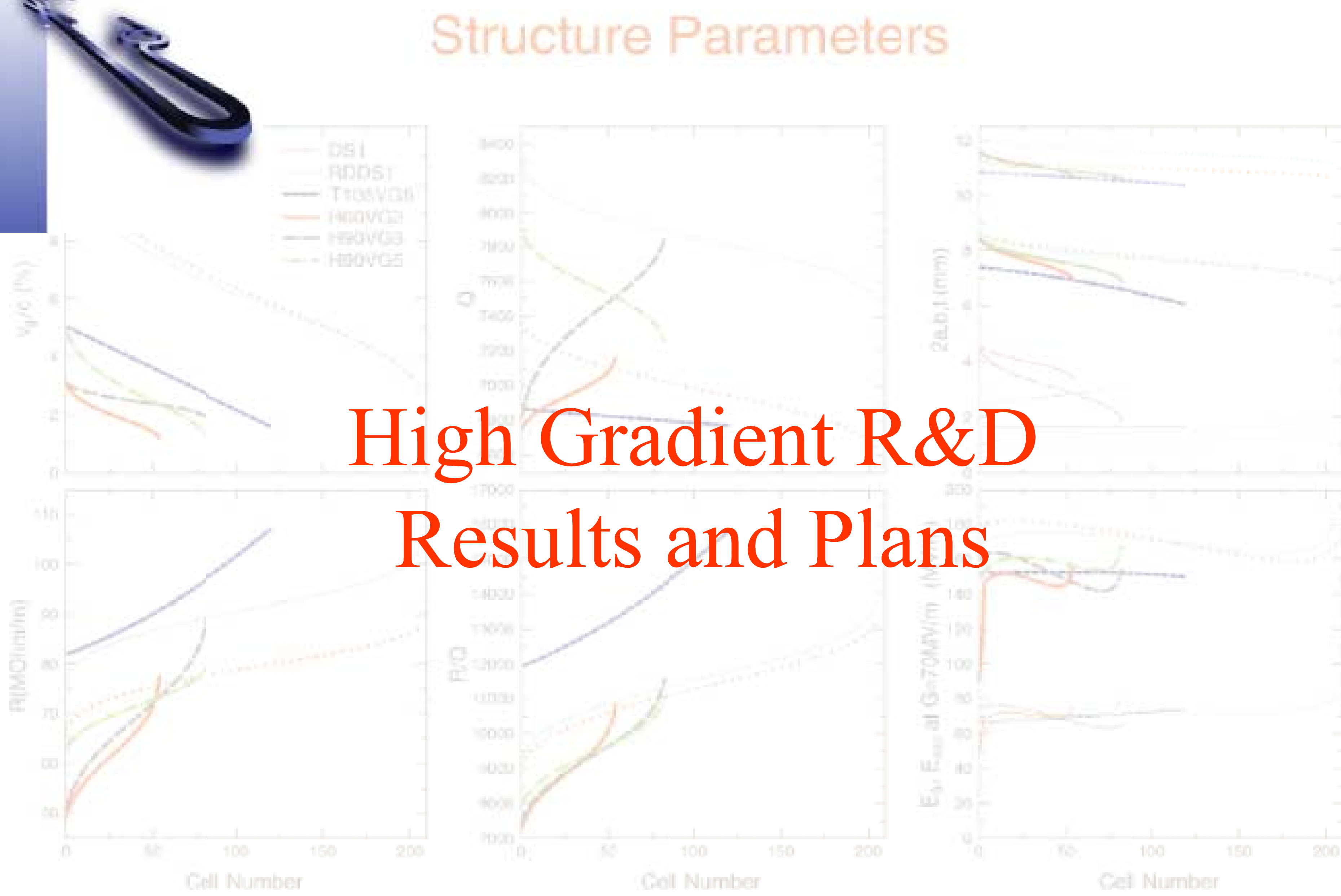


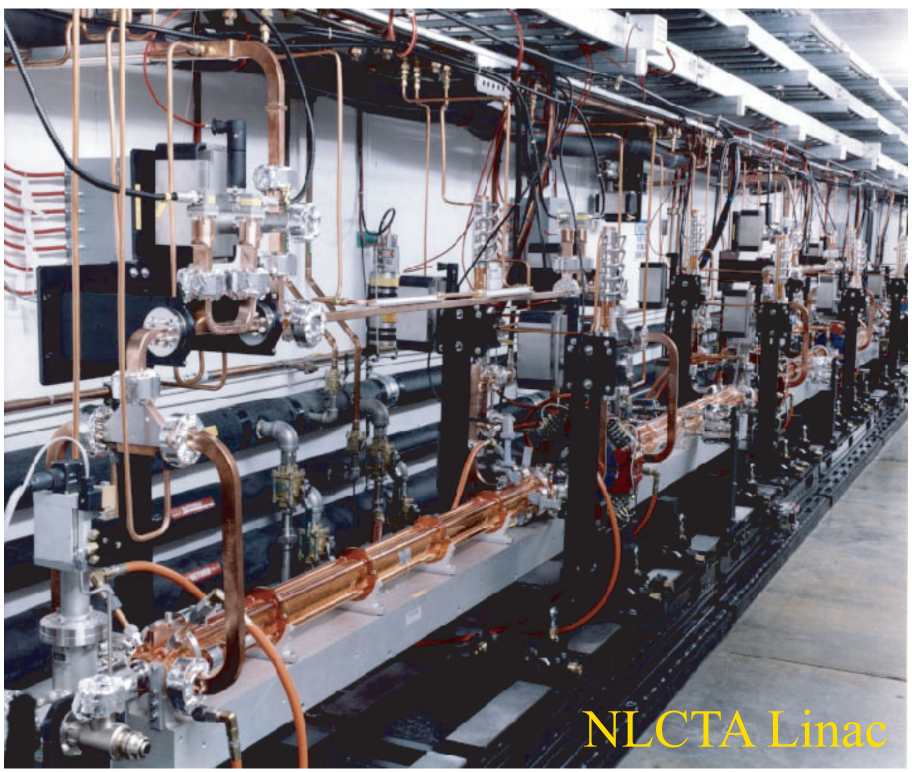
High Gradient R&D Results and Plans

Chris Adolphsen

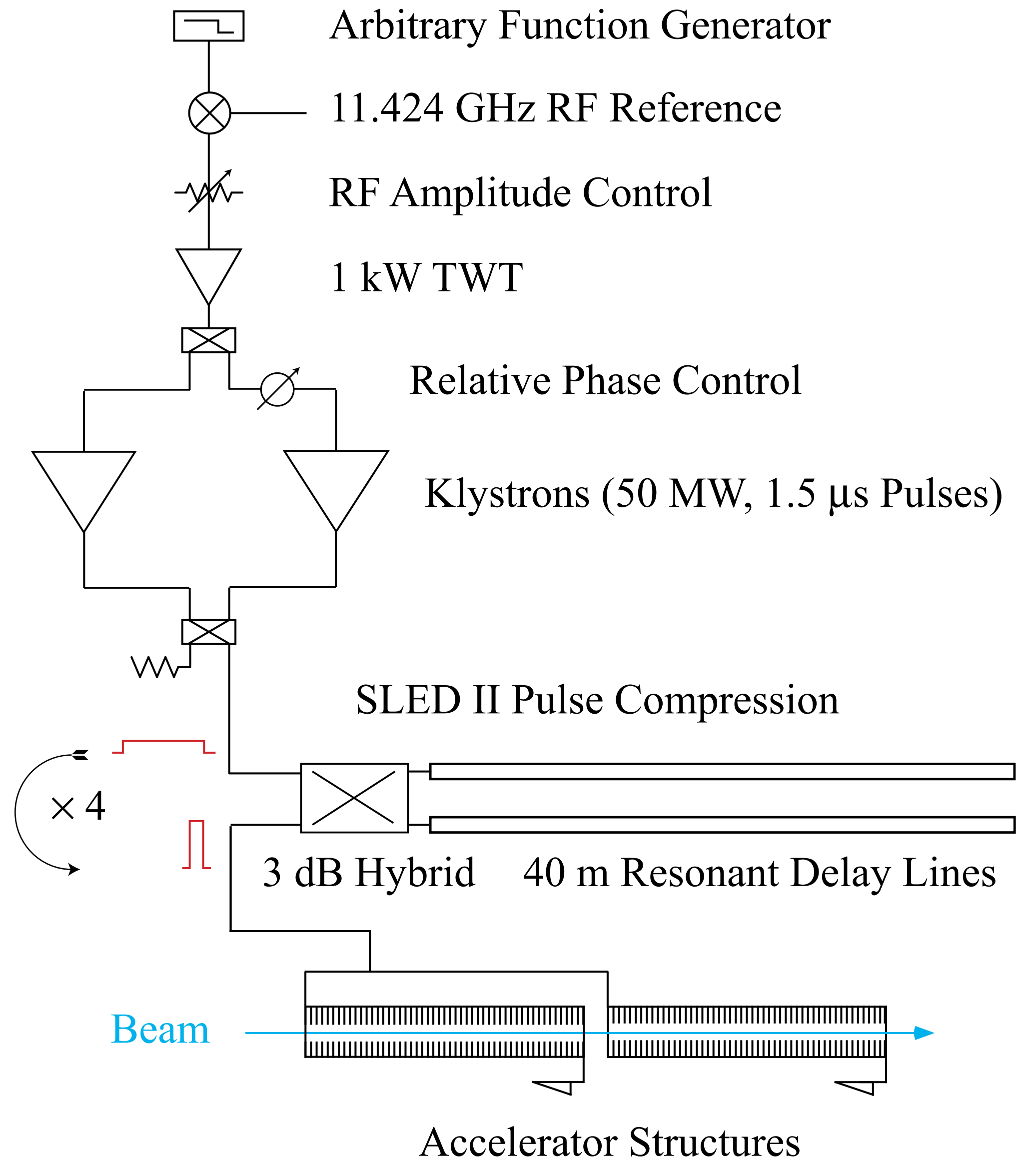
High Gradient Studies at NLC Test Accelerator (NLCTA)

Contributors

C. Adolphsen, B. Baumgartner, G. Bowden, D. Burke, J. Cornuelle, V. Dolgashev, J. Frisch, E. Garwin, R. Kirby, K. Jobe, R. Jones, F. LePimpec, Z. Li, G. Loew, R. Loewen, D. McCormick, R. Miller, C. Nantista, C.K. Ng, M. Ross, R. Ruth, T. Smith, S. Tantawi, J. Wang and P. Wilson



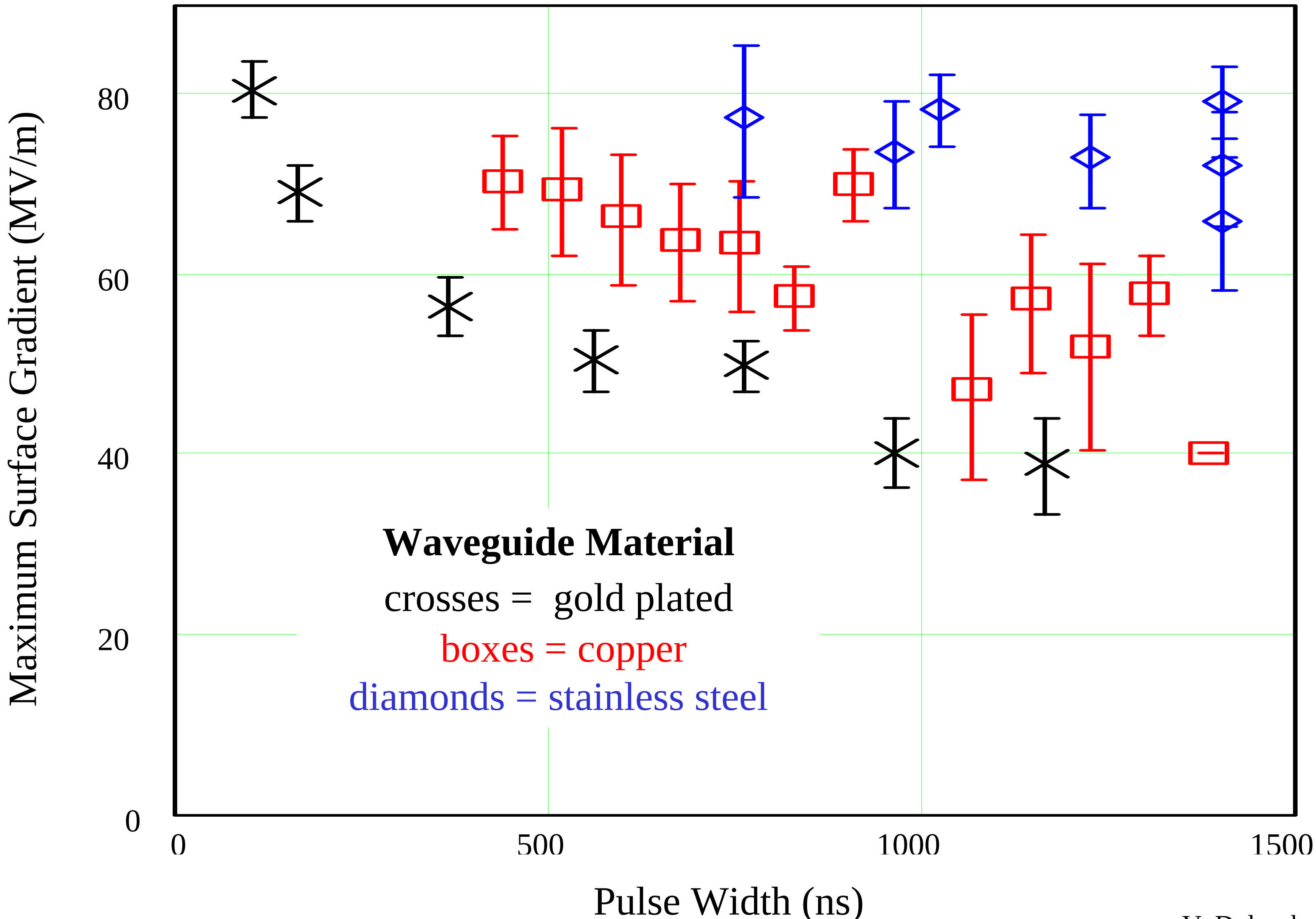
NLCTA Linac RF Unit (One of Two)



Program to Improve High Gradient Performance

- Compare performance versus different:
  - Initial structure group velocity (5 % and 3% c) and length (20, 53 and 105 cm)
  - Cell machining (single and poly diamond) and cleaning (etch time) methods
  - Structure type: standing-wave -vs- traveling-wave.
  - ➯ Thus far have processed 12 structures (5000 hours operation at 60 Hz).
- Systematic study of rf breakdown
  - Measure RF, light, sound, X-rays, currents and gas associated with rf breakdown in structures, waveguides and single cavities.
  - Simulate breakdown effect on RF transport with 'MAGIC' particle-in-cell code.
  - Measure surface roughness/cleanliness/damage with SEM, EDX, XPS and AES.
- Improve structure handling and cleaning methods
  - Adopted better degassing procedure that includes:
    - Wet and dry H_2 firing
    - 650 °C vacuum bake for 16 days
    - 225 °C in-situ bake for 7 days.

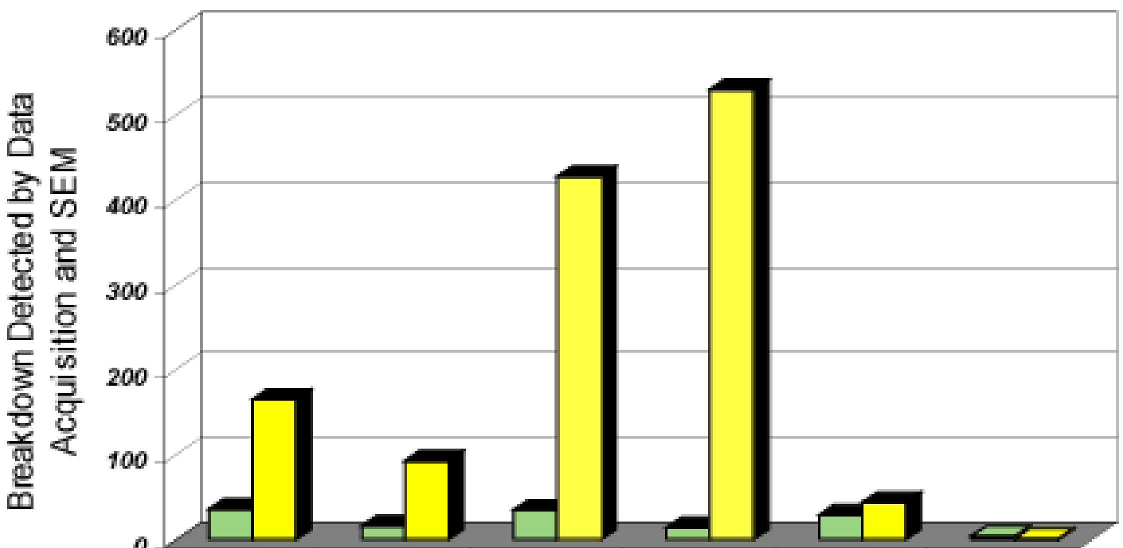
Breakdown Threshold Gradient -vs- Pulse Width in 16% c Group Velocity Waveguides



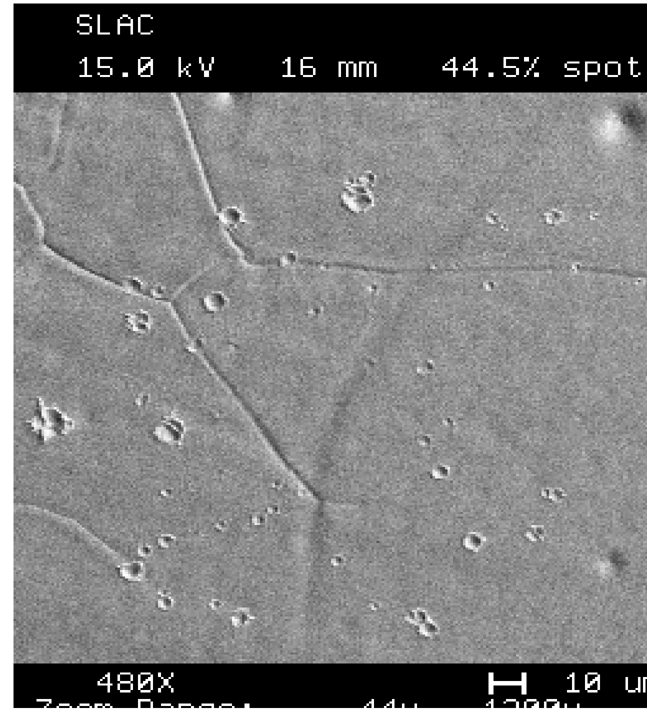
V. Dolgashev, S. Tantawi

‘Windowtron’ RF Breakdown Studies at SLAC

(200 MV/m Max Surface Field, 240 ns Pulse Widths)



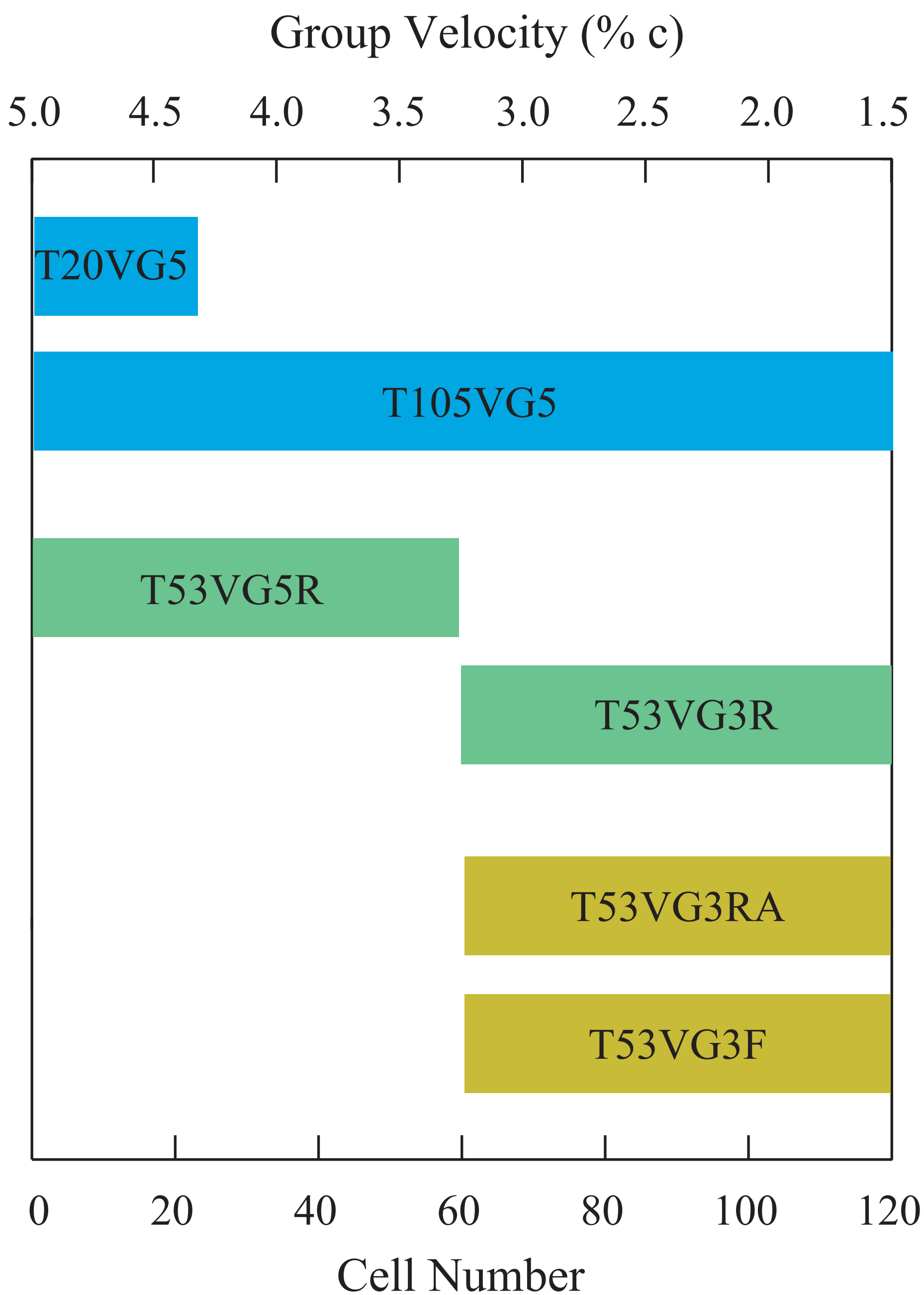
	LQ1	LQ2	LQ3	LQ4	HQ1	HQ2
Data Acq.	36	16	35	14	29	4
SEM	165	93	428	530	44	1



(Left) More surface damage (yellow columns) was visibly observed on the cavity noses processed in the four low Q_{ext} cavities (LQ) compared to the two high Q_{ext} cavities (HQ). The number of breakdown events (> 10% missing energy) detected while processing (green columns) were significantly lower than the number of craters detected. **(Right)** A SEM photograph showing how breakdown sites appear in clusters in the low Q_{ext} cavity experiments.

L. Laurent, D. Sprehn

T-Type Structures Tested to Date

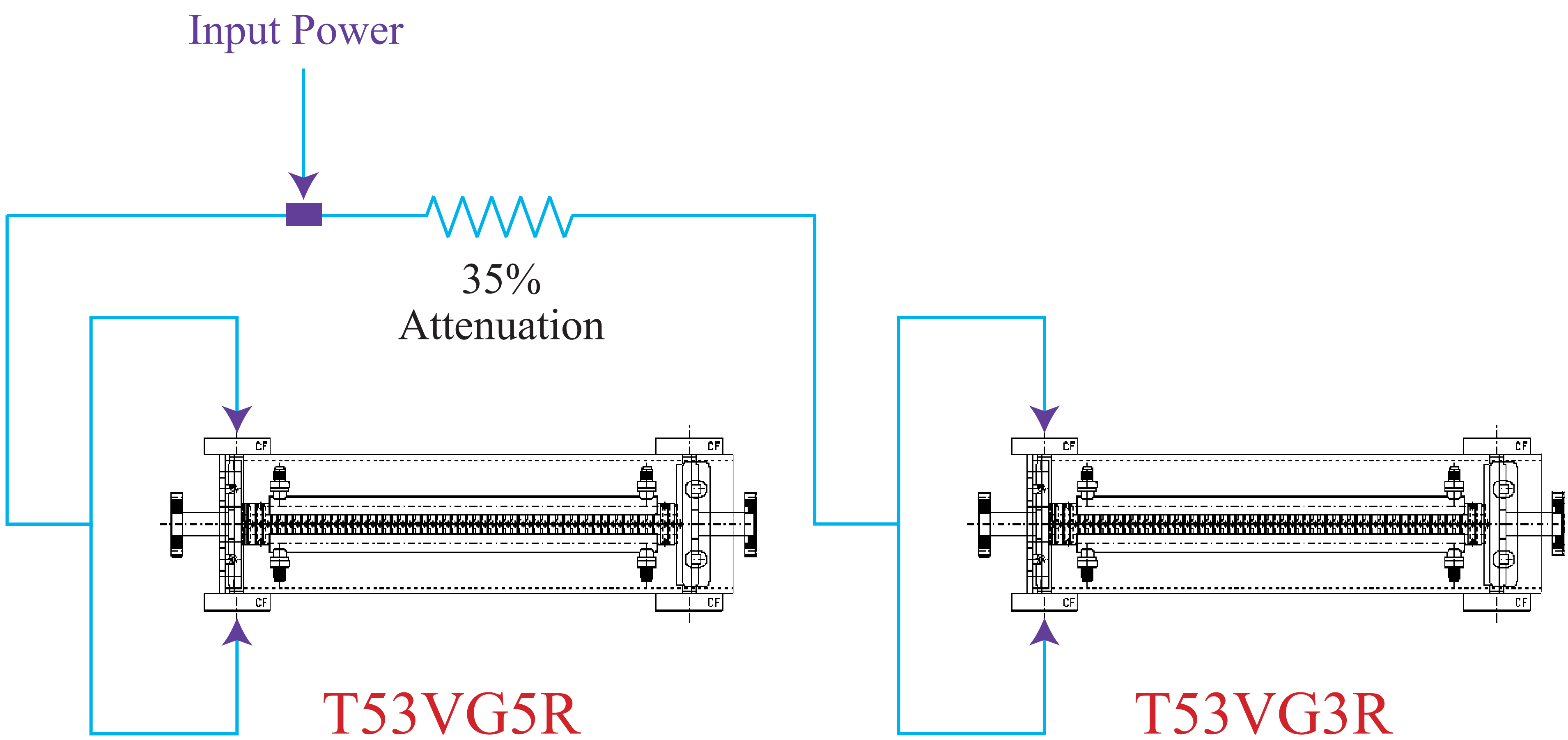


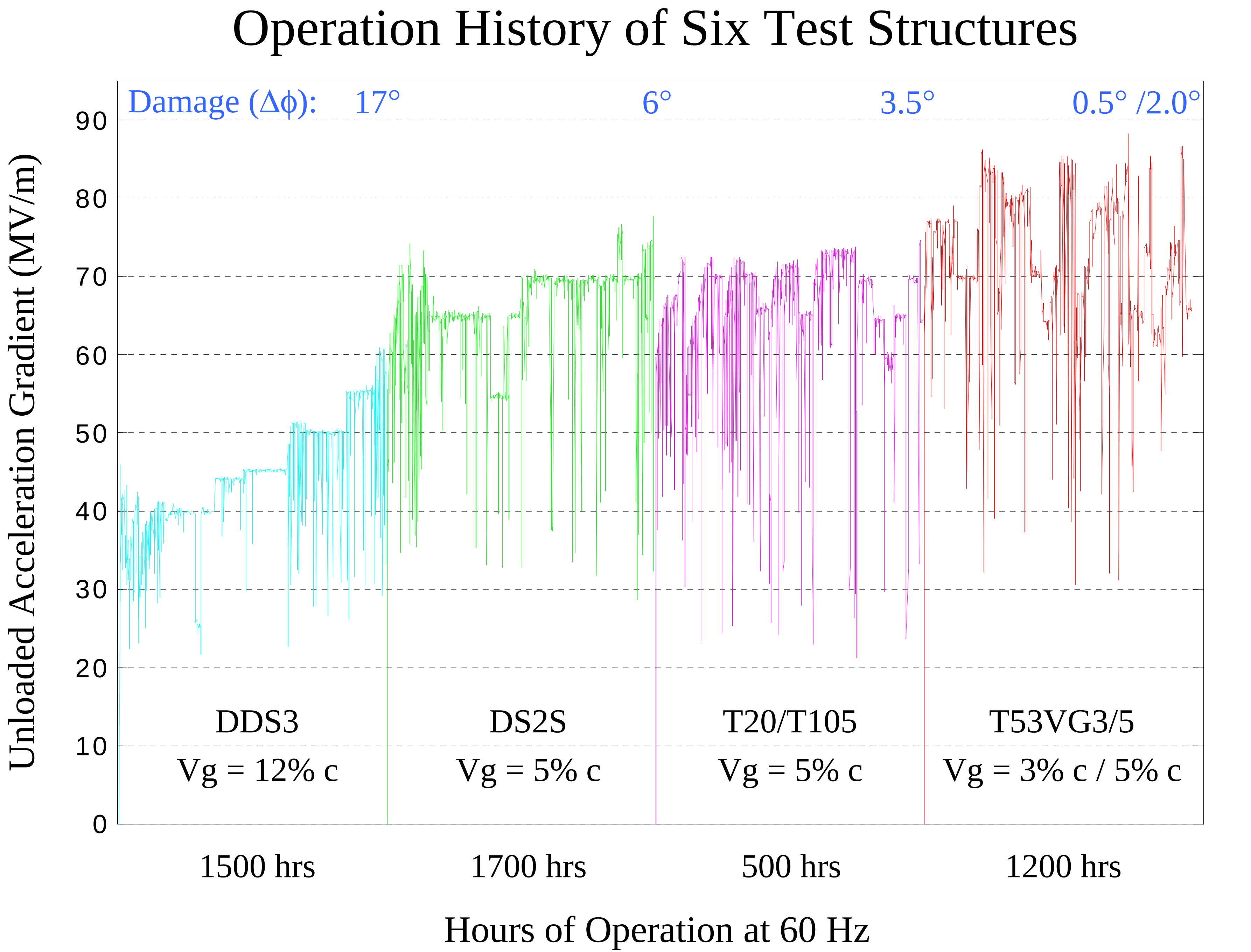
Cell Machining	Etch Depth for Cell Cleaning	Input Coupler
Diamond Turned	0.3 microns	Standard
Conventionally Machined	3 microns	Standard
Conventionally Machined	1.5 microns	Low Field/ Low Impedance
Diamond Turned	No Etch	Standard

T53 Structure Layout in NLCTA

VG3/VG5 Gradient = 1.06

VG3/VG5 Peak Surface Field = 1.01



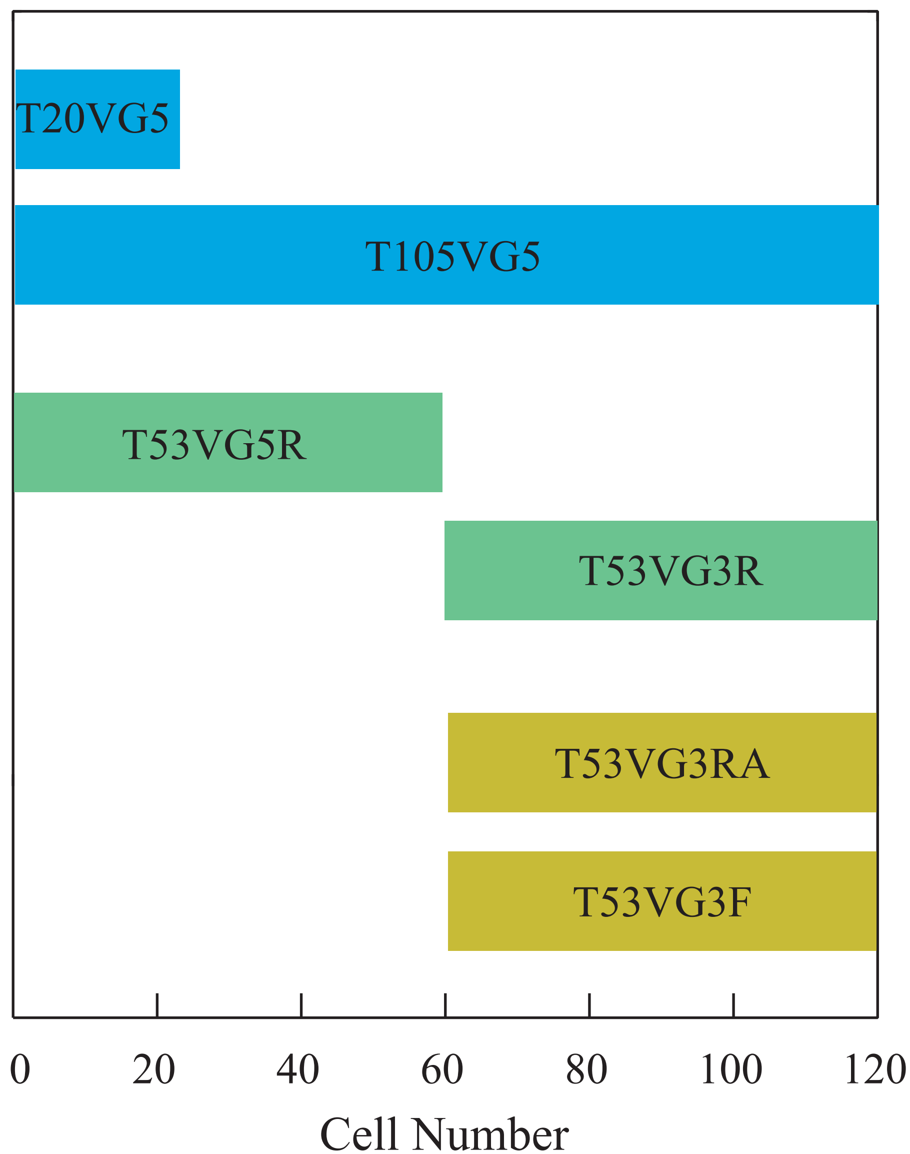


Operation History of Six Test Structures
Damage (Δφ): 17° 6° 3.5° 0.5° /2.0°
Unloaded Acceleration Gradient (MV/m)
90
80
70
60
50
40
30
20
10
0
DDS3
Vg = 12% c
DS2S
Vg = 5% c
T20/T105
Vg = 5% c
T53VG3/5
Vg = 3% c / 5% c
1500 hrs
1700 hrs
500 hrs
1200 hrs
Hours of Operation at 60 Hz

Structure Performance Metrics

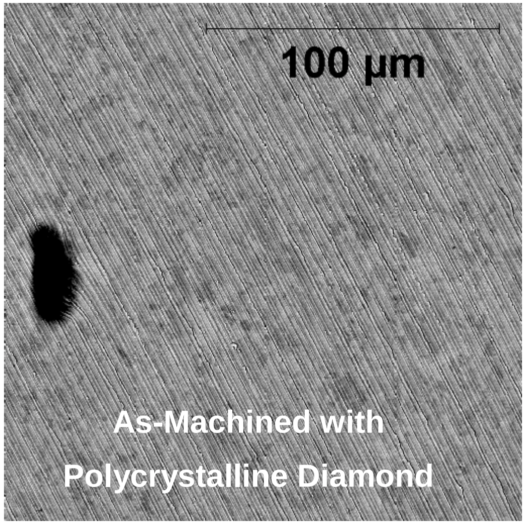
- Time (or # of trips) it takes to increase the gradient (process) to a level about 10% above the desired operating value.
- Trip rate at the operating gradient (70 MV/m in NLC).
- Damage (phase shift) from processing and operation.

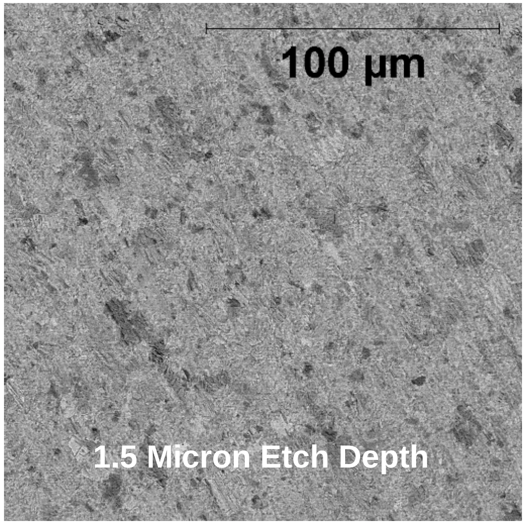
Number of Breakdowns to Process to ≈ 75 MV/m with 240 ns Pulses

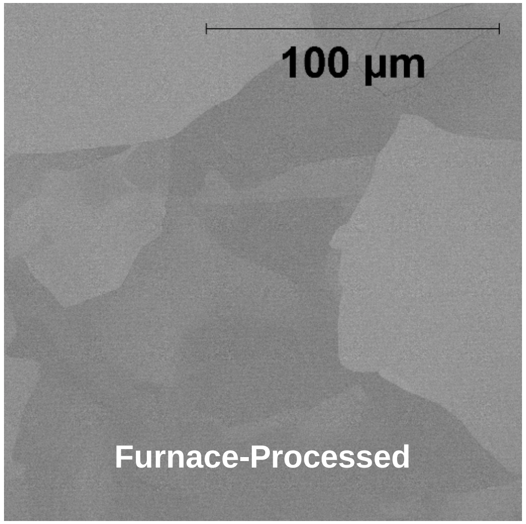


	Cell Machining	Etch Depth for Cell Cleaning
4700	Diamond Turned	0.3 microns
3800		
300	Conventionally Machined	3 microns
350		
2500	Conventionally Machined	1.5 microns
2400	Diamond Turned	No Etch

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.

Bob Kirby

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

Structure Performance Metrics

- ✓ Time (or # of trips) it takes to increase the gradient (process) to a level about 10% above the desired operating value.

- Trip rate at the operating gradient (70 MV/m in NLC).

- Damage (phase shift) from processing and operation.

What is a Tolerable Trip Rate for NLC ?

Each NLC Linac contains ≈1000, six structure, independently powered girders.

If allow

10 seconds for a girder to ramp to full power after a structure trip

2% of girders to be reserved for hot-swapping with these 'tripped' units,

Then can 'comfortably' tolerate a trip rate of

1 per 3 hours per 90 cm structure running at 120 Hz in the NLC

- or equivalently -

1 per 10 hours per 53 cm structure running at 60 Hz in NLCTA.

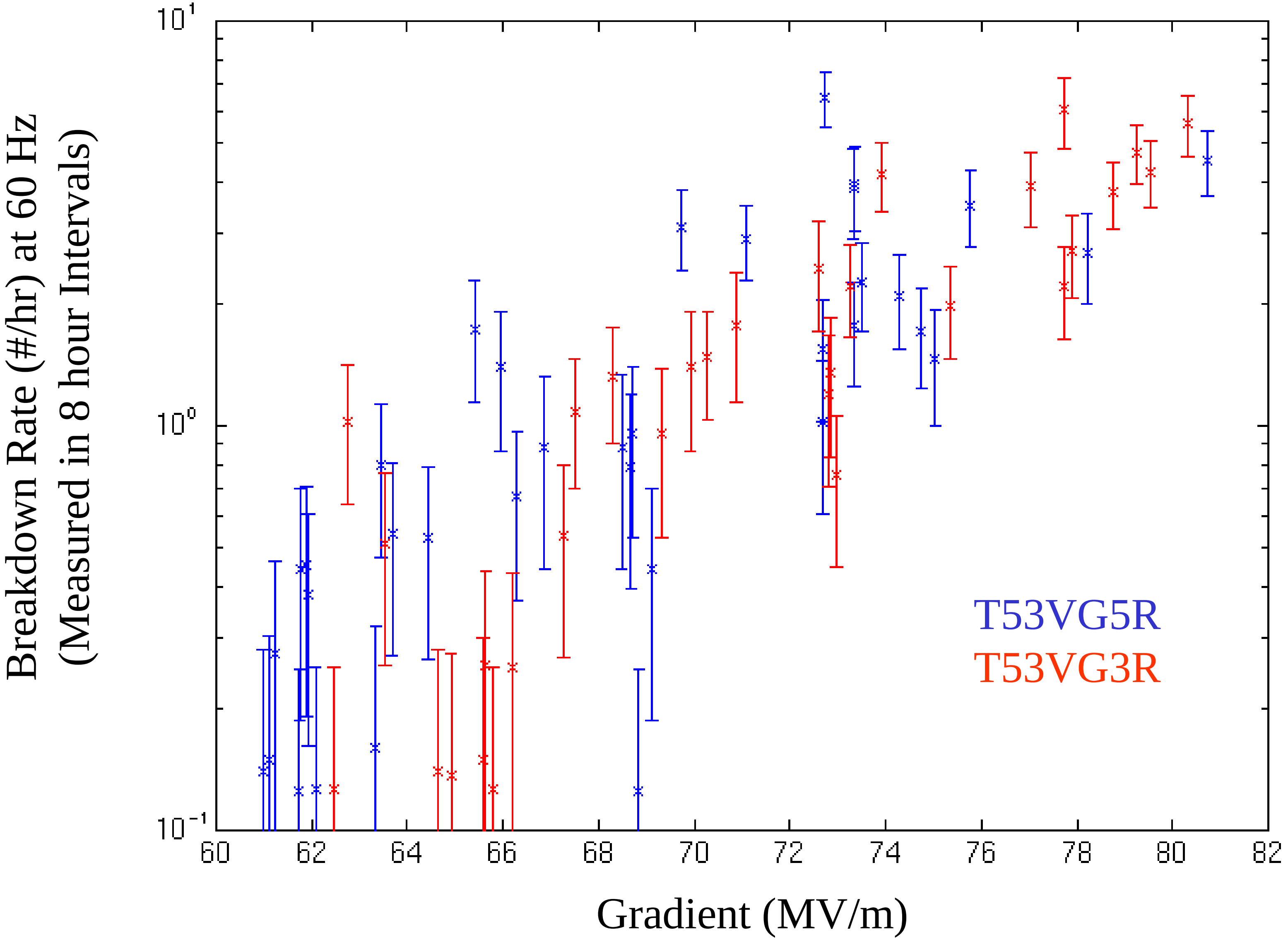
Have achieved trip rates with the T53VG3 structures in NLCTA of

1 per 5 hours and lower in the structure body at 70 MV/m, 400 ns

1 per 7 hours in the full structure at 65 MV/m, 400 ns.

T53VG3/5 Breakdown Rate -vs- Gradient

(Last 500 hours of Run, 240 & 400 ns Pulse Widths, Raw Counts Summed)

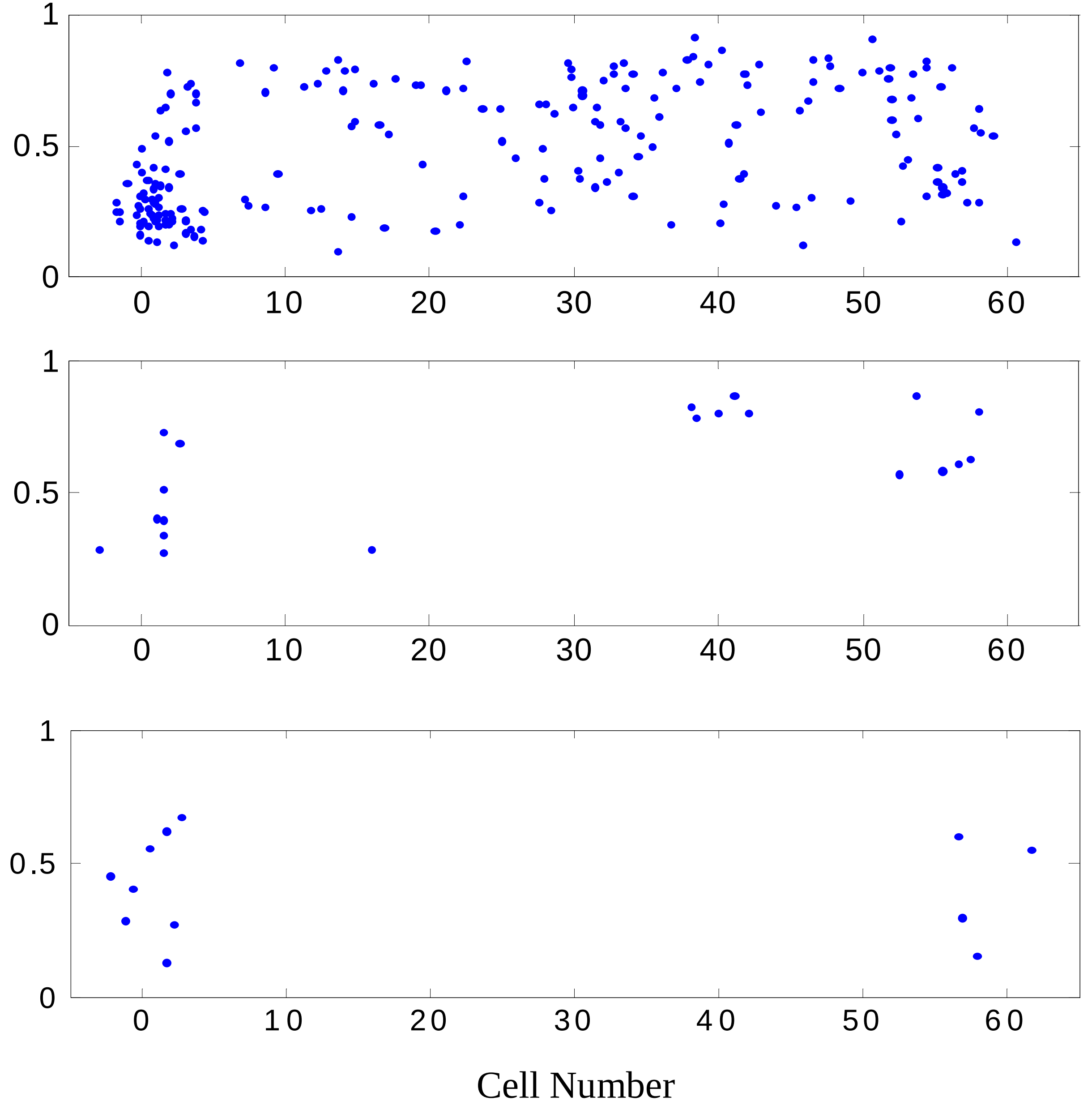


T53VG3R: Fractional Missing Energy -vs- Breakdown Location

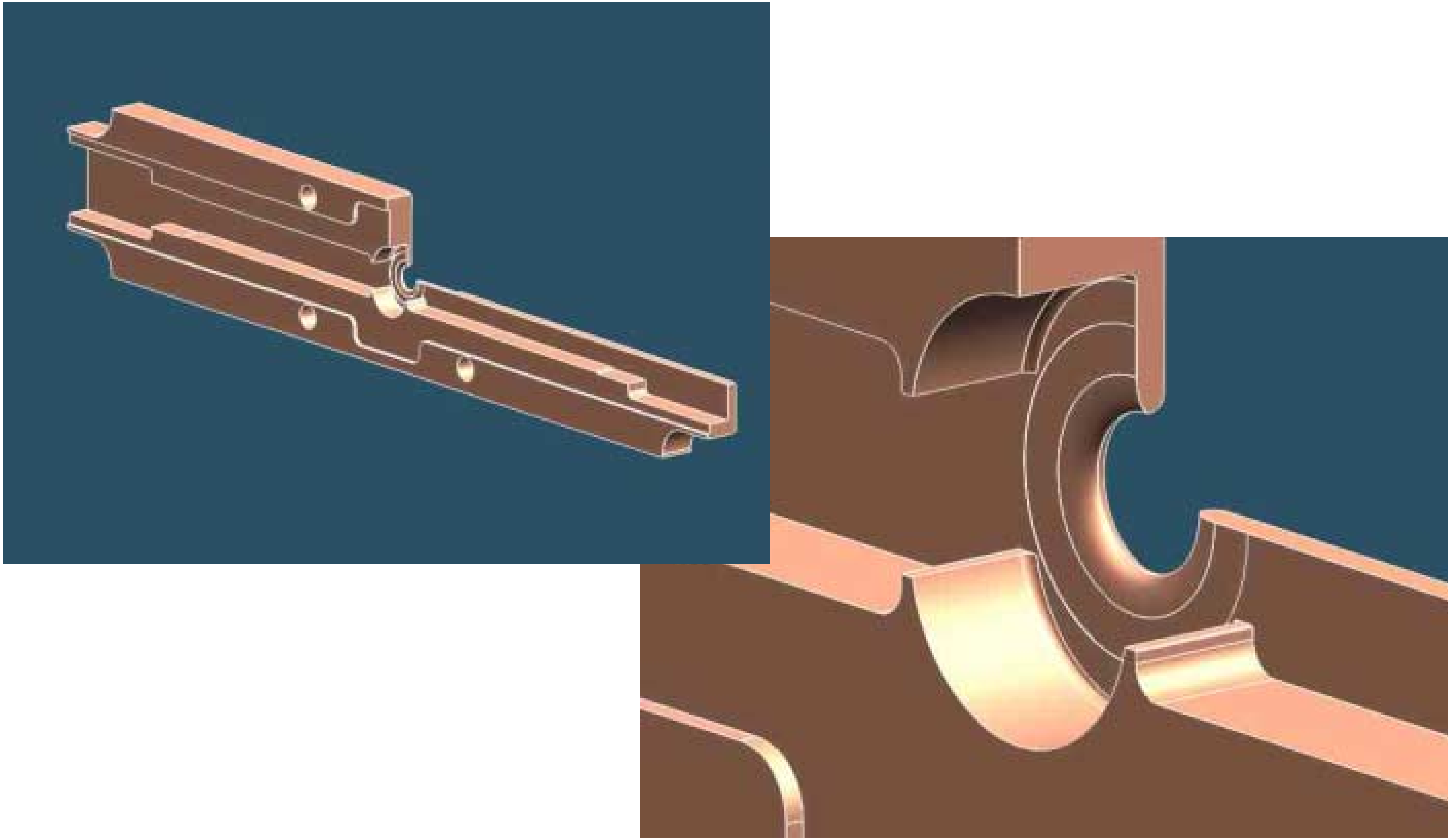
During Processing from
70 to 82 MV/m, 170 & 240 ns PW
RF on 60 hr

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 70 MV/m, 480 ns Pulse Width
RF on 12 hrs, Trip Rate = 1.1 / hr



T53VG3RA Input Coupler

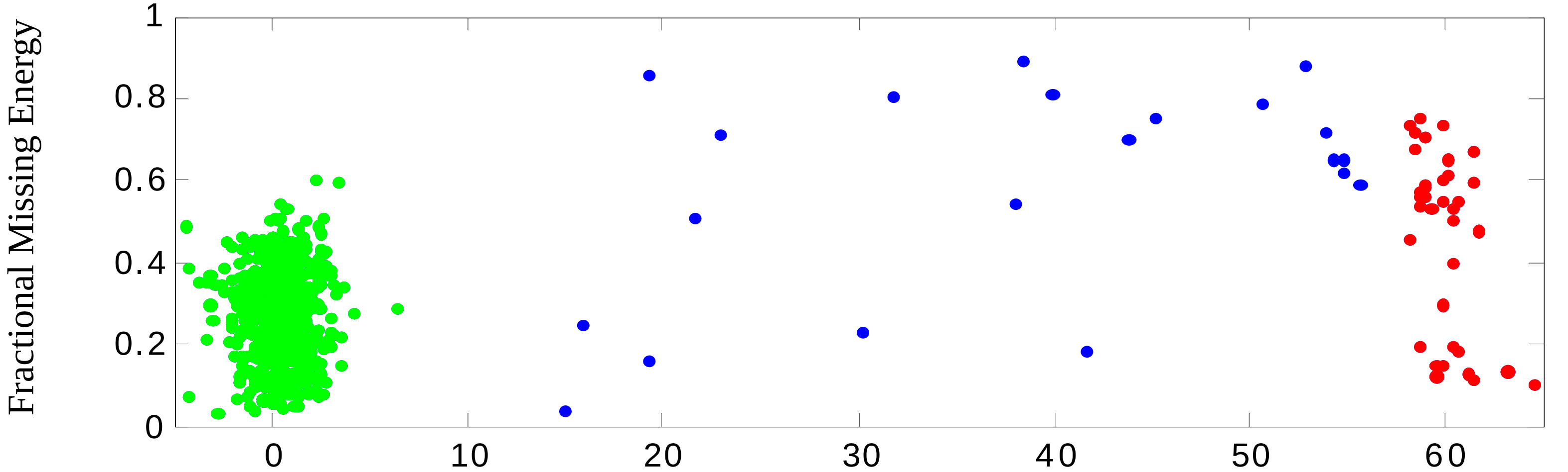


Juwen Wang

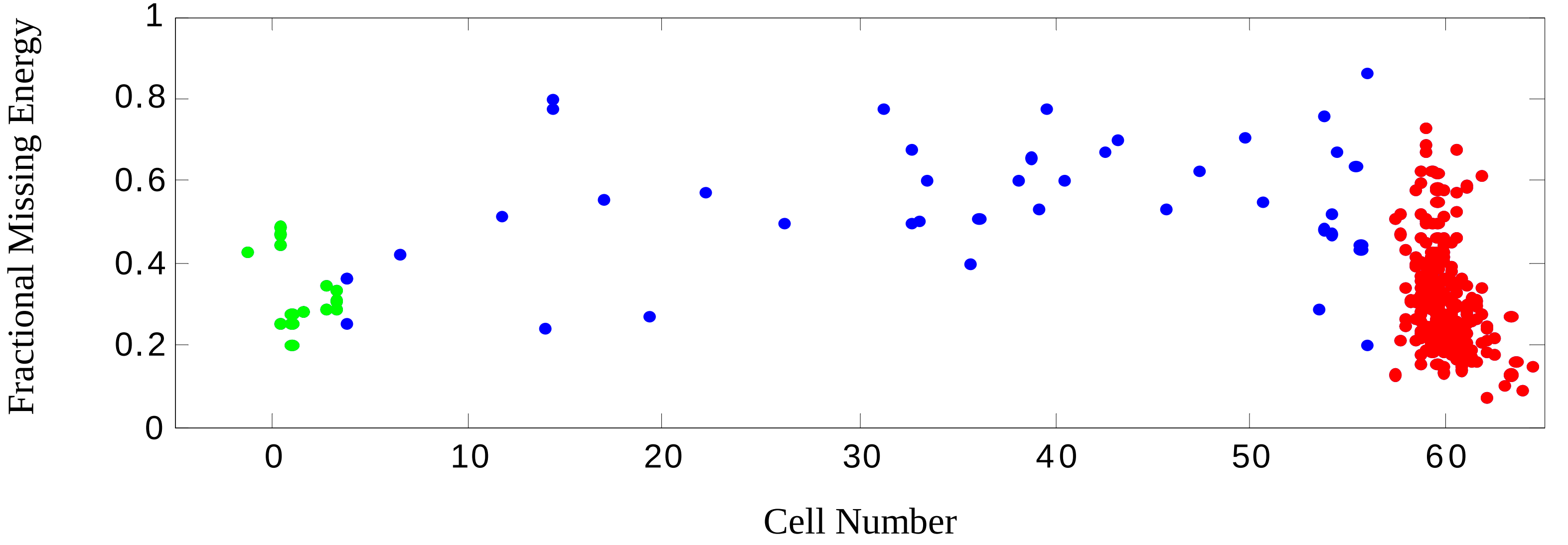
Breakdown Statistics for Latest Structures

(120 Hours, 60 Hz, 400 ns Pulse Width Operation at 73 MV/m)

T53VG3RA (Low Field/Impedance Input Coupler, Standard Output Coupler)



T53VG3F (Standard Input/Output Coupler)

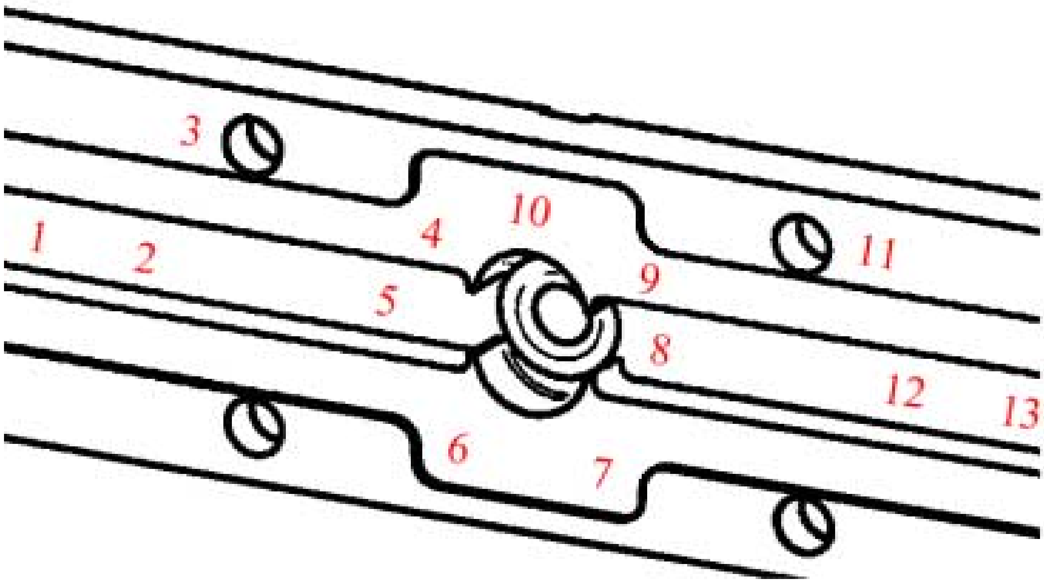


Structure Breakdown Rate Comparison

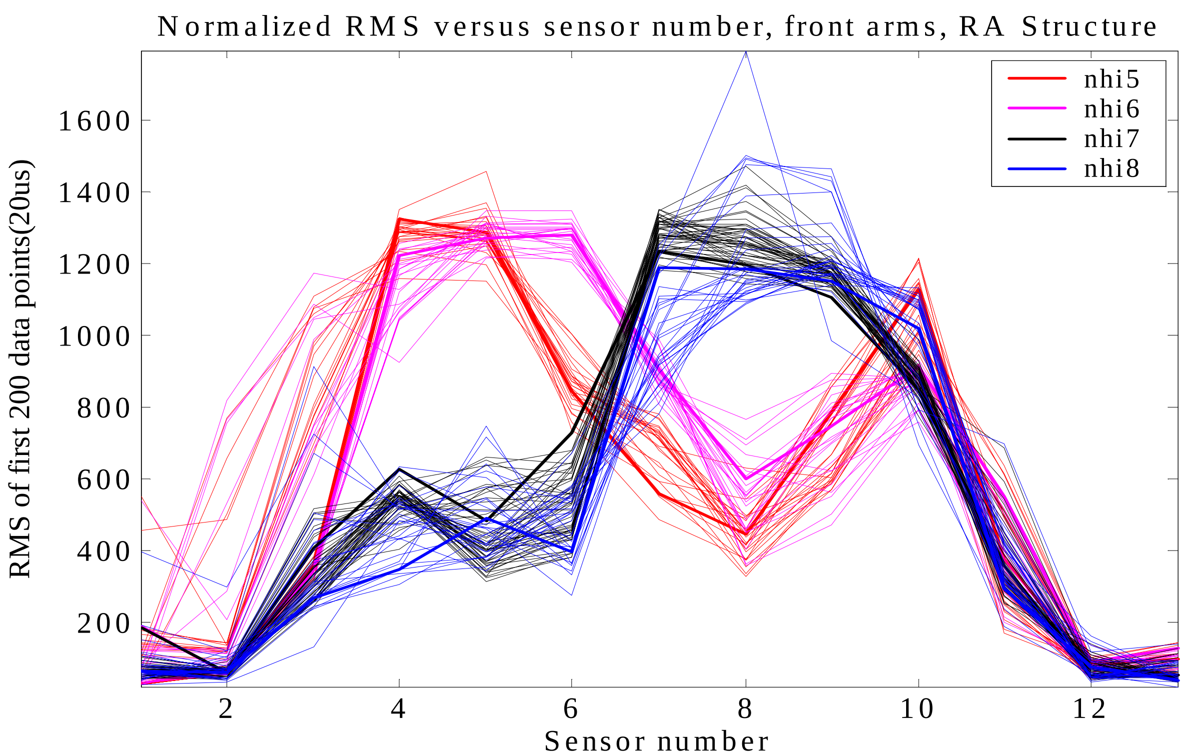
Structure	Gradient (MV/m) / Pulse Width (ns)	Input Coupler Rate (#/hr)	Body Rate (#/hr)	Output Coupler Rate (#/hr)
DS2S	70/240	4.7*	0.4+	< 0.1
T20VG5	70/240	1.1	0.9	1.1
T105VG5	70/240	1.7*	0.3+	< 0.1
T53VG5R	73/240	0.4	0.2	0.2
T53VG3R	70/480	0.7	< 0.1	0.3
T53VG3RA	73/400	5.2	0.2	0.3
T53VG3F	73/400	0.16	0.3	1.9

* = Rate in first 10 cells, + = Rate in body excluding first 10 cells

T53VG3RA Input Coupler with Front Plate Removed (Numbers Indicate Sensor Locations)



Acoustic Sensor Response to Input Coupler Breakdowns

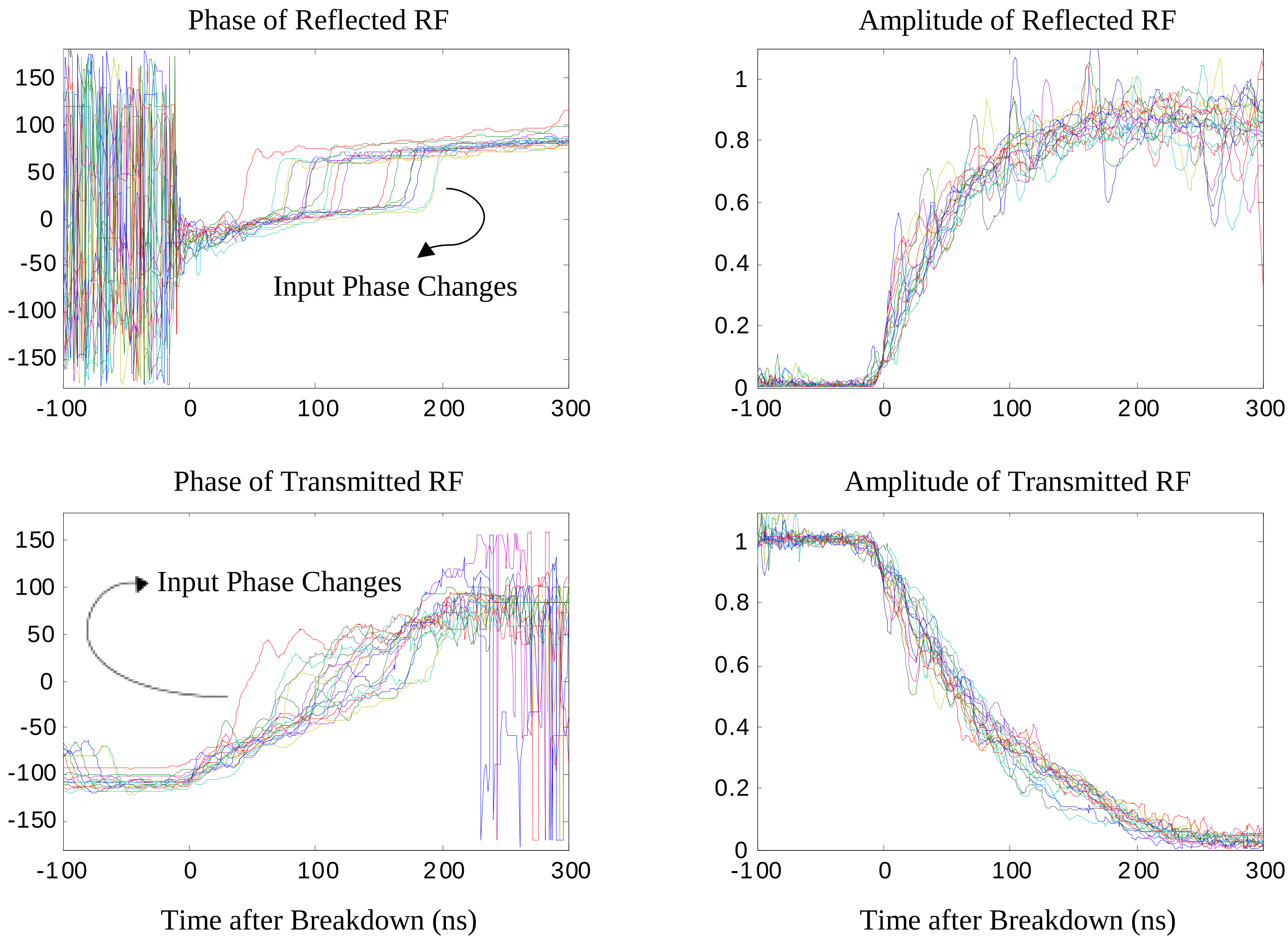


Sensor Signal Strength -vs- Sensor Location: Each Line is One Event, Color Coded by Pattern

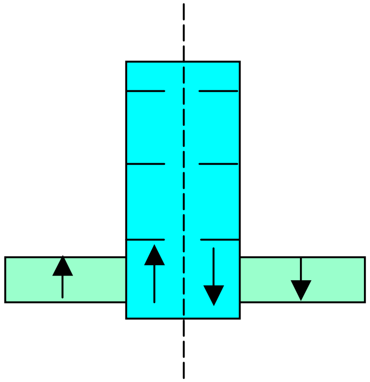
J. Nelson, J. Frisch, D. McCormick, M. Ross

T53VG3RA Input Coupler Events During First 200 ns of Pulse

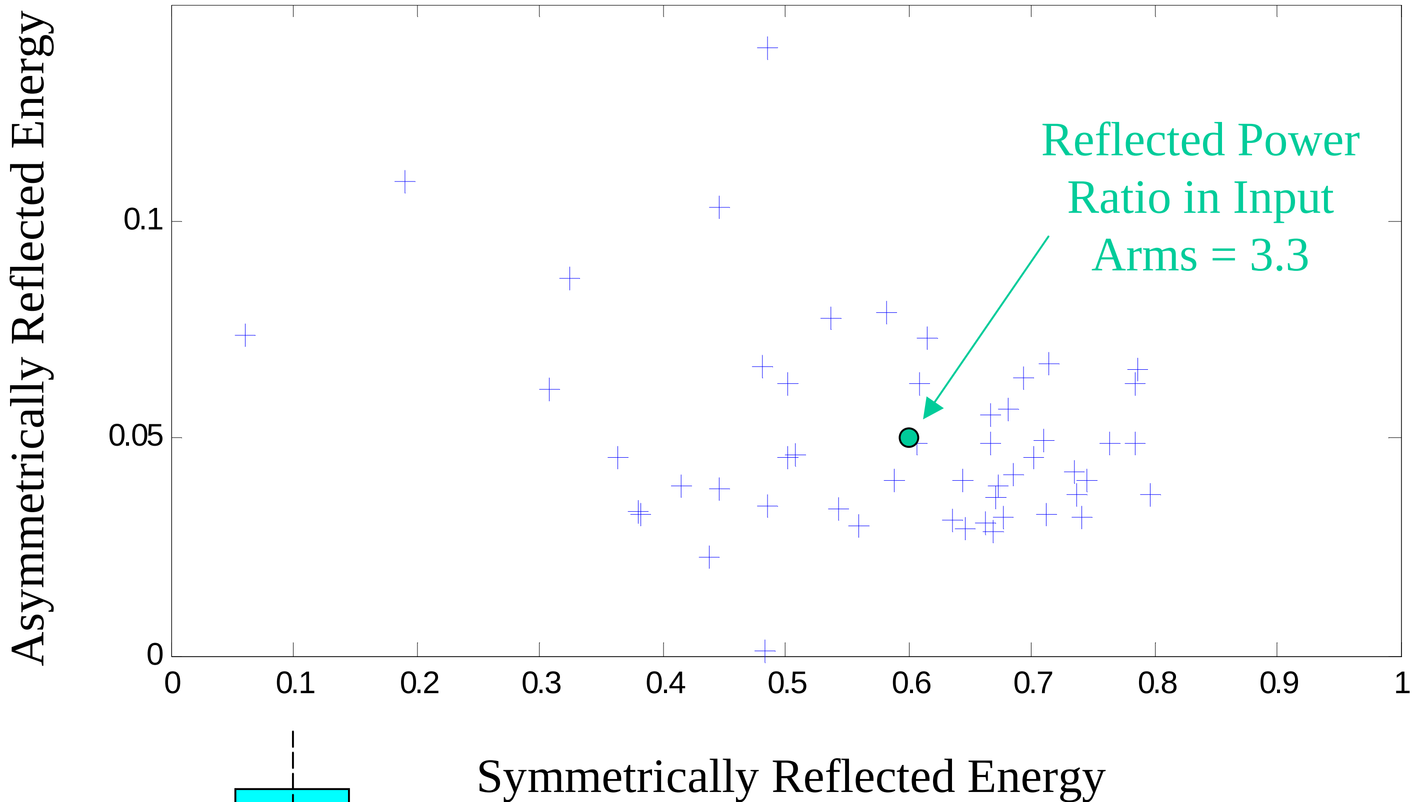
73 MV/m, 400 ns Pulse Width

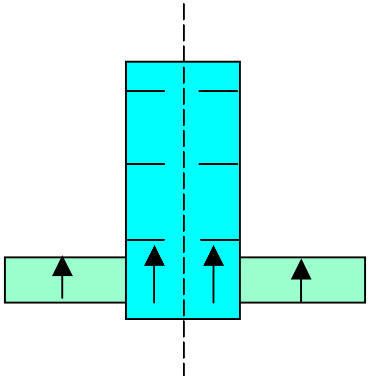


Correlation of Fractional Asymmetric and Symmetric Reflected Energy from T53VG3RA for Input Coupler Breakdowns



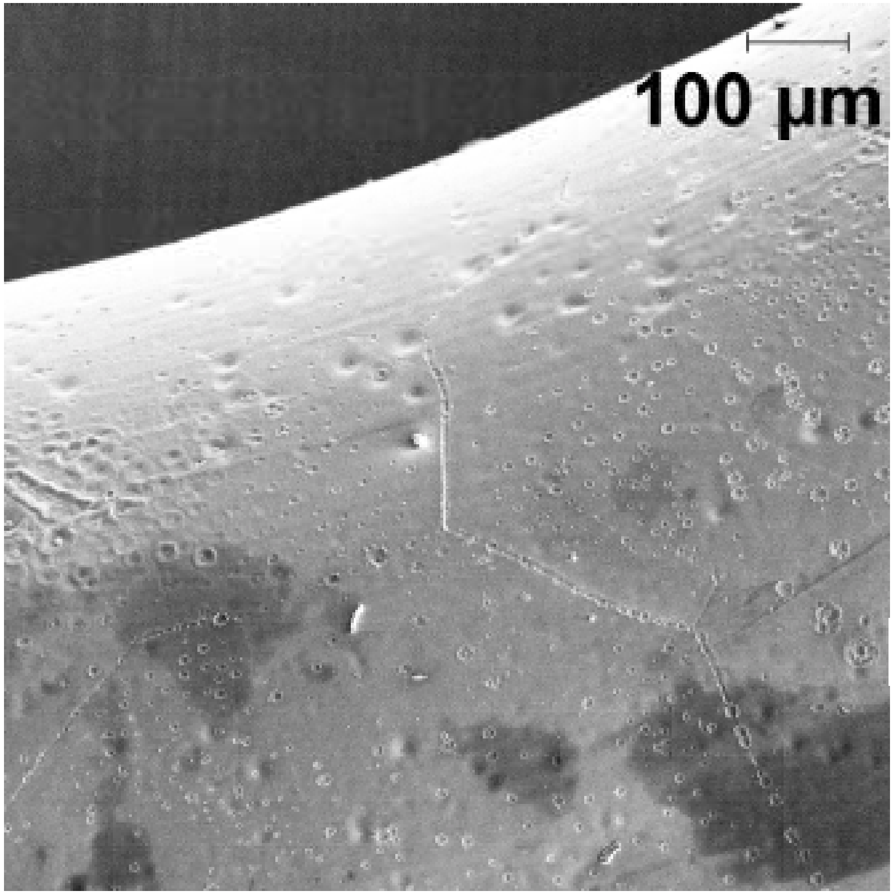
Structure and Input Couplers

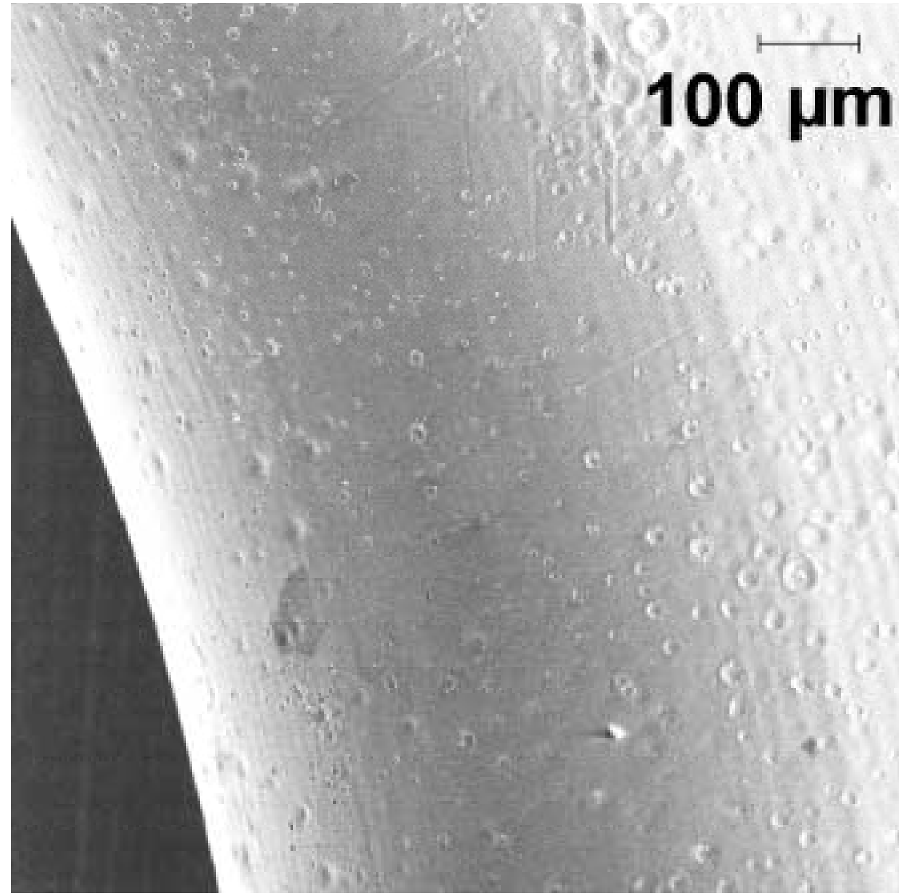




Ratio of Events with Max Reflected Power in Right/Left Inputs ~ 1

Pitting on the T53VG3R Input Coupler Iris



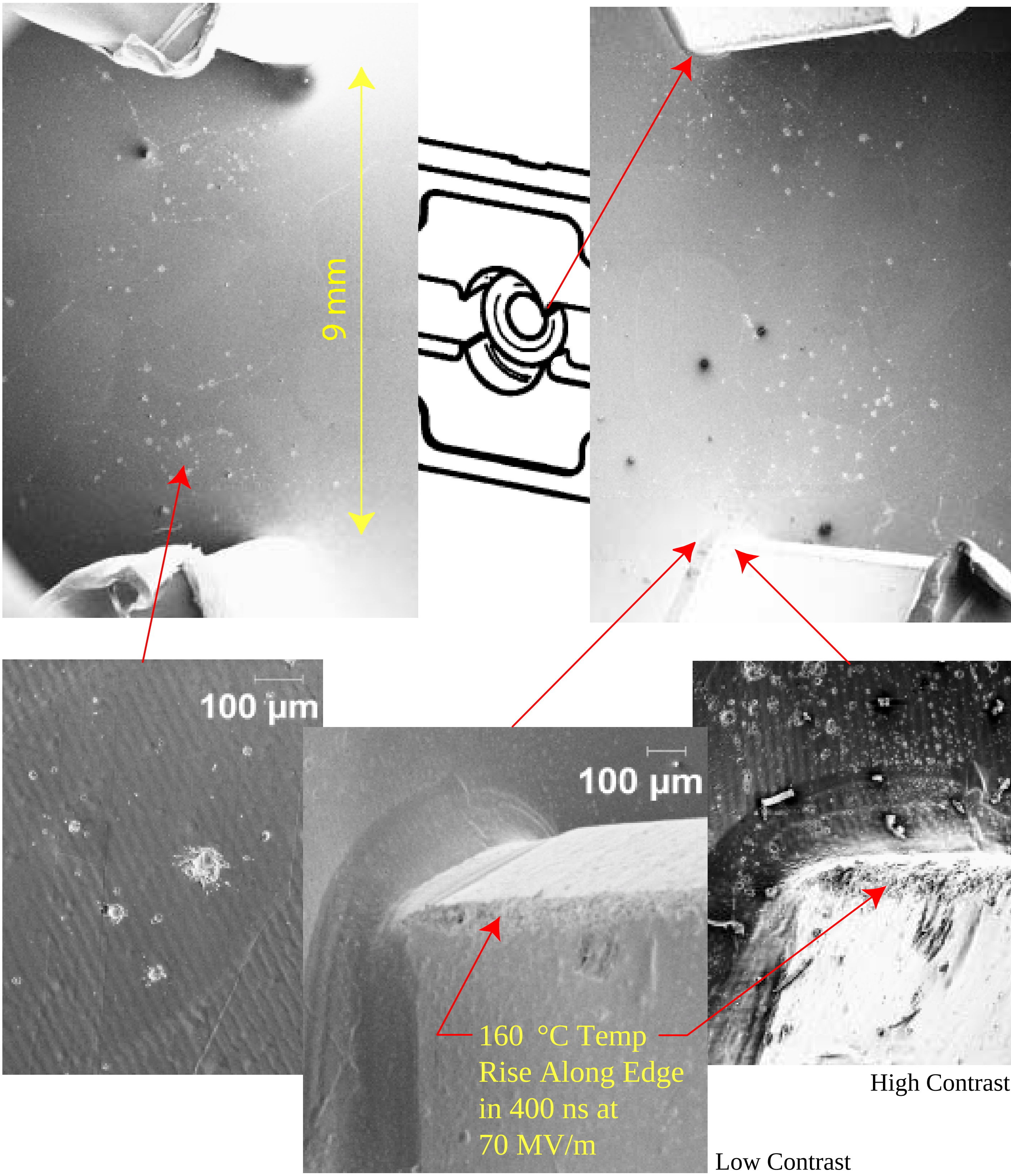


Rough Estimate of Number of Pits on Iris = 30,000

Number of Coupler Breakdown Events = 1500

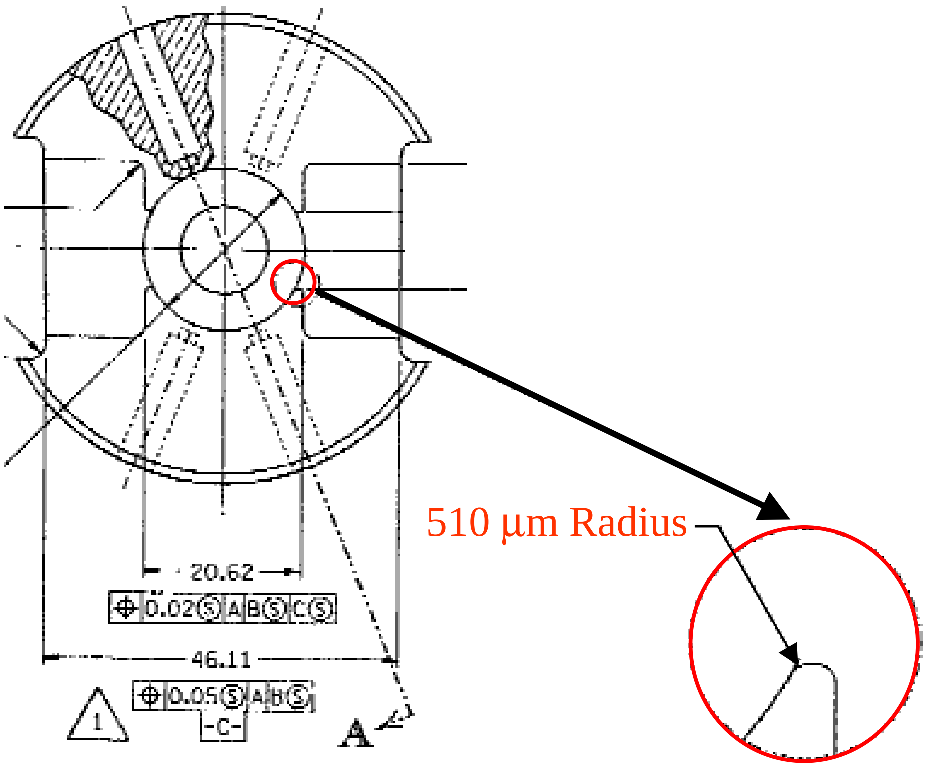
➥ Number of Pits per Breakdown = 20

SEM Photos of T53VG3R Input Coupler WG Openings

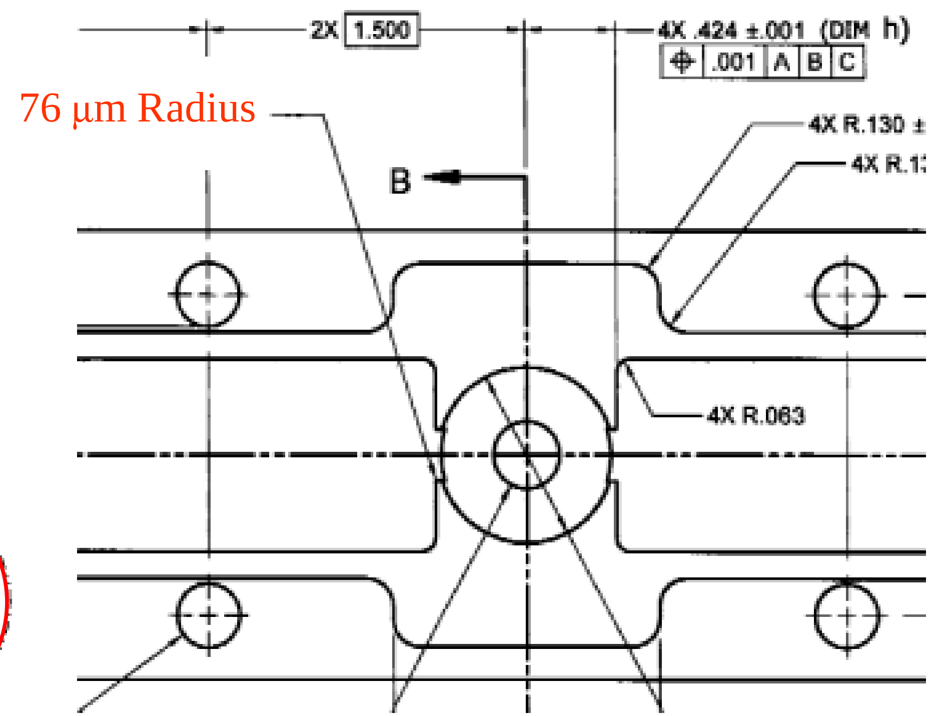


Input/Output Coupler Cells

RDDS1 and Earlier
DDS and DS Structures



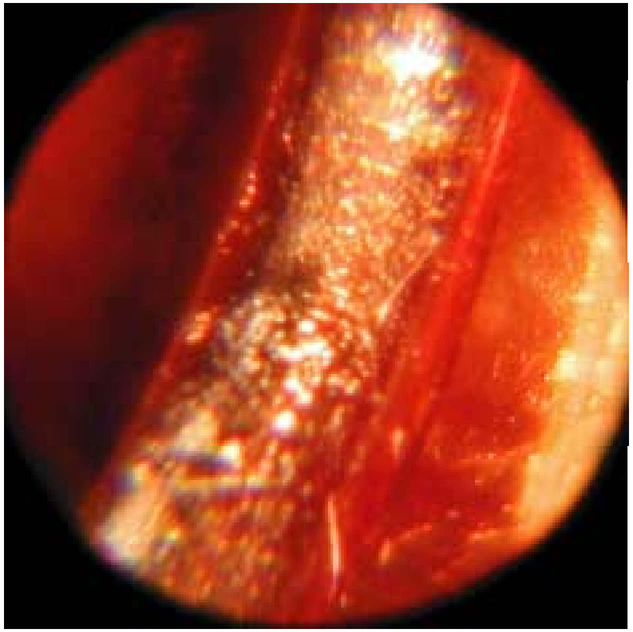
DS2S, T Structures
And Current H Structures



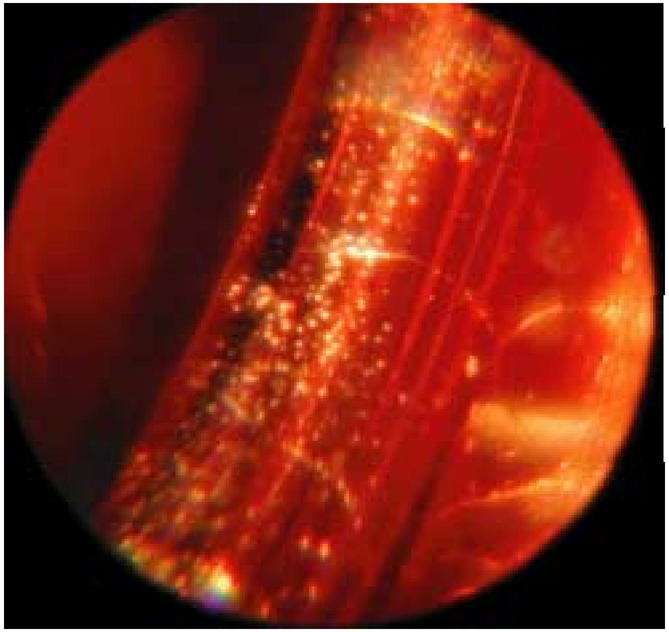
➔ Will Use 3000 µm Radius in Future Structures (ΔT = 20-40 °C)

T53VG5R Iris Boroscope Photos

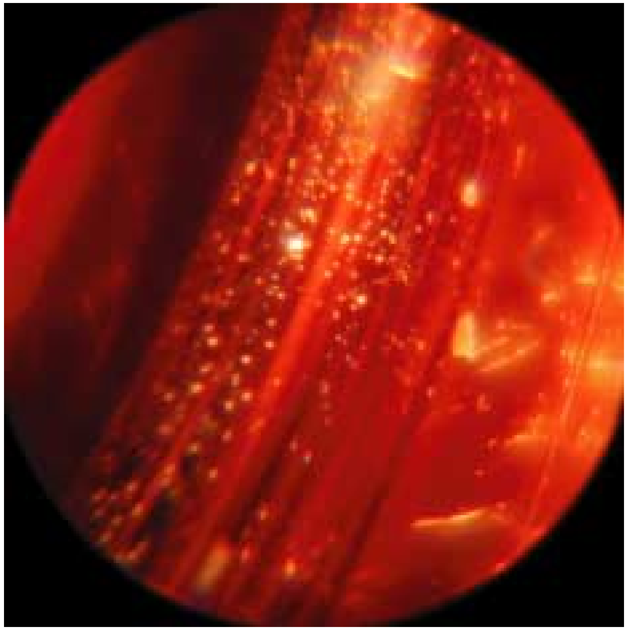
Coupler Iris (= 1)



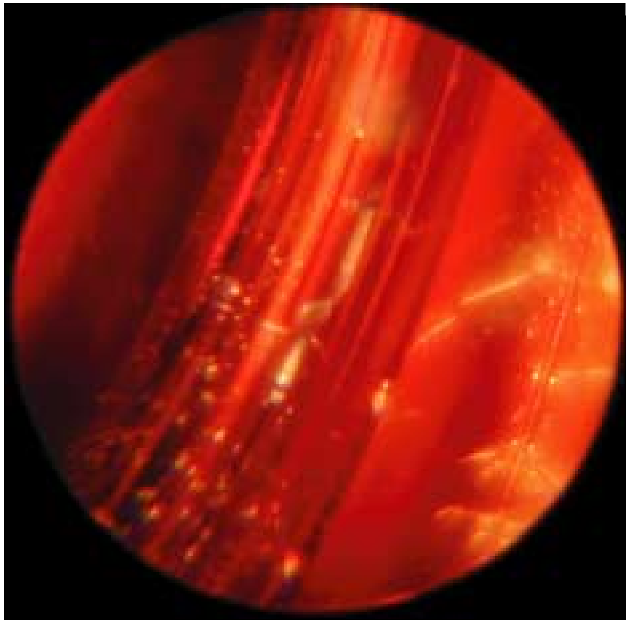
Iris 2



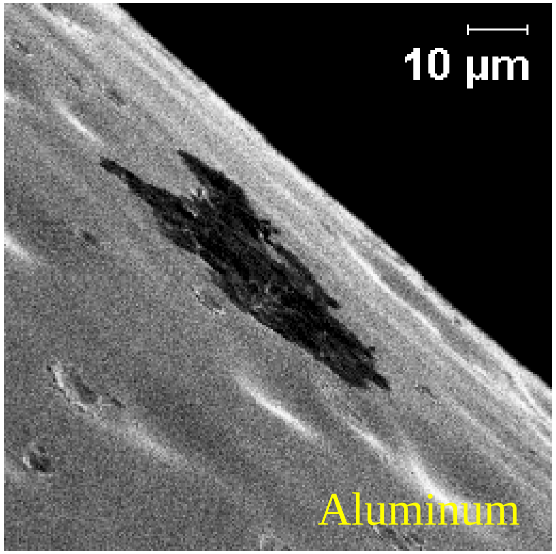
Iris 3

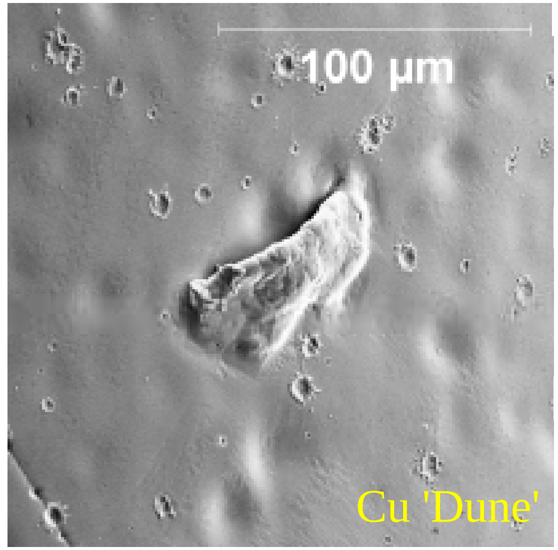


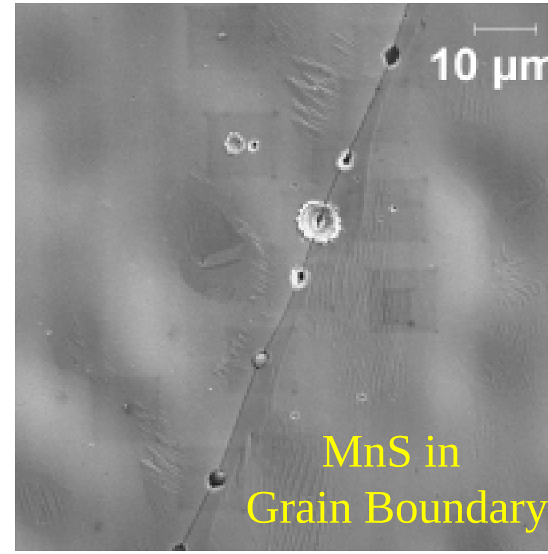
Iris 4

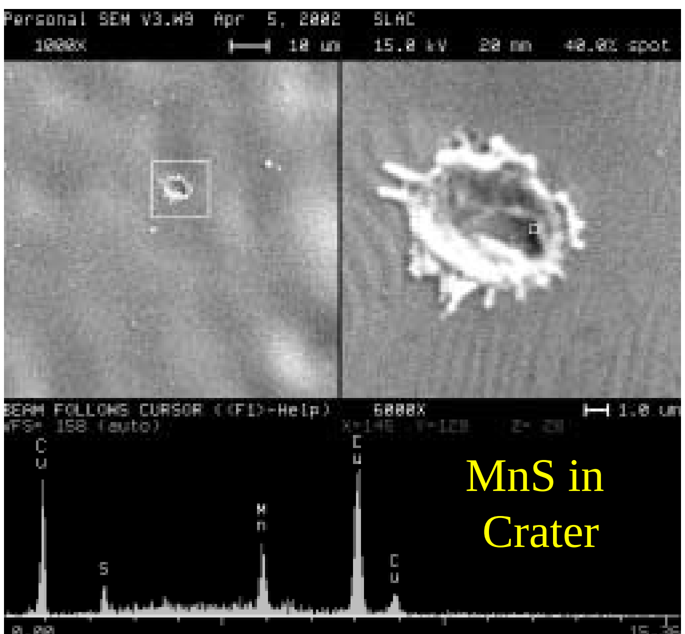


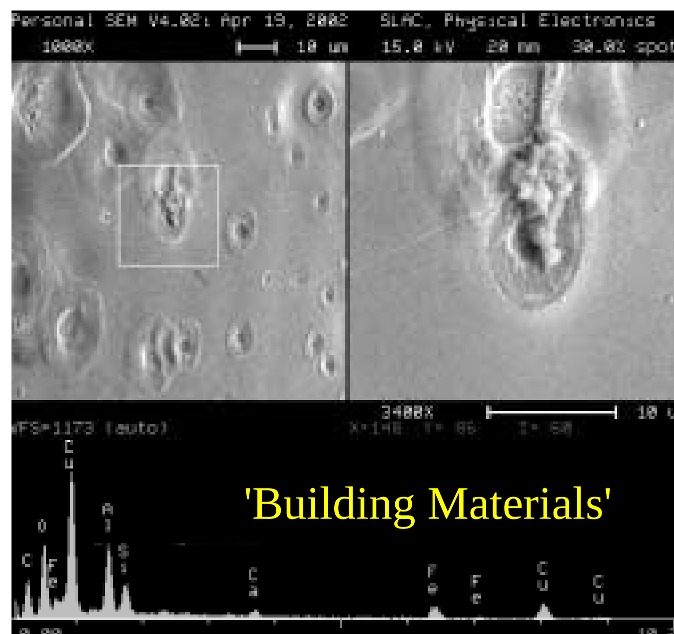
SEM Photos of T53VG3R Input Coupler Iris Features











Inline Taper Style Input Coupler

H60VG3 inline taper 23cell model

n	a	b	t	anose
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
3	5.33000	11.74007	4.70000	4.20000
2	5.75000	12.22401	5.40000	4.80000
1	6.50000	12.72889	5.80000	4.60000
1	6.50000	12.72889	5.80000	4.60000
2	5.75000	12.22401	5.40000	4.80000
3	5.33000	11.74007	4.70000	4.20000
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
4	5.27621	11.49779	4.44535	2.22268
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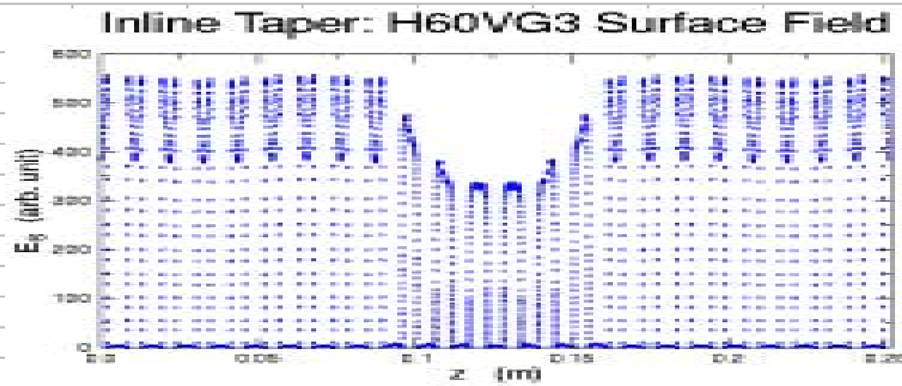
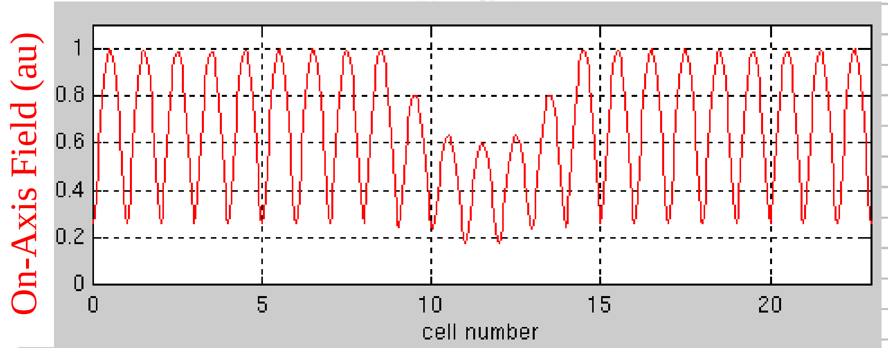
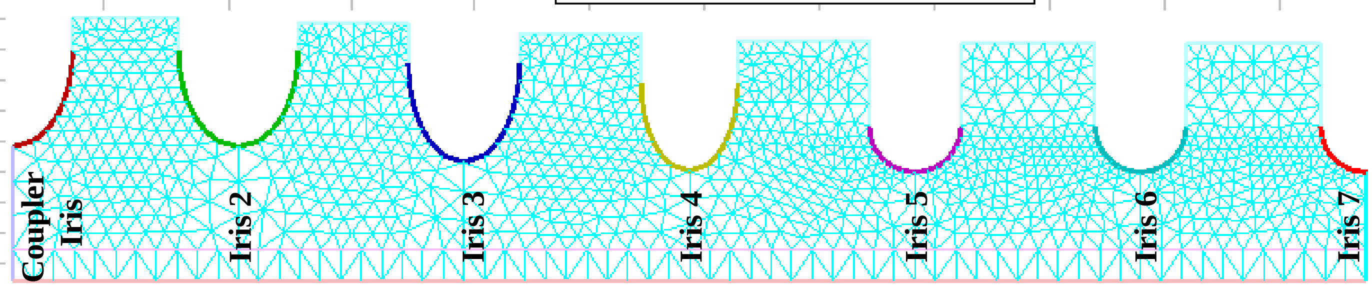


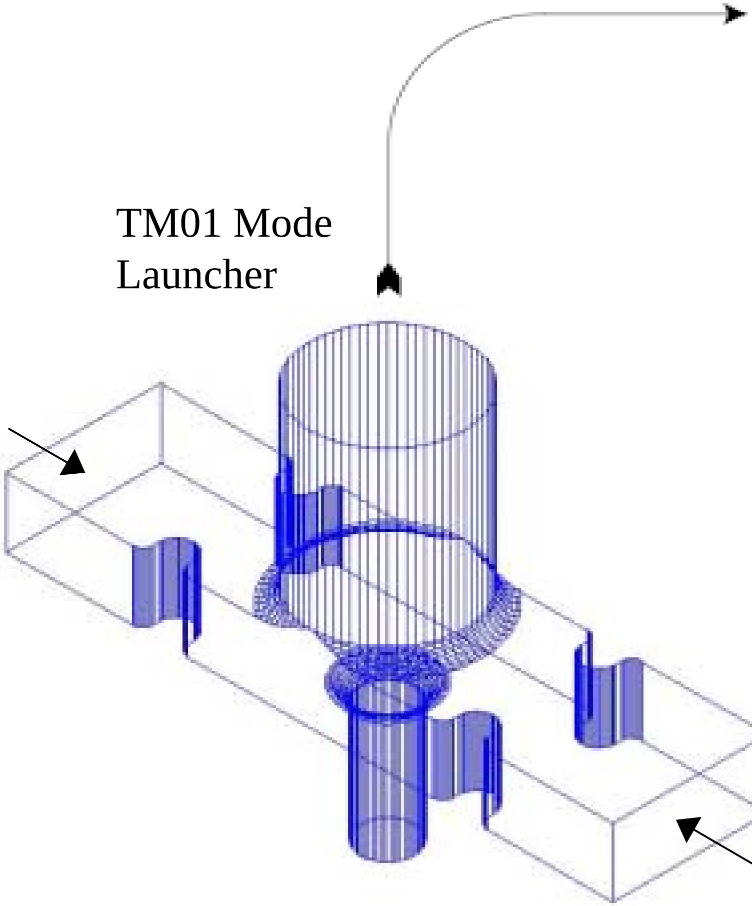


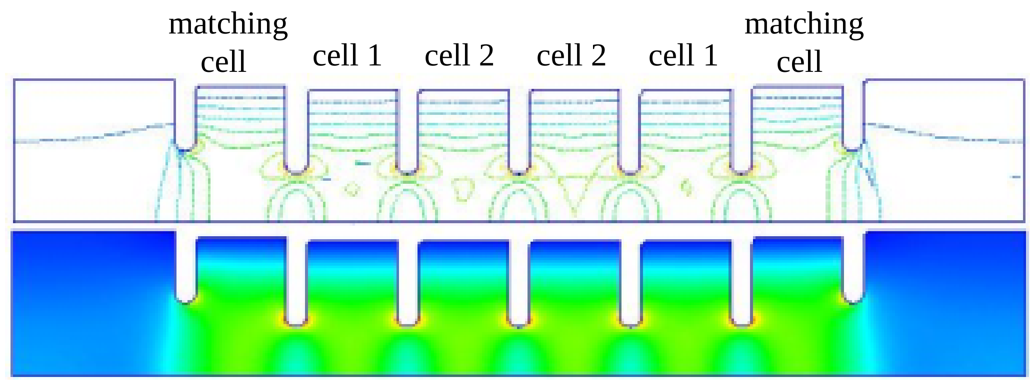
$$b_{ave} = \frac{b_l * 0.5 * (L - t_l) + b_r * 0.5 * (L - t_r)}{L - 0.5 * (t_l + t_r)}$$



Zenghai Li

Mode-Convertor Type Input Coupler





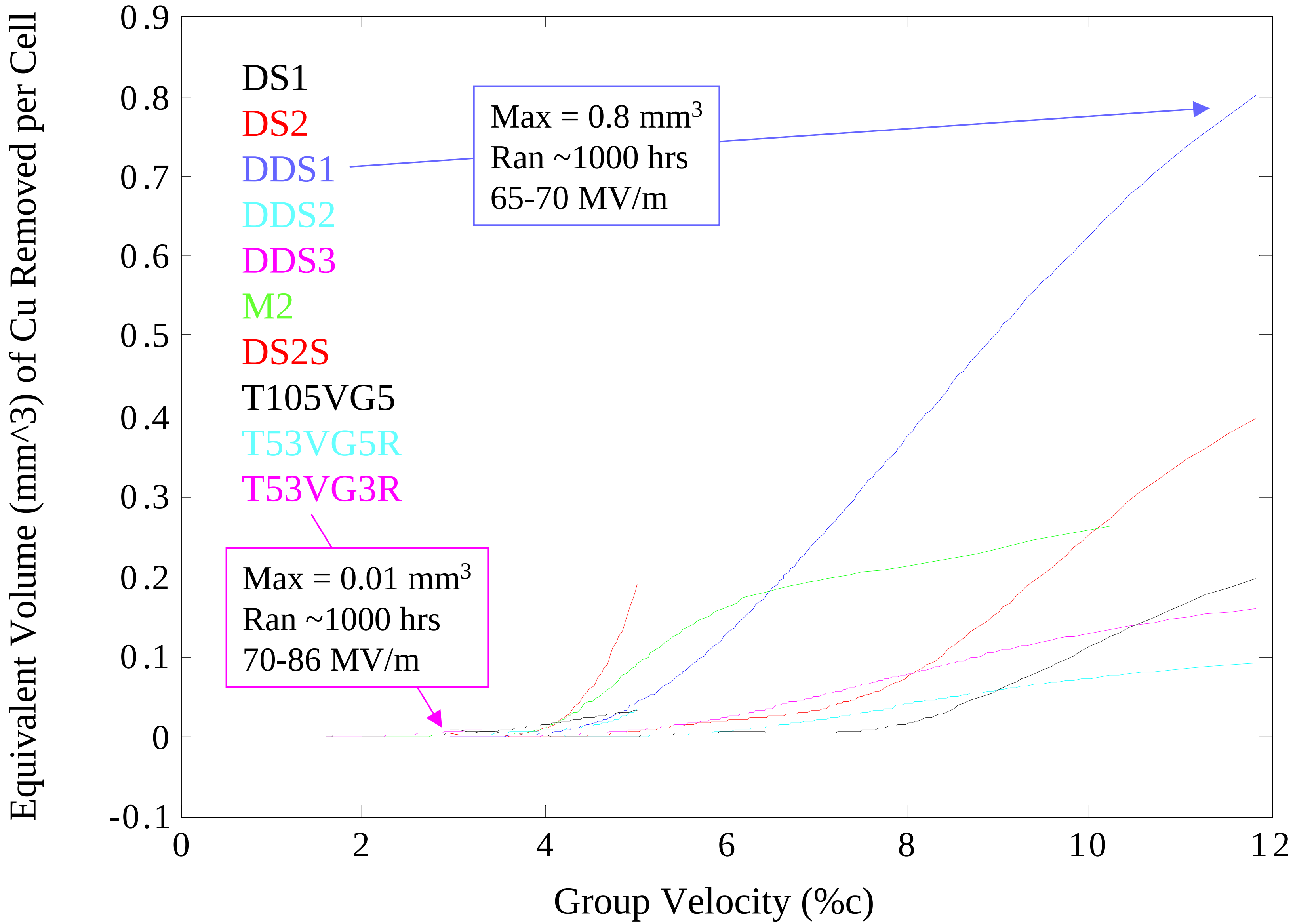
Field Plots for Waveguide Matching into Traveling-Wave Accelerator Structure

C. Nantista, S. Tantawi, and V. Dolgashev

Structure Performance Metrics

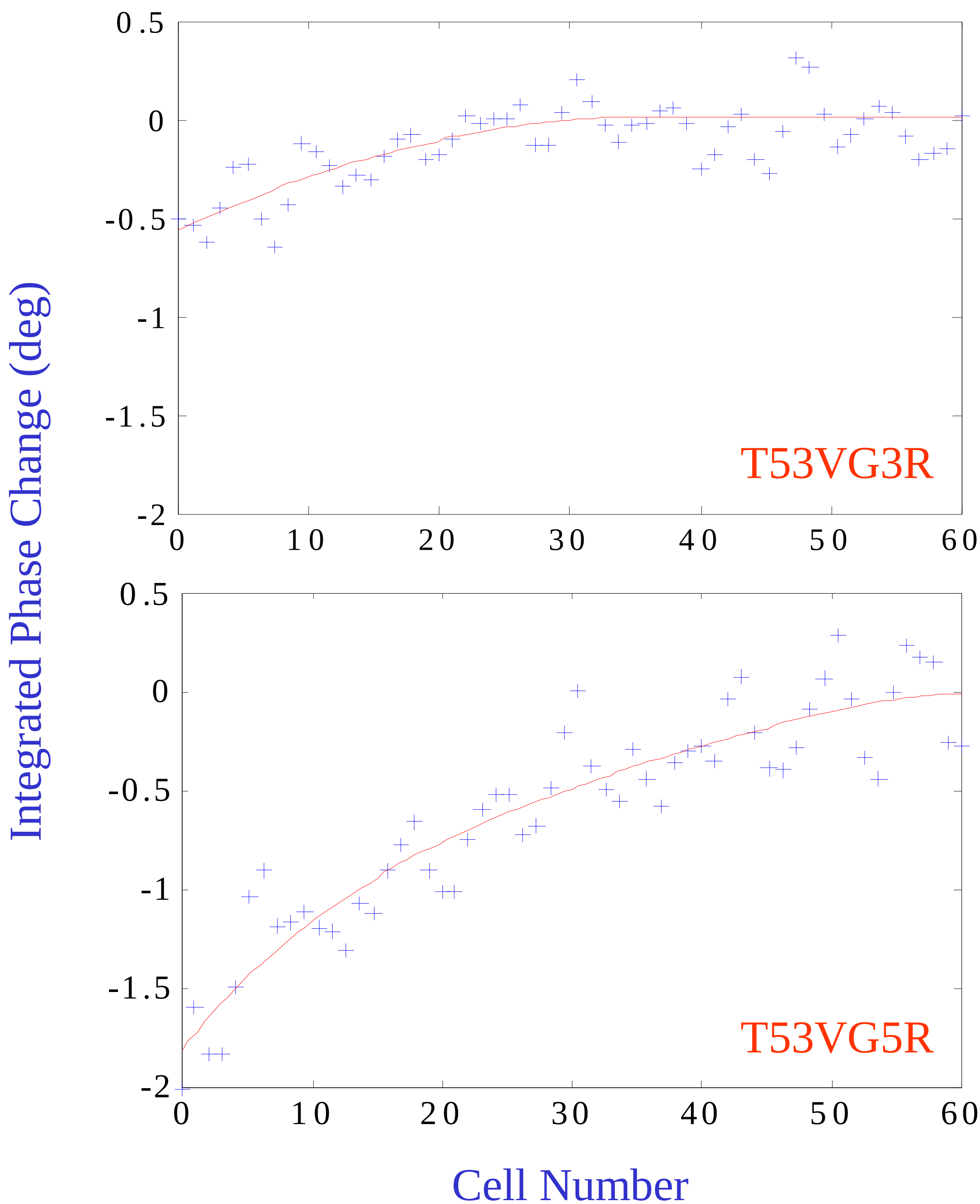
- ✓ Time (or # of trips) it takes to increase the gradient (process) to a level about 10% above the desired operating value.
- ✓ Trip rate at the operating gradient (70 MV/m in NLC).
- Damage (phase shift) from processing and operation.

Structure Damage

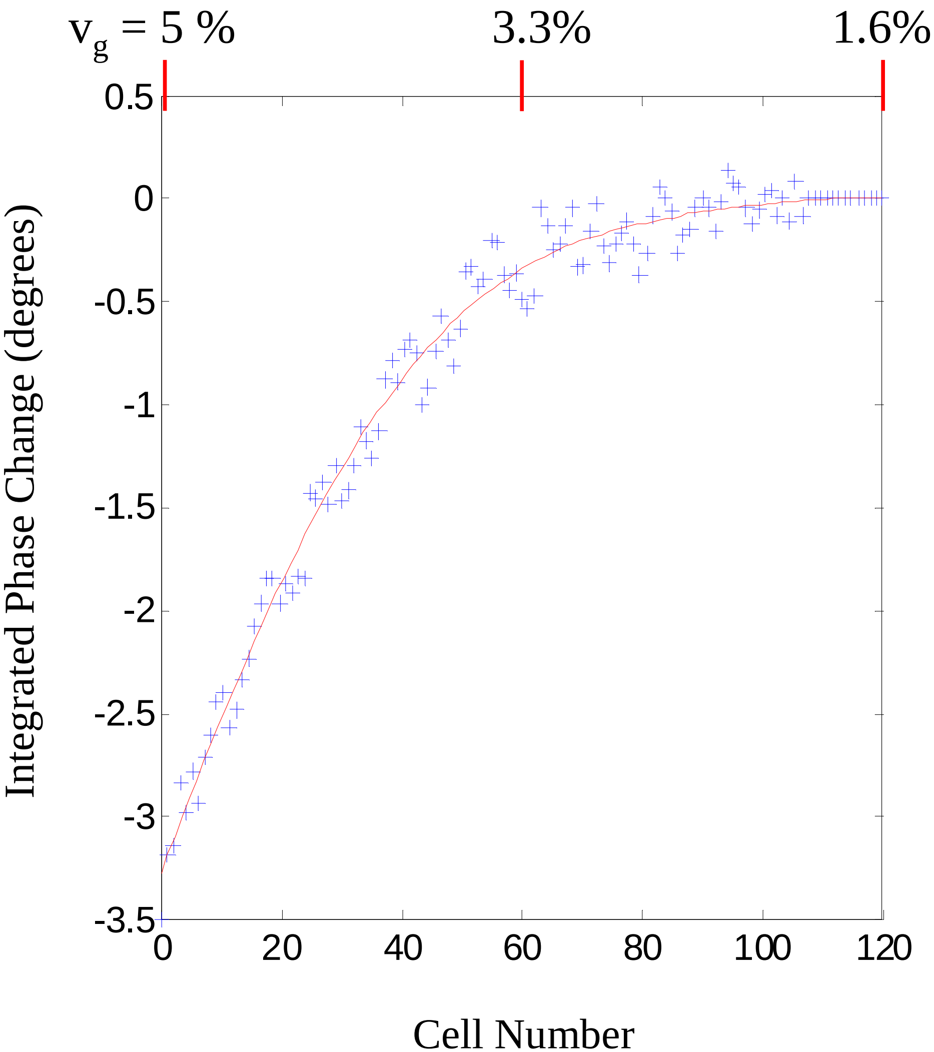


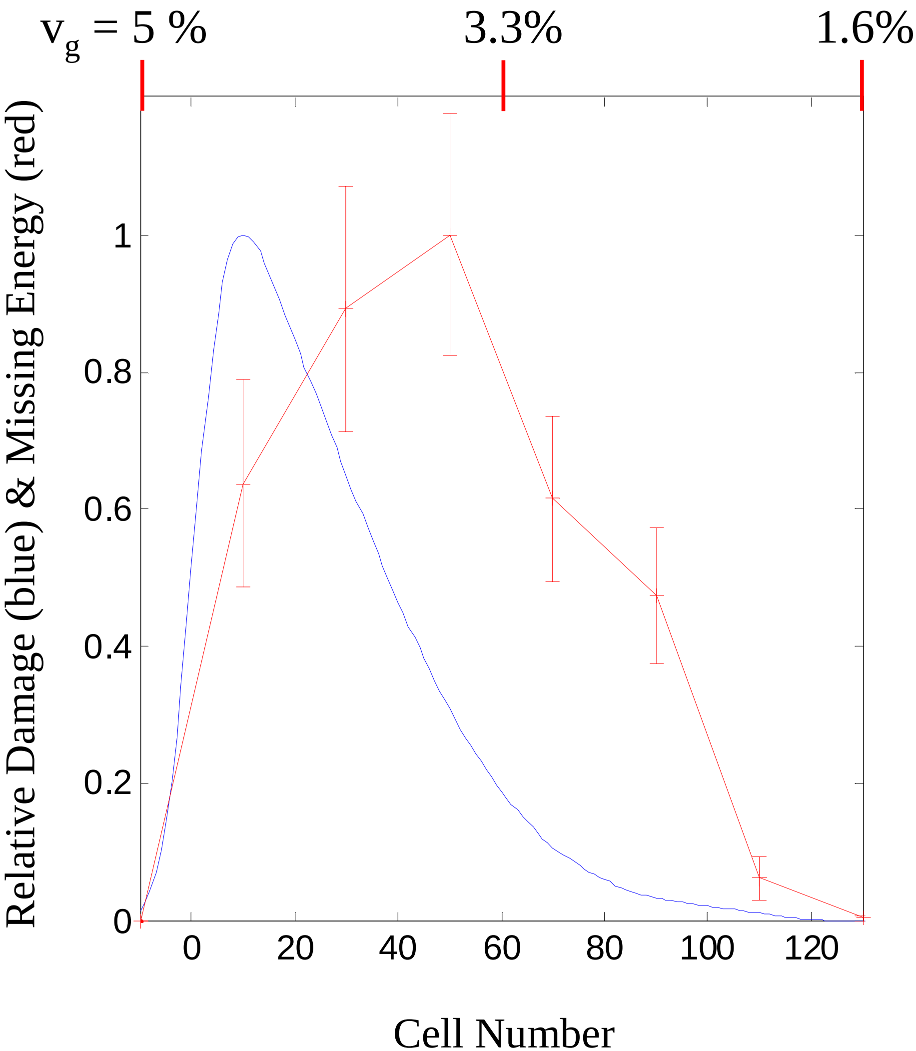
Bead Pull Measurements of T53VG3/5 Integrated Phase Change (deg) After 1200 hours of Operation

Ratio of T53VG5R to T53VG3R
Phase Shift per Breakdown = 5



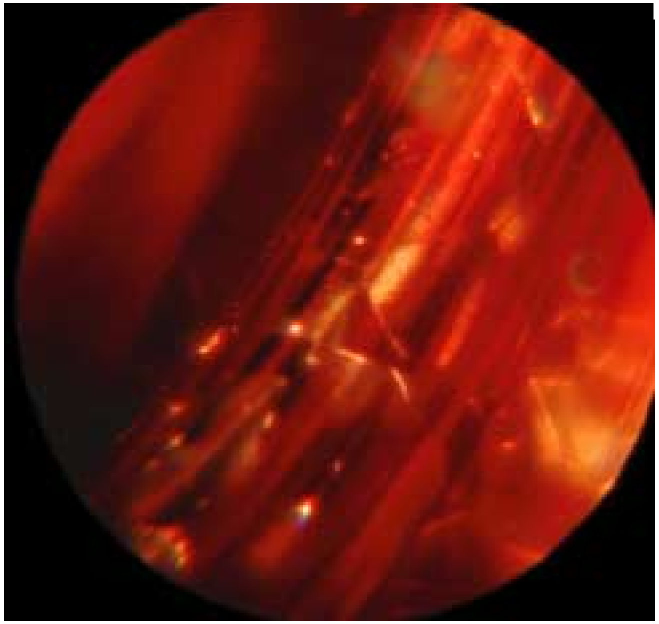
T105VG5 Damage and Missing RF Energy Distributions



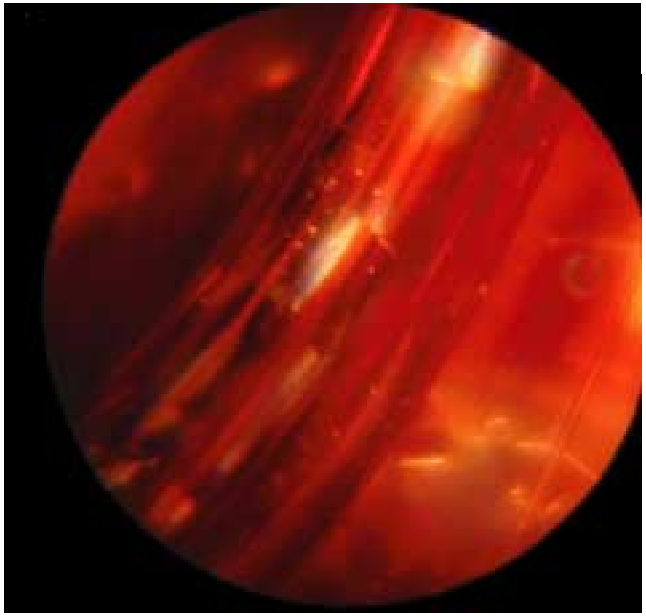


T53VG5R Iris Boroscope Photos

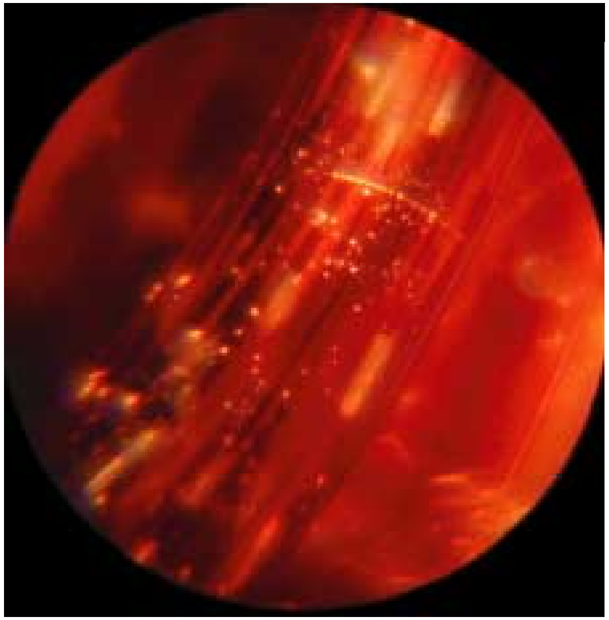
Iris 11



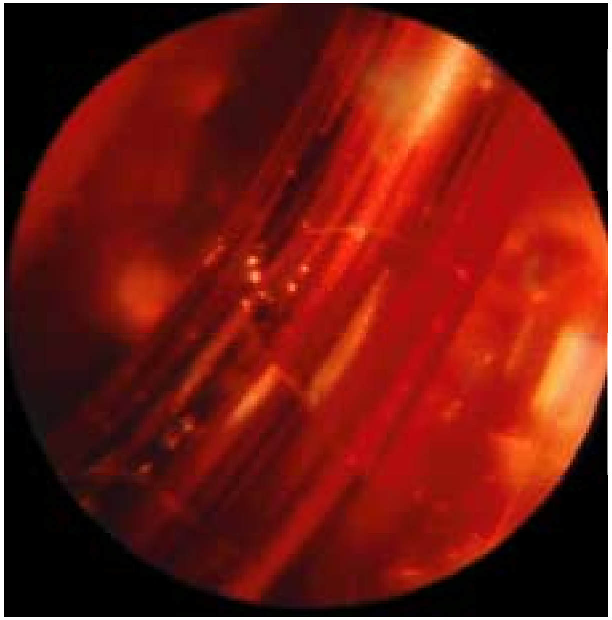
Iris 12



Iris 13



Iris 14



What is a Tolerable Phase Advance Change for NLC ?

A phase advance change reduces the effective structure gradient.

Suppose, as a worst case,

Phase change increases at a constant rate

No attempt is made to correct it (e.g., increase temperature),

Then for a phase change of 0.5° per 1000 hours of 120 Hz operation,

Effective gradient decreases 5% in 20 years.

For the first T53VG3 structure, the total phase change was

0.8° per 1000 hours of equivalent 120 Hz operation.

Lessons Learned from the ‘T’ Structures

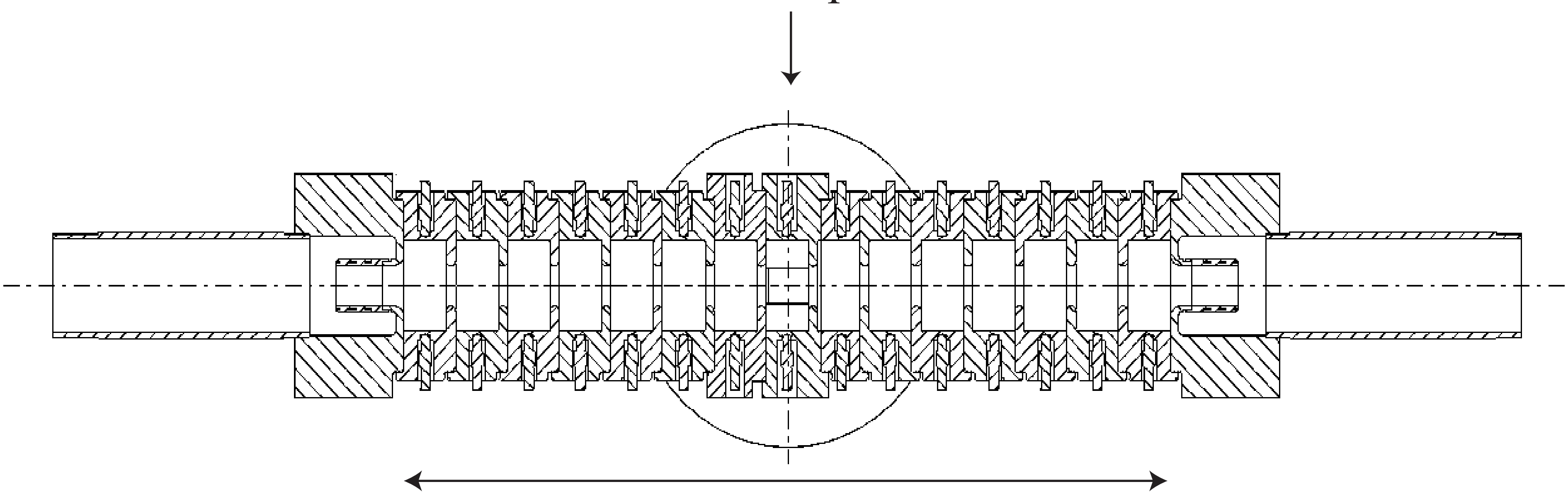
- Can achieve higher gradients with less damage at lower group velocity – 70 MV/m is well below the ‘spitfest’ regime in these structures.
- Breakdown rate is dominated by coupler events and is unacceptably high. These events are likely related to pulse heating at the waveguide openings in the coupler cells.
- Can achieve tolerable breakdown rates in the body of the structures at 70 MV/m, 400 ns.
- Although adopted better handling and pre-processing procedures for the structures, still have large variation in the initial processing rate.

S20PI - First Prototype Standing Wave Cavity

Beta = 1.0, Rs = 68.3 MΩ/m, Q_o = 8860

Field Risetime = 124 ns, Bandwidth = 450 MHz

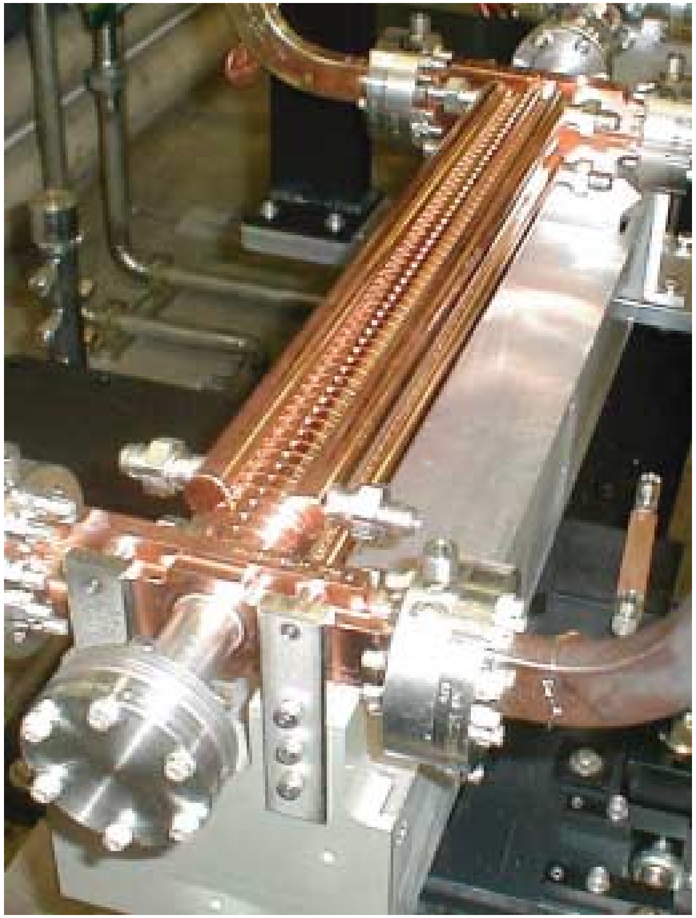
Center Feed: 14 MW Input Yields 70 MV/m



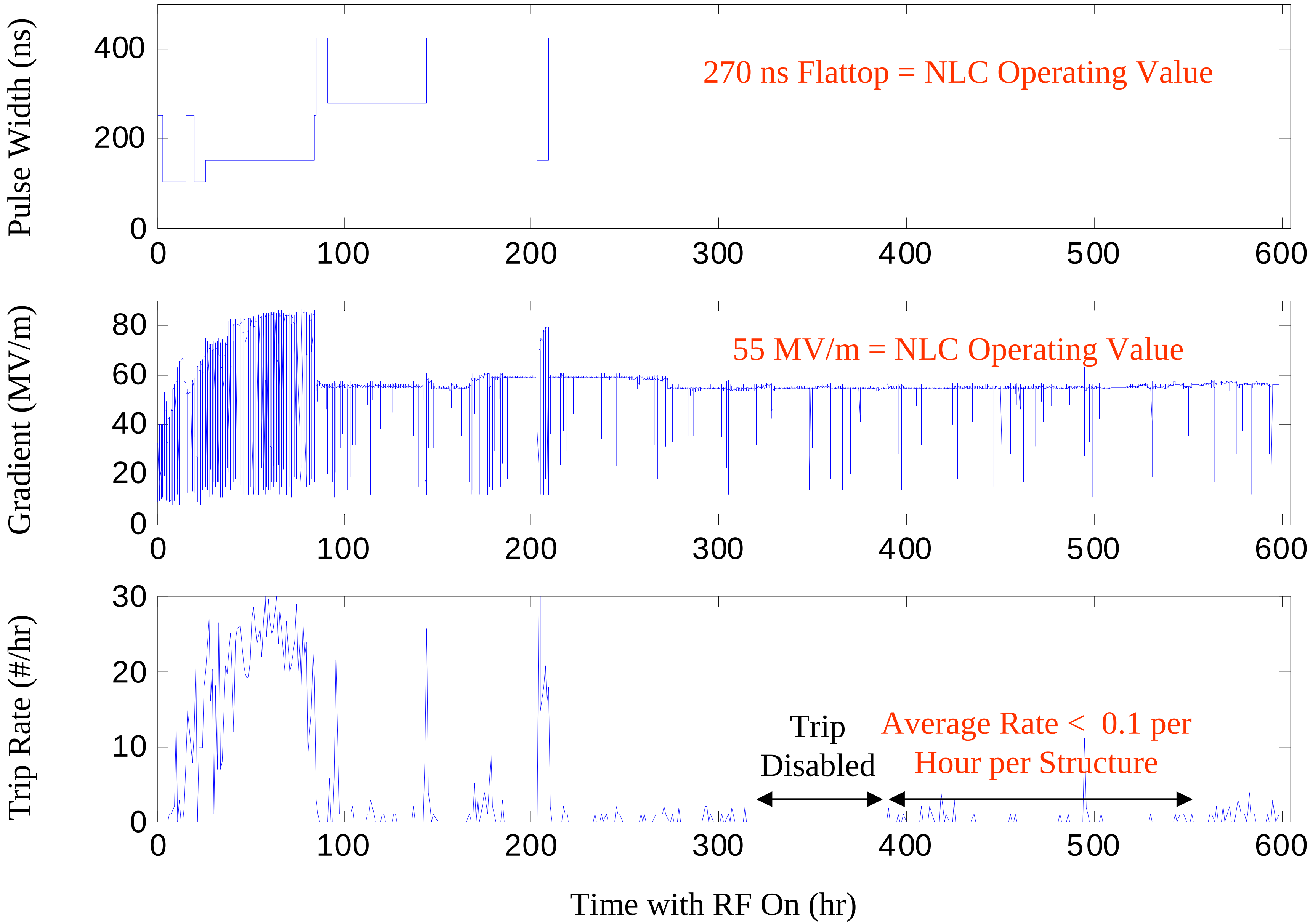
15 Cells, 194 mm

S20PI Assembly in NLCTA

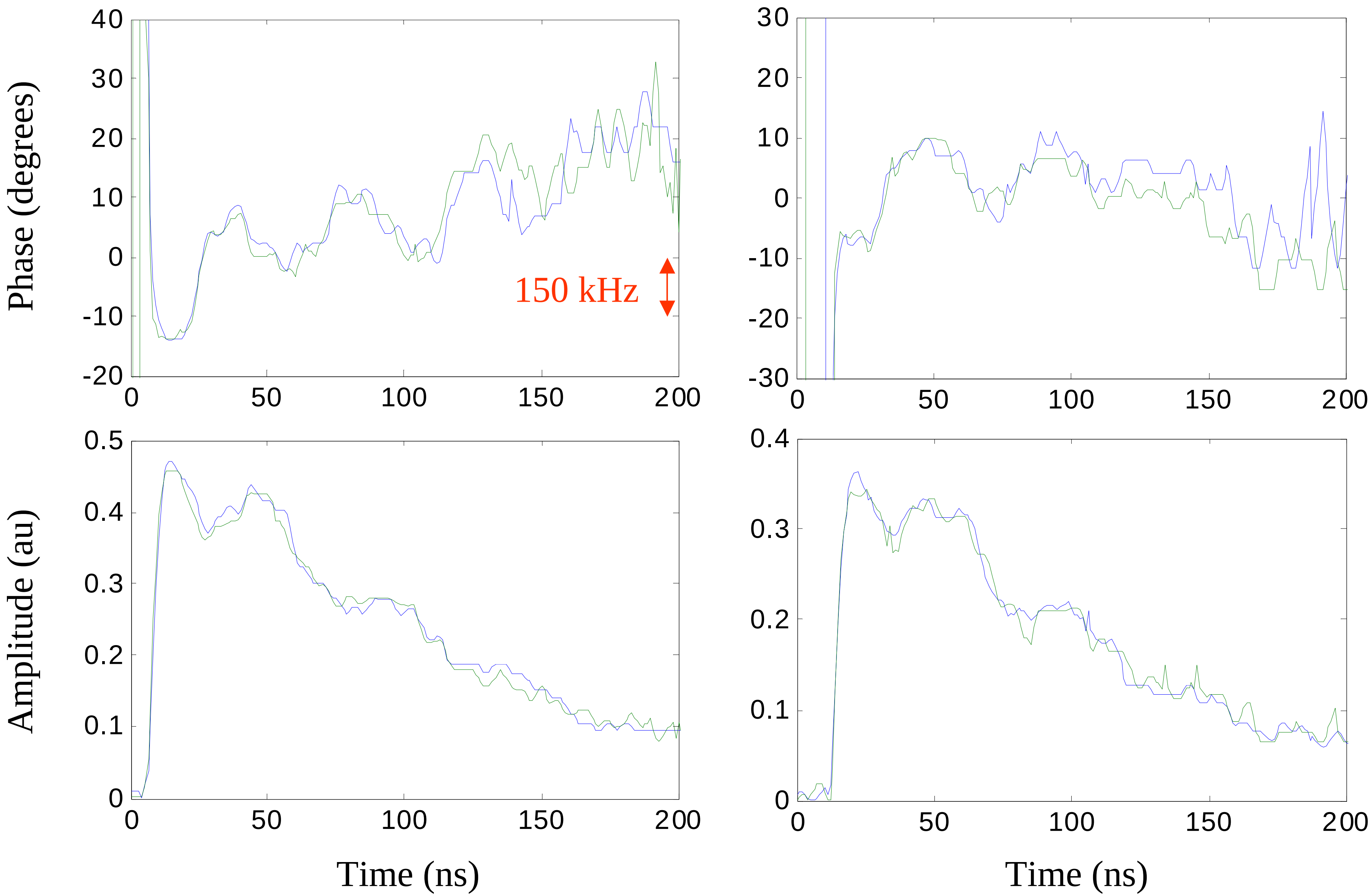
T53VG3R



SW20PIL Processing History



SW20PIL Beam Induced RF Measurements
Before (green) and After (blue) 600 Hours of Operation



Next Generation TW X-Band Structure

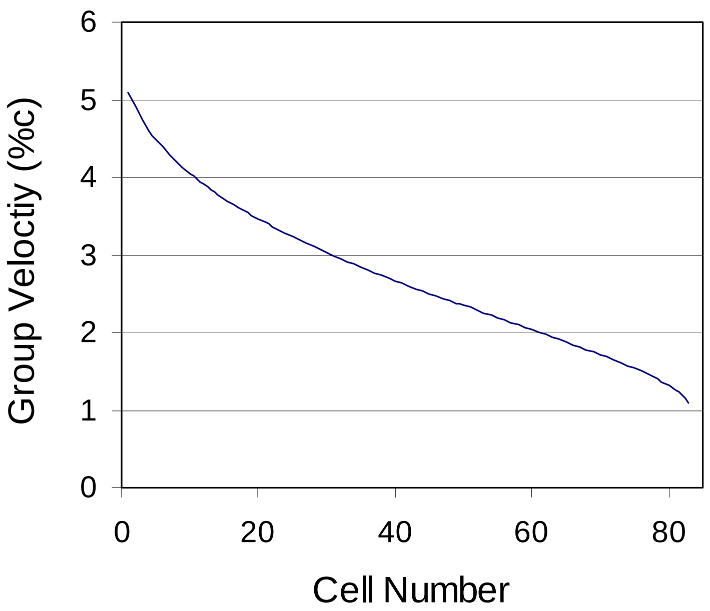
Increase Phase Advance to 150^0/cell (from 120^0/cell)

To Achieve Lower Group Velocity: 5.1 → 1.1 % (11.8 → 3.0 %)

with

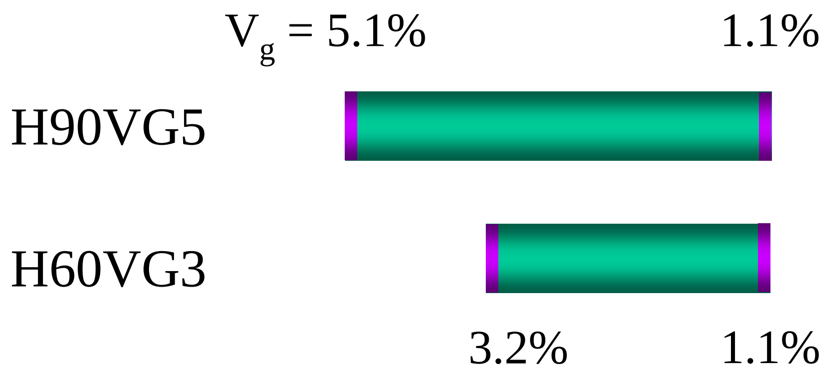
Same Average Iris Radius / $\lambda = 0.18$

- Structure Length: 0.9 m (1.8 m)
- Cell Length: 10.9 mm (8.7 mm)
- Number of Cells: 83 (206)
- Input Power: 85 MW (170 MW)
- Unloaded Grad: 70.0 (72.4 MV/m)
- Es/Ea: 2.5 → 2.1 (3.0 → 2.2)



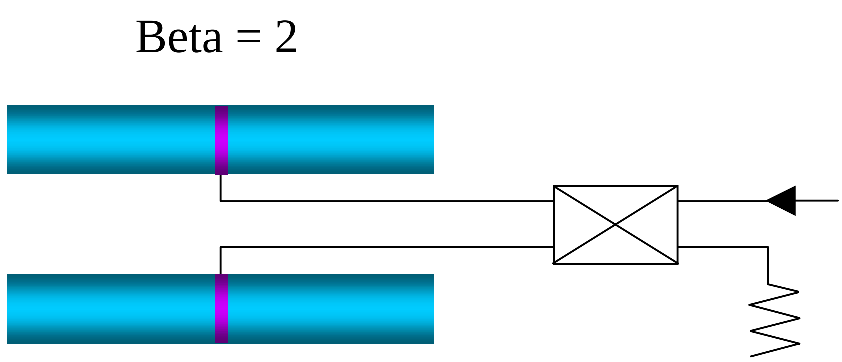
Next Round of NLCTA Tests

May-Aug



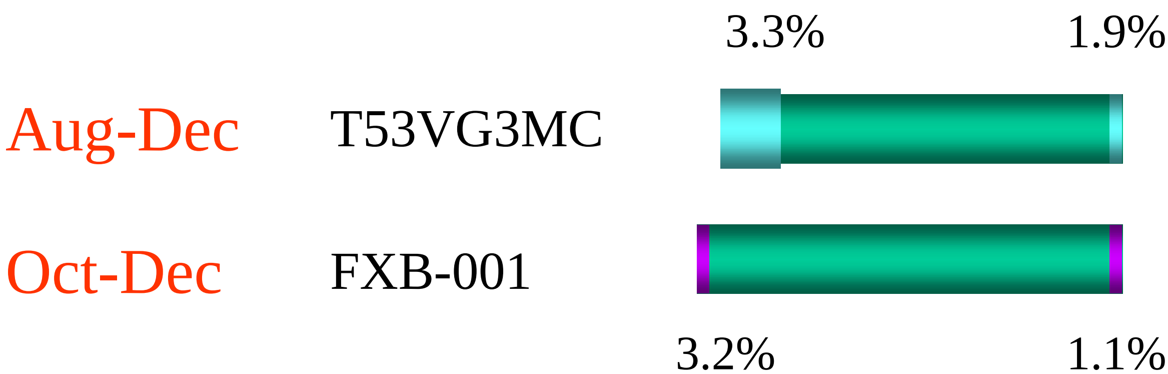
Tests higher phase advance per cell (150 deg) structures with low group velocity and a larger iris size ($a/\lambda = 0.18$) for acceptable wakefields in NLC. Structures are detuned and have reduced field couplers.

May-July

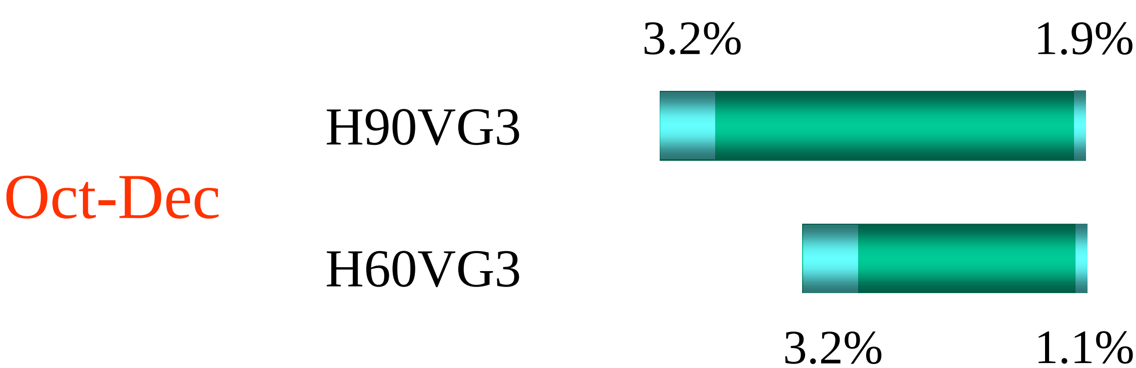


Tests one of three standing wave structure types (S20a565R) being developed to provide detuning. Structures have reduced field input couplers and a lower surface-to-accelerator field ratio (2.1 versus 2.6 in previous tests).

Following Round of NLCTA Tests



First test of mode-converter input coupler and reduced temperature rise output coupler with a T-type structure. Also test a 150 degree phase advance structure (H60VG3 design) built by FNAL.

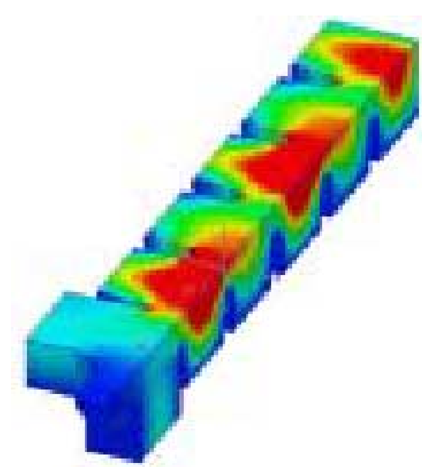


Tests of detuned, high phase advance structures with in-line taper input couplers and reduced field output couplers. All couplers have a reduced temperature rise design.

Future Tests & Structures

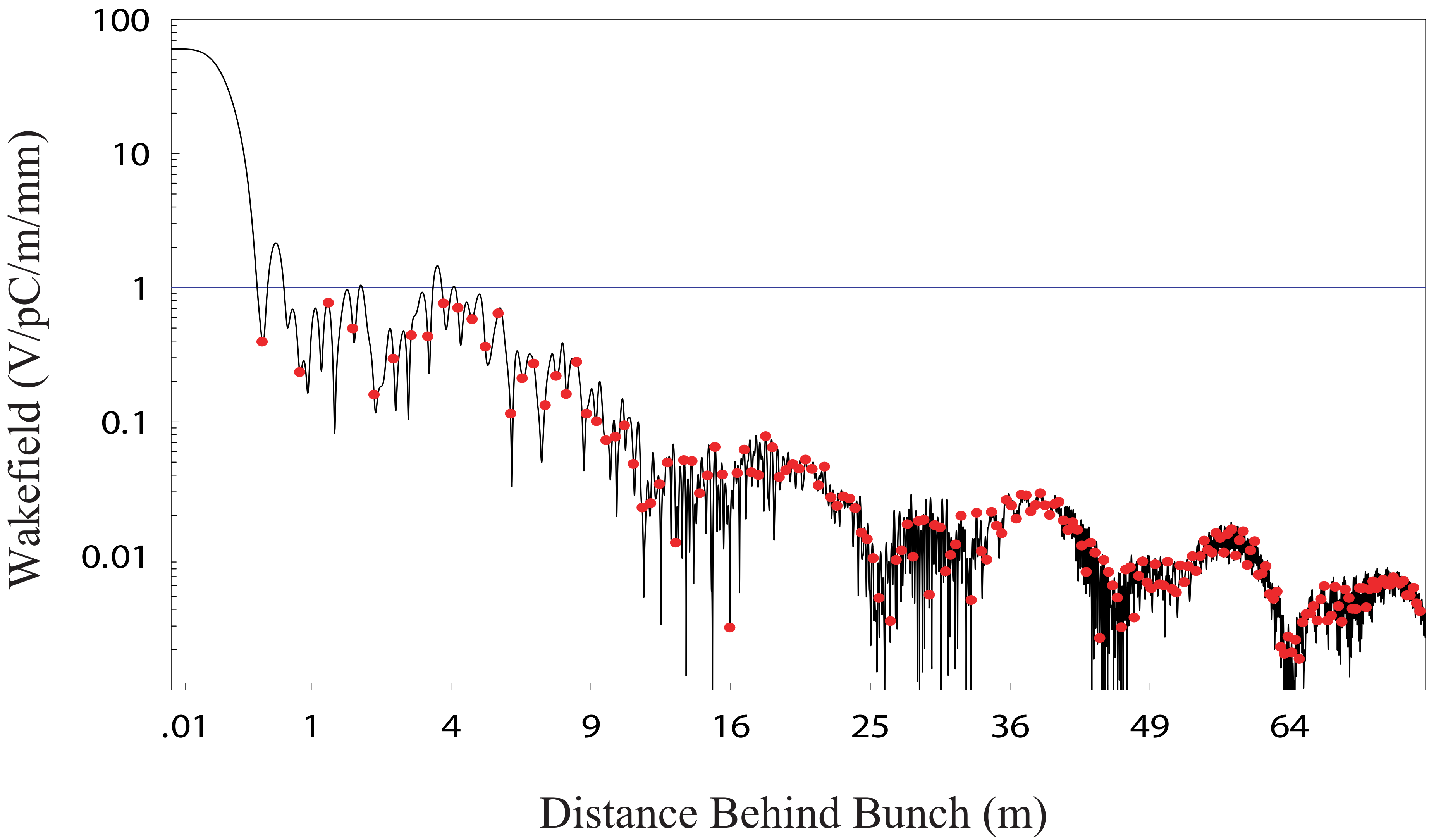
- Tests
  - Continue Autopsy of T53 Structures.
  - Study High Pressure Water Cleaning, Glow Discharge Cleaning, and HV DC Pre-Processing.
- TW Structures
  - H60VG3 with Manifold Damping (H60DDS).
    - Concerned with temperature rise near manifold coupling slots (saw 'soft' breakdowns throughout DDS3).
  - Structure with Constant Loaded Gradient.
  - Structure with Stainless Steel or Mo Iris Tips.
- SW Structures
  - S20 with Various Iris Radii – Set Would Provide Wakefield Detuning.
  - S20 with HOM (15,17,21 GHz) Waveguide Loads (Q ~ 600).

14.8 GHz SW Dipole Field Pattern with a Broadband HOM Coupler



Example of Long-Range Transverse Wakefield for H60VG3 with Manifold Damping and Three-Fold Interleaving

(Red = Subsequent Bunch Locations)



Roger Jones

High Gradient Summary

- Attacking High Gradient Problem on Many Fronts
- Encouraged by the Results During the Past Year
  - Approaching Required NLC Performance Levels with Low Group Velocity Traveling Wave Structures
  - Standing Wave Structures Appear to be a Viable Alternative
- A High Priority Remains to Develop Structures with Appropriate Iris Size and Wakefield Suppression
- Longer Term Structure Testing Will Be Part of the Eight-Pack Program at NLCTA