3D-Printed Aluminum Alloy Beam Window for COMET Project in Phase-1

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working with
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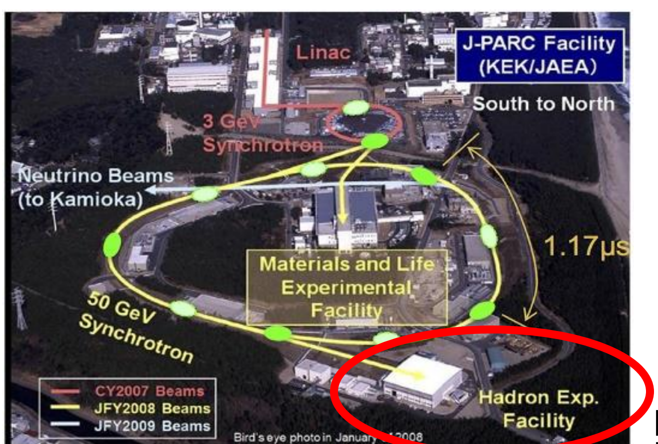
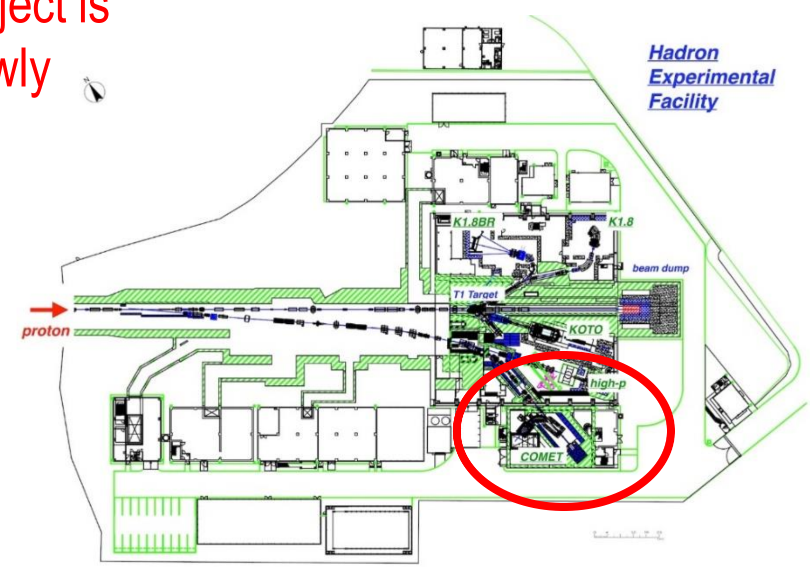
Outline

- Background of R&D
- R&D results of COMET phase-α: Ti-6Al-4V windows
- R&D progress for phase-1 window
- Future plans

Proton beam spec.
Intensity: 8 [GeV]
Power: phase - α: 0.3 [kW]
phase - I: 3.2 [kW]
phase - II: 56.0 [kW]

COherent Muon to Electron Transition (COMET) project is exploring the lepton flavor violation process by a newly constructed beam line.

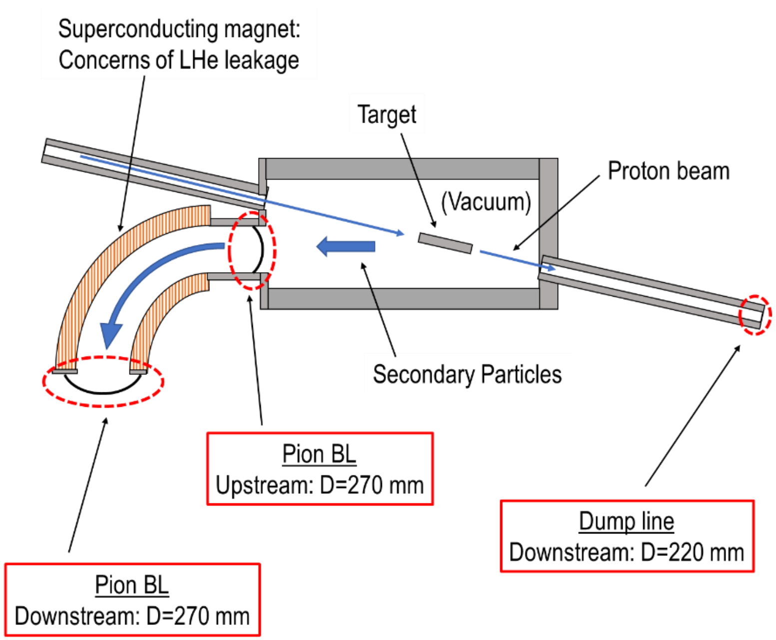




[1] "COMET Phase-I technical design report", Prog. Theor. Exp. Phys. (2020).
[2] "Present status of COMET target at J-PARC", S. Makimura et al. Proc., PASJ, Ann. Meeting, (2020).

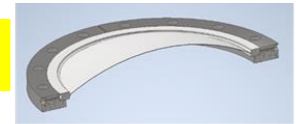
Background of this R&D

- The initial experimental phase, phase-α was successfully completed with the proton beam power 0.3 [kW].
- Developed three windows made of Ti-6Al-4V are built-in the beamline.



- Pressurized by water: 0.9 [MPa]
- Evacuated, He leak rate: 10^{-10} [Pa.m^3/s]

CAD, Analyses



⇩

3D-printing (AM)

⇩

HIP
(Hot Isostatic Pressing)

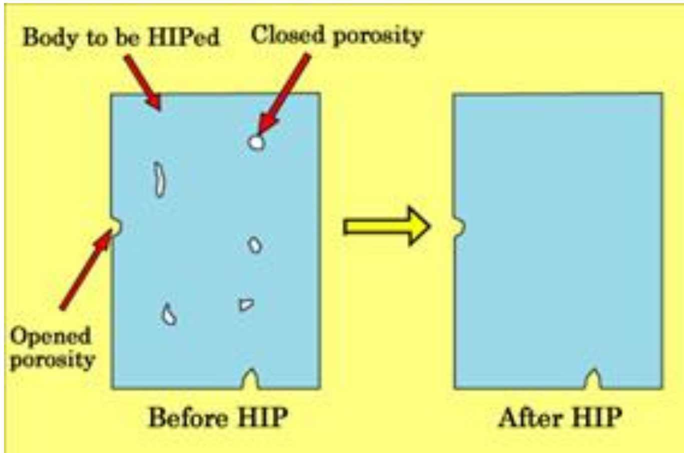
⇩

Polishing w/ thickness tailoring

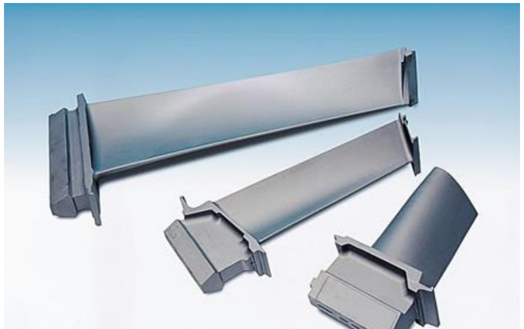
t0.43-φ270 mm

Note... Heat treatment: Hot Isostatic Pressing (HIP)

Eliminating Internal Pores

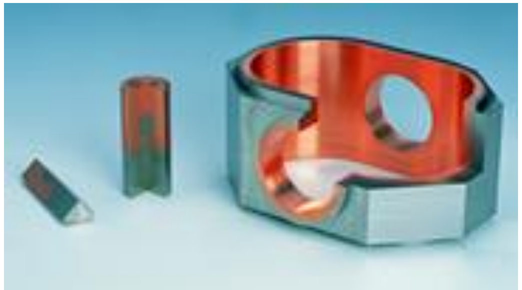


Work Size : φ2,050 x 4,200 [mm]
*Largest Class in The World
Max. Weight ： 28 [ton]
Max. temp. ： 1,350 [ºC]
Max. Pressure ： 118 [MPa]



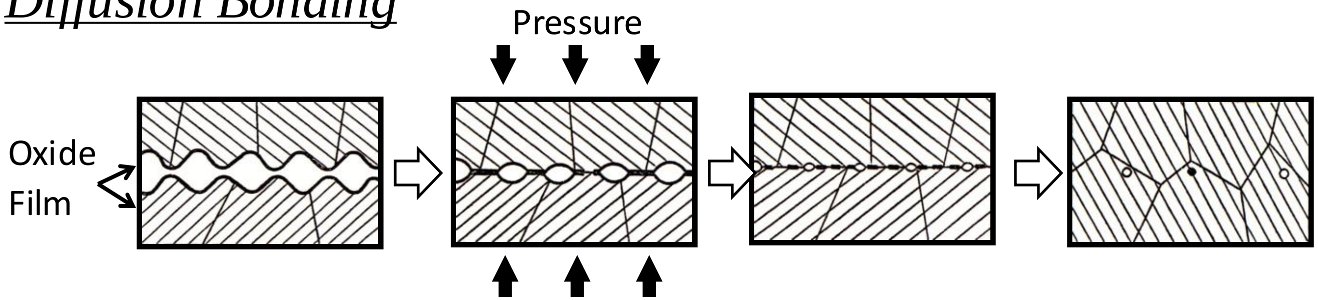
Turbine Blade

Aluminum Body + Stainless Tube



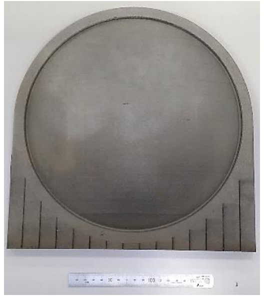
Stainless Steel + Copper

Diffusion Bonding

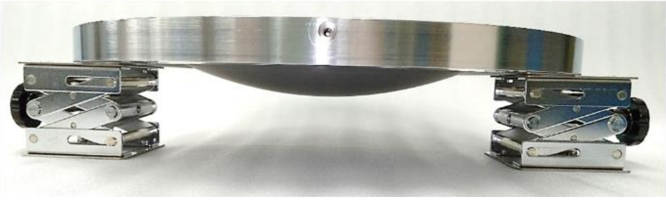


Outcomes for Phase-α: Ti-6Al-4V windows

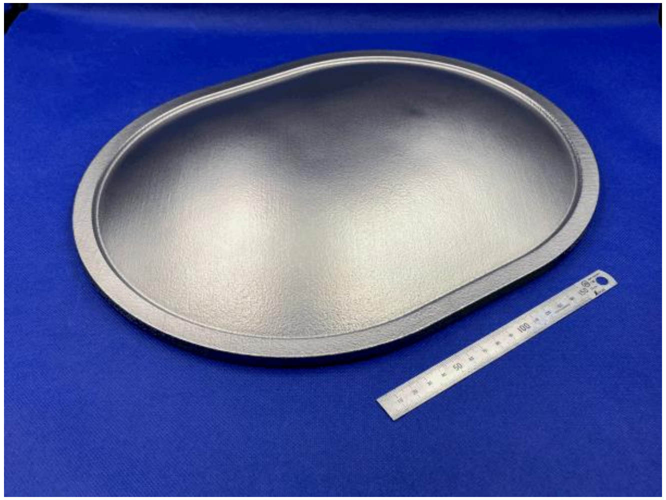
We produced a dome of 270 / 220 [mm] to mate with the rotatable flange, and a 62 [mm] dome with a vacuum flange as a single body etc.



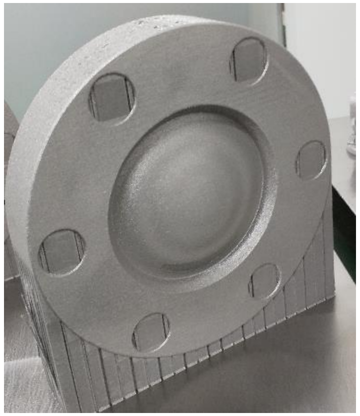
(Just fabricated)



*Dome direction/ sense is switchable for pressure side.



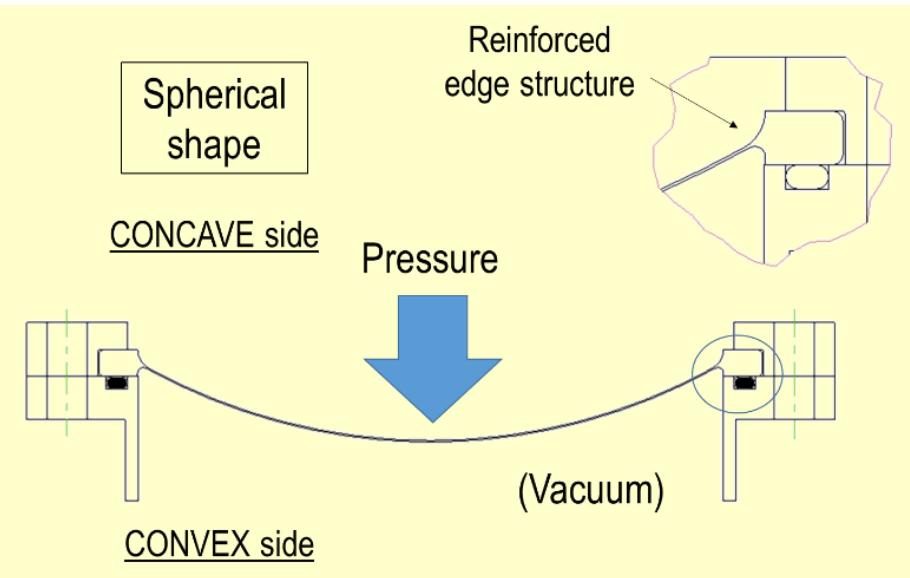
Racetrack: 350 x 270

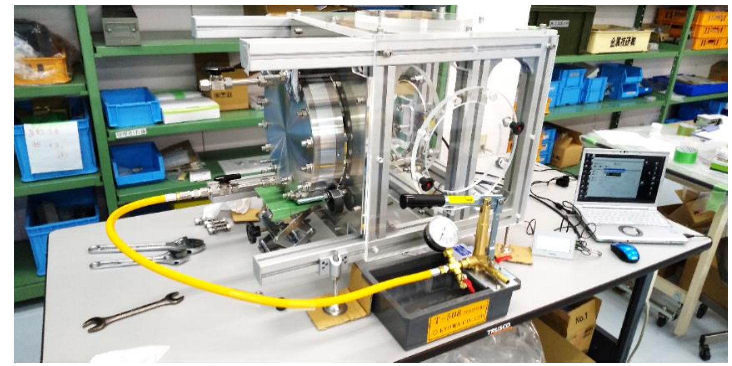


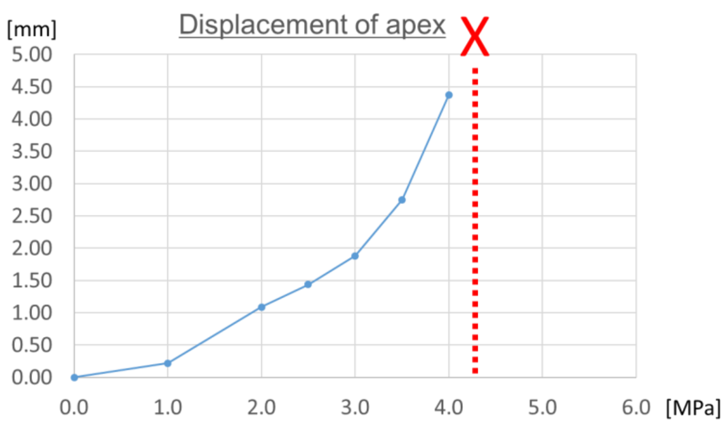
Dome w/ Bessel func. curve

Outcomes for Phase-α: pressure test for t0.5-220 diam.

- Tested and withstands over 4.2 [MPa]
- Stress concentrated, but reinforced structure enhances the performance
- Pressurized 0.9 [MPa], design value → deformation 0.4 [mm]



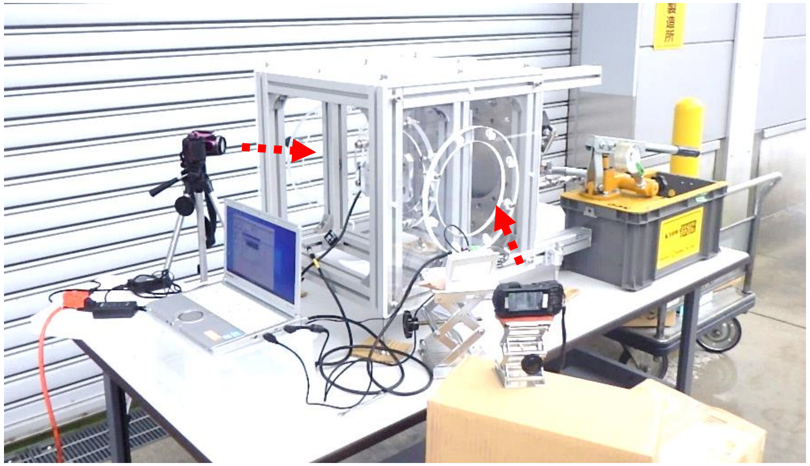


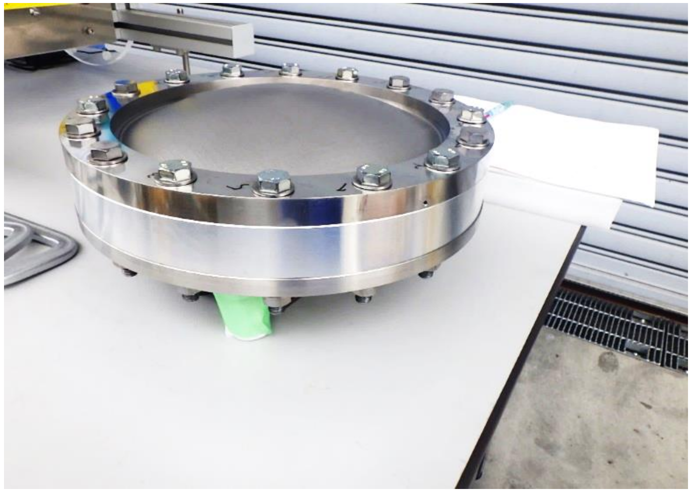


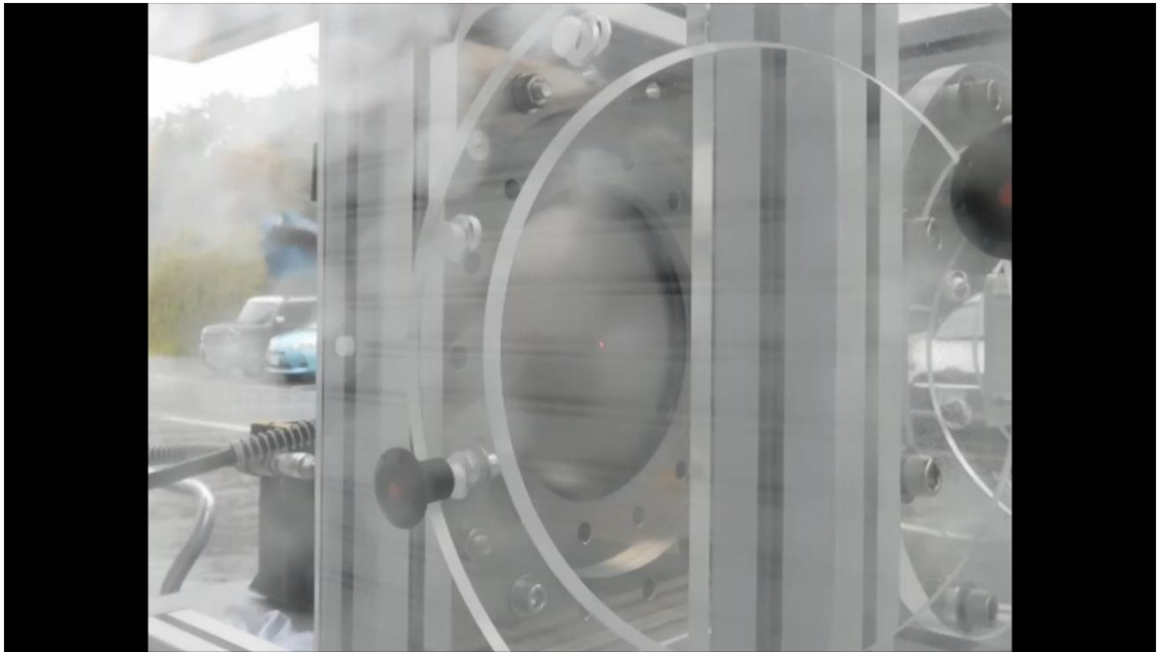
Exploded and Flipped... .

Outcomes for Phase-α: pressure test for t0.5-270 diam.

- Pressurized 0.9 [MPa], design value → deformation 0.7 [mm]
- Tested and withstands around 3 [MPa]







Centered red point is the laser distance meter's pointing at apex.

Outcomes for Phase-α: pressure test for t0.5-270 diam.

- Tested and withstood up to approximately 3 [MPa]
- Confirmed the starting area of fracture as expected ANSYS simulation results

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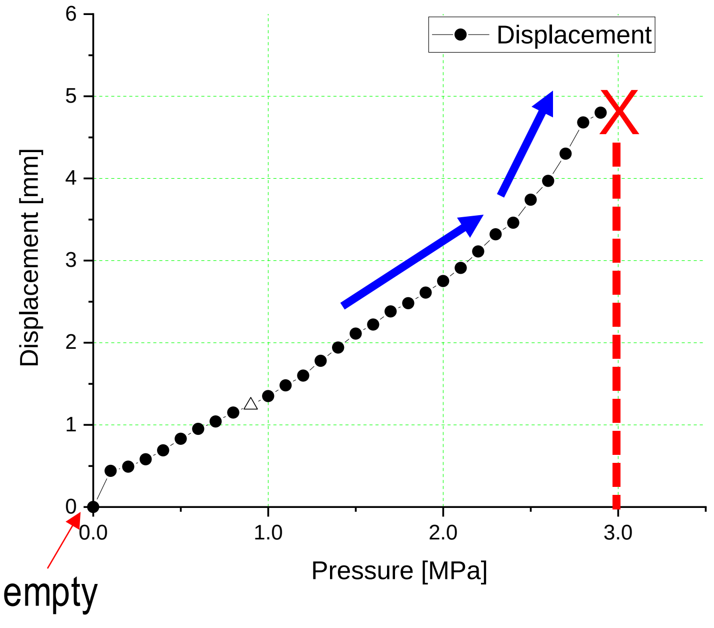
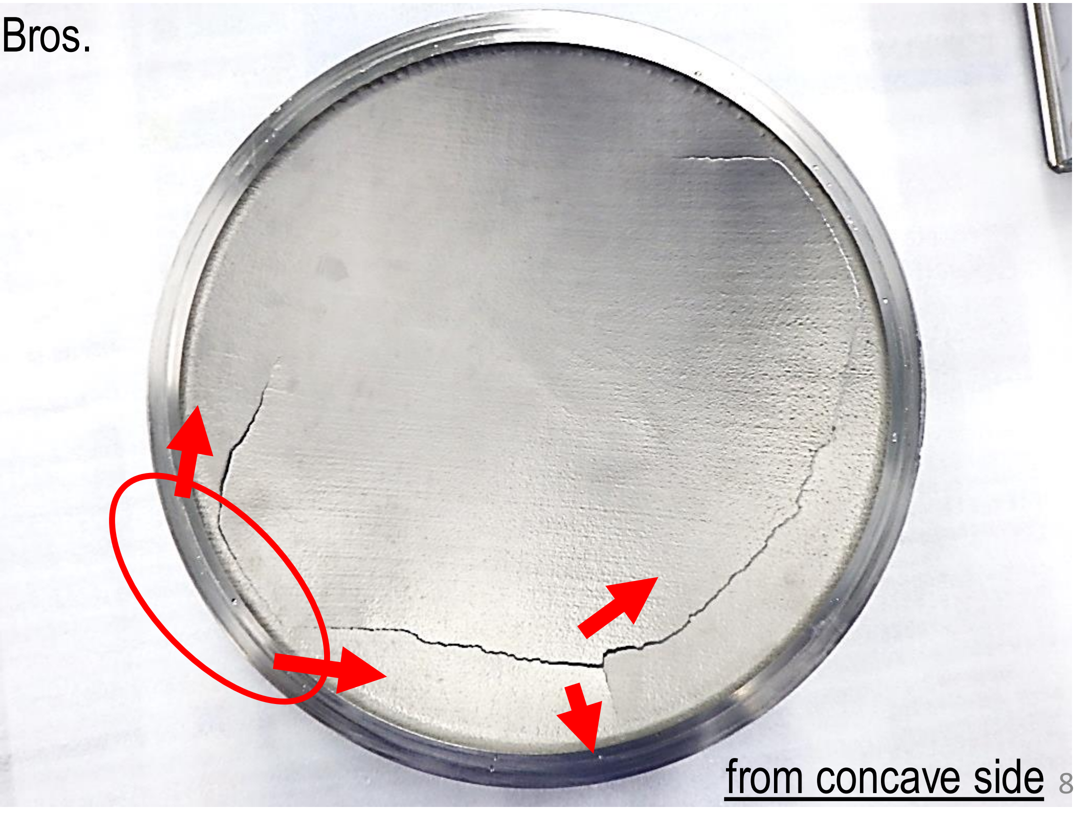
Not like this... but close.
Agent Smith - The Matrix (1999), Warner Bros.





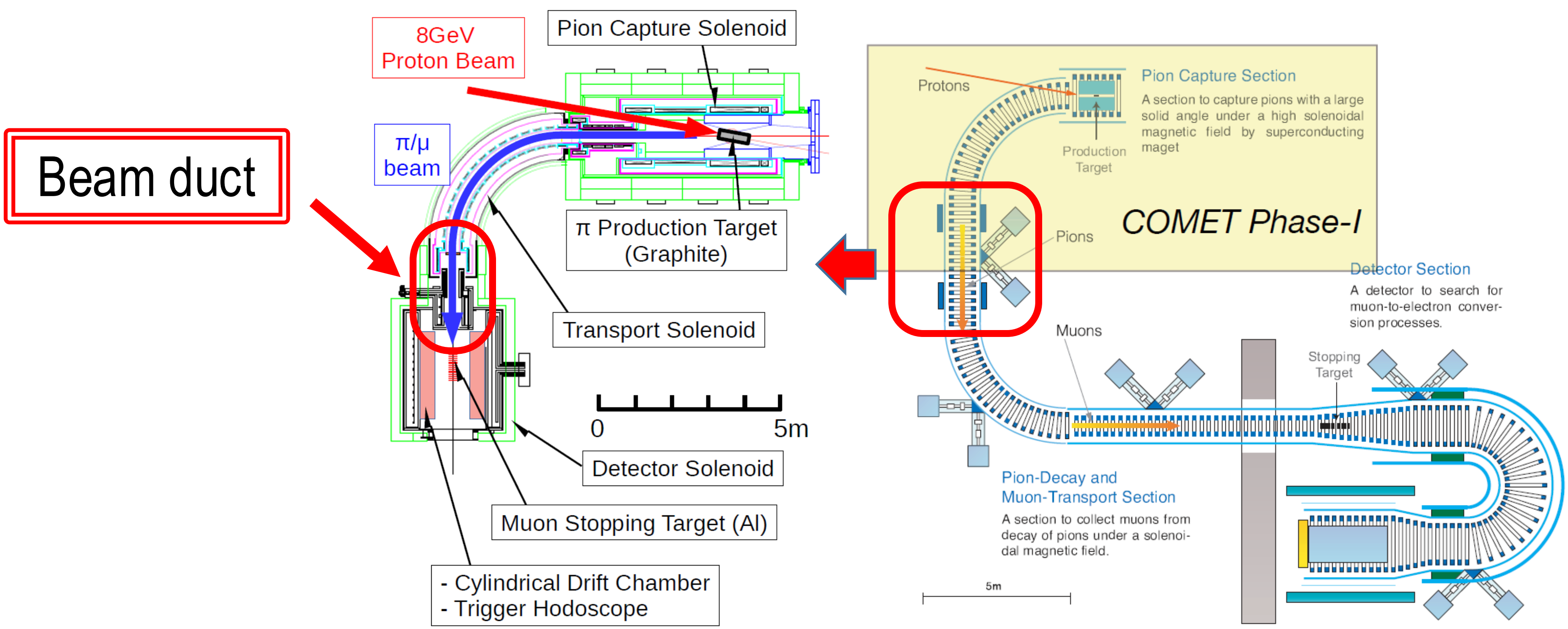
R&D subjects for windows in phase-1

- Developed phase-α windows can be adaptable for each installed place.

  ↓

  Not shown here but, the vacuum seals for Ti-6Al-4V windows needed to be replaced to metal seals, then tested OK. (w/ Helicoflex compatible ones.)

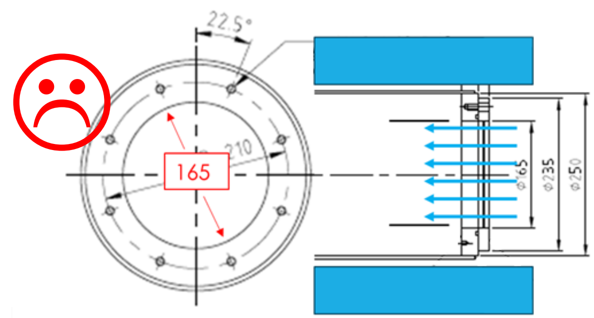
- The window for the beam duct needs to be newly developed, then we focused on the window R&D.



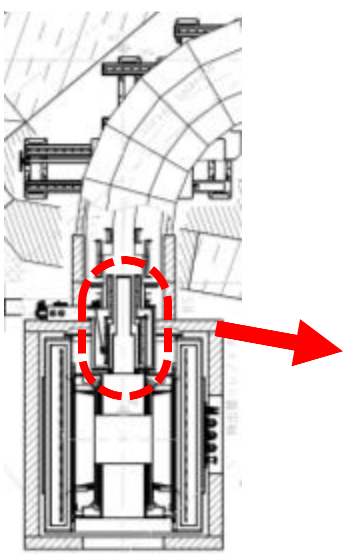
R&D subjects for windows in phase-1(cont.)

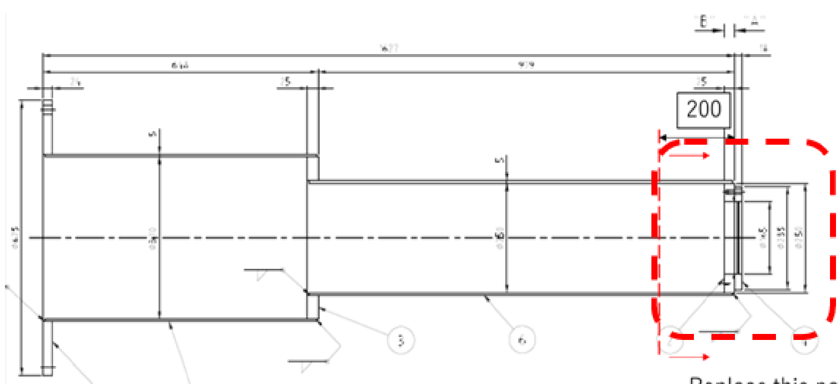
- Spatial availability: diam. 250 [mm] duct is installed in diam.260 [mm] outer cylinder
- Beam passing performance: high transmission efficiency with minimizing the nuclear heat generation by beam energy loss, with large area

- Withstands 0.1 [MPa] pressure difference (@ operational condition from convex side) while in emergency at LHe quench, 0.6 [MPa] pressure from concave side.
- Environment: -60 [ºC] to Room temp.
- Installable to diam. 260 [mm] outer cylinder
- Beam passing area: ÷t0.5 - diam. 230 [mm]

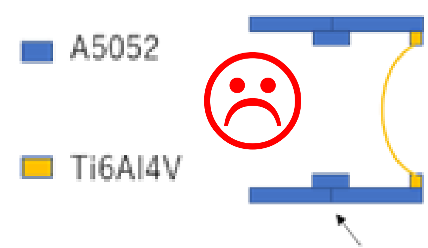


Exit of pion beamline by flange-type
Fabricated beam duct, Aperture size D=165





Replace this part.

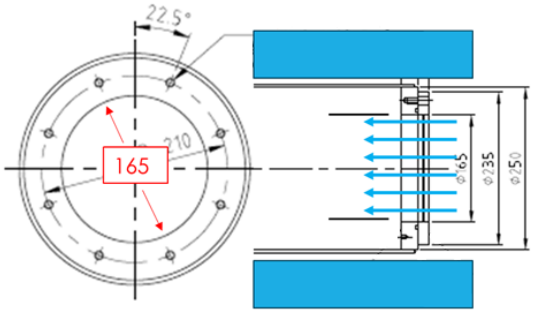


Duct material: JIS-A5052 (EN-AW-5052)

R&D criteria and advantages of all Al.-alloy window

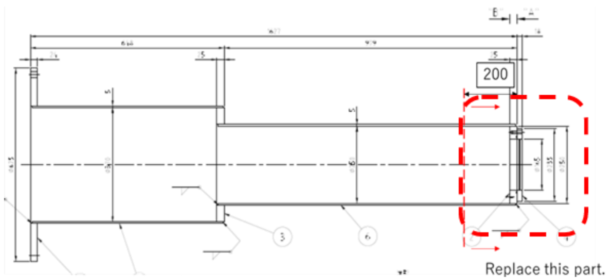
- Minimize spatially the joining part to maximize beam passing area
- Material density: low
- Thickness of beam passing area: thin and large as possible

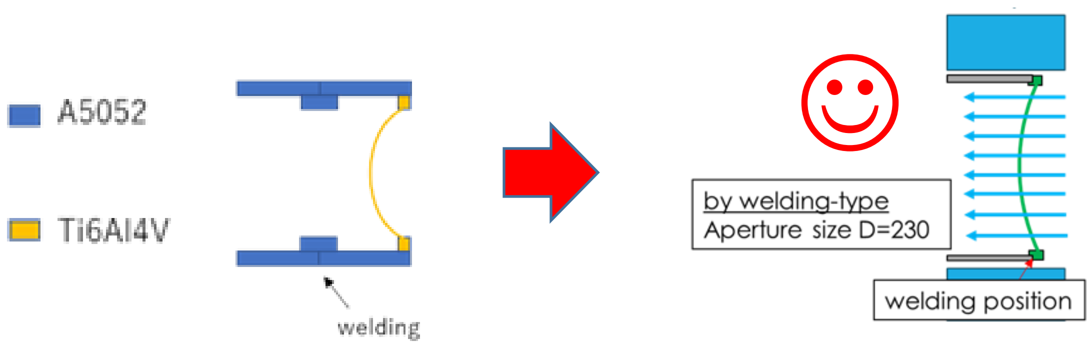
Manufacture the window using Aluminum alloy to weld directly onto JIS-A5052 beam duct, maximizing the passing area, also reinforcing the structure by AM/ Additive manufacturing.



Exit of pion beamline by flange-type
Fabricated beam duct, Aperture size D=165

N.B. Aluminum alloy AlSi10Mg features fast radioactive decay.



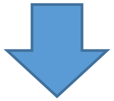


by welding-type
Aperture size D=230
welding position

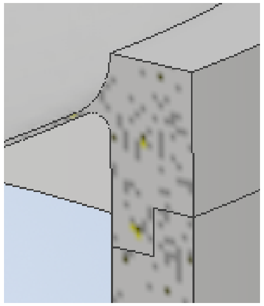
Duct material: JIS-A5052 (EN-AW-5052)

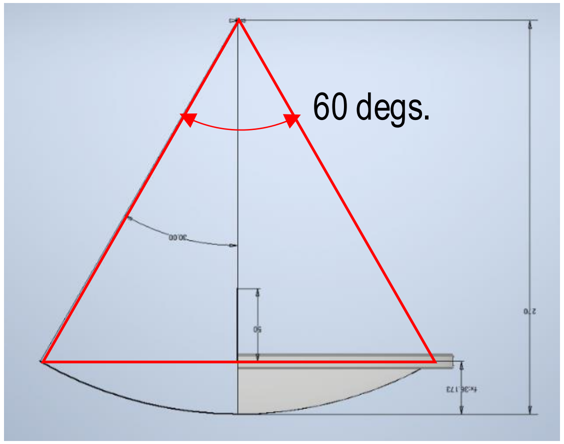
R&Ds: Issues to be solved and designed structure

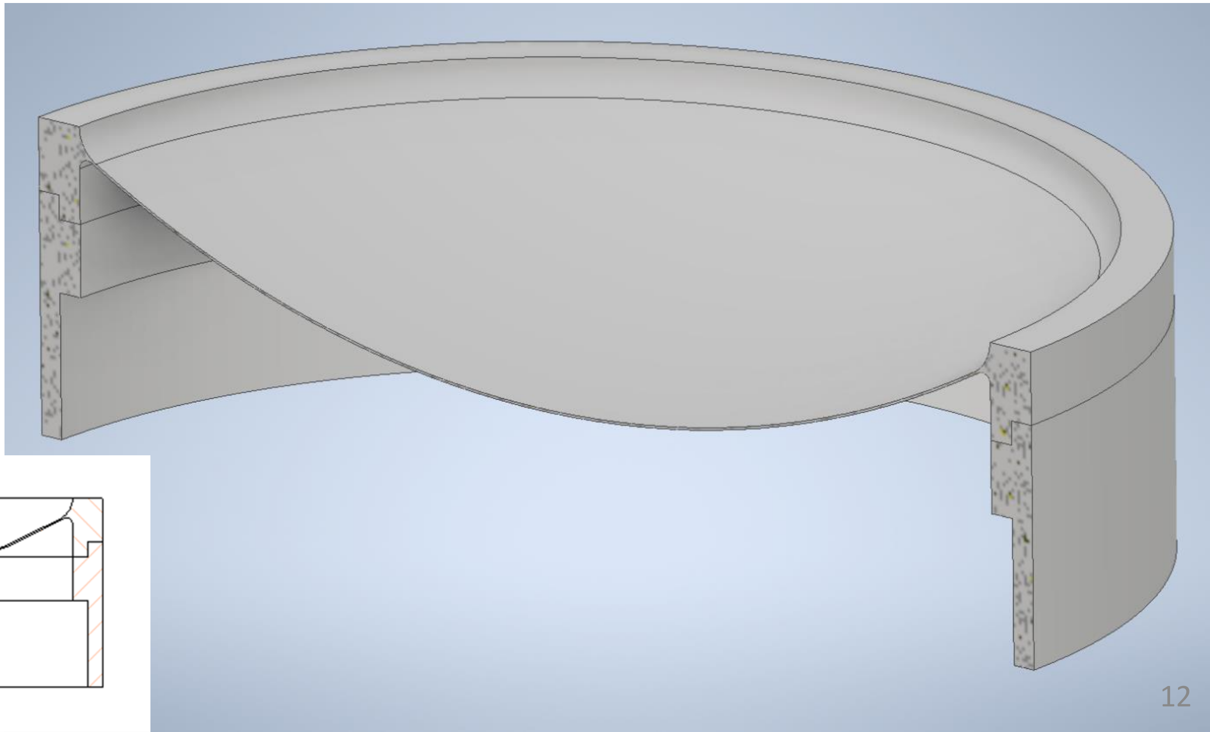
- Withstands sufficient pressure conditions from both faces? → window thickness?
- Welding ability/ easiness to the duct? → connection structure?
- Manufacturability by AM/ 3D-printing? → entire figure?

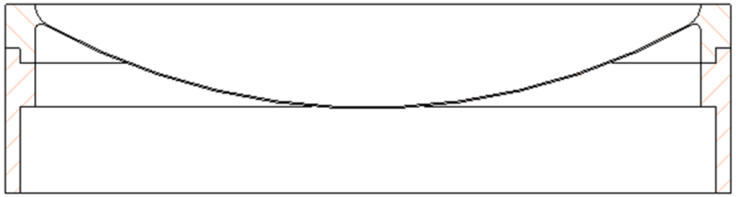


- Applied beam passing area design, taken from phase-α windows
- Employed spigot joint to connect to the duct



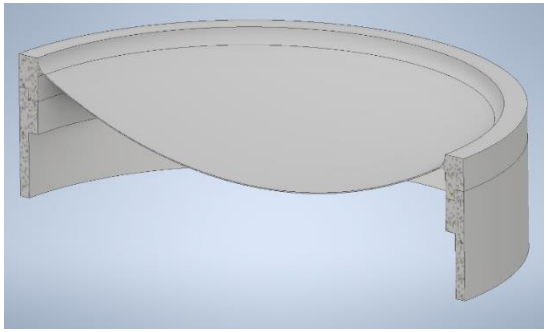






R&Ds: HIP temperature setting for AlSi10Mg

- Maximize material strength as *high* as possible
- Window thickness needs to be decided as *thin* as possible



Manufacturing steps:
AM/3D-pringting +HIP
(+ post thermal treatments)

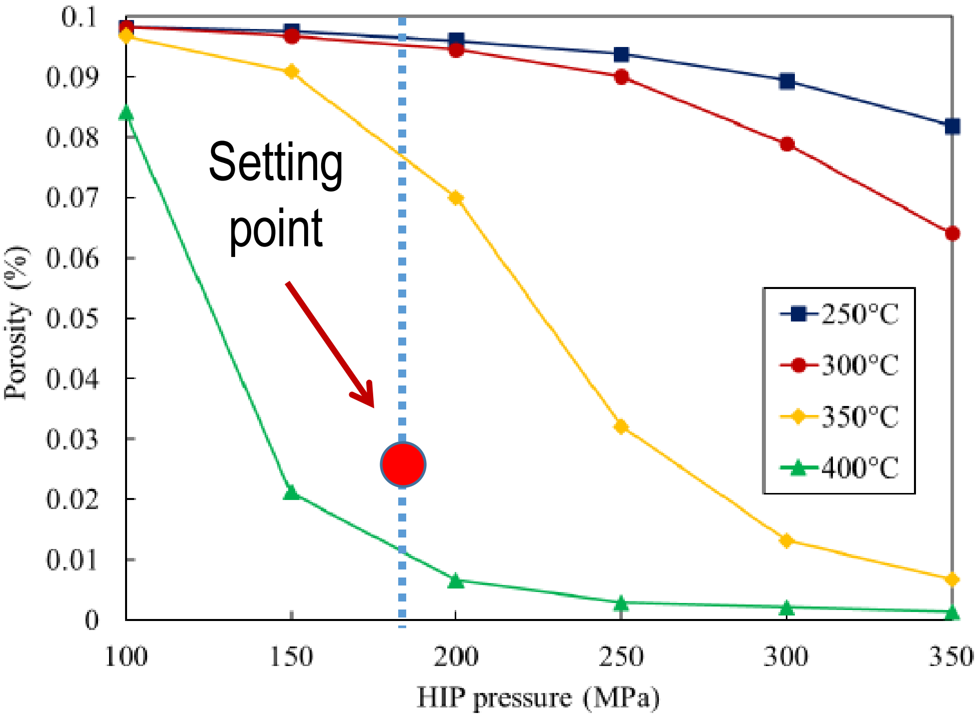


Fig. 2 Finite element simulation of porosity reduction with varying HIP pressure and temperature (applied during 2 hours)

Set HIP temperature to suppress degradation of the base material
→ chose balanced point of porosity (less pores) and proof stress value

** Hot isostatic pressing of laser powder bed fusion AlSi10Mg: parameter identification and mechanical properties, J. Macías, 2022 Journal of Materials Science 57(12)

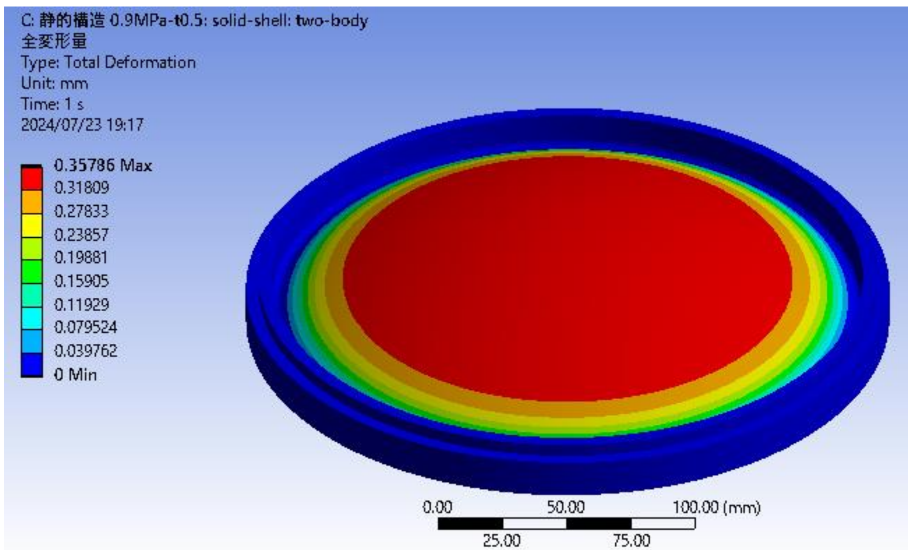
R&Ds: Structural analysis by ANSYS

Simulated with similar material properties

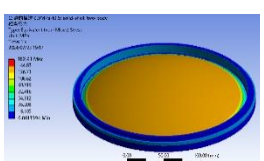
- AM as-built (AlSi10Mg): ANSYS built-in
- AM+HIP: AM+HIP (330 [ºC] -100 [MPa] condition)*

t0.5 - diam. 230 [mm]

Withstands: 0.6 [MPa] from concave

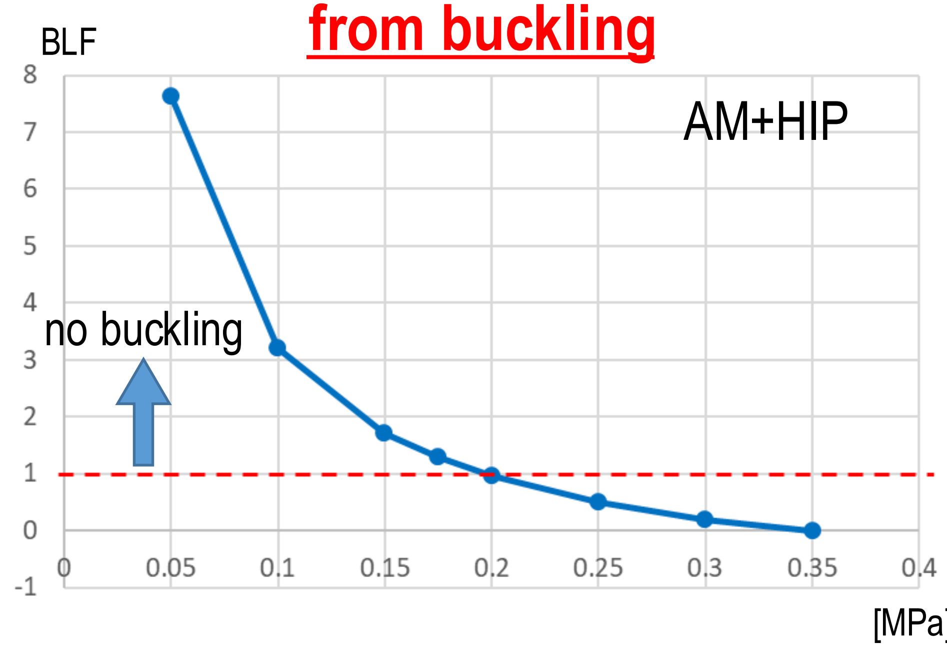


deformation: 0.36 [mm]



vM stress (proof -s): 162 [MPa]

Withstands: 0.2 [MPa] from buckling



* BLF/ Buckling Load Factor:
Safety factor against the targeted load

*Rosenthal, Israel et al. "POST-PROCESSING OF AM-SLM AlSi10Mg SPECIMENS: MECHANICAL PROPERTIES AND FRACTURE BEHAVIOUR." (2016)

Manufactured steps of windows and test pieces

As the first trial, manufactured windows and TPs together
to experimentally confirm/ adjust window thickness regarding tensile test results

CAD, Analyses

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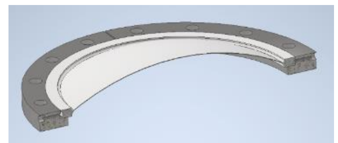

Additive manufacturing(AM-SLM)

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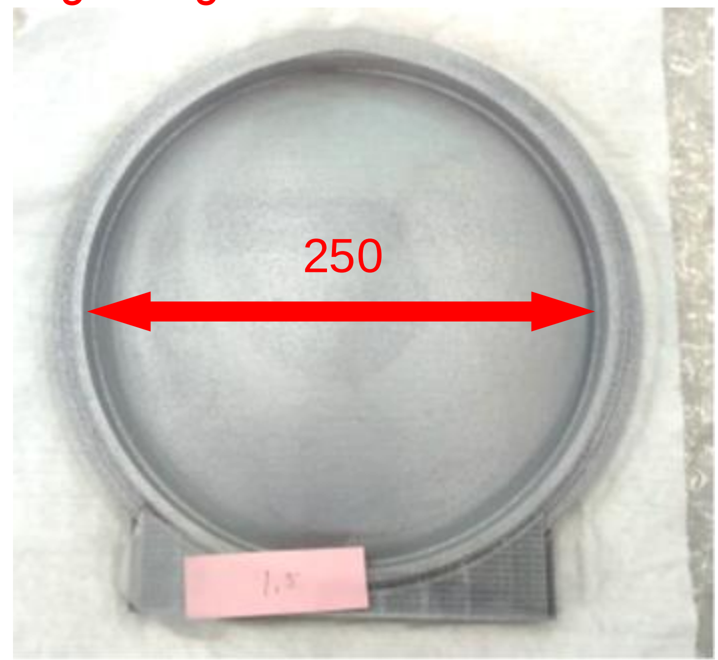
HIP
(Hot Isostatic Pressing)
380 ºC /180MPa × 4h

⇩

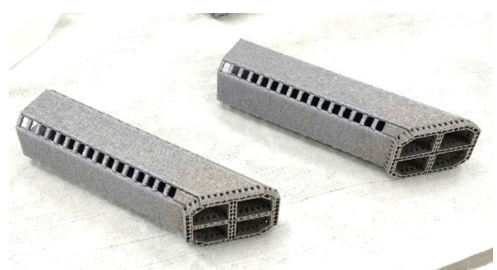
T6: 530 ºC × 6h
+quenching +aging 160 ºC x 3h

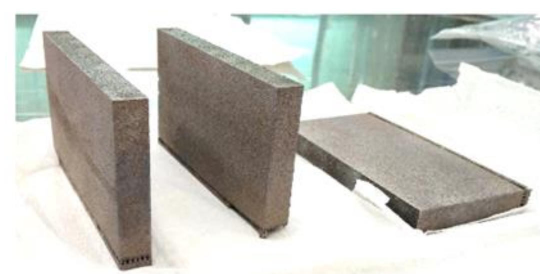
⇩

Thickness tailoring + polishing



As-built



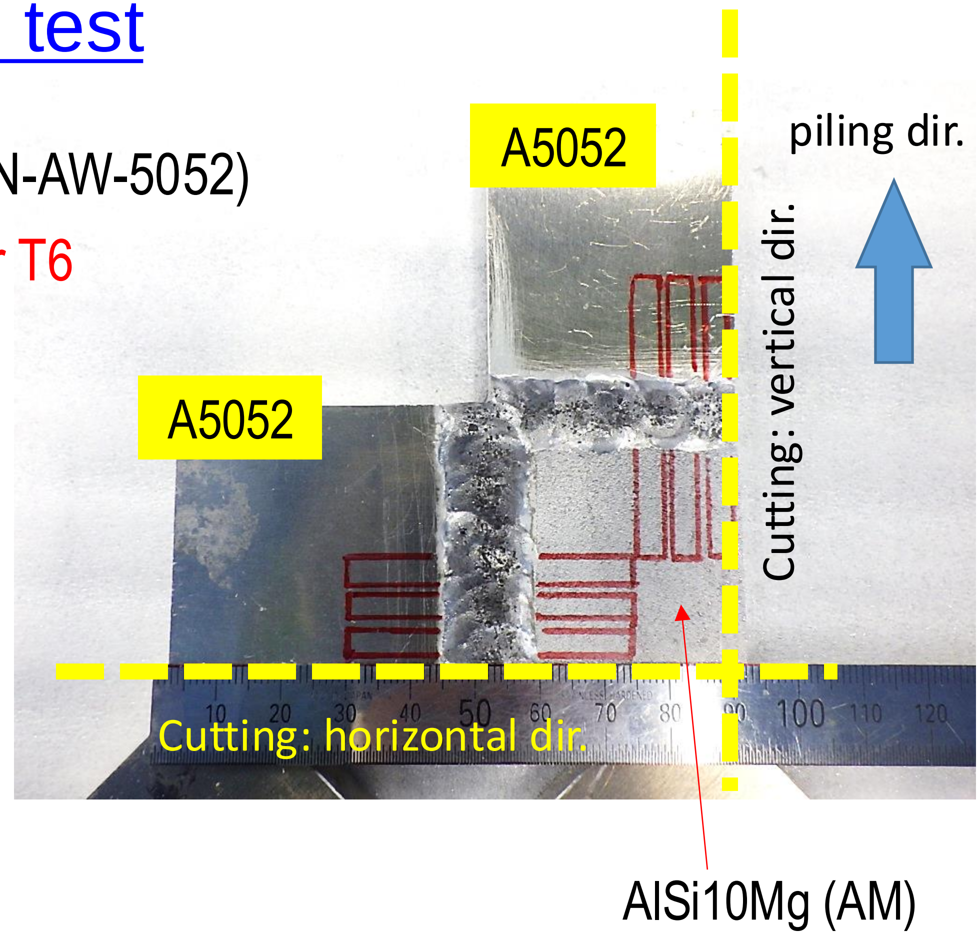


Tensile TP/ Welding TP

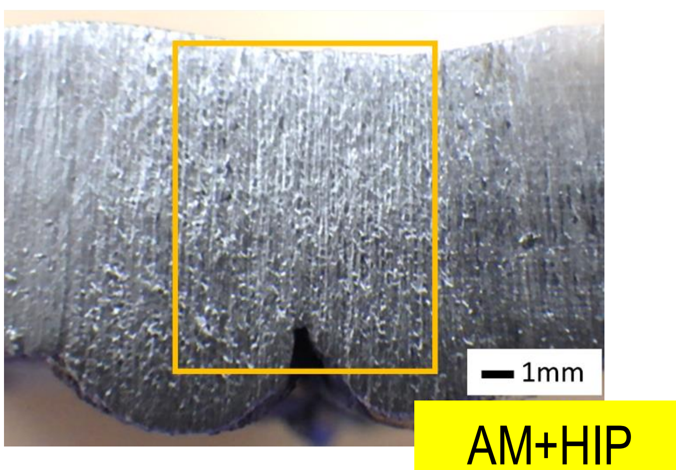
Current progress: welding test

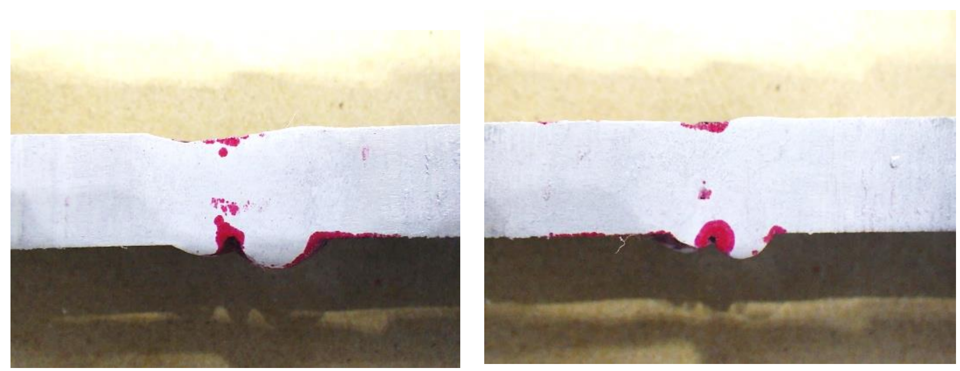
Welding: AlSi10Mg and JIS-A5052 (EN-AW-5052)

- Material conditions: AM+HIP and/or T6
- Welding: TIG
- Groove: V-shape, 90 degs.
- Filler metal: A4043



Both conditions seem OK! but...



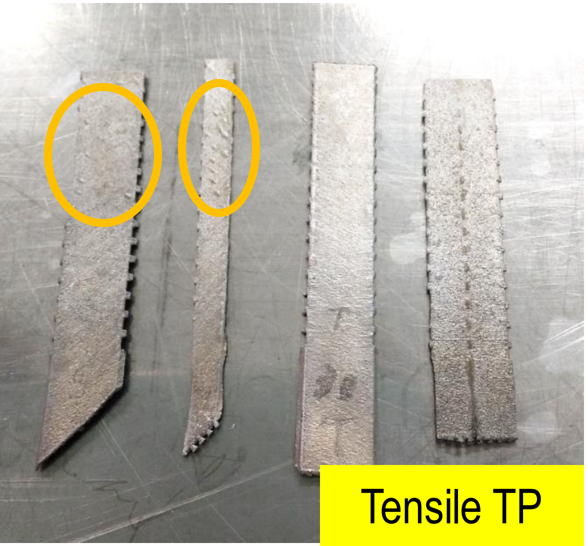


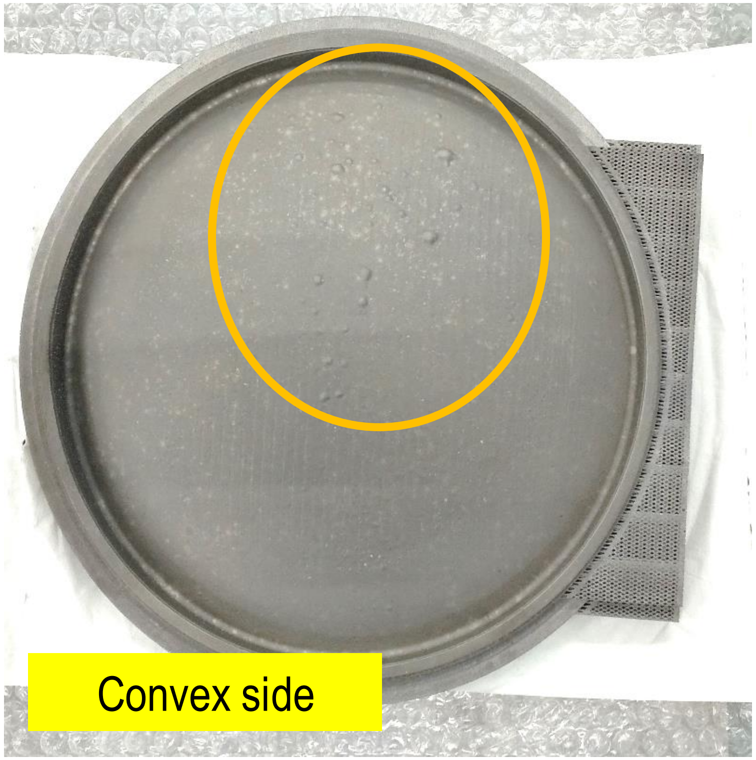
Penetration test: seems no blow holes?

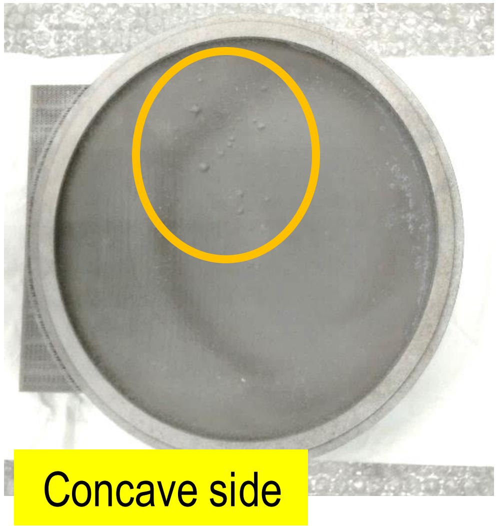
Current progress: post-treatment T6

T6: solution tr.+quenching + artificial aging
→ generated unfavorable local blistering/bubbling

- On the tested window and thinner (< t0.6) tensile TPs, blisters were generated, while thicker TPs suffered no generation.
- Bubbles might be caused by swelling of H_2 or H_2O which had been absorbed at powder/ before AM, or confined N_2 which is of AM atmosphere.







Summary and future plans

- Beam window for phase-1 is under development by using 3D-printed AlSi10Mg.
- We have manufactured four trial windows, tensile and welding test pieces, and the tests are underway.
- The windows are built by AM then HIP and/or T6 treated, intending to improve porosity with sufficient strength especially in the thin part.
- Lower temp. HIP condition 380 [ºC] was employed to suppress strength degradation of base material.
- Welding test by conventional TIG shows no blow holes generated upon visual inspection and penetration test.

  → Tensile test for validating beam passing thin part strength is in preparation.
  → Electron Beam welding is also planned to test.

- T6 treatment is unsuitable for such thin AM parts - generated blisterings/ bubbles.

  → Other treatments, peening by laser or by shots is planned to strengthen the beam passing area.

- Then we will proceed to the welding test, bursting test of beam window(s), etc.