CEPC High Q Cavity Study


2017.07.07, IHEP CAS
Contents

1. Introduction
2. N-doping, N-infusion
3. Nb$_3$Sn and Fe-based superconductor film
4. 650 MHz cavity for CEPC main ring
5. 1.3 GHz cavity for CEPC booster
6. Summary
# CEPC Cavity Specification

**New!**

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Vertical test</th>
<th>Horizontal test</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 MHz 2-cell Cavity</td>
<td>4E10 @ 22 MV/m</td>
<td>2E10 @ 16 MV/m</td>
<td>336</td>
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<tr>
<td>1.3 GHz 9-cell Cavity</td>
<td>3E10 @ 25 MV/m</td>
<td>2E10 @ 20 MV/m</td>
<td>160</td>
</tr>
</tbody>
</table>

Similar as E-XFEL, LCLS-II, ILC

Very high!
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High Q cavity through N-doping

- Research Content: Increasing $Q_0$ (at high Electric field) of SC cavity through **N-doping**, Nb$_3$Sn……

- Target: $Q_0 = 4 \times 10^9$ @ $E_{acc} = 22$ MV/m (650 MHz cavities for vertical test at 2K)

![Graph showing $Q_0$ vs. $E_{acc}$ at different temperatures and doping levels](image)

N-doping for 1.3 GHz cavity

N-doping for PIP-II 650 MHz single-cell cavity
### N-doping application: LCLS-II

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Eacc [MV/m]</th>
<th>$Q_0$ (2K) @16MV/m</th>
<th>Max Gradient Reached * [MV/m]</th>
<th>Usable Gradient ** [MV/m]</th>
<th>FE onset [MV/m]</th>
<th>$Q_0$ (2K) @16MV/m***</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB9AES021</td>
<td>23</td>
<td>3.1E+10</td>
<td>19.6</td>
<td>18.2</td>
<td>14.6</td>
<td>2.6E+10</td>
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<td>TB9AES019</td>
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<td>2.8E+10</td>
<td>17</td>
<td>16.8</td>
<td>15.6</td>
<td>2.6E+10</td>
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<td>TB9AES026</td>
<td>21.4</td>
<td>2.6E+10</td>
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<td>17.2</td>
<td>No FE</td>
<td>2.7E+10</td>
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<td>TB9AES024</td>
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<td>16.0</td>
<td>No FE</td>
<td>2.5E+10</td>
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<td>TB9AES028</td>
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<td>14.9</td>
<td>13.8</td>
<td>11.5</td>
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<tr>
<td>TB9AES016</td>
<td>18</td>
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<td>16.7</td>
<td>14.5</td>
<td>2.9E+10</td>
</tr>
<tr>
<td>TB9AES022</td>
<td>21.2</td>
<td>2.8E+10</td>
<td>17.4</td>
<td>17.1</td>
<td>12.7</td>
<td>3.2E+10</td>
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<tr>
<td>TB9AES027</td>
<td>22.5</td>
<td>2.8E+10</td>
<td>16.8</td>
<td>16.6</td>
<td>13.8</td>
<td>2.5E+10</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>22.1</strong></td>
<td><strong>2.8E+10</strong></td>
<td><strong>17.0</strong></td>
<td><strong>16.6</strong></td>
<td><strong>14.7</strong></td>
<td><strong>2.7E+10</strong></td>
</tr>
<tr>
<td><strong>Total Voltage</strong></td>
<td><strong>176.4</strong></td>
<td></td>
<td></td>
<td></td>
<td>136.2</td>
<td>132.5</td>
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</tbody>
</table>

Immediate application: LCLS-II, 2.7e10@16MV/m.

Preliminary results for 1st LCLS-II cryomodule (FNAL)
N-doping recipe adopted by LCLS-II

1. 800°C/900 °C anneal 3 hours for Hydrogen degas
2. Nitrogen injection 2 minutes at ~3.5 Pa
3. Nitrogen anneal 6 minutes
4. Nature cooldown
Two steps of N-doping at IHEP

- 1st step: N-doping of Nb sample, Secondary Ion Mass Spectrometry (at Tsinghua University)—N concentration within Nb surface increase or not?
- 2nd step: cavity N-doping, Electric Polishing, vertical test—Q increase or not?
N-doping of Nb samples at IHEP

- The furnace is equipped with diffusion pump, which is not oil-free and dirty.
- Many times of Nb sample N-doping experiments, SIMS results show they all failed.
**N-doping of Nb samples at OTIC**

- Oil-free pumping system: two COOLVAC10000 CL-V (DN500 ISO-K, N₂ pumping speed 10 000l/s) cryo-pumps by Leybold, one roots pump (1200L/S) and one screw pump.

- The heater is made by Tantalum, not molybdenum. N-infusion isn’t allowed, because people worry that N₂ injection at 120C may harm the heater.
SIMS

- N and H are key elements of N-doping, so SIMS is adopted to study their distribution along the depth in the Nb surface.
- The SIMS machine we use is made by ION-TOF GmbH (Germany). The type is TOF.SIMS 5-100.
- 1st ion beam: Bi3++, 1keV, 45deg inject, scan area 100*100 um.
- Sputtering beam: Cs+, 1keV, 45deg inject, Sputtering speed=0.14nm/s for SiO₂ (14 um need 28 hours).

Principle of SIMS

Nb Sample (10*10mm)
SIMS ongoing

SIMS experiments at Tsinghua University
SIMS result before N-doping

Intensity of N (before N-doping)
SIMS result after N-doping at IHEP

Intensity of N (no change)
SIMS result after N-doping at OTIC

Intensity of N increase obviously after N-doping. Meanwhile, Intensity of H decrease after N-doping.

Intensity of NbN, CsN also increase after N-doping.

After ~5 um EP, N, NbN and CsN all disappear.
SIMS for N-doped sample (~100um)

- Nitrides?
- Flat up to ~10um 
- Then gradually decrease (down to lower limit)
- N behavior seems to be similar
What does N treatment do? N depth profiles by SIMS

Concentration of N atom and Nitrides measured by SIMS added to one curve?
Intensity of N is different from last figure.

Only about 40 ppm of N is enough.
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**Nb$_3$Sn**

- Niobium cavity coating with Nb$_3$Sn can work at 4.2K, which saves much cost than 2K.
- Nb$_3$Sn is predicted to have 2x magnetic field limit of niobium.
Schematic of Nb$_3$Sn furnace

 Nb$_3$Sn Coating Furnace at IHEP (complete in 2018)

Cornell Nb$_3$Sn Coating Furnace
Fe-based Superconductor for SRF Cavity

<table>
<thead>
<tr>
<th></th>
<th>Fe原子间距 (Å)</th>
<th>铁与近邻原子间距 (Å)</th>
<th>铁层间距 (Å)</th>
<th>超导转变温度 (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROFeAs (1111 结构)</td>
<td>2.84</td>
<td>107.4</td>
<td>8.3</td>
<td>~56</td>
</tr>
<tr>
<td>AFe₂As₂ (122 结构)</td>
<td>2.77</td>
<td>108.9</td>
<td>6.5</td>
<td>~38</td>
</tr>
<tr>
<td>LiFeAs (111 结构)</td>
<td>2.67</td>
<td>112.7</td>
<td>6.3</td>
<td>~18</td>
</tr>
<tr>
<td>FeSe (11 结构)</td>
<td>2.65</td>
<td>112.2</td>
<td>5.5</td>
<td>~11</td>
</tr>
</tbody>
</table>

- World’s first 100 m Fe-based superconducting wire by IEE, CAS, China (Aug. 2016)
- High Tc Superconductivity Collaboration of China (lead by Yifang Wang) has decided to push the use of Fe-based superconductor in SRF.
Fe( TeSe ) Thin Film Study at IHEP

- SrTiO\textsubscript{3} substrate with Nb doping (for better electrical conductivity)
- Preparation method: Pulsed Laser Deposition (PLD)
- Research on oxidation of Fe( TeSe ) thin film
- Next step: make proper Fe-based material for SRF application.
Rs measurement of film

“Mushroom” Cavity
- Probe $H_{\text{max}}$ with pulsed rf

Nantista SLAC PAC 2005

<table>
<thead>
<tr>
<th>$f$ (GHz)</th>
<th>$A_{\text{Sample}}$</th>
<th>$A_{\text{rf}}$</th>
<th>$R_{\text{sens}}$ (Ω)</th>
<th>$B_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4</td>
<td>19.6 cm$^2$</td>
<td>~8 cm$^2$</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

- Superconducting materials test cavity
  - No surface electric fields (no multipactoring)
  - Magnetic field concentrated on bottom (sample) face

- X-band (~11.424 GHz):
  - High power available
  - Fits in cryogenic Dewar
  - Relatively large (2-3") samples required
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650 MHz Single Cell Cavity Test before N-doping

- Old RF design: $B_p / E_{\text{acc}} = 4.75 \text{ mT}/(\text{MV/m})$
- Shielded dewar, remnant magnetic field 20 mG. Additional magnetic shield around cavity.
- Fine grain, 130um BCP + 3 h 750 C annealing + 30um BCP + 120 C bake 48 h
RF design of 650MHz 2-cell cavity

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/Q (Ω)</td>
<td>212.731</td>
</tr>
<tr>
<td>G</td>
<td>284.113</td>
</tr>
<tr>
<td>Ep/Eacc</td>
<td>2.38</td>
</tr>
<tr>
<td>Bp/Eacc [mT/(MV/m)]</td>
<td>4.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Port</th>
<th>P (W) (U=1J)</th>
<th>Qe (all ports)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td>0.001867</td>
<td>2.19E12</td>
</tr>
<tr>
<td>Port 2</td>
<td>0.001352</td>
<td>3.02E12</td>
</tr>
<tr>
<td>Port 3</td>
<td>0.005441</td>
<td>7.51E11</td>
</tr>
<tr>
<td>Port 4</td>
<td>0.003435</td>
<td>1.19E12</td>
</tr>
<tr>
<td>Port 5</td>
<td>0.003320</td>
<td>1.23E12</td>
</tr>
</tbody>
</table>

Qe (all ports) : 2.65E+11. If Q0 = 4E10, then Q0 (measured) decrease to 3.48E10.
df/dp simulation

Deformation @ 2 Bar

Stress @ 2 Bar
Mechanical analysis

- $\frac{df}{dp}$
  - $-68.7 \text{ Hz/mbar}$
  - The stress under 2 bar (44.5 MPa)
- Tuning
  - Tuning sensitivity $s$: $310 \text{ kHz/mm}$
  - Stiffness $k$: $16001\text{N/mm}$
- LFD
  - LFD coefficient $=-4.16 \text{ Hz/(MV/m)^2}$
A prototype of 650 MHz 2-cell cavity has begun fabrication at IHEP factory.
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1.3 GHz cavity for CEPC booster

- 1\textsuperscript{st}, high gradient, 35MV/m at May 2018.
- 2\textsuperscript{nd}, high Q.
- Tesla type: Single-cell ----- 2-cell ----- 9-cell
6. Summary

- N-doping collaboration: N-doping related experiments of Nb samples and 1.3GHz (650 MHz) cavities both at KEK and IHEP. Those include N-doping/N-infusion in furnace at IHEP or KEK, material analysis (SIMS, TEM, SEM, XPS...) at IHEP or KEK, surface process and vertical test of cavity at KEK.

- We've already two 650MHz single-cell cavities for N-doping on hand now, which have received BCP and vertical test at IHEP. We can send the 650MHz Solid state amplifier (>300W) to KEK for vertical test, too.

- We've several 1.3 GHz single-cell cavities (Tesla-type) on hand. They can all be shipped to KEK for N-doping and vertical test.

- In late 2016, one 1.3 GHz 9-cell cavity received surface process and vertical test at KEK, which reach 8e9@24MV/m.
6. Summary

Low $Q_0$ at low field

TESLA cavity $G = 271 \, \Omega$

@ 1MV/m

$Q_0 = 1.19E10 \, @ \, 1.93 \, K$

$(R_{BCS} \, @ \, 1.93 \, K = 8.2 \, \text{n}\Omega)$

$Q_0 = 1.34E10 \, @ \, 1.73 \, K$

$(R_{BCS} \, @ \, 1.73 \, K = 3.2 \, \text{n}\Omega)$
6. Summary

- Nb cavity coating with Nb$_3$Sn: high temperature coating technique exchange, material analysis (SIMS, TEM, SEM, XPS…) at IHEP or KEK, surface process and vertical test of cavity at KEK.
- Fe-based superconductor: make film (IHEP), material analysis (SIMS, TEM, SEM, XPS…) at IHEP or KEK, measurement of $T_C$, $H_{C,RF}$, $R_s$ at KEK. Cavity coating with film is difficult nowadays.
Thanks for your attention!