Recent results for power coupler R&D in KEK/STF

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TOSHIBA ELECTRON TUBES & DEVICES

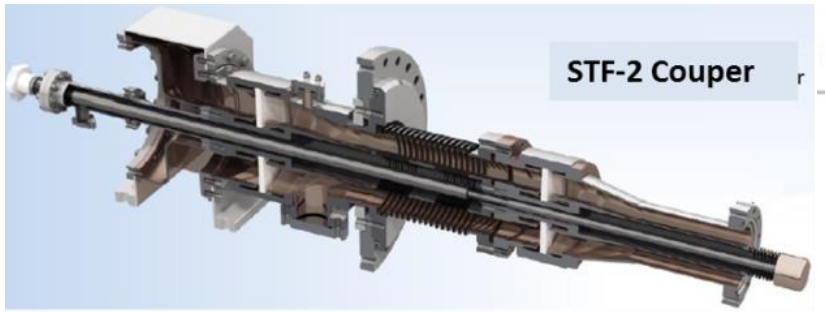
NOMURA PLATING
株式会社野村鍍金

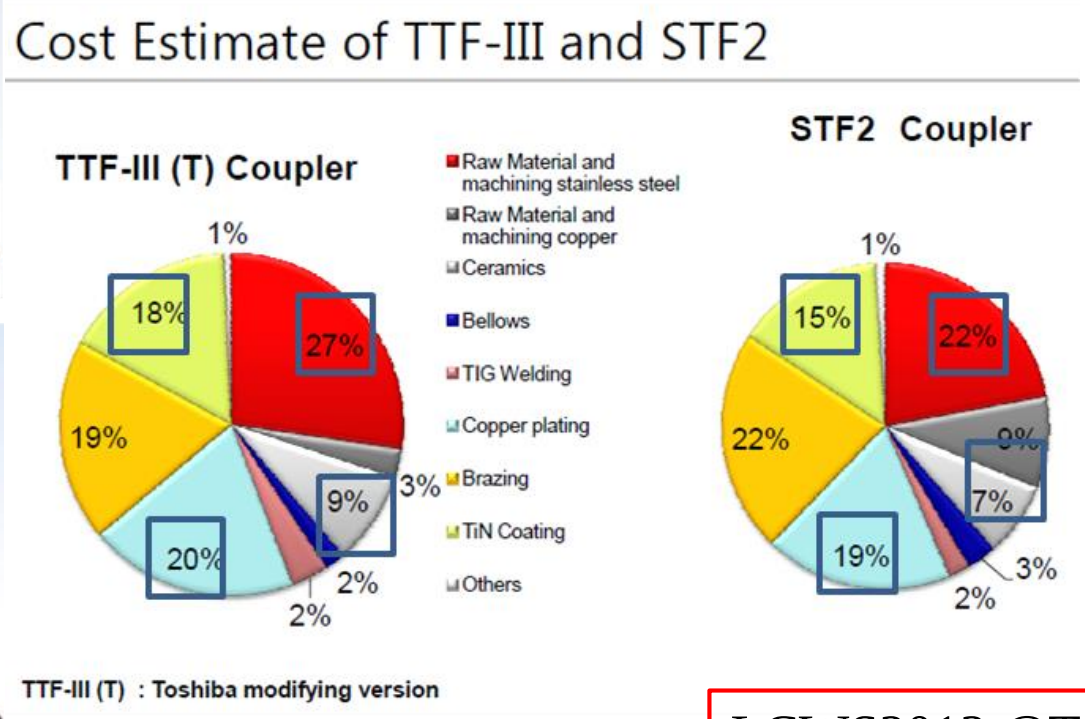
ULVAC タイゴールド株式会社 Tigold Corporation

Outline

- Cost reduction in power coupler
- R&D Items
  - TiN coating-free ceramic
  - Copper plating
  - Ceramic property
  - TiN coating
- Summary

Cost reduction in power coupler





LCWS2013 @Tokyo

Cost reduction:
35%(SRF)*15%(coupler)*30%(reduction) → ~1.5%(of ILC total value in TDR)

KEK is concentrating on study for TiN coating, copper plating, and ceramic since 2013!

TiN coating-free ceramic as new material

				99.8% Alumina for RF Application (A479B)	AH100A	LSEEC
Electrical Property	Volume Resistivity		ohm·cm	min. 1 X 10^{14}	min. 1 X 10^{14}	-
	Surface Resistivity		ohm/□	8.9 X 10^{14}	7.4 X 10^{15}	1.2 X 10^{14}
	SEE Coefficient		-	11.4	4.6	3.2
	Dielectric Constant	1MHz	-	9.9	10.2	-
		8GHz	-	9.9	10.0	10.0
	Dielectric Loss Angle	1MHz	-	1 X 10^{-4} *1	1 X 10^{-4} *1	-
		8GHz	-	4 X 10^{-5}	1 X 10^{-4}	3 X 10^{-3}
Mechanical Property	Ave. Flexural Strength(RT) ASTM D2442 TYPE3		MPa	300	330	
	Young's Modulus		GPa	370	380	
	Poisson Ratio		-	0.23	0.25	
Thermal Property	Thermal Conductivity (RT)		W/mK	29	24	-
	Coeff. Thermal Expansion	RT-400deg.C	ppm/K	7.0	7.4	-

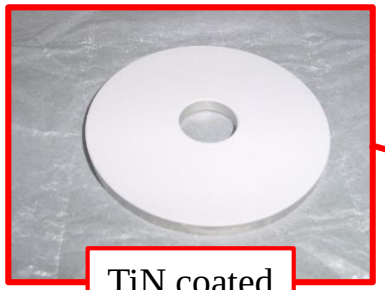
TiN coating is not necessary, because of lower SEE.

But, this ceramic has higher dielectric loss tangent!

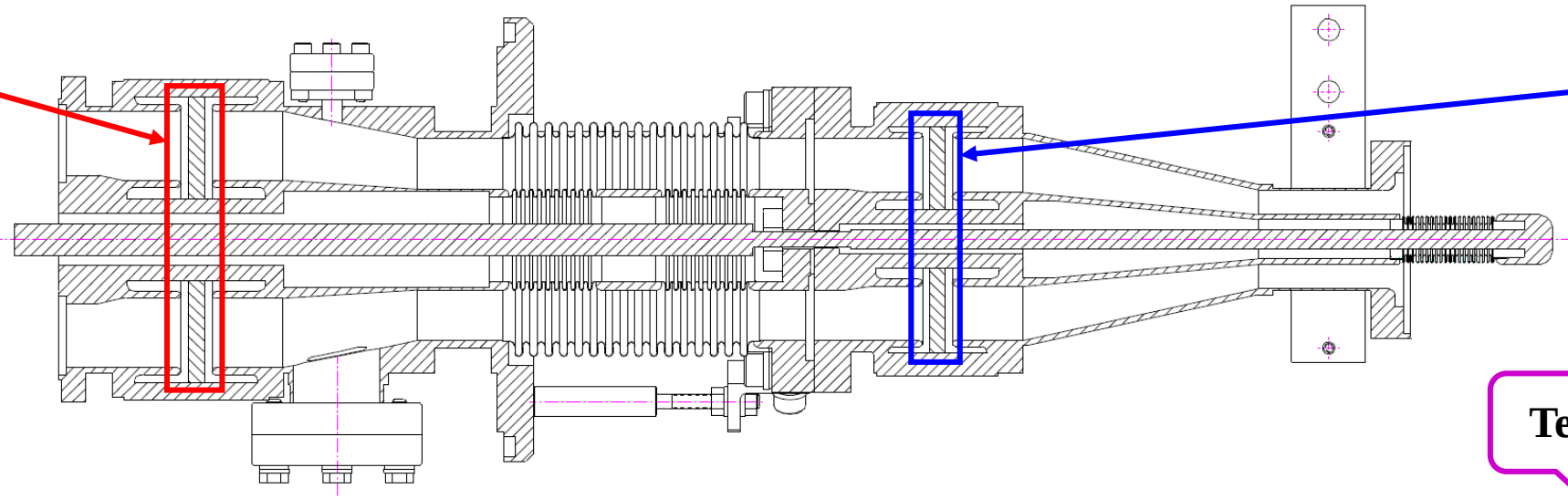
Heating can be generated.

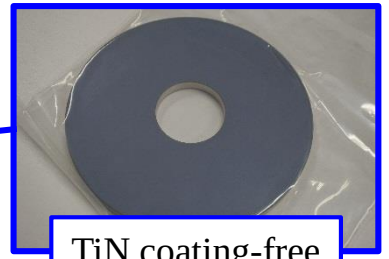
K. Iwamoto, et al., in TTC meeting 2014

STF-type power coupler with TiN coating-free ceramic



TiN coated





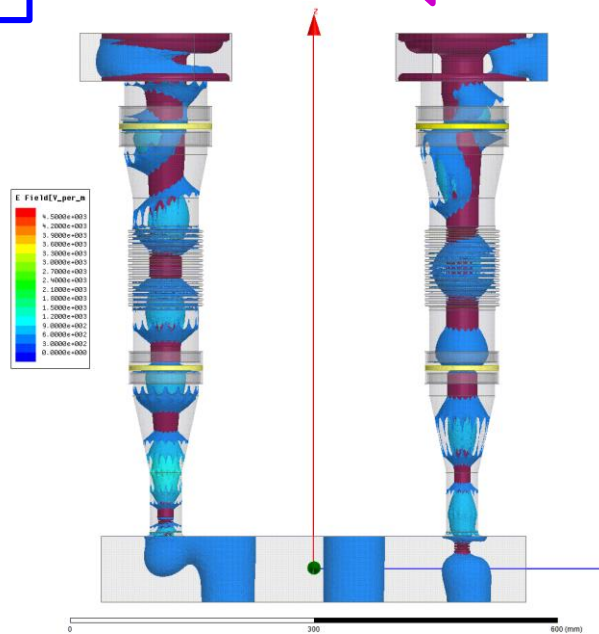
TiN coating-free

Warm part

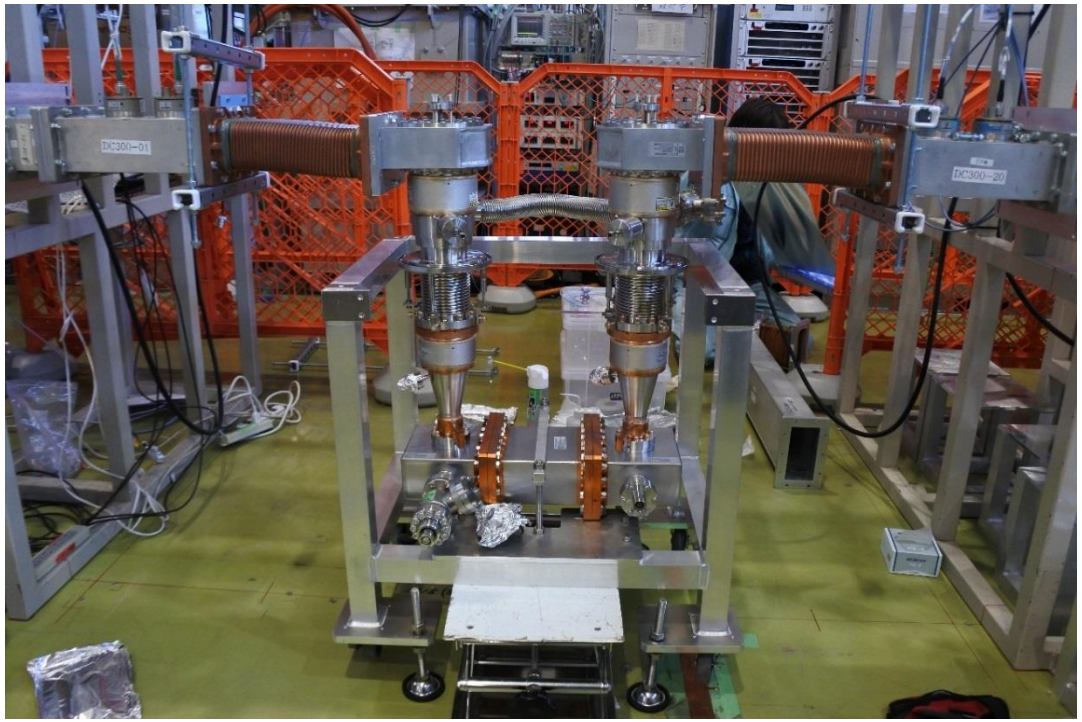
Cold part

Test stand model

Ceramic	TiN coating
Cold window (KYOCERA, LSEEC)	free
Warm window (NTG/NTK, HA95)	10 nm (single side)



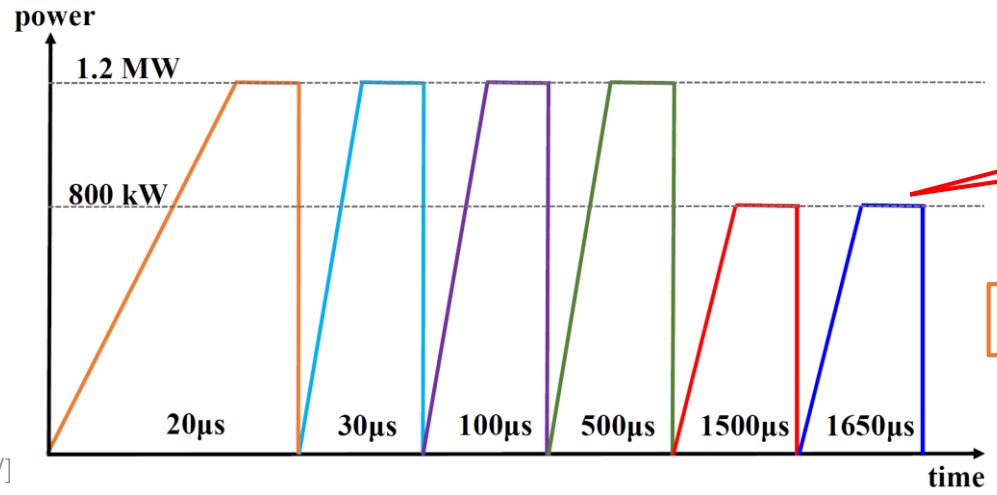
High power test at test bench



Technical interlock system

- ◆Warm/Cold vacuum level (2x10^{-4} Pa)
- ◆Arc sensor @Warm window/waveguide system
- ◆Forward/backward power limit

※ No TIL for electron emission @Cold window

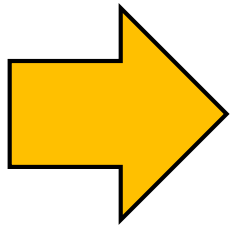


Goal: 1 hour keeping @800 kW

rep. rare: 5 Hz

Drastic progress in high power test after F.Y. 2016

- Ultrapure water rinsing
- Enormous electron emission
- Unusual heating



- **Ultrasonic rinsing**
- No electron emission
- Little heating

Comparison of Ultrasonic Rinsing Methods

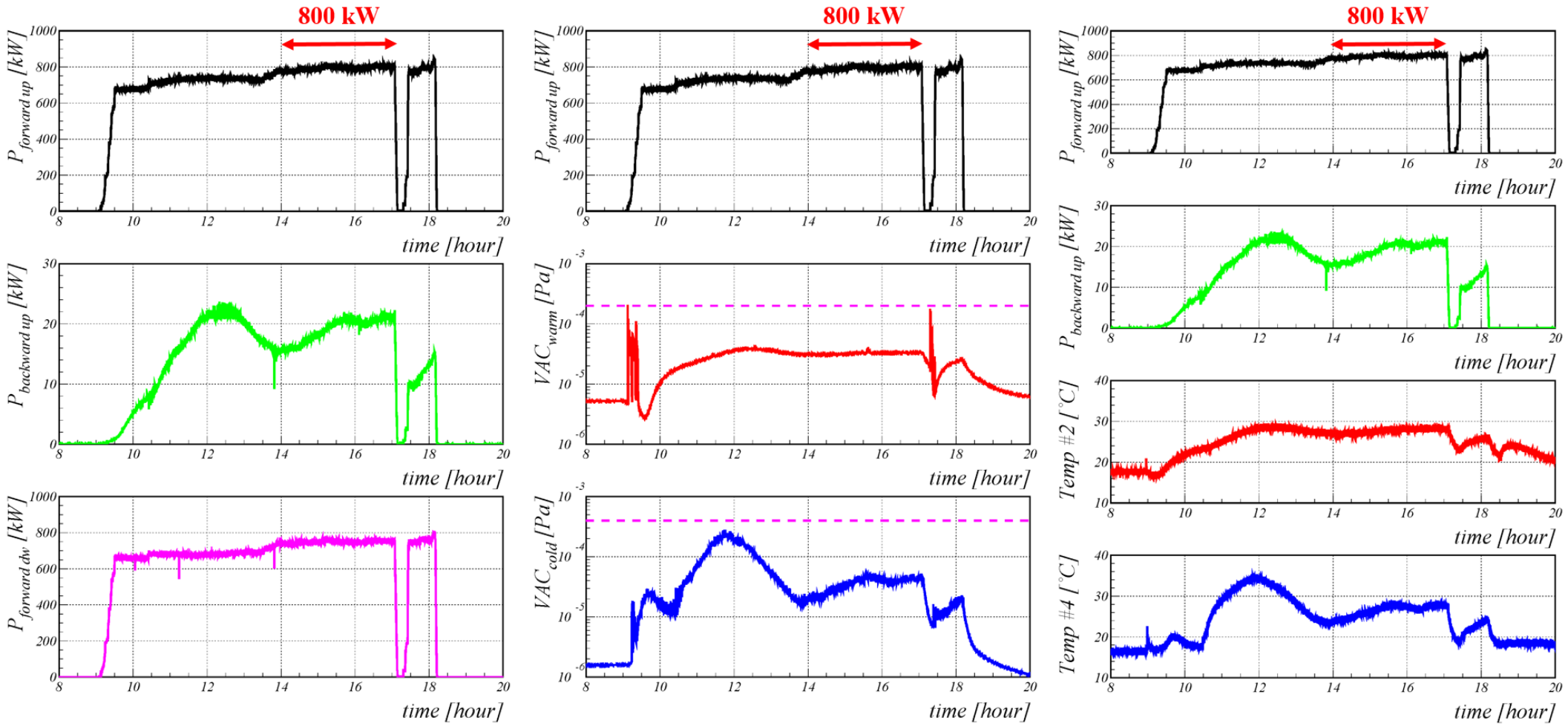
Company/Institute	TETD (M. Ishibashi)	LAL/IN2P3 (W. Kaabi)	IRFU/CEA (C. Arcambal)	
Project	FRIB	E-XFEL	ESS	
Vendor	KAIJO	BANDELIN SONOREX TECHNIK RM 180 UH	VWR (USC2600TH)	Branson Ultrason (B 8525-36)
Power [W]	120 ~ 1200 (600)	2000	300	3000
Power per liter [W/ℓ]	0.26 ~ 2.56 (w/ WRS)	10 (at max.)	12	8.6
Frequency [kHz]	38	40	45	25
Water temperature [℃]	~25	50	50 ~ 60	
Detergent		Tickopur R33 (2.5 %)	Tickopur R33 (5%)	Tickopur R33 (2.75%)
Time duration [min]	30	15	10	
Bath size [ℓ]	468	200	25	350

High power test at test bench

WEPML053 @IPAC18

Trend graph at 1.65 msec/5 Hz

The goal for high power test at bench was achieved!



We never observed electron emission and arc signal during keeping at 800 kW.

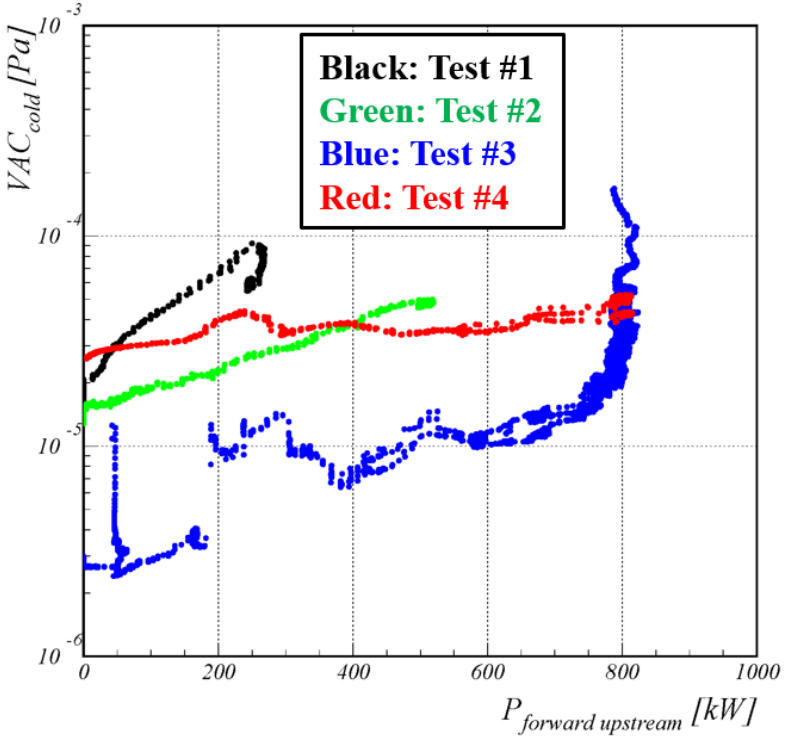
High power test at test bench

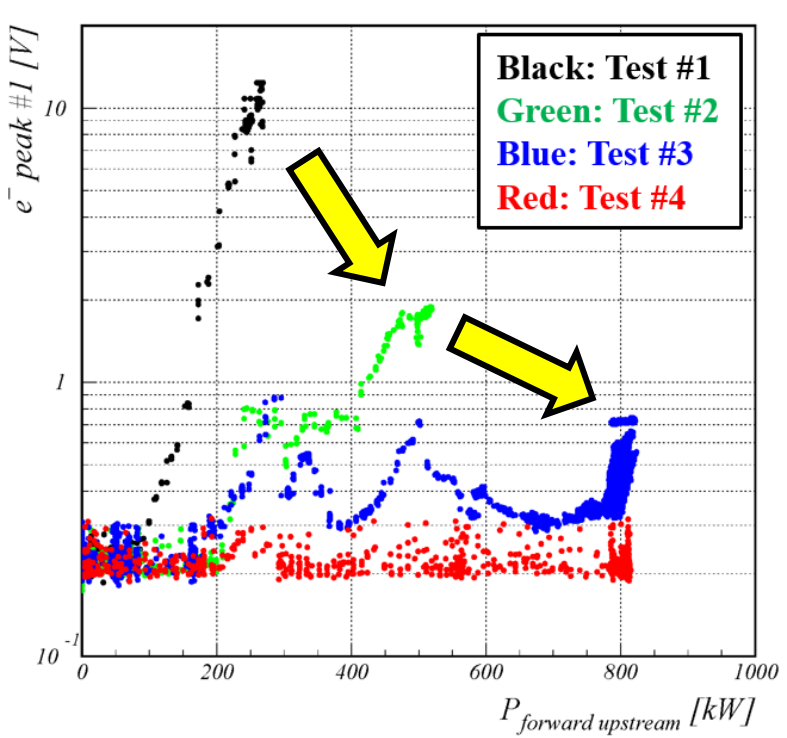
WEPML053 @IPAC18

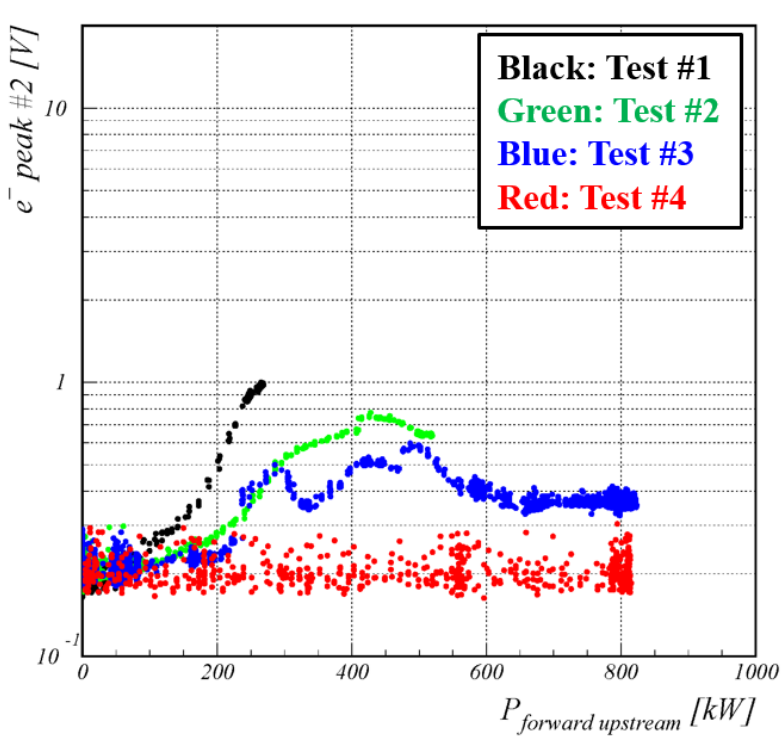
Ultrasonic rinsing had drastic effect for reduction of electron emission!

Test #1: Black (w/o USR)
Test #2: Green (0.3 W/ℓ)
Test #3: Purple (1.3 W/ℓ)
Test #4: Red (3.8 W/ℓ)

Scattered plot at 1.65 msec/5 Hz

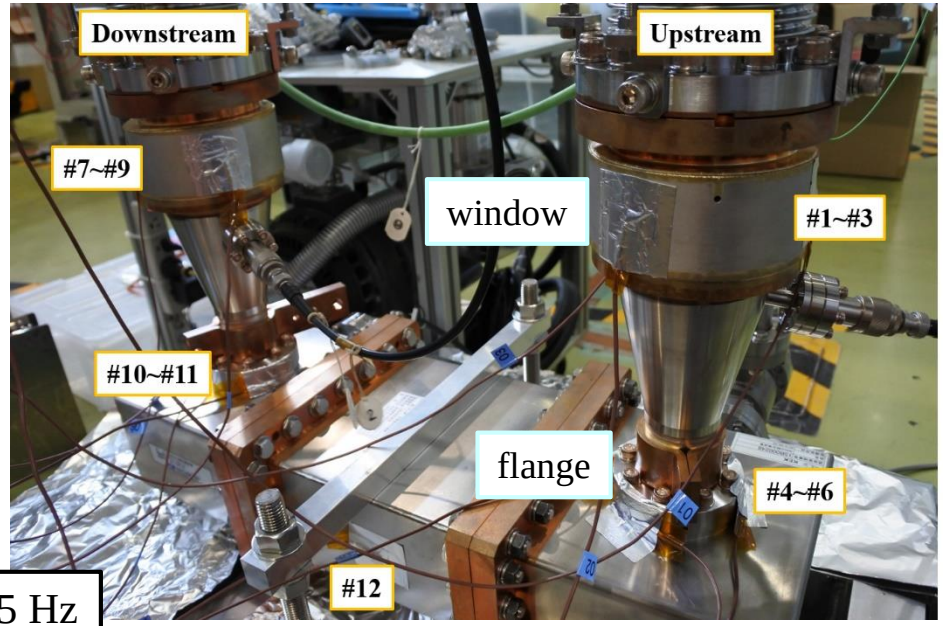


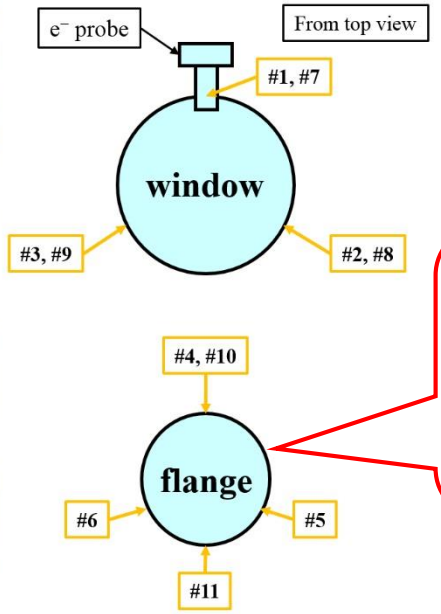




Strange heating phenomena

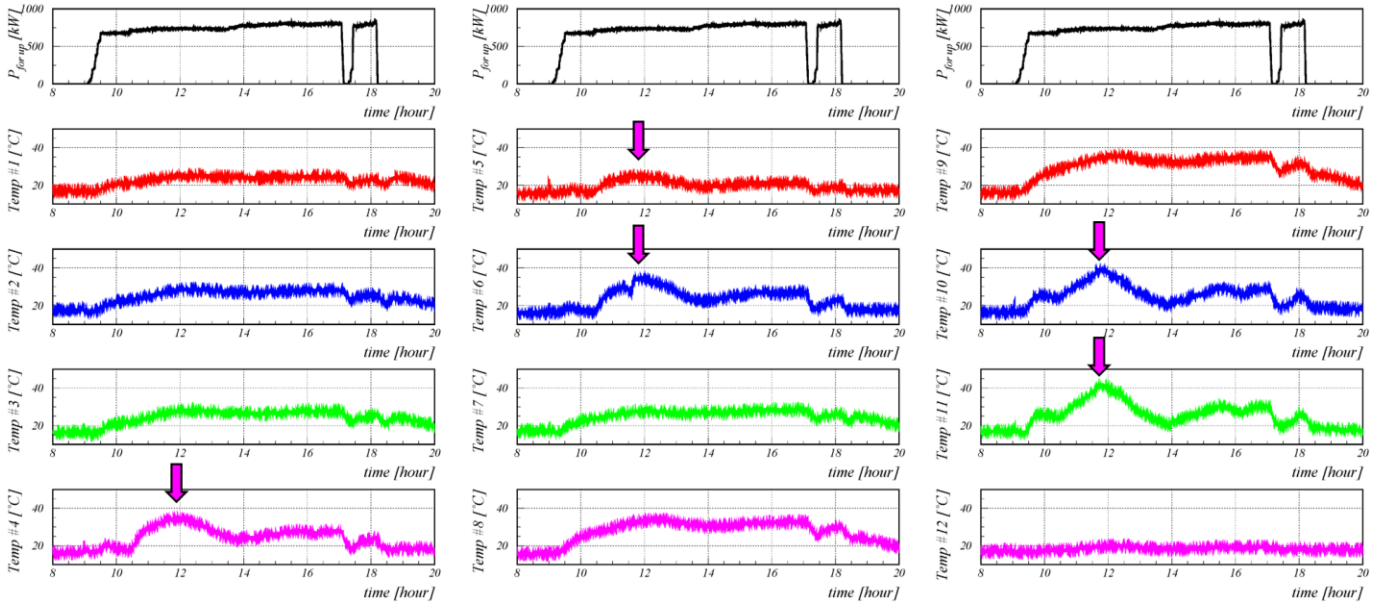
WEPML053 @IPAC18





During keeping at 750 kW, heating at both flanges gradually decreased like RF conditioning!

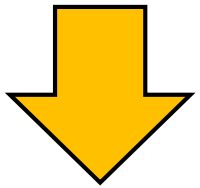
Temperature trend at 1650 μsec/5 Hz



“Updated understanding” for TiN coating-free ceramic

Available for normal conducting accelerator, waveguide, klystron

Not available for superconducting cavity due to heating phenomena



We can try more powerful ultrasonic rinsing!
Heating phenomena may disappear completely.

Next step for high power test

- ✓ Ultrasonic rinsing → more powerful machine
- ✓ Baking → 150℃ or higher
- ✓ High power test → higher power level, cross check for measurement system

KEK sends power couplers to LAL

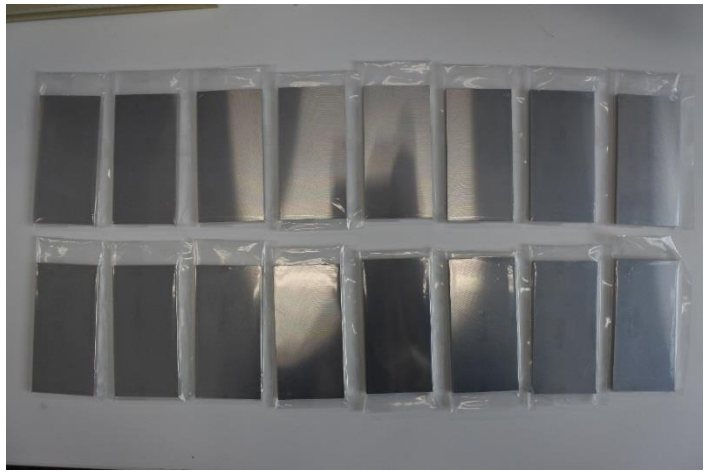
Ultrasonic rinsing machine
Baking furnace
High power test stand
are still available at LAL

Research on copper plating

- Research on change after brazing process (heat treatment)
  - RRR measurement in KEK/CEA
  - Analysis of Cu-Ni inter-diffusion by SIMS in LAL
  - Research on plating thickness by KEK/LAL
- Research on adhesion strength
  - Peeling test done by KEK
  - Ultrasonic rinsing test by CEA and LAL
- Cross check for RRR measurement system between KEK and CEA
  - Target RRR: 20 ~ 40 (for ESS)
  - RRR measurement done using same sample by KEK and CEA
- Research on acid temperature dependence (for more effective process)
  - Possible cost reduction (suggested from a vendor)

Three SUS316L samples for copper plating study

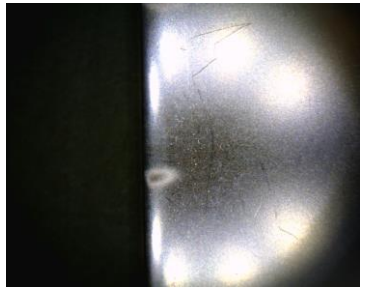
Plate shape



Like head of inner conductor

Bar shape

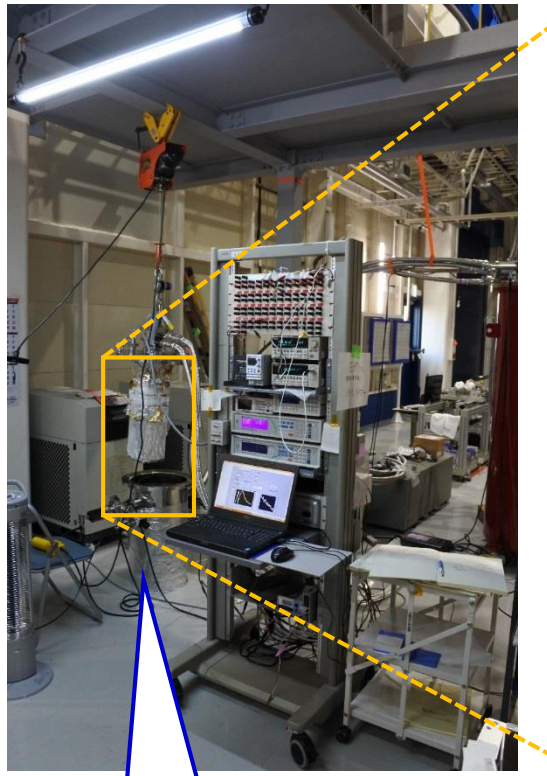
For adhesion test



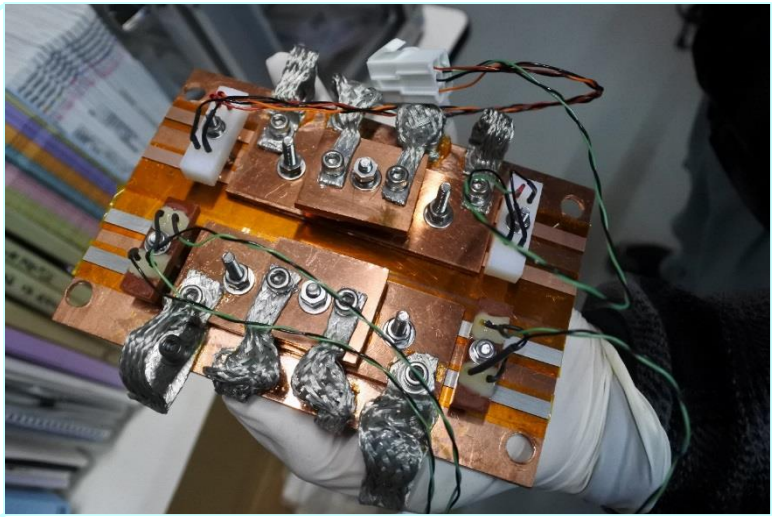
For RRR measurement

In F.Y. 2017, adhesion test was done by KEK-CEA collaboration.
The results were presented in LCWS2017 at Strasbourg.

Commissioning test for RRR measurement in KEK

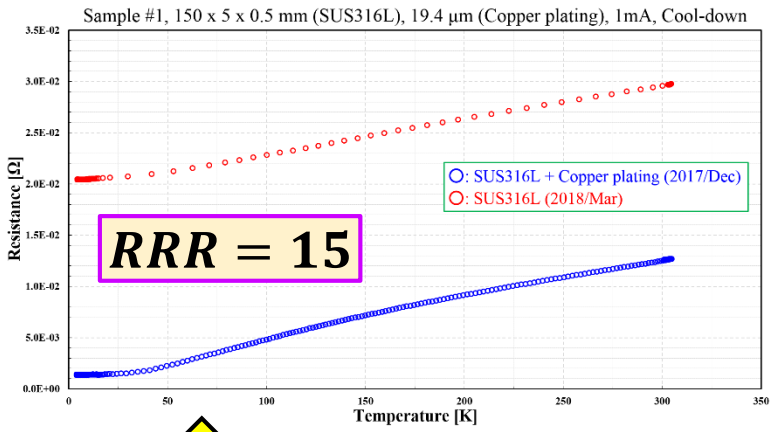


Small cryostat



SUS316L

Copper plating on SUS316L



Commissioning test

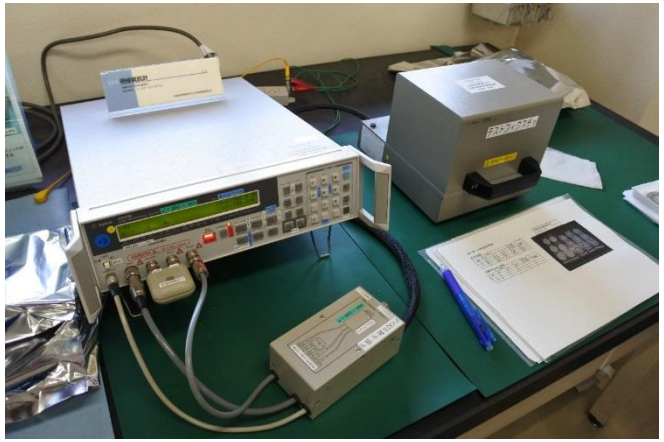
$$RRR = \frac{\rho_{300K}}{\rho_{4K}} = 30\sim50\ (target)$$

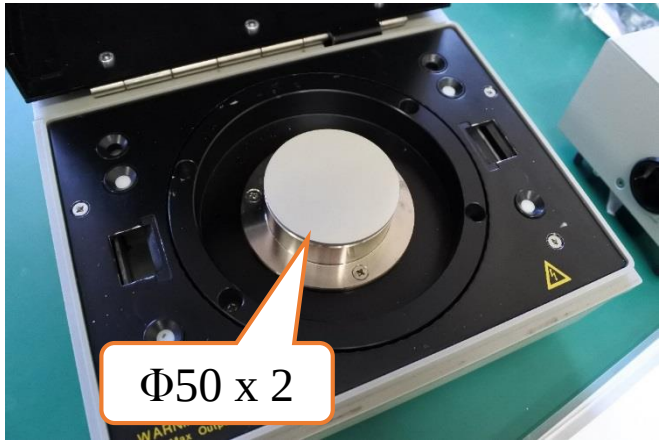
Too low! Investigation in progress

Research on ceramic properties

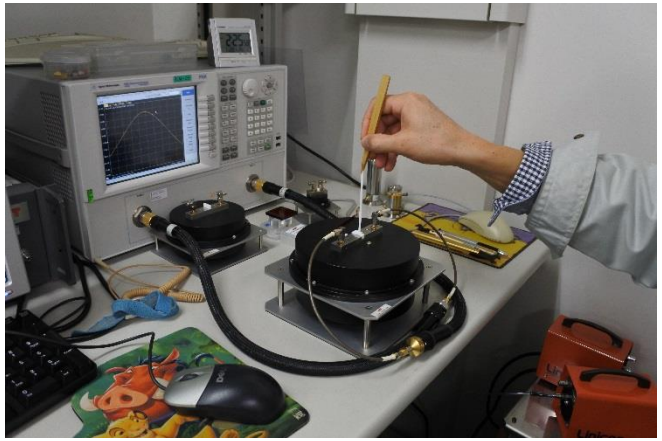
KEK is researching properties for six kinds of ceramics fabricated by four companies

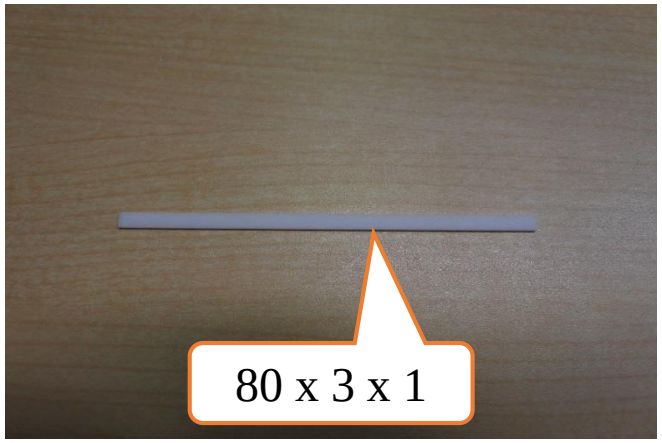
Surface/Volume resistance



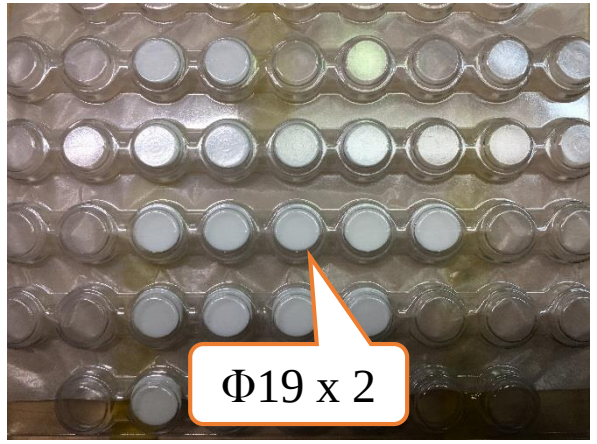


Relative permittivity
Dielectric loss angle





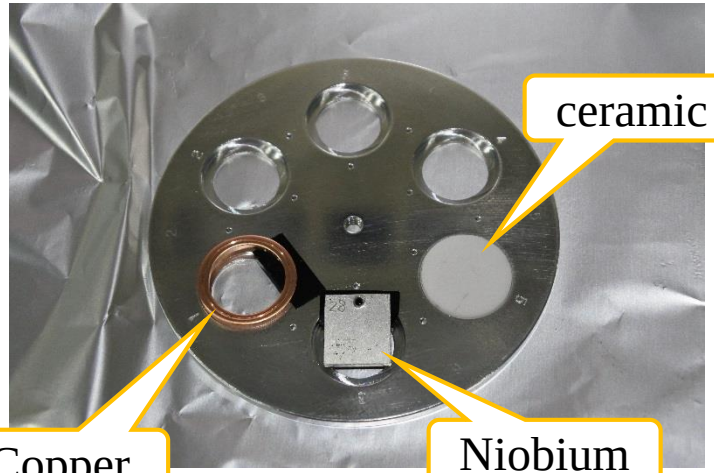
Secondary electron emission



Commissioning test for scanning electron microscope

Measurement device

We need pulsed beam for measurement of SEE, because ceramic is insulator!
Then, beam blanker is operated by pulsed mode.



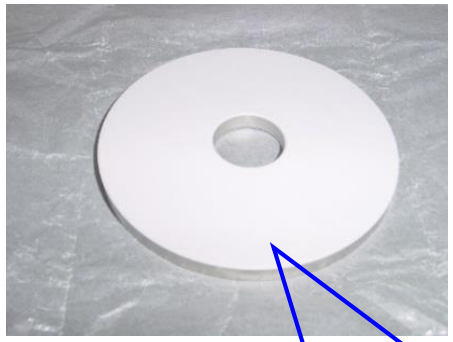
- Commissioning test is under progress using some metal samples
- It's a little bit difficult to adjust pulsed beam for measure of ceramic samples
- Research on TiN coating
- Research on ultrapure water rinsing
- Research on ultrasonic rinsing (@TETD, CEA, LAL)
- Research on ozonized water rinsing

Study for TiN coating with TIGOLD Corporation

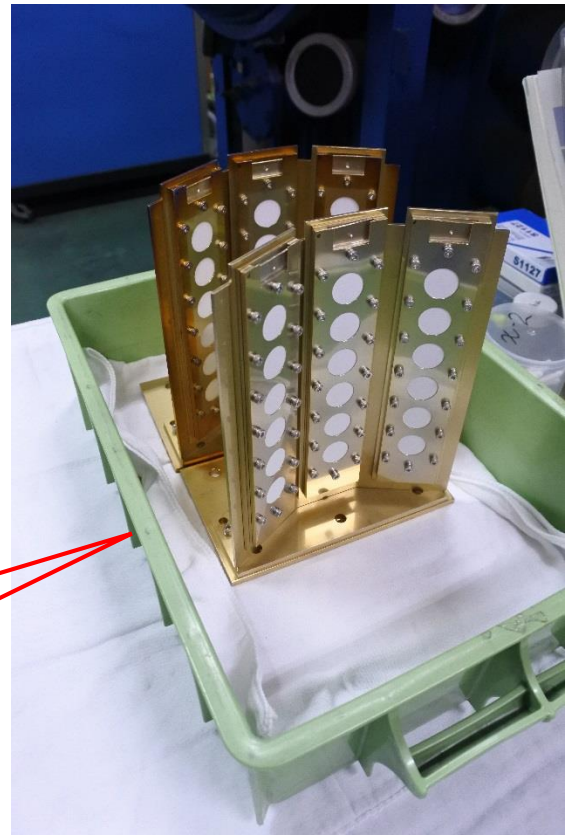
Recently, KEK started the study on TiN coating with TIGOLD corporation.
The main purpose:

- More effective & Larger quantity
- Cost reduction

Vacuum furnace for TiN coating @TIGOLD



Ceramic for STF power coupler



TiN coating for ceramic samples

Target thickness: 10 ± 2 nm

Summary

- TiN coating-free ceramic passed the power specification at test bench
- Ultrasonic rinsing for power couplers has drastic reduction of electron emission
- Commissioning test for RRR measurement of copper plating is done
- SEE measurement for ceramic samples are under progress
- Study for TiN coating is just started

Thank you very much

Backup slides

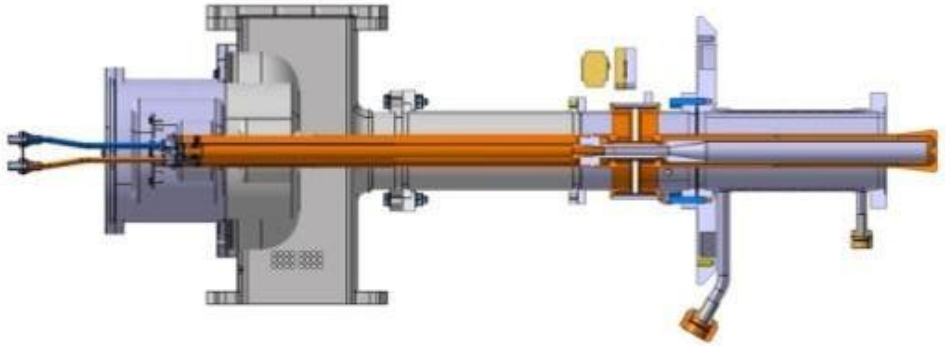
Specification of power coupler in each project

Project	ESS	E-XFEL	STF-2	ILC
Laboratory	IRFU/CEA	LAL/IN2P3	KEK	
Type	Coaxial structure			
# of RF windows	1	2	2	2
# of couplers	120	808	12	~16,000
RF frequency	704.42 MHz	1.3 GHz	1.3 GHz	1.3 GHz
RF power in beam operation	1.1 MW	120 kW (195 kW at max.)	?	189 kW
RF pulse width	3.6 msec	1.40 msec	1.65 msec	1.65 msec
RF repetition rate	14 Hz	10 Hz	5 Hz	5/10 Hz
RF duty	5 %	1.4 %	0.8 %	0.8/1.6 %
Set position of Q_{ext}	7.6×10^5	4.6×10^6	5×10^6	5.5×10^6
Range of Q_{ext}	fixed	$10^6 \sim 10^7$	$3\sim7 \times 10^6$	$10^6 \sim 10^7$
Cooling for inner conductor	Water			

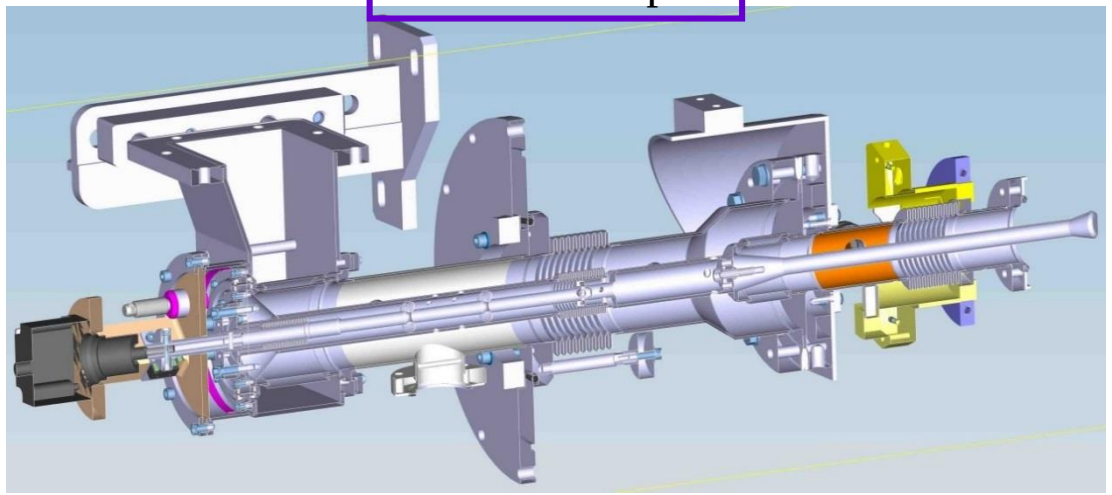
※ C. Arcambal, E Cenni ※ W.D. Möller, W. Kaabi

Power couplers in pulsed operation

ESS Coupler



E-XFEL Coupler



STF-2 Coupler

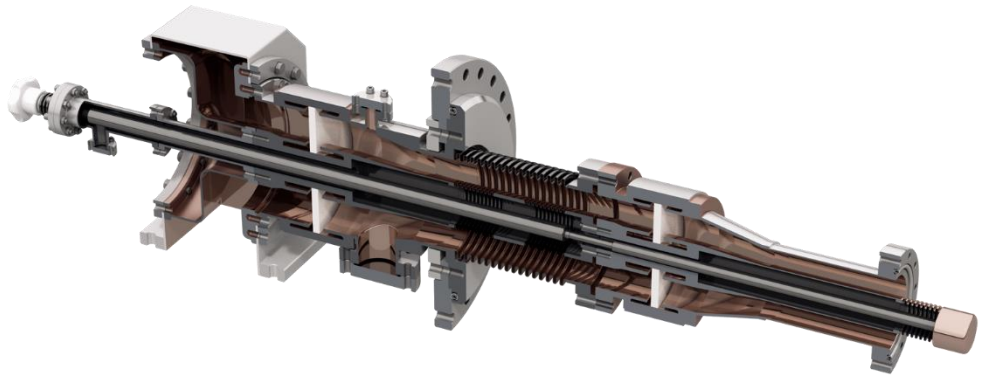
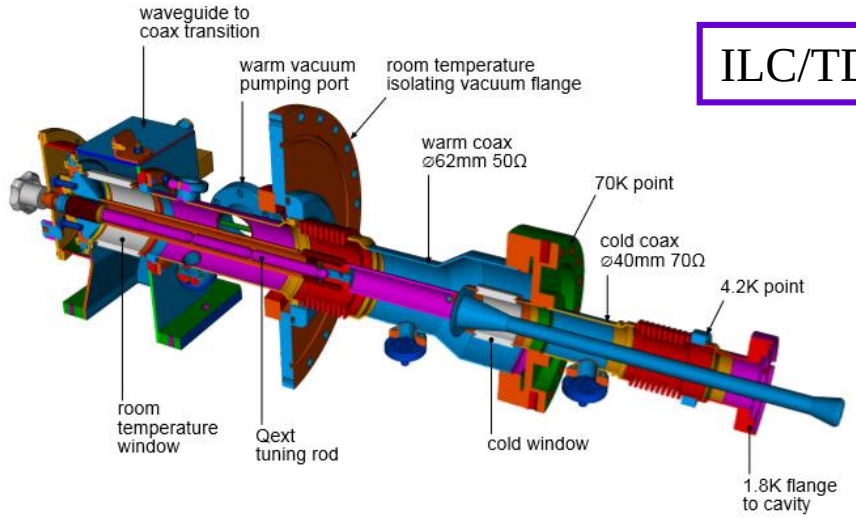


Figure 3.6
Schematic drawing of TTF-III (XFEL) input coupler.

ILC/TDR



ILC-TDR (for Power coupler specification)

These figures are shown on Page 35 in ILC-TDR Vol.3 Part-II.

Figure 3.6
Schematic drawing of TTF-III (XFEL) input coupler.

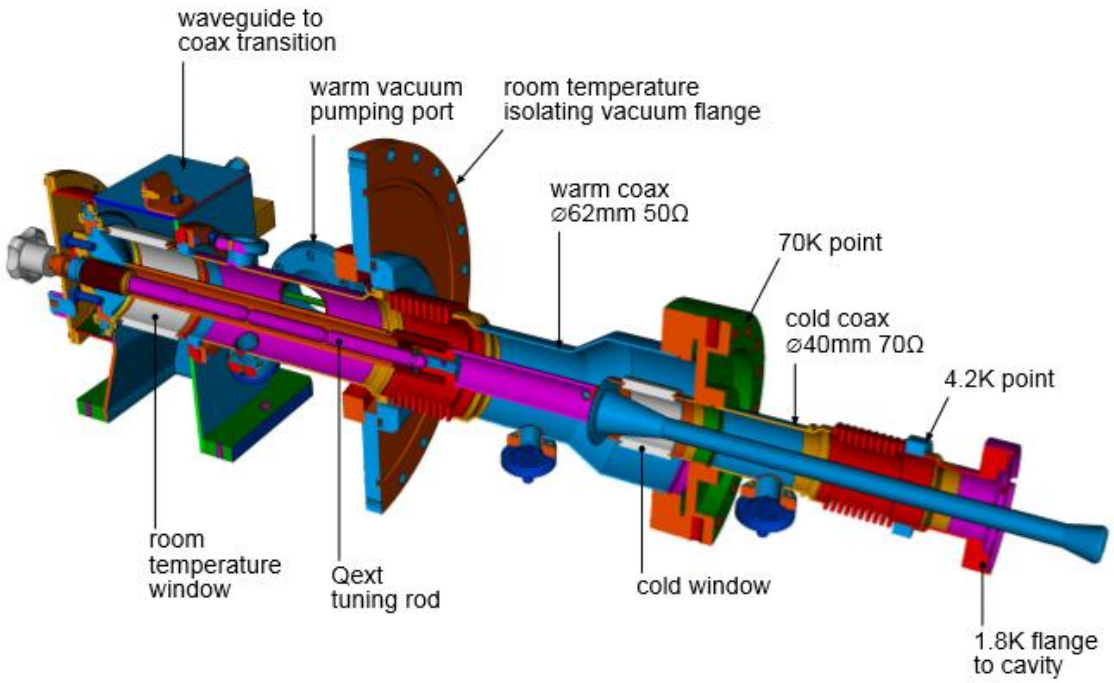


Table 3.7
Main specifications of the input coupler. The parameters represent the approximate maximum expected values during operation, including possible upgrades.

Parameter	Specifications
Frequency	1.3 GHz
Operation pulse width	1.65 ms
Operation Repetition rate	5 Hz / 10 Hz
Maximum beam current	8.8 mA
Accelerating gradient of cavity	31.5 MV/m ± 20%
Required RF power in operation	∼ 400 kW
Range of external Q value	$(1.0 \sim 10.0) \times 10^6$ (tunable)
RF process in cryomodule	> 1200 kW for ≤ 400 µs pulse width > 500 kW for > 400 µs pulse width
RF process with reflection mode in test stand.	> 600 kW for 1.6 ms pulse width
RF process time	< 50 hours in warm state < 20 hours in cold state
Approximate heat loads	< 0.01 mW (2K static) 0.07 W (5K static) 0.6 W (40K static) < 0.02 W (2K dynamic) 0.12 W (5K dynamic) 1.6 W (40K dynamic)
Number of windows	2
Bias voltage capability	Required

Summary of ceramic samples

Vendor	Ceramic name	Scale	Purpose of use	Coating	# of sample
Vendor A	Sample A	φ19 x 3	δ_{SEE}	TiN / Free	20
Vendor B	Sample B	φ19 x 2	δ_{SEE}	Free	10
	Sample C	φ19 x 1	δ_{SEE}	TiN / Free	6
	Sample B (retest)	φ50 x 2	ρ	Free	9
	Sample C (retest)	φ50 x 2	ρ	TiN / Free	6
	Sample B (done)	80 x 3 x 1	ε, tanδ	Free	5
	Sample C (done)	80 x 3 x 1	ε, tanδ	Free	5
Vendor C	Sample D	φ19 x 2.73	δ_{SEE}	TiN / Free	25
	Sample E	φ19 x 2.99	δ_{SEE}	TiN / Free	25
	Sample D	φ19 x 2.73	δ_{SEE}	Cr_2O_3 / Free	20
	Sample E	φ19 x 2.99	δ_{SEE}	Cr_2O_3 / Free	20
	Sample D (done)	80 x 3 x 1	ε, tanδ	Free	9
	Sample E (done)	80 x 3 x 1	ε, tanδ	Free	11
Vendor D	Sample F	φ19 x 2	δ_{SEE}	TiN / Free	20
	Sample F	80 x 3 x 1	ε, tanδ	Free	5
	Sample F (retest)	φ50 x 2	ρ	Free	6

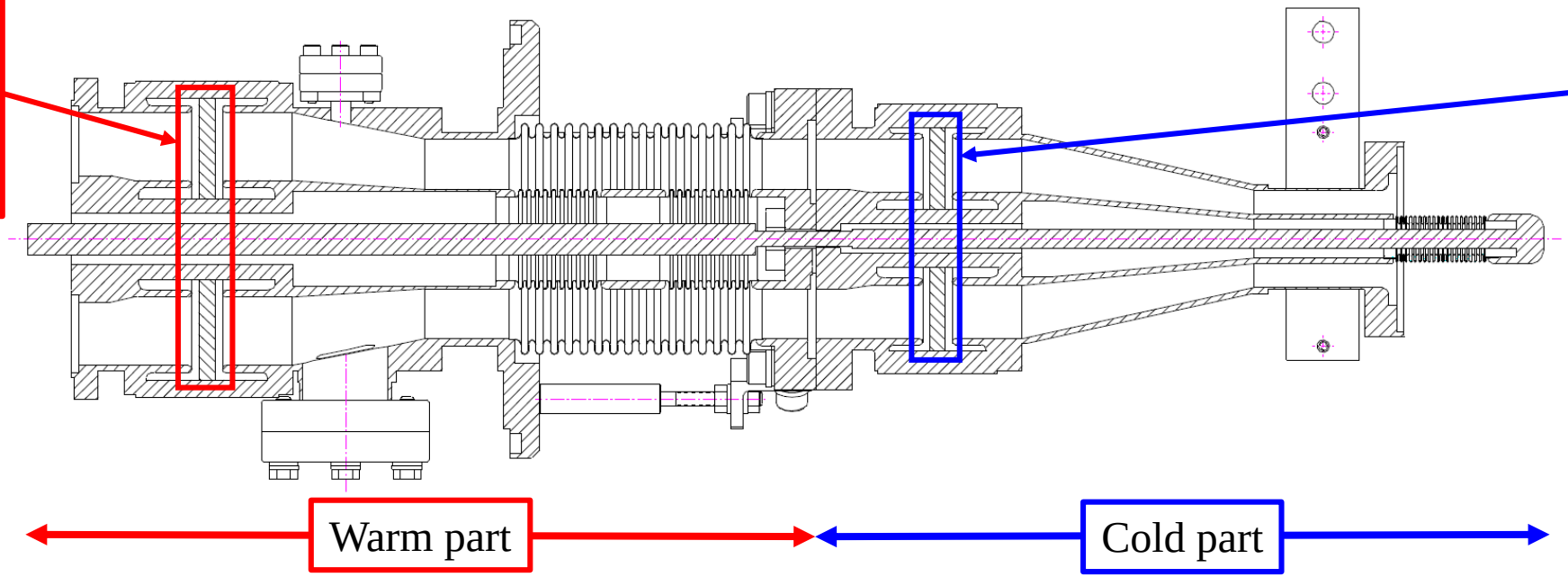
Necessary ceramic property

Longer RF pulse operation needs ceramic with lower dielectric loss tangent.

RF duty	**~1%**	**~10%**
Percent of Al_2O_3	> 95%	> 99%
Surface resistivity	$10^{14\sim15}$ Ω/☐ @25℃	$10^{14\sim15}$ Ω/☐ @25℃
Relative permittivity	9~10 @1GHz	9~10 @1GHz
Dielectric loss tangent	~10^{-4} @1GHz	~10^{-5} @1GHz
Secondary electron emission coefficient	~2 (5 as production)	<2 (5 as production)

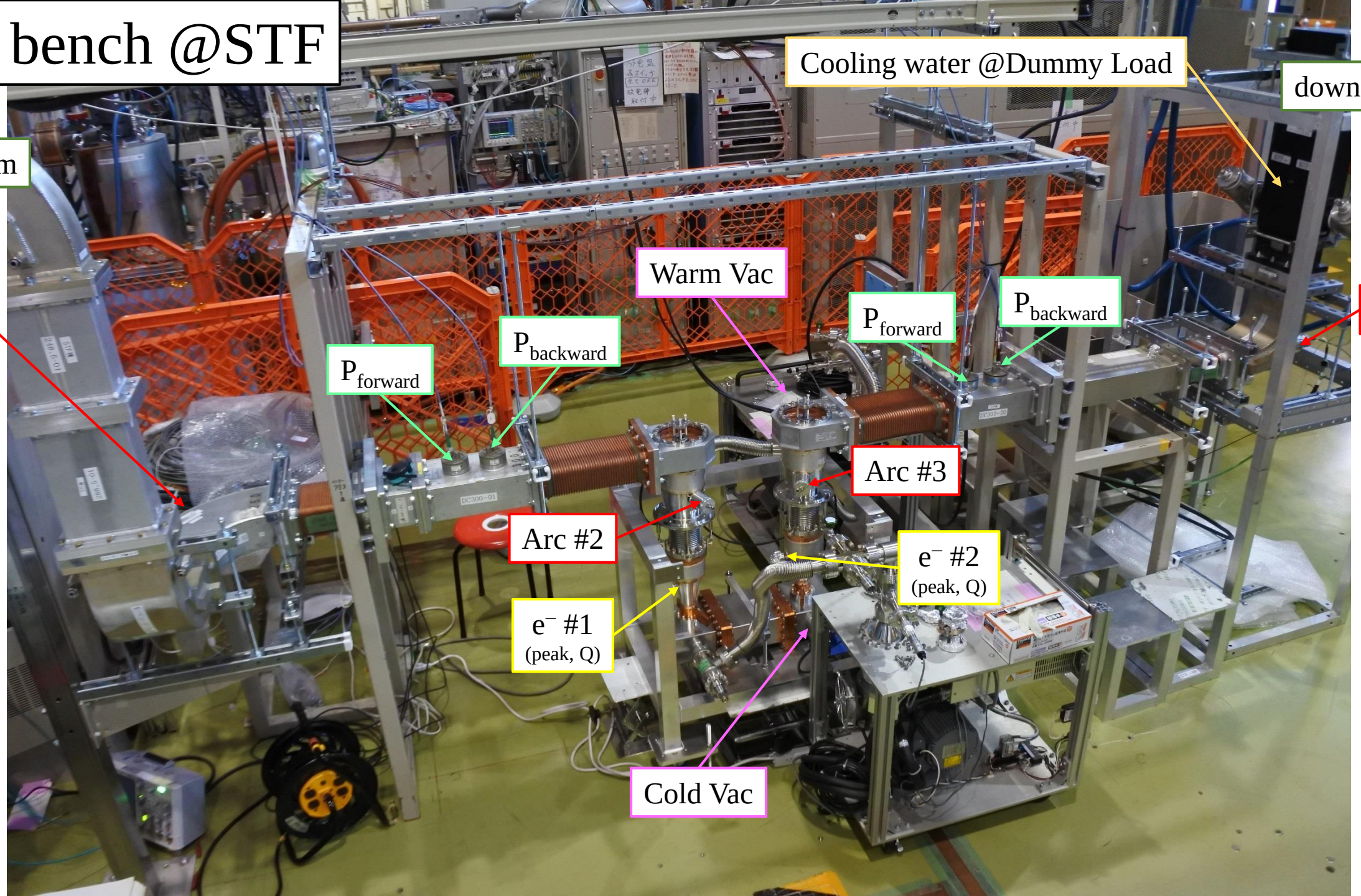
Specification for secondary electron emission coefficient is not clear.

STF-type power coupler



Ceramic	Thickness	Inner diameter	Outer diameter	TiN coating
Cold window (KYOCERA, LSEEC)	6.2 mm	24.0 mm	92.0 mm	free
Warm window (NTG/NTK, HA95)	6.6 mm	33.0 mm	116.0 mm	10 nm (single side)

Test bench @STF



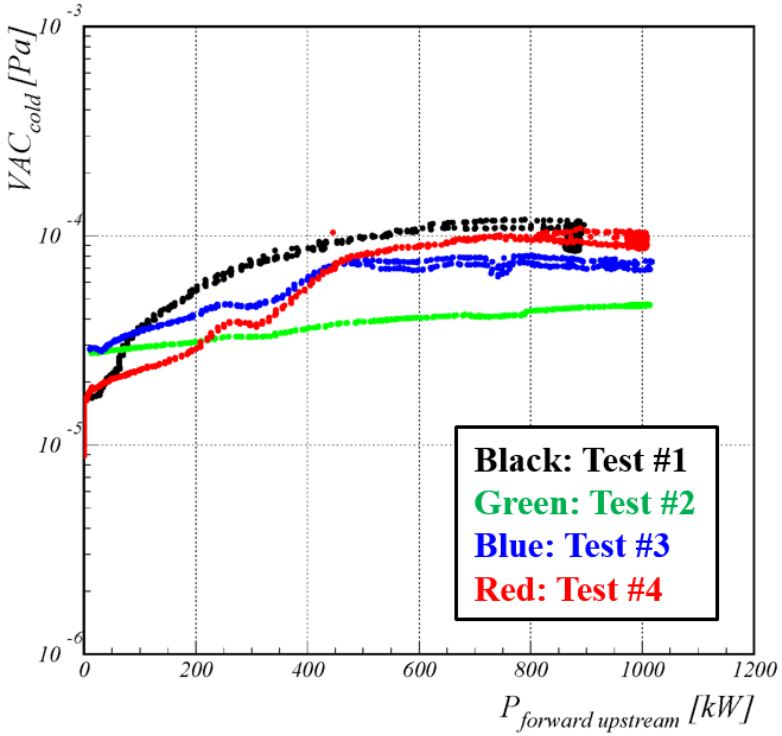
High power test at test bench

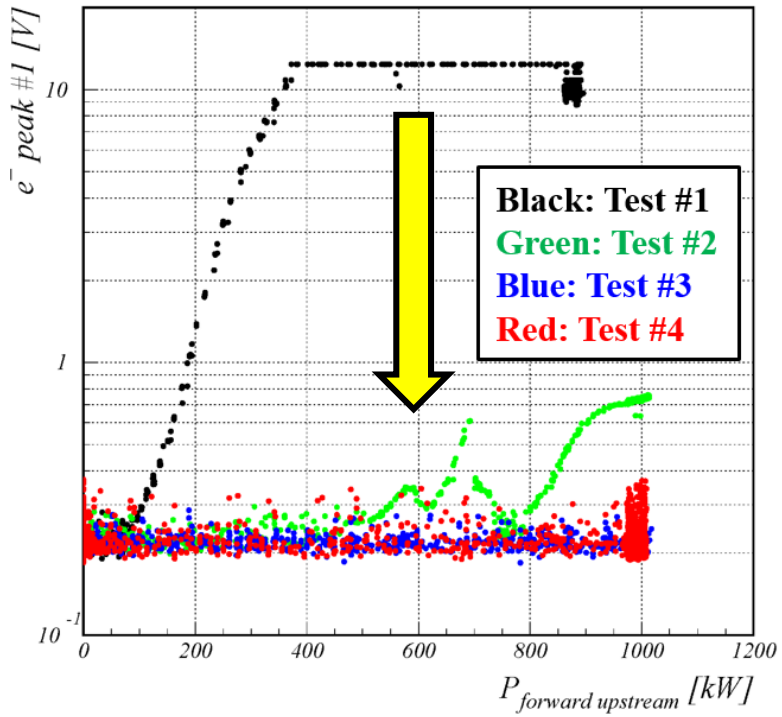
WEPML053 @IPAC18

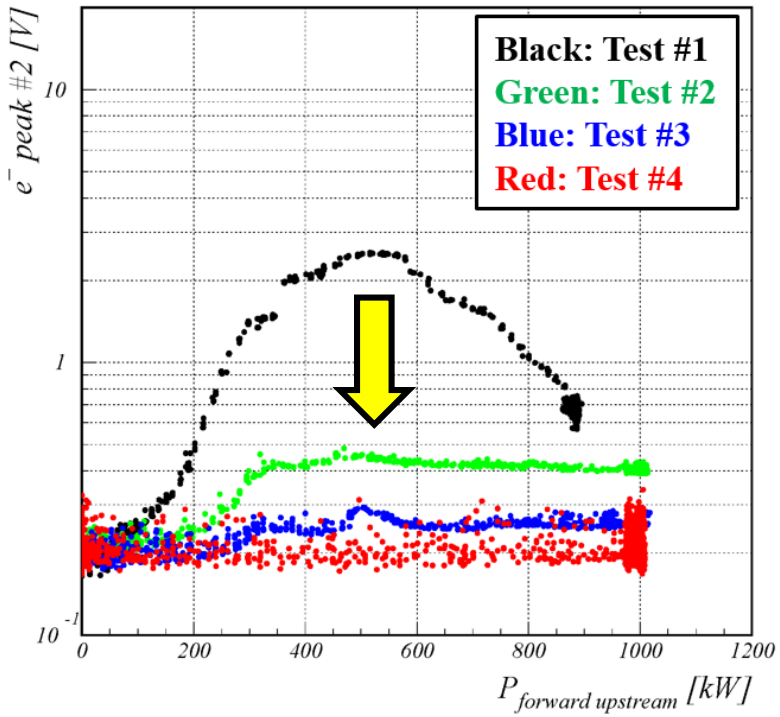
Ultrasonic rinsing had drastic effect for reduction of electron emission!

Test #1: Black (w/o USR)
Test #2: Green (0.3 W/ℓ)
Test #3: Purple (1.3 W/ℓ)
Test #4: Red (3.8 W/ℓ)

Scattered plot at 500 μsec/5 Hz

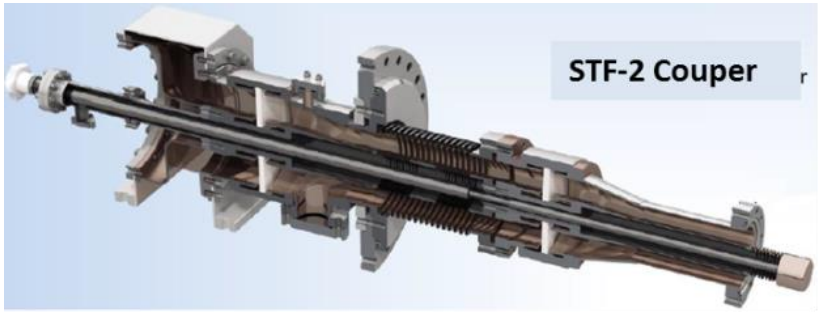


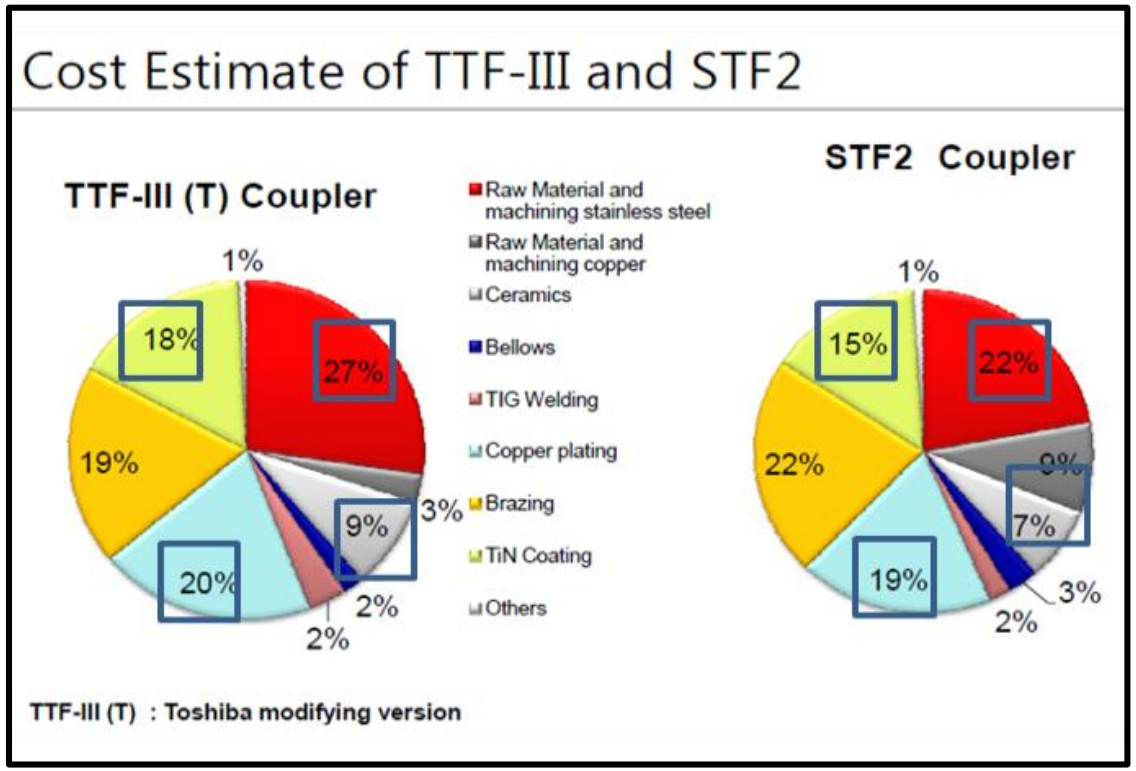




Cost reduction for power coupler

The amount for TiN coating is **15-18%** for the both couplers.





More complicated processes than cavity fabrication:

Brazing, Plating, Coating, Welding, Machining, Various materials

→ Comparable cost to cavity

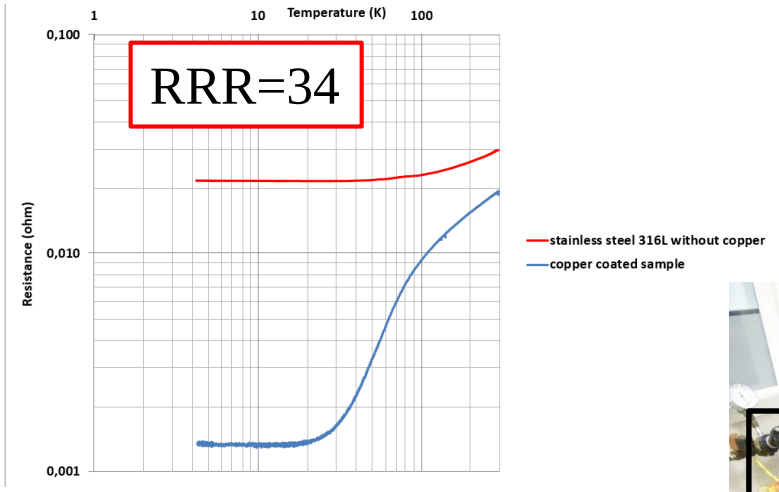
Reason for double RF windows → Much lower risk (contamination, vacuum leakage)

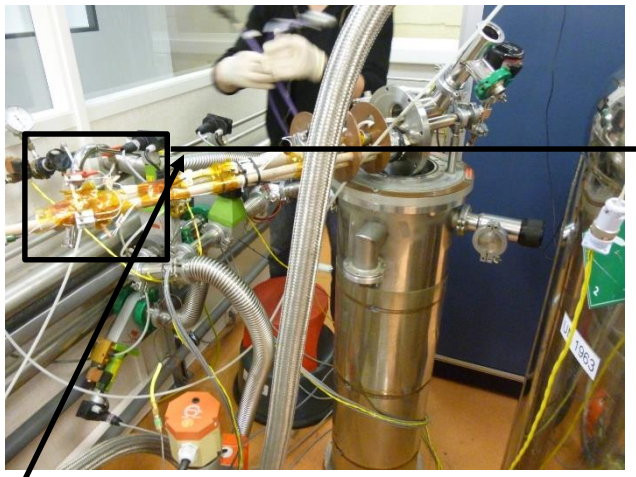
"Prospective" Cost Reduction: 20%↓ (power coupler)

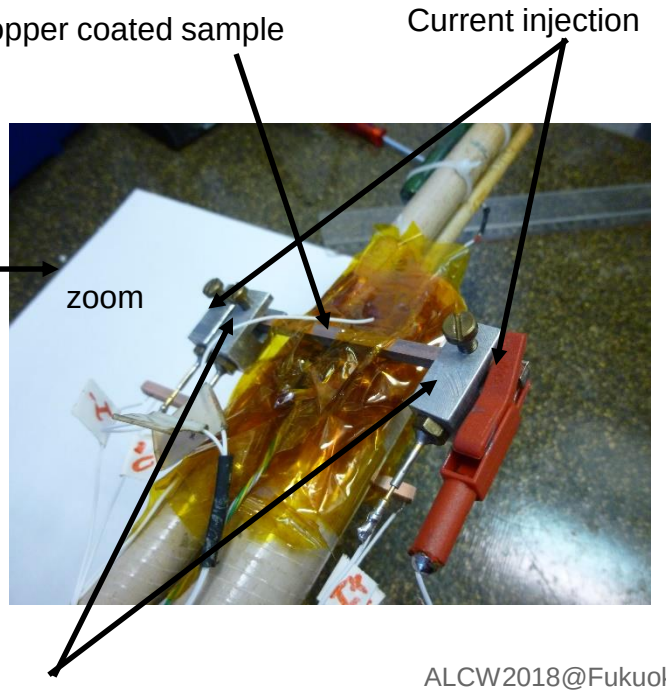
RRR MEASUREMENT AT CEA SACLAY

- Validation of the RRR on rectangular samples with maximum size : 4mm (width) x 4mm (thickness) and 100mm for the length
- For ESS couplers, use of rectangular samples with dimensions: 2 mm x 1 mm and 100mm for the length. Thickness of the copper coating: 10µm. These samples are cut from a cylinder similar to the double wall tubes of the couplers (similar in terms of length and diameter, and stainless steel).

C. Arcambal



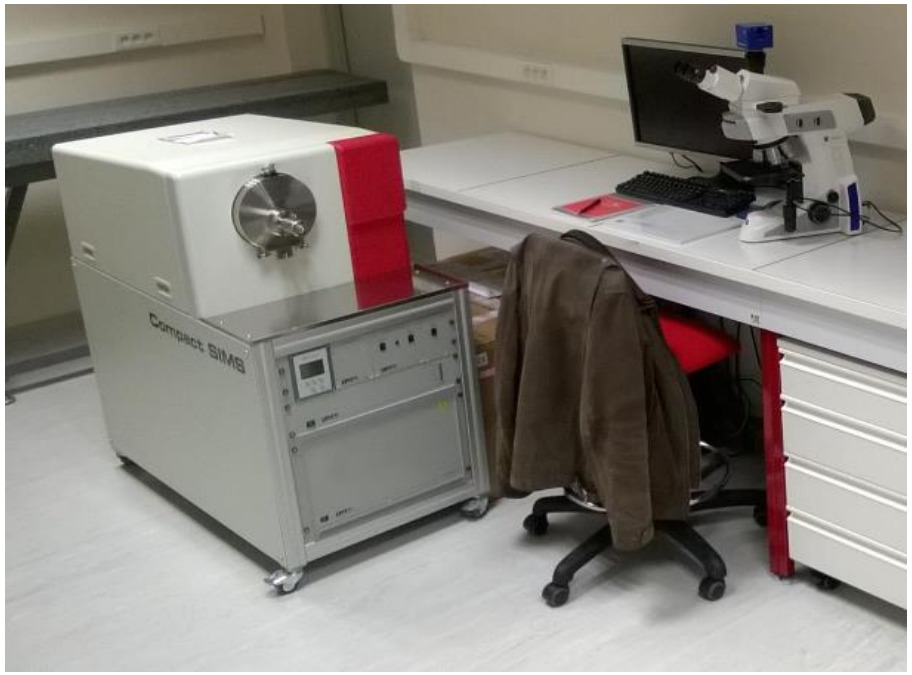




Measurement system to be put in the cryostat

Measurement point (voltage)

Compact SIMS from Hiden Analytical



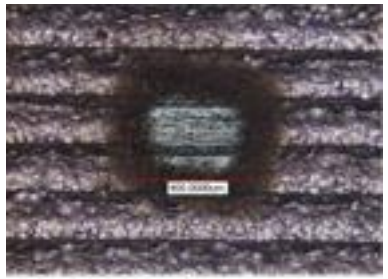
Parameters:
Beam Energy/current: 1 to 5 keV/ up to 400nA
Gas: Oxygen or Argon
Beam size: < 50µm for surface analysis and 80 µm for in depth concentration profile analysis
Resolution: 2 nm

W. Kaabi

The instrument offers 2 possible working modes:

- Static SIMS: Surface scanning for 2D analysis.
- Dynamic SIMS: Elements concentration profile Vs. sample depth

Example: Influence of a 400C cycle on Cu and Ni distribution in copper coated stainless steal.


Crater created by SIMS Analyses