High Gradient R&D Results and Plans

Chris Adolphsen
Multi-Prong Program to Improve High Gradient Performance

- **Structure Parameters**
  - Compare Performance of Traveling Wave Structures with Different
    - ✓ Initial Group Velocity (5% and 3%)
    - ✓ Lengths (20, 50 and 100 cm)
  - Test 15 Cell Standing Wave Cavity

- **RF Processing**
  - ‘Gentler’ Processing of a Standard 12% Group Velocity Structure
  - Systematic Study of Breakdown Events (Measure RF, Light, Sound, X-Rays, Currents and Gas) in Structures, Waveguide and Single Cavities

- **Materials and Handling**
  - Wet Hydrogen Firing / Extended Vacuum Bake / In-Situ Bake of Test Structures
  - Surface Cleanliness/Damage Measurements with SEM and Auger
  - Test Different Cleaning Techniques: For example, Ultra Pure Water Rinsing, Glow Discharge Cleaning and High Pressure Water Rinsing

- **Theory and Modeling**
  - Use ‘MAGIC’ Particle-in-Cell Code to Simulate Breakdown Effect on RF
Recently Completed Structure
Tests at NLCTA
(May – Oct, 2001)

5.0% 3.3%

T53VG5

T53VG3

1.6%

Tested if lower group velocity leads to less damage in the same length structure (split power 60/40 to yield the same gradient when run in parallel).

Beta = 1

S20PI_B1

Tested gradient limits in a 15 cell standing wave cavity with field rise time = 124 ns
S20PI Assembly in NLCTA

T53VG3
T53 Structure Layout in NLCTA

VG3/VG5 Gradient = 1.06
VG3/VG5 Peak Surface Field = 1.01

Input Power

35% Attenuation

T53VG5

T53VG3
T-Type Structures Tested to Date

Group Velocity (% c)

Cell Number

<table>
<thead>
<tr>
<th>Cell Machining</th>
<th>Etch Depth for Cell Cleaning</th>
<th>Heat Treatment</th>
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</thead>
<tbody>
<tr>
<td>Diamond Turned</td>
<td>0.3 microns</td>
<td>Wet/Dry H₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vac/In-situ Bake</td>
</tr>
<tr>
<td>Conventionally Machined</td>
<td>3 microns</td>
<td>Wet/Dry H₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vac/In-situ Bake</td>
</tr>
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</table>
Structure Pre-Processing Procedure

- New Process: Wet Hydrogen Firing
  - 950 °C for 60 Minutes at Dewpoint of 5 °C / 41 °F
  - Followed by Dry Hydrogen Firing to Remove Chrome Oxide
    - (Dry Hydrogen Firing Considered Harmless)

- Modified Process: Vacuum Bakeout (Exhaust)
  - Was: 5 Days at Around 450 °C
  - Changed to: 16 Days at 650 °C

- Modified Process: Post-Bakeout Handling
  - Was: “Standard” SLAC Vacuum Practice
  - Changed to: “Particulate-Free” Vacuum Practice

- New Process: In-Situ Bakeout
  - 220 °C for Approximately 7 Days
T53VG5/T53VG3 Processing History

T53VG3 Structure Gradient (MV/m)

Process To 77 MV/m

Process To 86 MV/m

Measure Breakdown Rate Dependence on Gradient

Time with RF On (hr)
Breakdown Rate Distributions
During Initial Processing to 73-77 MV/m

Totals for 350 hrs Ops.
T20VG5: 4700
T105VG5: 3800

Totals for 140 hrs Ops.
T53VG5: 300
T53VG3: 350
Etching Studies With Copper Coupons

- Goal is to determine the effect of etch depth on surface finish and sub-surface “features, debris or contaminants” on OFE copper, using same processing for T53 and T20/T105 structures.
- Photoelectron spectroscopy shows that the surface is UHV-quality clean after minimal etching and continues to improve with further processing.
- Etching removes particles; long etching times reveal grain edges, voids, pits, and generally increase surface roughness.
- 0.3 micron (SC-diamond) and 1.5 micron (poly-diamond) etching is sufficient to remove machining lines.
- Furnace processing washes out the effect of etch time on surface features.
Breakdown Rate Distributions During Full Running Periods

Totals for 470 hrs Ops.
T20VG5: 5200
T105VG5: 4000

Totals for 1160 hrs Ops.
T53VG5: 2200
T53VG3: 3300
Breakdown Rate Correlations
(24 hr Samples – Full Running Periods)

T105VG5 Trips per Hour

T20VG5 Trips per Hour

T53VG5 Trips per Hour

Slope = 1.3

Slope = 1.5
T53VG3/5 Breakdown Rate -vs- Gradient
(Last 500 hours of Run, 240 & 400 ns Pulse Widths, Raw Counts Summed)
T53VG3: Fractional Missing Energy -vs- Breakdown Location

During Processing from 70 to 82 MV/m, 170 & 240 ns PW
RF on 60 hr

After Processing to 86 MV/m:
Run at 85 MV/m, 240 ns PW
RF on 7 hr

After Processing to 86 MV/m
Run at 73 MV/m, 240 ns PW
RF on 20 hr
Effect of Power Reflected from Structure Loads

10% Over-Voltage at Downstream End of Structure

T53VG3 at 85 MV/m

Tantawi/Dolgashev
**Comparison of Breakdown Rates at Three Gradients**

To Estimate the Effect of 17% Higher Coupler Iris Surface Field

(240 ns Pulse Length, 60 Hz Operation)

<table>
<thead>
<tr>
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<th>62 MV/m</th>
<th>73 MV/m</th>
<th>85 MV/m</th>
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<tbody>
<tr>
<td><strong>T53VG5</strong></td>
<td>3 / 51 hr</td>
<td>35 / 39 hr</td>
<td>33 / .75 hr</td>
</tr>
<tr>
<td></td>
<td>0.06 / hr</td>
<td>0.9 / hr</td>
<td>44 / hr</td>
</tr>
<tr>
<td><strong>T53VG3</strong></td>
<td>1 / 32 hr</td>
<td>18 / 20 hr</td>
<td>33 / 7 hr</td>
</tr>
<tr>
<td></td>
<td>0.03 / hr</td>
<td>0.9 / hr</td>
<td>5 / hr</td>
</tr>
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</table>
T53VG3: Fractional Missing Energy -vs- Breakdown Location for Longer Pulse Widths (400 ns for NLC)

After Processing to 86 MV/m:
Run at 70 MV/m, 480 ns Pulse Width
RF on 12 hrs, Trip Rate = 1.3 / hr

After Processing to 86 MV/m
Run at 65 MV/m, 400 ns Pulse Width
RF on 36 hr: Trip Rate = 0.14 /hr
T53VG3RA Input Coupler

Juwen Wang
What is a Tolerable Trip Rate for NLC?

Each NLC Linac contains 936 girders each supporting six, 0.9 m structures that are powered by one DLDS feed. Each girder can be independently powered.

Suppose

- If any structure on a girder breaks down, power to girder is shut off on next pulse, and then ramped up over a period of 10 seconds, out-of-time with the beam.
- 2% of girders (~19) are reserved for hot-swapping with these 'tripped' units.

Then for a trip rate of 1 per 3 hours for a 0.9 m structure running at 120 Hz,

- 0.5% of girders (~5) would be tripped on average (swap one every 2 seconds).
- Number of tripped girders would exceed 2% about once a year.
- Beam energy would fluctuate > 0.1% only once per year due to multiple breakdowns: the 90% FF energy bandwidth is +/- 0.5%.

At 65 MV/m, the measured T53VG3 trip rate scaled to NLC operation is 1 per 2.4 hours, dominated by input coupler breakdowns. Goal is at least a factor of 10 reduction using a new coupler design.
T105VG5 Damage and Missing RF Energy Distributions

$v_g = 5\%$  |  3.3\%  |  1.6\%

Integrated Phase Error (degrees)

Cell Number

Relative Damage (blue) & Missing Energy (red)

Cell Number
T53VG5 and T53VG3 Phase Shift (degrees) -vs- Cell Number
T53VG5 and T53VG3 Damage and Missing RF Energy Distributions

\[ v_g = 5\% \quad 3.3\% \quad v_g = 3.3\% \quad 1.6\% \]

Relative Damage (blue) & Missing Energy (red)

Cell Number

Cell Number
DDS3 and DS2S Damage and Missing RF Energy Distributions

DDS3 (60 MV/m)

\[ v_g = 11.8\% \]

5.1% 3.0%

Cell Number

DS2S (73 MV/m)

\[ v_g = 5.1\% \]

3.0%

Cell Number
Structure Damage

<table>
<thead>
<tr>
<th>Structure</th>
<th>Scale Factor</th>
<th>Max Gradient</th>
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<tr>
<td>DS2S</td>
<td>.16</td>
<td>73</td>
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<tr>
<td>DDS1</td>
<td>.70</td>
<td>70</td>
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<tr>
<td>MC</td>
<td>0.46</td>
<td>54</td>
</tr>
<tr>
<td>T105VG5</td>
<td>1</td>
<td>72</td>
</tr>
<tr>
<td>T53VG3</td>
<td>1</td>
<td>86</td>
</tr>
</tbody>
</table>

Equivalent Volume (mm^3) of Cu Removed per Cell

Group Velocity (%c)
What is a Tolerable Phase Advance Change for NLC?

A change in the phase advance along a structure produces an effective gradient reduction.

Suppose

- As a worst case, phase change increases at a constant rate (processing experience suggests otherwise).
- Phase change is the same in all structures and has the pattern measured for T105VG5.
- No attempt is made to offset phase change (e.g., changing operating temperature).

Then for a phase change of $0.5^\circ$ per 1000 hours of 120 Hz operation,

- Effective gradient decreases 5% in 20 years (7000 hours operation per year).
- Total phase change is $70^\circ$ during this period.

The T53VG3 phase change measured during processing/operation at an average gradient greater than 70 MV/m is $0.8^\circ$ per 1000 hours when scaled to NLC operation.
Next Round of Low $v_g$ Structure Tests
(Starts Next Week)

$v_g = 3.3\% \quad \quad \quad 1.6\%$

T53VG3F

T53VG3RA

Goals

- Test if single-diamond turned, non-etched cells process the same as conventionally machined, 1.5 micron etched cells.

- Test if a lower field, lower impedance input coupler reduces breakdown in the coupler region.

- Develop processing/run protocol to qualify structures for NLC operation. Protocol being considered:

1) Process to 80 MV/m at 60 Hz with 400 ns pulses
   - Run for one month or until trip rate < 1 /hour.
   - Use 1-2 min. ramp time to limit damage from secondary breakdowns.
   - At end of period, measure trip rate and phase shift (with bead pull?).

2) Run at 70 MV/m at 60 Hz with 400 ns pulses
   - Run until end of February (integrate > 1000 hours).
   - Use 10 second ramp time.
   - At end of period, measure trip rate and phase shift with bead pull.
   - Required sensitivity to do NLC qualification: trip rate < 1/6 per hour, phase shift < 1/4 degrees per 1000 hours.
Low Group Velocity, High Phase Advance Structure Tests in 2002

March-July

<table>
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<tr>
<th></th>
<th>5.1%</th>
<th>1.1%</th>
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<tbody>
<tr>
<td>H90VG5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H60VG3</td>
<td></td>
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</table>

3.2% 1.1%

Tests higher phase advance per cell (150 deg) structures that are low group velocity and have a larger iris size ($a/\lambda = 0.18$) for acceptable wakes in NLC. Structures are detuned and have a low-field coupler cell.

July-Sept

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<th>1.9%</th>
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</tr>
<tr>
<td>H60VG3</td>
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3.2% 1.1%

Further test of high phase advance structures. Structures will have in-line tapers, a low field output coupler cell and will be detuned. FNAL will also build at least one H-type structure to be tested at this time.
Examples of Wakefield Calculations For H-Type Structures

H90VG5 will Local Damping (purple) and Manifold Damping (blank/red)

H90VG3 with 3-Fold Interleaving and Local Damping
# H60VG3 Inline Taper

## 23-cell model

<table>
<thead>
<tr>
<th>n</th>
<th>a</th>
<th>b</th>
<th>t</th>
<th>noise</th>
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<td>5.27621</td>
<td>11.49779</td>
<td>4.44535</td>
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<td>12.22401</td>
<td>5.40000</td>
<td>4.80000</td>
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\[
b_{ave} = \frac{b_i \cdot 0.5 \cdot (L - t_i) + b_j \cdot 0.5 \cdot (L - t_j)}{L - 0.5 \cdot (t_i + t_j)}
\]
S20PI - First Prototype Standing Wave Cavity

Beta = 1.0, Rs = 68.3 MΩ/m, Qo = 8860
Trise = 62 ns, Bandwidth = 450 MHz

Center Feed: 14 MW Input Yields 70 MV/m

15 Cells, 194 mm
SW Structure
Input Power
(nonlinear, au)

Distribution of Breakdown Times for SW1

Distribution of Breakdown Times for SW2

Time (ns)
SW1 Breakdown Events

Blue = Reflected RF Power, Green = Input Power after Breakdown

'Soft' Event

Power (MW)

Time (ns)

25
20
15
10
5
0

600 800 1000

'Hard' Event

Power (MW)

Time (ns)

25
20
15
10
5
0

600 800 1000

RE_DAT_5
Standing Wave Structure Performance

Breakdown Rate of Pair (#/hr) at 60 Hz (Measured in 4 hour Intervals)

SW Gradient (MV/m) with 270 ns Flattop
Beam Induced RF in SW1 Before (green) and After (blue) 250 hours of Processing. Phase Change Corresponds to a 340 kHz Frequency Increase.
Beam and Drive RF Based Frequency Measurements of the Standing Wave Structures

<table>
<thead>
<tr>
<th></th>
<th>Δ Freq Before Processing</th>
<th>Δ Freq After 900 hrs of Operation</th>
<th>Change</th>
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<tbody>
<tr>
<td>SW1</td>
<td>200 kHz</td>
<td>700 kHz</td>
<td>+ 500 kHz</td>
</tr>
<tr>
<td>SW2</td>
<td>400 kHz</td>
<td>800 kHz</td>
<td>+ 400 kHz</td>
</tr>
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</table>
Frequency Change after High Power Test
for SW20PI Section - I

DeltaF

Frequency Change (MHz)

Cell Number

1  2  3  4  5  6  7  8  9  10  11  12  13  14  15
Pitting on the Iris of the Coupler Cell in One of the Standing Wave Structures
Next Two Rounds of Standing Wave Structure Tests

Oct - March

S20PIL

Beta = 1

Tests diamond-turned version of design recently tested (15 cells, 20 cm long). Tuned to have lower (-14%) field near the input coupler.

March - July

S20a565R

Beta = 2

Tests one of three standing wave structure types being developed to provide detuning. Will have a low-field coupler and a lower surface-to-acceleration field ratio.
High Gradient Summary

- Encouraged by recent low group velocity structure tests
  - T53VG3 operates at close to tolerable NLC levels
- Will now focus on proving operability at 70 MV/m: need to
  - Improve coupler design to eliminate the soft breakdowns that dominate rate after initial processing.
  - Quantify phase advance change during operation at nominal gradient.
  - Increase statistics – plan to have 11 m of structures operating in Eight-Pack Test.
- A high priority remains to develop high gradient structures that meet NLC requirements on iris size and wakefield suppression.
  - Beginning tests of high phase advance structures next March that have the nominal NLC iris radii and are detuned.
  - Designing manifold damped versions of these structures.
- Continue to evaluate standing wave structures as a higher-gradient, longer-term alternative to the current traveling wave approach.
Eight-Pack Project Structures in NLCTA

Second Girder Installed
First Girder Installed
(Fed by Long Delay Line)