2ND MUON COMMUNITY MEETING
12TH TO 14TH JULY, 2021

MUON PRODUCTION TARGET AT J-PARC

J-PARC, KEK-IPNS
SHUNSUKE MAKIMURA

SELF INTRODUCTION & CONTENT

Name: Shunsuke Makimura

In charge of pion/muon production target at J-PARC

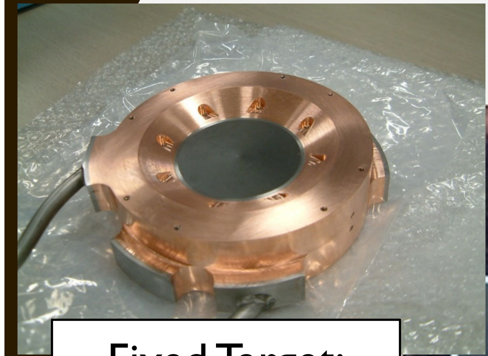
(MLF muon target (-2019), COMET target (2019-))

1. J-PARC MLF target
2. J-PARC COMET target
3. Inner-solenoid shield
4. Toward Phase 2
5. Summary

I love a mechanical design, and recently, am attracted to R&D of target materials.

GUNDAM is made of GUNDARIUM alloy.

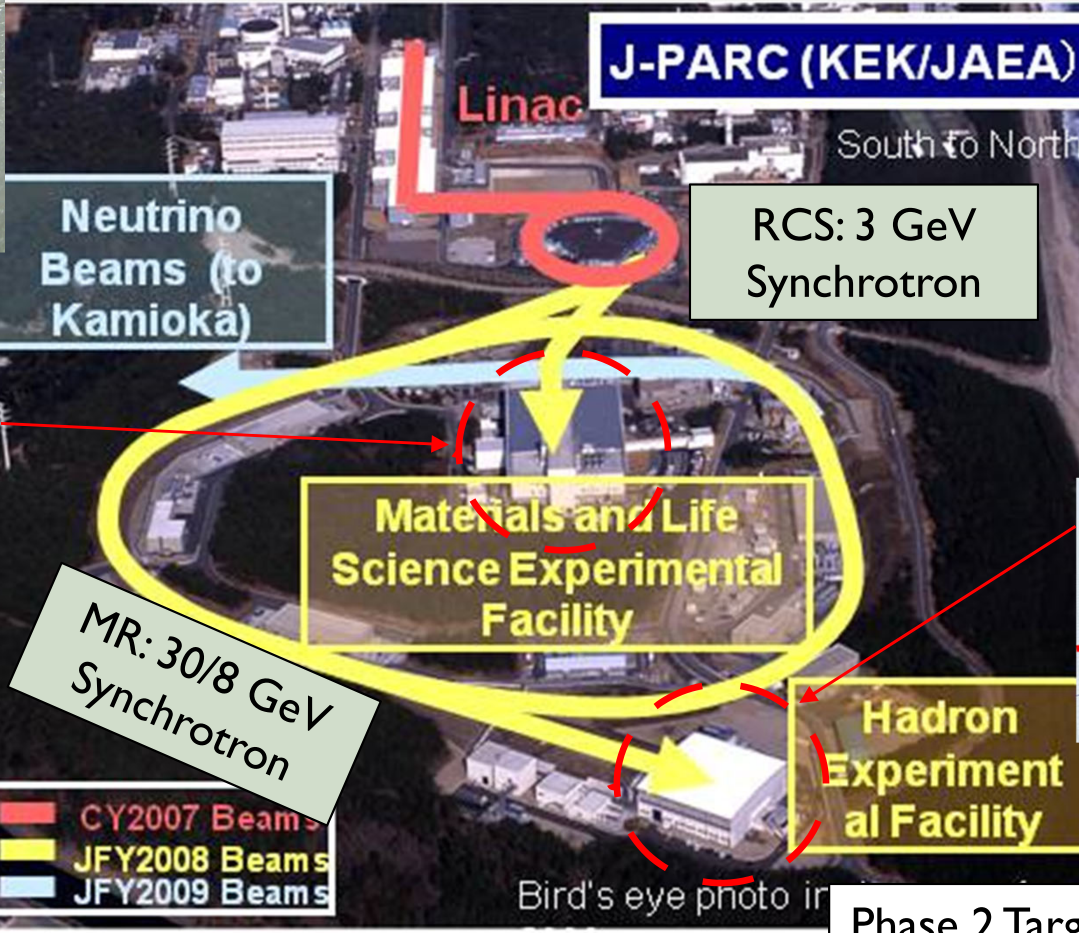
MLF MUON TARGET & COMET TARGET



Fixed Target: 2008-2014

MLF Target: Graphite

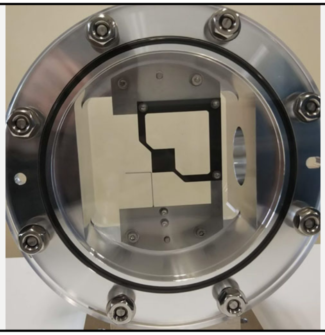
Rotating Target: 2014-



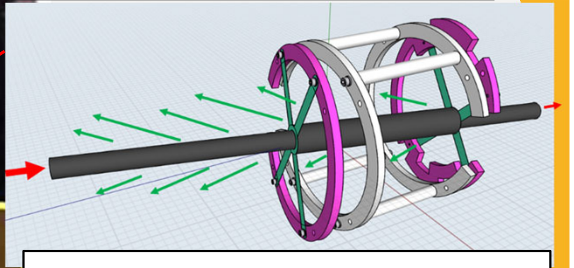
RCS: 3 GeV Synchrotron

MR: 30/8 GeV Synchrotron

COMET Target



Phase α Target: 2022- C/C composite



Phase 1 Target: 2023- Graphite

Phase 2 Target: Tungsten
Radiation/ Water cooling

From the past to the future,

various muon production target at J-PARC

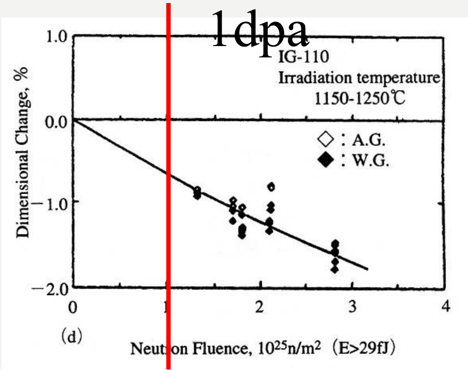
1. MLF TARGET IN J-PARC

FIXED TARGET
ROTATING TARGET

MUON PRODUCTION TARGET

- Target material is polycrystalline graphite, IG-430U.
- To extend lifetime, the fixed target was replaced with rotating target that disperse the radiation damage of graphite.

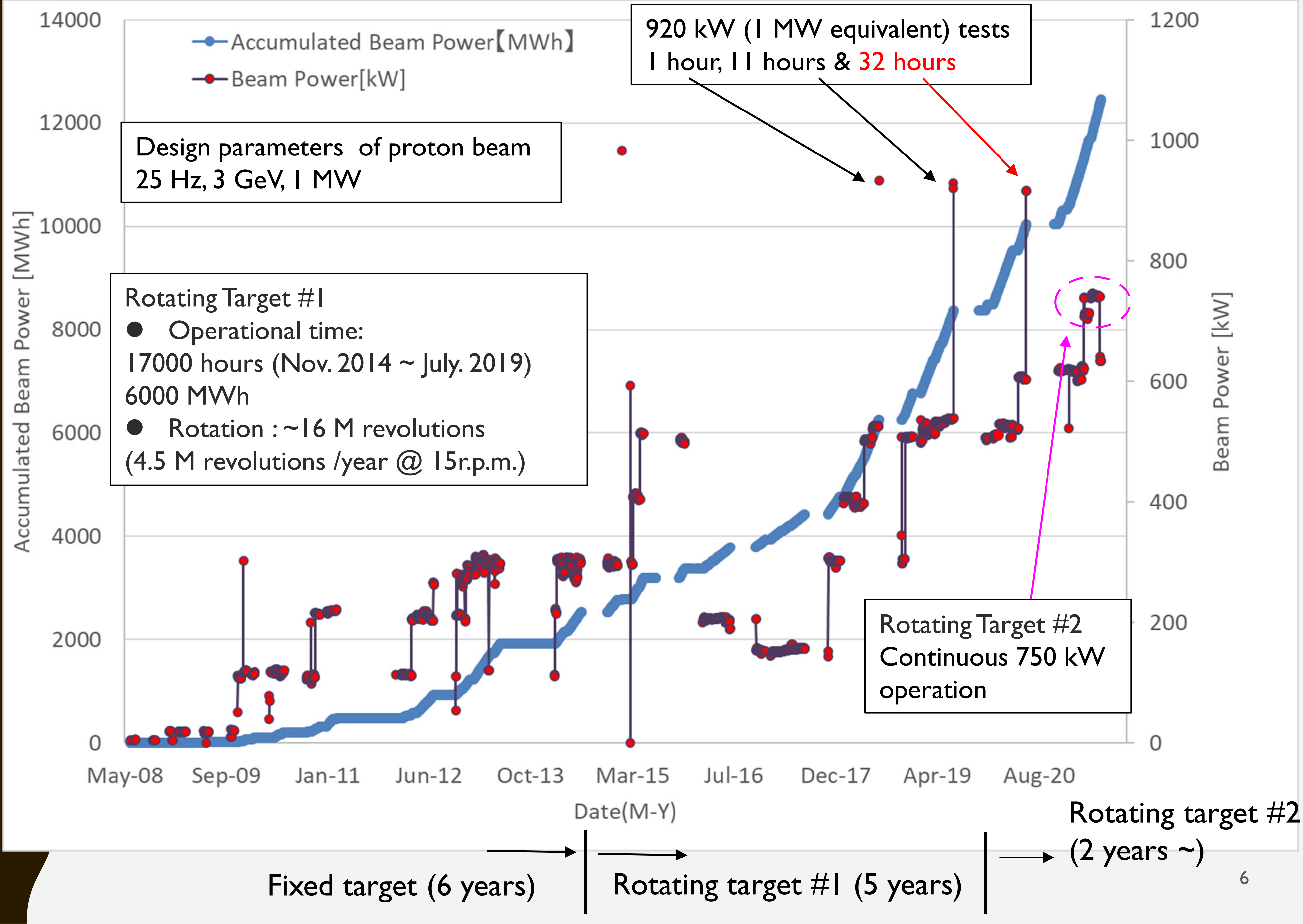
Fixed target, from 2008 to 2014
Lifetime: Irradiation damage of graphite
1 year at 1 MW operation



H. Matsuo, graphite1991
[No.150] 290-302

Rotating target, installed in 2014
Lifetime: Bearings
Aiming Lifetime: 10 years at 1 MW operation

HISTORY OF MLF MUON TARGET



920 kW (1 MW equivalent) tests
1 hour, 11 hours & 32 hours

Design parameters of proton beam
25 Hz, 3 GeV, 1 MW

Rotating Target #1

- Operational time:

17000 hours (Nov. 2014 ~ July. 2019)
6000 MWh

- Rotation : ~16 M revolutions

(4.5 M revolutions /year @ 15r.p.m.)

Rotating Target #2
Continuous 750 kW
operation

Fixed target (6 years)

Rotating target #1 (5 years)

Rotating target #2
(2 years ~)

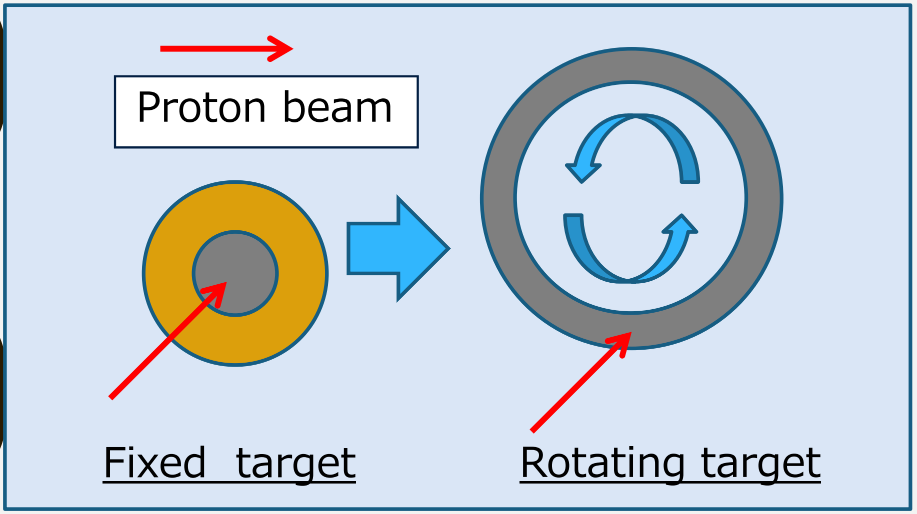
MUON ROTATING TARGET SINCE 2014

- Rotating target method is applied to distribute the irradiation damage of graphite to a wider area.
- Cooling by thermal radiation
- Lifetime of graphite: 30 years
- Lifetime is determined by solid lubricant of bearings

Solid lubricant;

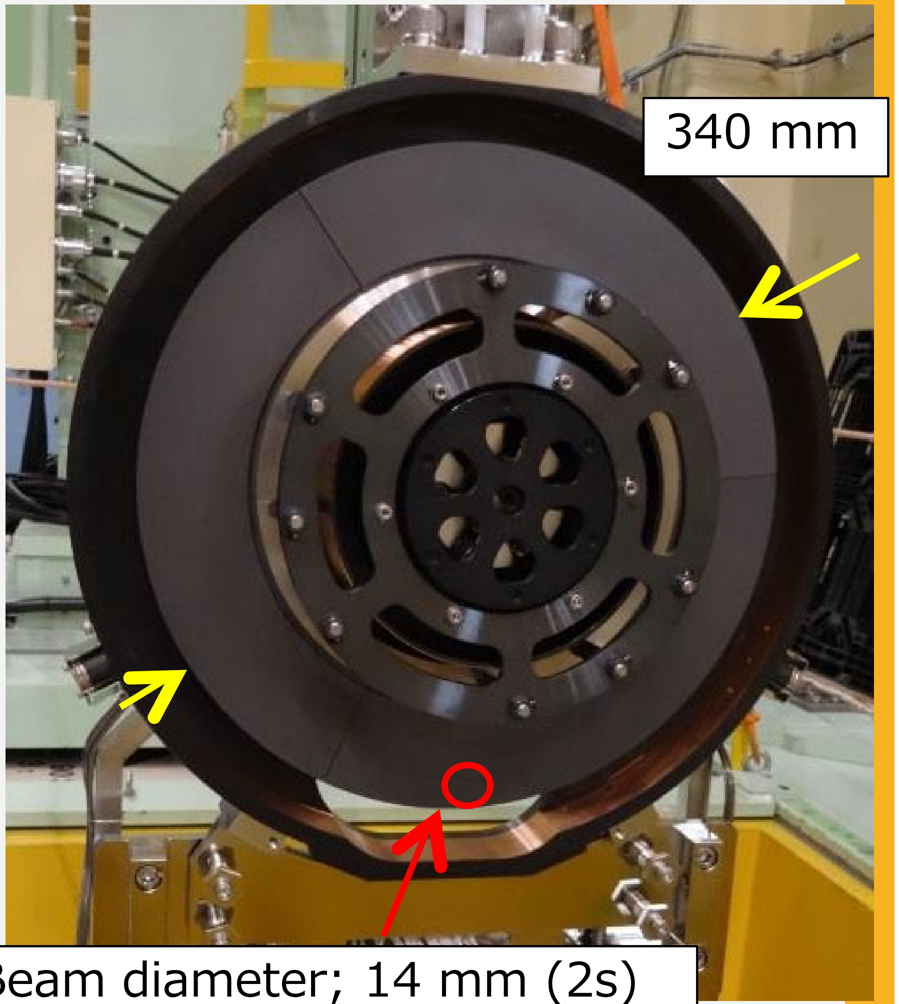
- ➢ Silver coating with MoS2, Lifetime: < 1 year
- ➢ Tungsten Disulfide at J-PARC MLF

Aiming lifetime; 10 years


Proton beam

Fixed target

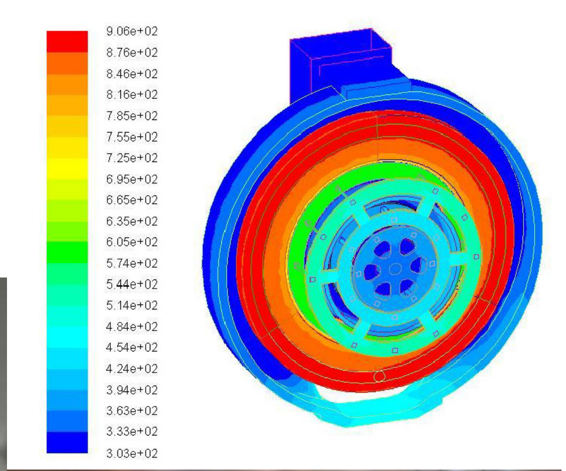
Rotating target

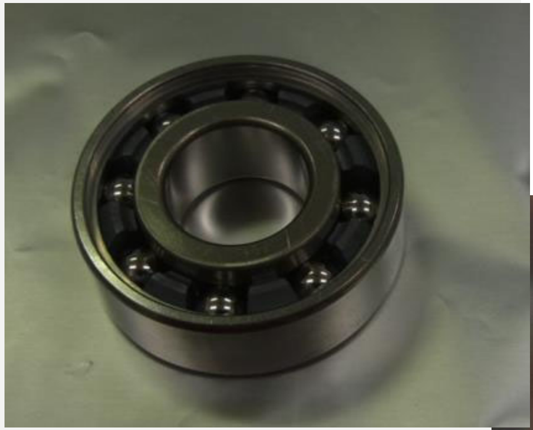


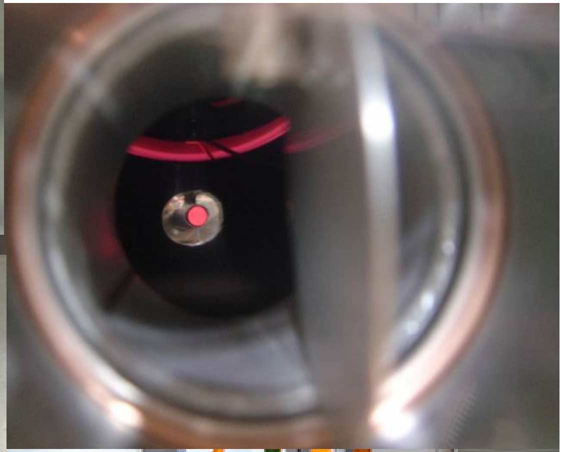
P-Beam diameter; 14 mm (2s)
4kW heat @ 1MW proton beam
Thickness of graphite 20 mm

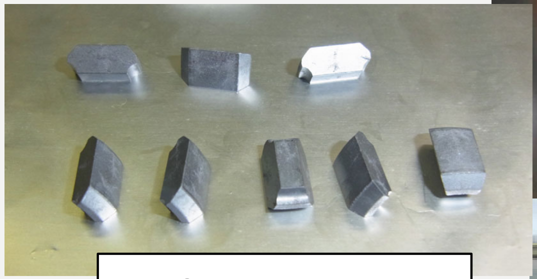
DEVELOPMENTS OF MUON ROTATING TARGET

- Validation for FEM simulation
- Duration tests for WS_2 lubricants in vacuum & at high temperature.
- Actual operation: 15 r.p.m.
- Accelerated test: 300 r.p.m.
- Stable operation with 5 x 10^6 revolutions
- Finally, rotating target was installed in 2014.



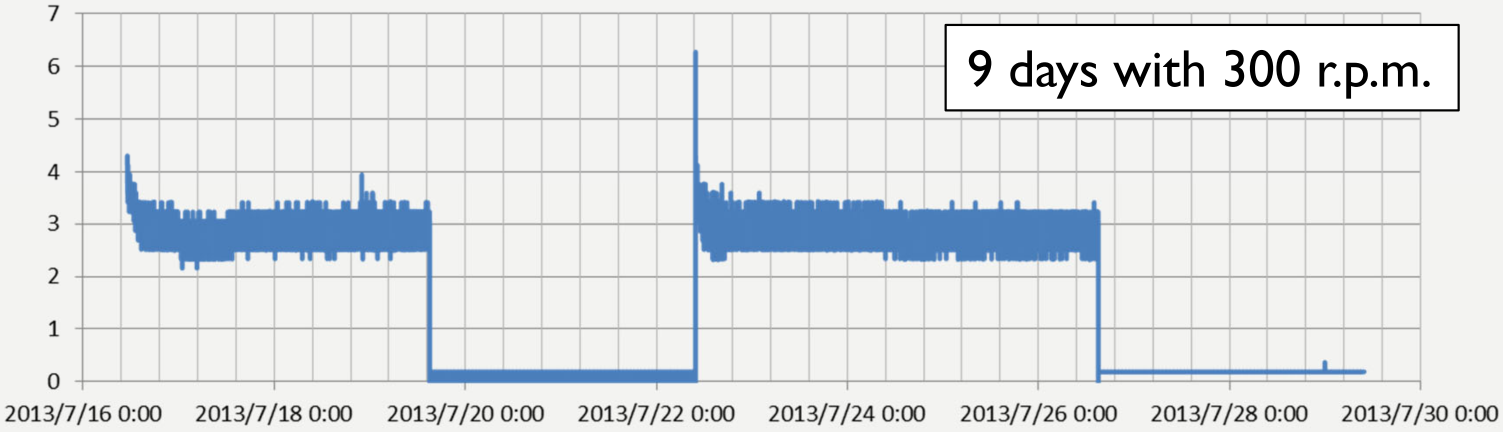






WS_2 lubricants

Motor Torque (x 10%)



9 days with 300 r.p.m.

Infrared camera

Supplied by Shiro Matoba who is in charge of MLF target now.

◎Direct observation with the infrared camera was successful. (Figure 1, Figure 2)
○The decrease in thermal conductivity due to radiation damage is being measured.
X Frequent outages due to radiation errors → More resistant to radiation
! Calculated thermal conductivity by IR camera = 144 W/m·K (IG430U :140 W/m·K)

Fig. 1 Infrared camera image at 1 MW

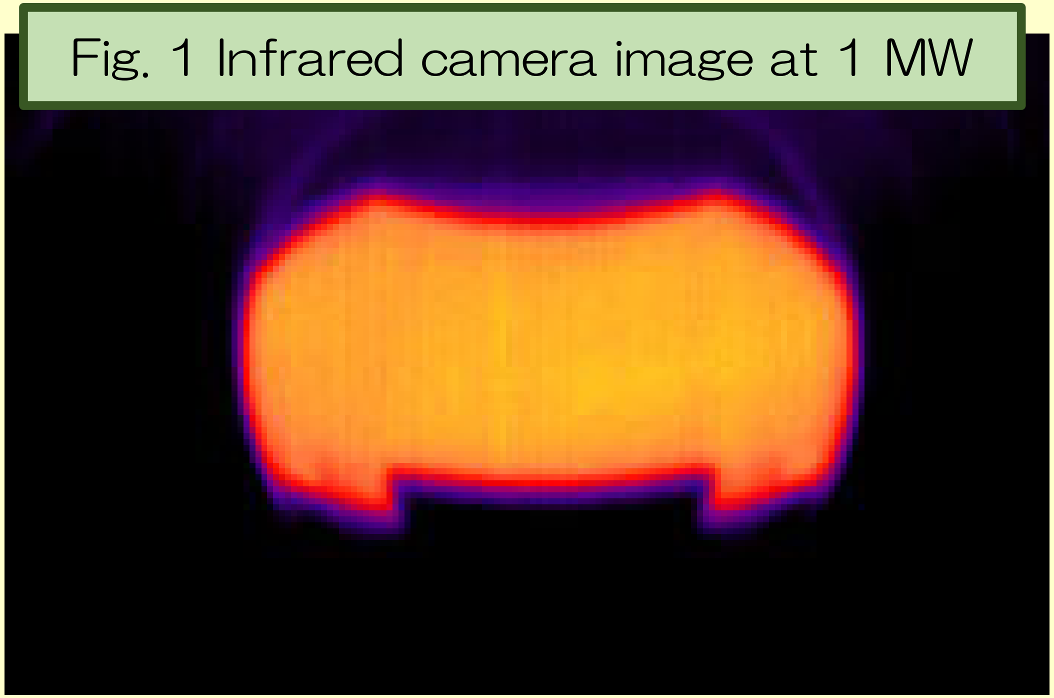


Photo of the target taken with a digital camera during the beam stop.

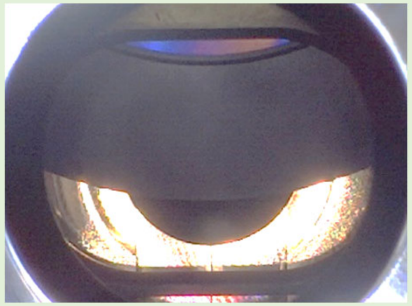
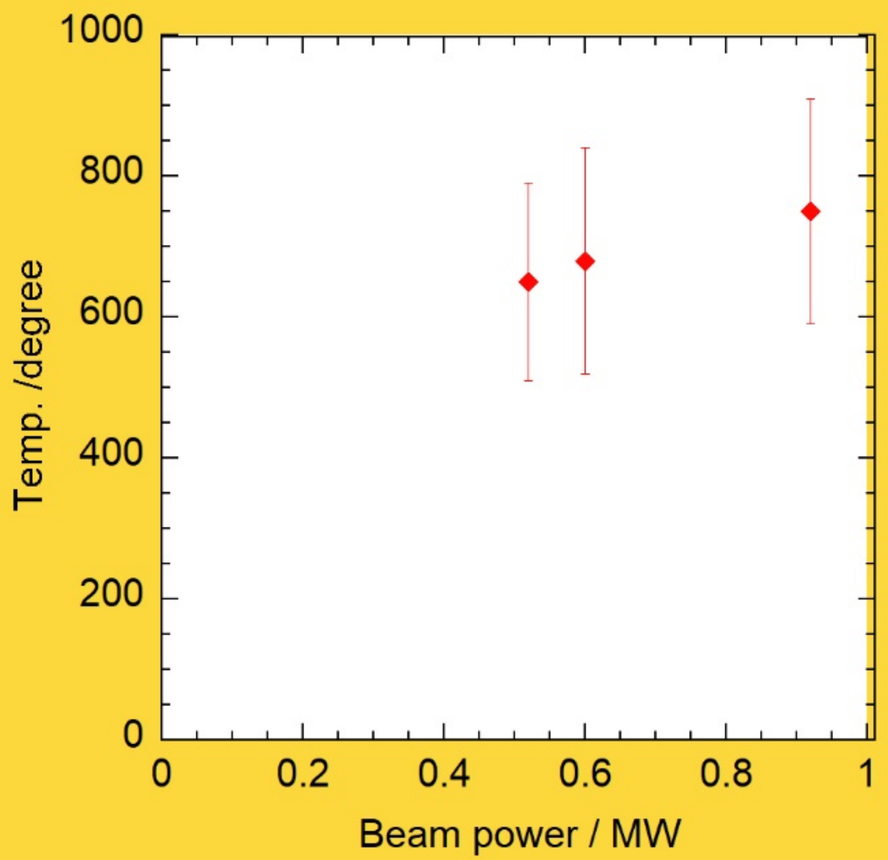


Fig. 2. Beam power dependence of muon target temperature

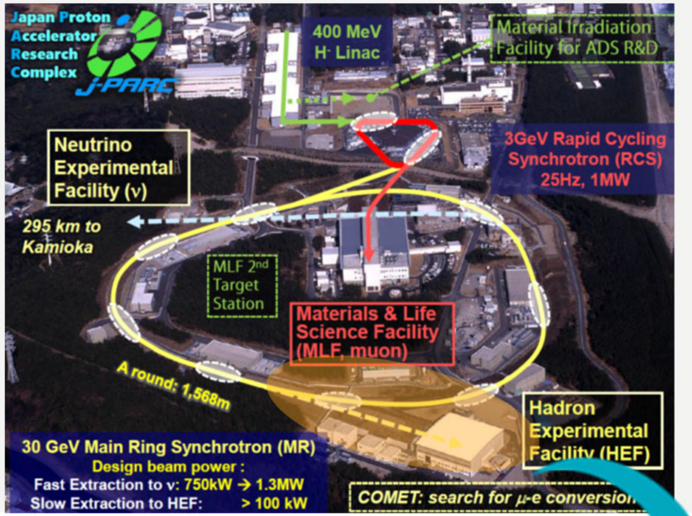


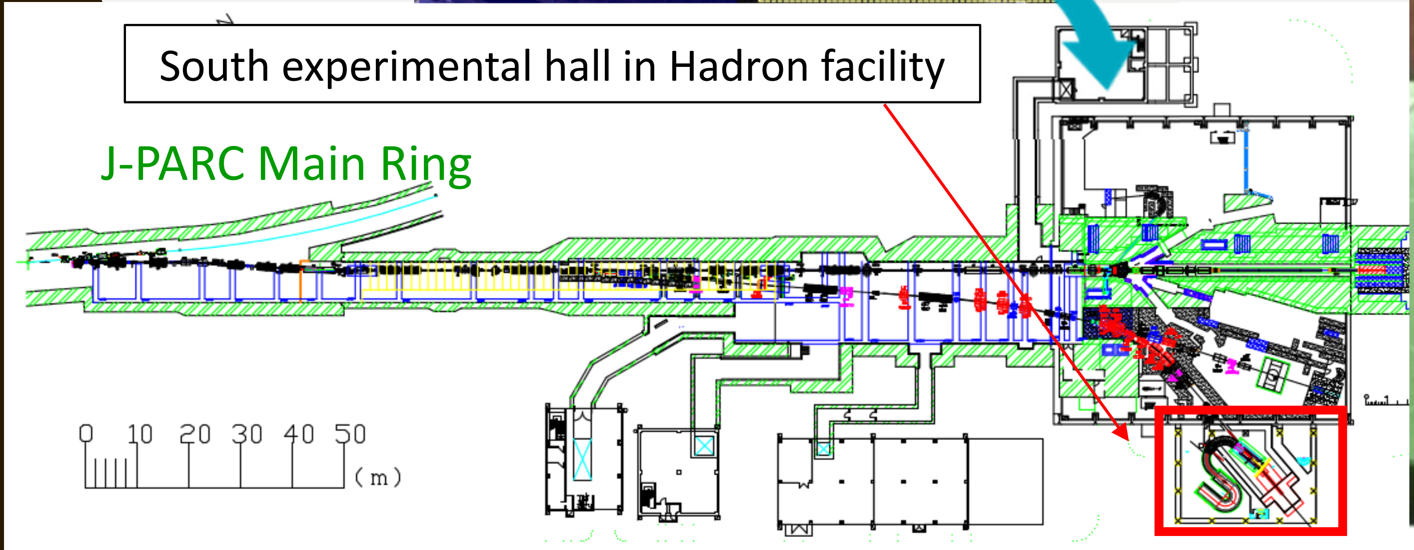
2. COMET TARGET

PHASE ALPHA TARGET
PHASE 1 TARGET

COMET FACILITY

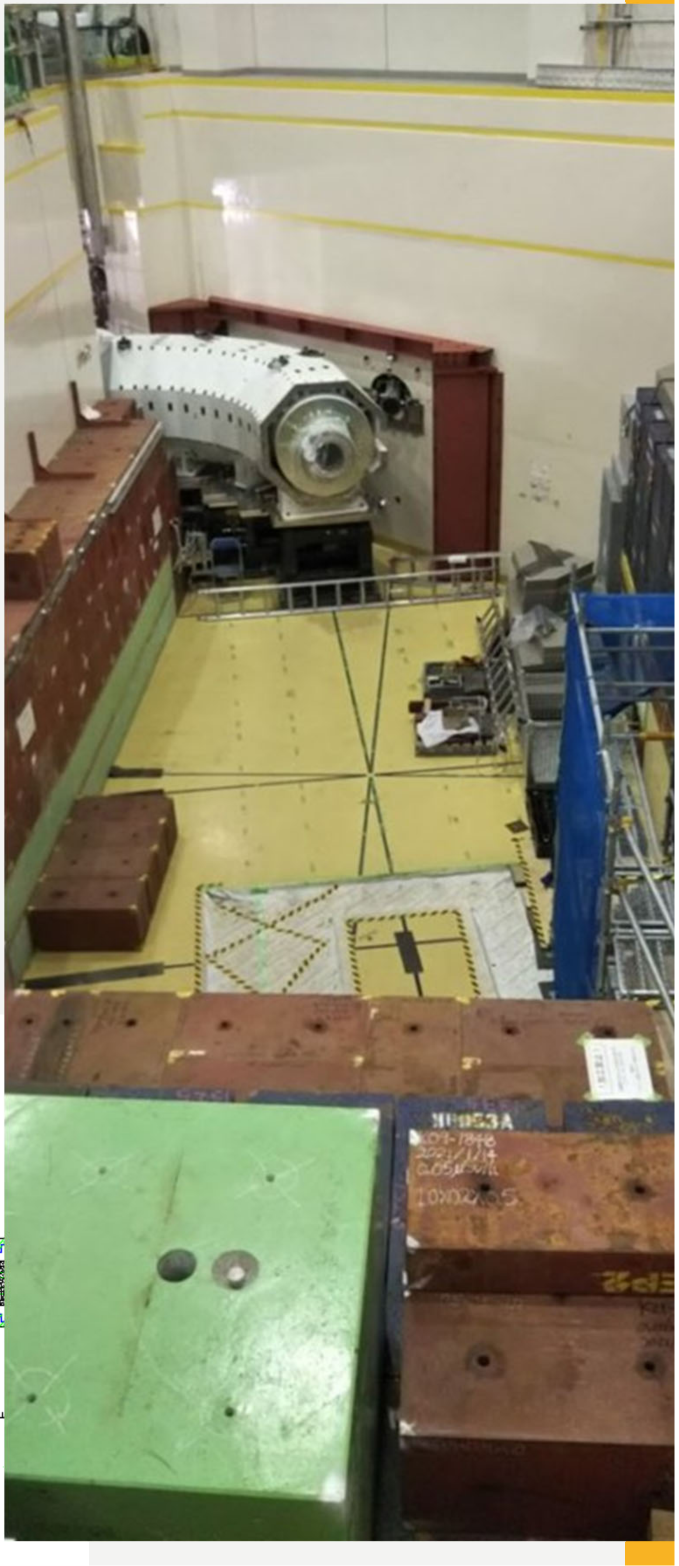
1. Located beside Hadron experimental facility
2. 8 GeV proton beam is supplied from Main Ring that normally supplies 30 GeV proton beam.





South experimental hall in Hadron facility

J-PARC Main Ring



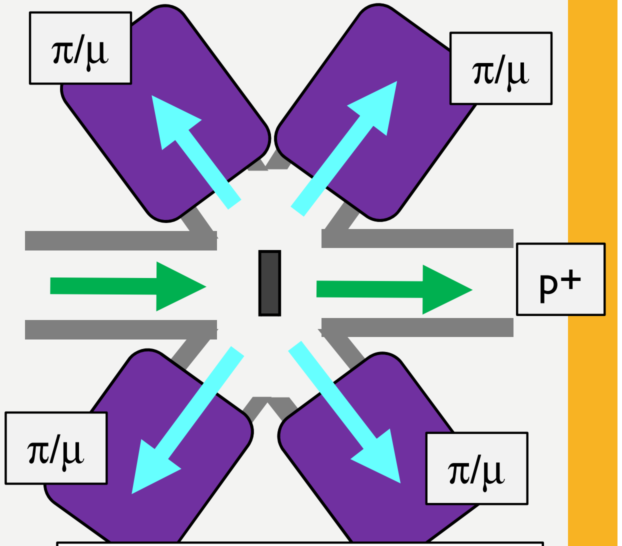
COMET TARGET
TO OBTAIN INTENSE MUON BEAM

- Conventional muon target (e.g. MLF target):

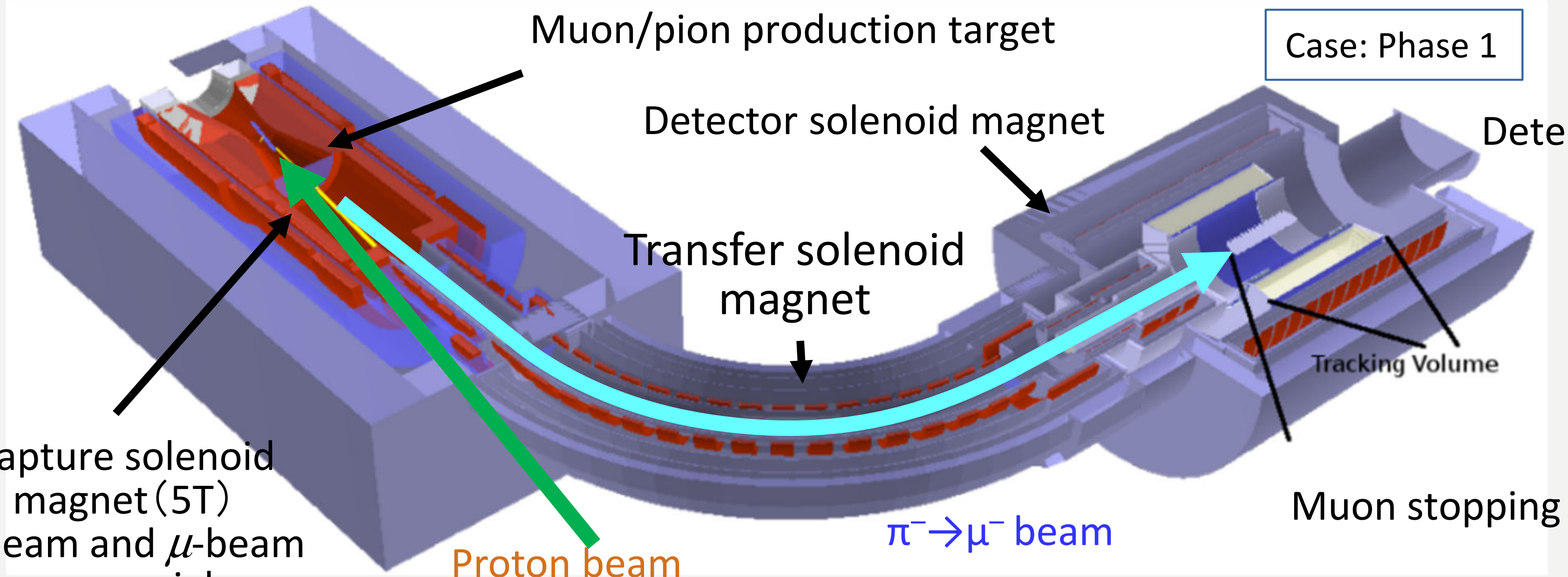
Muon is captured with small solid angle by magnets beside a proton beamline.

- COMET target

The target is placed in a super-conducting capture solenoid magnet. Large acceptance of Muon is expected.



Conventional muon target



Muon/pion production target

Case: Phase 1

Detector solenoid magnet

Detectors

Transfer solenoid magnet

Tracking Volume

Capture solenoid magnet（5T）
p-beam and μ-beam are coaxial.

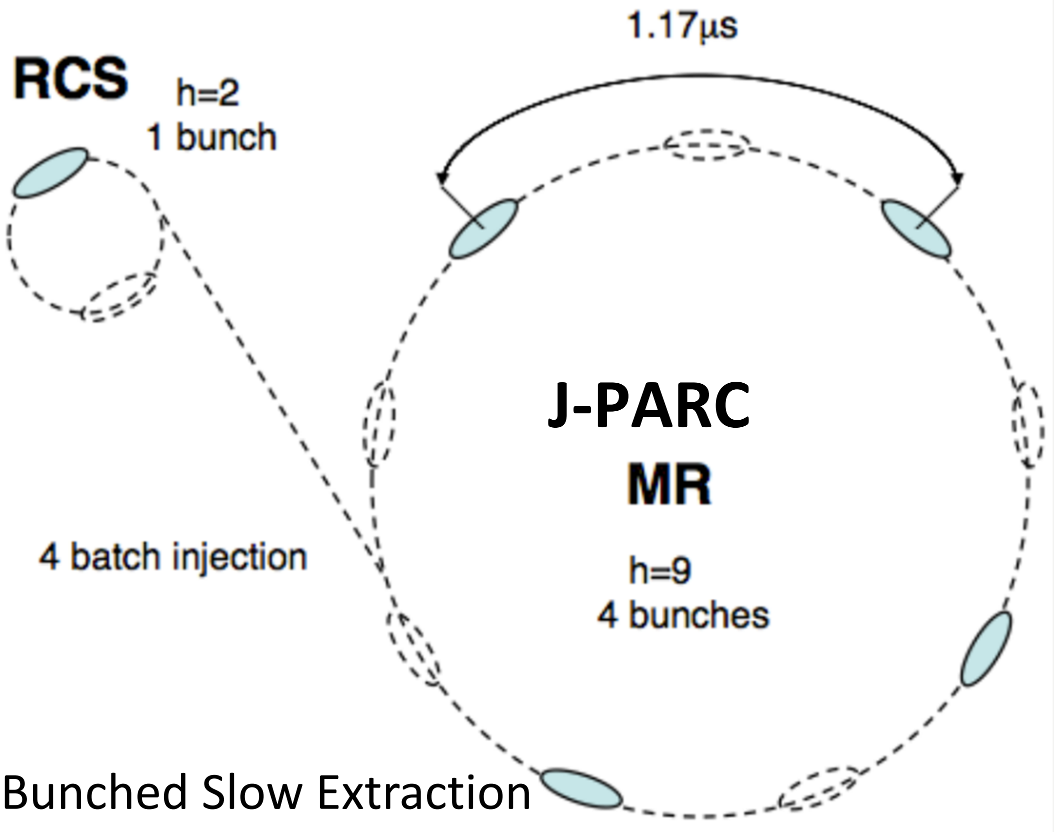
Proton beam

$\pi^- \rightarrow \mu^-$ beam

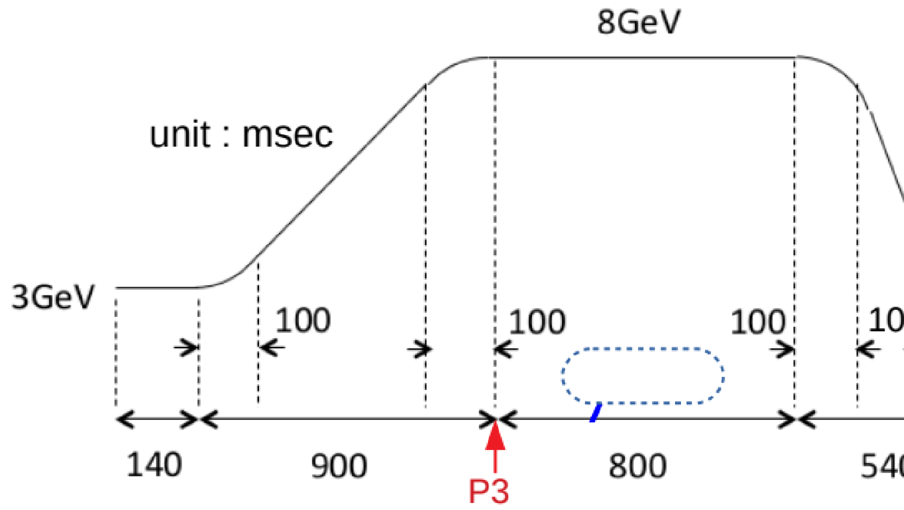
Muon stopping target

- Beam loss is not high, but heat density is high (σ = 1.8 mm).
- Difficult to disperse the high-density heat. (e.g., cannot be rotated)
- Shielding of superconducting magnet must be considered.

PARAMETERS OF PROTON BEAM



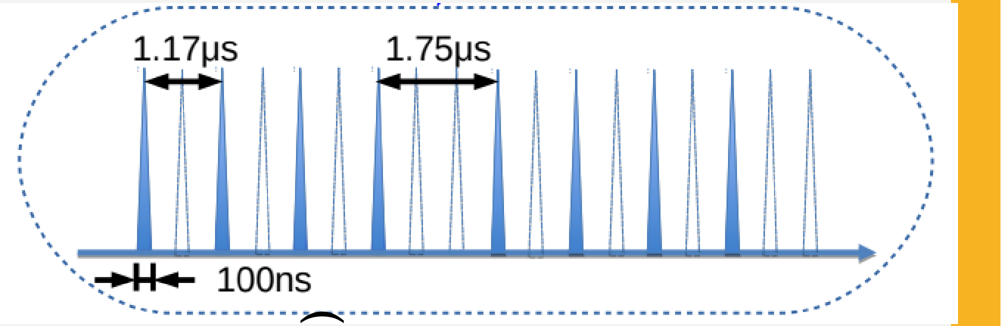
Bunched Slow Extraction

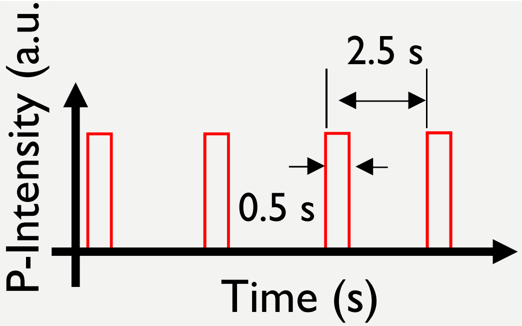


Extraction: 0.5 sec.

Case: COMET Phase1

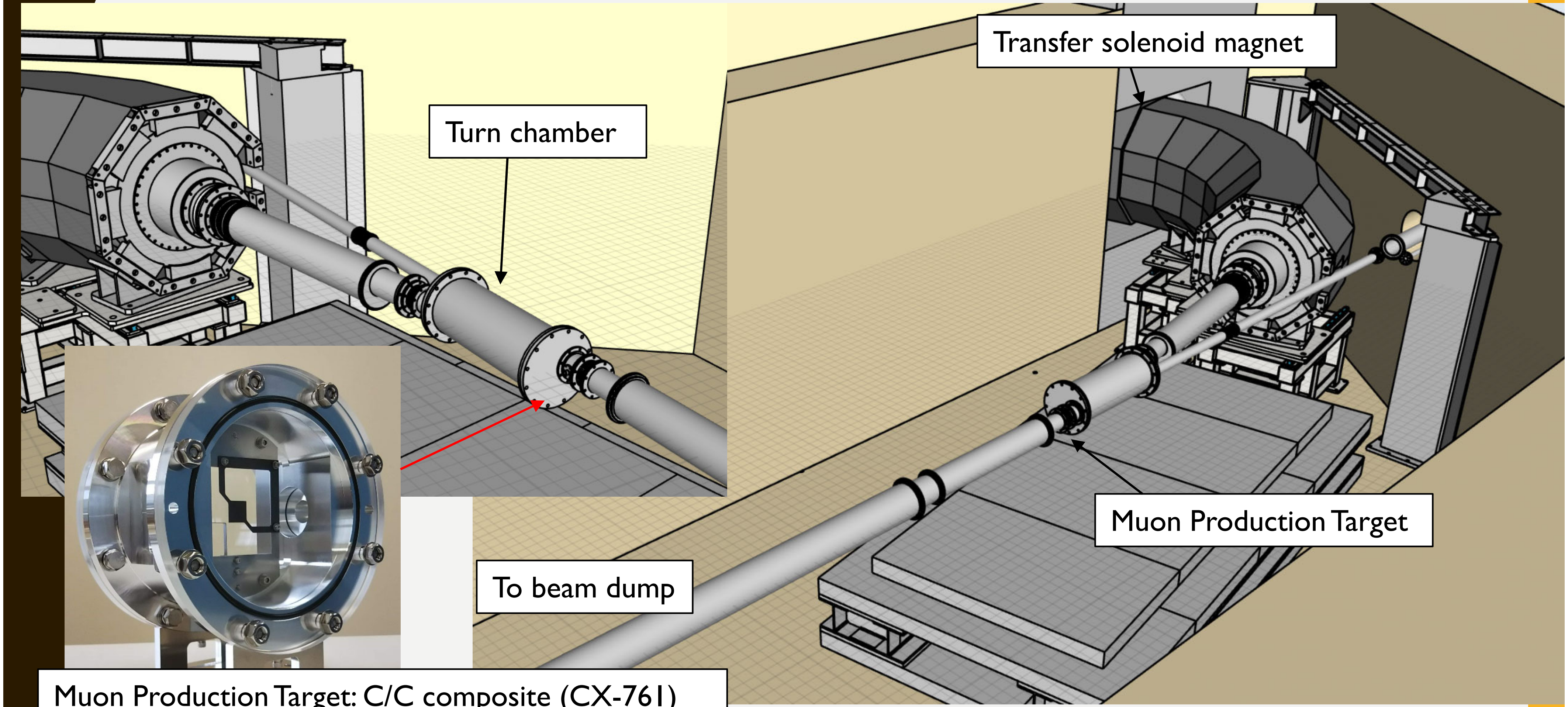
energy	8GeV
power	3.2 kW
proton / bunch proton / spill	1.6×10^{7} 6.2×10^{12}
cycle extraction	2.5 sec. 0.5 sec.





Case: Phase2
Power 56 kW

PHASE ALPHA, DEC. 2022-
~PILOT TEST OF PROTON AND MUON TRANSPORT



Muon Production Target: C/C composite (CX-761)

- 20 x 20 mm, t=1.1 mm
- d=1.58 g/cc
- Candidate of target support in Phase 1

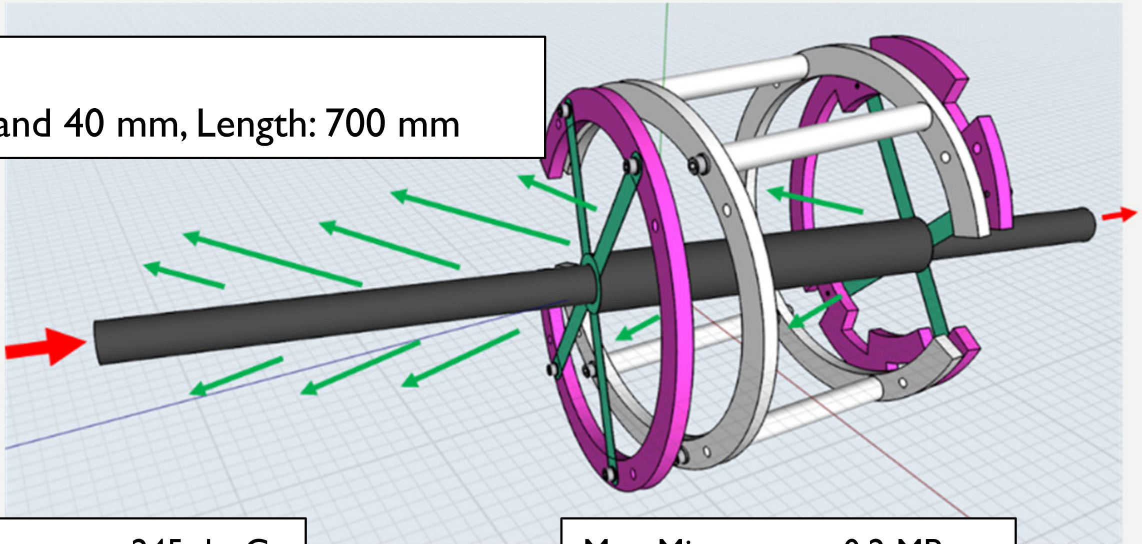
Capture solenoid magnet is replaced with vacuum ducts in Phase alpha.

Muon production target: 1-mm thick Carbon/carbon composite

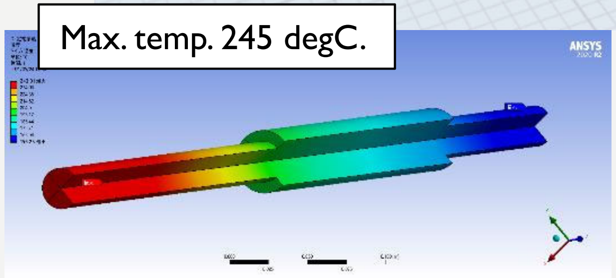
MUON PRODUCTION TARGET IN PHASE 1

Graphite target, IG-430U floats on the center axis of the capture solenoid magnet.

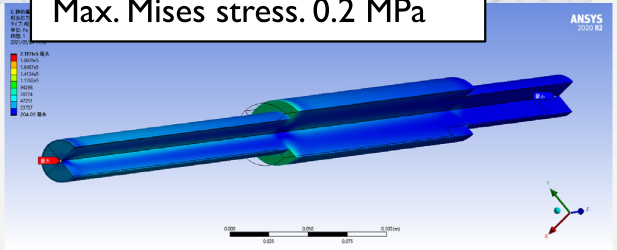
Graphite
Diameter: 26 mm and 40 mm, Length: 700 mm

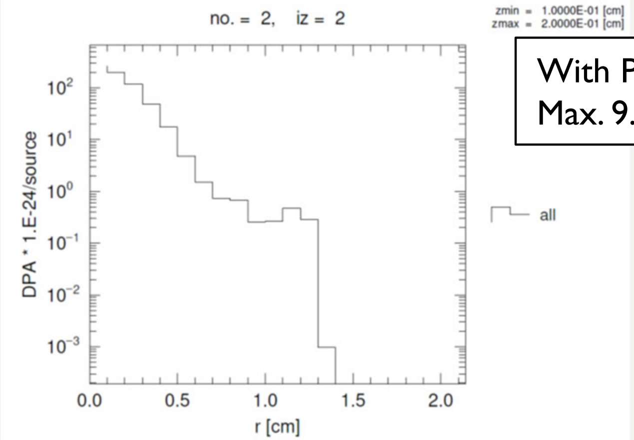


Max. temp. 245 degC.



Max. Mises stress. 0.2 MPa



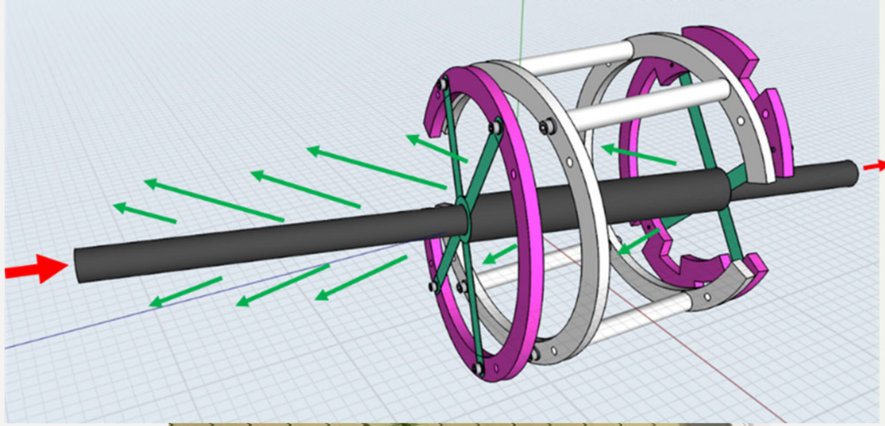


With Phase 1, 150 days operation
Max. 9.6 x 10^{-3} dpa,

PHITS & ANSYS simulation
By N. Kamei in KEK-IPNS mechanical group

Not severe!!

TARGET SUPPORT



Target support

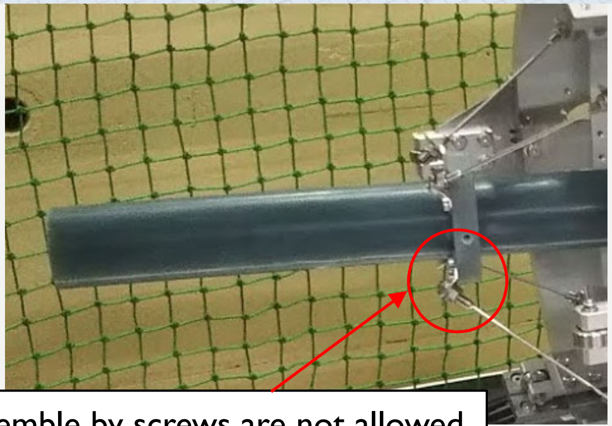
- Should not disturb the muon transport
- Will be irradiated by proton beam

Material & Structure

- Refractory material
- Non-bulk material
- Low-density is preferable

Table: Maximum temperature of the target support, when the direct irradiation takes place on the support

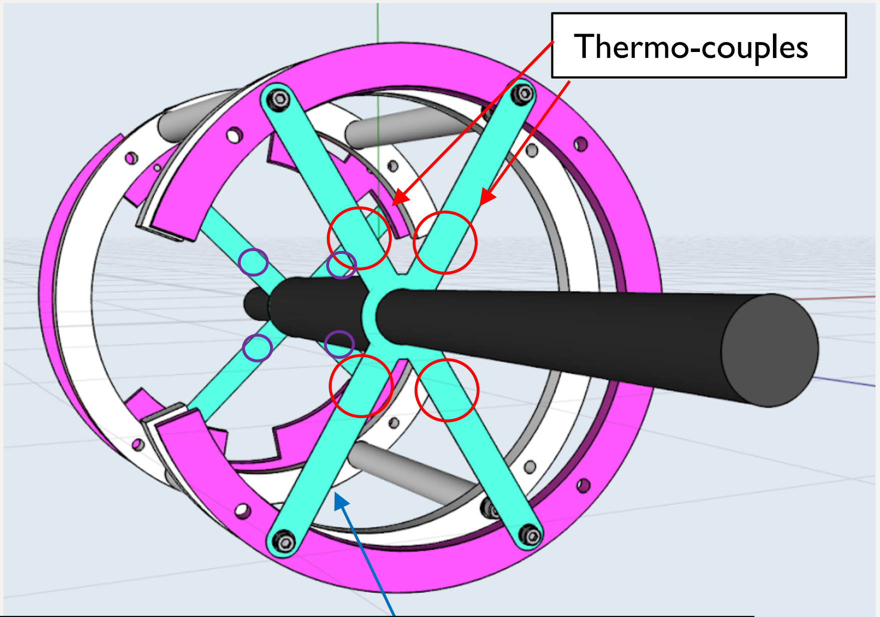
	SS304 t=0.5 mm	Ti-6Al-4V t=0.5 mm	C/C composite t=1 mm
Emissivity	0.3	0.3	0.9
Max. temp. degC	560	440	<245



Assemble by screws are not allowed.

Measurements of beam position on the target

- 4 thermo-couples on the upstream
- 4 thermo-couples on the downstream
- Balance can inform the beam position
- D=0.5 mm, SS304 sheathed thermocouples
- Experiences in MLF muon target



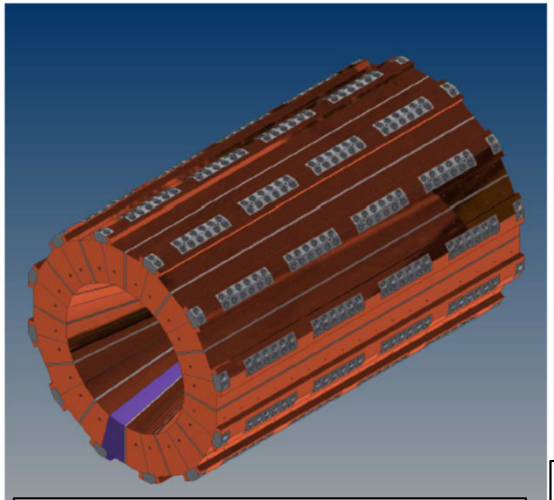
Thermo-couples

C/C material, CX761 is one of the candidates as the target support.

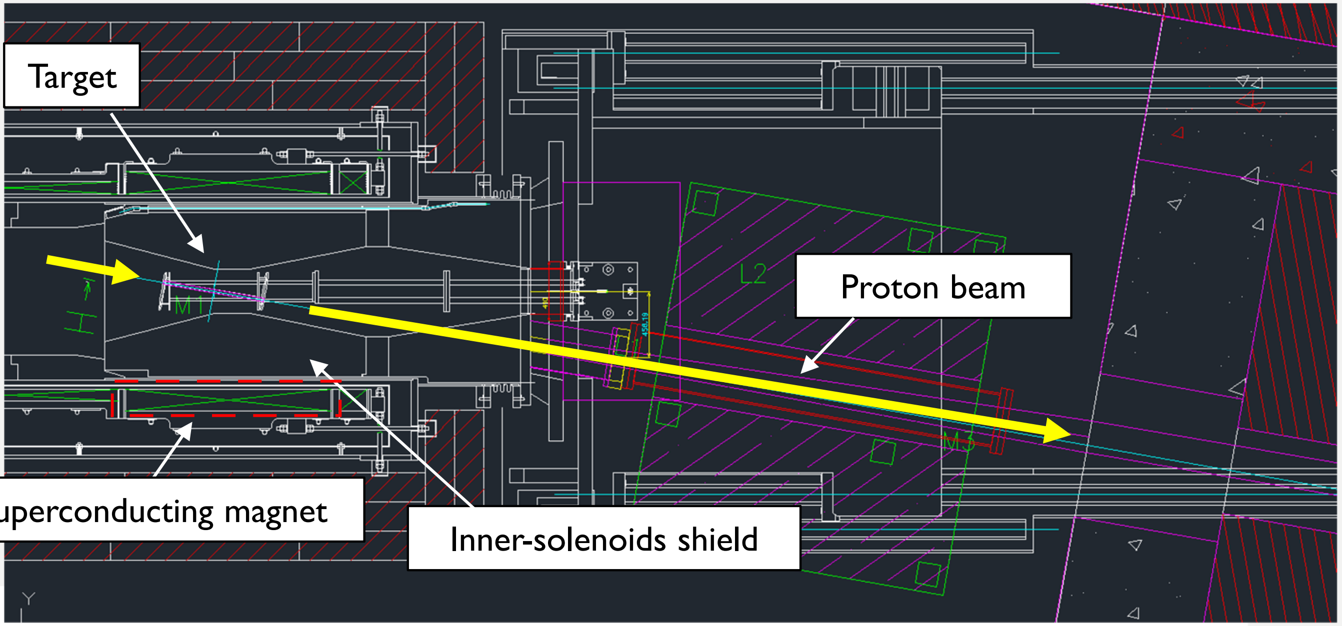
3. INNER-SOLENOID SHIELD

OVERVIEW OF INNER SOLENOID SHIELD

- Inner solenoid shield protects the superconducting solenoid magnet from the radiation originating the proton irradiation on the target.



Assembling of long pieces

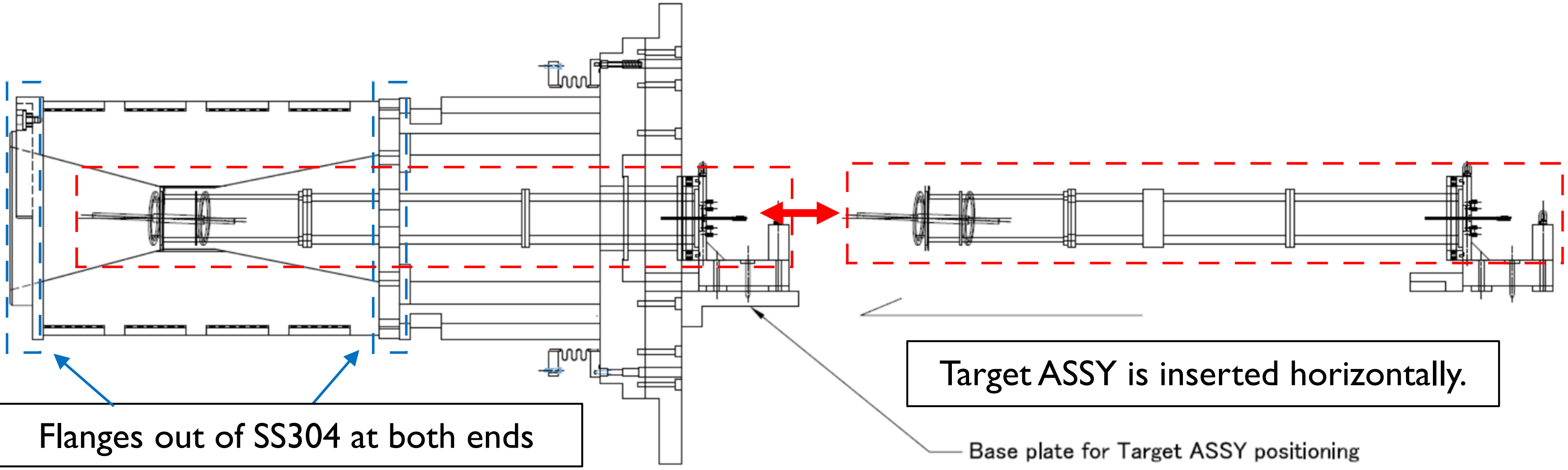


Target

Proton beam

Superconducting magnet

Inner-solenoids shield



Target ASSY is inserted horizontally.

Flanges out of SS304 at both ends

Several long pieces of shields are integrated with stainless-steel (SS304) flanges at both ends.

MATERIAL OF INNER SOLENOID SHIELD

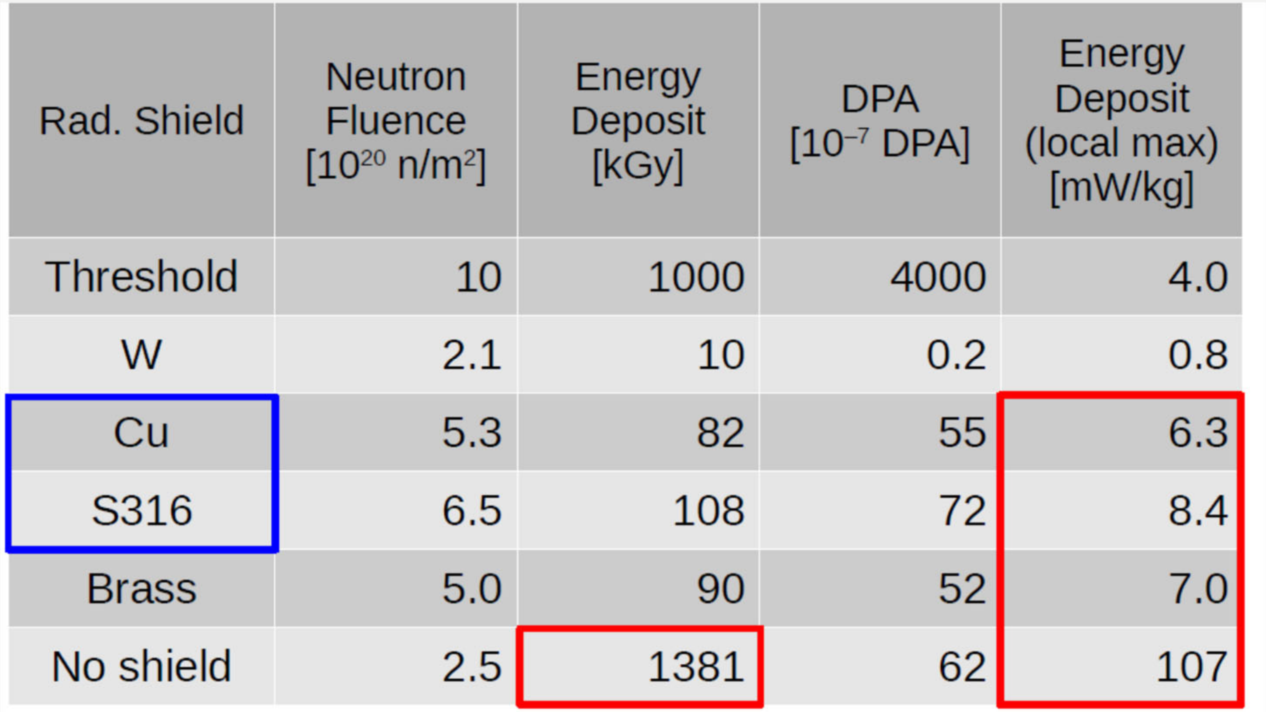
- The Material of the inner solenoid shield needs high density, non-magnetism, small outgas, availability, and "LOW COST"
- The COST & shielding ability: Tungsten > Copper > SS304

Tungsten cannot be used in Phase I because it costs too much.

Threshold of Damage (Investigated by Cryogenic group)

1. Neutron fluence < 10^{21} [n/m^2] (recovered by annealing)
2. Displacement-per-atom < 4 x 10^{-4} [DPA] (recovered by annealing)
3. Radiation damage << 1 MGy
4. Heat load < 4 mW/kg (conservative design: limit from refrigerator capacity for phase1)

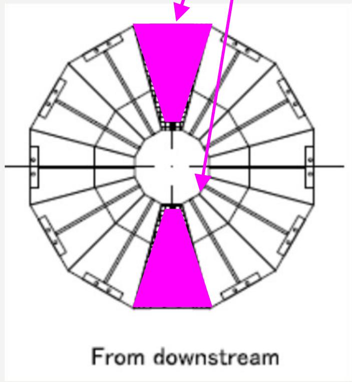
M. Yoshida et al., Proc. AIP Conf., 2011, vol. 1435, pp. 167–173.
J.A. Horak et al., J. Nucl. Mater., vol. 49, pp. 161–180, 1973.
Ye Yang, et al., IEEE trans. appl. supercond., Vol.28 No.3, 4001405, 2018.



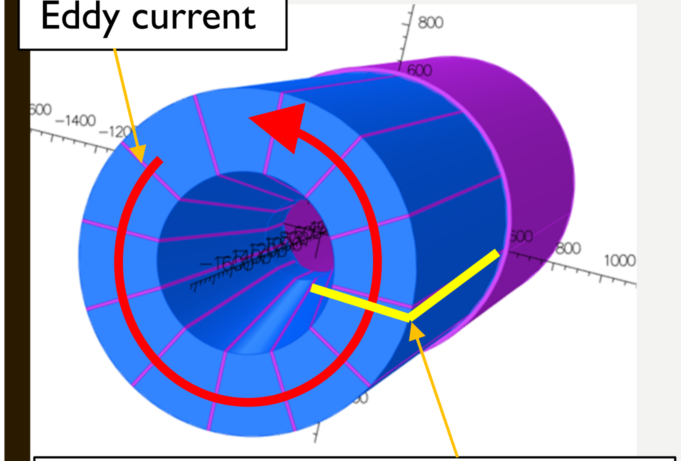
Rad. Shield	Neutron Fluence [10^{20} n/m^2]	Energy Deposit [kGy]	DPA [10^{-7} DPA]	Energy Deposit (local max) [mW/kg]
Threshold	10	1000	4000	4.0
W	2.1	10	0.2	0.8
Cu	5.3	82	55	6.3
S316	6.5	108	72	8.4
Brass	5.0	90	52	7.0
No shield	2.5	1381	62	107

150 days @Phase I (3.2 kW) through MARS simulation

SS304: mandatory for structural material

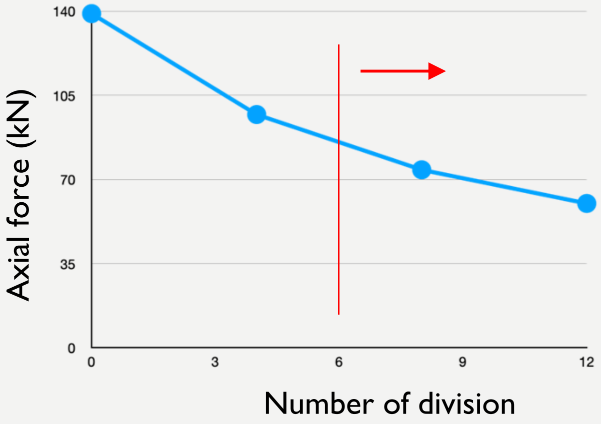


LORENTZ FORCE IN QUENCH INCIDENT



Eddy current

SS304 plates in each gaps, t=10 mm



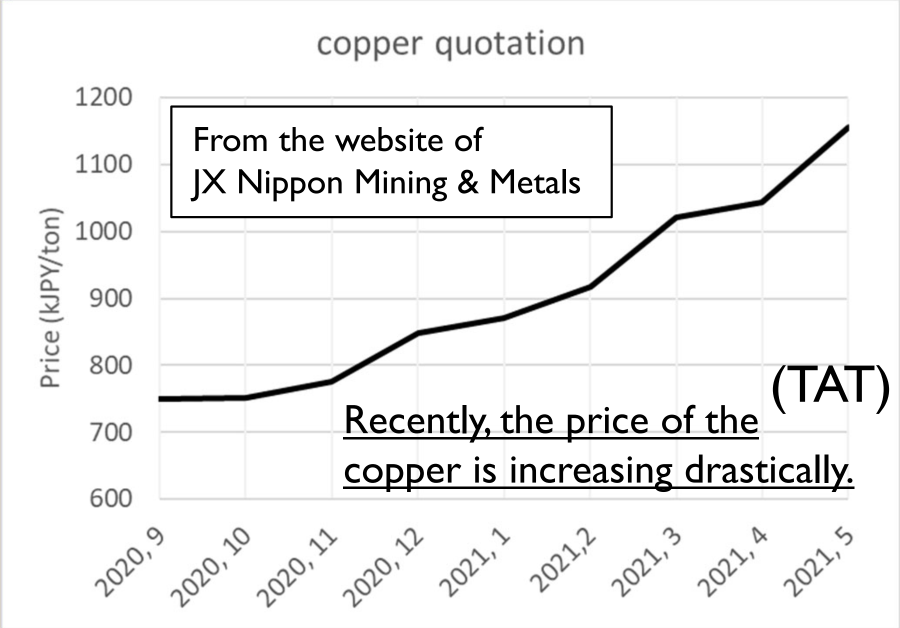
Cu shield will be divided to more than 6 pieces.

Lorentz force occurs by a sudden drop of the magnetic field.

- Hoop direction of the eddy current is dominant.
- High electric resistivity of the shield material decreases the force. SS304 decreases more than copper.
- Analysis of copper shield: Dividing the copper shield into several pieces with SS304 plates

The current of the magnet exponentially decreases with time constant of 60 seconds.
OPERA simulation by Sumi in cryogenic group

MISFORTUNE: MARKET PRICE OF COPPER

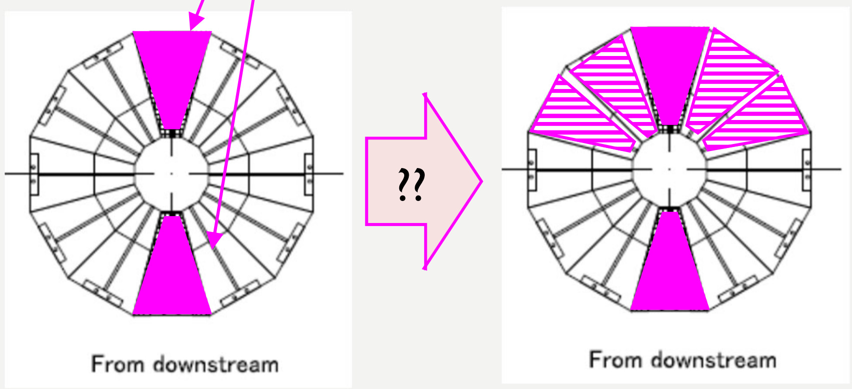


From the website of
JX Nippon Mining & Metals

(TAT)

Recently, the price of the copper is increasing drastically.

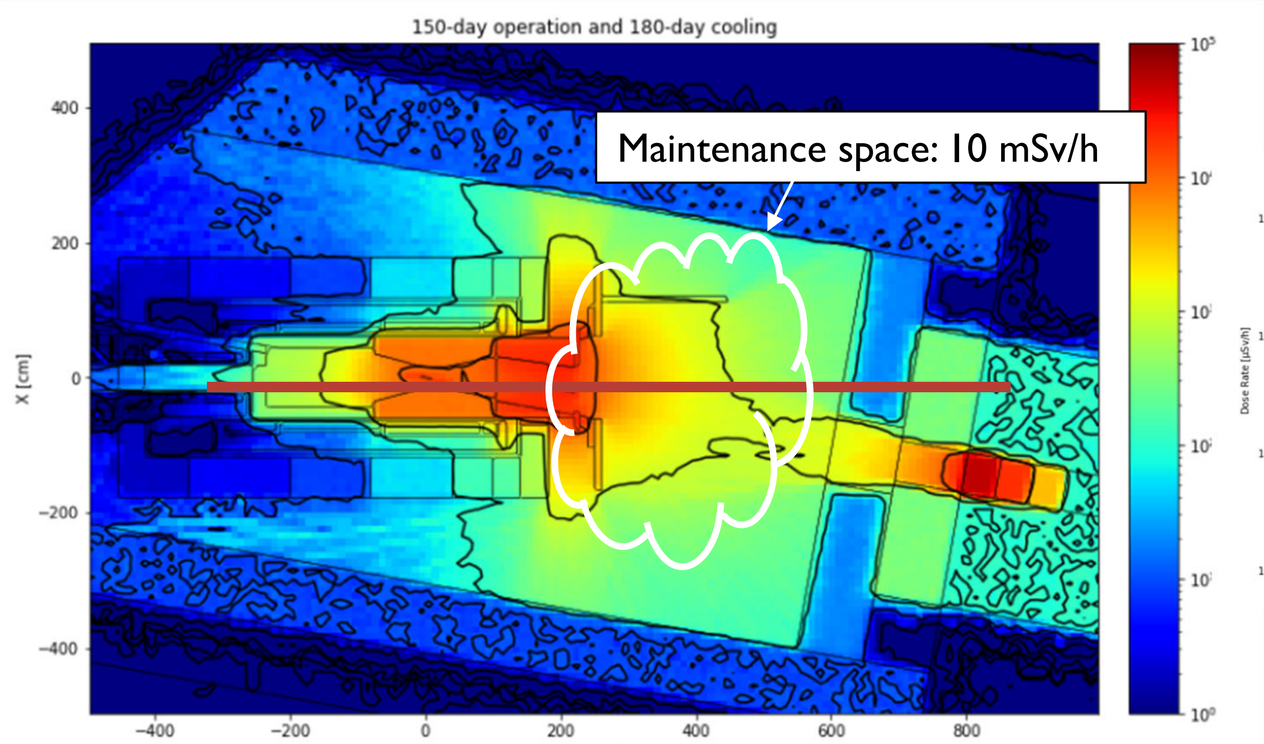
Some of pieces of copper, on which the beam loss is low, may be replaced with SS304.



SS304?? Or more?

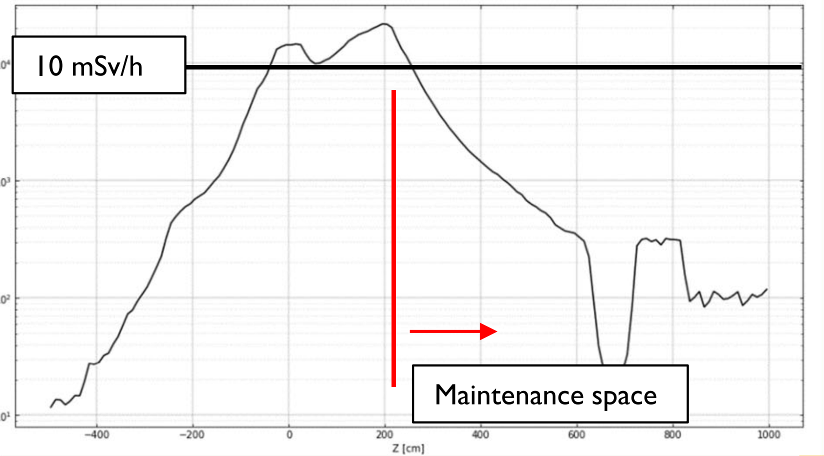
RESIDUAL RADIATION DOSE AT MAINTENANCE SPACE

Residual radiation dose on the downstream of target is high.



Maintenance space: 10 mSv/h

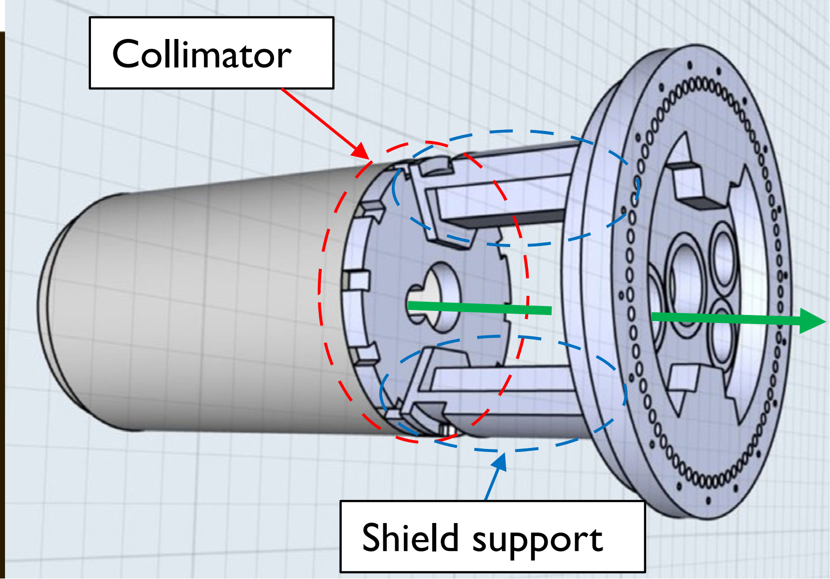
PHITS simulation, under collaboration with Kyusyu University



10 mSv/h

Maintenance space

Residual radiation dose on the brown line with 150-days operation in Phase 1 and 180-days cooling



Collimator

Shield support

Proton beam

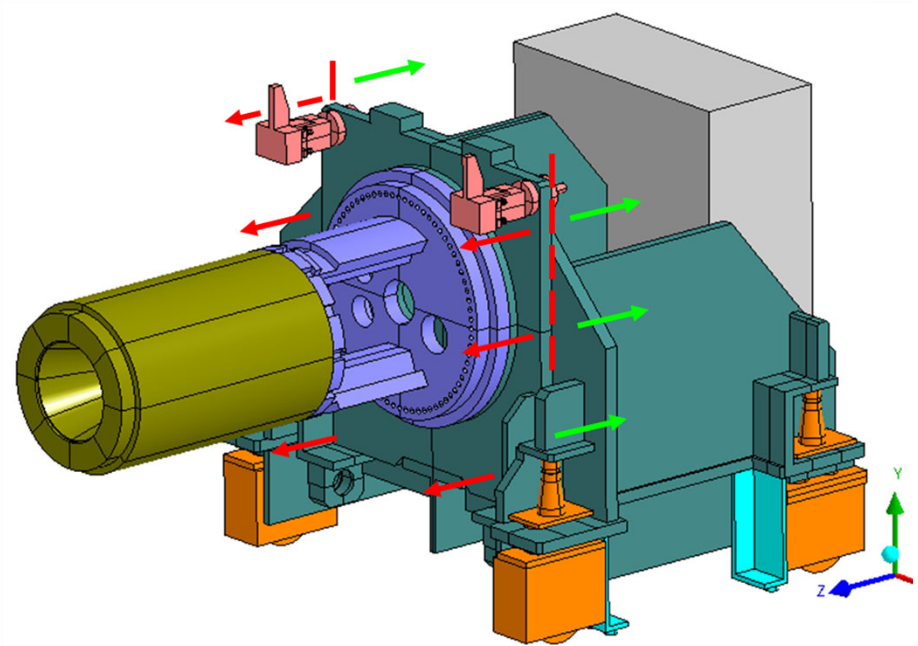
- The supports for the shield should far from proton beam path.
- Collimator just on the downstream of the shield reduce the dose.

Further study by Monte-Carlo simulation will be conducted.

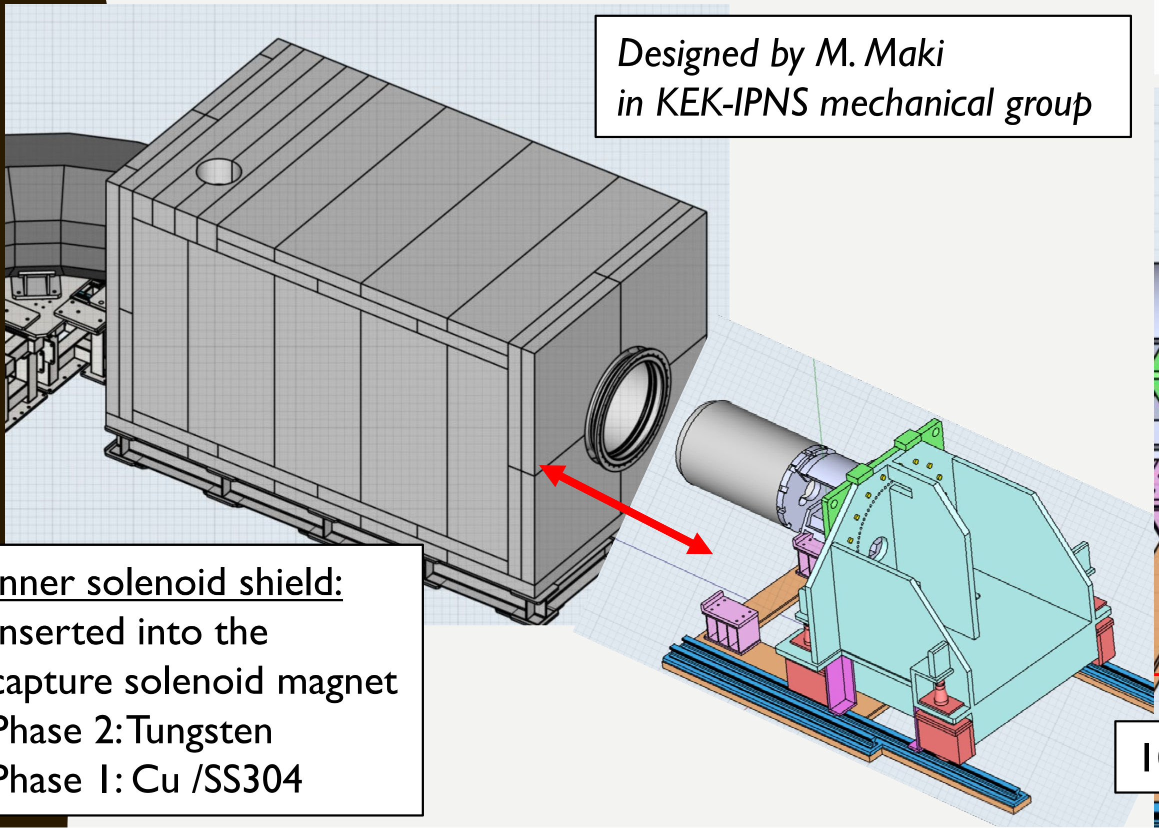
Remote maintenance scenario must be also considered.

REPLACEMENT OF THE SOLENOID SHIELD

- The inner solenoid shield can be inserted and be pulled out by the shield carriage.
- The shield carriage is disassembled and is removed during beam operation to avoid its activation.
- The structural plates of the shield carriage are composed of 100-mm thick iron, which has a function of a radiation shield.

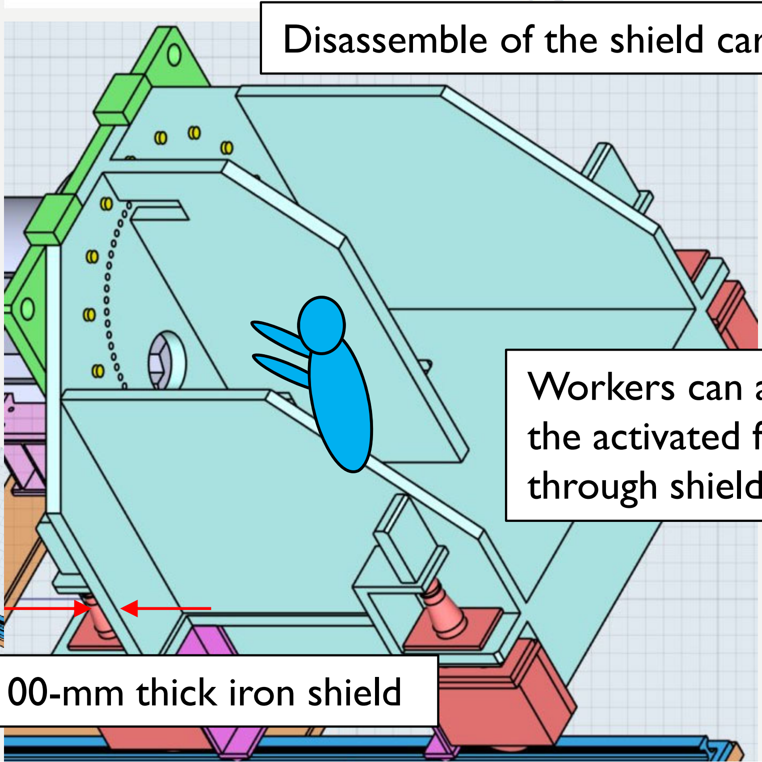


Disassemble of the shield carriage



Designed by M. Maki
in KEK-IPNS mechanical group

Inner solenoid shield:
Inserted into the capture solenoid magnet
Phase 2: Tungsten
Phase 1: Cu /SS304



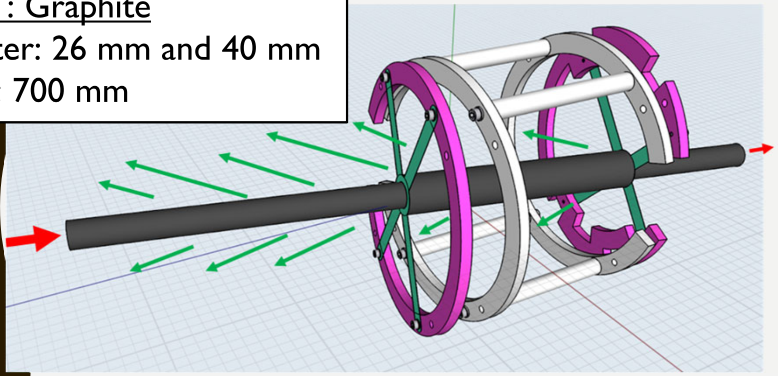
Workers can access the activated flange through shielding.

100-mm thick iron shield

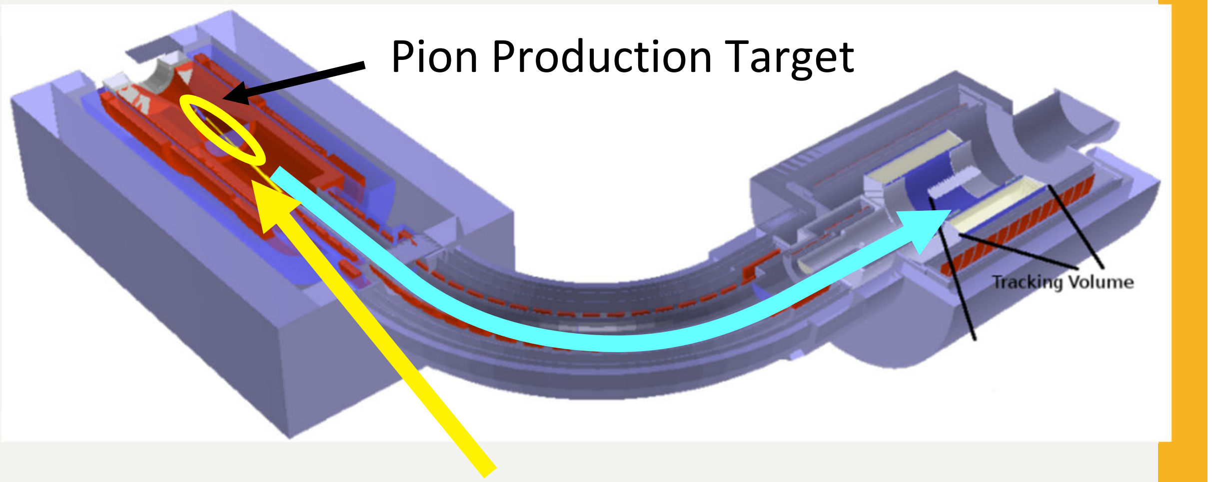
4. TOWARD PHASE 2

WHY TUNGSTEN TARGET?

- The higher density of target material, the lower spatial volume of muon source
- The lower spatial volume, the higher capture and transport efficiency of muon



Phase I: Graphite
Diameter: 26 mm and 40 mm
Length: 700 mm



COMET	Graphite	Tungsten
Density (g/cc)	1.8	19.2
Diameter & Length (cm)	2.6 & 60	1 & 16
Capture & Transport efficiency	0.33	1

3-times higher efficiency in tungsten than in graphite with common proton intensity

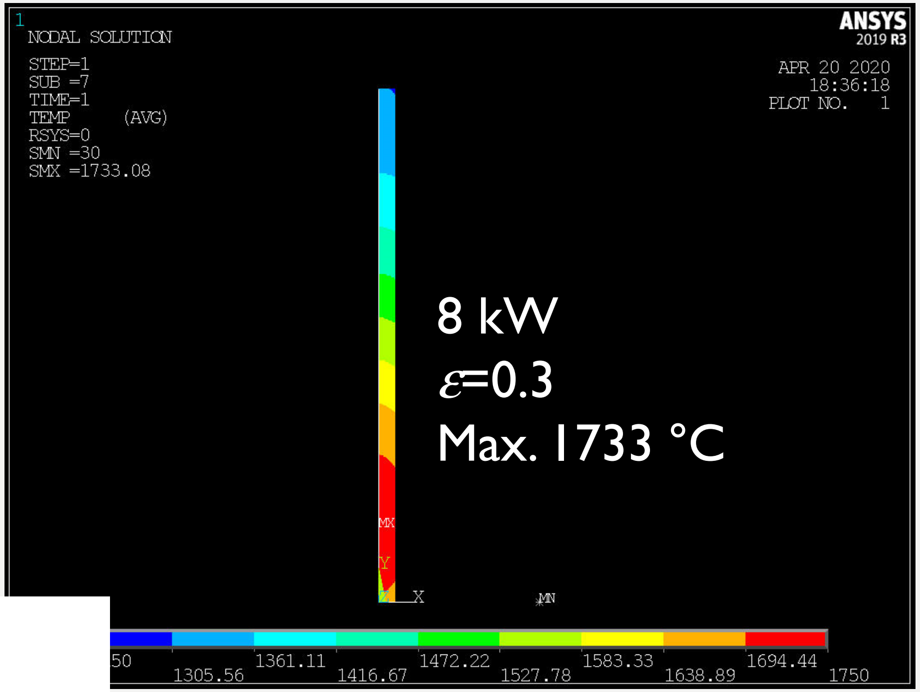
Higher heat density and embrittlement of W must be carefully considered.

THERMAL RADIATION COOLING W TARGET

Tungsten; radius=5 mm, length =160 mm
σx=1.46 mm, σy = 1.36 mm
Averaged to axisymmetric heat density.

<u>ITER-GRADE tungsten for fusion reactor</u>
(Pure tungsten with heavy plastic working)
Maximum available temperature: 1200 °C
<u>Even 8 kW is far from realistic.</u>

- ➢ <u>Geometry to improve cooling capability</u>
- ➢ <u>or Material development</u>



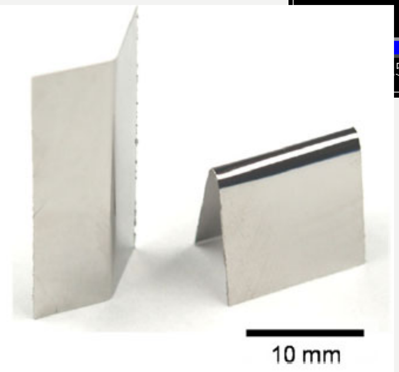
```
1
NODAL SOLUTION

STEP=1
SUB =7
TIME=1
TEMP       (AVG)
RSYS=0
SMN =30
SMX =1733.08
```

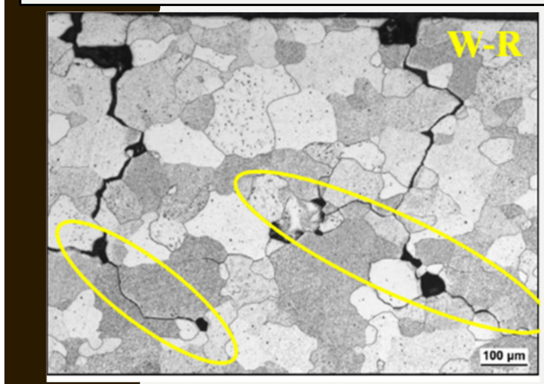
```
ANSYS
2019 R3
APR 20 2020
18:36:18
PLOT NO.    1
```

8 kW
ε=0.3
Max. 1733 °C

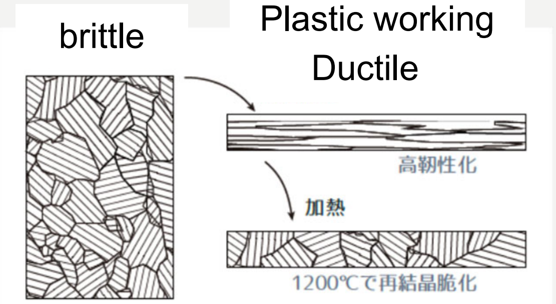
- ✓ Tungsten is brittle, because grain boundary is weak.
- ✓ Brittleness is improved by heavy plastic working.
- ✓ High temperature undo the improvement



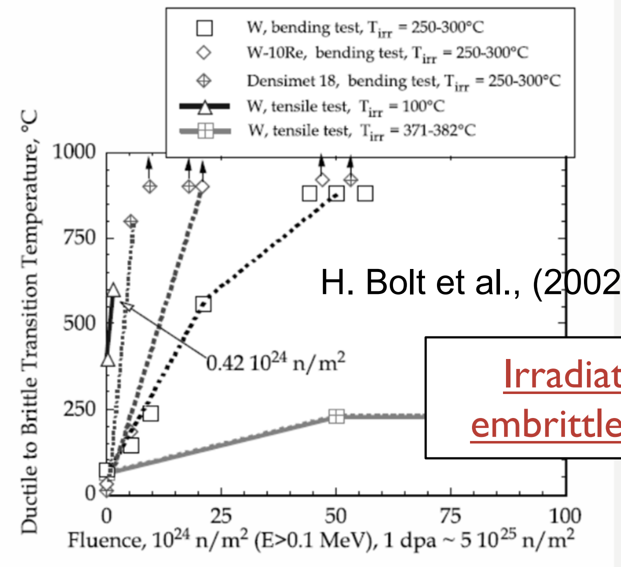
J.Reiser et al. JNM, 423 (2012) 1.



G. Pintsuk et al.



<u>Recrystallization embrittlement</u>



H. Bolt et al., (2002)

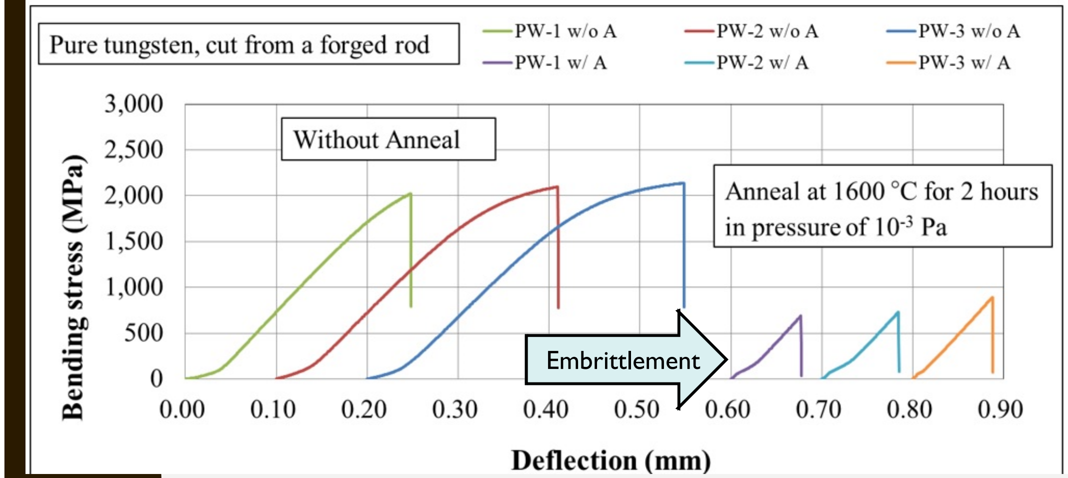
<u>Irradiation embrittlement</u>

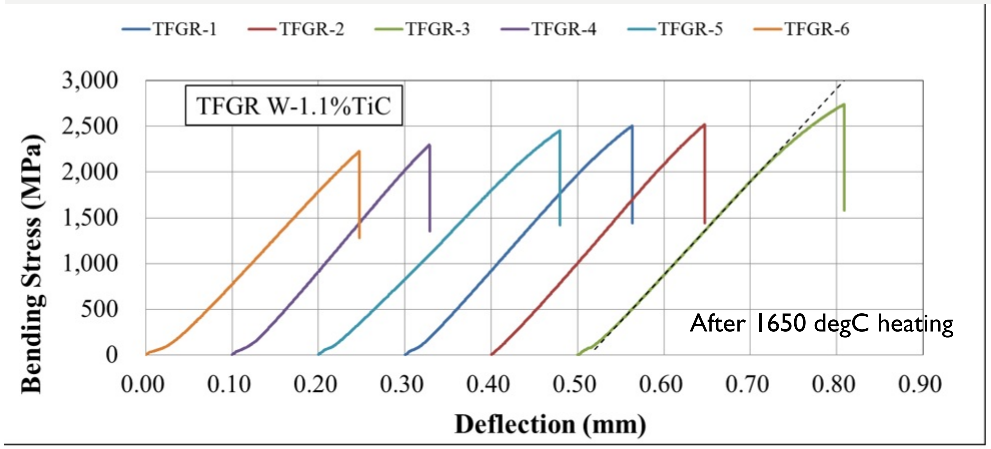
Ductile to Brittle Transition Temperature should be less than room temperature.

MATERIAL DEVELOPMENT OF NOVEL TUNGSTEN

Toughened Fine-Grained Recrystallized W-TiC

S. Makimura et al., Materials Science Forum, Spallation Materials Technology, Vol. 1024, pp 103-109

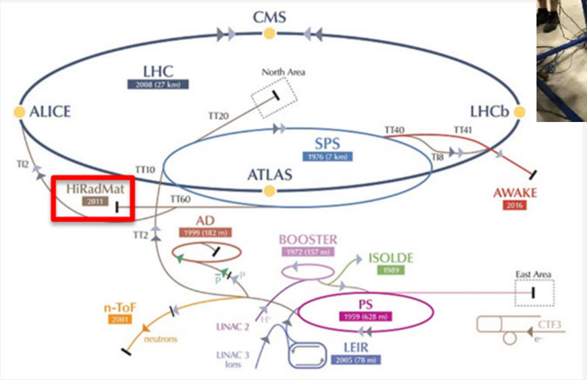


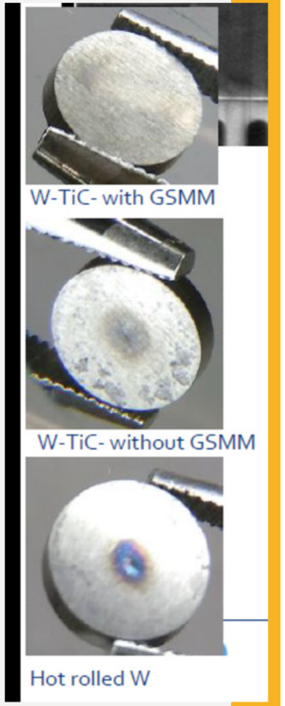


Stress-deflection curve on bending tests, comparing pure tungsten (left) & TFGR W-TiC (right).

- Under academic-industrial collaboration with Metal technology Co., LTD and Sunric Co., LTD.
- Reinforced of GBs by segregation of TiC
- Recrystallization embrittlement doesn't take place.
- In the H.E. proton irradiation test at HiRADMAT, CERN, no crack was observed only at W-TiC.

H.E. p-irradiation tests at CERN

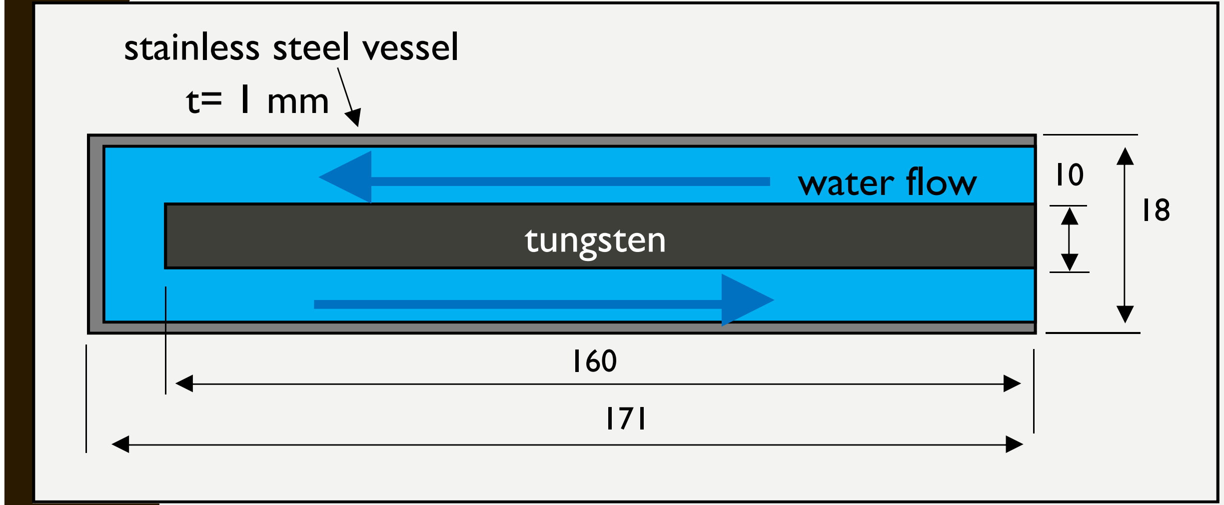


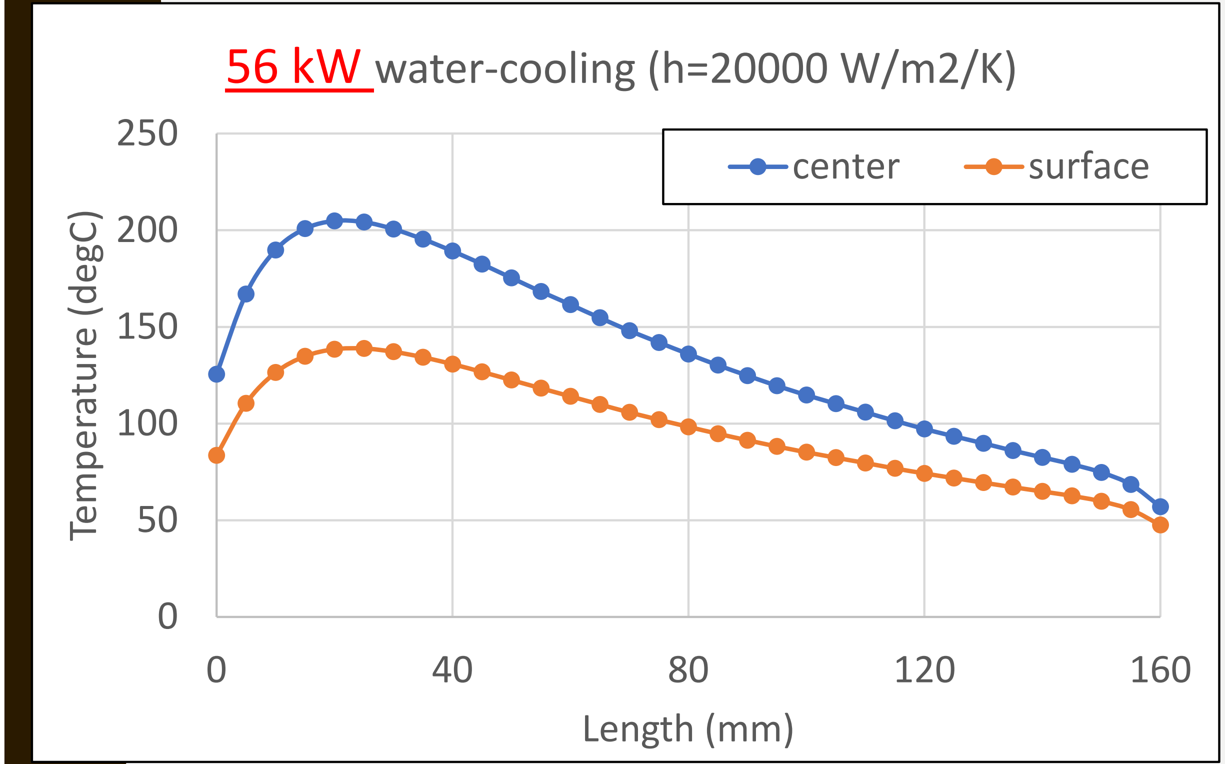


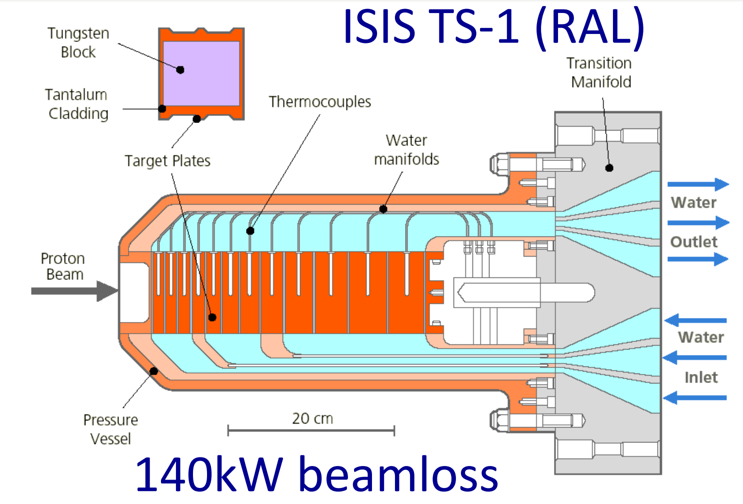
I really appreciate to Marco Calviani and CERN team.

Claudio Torregrosa et al., Technical RaDIATE meeting, 07/12/2020

WATER-COOLING W TARGET FOR 56-KW PHASE 2







Good example in the past

Maximum temperature on surface gives the limitation to avoid film boiling. It should be below 120 °C that is determined from boiling point (130 °C) of 1 MPa water.

Thermal transfer coefficient:
20000 W/m2/K

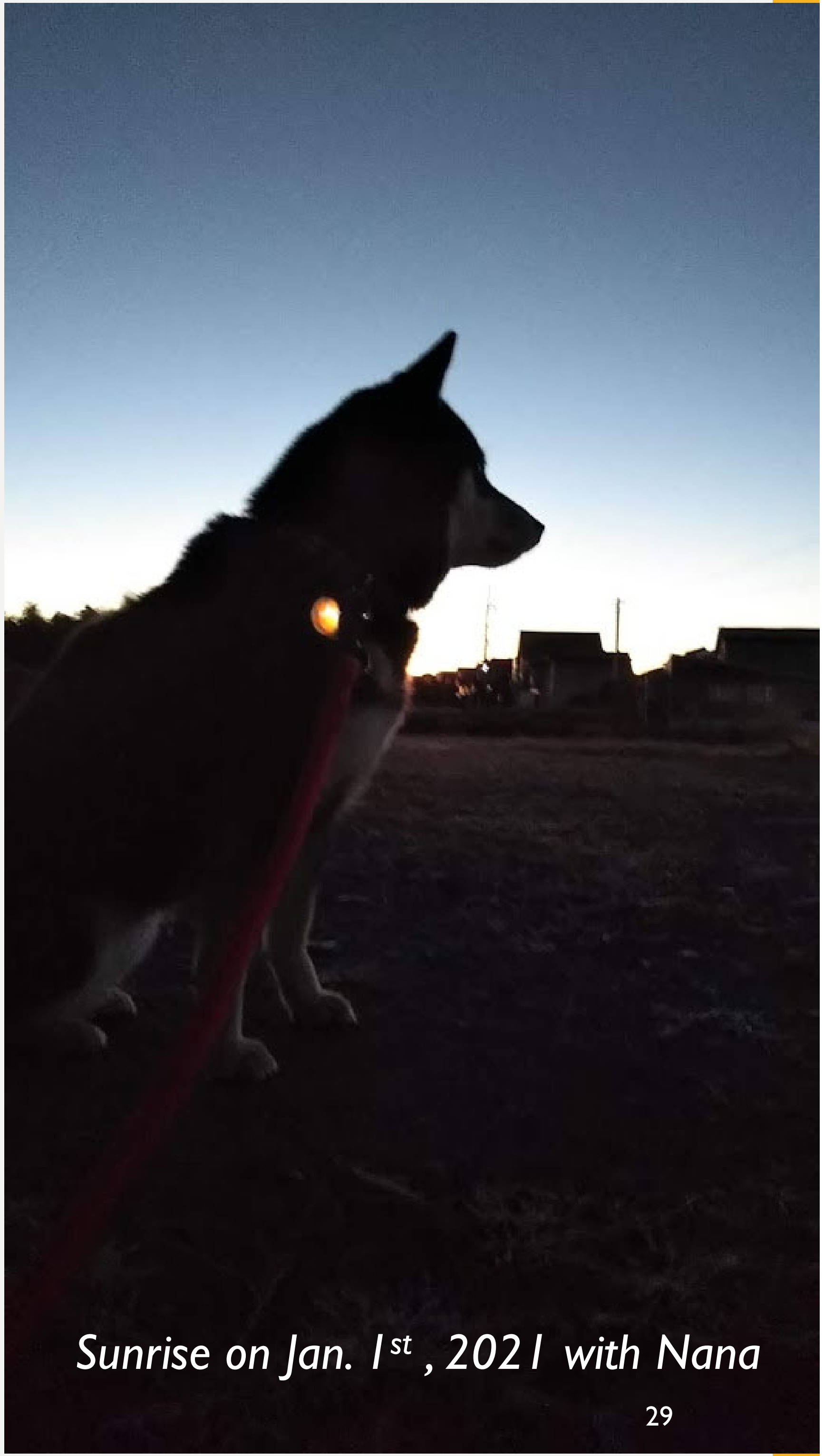
Realistic, but optimization is required.

SUMMARY

SUMMARY

- Proton beam operation by the muon rotating target at MLF has been successfully conducted.
- The construction of the COMET facility is on going, and the experiment will start in Dec. 2022.
- Construction of Target, target support, inner solenoid shield, shield carriage, novel tungsten alloy is on going.
- We are ready for collaboration in muon collider.

Thanks for your attention.



Sunrise on Jan. 1st , 2021 with Nana