Design and Performance of the MARS System

Magnetically Actuated Rail System for the ITACA TPC

ITACA Collaboration

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Abstract

This document outlines the mechanical design and kinematic performance of the Magnetically Actuated Rail System (MARS) for the ITACA detector. We present a conceptual design based on a hermetic coaxial magnetic drive capable of positioning a CMOS ion sensor at any coordinate (r, θ) within the TPC volume. The design features a re-entrant well geometry to maximize radiopurity and utilizes a symmetric "Propeller" arm configuration for mechanical balance. We also detail the pressure vessel dimensions required to house a 260×260 cm fiducial volume shielded by 15 cm of internal copper.

1 Detector Description and Vessel Sizing

The ITACA detector is designed around a large, monolithic Time Projection Chamber (TPC) filled with enriched xenon gas at 15 bar. The design prioritization is radiopurity, maximizing the active fiducial volume, and ensuring full tracking capability.

1.1 Internal Layering (Anode to Cathode)

The detector components are arranged vertically. Starting from the top (Anode) and moving downwards into the TPC volume:

1. **Inner Copper Shield (Top):** A 15 cm thick layer of ultra-pure oxygen-free high thermal conductivity (OFHC) copper providing the primary radiogenic shield for the anode region.
2. **Dense Silicon Plane (DSP):** A thin Kapton foil carrier board populated with Silicon Photomultipliers (SiPMs) for tracking (xy) and energy ($S2$) reconstruction.
3. **Light Guide Honeycomb:** A 7 mm thick structure composed of optical rods coupled to individual SiPMs. This honeycomb acts as a light guide to collect EL photons while shielding the sensors from the high-field region.
4. **FAT-GEM Structure:** A 5 mm thick amplification structure (Field Assisted Transparent Gas Electron Multiplier) responsible for generating the Electroluminescence (EL) signal.
5. **Fiducial Drift Volume:** The active detection region begins immediately below the FAT-GEM. It extends for a length of $L_{\text{fid}} = 260$ cm.
6. **Cathode Grid:** A highly transparent wire mesh defining the bottom of the drift field.
   - **Bias Voltage:** The cathode is held at a positive potential of **+500 V** relative to ground to facilitate ion extraction.
7. **MARS Mechanics Region:** A compact **14 cm vertical zone** allocated for the moving truss arm and ion plate.

- Since the magnetic hub mechanism is located *below* the copper shield (in the re-entrant well), this region only requires height for the aerodynamic arm profile (∼8 cm) and safety clearances (∼3 cm top/bottom) to the High Voltage cathode.

8. **Inner Copper Shield (Bottom):** A 15 cm thick copper shield lining the floor of the vessel.

   - **Penetration:** This layer is solid except for a narrow central bore (Ø ≈ 50 mm) allowing the titanium drive shaft to connect the external hub to the internal truss.

1.2 Ion Extraction Module (The Sensor Payload)

To protect the CMOS sensors and ensure efficient ion collection, the Ion Plate is designed as a miniature, inverted TPC operating at low voltage.

- **Topology:** The extraction field is established between the Cathode (+500 V) and the Sensor Plane (0 V / Ground).
- **Intake Grid (+300 V):** Located 5 mm below the Cathode. The 200 V difference creates a strong extraction field ($E \approx 400$ V/cm) that pulls positive ions through the cathode mesh.
- **Field Cage (The "Mini-TPC"):** A stack of **6 field-shaping rings** degrades the voltage linearly from +300 V to Ground over 20 mm, maintaining a uniform internal drift field of ∼150 V/cm.
- **Sensor Plane (Ground):** The CMOS pixel sensors are held at **Ground Potential**, simplifying readout.

1.3 Pressure Vessel Sizing

To accommodate the described internal components, the Titanium Grade 5 pressure vessel must have the following minimum internal dimensions:

Internal Diameter (ID_{PV})

$$\begin{aligned} ID_{\mathrm{PV}} &= D_{\mathrm{fid}} + 2 \times (\text{Field Cage}) + 2 \times (\text{Clearance}) + 2 \times (\text{Copper Shield}) \\ &= 260 \text{ cm} + 2(5 \text{ cm}) + 2(2 \text{ cm}) + 2(15 \text{ cm}) \\ &= 260 + 10 + 4 + 30 \\ &= \mathbf{304} \text{ cm} \quad (\approx 3.05 \text{ m}) \end{aligned}$$

Internal Height (H_{PV})

$$\begin{aligned} H_{\mathrm{PV}} &= H_{\mathrm{Shield}}^{\mathrm{top}} + H_{\mathrm{DSP}} + H_{\mathrm{LG}} + H_{\mathrm{GEM}} + L_{\mathrm{fid}} + H_{\mathrm{Mech}} + H_{\mathrm{Shield}}^{\mathrm{bot}} \\ &\approx 15 + 0.5 + 0.7 + 0.5 + 260 + \mathbf{14} + 15 \\ &= \mathbf{305.7} \text{ cm} \quad (\approx 3.10 \text{ m}) \end{aligned}$$

1.4 Wall Thickness Calculation

Using the ASME Boiler and Pressure Vessel Code (Section VIII, Division 1) for a thin-walled cylindrical shell with $P = 15$ bar (1.5 MPa) and Titanium Gr.5 ELI ($S \approx 200$ MPa):

$$t = \frac{1.5 \times 1520}{200 \times 1.0 - 0.6 \times 1.5} \approx \mathbf{11.5} \text{ mm} \tag{1}$$

Adding corrosion and manufacturing tolerances, we select a nominal wall thickness of **14 mm**.

2 MARS System Architecture

2.1 The Drive Mechanism: Dual-Concentric Magnetic Coupling

The actuation utilizes a hermetic, through-wall magnetic transmission. To control both degrees of freedom (r, θ) without dynamic seals, the system employs a **Dual-Concentric** design.

- **Geometry:** A Titanium "well" protrudes 200 mm *below* the bottom flange.
- **External Stator (Air Side):** Two independent servo motors drive two concentric magnetic rings positioned around the outside of the titanium well.
- **Internal Rotor (Xenon Side):** Inside the well, two corresponding magnetic rotors are nested concentrically. Each internal rotor is magnetically locked to its corresponding external ring, allowing independent torque transmission through the static wall.

2.2 The Coaxial Hub Assembly

The connection between the magnetic drive and the truss arm relies on a nested shaft design that decouples azimuthal rotation (θ) from radial extension (r).

1. **Outer Shaft (The Azimuthal Drive):** The **outer magnetic rotor** drives a hollow Titanium shaft (Ø40 mm) that rises from the well.
   - **The Yoke:** This shaft terminates in a structural **Central Yoke**. The two "Aero-Truss" arms are bolted rigidly to this yoke.
   - **Motion:** Rotation of the outer shaft directly rotates the entire truss structure (θ coordinate).
2. **Inner Shaft (The Radial Drive):** The **inner magnetic rotor** drives a solid shaft (Ø15 mm) running concentrically inside the hollow outer shaft.
   - **The Drive Pulley:** This shaft extends slightly above the Central Yoke and carries the **Master Timing Pulley**.
   - **Motion:** This shaft rotates independently. The relative rotation between the Inner Shaft and the Outer Shaft drives the internal belt loop, extending or retracting the Ion Plate (r coordinate).

2.3 Mechanical Structure: The "Aero-Truss"

To minimize inertial mass while maximizing stiffness, the truss arm utilizes a **triangular space frame** wrapped in a radiopure skin.

1. **Structural Skeleton:** The core load-bearing structure consists of three Titanium Grade 5 longerons (10 mm Ø $\times$ 1 mm wall) arranged in a triangular prism configuration to resist torsional twisting.
2. **Aerodynamic Skin (HDPE):** The skeleton is wrapped in a thin (0.5 mm) sheet of **High-Density Polyethylene (HDPE)**.
   - **Shape:** The HDPE skin forms a symmetrical **NACA 0012 airfoil** profile around the triangular frame. This reduces hydrodynamic drag coefficient (C_d) to < 0.3.
   - **Radiopurity:** HDPE is selected for its extreme radiopurity (replacing PEEK) and chemical inertness in xenon.

3. **Mass Budget:**
   - Titanium Skeleton: 1.3 kg
   - HDPE Skin: 0.3 kg
   - Hardware: 0.5 kg
   - **Total Arm Mass:** $\sim$**2.1 kg** per side.

2.4 Mechanical Guidance System

The arm tip is supported vertically by a peripheral **OFHC Copper Rail**. The interface uses **HDPE or Vespel SP-3 rollers** to glide on the copper surface, ensuring the arm remains parallel to the cathode grid within ± 0.5 mm tolerance.

3 Kinematics and Speed Estimation (Dual Arm)

We evaluate the performance of the Dual-Arm "Propeller" system in 15 bar xenon with $\tau_{\max} = 140$ Nm.

3.1 Inertial Loads (Lightweight Design)

$$I_{\text{truss}} \approx 1.8 \text{ kg m}^2 \quad \text{(Lightweight Aero-Truss)} \tag{2}$$

$$I_{\text{plates}} = 2 \times (0.6 \times 1.3^2) \approx 2.0 \text{ kg m}^2 \tag{3}$$

$$I_{\text{total}} \approx \mathbf{3.8} \text{ kg m}^2. \tag{4}$$

3.2 Equation of Motion

With drag still dominating, the equation for a 90° rotation is:

$$140 = \left(3.8 \times \frac{6.28}{t^2}\right) + \frac{90}{t^2} \approx \frac{114}{t^2}. \tag{5}$$

$$t_{\min} = \sqrt{\frac{114}{140}} \approx \mathbf{0.90} \text{ s}. \tag{6}$$

4 Fluid Dynamics Considerations

4.1 Justification of Settling Time

In high-pressure xenon, the kinematic viscosity is low ($\nu \approx 2.6 \times 10^{-7}$ m^2/s), meaning turbulence persists longer than in air. The "Settling Time" (t_{settle}) is justified by the Large Eddy Turnover timescale (τ_{eddy}).

$$\tau_{\text{eddy}} \approx \frac{L}{U} \approx \frac{0.1 \text{ m}}{2.0 \text{ m/s}} = 0.05 \text{ s}. \tag{7}$$

Turbulent energy dissipation typically requires 20 turnover cycles for the wake velocity to decay below 10% of the initial value (i.e., to drop below the ion drift velocity of ~ 10 cm/s).

$$t_{\text{settle}} \approx 20 \times \tau_{\text{eddy}} = 20 \times 0.05 = \mathbf{1.0} \text{ s}. \tag{8}$$

4.2 Fiducial Volume Efficiency

$$t_{\text{total}} = 0.90 + 1.0 \approx 1.9 \text{ s.} \tag{9}$$

$$Z_{\text{dead}} = 10 \text{ cm/s} \times 1.9 \text{ s} \approx 19.0 \text{ cm.} \tag{10}$$

$$\epsilon_{\text{geo}} = \frac{260 - 19.0}{260} \approx \mathbf{92.7}\%. \tag{11}$$

5 Conclusion

The ITACA detector utilizes a Titanium Grade 5 pressure vessel ($\varnothing 3.05 \times 3.10$ m) to house a 15 cm copper-shielded fiducial volume. The MARS system, using a re-entrant magnetic drive and a lightweight, aerodynamic "Aero-Truss" arm (HDPE skin), achieves sub-second positioning ($t \approx 0.9$ s). The active **Ion Extraction Module** ensures efficient collection of ions across the cathode boundary through a low-voltage (500V to Ground) extraction field.