Cavity development for TESLA

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• Cavity basics
• History:
  – Limitations and solutions
    » Material inclusions
    » Weld defects
    » Field emission
    » Increased surface resistance at high field
• Performance of 9-cell cavities (TESLA-500)
• R&D for TESLA-800
  – Surface Preparation
  – Manufacturing techniques
  – Superstructure
  – Piezoelectric tuner
TESLA Cavities
Cavities for TESLA - RF surface resistance

Quality factor:

\[ Q_0 = \frac{f}{\Delta f} = \frac{270 \text{ Ohm}}{R_s} \]

‘Natural’ Bandwidth:

\[ \Delta f \approx 0.1 \text{ Hz} \]

\[ \Rightarrow Q_0 \approx 10^{10} \]

RF surface resistance:

\[ R_s = \frac{A e^{-\frac{\Delta}{k_B T}}}{T} + R_{\text{res}} \]

Line width with main coupler:

\[ \Delta f \approx 300 \text{ Hz} \]

\[ \Rightarrow Q_0 \approx 10^6 \]

\[ f_0 = 1.300.000.000 \text{ Hz} \]

\[ R_{\text{BCS}(T)} \]

\[ R_{\text{RES}} \]

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03.07.2001
Best continuous wave test of TESLA cavity

Test temperature: 2K

Specifications:

E_{acc} = 23.4 \, \text{MV/m} \at\, Q_0 = 1\times10^{10} \text{ for TESLA-500}
E_{acc} = 35 \, \text{MV/m} \at\, Q_0 = 5\times10^9 \text{ for TESLA-800}

Theoretical limit: \, E_{acc} \approx 50 \, \text{MV/m}
RF magnetic field exceeds first critical field of niobium

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Challenges for TESLA cavities

– Accelerating gradient
  • For 500 GeV center-of-mass
    – $E_{\text{acc}} = 23 \text{ MV/m} @ Q_0 = 1 \cdot 10^{10}$
  • For energy upgrade to 800 GeV
    – $E_{\text{acc}} = 35 \text{ MV/m} @ Q_0 = 5 \cdot 10^9$

– Pulsed operation
  • Frequency detuning due to Lorentz force requires additional RF power

– What material quality is really needed?
– What is the best manufacturing technique?
– How to prepare the best surface for RF superconductivity?
– How to compensate the Lorentz-force detuning?
Production and preparation of TESLA cavities

- Niobium sheets (RRR=300) are subjected to eddy-current scanning to avoid foreign material inclusions like tantalum and iron
- Deep-drawing of subunits (half-cells, etc.) from niobium sheets
- Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Chemical etching to remove damage layer and titanium getter layer
- High pressure water rinsing as final treatment to avoid particle contamination
Detailed preparation sequence for niobium cavities

- removal of the damage layer by chemical etching
- 2 hours heat treatment at 800 C - remove hydrogen and stress anneal
- 4 hours heat treatment at 1400 C with titanium getter for higher thermal conductivity to stabilize defects
- removal of the titanium layer by chemical etching
- field flatness tuning
- final 20 μm removal from the inner surface by etching
- high pressure rinsing (HPR) with ultrapure water
- drying by laminar flow in a class 10 cleanroom
- assembly of all flanges, leak-check
- 2 times HPR, drying by laminar flow and assembly
- of the input antenna with high external Q
Example of a material defect

Heating on the outside surface measured with carbon resistors

Defect found with X-ray technique: Tantalum
Eddy current scanning

- Large tantalum inclusions (~200 µm) and places with irregular patterns from surface preparation (grinding)

Grinding mark
Benefit of the high temperature heat treatments
Latest production of TESLA-type nine-cell cavities

Test temperature: 2K
Results of cavity productions

- Improved welding
- Stricter niobium quality control

\[ \langle E_{acc} \rangle \text{ for } Q_0 \geq 10^{10} \]

Module performance in the TTF LINAC

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Preparation for LINAC operation

1. continuous wave acceptance test with low power
2. full systems test with high power coupler
   - pulsed test with:
     • $500 \mu s$ rise time
     • $800 \mu s$ flat-top
     • 10 Hz repetition rate

Test temperature: 2K

Results scatter around $E_{acc, cw} = E_{acc, pulse}$
Yield of cavities from CW test

- First production
- Second production
- Third production

Yield [%]

Eacc [MV/m]
R&D

• Surface preparation
  – Electropolishing
  – ‘In-situ’ Bakeout

• Cavity Production
  – Spinning
  – Hydroforming
  – Nb-Cu clad cavities

• Pulsed operation
  – Stiffening
  – Piezo-electric tuner

• Linac fill factor -> Superstructure
Electropolishing of 1-cell cavities (Scheme)

- EP electrolyte
- 90 % H₂SO₄
- 10 % HF
- 30 °C
- 0.5 µm/min removal of material

Standard Etch
Electropolishing

200 µm
200 µm
KEK results for electropolished niobium cavities
K. Saito et al. KEK 1998/1999

One-cell cavities
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Test temperature: 1.6 K

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Electropolished cavities

EP at CERN, Measurements at CERN, CEA and DESY 2000/2001

Test temperature: 1.6 K

Test temperature: 2 K

One-cell cavities

TESLA 500

TESLA 800

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

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Electropolished TESLA nine-cell cavity
EP at Nomura Plating and KEK, Test at DESY

Test temperature: 2K

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Etching versus Electropolishing

- **Etching**
  - Average: 24 MV/m

- **Electropolishing**
  - Average: 35.7 MV/m

**Graph Details**
- **Eacc [MV/m]**
- **Number of cavities**

**Additional Notes**
- Lutz Lilje DESY
- 03.07.2001
Improve by ‘In-situ’ baking

Strong degradation of the quality factor - No field emission!

- Electropolishing
- + after 120 °C in-situ baking

E_{acc} [MV/m]

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In-situ Baking

- Heating of the cavity to 100 - 120 °C
- Duration: ca. 40 hours
- Pressure below $10^{-6}$ mbar
- Inert gas atmosphere on the outside
Air exposure of a baked niobium surface
Spun and EP cavities

Palmieri (INFN-LNL), Saito (KEK)
Hydroforming and EP

Kneisel TJANF
Kaiser, Singer DESY
Saito KEK

One-cell cavity

Mould

Axial displacement

Water pressure

Gap closed on hydro forming

Test temperature: 2K

- 250 µm standard etch
- 100 µm e-polishing

DESY Seamless Cavity
1K2
TEST at JLab

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TESLA 2 x 9 Superstructure
J. Sekutowicz, M. Liepe et al.

Benefits:
- 6% larger active accelerating length as compared to normal nine-cell design
- less main and HOM couplers

Field profile:
Comparison of two accelerating schemes for TESLA-500 (nine-cell vs. superstructure)

<table>
<thead>
<tr>
<th>Layout</th>
<th>$L_{\text{active}}$ [m]</th>
<th>$E_{\text{acc}}$ [MV/m]</th>
<th>No. of power coupler</th>
<th>No. of HOM coupler</th>
<th>No. of freq. tuners</th>
<th>Filling factor $L_{\text{active}}/L_{\text{total}}$</th>
<th>$P_{\text{trans}}$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-cell</td>
<td>1.04</td>
<td>23.4</td>
<td>20592</td>
<td>41184</td>
<td>20592</td>
<td>78.6</td>
<td>232</td>
</tr>
<tr>
<td>2x9-cell</td>
<td>2.08</td>
<td>22</td>
<td>10926</td>
<td>32778</td>
<td>21852</td>
<td>84.8</td>
<td>437</td>
</tr>
</tbody>
</table>
Superstructure
J. Sekutowicz, M. Liepe et al.

- higher fill factor $L_{\text{acc}} / L_{\text{total}}$
- less RF couplers

Table 1: Parameters of Cu model of the superstructure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of cells, $M \times N$</td>
<td>$4 \times 7$</td>
</tr>
<tr>
<td>number of HOM / input couplers</td>
<td>$5 / 1$</td>
</tr>
<tr>
<td>radius of mid / end iris [mm]</td>
<td>$35 / 57$</td>
</tr>
<tr>
<td>fill factor</td>
<td>0.875</td>
</tr>
<tr>
<td>$k_{cc}$, cell-to-cell coupling</td>
<td>0.019</td>
</tr>
<tr>
<td>$k_{ss}$, cavity-to-cavity coupling</td>
<td>$3.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>field instability factor, $N^2 / k_{cc}$ [10^3]</td>
<td>2.6</td>
</tr>
<tr>
<td>$(R/Q)/$length [$\Omega/m$]</td>
<td>906</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$\approx 27000$</td>
</tr>
</tbody>
</table>
New tuner development for the TESLA cavities

- mounted on the helium tank
- needed for the superstructure
- first tests successful
Pulsed acceleration at TESLA

Superconducting cavities at high gradients $\Rightarrow$ Pulsed operation to reduce average cryogenic losses

*Pulsed operation: 500 μs fill time + 800 μs constant gradient 10 Hz repetition rate*
Frequency detuning during RF pulse

Frequency detuning due Lorentz forces of the electromagnetic field in the cavites:

$$\Delta f = K \cdot E_{\text{acc}}^2$$

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

Remember:

Cavity bandwidth with main coupler is $\approx 300 \text{ Hz}$
Piezoelectric tuner
M. Liepe, S. Simrock, W.D.-Moeller

Piezo-Actuator:
I=39mm
U_{max}=150V
\Delta I=3\mu m \text{ at } 2K
\Delta f_{\text{max,static}}=500\text{Hz}
Frequency stabilisation during RF pulse using a piezoelectric tuner

M. Liepe, S. Simrock, W.D.-Moeller

Beam on

Frequency detuning of 200 - 250 Hz compensated!
Conclusion

– Cavity technology for TESLA-500 well established
  • Third production of TTF cavities reaches specified gradient of 23,5 MV/m with a comfortable margin.

– Cavity R&D for TESLA-800 is well advanced
  • Several electropolished one-cell cavities reproducibly allow very high surface fields corresponding to accelerating gradients $E_{\text{acc}} \geq 40$ MV/m.
  • First promising results on nine-cell cavities. Test series in collaboration with KEK and Nomura Plating under way.
  • Hydroformed and spun one-cell cavities achieve $E_{\text{acc}}$ around 40 MV/m. Multi-cell cavities are in preparation.
  • Superstructure concept increases fill factor by 6 % as compared to baseline and allows cost savings
  • Active frequency stabilisation allows pulsed operation at 35 MV/m