Design of the 9-cell superconducting cavity for EUV light source accelerator

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5. Summary
1-1 Introduction of EUV light source

- Lithography for LSI needs short wavelength and high power to continue to meet the Moore’s Law.
- **13.5nm** EUV (Extreme Ultra-violet) light is the strongest candidate for new generation light source, because this wavelength is matched to Mo/Si multilayer mirror system.
- High light power source also required for mass production.
- 13.5 nm and 250 W LPP (Laser Produced Plasma) has been developed for 30 years.
- In near future, a new light source which has 13.5nm or more short wavelength and high power will be required.
1-1 Introduction of EUV light source

- LPP needs 20kW high power CO$_2$ laser. The conversion efficiency from CO$_2$ laser to EUV light is ~5%. LPP EUV power will be limited at several hundred Watts.
- CW ERL+FEL accelerator is the strongest candidate for next light source.
- We started designing 13.5 nm and 10 kW class EUV accelerator.

ERL+FEL accelerator size is acceptable, because the size fit to regular factory site.
1-1 Introduction of EUV light source

- KEK has the experience of cERL and STF development.
- cERL commissioning is still in progress. Beam current will be increased to 10 mA.
- STF is the superconducting cavity test facility for ILC.

### KEK-cERL (PEARL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>35 MeV</td>
<td>20 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>10 mA</td>
<td>0.95 mA</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>0.1 (@7.7 pC/bunch)</td>
<td>0.3 (@0.5 pC/bunch)</td>
</tr>
<tr>
<td></td>
<td>1 (@ 77 pC/bunch)</td>
<td>1-2 (@ 7.7 pC/bunch)</td>
</tr>
<tr>
<td>Bunch repetition</td>
<td>1.3 GHz</td>
<td>1.3 GHz (usual)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>162.5 MHz (for LCS)</td>
</tr>
<tr>
<td>Pulse length (rms)</td>
<td>1-3 ps: usual</td>
<td>1-3 ps: usual</td>
</tr>
<tr>
<td></td>
<td>~100 fs: compression</td>
<td>~150 fs: compression</td>
</tr>
<tr>
<td>Main Linac gradient</td>
<td>15 MV/m</td>
<td>8.2 MV/m</td>
</tr>
</tbody>
</table>

### KEK-STF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stage QB project</th>
<th>Target</th>
<th>Stage Phase 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>40 MeV</td>
<td>21.5 MeV</td>
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<tr>
<td>Beam current</td>
<td>10 mA</td>
<td>8.7 mA</td>
<td></td>
</tr>
<tr>
<td>Bunch length</td>
<td>12 ps (FWHM)</td>
<td>10 ps (FWHM)</td>
<td></td>
</tr>
<tr>
<td>Pulse repetition</td>
<td>5 Hz</td>
<td>5 Hz</td>
<td></td>
</tr>
<tr>
<td># of bunch/pulse</td>
<td>162,500</td>
<td>2437</td>
<td></td>
</tr>
</tbody>
</table>

Emittance is higher than target value because main linac voltage links to injection energy.

STF 2.0 cavities setup was finished. STF2.0 beam operation will be started from 2017.
### KEK- EUV Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Target value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>13.5 nm</td>
</tr>
<tr>
<td>EUV Power</td>
<td>10 kW</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>60 pC</td>
</tr>
<tr>
<td>Beam energy</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>162.5 MHz</td>
</tr>
<tr>
<td>Average current</td>
<td><strong>9.75 mA</strong></td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td><strong>12.5 MV/m</strong></td>
</tr>
<tr>
<td>Number of cavities</td>
<td>64 units</td>
</tr>
</tbody>
</table>

- KEK and Japanese industries organized EUV-FEL light source study group for industrialization since 2015.
- Bunch length at main linac will be 1-3 ps.
- Main linac has 64 units of 9-cell superconducting cavity.
- EUV beam current is lower than KEK-cERL target. Therefore, the requirement of the HOM damping efficiency decreases on EUV.
  - cERL operated at 8.5 MV/m, because it has the large iris to damp HOM powerfully.
  - We redesign the cavity shape to realize stable 12.5 MV/m CW operation.
2-1 EUV cavity parameters

**Concepts of Cavity design**

- EUV cavity was designed based on KEK-cERL main linac ⇒ Large beam pipe + Beamline damper
- EUV beam pipe diameters is Φ100mm and Φ110mm ⇒ Make asymmetry actively and damp high frequency HOMs.
- The center cell shape is TESLA cell to decrease Ep/Eacc=2 ⇒ Stable operation at 12.5 MV/m

<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>KEK-EUV</th>
<th>KEK-cERL</th>
<th>TESLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td><strong>Iris diameter (mm)</strong></td>
<td><strong>70</strong></td>
<td><strong>80</strong></td>
<td><strong>70</strong></td>
</tr>
<tr>
<td>R/Q (Ω)</td>
<td>1009</td>
<td>897</td>
<td>1036</td>
</tr>
<tr>
<td>G (Ω)</td>
<td>269</td>
<td>289</td>
<td>270</td>
</tr>
<tr>
<td>Ep/Eacc</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Hp/Eacc (mT/(MV/m))</td>
<td>4.23</td>
<td>4.25</td>
<td>4.26</td>
</tr>
<tr>
<td>BBU limit</td>
<td>&gt;190 mA (EUV)</td>
<td>~600 mA (3GeV ERL)</td>
<td>~10 mA (3GeV ERL)</td>
</tr>
</tbody>
</table>
2-2 Concepts of EUV module

- EUV module consists 4+4 cavities and the design based on STF and ERL module.
- Coupler position is opposite direction each cavity, because the beam pipe sizes are different.
- Input coupler and tuner are same type of ERL and STF.
- HOM damper needs new development.
2-2 Concepts of EUV module

**Input coupler**
- Pulse version was designed for STF and modified for CW at cERL.
- **cERL coupler working well** (very similar specification with EUV)
- $Q_{ext}=2\times10^7$ require 4~5 kW input power for $E_{acc}=12.5$ MV/m
- Apply for EUV with some trial of compact version.

**Frequency tuner**
- Rough tuning by Slide-Jack tuner controlled by motor
  - Full stroke 3mm (~1MHz)
- Fine tuning by piezo tuner
  - Precision $\leq$nm
- **Working very well at cERL and STF**
- Apply for EUV
3-1 Test piece of the HOM damper

- cERL HOM absorber (ferrite) has cracks ⇒ not good for SRF usage.
- AlN (Sienna Tec. : STL-150D) is strong candidate for absorber.
  - AlN is tested at Cornell and DESY
- We started the measurement of RF parameter, outgassing and brazing.

RF parameter measurement

- RF parameters are measured by Nicolson-Loss method.
- 80K data was taken in nitrogen gas atmosphere.
- Test sample and RF cables did not touch liquid nitrogen.
- Room temperature data agrees well with the Sienna tec. Data.
- 80K tangent delta keeps high value at high frequency.
- We will try to take more high frequency data.
SEY of AlN samples:
- SEY was measured after applying ~150 °C baking.
- Baking time is 0, 2, 7, 24, 48, 120, 192 and 312 hours
- SEY saturated after 48 hour baking.

Comparison of SEY with other materials:
- SEY measured around 250 eV were compared between materials.
- Horizontal axis is baking time.
- Red line is AlN.
- AlN is lower than Al
Outgassing rate of AlN ring was measured after 48h x150 °C baking. After 1000h baking, outgassing rate is lower than $10^{-8}$ Pa·m$^3$/s·m$^2$. 

Outgassing rate ~ Measured by Shinji Terui (KEK)
3-4 Brazing test

- AlN cylinder was brazed in the copper cylinder which has the comb pattern.
- Ultrasonic testing in the water bath was done after brazing.
- Point A is outside of AlN. It has the second peak at 73us.
  \( \Rightarrow \) The boundary of copper and water reflects the ultrasonic wave.
- Point B is inside of AlN. It does not have second peak around 73 us.
  \( \Rightarrow \) Copper and AlN is touched.
- The color of scanning image shows the echo height.
- Touched points are not bright. It suggest the joint strength is poor.

- We tried thermal test. Unfortunately, AlN cylinder came off after first 80K thermal cycle.
- Machining error or brazing parameter error are suspected.
- We search the best condition for brazing.

Test piece of brazing
4-1 Cavity design concept for damping HOMs

- EUV cavity was designed focusing on the low frequency HOMs.
- Passband of 9-cell HOMs are ruled by the center cell
  ⇒ $R/Q$ and $Rt/Q$ changes are small
  ⇒ To lower the impedance $R$ and $Rt$, $Q_{ext}$ control is required
- We did the frequency matching to lower $Q_{ext}$ because HOMs are pass through the end cells and damped at beam line damper

Step3: Search best frequency of end cell
- Tuning curve method can calculate only $\pi$ mode frequency.
- If the highest impedance mode is not $\pi$ mode, end cell frequency searching is required.

Cell design process

Step1: Calculate frequency

Center cell ⇒ Eigen mode solver
End cell ⇒ Tuning curve method
  (this method can calculate only $\pi$ mode)

Response matrix of end cell HOM frequency was made by this method.

Step2: Search Minimum $Q_{ext}$ shape

End cell shapes were designed by using the matrix. There are many shapes which agree with a target frequency
  ⇒ Select minimum $Q_{ext}$ shape
4-2 Center cell passband

Step 1
- EUV center cell is TESLA shape.
- We will try to match end cell frequency to center cell passband.

Passband of TESLA center cell
4-3 Beam pipe diameter

• φ100mm and φ110mm beam pipes are selected.
• Beam pipe diameters are minimized to suppress leaking accelerating field.
• Different diameters are selected to make the asymmetry actively and damp the high frequency HOMs.
• TE11 cutoff frequencies of 100mm and 110mm beam pipe are 1600MHz and 1760MHz.
• High impedance TE111 dipole HOM is damped by both beam line damper.
• Monopole cutoff frequencies are lower than all monopole HOMs.

<table>
<thead>
<tr>
<th>Beam pipe diameter</th>
<th>Cutoff monopole (TM01)</th>
<th>Cutoff Dipole (TE11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ110</td>
<td>2086.4</td>
<td>1597.1</td>
</tr>
<tr>
<td>φ100</td>
<td>2295.0</td>
<td>1756.8</td>
</tr>
</tbody>
</table>

Passband of TESLA Center Cell

Formula of cutoff

Monopole TM01-mode

\[ f_{TM} = \frac{c}{2\pi} \left( \frac{j_{mn}}{a} \right) = \frac{229.50}{\phi} [MHz] \]

Dipole TE11-mode

\[ f_{TE} = \frac{c}{2\pi} \left( \frac{j'_{mn}}{a} \right) = \frac{175.68}{\phi} [MHz] \]
4-4 End Cell design

**Step 1**
- End cell frequency was calculated by tuning curve method because end cell and beam pipe have strong coupling.
- Tuning curve method can separate cell and beam pipe frequency.
- Imaginary short plane is the magnetic boundary.
- Therefore this method can calculate only $\pi$ mode frequency.

Frequencies are calculated with various beam pipe length.

Red line is the cavity resonance
green curve is the beam pipe resonance.
4-4 End Cell design

Step 1

- Frequency and Qext response of TM010,TE111,TM110,TM011 were calculated.
  ⇒ Response matrix was created
- Cell length and iris diameter have the major effect.
- Modify the end cell shape by using the response matrix.
  ⇒ End cell π mode frequency can be adjusted to the target frequency.
  ⇒ But target frequency sweep is required because other end cell passband are unknown.
- We tried to found the best end shape which matches center cell π mode frequency
  ⇒ But, there is no shape which matches more than 3 HOMs at once by this matrix method.
- Matching HOMs were divided into each end cell.
  ⇒ Φ100mm BP cell adjust to TE111 and TM011.
  ⇒ Φ110mm BP cell adjust to TM110 and TM011.
4-4 End cell design

**Step 2 Example** (Φ110mm BP cell)
- TE111 and TM011 end cell frequency adjust to center cell $\pi$ mode.
  $\Rightarrow$ Delta means the difference from center cell $\pi$ mode frequency
- Gray color area is constrained condition.
  - Re-entrant shape is not better for HPR or other water cleaning.
  - Pressing can be possible.
  - If change amount is higher than 20mm, the shape become triangle shape.
- The star shows the minimum Qext shape. This is a candidate.

Constrained conditions
- Not re-entrant shape: $\text{Xlen}-A1-A2>0\text{mm}$
- Pressing is possible: Absolute value $>5\text{mm}$
- Feasible shape: Change amount $<20\text{mm}$

**TE111 Qext of Φ110 BP cell**
Condition $\Delta f(\text{TE111})=0\text{MHz}$, $\Delta f(\text{TM011})=0\text{MHz}$

Minimum Qext. This is a candidate.
4-5 Optimization for Dipole HOMs

- The end cell frequency was swept to match the high impedance passband mode.
- Target impedance is 5.5x10^4 which BBU threshold is 200mA.
- Legend shows the delta frequency from center cell π mode.
- All Shapes satisfy dipole mode target.
- We focused on monopole HOMs.

φ110BP cell tuning for **TE111**

φ100BP cell tuning for **TM110**
4-6 Optimization for Monopole HOMs

- Highest impedance of monopole HOM is the TM110-$\pi$/9 mode.
- Both end cells were tuned to minimize the highest impedance mode.
- Minimum value of $R/Q*Q_{ext}$ is $5 \times 10^4$ Ohm. Both delta frequencies are about +5MHz.

$\Rightarrow$ Heating Power is 20W if the beam repletion hits the HOM frequency.

Monopole HOM Power

$$P_b = \left(\frac{R}{Q}\right)Q_{ext}I_0^2$$

$$= 5 \times 10^4 \times (0.02 A)^2 = 20 W$$
Parameters of EUV cavity

- Ep/Eacc is 2.0 because the center cell is TESLA shape.
- EUV monopole HOM is lower than cERL because the cERL was optimized for dipole HOMs.

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Acc.

Monopole HOM

- R/Q*Q_{ext} (Ohm)

Dipole HOM

- R/Q*Q_{ext}/f (Ohm/cm²/GHz)
  - Target 5.5x10^4
Summary

• EUV cavity has been designing for EUV-ERL/FEL accelerator.
• Cryomodule has been designing based on STF+ERL cryomodule.
• Damper development is important for EUV
• We have measured the RF parameter, outgassing, SEY, brazing.

• Cavity designed based on KEK-cERL +TESLA cavity.
  ⇒ TESLA center cell + beam line damper
• Maximum impedance of Dipole HOM is $3 \times 10^4$ Ohm/cm$^2$/GHz.
  ⇒ BBU limit is more than 190 mA.
• Maximum impedance of Monopole HOM is $5 \times 10^4$ Ohm.
  ⇒ This HOM power is lower than 20 W