MACE Phase-I and Its Detector System

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Yinyuan Huang（黄胤元）

on behalf of the MACE working group

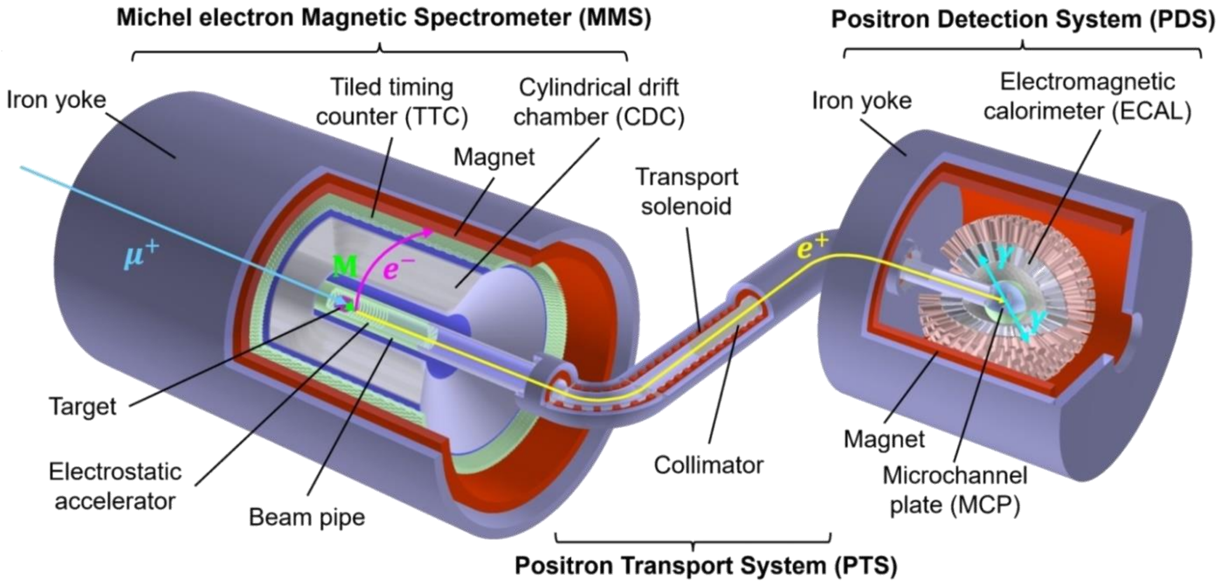
huangyy378@mail2.sysu.edu.cn

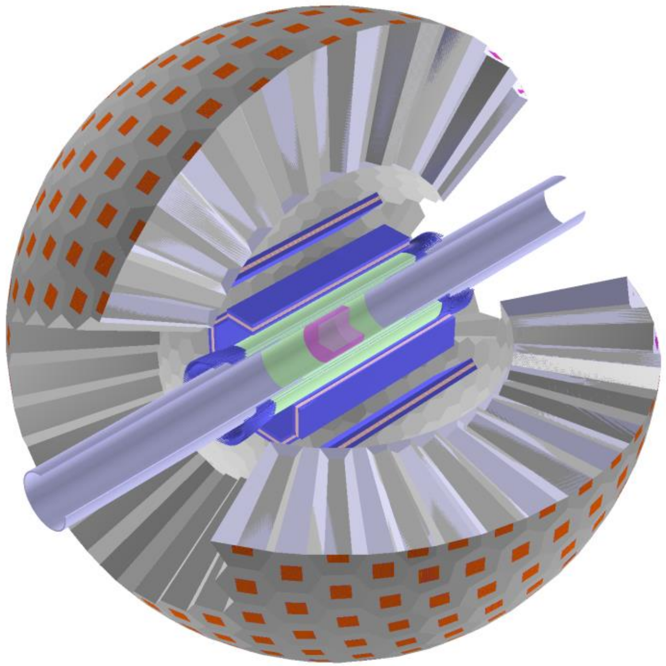
Introduction: MACE & MACE Phase-I

The Muonium-to-Antimuonium Conversion Experiment (MACE) aims at searching for CLFV process $\mathrm{M} \to \overline{\mathrm{M}}\ (\mu^+ e^- \to \mu^- e^+)$.

MACE Phase-I mainly plans to search for

- muonium rare Decay $\mathbf{M}\to\boldsymbol{\gamma\gamma}$
- muon rare decay $\boldsymbol{\mu}^+\to\boldsymbol{e}^+\boldsymbol{\gamma\gamma}$
- A sensitivity of $\mathcal{O}(10^{-12})$ is excepted





Challenges:

- Detect photon and charged particle with high energy
- Need a low-material-budget inner tracker system

Physical Goals

Main physical goals:

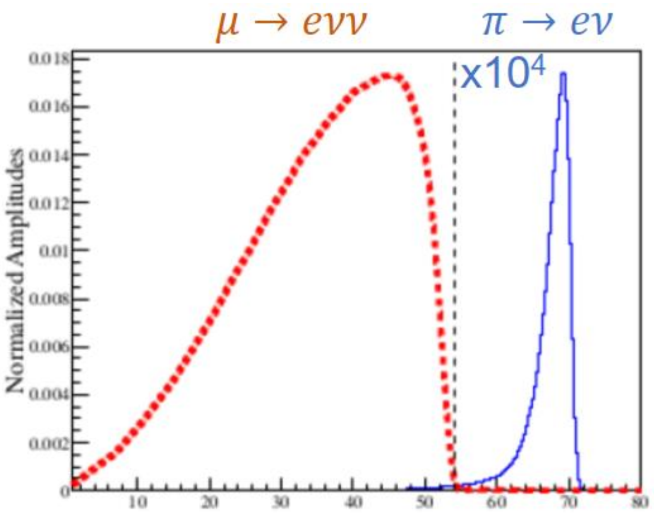
- $\mathrm{M} \to \gamma\gamma$ (unsearched)
- $\mu^+ \to e^+\gamma\gamma$ (1986 Crystal Box: $\mathcal{B}(\mu^+ \to e^+\gamma\gamma) < 7.2 \times 10^{-11}$)

Phys. Rev. D **38**, 2077

Other physical goals:

- **Probing new particle or interaction, e.g.**
  - $\mu^+ \to e^+X, X \to \gamma\gamma$
- **Lepton Flavor Universality, e.g.**
  - $\pi^+ \to e^+\nu_e$

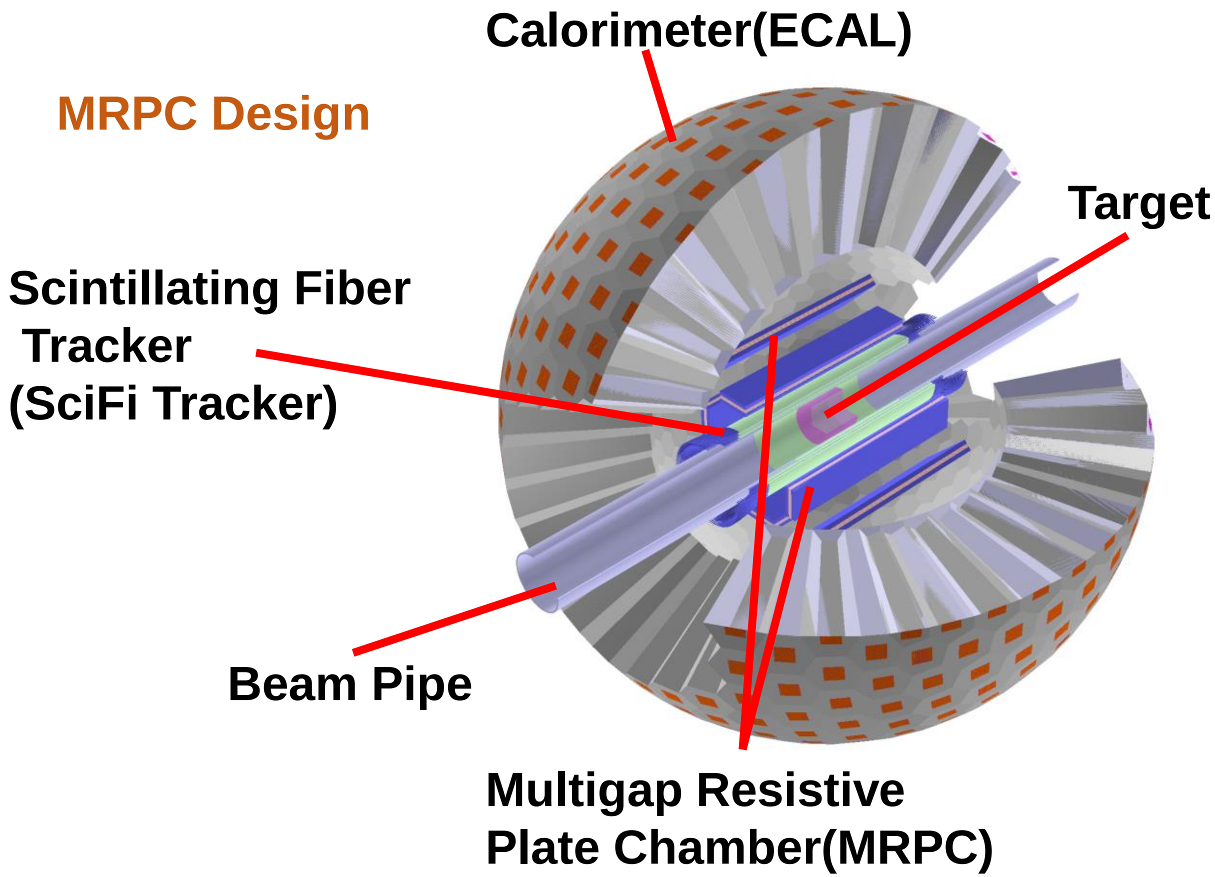
  (***if pion beamline available***)
- **……**

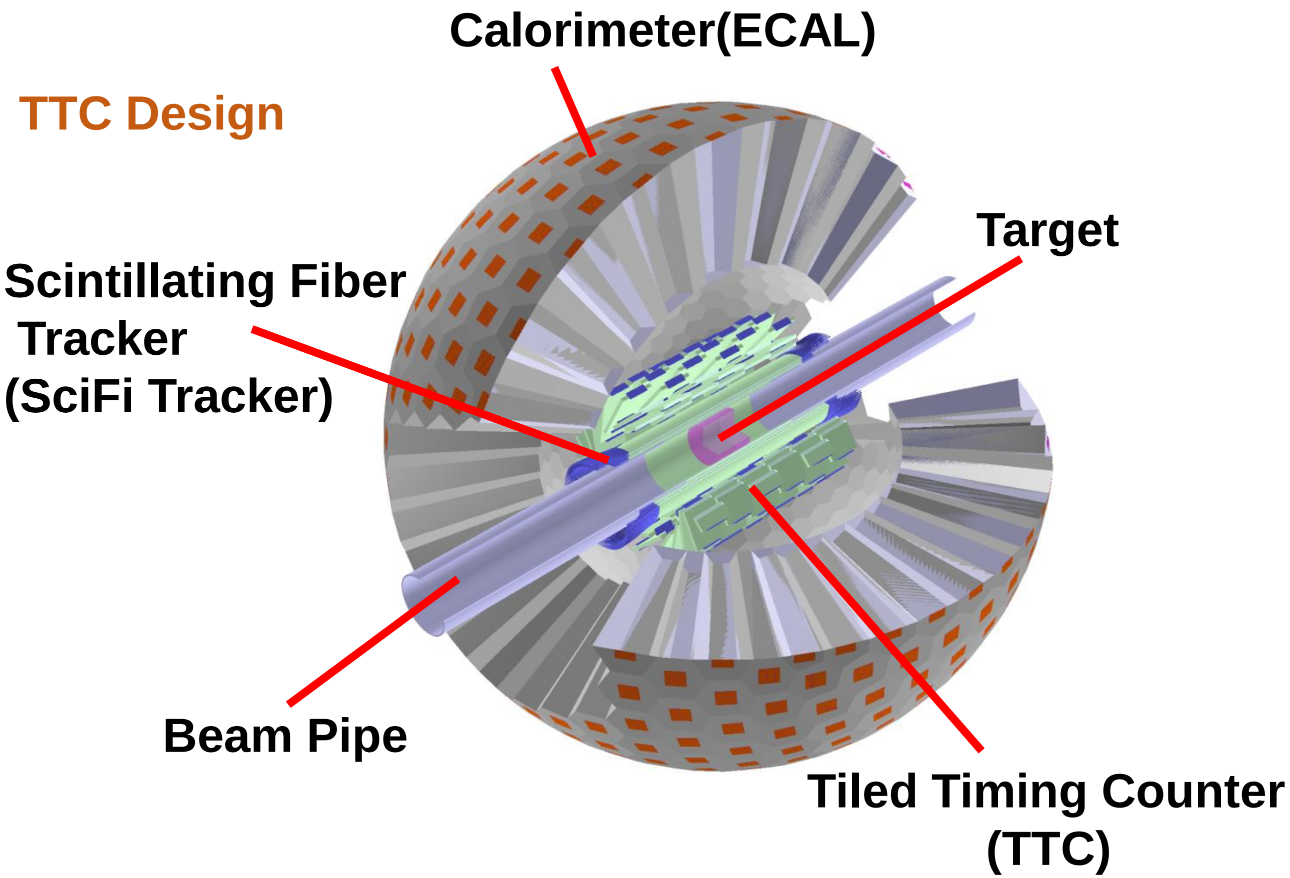


https://indico.fnal.gov/event/59896/contributions/280027/

Process	Beamline	Goal
$\mathrm{M} \to \gamma\gamma$	Surface Muon	New physics beyond Standard Model
$\mathrm{M} \to e^+e^-$		
$\mu^+ \to e^+\gamma$		
$\mu^+ \to e^+\gamma\gamma$		
$\mu^+ \to e^+X$		New particle or interaction
$\mathrm{M} \to \phi^*\gamma$		
$\mu^+ \to e^+\nu_e\,\bar{\nu}_\mu$		Precision tests of Standard Model
$\mu^+ \to e^+\nu_e\,\bar{\nu}_\mu\gamma$		
$\pi^+ \to e^+\nu_e$	Pion	Precision tests of Standard Model

Design of MACE Phase-I Detector System





I. Surface muon stop in target
II. (Muon capture electron→muonium)
III. Muonium/muon decay

IV. SciFi Tracker measures charged tracks
V. ECAL measures energy of tracks
VI. PID: SciFi + ECAL

Electromagnetic Calorimeter

Measures energy up to ~50 MeV

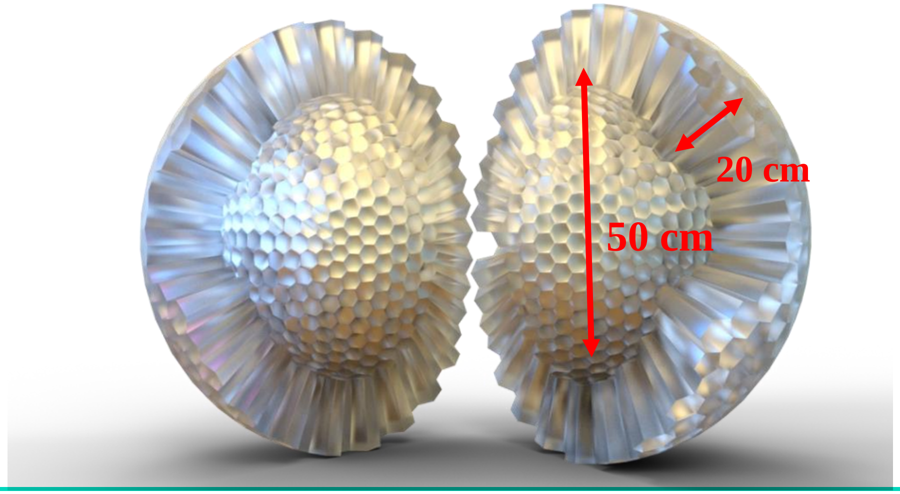
Properties of BGO:

- **High density**
- **non-deliquescent**
- decay time: 300 ns

Geometry: Class I GP(8,0) Goldberg polyhedron, >**$12X_0$**

568 modules, 82% coverage

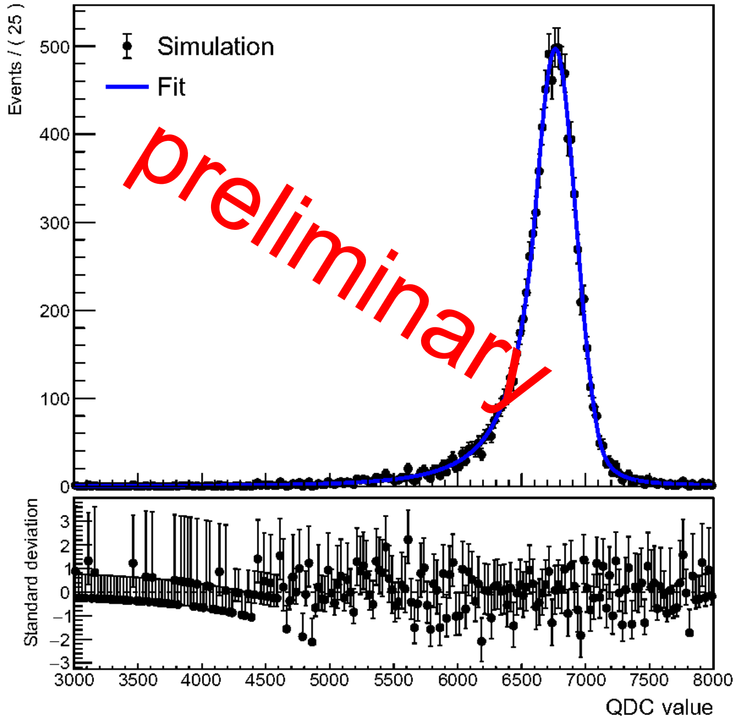
Sensor: SiPM arrays (**50%** PDE at max.)



Credit: Siyuan Chen

Baseline performance:

- An energy resolution of ~3% at 50 MeV
- A timing resolution of ~1 ns



Another scintillator scheme: glass scintillator

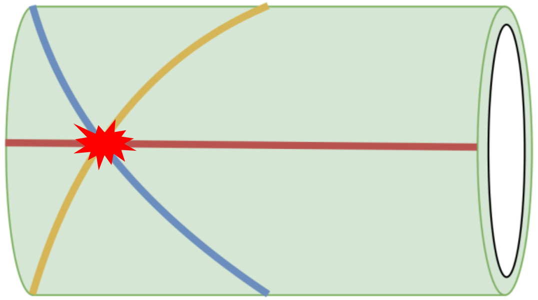
- Low price
- Higher time resolution (< 500 ps expected)

Scintillating Fiber Tracker

Detect hit point of charged particle

Why Scintillating fiber tracker?

- High event rate
- Low material budget
- High spatial & time resolution

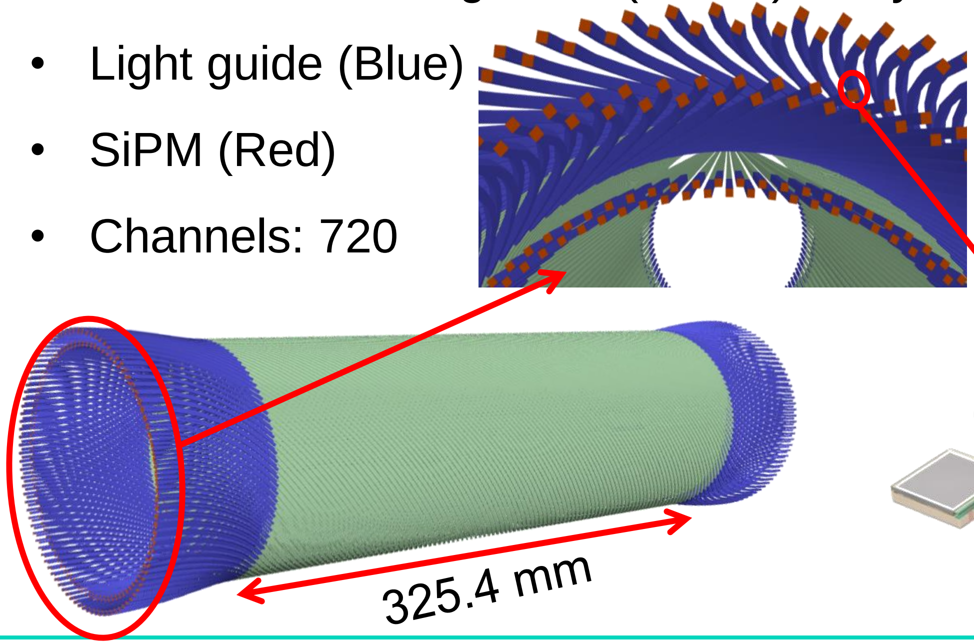


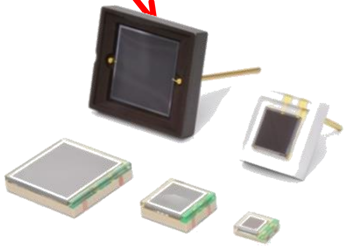
Baseline performance:

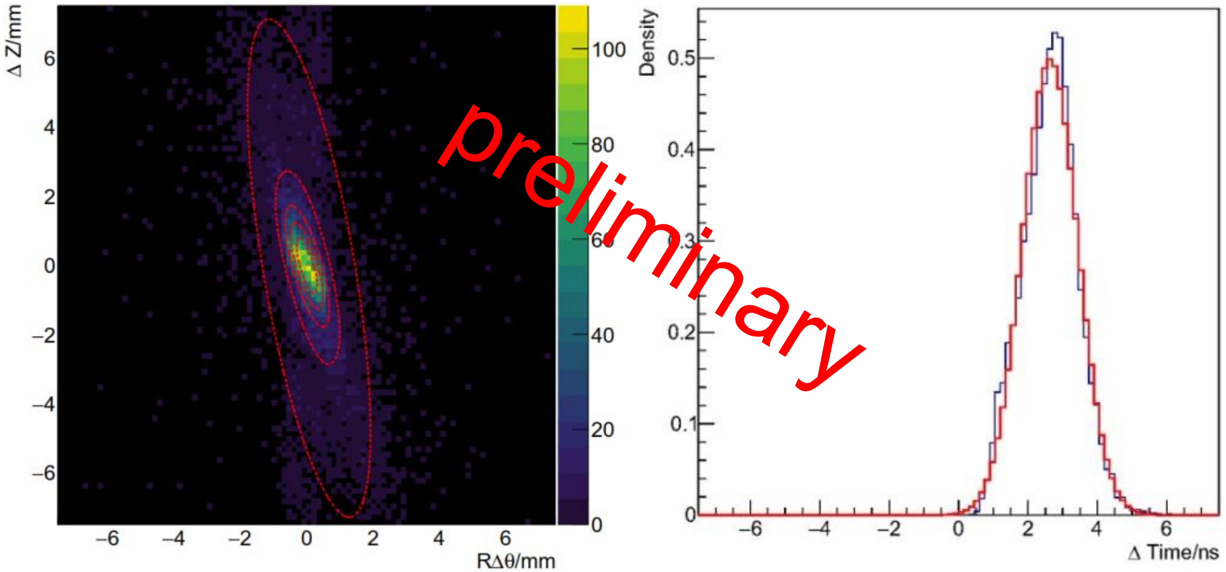
- Detect efficiency: 85%
- Spatial resolution:~1 mm
- Time resolution: 0.8 ns

Detector design:

- Plastic Scintillating Fiber (Green): 3 layers twisting
- Light guide (Blue)
- SiPM (Red)
- Channels: 720







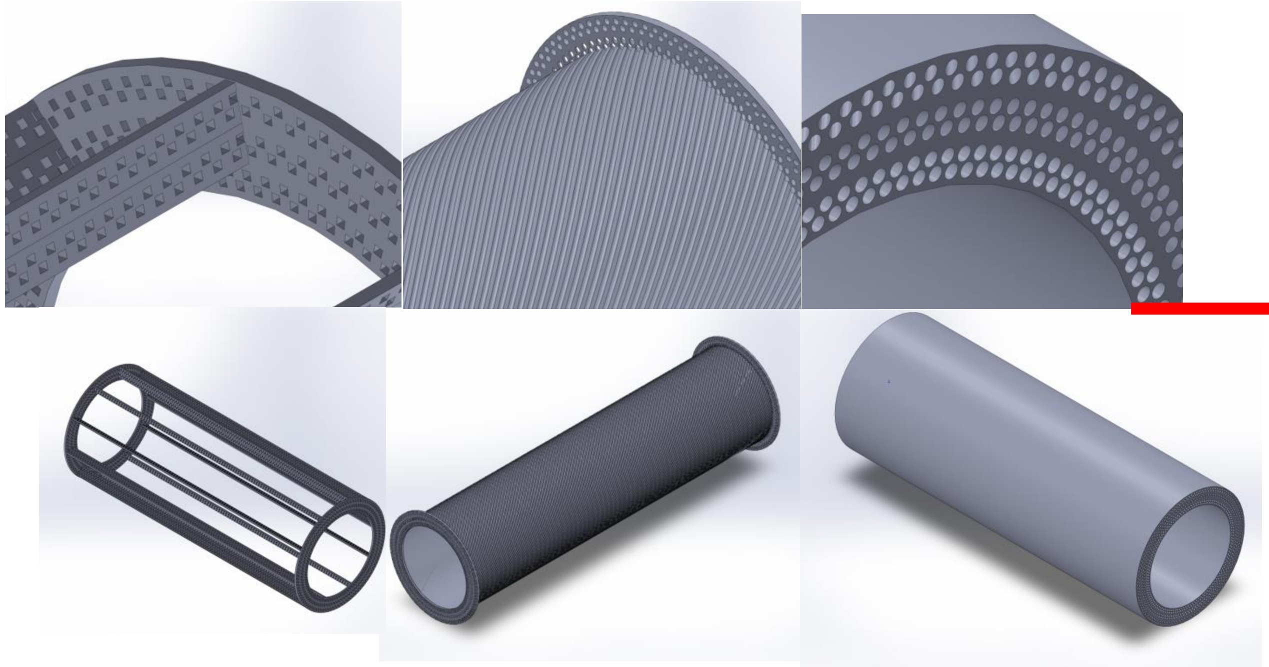
Scintillating Fiber Tracker

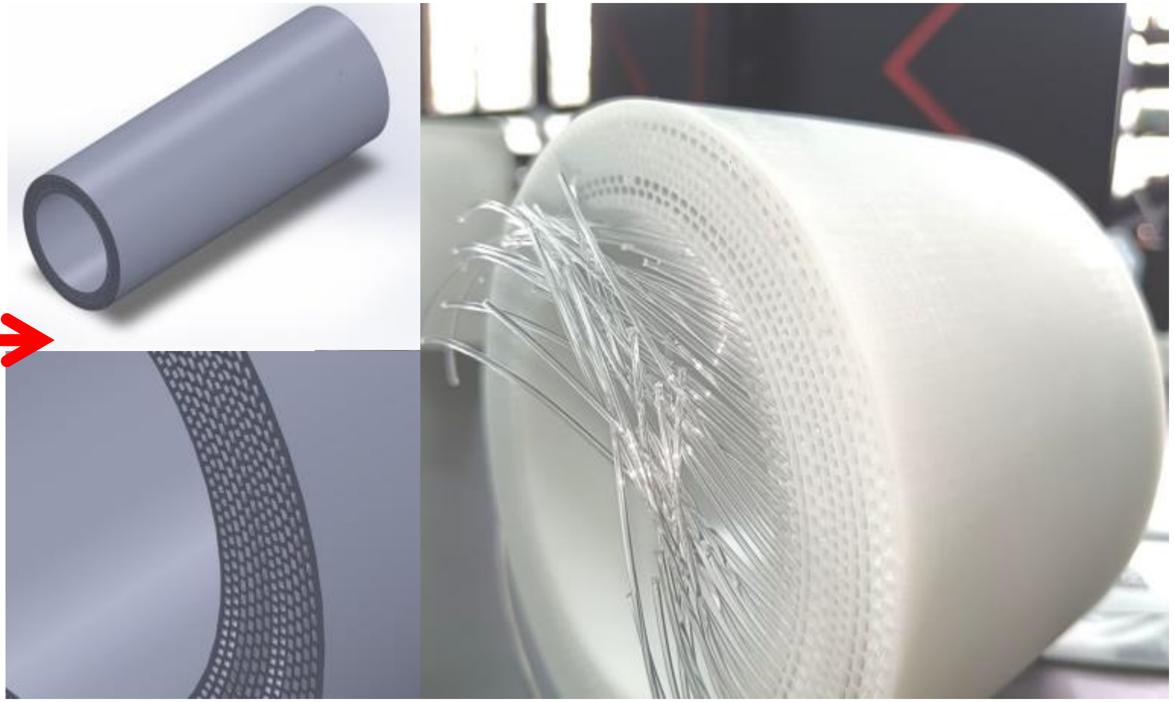
Bracket Design：

- Optimized to keep structure strength while add fiber number as much as possible
- use plastic to reduce material budget

Next step:

- 3 layers fiber → 6 layers fiber
- Reconstruct hit point → reconstruct track
- A ~2 degrees angular resolution is excepted



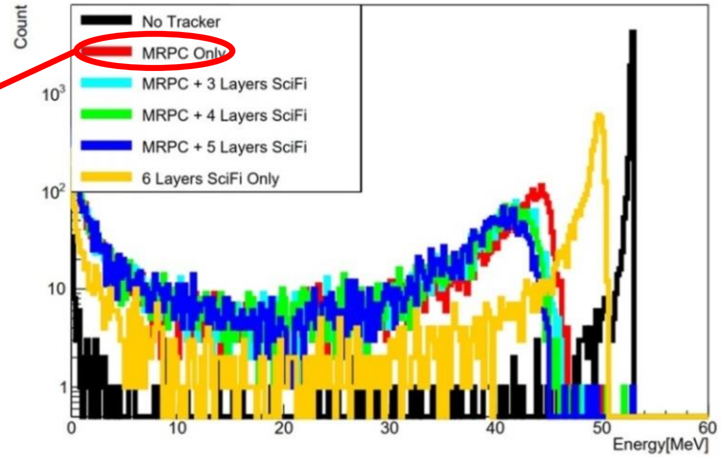


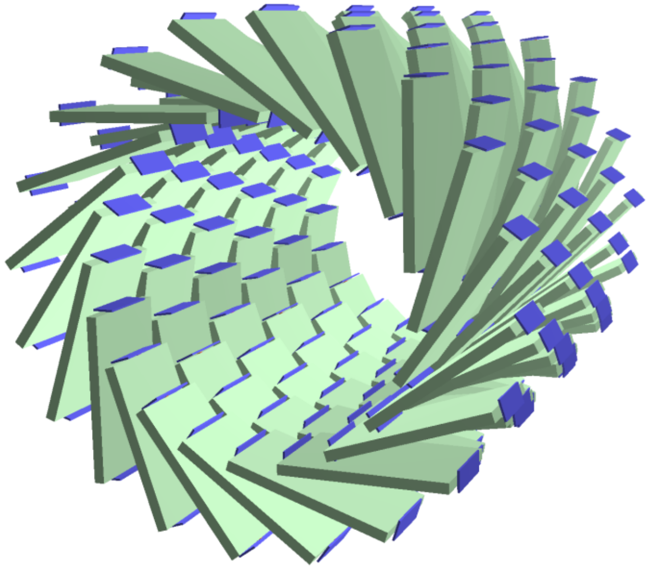
Multigap Resistive Plate Chamber / Tiled Timing Counter

Measure the flight time of particle

Properties of MRPC

- Excellent time resolution ($\mathcal{O}(10)$ ps)
- High material budget

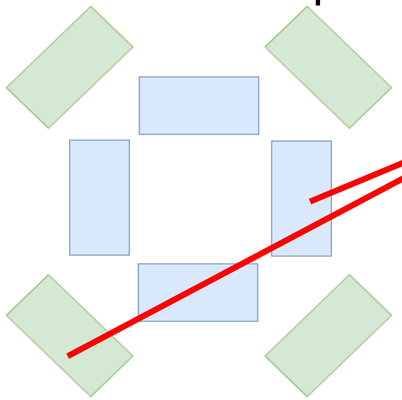


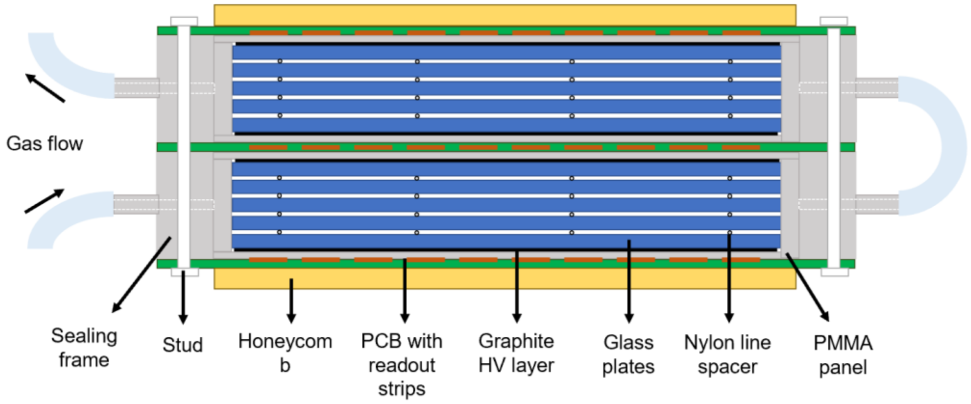


Credit: Hao Jiang

Geometry:

- 8 units in total
- Four inner units arranged in a square
- Four outer units located in the corners of the square





Credit: Yi Wang

Properties of TTC

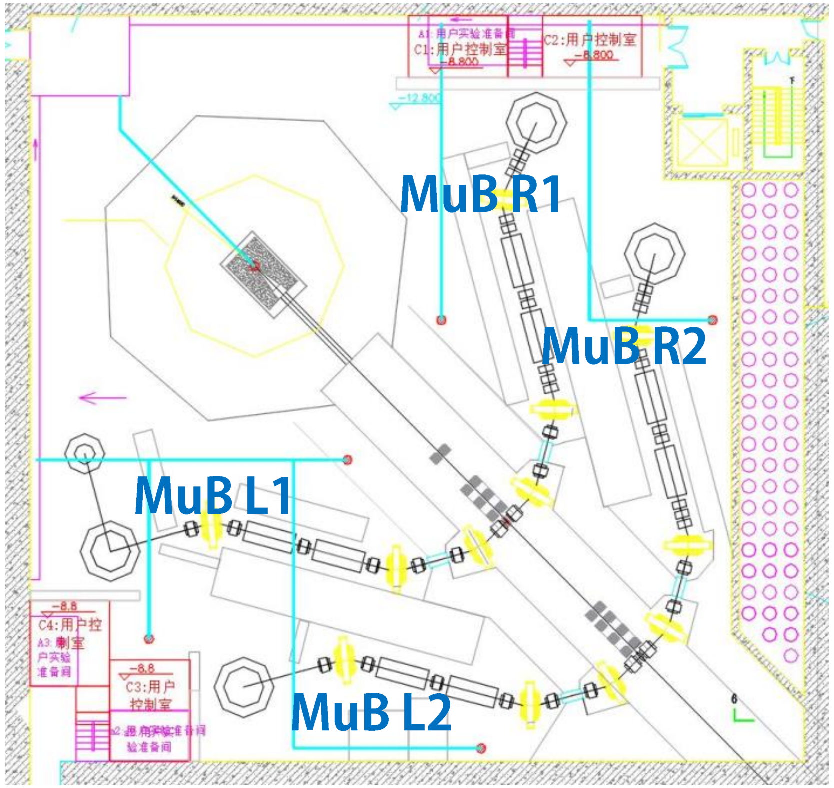
- Good time resolution ($\mathcal{O}(100)$ ps)
- Low material budget

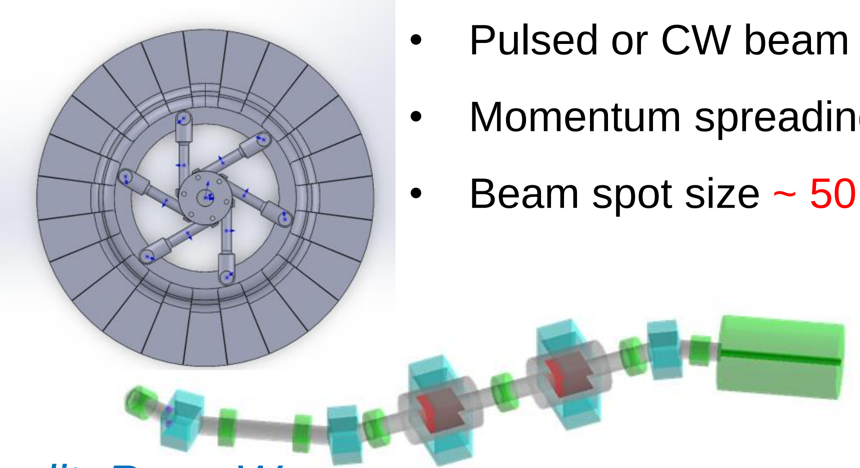
The geometry design of TTC is in progress

Beamline

MACE Phase-I will operate at CiADS

- Proton beam energy: 500~600 MeV (surface muon beam)
- Proton intensity : 500 uA ($10^7 \mu^+/s$)
- Time structure: continuous wave

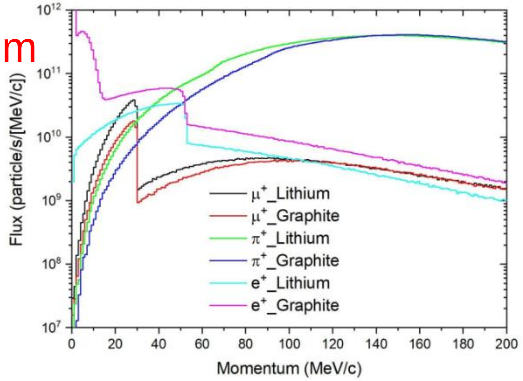




Credit: Rong Wang

Phase-I requirement:

- 10^6 ~ 10^7 μ⁺ OT /s (1986 crystal box: $4 \times 10^5 \mu^+/s$)
- Pulsed or CW beam
- Momentum spreading: $\Delta p/p$ ~ 10%
- Beam spot size ~ 50 mm



Beam Power	Target	Beamline	Intensity (μ^+/s)		Spin Pol.	background
			Full size	Φ30 mm		
300 kw	Graphite	Full-solenoid	>5E8	~1E8	~94%	<0.1%
		Mixing	>5E7	~1E7	~99%	
3 MW	Lithium	Full-solenoid	>1E10	~2E9	~94%	
		Mixing	>1E9	~2E8	~99%	

Timeline

Conceptual design	We are here	Phase-I Technical design & prototype	Phase-I installation	Phase-I Physics run & Phase-II Technical design		MACE Phase-II
2024		2025	2026	2027	2028	2028+

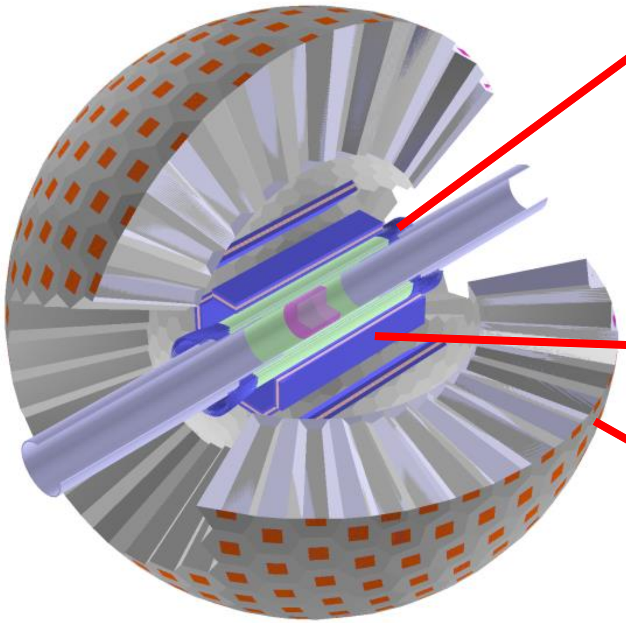
- Phase-I: $\mathcal{O}(10^{-12})$ sensitivity for rare muonium/muon decay
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, 10^6 ~ 10^7 μ^+ OT /s
  - Pulsed or CW beam
  - Momentum spreading: $\Delta p/p$ ~ 10%
  - Beam spot size ~ 50 mm

- Phase-II: $\mathcal{O}(10^{-13})$ sensitivity for muonium conversion
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, 10^8 μ^+ OT /s
  - Pulsed beam, repetition rate 20 ~ 50 kHz
  - Momentum spreading: $\Delta p/p$ ~ 10%
  - Beam spot size ~ 50 mm

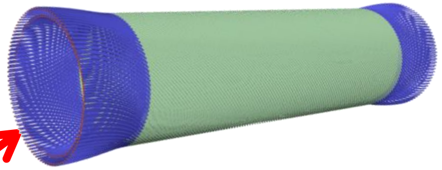
Summary and outlook

MACE Phase-I

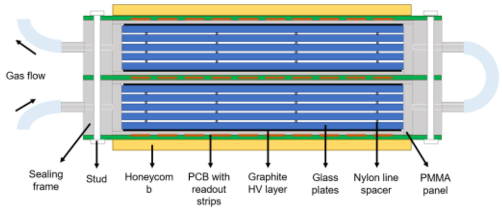
- Physical goal
  - Towards $\mathcal{O}(10^{-12})$ sensitivity:
  - muonium rare decay $\mathbf{M}\to\gamma\gamma$
  - muon rare decay $\mu\to e\gamma\gamma$
- Detector system

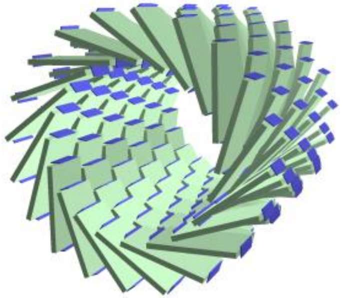


SciFi Tracker:



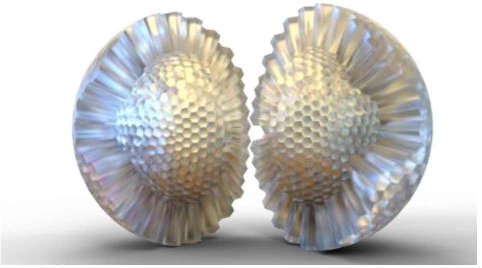
Eff.: 85%
Spatial Res.: ~1 mm
Time Res.: 0.8 ns





MRPC/TTC: Time Res.: $\mathcal{O}(10)$ / $\mathcal{O}(100)$ ps

ECAL:



Energy Res.: ~3% at 50 MeV

Time Res.: ~1 ns

- Outlook
  - More physical goals
  - Detector prototype & technical design

Thanks!