

J-PARC Hadron Production Target

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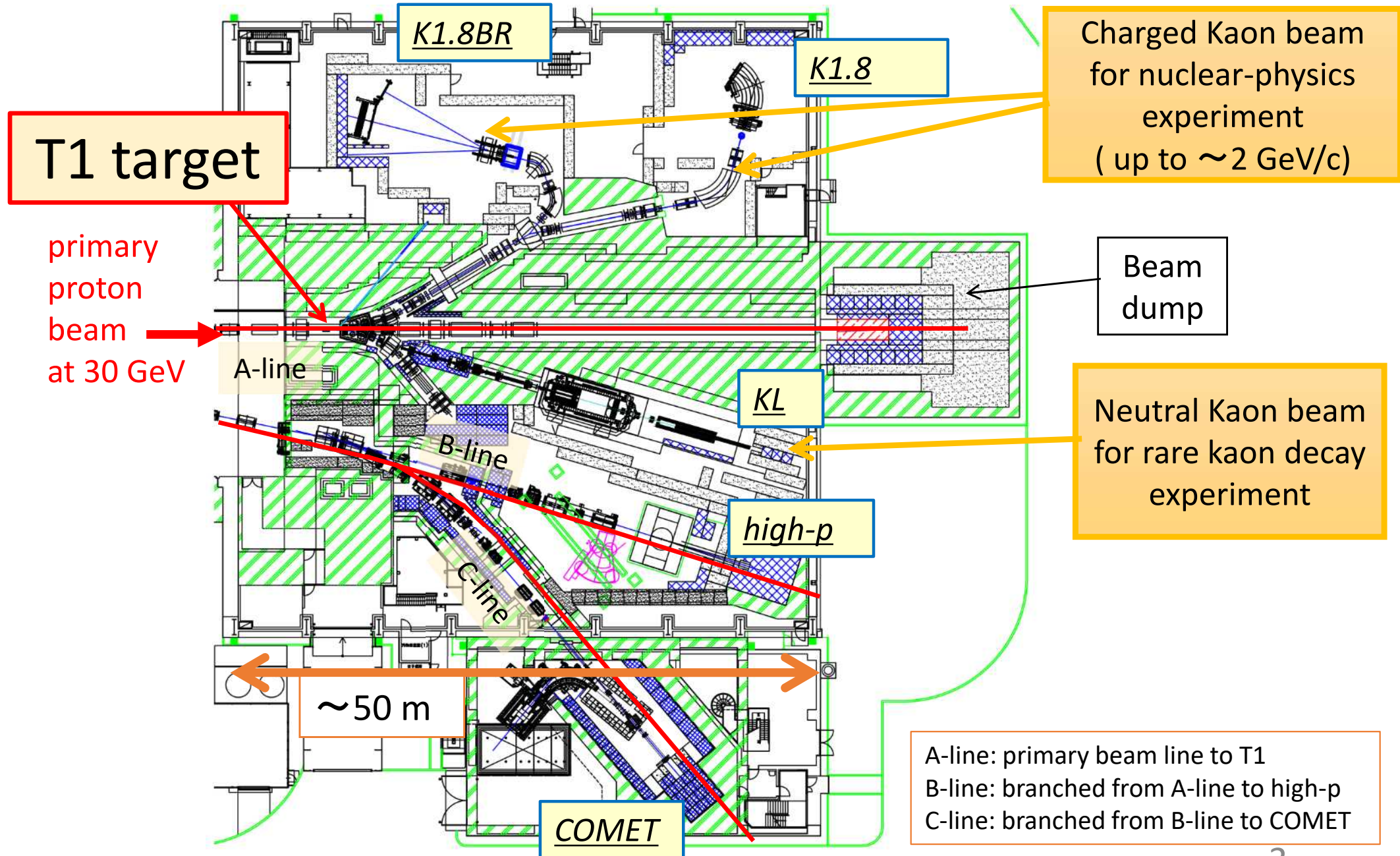
KEK/J-PARC

Oct, 2024

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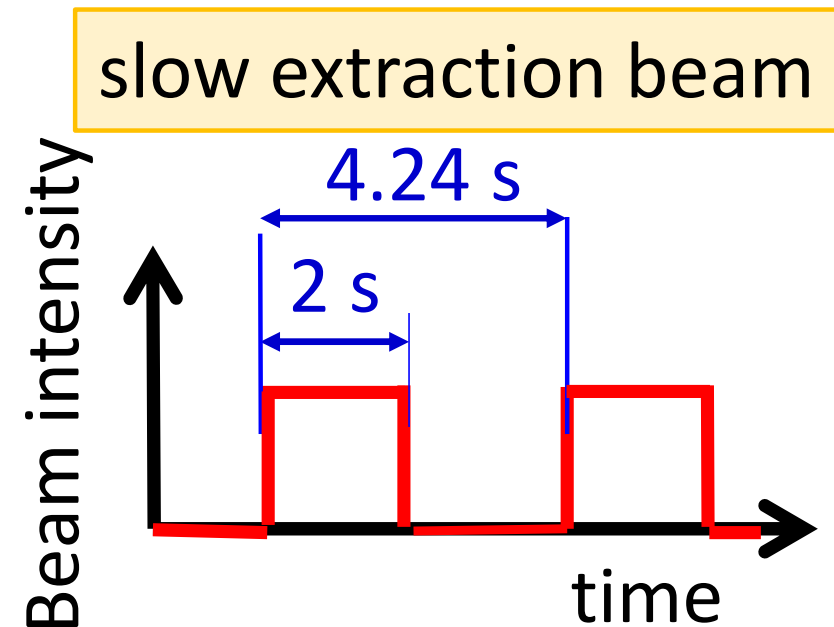
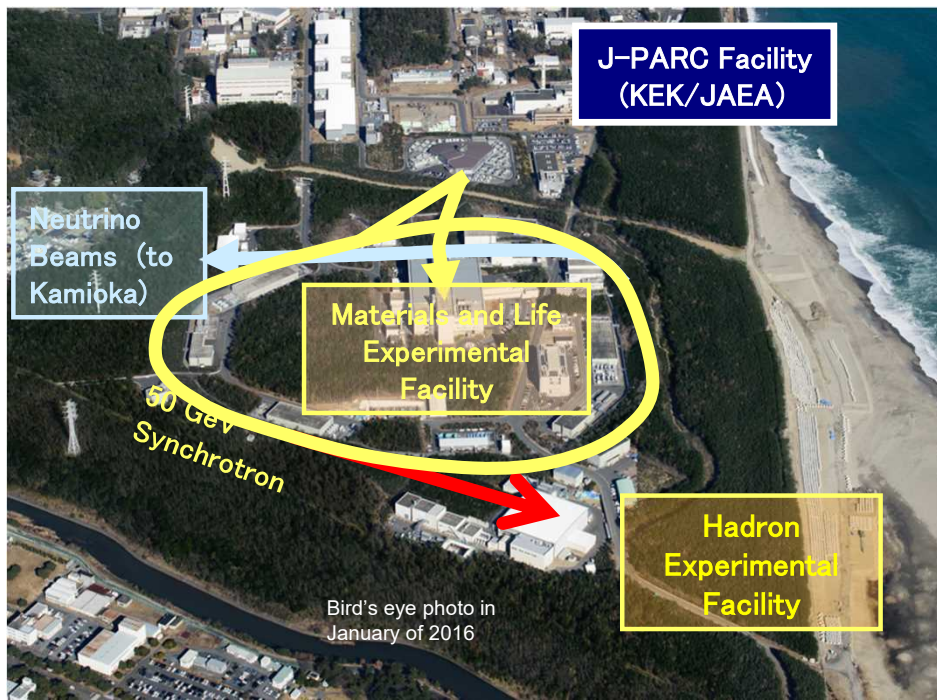
- Hadron Experimental Facility and beam condition
- Previous and Current Target
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 - Manufacturing test of whole pure-tungsten disk
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Hadron Experimental Facility at J-PARC



Beam conditions for T1 target

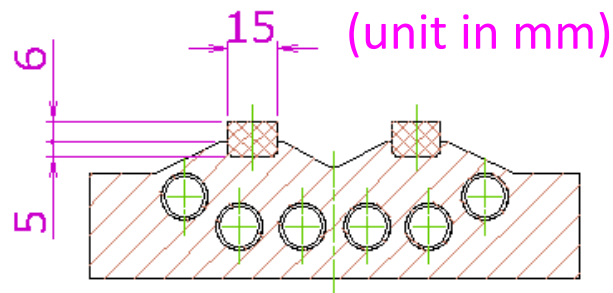
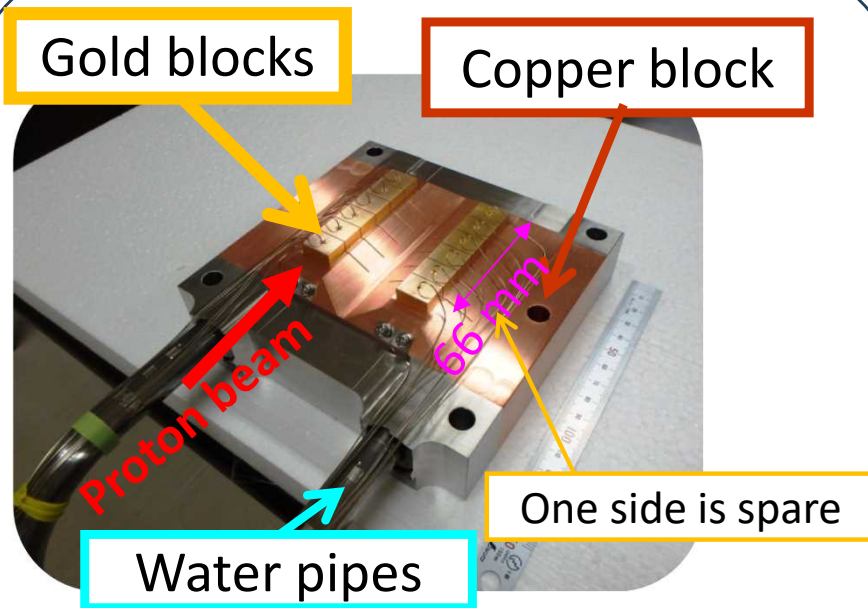
- Primary proton beam energy: 30 GeV
- Spill structure: 2-s DC extraction and **4.24-s** repetition cycle
- Beam size at T1: $\sigma_H \sim 2.5$ mm, $\sigma_V \sim 1.0$ mm
- Beam loss at T1: 50% (max.)
- Beam-direction length of T1 : 66 mm (max.)
(Secondary beamline optics determined the beam size and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



Previous and current production target

→ Indirectly Water-cooled Fixed type

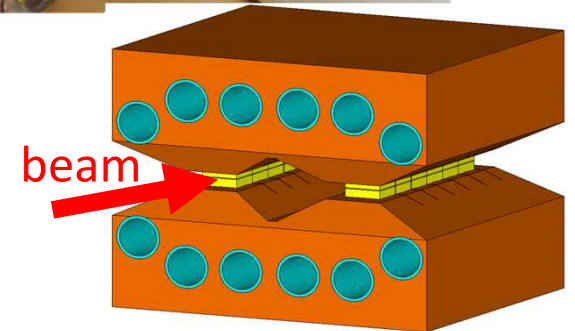
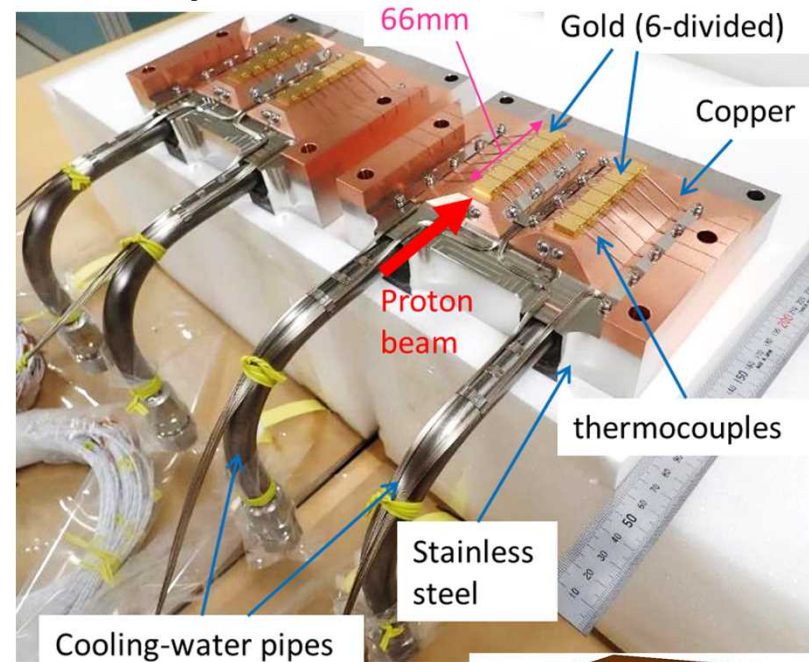
Previous target



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

Current target (in service)

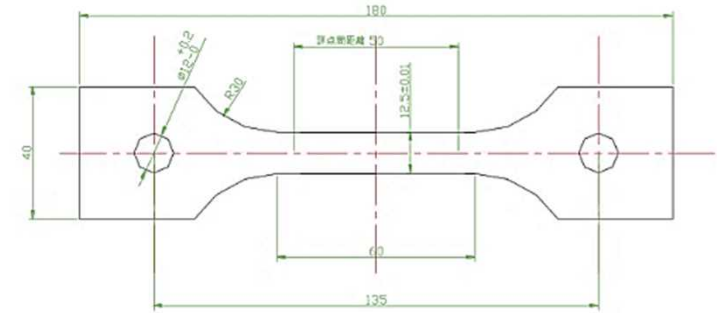
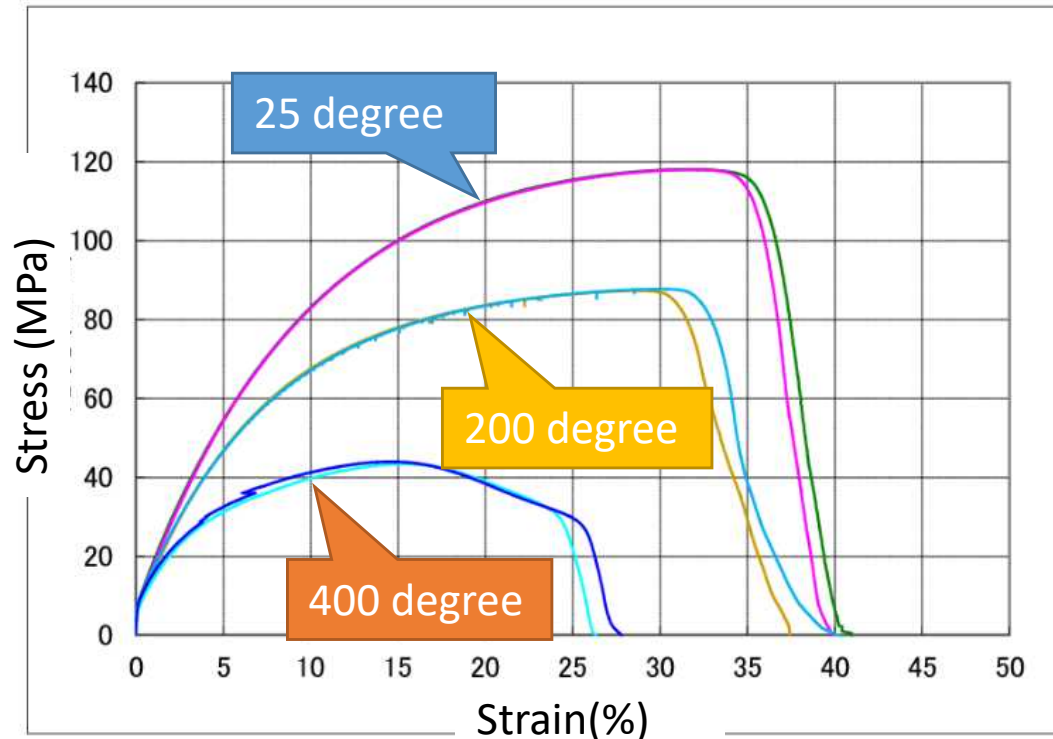
Phys. Rev. Accel. Beams 25, 063001



Up to **115 kW** beam power (4.24s-cycle),
82 kW stable operation was achieved.
As of now, $0.9\text{E}+20$ 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

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

10^4 fatigue strength: tensile strength/2

10^7 fatigue strength: tensile strength/3

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

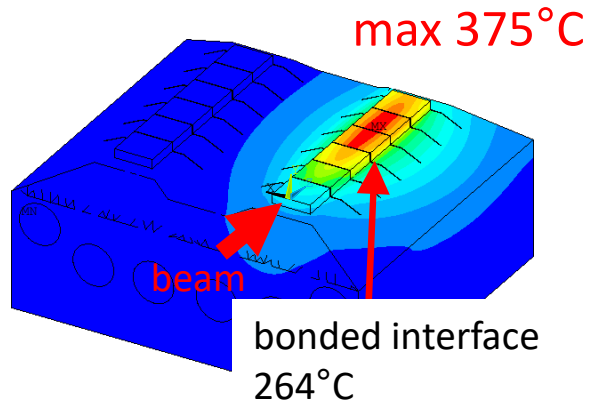
fatigue strength of gold in literatures:
 \approx tensile strength $\times 0.7$ (@ 10^4)、 $\times 0.4$ (@ 10^7)

safety factors

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

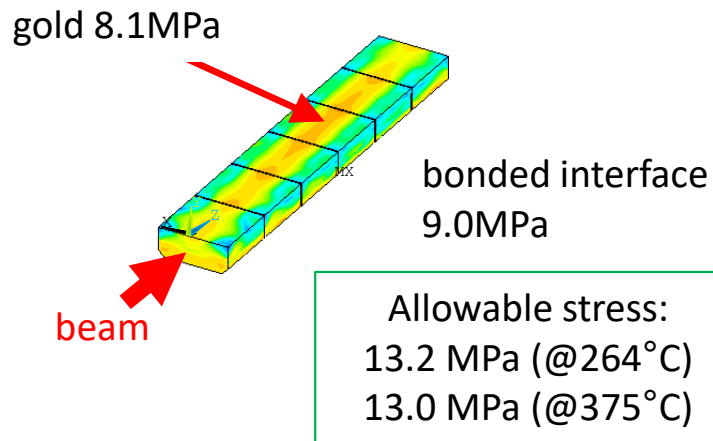
95 kW (5.2-s cycle)

temperature



* only lower block is shown

von Mises stress



	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

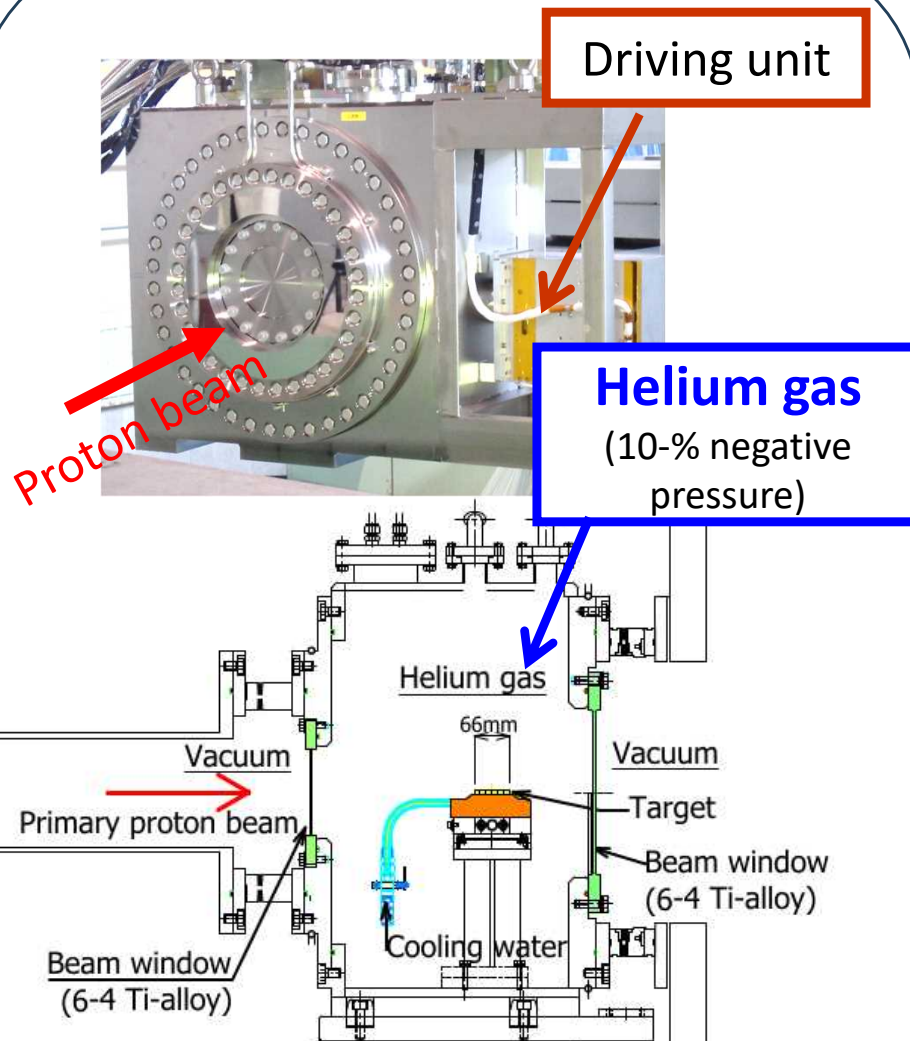
* For 97kW beam, stress amplitude on high-cycle fatigue (8.0MPa) exceeds the limit (7.5MPa) (gold temp.: 394°C)



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

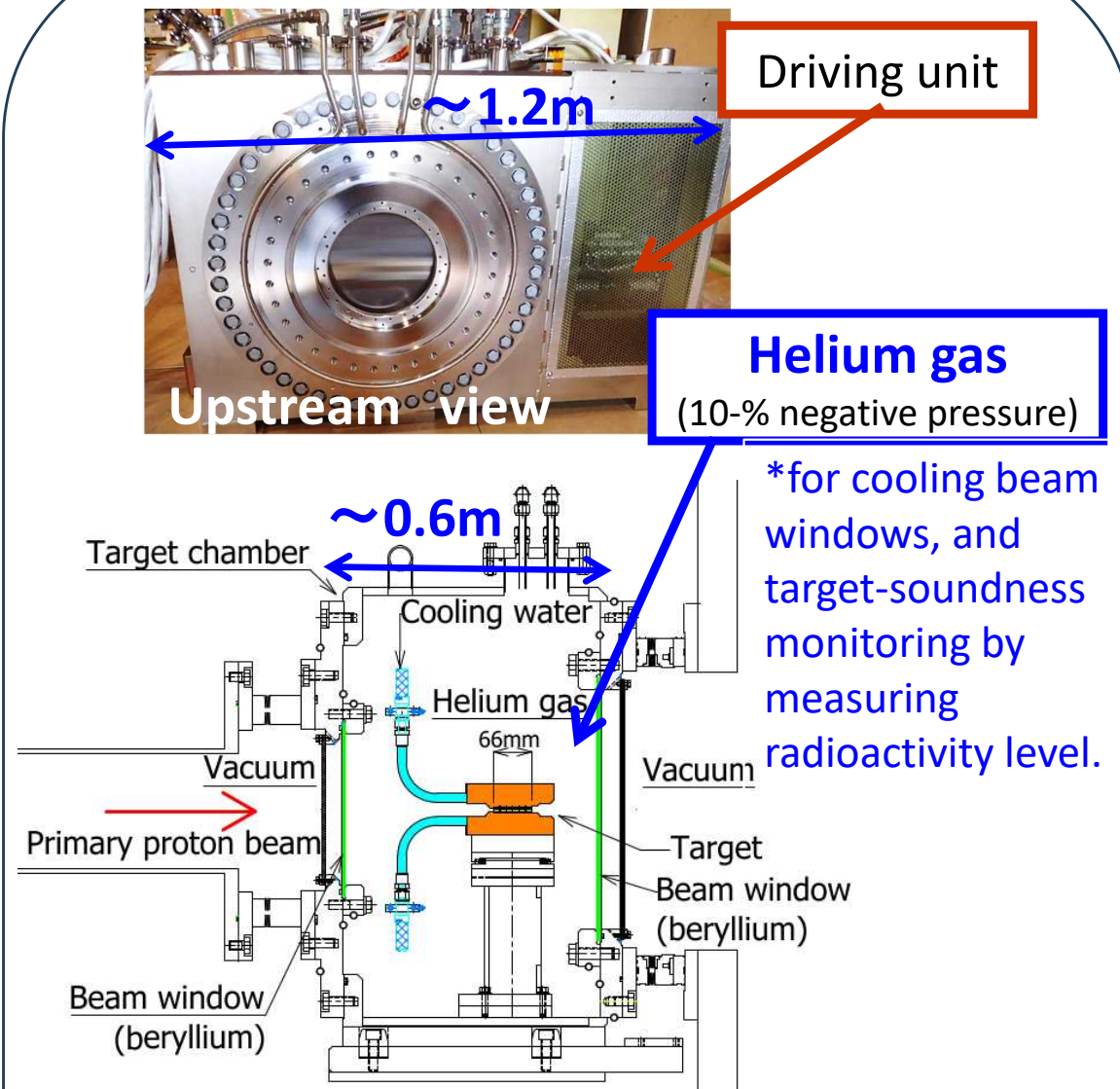
Previous and current target chamber (gas-tight chamber)

Previous target chamber



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

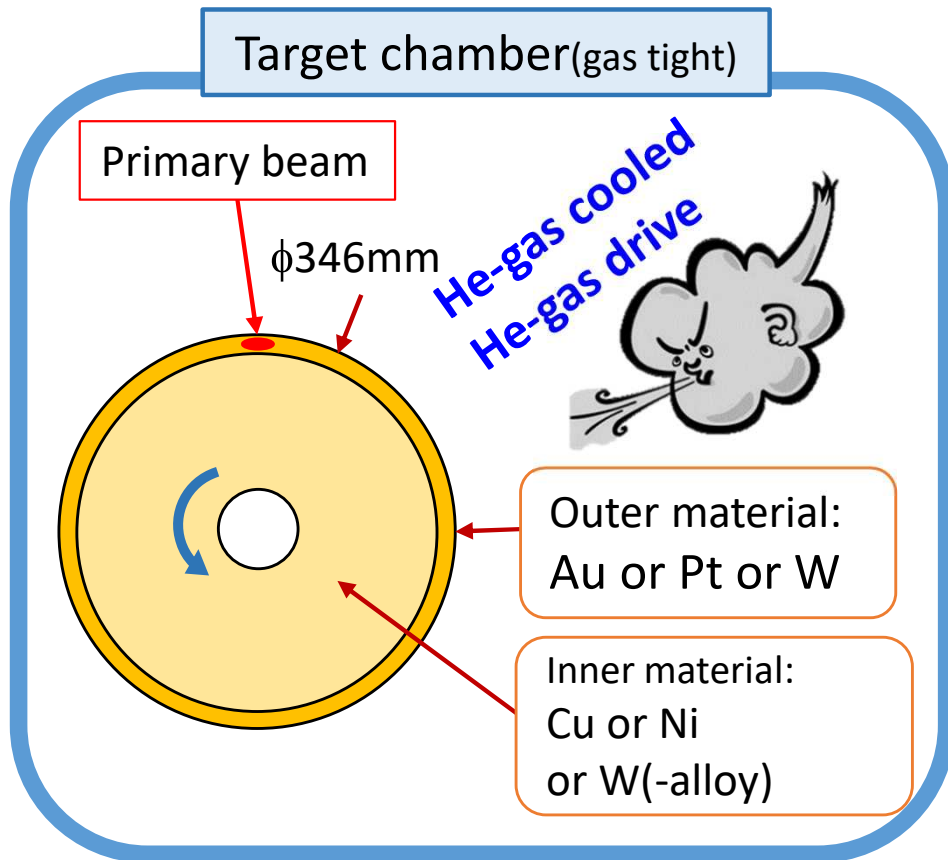
Current target (in service)



Up to **115 kW** beam power (4.24 s cycle). As of now, $0.9\text{E}+20$ protons on target.

Next Production Target ~ Conceptual Design ~

→ Directly He-gas-cooled Rotating-disk type

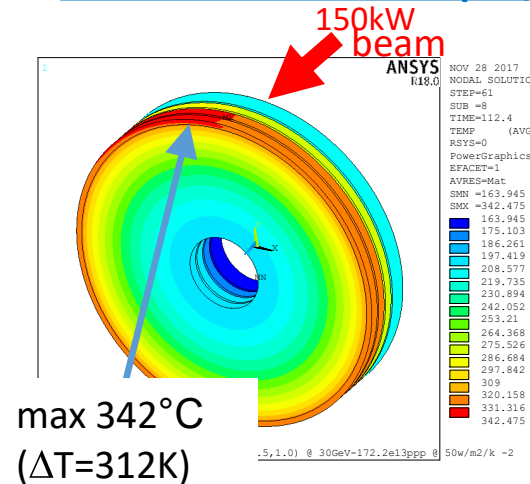


- Rotating disk: heat load and radiation damage can be distributed in larger areas.

Max. beam power: **150 kW** (plan)

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

Thermal calculation (Au, **150-kW**) *Preliminarily



Assuming $50 \text{ W/m}^2/\text{K}$.
(Geom.: 4 separate flat disks)

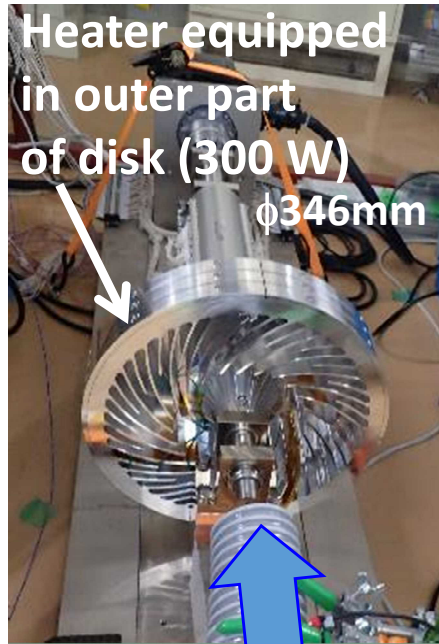
He-gas rotation drive like wind turbine is planned for rotation.

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

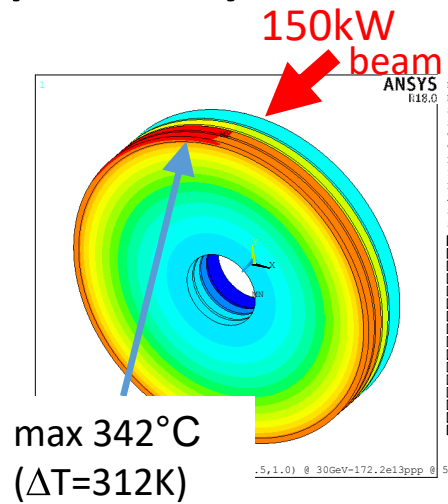
Engineering points:

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

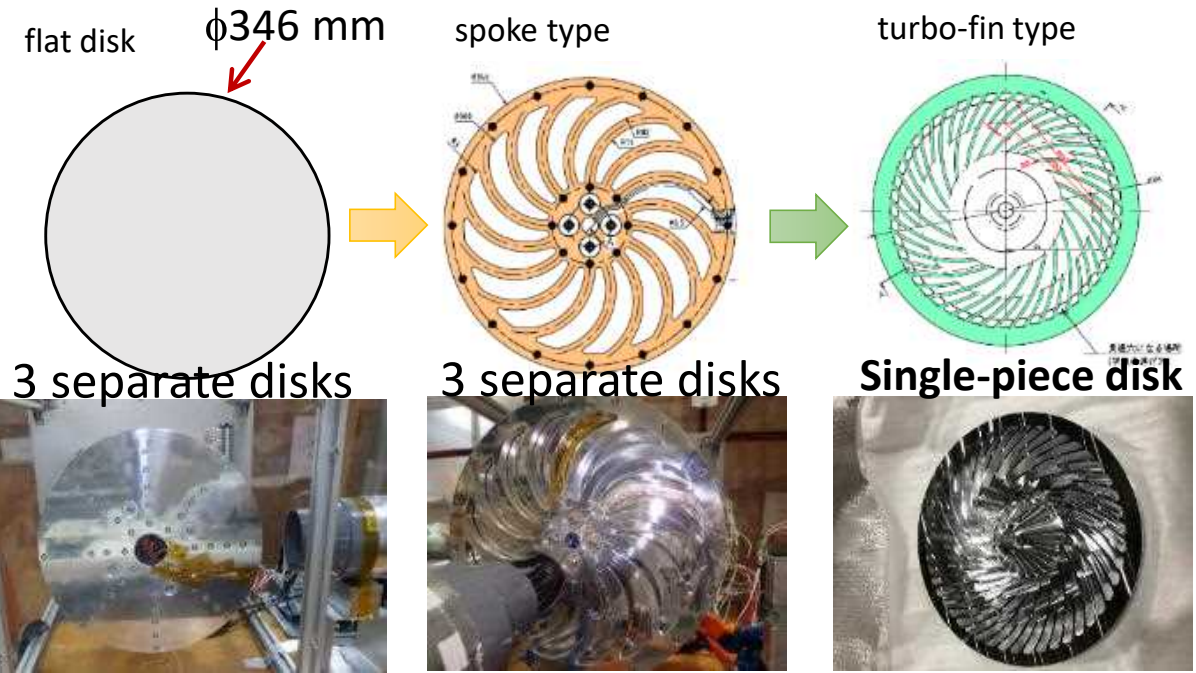
Cooling capability measurement by test bench (in air)



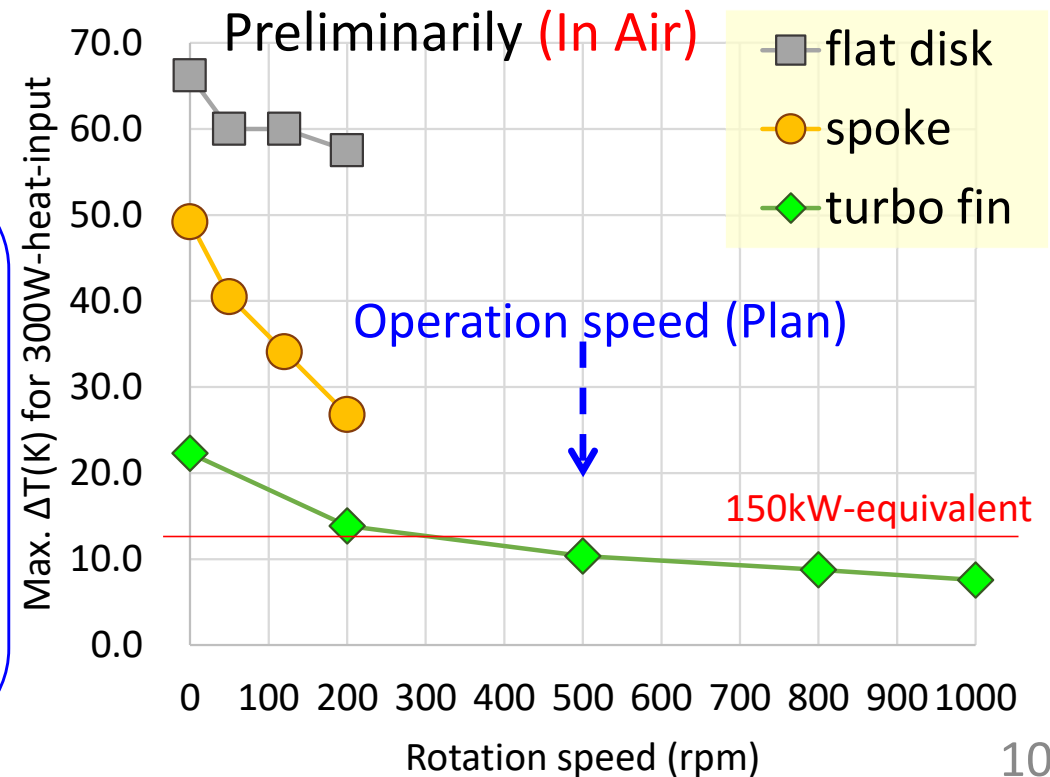
Temperature-controlled air



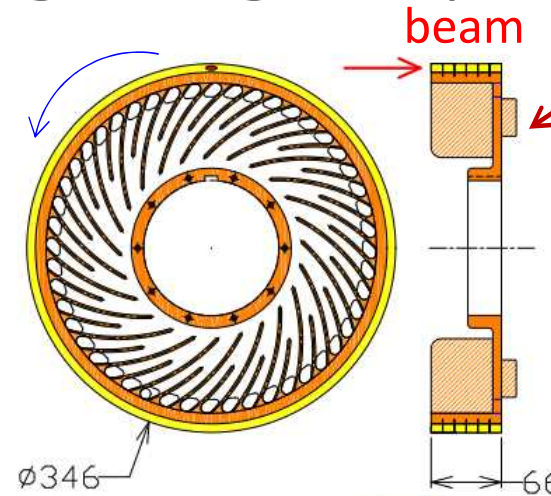
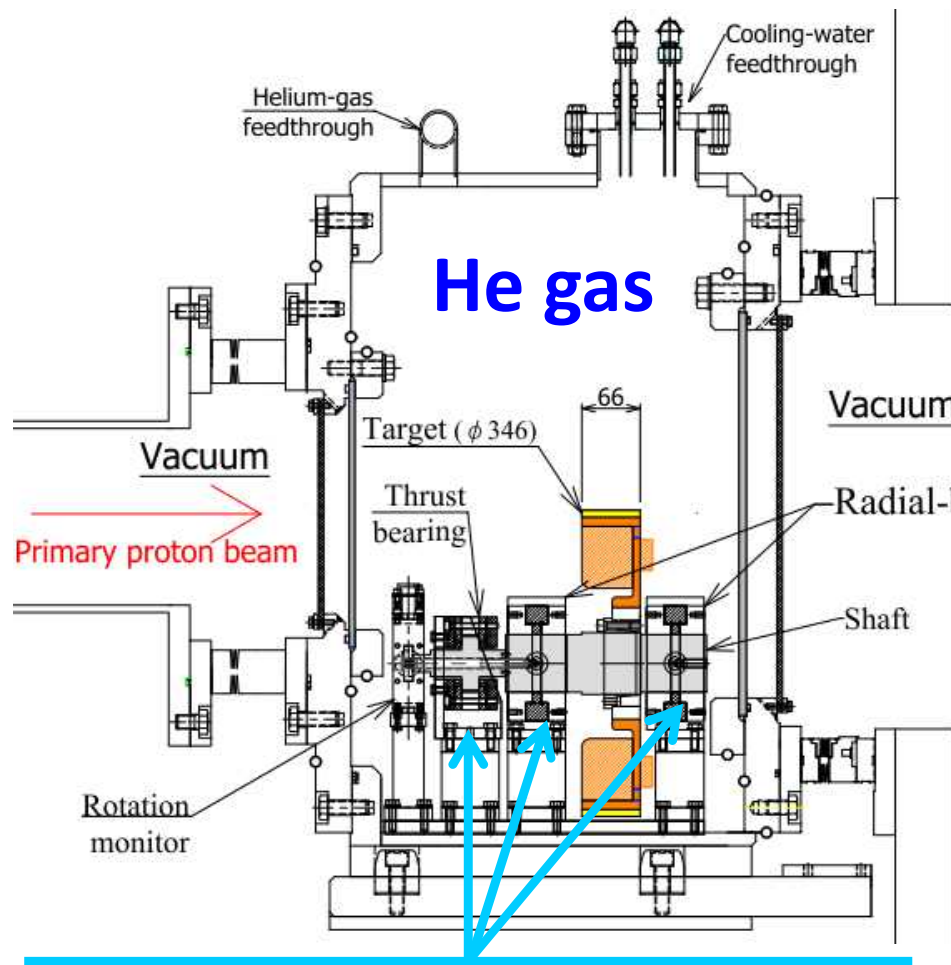
equivalent to $\Delta T = 13\text{K}$ in test bench from the difference of coolant (He/air) and heat deposition



- ✓ The cooling capability of turbo-fin shape at 500 rpm seems good enough for 150-kW beam operation.
- Also, direct measurements in helium gas were performed. The evaluation is underway.

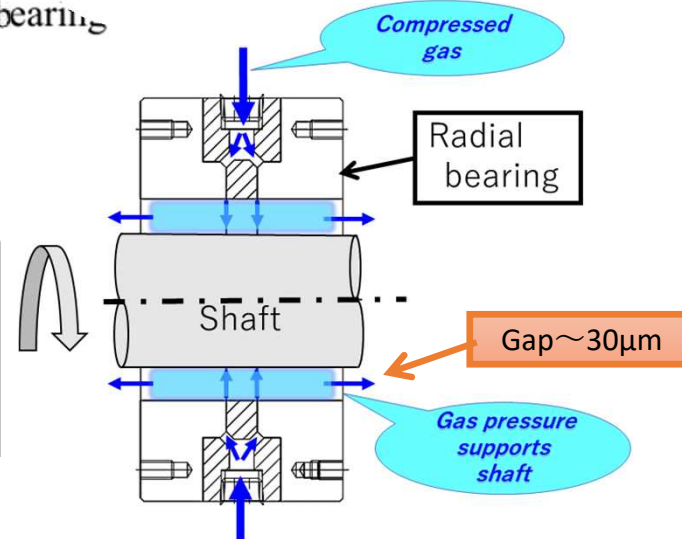


Design of the rotating target (plan)



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

- ✓ 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)

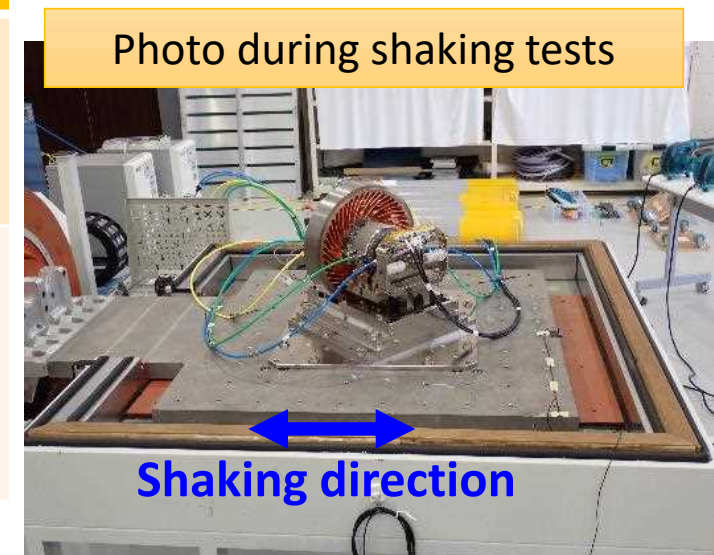
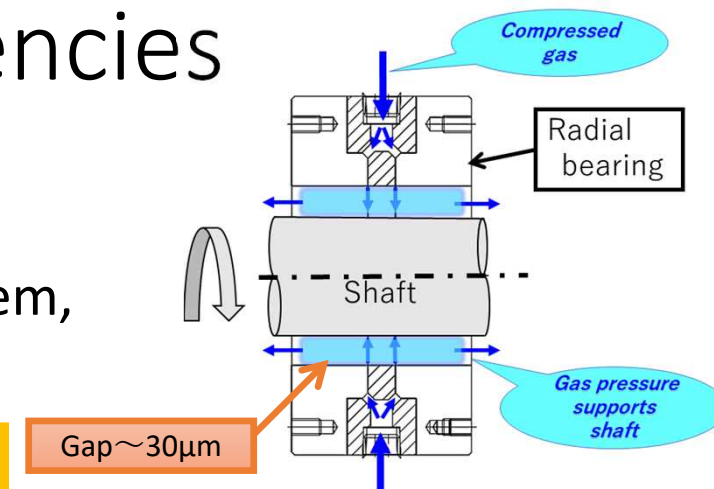
* The robustness of the rotation system with the gas bearings should be checked, especially for emergencies; big earthquake or power outage (gas-supply stop).

Rotation system tests for emergencies

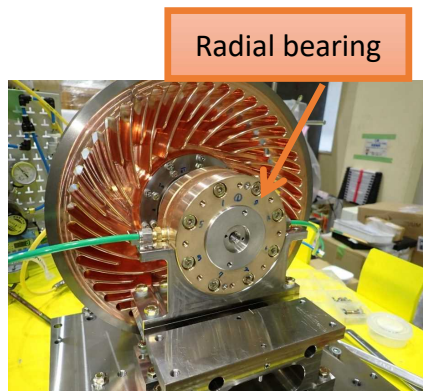
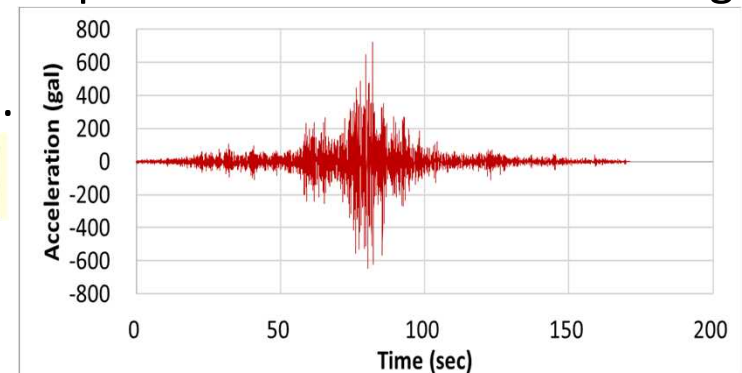
- Once the shaft touches the bearing during rotation, a seizure (burn-in) may occur. The shaft may get stuck.
- Major concern is the robustness of the gas-bearing system, especially for emergency cases.

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*.

*By changing the bearing material from SUS to Bronze alloy, the hard-landing tests were passed.



Input data for horizontal shaking



Photos after 100-times hard-landing tests.

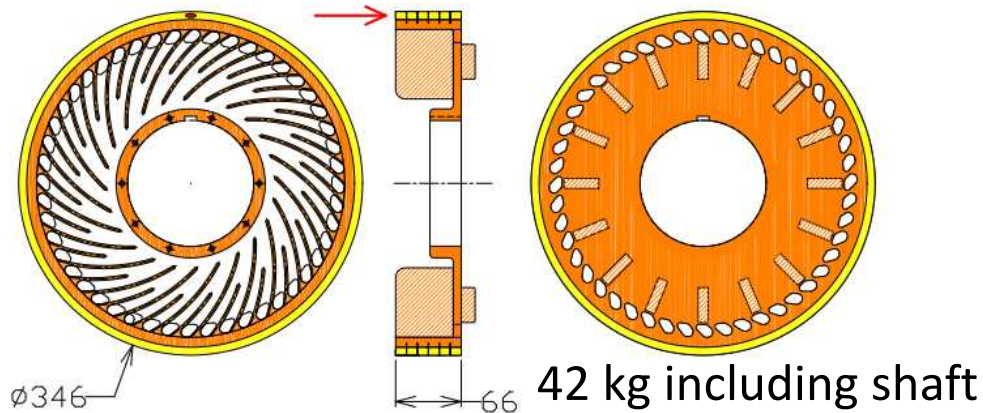


R&Ds of Rotating Target: Trial fabrication of the disk

Plan for the disk materials:

Outer is Gold or Platinum, Inner is Copper

→ But the material seems very expensive.



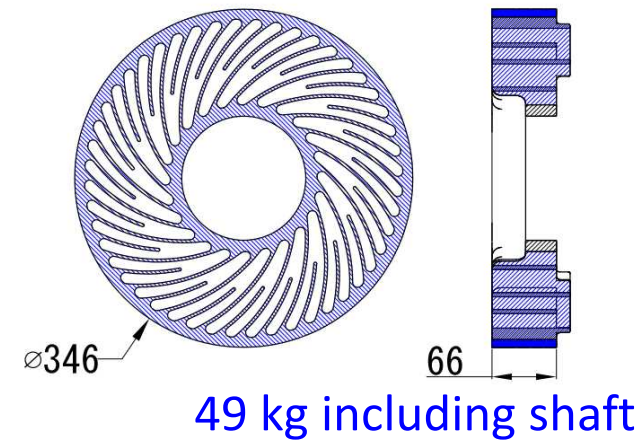
Dummy disk for rotation test:

Inner : pure copper
Outer: tungsten alloy
(W-95%, Ni-2%, Cu-1%)
instead of gold.

- ✓ 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**



Engineering difficulties:

- ✓ Difficult-to-machine material.
 - ✓ Single-piece large tungsten material can not be procured*.
- *So far, 350x350mm² 12mm-thick is maximum size.
- 7 plates have to be bonded.

Manufacturing trial

- ✓ Bonding test.
- ✓ Machining test.

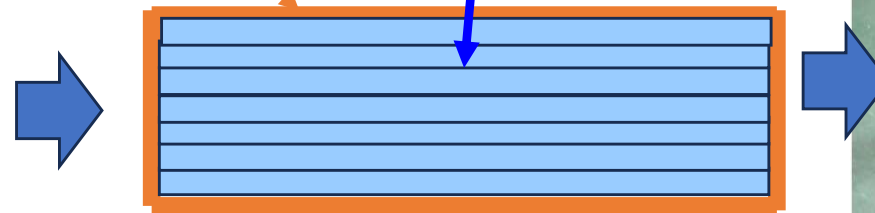
Trial fabrication of whole pure-tungsten disk ~ Bonding ~

Pure tungsten
□350 -t12mm



Pure tungsten($\phi 350$ -7xt12)

SUS-capsule



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

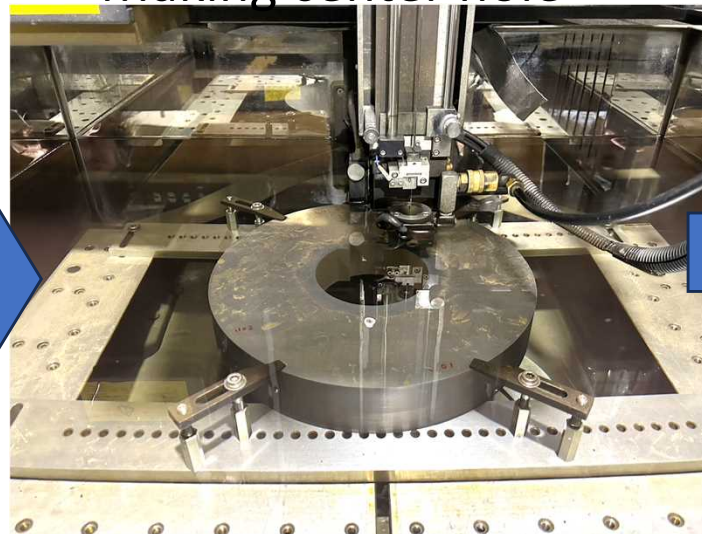
After HIP bonding
(with SUS capsule)



Removing capsule

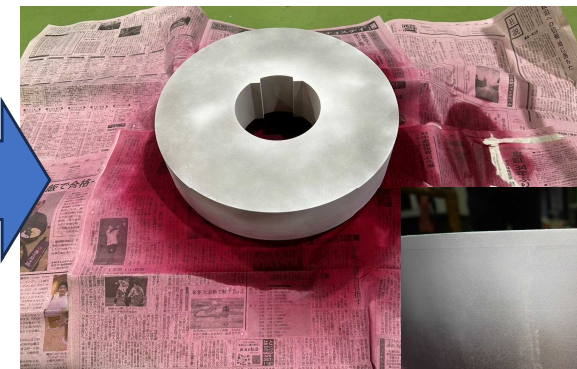


Making center hole



Color check

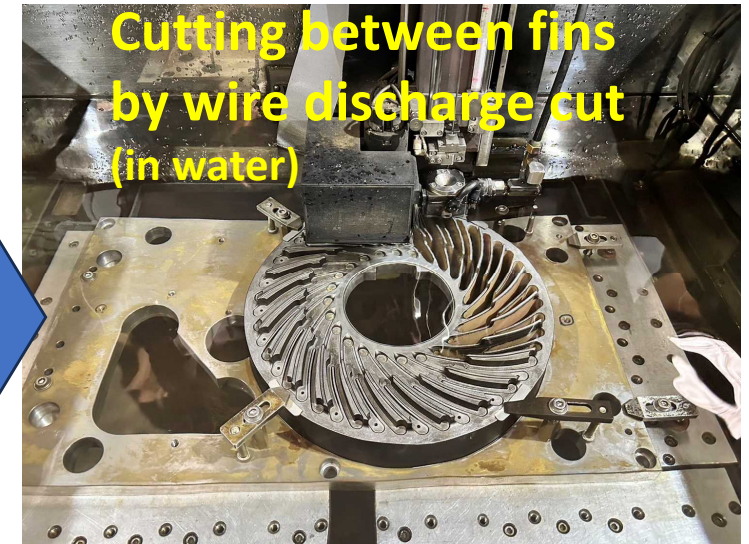
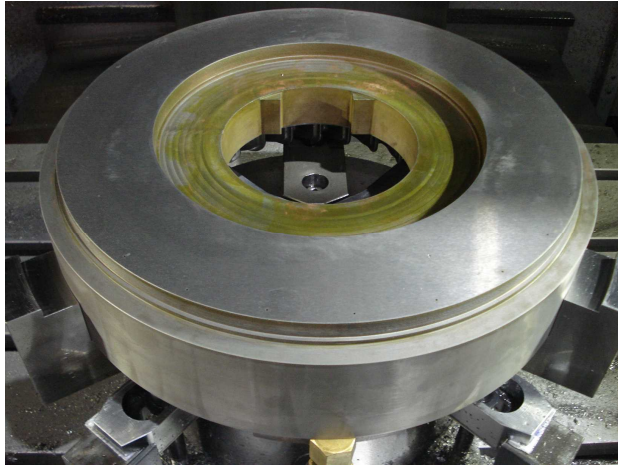
→ No crack can be found.



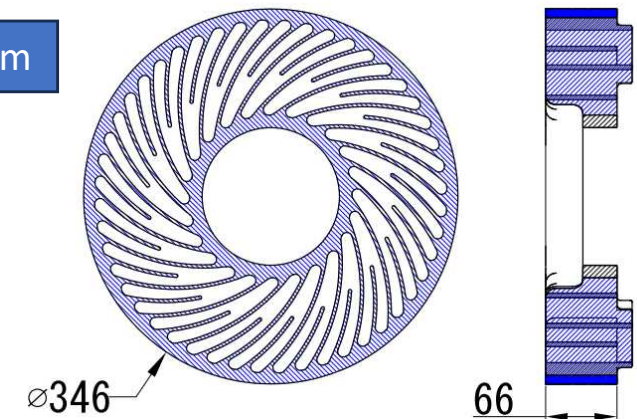
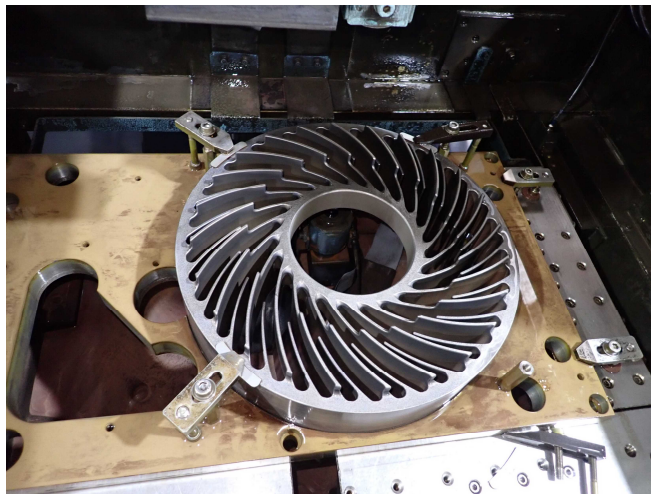
- ✓ Bonding seems to have succeeded.
→ Detail evaluations(bonding strength, interface observation) are underway.

Trial fabrication of whole pure-tungsten disk ~Machining~

Shaping fin(R part) by machining.



After all machining process.



- ✓ **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.

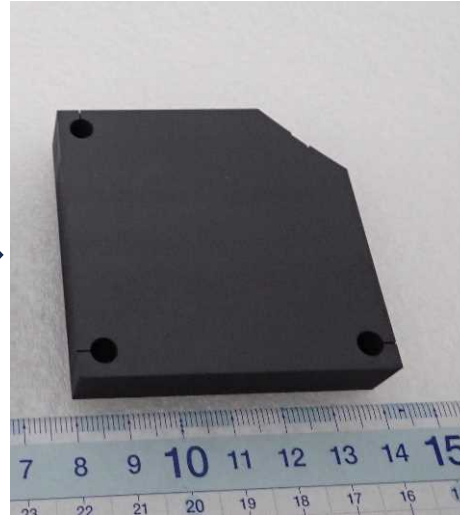
Black coat test for pure tungsten to increase emissivity

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

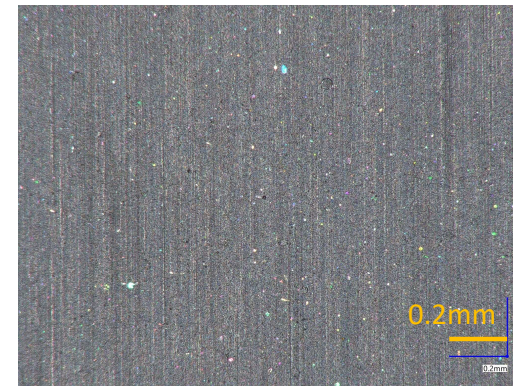
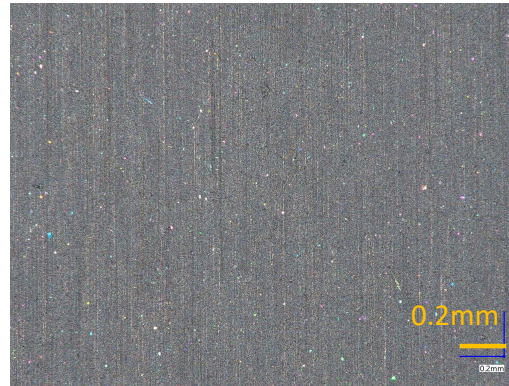
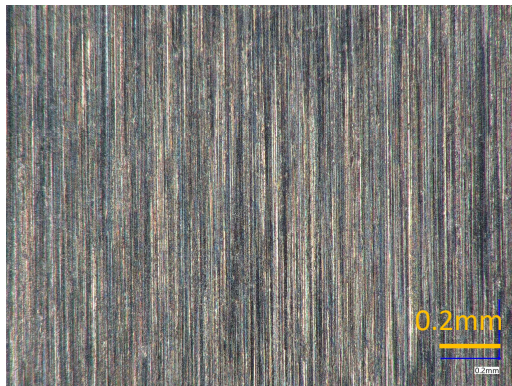
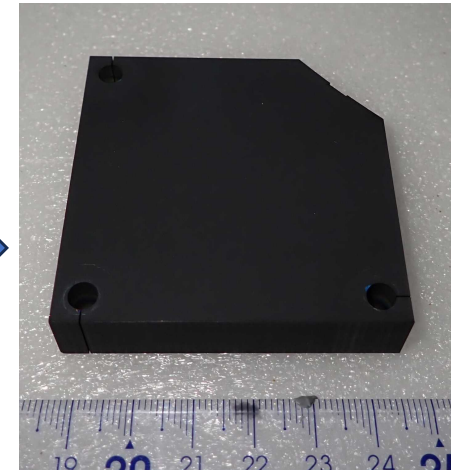
Base tungsten plate
(after chemical polishing)



TiAlN (3 μ m-thick) coating
by ion-plating



After 10 heat cycles
between 30°C \leftrightarrow 400°C.



Emissivity_(average betw. 2~22 μ m)
0.07~0.08

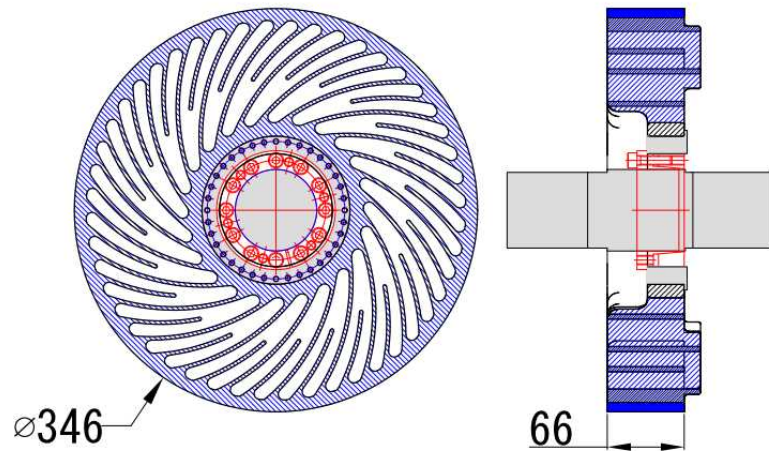
Emissivity: 0.60

Emissivity: 0.58

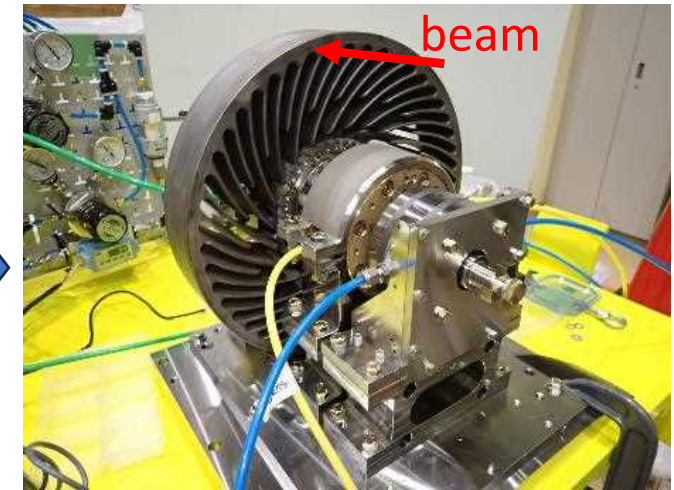
No big change (no flaking off) after 10 cycles betw. 30°C ~ 400°C. It seems a stable coating.

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

R&Ds of Rotating Target: Rotation test with the pure-W disk



Basic rotation tests.



Rotation test with wind-turbine method



- Whole pure-tungsten disk is 7 kg heavier than the dummy disk (W-alloy+ copper disk).
- Rotation tests have to be done.
- ✓ Dynamic balance adjustment was done.
- ✓ Rotation drive at the rated speed (500 rpm) was confirmed.
- ✓ The driving test with the wind turbine method at 500 rpm was confirmed.

Next: Long-term rotation test (under preparation).

Summary

- Indirectly water-cooled fixed target made of gold, up to 115 kW for 4.24s-cycle, is now in service.
 - 82-kW stable beam operation was achieved in Apr. 2024.
- 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 for emergencies.
 - Full-size pure-tungsten disk was manufactured as a trial.
 - Evaluation of the quality (bonding strength etc.) is underway.
 - Basic tests of the rotation system with the pure-W disk were passed.

Next step

- Remaining major R&D:
 - Preparation of the long-term(~ 1000 hrs) rotation test is now in progress.
 - Developments of the disk monitors (displacement sensor and infrared thermometer) are in progress.
- The design of the new target will be determined in FY2025 (hopefully).