Production Target at J-PARC Hadron Experimental Facility

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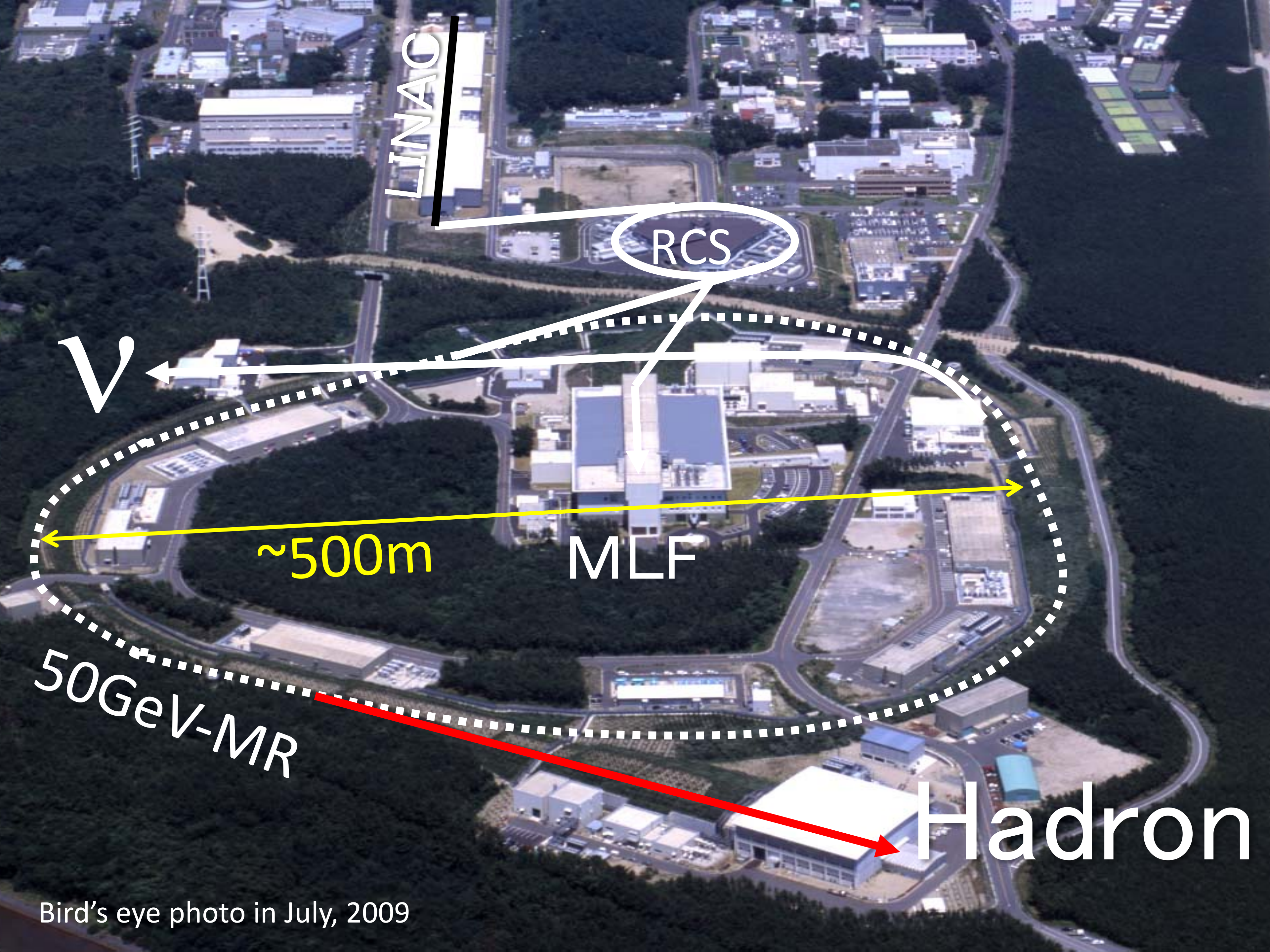
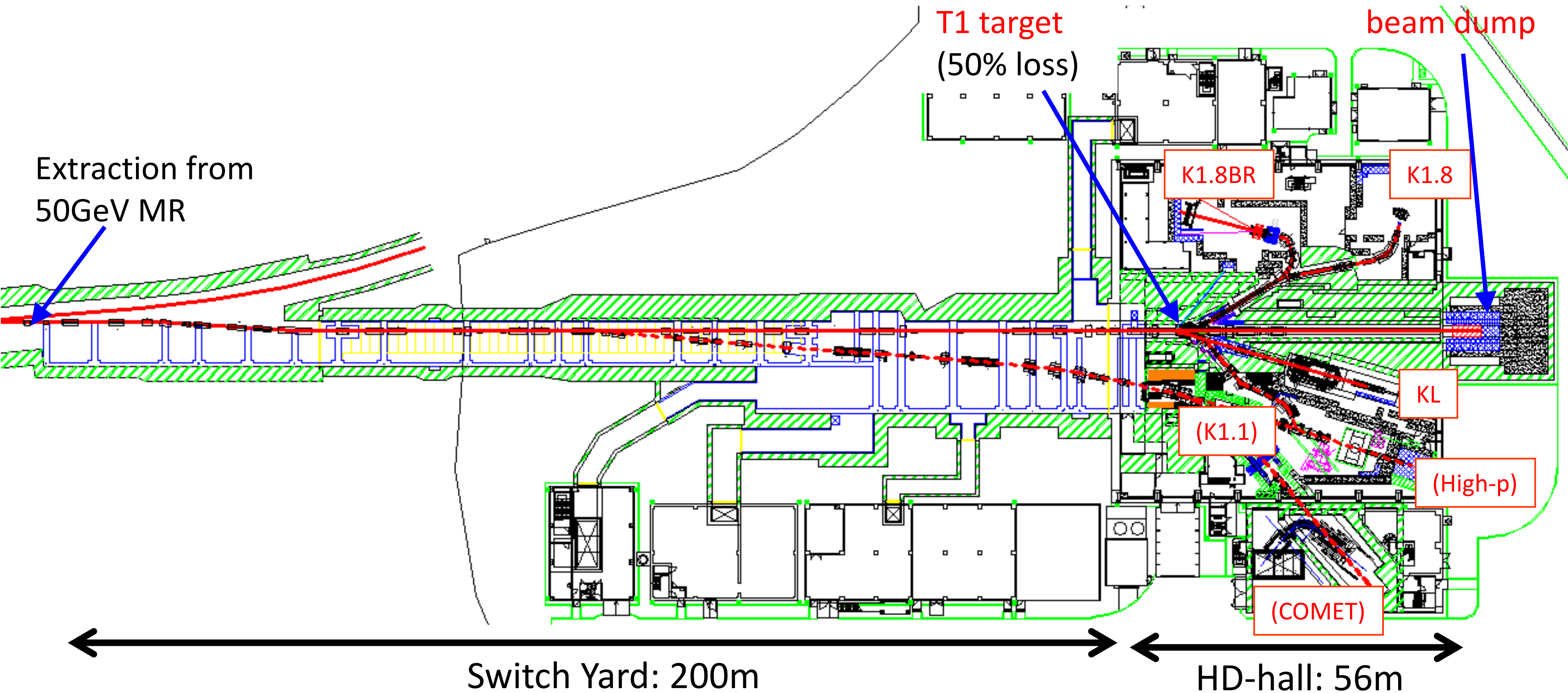
KEK / J-PARC Center



LINAC
RCS
ν
~500m
MLF
50GeV-MR
Hadron
Bird's eye photo in July, 2009

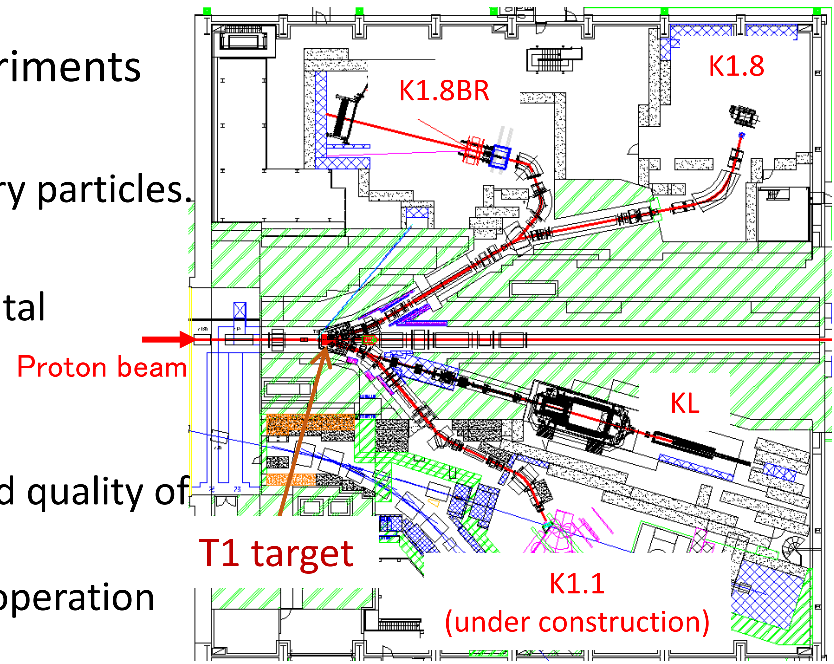
Hadron Experimental Facility (HD-hall)



- ✓ Various secondary beams: π, K, p-bar, ….
- ✓ Currently only one production target: T1
- ✓ KL: kaon rare decay
- ✓ K1.8, K1.8BR, (K1.1): strangeness nuclear physics, etc.
- ✓ New primary beam lines are now under construction (high-p, COMET)

Requirements for Production Target

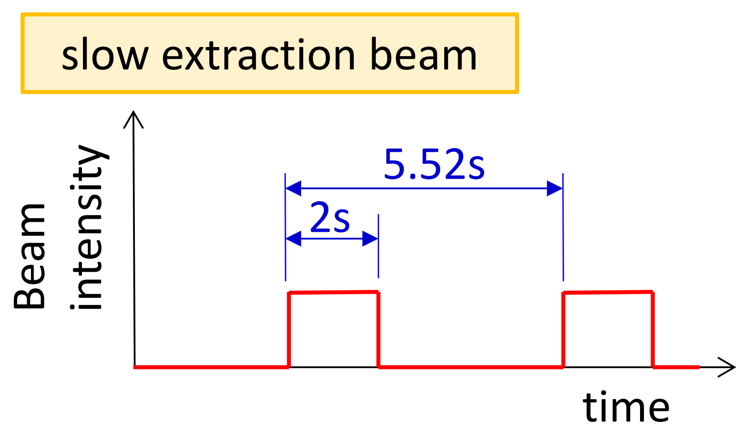
- Target to produce secondary beams (Kaons, pions, antiprotons, ...) for particle and nuclear physics experiments
  - Charged secondary beam lines: K1.8, K1.8BR, (K1.1)
  - → Point source is desirable in order to separate secondary particles.
  - Neutral secondary beam line: KL
  - → Point source is desirable in order to reduce experimental background.



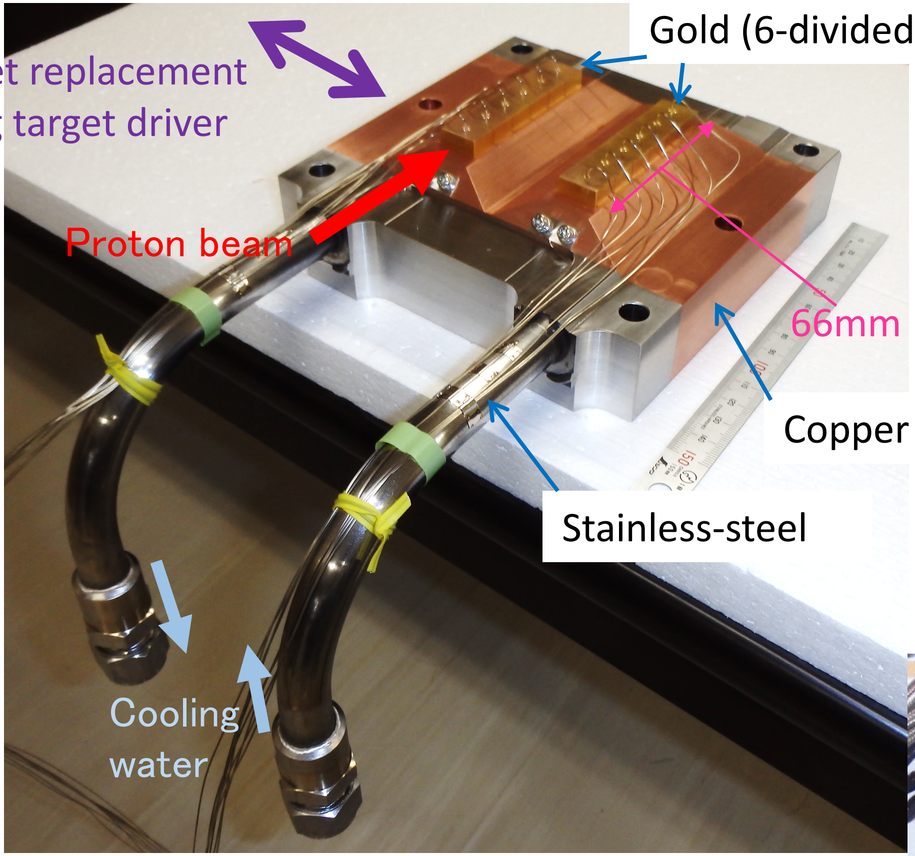
- Requirements
  - ① Large mass number and high density for intensity and quality of secondary beams
  - ② Radiation hardness and chemical stability for stable operation
  - ③ Sufficient cooling efficiency for high-intensity beam

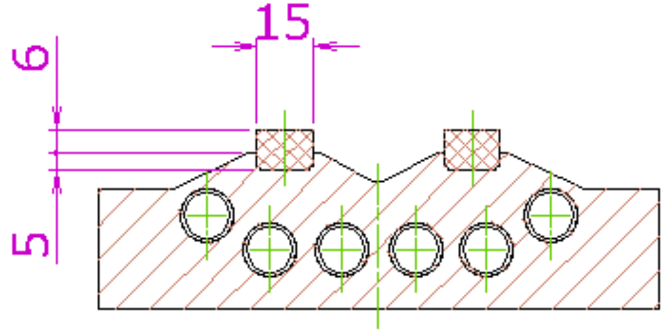
Beam conditions

- Primary proton beam energy: 30 GeV
- Spill structure: 2-sec extraction and 5.52-sec repetition
- Beam loss at target: 50%
- Beam size at T1 target: (σ_x, σ_y) = (2.5mm, 1.0mm)



Current Hadron Target

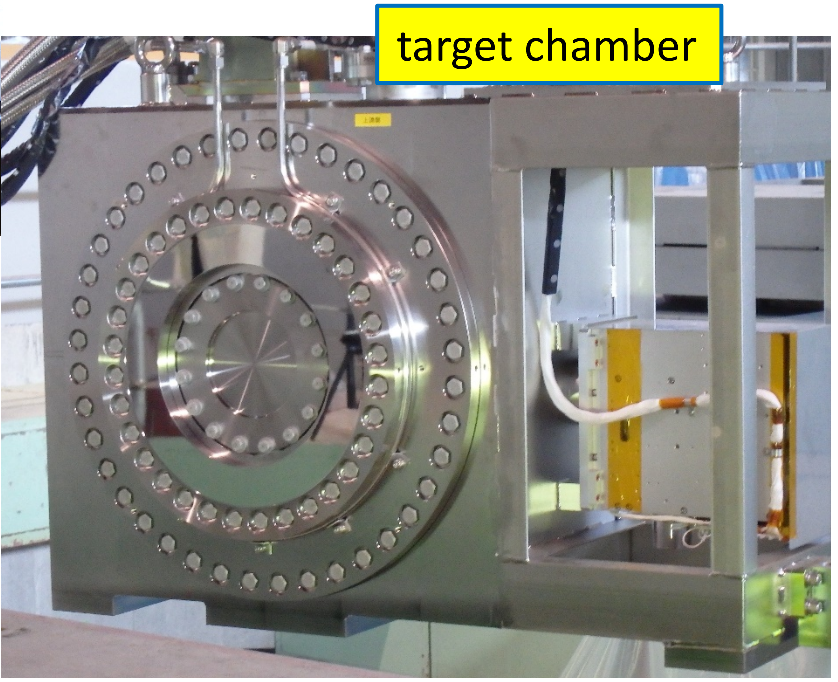




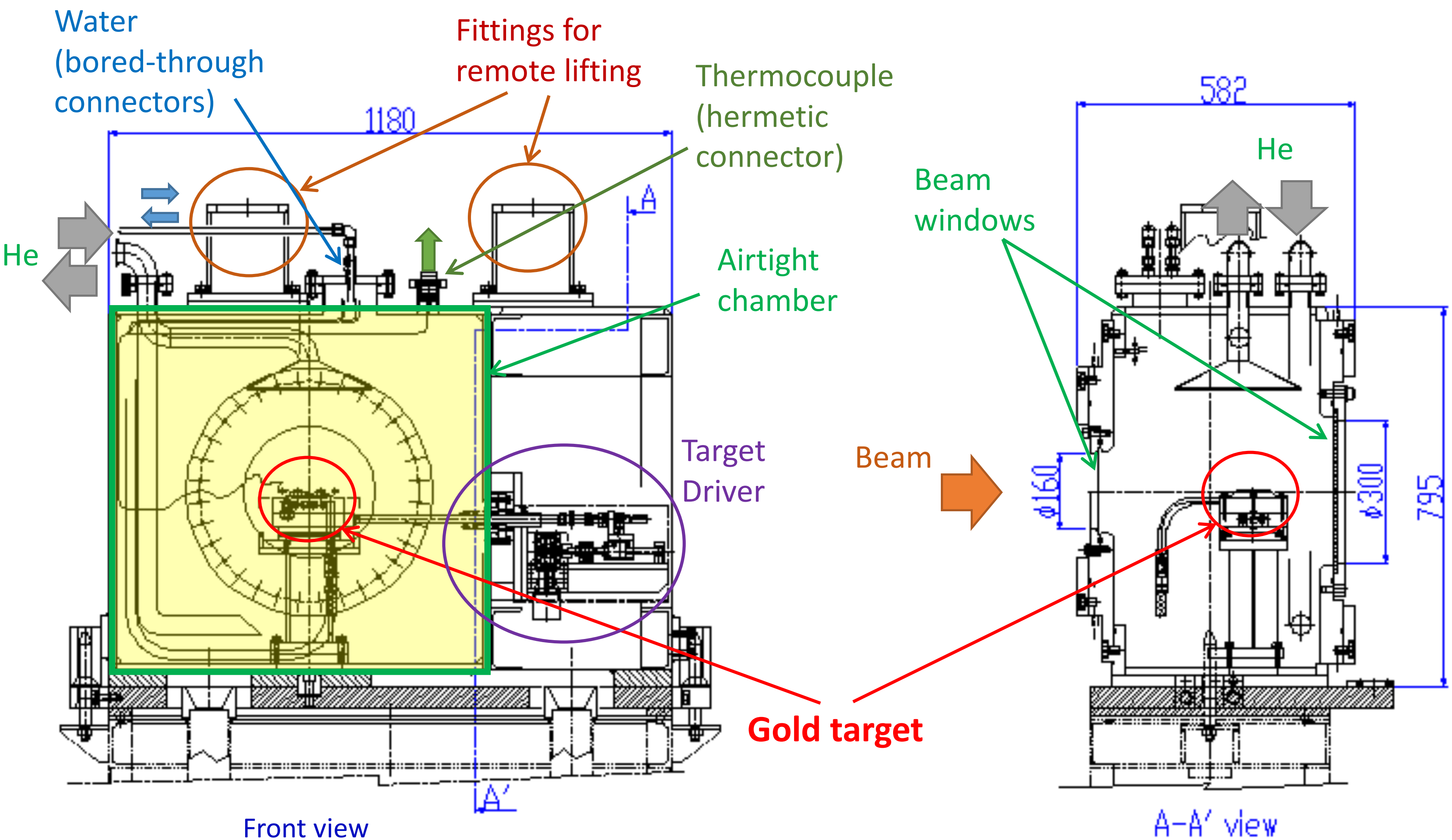
Cross−sectional view

*Gold, copper, and stainless-steel are bonded by HIP (Hot Isostatic Pressing)

- Up to 50 kW beam
- Indirectly water-cooled
- Gold was chosen due to the good thermal conductivity and thermal expansion coefficient close to that of copper
- Involved in airtight chamber and He gas is circulated to monitor the target soundness



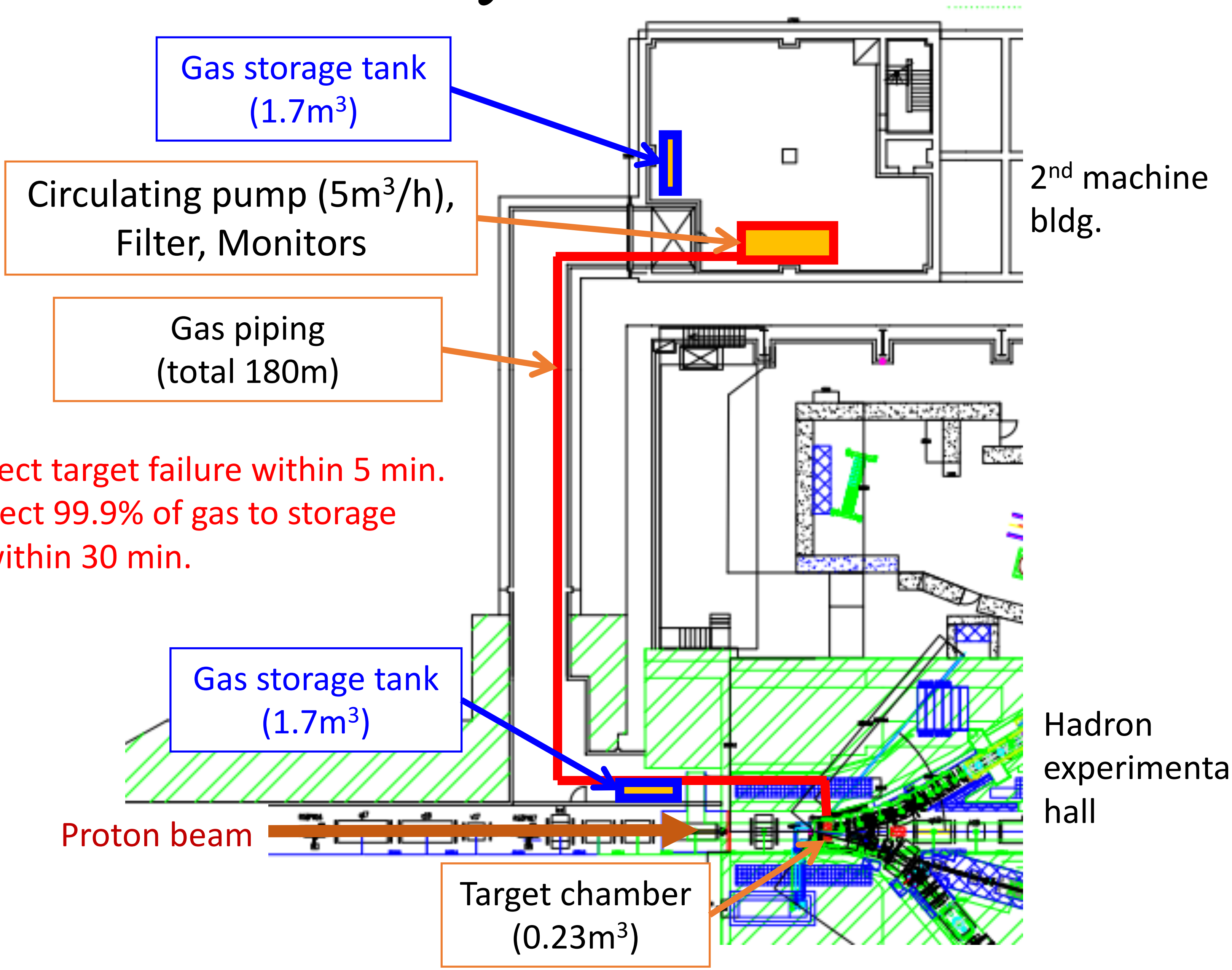
Structure of Target chamber



Since the beam windows are always exposed to a primary beam directly,
we designed the windows to keep their soundness even in the case of 5-μs pulse beams.

* 5-μs = revolution of Main Ring

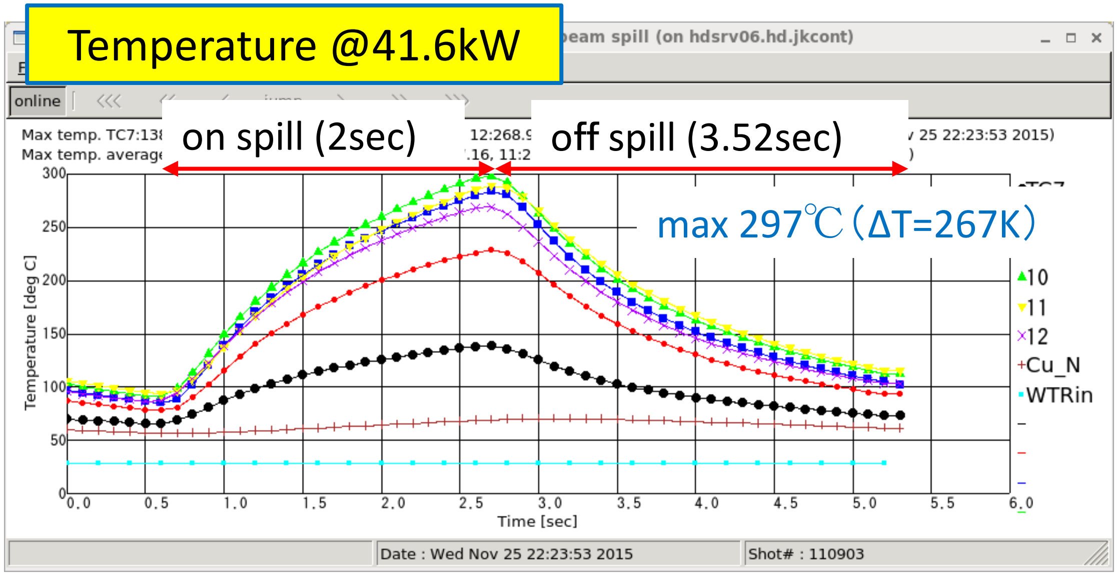
Gas-Circulation System



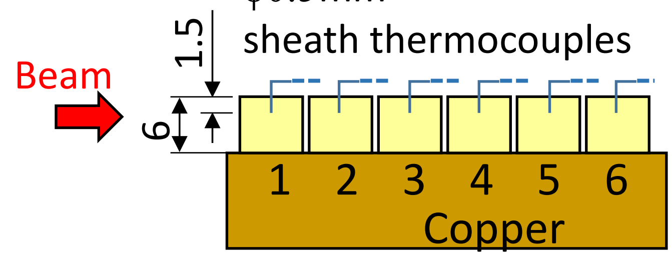
- To detect target failure within 5 min.
- To collect 99.9% of gas to storage tank within 30 min.

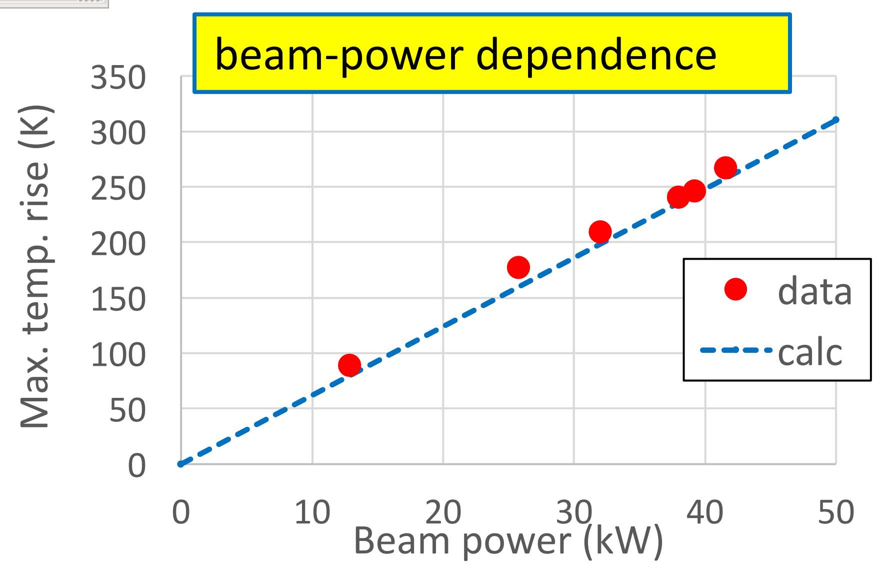
Beam Operation

- Installation: Sep. 2014
- Beam ope.: Apr. 2015 -



Temperature of each gold piece is measured with thermocouples every 100ms





Measured temperature was in good agreement with calculation

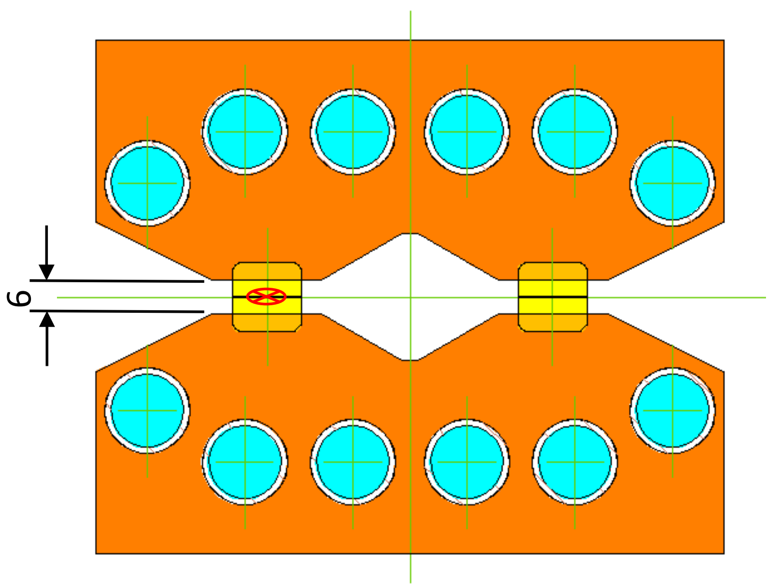
Upgrade Plan of Production Target

- Current
  - indirectly water-cooled gold target
  - up to 50 kW
- Next
  - indirectly water-cooled gold target with improved structure
  - up to 80 kW
  - fabrication process is established
  - will be installed in 2019
- Next to next
  - directly cooled rotating euro-coin target
  - water or He-gas cooled
  - up to 150 – 200 kW
  - several R&Ds are in progress
  - will be installed in 2022?

Indirectly water-cooled fixed target

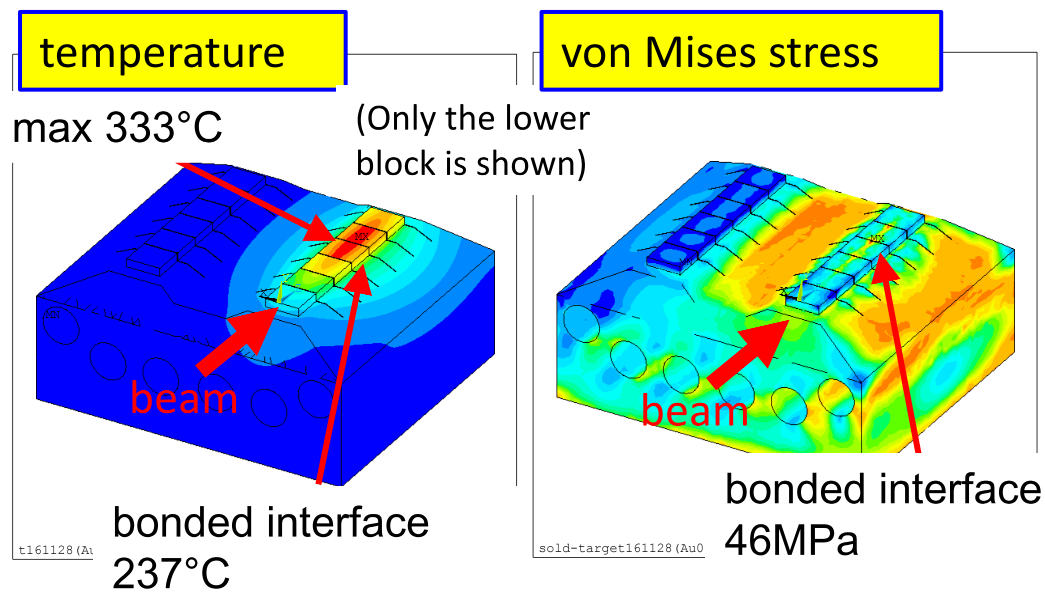
- Gold target with copper cooling block is turned over and stacked on another gold target.
- Each of the gold targets has almost same structure as current target.
- Size of gold is optimized for secondary-beam yield and cooling efficiency.
- ~80 kW proton beam can be accepted.
- Fabrication process is already established.

➡ Ready to manufacture



View from upstream

Results of thermal analysis (80kW, 5.52s cycle)

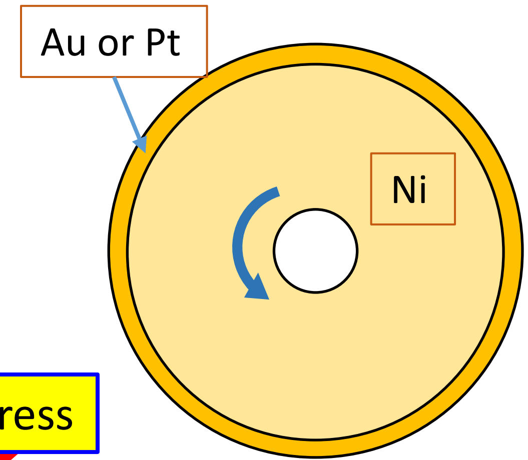


Design margin: 2.7

vertical expansion: max 0.10mm

Directly cooled rotating target

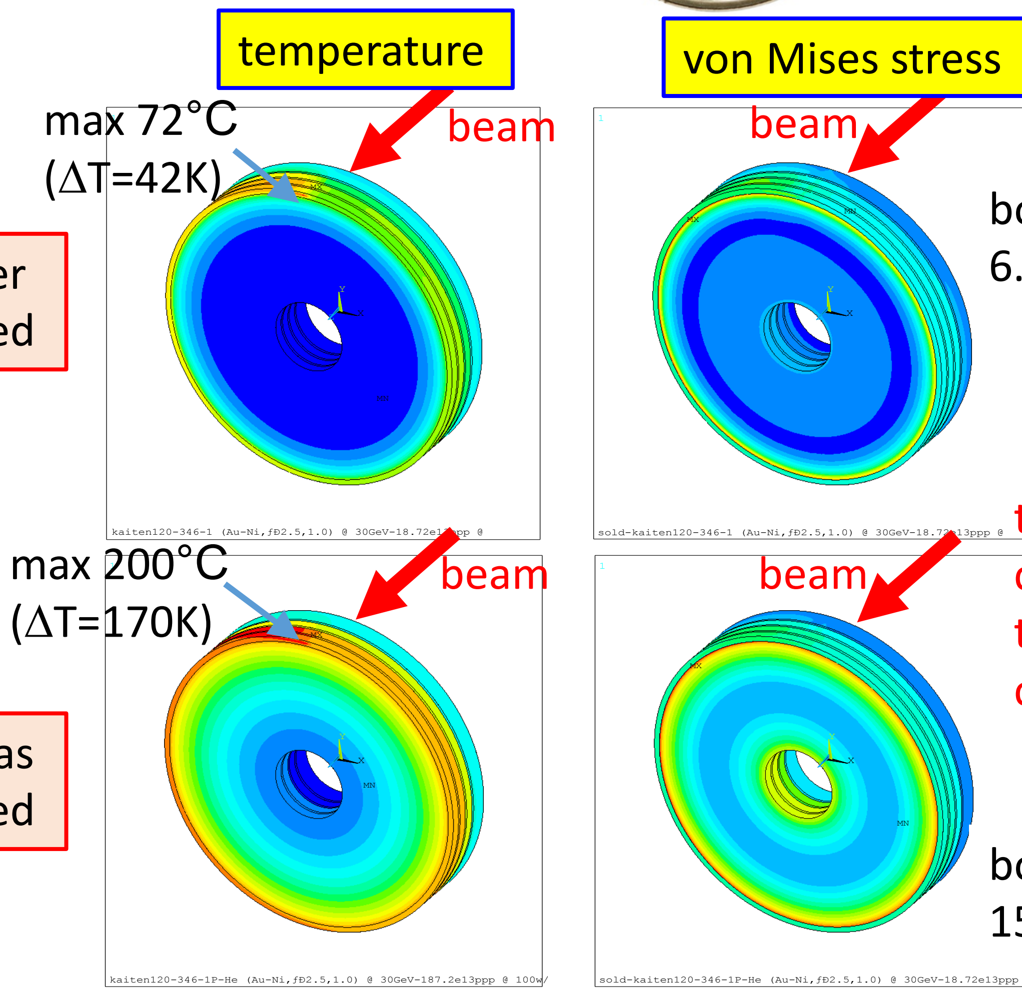
- “Euro Coin” target
  - nickel disks with gold or platinum edge
- Water cooled or He-gas cooled
- Several R&Ds are in progress



Results of thermal analysis (Au, 150kW, 5.52s cycle)

water cooled

He gas cooled



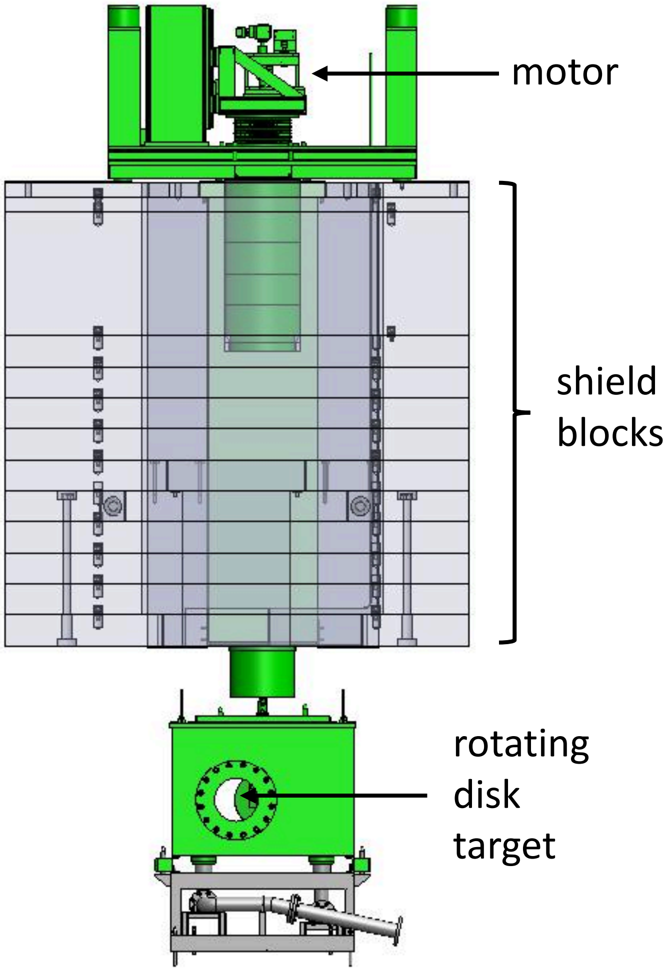
bonded interface 6.3MPa

thermal stress is considerably smaller than that of indirectly cooled target

bonded interface 15MPa

Rotating method

Previous design



issues:

- airtightness of chamber
- large system in high-radiation area

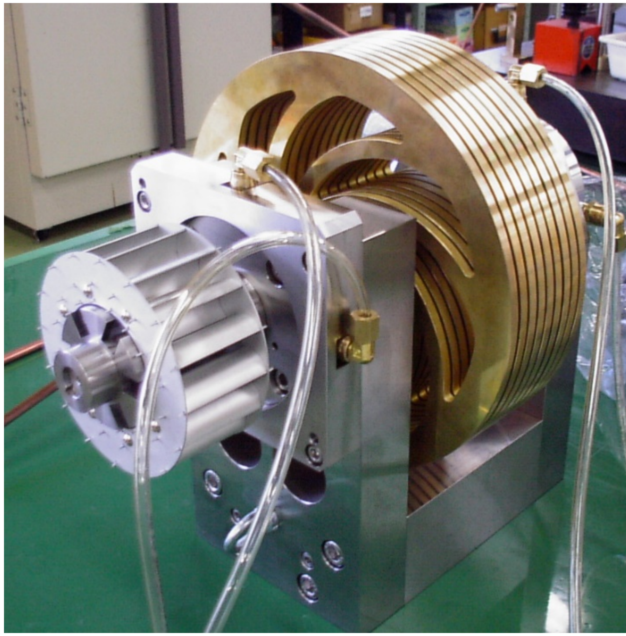
New idea

water turbine

He gas turbine

No need for motor and long shaft

- airtightness of chamber can be achieved easily
- simple and small components in high-radiation area



Comparison of cooling/rotating methods

water

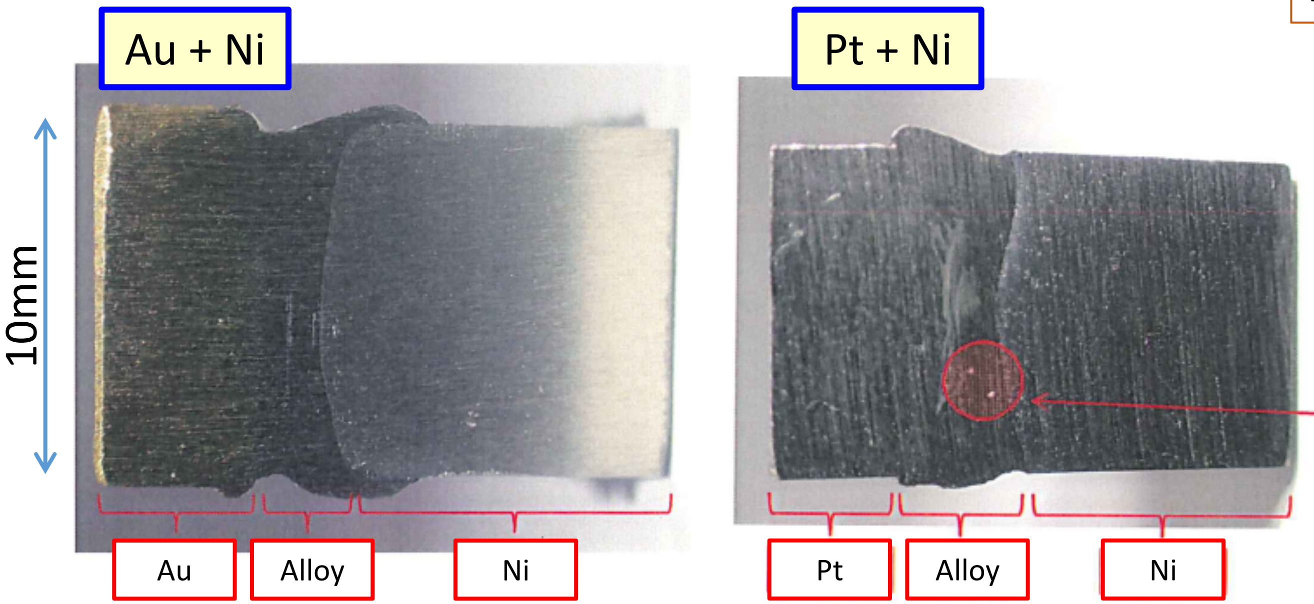
- good cooling efficiency
  - capable of higher beam power
- large rotating torque
- need corrosion resistance
- large amount of tritium generation
- need R&Ds of water circulation system
  - pumping up from bottom tank
  - ion exchanger
  - recombinator
- also need He-gas circulation system
  - moisture is contaminated to He gas

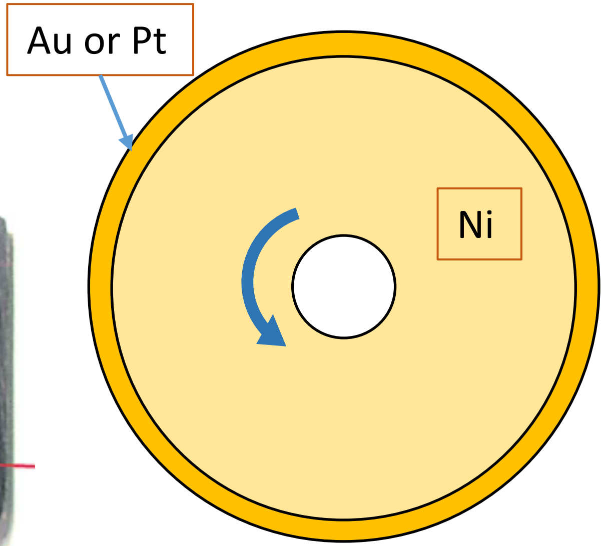
He gas

- clean (small amount of NOx, H gas, and tritium generation)
- no need for water circulation system
- cooling efficiency is unknown
- rotating torque is unknown
- need large-flow He-gas circulation system

Bonding test of "Euro Coin"

Electron Beam Welding

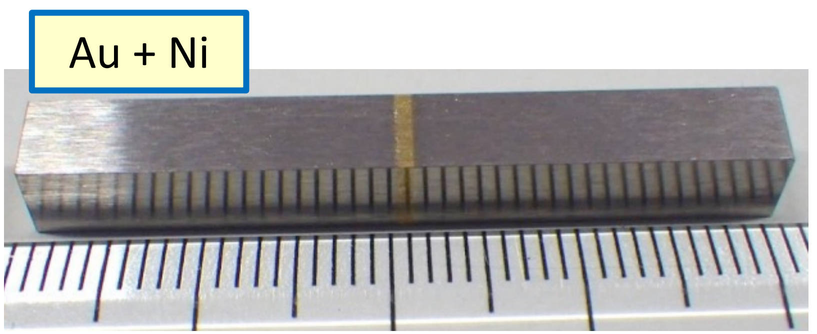




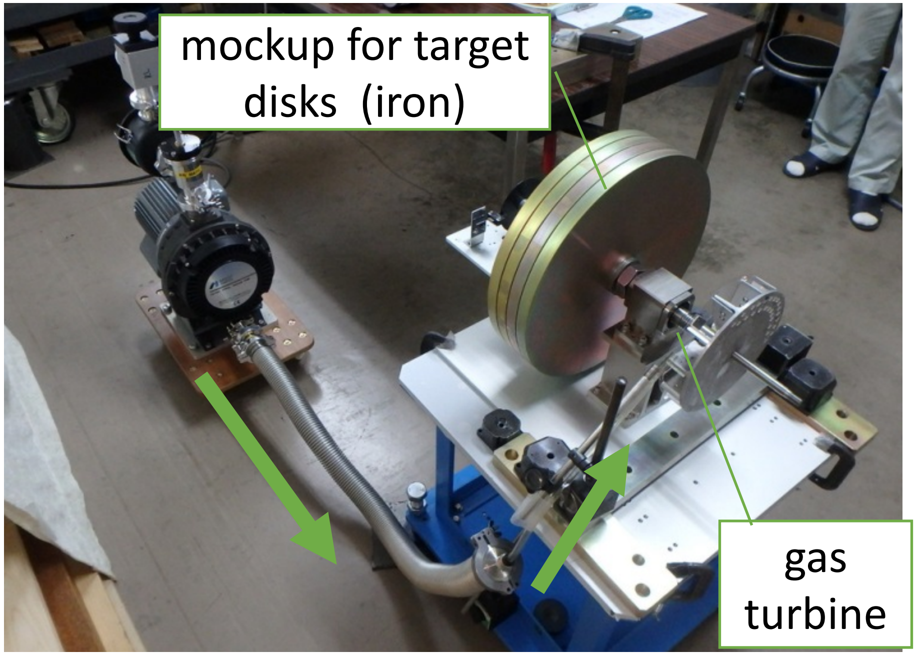
- alloy layer is thick (~2mm)
- beam was deflected to gold side
- need more optimization

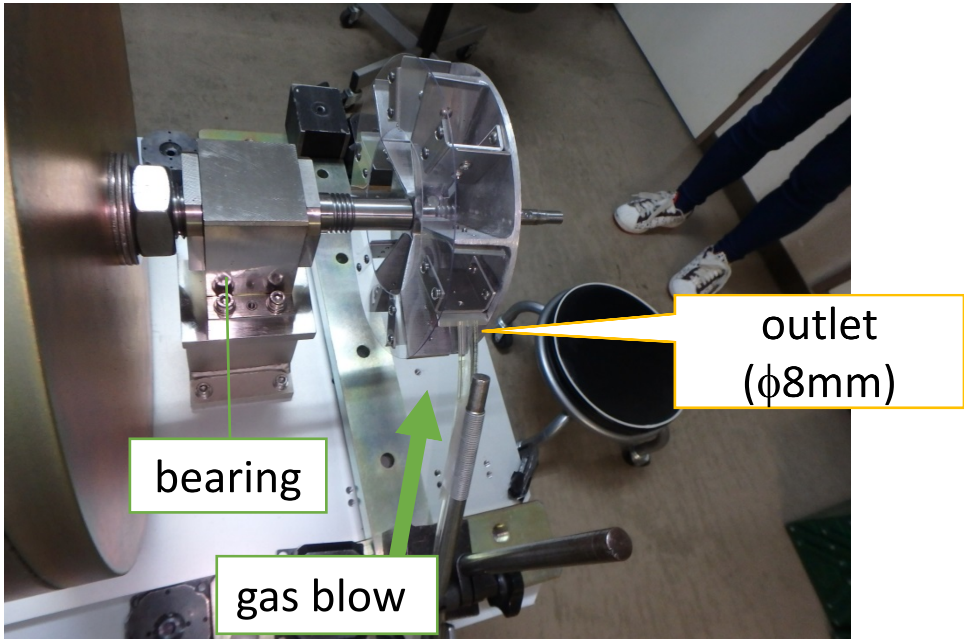
Hot Isostatic Pressing

- applied to current hadron target (Au+Cu)
- thin boundary layer (several ten microns) between Au(Pt) and Ni



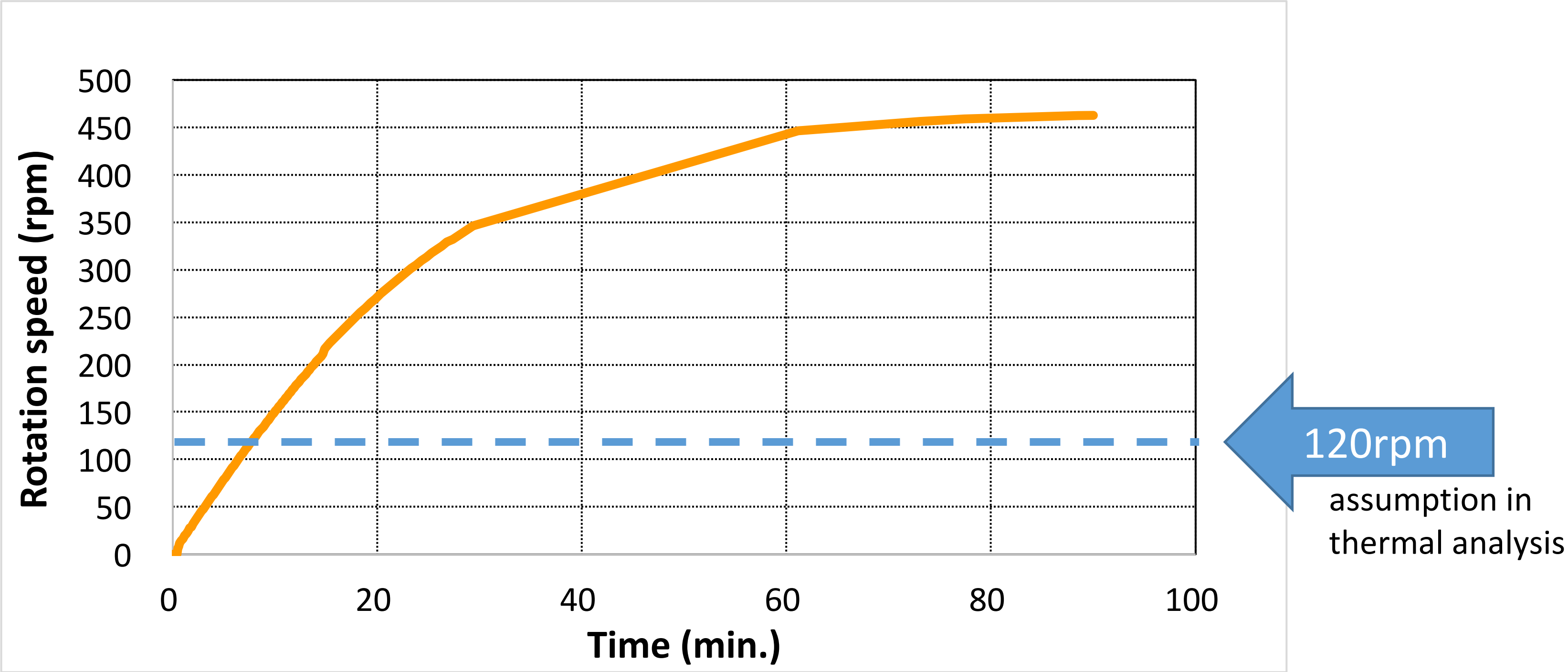
Gas turbine test





- Simple rotation test using exhaust of scroll pump
- The gas turbine (plate fan) was prepared by disassembling and modifying a commercial blast fan

Result of gas turbine test



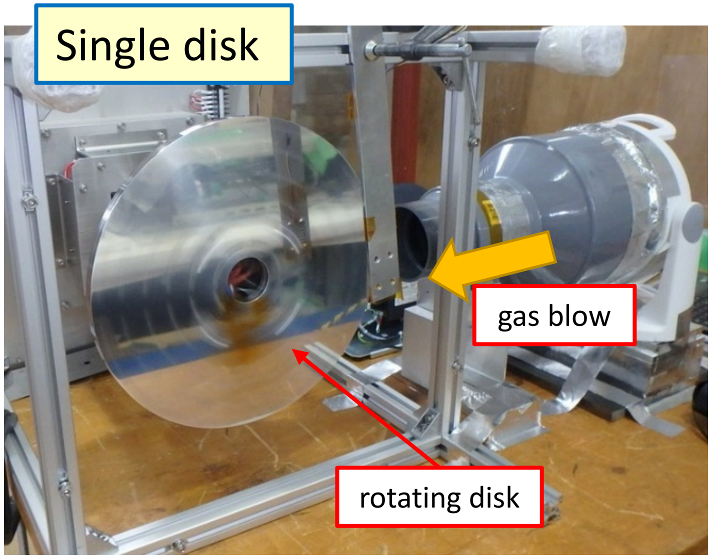
Target disks can be driven even with flow rate of scroll pump (~35 l/min)

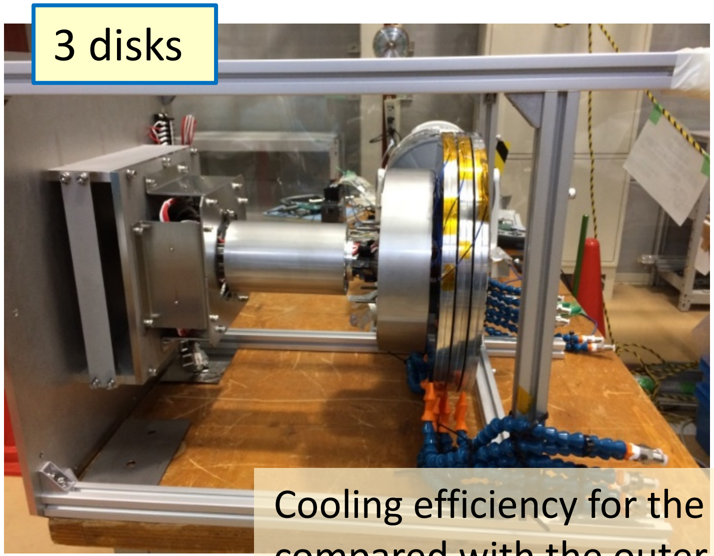
Next step

- rotation test with He gas
- rotation speed control (feedback system)
- bearing, rotation speed monitor, ...

Efficiency of He-Gas Cooling

Simple flat disk(s)

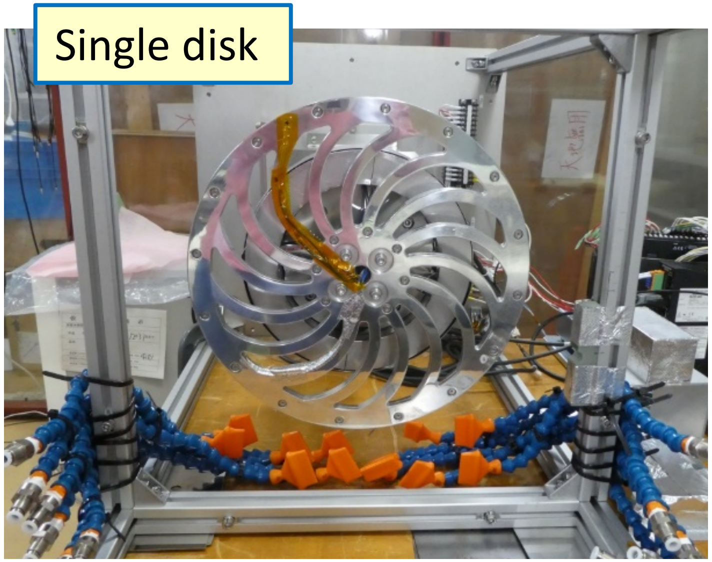


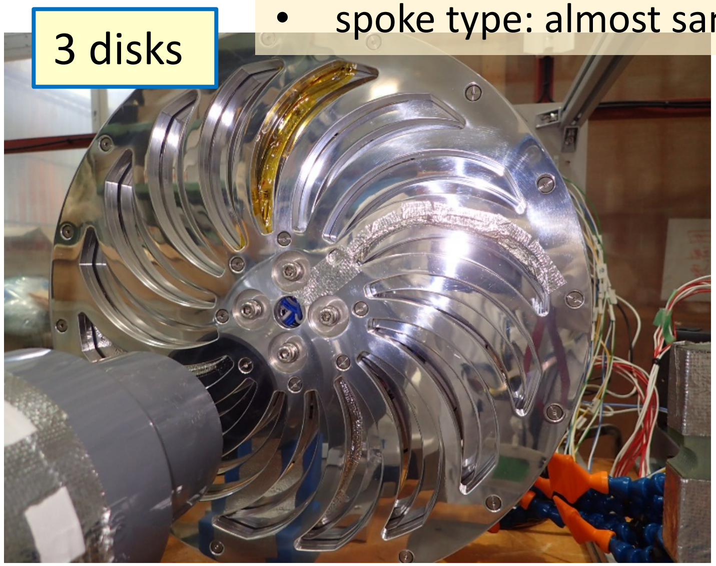


Cooling efficiency for the inner disk compared with the outer disks

- flat type: less than half
- spoke type: almost same

Spoke-type disk(s)





Beam Windows of Target Chamber

Current: **Titanium alloy (Ti-6Al-4V)**

- Thermal stress:

  OK up to 10^7 cycles (~ 15k hours)

- Accumulated strain due to creep deformation:

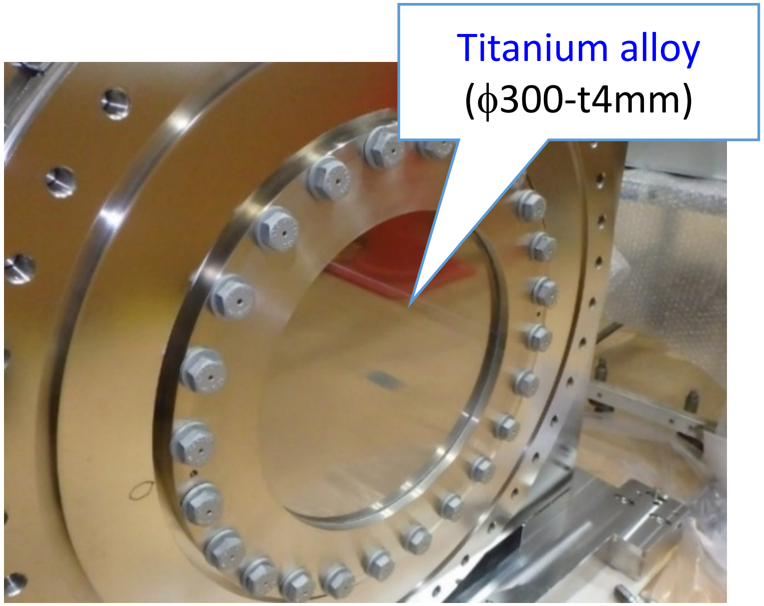
  will reach the endurance limit (1 %)

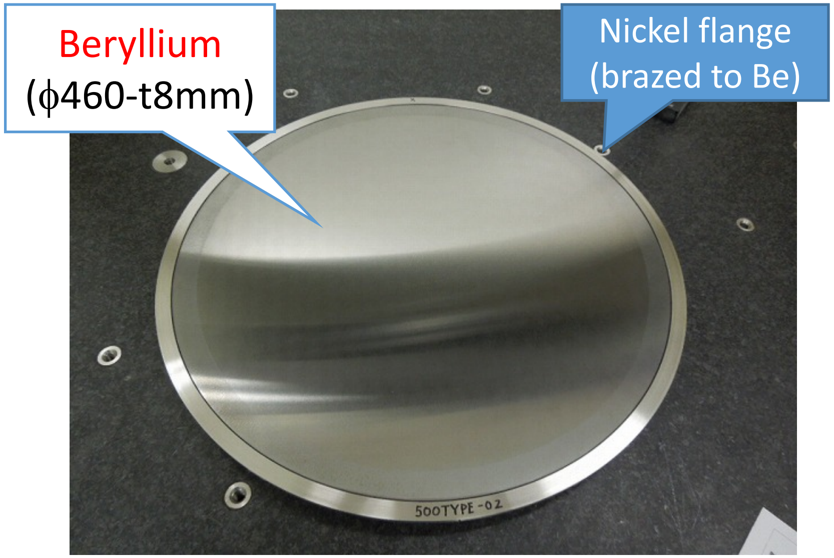
  in ~50 kW x 7.5k hours

=> This limited the life of current target

Next: **Beryllium** or **Titanium alloy**

(with improved cooling)





Soundness of Be windows (80kW)

S_M: design stress intensity (=UTS/3.5)

Material	Case		Estimated Stress	Allowable Stress
Upstream Beryllium 3 mm^t	Maximum static stress by atmospheric pressure		48 MPa (edge) 31 MPa (center)	133 MPa (1.5xS_M @100°C)
	Equivalent stress amplitude in normal operation	Shot by shot	3.7 MPa (ΔT=3.6K)	126 MPa (10^7 fatigue str. @100°C x1/2)
		Average temp.	3.8 MPa (ΔT=3.9K)	126 MPa (10^4 fatigue str. @100°C x1/2)
	Thermal stress range by 5-μs beam		166 MPa (ΔT=93K)	256 MPa (3xS_M @150°C)
Downstream Beryllium 6 mm^t	Maximum static stress by atmospheric pressure		42 MPa (edge) 27 MPa (center)	133 MPa (1.5xS_M @100°C)
	Equivalent stress amplitude in normal operation	Shot by shot	2.8 MPa (ΔT=3.2K)	126 MPa (10^7 fatigue str. @100°C x1/2)
		Average temp.	17.2 MPa (ΔT=18K)	126 MPa (10^4 fatigue str. @100°C x1/2)
	Thermal stress range by 5-μs beam		151 MPa (ΔT=93K)	256 MPa (3xS_M @150°C)

In all cases, estimated stress are lower than allowable stress.

*allowable stresses are according to JIS-B8266.(construction for pressure vessels)

Soundness of Ti-alloy windows (80kW)

S_M: design stress intensity (=UTS/3.5)

Material	Case		Estimated Stress	Allowable Stress
Upstream Ti-alloy (6Al,4V) 2 mm^t	Maximum static stress by atmospheric pressure		145 MPa (edge) 176 MPa (center)	430 MPa (1.5xS_M @450°C)
	Equivalent stress amplitude in normal operation	Shot by shot	53 MPa (ΔT=138K)	206 MPa (10^7 fatigue str. @450°C x1/2)
		Average temp.	80 MPa (ΔT=153K)	306 MPa (10^4 fatigue str. @400°C x1/2)
	Thermal stress range by 5-μs beam		242 MPa (ΔT=480K)	502 MPa (3xS_M @600°C)
Downstream Ti-alloy (6Al,4V) 4 mm^t	Maximum static stress by atmospheric pressure		119 MPa (edge) 162 MPa (center)	430 MPa (1.5xS_M @450°C)
	Equivalent stress amplitude in normal operation	Shot by shot	21 MPa (ΔT=82K)	206 MPa (10^7 fatigue str. @450°C x1/2)
		Average temp.	148 MPa (ΔT=351K)	306 MPa (10^4 fatigue str. @400°C x1/2)
	Thermal stress range by 5-μs beam		234 MPa (ΔT=350K)	310 MPa (3xS_M @800°C)

In all cases, estimated stress are lower than allowable stress.

*allowable stresses are according to JIS-B8266.(construction for pressure vessels)

Radiation Issues for Beam Windows

Estimated by PHITS(damage, radioactivity) and MARS(residual dose)

After 80kW x 2500 hours (= 1.5 x 10^{20} protons) irradiation

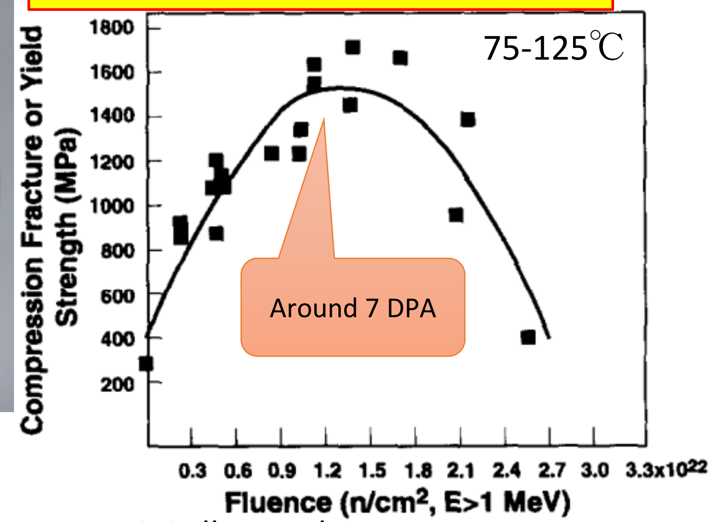
	Peak radiation damage (R=0mm)	Residual dose at contact after 3 months cooling	Radioactivity after 10 min. cooling
Ti-alloy (6Al,4V)	1.2 DPA	980 mSv/h	46 GBq (57 nuclides)
Beryllium	0.014 DPA	6.3 mSv/h	2.7 GBq (2 nuclides)

Both damage rate and radioactivity for Be are much lower than those for Ti alloy.

Other beam windows we use:

Thin Aluminum-alloy (Al-4.5Mg-0.7Mn, or Al-4.5Zn-2Mg) for vacuum separation between high- and low-vacuum sections

Strength of Be after irradiation



D.S.Gelles et al, J. of Nucl. Materi. 212-215 (1994) 29-38

We are very interested in the radiation-damage effects for these materials.

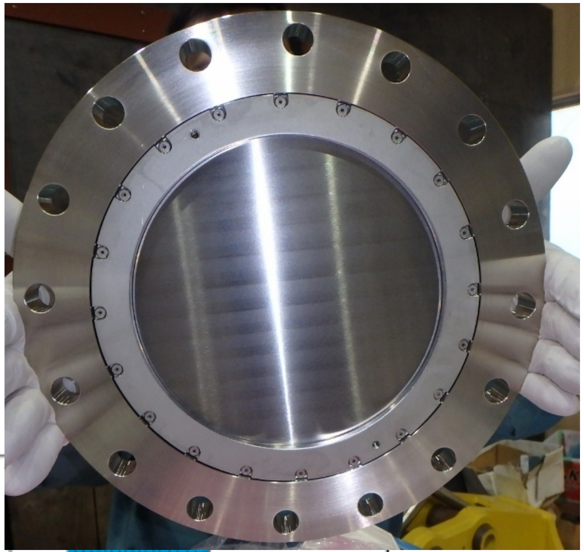
Summary of Hadron Target

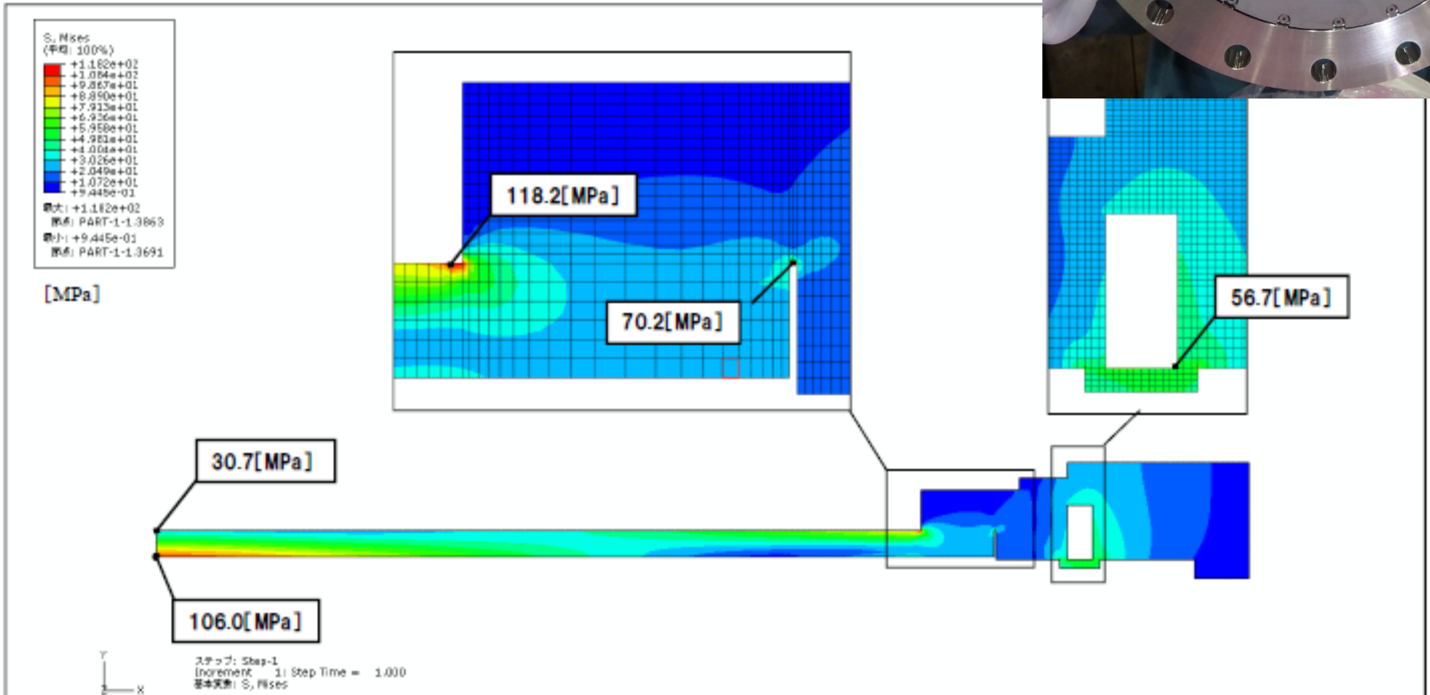
- Current
  - indirectly water-cooled gold target
  - Ti-alloy window
  - up to 50 kW
- Next
  - indirectly water-cooled gold target with improved structure
  - Be window
  - up to 80 kW
  - fabrication process is established
  - will be installed in 2019
- Next to next
  - directly cooled rotating euro-coin target
  - water or He-gas cooled
  - up to 150 – 200 kW
  - several R&Ds are in progress

back up

Design of Beam Window for Next Target

- Material : Beryllium
- It can be applied up to 270kW by tentative estimation and detail analysis is in progress.
- Radiation-damage rate is very low : 0.04DPA/7500hours.
- Manufacturing process was established in 2009.
- Additional studies such as strength tests are in progress.





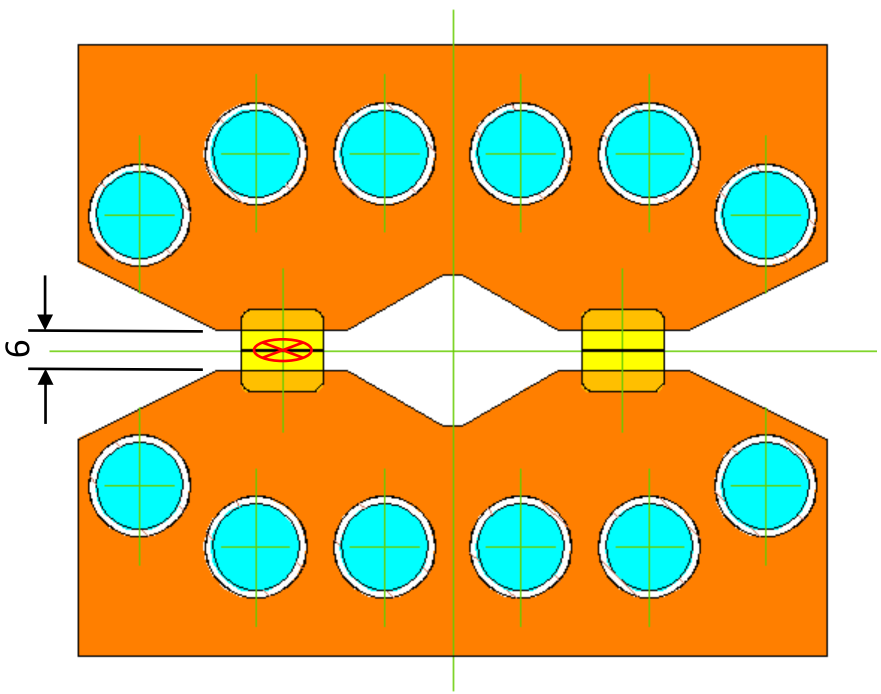
Stress estimation for 270kW beam.

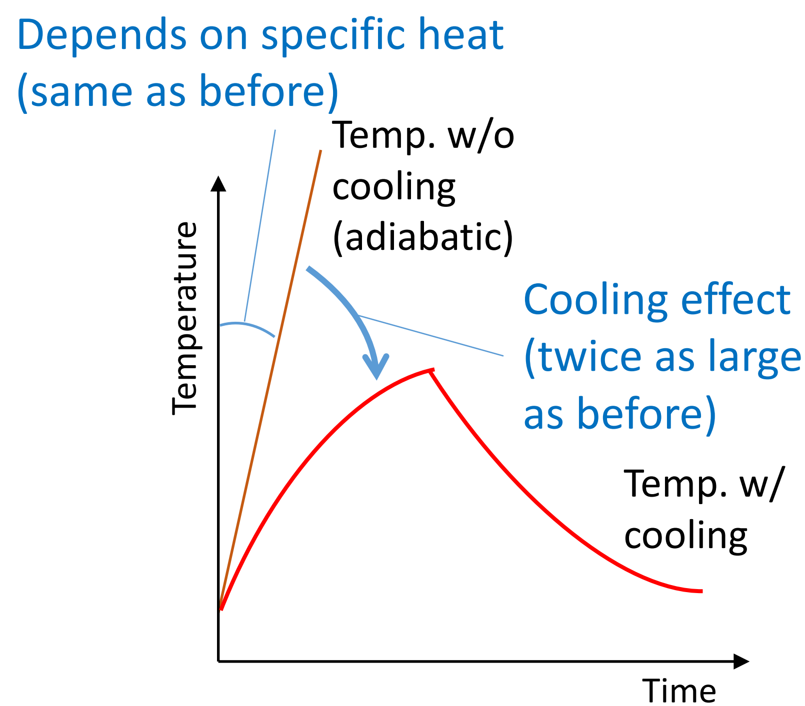
ミーゼス相当応力分布図(820.8sec)

Why not 100kW?

- The temperature rise in 1 spill depends on the cooling efficiency and the size (heat capacity) of the gold target exposed to the beam.
- The cooling efficiency is twice the current target, but the heat capacity is not.

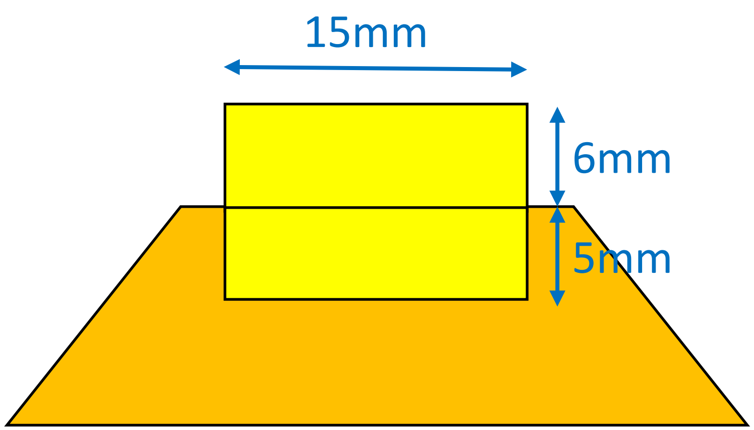
The temperature rise of the new target with the 100kW beam in 1 spill is higher than the 50kW case of the current target



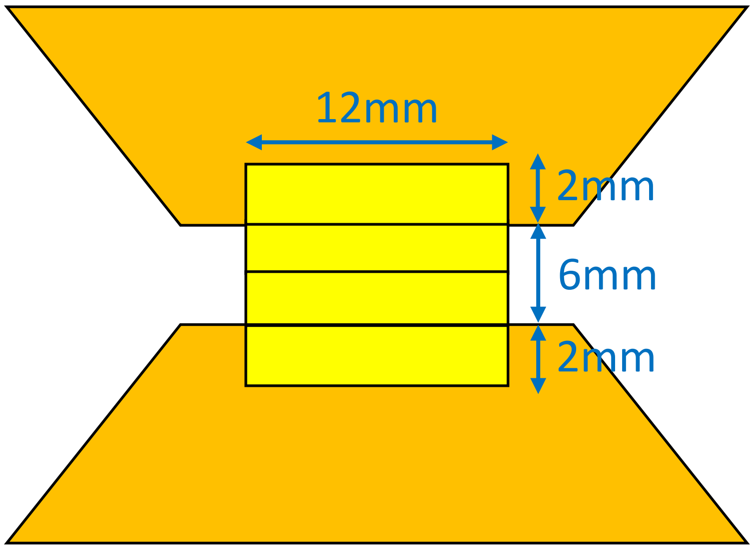


Size of gold target

Size of gold is optimized for secondary-beam yield and cooling efficiency.



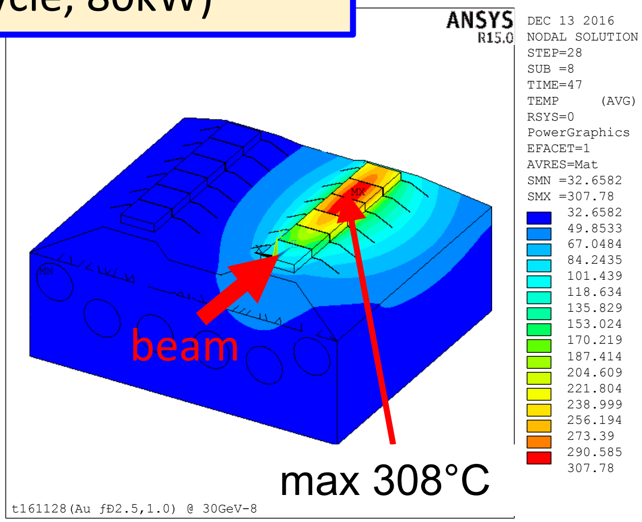
Current 50kW target



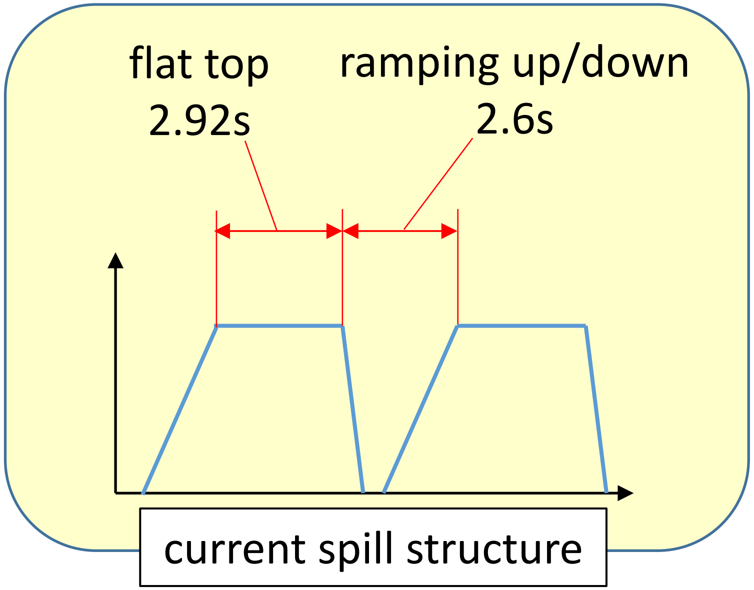
Next 80kW target

Maximum Beam Power

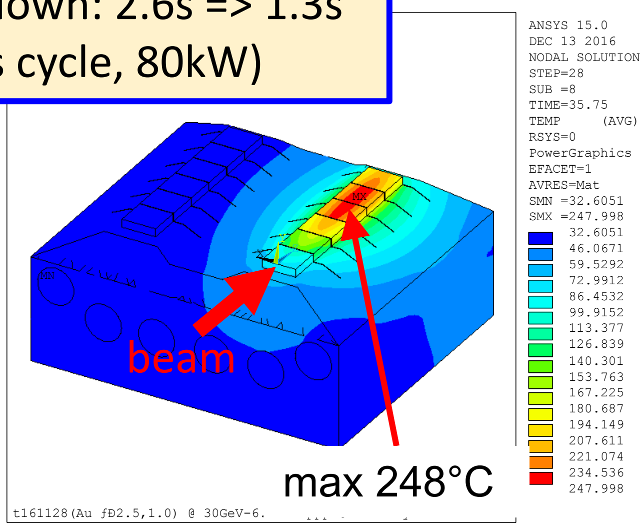
flat top: 2.92s => 2.4s
(5s cycle, 80kW)



max. beam power:
87kW?



moreover, ramping up/down: 2.6s => 1.3s
(3.7s cycle, 80kW)

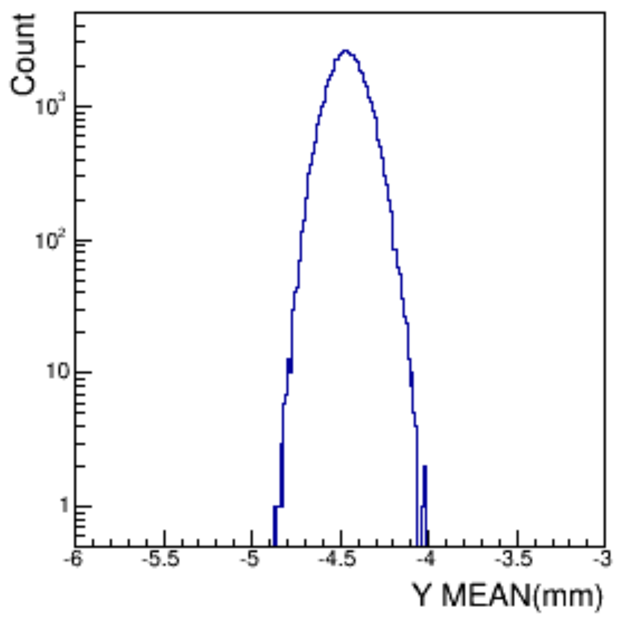


max. beam power:
111kW?

These are simple estimations by assuming allowed temperature rise is same as that for 5.52s cycle and 80kW. Detailed consideration is needed to determine the maximum power for operation.

Stability of Beam Position (V)

Time projection of vertical beam position measured with the profile monitor just upstream of the target in previous run

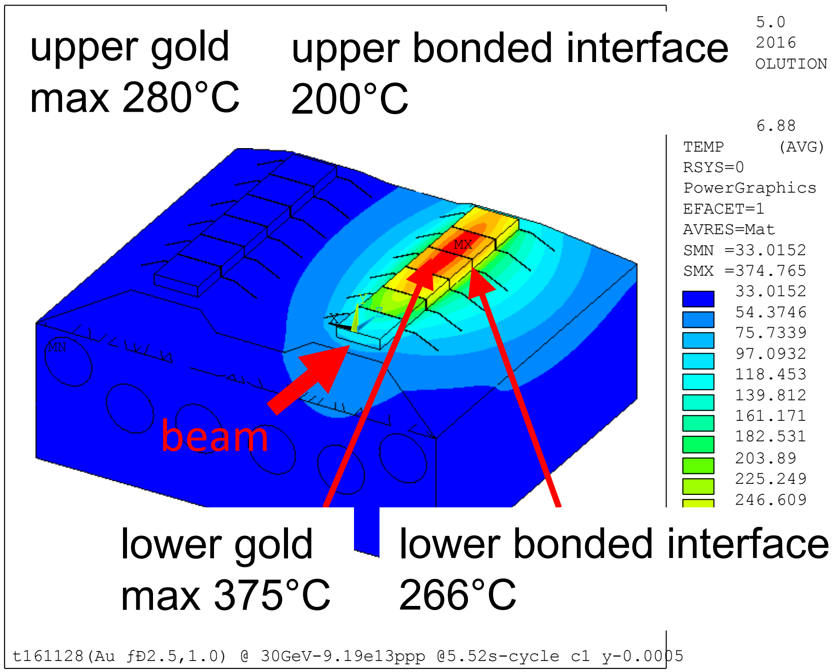


very stable in rage of +/- 0.5mm

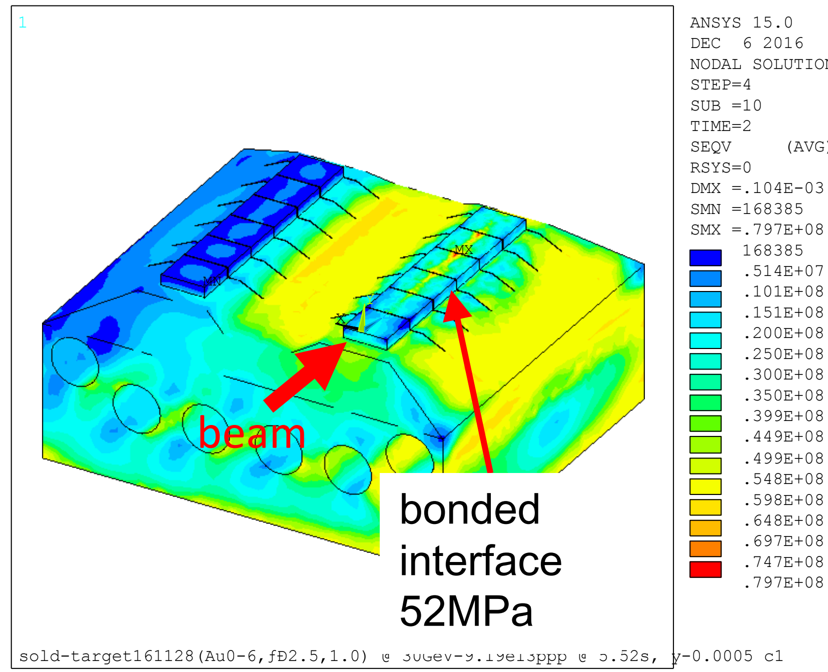
Thermal Analysis (80kW, 5.52s Cycle)

In case beam shifts 0.5mm lower continuously

temperature



von Mises stress



Bonding strength:
171MPa(@25°C)
137MPa(@200°C)
76MPa(@400°C)
linear interpolation:
117MPa(@266°C)

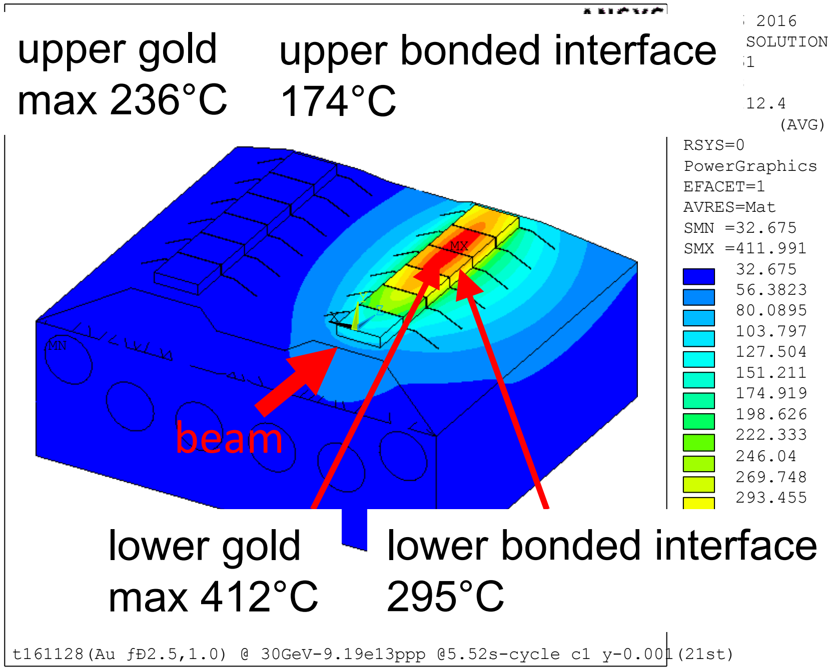
vertical expansion:
upper gold: max 0.08mm
lower gold: max 0.10mm

Design margin: 2.3

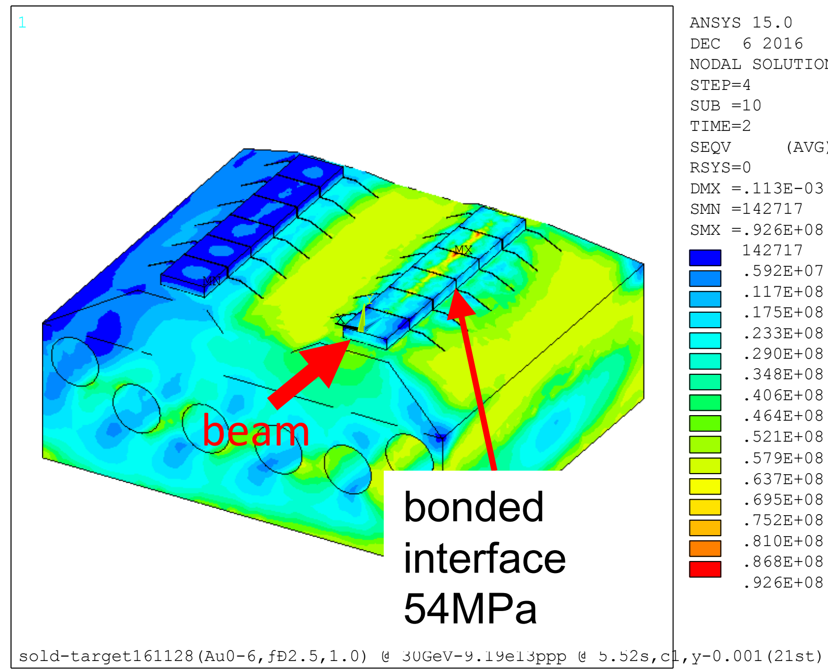
Thermal Analysis (80kW, 5.52s Cycle)

In case beam shifts 1mm lower in 1 spill

temperature



von Mises stress



Such an unusual beam can be detected by plural monitors (target temperature, profile monitor, magnet current) and be aborted during spill

"SX Abort"

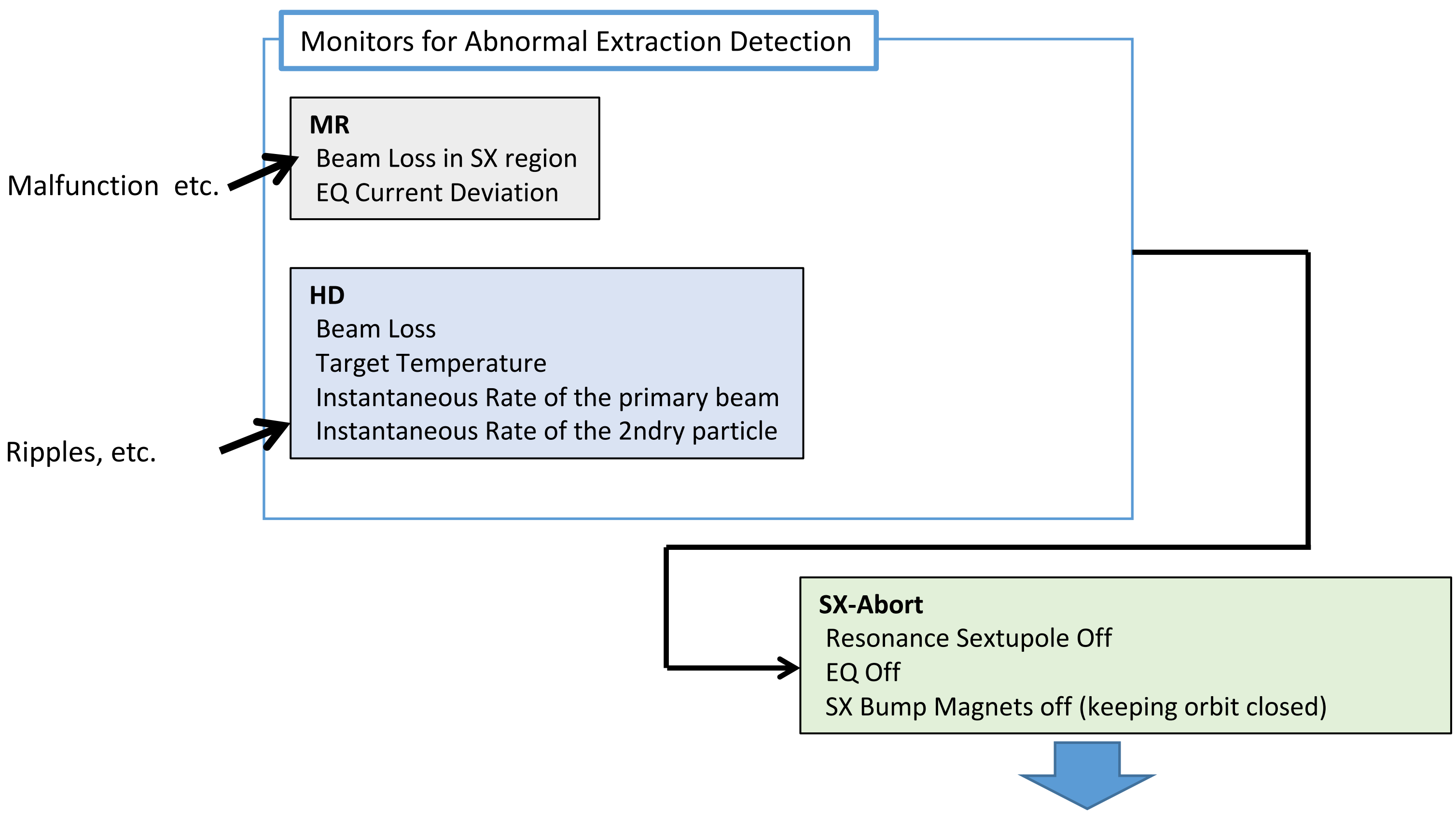
Bonding strength:
171MPa(@25°C)
137MPa(@200°C)
76MPa(@400°C)
linear interpolation:
108MPa(@295°C)

vertical expansion:
upper gold: max 0.07mm
lower gold: max 0.11mm

Design margin: 2.0

SX-Abort system

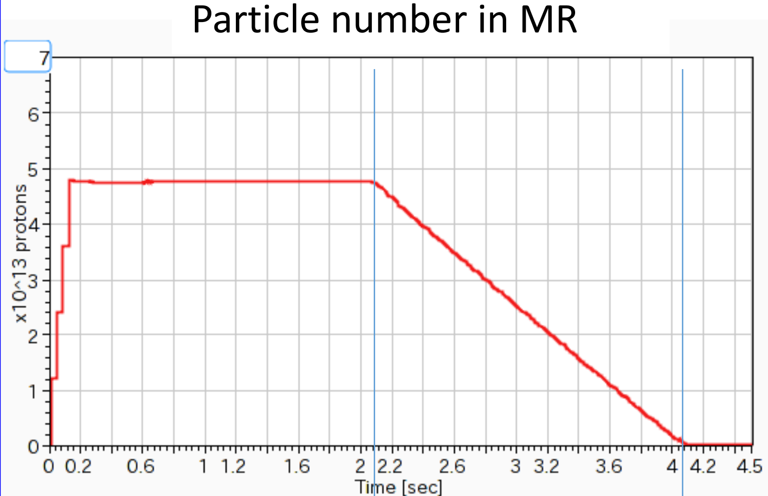
- **Installed during the summer, 2015.**
- **A part of the Machine Protection System (MPS).**
- **A strong tool to protect equipment (beam duct, target, …) from abnormal hit of the primary beam.**

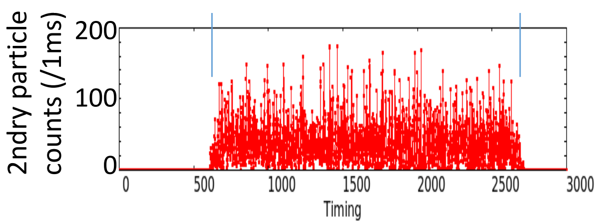


Extraction stops even after the extraction started, and the beam continues to circulate in the MR, and is kicked to the aborting dump at the end of the spill.

Example of SX-Abort shot

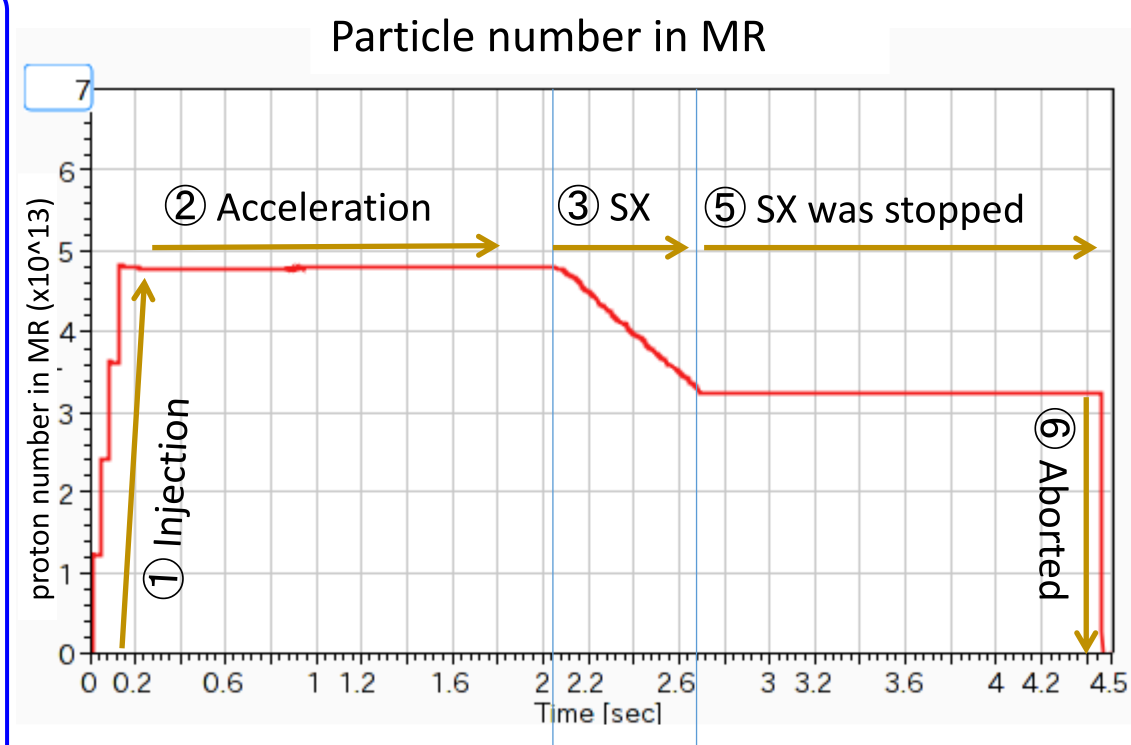
Normal operation

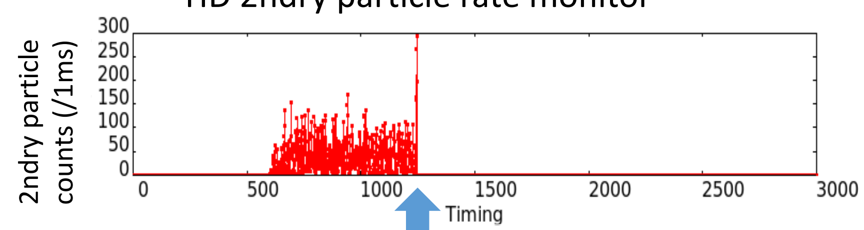




Unusual beam

2015-12-17 03:23
RUN65 shot 397185



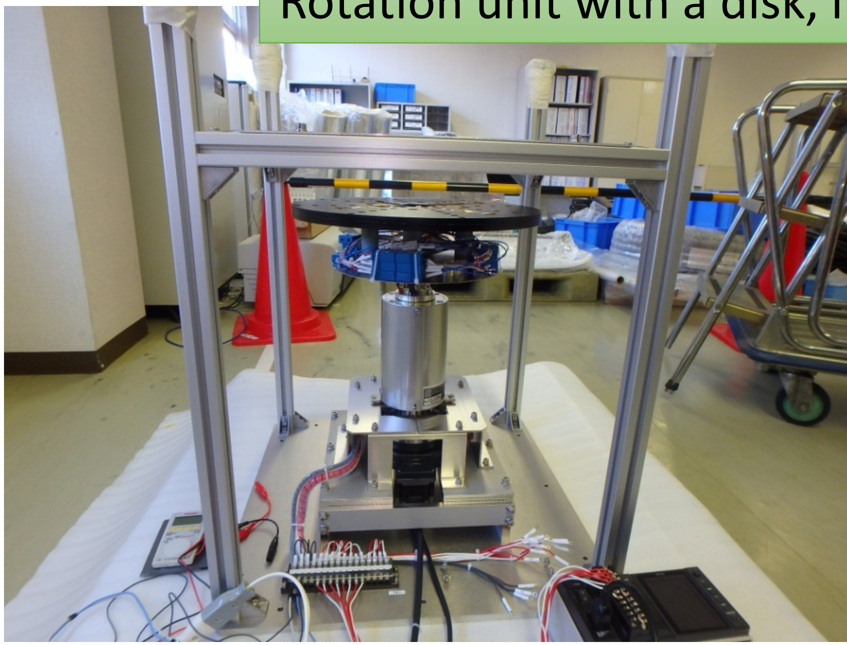


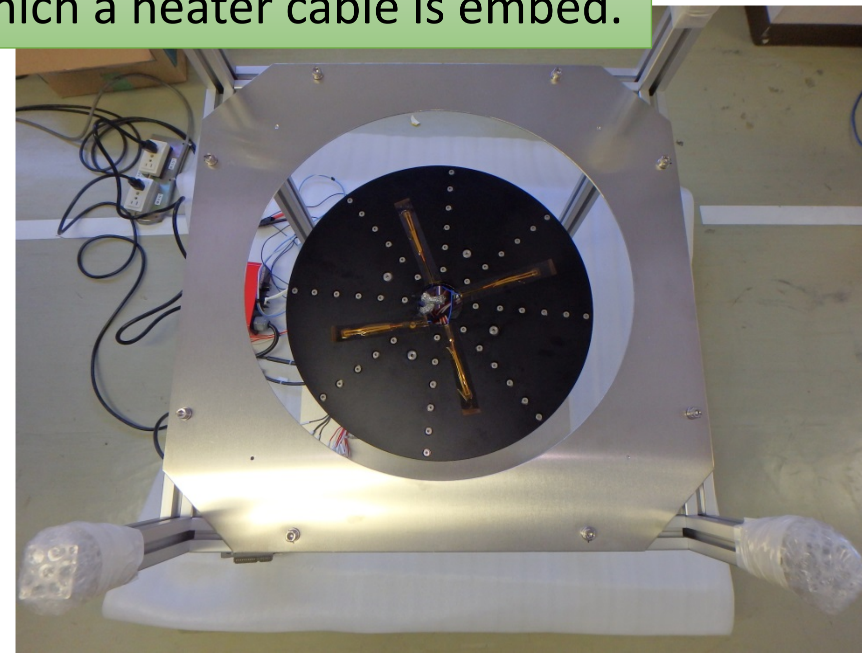
④ over the threshold
→ SX-Abort

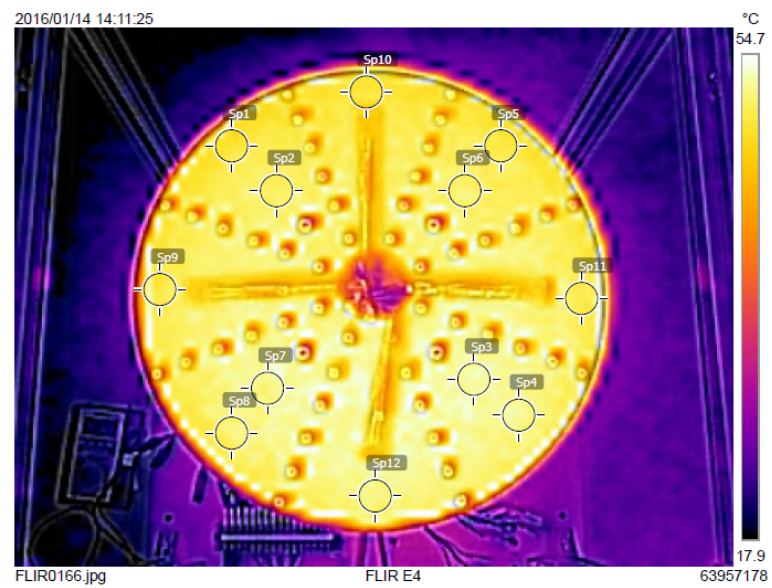
The system worked properly, and protected hadron equipment several times during the fall beam time.

Basic R&D for cooling efficiency by gas

Rotation unit with a disk, in which a heater cable is embed.



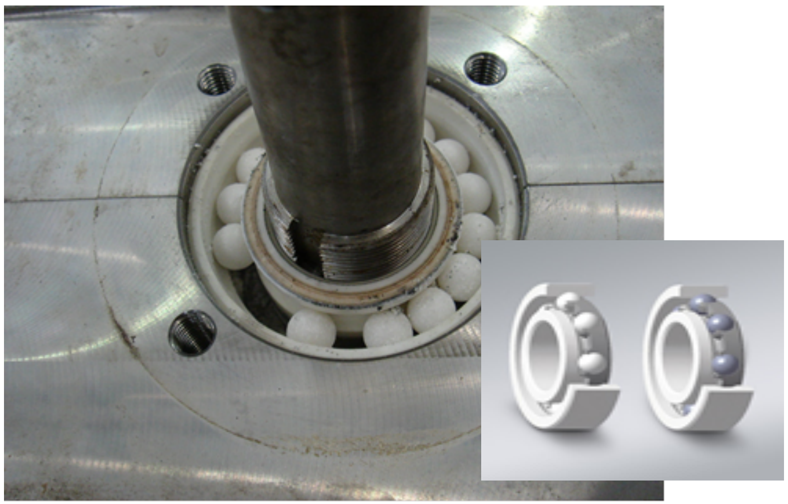




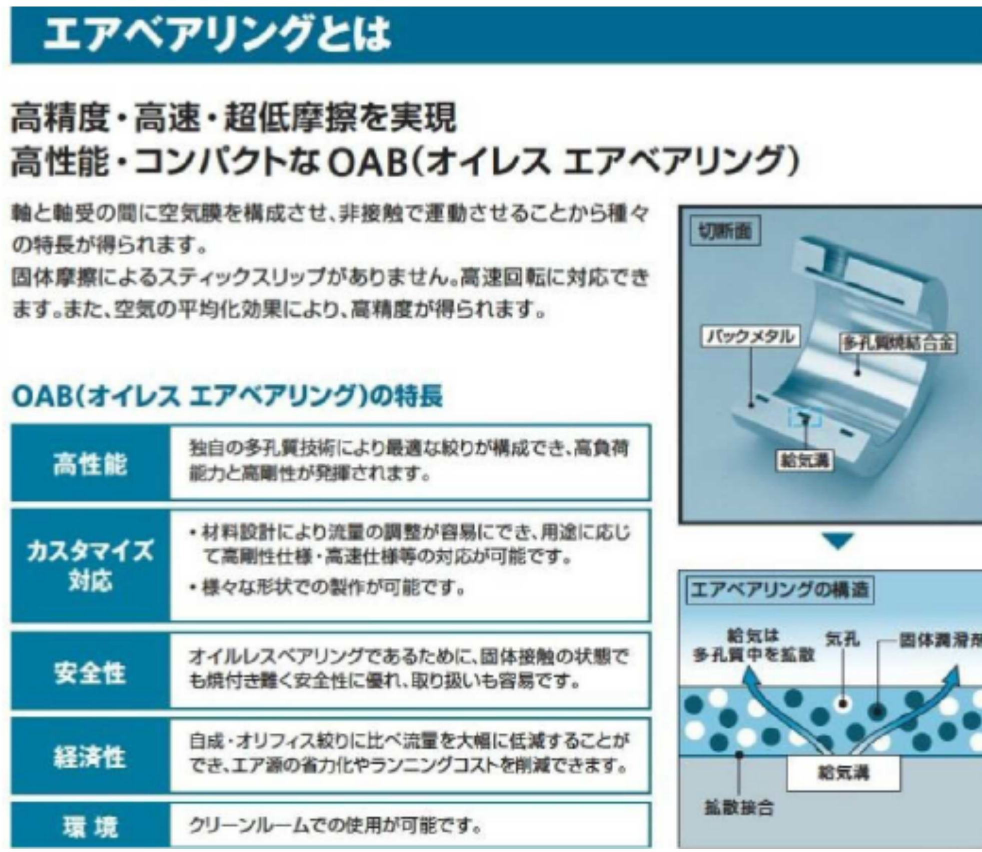
Thermography shows the heat distribution is uniform

Bearing

- ceramic bearing (in case of water cooling)
- all stainless steel + WS_2 lubricant (in case of gas cooling)



- air bearing (in case of gas cooling)
  - long life
  - stable air supply is a key



エアベアリングとは

高精度・高速・超低摩擦を実現
高性能・コンパクトなOAB(オイレス エアベアリング)

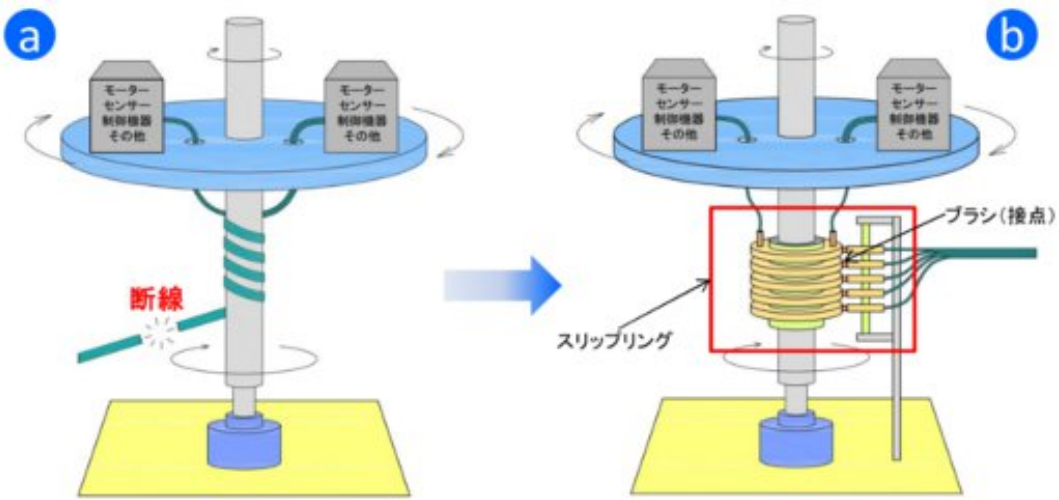
軸と軸受の間に空気膜を構成させ、非接触で運動させることから種々の特長が得られます。
固体摩擦によるスティックスリップがありません。高速回転に対応できます。また、空気の平均化効果により、高精度が得られます。

OAB(オイレス エアベアリング)の特長

高性能	独自の多孔質技術により最適な絞りが構成でき、高負荷能力と高剛性が発揮されます。
カスタマイズ対応	・材料設計により流量の調整が容易にでき、用途に応じて高剛性仕様・高速仕様等の対応が可能です。 ・様々な形状での製作が可能です。
安全性	オイルレスベアリングであるために、固体接触の状態でも焼付き難く安全性に優れ、取り扱いも容易です。
経済性	自成・オリフィス絞りに比べ流量を大幅に低減することができ、エア源の省力化やランニングコストを削減できます。
環 境	クリーンルームでの使用が可能です。

Temperature monitor for rotating target

- thermocouples + slip rings
  - thermocouples are directly fixed to the target disks
  - life of slip ring using carbon brush is about 8000 hours (can be applied for calibration)
  - searching for long-life type...



- fiber-brush type

- radiometer
  - measures radiation from target disks
  - the sensor is located inside of the target chamber
  - basic test using a commercial radiometer (thermopile)
- fiber thermometer
  - infrared rays are transported through a quarts window and an optical fiber to outside of the target chamber and shielding
  - radiation hardness?

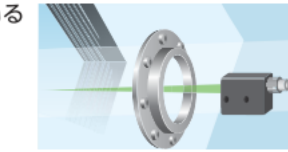
ファイバーで赤外線を伝達するタイプの放射温度計が昨年度に発売された from ジャパンセンサー（おもに高温測定用）

シリーズ	T型			
温度計型式	FTKX-TNE0100	FTKX TNE0180	FTKX-TNE0240	F PN
温度範囲	100〜1500℃※注3	180〜2000℃※注3	240〜2000℃※注3	2 1
実効波長	1.95〜2.5μm			
検出素子	InGaAs			

100℃から1500℃
（ファイバーを10mにすると測定下限150℃）

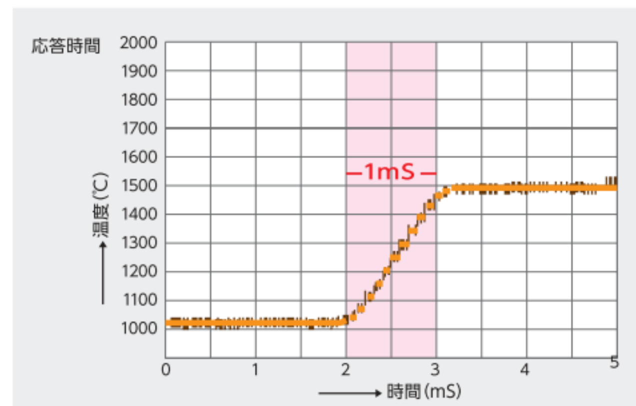
窓越し測定可

石英を透過する波長を使用しているため、窓越しの測定が可能です。

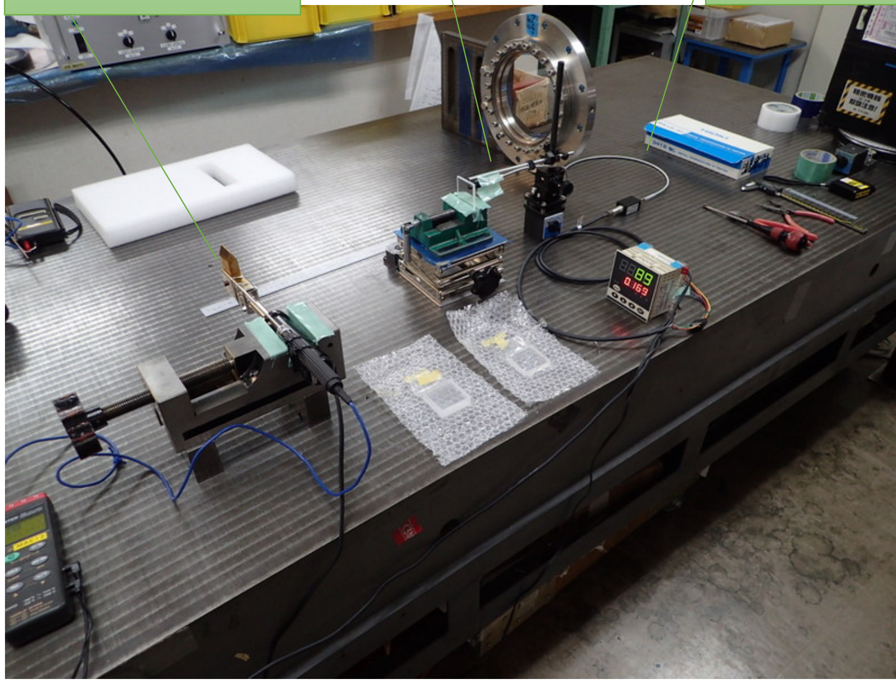


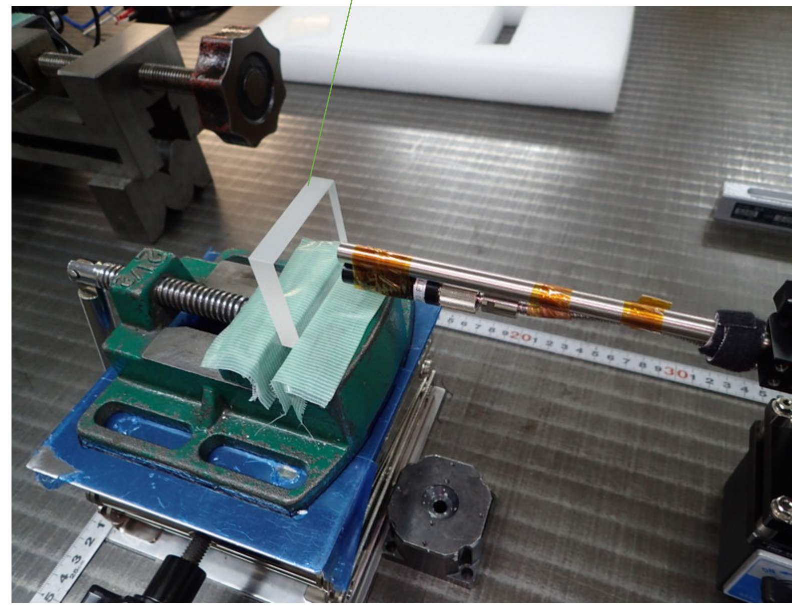
確実に測温

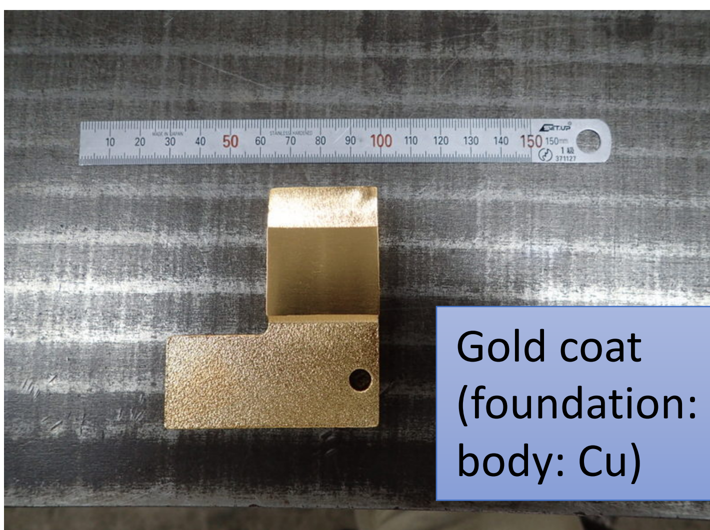
世界最高クラスの高速応答1mS（0.001秒）で急激な温度変化を見逃す事はありません。

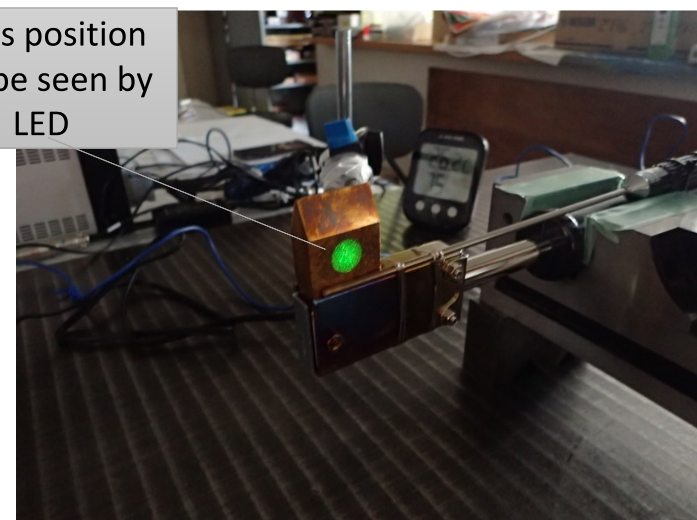


- 光沢金属（特に金）は測れるかわからない。


soldering iron
lens
quarts fiber

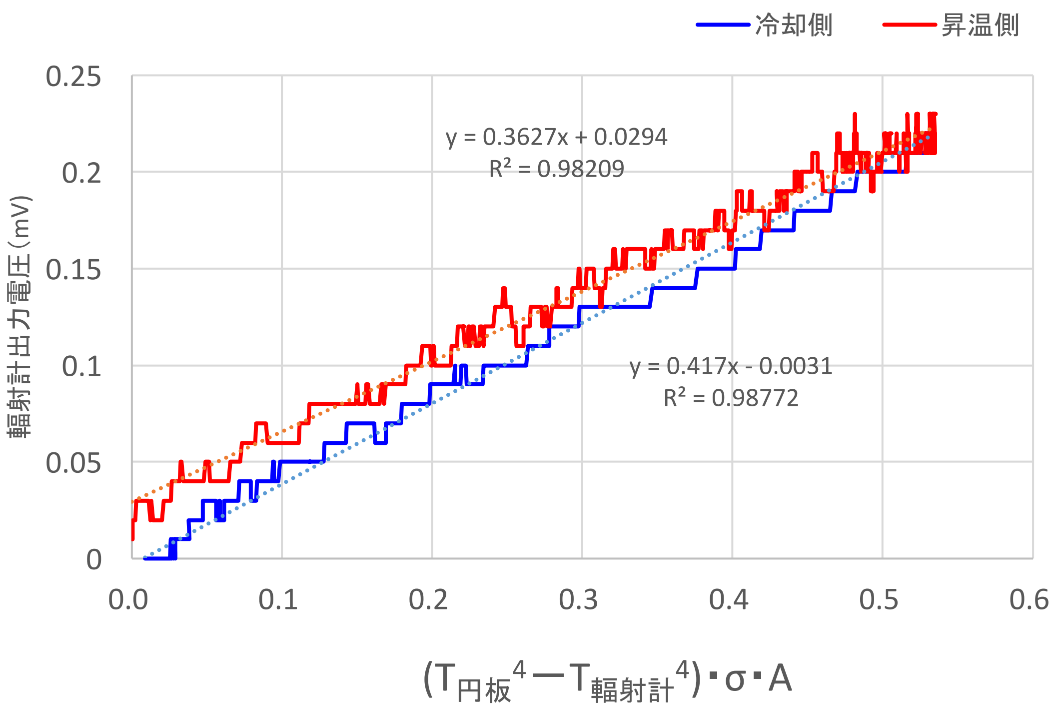

quarts plate

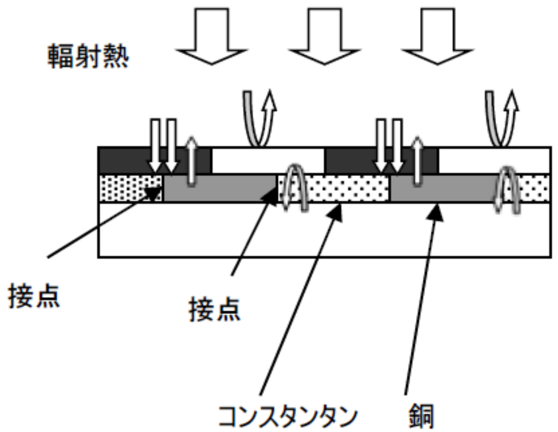

Gold coat (foundation: Ni, body: Cu)


focus position can be seen by LED

Test of radiometer (tentative)

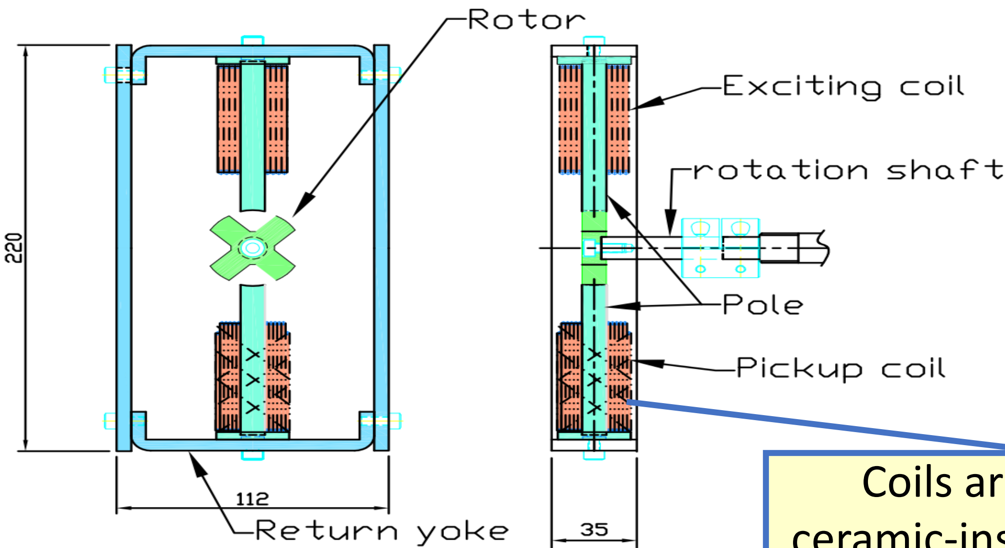
0 rpm, w/o blower,
radiation factor = 0.076





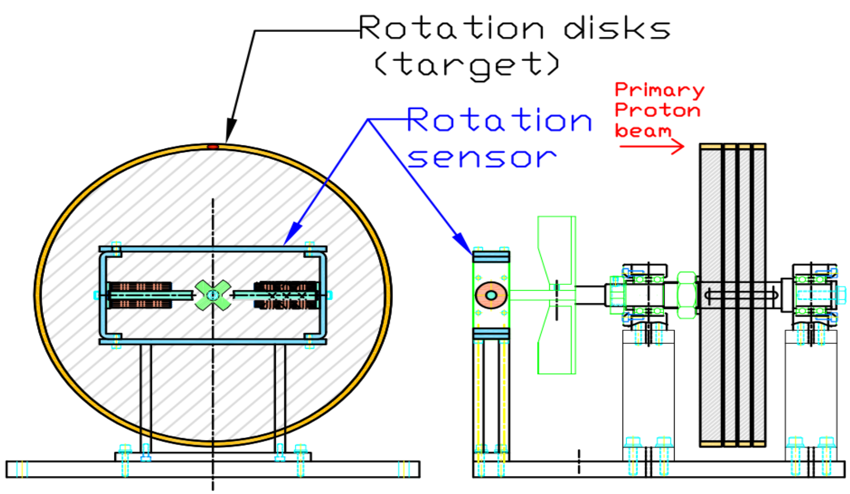
ΔT 50K -> 0.15mV output
0.003 mV/K/9cm²

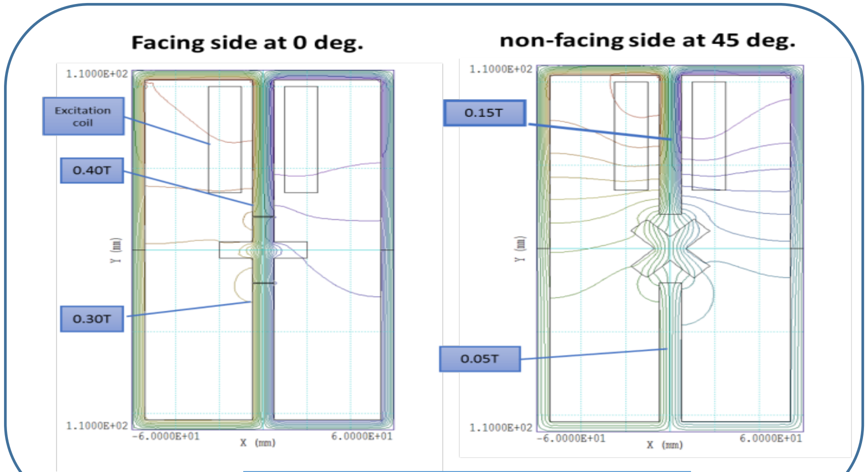
Radiation-hard rotation meter



- Range: 40 - 200 rpm
- Accuracy: within +/- 5% (@120rpm)
- Radiation hardness: > 1000 MGy

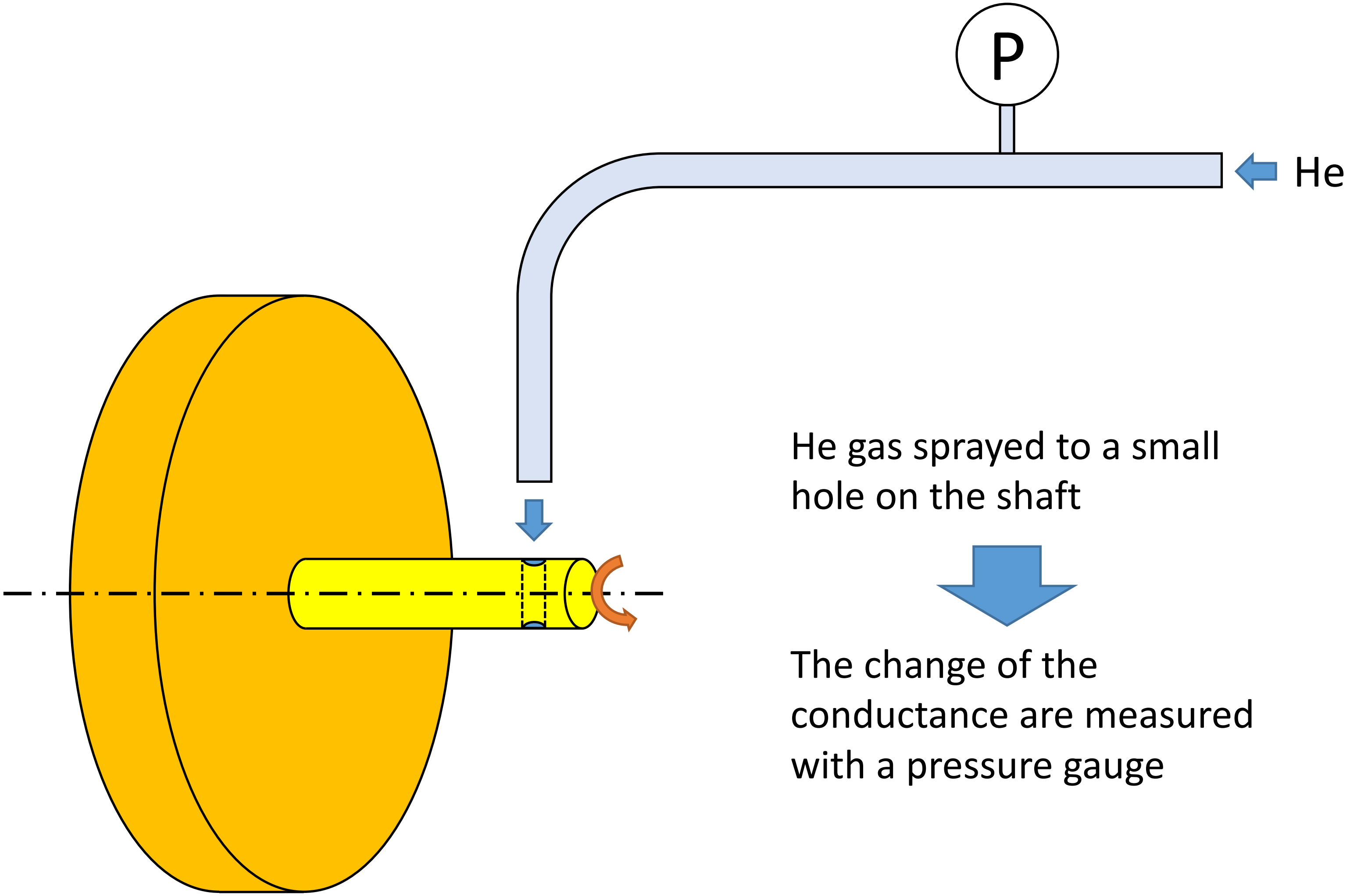
Coils are made of ceramic-insulated cables





Magnetic field analysis

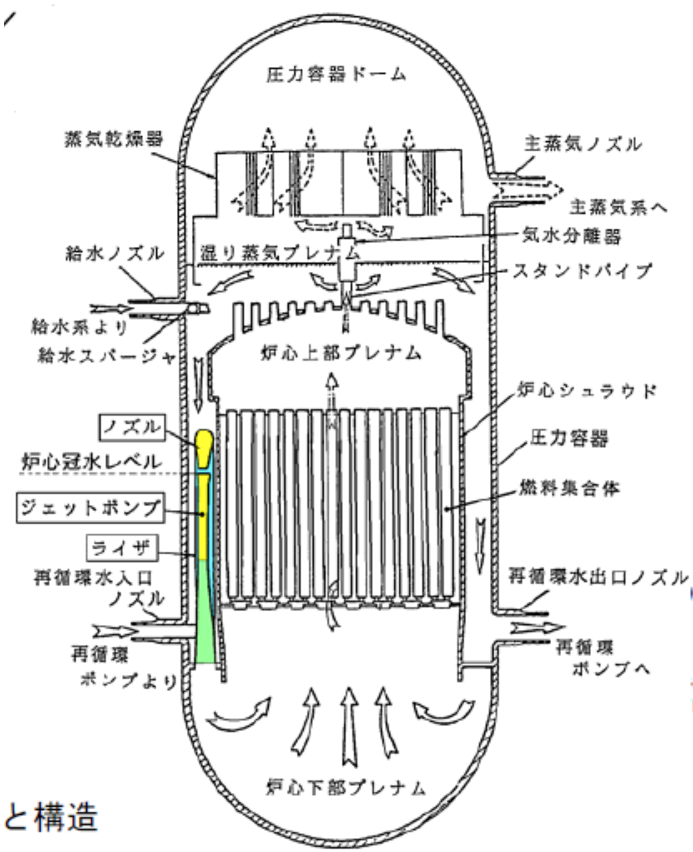
Another Option of Rotation Meter



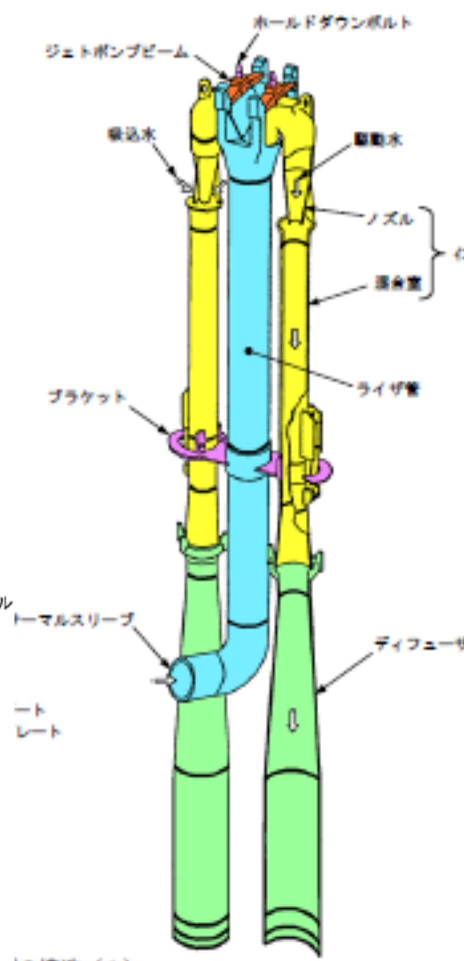
He gas sprayed to a small hole on the shaft

The change of the conductance are measured with a pressure gauge

Jet Pump



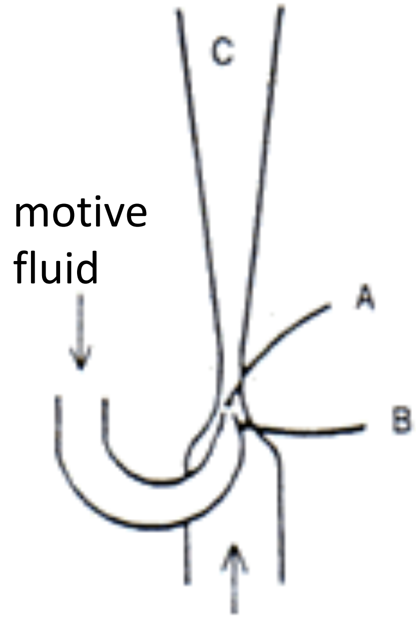
と構造



の構造（1）

frequently used in BWR

- consist of pipe only
- no driving parts

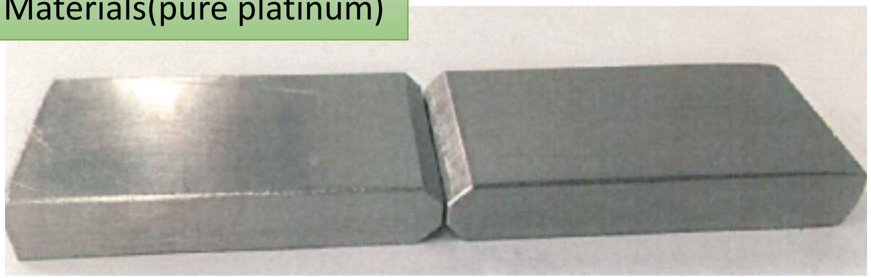


1. high flow velocity = low pressure at A
2. water is sucked up from bottom (B)

Forming test of thick curved platinum plate

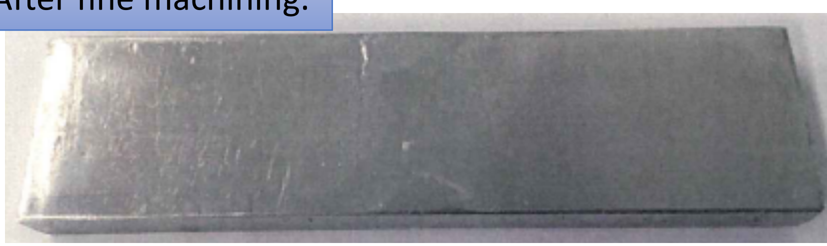
Production of thick and Long platinum bar.

Materials(pure platinum)



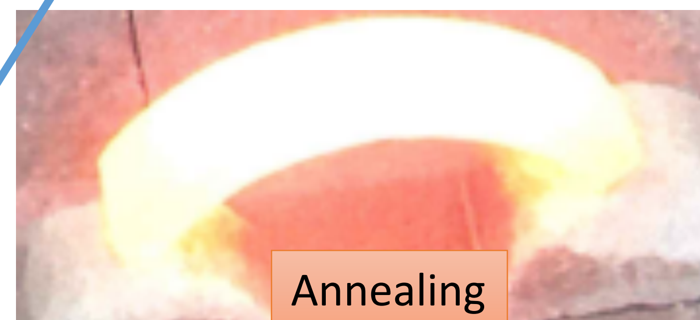
Welding

After fine machining.



Forming test.

Press forming

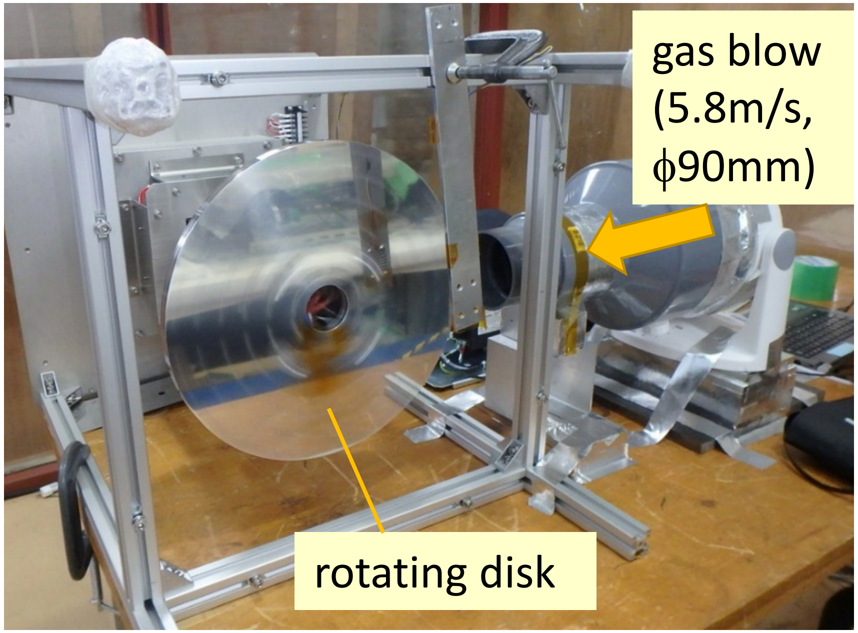


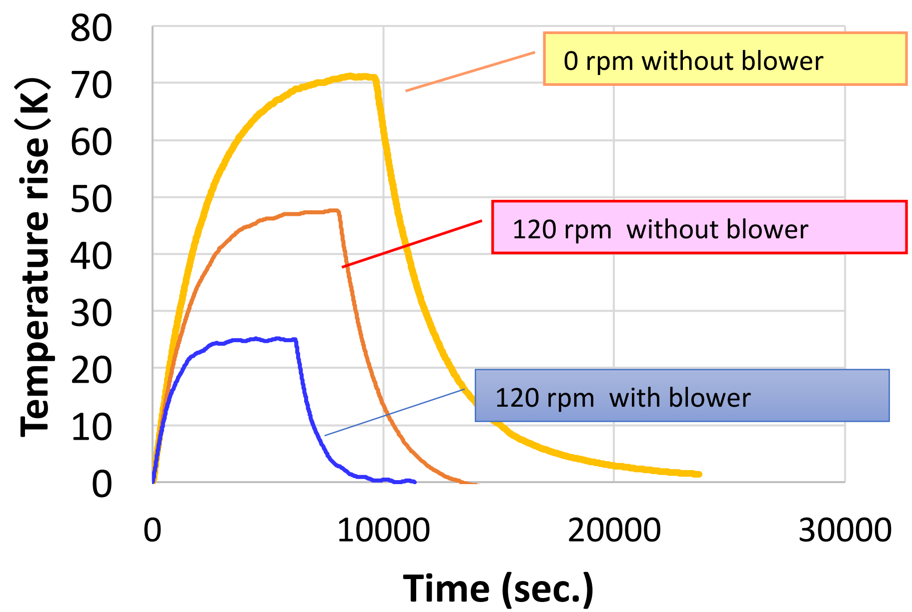
Annealing

After fine adjustment(forging)

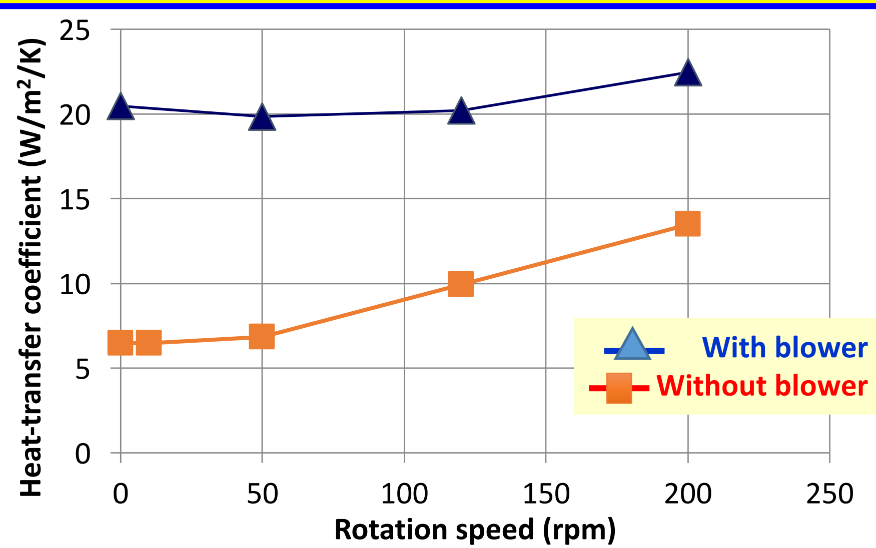
Forming of a test peace has been successfully done with good accuracy (radius accuracy of 0.1mm level).

Basic R&D for cooling efficiency by gas



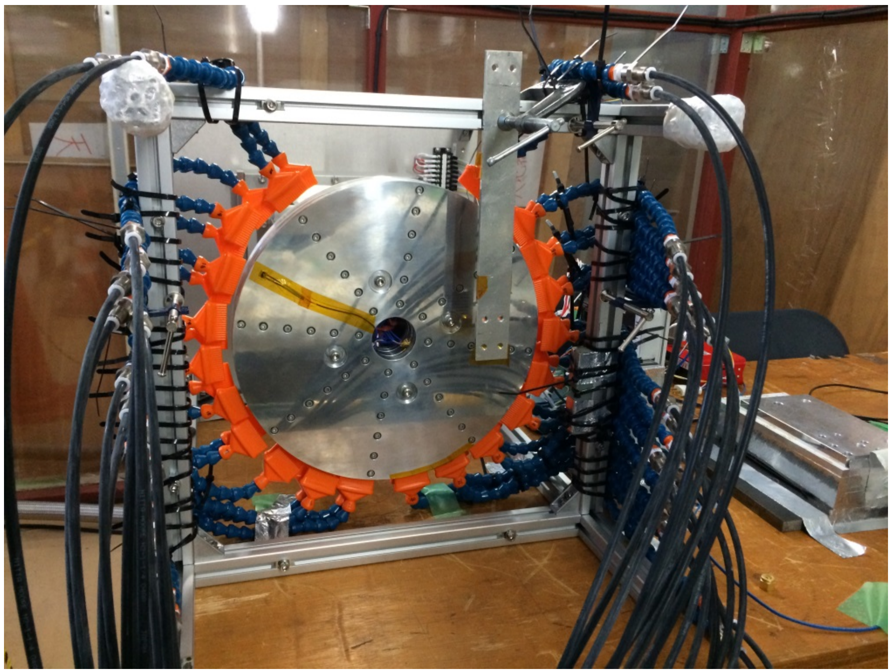


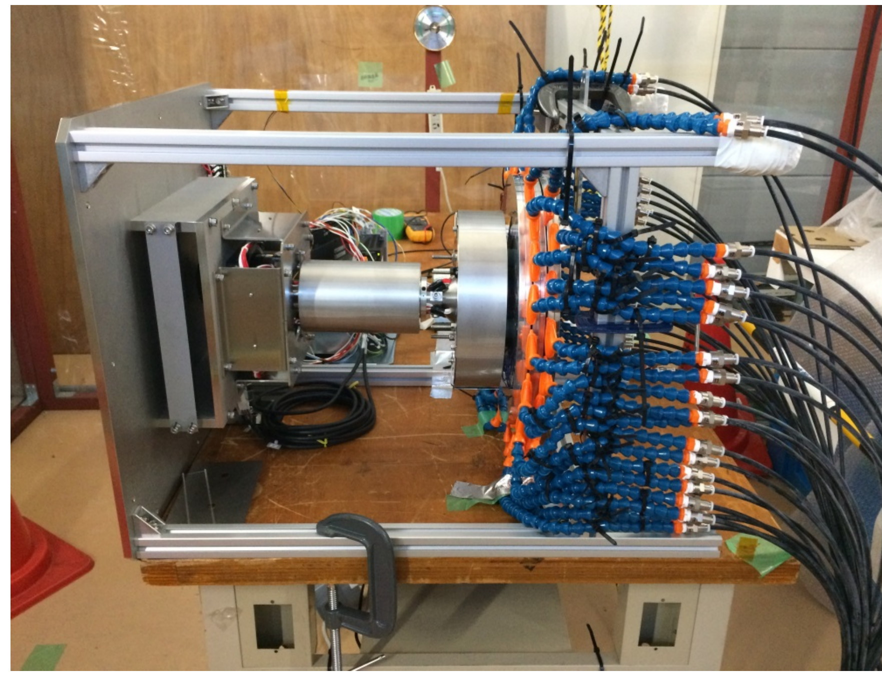
Cooling efficiency for single disk (Preliminary result)



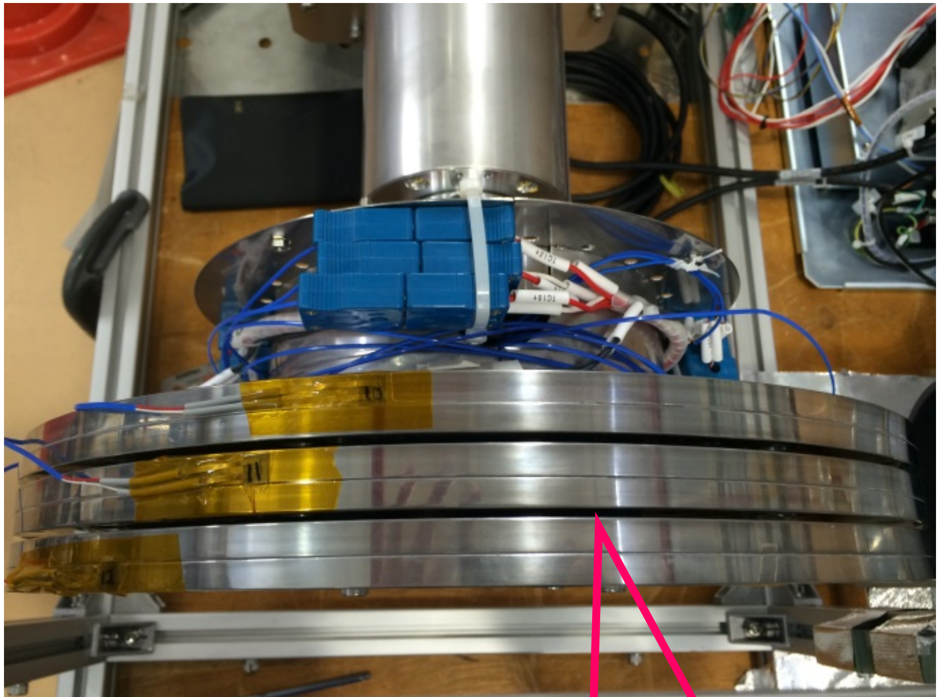
Blowing with nozzles

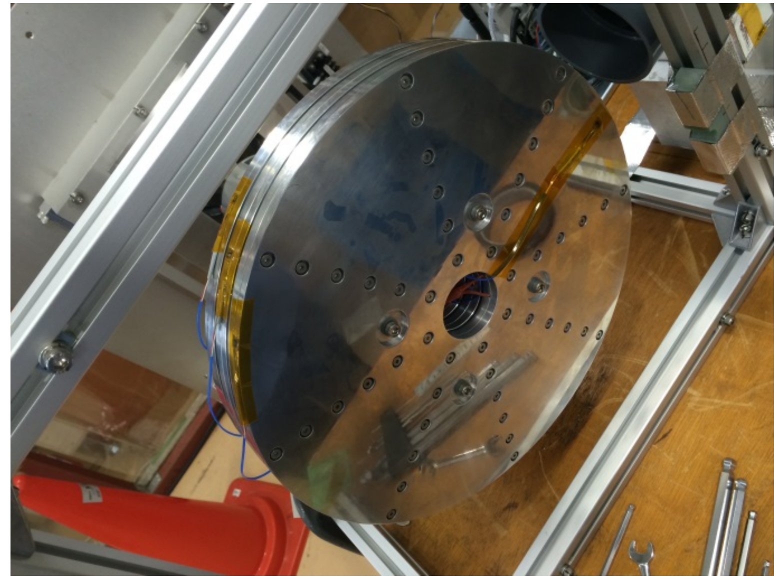
force blowing to gap between disks

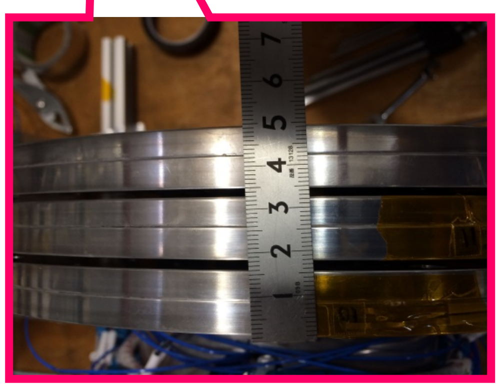




Cooling efficiency of 3 disks

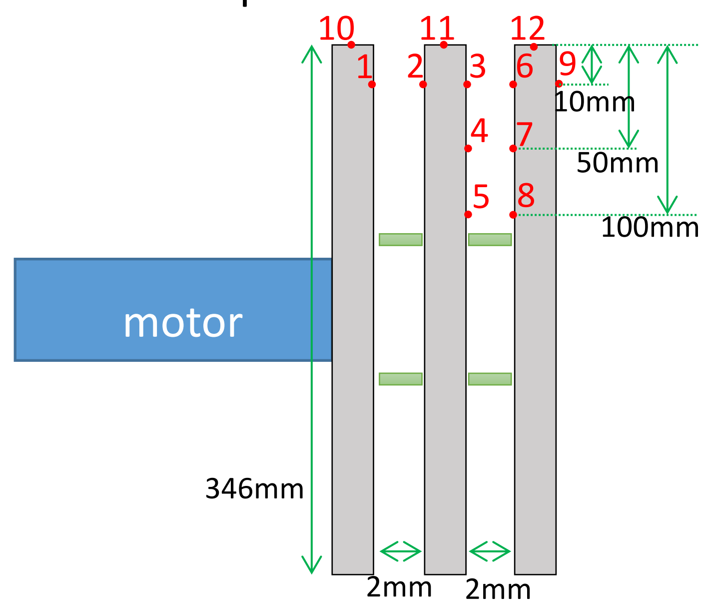






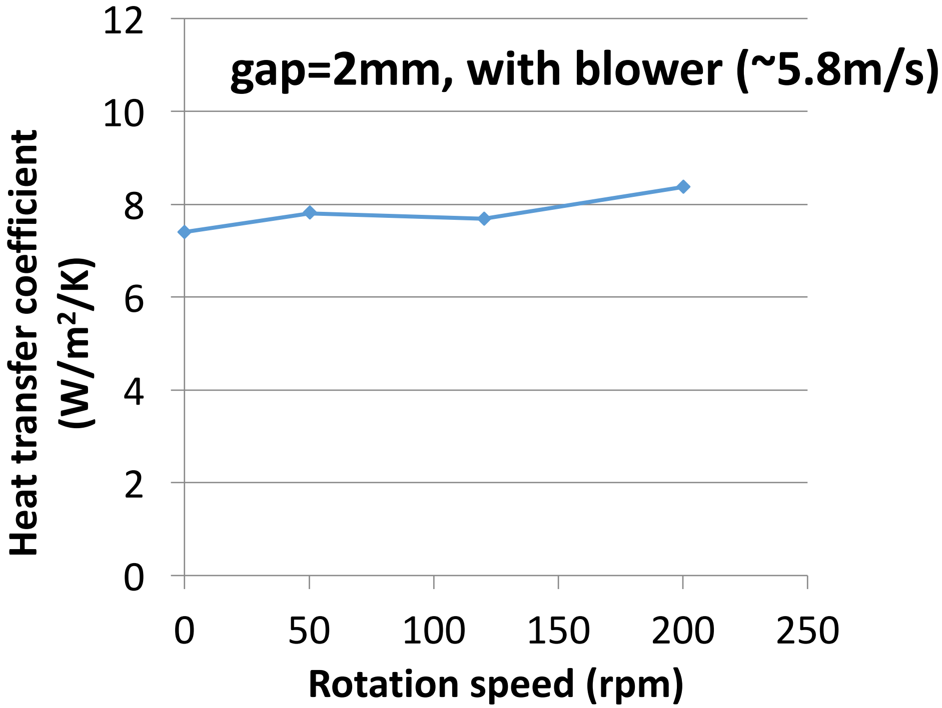
2mm gap

thermocouples location



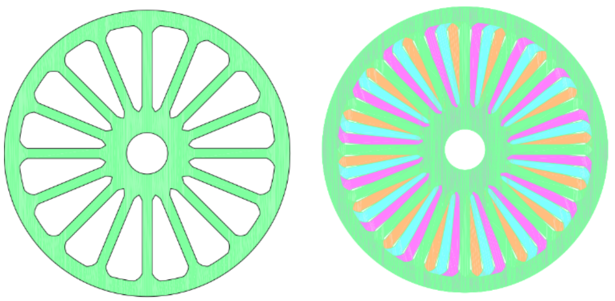
Preliminary Result

Cooling efficiency of 2nd (inner) disk

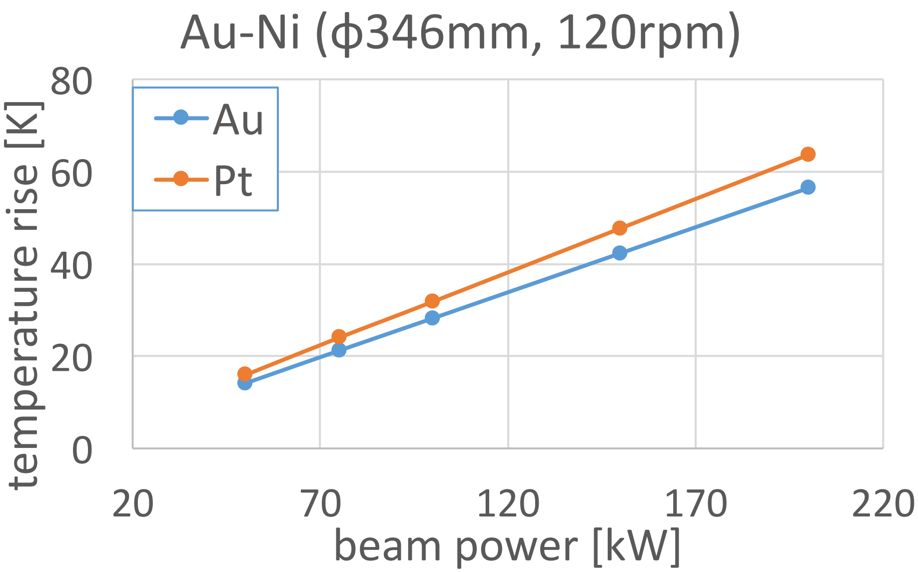


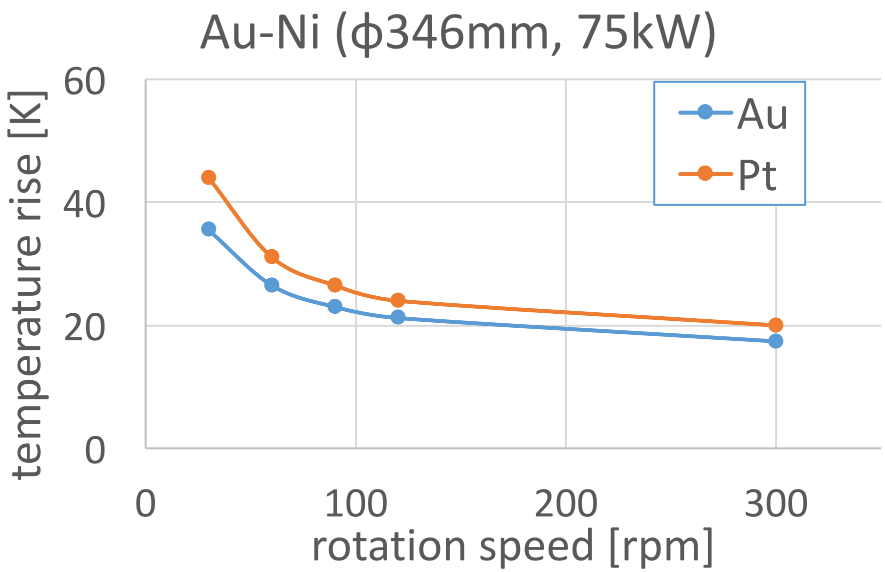
Measured efficiency was lower than that of single-disk case

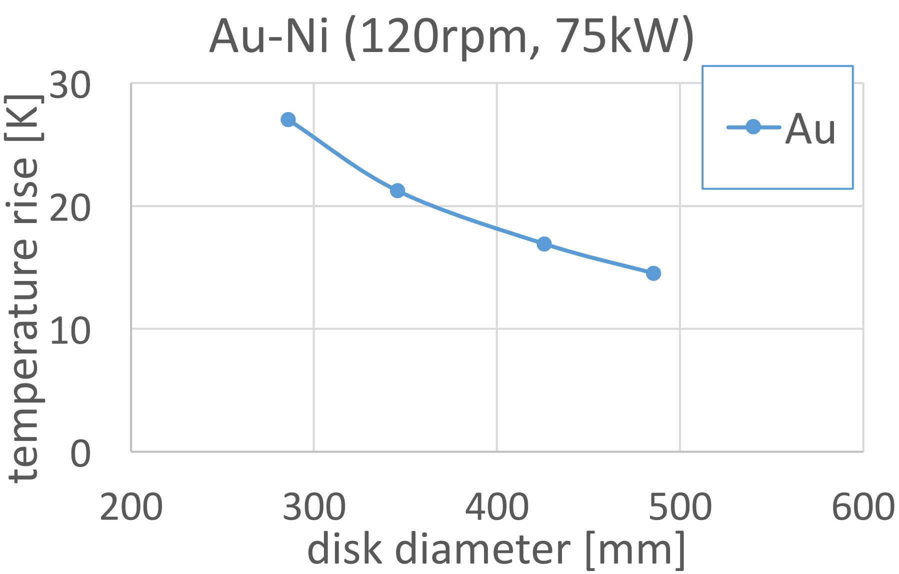
➡ gap dependence
improve blowing method
groove at surface?
spoke structure?



Rotating target (water cooled)



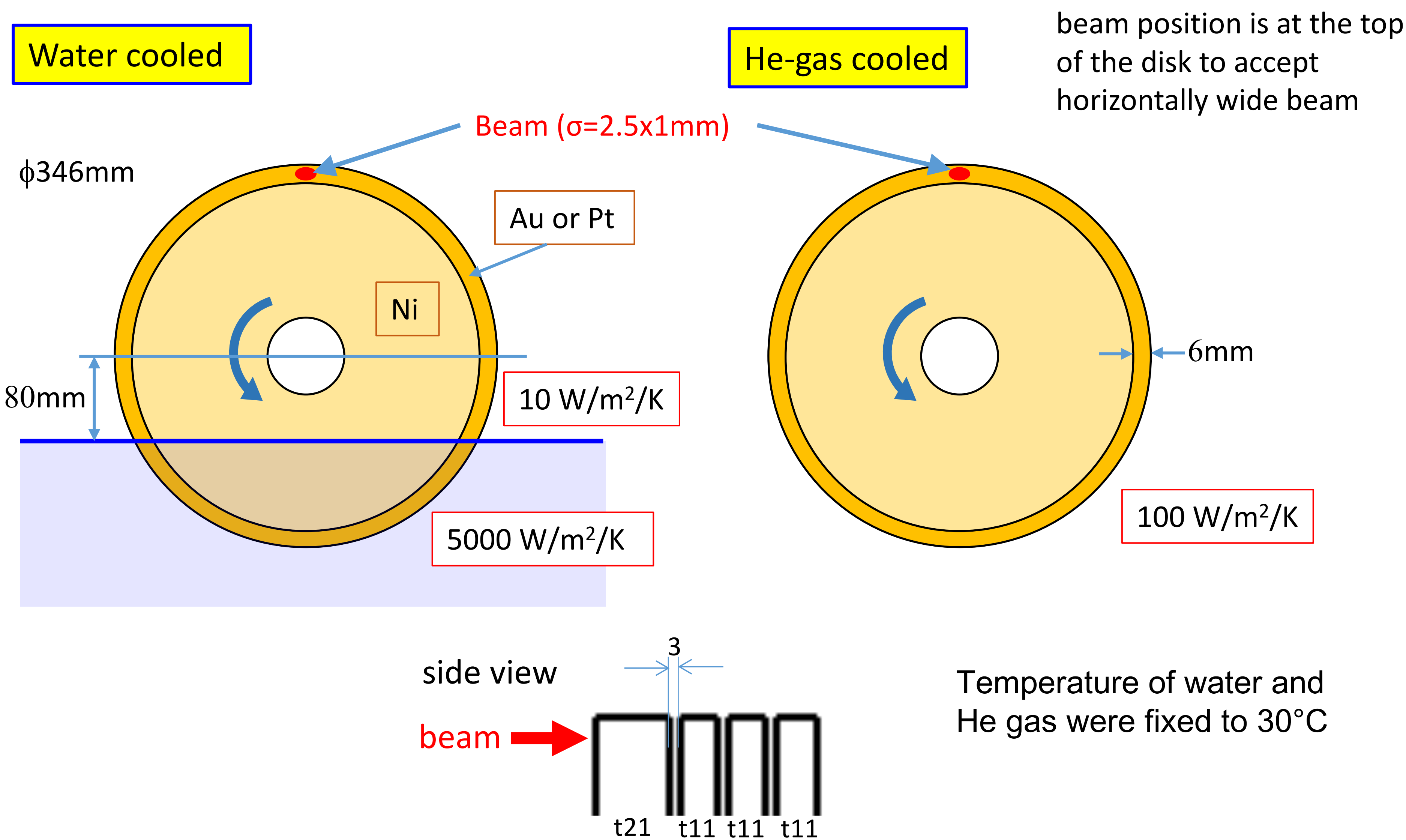




temperature rise is

- proportional to beam power
- inversely proportional to disk diameter
- decreased with higher rpm but not changed so much over 120 rpm

Thermal Analysis Model



Temperature of water and He gas were fixed to 30°C

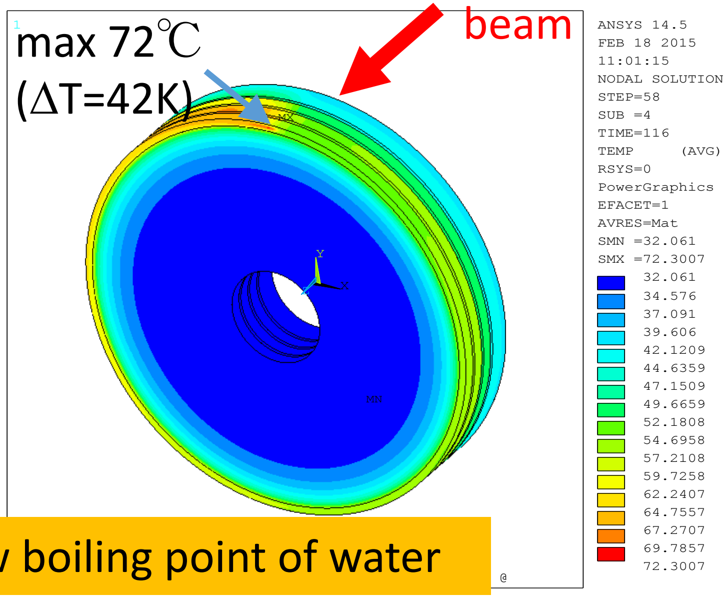
Thermal Analysis (Water cooled)

150kW,
ϕ346mm, 120rpm

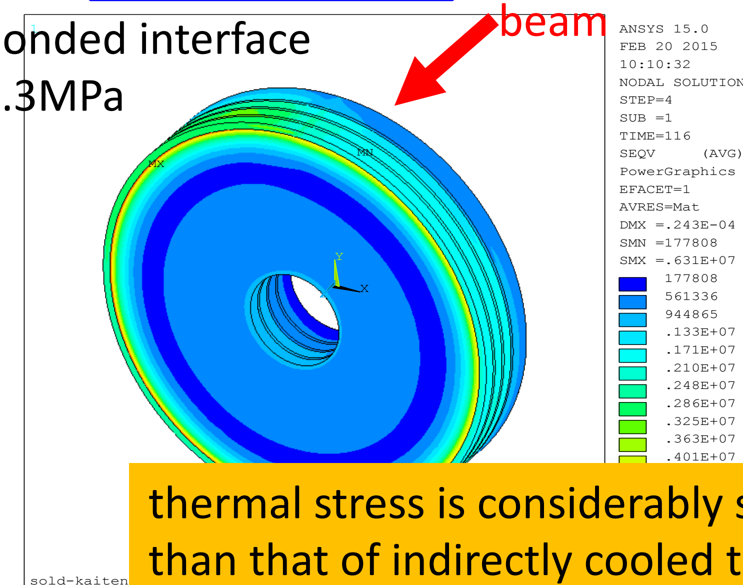
temperature

von Mises stress

Au

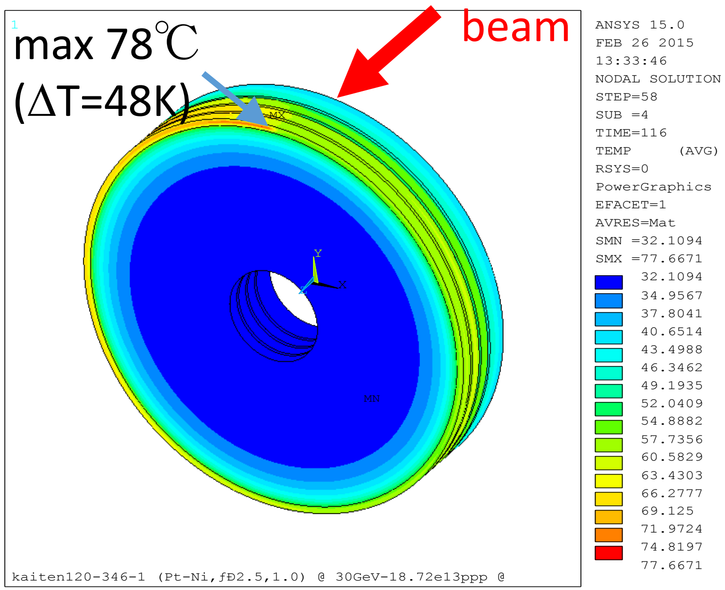


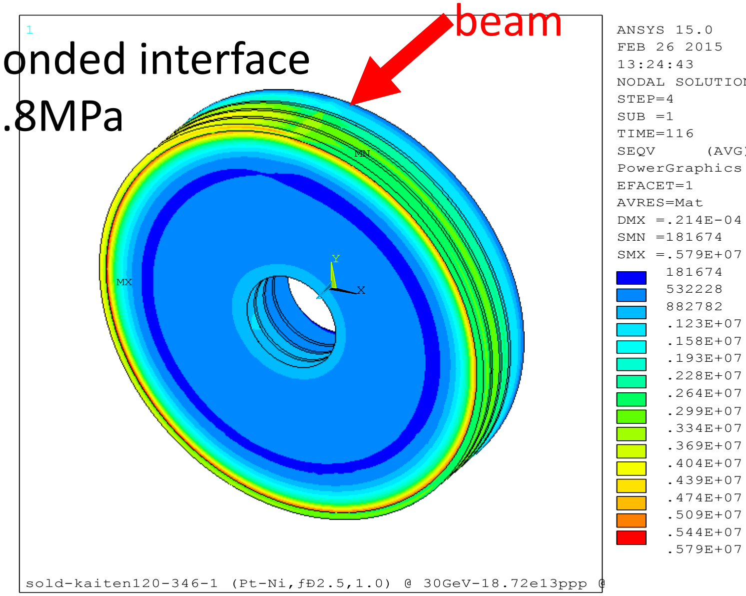
below boiling point of water



thermal stress is considerably smaller than that of indirectly cooled target

Pt



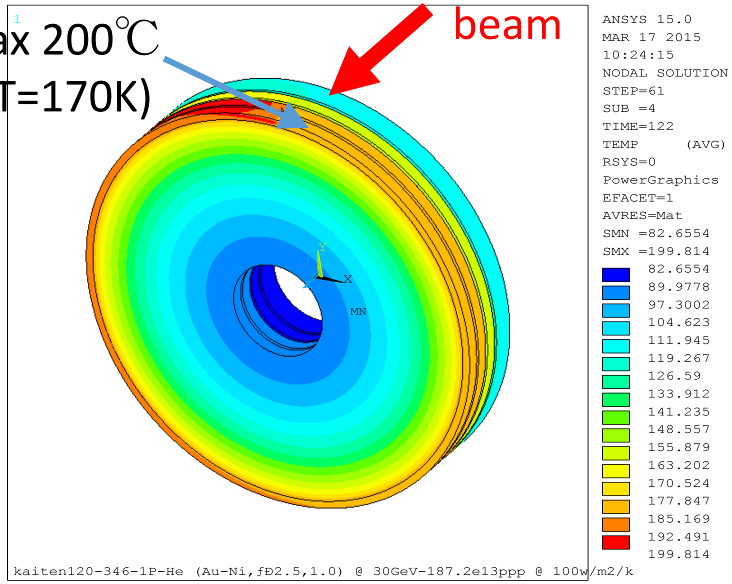


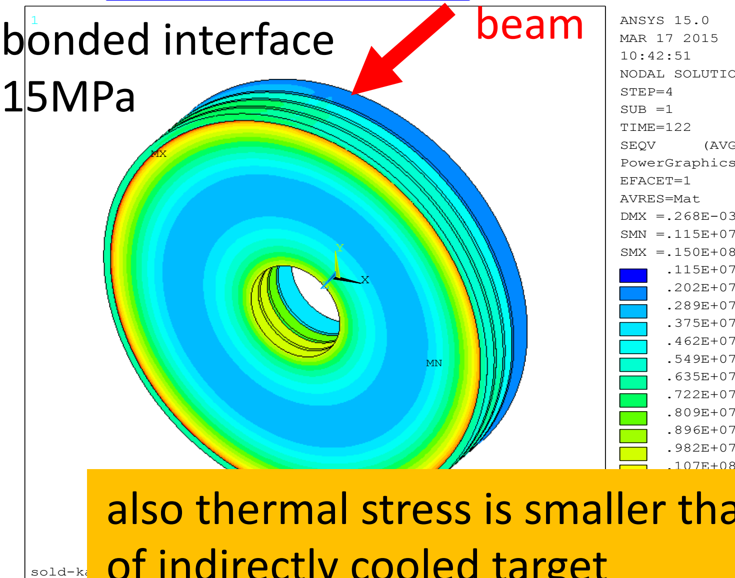
Thermal Analysis (He-gas cooled)

150kW,
ϕ346mm, 120rpm

temperature | **von Mises stress**

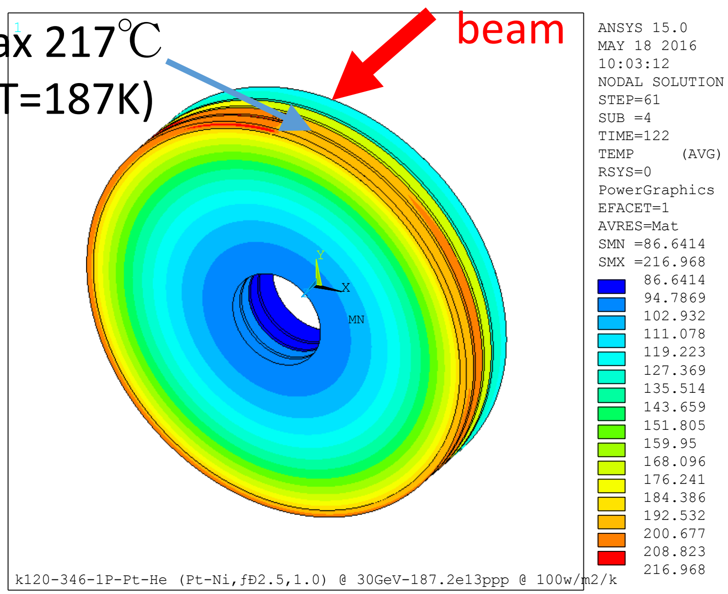
Au

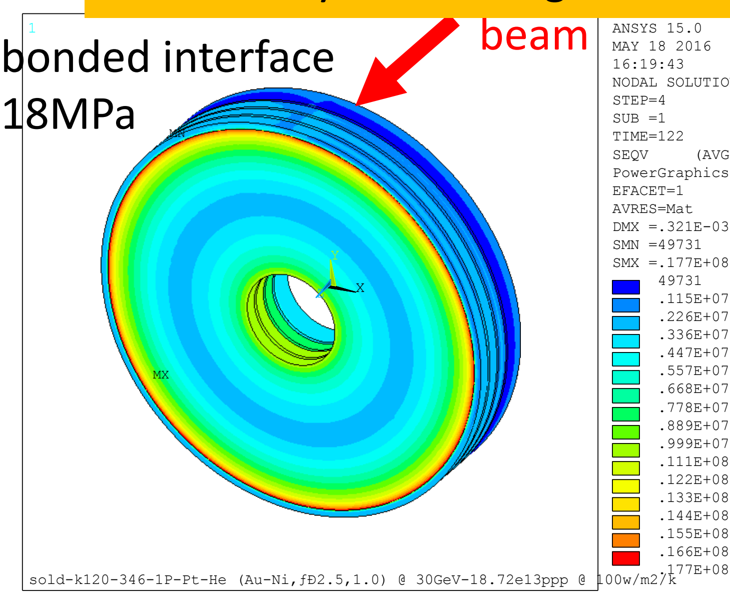




also thermal stress is smaller than that of indirectly cooled target

Pt

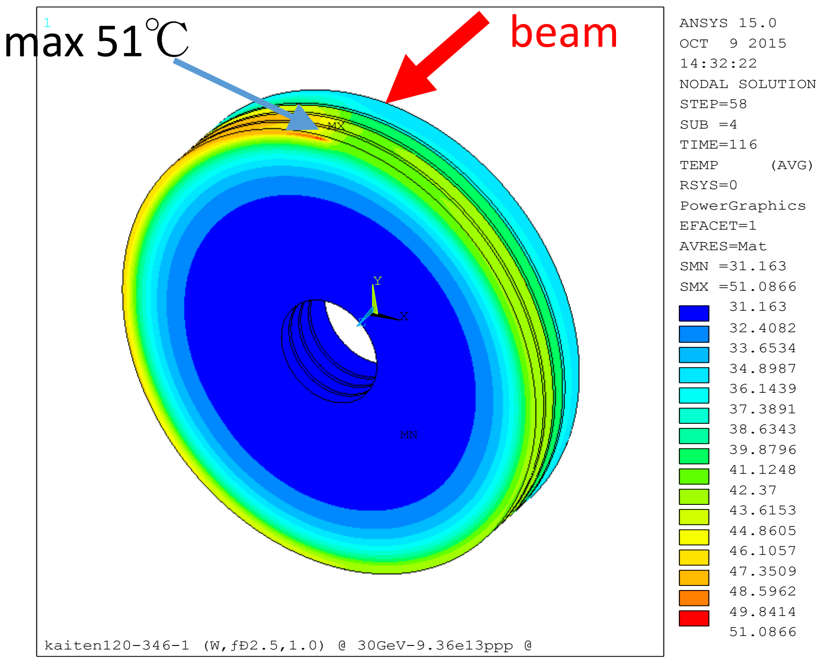




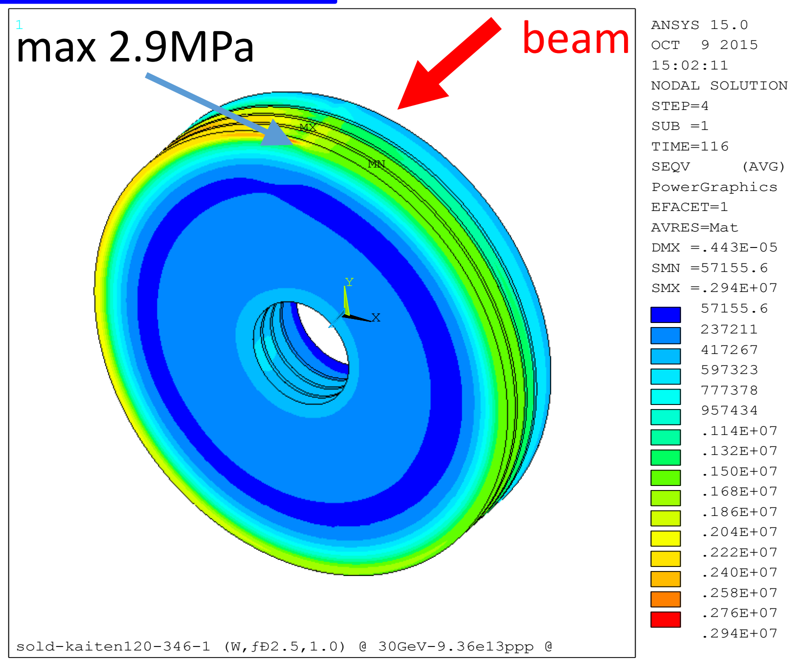
Thermal Analysis (water cooled)

W, ϕ346mm, 120rpm, 75kW

temperature

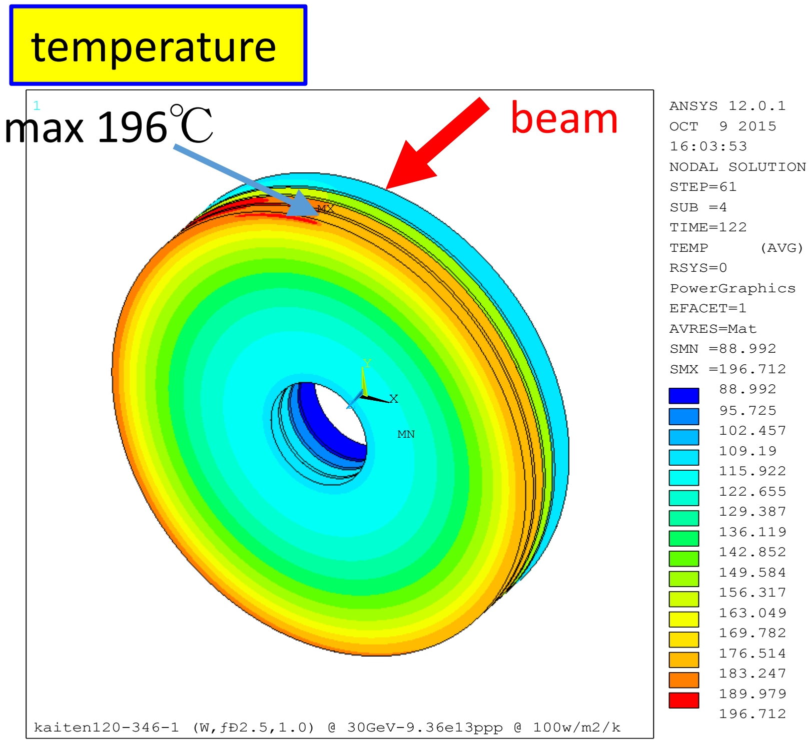


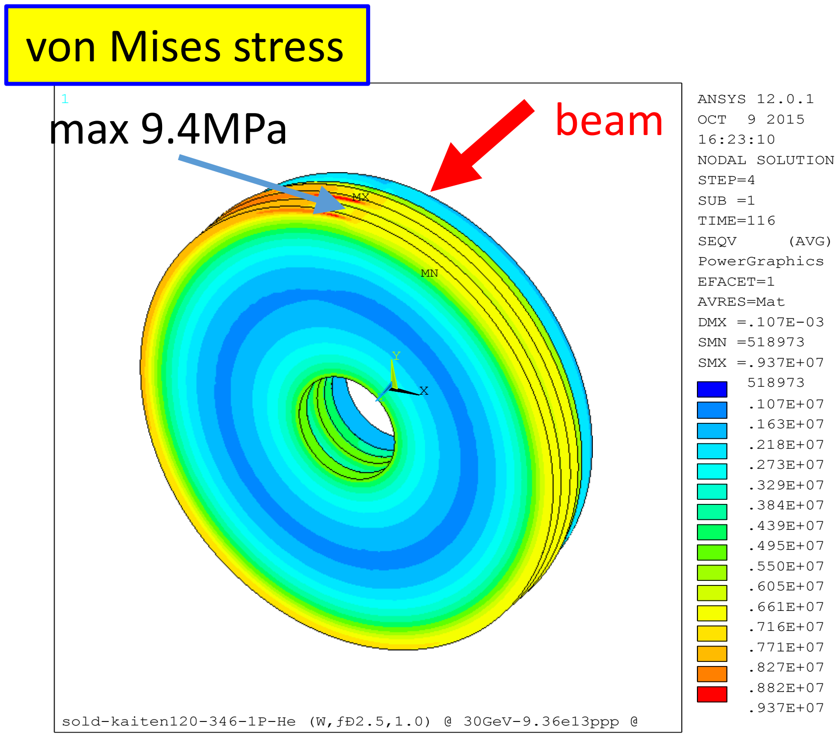
von Mises stress



Thermal Analysis (He-gas cooled)

W, ϕ346mm, 120rpm, 75kW





Beam Loss

- water-cooled rotating Ni 54mm: 30% loss
- old Pt 60mm: 50% loss
- current Au 66mm: 48% loss
- water-cooled rotating Au 57mm: 43% loss
- water-cooled rotating Pt 57mm: 48% loss
- vertically divided Au 66mm: 42% loss
- vertically divided Au 66mm (2pieces not divided): 44% loss
- obliquely divided Au 66mm: 43% loss

Beam window

- Materials of beam windows in the Hadron primary beamline,
  - Target chamber and pipe end (boundary between air pressure):
    - Titanium alloy (Ti-6Al-4V)
    - Beryllium (S-200F)
  - For vacuum separation between high and low vacuum:
    - Thin Aluminum-alloy (Al-4.5Mg-0.7Mn, or Al-4.5Zn-2Mg)

- For 10000-hrs operation in 50kW, (σ_x2.5mm,σ_y1mm) :
  - 2.2 DPA for titanium alloy
  - 0.08 DPA for the beryllium

  (estimated by PHITS)

- We are very interested in the radiation-damage effects for these materials.