Input coupler activities at KEK

at CERN, 2015’ June 23

Eiji Kako (KEK, Japan)

OUTLINE

- Introduction of KEK couplers
- Lots of failure reports

Discussion Topics

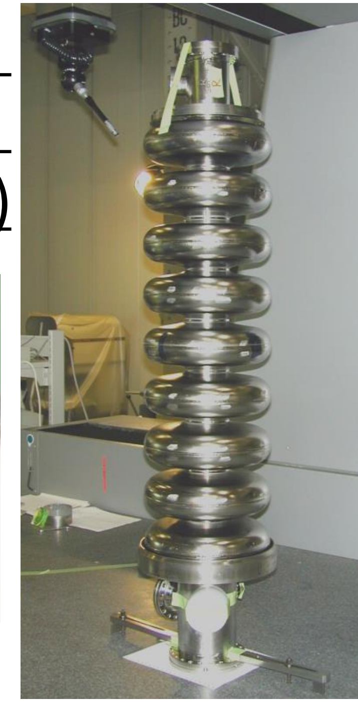
I remind you the topics we agreed to talk about:

- Design: maximum power per coupler ? multi coupler per cavity ?
- Construction: choice of material and of techniques of construction, coating
- Series production: fabrication, cleaning, handling and assembly
- Series production by industrials: modification of the processes, industrial alternative proposals, ...
- Cleaning and assembly: which clean room is really needed ? For FPC alone? For FPC onto cavity?
- Tests: prototype processes versus series processes, RF test boxes, amplifiers for tests
- Statistics of couplers operated in accelerators
- Diagnostics during R&D and prototyping, versus diagnostics during operation in accelerators
- Degradation of characteristic over time of operation

Superconducting Cavities Developed at KEK

TRISTAN 508MHz 5-cell Cavity

J-ADS 972MHz
9-cell Cavity
(β=0.73)



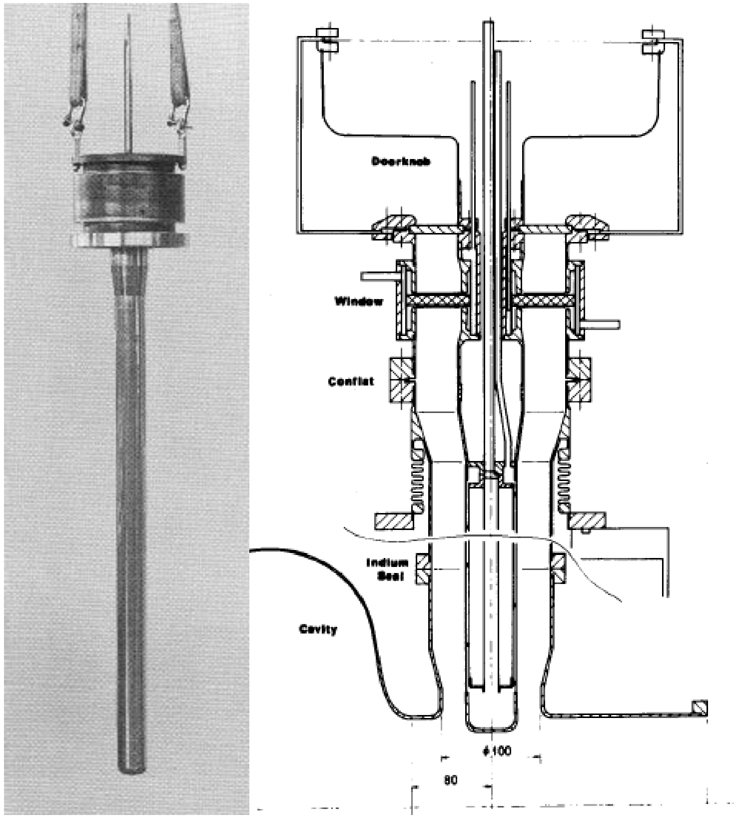
KEKB 508MHz 1-cell Cavity

cERL Injector
1.3GHz 2-cell Cavity

cERL ML
1.3GHz 9-cell Cavity

STF 1.3GHz 9-cell Cavity

TRISTAN-type High Power Input Couplers at KEK



Original design :

508 MHz TRISTAN Input Coupler

S. Noguchi, E. Kako, K. Kubo

(4^{th} SRF-WS, 1989)

972 MHz J-ADS Input Coupler (KEK)

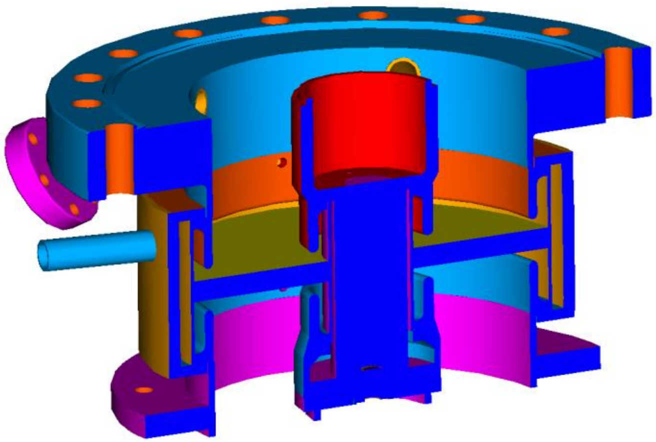
1.3 GHz cERL Injector Input Coupler (KEK)

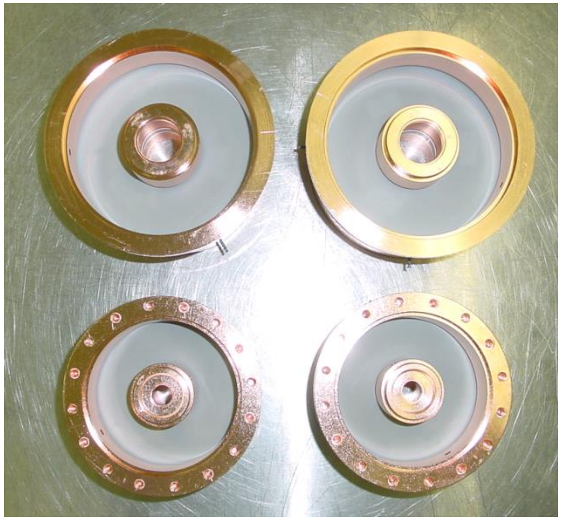
1.3 GHz STF-1 Input Coupler (KEK)

1.3 GHz STF-2 Input Coupler (KEK)

TRISTAN-type RF Windows

Tristan-type coaxial disk ceramics RF window with choke structure

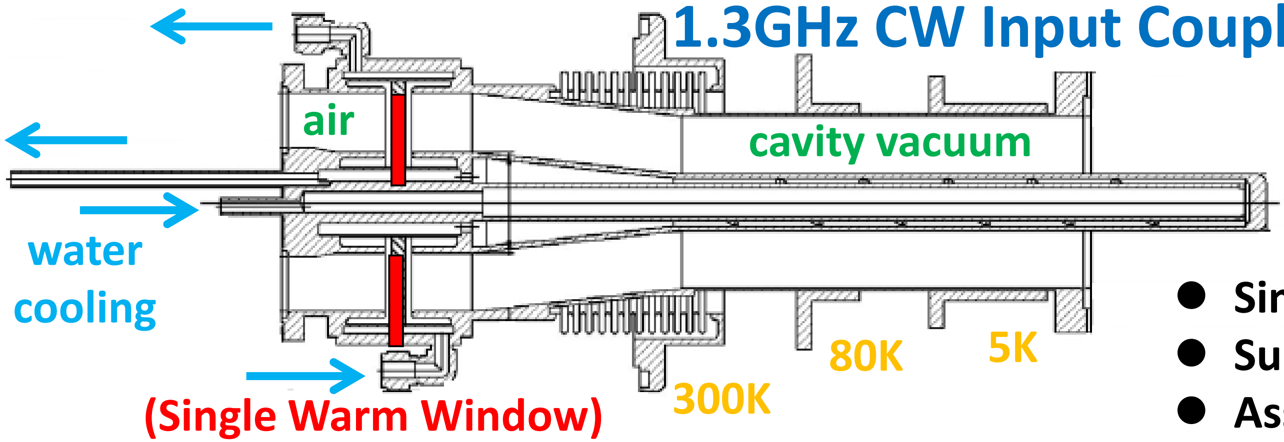




RF windows after 1st brazing

Al_2O_3 ceramics with metalizing

1.3GHz CW Input Coupler for cERL Injector



- Simple structure
- Suitable for cooling
- Assembly with cavity in CR

High Power Performance of TRISTAN-type Couplers

Facility	Frequency	Window type Coupling	Maximum RF Power
TRISTAN /KEK	508 MHz	1, Coax. Disk Fixed	Test-stand, 200 kW, CW Operation, 70 kW, CW
KEKB /KEK (T. Mitsunobu)	508 MHz	1, Coax. Disk Fixed	Test-stand, 800 kW, CW Operation, 380 kW, CW
J-ADS /KEK-JAEA	972 MHz	1, Coax. Disk Fixed	Test-stand, 2.0 MW, pulse Operation, 350 kW, pulse
cERL-Inj. /KEK	1300 MHz	1, Coax. Disk Fixed	Test-stand, 40 kW, CW Operation, 10 kW, CW
cERL-ML /KEK (H. Sakai)	1300 MHz	2, Coax. Disk Variable	Test-stand, 40 kW, CW Operation, 15 kW, CW
STF-2 /KEK	1300 MHz	2, Coax. Disk Variable	Test-stand, 1.5 MW, pulse Operation, 450 kW, pulse

Important Technical Issues for Input Couplers

- Ceramics window : material, purity
- Metalizing of ceramics
- Copper plating : thickness, RRR, adhesion, pits, uniformity
- TiN coating : thickness, uniformity
- Joining by Brazing
- Welding by TIG, Laser, E-beam

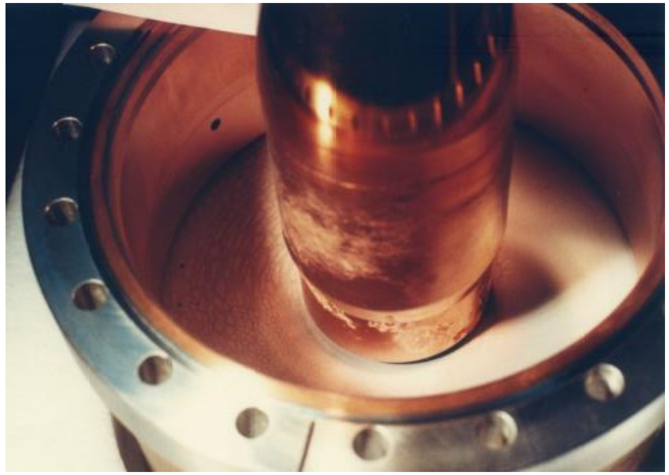
- RF properties
- Thermal characteristics
- Mechanical analysis
- Multipacting simulation

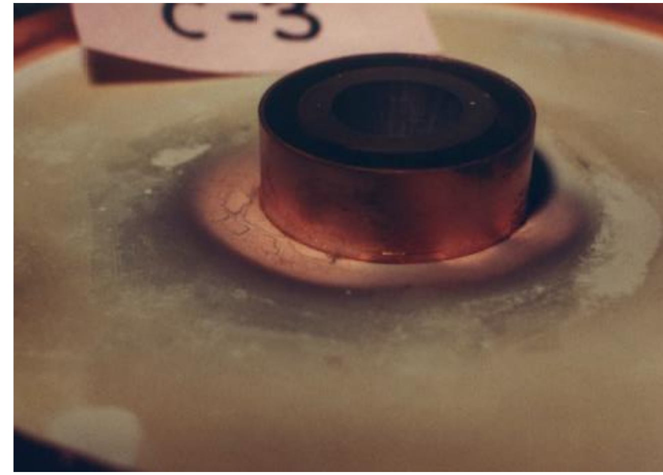
- Cleaning procedure
- Assembly in clean room

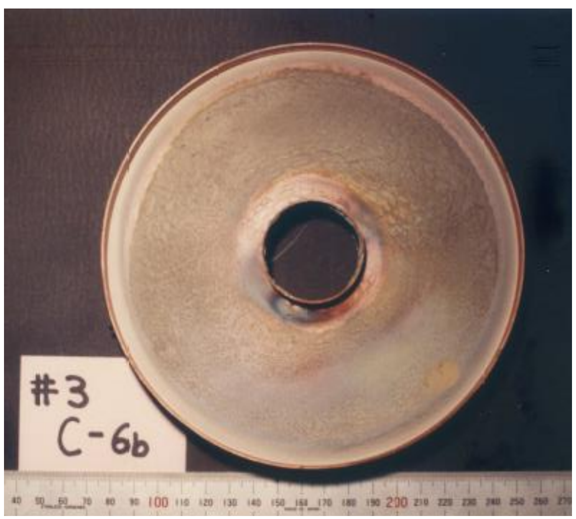
About 27 years ago in TRISTAN at KEK

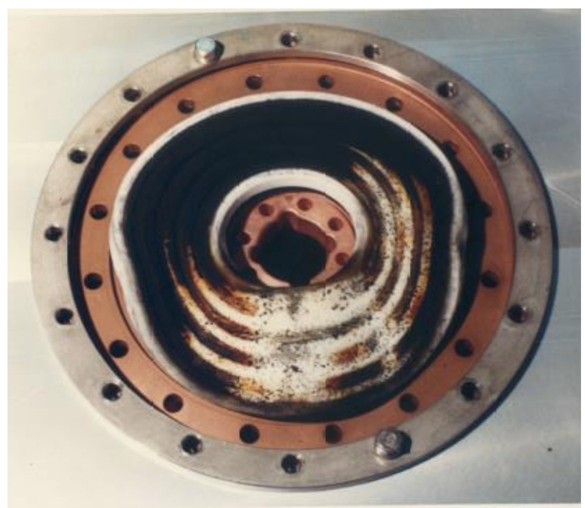
508MHz,
CW 50kW
Input coupler with one warm window and water cooling

(at test stand, 1988')









In the initial stage,
no TiN coating
no Arc sensor

↓

Importance of TiN coating and Interlock system

About 25 years ago in TRISTAN at KEK

Summary of RF window troubles during module-operation in TRISTAN
(32, 5-cell cavities operated with beam; total 56 couplers tested)

Date	Cavity	Temp.	Status	Damage	Cure
1989, Jan.	11B #3	4.4 K	Conditioning	Crack	Disassembly of cryomodule
1989, Feb.	10B #1	4.4 K	Beam operation	Pin-hole	Replacement of coupler in tunnel
1989, Oct.	10B #1	300 K	Warm-up	Pin-hole	Replacement of coupler in tunnel
1990, Jan.	10D #2	4.4 K	Conditioning	Burnt PE disk	Replacement of coupler in tunnel
1991, Jan.	10C #3	4.4 K	Conditioning	Crack by serious arcing	Disassembly of cryomodule
1991, July	10A#2	4.4 K to 300K	Beam operation	Cooling water leaked into cavity	Disassembly of cryomodule

(E. Kako: PAC91, p2408)

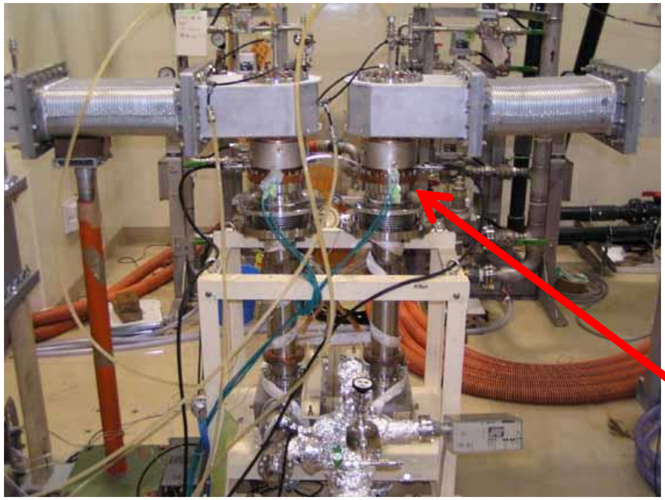
About 15 years ago in 972MHz couplers for J-ADS

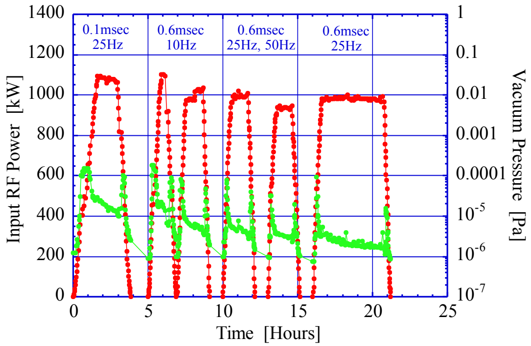
Design Values ;

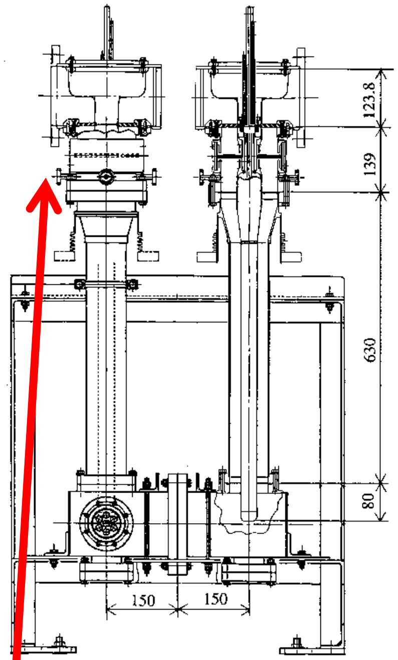
Q_{ext} = 5x10^{5}

Input RF Power = 300kW

(Beam Current = 30mA)







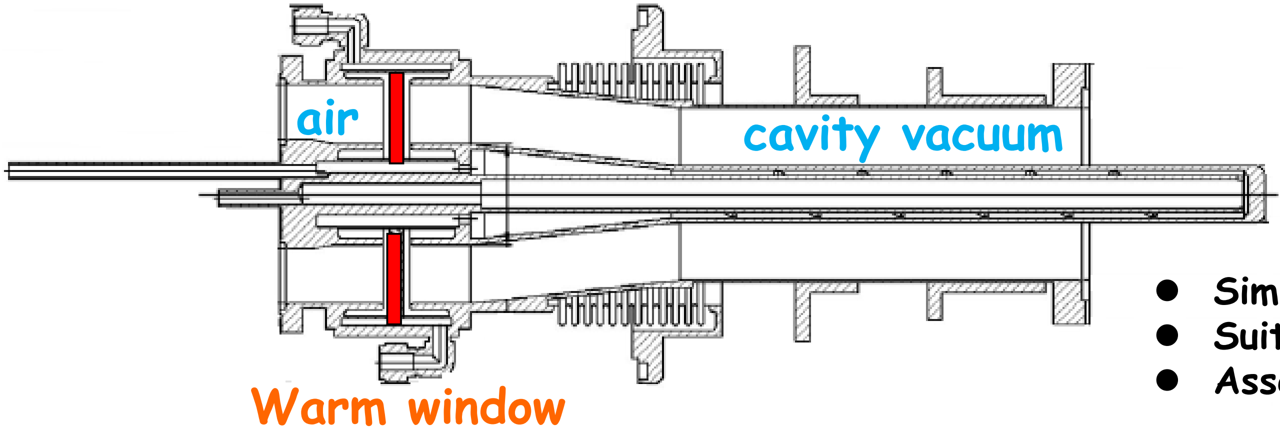
- **Vacuum gauge**
- **Arc sensor**
- **Electron pick-up**

Max. Input RF Power
(0.6ms, 25Hz) ;
Through = 2.0 MW
Reflection = 800 kW

(E. Kako: SRF03, TuP016)

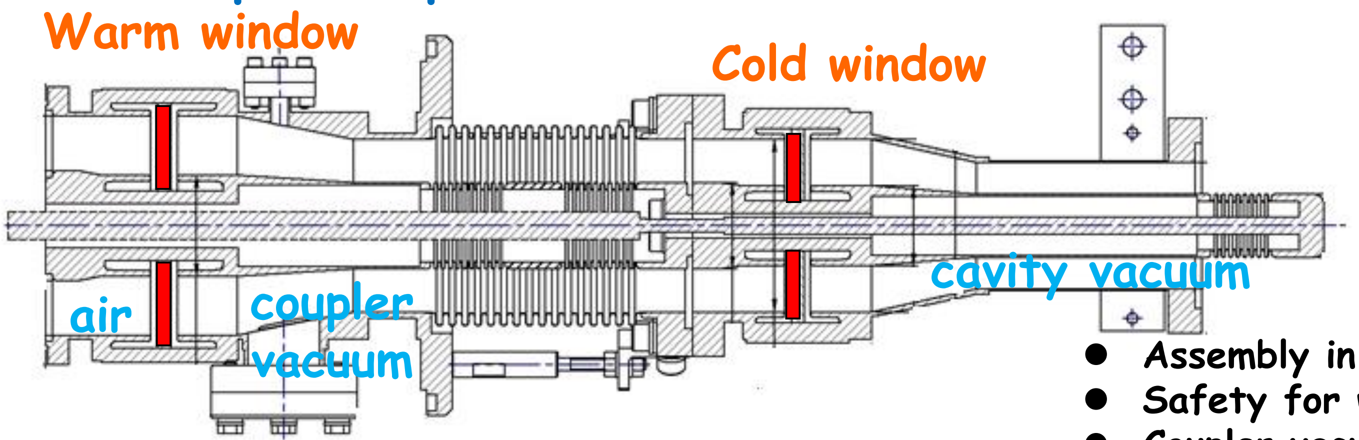
10 years ago: CW and Pulsed Input Couplers at KEK

CW Input Coupler for cERL Injector CM (Single Warm Window)



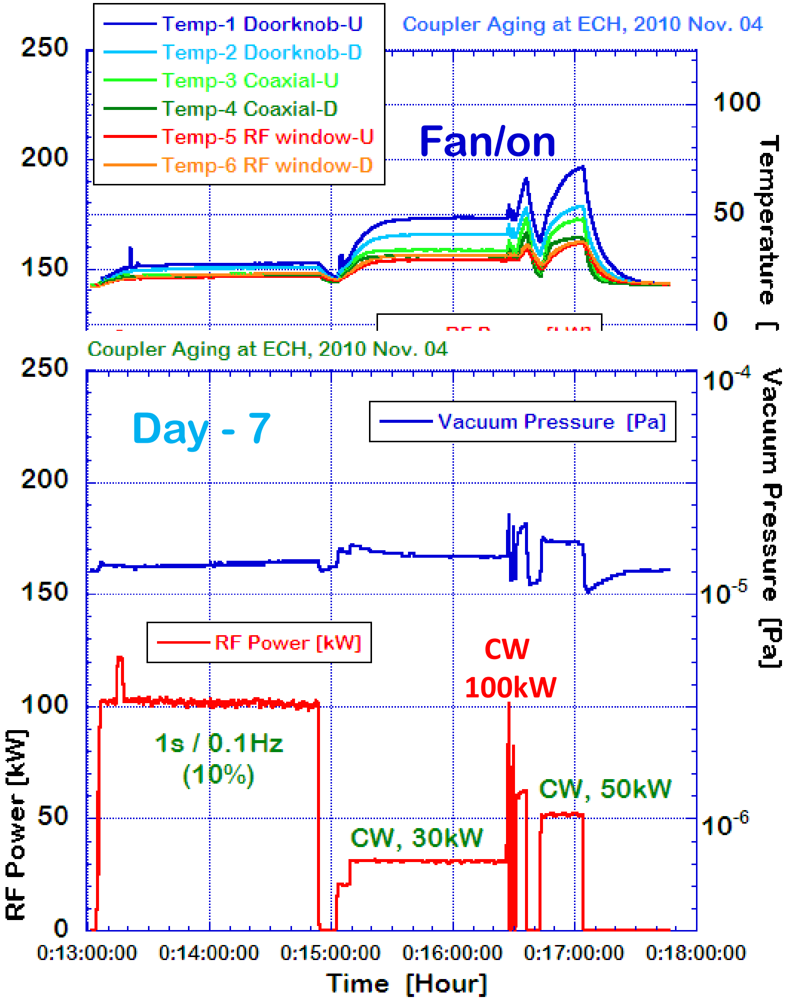
- Simple structure
- Suitable for cooling
- Assembly with cryomodule

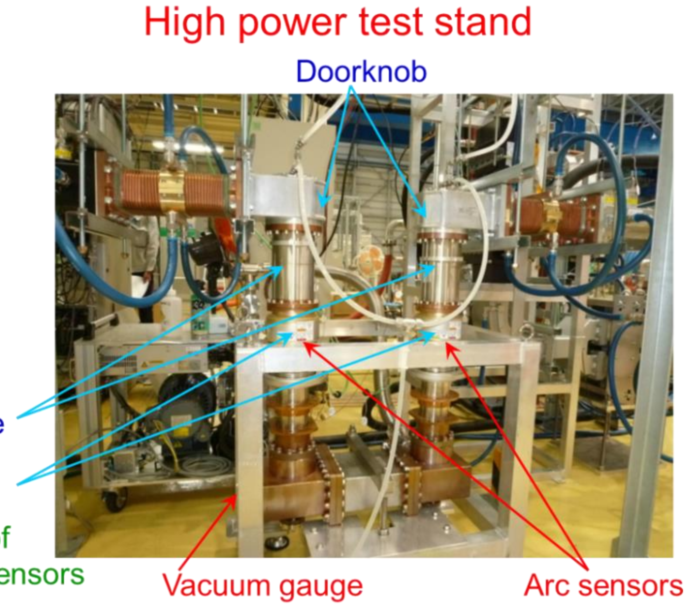
Pulsed Input Coupler for STF2 CM (Double Windows)



- Assembly in clean room
- Safety for window failure
- Coupler vacuum for cold window

1.3 GHz CW Input Couplers for cERL Injector Cryomodule



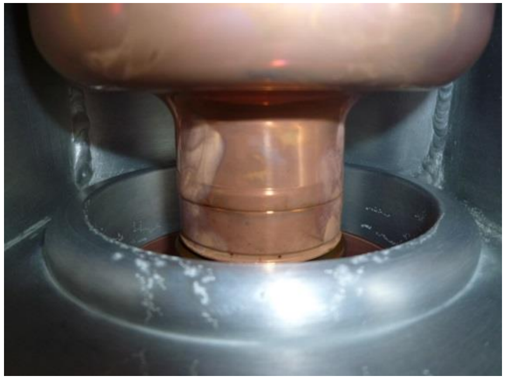


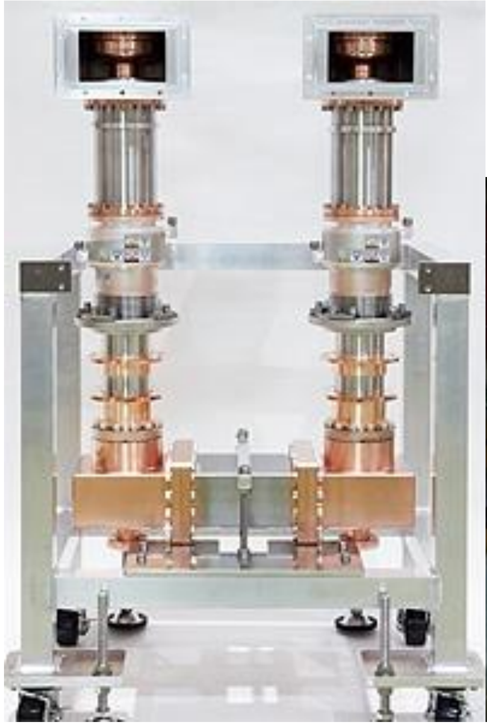
Conditioning Results

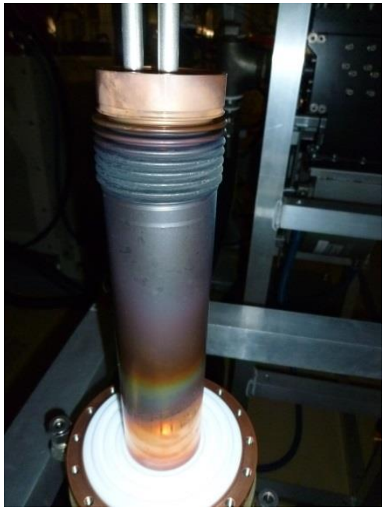
- 1ms, 10Hz, (1%) 200kW for 2h
- 1s, 0.1Hz, (10%) 100kW for 2h
- CW 30kW for 1.5h
- CW 100kW for 1 min
- CW 50kW for 0.5h

(E. Kako: IPAC12, p2230)

1.3 GHz CW Input Couplers for cERL Injector Cryomodule

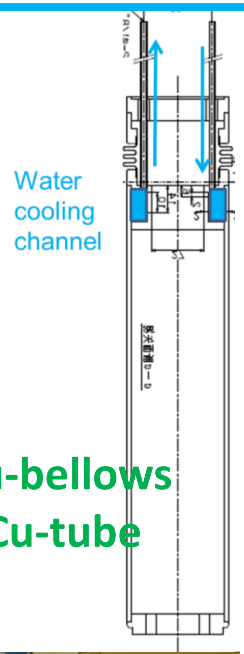






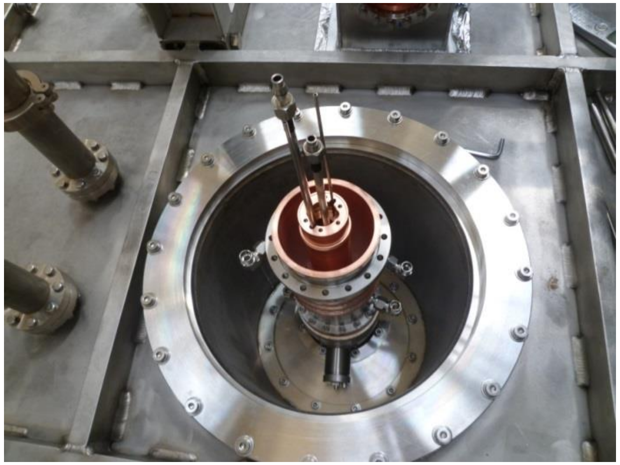
Excessive heat-up

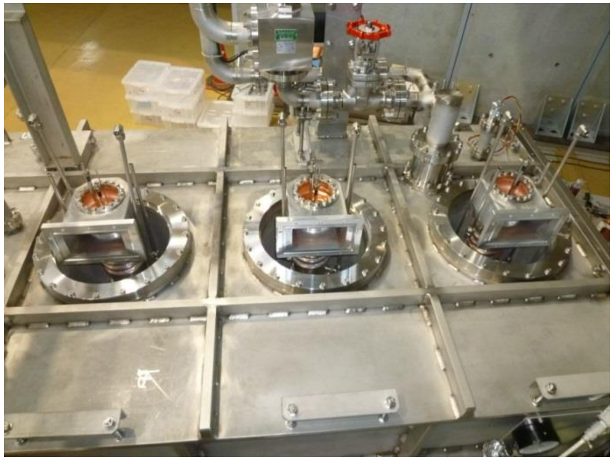
Inner conductor

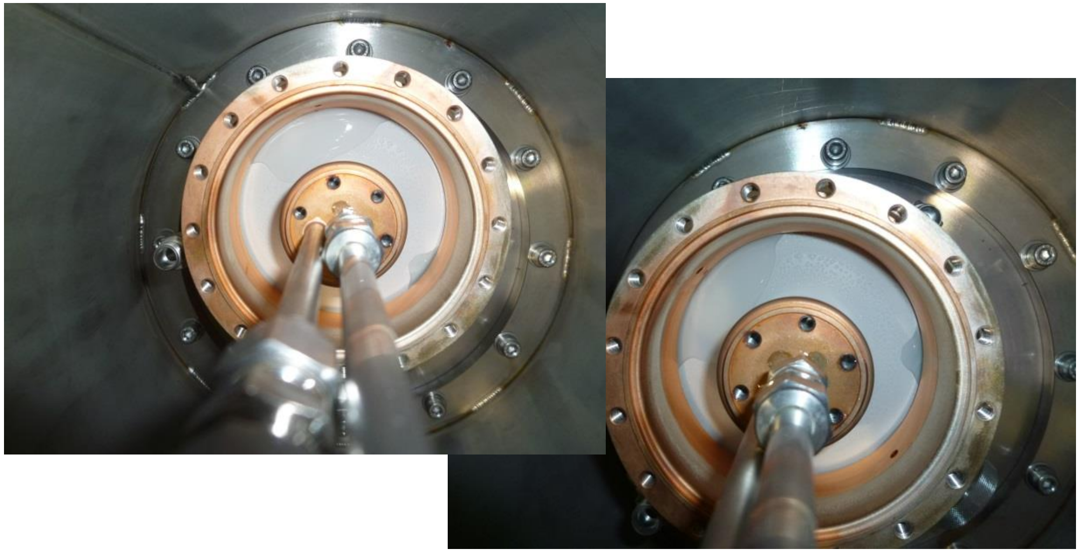


Outer conductor

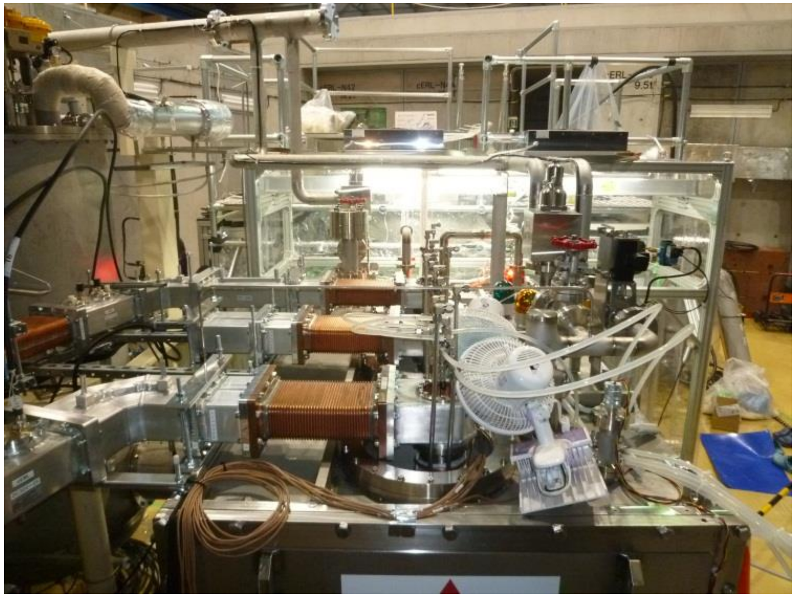
1.3 GHz CW Input Couplers for cERL Injector Cryomodule







Droplet of water on ceramic during cool-down



Lessons and learned from Cryomodule Operation

STF Phase-1

Four 9-cell cavities (2008')

4 x STF1 input couplers

Total 22 STF-1, -2 input couplers were fabricated and tested.

S1-Global

(4+4) 9-cell cavities (2010')

4 x STF2 input couplers

STF2 - Capture Cryomodule

Two 9-cell cavities (2011')

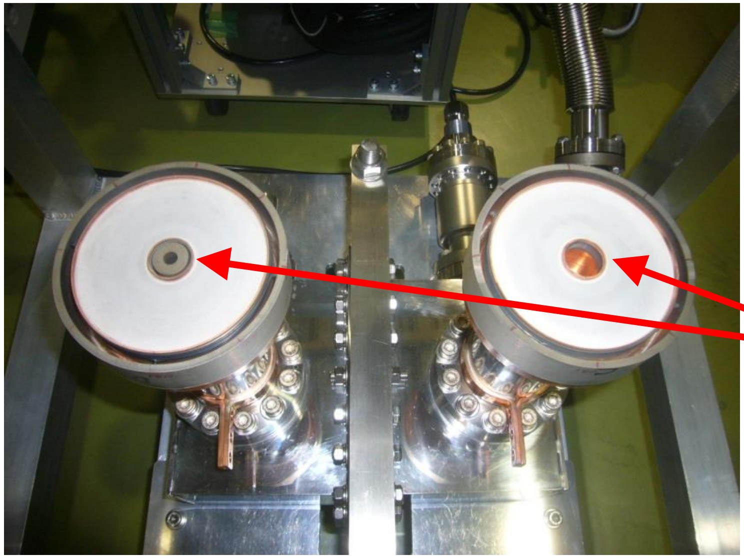
2 x STF2' input couplers

STF2 – CM1+2a Cryomodule

Twelve 9-cell cavities (2015')

12 x STF2'' input couplers

Four STF-1 Input Couplers after Disassembly



Leak check after Cryomodule Tests

Warm windows :

No.1 Coupler, OK
No.2 Coupler, OK
No.3 Coupler, OK
No.4 Coupler, OK

Cold windows (80K) :

No.1 Coupler, Leak rate = $2.x10^{-4}$ Pam^3/s
No.2 Coupler, Leak rate = $3.x10^{-5}$ Pam^3/s
No.3 Coupler, Leak rate = $4.x10^{-5}$ Pam^3/s
No.4 Coupler, OK

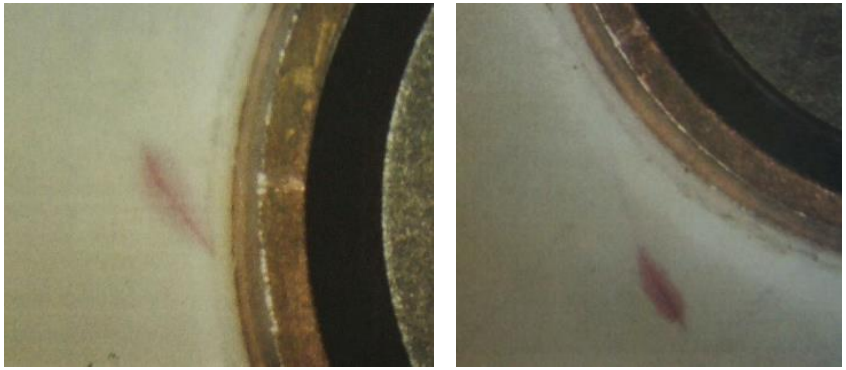
Leak at brazing of inner conductor
after a few thermal cycles
(not the first cool-down)

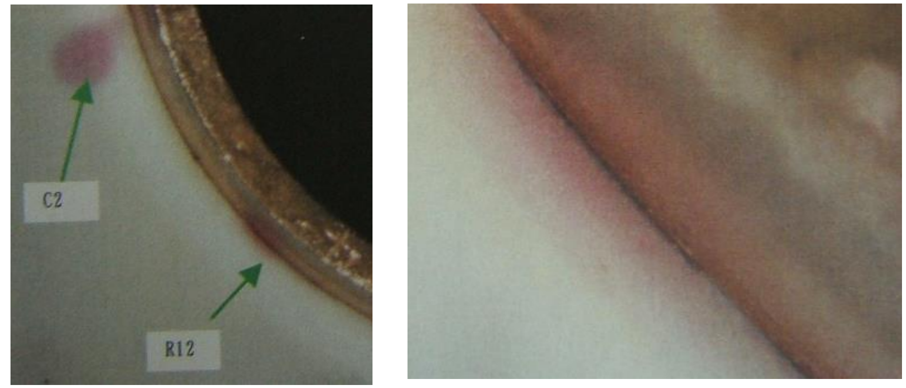
Cracks due to thermal strain at 80 K

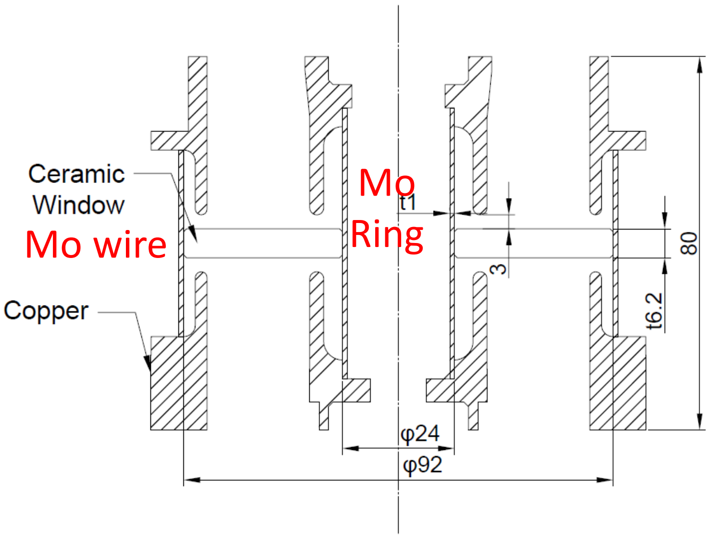
No.1 Coupler

by color check

No.3 Coupler

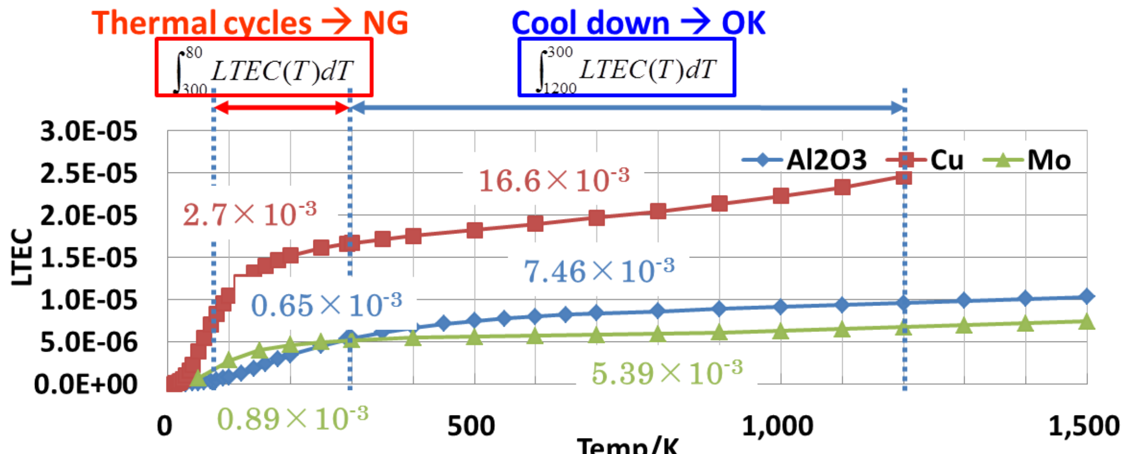






Linear Thermal Expansion Coefficient of Cu, Ceramics, Mo

Actual shrinking amount : - Δ length=length × ∫LTEC dT

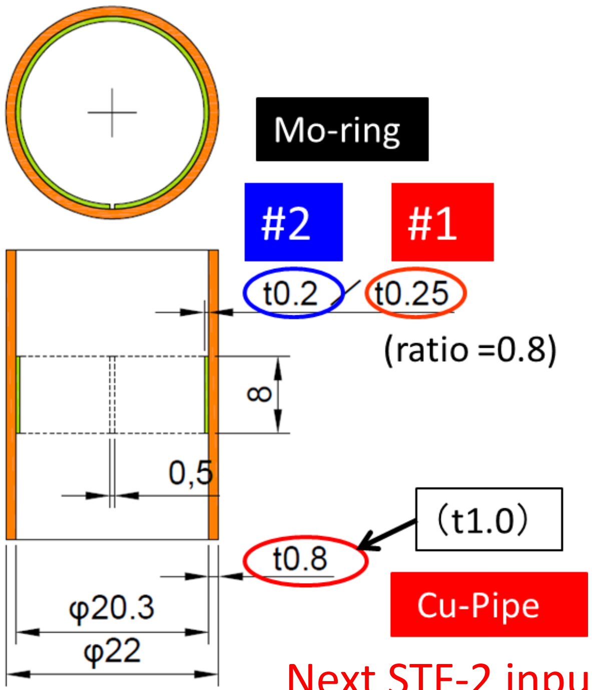


Thermal cycle tests of improved structure

#1: Mo,0.25t
#2: Mo,0.20t

Sample #1, #2 (2009 Sep ～Oct)

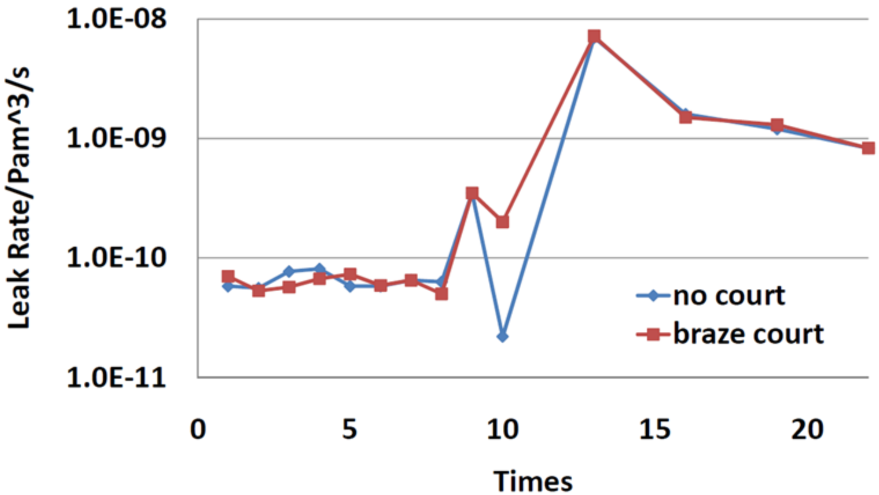
	Test1	Test2	Test3	Test4	Test5	Test6
#1	2.2E-09	1.6E-09	1.7E-09	2.6E-09	3.2E-08	1.8E-08
#2	2.8E-09	1.6E-09	1.9E-09	1.3E-04	1.2E-04	1.3E-04



#3: Mo,0.25t
#4: Mo,0.25t

OK, no leak:
20 thermal cycles between 80K and 300K

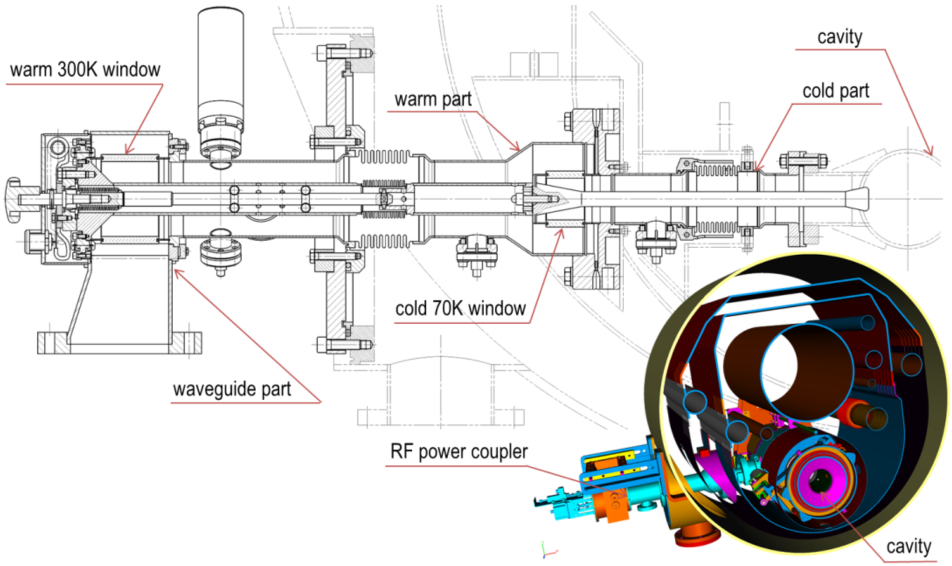
Sample #3, #4 (2010 Apr ～Jun)

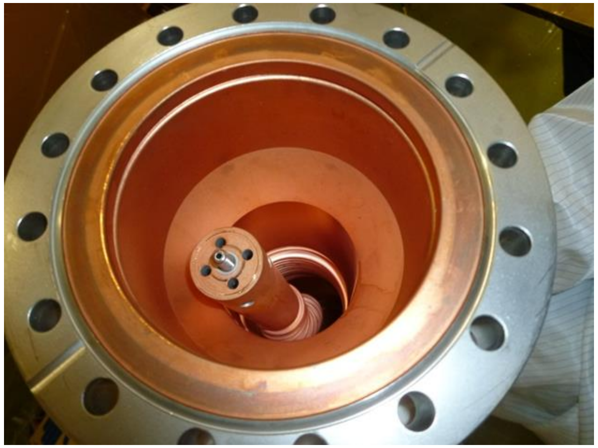


Next STF-2 input couplers for S1-G were fabricated after the thermal cycles.

What did we learn from S1-Global ?

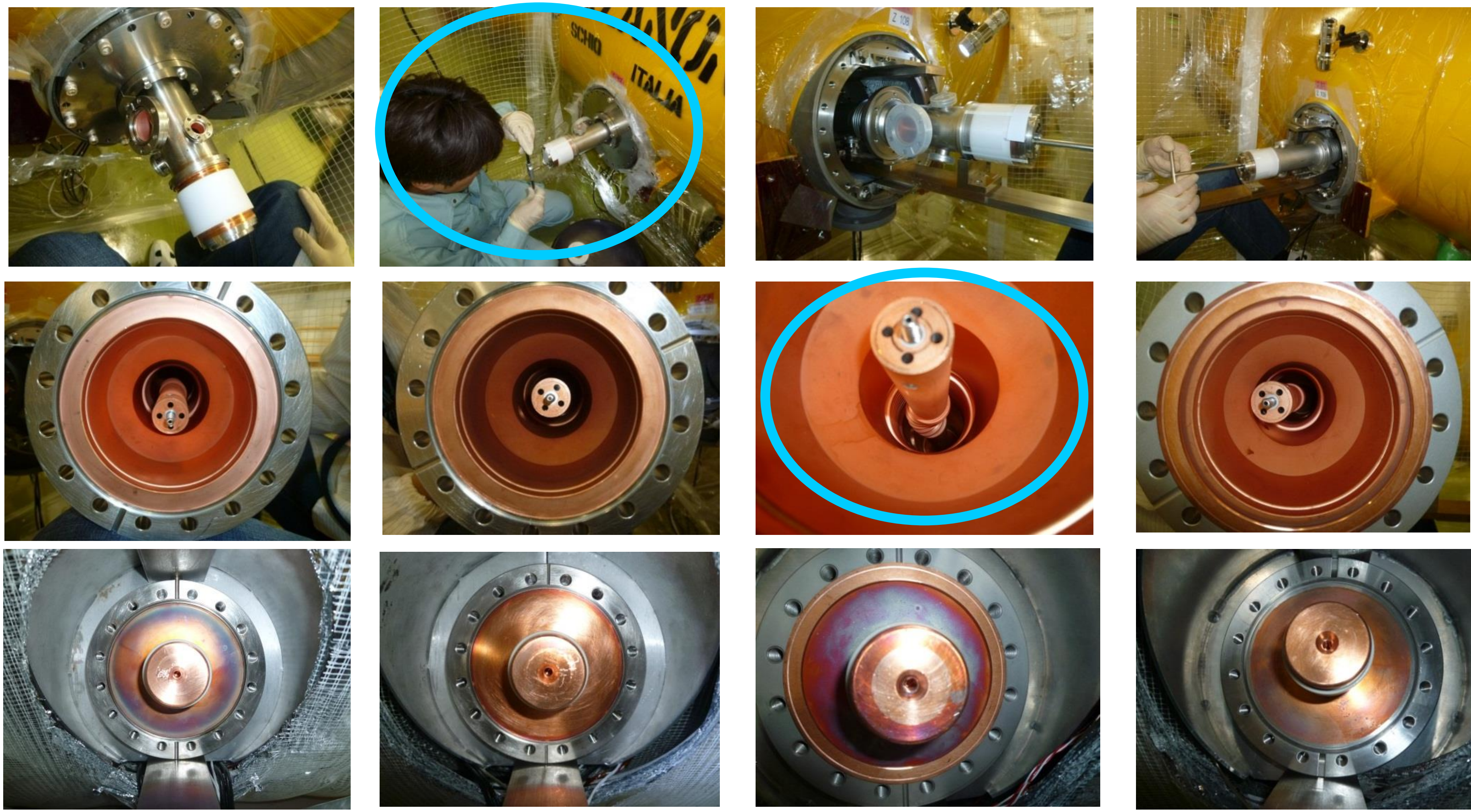
- **Broken TTF-3 input coupler during disassembly.**





What did we learn from S1-Global ?

C1/ FNAL | C2/ FNAL | C3/ DESY | C4/ DESY



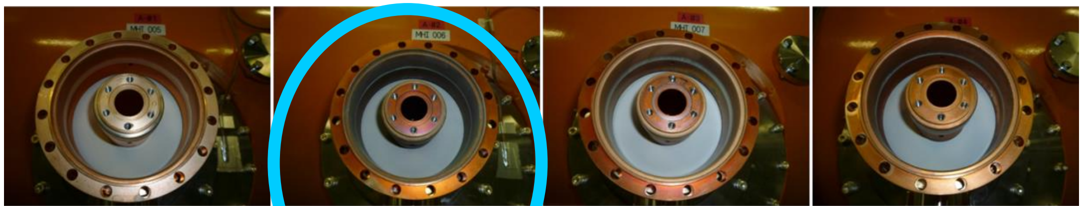
Discoloration of Cu plating in TTF-3 input couplers from DESY and FNAL

Discoloration of Cu plating: comments by company

1. Cu and Ag are usual metals to cause discoloration easily.
2. Especially, discoloration after plating is formed at hollow spots in a rough surface.
3. To avoid discoloration , copper pyrophosphate ($Cu_2P_2O_7$) for plating and chromate for surface-finishing were used in the past. Currently, special shiny copper pyrophosphate with additive free is used for KEK couplers.
4. To avoid discoloration , works after finishing Cu-plating are very important. Disassembly of the plating-jigs is immediately carried out in a hot pure-water bath at 40^{o}C. After this, rinsing with methanol and complete drying in a hot wind furnace are carried out. Finally, surface of Cu-plating is covered by a special non-rust paper, and it is kept in a PE bag together with silica-gel for delivery.
5. In case of whole light discoloration, rinsing with weak sulfuric-acid and careful rinsing with pure-water are applied.
6. Discoloration is not so many troubles in this company. (in my experience)

What did we learn from S1-Global ?

Doorknob side (air)

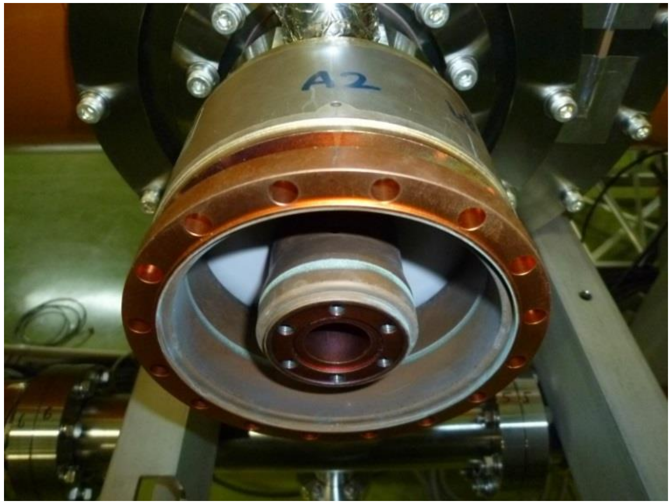


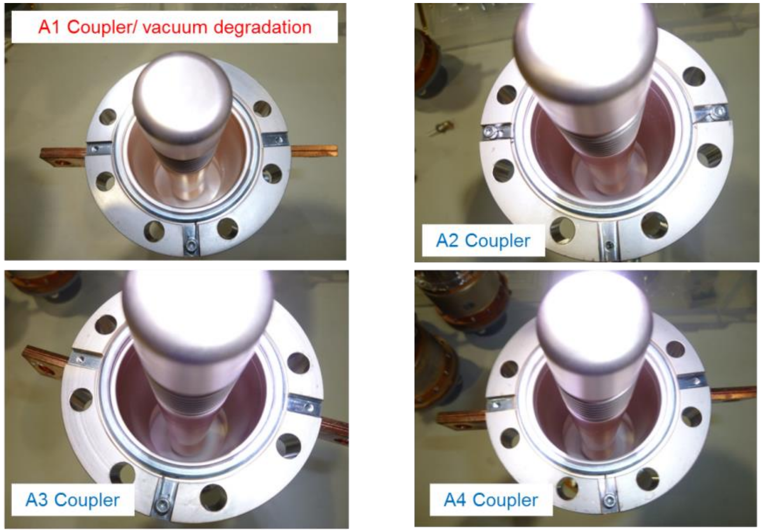
A1/MHI-05 (no leak) | A2/MHI-06 (no leak) | A3/MHI-07 (no leak) | A4/MHI-09 (no leak)

Vacuum side (connection with cold window)

Cold window (warm side)

A1/MHI-05 (no leak) | A2/MHI-06 (no leak) | A3/MHI-07 (no leak) | A4/MHI-09 (no leak)





Cold couplers

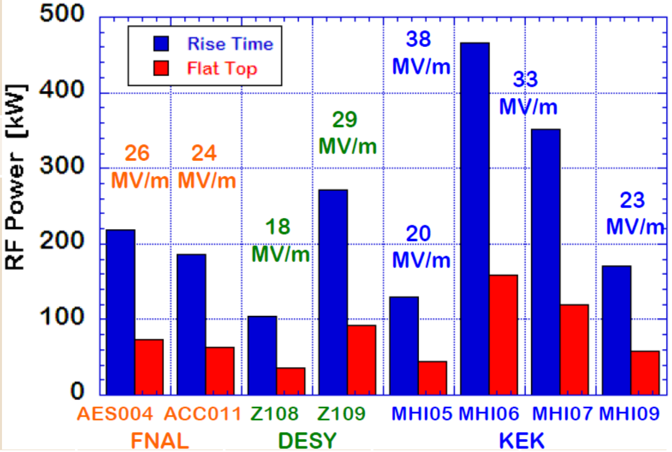
No visible mark due to discharge was found in four cold couplers.

What did we learn from S1-Global ?

Dynamic loss measurements in S1-G Cryomodule (2010')

	TTF3		STF2			TTF3	STF2				
	C-4	C-1	A-3	A-2	A-2	4 C Cavities	4 A Cavities	4 C Cavities	4 A Cavities	7 Cavities	7 Cavities
Date	Nov. 17	Nov. 19	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 30	Dec. 2	Dec. 3	Dec. 9	Dec. 10
Gradient	28 MV/m	25.2 MV/m	32.3 MV/m	38 MV/m	32 MV/m	32 MV/m Detune	32 MV/m Detune	20 .0 MV/m	26.9 MV/m	25.4 MV/m	20.4 MV/m
Dynamic Loss	0.84 W	1.44 W	2.8 W	4.8 W	2.6 W			2.7 W	6.9 W	9.6 W	4.8 W
Detuned Loss	0.09 W	0.18 W	0.7 W	1.8 W	1.2 W	0.5 W	4.6 W	0.2 W	2.5 W	2.6 W	1.6 W
Dynamic Loss at Cavity	0.75W	1.26 W	2.0 W	2.9 W	1.3 W						
Q_0	8.8E9	4.3E9	4.3E9	4.2E9	6.5E9						

Dynamic losses of KEK couplers was 9 times larger than those of TTF3 couplers.

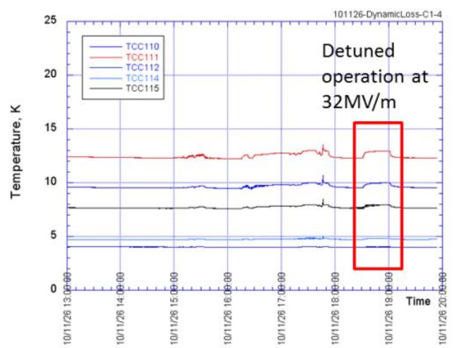


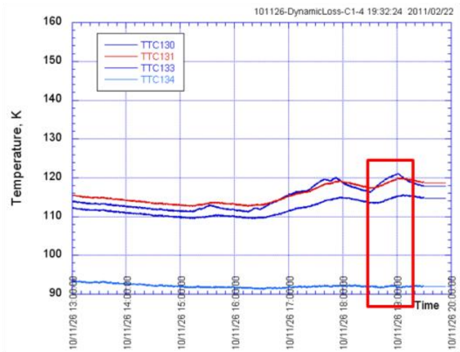
What did we learn from S1-Global ?

Direct comparison of dynamic loss between TTF-3 and STF-2

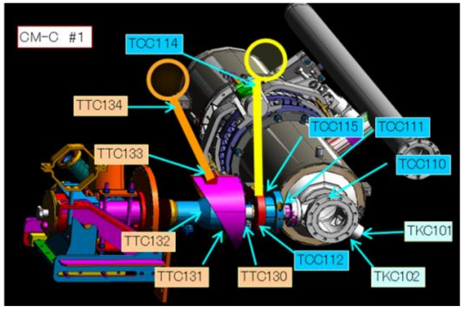
TTF-3 Input Coupler

Temperature change during detuned 32MV/m
Module-C





Cavity-C1

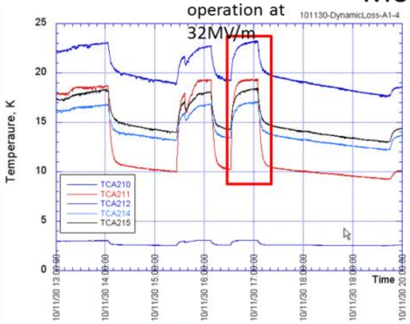


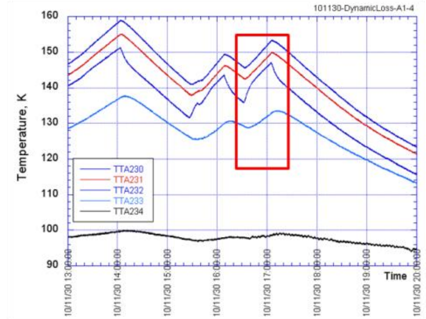
For 30 min. operation,
$\Delta T_{@TCC111}$=0.7K (12.3K->13.0K)
$\Delta T_{@TTC130}$=5K (116K->121K)

STF-2 Input Coupler

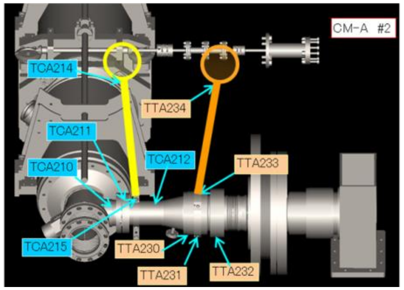
Temperature change during detuned 32MV/m
Module-A

Detuned
operation at
32MV/m





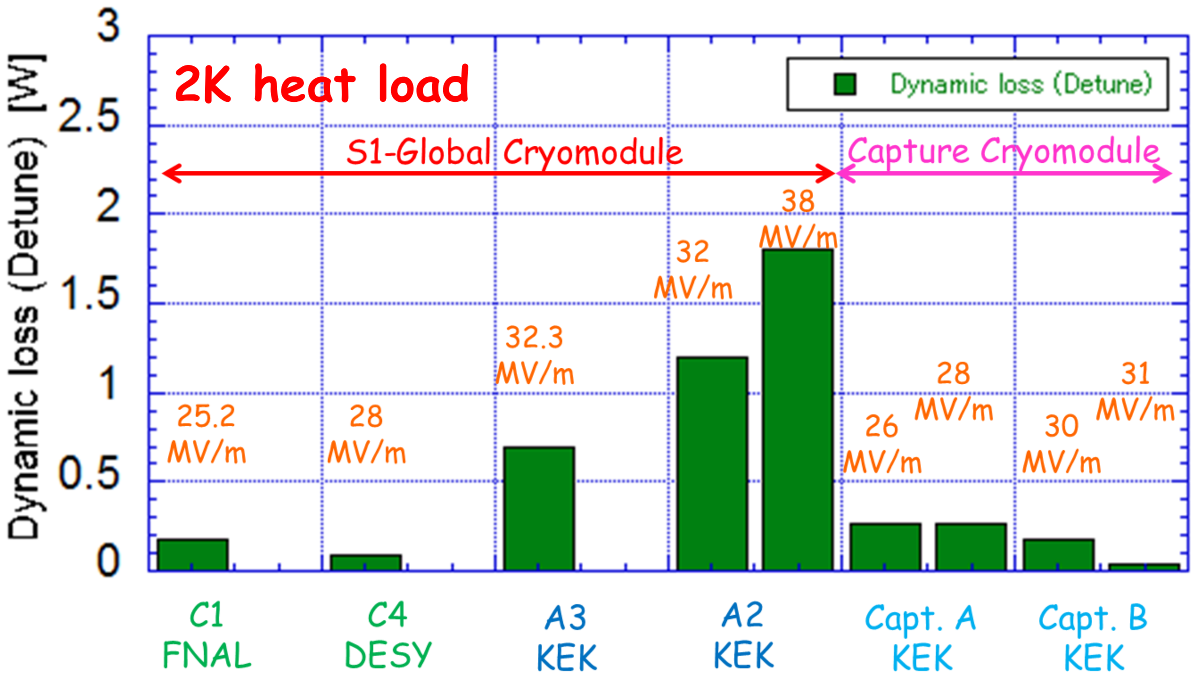
Cavity-A2



For 30 min. operation,
$\Delta T_{@TCA211}$=9K (10.3K->19.3K)
$\Delta T_{@TTA230}$=10K (137K->147K)

Much higher temperature rises
were observed in KEK-STF2 coupler.

What did we learn from S1-Global ?



Cu 3 μm | Cu 3 μm | Cu 5 μm | Cu 10 μm

ILC Specification
< 0.02 W (2K dynamic)

STF-2' (A) input coupler
SUS 0.8t + Cu 5 μm
Capture Cryo. - MHI-12

STF-2' (B) input coupler
SUS 0.8t + Cu 10 μm
Capture Cryo. - MHI-13

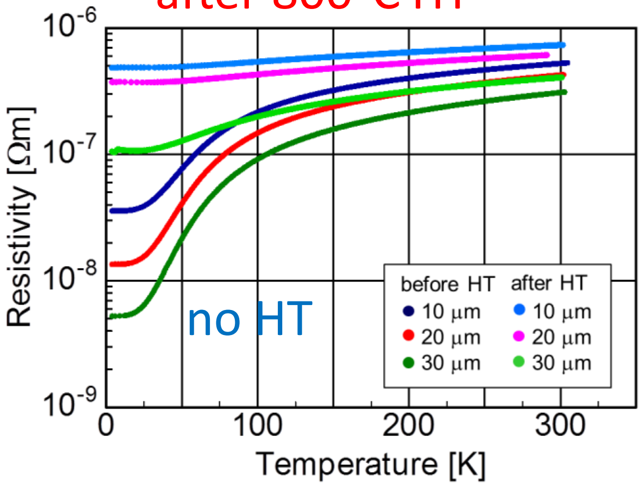
80K anchor

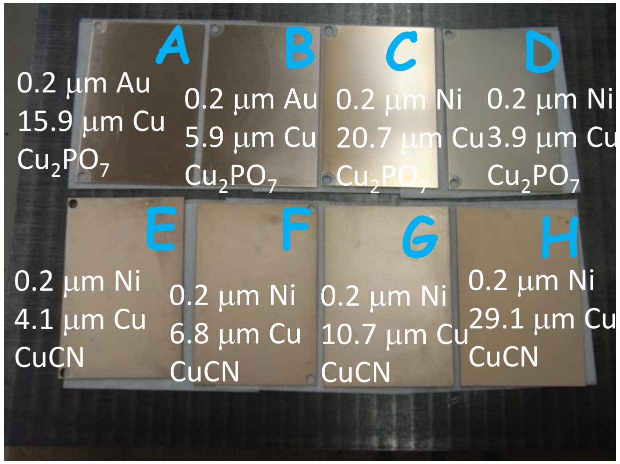
5K anchor

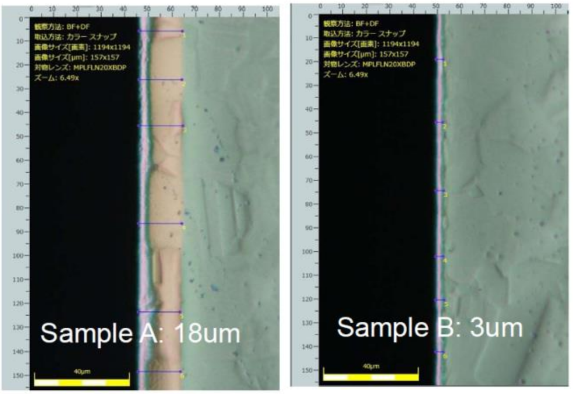
Quality control of Cu-plating and thermal anchors with efficient cooling are also important to reduce heat loads.

Quality control of Cu-plating (1) : low RRR

after 800°C HT

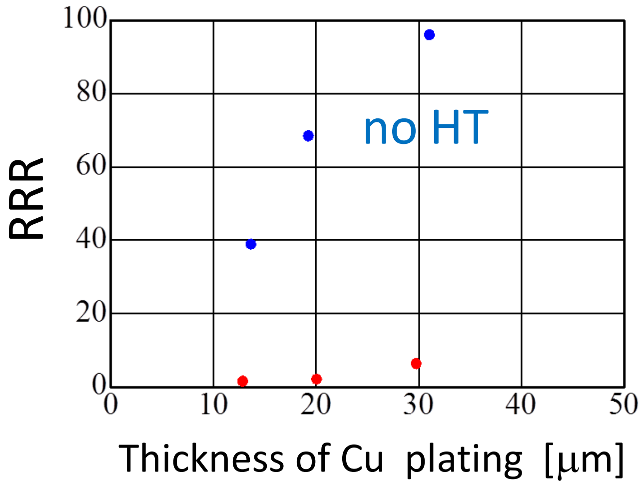




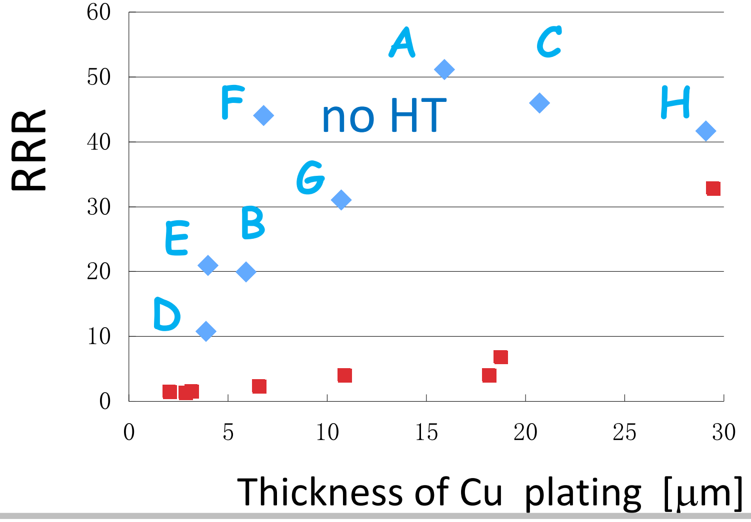


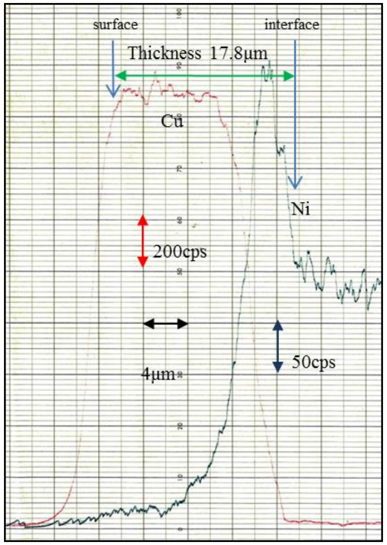
Cross-section of Cu plating

After 800°C HT in Vacuum Furnace



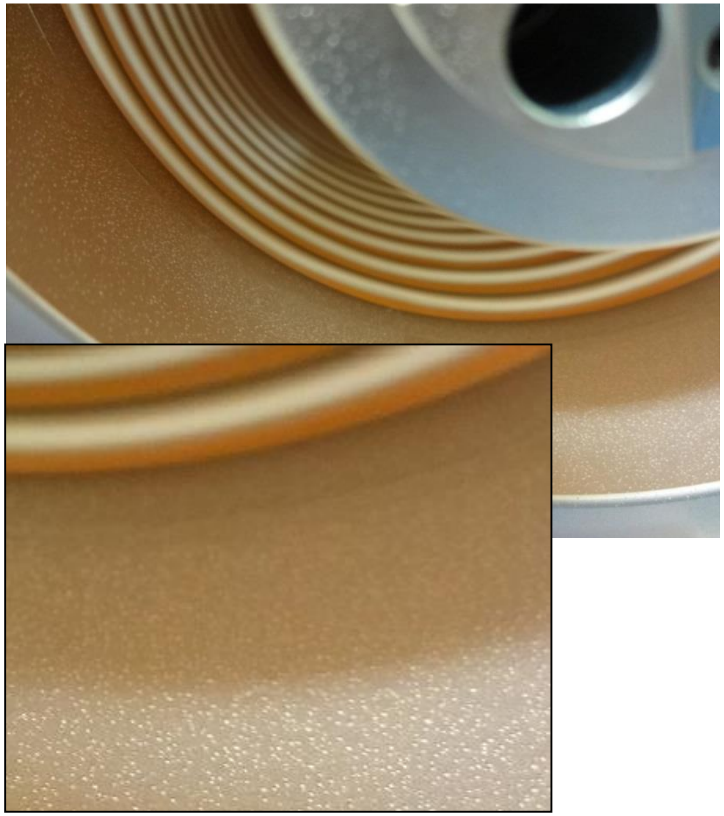
After 800°C HT in Hydrogen Furnace

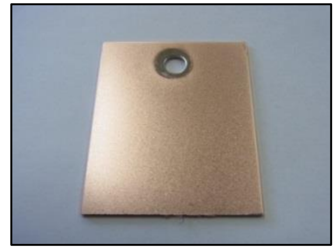


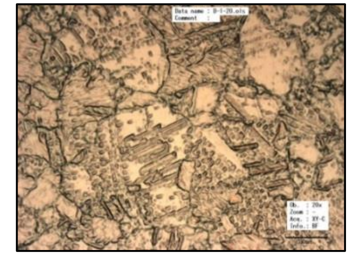


after 800°C HT

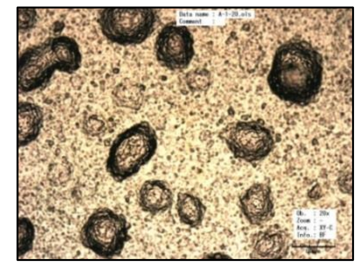
Quality control of Cu-plating (2) : projection



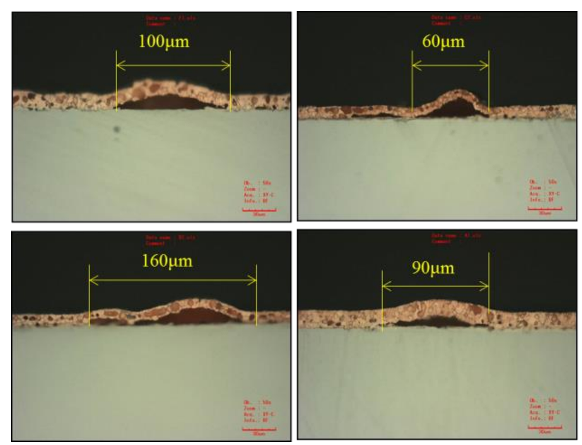


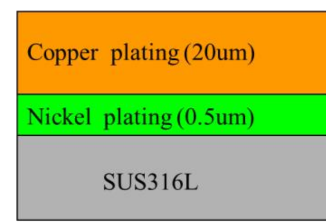


Test piece with smooth surface



Test piece with micro-projections

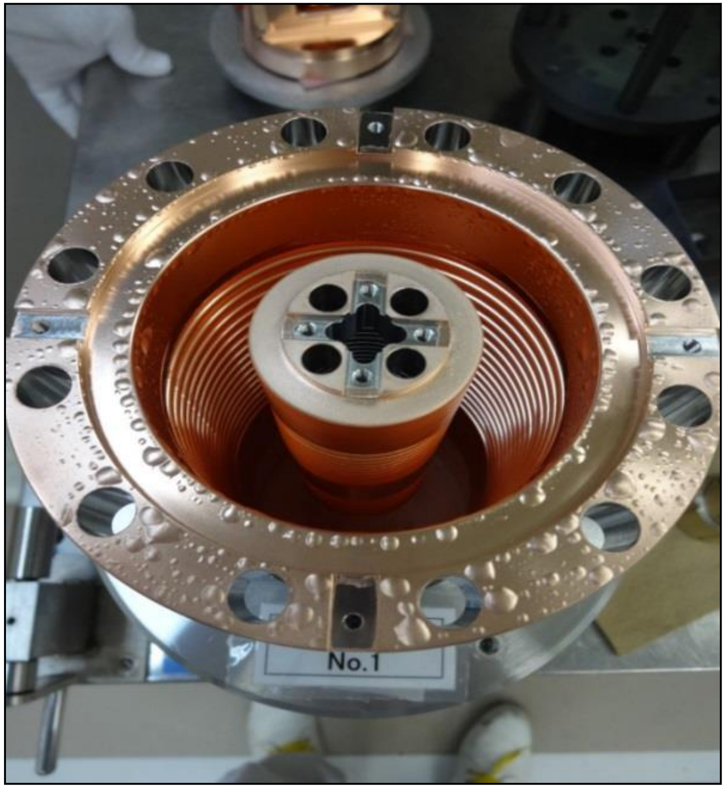




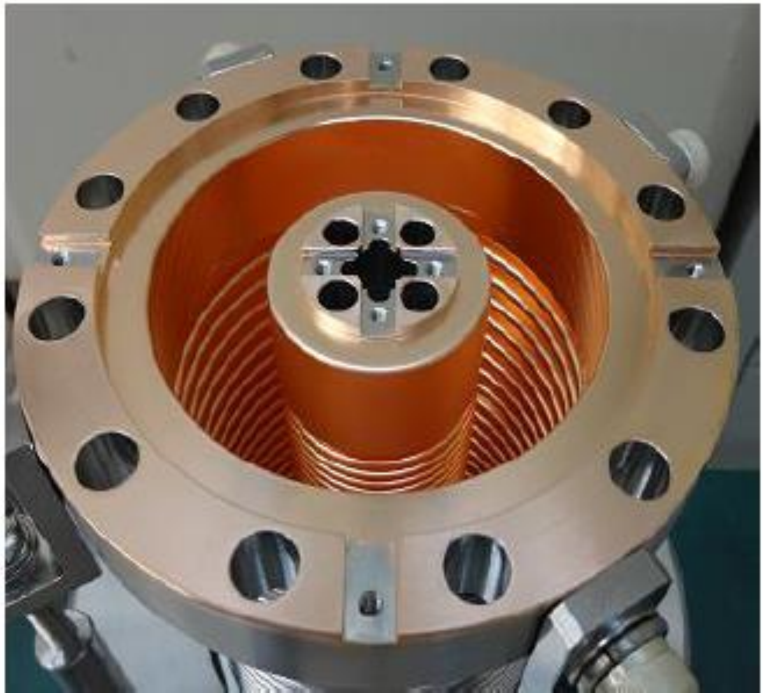
This figure is cross-section model of plating to sus316L

Micro-projection (ϕ100µm) were formed after brazing at 800°C.
The cause was organic carbon contamination in an old solution.

Quality control of Cu-plating (3) : swelling



Smooth surface (Ni-strike)



Large size of swellings (ϕ 5-10 mm) were formed after brazing at 800°C. The cause was inadequate plating parameters on plating area (S) and volume of solution (V) in case of Au-strike: Large bath (V) for acid solution is important, because of constant current density.

LAL TTF-V Input Couplers conditioning at KEK

January, 2009

Assembly in clean room ;
pumping ports & vacuum gauges

↓

Baking at 130^{o}C for 60 h

↓

Set-up of
High Power Test Stand

Step 1 : Target for XFEL (Feb. 2009)

400 μs, 1.0 MW

1.5 ms, 0.5 MW, 5 Hz

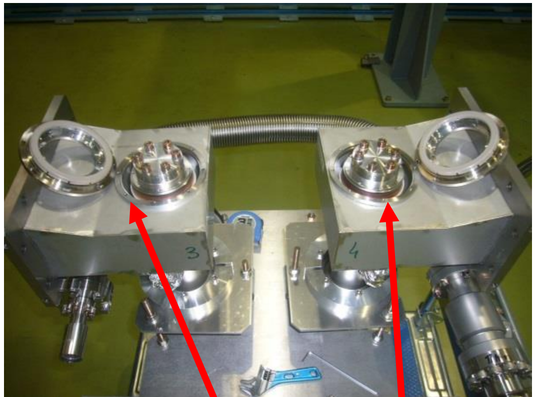
Step 2 : Target for ILC (Mar. 2009)

400 μs, 2.0 MW, 5 Hz

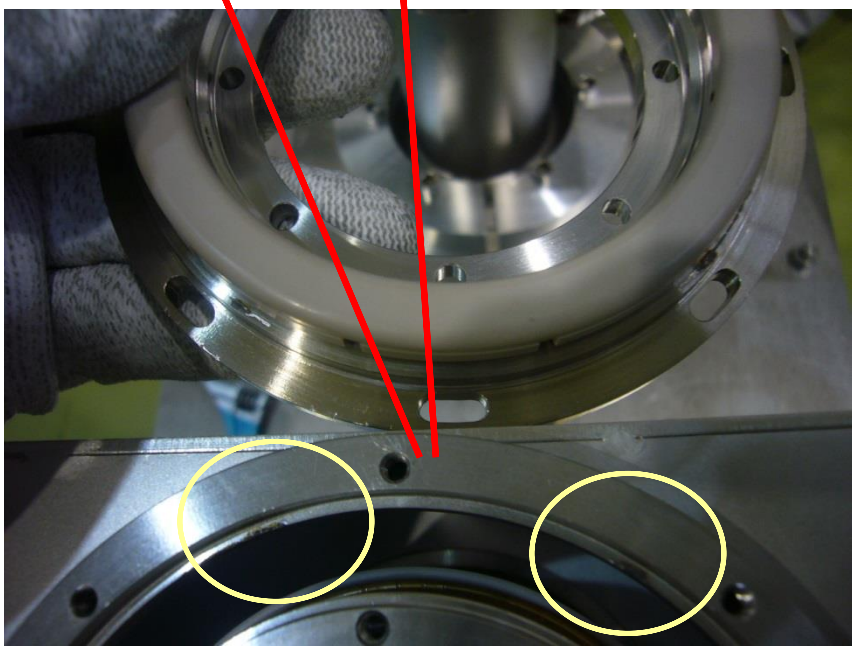
Step 3 : Target for ILC (May. 2009)

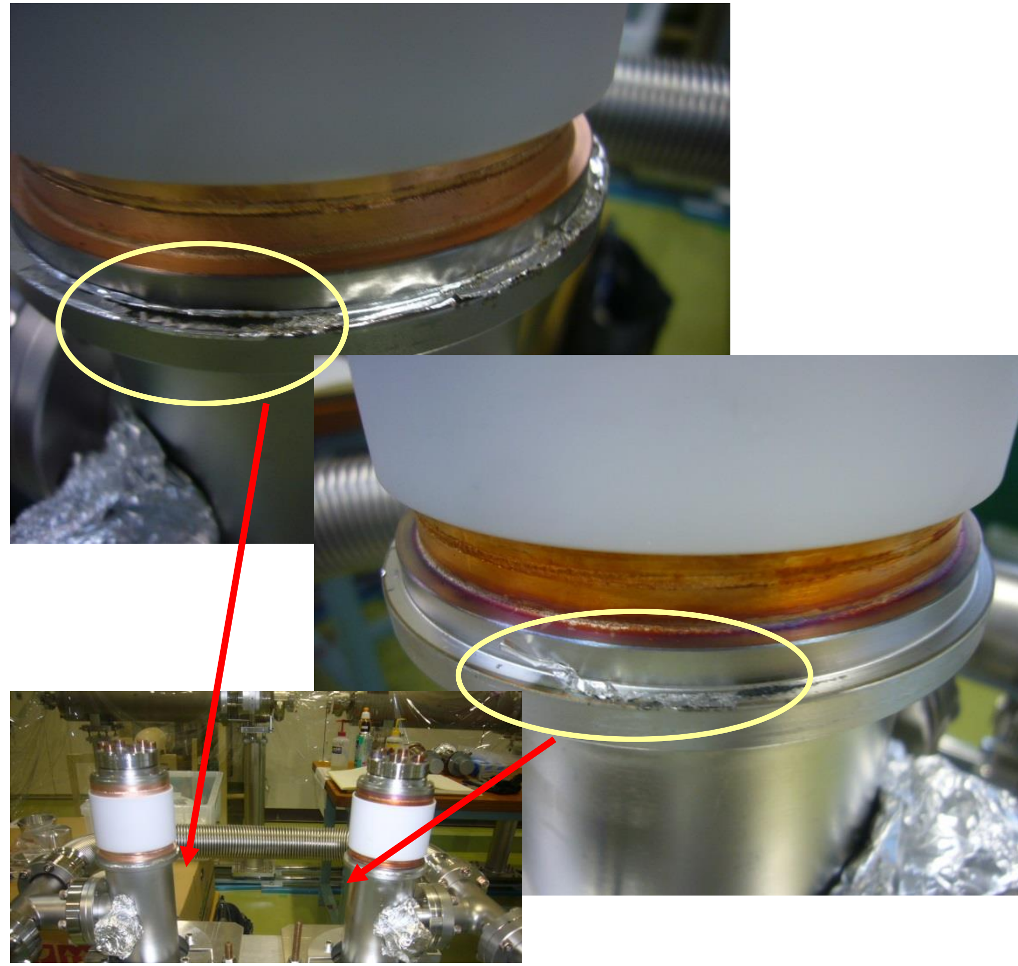
1.5 ms, 1.0 MW, 5 Hz

LAL TTF-V Input Couplers conditioning at KEK



After
conditioning
at 2MW/5Hz





After disassembly,
traces due to RF discharge were found.

CONCLUSION

- This WS is a very good chance to exchange our experiences and knowledge on fundamental power couplers (FPC).
- We should continue this kind of meeting by experts and beginners.

Thank you for your attention.