R&D Activities for ARES Upgrade

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Outline

1. R&D programs for SuperKEKB
2. L-band HOM-load test stand
3. Input couplers with TiN coating
4. New copper electroplating for S-cav
5. Summary

KEKB Review
@KEK
2005.02.22
3-cavity system stabilized with the π/2-mode operation consists of

- HOM-damped accelerating cavity (A-cav)
- Energy-storage cavity with TE_{013} (S-cav)
- Coupling cavity (C-cav) with a parasitic-mode damper
Accelerator Resonantly-coupled with Energy Storage

3-cavity system stabilized with the \( \pi/2 \)-mode operation

consists of

- HOM-damped accelerating cavity (A-cav)
- Energy-storage cavity with TE\(_{013} \) (S-cav)
- Coupling cavity (C-cav)

with a parasitic-mode damper
Upgrade Items toward

Measures against

🔍 **Larger detuning**
→ Increase the energy ratio: $Us/Ua = 9 \rightarrow 15.$
→ Reported in the previous KEKB review
→ Skipped this time

🔍 **Higher HOM powers**
→ HOM-load upgrade

🔍 **Higher input RF powers** (400kW/cav $\rightarrow$ 800kW/cav)
→ TiN coating on the coaxial line
→ Coupler test stand upgraded for $\sim$800kW(CW)
[1] **Construction of a new L-band HOM-load test stand**
   - Using 1.25GHz klystron (1.2MW, CW)
   - The 1st stage just finished

[2] **Input couplers with TiN coating**
   - Against multipactoring in the coaxial line
   - TiN (Titanium Nitride) has low secondary-electron yields and is good for vacuum.
   - Two couplers have been completed.
   - Being tested in the upgraded coupler test stand up to 800kW.

[3] **New highly-pure copper electroplating for S-cav**
   - The old facility has been retired.
   - Reusing a facility being used for J-PARC.
[1] L-band HOM Test Stand

Two Bullet-shaped SiC-absorbers at the end of the HOM WaveGuide

SiC-tiles in the Grooved Beam Pipe

ARES HOM-damped Structure

Monopole HOMs
Dipole (V) HOMs
Dipole (H) HOMs

(Side view)

beam

beam

1000mm
SiC Absorbers

- In the HOM Wave Guide (WG)
  - Direct water cooling
  - Limit: >26kW/cav (HPT)

- In the Grooved Beam Pipe (GBP)
  - Indirect water cooling
    - via the copper plate
  - Limit: ~3.6kW/cav (HPT)

Max. power which can be supplied by the old L-band klystron.
HOM Extrapolation for Super-KEKB LER

- **HOM in WG load (LER):**
  - 26kW/cav (HPT)
  - 80kW/cav (SuperKEKB)
  - Need HPTs over 26kW
  - Increase # of absorbers /WG
  - Enhanced water cooling

- **HOM in GBP load (LER):**
  - 3.6kW/cav (HPT)
  - 20kW/cav (SuperKEKB)
  - Need direct water cooling like in...

<table>
<thead>
<tr>
<th>(KEKB)</th>
<th>(Super-KEKB)</th>
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<tbody>
<tr>
<td>Nb: 1224 → 4896 (full)</td>
<td></td>
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<tr>
<td>σz: 7mm → 3mm</td>
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| 2 x GBP (Nb=1224, BL=7mm) |
| 2 x GBP (Nb=4896, BL=4mm) |
| 2 x GBP (Nb=4896, BL=3mm) |
| 4 x HOM WG (Nb=1224, BL=7mm) |
| 4 x HOM WG (Nb=4896, BL=4mm) |
| 4 x HOM WG (Nb=4896 BL=3mm) |
Winged chamber loaded with SiC Absorbers
(used in the movable-mask sections)


→ Can be a prototype.

Directly water-cooled SiC bullet
New A-cav Design with Winged Chambers

Directly water-cooled SiC bullet
We cannot test HOM loads with high powers for SuperKEKB.

More powerful klystron is needed to upgrade the HOM loads.
Construction of New Test Stand for the HOM-load Upgrade

- Reusing an L-band klystron, which is capable of 1.2 MW CW power (freq. = 1.25 GHz).

- Operating conditions (HV & cooling system etc.) are going to be regulated for our purpose.

- The 1st stage of the construction has been just finished.
D01C/ARES HOM-load Test Stand

Output from the klystron

L-band klystron

Water dummy load
The 1\textsuperscript{st} RF Power Comes!

\textit{→ Tuning to deliver more RF power up to 100 kW}

Output power beyond the max. obtained in the old L-band test stand (3.3kW)
[2] Input Couplers with TiN Coating

The problem is the *multipactoring* in the coaxial line.

Example of the TV-camera snapshots of the *multipactoring* in the coaxial line.
Simulation Study

- Solving eq. of motion with the Runge-Kutta method
- Assuming the SEY of conditioned copper
- Count number of collisions.

Example of the Orbits
On Which Side?

On the **inner** conductor

On the **outer** conductor

Almost **single-side** multipacting on the **outer** conductor
Coating Area
Setup of the TiN Coating
(DC Sputtering)

- 3E-4Pa before coating
- Injected gas: Ar and N₂
- Being used for TiN coating (10nm) of RF Ceramic windows

Outer conductor
Ti electrode
Studies on

- **Total gas pressure**
  - 5 Pa
  - 11 Pa
  - 16 Pa
  - 21 Pa
  - 24 Pa

- **Gas mixture ratio (Ar:N₂)**

- **Thickness meas.**
  - ~50nm
  - done by direct observation using SEM

- **Secondary electron yields**

Two input couplers have been TiN-coated with the final condition.

(taken on 2004.11.10)
After Coating
Fabrication

Leak test

Tested in the upgrade coupler test stand
Old Setup of the Coupler Test Stand

- No RF output
  - S-cav works as a dummy load.
  - Input powers are limited: <400kW.
Coupler Test Stand
Upgraded for Higher Power Capability: 400→800kW

Input coupler used as output coupler

To 1-MW Water Dummy Load

From 1-MW CW Klystron

1MW DL
Another characteristic:
The coupling-loop angles of the input and output couplers are set to be the same.

- No reflection ($\Gamma \approx 0.0$)
- No Z-dependence

The hardest ordeal for couplers
Power History
(Data taken in 2005.02.01-10 @D01A/ARES TS)

$P_{\text{target}} > P_{\text{klv-out}}$

Any operating condition can be simulated in the test stand by changing the coupling-loop angles of the input and output couplers!

To be compared with results on a coupler w/o TiN coating

To be tested in the D04C station? ("genuine" test stand?)

Routes of the old and upgraded test stands

(β=3)  (β=1)
[3] New Copper Electroplating for S-cav

S-cav is made from iron with copper electroplating.

- Present S-cav —— electroplating in a pyrophosphate bath
  - With brightener → little defect on the surface
  - The facility has been retired.

- S-cav for SuperKEKB —— new electroplating in an acid sulfate bath
  performed in the periodic reverse (PR) process
  
  H. Ino, et. al, "Advanced copper lining for accelerator components”,

  - Without brightener → high purity, high electric conductivity (102% IACS),
    but possible defects on the surface
  - Using the facility being used for J-PARC

Ex. DTL tank
Difference between J-PARC and SuperKEKB

- **J-PARC case**
  - Thickness: ~1mm → Mechanical polishing (~0.5mm) → Electrolytic Polishing (EP)

- **SuperKEKB case**
  - Thickness: ~0.2mm → Electrolytic Polishing (EP)

Studies on

- **Thickness** (targets)
  - Ground (alkalinity): ~50µm
  - Main (acidity): ~150µm
  - Electrolytic Polishing: about -40µm

- **Less defect**
- **Electric performance**
  → Check $Q_0$. 

![Copper (100% IACS) Skin Depth Chart](image)
Pillbox Test Cavity

Diameter: 451.2mm
Height: 260.0mm

Made from iron (SS400)

(After copper electroplating)

(Before copper electroplating)
Theoretical Calculation of $Q_0 (=Q_0(\text{cal}))$

Analytical solution of the electromagnetic field in the pillbox cavity

**TE$mn\!p$ mode**

\[
\begin{align*}
E_x &= A \frac{j \omega \mu_0}{k} \frac{m}{r} J_m \left( \frac{1}{b} \right) \sin m\theta \sin \frac{p \pi z}{d} \\
E_y &= A \frac{j \omega \mu_0}{k} \frac{1}{b} J_m \left( \frac{1}{r} \right) \cos m\theta \sin \frac{p \pi z}{d} \\
E_z &= 0 \\
H_z &= A \frac{1}{k} \frac{p \pi}{d} \frac{m}{b} J_m \left( \frac{1}{b} r \right) \cos m\theta \cos \frac{p \pi z}{d} \\
H_y &= -A \frac{1}{k} \frac{p \pi}{d} \frac{m}{b} J_m \left( \frac{1}{b} r \right) \sin m\theta \cos \frac{p \pi z}{d} \\
H_x &= A j \phi \left( \frac{1}{b} r \right) \cos m\theta \sin \frac{p \pi z}{d}
\end{align*}
\]

**TM$mn\!p$ mode**

\[
\begin{align*}
E_x &= -A \frac{j \omega \mu_0}{k} \frac{1}{d} \frac{p \pi}{b} J_n \left( \frac{1}{b} \right) \cos m\theta \sin \frac{p \pi z}{d} \\
E_y &= A \frac{1}{k} \frac{p \pi}{d} \frac{m}{r} J_n \left( \frac{1}{b} \right) \sin m\theta \sin \frac{p \pi z}{d} \\
E_z &= A \frac{j \omega \sigma}{k} \left( \frac{1}{b} \right) \cos m\theta \cos \frac{p \pi z}{d} \\
H_z &= -A \frac{j \omega \epsilon_0}{k} \frac{1}{d} \frac{m}{b} J_n \left( \frac{1}{b} r \right) \sin m\theta \cos \frac{p \pi z}{d} \\
H_y &= -A \frac{j \omega \sigma}{k} \frac{1}{d} \frac{m}{b} J_n \left( \frac{1}{b} r \right) \cos m\theta \cos \frac{p \pi z}{d} \\
H_x &= 0
\end{align*}
\]

$Q_0(m,n,p) = \frac{U}{P_{wall}}$

\[
\begin{align*}
U &= \frac{E_0}{2} \int_{\text{cavity}} dV \mid \vec{E} \mid^2 = \frac{H_0}{2} \int_{\text{cavity}} dV \mid \vec{H} \mid^2 \\
P_{wall} &= \frac{1}{2} \sqrt{\frac{\omega \mu}{2\sigma}} \int_{\text{cavity}} dS \mid \vec{H} \mid^2
\end{align*}
\]

Assuming

- **100%IACS** electric conductivity (=$1/1.72E-8\Omega m$)
- **Flat surface** (i.e. no defect)
IACS

- International Annealed Copper Standard
- 100% IACS electric conductivity: $1/1.72 \times 10^{-8} \Omega \text{m}$
- The electric conductivity of the highest-class oxygen-free copper: 102% IACS

Cf. Electroplating in an acid sulfate bath w/o brightener: 102% IACS
$TE_{mnp}$ Waves

Copper Pillbox with
Diameter: 451.2 mm
Height: 260.0 mm

$(m = 0 \sim 4)$
$(n = 1 \sim 3)$
$(p = 1 \sim 6)$

$Q_0 (\text{cal}) / 10000$

Resonance Frequency [GHz]
After Trial and Error…

Copper Electroplating in an acid sulfate bath w/o brightener (PR process)
After Trial and Error…

Copper Electroplating in an acid sulfate bath w/o brightener (PR process)
After Trial and Error…

Copper Electroplating in an acid sulfate bath w/o brightener (PR process)

Barrel
Fine!

Endcap

Electrolytic polishing

Gorgeous!
Thickness Measurement

Barrel before electrolytic polishing

Distance from the edge [mm]

Thickness [µm]

- 1
- 3
- 5
- 7
Setup of the $Q_0$ Measurement
Setup (close view)

Loop couples with magnetic field.

Antenna couples with electric field.
Results of the $Q_0$ Measurements

Electroplating in a *pyrophosphate* bath with *brightener* (applied to the present S-cav's) (no temperature correction)
Results of the $Q_0$ Measurements

Electroplating in an acid sulfate bath without brightener before electrolytic polishing (@20degC)

Electroplating in a pyrophosphate bath with brightener (applied to the present S-cav's) (no temperature correction)

Frequency dependence comes from defects on the surface.
Results of the $Q_0$ Measurements

- Electroplating in an **acid sulfate** bath **without brightener** after electrolytic polishing (@20degC)
- Electroplating in an **acid sulfate** bath **without brightener** before electrolytic polishing (@20degC)
- Electroplating in the **pyrophosphate** bath **with brightener** (applied to the present S-cav's) (no temperature correction)

**No defect!**

DC electric conductivity (102% IACS)

Frequency dependence comes from defects on the surface.

TM modes

TE modes

$Q_0$ (meas) / $Q_0$ (calc) [%]

Resonance Frequency [MHz]
Next Step: Vacuum Test

- The test cavity has been fabricated.
- The electroplating is ongoing.
- A vacuum test will be done next month.
Summary

- ARES R&D programs are ongoing well.

- A new L-band test stand has been constructed
  - For the HOM-load upgrade.
  - The 1st stage has been finished.
  - To be tuned for supplying high powers.

- Input couplers with TiN coating
  - Against multipactoring in the coaxial line.
  - Two TiN-coated couplers have been completed.
  - Being tested in the upgraded coupler test stand up to 800kW(CW).

- New highly-pure copper electroplating for S-cav
  - On the slightly different condition from J-PARC.
  - The electric performance is estimated to be excellent.
  - A vacuum test to be done next month.