

## CONDITIONING OF INPUT COUPLERS FOR KEKB SUPERCONDUCTING CAVITIES

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### Abstract

Four additional superconducting cavities were installed in the KEKB HER ring in August 2000. Up to now the superconducting cavities have been operated under a beam of 870mA in the HER. The input coupler has been used to feed a power exceeding 380 kW stably with high current. We describe the status of conditioning for four couplers.

The KEKB coupler has multipacting power levels below 300kW. After enough processing with bias voltage, no pressure increase could be observed at power feeds up to 300kW. RF processing with bias voltage is effective in suppressing multipacting. We will discuss the multipacting power levels, the discharge near the window and processing for beam operation.

### 1 INTRODUCTION

KEKB is a double ring collider of 3.5 GeV positrons in a low energy ring (LER) and 8 GeV electrons in a high energy ring (HER). It was designed to accelerate ampere-class currents, 2.6A for the LER and 1.1A for the HER. The eight superconducting cavities have been operated under a beam of 870mA in the HER. The input coupler has been used to feed a power exceeding 380 kW with high current.

It is necessary to process the coupler for high power operation. Knowing that electron bombardment is effective for surface cleaning, we decided to use multipacting with bias voltage for processing. We estimated multipacting power levels by numerical simulation and confirmed them by measurement using a new coupler test stand.

This paper describes the status of the couplers for the additional four cavities installed in 2000, the estimation of multipacting levels in the coupler, its measurement, and an investigation of the effect of RF processing with bias voltage.

### 2 STRUCTURE OF INPUT COUPLER

The input couplers for the KEKB superconducting cavities were developed for high current operation based on the TRISTAN coupler [1]. The structure and parameters of the couplers are discussed in another report [2]. The points of improvement are the following:

- (1) The choke structure around the window is changed to a 4mm gap from 3mm to reduce the field on the window surface to 70% of its former value.
- (2) The cooling system is strengthened to handle the higher heat loss. The coaxial pipe is cooled by an 8 l/min He gas flow, with outside copper fins to maintain uniform temperature.
- (3) A doorknob transition section is used to supply bias voltages of  $\pm 2000$ V for processing.
- (4) A monitor port near the window monitors vacuum and electron current, in addition to discharge light.

### 3 STATUS

The installation and conditioning of four additional couplers was carried out between January and September, 2000. The process of coupler commissioning were the following:

#### (1) Rinsing and baking

The coupler as received is rinsed by ozonized pure water, and set on the coupler stand. The ozonized pure water rinsing is effective in removing window surface contamination. The coupler is baked at 100 deg for 1 day. The baking temperature is limited by the melting point of the indium shield.

#### (2) Processing at coupler power stand

The processing is begun up to a power of 400kW with 30% reflected wave or travelling wave. The coupler is operated using partial reflected waves under 30% in order to process a wide area of the coaxial line.

#### (3) Horizontal test

The input coupler has to be opened to air for assembly into the cryo-module. Each coupler was processed with bias voltage between +2000V and -2000V up to a power of 300kW. After assembling into the cryo-module, the coupler power operation without beam current is only standing wave. The processing area of coaxial line is limited in the standing wave mode, but it can be expanded to a wider area by using a bias voltage.

#### (4) Installation in the KEKB tunnel

At 4K operation, the cavity surface absorbs gas like a cryo-pump. When the cavity is warmed up after beam operation, a large amount of absorbed gas comes out. Therefore every time the cavity is warmed up, coupler processing needs to be carried out.

Table 1 summarizes the status of the four couplers. The amount of outgassing during the processing is over 1 torr\*1 after opening to the air, and under 0.7 torr\*1 when kept in vacuum.

Table 1. Status of input couplers

-	5(D10-A)	6(D10-B)	7(D10-C)	8(D10-D)
Choke gap	4 mm	4mm	3mm	3 → 4mm
1.Processing at the coupler stand (300K)				
Baking	90°C×20hr	80°C×30hr	95°C×30hr	105°C×25hr
reflection	30%	30%	60%	30%
process time[hr]				
no-bias	2.0/360kW	8.1/420kW	3.8/300kW	6.7/420kW
vacuum [torr]	2.7×10 <sup>-7</sup>	2.7×10 <sup>-7</sup>	5.2×10 <sup>-7</sup>	3.9×10 <sup>-7</sup>
outgas [torr-l]	-	-	-	-
bake90°1day	1.7	4.4	4.6	3.4
RF process	1.1	2.8	1.4	2.5
2.Horizontal test				
At 300K				
Process time[hr]				
no-bias	2.4/300kW	3.5/300kW	6.0/300kW	2.5/300kW
vacuum [torr]	2.9×10 <sup>-9</sup>	2.0×10 <sup>-9</sup>	1.8×10 <sup>-9</sup>	1.7×10 <sup>-9</sup>
outgas[torr-l]	2.1	3.1	2.4	2.1
At 4K				
Vacuum [torr]	1.3×10 <sup>-9</sup>	5.5×10 <sup>-10</sup>	5.4×10 <sup>-10</sup>	4.2×10 <sup>-10</sup>
External Qvalue	7.8×10 <sup>4</sup>	7.0×10 <sup>4</sup>	6.6×10 <sup>4</sup>	5.9×10 <sup>4</sup>
3.Beam operation in KEKB tunnel				
3.1 After installation in KEKB tunnel (2000.9)				
At 300K				
process time[hr]	Exchange the coupler			
no-bias	2.5/300kW	3.6/300kW	5.5/300kW	2.6/300kW
vacuum [torr]	1.7×10 <sup>-9</sup>	1.2×10 <sup>-9</sup>	4.4×10 <sup>-9</sup>	1.1×10 <sup>-9</sup>
outgas[torr-l]	2.3	1.3	1.0	0.4
At 4K				
Vacuum [torr]	4.9×10 <sup>-10</sup>	3.1×10 <sup>-10</sup>	2.5×10 <sup>-10</sup>	2.5×10 <sup>-10</sup>
Operation	Beam operation	Beam operation	No RF Operation	No RF Operation
3.2 After beam operation at current 600mA [ 150kW] (2001.1)				
At 300K				
process time[hr]	Cavity leak			
no-bias		1.0/300kW	1.0/300kW	1.5/300kW
vacuum [torr]		1.3×10 <sup>-9</sup>	1.2×10 <sup>-9</sup>	1.4×10 <sup>-9</sup>
outgas[torr-l]		0.7	0.3	0.7
At 4K				
Vacuum [torr]		2.6×10 <sup>-10</sup>	2.3×10 <sup>-10</sup>	2.3×10 <sup>-10</sup>
Operation	No cavity	Beam operation	Beam operation	Coupler window leak
3.3 After beam operation at current 800mA [ 270kW] (2001.9)				
At 300K				
process time[hr]	Assemble a cavity			Exchange the coupler
no-bias	2.1/300kW	0.4/300kW	0.9/300kW	1.7/300kW
vacuum [torr]	2.1×10 <sup>-9</sup>	1.1×10 <sup>-9</sup>	1.6×10 <sup>-9</sup>	2.0×10 <sup>-9</sup>
outgas[torr-l]	1.6	0.4	0.2	1.0
At 4K				
Vacuum [torr]	2.5×10 <sup>-10</sup>	2.2×10 <sup>-10</sup>	3.2×10 <sup>-10</sup>	3.8×10 <sup>-10</sup>

Exchange the coupler : One case is monitor port break  
 Another case is window leak  
 No RF operation: Two cases are monitor cable break.

## 4 SIMULATION OF MULTIPACTING LEVELS IN THE COAXIAL LINE

We observed increases in vacuum pressure, electron current and discharge light during processing and beam operation. These phenomena can be caused by multipacting. Therefore we have carried out a numerical simulation to calculate the multipacting levels for the coaxial line as a function of power transmission. The levels are confirmed with measurements using a new coupler test stand.

### 4.1 Method of calculations

The equations of motion of a relativistic electron in an electromagnetic field E,B are generated by the formulas where

$$\frac{\partial \vec{v}}{\partial t} = \frac{e}{m \gamma} (\vec{E} - \vec{v} \times \vec{B} - \frac{1}{c^2} (\vec{v} \cdot \vec{E}) \vec{v}) \quad (\text{eq.1})$$

$$\frac{\partial x}{\partial t} = \vec{v} \quad (\text{eq.2})$$

v, x: 3-dimensional velocity and position of electron  
 e, m: charge, mass of the electron  
 γ : Lorentz gamma

In the case of a coaxial line, the electromagnetic fields are given by the following :

$$E_r = \frac{U}{r \cdot \ln(b/a)} \cdot \{ \cos(\frac{\omega}{c} \cdot z - \psi) - \Gamma \cdot \cos(\frac{\omega}{c} \cdot z + \psi) \} + \frac{V_b}{r \cdot \ln(b/a)} \quad (\text{eq.3})$$

$$B_\phi = \frac{U}{c \cdot r \cdot \ln(b/a)} \cdot \{ \cos(\frac{\omega}{c} \cdot z - \psi) + \Gamma \cdot \cos(\frac{\omega}{c} \cdot z + \psi) \} \quad (\text{eq.4})$$

where a,b: inner and outer conductor radius  
 ω: frequency  
 ψ: phase  
 Γ: voltage reflection coefficient

The calculations were done as follows:

- 1) Set the initial conditions of electromagnetic fields (power, reflection, bias voltage) and electron (energy, RF phase, position).
- 2) Integrate the equation of motion of the electron by the Runge Kutta-Gill method.
- 3) Stop the tracking when the electron trajectory collides with the wall.
- 4) When the primary electron collides with the wall, check the multipacting condition, i.e. the electric field is in the positive direction to accelerate the secondary electron:  $E^* v_2 > 0$ .
- 5) If the multipacting condition is satisfied, calculate the impact energy of the primary electron, the secondary electron emission coefficient, the RF order, etc. And set the initial energy of the secondary electron to 5eV and its emission angle relative to the surface at 90°, and start tracking again from the collision point.
- 6) Repeat up to emission count  $I_{\max}$  set from initial input data. Calculate the total coefficient  $\Delta = \prod_{i=1, \text{II}} \delta$ .
- 7) If the multipacting condition isn't satisfied or the emission count I reaches the maximum value, stop the calculation. Repeat the simulation with a different initial position and phase.

### 4.2 Estimation of multipacting power level

#### (1) Travelling wave

We show the results of simulation for two case of traveling waves for the KEKB coupler coaxial line. The

first case is a 50Ω line of inner/outer diameter 52/120mm and second case is the niobium cavity port of outer diameter 100mm.

We search for the resonance condition for each initial RF phase, input power and electron starting point with a bias voltage of 0V. If the primary electron survives after 100 collisions with the wall, it is judged to fit the multipacting resonance condition. Table 2 summarizes the multipacting power levels calculated in the simulation. Fig. 1 shows the multipacting power levels on a 50Ω line, i.e. the number of collisions with the wall, the order of RF period and the impact energy of the primary electron. Power levels below 300kW that fit the multipacting condition exist at 225kW for 7th order in case1, and at 195kW and 290kW for 5th and 4th order in case2. These results are in agreement with the scaling law[3].

Fig. 2 shows the energy distribution of the impact energy for the 225kW power level of in case 1. In this case, the resulting impact energy of 392V has a high value of secondary electron emission (SEE) coefficient. The other 2 power levels in case2 have lower impact energies 153V and 255V, in the range of low SEE coefficient.

In the travelling wave operation of the coaxial line careful processing of the 225kW multipacting power level is needed.

Table 2 Multipacting power levels in coaxial line (travelling wave)

	Case1	case2
Outer diameter (mm)	120	100
Inner diameter (mm)	52	52
Power level of one point multipacting (kW)		
RF order 7	225	
6	372	
5	460, 520	195
4	728, 762-790	290
3	1190	470-485
2	1150	900-990
1		
Power level of two point multipacting (kW)		
		1020-1150

(2) Reflected wave

Multipacting levels were estimated for partial reflected and standing waves. Many power levels satisfy the multipacting resonance condition below the power of 300kW in the reflected wave. Fig. 3 shows the results of simulation for the standing wave. The number of collisions with the wall, the position on the coaxial line and the impact energy of the primary electron are shown. The range of positions satisfying the multipacting resonance condition is limited in standing wave operation.

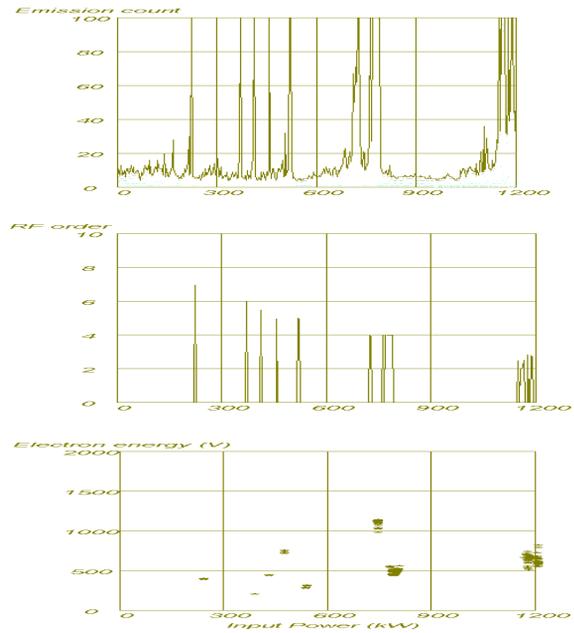


Fig. 1 Multipacting power level of 50 ohm coaxial line for KEK inner/outer diameter 52/120mm, in travelling wave operation

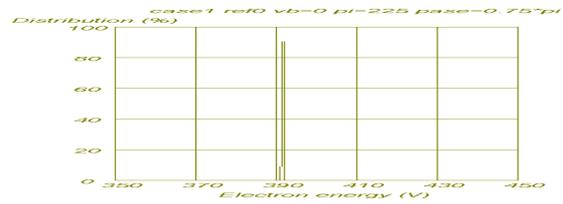


Fig. 2 Energy distribution of the impact energy in 225kW multipacting power level

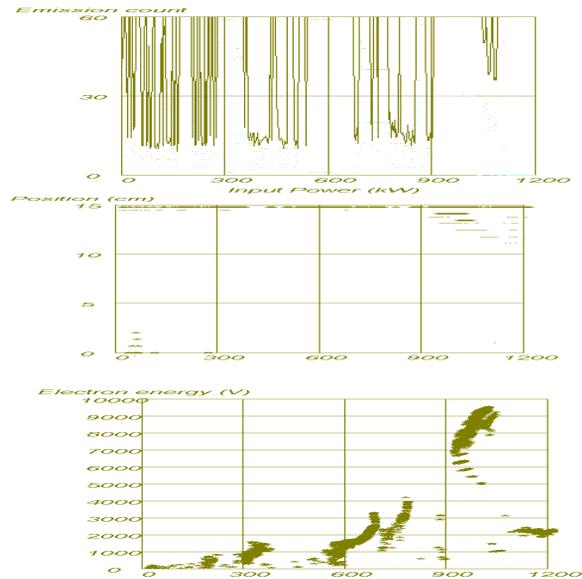


Fig. 3 Multipacting power level of 50 ohm coaxial line for KEK inner/outer diameter 52/120mm, in standing wave operation

## 5 MEASUREMENT ON COUPLER TEST STAND

### 5.1 Coupler test stand

The coupler stand formerly used for processing was limited to vacuum pressure of order  $10^{-7}$  torr and in baking temperature to 100 degrees. For the detailed measurement of the coupler processing reported here, a new coupler test stand was constructed (see Fig. 4). It is pumped by a 400l/sec ion pump, achieving a pressure level of  $10^{-9}$  torr. The outer conductor is equipped with five monitor ports to help identify the points producing multipacting. The monitors consist of an arc sensor for detecting discharge, a vacuum gauge, an electron probe and a view port near the ceramic window. Four electron probes are placed in the coaxial line.

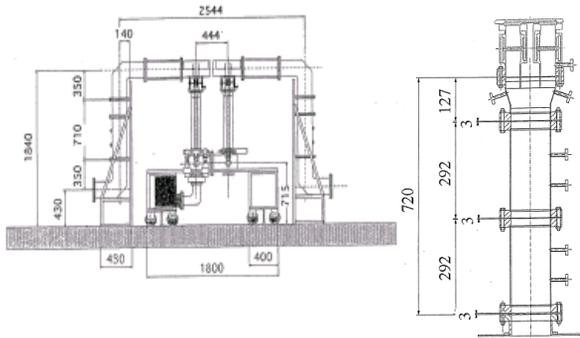


Fig. 4 The new coupler test stand

### 5.2 Measurement of the multipacting power levels in the coaxial line

Multipacting has been observed in the coaxial line. Fig. 5 shows the relation between the vacuum pressure and the input power for travelling wave operation. The power level for increased pressure is  $200\text{kW} \pm 20\text{kW}$  in travelling wave operation, almost the same as the multipacting level found in the simulation. Fig. 6 shows the monitoring signals from the electron probes. The electron current in the coaxial line is greater than that near the window. This suggests that one point multipacting occurs at the outer conductor.

In the processing of this power level, the main component of desorbed gas is  $\text{H}_2$  from the outer conductor surface.

Pressure  $1 \cdot 10^{-4}$  Pa/full scale

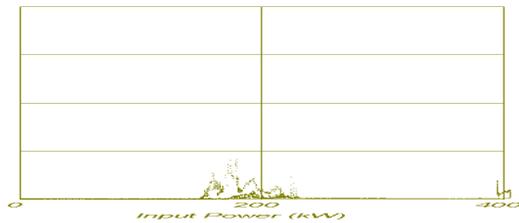
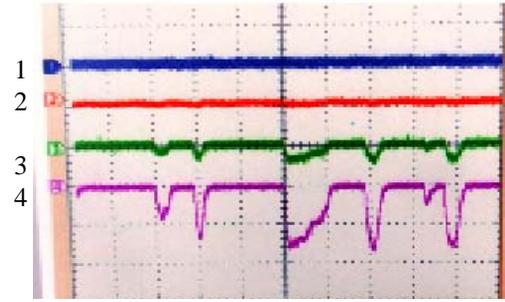


Fig. 5 Coupler processing with travelling waves: vacuum vs power level.



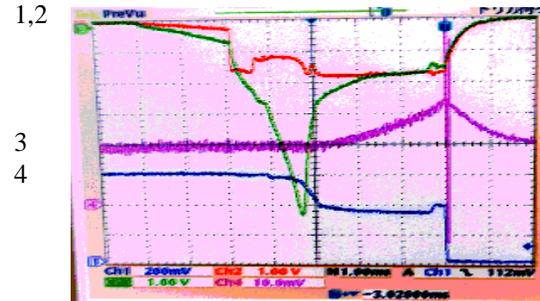
x-axis:10ms/1div

Fig. 6 Monitoring signals from electron probes (multipacting on the coaxial line)

- 1:electrons near the window in the downstream coupler
- 2:electrons in the coaxial line in the downstream coupler
- 3:electrons near the window in the upstream coupler
- 4:electrons in the coaxial line in the upstream coupler

### 5.3 Measurement of arcing near the ceramic window

We observed arcing and multipacting near the ceramic window during the initial conditioning. Fig. 7 shows the monitoring signal at the arc sensor. At first the electron current near the ceramic window rises exponentially. When the electron current reaches a peak, the discharge light starts to increase. At the same time power is absorbed in the coupler. This makes clear that multipacting near the ceramic window leads to arcing, and the power is absorbed by the growth of the discharge. As this power absorption is dangerous, the arc sensor (used to trigger a power interlock) is effective in protecting the window from breaking.



x-axis : 1ms/1div

Fig. 7 The monitoring signal at the interlock arc sensor.

- 1: (red) electrons in the coaxial line
- 2: (green) electrons near the window
- 3: (purple) light signal from arc sensor
- 4: (blue) reflected power decrease 36kW->16kW (input power is constant at 36kW)

The multipacting power level in the window structure is estimated from the operation of the arc sensor. Fig. 8 indicates the number of arc sensor-initiated shutdowns. We suppose that the power below 50kW is a multipacting level in standing wave operation where the maximum field is at the window. Because the number of arc interlock triggers depends on the contamination of the

ceramic,[2,4] the multipacting must grow on the ceramic window.

During the discharge, the main components of desorbed gas are CO and CO<sub>2</sub> near the window.

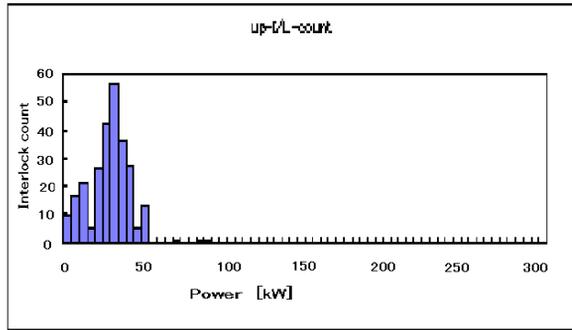


Fig. 8 The number of triggers of arc sensor interlock

## 6 PROCESSING WITH BIAS VOLTAGE

As multipacting levels exist for power below 300kW, the coupler needs conditioning to permit operation. In processing, we observe electron current at first, and then an increase in pressure with a time delay of about 100msec. This means that the electron bombardment is effective for surface cleaning. We opted to use multipacting with bias voltage for processing, especially on the metal surface.

Fig. 9 shows the positions on the coaxial line that satisfy the multipacting resonance condition for power between 0 and 300kW with bias voltage  $\pm 2000V$  and standing wave operation. Processing without bias voltage is limited to the area of the nodes of the standing waves. RF processing with bias voltage is effective in expanding the multipacting area along the coaxial line.

In the case of KEKB conditioning, no pressure increase could be observed in the power feed without bias voltage after processing with bias voltage had been carried out. Bias mapping indicated the pressure increase is useful to check the state of the coupler. After enough processing, it shows only the multipacting levels caused by the coupler structure. It is the same form as with normal couplers, as shown in Fig. 10.

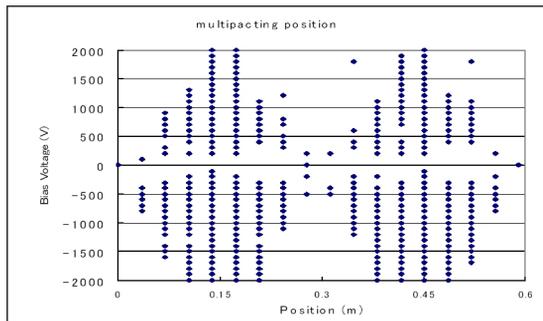


Fig. 9 The positions satisfying the multipacting resonance condition (power 0-300kW, bias voltage  $\pm 2000V$ , with standing waves)

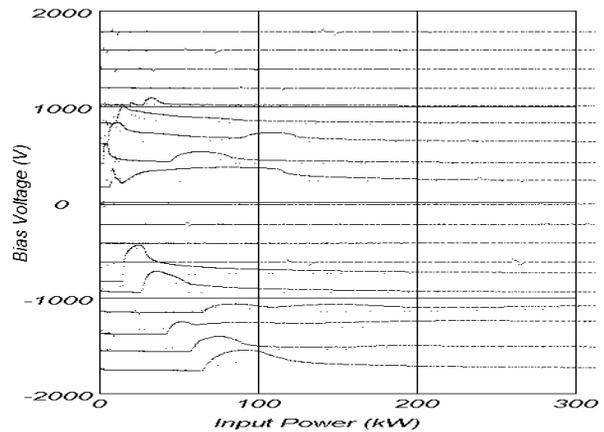


Fig. 10 Bias mapping of the pressure increase (in the case of cavity D10A in horizontal test)

## 7 SUMMARY

Multipacting power levels are checked by simulation and measurement. The KEKB coupler has multipacting power levels below 300kW. After enough processing with bias voltage, no pressure increase could be observed in the power feed without bias voltage. RF processing with bias voltage is effective in expanding the multipacting area of the coaxial line. We suppose that multipacting processing with bias voltage desorbs gas and also changes the condition of the surface.

The discharge near the window is caused by multipacting, and is dangerous because of power absorption. The arc sensor is effective in protecting the widow from breaking.

We will study how to process with bias voltage near the window more safety and predict the life of the window.

## REFERENCES

- [1] S.Noguchi et al, 4th Workshop on RF Superconductivity, Vol.1 p.397
- [2] Y.Kijima et al, this conference
- [3] E.Somersalo et al, Particle Accelerators, Vol.59, pp.107-141
- [4] Y.Kijima et al, Proceedings of EPAC 2000, Vienna, Austria