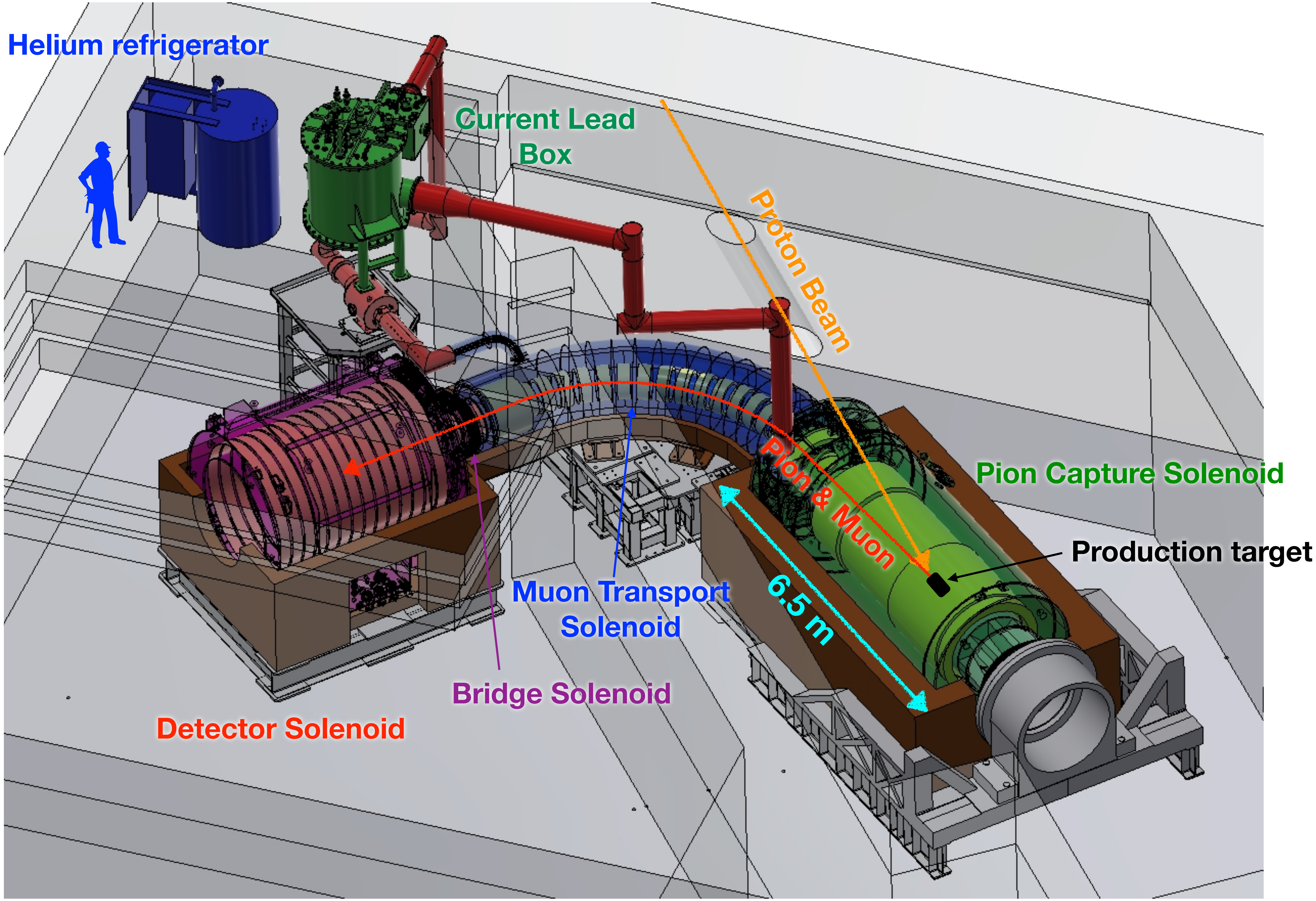
COMET実験　輸送ソレノイド磁石磁場測定

角 直幸 / J-PARC低温セクション

計測システム研究会2025@J-PARC　2025年11月18日

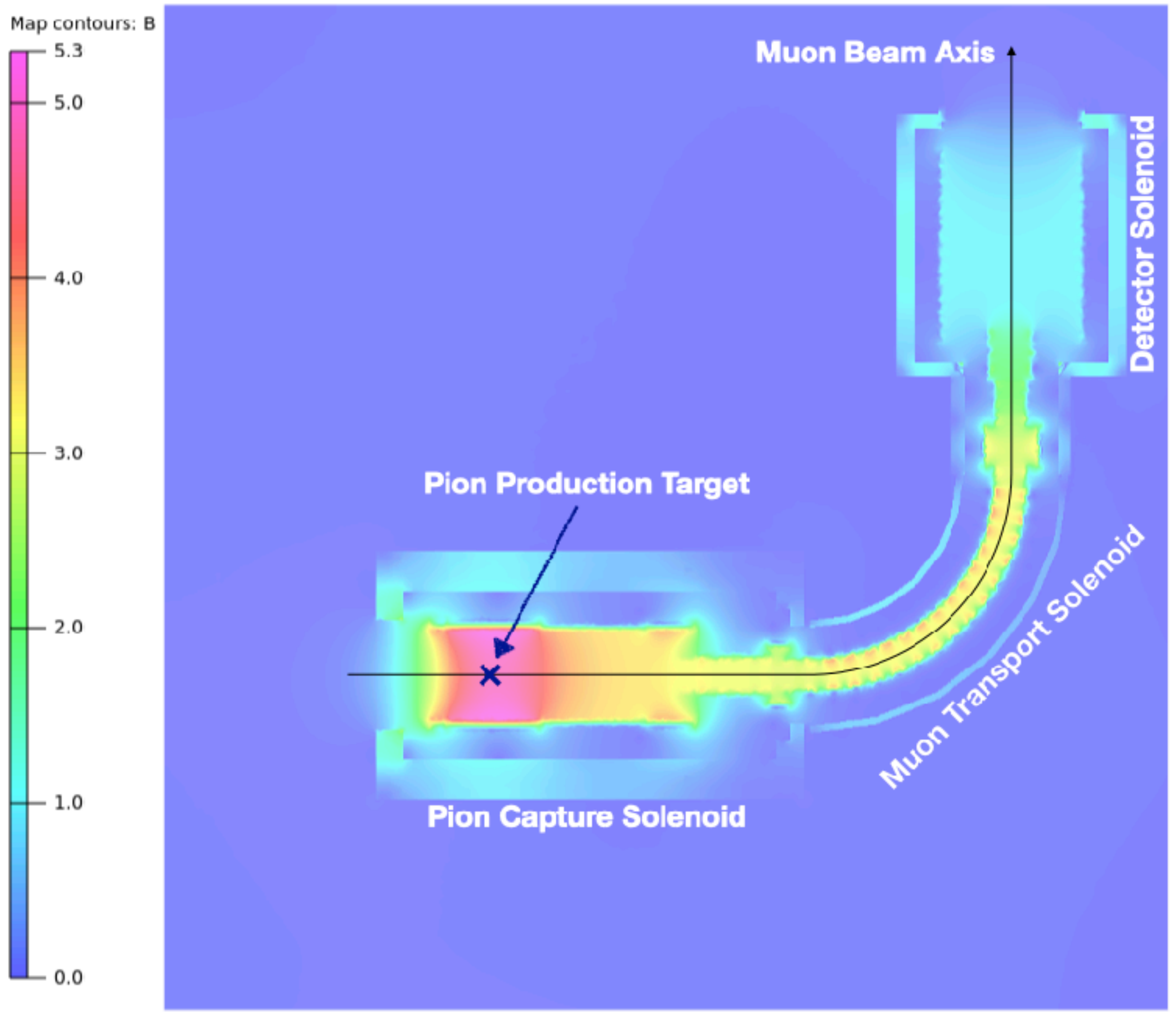
COMET Phase-I beamline

Superconducting magnets are used throughout the beamline.

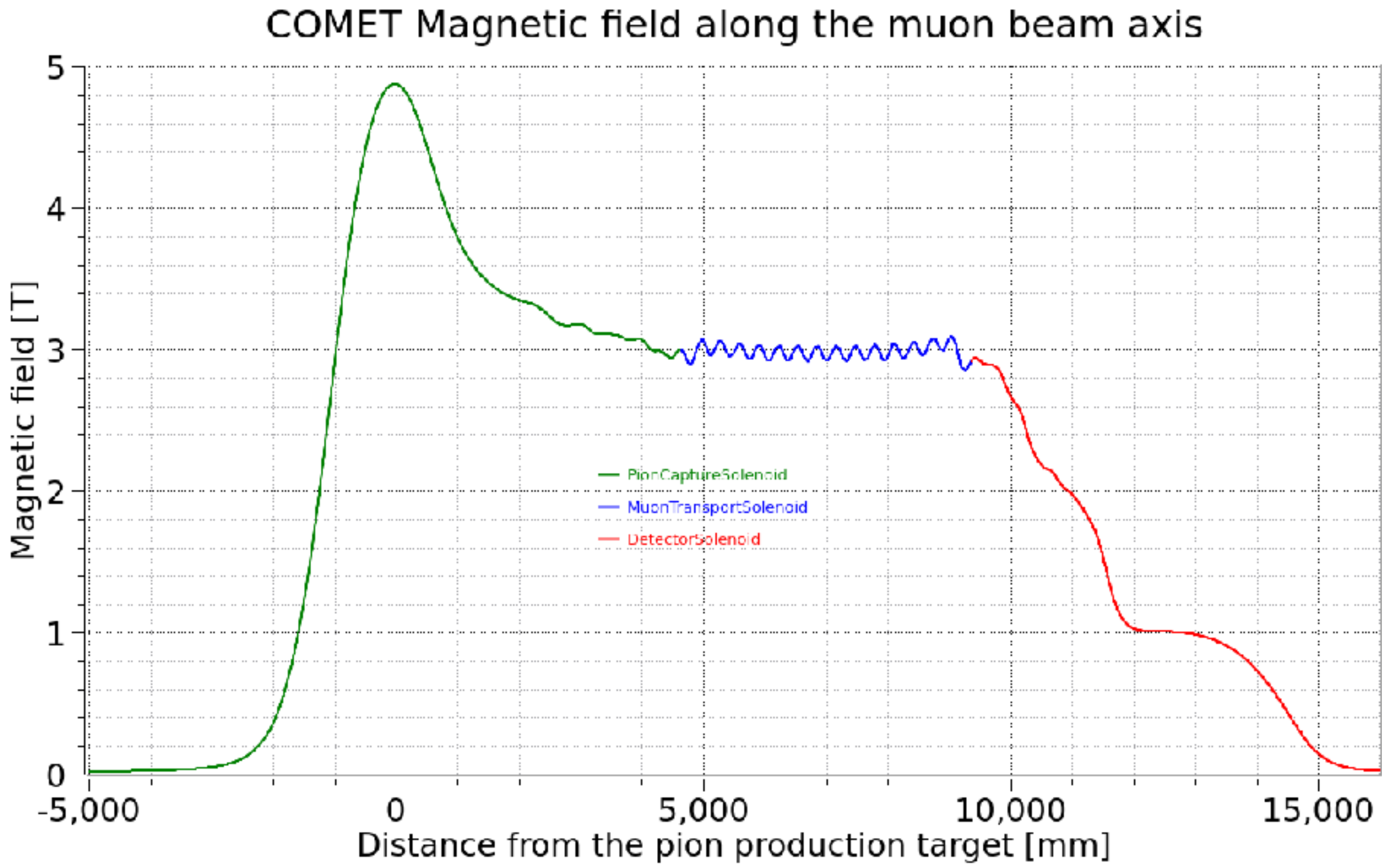


Magnetic field design

- The magnetic field design of COMET is based on finite element method simulation.
  - **Pion Capture Solenoid**
    Solenoid magnetic field (**5 T**) converges pions and sends them to downstream beamline
  - **Muon Transport Solenoid**
    Selective transport of negative muons with a momentum of several tens of MeV/c in a solenoid field (**3 T**) and a dipole field (**50 mT**)
  - **Detector Solenoid**
    Solenoidal magnetic field (**1 T**) acts as a spectrometer to measure the momentum of electrons



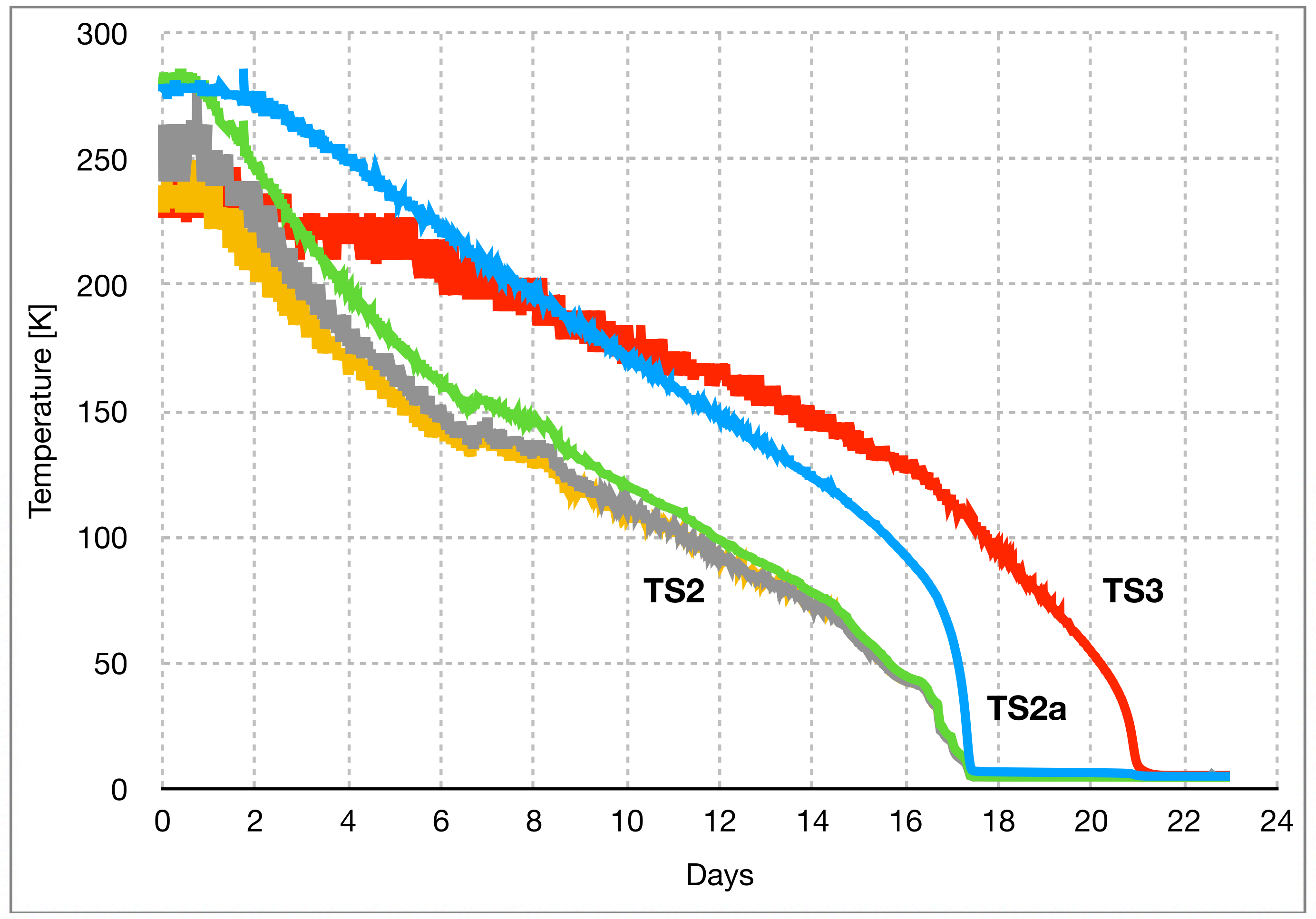
Magnetic field distribution in the plane of the beam axis

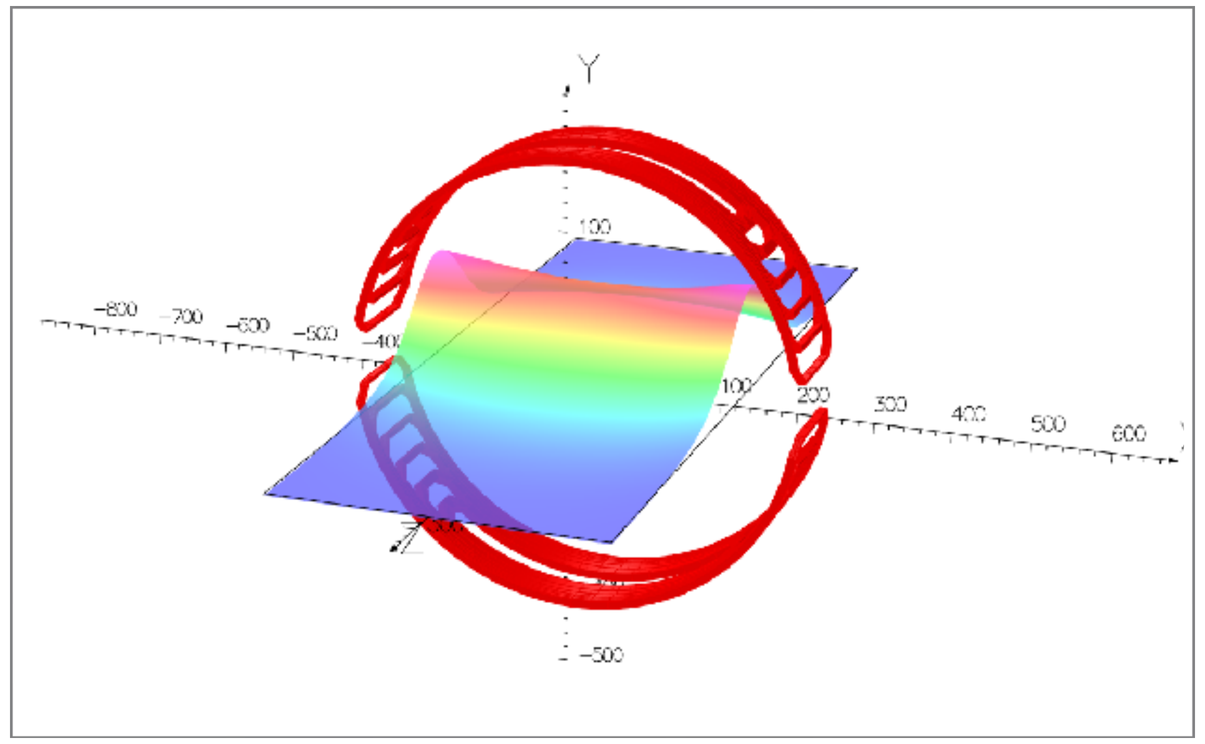


Magnetic field distribution on the beam axis
in the COMET Phase-I experiment

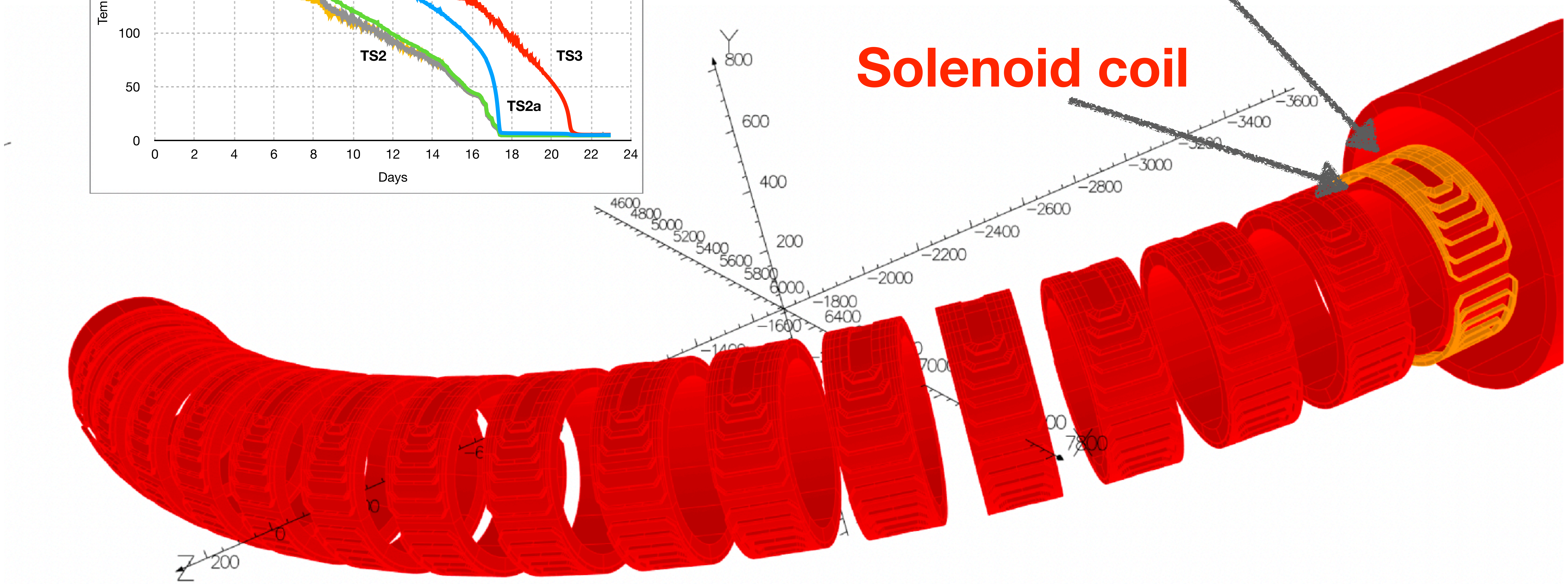
Muon Transport Solenoid (MTS)

- MTS consists of 18 solenoid coils,
  with a dipole coil on each coil except at both ends.
  - It take three weeks to cool down (4.6-5.3K)
    by helium refrigerator.





Dipole coil

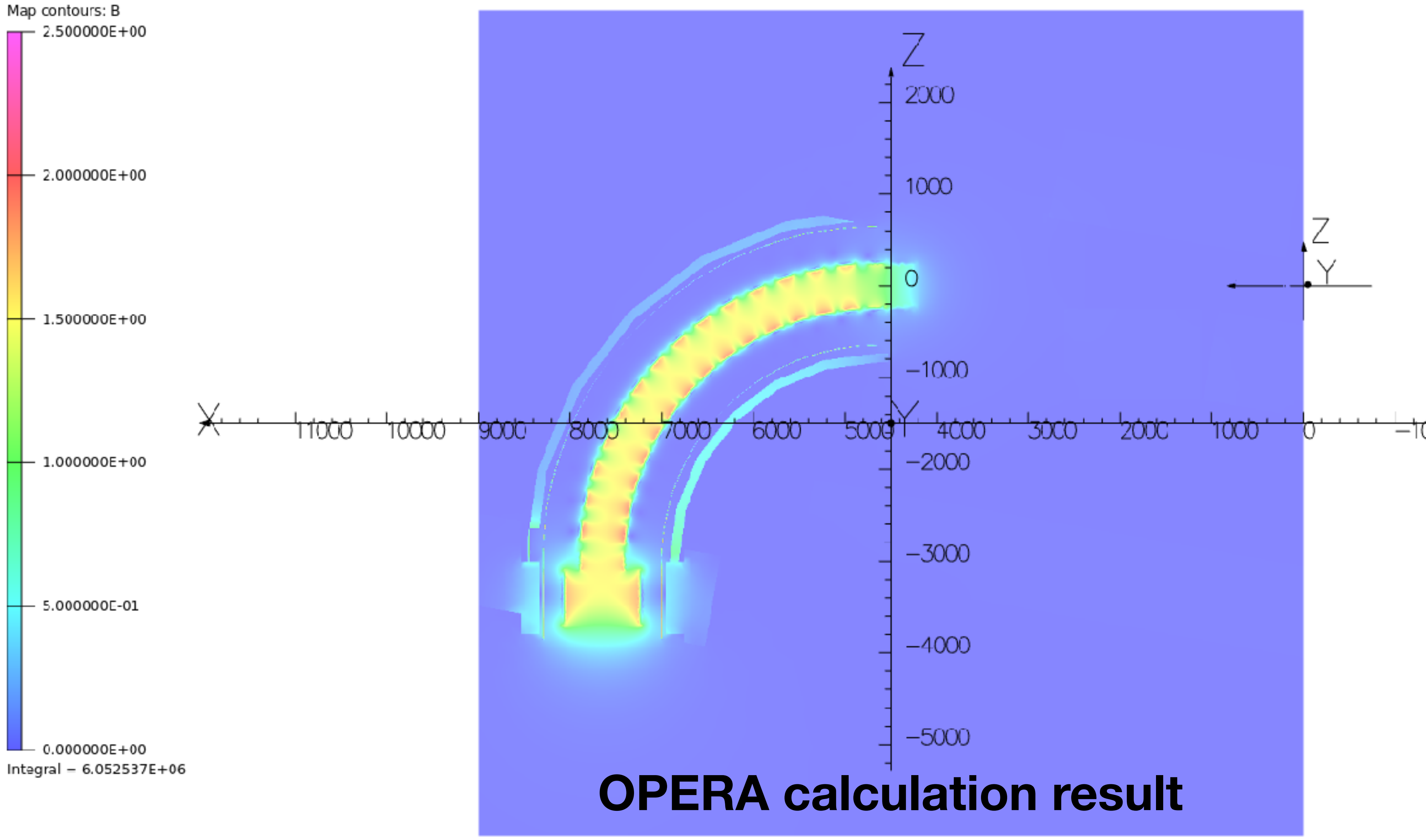


Solenoid coil

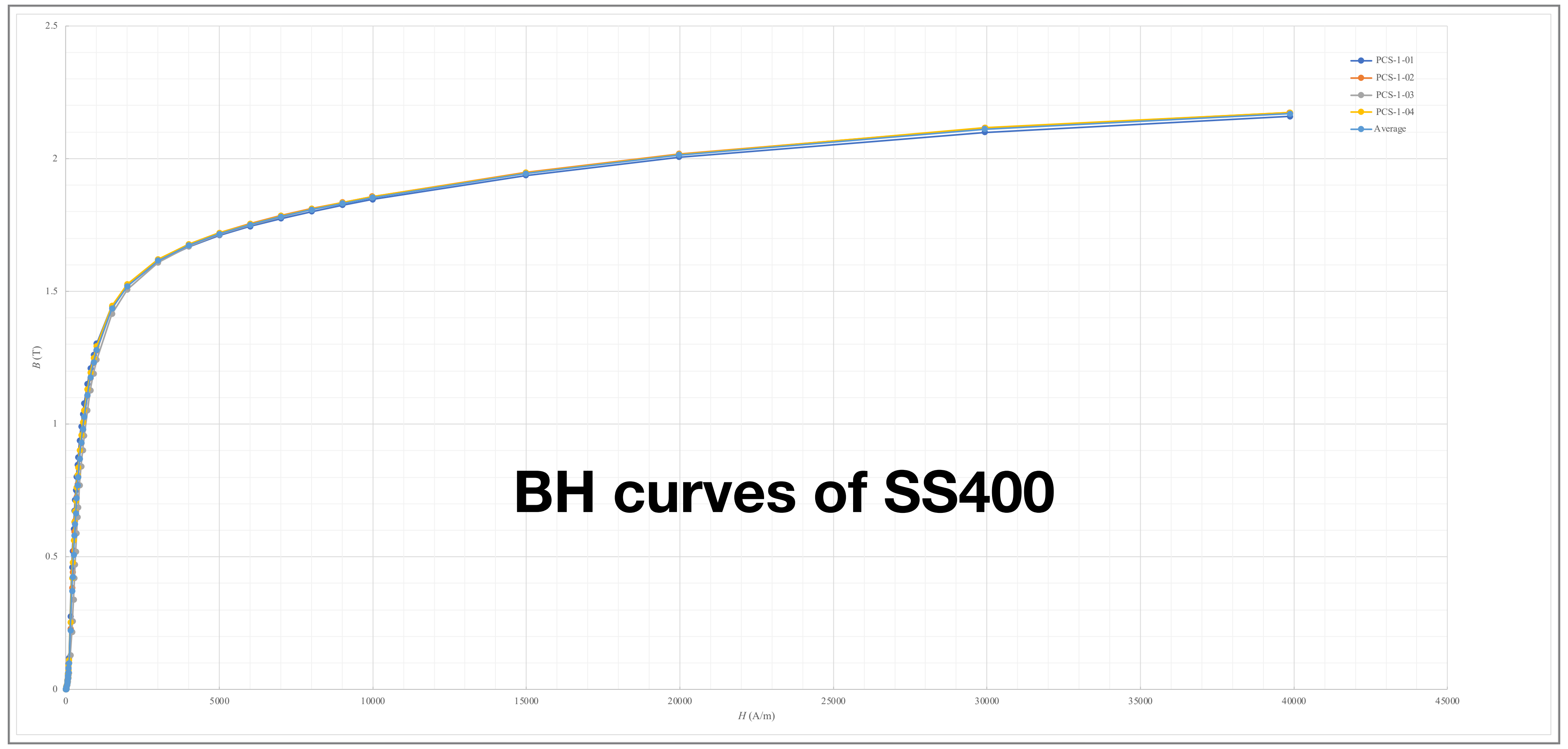
Calculation

- OPERA 3D calculation
  Finite Element Method (FEM)
  - COMET Phase-α geometry
  - MTS solenoid & dipole
  - MTS iron yoke
  - Iron shield around target

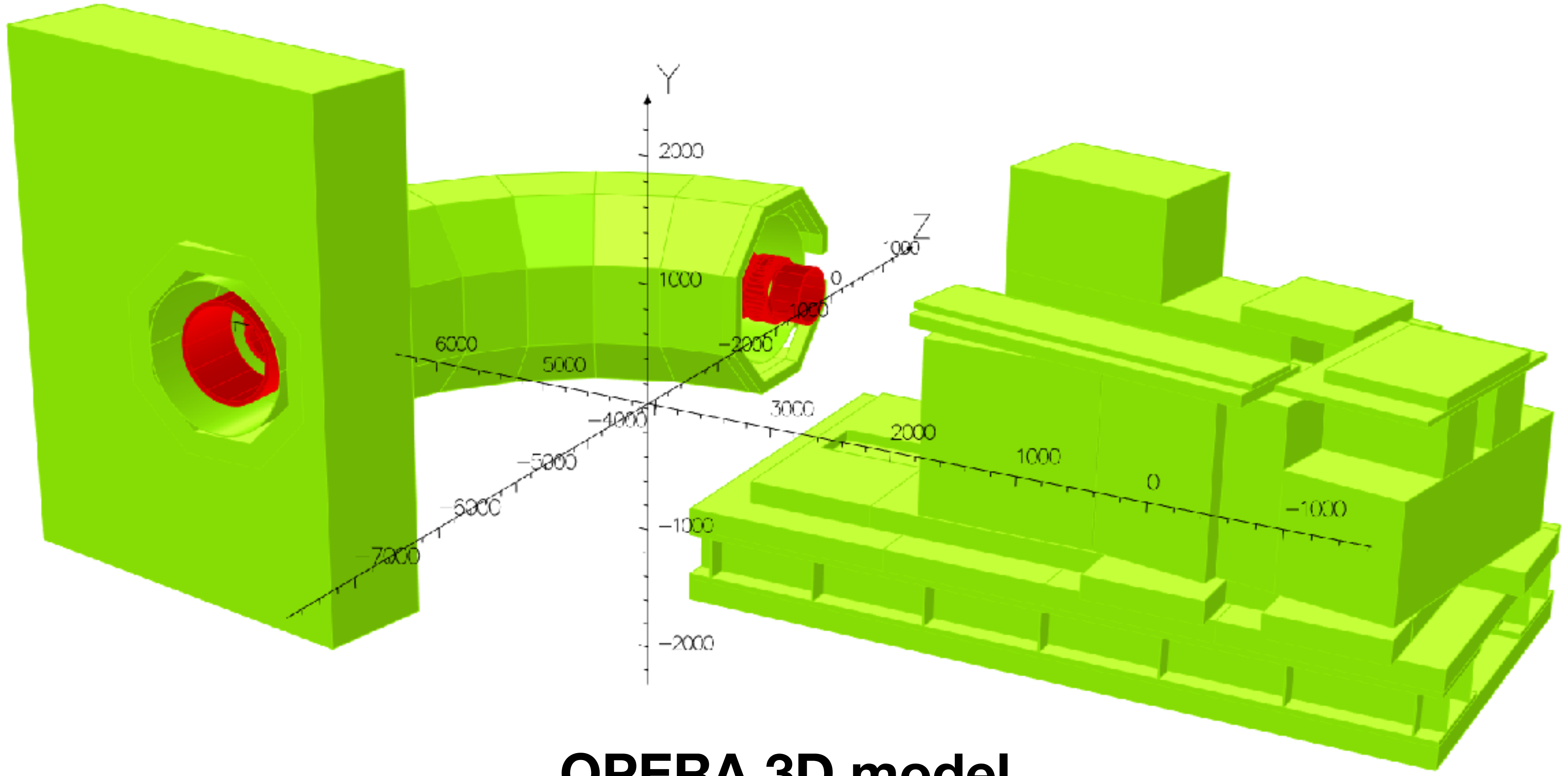
- We use SS400 steel (JIS), which is distributed and relatively cheap, for the iron yoke.
  - The magnetic properties are not specified.
  - We have measured the BH curve of SS400 samples and used it in our calculations.



OPERA calculation result



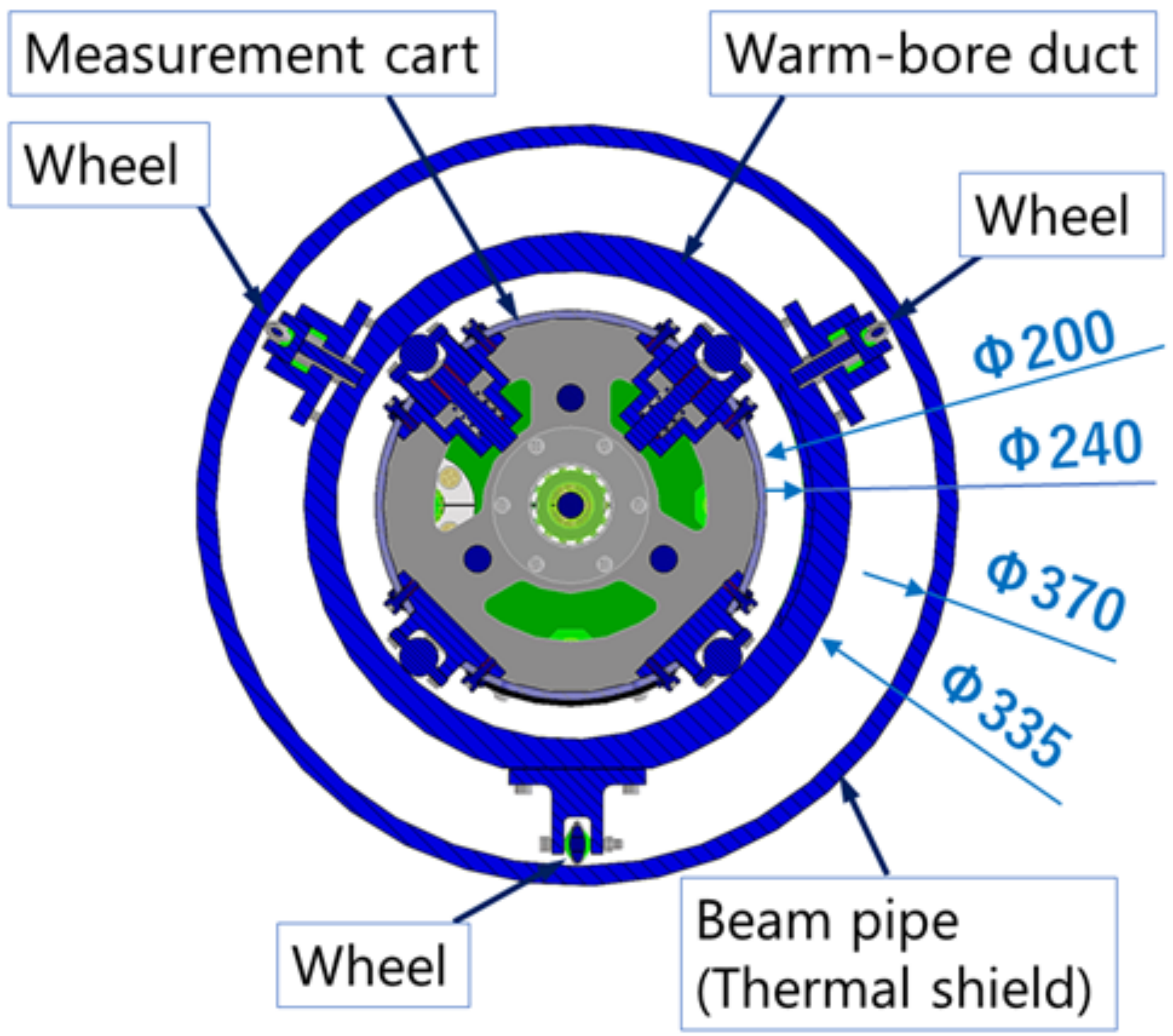
BH curves of SS400

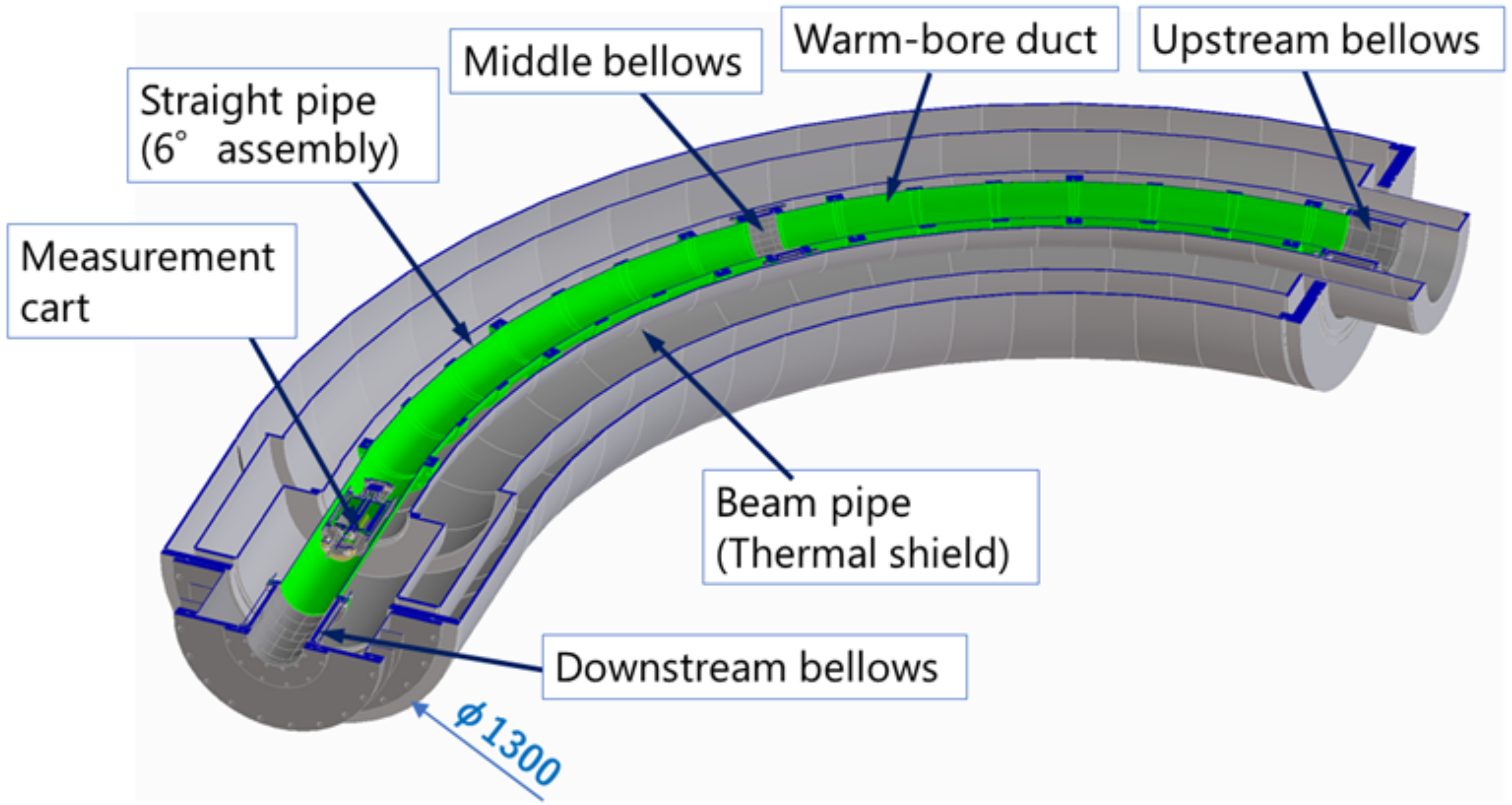


OPERA 3D model

MTS field measurement

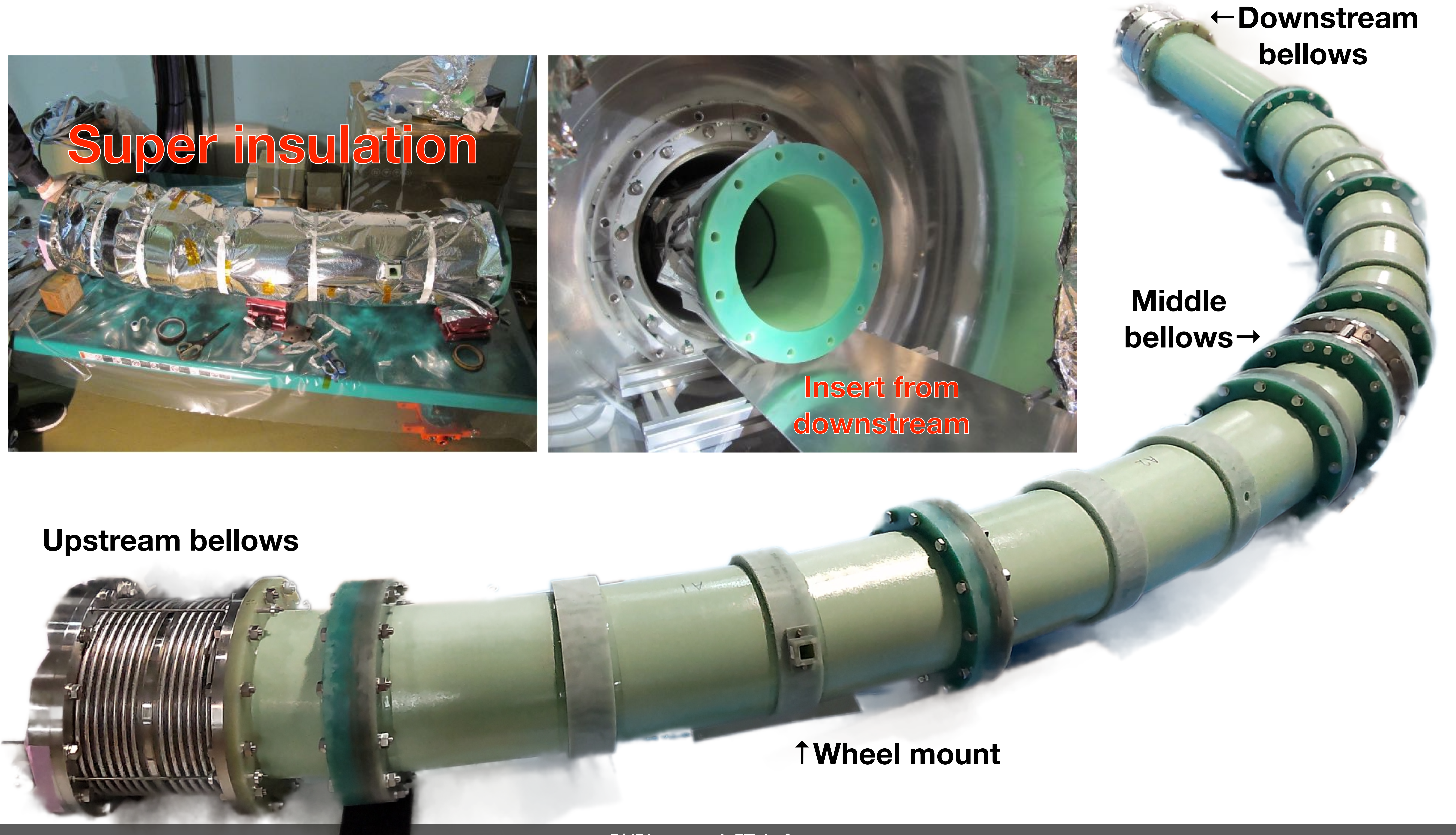
- The purpose of the measurement is to confirm
  that the magnet generates the magnetic field as designed in ~1%.
- There are three difficulties. MTS inner bore is
  - **curved !**
  - **vacuum !!**
  - **cold (~50K) !!!**
- We made and inserted warm-bore ducts and bellows in the cold bore.
  - Temporary warm-bore for field measurement.
  - An measurement cart with 3-axis Hall probes.





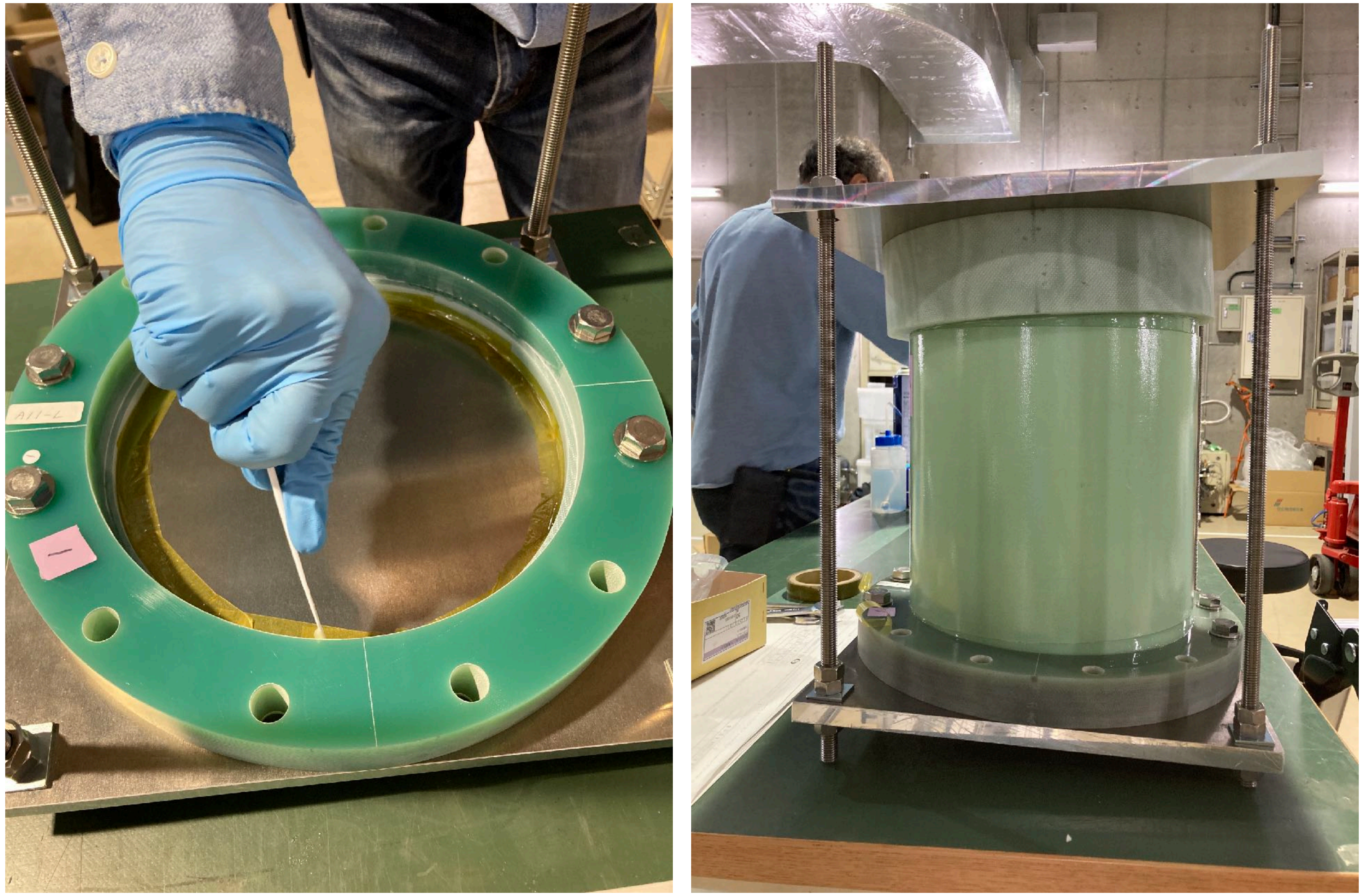
Warm-bore ducts

- The worm-bore ducts are made of G10 pipes and sleeves glued together.
  - The bellows are made of low-carbon stainless (less magnetization).
  - They are wrapped with a thermal radiation shield (super insulation).



Warm-bore ducts production & pressure test

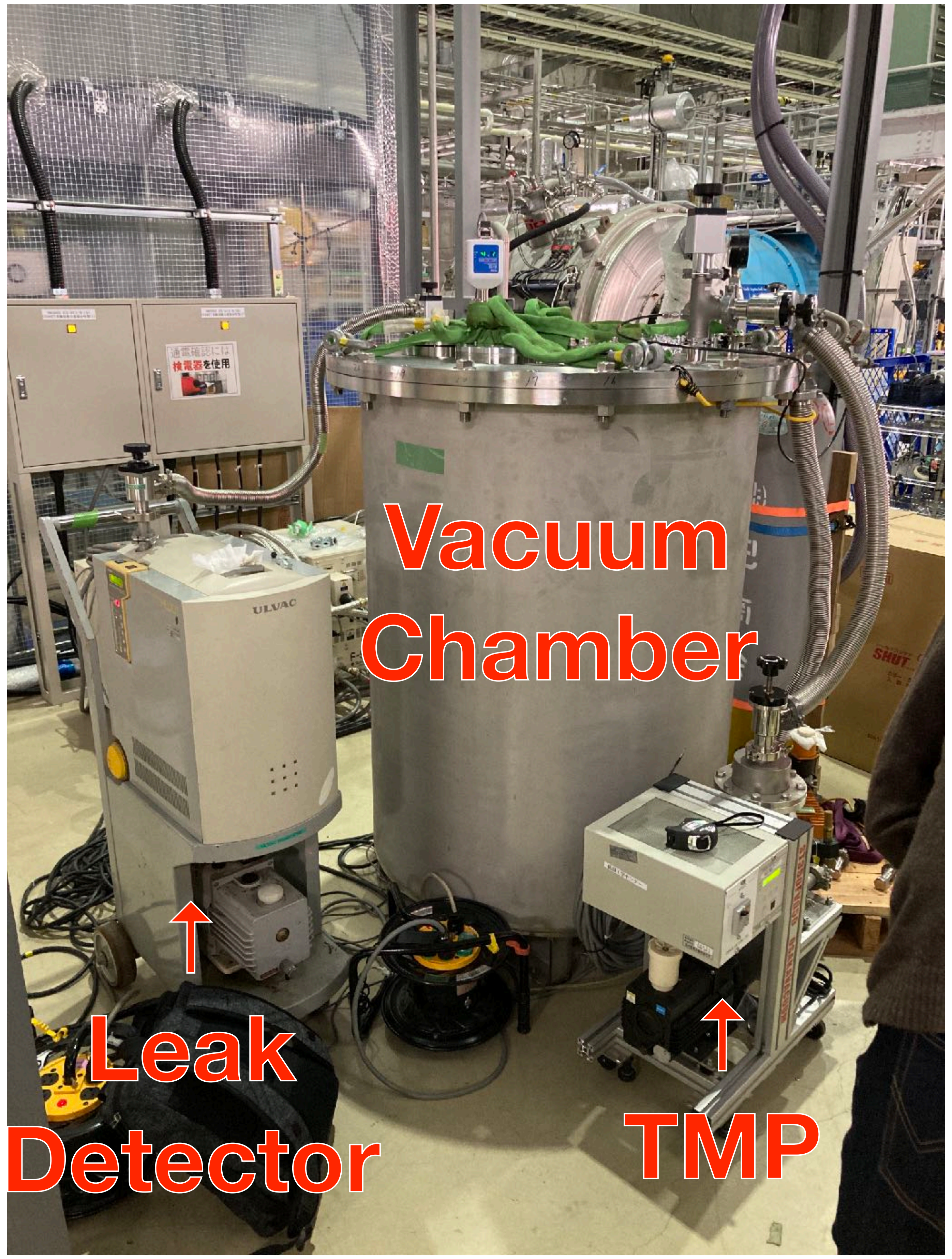
- The G10 flange and pipe were bonded using adhesive (Araldite 24 h curing).
  - The flange and sleeve have 3-degree inclined grooves, providing a 90-degree curve with 30 sections.
  - Pressure test was performed at +1atm.
    Leave overnight, then no pressure reduction was observed.



Pressure test +1atm

Warm-bore ducts leak test

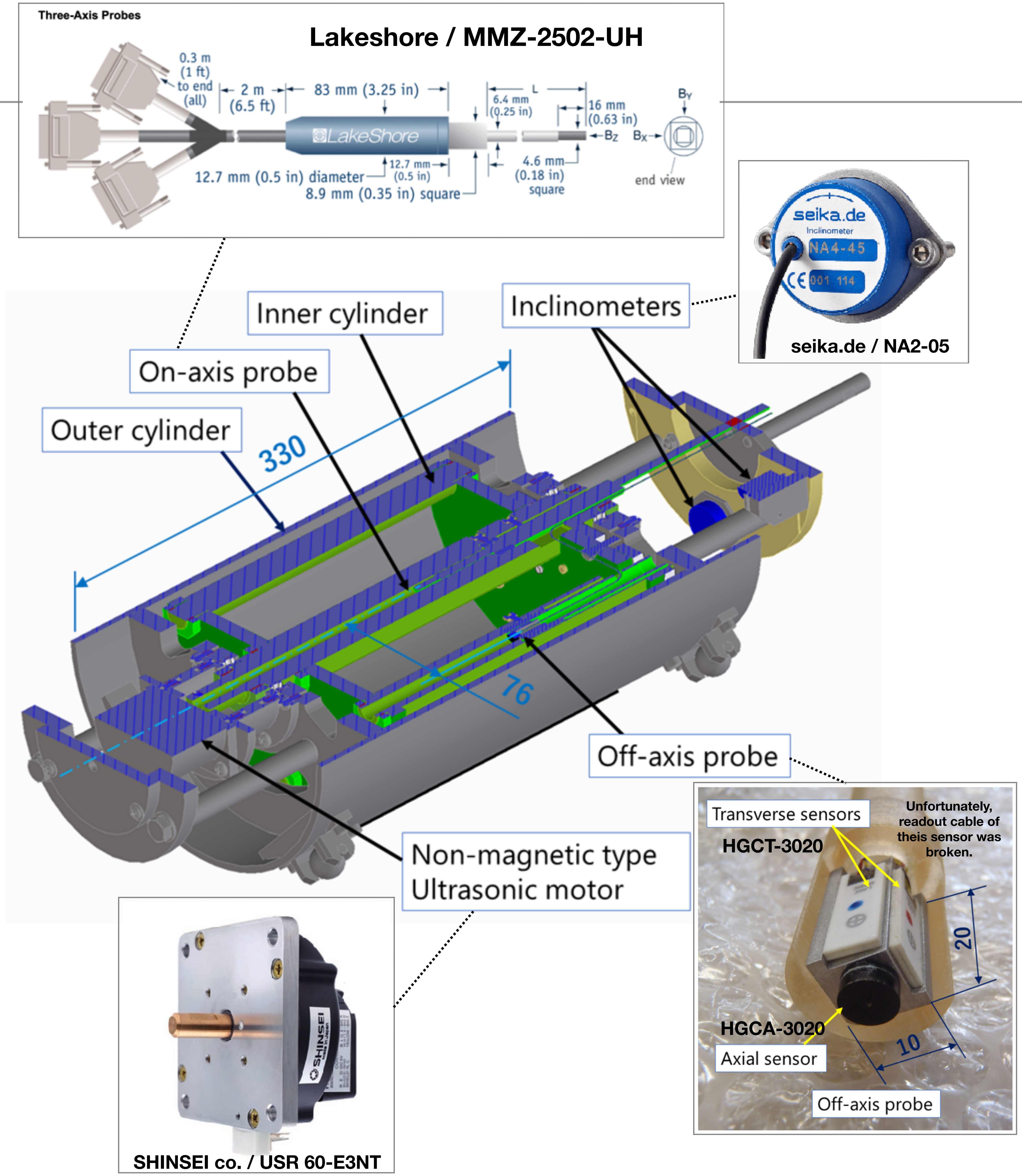
- Bell jar test : The G10 duct was put into a vacuum chamber, the surrounding was evacuated, then filled the duct with He gas.
- Leak was found at ~10^{-7} Pa*m^3/s (Requirement : ~10^{-9} Pa*m^3/s)
  - We polished the flange with sandpaper, but it only made it worse.
  - Applying a lot of vacuum grease to the flange stopped the leak.
  - We suspect that blocking the tunnel running along the fibers in G10 would be effective.

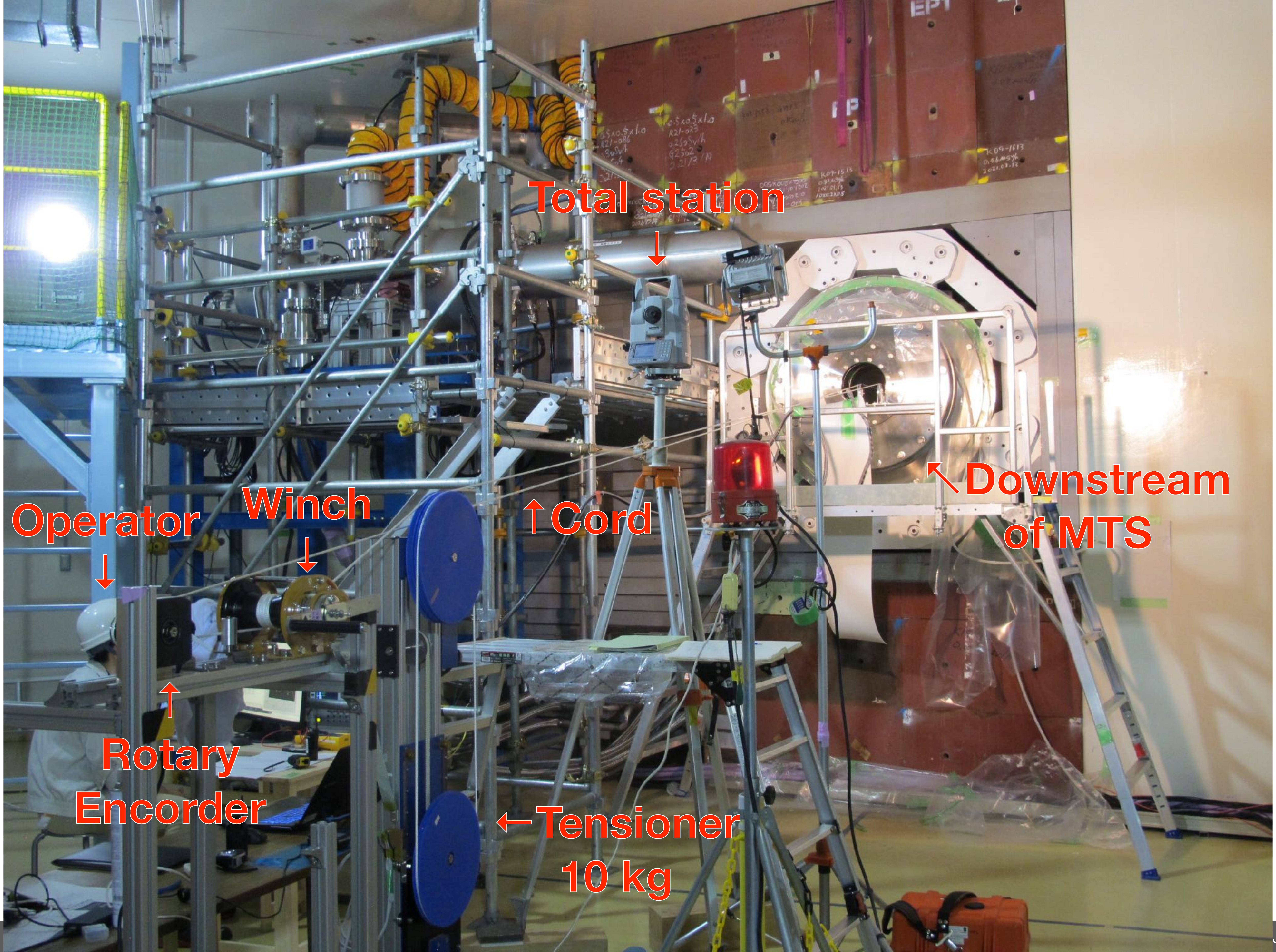


Measurement cart

- The cart carries…
- **On-axis probe**
    - Set on center of the cart
    - Three-axis Hall probe
- **Off-axis probe**
    - Set at 76 mm from center
    - Three independent sensors are assembled at right angles to each other.
- **Non-magnetic Ultrasonic motor**
    - Rotate both probes 360°
    - It has rotary encoder Resolution = 0.36°
- **Inclinometers** to measure angle of the cart
    - Tilt : ±5° (0.001º)
    - Roll : ±10° (0.002º)

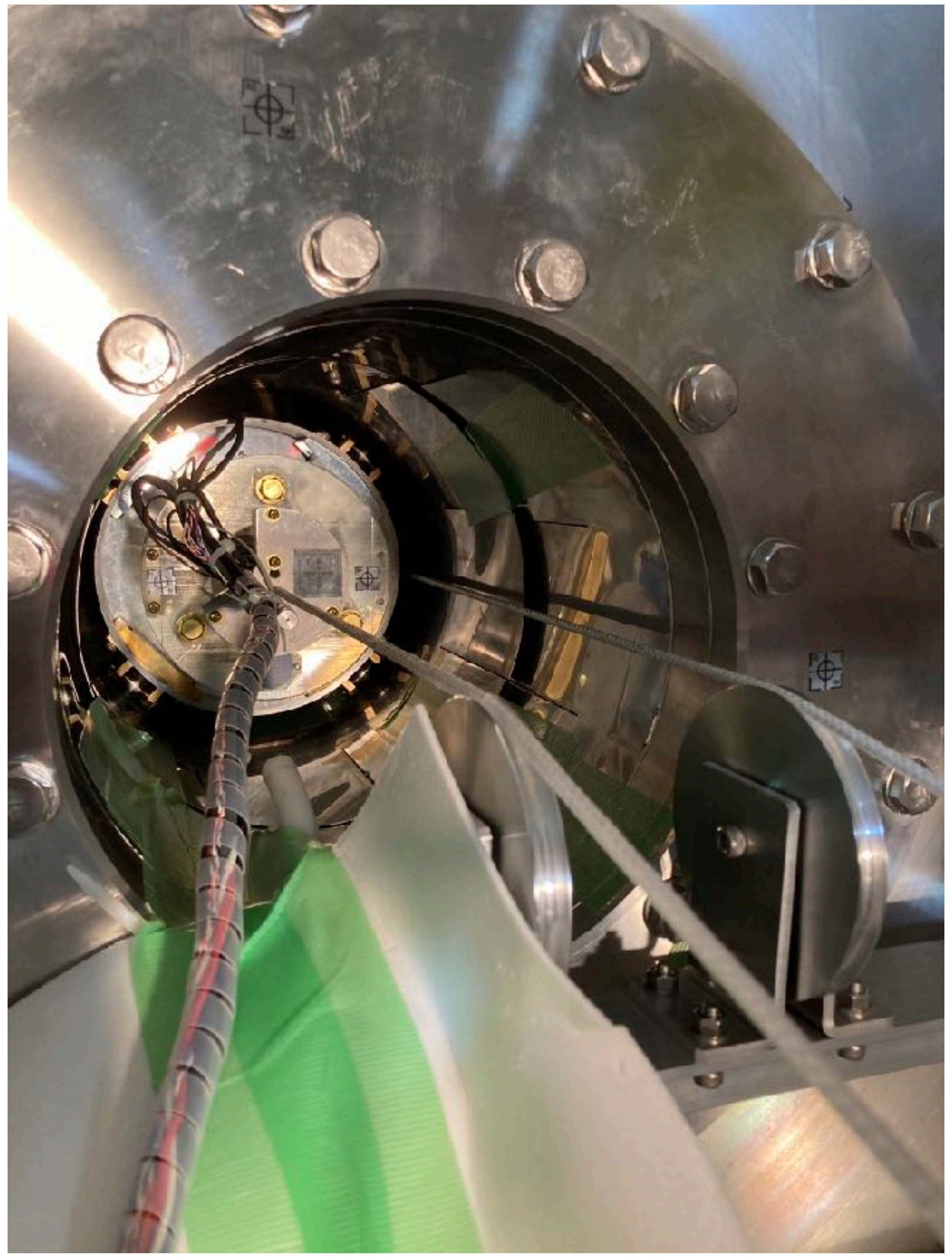
- The cart has spherical tires and can be pulled by cord.

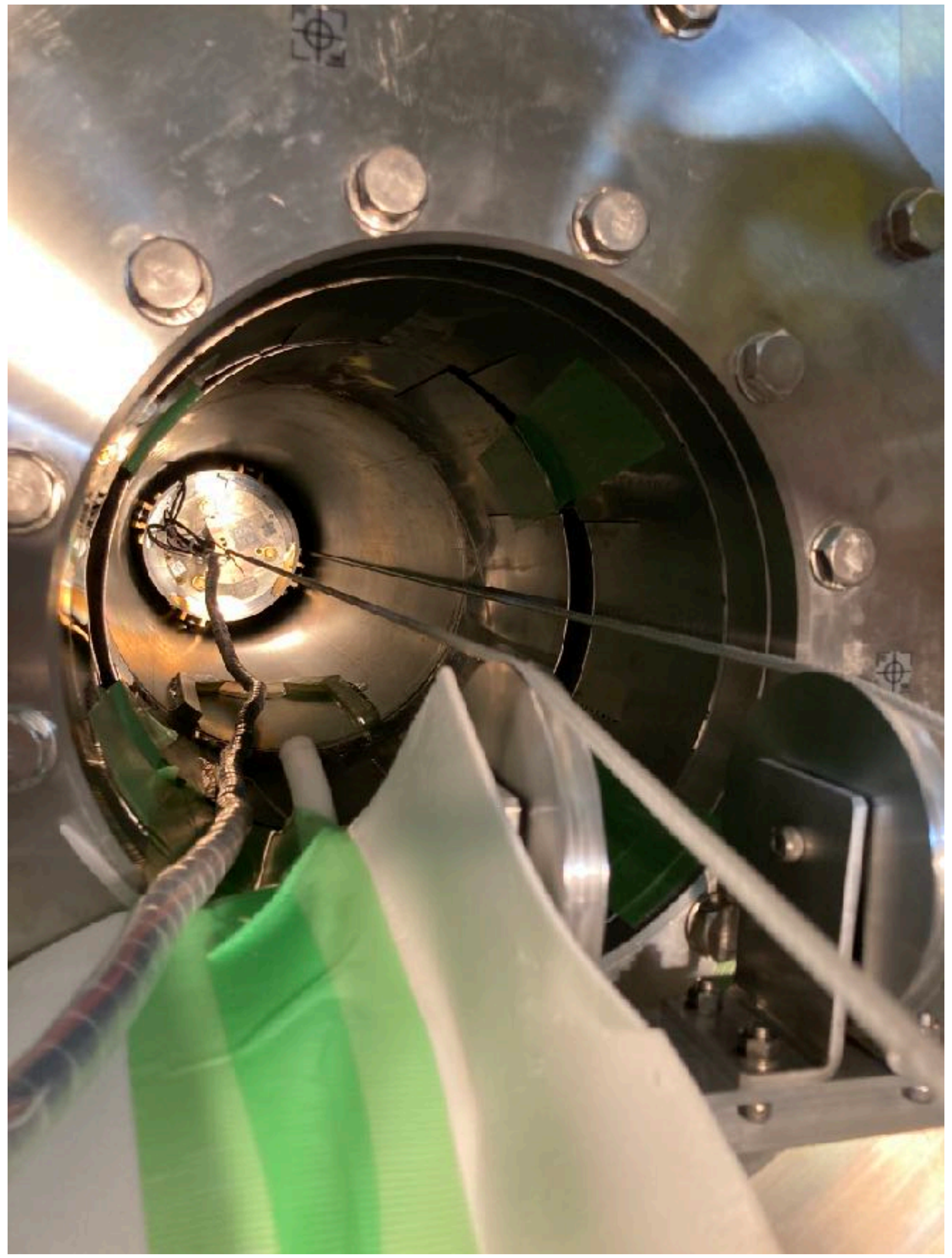



Total station
Downstream of MTS
Operator
Winch
Cord
Rotary Encorder
Tensioner 10 kg

Measurement cart

- There is a rotary encoder at the end of the loop, but the cord slipped.
  - Therefore, we marked on the cord and measured the distance.
    A classic but reliable method
  - We also measured the position of cart
    by the total station as far as it can be seen.

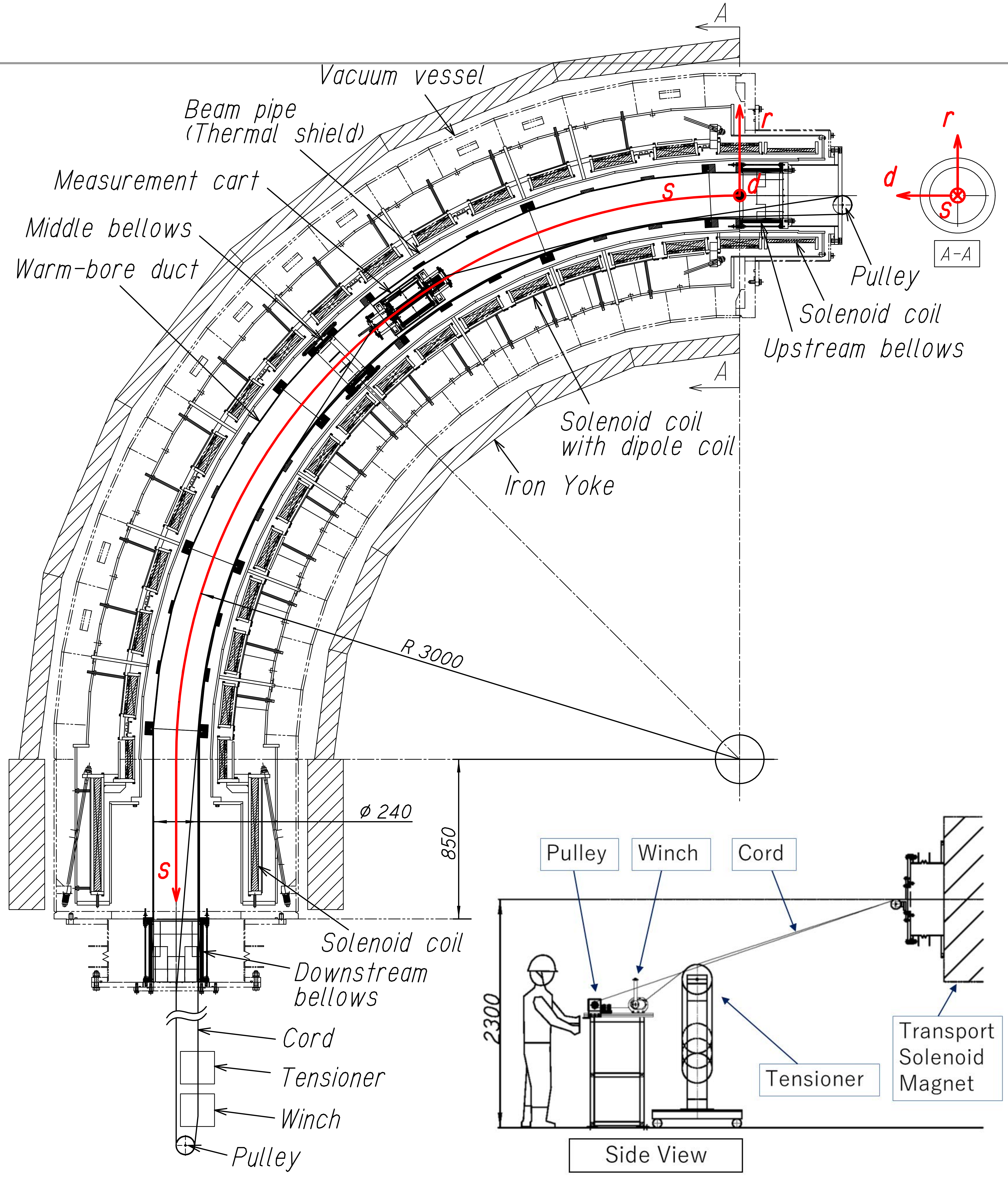


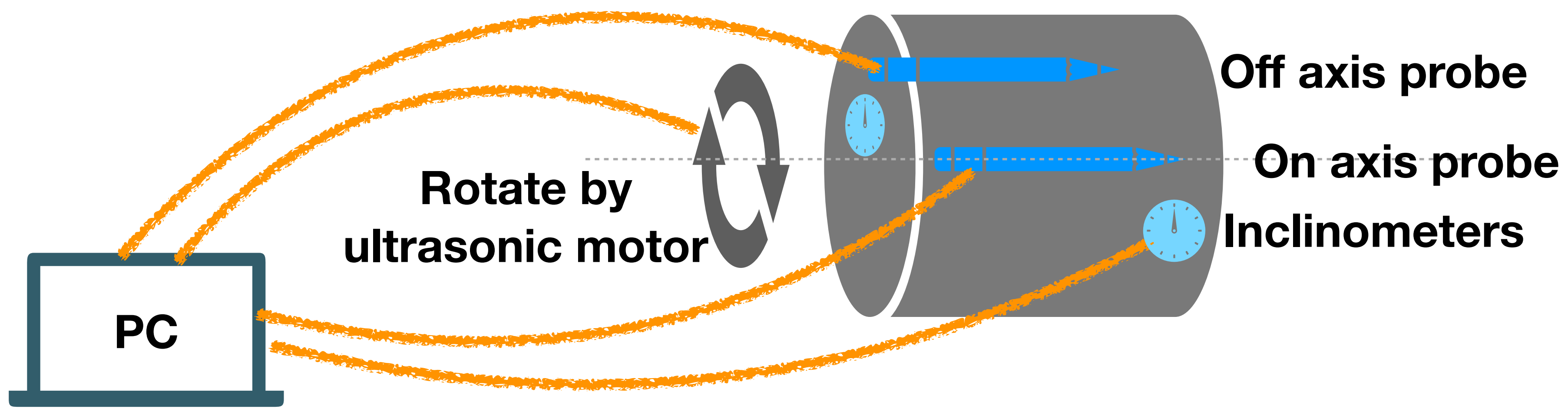


Measurement scheme

- Measurement cycle
  - Excitation magnet
  - Move cart home position
  - Start measurement sequence
    - Ultrasonic motor rotates probes in the cart and measure there field
  - Rotate winch to the next position
  - Start the sequence
  - Repeat them to the other side
- Measurement period one week in July 2022. Day and night shift

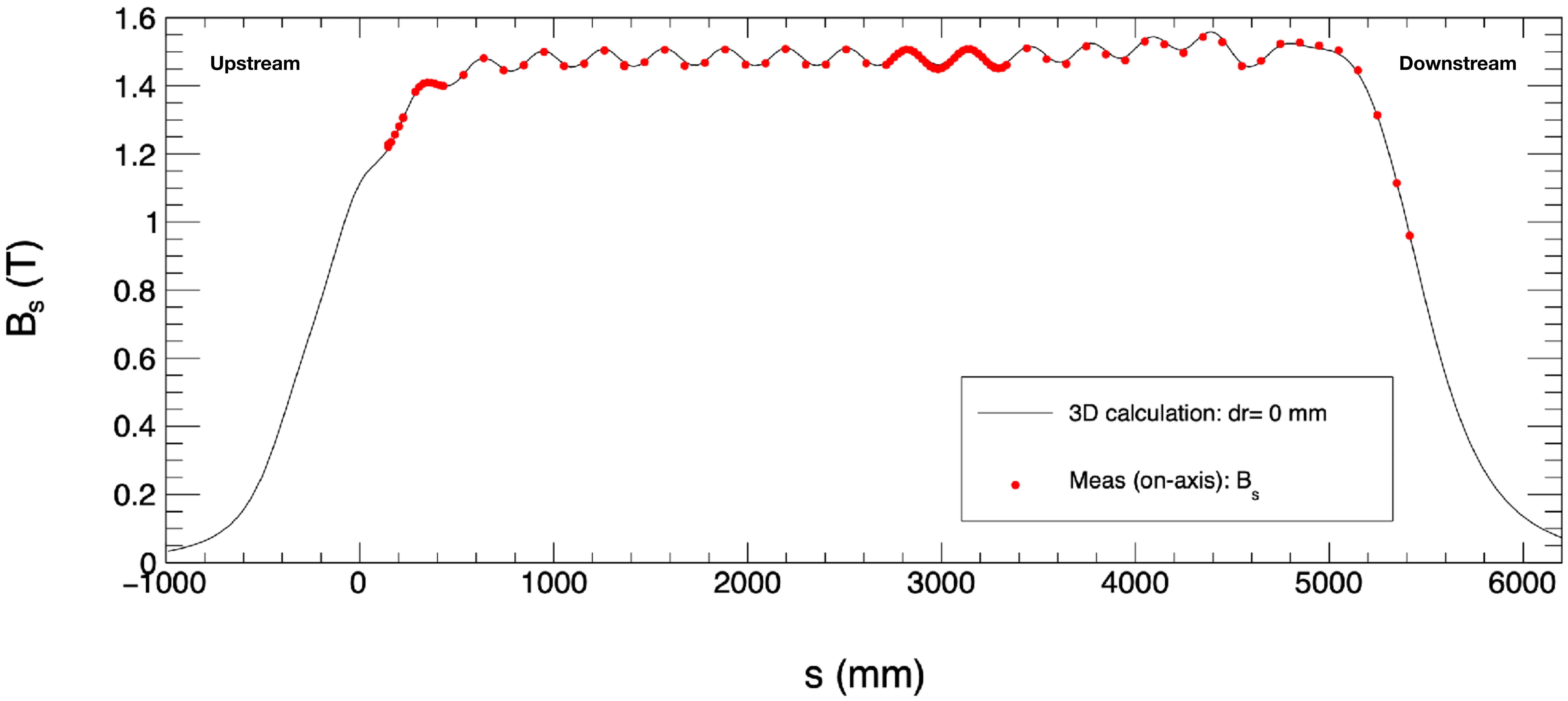
- We defined curved axis along solenoid magnets.
  - **s : Solenoid axis**
  - **d : Dipole axis**
  - **r : Radial axis**





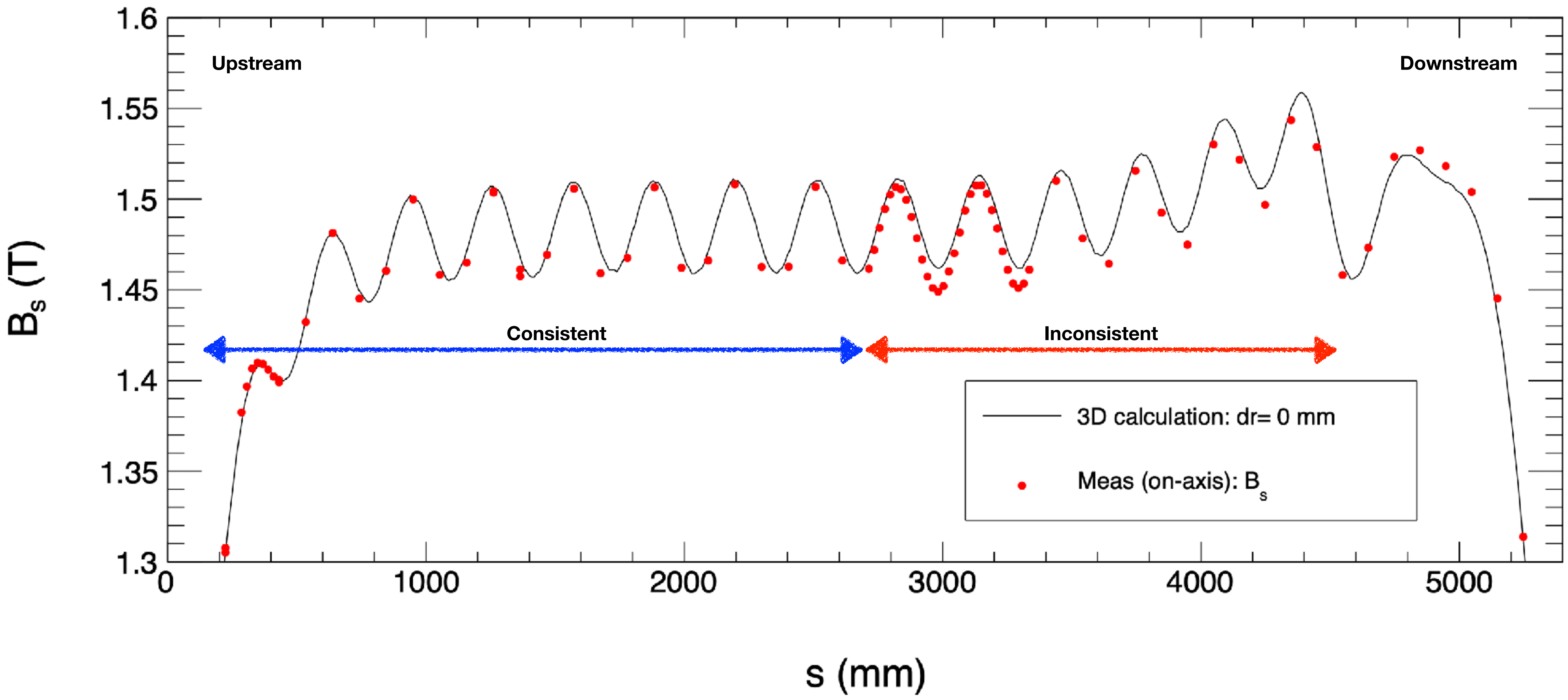
Bs : Solenoid @1.5 T (105 A)

- MTS original field is 3 T (210 A), but it was limited to half at this time because of coil protection problem (Now overcome).
- Comparison solenoid field (Bs) of measurement and calculation.
  - It looks good agreement with calculation.



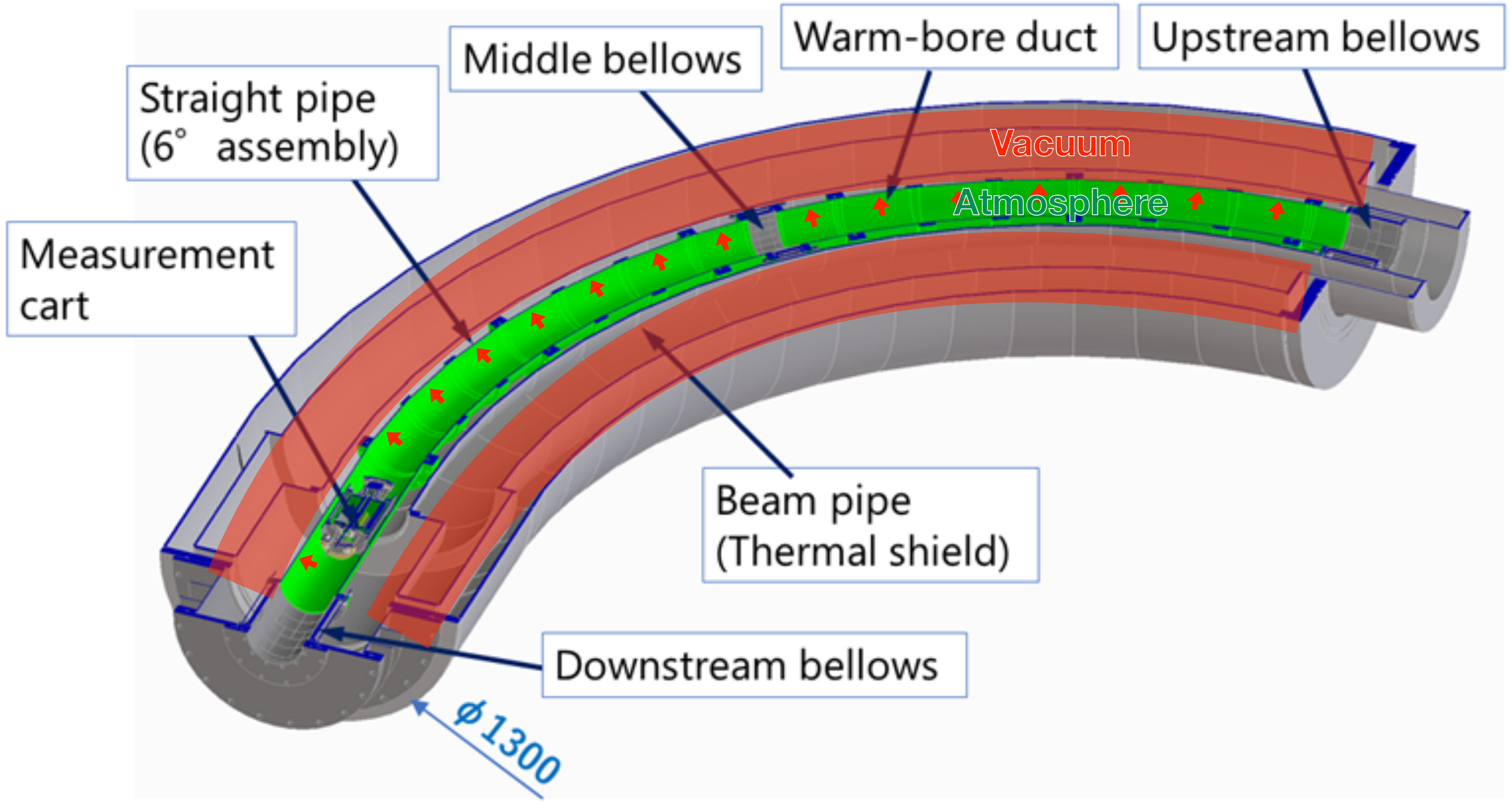
Bs : Solenoid @1.5 T (105 A)

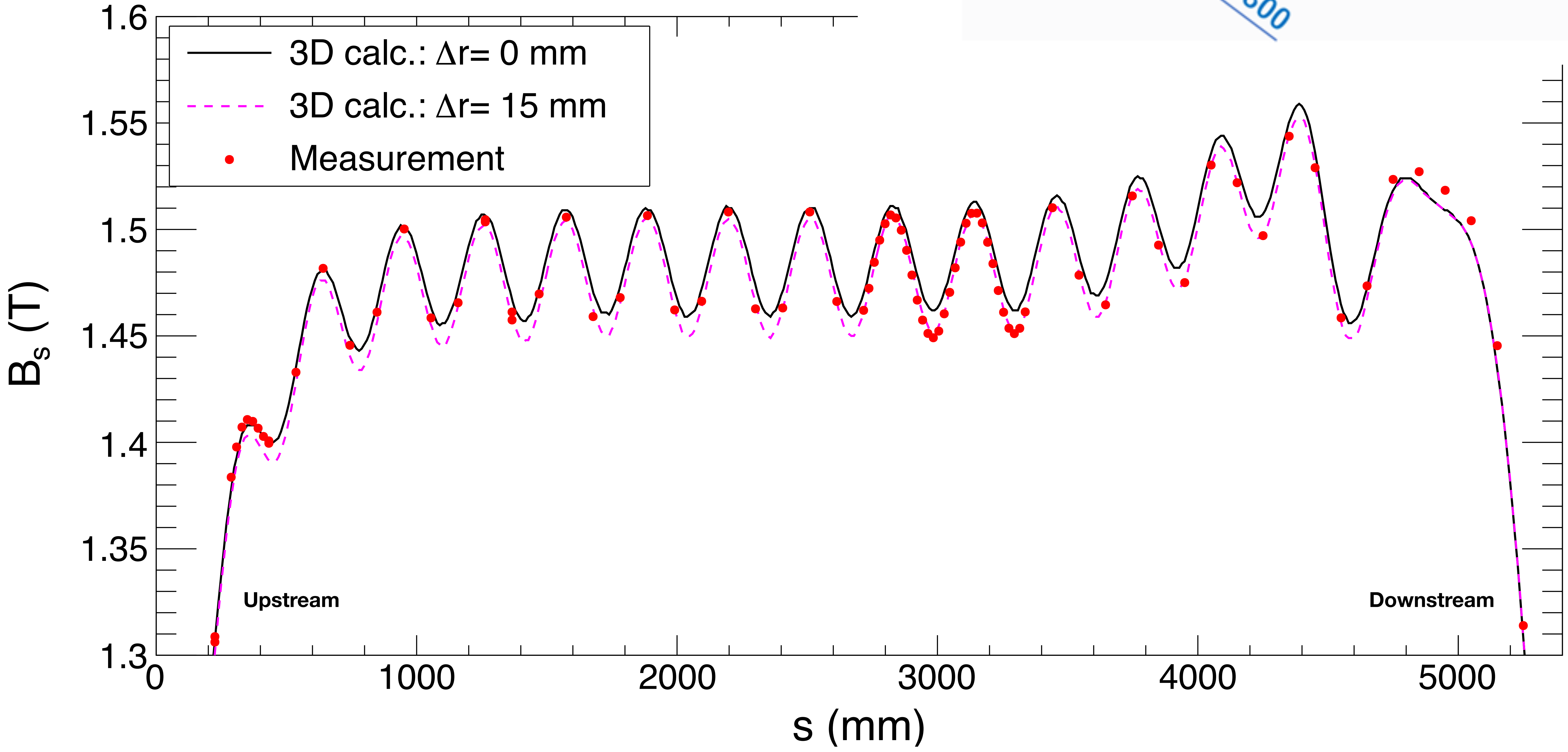
- MTS original field is 3 T (210 A), but it was limited to half at this time because of coil protection problem (Now overcome).
- Comparison solenoid field (Bs) of measurement and calculation.
  - It looks good agreement with calculation.
  - Zooming in, the upstream is relatively consistent, but the downstream is not.



Bs : Solenoid

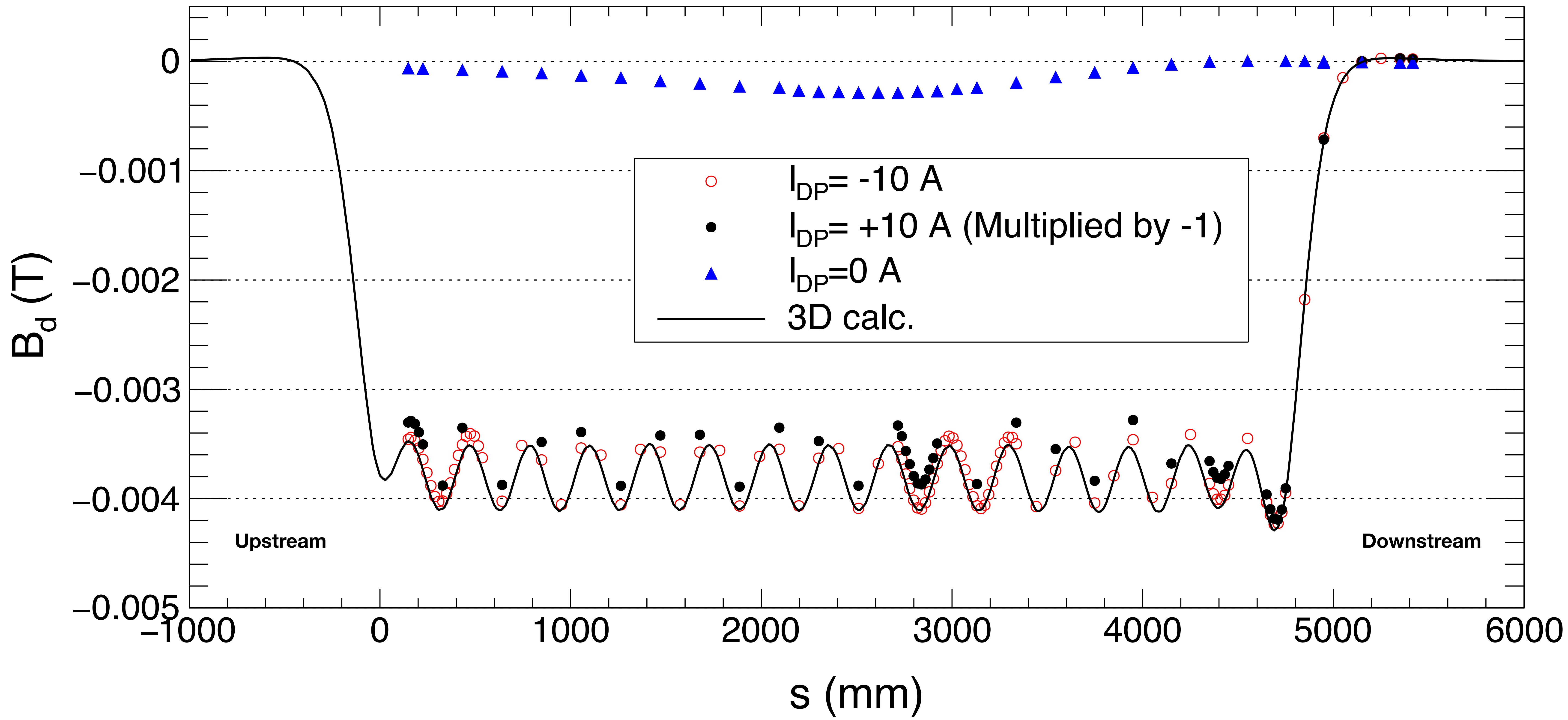
- The cause of that was the warm-bore duct was pushed by atmospheric pressure and moved outside of curvature.
- Total station suggests it is about 15 mm.
- Then data and calculation are consistent.





Br : Dipole @±4 mT (±10 A)

- The dipole field was measured at ±4 mT (±10 A)
  instead of maximum value of ±50 mT (±175 A), because of another coil protection reason.
- Iron yoke residual magnetization can be seen at 0 A.
  - However, it is negligible at ±175 A.
- Difference between ±10 A is 5%, and difference to calculation is 3%.



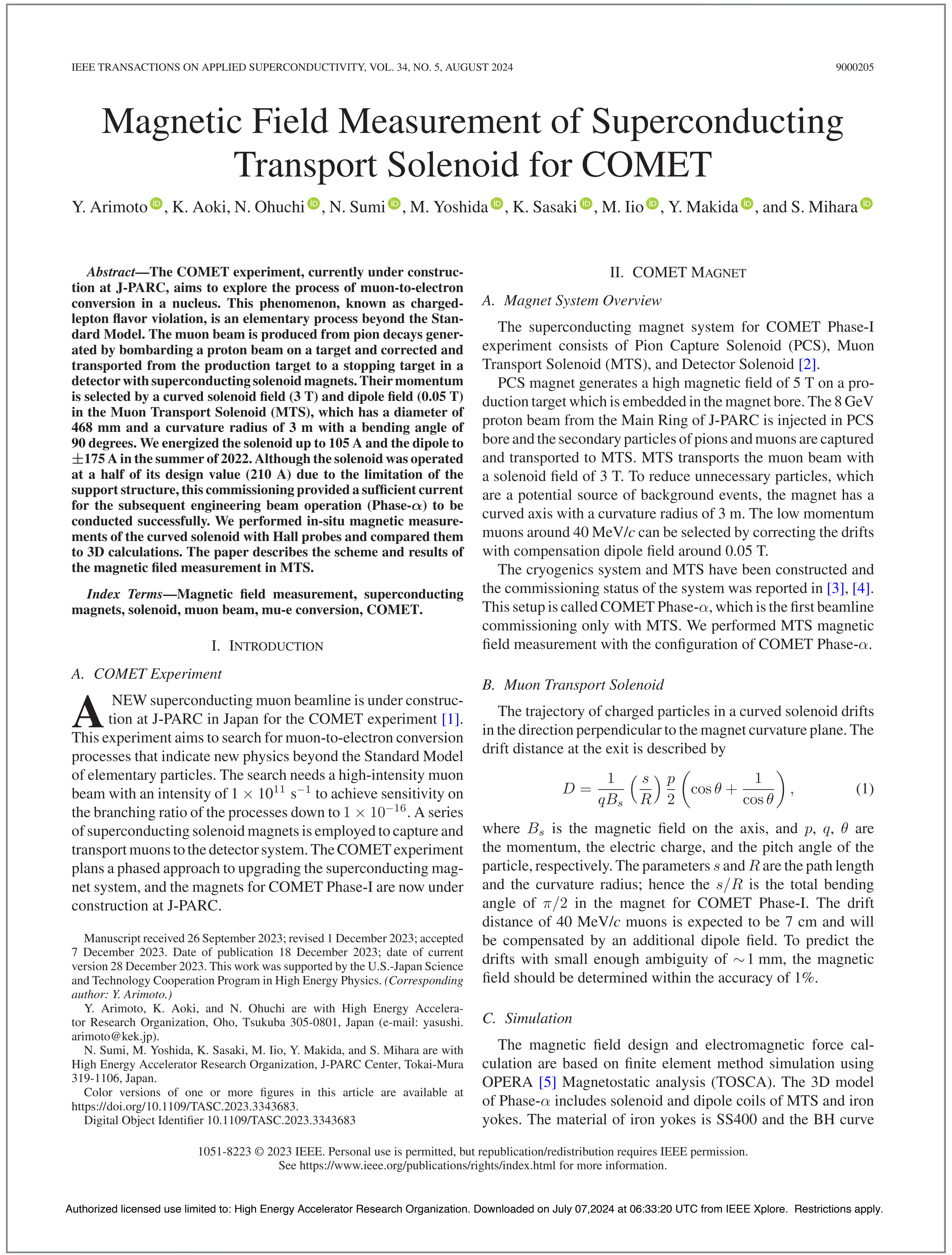
Publication

- The result of MTS field measurement was published.
- **Magnetic Field Measurement of Superconducting Transport Solenoid for COMET**
  IEEE Transactions on Applied Superconductivity, VOL. 34, NO. 5, AUGUST 2024
  https://ieeexplore.ieee.org/document/10363637

- Error budgets of Bs field measurement
  - Largest error comes from cart position.
  - Total uncertainty is 0.4%

ERROR BUDGETS

Source of uncertainty	Value	Unit	δ_B [T]
Deformation of warm-bore duct	10	mm	5×10^{-3}
Cart axial position	5	mm	3×10^{-3}
Hall probe: #3 (zero drift)	4×10^{-5}	T	4×10^{-5}
Hall probe: #3 (relative)	4×10^{-4}		6×10^{-4}
Precision of rotary encoder	0.8	mrad	4×10^{-8}
Cart angle	20	mrad	3×10^{-4}
OPERA FEM	3×10^{-4}	T	3×10^{-4}
OPERA Meshing size	2×10^{-4}	T	2×10^{-4}
OPERA Iron BH curve	2×10^{-4}	T	2×10^{-4}
Fabrication error of coils	1	mm	
Coil current	0.1	A	7×10^{-4}



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Magnetic Field Measurement of Superconducting Transport Solenoid for COMET

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***Abstract*—The COMET experiment, currently under construction at J-PARC, aims to explore the process of muon-to-electron conversion in a nucleus. This phenomenon, known as charged-lepton flavor violation, is an elementary process beyond the Standard Model. The muon beam is produced from pion decays generated by bombarding a proton beam on a target and corrected and transported from the production target to a stopping target in a detector with superconducting solenoid magnets. Their momentum is selected by a curved solenoid field (3 T) and dipole field (0.05 T) in the Muon Transport Solenoid (MTS), which has a diameter of 468 mm and a curvature radius of 3 m with a bending angle of 90 degrees. We energized the solenoid up to 105 A and the dipole to ±175 A in the summer of 2022. Although the solenoid was operated at a half of its design value (210 A) due to the limitation of the support structure, this commissioning provided a sufficient current for the subsequent engineering beam operation (Phase-α) to be conducted successfully. We performed in-situ magnetic measurements of the curved solenoid with Hall probes and compared them to 3D calculations. The paper describes the scheme and results of the magnetic filed measurement in MTS.**

***Index Terms*—Magnetic field measurement, superconducting magnets, solenoid, muon beam, mu-e conversion, COMET.**

I. INTRODUCTION

A. COMET Experiment

A NEW superconducting muon beamline is under construction at J-PARC in Japan for the COMET experiment [1]. This experiment aims to search for muon-to-electron conversion processes that indicate new physics beyond the Standard Model of elementary particles. The search needs a high-intensity muon beam with an intensity of 1×10^{11} s^{-1} to achieve sensitivity on the branching ratio of the processes down to 1×10^{-16}. A series of superconducting solenoid magnets is employed to capture and transport muons to the detector system. The COMET experiment plans a phased approach to upgrading the superconducting magnet system, and the magnets for COMET Phase-I are now under construction at J-PARC.

II. COMET MAGNET

A. Magnet System Overview

The superconducting magnet system for COMET Phase-I experiment consists of Pion Capture Solenoid (PCS), Muon Transport Solenoid (MTS), and Detector Solenoid [2].

PCS magnet generates a high magnetic field of 5 T on a production target which is embedded in the magnet bore. The 8 GeV proton beam from the Main Ring of J-PARC is injected in PCS bore and the secondary particles of pions and muons are captured and transported to MTS. MTS transports the muon beam with a solenoid field of 3 T. To reduce unnecessary particles, which are a potential source of background events, the magnet has a curved axis with a curvature radius of 3 m. The low momentum muons around 40 MeV/*c* can be selected by correcting the drifts with compensation dipole field around 0.05 T.

The cryogenics system and MTS have been constructed and the commissioning status of the system was reported in [3], [4]. This setup is called COMET Phase-α, which is the first beamline commissioning only with MTS. We performed MTS magnetic field measurement with the configuration of COMET Phase-α.

B. Muon Transport Solenoid

The trajectory of charged particles in a curved solenoid drifts in the direction perpendicular to the magnet curvature plane. The drift distance at the exit is described by

$$D = \frac{1}{qB_s}\left(\frac{s}{R}\right)\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right), \qquad (1)$$

where B_s is the magnetic field on the axis, and p, q, θ are the momentum, the electric charge, and the pitch angle of the particle, respectively. The parameters s and R are the path length and the curvature radius; hence the s/R is the total bending angle of $\pi/2$ in the magnet for COMET Phase-I. The drift distance of 40 MeV/*c* muons is expected to be 7 cm and will be compensated by an additional dipole field. To predict the drifts with small enough ambiguity of $\sim$1 mm, the magnetic field should be determined within the accuracy of 1%.

C. Simulation

The magnetic field design and electromagnetic force calculation are based on finite element method simulation using OPERA [5] Magnetostatic analysis (TOSCA). The 3D model of Phase-α includes solenoid and dipole coils of MTS and iron yokes. The material of iron yokes is SS400 and the BH curve

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2023.3343683.

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Summary

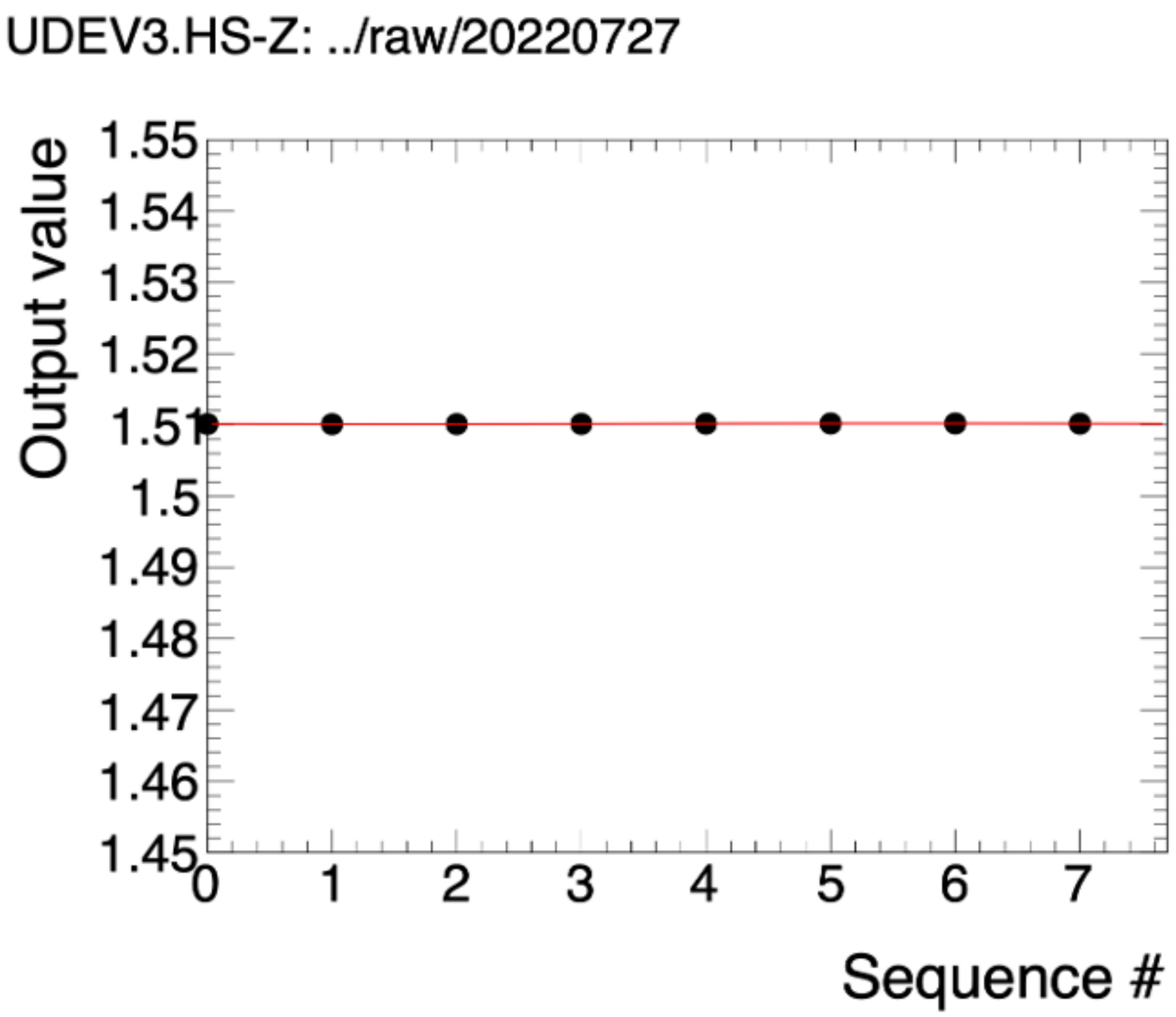
- The COMET experiment uses superconducting magnets throughout the beamline.
  - Magnetic field measurement is important for manufacturing check and simulation.

- There are three difficulties.
  Muon Transport Solenoid (MTS) inner bore is
  - **curved !**
  - **vacuum !!**
  - **cold (~50K) !!!**

- We made and inserted warm-bore ducts and bellows in the cold bore.
  - Temporary warm-bore for field measurement.
  - An measurement cart with 3-axis Hall probes.

Backup

Raw data : Solenoid @1.5 T (105 A)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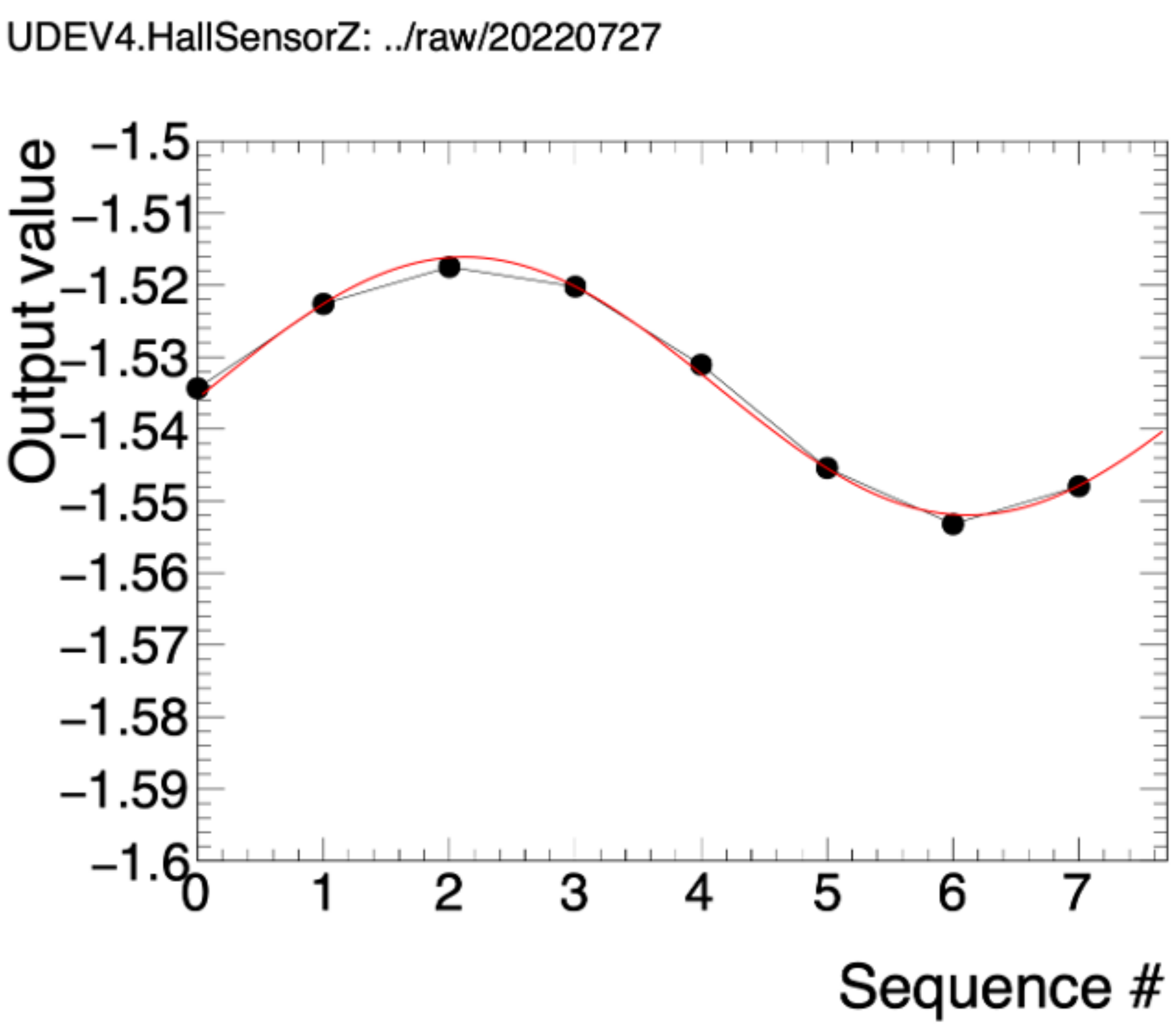
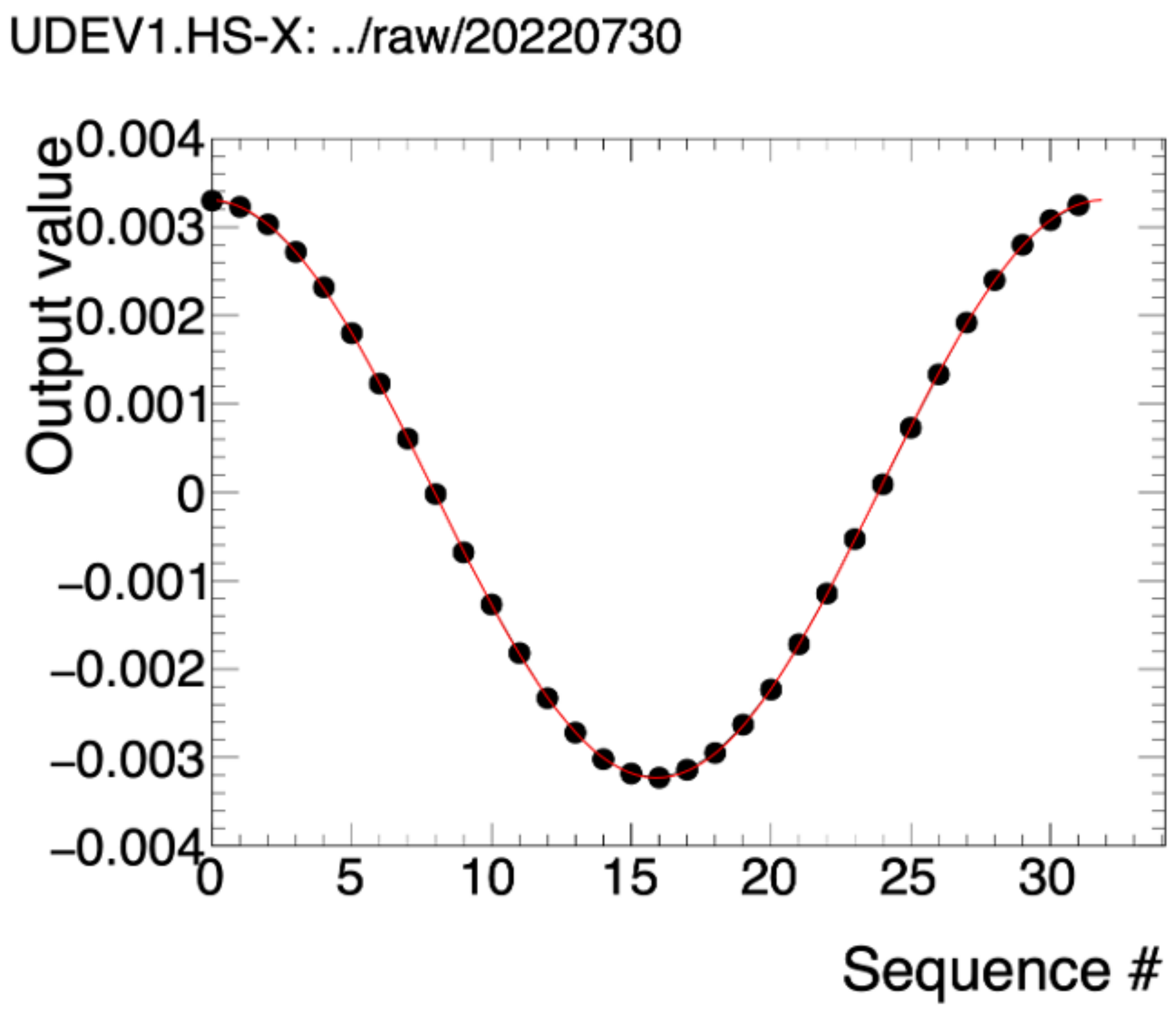
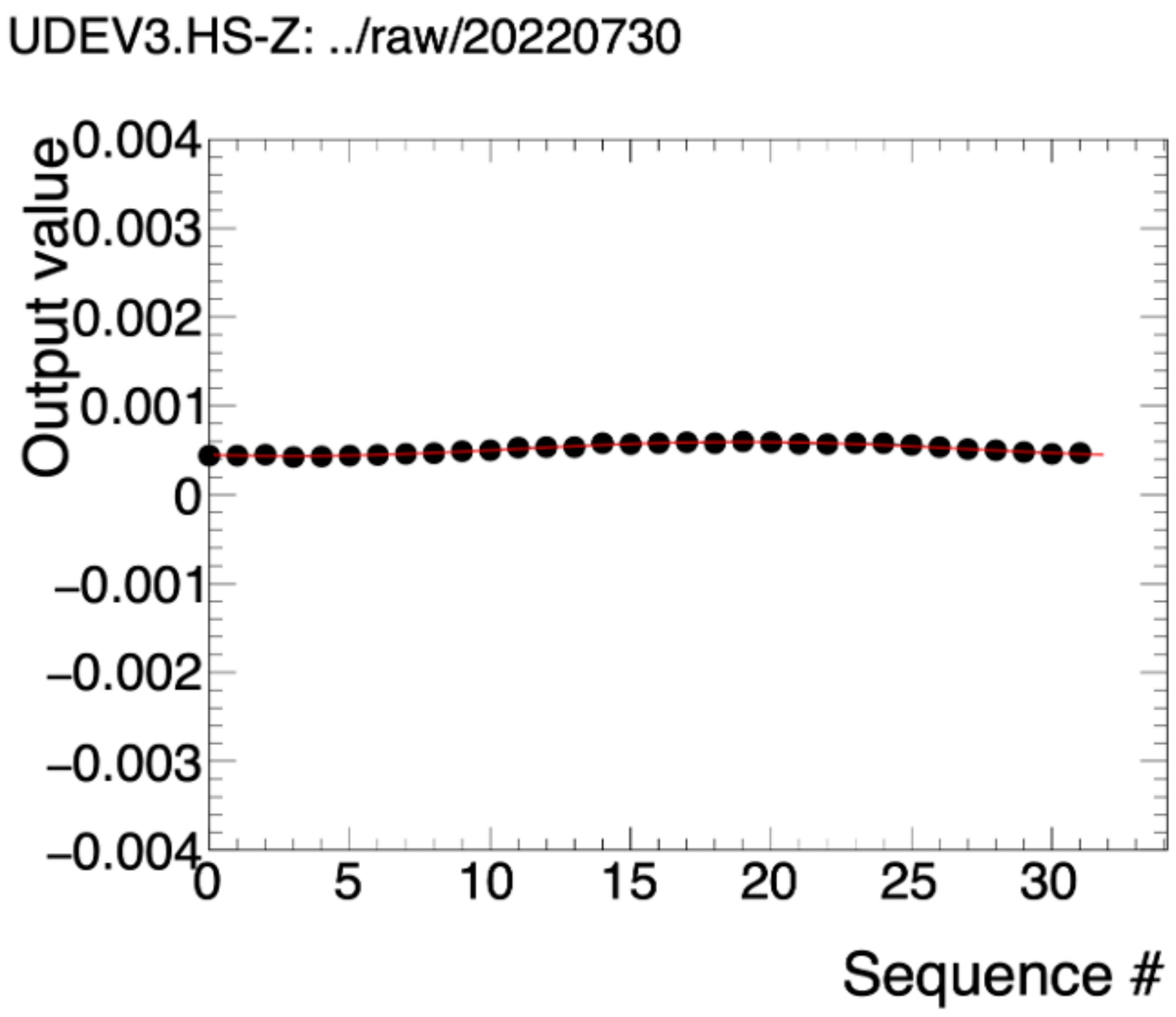
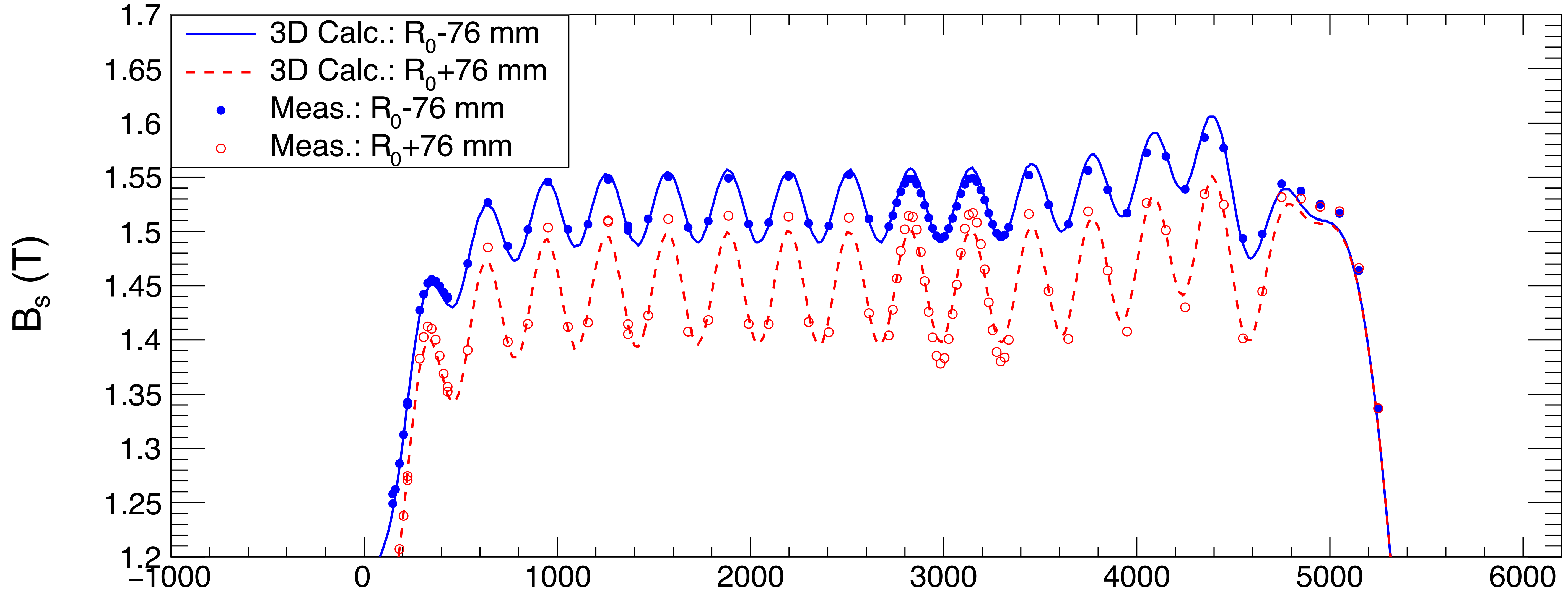

UDEV4.HallSensorZ: ../raw/20220727

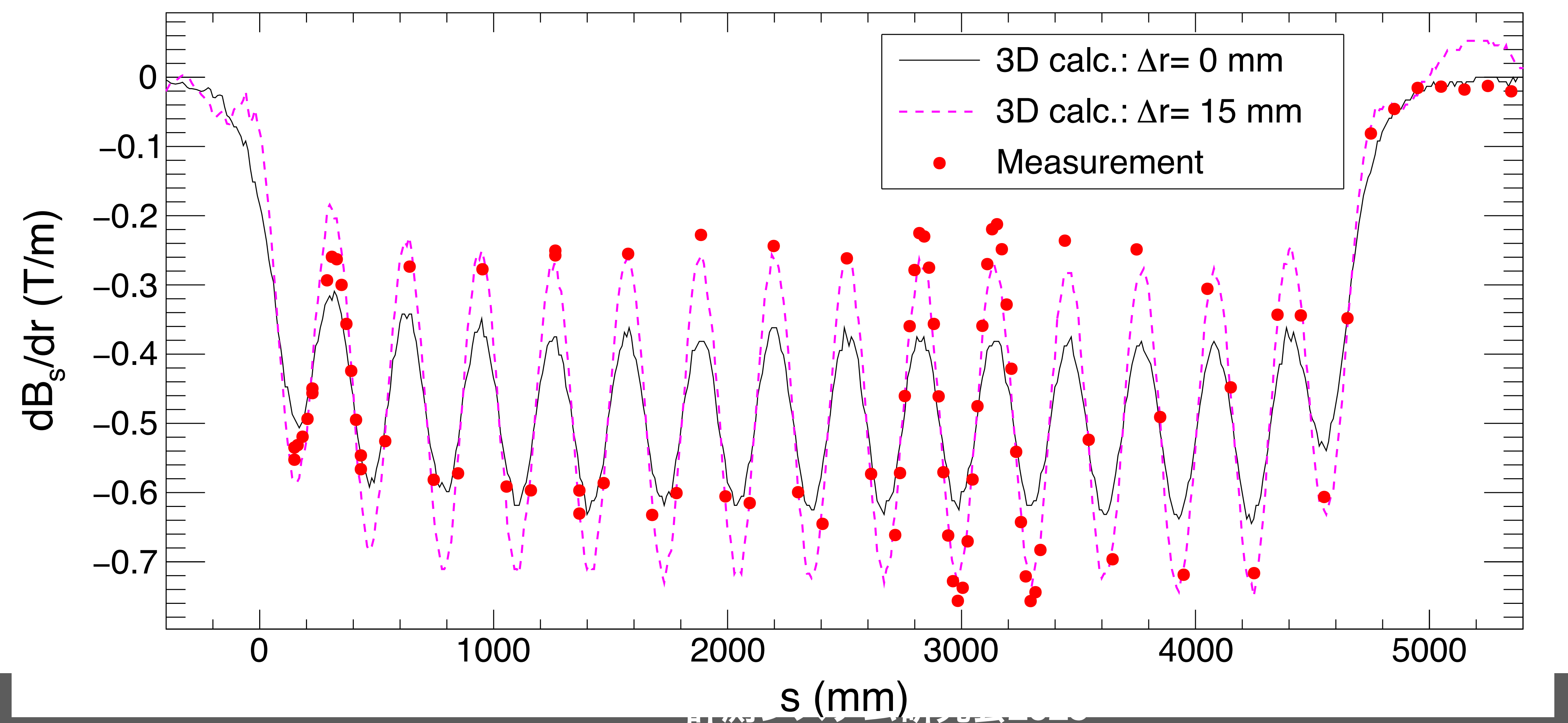
Raw data : Dipole @-4 mT (-10 A)





Solenoid:105 A, off axis probe:ds=13.6 mm





Pion Capture Solenoid

PCS field measurement

- The magnetic field was measured at the factory in July 2024.
  - Measured at a low current 0.75 A, which is 0.03% of operation current 2700 A.
  - The coils are at room temperature ~22°C.
  - Without iron yoke
  - Moving a 3-axis Hall element along an aluminum rail
  - Probe positions were monitored using a laser distance meter.

Measurement result

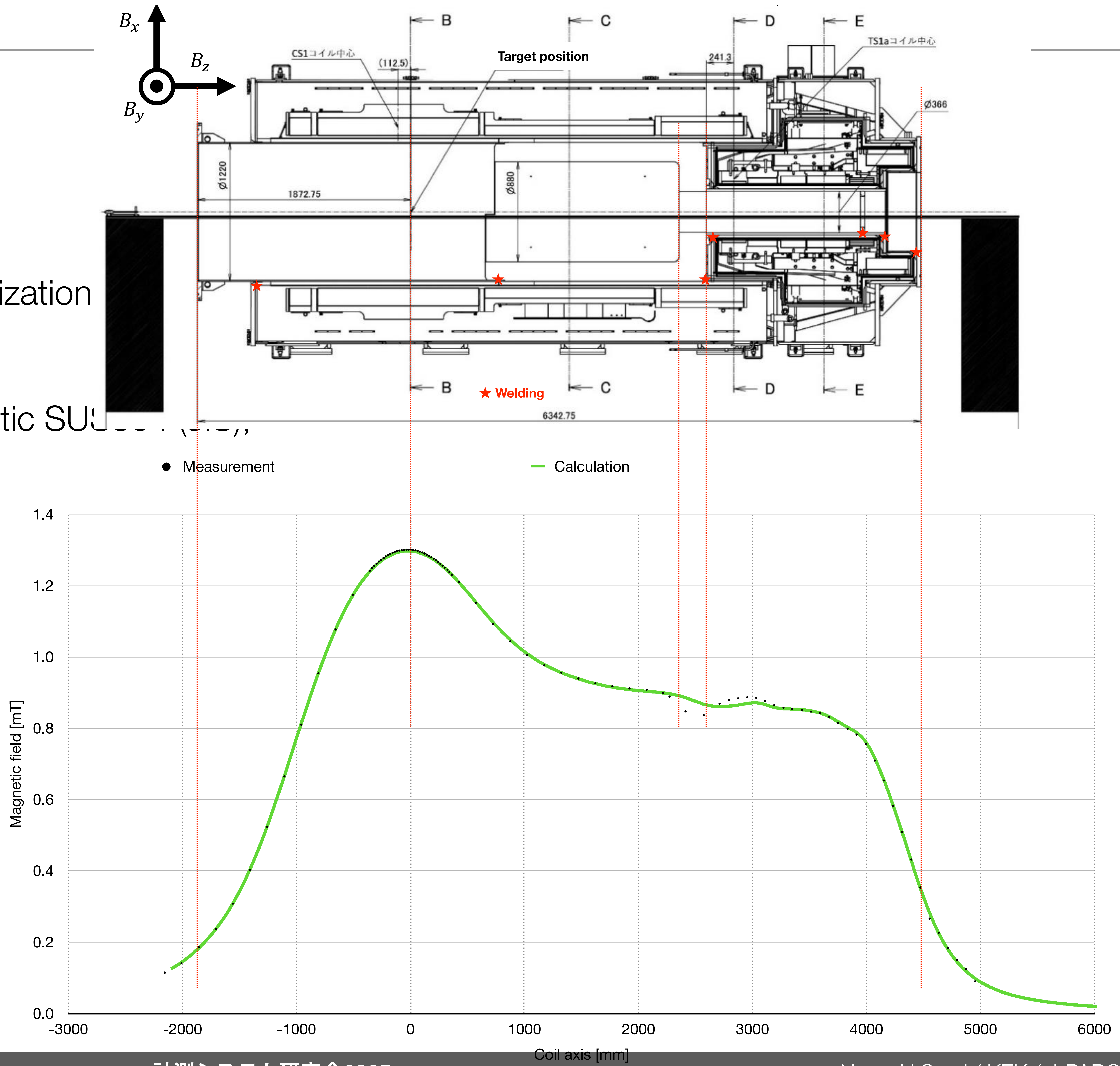
- Good agreement with calculation except for z~2500 mm.
  - ΔB ~ -40 μT
  - ΔB/B ~ -5%

- We think this discrepancy is due to magnetization of the stainless steel.

- The stainless steel used here is non-magnetic SUS but it may become magnetic when welded or machined.

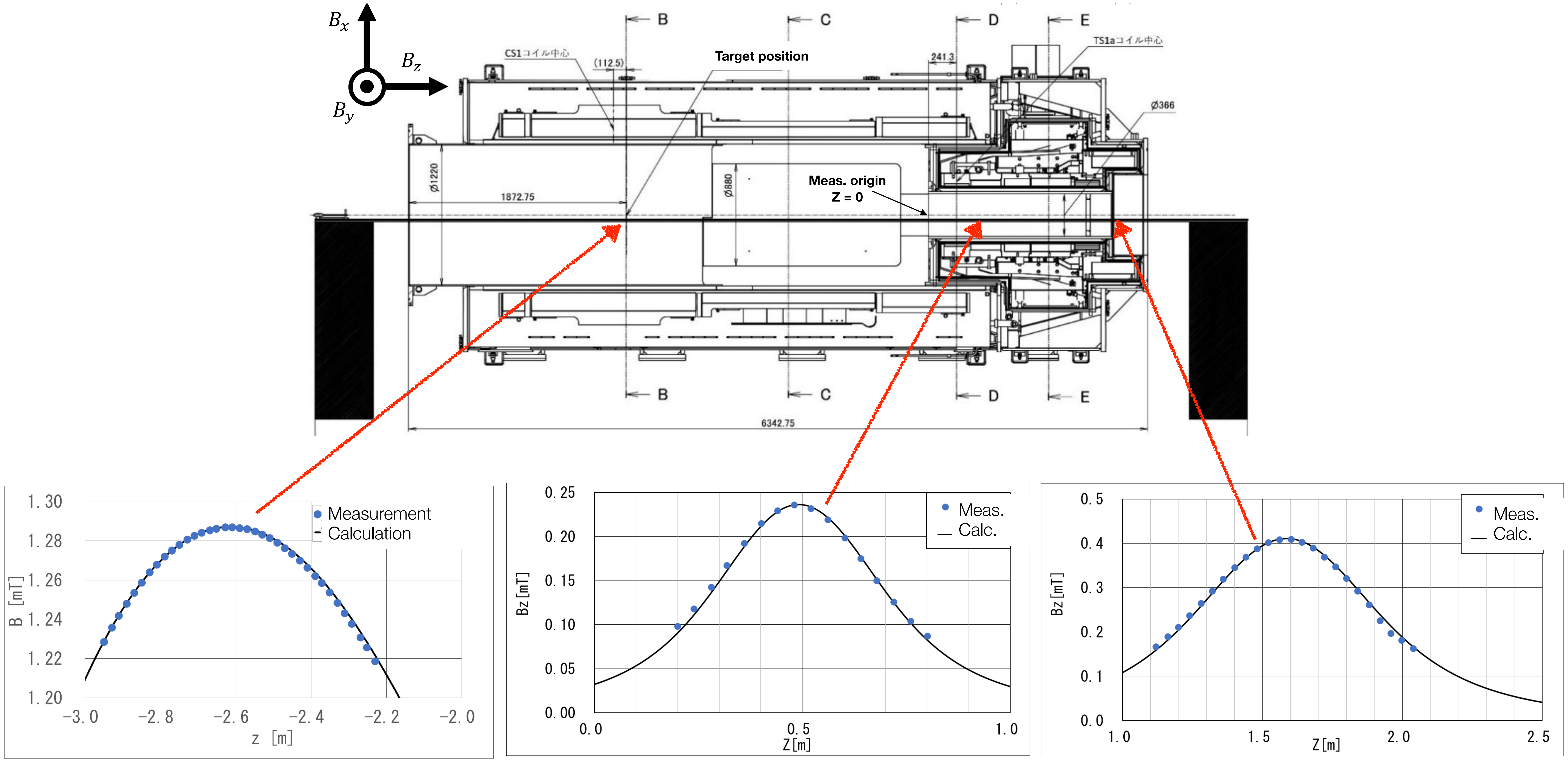
- Further investigation is ongoing.

- Is there any problem with coil itself?



Coil health check

- **Coil position**
  - Peak position of CS1 is consistent with calculation.
  - TS1b and TS1f were excited independently using trim cables.
    These positions are also consistent with calculation.



CS1 peak **TS1b** **TS1f**

Coil health check

- **Coil resistance**
  - Coil resistances were precisely measured using a four-terminal measurement method.
  - Coil temperatures were measured with thermocouples and correction was applied.

  - Good agreement with calculation.
  - No layer-to-layer short was observed.

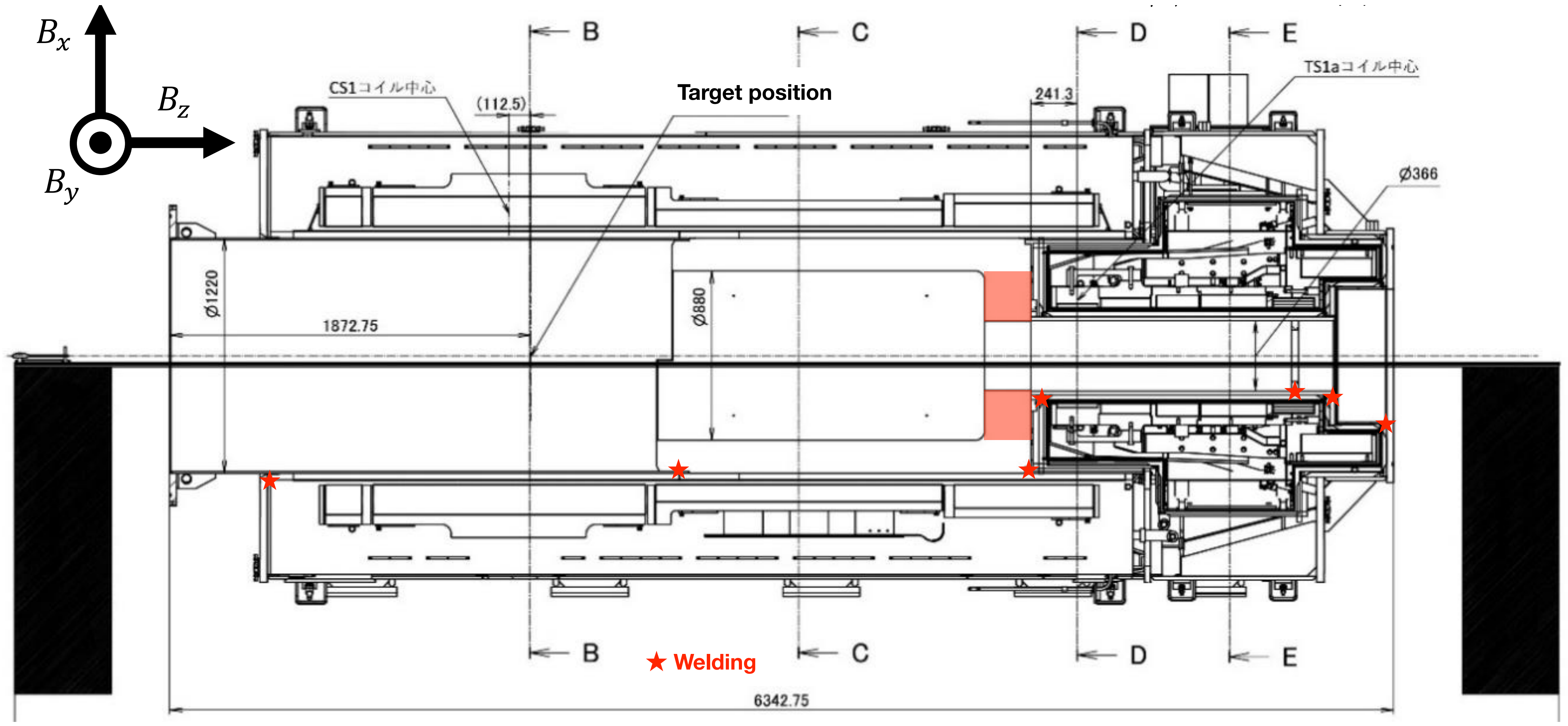
  - And no ground fault was observed at 500V by a withstand voltage tester.

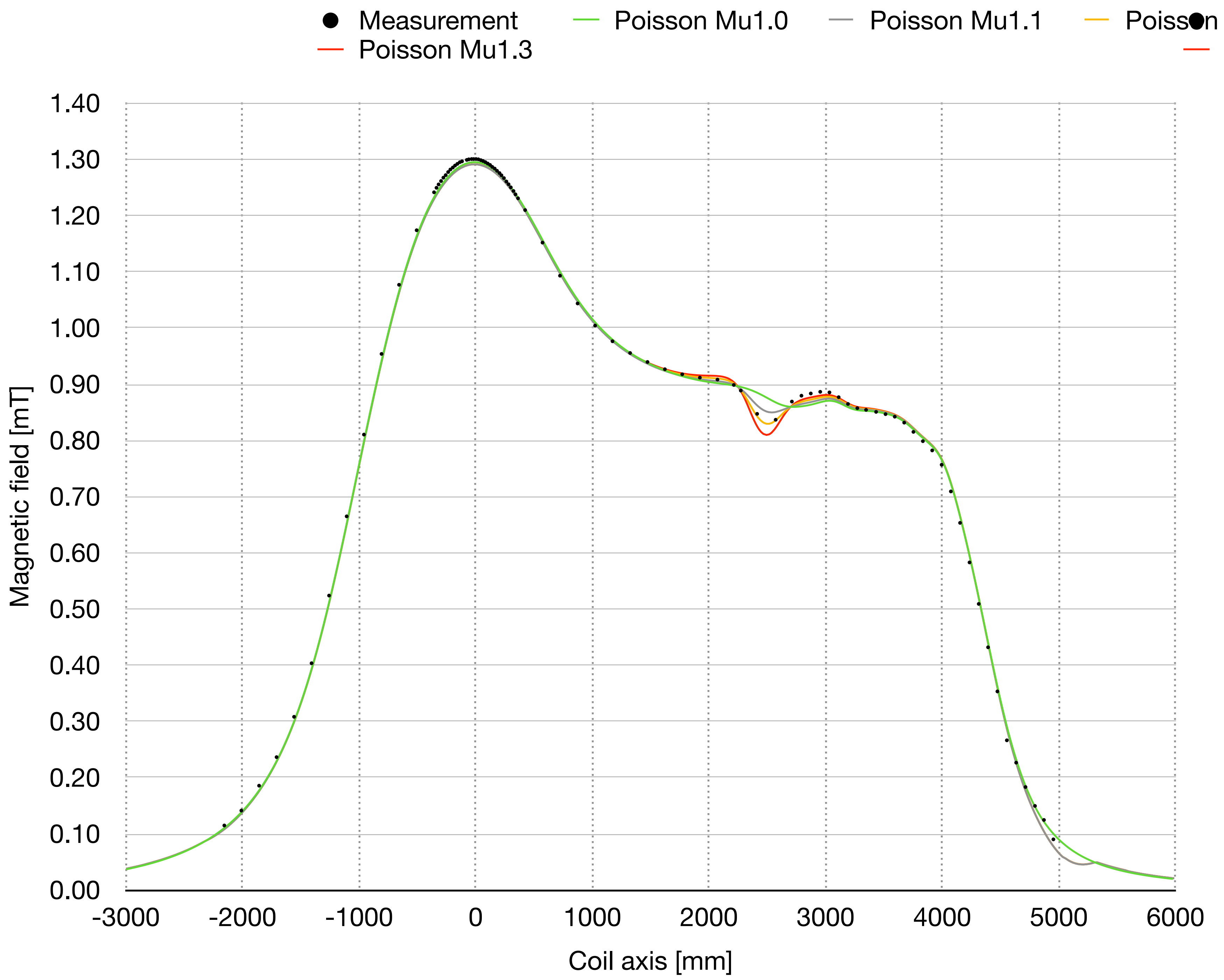
  ⇒ The coils are healthy.

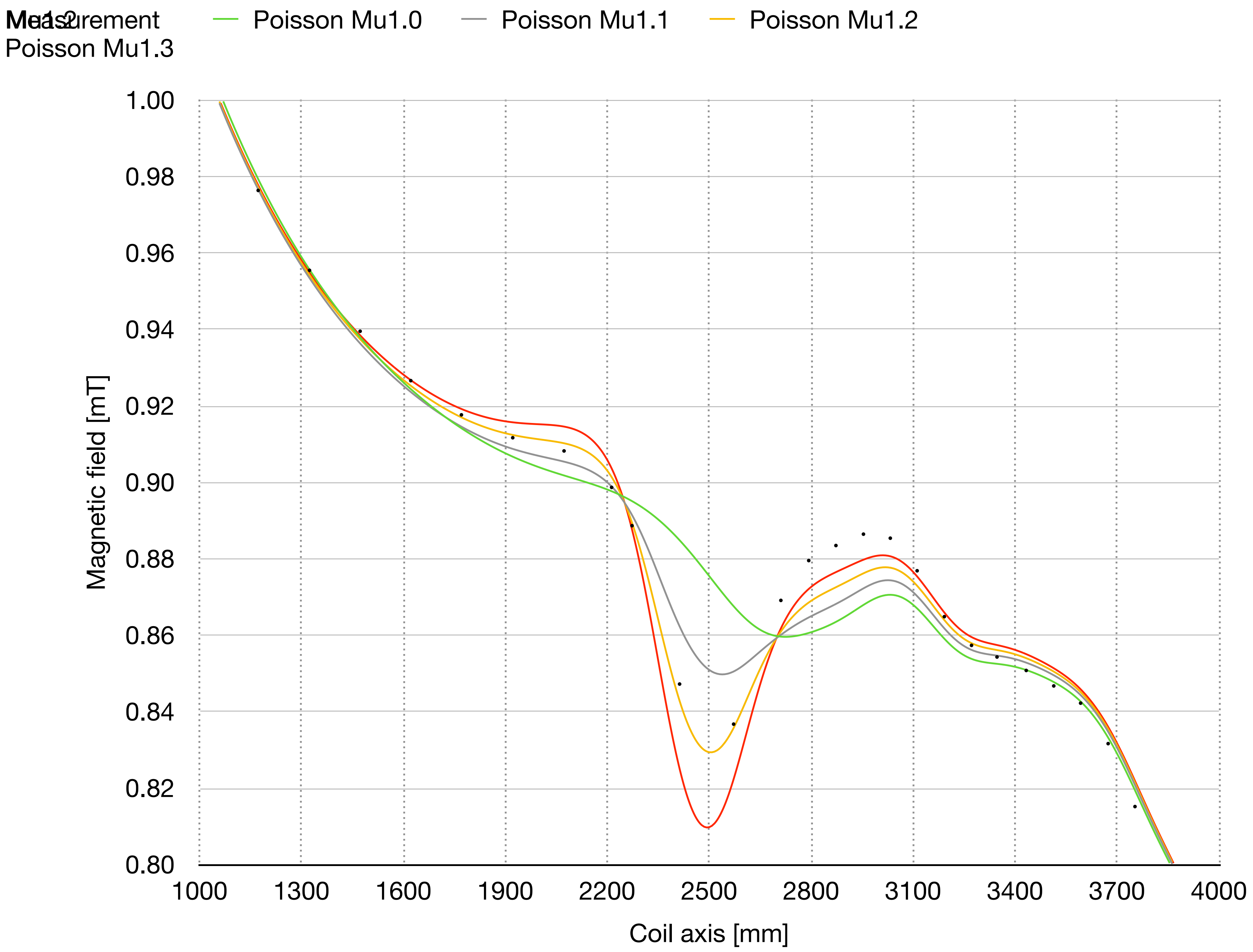
[Ω]	CS0	CS1	MS1	MS2	TS1a	TS1b	TS1c	TS1d	TS1e	TS1f	TOTAL
Calculation	0.58298	4.58389	2.55119	1.76758	0.025648	0.098008	0.111766	0.178786	0.081499	0.476524	10.457871
Measurement	0.58442	4.57139	2.56958	1.76714	0.025746	0.097191	0.110148	0.176819	0.081051	0.476562	10.460047
Difference	0.00144	-0.0125	0.01839	-0.00044	0.000098	-0.000817	-0.001618	-0.001967	-0.000448	0.000038	0.002176
Ratio	1.0025	0.9973	1.0072	0.9998	1.0038	0.9917	0.9855	0.9890	0.9945	1.0001	1.0002

Stainless steel shield magnetization

- We suspect magnetization of the stainless steel sh
  - Red filled area
    magnetic permeability
    μ = 1.0 ~ 1.3

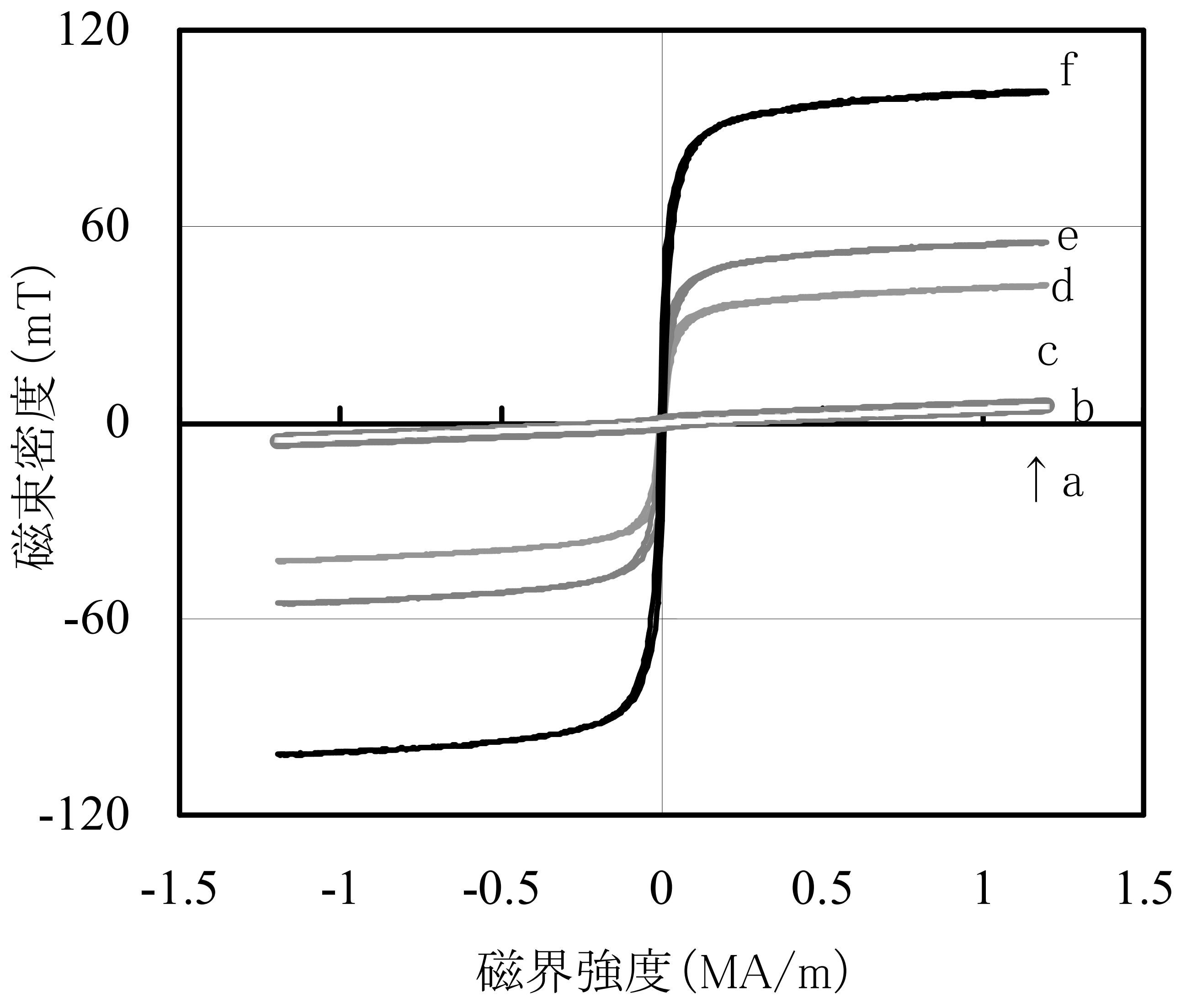






Stainless steel permeability

- The magnetization of the processed SUS304 begins to saturate at 0.1 MA/m and completely saturates at 0.8 MA/m (1 T).
  - The stainless steel shield will be 3 T at operation. ⇒ The magnetization can be ignored.



a：加工率 0%　b：加工率 12%　c：加工率 22%
d：加工率 32%　e：加工率 34%　f：加工率 37%

図2　加工率による磁化特性曲線の変化

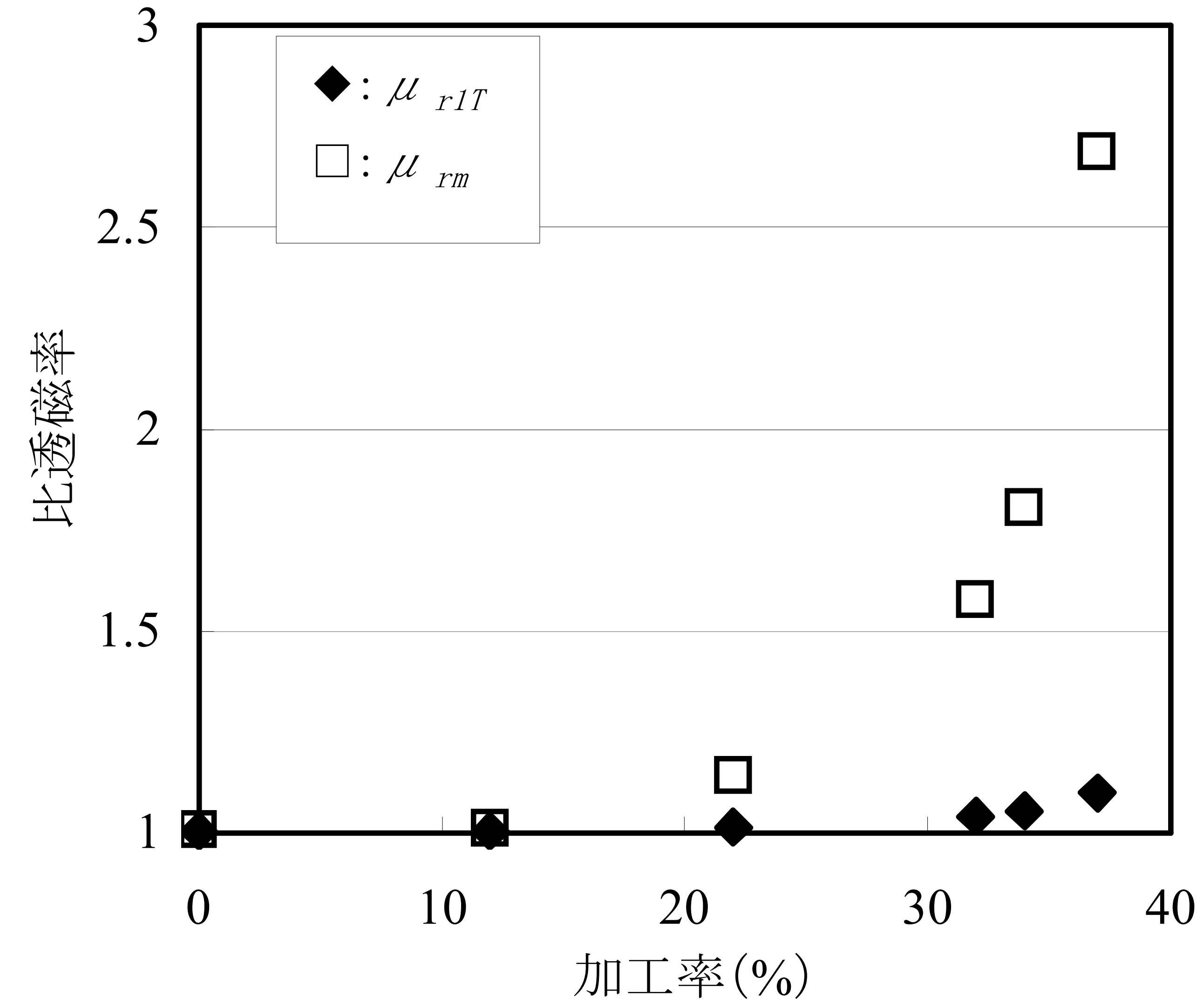
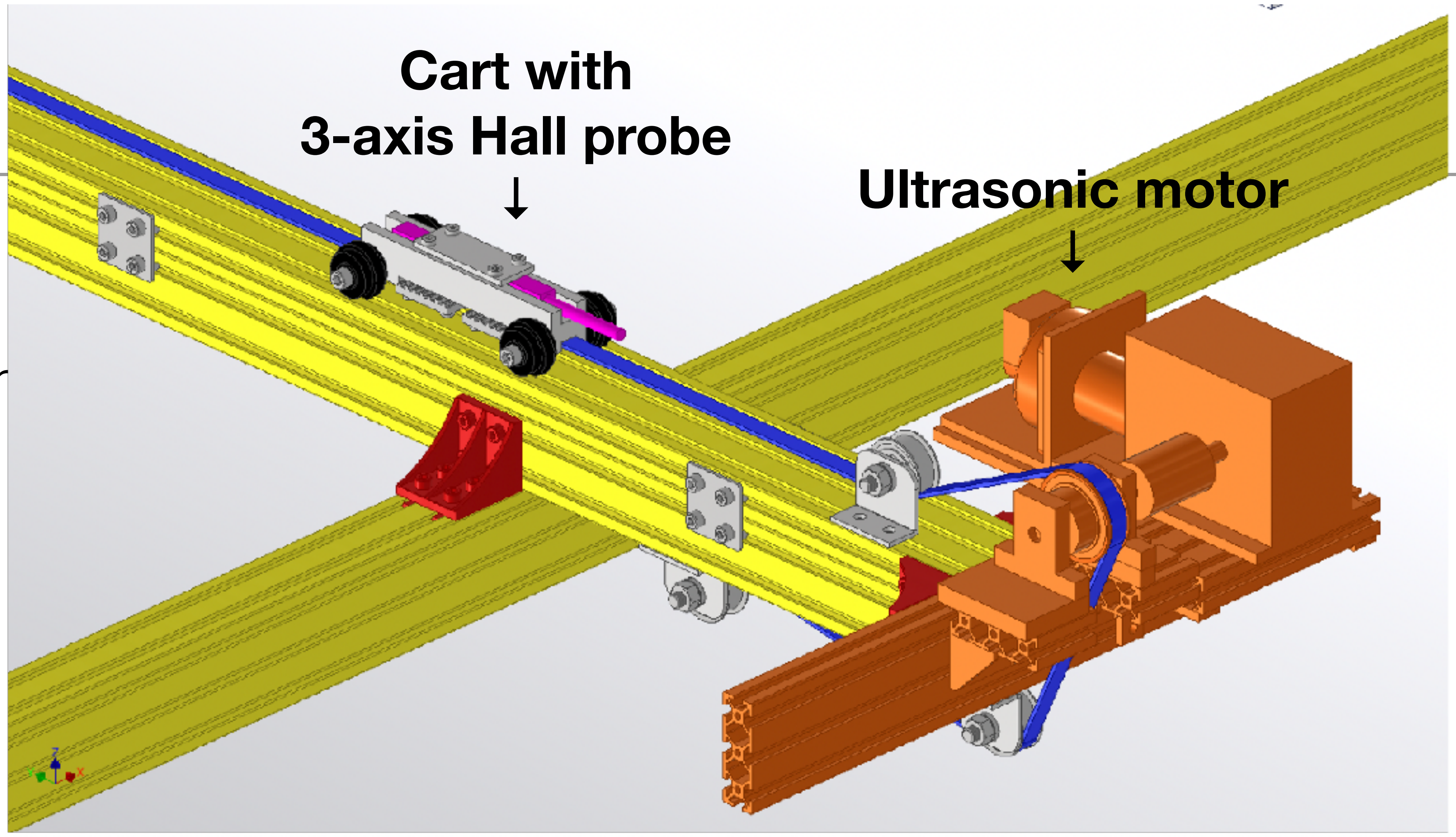


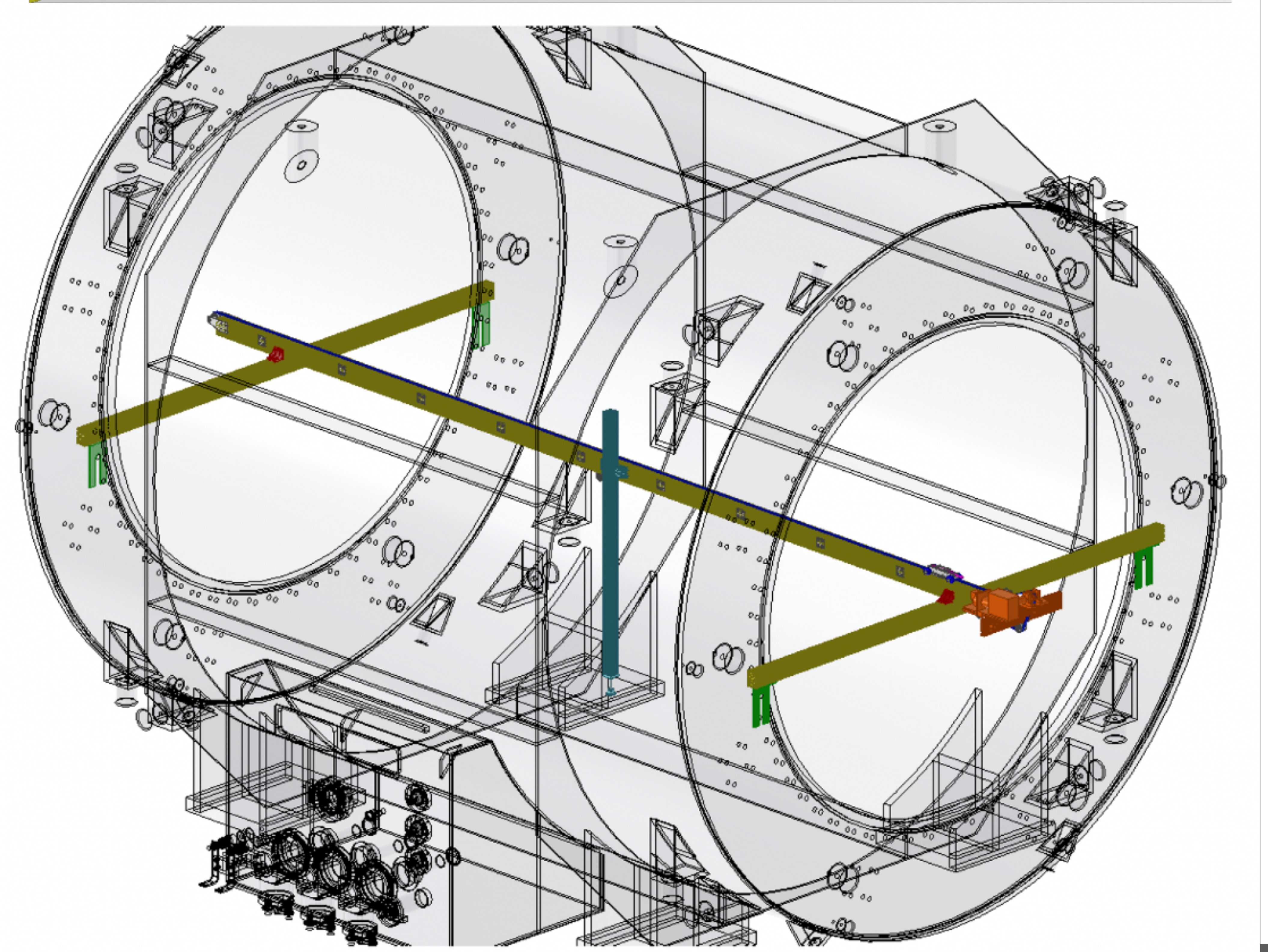
図3　加工率と比透磁率との関係

Detector Solenoid

DS field measurement

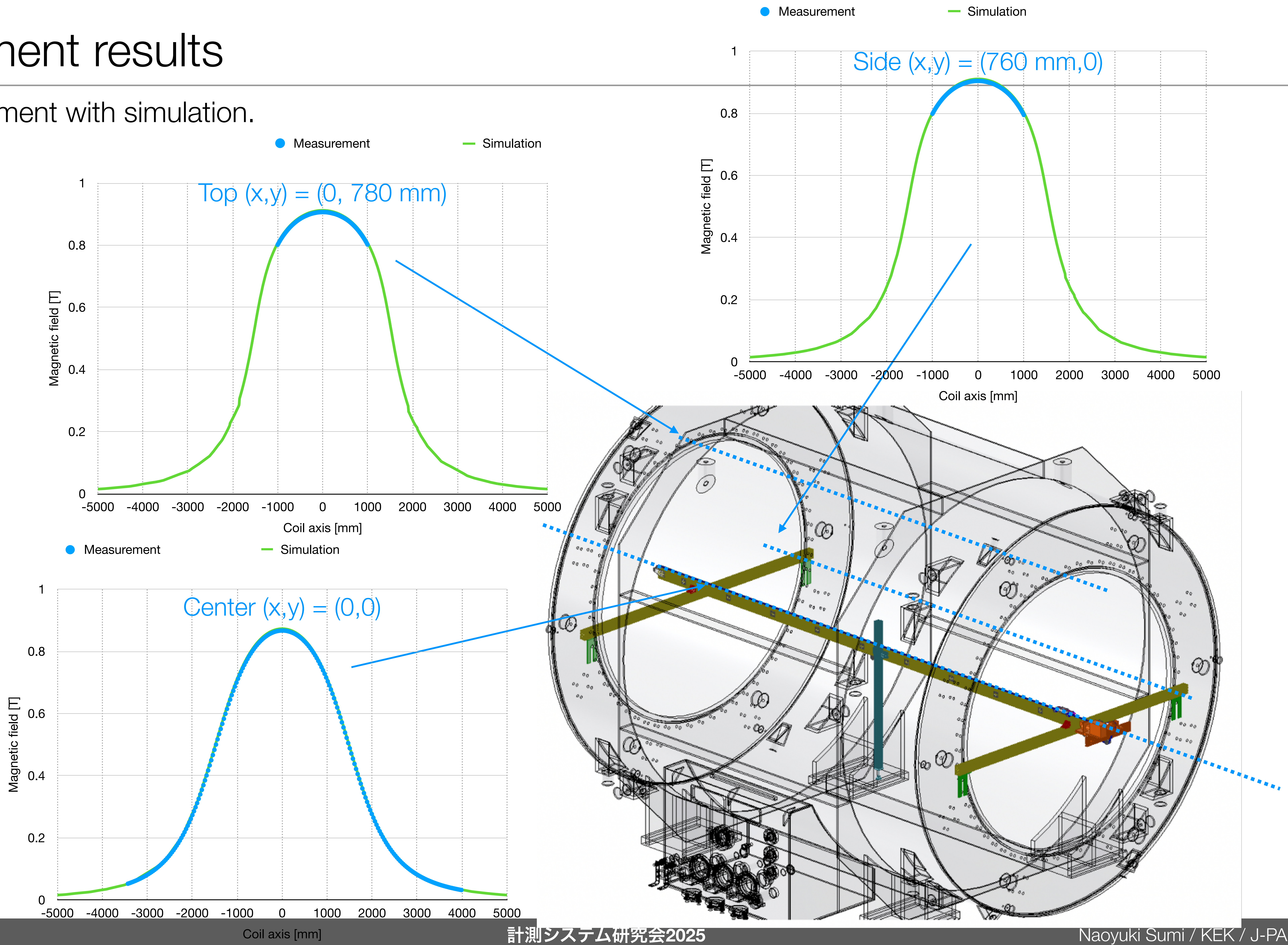
- The field was measured at the factory in June 2024.
  - Measurements were made by moving a 3-axis Hall eler
  - Probe position was measured by a rotary encoder.
  - Cryo temperature
  - Without iron yoke
  - Applied current was operation current of 189 A.





Measurement results

- Good agreement with simulation.



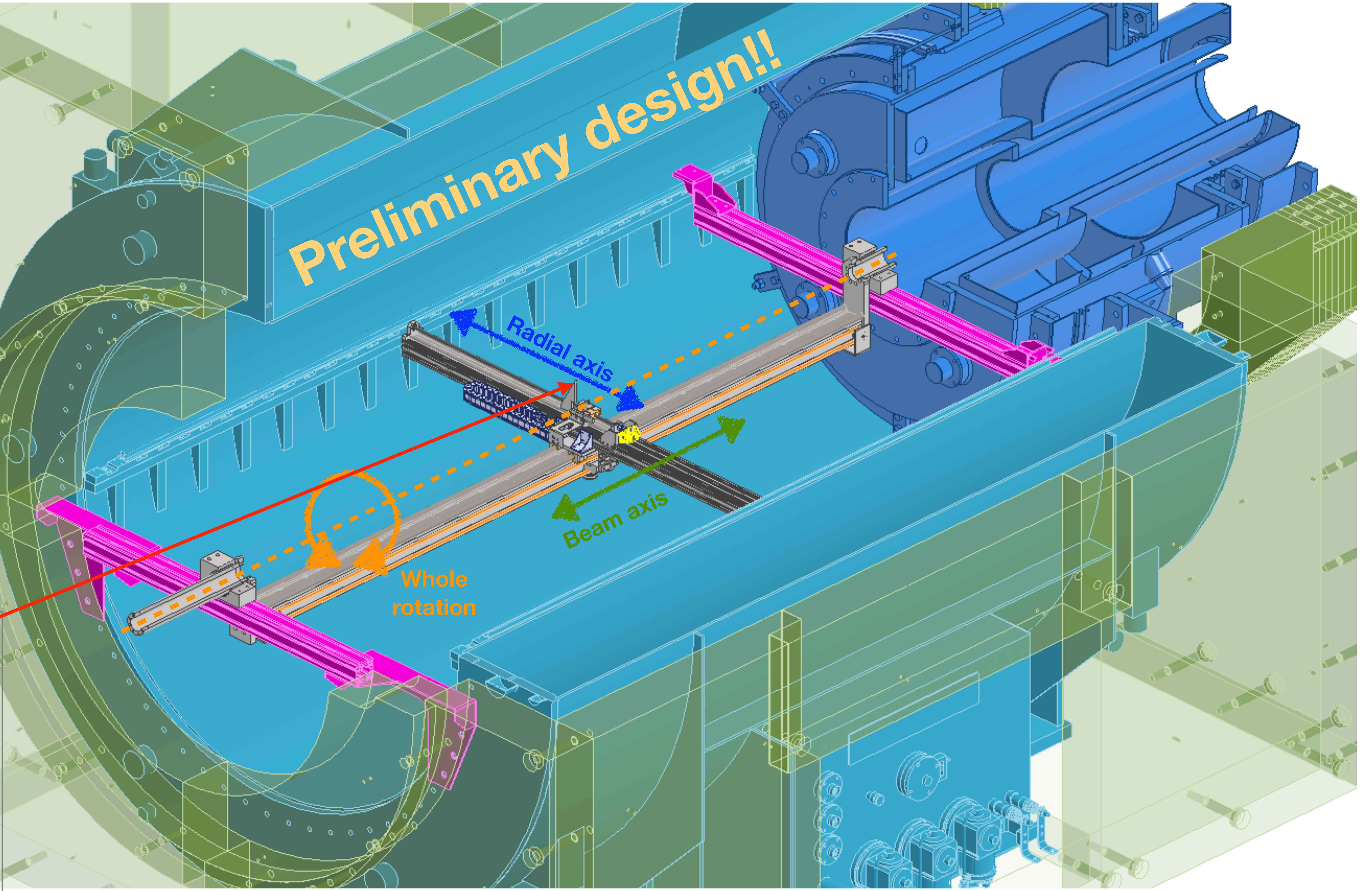
DS field measurement

- Design and preparation of DS field measurement is ongoing.

- The calibrated 3-axis hall probe is mounted on a cart with retroreflectors.
- Position and angle of the probe will be measured with a laser tracker.
- Move probe along three axes
  - **Beam axis**
  - **Radial axis**
  - **Whole rotation**

- Target accuracy 0.1%
- Measurement area
  - L 1700 mm
  - R 800 mm
- Measurement pitch TBD

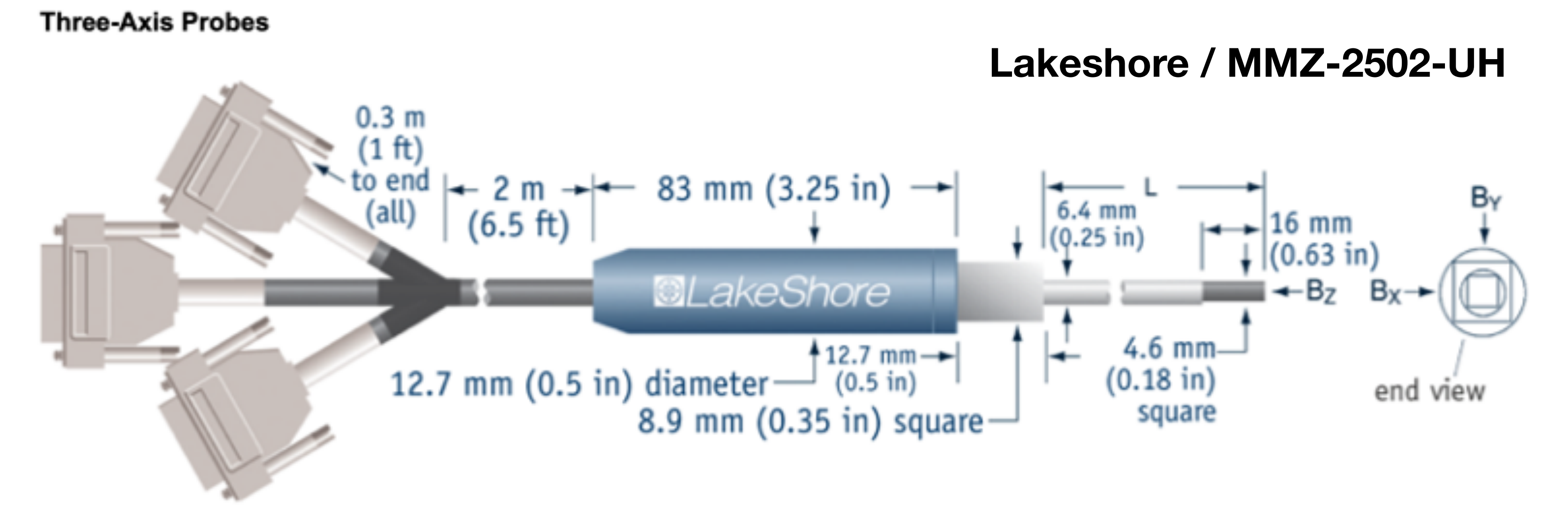
- Note : MTS is also excited.




Laser Tracker ATS600


SHINSEI co. / USR 60-E3NT


Retroreflector



Lakeshore / MMZ-2502-UH

COMET magnets summary

- Field measurement status are summarized in following table.

	When?	Measured current (Operation current)	Condition	Consistent with calculation?	Any plan for further measurement?
Pion Capture Solenoid	July 2024	0.75A (2700 A)	Room temp. Without iron yoke	Mainly Yes Partially No (Stainless magnetization)	Yes With iron yoke at COMET hall
Muon Transport Solenoid	July 2022	Solenoid 105 A (210 A) Dipole ±10 A (±175 A)	Cryo temp. With iron yoke	Yes ΔB/B < ±0.4%/±3%	No
Bridge Solenoid	May 2025	135 A	Cryo temp. Without iron yoke	Yes ΔB/B < ±1%	Yes At COMET hall with DS
Detector Solenoid	June 2024	95 & 189 A (189 A)	Cryo temp. Without iron yoke	Yes ΔB/B < ±1%	Yes With iron yoke at COMET hall

Future field measurements

- The system used for DS measurements will be used with minor modification.
  - The modification is changing the support structure from double-sided to single-sided with poles.
  - Before detectors and shield installation.

- Measurement Areas
  - **Green**
    PCS target volume
    toward the beam window
    between MTS
  - **Blue**
    PCS proton beam duct
    Preparing other guide rail
  - **Red**
    DS and BS volume
    toward the beam window
    at BS upstream