Design and Performance Evaluation of the Silicon Strip Detector Cooling System for J-PARC Muon g-2/EDM Experiment

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J-PARC muon g – 2/EDM Experiment

Anomalous magnetic moment (g−2)

- Experimental value: 0.12ppm (FNAL)
- Discrepancy with the Standard Model
  — Unresolved... dependent on HVP

~0.1ppm independent measurement

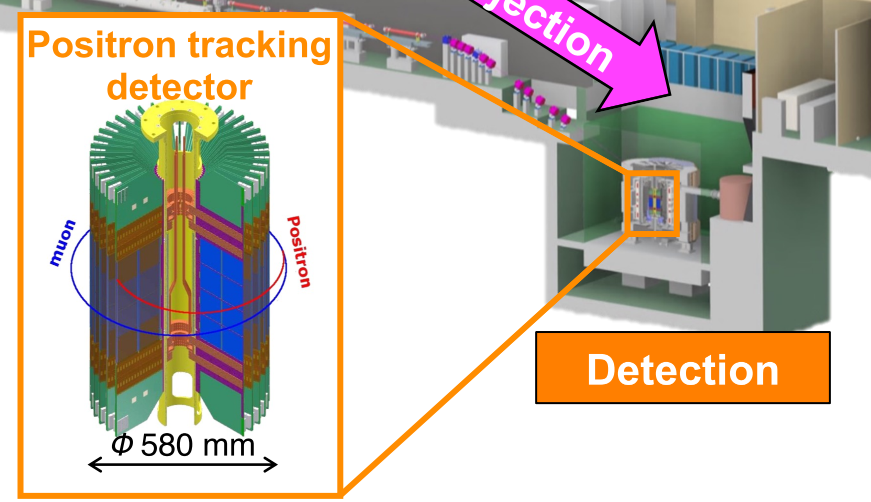
Electric dipole moment (EDM)

- Time-reversal violation → CP violation
- Experimental upper limit: ~10^{-19} e·cm
  ≫ Theoretical prediction: ~10^{-38} e·cm

Target sensitivity: 10^{-21} e·cm

Verification of muon g−2 and enhancing muon EDM sensitivity

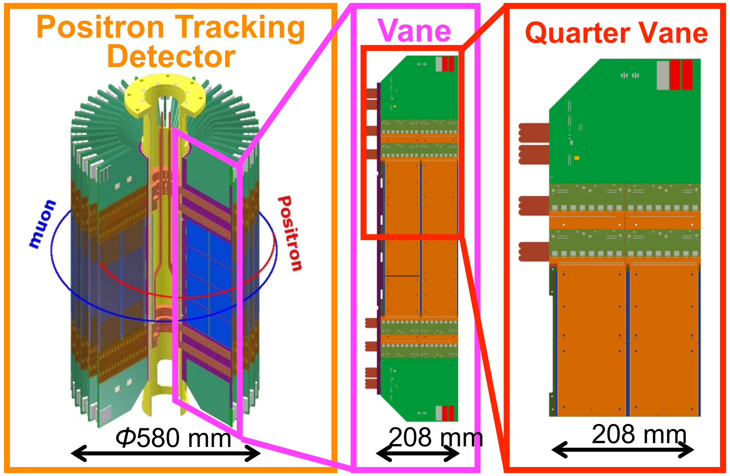
▼ Overview



Features

- Low-emittance muon beam
- Electric-field-free beam focusing
- Compact 3 T uniform magnetic field
- Positron tracking for decay detection

Positron tracking detector



Detector Design & Requirements

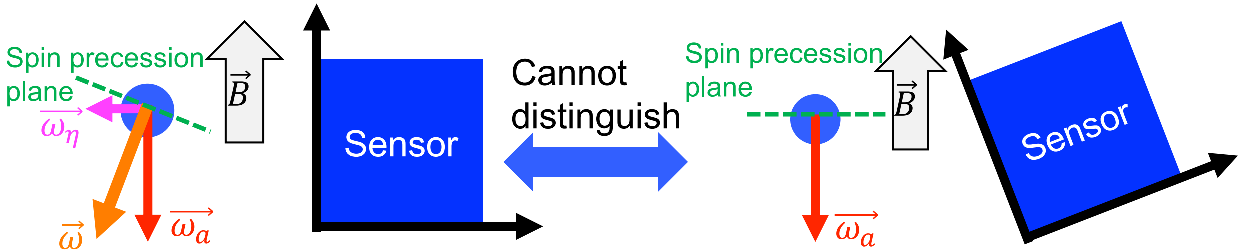
- e^+ trajectory reconstruction via (t, x)
- 40 “Vane” radial configuration
- Operating in **3 T field & vacuum (0.1 atm)**

EDM Systematic Uncertainties & Alignment

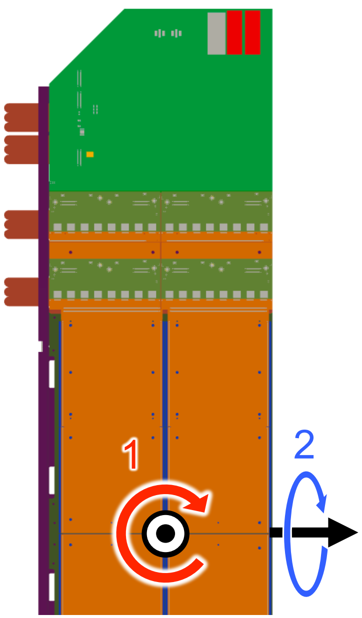
- Manage Misalignment (Major Error)

A system with a finite EDM as seen from a normal sensor

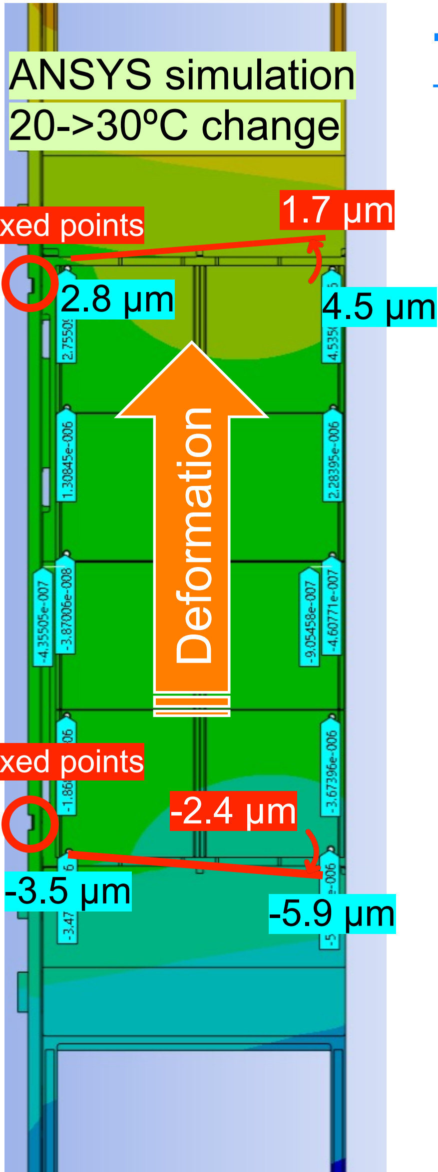
A system with EDM = 0 as seen from a tilted sensor



- Systematics control & mitigation
  - Assembly with CMM metrology
  - Thermal stabilization to minimize deformation effects
  - Laser alignment monitor & Track-based alignment
- Required tolerances for 10^{-21} e·cm
  1. **Vane plane rotation: ~10 μrad**
  2. **Vane thickness rotation: ~200 μrad**



Thermal Stability & Alignment Requirements



Tolerance vs. Deformation

- **Alignment Requirement: 2 µm** (20 cm × **10 µrad**)
- Thermal Deformation: **2.4 µm**

(Expected total rotational displacement for a **ΔT=10 ºC** global change)

① Steady-state Deformation (measurable)

- Monitored via the Alignment System
- Rotational components analyzed through simulations

Requirement: Vane plane rotation ~10 µrad

② Short-timescale Deformation (Unmeasurable)

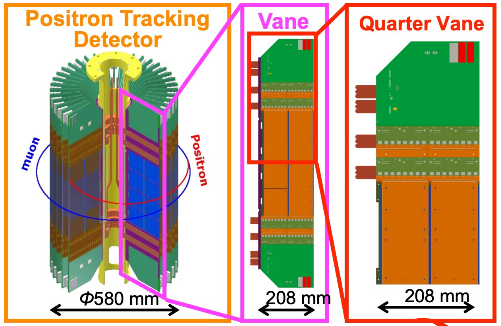
- Caused by temperature fluctuations; a primary source of misalignment
- Mitigation: Requires strict thermal stabilization

2 µm Alignment Requirement → ΔT < 8.3 ºC

Cooling System Design

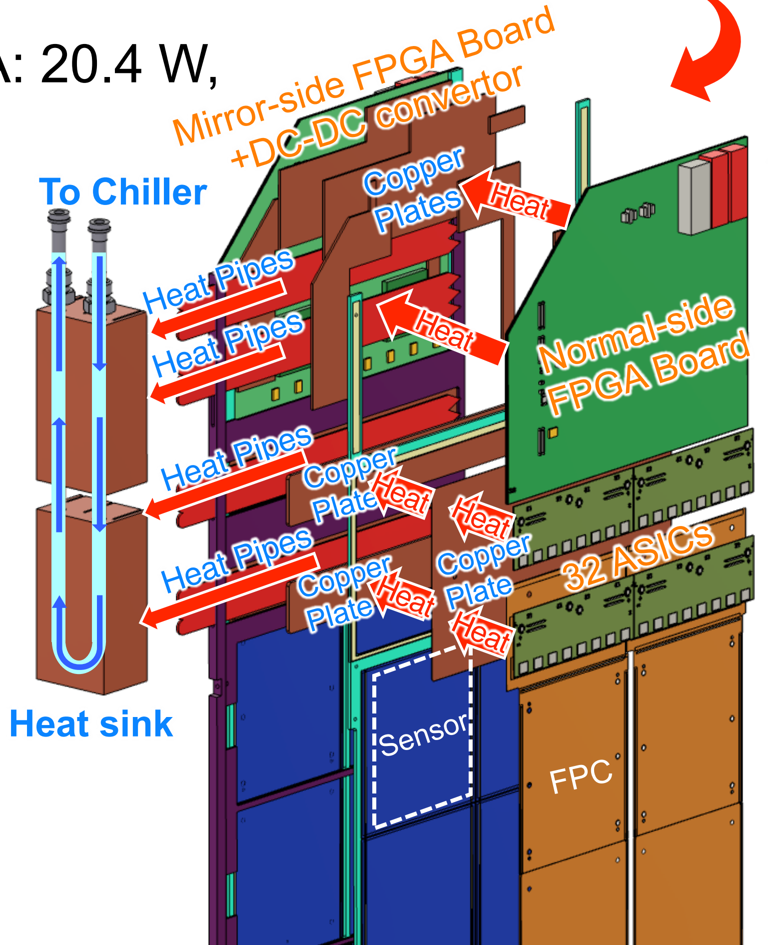
Requirements

- Compact: **Thickness < 3 mm** per “Quarter-Vane”
- Environment: Vacuum (0.1 atm) & 3 T Magnetic Field
- Material: Non-magnetic Copper Construction
- Total heat load: **8.5 kW (160 Q-Vane)**
  - **Q-Vane: 53.6 W** (ASIC: 28.2 W, FPGA: 20.4 W, DC-DC converter: 5 W)
- Temperature Stability: IC thermal safety & sensor deformation control



Structure

- Heat Pipes: High-conduction (~100x Cu) from FPGA/ASIC to heat sink
- Copper Plates: Ensure heat paths to heat pipes
- Heat Sink: Constant 10 ºC (water-cooled by external chiller)

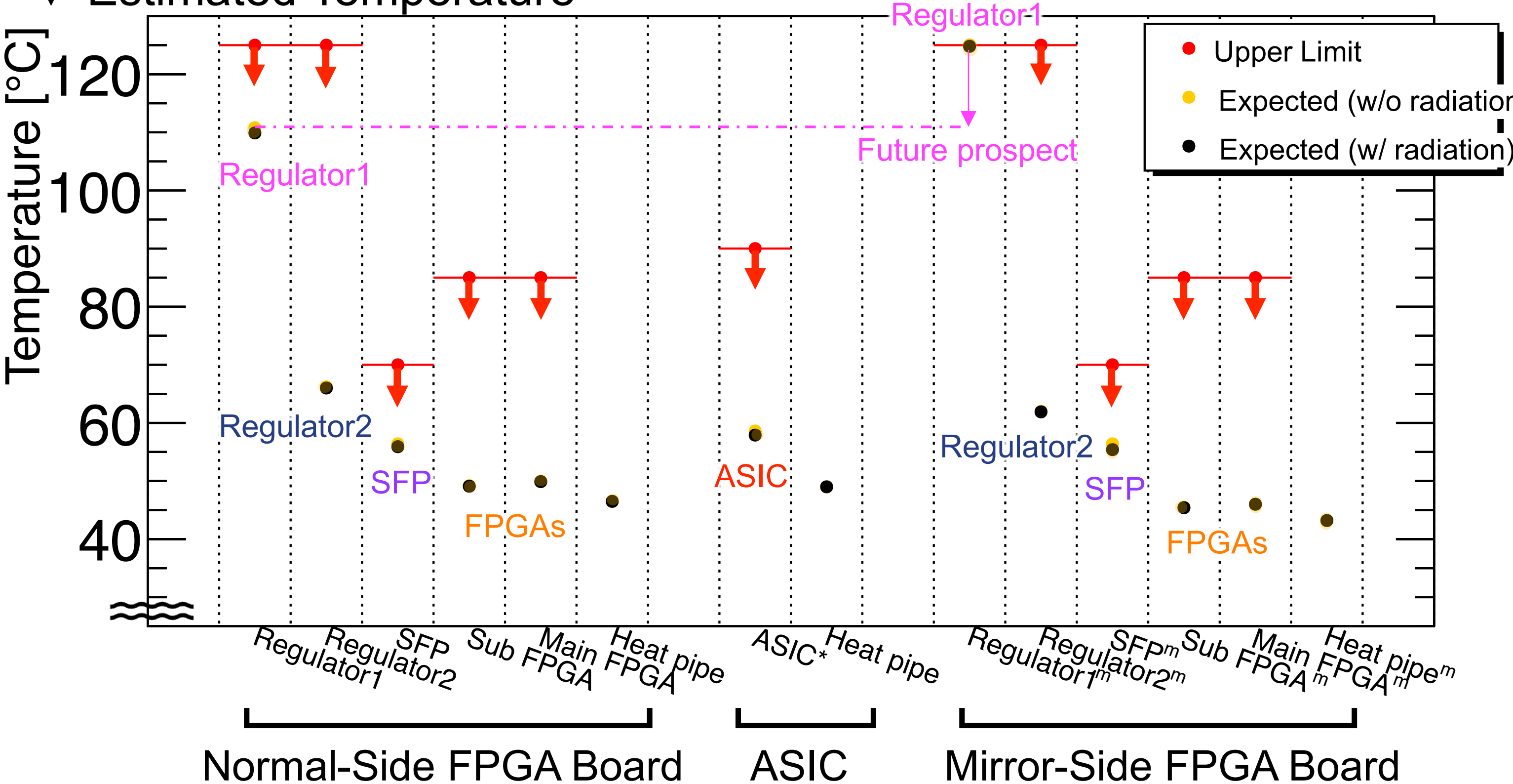


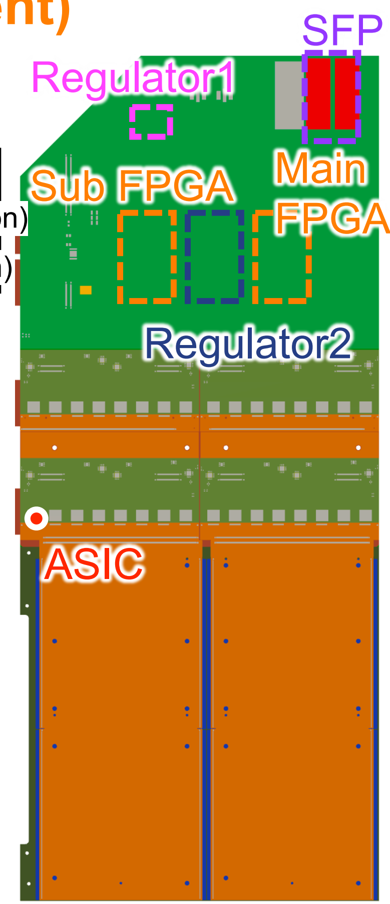
Simulation Results in Real Operation

Estimated Temperature by Simulation (ANSYS) in 40-Vane Real Configuration

- **IC Safety: All ICs cooled below operational limits**
- **Thermal Deformation: 6.2 μrad (<10 μrad: Requirement)**

▼ Estimated Temperature





Critical Point: Tightest margin at Mirror-Side Regulator1

➢ Layout optimization matches Mirror-Side cooling performance to Normal-Side

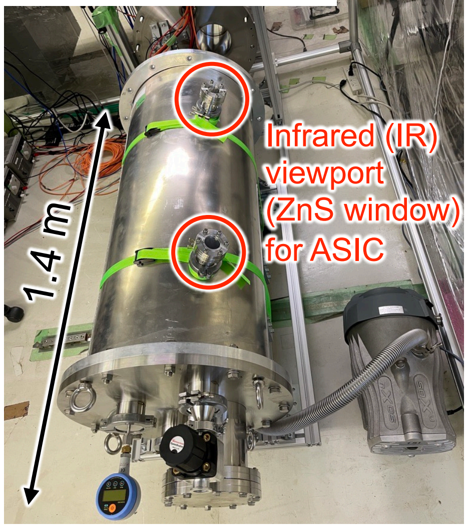
Cooling Test in Vacuum

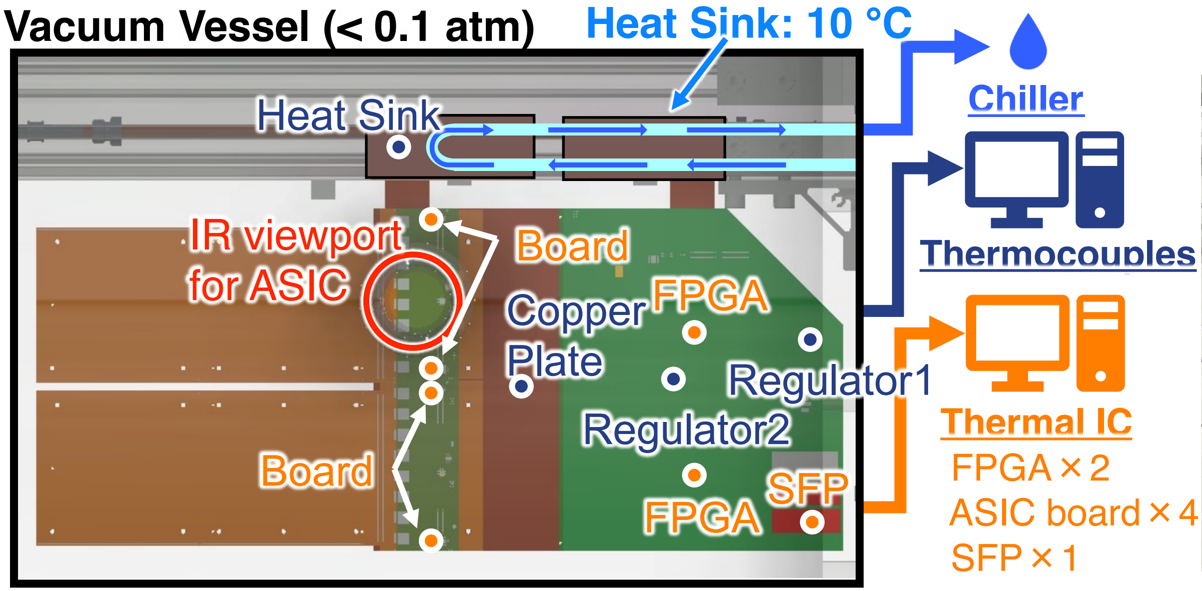
Validated cooling system functionality in a vacuum environment equivalent to real operation

Experimental Setup

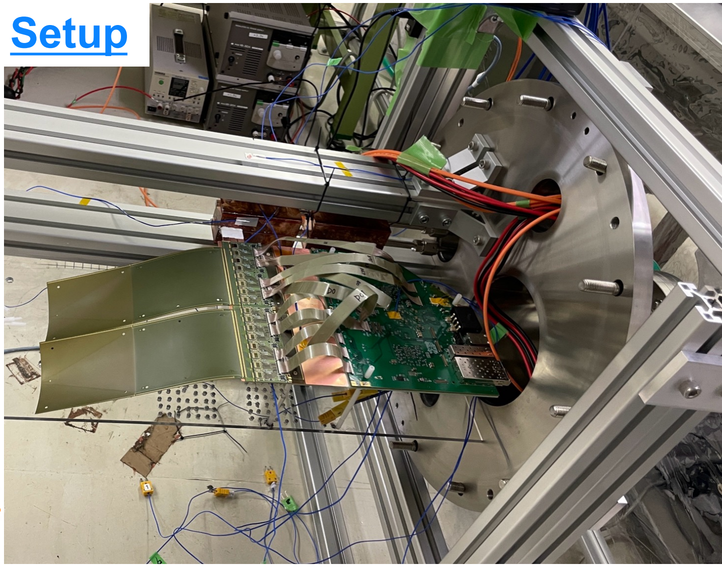
- Components: FPGA board + 16 ASICs
  (No DC-DC converters or sensors)
- Heat Load: Identical to real-operation power levels
- Vacuum Level: 4.3×10^{-2} atm
- Coolant: Water-cooled at 10 ºC via external chiller
- Radiation effects are evaluated via simulation

Vacuum Vessel





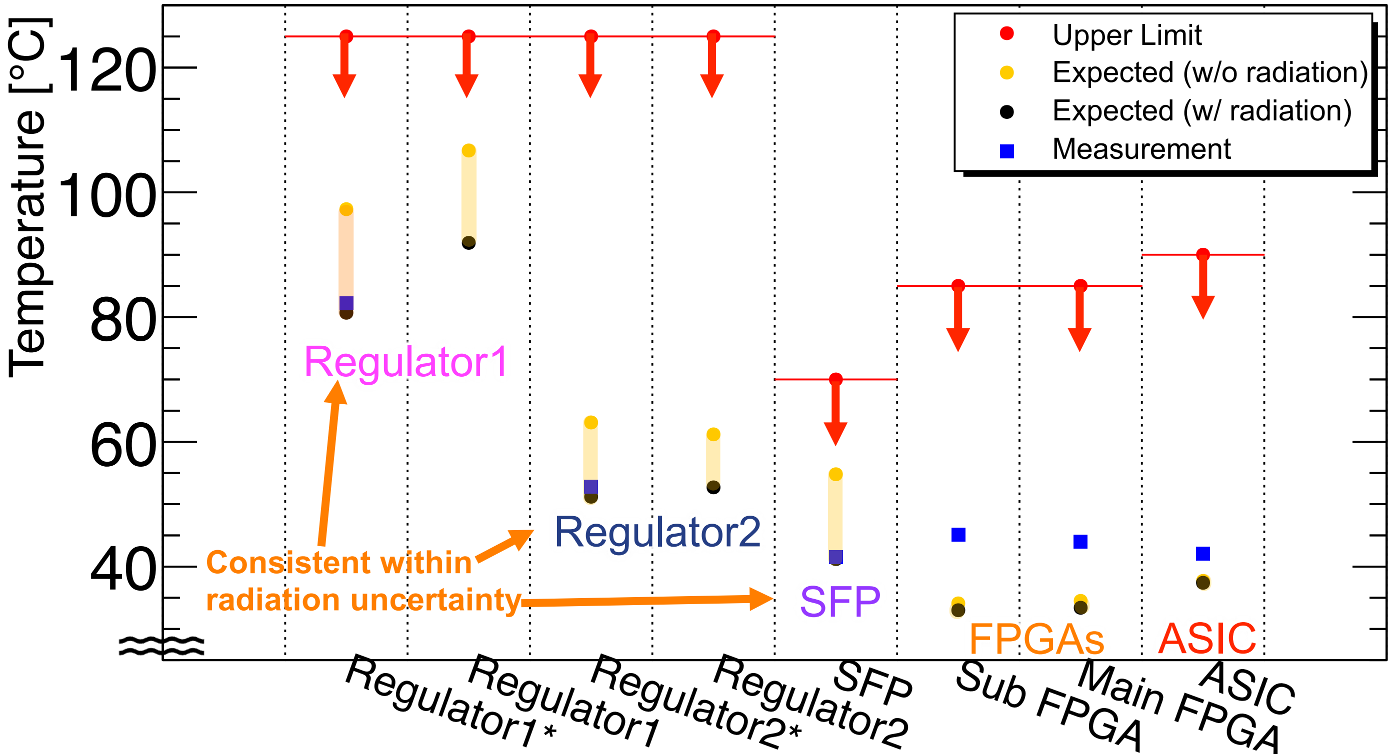
Setup

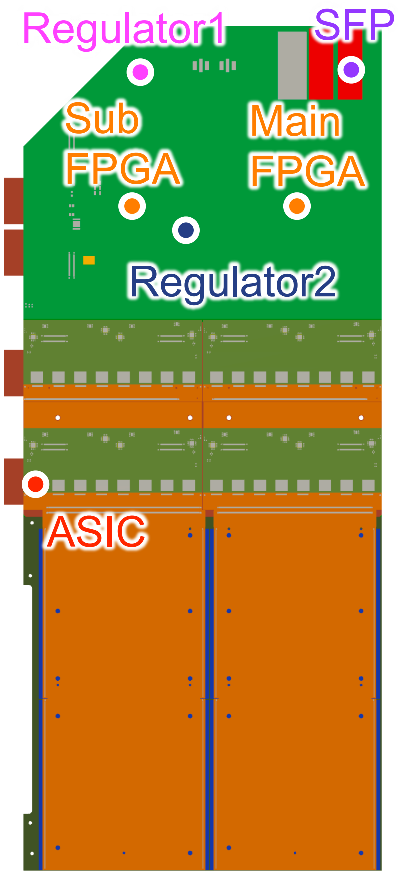


Validation: Simulation vs. Cooling Test

- All components confirmed below operational temperature limits
- **Stability ΔT = 0.3 ºC** (0.1 ºC chiller control) ≪ **Requirement: 8.3 ºC**
- Data-Simulation discrepancies are acceptable due to sufficient margins
  - ➢ Major uncertainty source identified as thermal contact resistance (currently using tape)

▼ Measured vs. Predicted Temperatures in Test Setup





*Estimated Core Temperature: Since the regulator core cannot be measured directly, values are calculated based on measured PCB surface temperatures

Summary and Future Prospect

Cooling System Validation

- Successful cooling test for the J-PARC muon g−2/EDM experiment
- **Thermal safety verified: All ICs maintained well below operational limits**
  - Data-Simulation discrepancies are acceptable due to sufficient margins (Major uncertainty source identified as thermal contact)

Thermal Stability

- **Thermal stability: ±0.3 ºC achieved**
  - Significantly exceeds the **8.3 ºC requirement** for deformation control

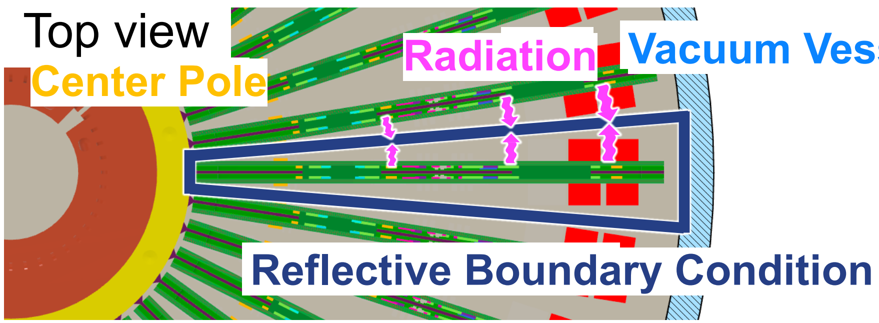
Future Prospect

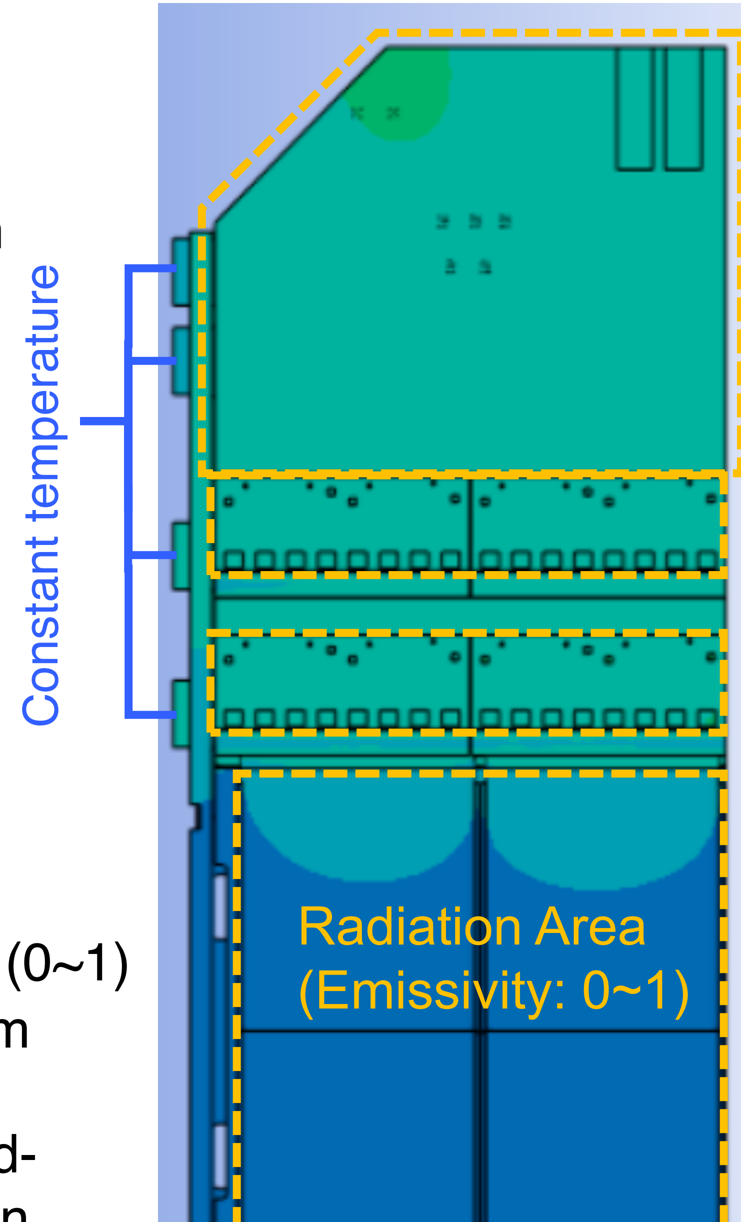
- Design Optimization: **Enhancing Thermal Symmetry**
  - To align Mirror-Side cooling performance with Normal-side, optimize component layout (FPGA/DC-DC)
- Reliability & Error Analysis
  - **Next Step**: Comprehensive cooling test with full-scale integration (FPGA + 32 ASICs + DC-DC) & Long-term stability (1–2 days)
  - Analyze systematic errors in EDM measurements caused by thermal deformation to further improve accuracy

Simulation Setup (ANSYS)

Boundary Conditions

- **Heat Load**: Calculated from measured power consumption
- **Heat Pipe**: Constant temperature based on independent measurements
- **Radiation**: Applied to large-area boards
- **Environment**: 40-Vane radial configuration modeled with face-to-face radiation

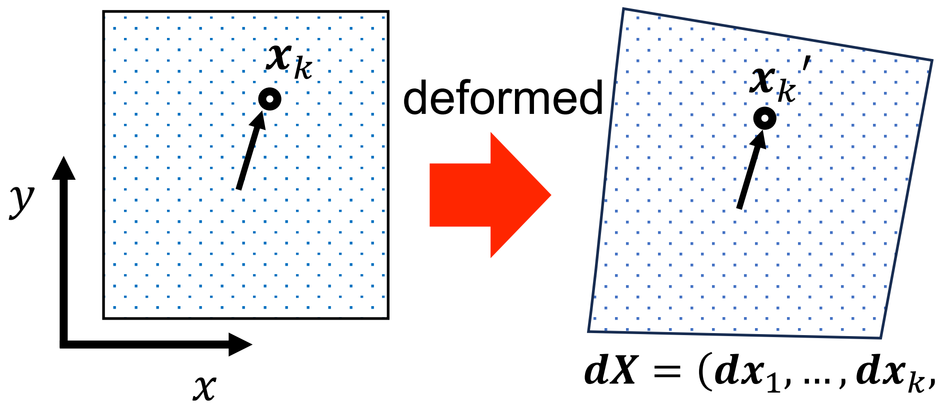




Uncertainties

- Emissivity: Accounted for over the full range (0~1)
- Sensor Position: ±1 °C uncertainty per 5 mm displacement
- Convection (0.1 atm): Not modeled, but hand-calculated to be less significant than radiation

Deformation analysis



Position of N points: $\boldsymbol{X} = (\boldsymbol{x}_1, \ \dots\ , \ \boldsymbol{x}_k \ \dots, \boldsymbol{x}_N)$

$$\boldsymbol{x}_k' = \boldsymbol{x}_k + \boldsymbol{dx}_k$$
$$\boldsymbol{X}' = \boldsymbol{X} + \boldsymbol{dX}$$

Extract the rotational component that affects the EDM

$$\boldsymbol{dX} = (\boldsymbol{dx}_1, \dots, \boldsymbol{dx}_k, \dots, \boldsymbol{dx}_N)$$

$$\boldsymbol{dX} = \sum a_i \boldsymbol{e}_i = a_{\mathrm{rot}} \boldsymbol{e}_{\mathrm{rot}} + \cdots, \qquad a_{\mathrm{rot}} = \boldsymbol{dX} \cdot \boldsymbol{e}_{\mathrm{rot}}$$

... consists of orthonormal components (next leading order)

- Rotation of all vanes ($x \to x\cos\theta - y\sin\theta\,, y \to y\cos\theta + x\sin\theta$)

$$\theta \ll 1 \to \theta \boldsymbol{dx}_{\mathrm{rot}_k} = \theta \begin{pmatrix} -y_k \\ x_k \end{pmatrix}, \quad \sqrt{\sum (x_k^2 + y_k^2)} = |\boldsymbol{dX}_{\mathrm{rot}}|$$

$$\boldsymbol{e}_{\mathrm{rot}} = \frac{(\boldsymbol{dx}_{\mathrm{rot}_1}, \dots, \boldsymbol{dx}_{\mathrm{rot}_k}, \dots, \boldsymbol{dx}_{\mathrm{rot}_N})}{|\boldsymbol{dX}_{\mathrm{rot}}|} = \frac{\boldsymbol{dX}_{\mathrm{rot}}}{|\boldsymbol{dX}_{\mathrm{rot}}|}$$

$$a_{\mathrm{rot}} = \boldsymbol{dX} \cdot \boldsymbol{e}_{\mathrm{rot}} = \frac{\sum(-dx_k y_k + dy_k x_k)}{|\boldsymbol{dX}_{\mathrm{rot}}|},$$

$$\theta_{\mathrm{rot}} \boldsymbol{dX}_{\mathrm{rot}} = a_{\mathrm{rot}} \boldsymbol{e}_{\mathrm{rot}} = a_{\mathrm{rot}} \frac{\boldsymbol{dX}_{\mathrm{rot}}}{|\boldsymbol{dX}_{\mathrm{rot}}|}, \qquad \theta_{\mathrm{rot}} = \frac{a_{\mathrm{rot}}}{|\boldsymbol{dX}_{\mathrm{rot}}|}$$

Physically meaningful value

Deformation analysis

- Requirement of alignment (fake EDM < 10^{-21} ecm)
  - Vane plane rotation θ_{rot} (XY): 10 μrad ⇔ 2 μm
  - Vane thickness rotation (Z): 200 μrad ⇔ 40 μm

	Requirements	Uniform temp. +10 ºC	Uniform temp. +30 ºC	**Real (w/ radiation) ~+15 ºC**	Real (w/o radiation) +30 ºC
X	**2 μm**	~6 μm	~20 μm	**~10 μm**	~17 μm
Y	**2 μm**	~12 μm	~40 μm	**~27 μm**	~37 μm
Z	**40 μm**	~3 μm	~10 μm	**~13 μm**	~20 μm
θ_{rot}	**10 μrad**	2.4 μrad	8.5 μrad	**6.2 μrad**	14.7 μrad

- Preliminary systematic error estimated from simulation

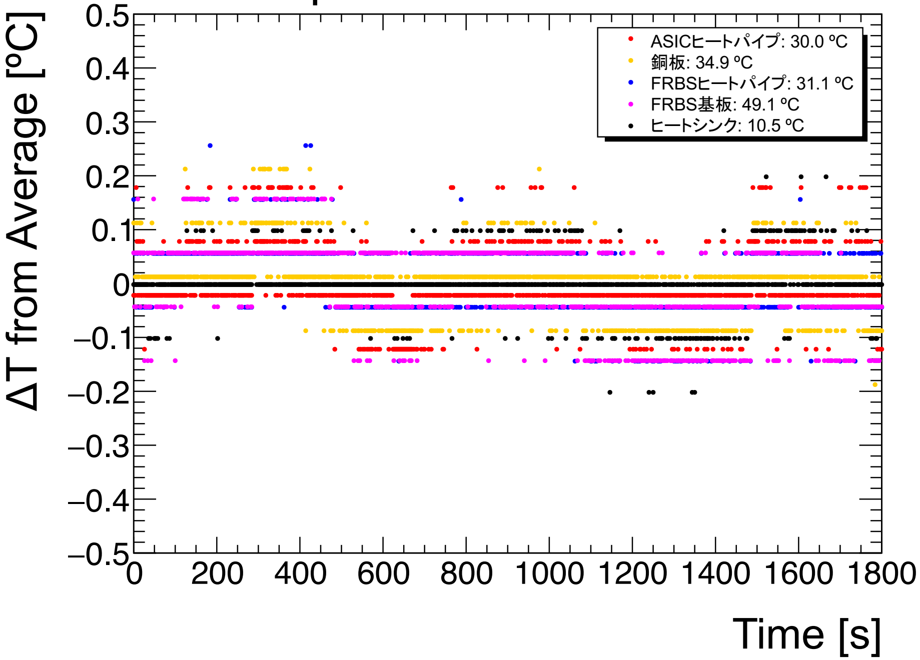
Error source	10^{-21} $[e \cdot \mathrm{cm}]$
Misalignment	**0.6 (6.2 μrad)**
Axial E-field	10^{-3} (E_z=1 mV/cm)
Radial B-field	10^{-5} (E_z=1 mV/cm)
Statistics	1.4 ($5.7\times10^{11} e^+$)
Total	1.5

➢ The systematics of the real operation should be updated based on measurements (temperature, alignment system)

Measurement of Thermal Stability

Confirmed temperature stability for all components for 30 minutes after reaching thermal equilibrium

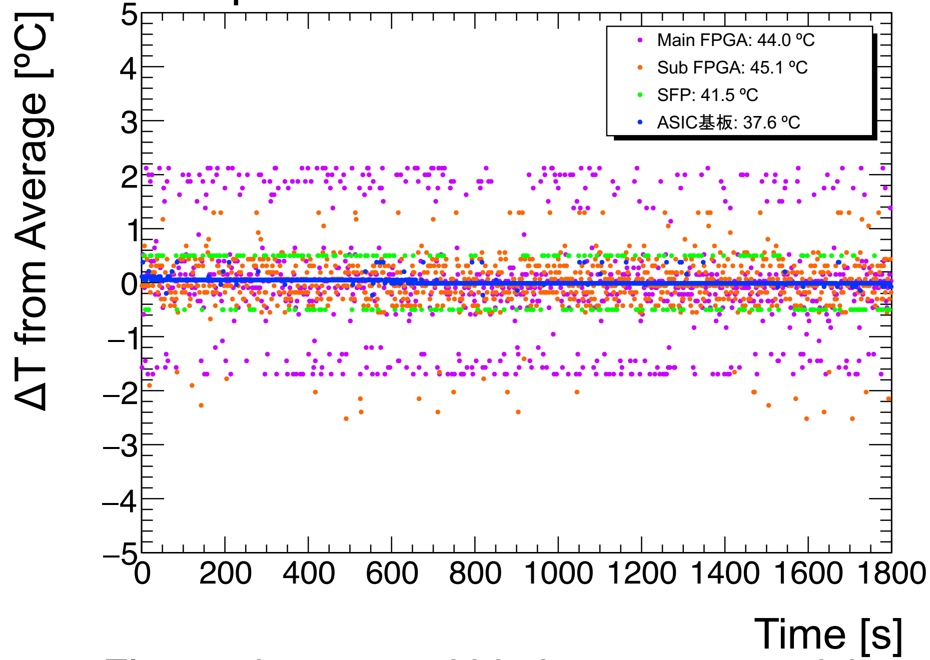
▼ Thermocouples



Stability within 0.3 °C

(Heat sink shows periodic 0.1 °C chiller control cycle)

▼ Temperature IC



Fluctuations are within its sensor precision (FPGA: 4 °C, SFP: 3 °C, ASIC: 1 °C)

- Stability under Constant Load: ≤ 0.3 °C maintained
  - Verified that heat load is independent of hit rate
- Expected to satisfy the 8.3 °C system stability requirement
  - Non-heating sensors will follow the high stability confirmed in other components

Analysis plan for convection

- **It is necessary to examine whether convection affects the temperature distribution:** A key dimensionless number for determining whether temperature differences can induce convection in a fluid is the **Rayleigh number**.

Rayleigh number: $Ra = \frac{g\beta\Delta T L^3}{\nu a}$

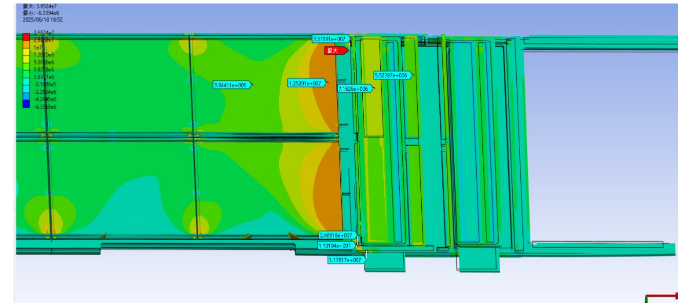
g: gravitational acceleration, β: thermal expansion coefficient
ΔT: temperature difference (assume 40 ºC), L: characteristic length (assume 1 m)
ν: kinematic viscosity$\propto 1/P$, a: thermal diffusivity $\propto 1/P$

1. Conduction-dominated: $Ra < 1708$
2. Laminar convection: $Ra \geq 10^4$, heat transfer coefficient: $h = \frac{0.59k}{L} \times (Ra)^{\frac{1}{4}}$ $[\mathrm{W/Km^2}]$
3. Turbulent convection: $Ra \geq 10^9$, heat transfer coefficient: $h = \frac{0.10k}{L} \times (Ra)^{\frac{1}{3}}$ $[\mathrm{W/Km^2}]$

- 0.1 atm (10 kPa): $Ra = 4 \times 10^7$ => convection effect need to be estimated
  - Heat transfer coefficient: $h = 1.2\ \mathrm{W/Km^2}$ < Radiation:$h = 6 \sim 7.5\ \mathrm{W/Km^2}$
  - Temperature effects should be estimated by simulation (radiation×1/5 => ~4 ºC?)
- 0.0005 atm (50 Pa): $Ra < 1708$ => no convection effect
  - Consider outgassing, conductance, vacuum pump (coating and baking?)

Preliminary evaluation of stress

- Maximum principal stress from simulation:
  - Adhesive: ~7 MPa
  - Sensor: ~10 MPa
  - G10 frame (local): ~37 MPa



- Stress requirements:
  - Adhesive: shear strength ➢ O(10) Mpa: From datasheet
  - Silicon, G10: yield strength ➢ O(100) Mpa?: From some papers

The safety factor is ~2, so there may be not so much margin

Future plans for stress evaluation

- Validate parameters such as thermal expansion coefficient and Young's modulus from measurement
- Check actual material strength
- Understand deformation regions with high stress in the simulation
  - Suspect that the lack of spatial margin in the simulation