Production Target at J-PARC Hadron Experimental Facility

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KEK/J-PARC

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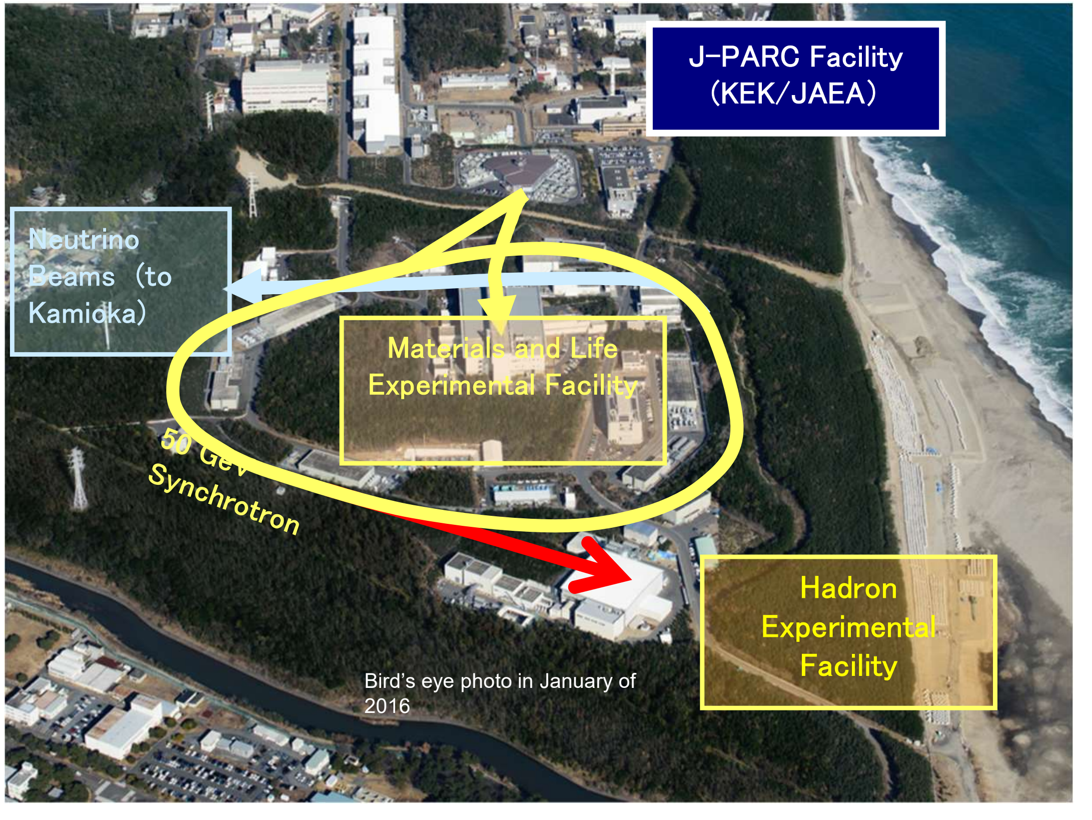
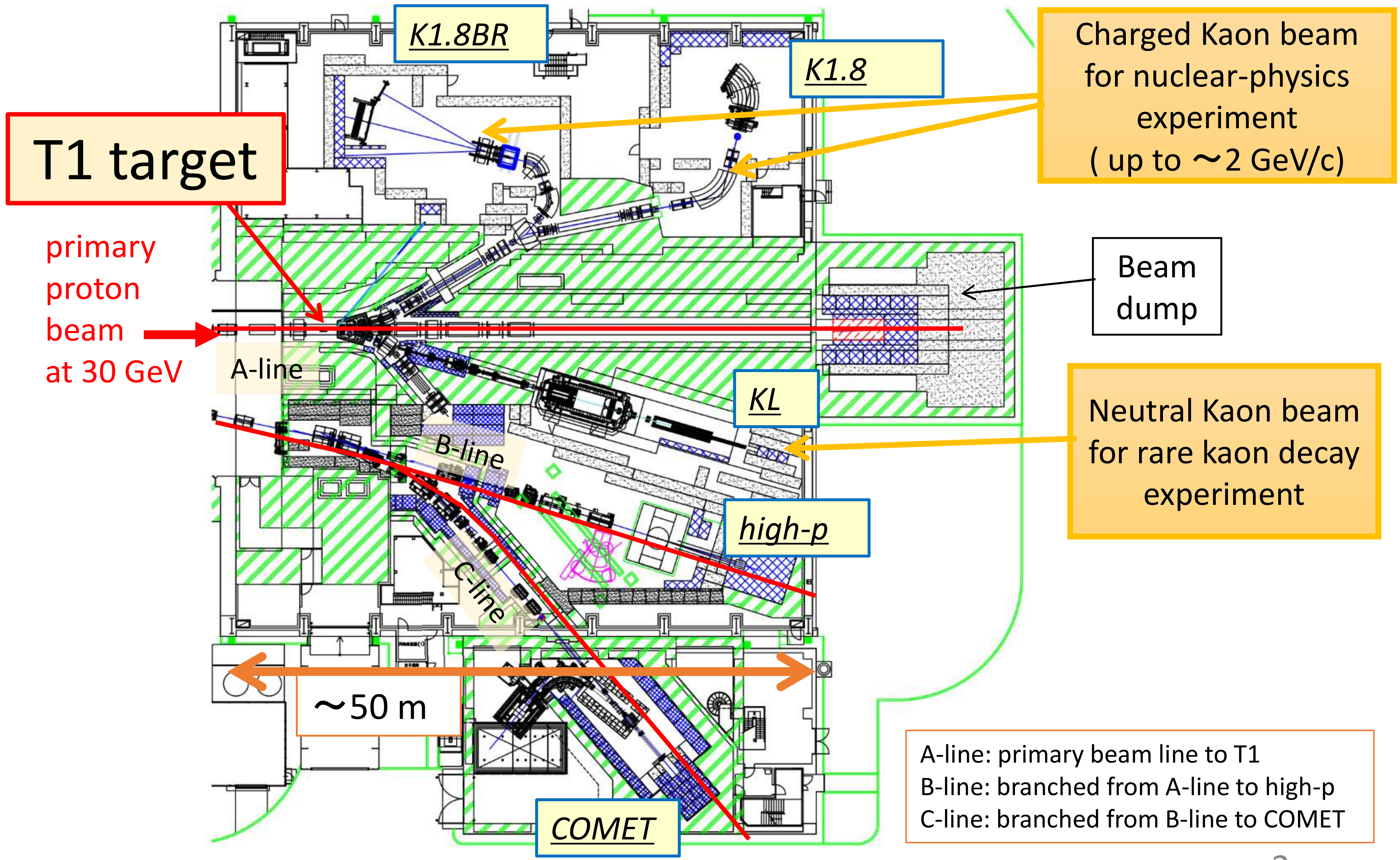
Outline

- Hadron Experimental Facility and beam condition
- Previous and Current Target
- New target development
- Summary



Hadron Experimental Facility at J-PARC

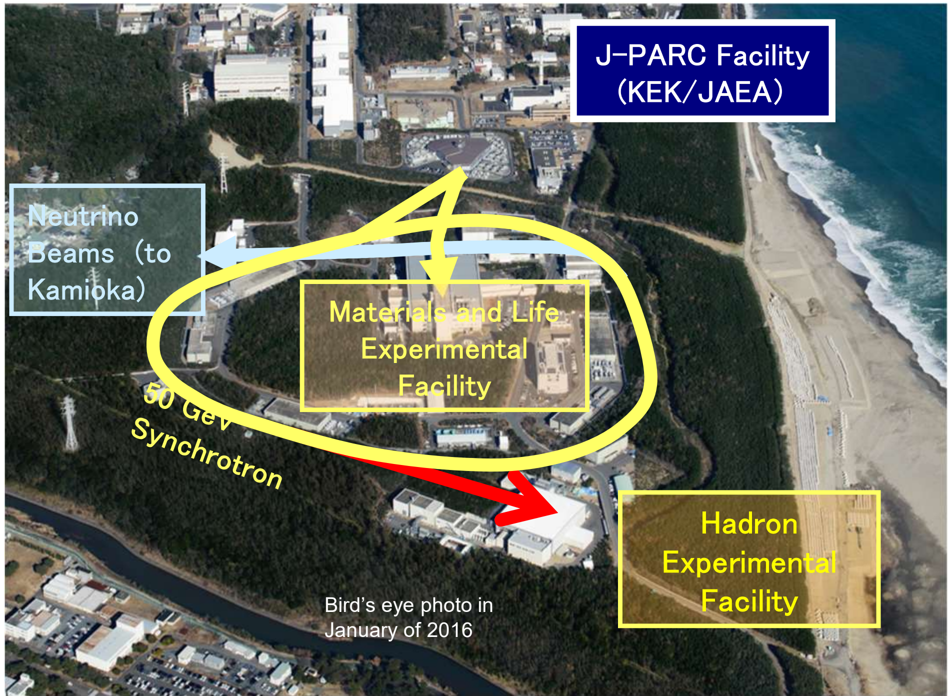


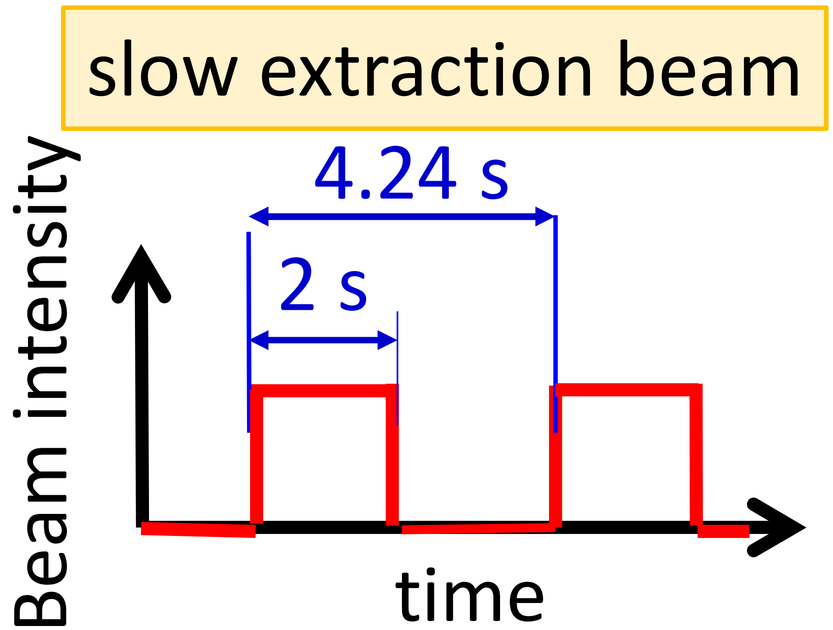
A-line: primary beam line to T1
B-line: branched from A-line to high-p
C-line: branched from B-line to COMET

Beam conditions for T1 target

- Primary proton beam energy: 30 GeV
- Spill structure: 2-s DC extraction and 4.24-s repetition cycle
- Beam size at T1: $\sigma_H \sim 2.5$ mm, $\sigma_V \sim 1.0$ mm
- Beam loss at T1: 50% (max.)
- Beam-direction length of T1 : 66 mm (max.)

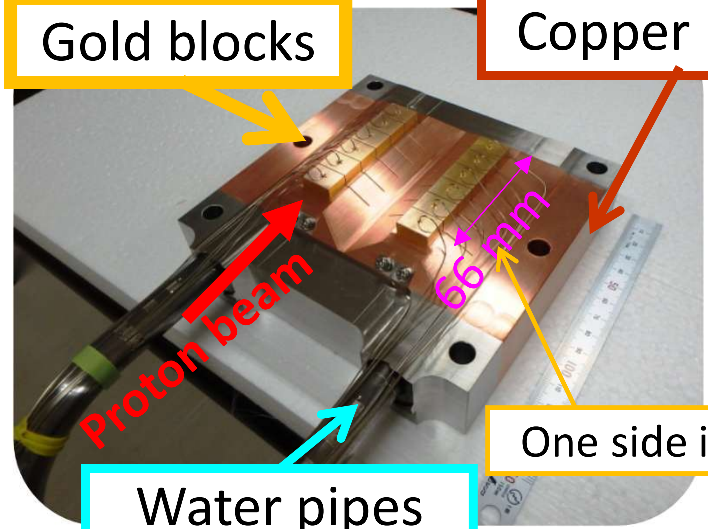
  (Secondary beamline optics determined the beam size and the length)

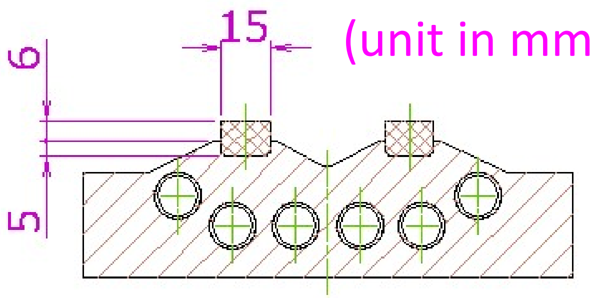




Previous and current production target
→Indirectly Water-cooled Fixed type

Previous target

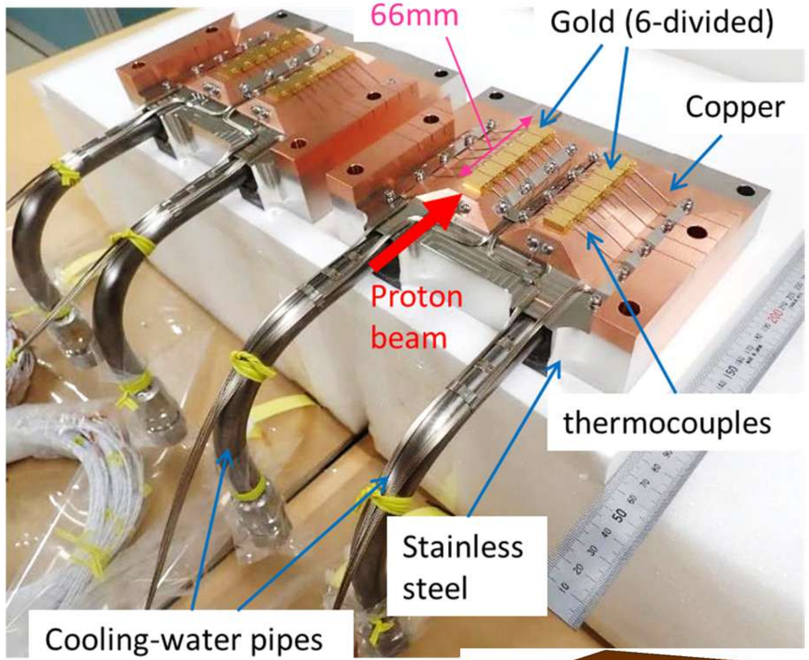


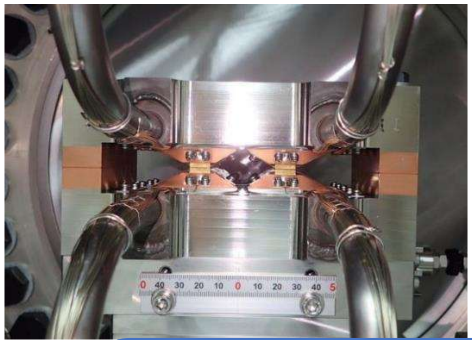


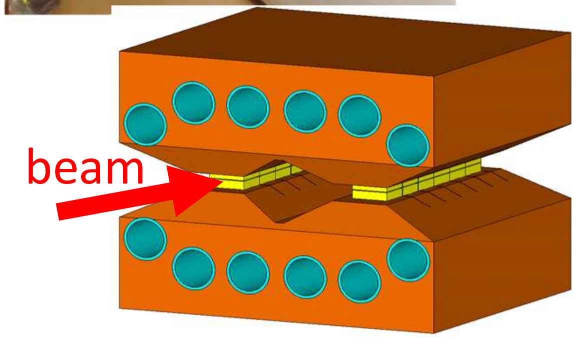
Up to 53 kW beam power.(41 kW in average)
Operated during 2014～2019.
In total, 1.5E+20 protons on target.
7.4 DPA estimated by PHITS (arc-dpa model). 3.1E+10^6 spills.
No damage was observed.

Current target (in service)

Phys. Rev. Accel. Beams 25, 063001



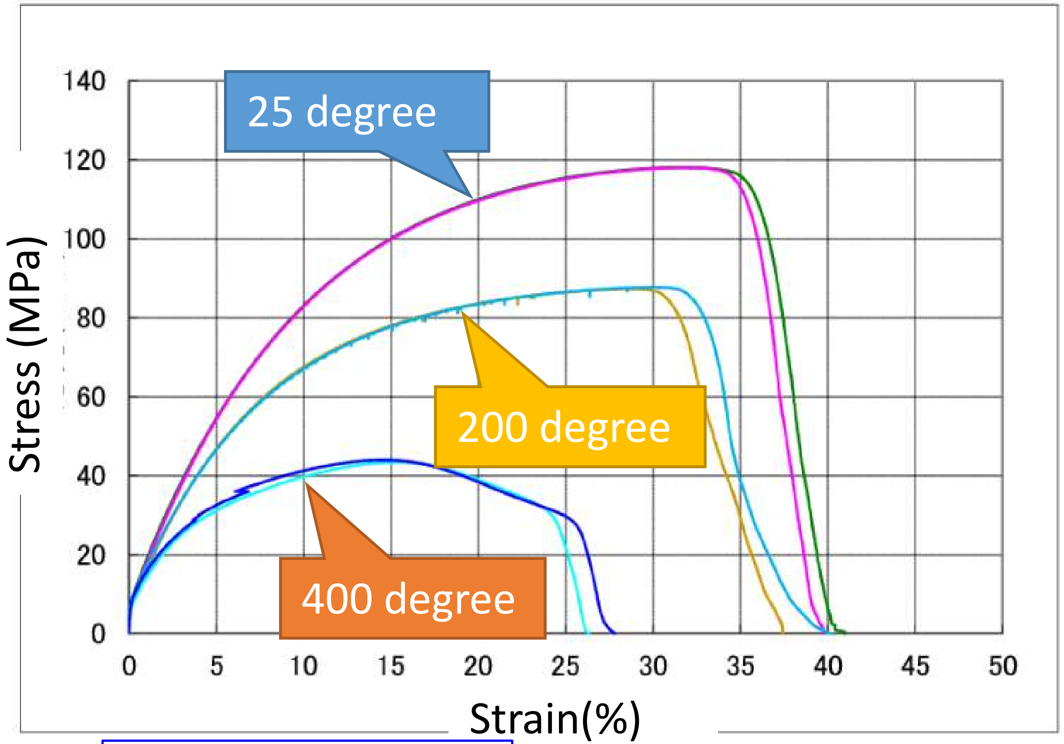


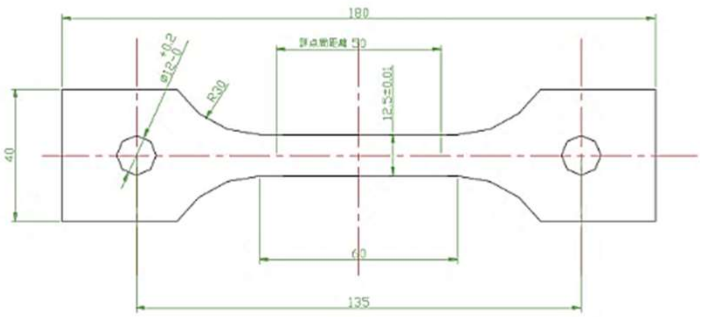


Up to 115 kW beam power (4.24s-cycle).
375°C in gold is expected for 115 kW.
92 kW stable operation was achieved.
As of now, 1.6E+20 protons on target.

Evaluations for Gold Target

We measured strength and stain-stress curve of bulk gold at high temperature by tensile tests





Temp (°C)	Tensile strength (MPa)	Yield strength (MPa)
25	118	8.6
200	87	7.8
400	43	7.6

The bonding strength between gold and copper was measured to be higher than the above values by shear tests.

Allowable stress

- thermal stress: $S_M \times 3$
- low-cycle fatigue (continuous ope.): 10^4 fatigue strength/2
- high-cycle fatigue (shot by shot): 10^7 fatigue strength/2

safety factors

design stress intensity $S_M = \min(S_B \times 0.85/3,\ S_y \times 0.85/1.5)$

S_B: tensile strength, S_y: yield strength

limit for welded pipes in JIS-B8266 (pressure-vessel standard)

10^4 fatigue strength: tensile strength/2

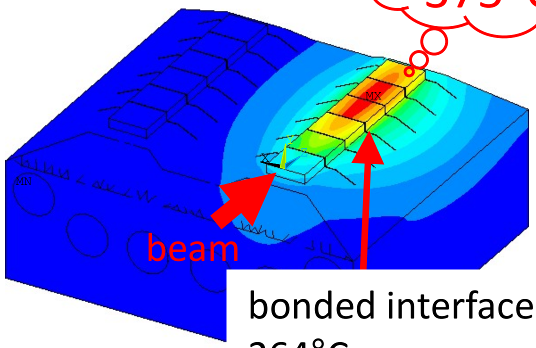
10^7 fatigue strength: tensile strength/3

fatigue strength of gold in literatures:
≈ tensile strength × 0.7 (@10^4)、× 0.4 (@10^7)

Results of Thermal Analysis for Current Gold Target in service (**Phys. Rev. Accel. Beams 25, 063001)**

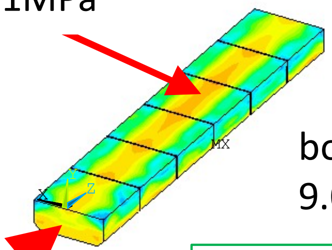
95 kW (5.2-s cycle)

temperature



* only lower block is shown

von Mises stress



Allowable stress:
13.2 MPa (@264°C)
13.0 MPa (@375°C)

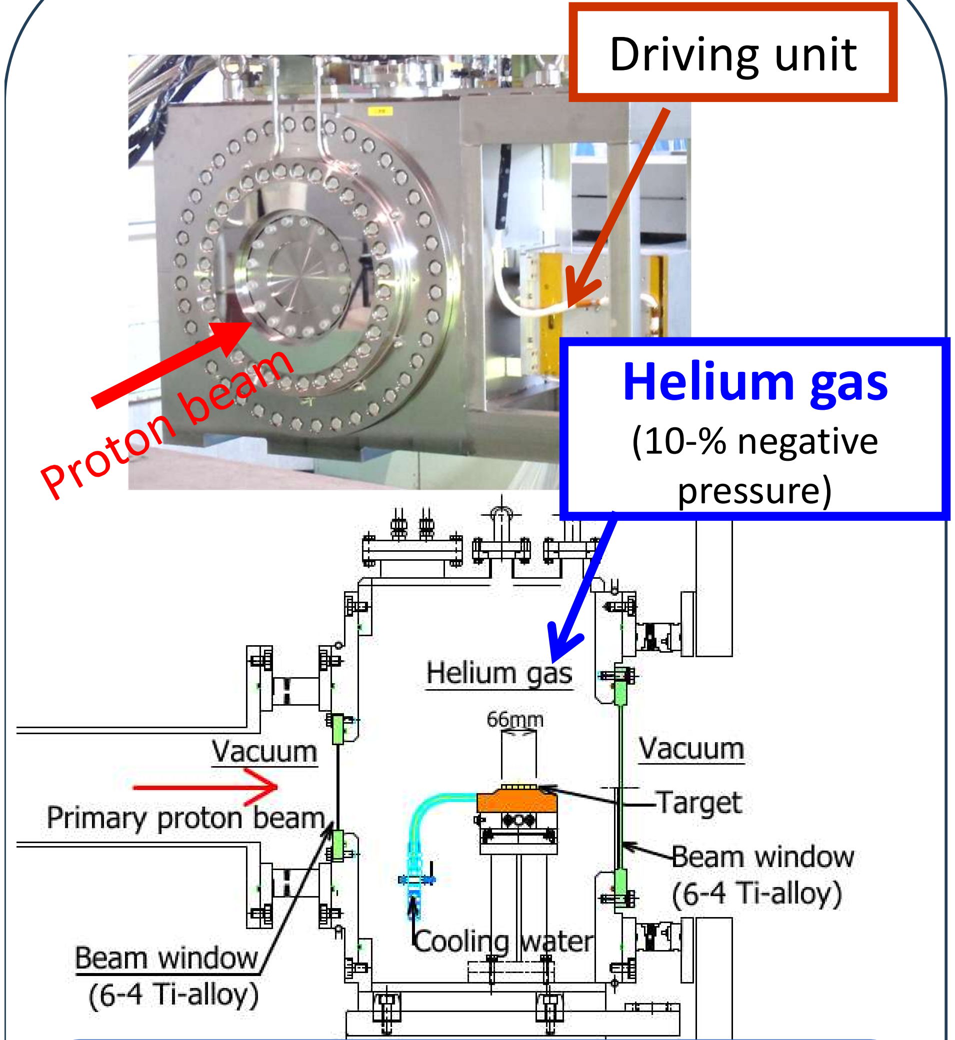
	Case	Estimated stress	Allowable stress
Gold (375°C)	Thermal stress	8.1 MPa	13.0 MPa
	Equivalent stress amplitude on high-cycle fatigue (shot by shot)	7.9 MPa	8.1 MPa
	Equivalent stress amplitude on low-cycle fatigue (continuous ope.)	8.2 MPa	12.2 MPa
Bonded Interface (264°C)	Thermal stress	9.0 MPa	13.2 MPa
	Equivalent stress amplitude on high-cycle fatigue (shot by shot)	9.0 MPa	12.2 MPa
	Equivalent stress amplitude on low-cycle fatigue (continuous ope.)	9.2 MPa	18.3 MPa

* For 97kW beam, stress amplitude on high-cycle fatigue (8.0MPa) exceeds the limit (7.5MPa) (gold temp.: 394°C)

Max beam power is 95 kW at 5.2s cycle (115 kW at 4.24s cycle)

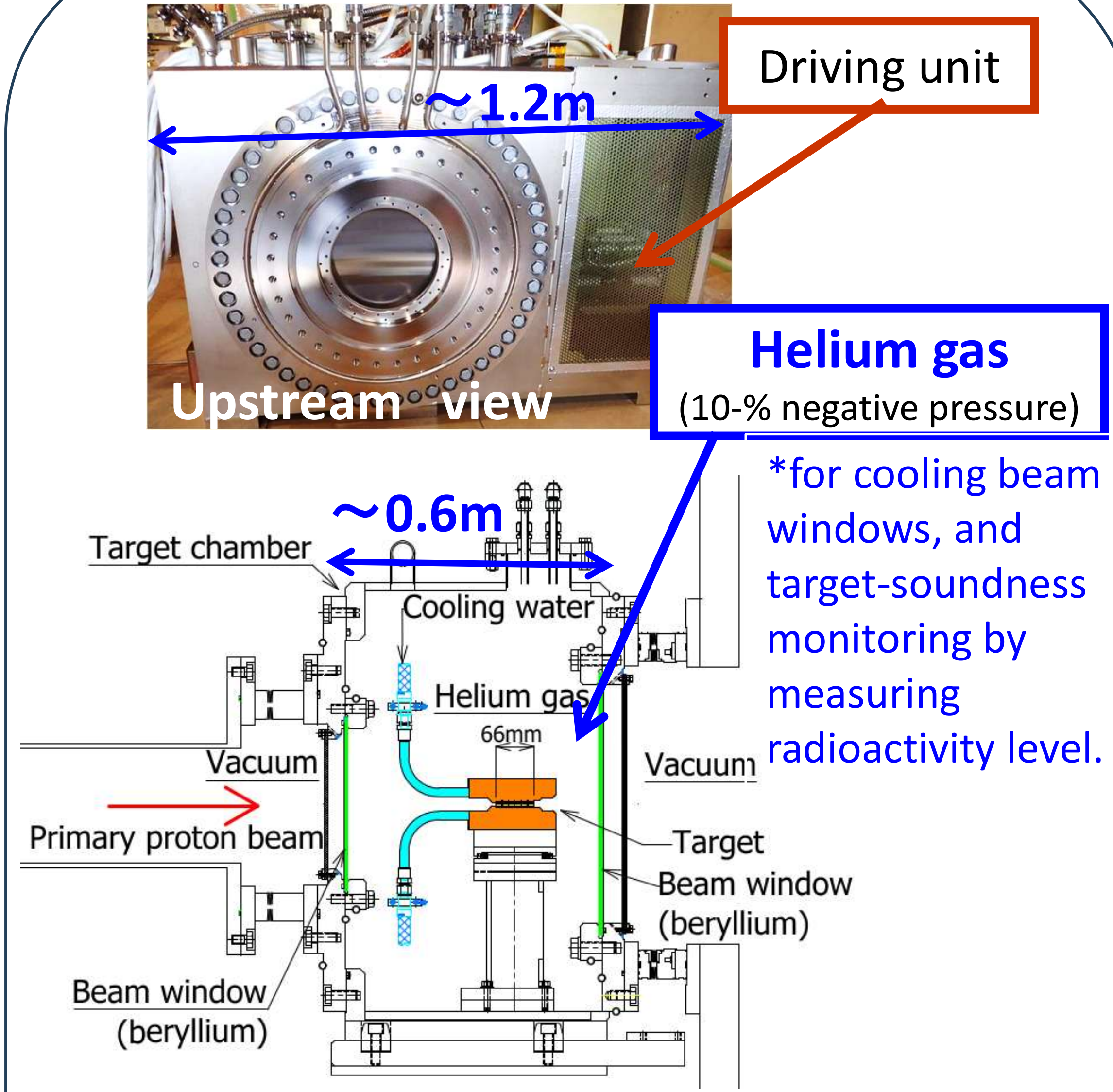
Previous and current target chamber (gas-tight chamber)

Previous target chamber



In total, 1.5E+20 protons on target.
Before replacing, the driving system was confirmed to work properly .

Current target chamber (in service)

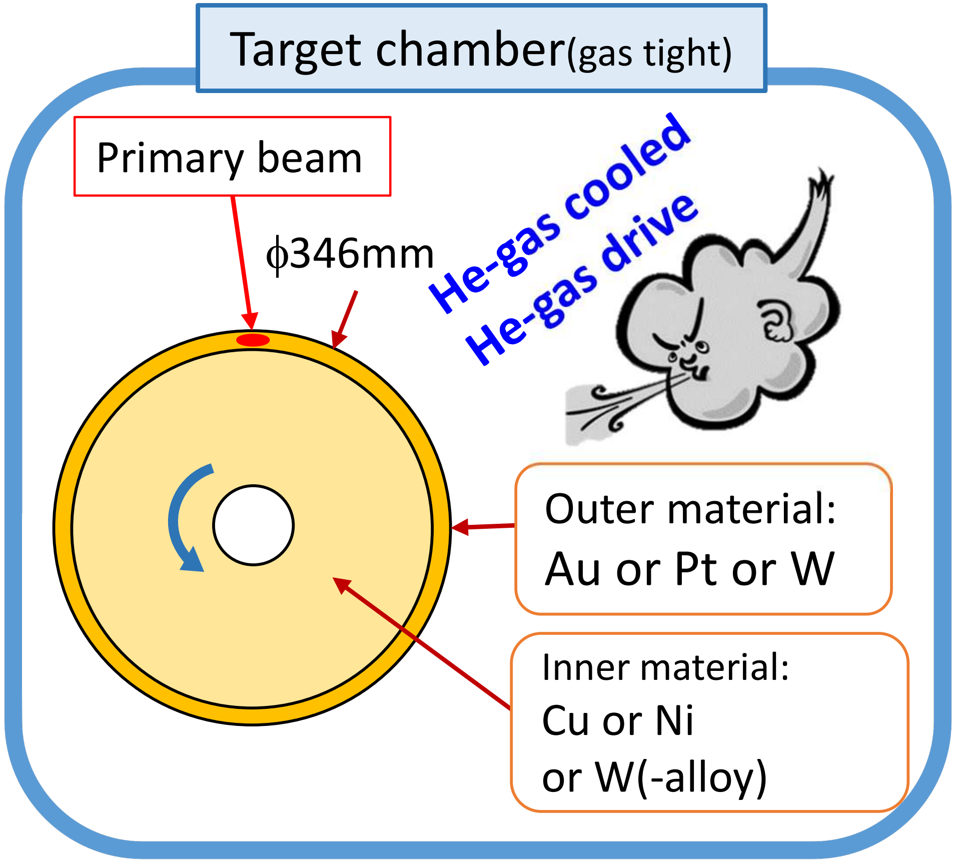


Up to 115 kW beam power (4.24 s cycle).
As of now, 1.6E+20 protons on target.

New Target Development

Next Production Target ～Conceptual Design～

→ Directly He-gas-cooled Rotating-disk type

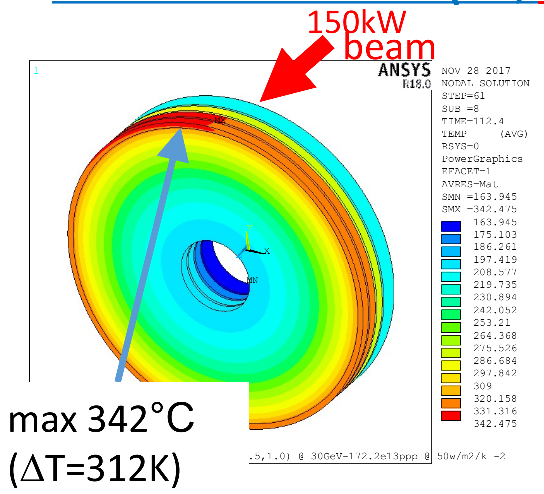


- Rotating disk: heat load and radiation damage can be distributed in larger areas.

Max. beam power: 150 kW (plan)

→For Gold, ～0.5 DPA by 5 years of operation.

Thermal calculation (Au, 150-kW) *Preliminarily



Assuming 50 W/m^2/K .
(Geom.: 4 separate flat disks)

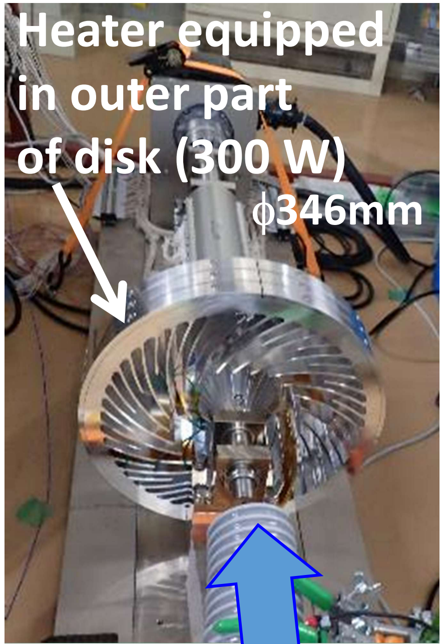
He-gas rotation drive like wind turbine is planned for rotation.

→ Hermetic rotation feedthrough and electric motor are unnecessary (→better reliability)

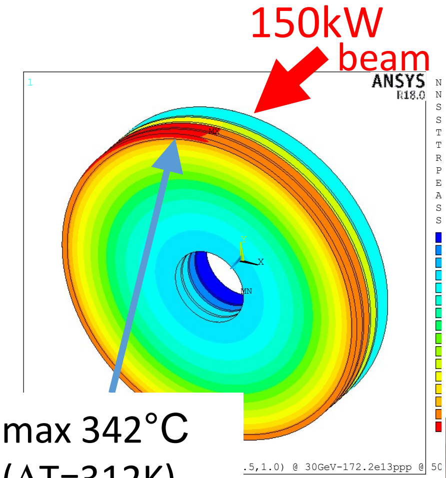
Engineering points:

- ✓ Sufficient cooling capability by He gas
- ✓ Fabrication of the complicated disk
- ✓ Rotating system :
  - ✓ Bearing lifetime (>5-years)
  - ✓ Sufficient rotation torque by He gas

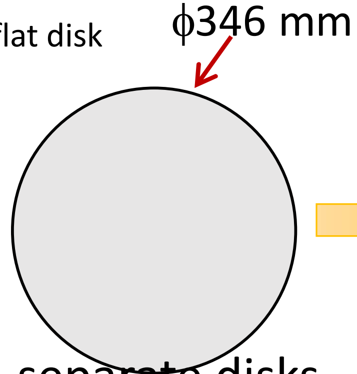
Cooling capability measurement by test bench (in air)

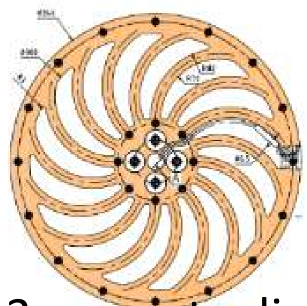


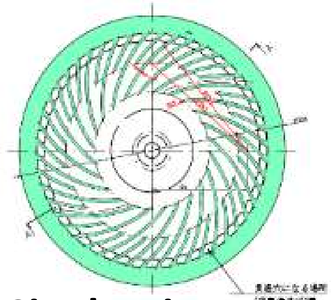
Temperature-controlled air



equivalent to ΔT=13K in test bench from the difference of coolant (He/air) and heat deposition



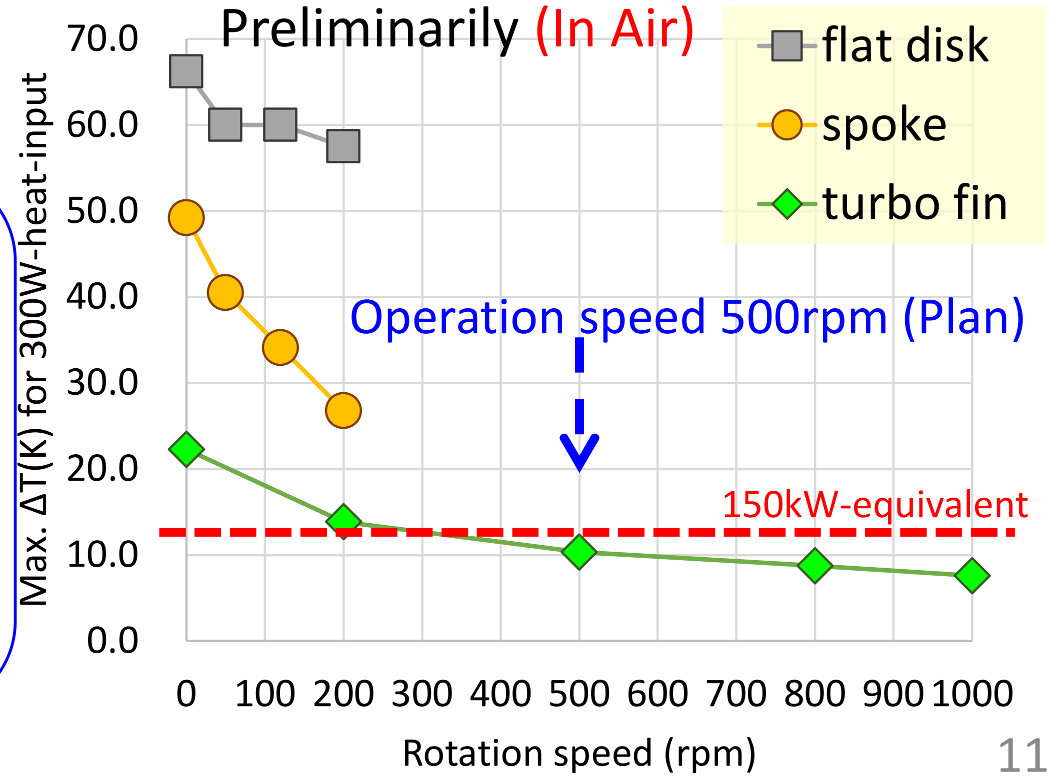




3 separate disks

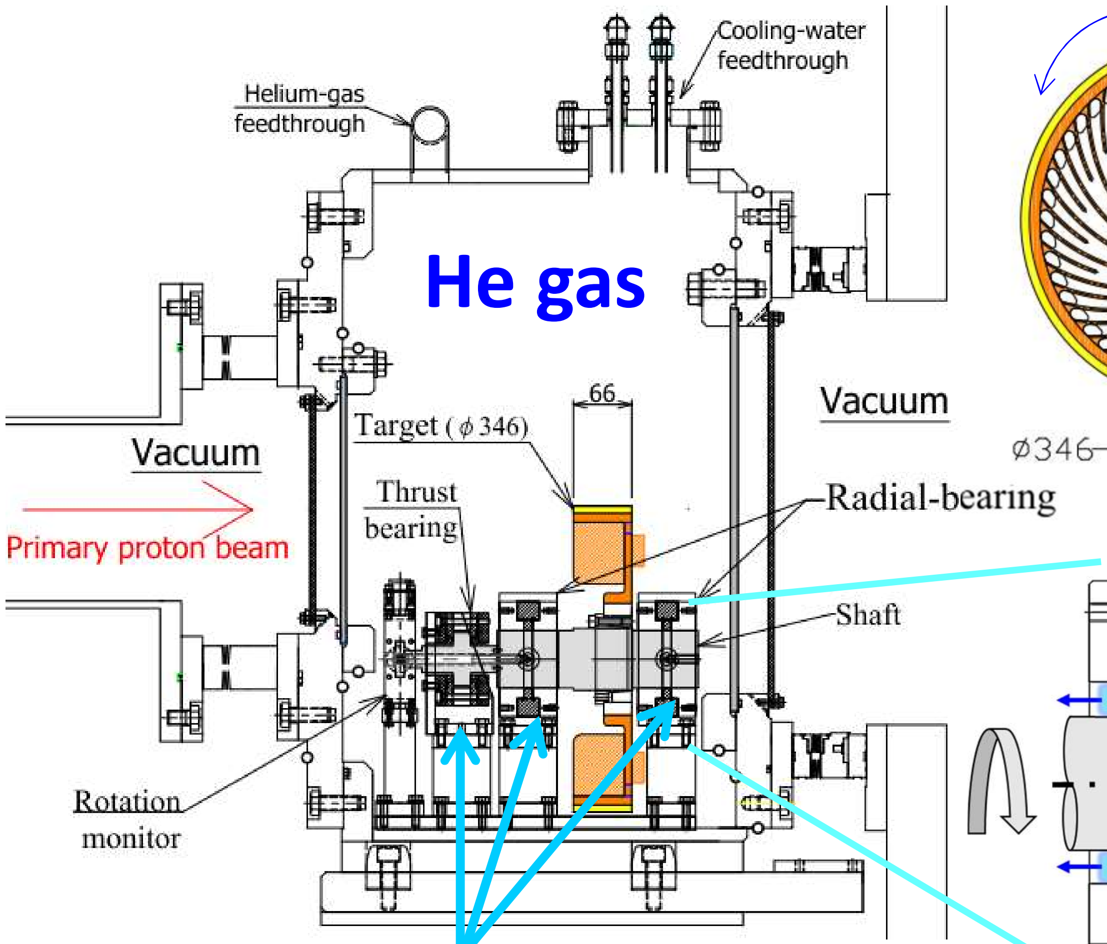
3 separate disks

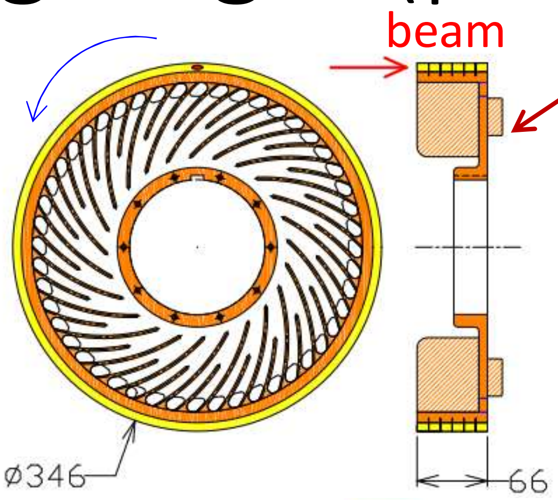
Single-piece disk



- ✓ The cooling capability of the turbo-fin shape at 500 rpm seems good enough for 150-kW beam operation.
- ✓ Also, direct measurements in helium gas were performed. The coolant difference was seen, and the criteria seem reasonable.

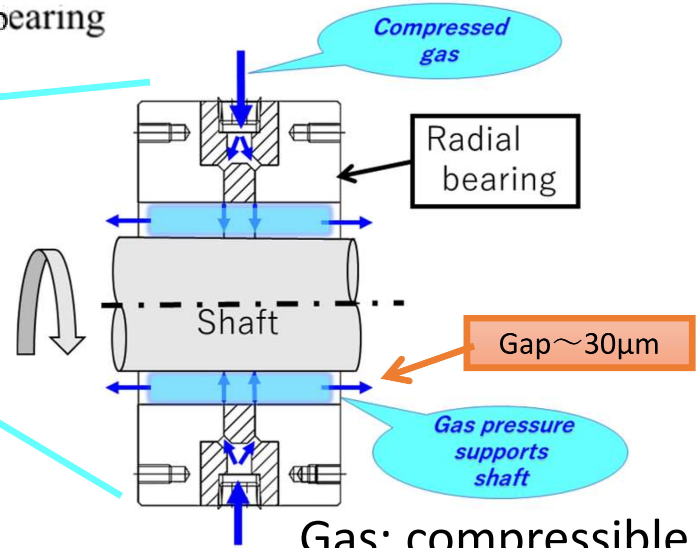
Design of the rotating target (plan)

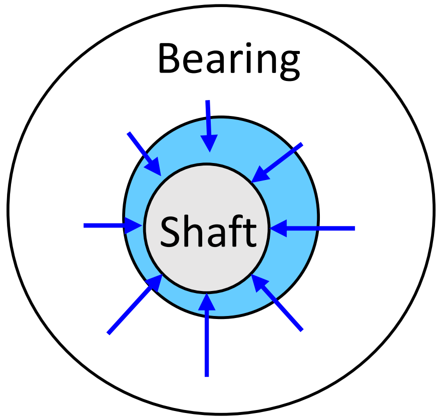




16 fins for rotation drive by He-gas blow

Diameter: 346 mm
Disk weight (including shaft):
～42 kg (Au+Cu disk)
～49 kg (W disk)





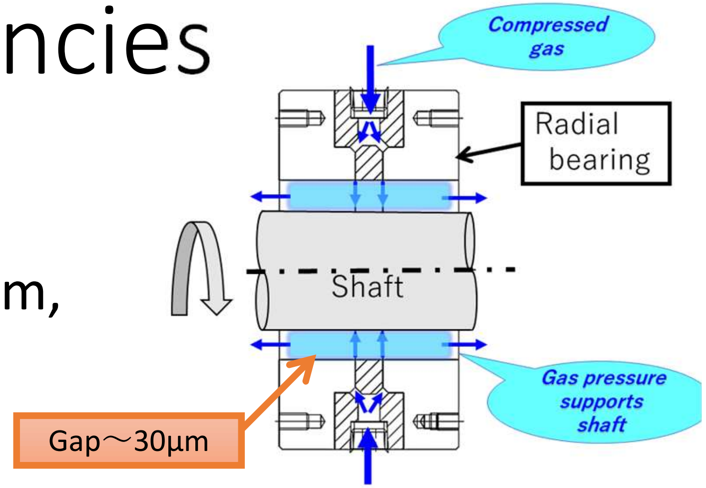
He-gas-lubricated bearing

Gas: compressible fluid→low stiffness

- ✓ Higher rotation speed is acceptable.
  (cf. rad-hard ball bearing: max. 330 rpm)
- ✓ No lifetime for stable operation.
  (cf. rad-hard ball bearing:
  5600 hours at 330rpm for Gold+Copper disk)

＊The robustness of the rotation system with the gas bearings should be checked, especially for emergencies; big earthquake or power outage (gas-supply stop).

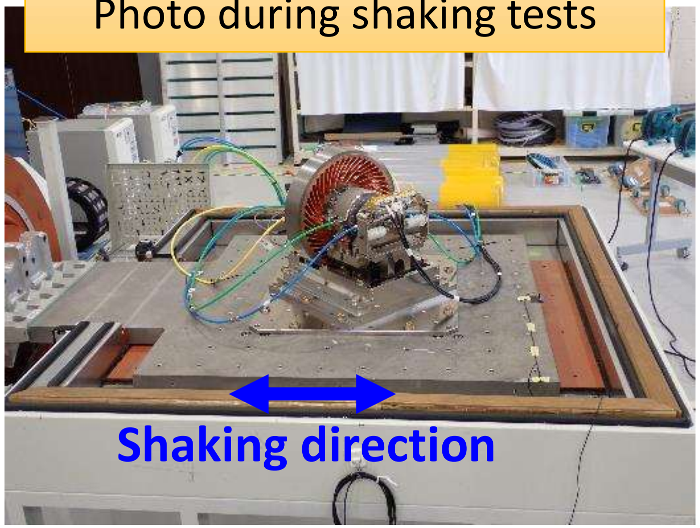
Rotation system tests for emergencies



- Once the shaft touches the bearing during rotation, a seizure (burn-in) may occur. The shaft may get stuck.
- Major concern is the robustness of the gas-bearing system, especially for emergency cases.

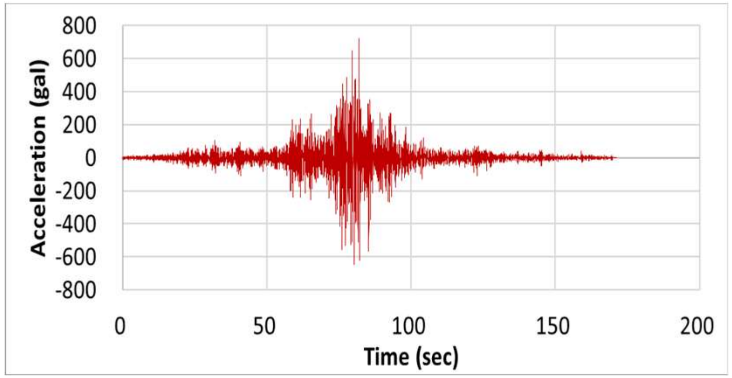
Case	Test	Result
Big earthquake	Shaking test at 0 and 500 rpm (for JMA seismic intensity 6+).	Passed (no rotation trouble)
Power outage or compressor trouble (gas-supply stop)	Hard-landing tests by gas-supply stop up to 600 rpm, and 100 times at 500 rpm.	Passed for the bronze-alloy bearing.

Photo during shaking tests

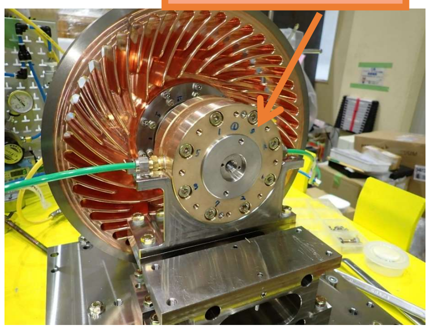


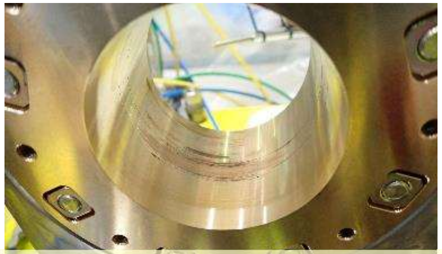
Robustness seems to be good enough even for the emergency cases.

Input data for horizontal shaking



Photos after 100-times hard-landing tests.



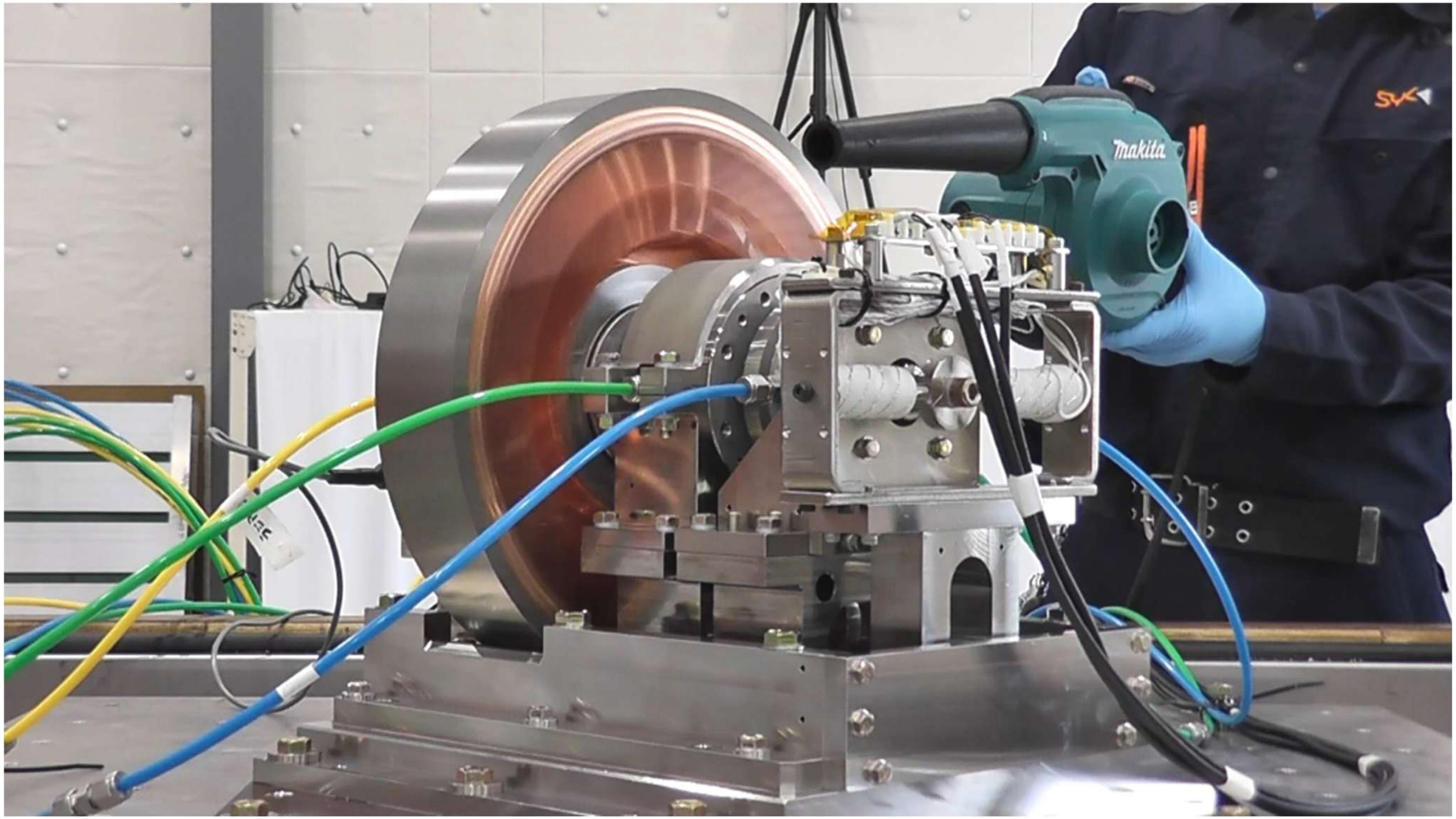


Bearing(bronze-alloy)

Shaft (super Invar)

Movie : Shaking test (assuming earthquake) at 500rpm (horizontal 45-deg direction for rotation system)

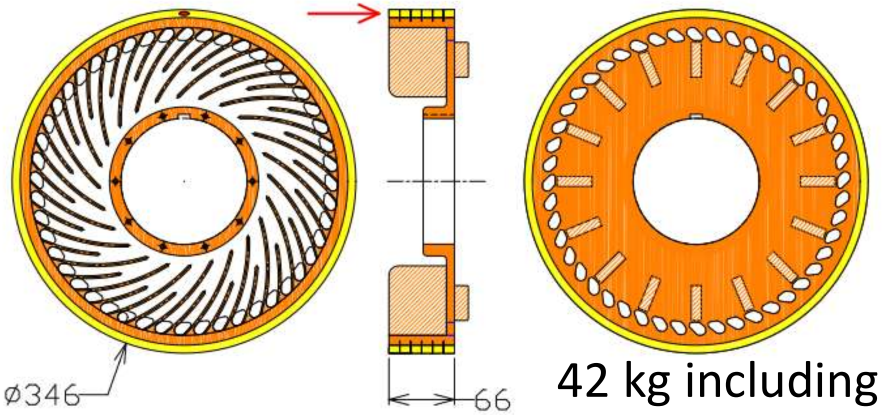
Input acceleration: 725 gal → Recorded : 940 gal (equivalent to seismic intensity of 7).



No rotation trouble occurred. → Bearing stiffness was confirmed to be high enough.

R&Ds of Rotating Target: Trial fabrication of the disk

Base plan for the disk materials:
Outer is Gold (or Platinum), Inner is Copper
→ But the material seems very expensive.



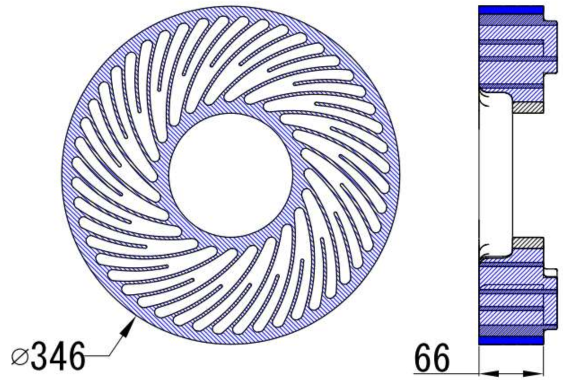
42 kg including shaft

Dummy disk for rotation test (outer: tungsten alloy)

- ✓ Machining copper disk to fin shape was demonstrated by this dummy disk.
- ✓ Bonding between Gold and Copper was achieved in the current fixed target.

→Key part of fabrication method seems to be established.

Alternative plan:
→ Whole pure-Tungsten disk



49 kg including shaft

Engineering difficulties:
- ✓ Difficult-to-machine material.
- ✓ Single-piece large tungsten material can not be procured*.

*So far, 350x350mm^2 12mm-thick is maximum size.
→7 plates have to be bonded.

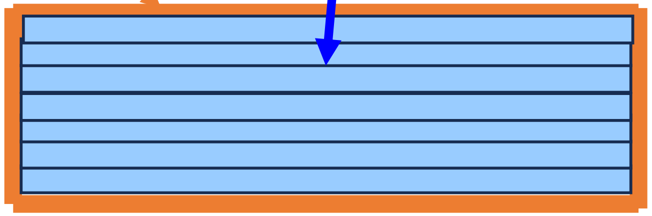
Manufacturing trial
- ✓ Bonding test.
- ✓ Machining test.

Trial fabrication of whole pure-tungsten disk ～Bonding～

Pure tungsten
□350 -t12mm
(rolled plate)

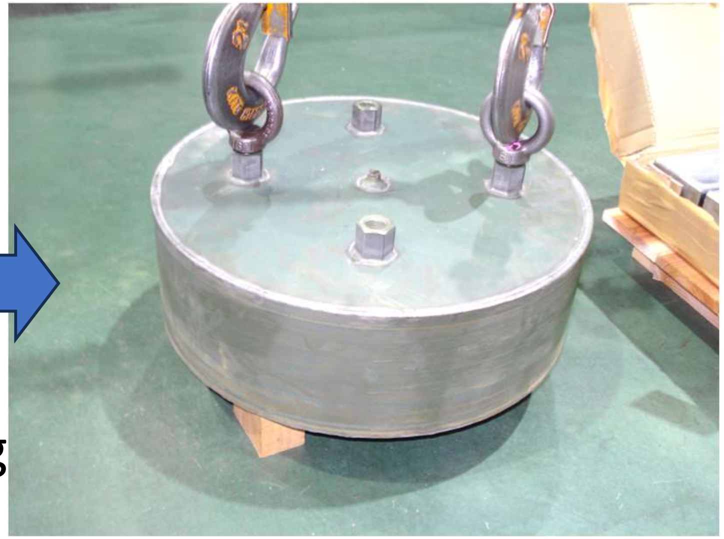
Pure tungsten(ϕ350-7xt12)

SUS-capsule



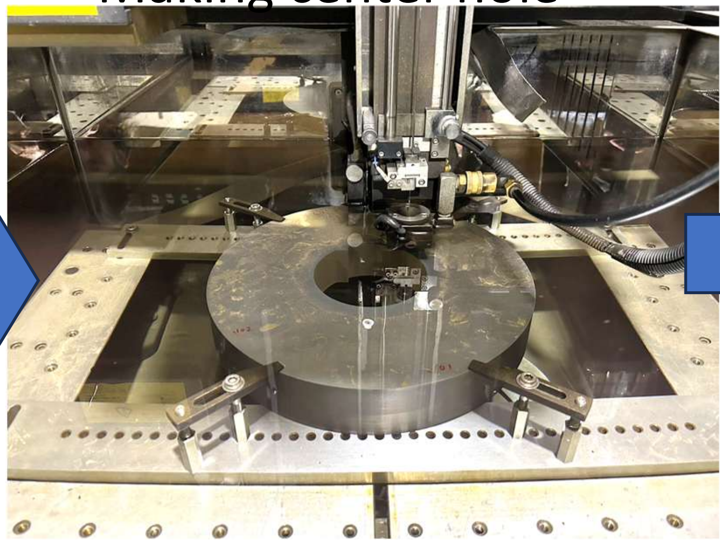
Hot Isostatic Pressing(HIP) bonding
(with thin Ni/Cu layer betw. W)

After HIP bonding
(with SUS capsule)

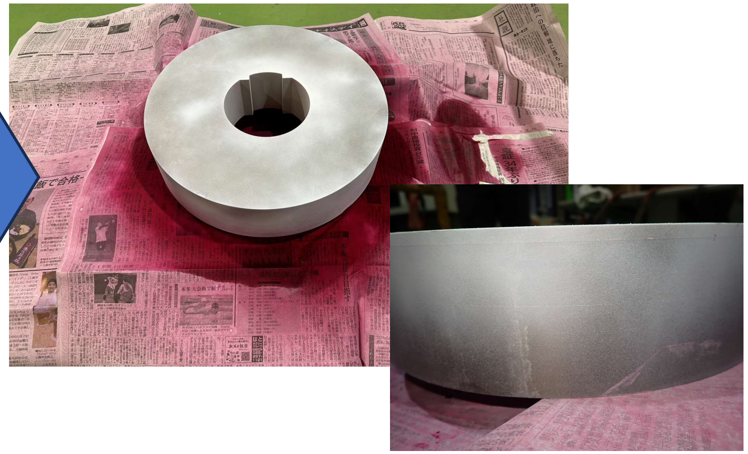


Removing capsule

Making center hole

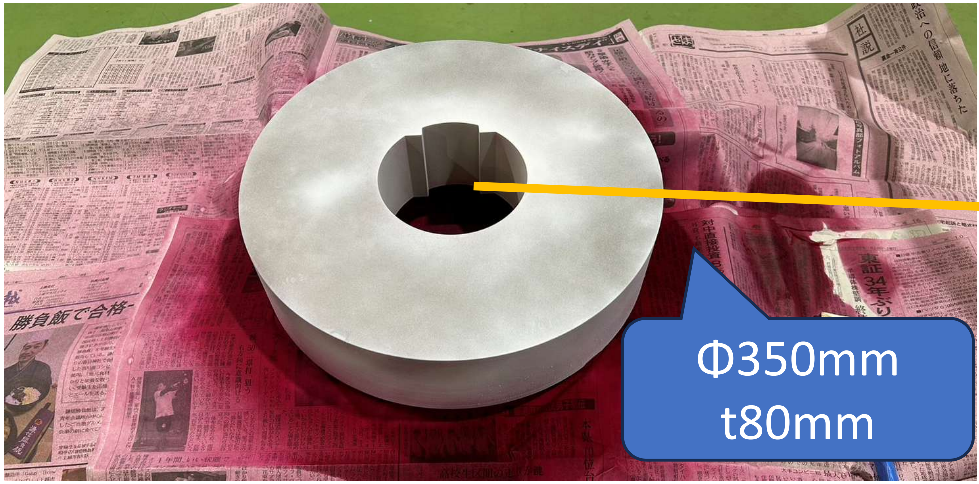


Penetrant inspection.
→No crack can be found.



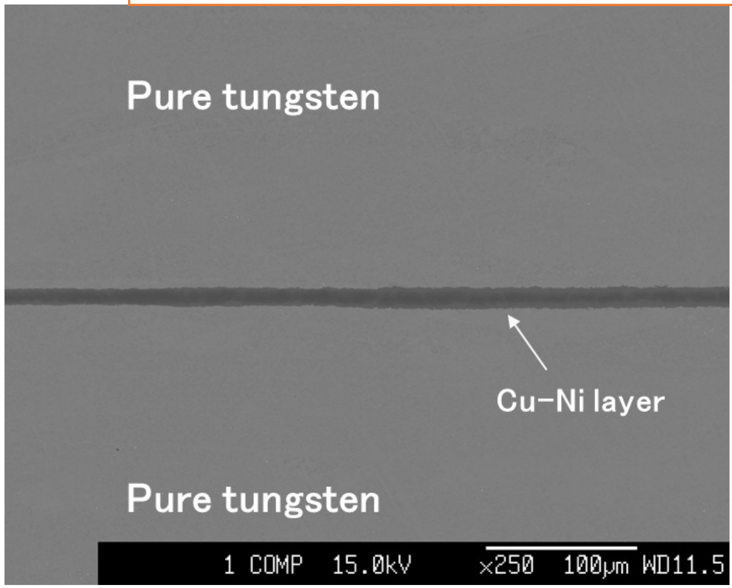
- ✓ Bonding seems to have succeeded.
  → Detail evaluations are underway.

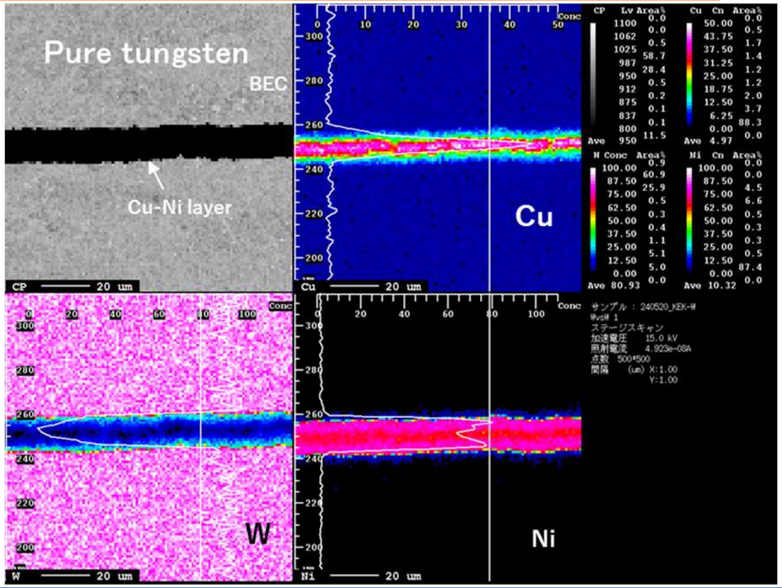
Inspection of the pure-tungsten bonded block



Center part

Microscopic(SEM) observation of the bonding interface



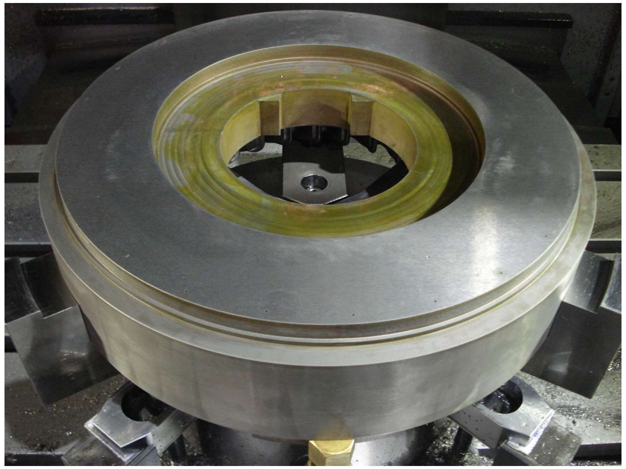


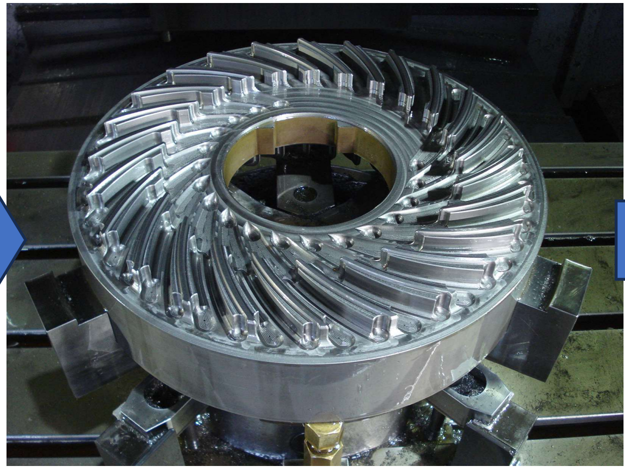
No defect was found.

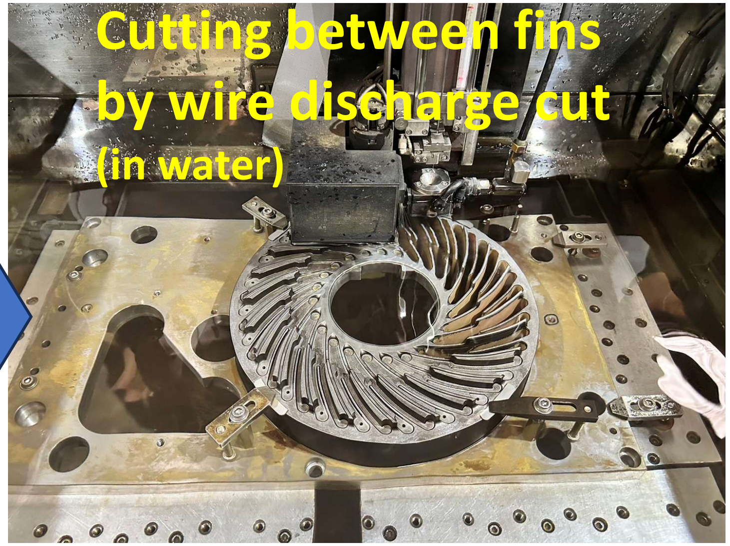
Cu: No diffusion to the tungsten side can be seen.
Ni: slight diffusion (< 2μm) to the tungsten side was seen.
Cu and Ni diffuse together (maybe forming a Cu-Ni alloy)

Trial fabrication of whole pure-tungsten disk ～Machining～

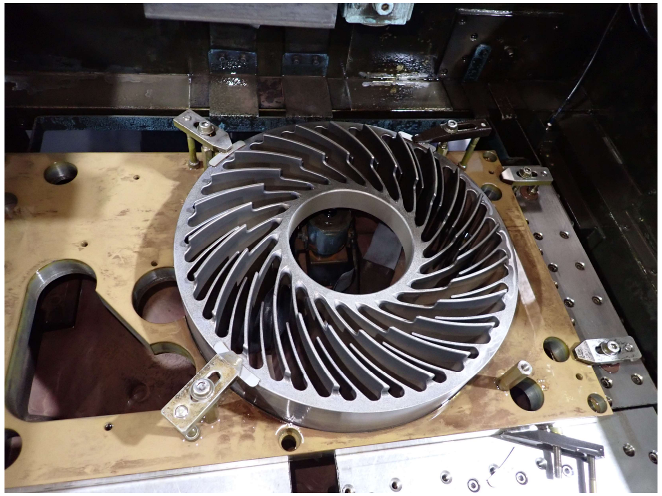
Shaping fin ends by machining (milling).



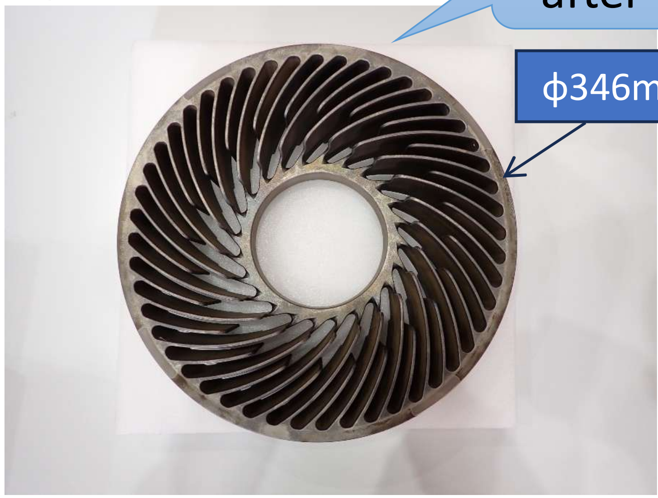




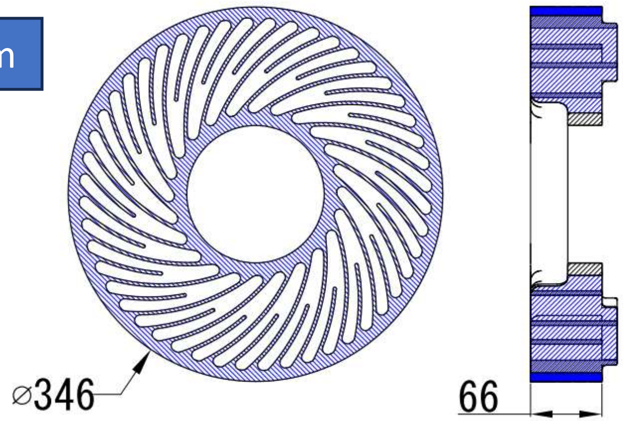
After all machining process.



No defect can be found
after machinig process.



ϕ346mm

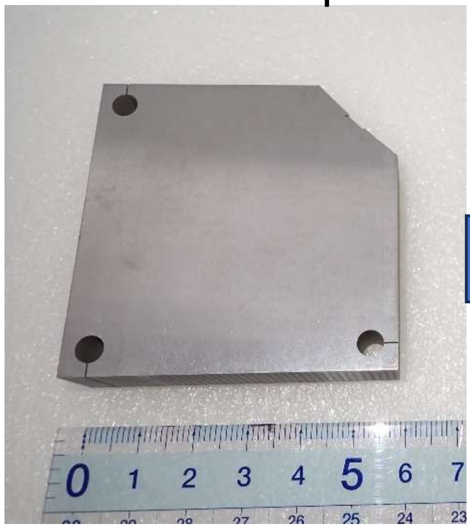


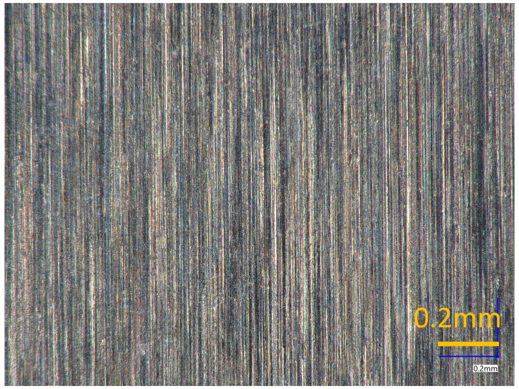
✓ Machining was completed. No defect can be found on the surface.
Next: Surface dirt (oxide layer) will be removed by chemical polishing.
Also, the outer surface is planned to be black coating (TiAlN) to increase emissivity.

Black coating for pure tungsten to increase emissivity

to enhance radiation cooling, and temperature monitoring by infrared thermometer.

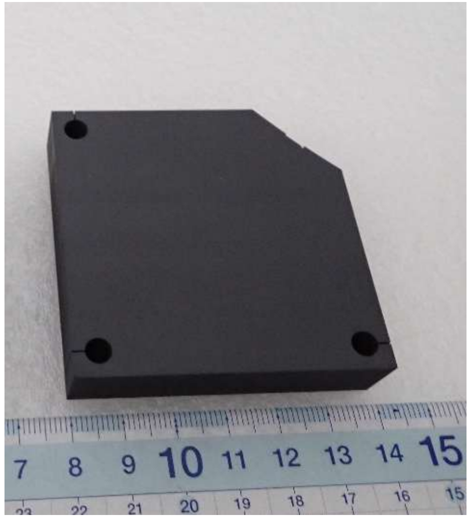
Base tungsten plate
(after chemical polishing)

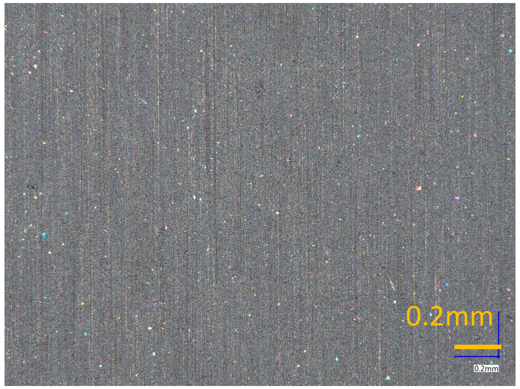




Emissivity 0.08
(average betw. 2～22μm)

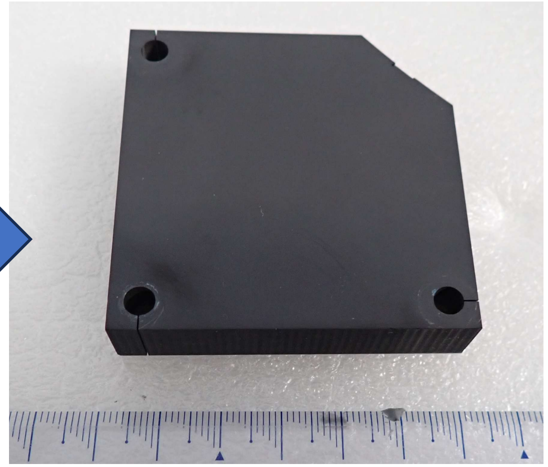
TiAlN (3μm-thick) coating
by ion-plating

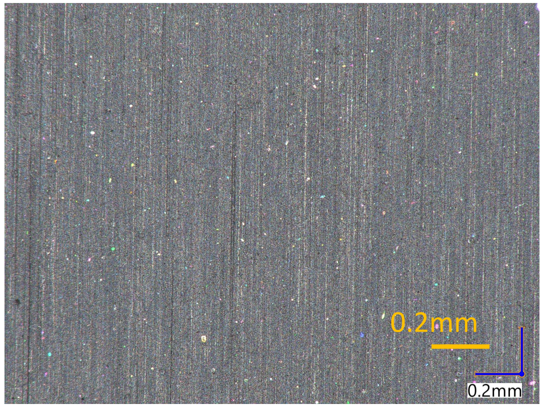




Emissivity: 0.60

After 100 heat cycles
between 30℃↔400℃.





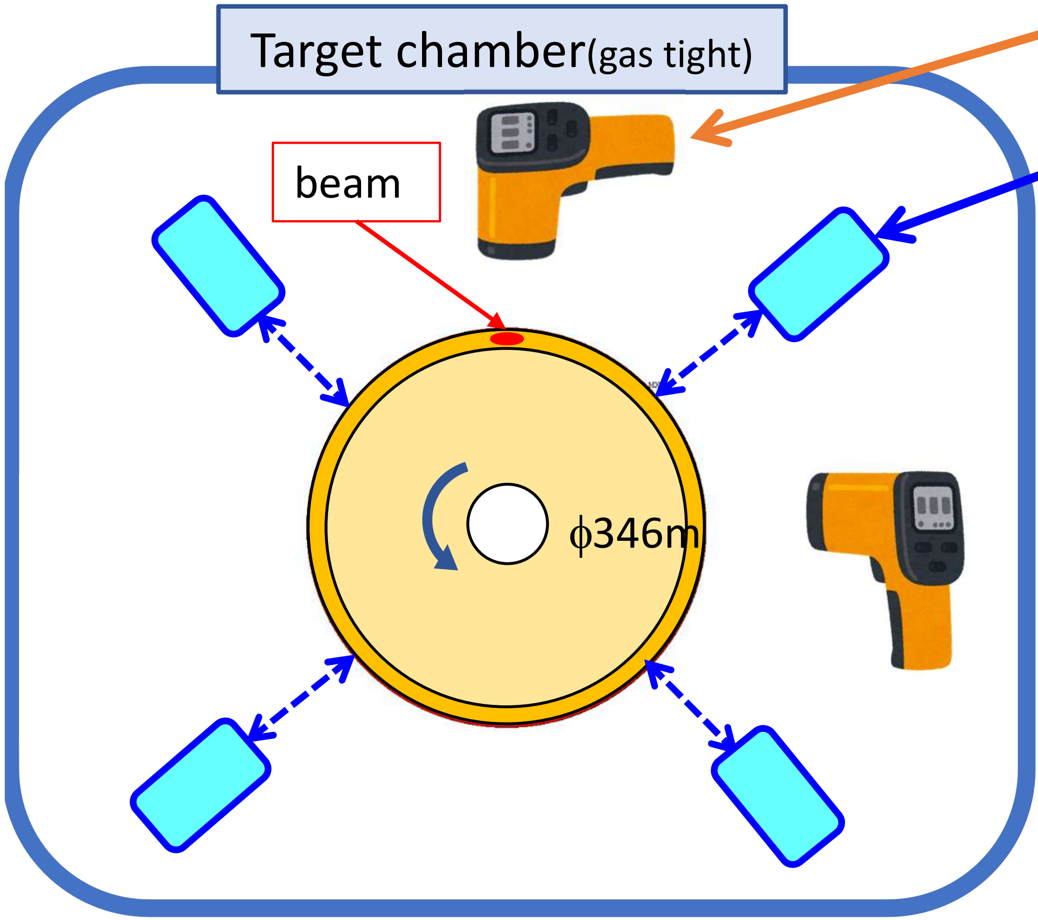
Emissivity: 0.56

*note: thermal expansion coefficient (10-6/K): W～5, TiAlN～8.

No big change (no flaking off) after 100 cycles betw. 30℃～ 400℃. It seems a stable coating.

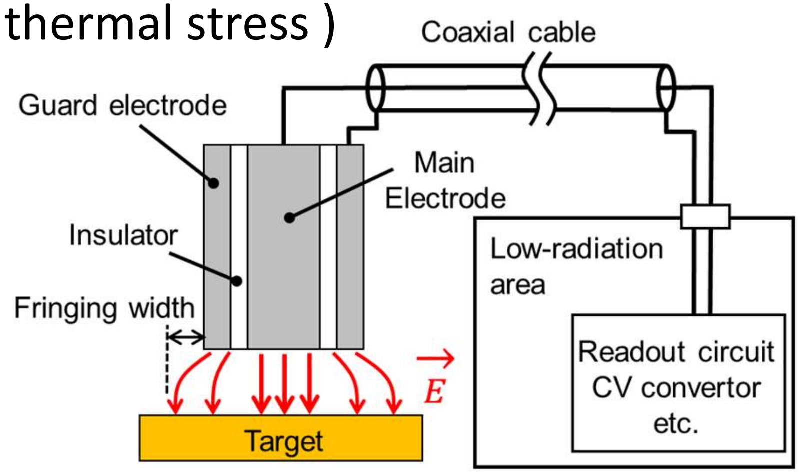
Developments of radiation-resistant disk monitoring sensors

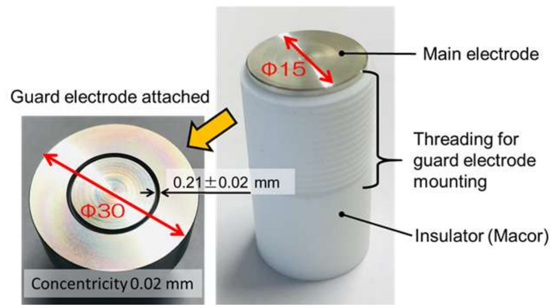
Infrared thermometer (next slide)



Displacement sensor

- ✓ To monitor rotation parameters (disk-center position, speed)
- ✓ To measure thermal expansion of the disk (→ thermal stress)





Poster presentation by F. Muto

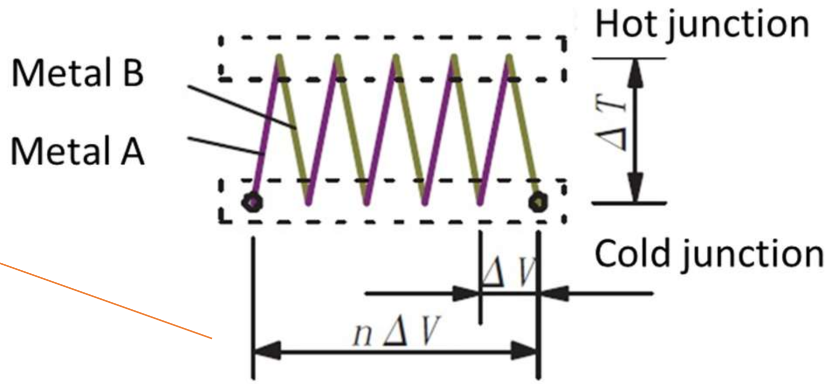
R&D of radiation-resistant infrared thermometer

Commercially available infrared thermometer

Commercially available

Thermopile

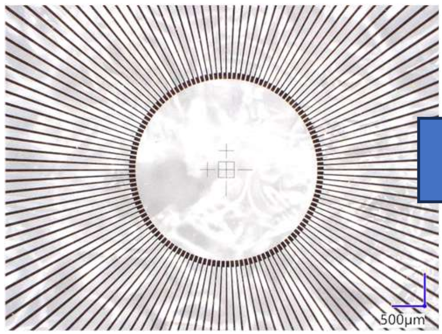
Basic structure of thermopile
→A series of thermocouples (passive elements)



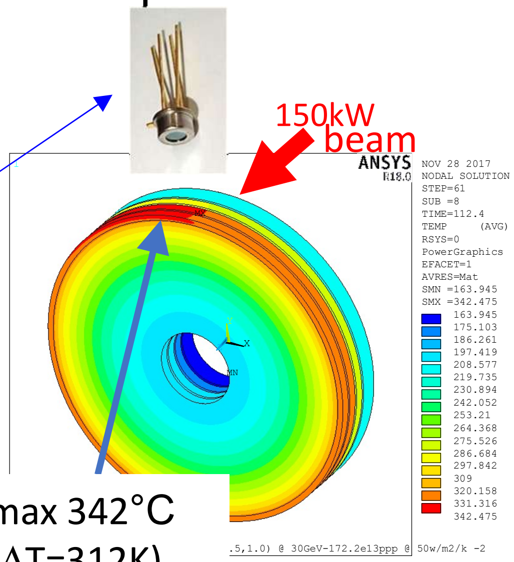
- ✓ Issue of the commercially available thermopile: thermocouples are doped polysilicon (semiconductor ←weak for radiation).
- ✓ By replacing the polysilicon with other metals (copper, nickel, etc), it is expected to be a radiation-resistant thermopile.

Trial production of thermopile
by the micro-machining technique in 2024-2025
(T. Yamaga, T. Itaba)

500 contacts with Cu and Ni



Realistic-shape production is planned in this FY.



max 342°C
(ΔT=312K)

Summary

- Indirectly water-cooled fixed target made of gold, up to 115 kW for 4.24s-cycle, is now in service.
  - 92-kW stable beam operation was achieved in Apr.-May 2025.
  - As of now, 1.6E+20 pots was irradiated.
  - c.f.) The previous target was achieved up to 1.5E+20 pots (7 DPA, 3×10^6 spills).

- To increase beam power up to 150 kW(plan), R&D for the He-gas-cooled rotating-disk type target is now in progress.
  - The rotation system with the gas bearings has been examined.
  - A full-size pure-tungsten disk was manufactured as a trial.

<u>Next step</u>

Poster presentation by F. Muto

- Remaining major R&D:
  - Evaluation of the stress analysis of the disk.
  - Developments of the radiation-resistant disk monitors (displacement sensor and infrared thermometer) are in progress.

- The whole design of the new target will be integrated in FY2026.