R&D of the T2K target

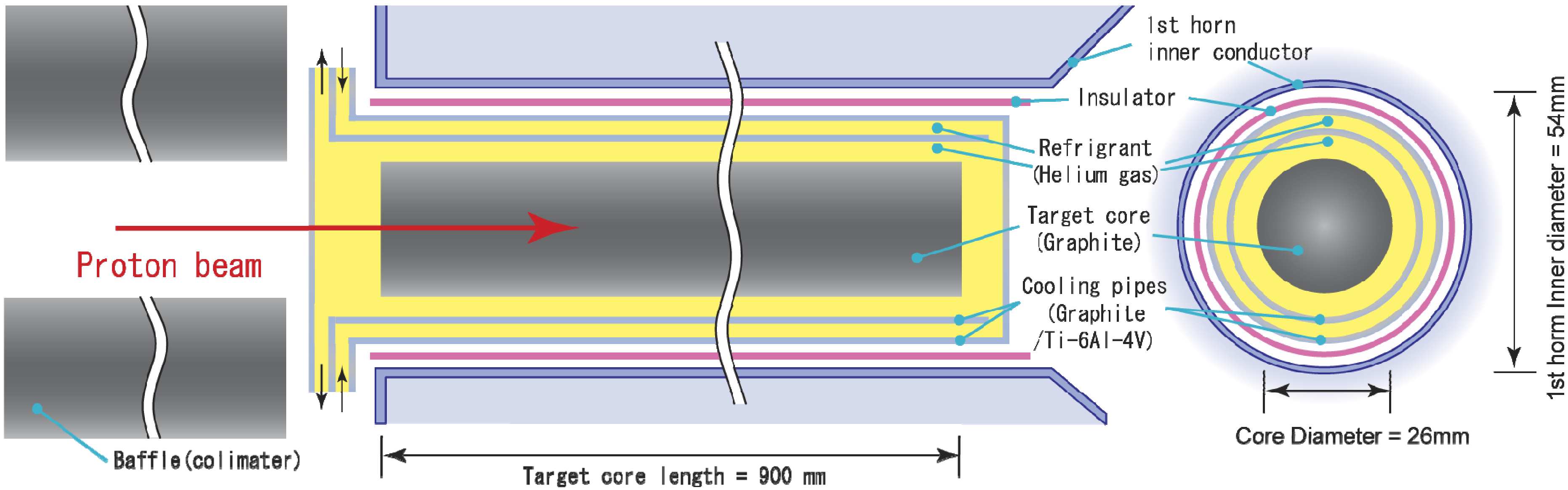
T. Nakadaira (KEK)

Contents

- Introduction
- Lifetime estimation of Target Graphite
  - Oxidization of Graphite
    → Conceptual design changed
- Prototype test of cooling pipe
  - Workability of thin Ti-alloy tube
  - Brazing between the graphite and Ti-alloy
  - Insulation by plasma-splayed ceramic
- He gas cooling
  - Flow scheme and Circulation system
  - Erosion of graphite by Helium gas
- Summary

Quick review: Target conceptual design

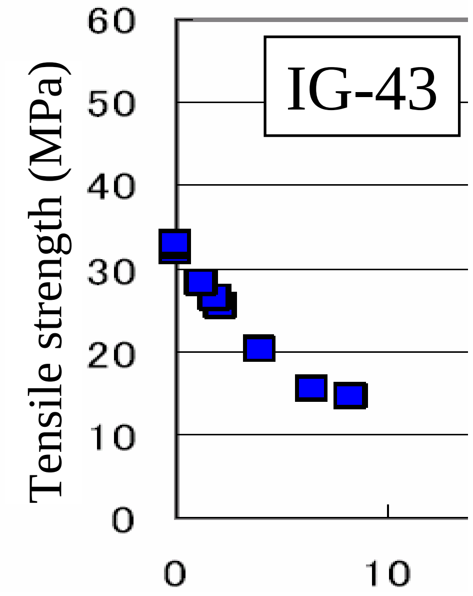
- Core: Isotropic-Graphite : IG-430 (Toyo Tanso Co. Ltd)
  - 26mmϕ, L=900mm
    (← Target diameter is changed while the beam size is not changed.)
  - Total energy deposit: 41kJ/spill for 30GeV (3.3×10^{14} protons / spill)
    → 19.6kW for 0.75MW beam (2.1sec cycle)
  - $\Delta T_{max} \approx$ 200K. σ_{eq} = 7.42 [MPa]
    ↔ Tensile strength (IG-430) = 37.2 [MPa]
- Helium cooling
  - Co-axial 2 layer cooling pipe: Graphite / Ti-6Al-4V



Oxidization of the target graphite

- The degradation of the tensile strength
  - Magnitude of the oxidization is measured by mass reduction.

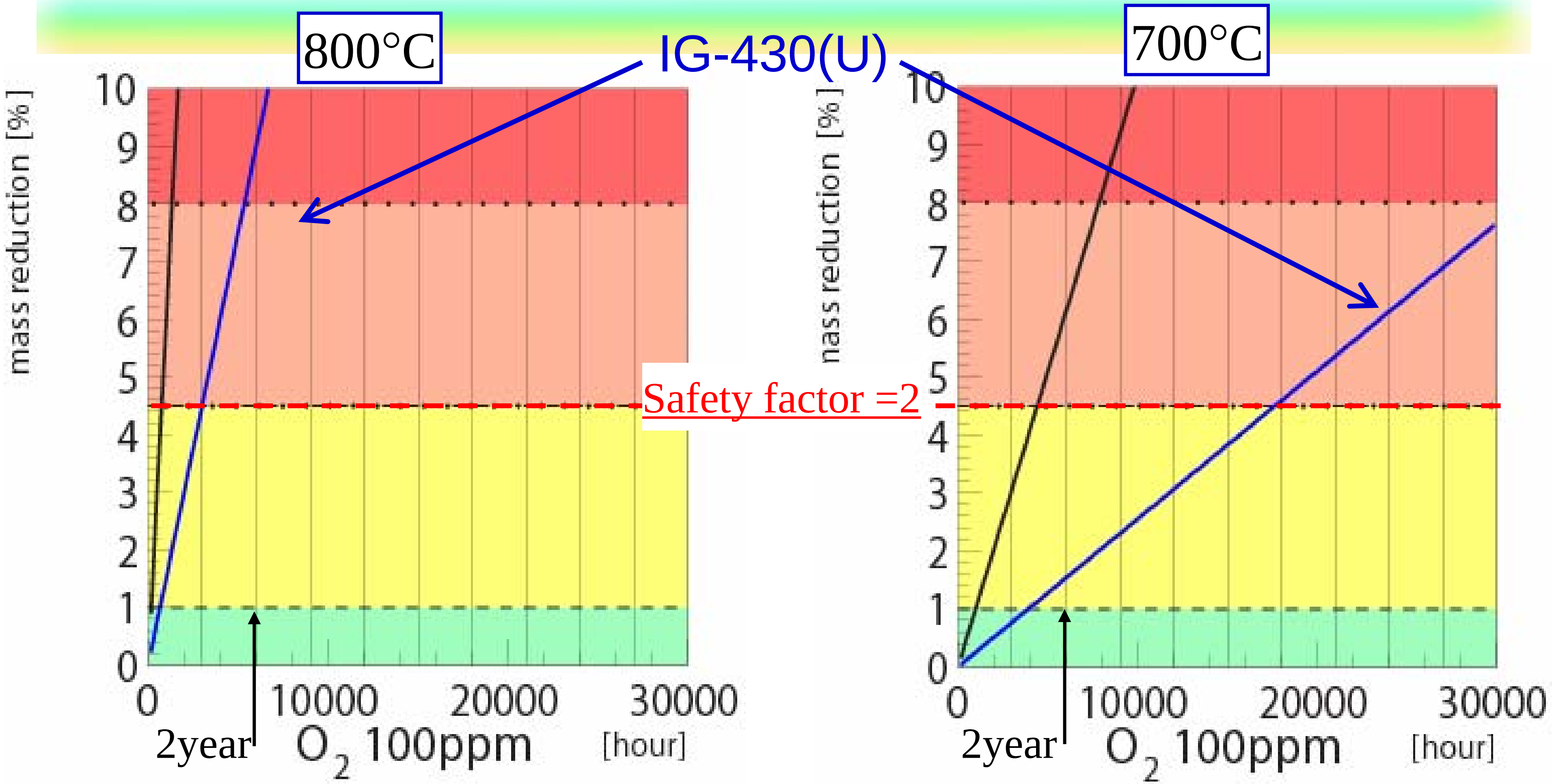
mass reduction [%]	Safety factor = strength/stress
0% (Before oxidization)	3.5
1%	3.0
4.5%	2.0
8%	☠ (crumble)



mass reduction
due to oxidization (mass%)

- Speed of Oxidization
  - He+O_2 1000ppm 800°C 50hour
    - IG-430,IG-430U (High purity grade)
      … 4.0×10^{-5} mass%/hour/ppm

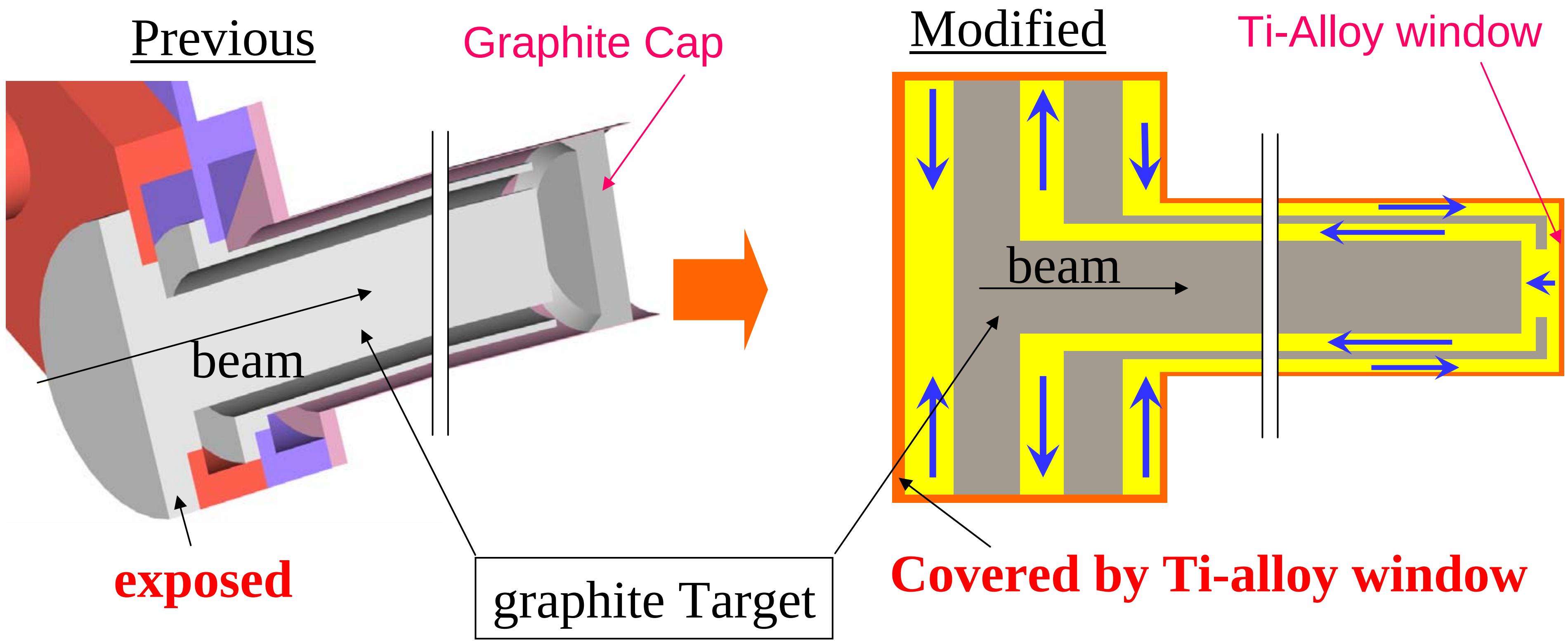
Target lifetime due to Oxidization



- Conservative estimation
  - Target center may become 700~800°C, but surface will be ~400°C.
- O2 contamination should be kept as much as lower.

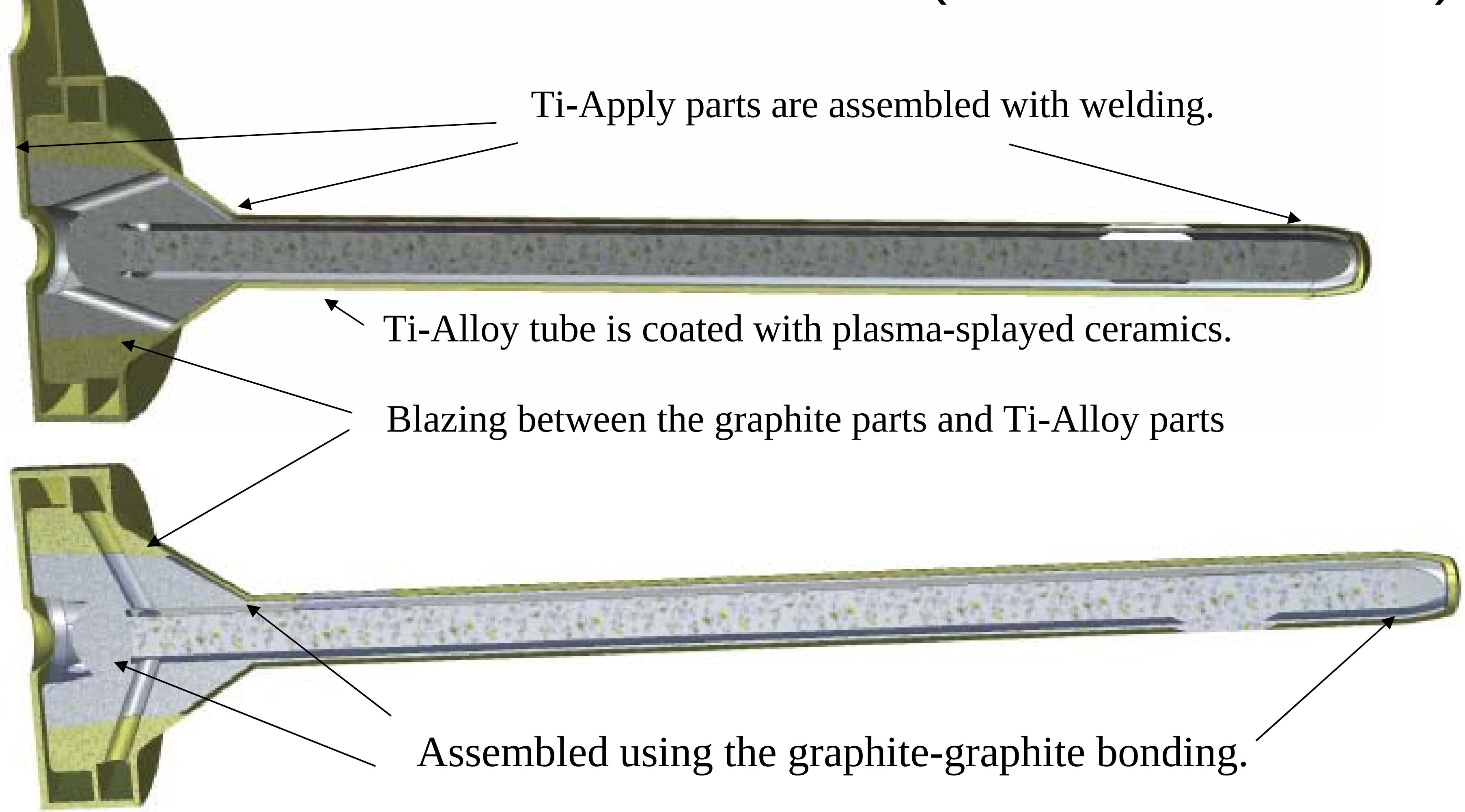
Modified conceptual design

- Ti-alloy container is needed to keep helium gas purity.
  - Change the downstream window material: Graphite → Ti-6Al-4V
  - Upstream of the target should be covered by another beam window.
  - Ti-window is chilled by helium gas for target cooling.



Detailed design

- Optimized for the He-gas flow and the cooling of the beam windows. (→ M. Fitton's Talk)

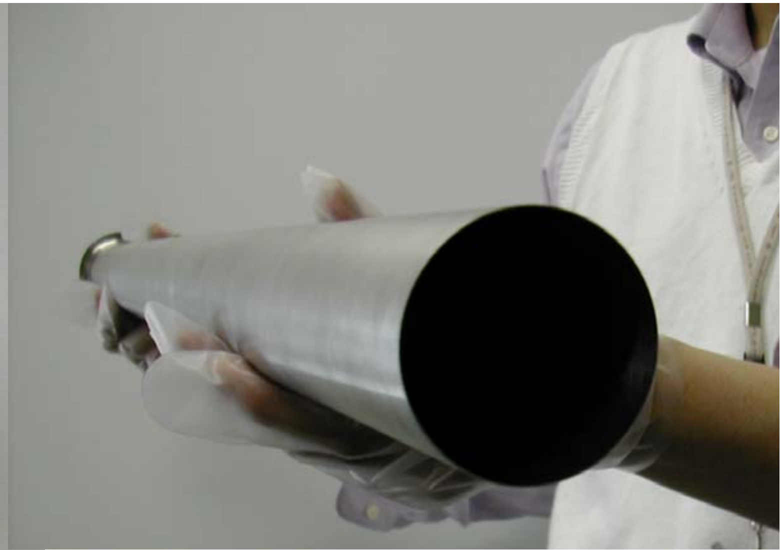


Target Segmented?

- Dynamic stress due to thermal shock by well aligned p-beam is estimated by FEM.
  → There is no advantage of segmentation.
- Study on 5mm off-center beam. (50GeV 30mmϕ)
  - Max. displacement … 4mm
  - Max. von Mises stress … 4MPa

Segment length (mm)	Max. Von Mises Stress (MPa)	
	Ansys	LS-Dyna
∞	7	---
900	7	8
15	10	10
3	8	7

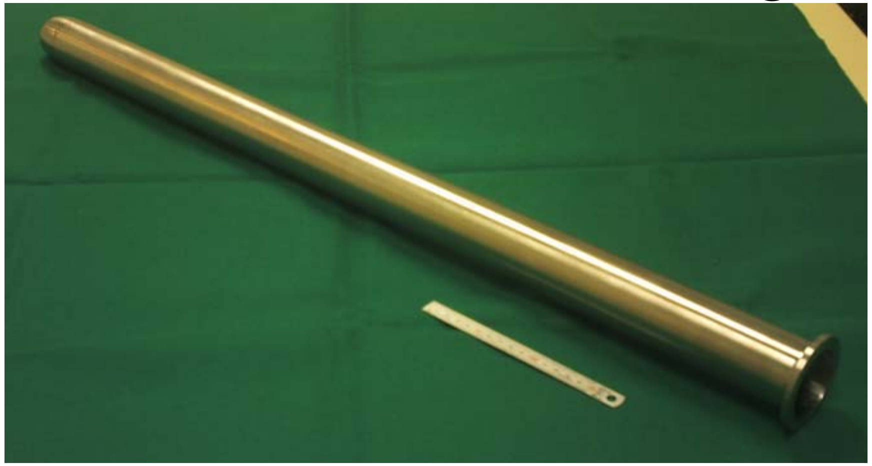




Ti-6Al-4V (t=0.3mm)


Ti-Alloy Outer-tube

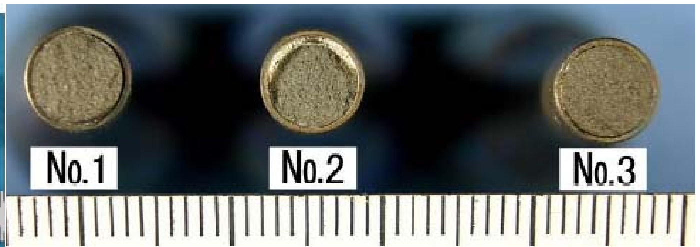
- Micro Plasma Welding

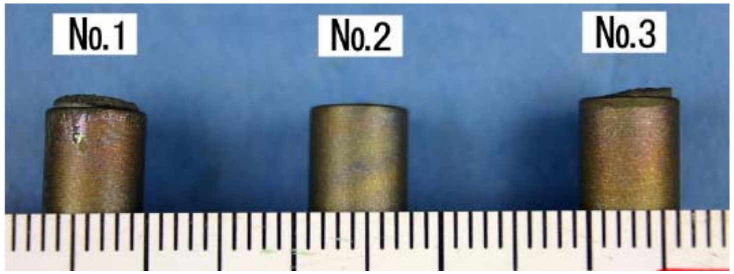


- Plasma-splaying ceramics

Graphite-Ti brazing @ high temp.

- Target will be supported by Ti-Alloy parts at the upstream end by brazing.
  - Brazing material: BAg-8 (JIS Z3261)+2%Ti or BPd-4(JIS Z3762)
- Expected average temperature of target is ~600°C
  → Is the brazing part strong enough at high temp.?
- Tensile strength @ 600°C is measured.
  → 26 MPa ~ 30 MPa *(preliminary)*
  - Parameter for the upstream part design is obtained.
    c.f. Tensile strength of graphite (IG-43) is 37.2 MPa.





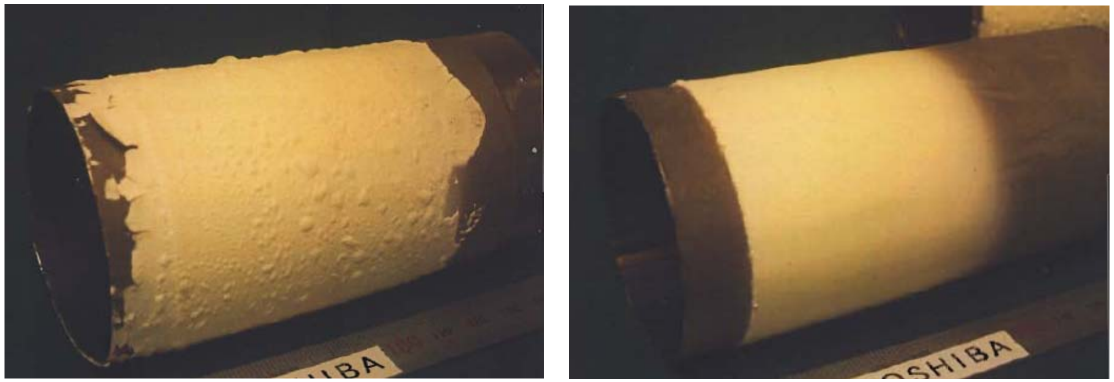
Plasma-splayed Ceramic layer

- Purpose: Insulation between the target and 1st horn inner conductor.
  - Expected voltage difference: ~900V.
  - The temperature in actual experimental condition is higher than this test. (70~80°C) : It become more severe. →Desired withstanding voltage: ~2kV
  - Plasma splayed ceramic has a porous structure. → It is necessary to seal pores by surface coating.
- We have tested 3 sealing materials.
  - 1 Al_2O_3-based and 2 SiO_2-TiO_2 based.
  - Insulation test (DC-voltage)
    - Measurement of the discharge voltage of the ceramic-layer + 1mm gap filled with helium gas.
  - The robustness at High temperature is checked.
    - 600°C 2hour

Plasma-splayed Alumina ceramic

Sealing material	Robustness @ High temp.	Insulation test	
		Temp.	Discharge volt.
w/o sealing	O.K @ 600°C	27°C	1.4 kV
Al_2O_3-based	☠ @ 400 °C	26°C	0.75 kV
SiO_2-TiO_2 based (1)	O.K @ 600°C	26°C	3.1 kV
SiO_2-TiO_2 based (2)	O.K @ 600°C	25°C	3.1 kV

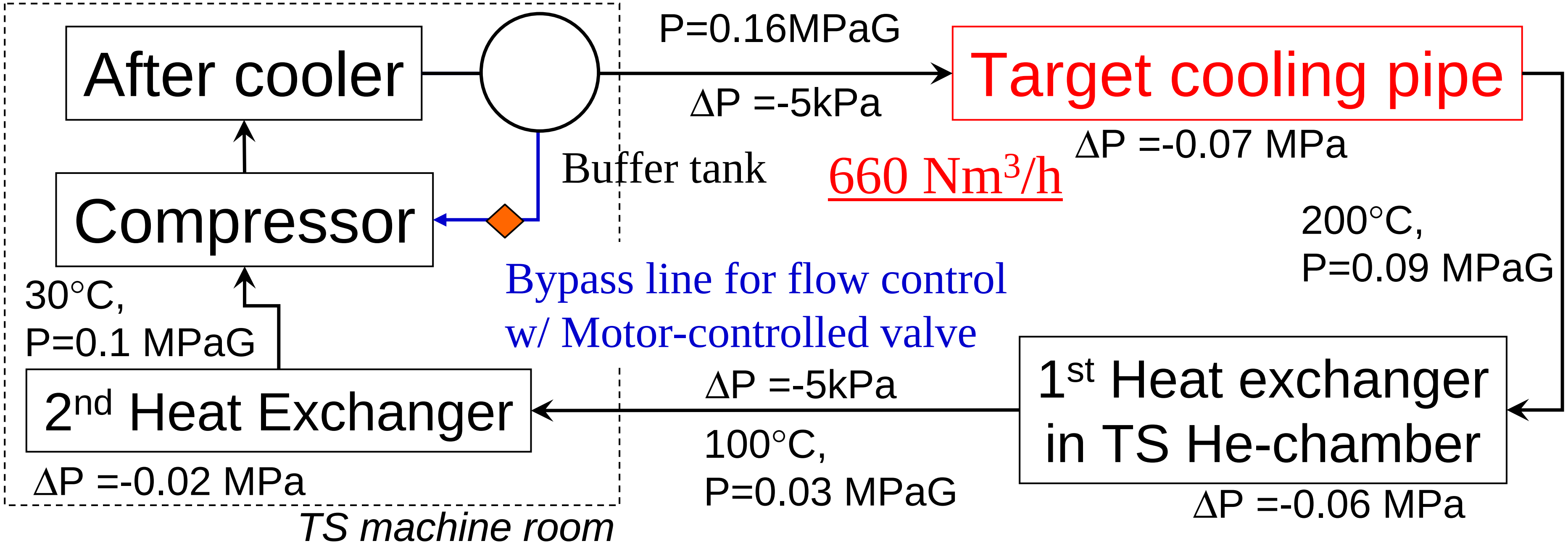
- Sealing with SiO_2-TiO_2 based material is in good shape.
- We plan to check the robustness after the exposure to a proton beam.



Ceramic w/ Al_2O_3 based sealing falls off the Ti-Alloy tube (400°C 1hour), while test piece without sealing is not damaged (600 ° C 2hour).

He system for target cooling

Supported by KEK IPNS Cryogenic G



- Total load for 30GeV including the cooling pipes is 23.6kW
  - Requirement for the refrigerant helium flow-rate : 26.7 [g/s] assuming the allowable gas temperature rise of 170K (30 °C → 200 °C)

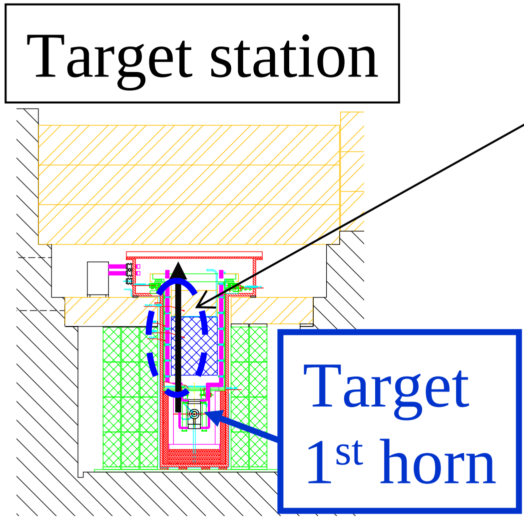
  → Specification for the Helium system for the target including 20% margin.
    - Heat load assumption: 28.3kW
    - Flow rate : 32[g/sec] = 660 [Nm^3/h] @ 0°C,1atm)
      720 [m^3/h] = 12000[l/min] @ 30°C,1atm

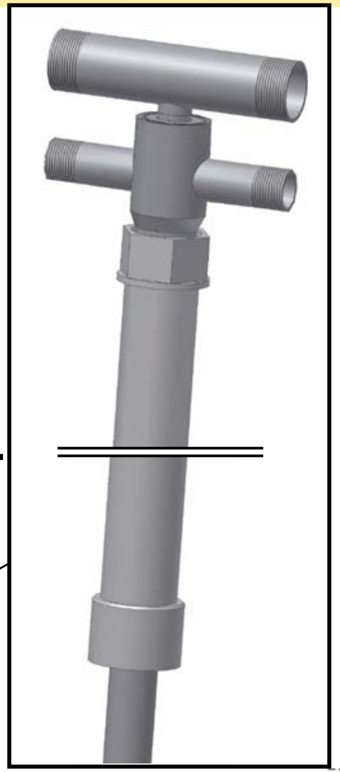
Helium gas system

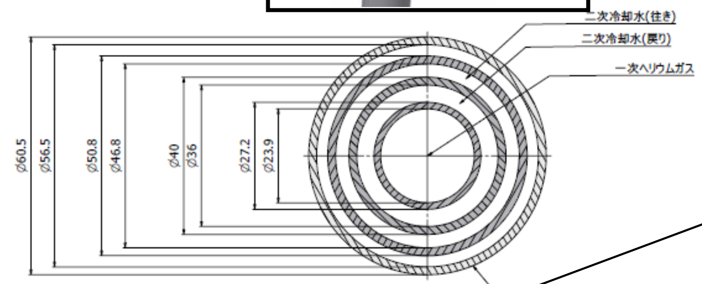
- Standalone test of the helium compressor
  - Achieved flow rate = 720 [Nm^3/h]
  - Power consumption: 34kW
  - Helium gas leak rate < 1.1×10^{-5}[Pa·m/s]
- Test operation of the helium system is started at KEK.
  - Basic operation of the system is tested.
    - Automatically stopped in abnormal conditions.
    - Flow rate control by the valve at the bypass line.

1st heat exchanger

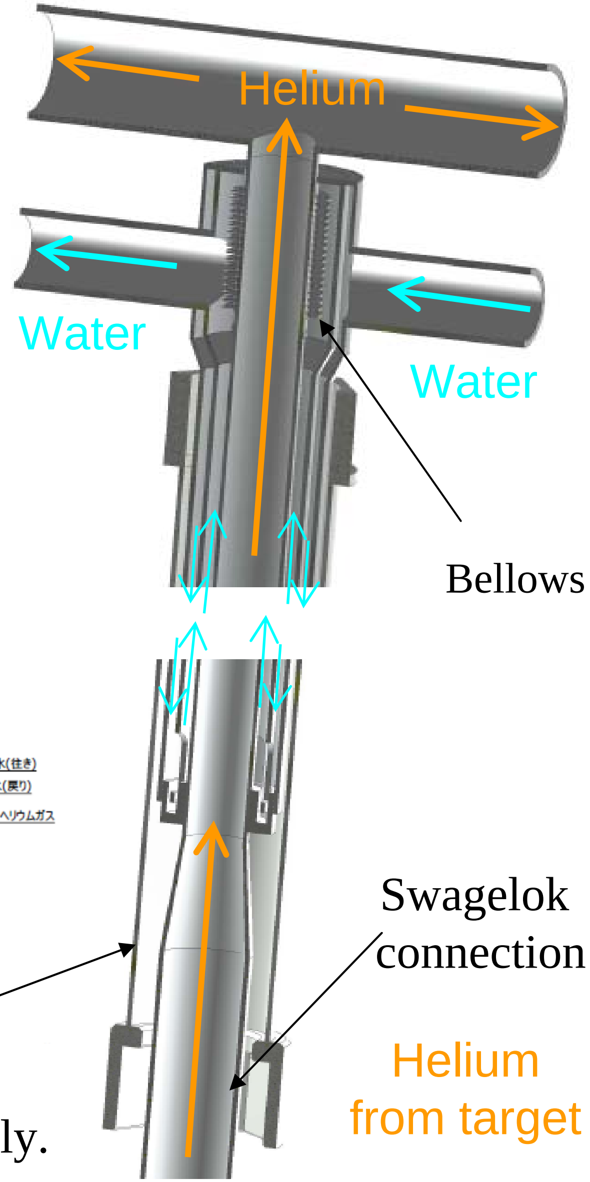
- 1st heat exchanger is installed in the iron wall of the horn support frame.
  - Minimize the outflow of head from high temperature He-gas.
- Prototype will be made in this year.





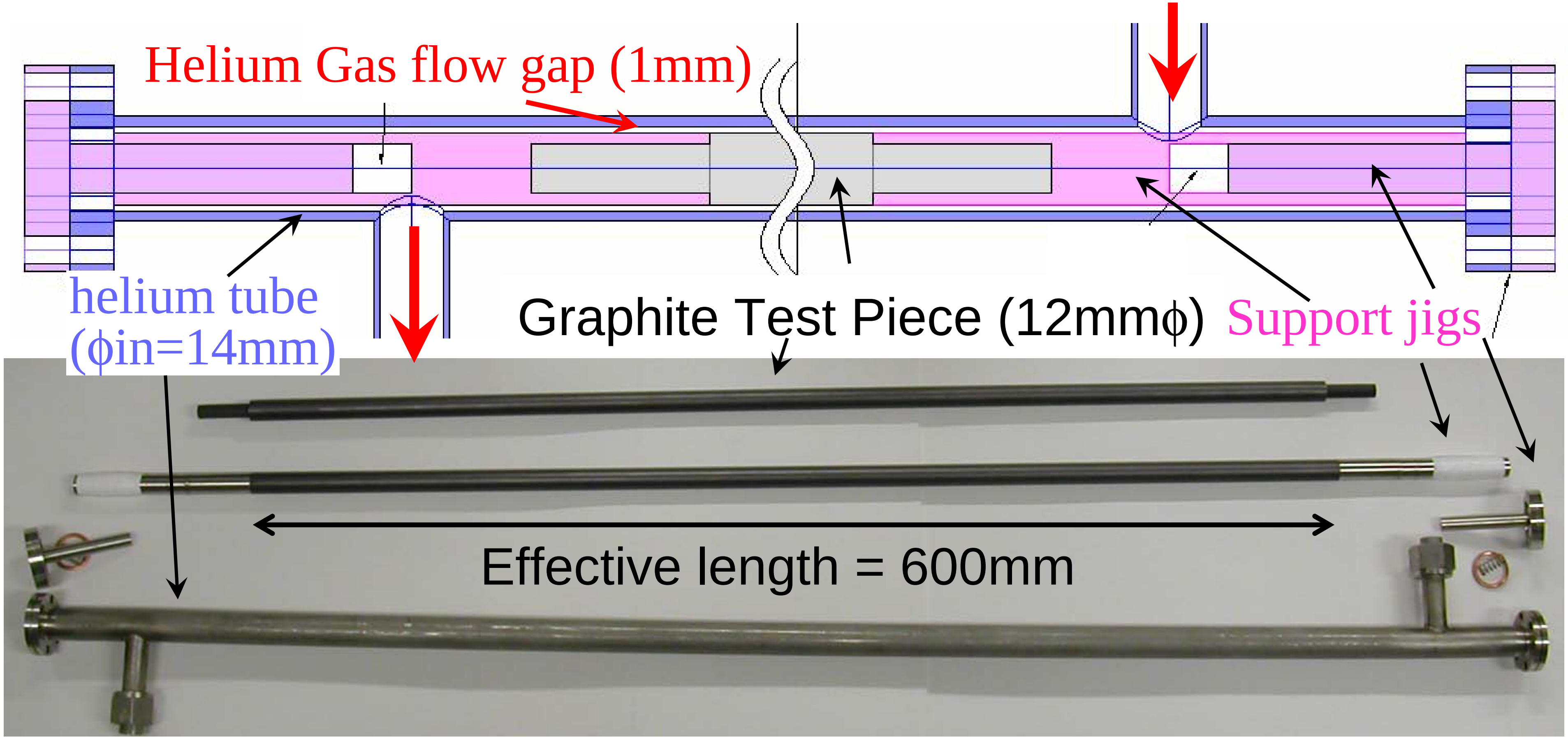


Pipe to connect/disconnect the swagelok connection remotely.

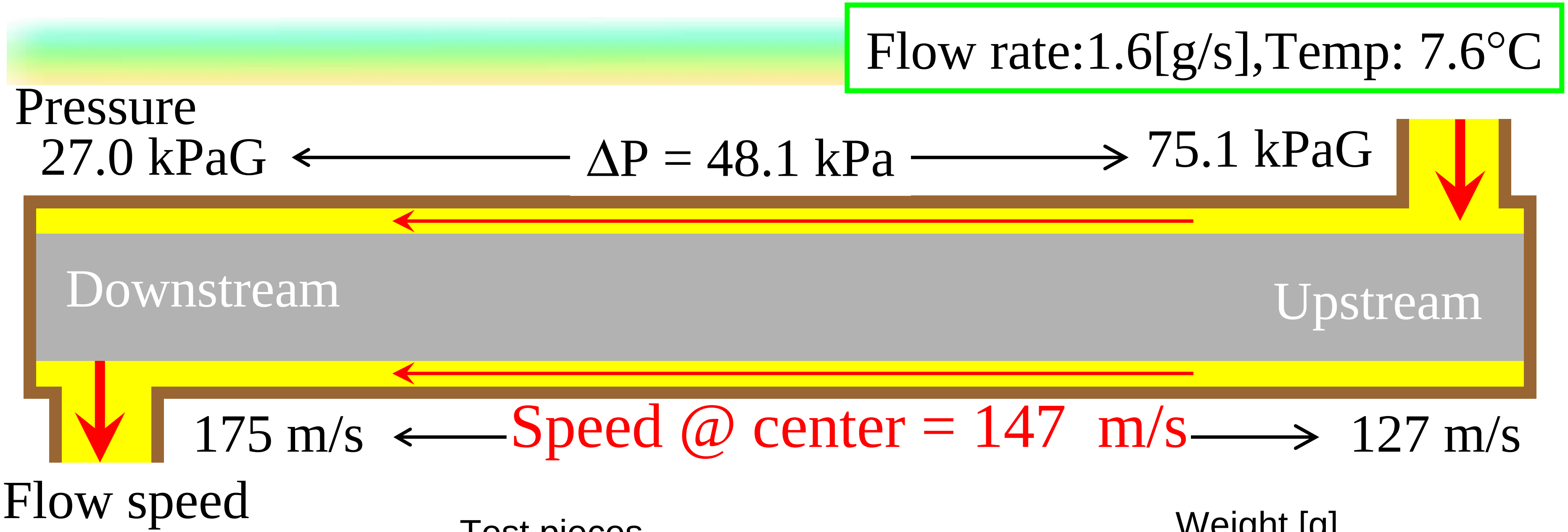


Measurement of erosion

- Measure the weight of the graphite test piece before and after exposing to the helium gas flow @ RT.
  - Helium flow direction is parallel to the graphite surface.



Test result … Effect is small!



	Test pieces (Run time: 167h 51m)	Weight [g] Before	After
1	Exposed to Helium gas flow	129.66	129.65
2	Control samples	129.63	129.62
3		129.81	129.80
4		129.90	129.89

Mass reduction rate / (surface/volume) < 4.1 [mass %/year/m]

→ Expected mass reduction for target < 0.15 [mass %/year] ,

by assuming the erosion effect ∝ (mass flow/cross section)^2

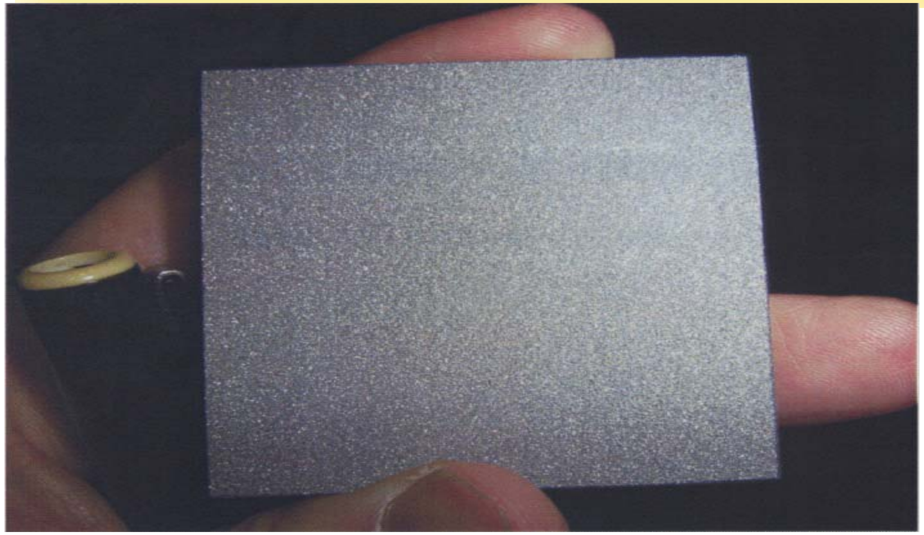
Summary

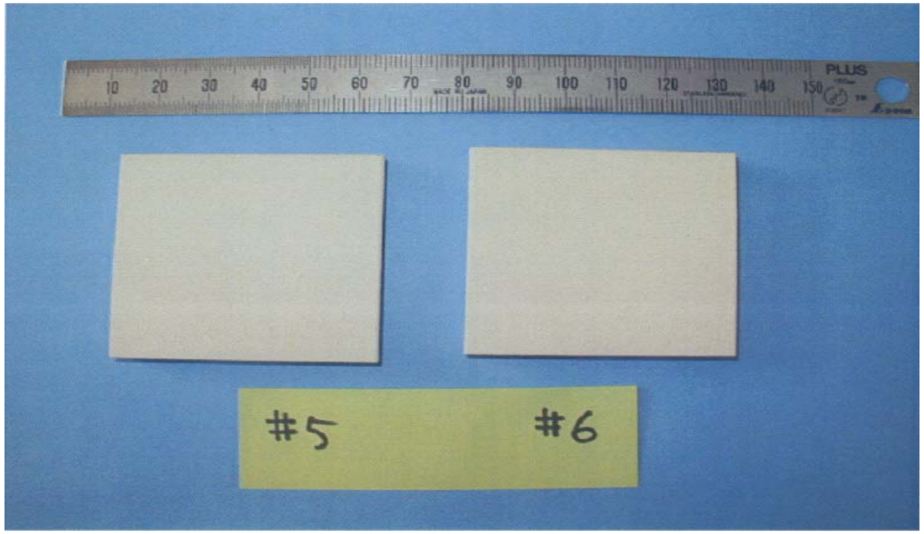
- Target design
  - Diameter 30mm → 26mm
  - Graphite parts should be covered by Ti-Alloy to reduce the oxidization.
- Target prototype
  - Prototypes of Ti-Alloy tube and the downstream beam window are made successfully.
  - Graphite–Ti-alloy brazing is strong enough @ 600°C.
  - Plasma-splayed Alumina ceramic coated with SiO_2-TiO_2 based sealing material is the candidate for the insulator between the target and 1^{st} horn.
- Helium circulation system
  - Helium compressor system is built.
  - 1^{st} heat exchanger is designed.
  - Erosion effect by high speed helium gas is expected to be small.
- Plan
  - JFY 2006
    - Prototype with the almost final design
    - Full scale test of He-gas cooling (~20kW)
  - JFY2007
    - Production of actual equipment → Install in 2008 autumn.

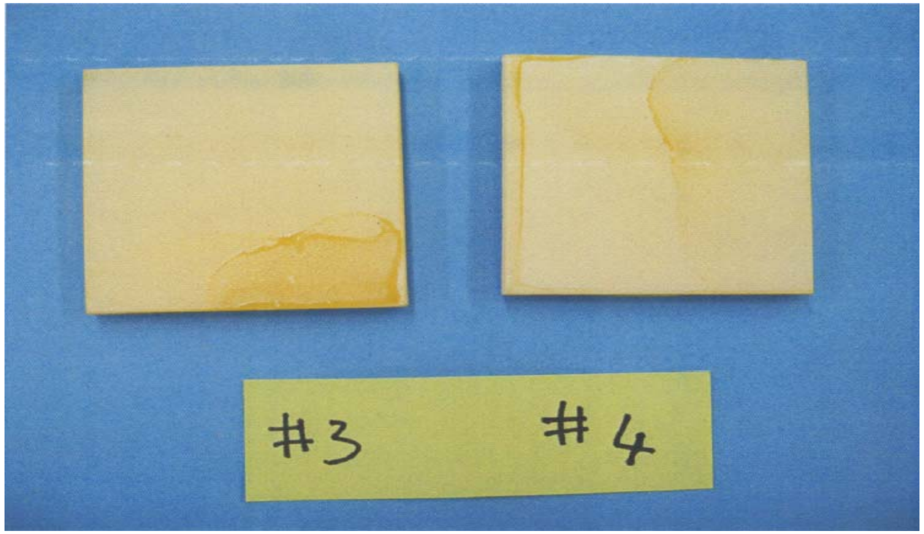
Backup

Plasma-splayed ceramics

Samples for measurement of the withstanding voltage @ KEK



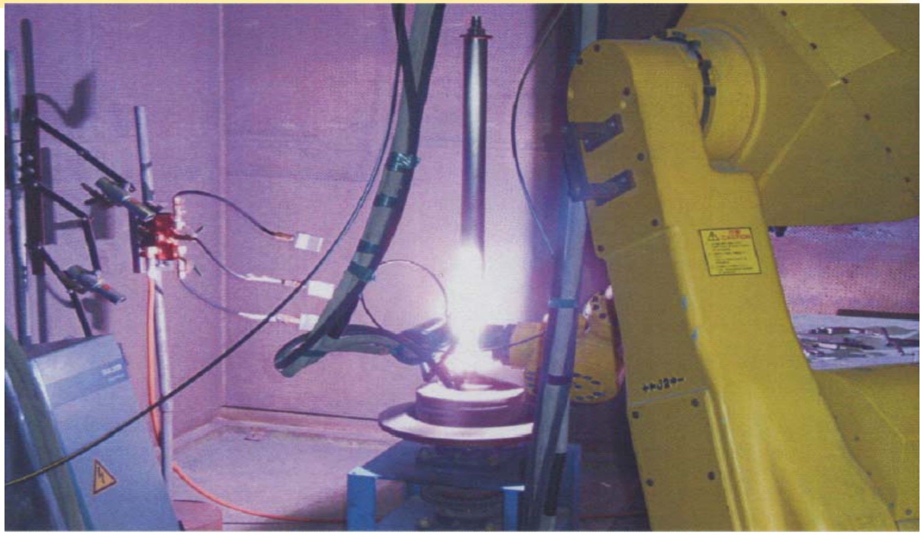




Surface coating for the sealing

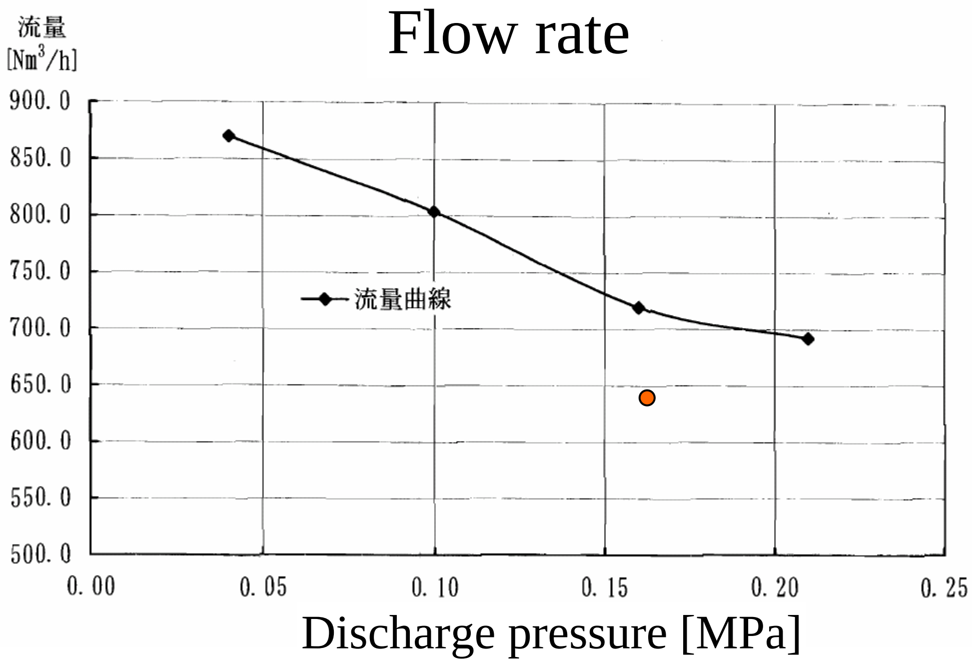
Plasma-splayed ceramics

Samples for measurement of heat resistance @ company.



Helium compressor

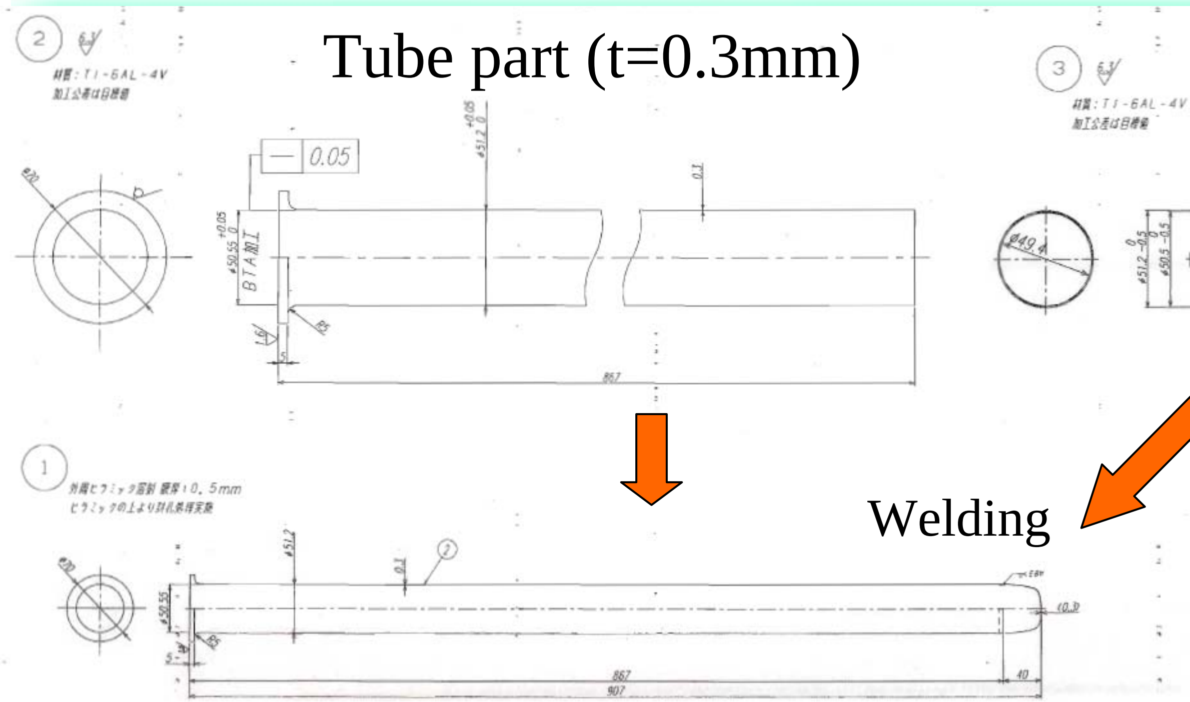
- Standalone operation test of the helium compressor
  - Suction = 0.01MPa, Discharge pressure=0.16MPa
    → Achieved flow rate = 720 [Nm^3/h]
    c.f. Flow rate in spec. is 660[Nm^3/h].
  - Power consumption: 34kW
  - Helium gas leak rate < 1.1×10^{-5}[Pa·m/s]



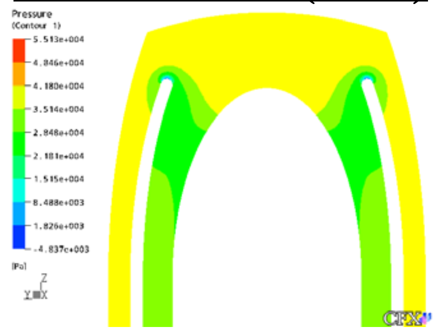
Insulation test of plasma-splayed ceramic

Sealing material	Robustness @ High temp.	Insulation test		
		Atm.	Temp.	Discharge volt.
w/o sealing	O.K	Air	27°C	5.2 kV
	@ 600°C	He	27°C	1.4 kV
Al_2O_3-based	☠	Air	26°C	4.7 kV
	@ 400 °C	He	26°C	0.75 kV
SiO2-TiO2	O.K	Air	25°C	> 6.2 kV
based	@ 600°C	He	26°C	3.1 kV
SiO2-TiO2	O.K	Air	25°C	> 6.2 kV
based	@ 600°C	He	25°C	3.1 kV

Outer Tube prototype



Down-stream shape optimization by J.Butterworth (RAL)

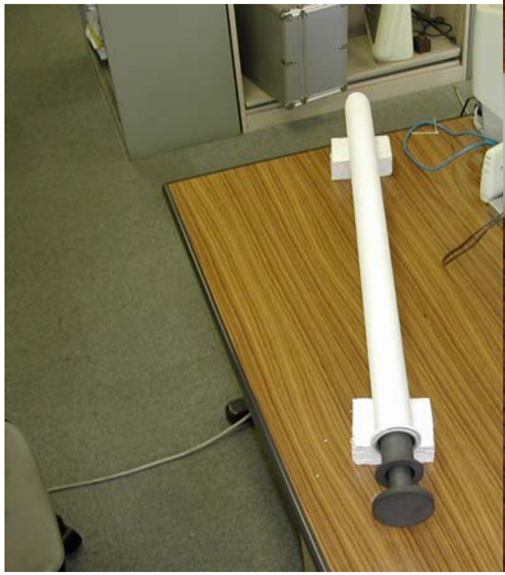


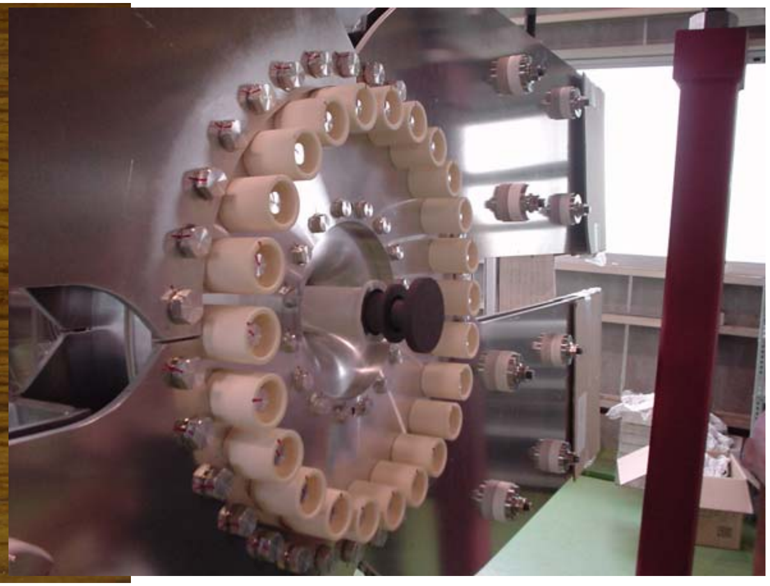
- Ti-6Al-4V (t=0.3mm)
  + Plasma-splayed alumina (Al_2O_3) (t=0.5mm) for the insulation between the target and 1st horn.
- Coating for sealing the pores of alumina on outer surface to increase the withstanding voltage.

Ti-Alloy Outer-tube

Target & Ti-Alloy pipe



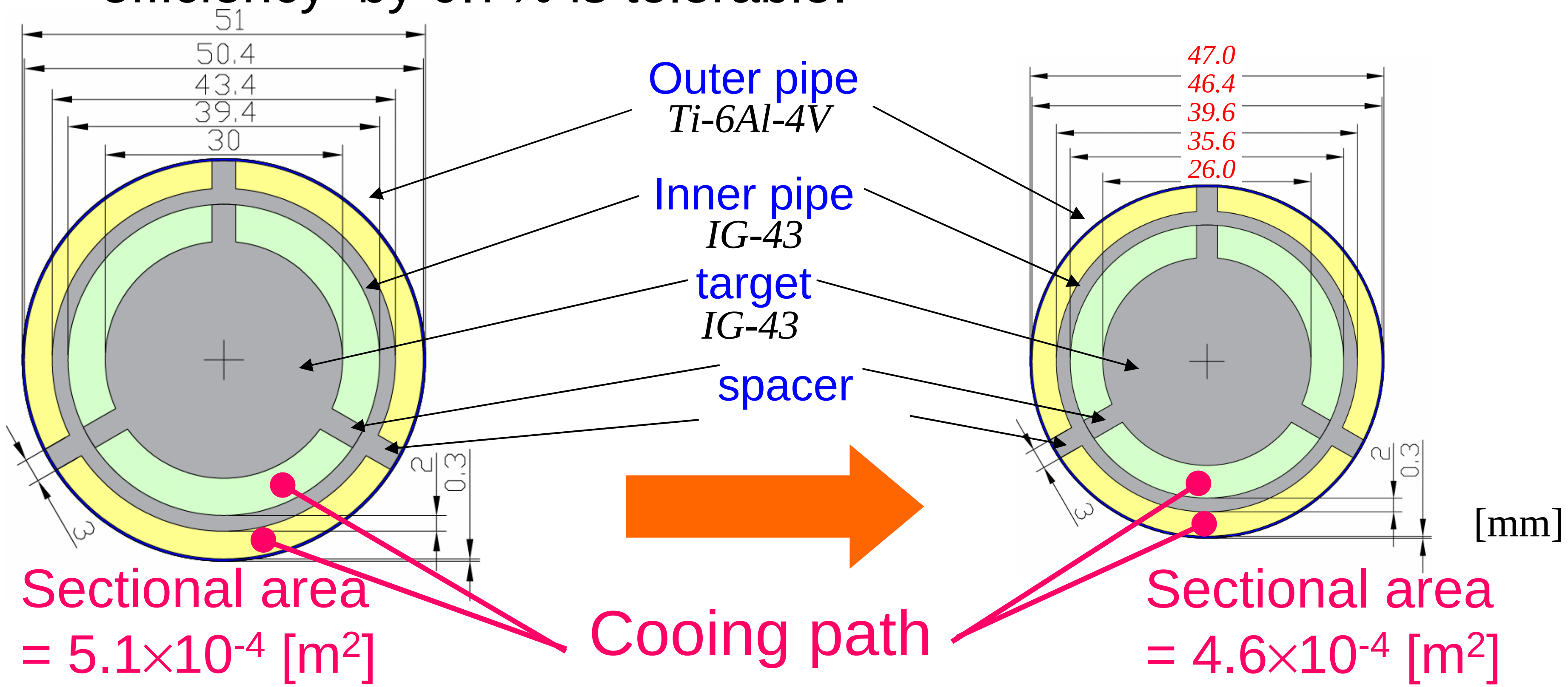





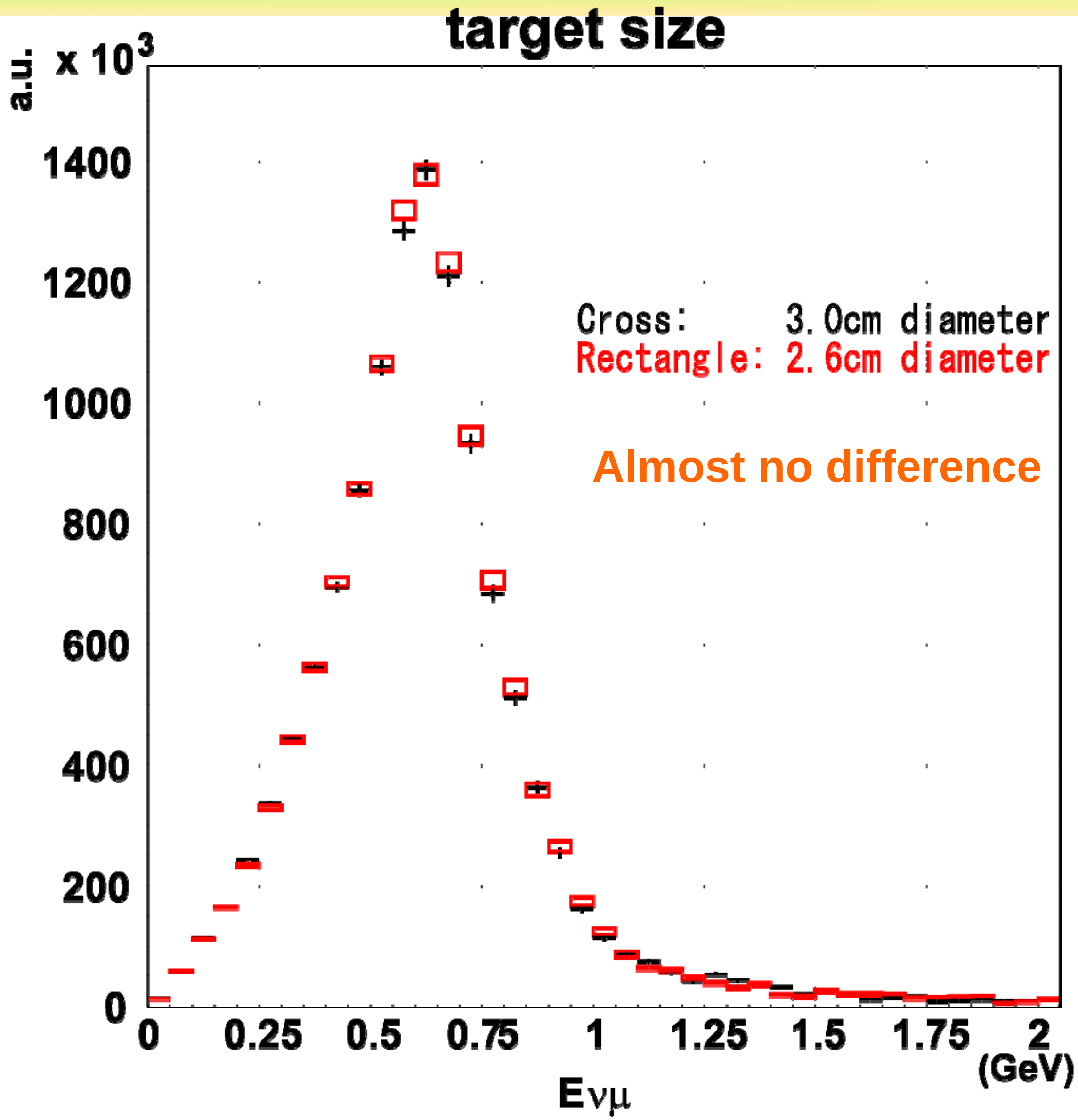
R_{target}	15 [mm]	13 [mm]	
ΔR (target ~ horn)	1[mm]	3[mm]	☺
Energy deposit (30GeV, $\sigma_x = \sigma_y$ =4.24mm)			
Target	44.0 [kJ/spill]	39.3 [kJ/spill]	☺
Inner Pipe	3.5 [kJ/spill]	3.5 [kJ/spill]	😐
Outer Pipe	1.1 [kJ/spill]	1.1 [kJ/spill]	😐
Insulator	1.6 [kJ/spill]	1.5 [kJ/spill]	😐
Targeting Efficiency For Gaussian beam	99.80% (0.19%loss)	99.09% (0.91%loss)	☹
Helium flow (T_{gas} < 200°C, suction=0.03MPa)			
Cross section	512.4 [mm^2]	459.3 [mm^2]	☠
Flow rate	543 [Nm^3/h]	491 [Nm^3/h]	☺
Avg. speed @ target	237 [m/s]	246 [m/s]	☹
ΔP @straight part+1st hex	0.0884 [MPa]	0.0833 [MPa]	☺

Target dimension

- Clearance between the outer tube and 1st horn
  - Previous design: Δr = 1mm
    → It is difficult to change the target remotely.
  - Reduce the target size by 2mm, if the decrease of targeting efficiency by 0.7% is tolerable.

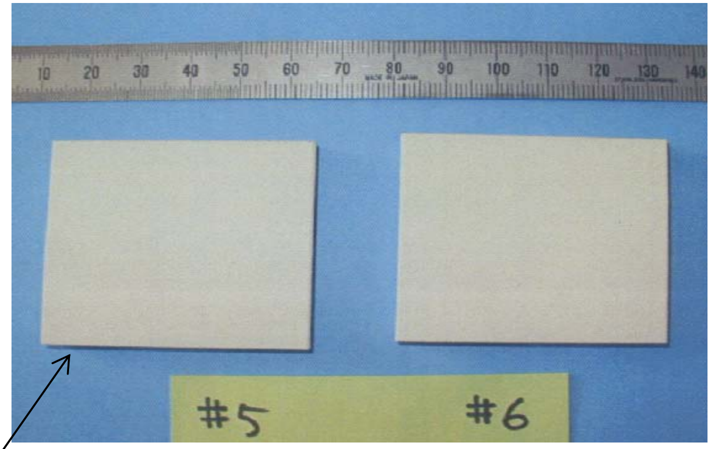


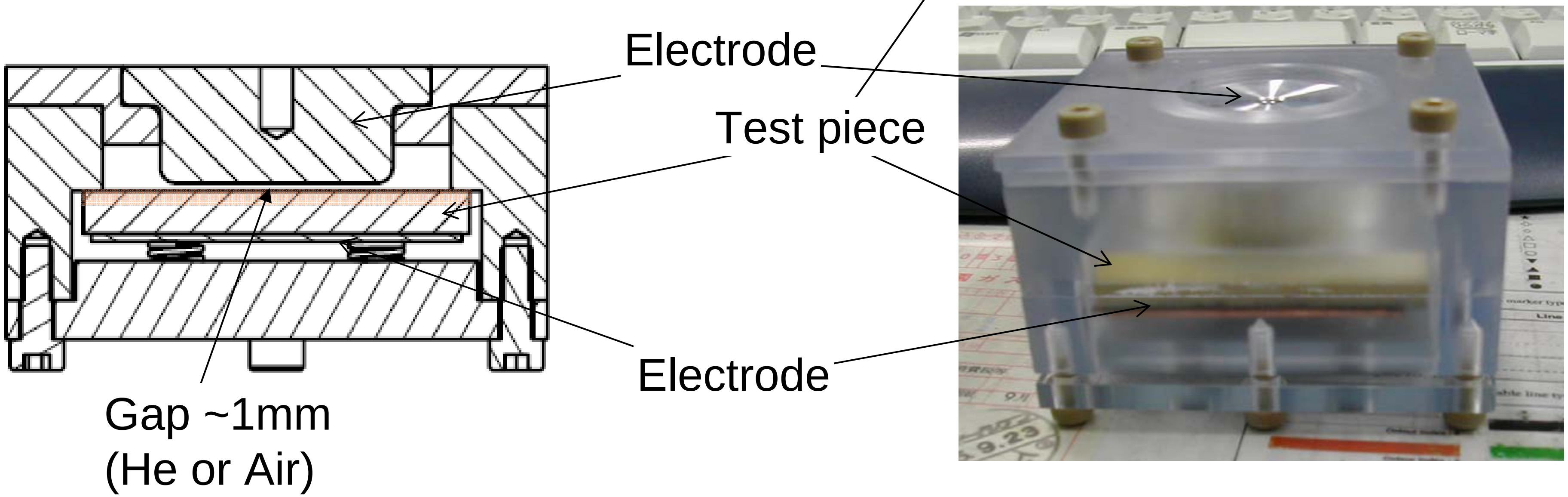
Neutrino Flux: ϕ=30mm vs.. ϕ=26mm



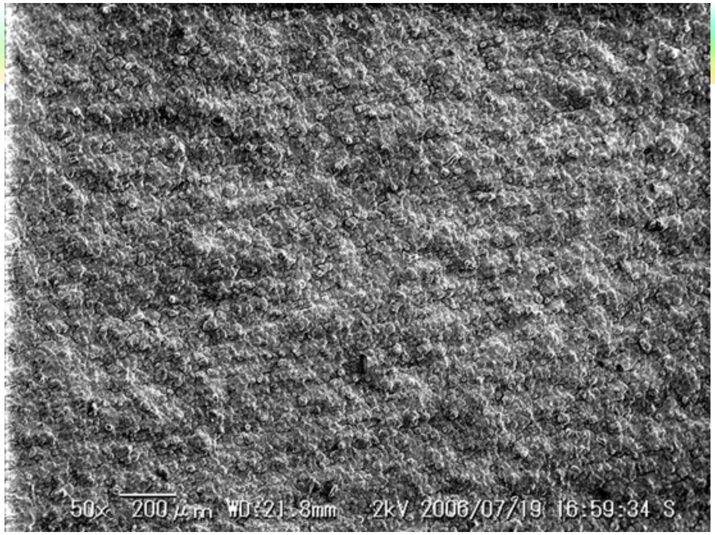
Insulation test of plasma-splayed ceramic

- Apply a DC high voltage to plasma-splayed ceramic across the 1mm gap.
- 2-type of test sample.
  - Ceramic with sealing pores
  - Ceramic without sealing pores.

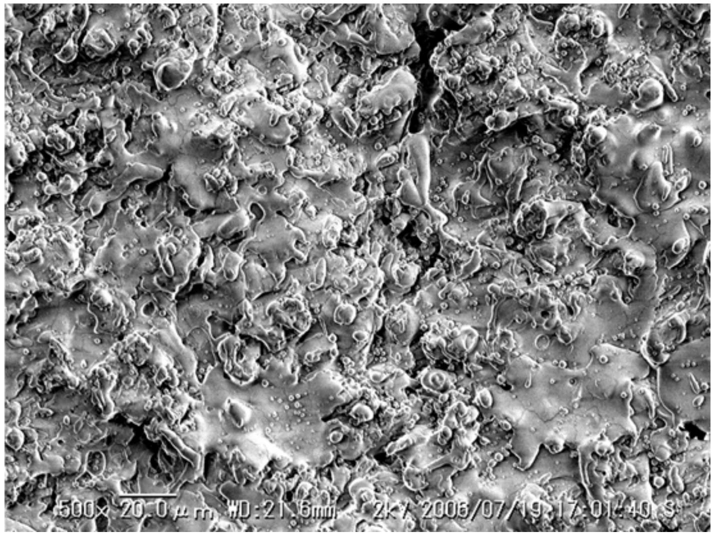




Surface of ceramic layer (SEM)

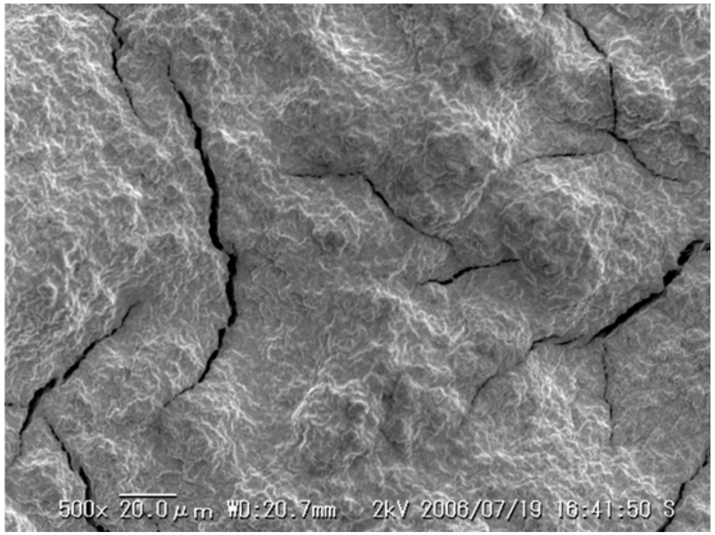


w/o sealing SEM(×50)



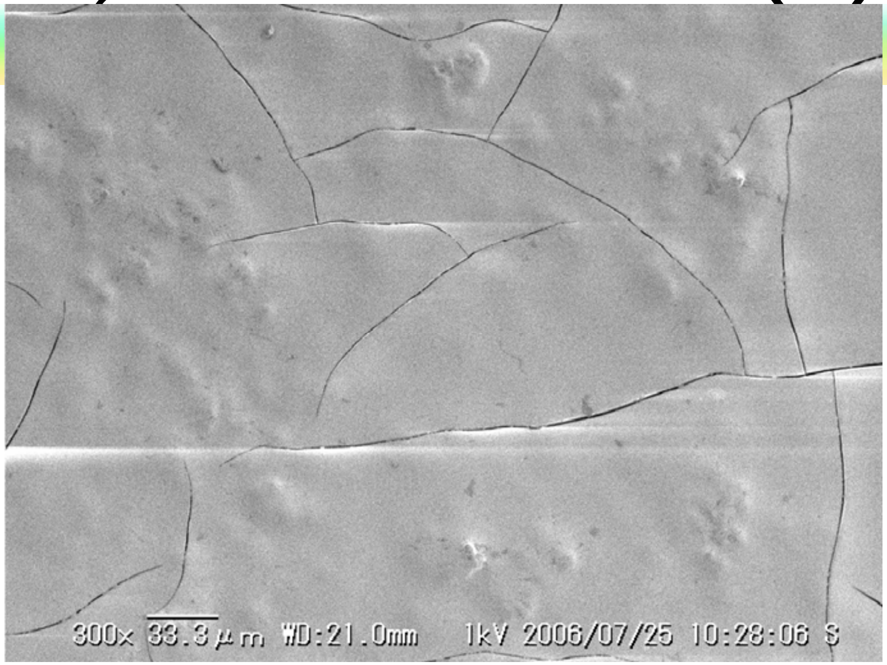
w/o sealing SEM(×500)

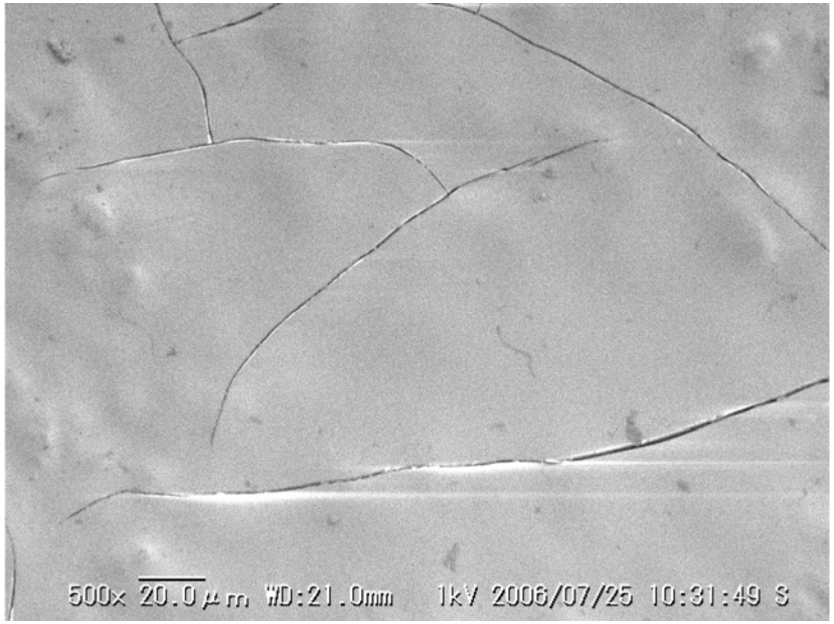
Sealing w/ Al_2O_3-based mat.(×50)



Sealing w/ Al_2O_3-based mat. (×500)

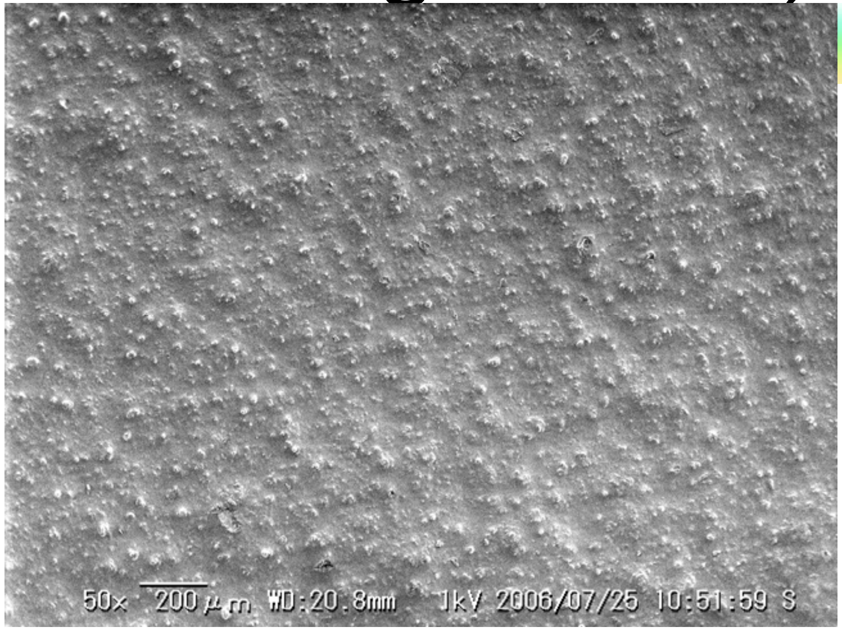
Sealing w/ SiO_2-TiO_2 -based mat. (1)

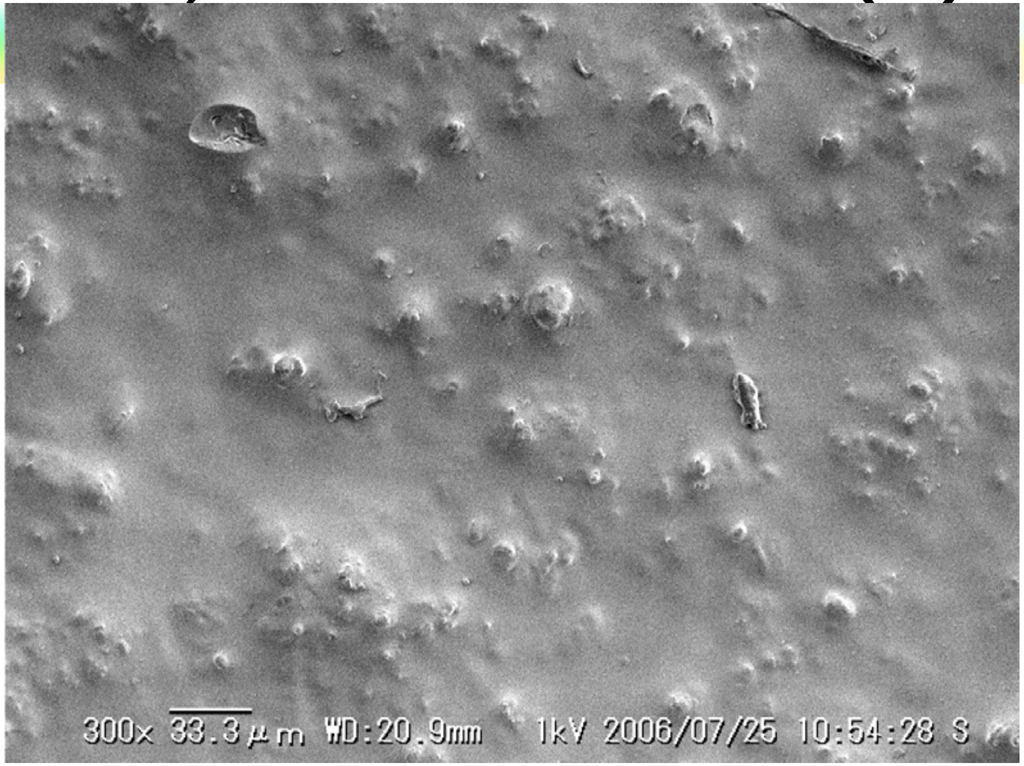


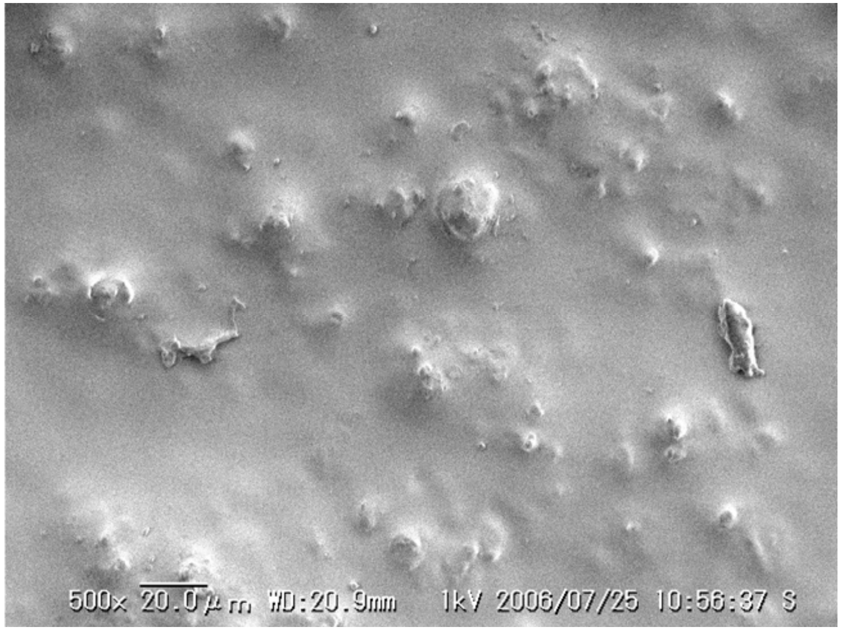


- Pictures by SEM.
- Transparent layer with thickness of ~50μm is observed by an optical microscope.

Sealing w/ SiO_2-TiO_2 -based mat. (2)







- No clack is observed.