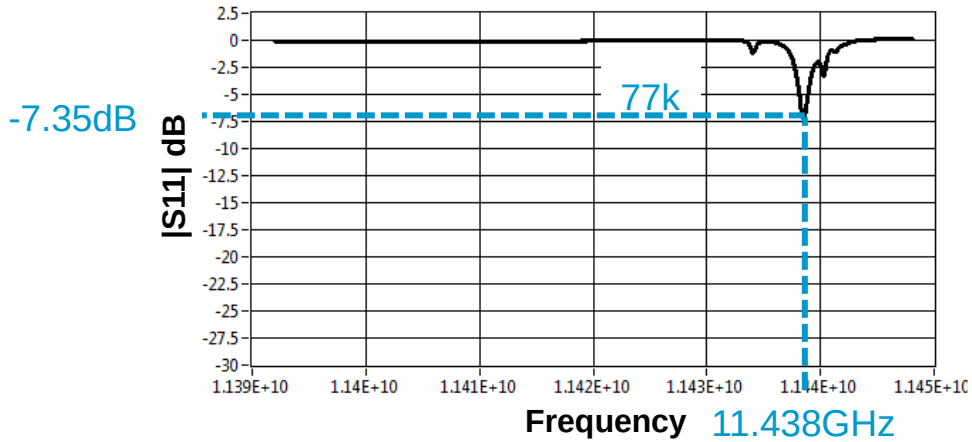

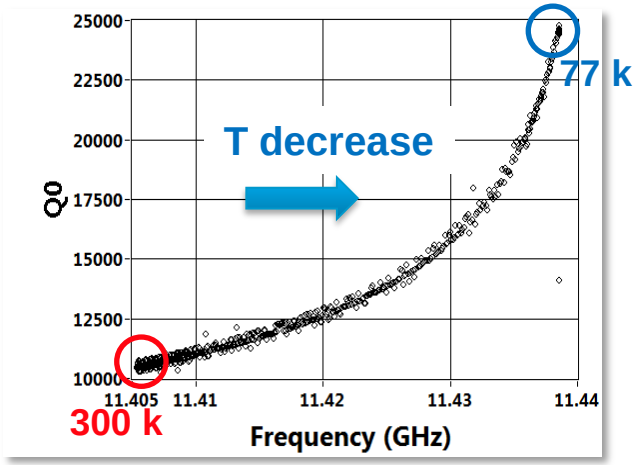

2.5X less power allows for heavy beam loading even at high gradient

Shunt impedance of 400MΩ\m

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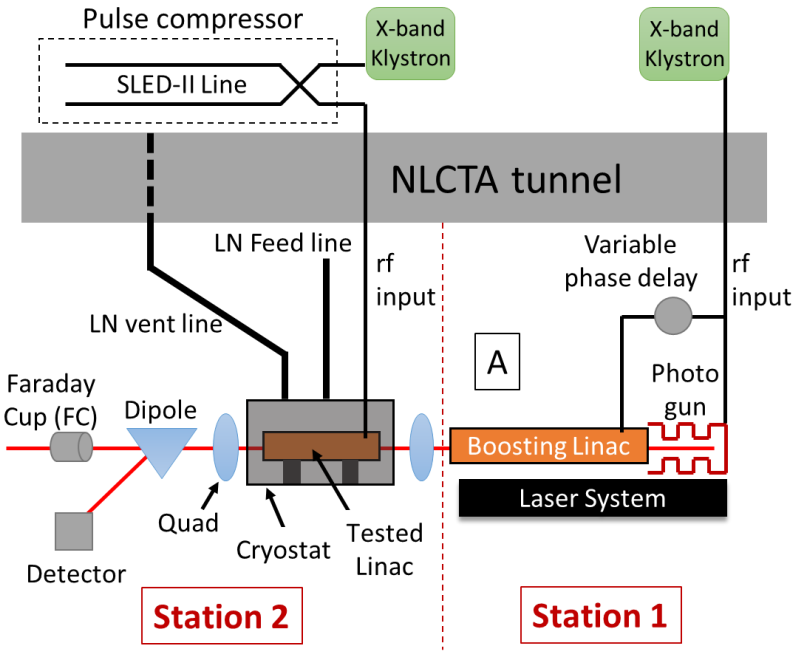
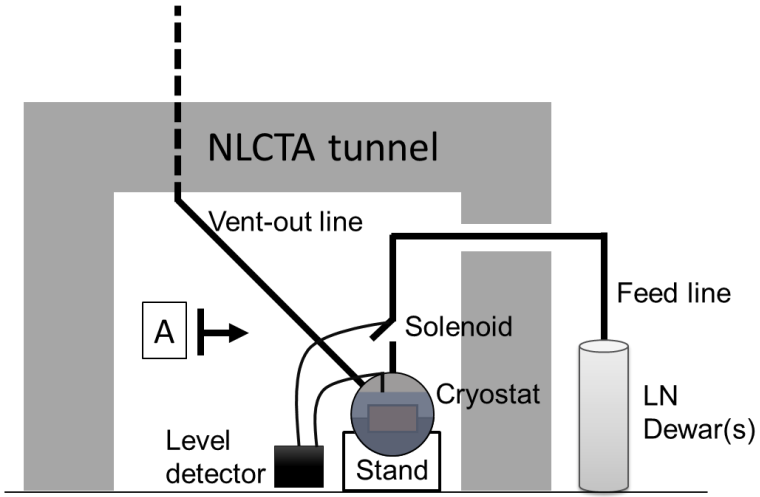
High-power test of the distributed-coupling structure (Xband, 20 cells) at LN cryogenic temperature (77k)

The high-power testing experiment was modified for LN cryogenic operation





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

Dramatic reduction in cost of system including cryogenics at 77K

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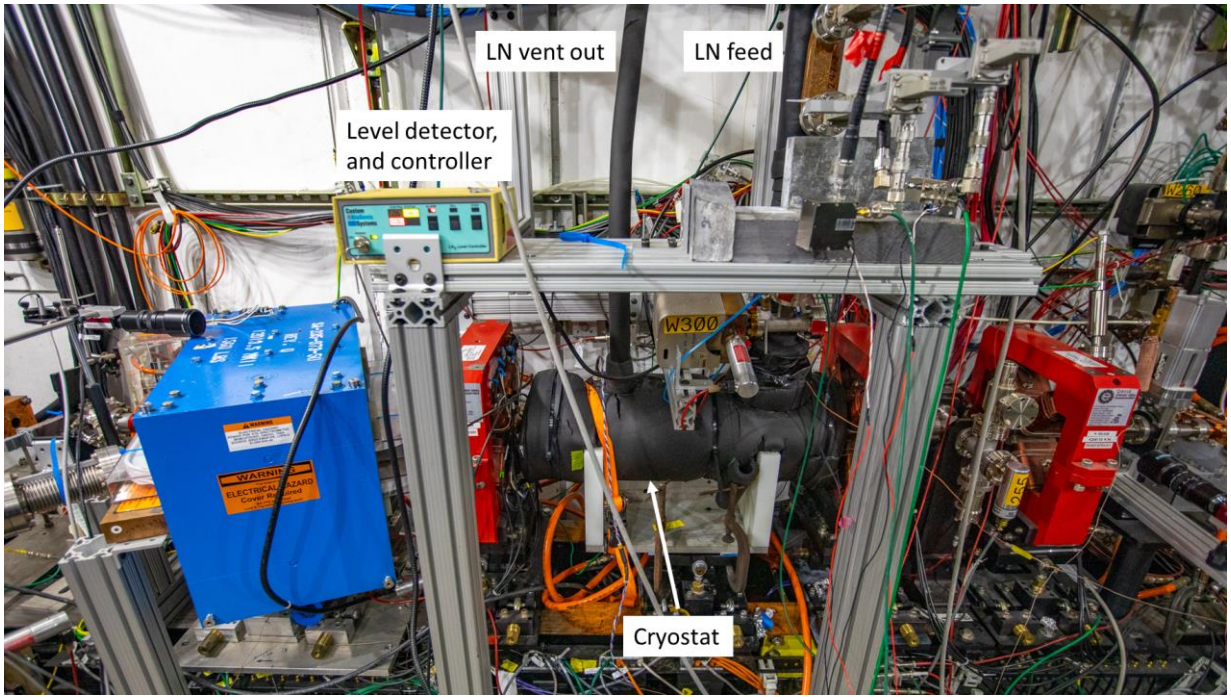

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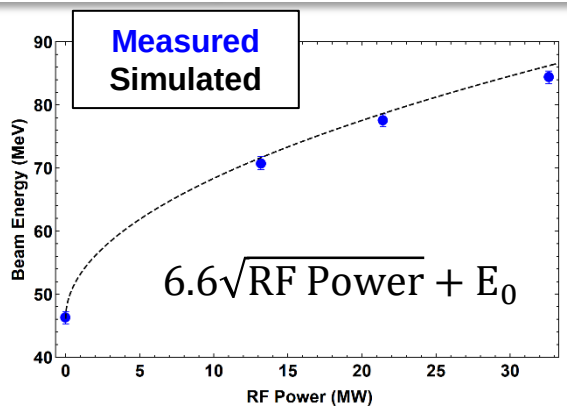
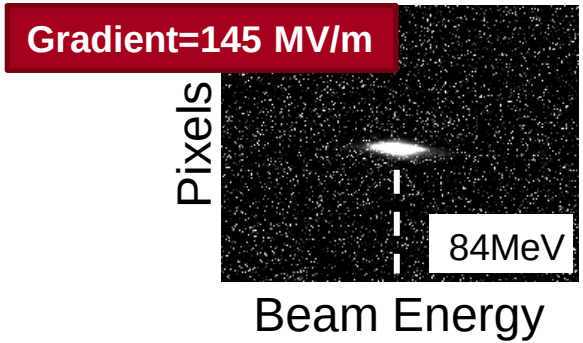
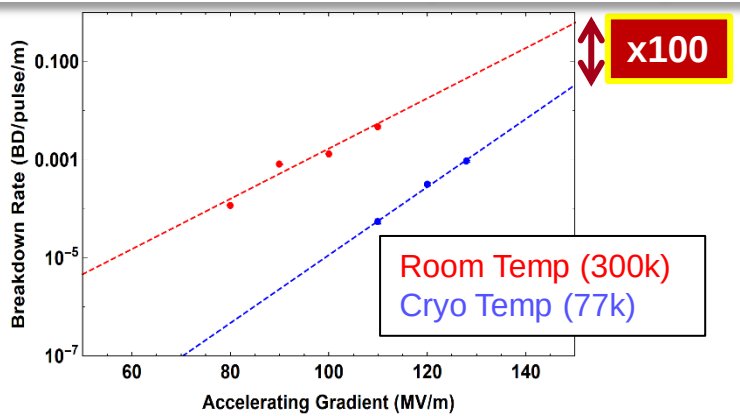
SLAC

Modeled structure gradient confirmed with electron beam





Reduced breakdown rates compared to 300k operation



Stepped pulse with flat gradient of 200ns

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

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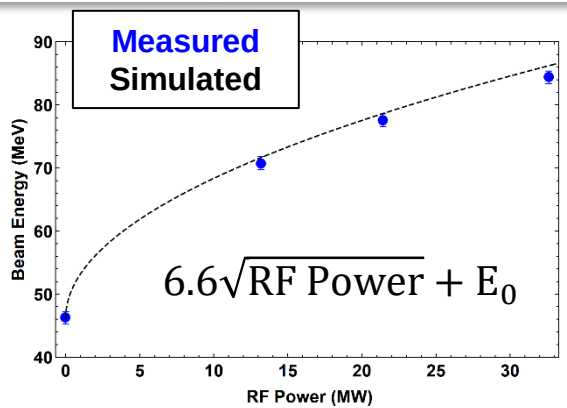

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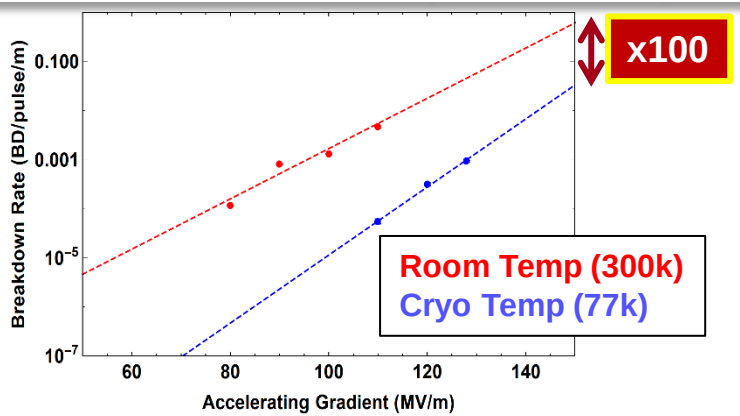

Stepped pulse with flat gradient of 200ns

	300k	77k
$\beta = Q_0/Q_e$	1	2.5
R_s (MΩ/m)	160	400
BDR	x_0	$x_0/100$

- Heavy beam loading
- High efficiency
- Low breakdown rate
- Cost-efficient with LN

Cryogenic operation pushes the limits of NC accelerator structures which open the door for a wide range of applications

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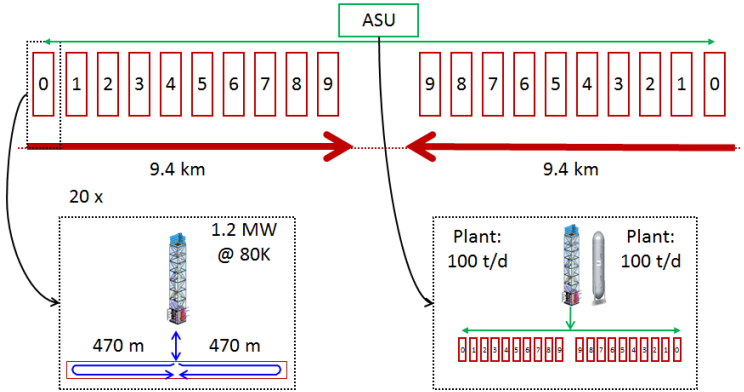
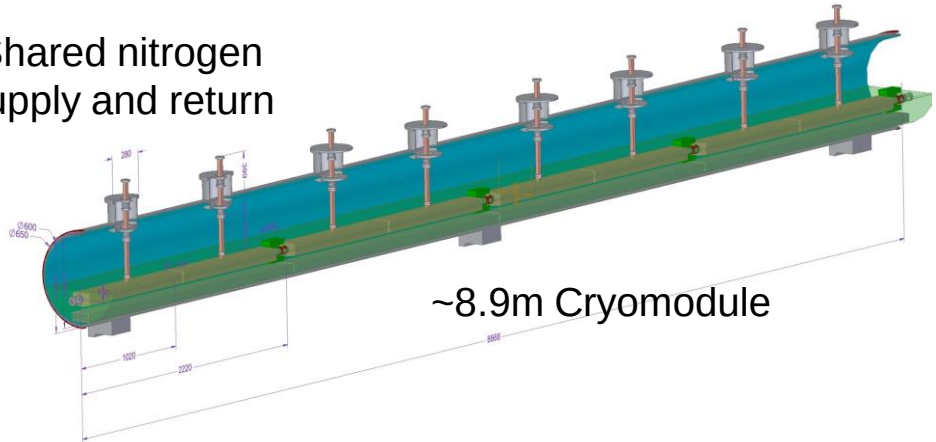
Advanced NCRF Linac Concept for a High Energy e+e- Linear Collider

- 20x Refrigeration Plants 1.2 MW @ 80K ~Elec. 7 MW each
- 1x GN2 100 tons LN2 /day ~Elec. 2 MW each

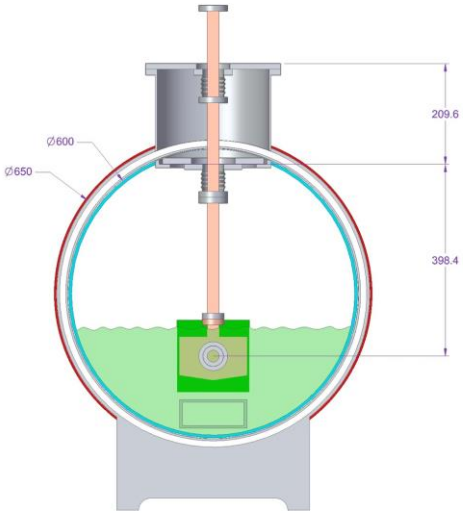


Shared nitrogen supply and return



~8.9m Cryomodule

Preliminary Cryomodule Design for High Average Power Implementation with ~90% Fill Factor



Oriunno, Breidenbach

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

Superconducting Distributed-Coupling Linac

Superconducting Distributed-Coupling Linac

- Optimized geometries
- Relaxed constraints on the cell-to-cell coupling

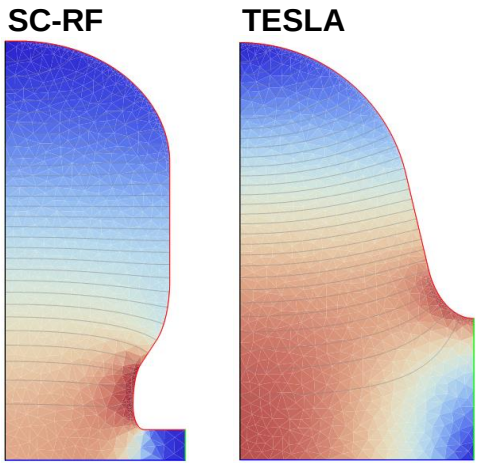
Transformation of SRF Accelerator Technology with Distributed Coupling Topology Investigation

- Assuming a quenching field limit of 230 mT (B_{sh} of Nb), the maximum achievable gradient in a TESLA cavity is ~ 55 MV/m.
- An SRF distributed-coupling structure can do much better.
- Parallel RF feed also allows for higher packing fraction of cavity cells which effectively **increases gradient another 20%!**

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**

70% higher gradient for same B_{quench}!

60% lower RF power loss!



Welander et. al., "Parallel-Feed SRF Accelerator Structures," IPAC18

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

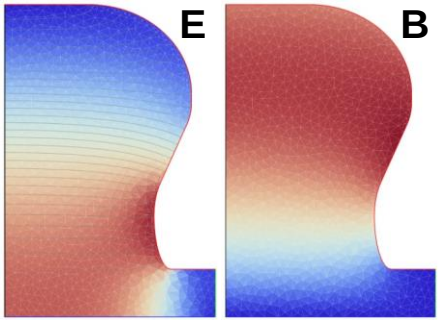
Realization of SRF distributed-coupling linac at X-band and 4k operation

Parameter	Value
a (cm) (aperture radius)	0.15
Q_0	7.16e6
Q_{ext}	2.8e5
R_{sh} (Ω/m)	1.20e11
E_{pk}/E_{acc}	2.05
B_{pk}/E_{acc} (mT/(MV/m))	3.57
R_{sh}/Q_0 (Ω/m)	1.67e4
P_{loss}/E_{acc}^2 (mW/m/(MV/m)^2)	8360

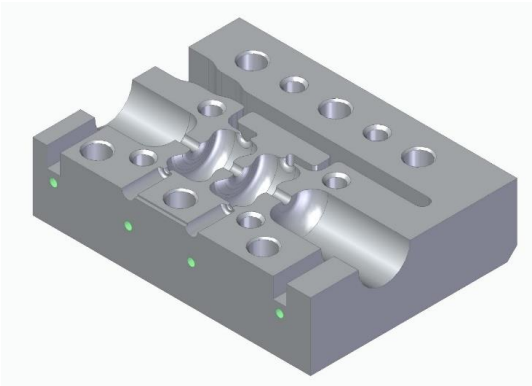
Table assumes operation at 4 K and a Nb surface resistance (R_s) of 34 $\mu\Omega$.

Nasr et. al., "The Design of Parallel-Feed SC RF Accelerator Structure," IPAC19

Cell design

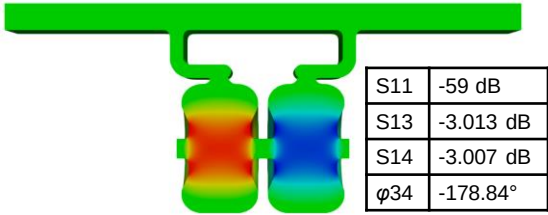


Solid model

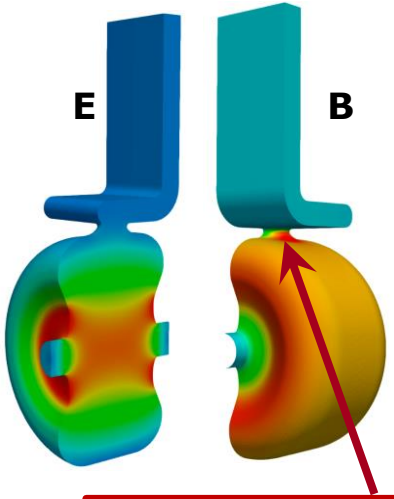


M. Nasr, P. Welander, Z. Li, S. Tantawi

Feeding network



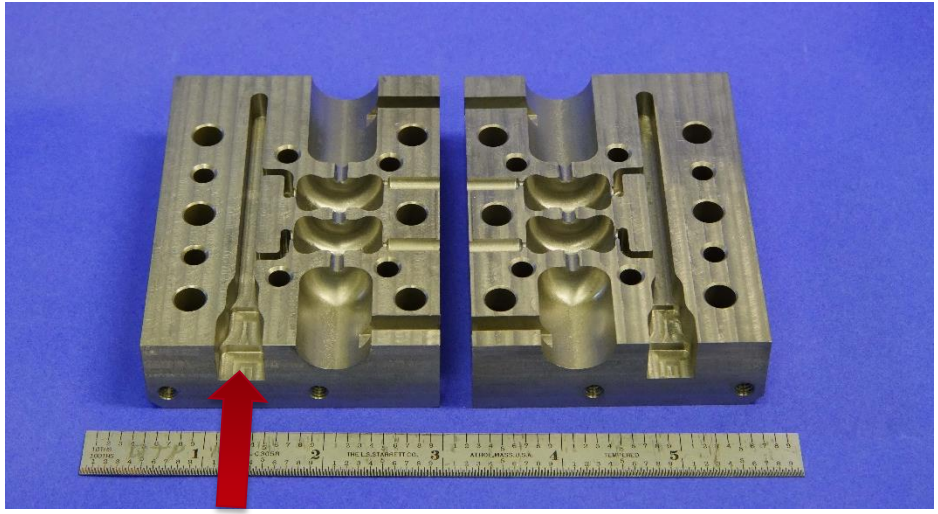
S11	-59 dB
S13	-3.013 dB
S14	-3.007 dB
φ34	-178.84°



Enhancement in B_{pk} of 8.6%

Realization of SRF distributed-coupling linac
Manufacturing and experimental setup

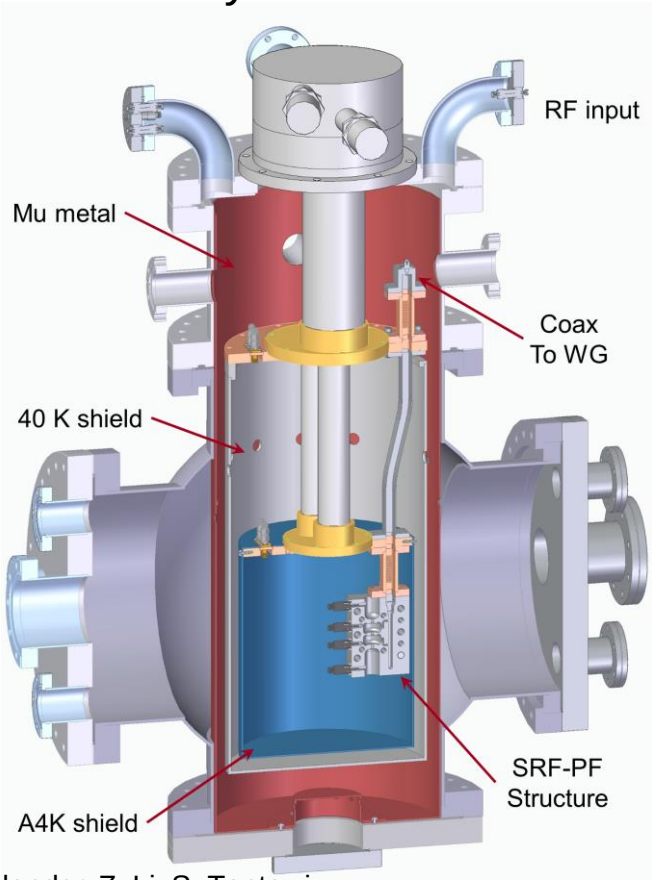
Manufacture structure from bulk Nb Halves



RF input

Nasr et. al., “The Design of Parallel-Feed SC RF Accelerator Structure,” IPAC19

Cryostat at 4K



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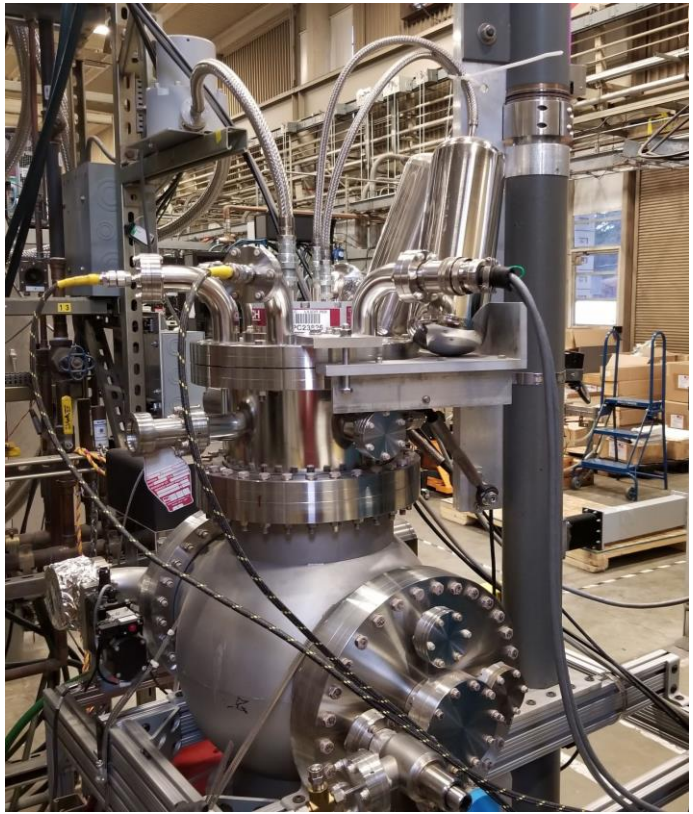

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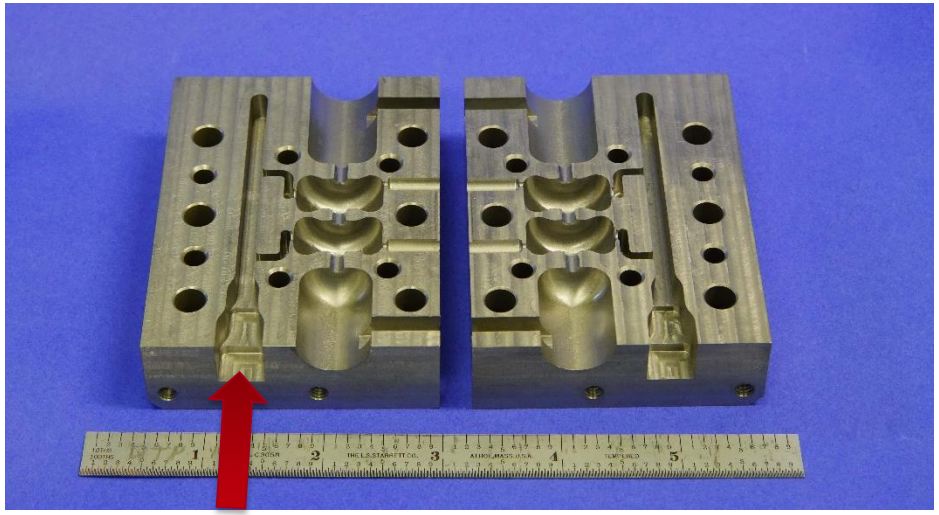

RF input

Nasr et. al., “The Design of Parallel-Feed SC RF Accelerator Structure,” IPAC19

Conclusion

- **Understanding the physics of breakdowns**
  triggered new research directions for high-gradient operation

- **Distributed-coupling technology**
  enables much flexible cell-design optimization and pushes the limitation of Linacs performance.

- **Cryogenic-copper accelerating structures**
  have the promise for a new frontier for beam brightness, efficiency and cost-capability

- **Superconducting distributed-coupling linacs**
  has the promise for substantial increase in the gradient limits and reduction in RF power loss

Acknowledgement

Advisor:

Sami Tantawi

Collaborators:

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Thanks!

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