Research and Development for Ultra High Gradient Accelerator Structures

S. Tantawi
For the SLAC team and collaborators
This work is made possible by the efforts of SLAC’s
  – S. Weathersby, C. Hast, ARD Test Facilities
  – Z. Li, Advanced Computation

In close collaboration with:
  – Y. Higashi, KEK, Tsukuba, Japan
  – B. Spataro, INFN, Frascati, Italy

**Single-Cell-PBG structures** done in collaboration with R. Temkin, B. Munroe, R. Marsh, MIT

**TW structures** done in collaboration with W. Wuensch and CERN CLIC team, T. Higo and the KEK team

**T18+resonat ring** done in collaboration with J. Haimson and Haimson Research Corporation, data processing A. Palaia from Uppsala University
International Collaboration on High Gradient Research
The Challenge

What gradient can be reliably achieved using warm technology?

  - The authors report experimental results showing that the Surface Electric Field limit at 9.3 GHz (X-Band) exceeds 572 MV/m in pulses of up to 4.5 microseconds
  - Results predict an on-axis gradient of at least 250 MV/m

• Reality sets in (by 2001):
  - The operating limit determined by experiments on the NLC Test Accelerator showed that high gradient accelerator structure operating at X-band would not survive long term operation without computer/feedback protection and the breakdown rate above 65 MV/m can not be tolerated for a collider application.

• The challenge: we wish to understand the limitations on accelerator gradient in warm structures

• Our goal is to push the boundaries of the design to achieve:
  - Ultra-high-gradient; to open the door for a multi-TeV collider
  - High rf energy to beam energy efficacy, which leads to an economical, and hence feasible designs
  - Heavily damped wakefield
Introduction and Motivations

• The collaboration started at the wake of the Cold vs warm decision that led to the creation of the ILC organization.

• Traditionally linear collider programs dictated the performance of accelerator structures. Our collaboration started with a different philosophy; we would like to find the fundamental limitations on structures and design a collider around an optimized structure.

• We had to address fundamentals early; these include, but are not limited to:
  - Frequency scaling
  - Geometry dependence
  - Materials
  - Surface processing techniques (etching, baking, etc.)
  - Theory
Research and Development Plan

Advanced Features
- Geometrical Effects
- Wake Field Damping
- Distributed Coupling
- Efficient Couplers

Basic Physics Research
- Surface Processing
- Materials
- Frequency Scaling

Test Facilities
- Theory and Modeling
- SW TS (KTL)
- Pulsed Heating (KTL)
- ASTA (KTL)
- NLCTA Station 1
- NLCTA Station 2
- NLCTA 2-Pack
- MIT 17 GHz
- CERN 30 GHz

Research on RF Sources
- Discrete RF Unit
- Two Beam Related

Optimization of Collider Parameters
Basic Physics Research Short/Compact Accelerator Structures

- **Brazed Structures**
  - **Geometrical Studies**
    - Standing wave structures have been studied extensively
    - Travelling wave structures are ongoing
    - Structures with wake field damping features
      - Photonic band gap
      - Choked structures
      - Slotted structures
  - **Material studies**
    - Limited to what one can get for the brazed structure
  - **Low temperature normal conducting structures**

- **Clamped Structures**
  - Material Studies
  - Mixed material structures
  - Surface coatings

- **Joined Structures**
  - Plated Joints
  - Electron Beam welding
  - Low Temperature brazing

- **Structures with View Ports for Fast Diagnostics for Breakdown Phenomenon**
Basic Physics Research Full Size Accelerator Structures

- Resonant Ring Structures
  - Geometrical Studies
  - Martial studies
- CERN Structures
- Dielectric Structures
- New Distributed Coupling Standing Wave Accelerator Structures

Basic Physics Research Others

- Pulsed Heating Setup
  - Material Studies
- Mixed E&H Setup
- Superconducting Material/Low Temperature Material Testing
  - Novel RF materials
  - Stratified materials

RF Sources Research

- Overmoded Magnetrons
- Massively Multimoded Klystrons
- Large signal codes
- Novel RF sources

There are other efforts in the group which is not the subject of this presentation.
High Power Tests of Single Cell Standing Wave Structures

• Low shunt impedance, $a/\lambda = 0.215$, 1C-SW-A5.65-T4.6-Cu, 5 tested
  • KEK=#1…KEK-#4
  • Frascati-#2

• Low shunt impedance, TiN coated, 1C-SW-A5.65-T4.6-Cu-TiN-KEK-#1, 1 tested

• Three high gradient cells, low shunt impedance, 3C-SW-A5.65-T4.6-Cu, 2 tested
  • KEK-#1…KEK-#2

• High shunt impedance, elliptical iris, $a/\lambda = 0.143$, 1C-SW-A3.75-T2.6-Cu-SLAC-#1, 1 tested

• High shunt impedance, round iris, $a/\lambda = 0.143$, 1C-SW-A3.75-T1.66-Cu-KEK-#1, 1 tested

• Low shunt impedance, choke with 1mm gap, 1C-SW-A5.65-T4.6-Choke-Cu, 2 tested
  • SLAC-#1
  • KEK-#1

• Low shunt impedance, made of CuZr, 1C-SW-A5.65-T4.6-CuZr-SLAC-#1, 1 tested

• Low shunt impedance, made of CuCr, 1C-SW-A5.65-T4.6-CuCr-SLAC-#1, 1 tested

• Highest shunt impedance copper structure 1C-SW-A2.75-T2.0-Cu-SLAC-#1, 1 tested

• Photonic-Band Gap, low shunt impedance, 1C-SW-A5.65-T4.6-PBG-Cu-SLAC-#1, 1 tested

• Low shunt impedance, made of hard copper 1C-SW-A5.65-T4.6-Clamped-Cu-SLAC#1, 1 tested

• Low shunt impedance, made of molybdenum 1C-SW-A5.65-T4.6-Mo-Frascati-#1, 1 tested

• Low shunt impedance, hard copper electroformed 1C-SW-A5.65-T4.6-Electroformed-Cu-Frascati-#1, 1 tested

• High shunt impedance, choke with 4mm gap, 1C-SW-A3.75-T2.6-4mm-Ch-Cu-, 2 tested
  • SLAC-#1
  • KEK-#1

• High shunt impedance, elliptical iris, ultra pure Cu, $a/\lambda = 0.143$, 1C-SW-A3.75-T2.6-6NCu-KEK-#1, 1 tested

• High shunt impedance, elliptical iris, HIP treated, $a/\lambda = 0.143$, 1C-SW-A3.75-T2.6-6N-HIP-Cu-KEK-#1, 1 tested

• High shunt impedance, elliptical iris, ultra pure Cu, $a/\lambda = 0.143$, 1C-SW-A3.75-T2.6-7NCu-KEK-#1, 1 tested

• Low shunt impedance, made of soft CuAg, 1C-SW-A5.65-T4.6-CuAg-SLAC-#1, 1 tested

• High shunt impedance hard CuAg structure 1C-SW-A3.75-T2.6-LowTempBrazed-CuAg-KEK-#1, 1 tested

• High shunt impedance soft CuAg, 1C-SW-A3.75-T2.6-CuAg-SLAC-#1, 1 tested

• High shunt impedance hard CuZr, 1C-SW-A3.75-T2.6-Clamped-CuZr-SLAC-#1, 1 tested

• High shunt impedance dual feed side coupled, 1C-SW-A3.75-T2.6-2WR90-Cu-SLAC-#1, 1 tested

Now 30th test is ongoing,
single feed side coupled
1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1
Geometrical Studies

Three Single-Cell-SW Structures of Different Geometries

1) 1C-SW-A2.75-T2.0-Cu
2) 1C-SW-A3.75-T2.0-Cu
3) 1C-SW-A5.65-T4.6-Cu
Different single cell structures: Standing-wave structures with different iris diameters and shapes; $\alpha/\lambda=0.215$, $\alpha/\lambda=0.143$, and $\alpha/\lambda=0.105$

Global geometry plays a major role in determining the accelerating gradient, rather than the local electric field.

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Geometrical Studies

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SLAC
NATIONAL ACCELERATOR LABORATORY
Test of Hard Copper

Hard Copper showed an observable improvements of annealed brazed structures

Clamped Structure with Hard Copper cells

High Gradient Structures--AAC 2010
Page 12
Experiments at cryo temperatures

- Refrigerator head
- Accelerating structure
Material Testing (Pulsed heating experiments)

Special cavity has been designed to focus the magnetic field into a flat plate that can be replaced.

Economical material testing method

Essential in terms of cavity structures for wakefield damping

Recent theoretical work also indicate that fatigue and pulsed heating might be also the root cause of the breakdown phenomenon.

Metallography: Intergranular fractures 500X

Max Temp rise during pulse = 110°C
Annealed Copper with large grain shows crystal pattern because damage is different for each crystal orientation.
System overview

Measurement ports:
Forward Power: 2 or 5
Reflected power: 4 or 3
Waveform measured by either a Peak Power Meter or a scope with mixers
Low power NWA measurement: 6, 7, or 3

System Diagram

Sami Tantawi, Thinfilms for SRF
Cavity Design

- **High-Q hemispheric cavity under a TE$_{013}$ like mode**
  - Zero E-field on sample
  - Maximize H-field on the sample, $H_{\text{peak}}$ on bottom is 2.5 times of peak on dome
  - Maximize loss on the sample, 36% of cavity total
  - No radial current on bottom

- **Copper cavity body**
  - No temperature transition or quenching
  - Higher surface impedance
  - Coupling sensitive to iris radius

- **Possible future Nb cavity body**
  - More precise $R_s$ characterization

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**Sample R=0.95”**

- $F_{\text{res, design}} = \sim 11.399\,\text{GHz}$
- $F_{\text{res, 290K}} = \sim 11.424\,\text{GHz}$
- $F_{\text{res, 4K}} = \sim 11.46\,\text{GHz}$
- $T_c \sim 3.6\,\mu\text{s}$ (using Q value for copper at 4K)

**Q**

- $Q_{0,4K} = \sim 224,000$
- $Q_{0,290K} = \sim 50,000$
- $Q_{0,4K} = \sim 342,000$ (Estimated for zero resistivity samples, using measured Cu sample results)
- $Q_e = \sim 310,000$

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Sami Tantawi, Thinfilms for SRF
Measurement results: 300nm MgB$_2$ on Sapphire

300nm MgB$_2$ thin film on Sapphire
Q vs T
H=10mT vs low power

MgB$_2$ thin film on Sapphire
Q vs H
T=3K, 04082010

300nm MgB$_2$ thin film on Sapphire substrate, provided by LANL and deposited at STI.

Sami Tantawi, Thinfilms for SRF
RF signals for breakdown in single-cell-SW structure

1C-SW-A3 .75-T2 .6-6N-HIP-Cu-KEK-#1

File: t04_09_10__09_41_24.dat  Shot: 9  Time Stamp: {9,44,6,203}

File: t04_09_10__09_41_24.dat  Shot: 10  Time Stamp: {9,44,6,218}
### Iris shaping for Standing-Wave $\pi$-mode structures

<table>
<thead>
<tr>
<th>Shunt Impedance</th>
<th>83 M$\Omega$/m</th>
<th>Quality Factor</th>
<th>8561</th>
<th>Peak $E_s/E_a$</th>
<th>2.33</th>
<th>Peak $Z_0H_s/E_a$</th>
<th>1.23</th>
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</table>

<table>
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<th>Shunt Impedance</th>
<th>104 M$\Omega$/m</th>
<th>Quality Factor</th>
<th>9778</th>
<th>Peak $E_s/E_a$</th>
<th>2.41</th>
<th>Peak $Z_0H_s/E_a$</th>
<th>1.12</th>
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<th>Shunt Impedance</th>
<th>102 M$\Omega$/m</th>
<th>Quality Factor</th>
<th>8645</th>
<th>Peak $E_s/E_a$</th>
<th>2.3</th>
<th>Peak $Z_0H_s/E_a$</th>
<th>1.09</th>
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</table>

<table>
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<tr>
<th>Shunt Impedance</th>
<th>128 M$\Omega$/m</th>
<th>Quality Factor</th>
<th>9655</th>
<th>Peak $E_s/E_a$</th>
<th>2.5</th>
<th>Peak $Z_0H_s/E_a$</th>
<th>1.04</th>
</tr>
</thead>
</table>

Shape optimization reduces magnetic field on the surface, and hence, we hope to improve breakdown rate with the enhanced efficiency.
- Iris profile designed to maximize shunt impedance, minimize peak surface magnetic field
### SW Cells $a/\lambda = 0.143$, $\pi$ Phase Shift
Field Normalized for 100MeV/m Acceleration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$T=1.66$ Round Iris</th>
<th>$T=2.6$mm Elliptical Iris</th>
<th>$T=2.2$mm Shaped Iris</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy [J]</td>
<td>0.189</td>
<td>0.189</td>
<td>0.186</td>
</tr>
<tr>
<td>Q-value</td>
<td>8820</td>
<td>8560</td>
<td>10090</td>
</tr>
<tr>
<td>Shunt Impedance [MOhm/m]</td>
<td>85.2</td>
<td>82.6</td>
<td>99.2</td>
</tr>
<tr>
<td>Max. Mag. Field [KA/m]</td>
<td>314</td>
<td>325</td>
<td>294</td>
</tr>
<tr>
<td>Max. Electric Field [MV/m]</td>
<td>266</td>
<td>203</td>
<td>268</td>
</tr>
<tr>
<td>Losses in one cell [MW]</td>
<td>1.54</td>
<td>1.59</td>
<td>1.32</td>
</tr>
<tr>
<td>$H_{max}Z_0/E_{acc}$</td>
<td>1.18</td>
<td>1.22</td>
<td>1.11</td>
</tr>
<tr>
<td>Max. $\text{Im}{E \times H^*}$ W/µm$^2$</td>
<td>42.8</td>
<td>44.4</td>
<td>56.5</td>
</tr>
<tr>
<td>Max. $\text{Im}{E \times H^*}/H^2$</td>
<td>417</td>
<td>407</td>
<td>650</td>
</tr>
</tbody>
</table>
Resonance at 11.424 GHz  \( \beta = 1.007 \)
RF Feed Using Biplanar Coupler

~ 7 cm

~ 3 cm

~ 24 cm
Current Mechanical Design

~25 cm
2.7 kg
Microwave Tuning and test

Field Amplitude

Cumulated Phase Change

$E_{acc\_out}/E_{acc\_in} \sim 1.5$

120°
An 11.424 MHz Dual Resonant Ring System for High Gradient Testing
CLIC/KEK/SLAC T18 Structures

Power Distribution to Achieve an Unloaded Accelerating Gradient of 108 MV/m

Jake Haimson
T18 embedded in the dual resonant ring at ASTA
Summary of T18 in resonant ring up to 21\textsuperscript{st} of June 2011

[Graphs showing the relationship between gradient [MV/m] and breakdown probability [1/pulse/m], and pulse heating [deg. C] and breakdown probability [1/pulse/m], with data points for 100 ns and 600 ns, with and without the ring.]

Valery Dolgashev, Jim Lewandowski and Stephen Weathersby, 1 June 2011
Results of tests of T18 with and without Jake Haimson’s resonant ring

- Structure in a ring recovers has less number of destructive breakdowns and recovers faster from such breakdowns.
- It seems that during stable operation (between destructive breakdowns and breakdown chains) the breakdown probability is the same with the ring and without it.
- In the current experiment structure with ring needed about 3 time less power for the same gradient then with the ring, with may help testing similar structure with moderate rf power.
North sign!
PBG Structure Fabricated at SLAC

SLAC National Accelerator Lab, 05 Nov, 2008
Breakdown Data

170 ns Pulse

**Electric Field** [MV/m]

**Gradient** [MV/m]

**Temperature Rise** [K]

**Magnetic Field** [kA/m]
Elliptical-rod Design at 11 GHz

- Standing wave design with 2 matching cells, one test cell
- Axially powered via TM$_{01}$ mode launcher
- Structure has elliptical inner rods
  - Spread large H field over larger region
  - → reduce pulsed heating

<table>
<thead>
<tr>
<th>Performance at 100 MV/m</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Power</td>
</tr>
<tr>
<td>Peak Surface E Field</td>
</tr>
<tr>
<td>Peak Surface Magnetic Field</td>
</tr>
<tr>
<td>Pulsed Heating for 150ns Flat Pulse</td>
</tr>
</tbody>
</table>

B. J. Munroe, MIT
Breakdown rate vs. gradient and pulse heating
for 2 disc-loaded and two PBG single-cell structures, *shaped* pulse 150 ns
(A5.65-T4.6-KEK-#4, A5.65-T4.6-Frascati-#2, A5.65-T4.6-PBG-SLAC-#1, A5.65-T4.6-PBG2-SLAC-#1)
Dual Moded RF Cavity for Studying Electric and Magnetic Field Mixing

TM01 mode

TE01 mode

For details see A.D. Yeremian talk Monday afternoon

A. D. Yeremian, V. A. Dolgashev, S. G. Tantawi 2011
X Band Full Choke Structure 1C-SW-A3.75-T2.6 View Port-Cu

Solid model by David Martin
Future work/Open Problems

• Full length accelerator structures based on standing wave cells:
  - These are being theoretically designed and modeled. The structure will feature parallel coupling and would look matched like any other traveling wave structure from the outside.
  - We hope to prove a structure capable of exceeding 140 MV/m gradient
• Wakefield damping features are being studied theoretically and experimentally.
• Accelerator structures made of copper alloys are being studied
• The effect of beam-loading on gradient needs to be verified.
• The development of theoretical understanding and Modeling of the RF breakdown phenomena is starting to take shape. However, this is still at its infancy.
Future work/Open Problems

• Future Developments of advanced concepts such as multimoded and multi-frequency structure, Photonic band gap, and dielectric structures will pave the way for a revolution in the art.

• We have to pay attention to these development and create the proper environment that enable its development. This needs sources and enhanced test facilities.

• Ultra High Gradient accelerator structures will be not live to its potential without the development of efficient RF sources to drive them. The development of these sources has to be given attention in the near future
  - These sources need to have high efficiency
  - operate at low modulator voltages, in hope of an in expensive modulators with short and fall and rise times.
  - Possibly with pulse shapes that mimic that needed for standing wave accelerator structures
  - Possibly with multi frequency output.

• To this end we need expand our collaborative research towards transformational RF source technology.

• We would go about this with the similar philosophy; we would like to open the door for fundamentally new ideas for RF sources, find the fundamental limitations on source designs and adopt around them the design of the system.
Summary

- The work being done is characterized by a strong national and international collaboration. This is the only way to gather the necessary resources to do this work.
- Magnetic field plays a very important role in determining the breakdown probability in a given structure.
- The experimental program to date has paved the ground work for the theoretical developments.
- With the understanding of geometrical effects, we have demonstrated standing and traveling wave accelerator structures that work above 100 MV/m loaded gradient.
- Standing wave structures have shown the potential for gradients of 150 MV/m or higher.
- Further understanding of materials properties may allow even greater improvements.
- We still have not demonstrated a full featured accelerator structure including wakefield damping. This is expected in the near future.
We have followed our published working plane and our effort is now paving the way for a new understanding of the gradient limits of room temperature accelerators and will allow us to break these barriers for the development of ultra-high gradient structures.

The availability of SLAC facilities which was developed over the years due to healthy RF technology developments were essential and continue to be essential for these research activity.

For this to have a healthy future it should be accompanied by a developmental and industrialization program that will maintain and enhance our essential capabilities.

The effort reported here is just a representative sample of our effort.