Distributed Coupling Linacs from Room to Cryogenic Temperature

Jefferson Lab, Accelerator Seminar

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G. Bowden, M. Breidenbach, Z. Li, E. Nanni, B. Weatherford, P. Welander

10/29/2020
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)

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![Breakdown Rate Correlated with Magnetic Field](image)


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

Pushing the limitations of high gradient acceleration

- New Optimized Geometries of Accelerating Structures
  - $f = 11.424 \text{ GHz}$, $R_s = 181 \text{ M}\Omega/\text{m}$

- Novel Manufacturing Techniques

- 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
Optimized Geometries using Distributed-Coupling Topology
Distributed coupling Linacs provides a new technology that enables much more flexible cell-design optimization.

The existing linac designs require 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


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


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

Verification using beam energy, dark current, and charge measurements

Results agree with the designed shunt impedance and predicted quality factor

M. Nasr, B. Weatherford, C. Limborg, S. Tantawi
Verification of accelerating parameters and study of breakdown mechanism in the first distributed-coupling linac

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

H field enhancement at coupler iris: $\times 2.28$

Breakdown measurements at 100 ns and 200 ns flat gradient.

Pulse heating lines matches for both pulses

H Field

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

M. Nasr et al. New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities’ Performance, IPAC’18
X-band, 11.424 GHz, iris diameter 0.1\(\lambda\)

**Target:** Maximize shunt impedance with peak surface E-field to gradient ratio of 2
New geometric-optimization approaches

X-band, 11.424 GHz, iris diameter 0.1λ

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

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

M. Nasr, Z. Li, and S. Tantawi
New geometric-optimization approaches

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

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

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

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

M. Nasr, Z. Li, and S. Tantawi
Next-generation distributed coupling linac: New geometric-optimization approaches and optimized ports

New geometric-optimization approaches

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

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

Optimized coupling ports

- Reducing magnetic field enhancement to from $\times 2.3$ to $\times 1.17$

M. Nasr, Z. Li, G. Bowden, and S. Tantawi
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 \(\propto (\text{gradient})^2\)**

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.

<table>
<thead>
<tr>
<th></th>
<th>(f_{\text{res1}}) (GHz)</th>
<th>(f_{\text{res2}}) (GHz)</th>
<th>(f_{\text{comm}}) (MHz)</th>
<th>(R_{\text{shunt}}) (MΩ/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_{\text{res1}})</td>
<td>2.856</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(f_{\text{res2}})</td>
<td>6.664</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(f_{\text{comm}})</td>
<td>952</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(R_{\text{shunt}})</td>
<td>155</td>
<td></td>
<td></td>
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</table>

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


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

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

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)

-27.5 dB
-2.5 dB
-7.5 dB
-12.5 dB
-17.5 dB
-22.5 dB
-27.5 dB

Frequency

11.405 GHz

M. Nasr, S. Tantawi, E. Nanni et. al.
Cold cold-test of the distributed-coupling structure (Xband, 20 cells Linac) at LN cryogenic temperature (77k)

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

Shunt impedance of 400MΩ\m

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

Dramatic reduction in cost of system including cryogenics at 77K

M. Nasr, S. Tantawi, E. Nanni et. al.
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M. Nasr, S. Tantawi, E. Nanni et. al.
High-power test of the distributed-coupling structure (Xband, 20 cells) at LN cryogenic temperature (77k)

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

Modeled structure gradient confirmed with electron beam

Reduced breakdown rates compared to 300k operation

<table>
<thead>
<tr>
<th></th>
<th>300k</th>
<th>77k</th>
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<tbody>
<tr>
<td>$\beta = Q_0/Q_e$</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>$R_s \ (\Omega/m)$</td>
<td>160</td>
<td>400</td>
</tr>
<tr>
<td>BDR</td>
<td>$x_0$</td>
<td>$x_0/100$</td>
</tr>
</tbody>
</table>

- 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

M. Nasr, S. Tantawi, E. Nanni et. al.
Advanced NCRF Linac Concept for a High Energy e+e- Linear Collider

- 20x Refrigeration Plants
- 1x GN2

1.2 MW @ 80K
100 tons LN2/day

~Elec. 7 MW each
~Elec. 2 MW each

Shared nitrogen supply and return

~8.9m Cryomodule

Bane et al., ArXiv 1807.10195 (2018)

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

Oriunno, Breidenbach
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%!

### Table: Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SC-PF</th>
<th>TESLA</th>
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</thead>
<tbody>
<tr>
<td>$\omega$ (aperture radius)</td>
<td>0.66</td>
<td>3.5</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>0.8e10</td>
<td>1.0e10</td>
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<tr>
<td>$R_{sh}$ (Ω/m)</td>
<td>2.4e13</td>
<td>9.8e12</td>
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<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>2.05</td>
<td>1.98</td>
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<tr>
<td>$H_{pk}/E_{acc}$ (mT/(MV/m))</td>
<td>2.41</td>
<td>4.17</td>
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<tr>
<td>$R_{sh}/Q_0$ (Ω/m)</td>
<td>3047</td>
<td>983</td>
</tr>
<tr>
<td>$P_{loss}/E_{acc}^2$ (mW/m/(MV/m)^2)</td>
<td>41.1</td>
<td>101.7</td>
</tr>
</tbody>
</table>

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

[Image: SC-RF TESLA diagram with annotations for 70% higher gradient and 60% lower RF power loss]
Realization of SRF distributed-coupling linac at X-band and 4k operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$a$ (cm) (aperture radius)</td>
<td>0.15</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>7.16e6</td>
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<tr>
<td>$Q_{ext}$</td>
<td>2.8e5</td>
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<tr>
<td>$R_{sh}$ ($\Omega$/m)</td>
<td>1.20e11</td>
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<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>2.05</td>
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<tr>
<td>$B_{pk}/E_{acc}$ (mT/(MV/m))</td>
<td>3.57</td>
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<tr>
<td>$R_{sh}/Q_0$ ($\Omega$/m)</td>
<td>1.67e4</td>
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<tr>
<td>$P_{loss}/E_{acc}^2$ (mW/m/(MV/m)$^2$)</td>
<td>8360</td>
</tr>
</tbody>
</table>

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

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

M. Nasr, P. Welander, Z. Li, S. Tantawi
Realization of SRF distributed-coupling linac
Manufacturing and experimental setup

Manufacture structure from bulk Nb Halves

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

Cryostat at 4K

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

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