Study of RF Breakdown in Normal Conducting Waveguides and Single Cell Structures

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Outline

• Waveguides
  – Different geometries
  – Different materials

• Single Cell Structures
Motivation

• **Predict** breakdown limits for practical structures of *different shapes, materials, circuits*

  To do this, we need to understand the physics of rf breakdown.

Difficulties

• Full scale structures are long, complex, expensive and difficult to simulate

Solution

• *High gradient waveguides* with gradients, power and pulse energy close to that of practical structures
• Single Cell Traveling Wave and Standing Wave Structures

*If we cannot understand small structures we will not be able to understand full scale structures*
Operating conditions for X-band traveling wave accelerating structures and high power waveguides

- RF power \(\sim 100\) MW
- Area of high electric field \(\sim 10\) cm\(^2\)
- Pulse width \(\sim 1\) \(\mu\)s
- Energy absorbed in the breakdown \(\sim 10\) J
- Distance between metal surfaces \(\sim 1\) cm
• The peak electric field **surface area equal** that of the low magnetic field waveguide
• For a given input power both waveguide have the **same peak electric field** — 80 MV/m at 100 MW of rf power
• **Ratio** between magnetic field in the middle of wide wall (maximum surface electric field) between both guides = 21
Field Distribution

Electric field

- Low magnetic field waveguide

Magnetic field

- High magnetic field waveguide
Breakdown threshold measurements for waveguides with different geometries

![Graph showing peak surface electric field vs. pulse length and power vs. pulse length for high and low magnetic field waveguides.](image-url)
Comparison of $\text{Power} \times \sqrt{\text{pulse widths}}$ for 3 accelerating structures and 2 copper waveguides

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400*pulse_width^{1/3}
```

```
Time [ns]
```

```
Power [MW] \times \sqrt{\text{pulse width [ns]}}
```

```
Number of breakdowns
```

```
Power [MW] \times \sqrt{\text{pulse width [ns]}}
```

```
0 500 1000 1500
```

```
500 1000 1500 2000 2500 3000
```

```
0 500 1000 1500
```

```
T53vg3MC
H60vg3_6c
H90vg3
```

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Accelerating structures
Waveguides
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“destruction limit”
Materials in low magnetic field waveguide

- Copper
- Stainless steel
- Gold
- Molybdenum

We like to thank Lisa Laurent and NLCTA team for their help with molybdenum waveguide experiment.
Molybdenum waveguide installed at NLCTA

Photomultiplier
Input RF From SLED pulse compressor
Input directional coupler
X-ray detector
Molybdenum waveguide
Scintillator
RF load
Output directional coupler
Processing of molybdenum waveguide

Peak power vs. measurement number
(one measurement every 2 sec)

Input pulse shape
Low magnetic field waveguides with different surface materials

No breakdowns, limited by available power
Limited by breakdowns in SLED

Breakdown threshold measurements for low-magnetic-field waveguides with different materials

Peak power vs. pulse width during processing of molybdenum waveguide
Comparison of Power*sqrt(Pulse Width) for low-magnetic-field waveguides made of different metal

Peak Power*sqrt(Pulse Width) vs. pulse width during processing for molybdenum waveguide

Breakdown Power*sqrt(Pulse Width) vs. pulse width for copper, gold and stainless steel
Waveguide Summary

• Macroscopic geometry is a very important parameter in breakdown phenomena. High magnetic field waveguide has a lower breakdown threshold than low-magnetic-field waveguide. The electric field gap is much smaller (1.3mm vs. 10mm) in the high magnetic field waveguide. This gap dependence contradicts a DC model of the breakdown, where breakdown threshold usually decreases with increased gap.

• Breakdown properties are strongly dependant on surface material. The stainless steel waveguide we tested had a higher breakdown threshold than copper. Gold had a lower threshold than copper.

• For molybdenum waveguide, direct comparison was possible only to gold waveguide. This comparison shows the superiority of the molybdenum waveguide. If we project molybdenum results using dependence $P*\sqrt{\text{pulse width}}$ to longer pulse width, we consider molybdenum superior to copper and possibly close to the performance of the stainless steel waveguide.
More tests

- Stainless still high magnetic field waveguide and chromium-plated low magnetic field waveguide were made at SLAC and available for the test
Single Cell Structures
Work on single cell traveling wave and standing wave structures is done in collaboration with Yasuo Higashi and Toshiyasu Higo from KEK
Single Cell Structures

Traveling Wave
- Fields are the same as in first cell of NLC structure T53VG3
- High electric and magnetic fields are *only in this cell* (not in couplers)
- *Reusable couplers* – mode launchers that transform the TE$_{10}$ mode of rectangular waveguide into the “accelerating” circular TM$_{01}$ mode

Standing Wave
- Fields in the middle cell of the SW structure are similar to fields of a large-aperture SW structure SW20a565
- Fields in the middle cell twice as high as in other two cells
- Breakdowns in one cell ⇒ *easy diagnostic*
- Small geometry ⇒ *easy simulation* with 3D particle and electromagnetic codes
**TM\textsubscript{01} Mode Launcher**

- **Surface electric fields in the mode launcher**
  
  \[ E_{\text{max}} = 49 \text{ MV/m for 100 MW} \]

- **Surface electric fields in T splitter**
  
  \[ E_{\text{max}} = 30 \text{ MV/m for 100 MW} \]

- **Cutaway view of the mode launcher**

- **Two mode launchers**

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**Surface electric fields in the mode launcher**

\[ E_{\text{max}} = 49 \text{ MV/m for 100 MW} \]
Single Cell Traveling Wave Structures
Amplitude of electric fields in single cell TW structure for 40 MW of input power.

Amplitude of magnetic fields in single cell TW structure for 40 MW of input power.

On axis electric field

Surface electric field

For 50 MW of input power this structure has 70 MV/m acceleration and 150 MV/m maximum surface field.
Cold Test With Single Cell Traveling Wave Structure

Reflection from single cell TW structure before and after tuning

On axis field profile for three single cell TW structures
High Power Test

High power test of single cell structures is done at Klystron Test Lab with great help of Chris Pearson, John Eichner, Lisa Laurent, Arnold Vlieks, Chuck Yoneda, John Glenn, John Van Pelt.
Single Cell Standing Wave Structures
Single Cell Standing Wave Structure
HFSS Calculation

To vacuum view port

RF power from mode launcher

Amplitude of electric fields for 10 MW input power

Amplitude of magnetic fields for 10 MW input power
Bead-Pull Measurements

On axis field profile for single cell SW structures
Single Cell Traveling Wave and Standing Wave Structures
Molybdenum Structures

Input cell of SW structure
Molybdenum Structures

Molybdenum SW structure

Molybdenum TW structure
Molybdenum-Copper Structures

Molybdenum-copper SW structure cells

Molybdenum-copper TW structure cells
Molybdenum-Copper Structures

Input of single cell SW structure

Interface of molybdenum and copper after etching
Status of Single Cell Structure Tests

• We started high power conditioning of SLAC-made single cell traveling wave structure. At present setup klystron is capable of delivering of 50 MW and 1.5 μs rf.

• We expect shipment of single cell standing wave structures from KEK this month (Y. Higashi).