High-Gradient Superconducting Radiofrequency Cavities for Particle Acceleration

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EPAC’06
29.6.2006

- Why Superconducting Accelerating Cavities?
- Limiting Mechanisms
- High Gradient Cavities
  - Surface Preparation
  - Fast Frequency Tuning
- Outlook
Thank You!

• To the TESLA Technology Collaboration for the support during the last years
• To many people for viewgraphs
Superconducting RF History:
Installed Accelerating Voltage

From Hasan Padamsee

Total >1000 meters
> 5 GV
Superconducting RF Present and Future: Accelerator Projects Featuring SRF Cavities

• Disclaimer: The focus is mostly on electron machines with beta =1
• LINACs
  – ILC, European XFEL, FLASH, ELBE, BESSY-FEL, MIT Bates, FERMILAB 8 GeV, SNS
• Recirculating LINACS
  – S-DALINAC, CEBAF, LUX, Arc-en-Ciel, Neutrino Factory/Muon Collider
• ERLs
  – JLAB FEL, JAERI, Cornell FEL, PERL (BNL), 4GLS, KEK-ERL, RHIC-II
• Storage rings
  – HEP
    • KEK-B, CESR, HERA, Tristan, LEP
  – Synchrotron Light
    • SOLEIL, CHESS, Canadian Light Source, Taiwan Light Source, DIAMOND

No guarantee for completeness...
Superconducting Cavities

- SC cavities offer
  - a surface resistance which is six orders of magnitude lower than normal conductors (NC)
  - high efficiency, even when cooling is included
    - large currents can be accelerated
    - high duty cycle up to continuous wave (cw) operation
  - low frequency, large aperture
  - high accelerating gradients
  - attractive for a wide range of projects and a lot of ideas
    - E.g. XFEL, Linear collider, Energy Recovery LINACS
Surface Resistance $R_s(T)$

Geometry factor:
$$Q_0 = \frac{G}{R_s}$$

Surface resistance:
$$R_s = \frac{A}{T} \omega^2 e^{-\frac{\Delta T_C}{k_B T}} + R_{res}$$

Typical Quality factor:
$$Q_0 > 1 \times 10^{10} \text{ at 2K}$$

- $G = 270$ Ohm
- $R_s = 700$ nOhm @ 4.2K
- $R_s < 10$ nOhm @ 2K
- $R_{BCS}(T)$
- $R_{RES}$

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Susceptibility Measurements: Niobium Properties

- Surface treatment does not change the bulk properties e.g. $B_c$ and $B_{c2}$
- Surface critical field $B_{c3}$ depends on surface preparation
  - Electropolishing (EP) vs. Standard etch (BCP)
  - Baking

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BCP</th>
<th>EP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$ [K]</td>
<td>9.263 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>$RRR$</td>
<td>≈ 300</td>
<td></td>
</tr>
<tr>
<td>surf. roughness [nm]</td>
<td>≈ 1</td>
<td></td>
</tr>
<tr>
<td>steps at grain bound. [µm]</td>
<td>1-5 µm</td>
<td>≲ 0.1 µm</td>
</tr>
<tr>
<td>$B_c(0)$ [mT]</td>
<td>180 ± 5</td>
<td></td>
</tr>
<tr>
<td>$B_{c2}(0)$ [mT]</td>
<td>410 ± 5</td>
<td></td>
</tr>
<tr>
<td>$J_c(0, 0)$ [A/mm$^2$]</td>
<td>240 ± 10</td>
<td>180 ± 10</td>
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</table>
Proof-of-Principle: TESLA Nine-cell Test (ILC Baseline Cavity)

Note the different test temperature in this low power performance test: 1.6 K –2K
Examples for Limiting Mechanisms

- **Understanding Multipacting**
  - A few computer codes developed
  - Spherical shape realized at Genova and qualified at Cornell & Wuppertal

- **Understanding Field Emission**
  - Emitters were localized and analyzed
  - Improved treatments and cleanness

- **Cure thermal Breakdown**
  - Higher RRR Nb
  - Deeper control for inclusions

1984/85: First great success

- A pair of 1.5 GHz cavities developed and tested (in CESR) at Cornell
- Chosen for CEBAF at TJNAF for a nominal $E_{acc} = 5$ MV/m

$E_{acc} > 5$ MV/m
Cleanroom Technology for SC Cavities

- the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a few µm
  - detailed material specification and quality control are done
  - tight specification for fabrication e.g. welds have been implemented
  - clean room technology is a must (e.g. QC with particle counts, monitoring of water quality, documentation of processes)

The inter-cavity connection is done in class 10 cleanrooms
Performance of FLASH Accelerator Module

A State-of-the-art module
- cryogenic type III
- latest coupler generation
- Etched (BCP) cavities

In single cavity measurements 6 out of 8 cavities reach 30 MV/m!

Equal power feeding $<E_{acc}> = 25$ MV/m

Cavity tests:
- Vertical (CW)
- Horizontal (10Hz)
- Module 5 (1Hz)
- Module 5 (5Hz)

Cavity 1 - AC62, 2 - AC61, 3 - AC65, 4 - AC66, 5 - AC79, 6 - AC77, 7 - AC63, 8 - AC60
Surface Preparation: Electropolishing

- Electropolishing (EP) of niobium surfaces is a key technology to achieve the highest electrical and magnetic surface fields.
- KEK/ Nomura Plating pioneered application of EP to elliptical niobium cavities since TRISTAN using a Siemens’ recipe from the 1970s.
- Since then EP has also been successfully applied to:
  - Low-Beta Quarter wave structures
  - TESLA nine-cells
Electropolishing Offers Improved Surface Quality
Electropolished 1.3 GHz Elliptical Niobium Cavities

K. Saito et al. KEK 1998/1999

Test temperature: 1.6 K

One-cell cavities

K-14 : half cell annealed at 1400ºC, EP
K-8 : BP. 760ºC annealed. EP
K-9 : BP, 760ºC annealed, EP
JL-1 : fabricated at CEBAF, CP, EP
K-11 : CP, 760ºC annealed, EP
K-22 : CP, EP

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Cavity Processing:
ANL $\beta=0.63$ Triple-Spoke Cavity, Area $\sim1.5 \, m^2$
ANL EP: Beta=0.63 Multi-Spoke Cavity

- Q-disease was observed; hydrogen degassing at 600 °C was performed at ANL.
- 2 K surface resistance decreased substantially after 600 °C bake.

No X-rays

Rs-Rbcs (Ohm)

No X-rays

T = 4.2 K (unchanged after bake)
Electropolishing Setup at DESY
TESLA Nine-Cells: Low-Power Results

\[ E_{\text{acc}} \text{ [MV/m]} \]

\[ \sigma \]

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EPAC 06
Edinburgh, Scotland  

16.07.2006
This module serves two purposes:

- Demonstration of high operational gradient
- Industry and partner labs to participate in assembly process
Work needed: Reproducibility in the EP Process

Avoiding field emission is an ongoing struggle!
Active Tuner

• Lorentz force detunes the cavity during one RF pulse
  – If detuning is too large extra RF power would be needed

• Actively compensate the detuning of the cavity during the RF pulse by mechanical means

• Piezoelectric elements are suitable for this application
Frequency detuning due to Lorentz forces of the electromagnetic field in the cavities:

\[ \Delta f = -K \cdot E_{acc}^2 \]

where \( K \approx 1 \text{ Hz} / (\text{MV/m})^2 \)

Remember: Cavity bandwidth with main coupler is \( \approx 300 \text{ Hz} \)
Proof-of-Principle: Piezoelectric Tuner
M. Liepe, S. Simrock, W.D.-Moeller

Piezo-Actuator:
l = 39 mm
U_{\text{max}} = 150 V
\Delta l = 3 \mu m \text{ at } 2 K
\Delta f_{\text{max,static}} = 500 Hz
Sensor-Actuator: Piezoelectric Elements in the Tuning Mechanism
RF Signals at 35 MV/m

Blue: With piezo
Red: Without piezo
Damping of the ringing between pulses (5Hz operation)

![Graph showing voltage on sensor-piezo with RF pulses at 5Hz operation. The graph compares compensated and uncompensated conditions.]
Frequency stabilization during RF pulse using a piezoelectric tuner

Blue: With piezo
Red: Without piezo

Frequency detuning of ~ 500 Hz compensated voltage pulse (~100 V) on the piezo. No resonant compensation
Resonant Excitation of the Cavity

Pulse Parameters:
- frequency = 219 Hz
- time shift = -9.5 ms
- amplitude = 24V
- offset = 24V
Frequency stabilization at 35 MV/m

Blue: With piezo
Red: Without piezo

Frequency detuning of $\sim 1000$ Hz compensated with resonant excitation of a mechanical cavity resonance at 230 Hz.

NOTE: This is rather an demonstration of the capability of active tuning. Application in a real machine needs investigation.
Work to be done for projects ahead

• XFEL
  – Transferring knowledge to industry
    • Cavity manufacture done in industry since the formation of the TESLA collaboration
      – Also for auxiliaries
    • Cavity Processes
      – Electropolishing has started
    • Module manufacturing and assembly
      – Studies with participation of industry in progress (see module 6)

• ILC
  – Proof-of-existence is there!
  – Need to increase yield of getting ‘good’ cavities
    • Surface preparation is the clue
  – Further look into cost reduction
    • Other cavity shapes
    • Other materials
  – Involve industry in an early stage

• Other projects (e.g. see Susan Smith’s Talk)
  – Higher beam currents
    • E.g. HOM damping
  – CW operation
    • E.g. Higher $Q_0$
Example of XFEL Industrialisation: Henkel

- Very high gradient (up to 40 MV/m), high $Q_0$ single-cell cavities have been prepared
- Study on improved quality control measures at DESY and Henkel
  - E.g. Improved parameter-control of electrolytes
- Upto three-cell 1.3 GHz cavities can be treated currently
ILC: Shapes

• TESLA shape
  – Baseline

• Alternative Shapes
  – Main Feature
    • Designed for
      – Lower $H_{\text{peak}}/E_{\text{acc}}$: magnetic field limit
    • Caveat
      – Higher $E_{\text{peak}}/E_{\text{acc}}$: field emission
  – ‘Low-Loss’ shape (LL)
    • Originally designed for lower cryo losses
  – Re-entrant shape (RE)
TESLA Cavity Design

• Frequency choice
  – Lower frequency better for
    • RF losses (BCS surface resistance)
    • Lower wakefields
  – 1.3 GHz klystrons were available

• Cavity RF Layout
  – Number of cells determined by maximum cell-to-cell coupling $k_{cc}$ (field flatness)
  – Low $E_{\text{peak}}/E_{\text{acc}}$ (less sensitive to field emission)
  – End cells asymmetric
    • Avoid trapping of TE121 higher order mode
    • Keep TM010 and first two dipole bands mode flat
1. Introduction: Evolution of the elliptical cavities cont.

Example: 1.3 GHz inner cells for TESLA and ILC

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<thead>
<tr>
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<tbody>
<tr>
<td>$r_{irisb}$ [mm]</td>
<td>35</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>$k_{cc}$ [%]</td>
<td>1.9</td>
<td>1.52</td>
<td>1.8</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td>-</td>
<td>1.98</td>
<td>2.36</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ [mT/(MV/m)]</td>
<td>4.15</td>
<td>3.61</td>
<td>3.76</td>
</tr>
<tr>
<td>$R/Q$ [Ω]</td>
<td>113.8</td>
<td>133.7</td>
<td>126.8</td>
</tr>
<tr>
<td>$G$ [Ω]</td>
<td>271</td>
<td>284</td>
<td>277</td>
</tr>
<tr>
<td>$R/Q^*G$ [$Ω^*Ω$]</td>
<td>30840</td>
<td>37970</td>
<td>35123</td>
</tr>
</tbody>
</table>

- Field flatness
- Max gradient (E limit)
- Max gradient (B limit)
- Stored energy
- Dissipation
- Dissipation (Cryo limit)
1. Introduction: Criteria, cont.

“Hunting” for high gradients goes together with “hunting” for low cryogenic loss.

$H^q$ on the Nb wall
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Single-Cells of Other Shapes

World Record! (Cornell / KEK)

Several cavities achieved more than 45 MV/m at high Q! (KEK)
Conclusion

• SCRF cavities have a broad range of applications
• Technology matured over the recent years
  – E.g. commercially available SCRF systems
• Challenges are the reproducibility of very high gradients and cost reduction
  – 35 MV/m has been demonstrated several times
  – A production-like process is under development
• A lot of working ongoing for the XFEL and ILC
  – It is a big asset for both of them that they still can profit from each other
• Single-cells have shown more than 50 (!) MV/m
  – First tests on multi-cells are underway
Backup
Cavity Test Inside a Module (ctd.)

- One of the electropolished cavities (AC72) was installed into an accelerating module for the VUV-FEL
- Very low cryogenic losses as in high power tests
- Standard X-ray radiation measurement indicates no radiation up to 35 MV/m
Time evolution of accelerating gradient

Distribution of Maximum Operational SRF Cavity Gradients in CEBAF by Type of Limitation

- FE-Induced arcing (3/day)
- FE loading & radiation
- Quench
- Other

Max Gradient for Ops (MV/m)

# Cavities

Avg. = 8.4 MV/m

Number of cells

After Standard etch Average
28.9 +/- 1.1 MV/m

After EP Average
35.6 +/- 2.3 MV/m

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Goals of the TESLA Test Facility Linac

Test all the components in a real linac environment with e⁻ beam

One standard 9-cell TESLA accelerating structure operated as a π-mode standing-wave cavity.

One 230 kW rf power coupler, an rf pick up antenna and two Higher Order Mode antennas are assembled to each cavity.

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