Progress of MELODY

Muon station for sciEnce technoLOgy and inDustrY

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CSNS

IHEP

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Outlines

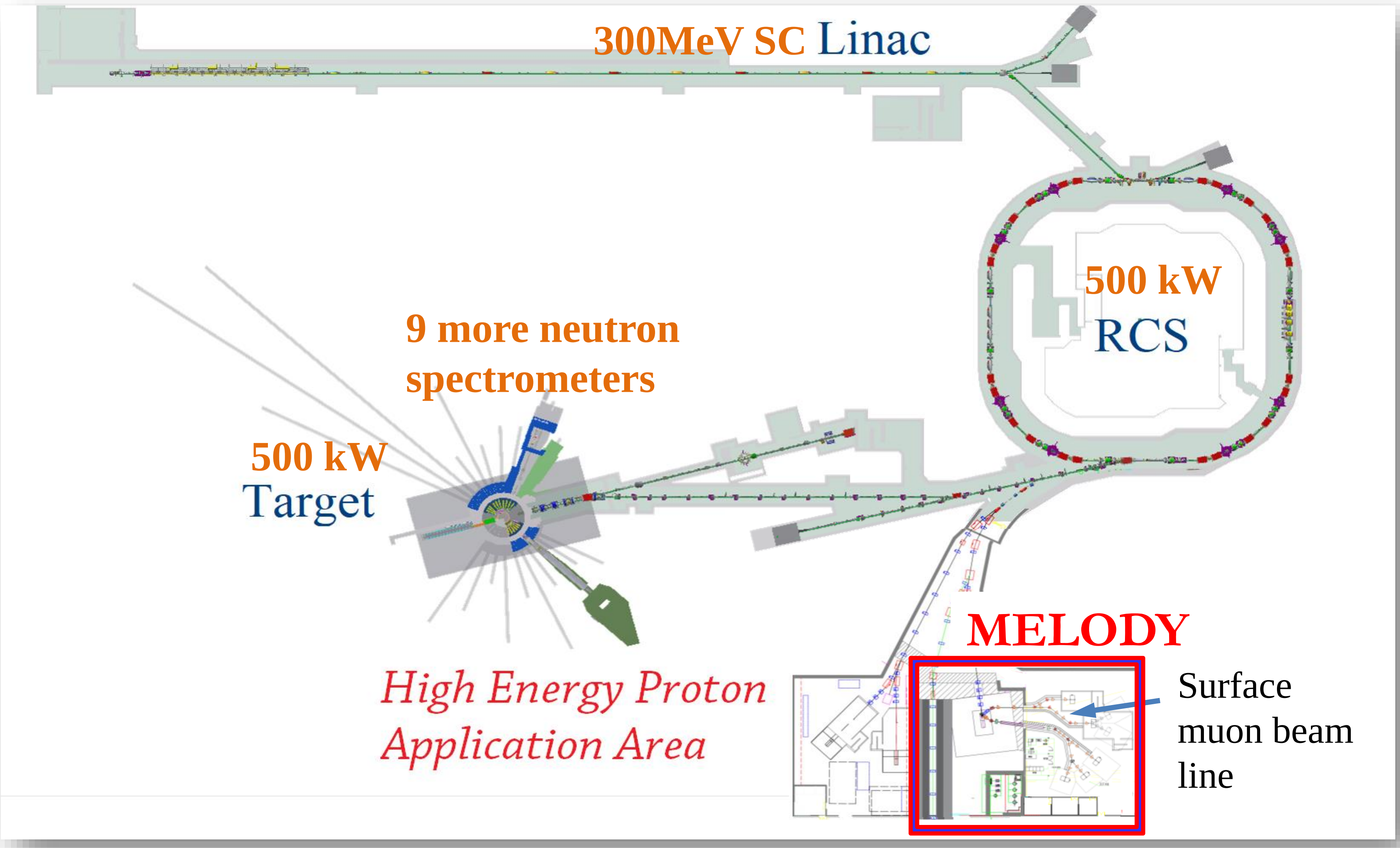
- China Spallation Neutron Source
- Design of MELODY
- Application of MELODY
- Future of MELODY
- Summary

China Spallation Neutron Source

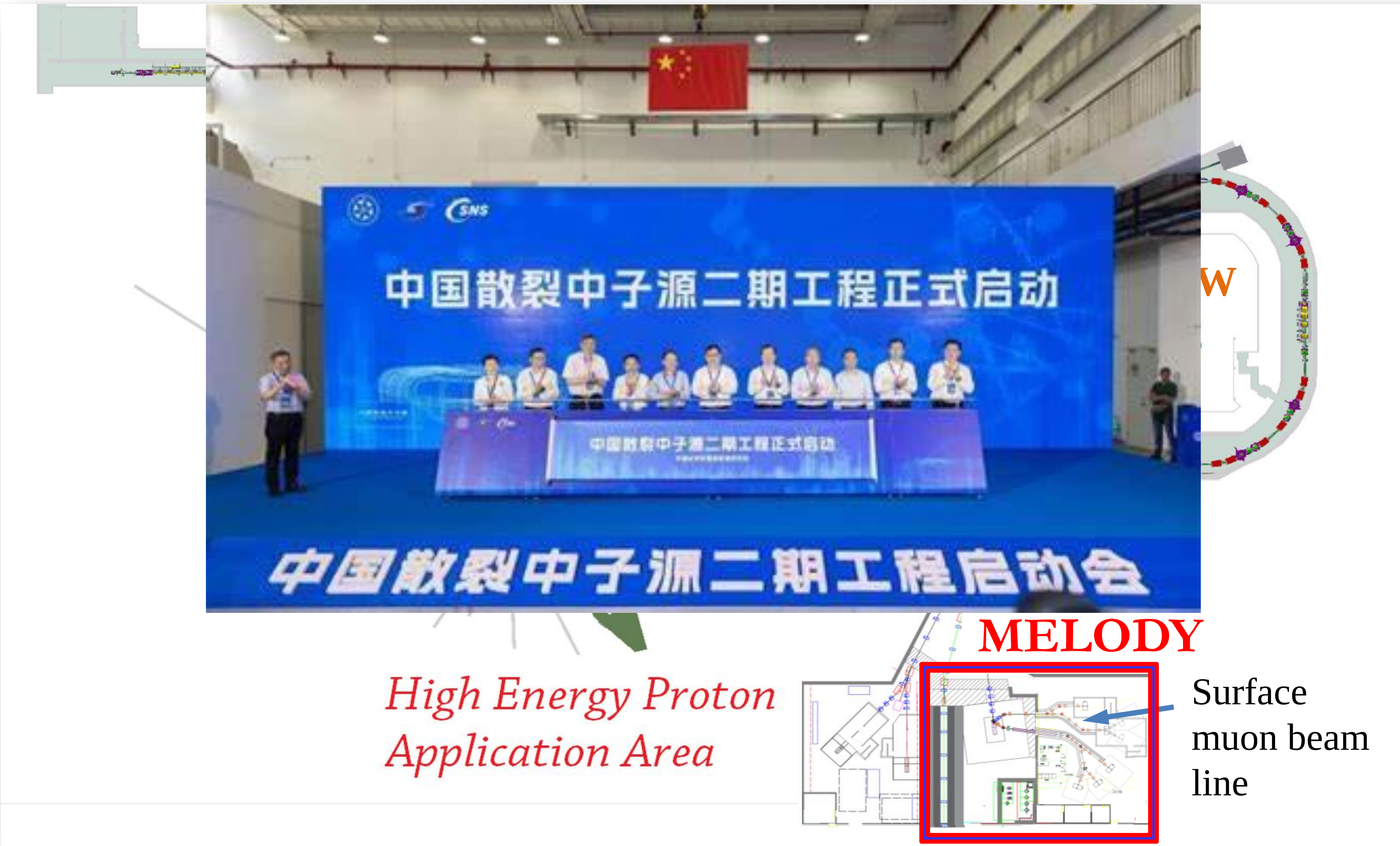
China Spallation Neutron Source（CSNS)

Accelerator: 100kW 25Hz 1.6GeV proton beam
Neutron Spectrometers: 7 built and 3 under construction

CSNS II Project (Approved on Jan. 11, 2023)

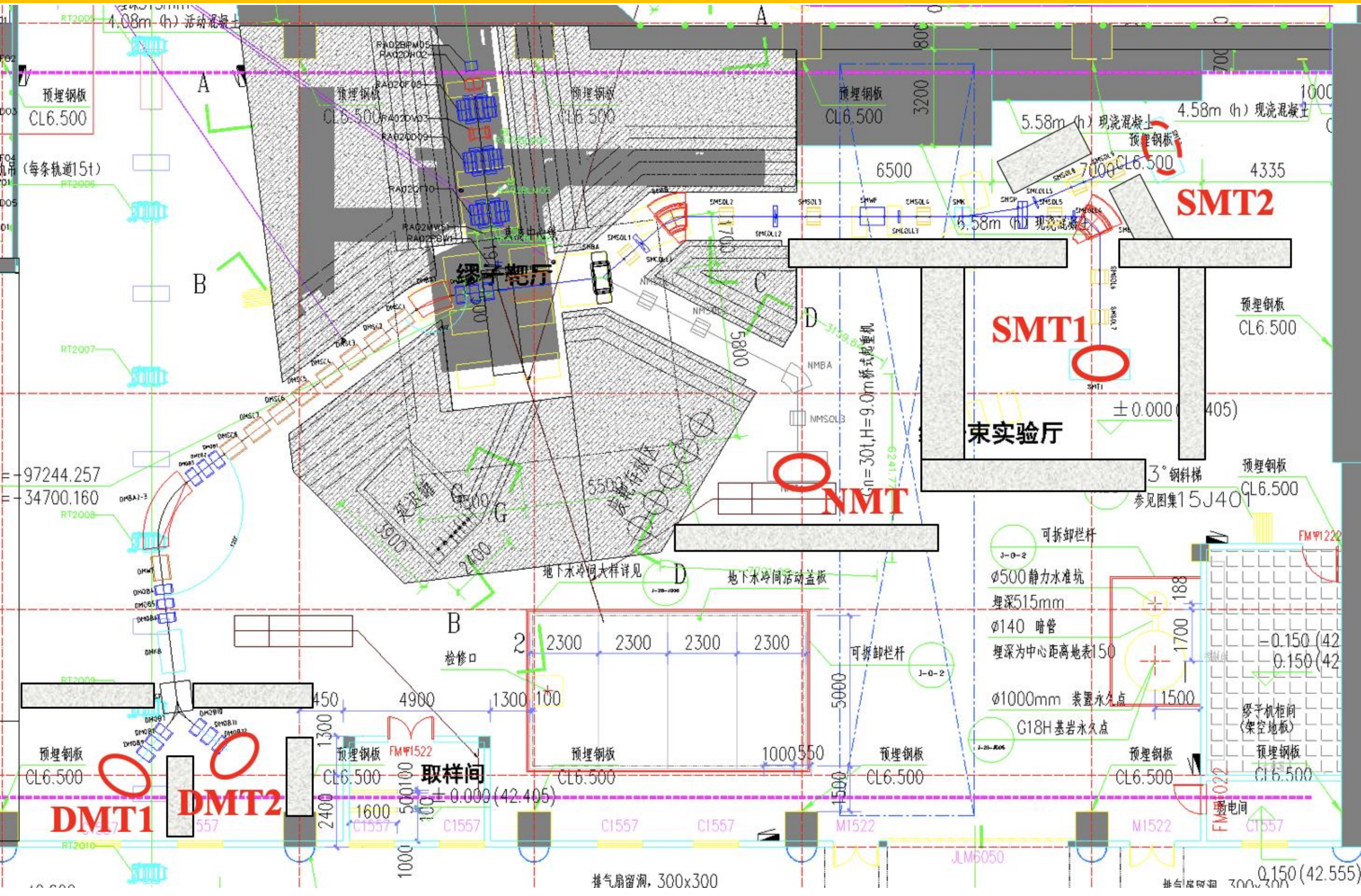


CSNS II Project (Approved on Jan. 11, 2023)



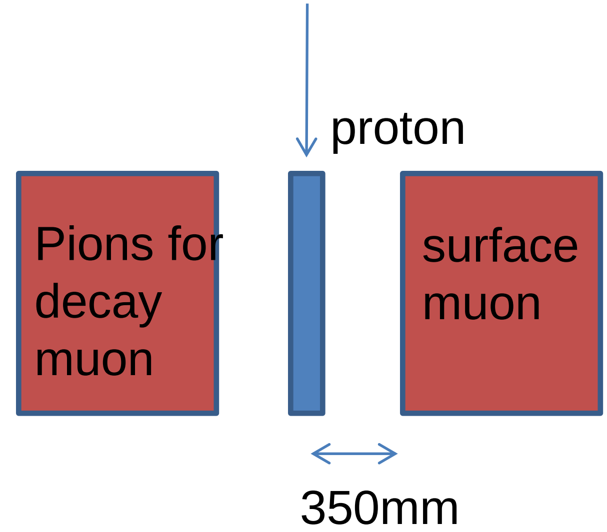
Architectural Design of MELODY

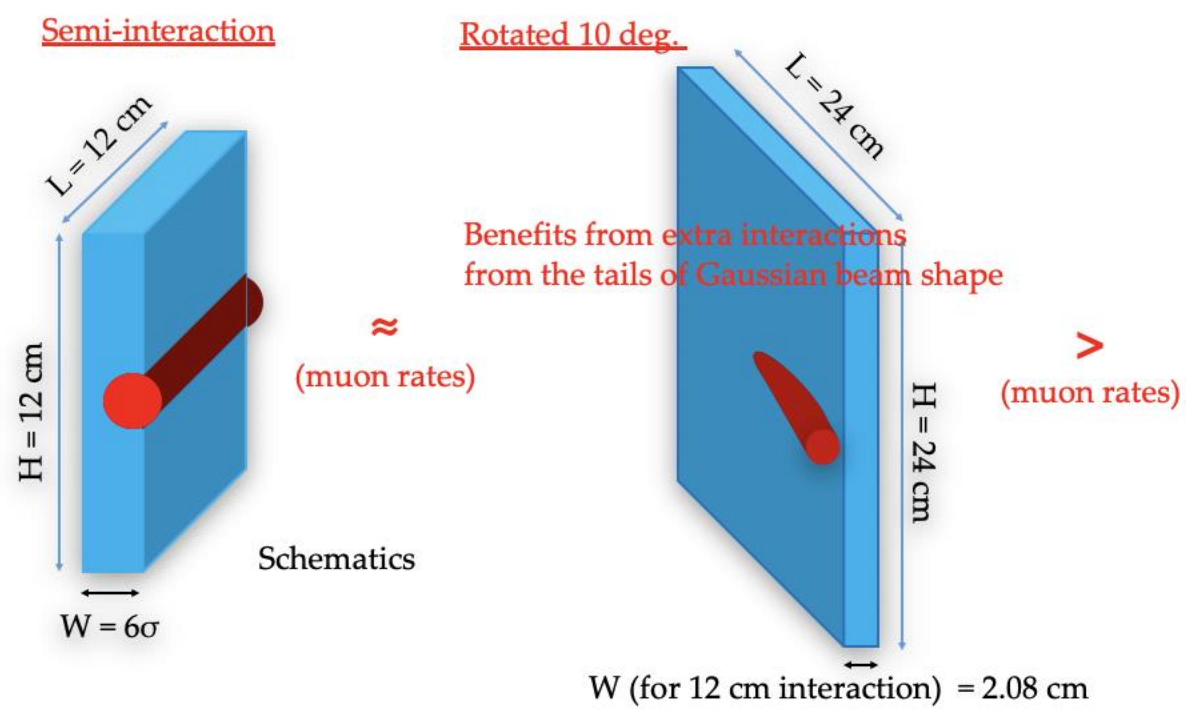
Overall of MELODY



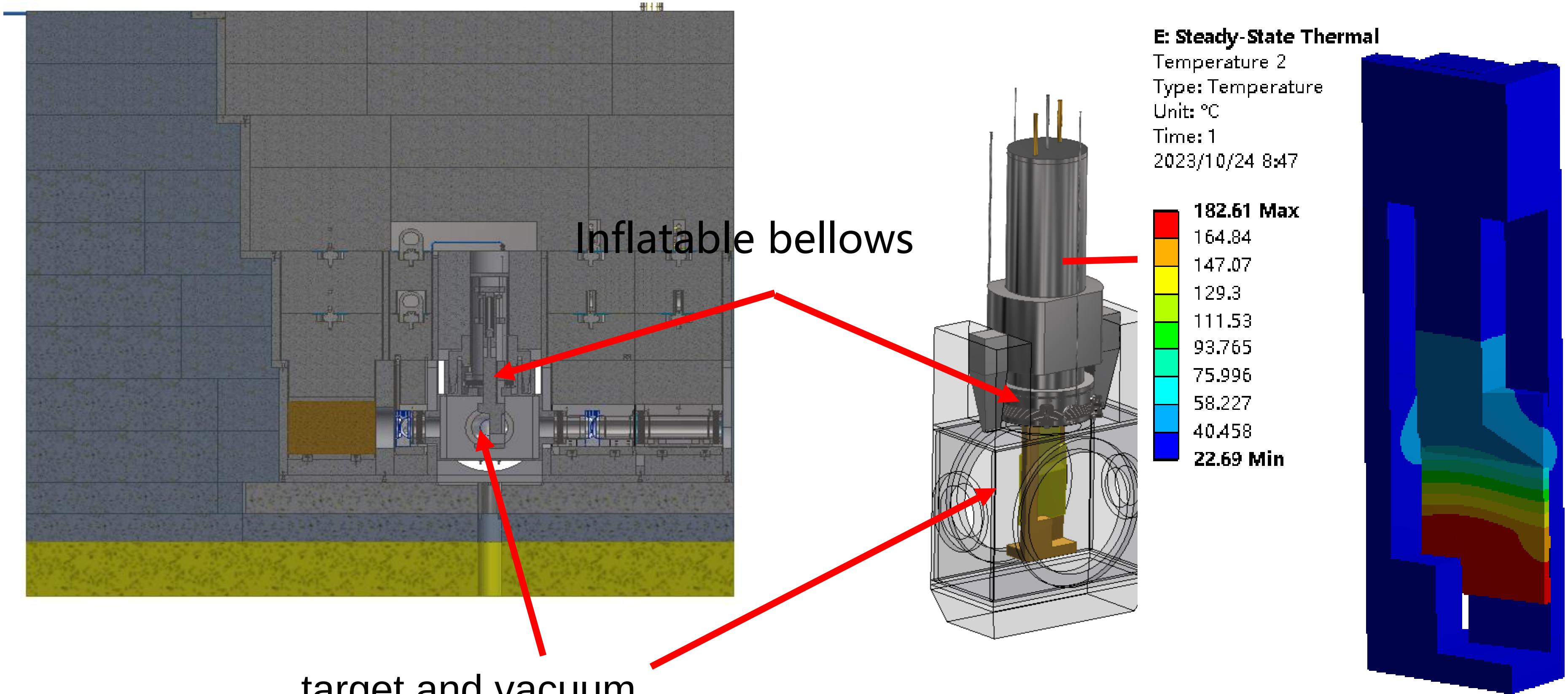
Muon Target

- Collect muons and pions on one side of target
- Optimize the surface muon production with semi-interaction strategy





Target design



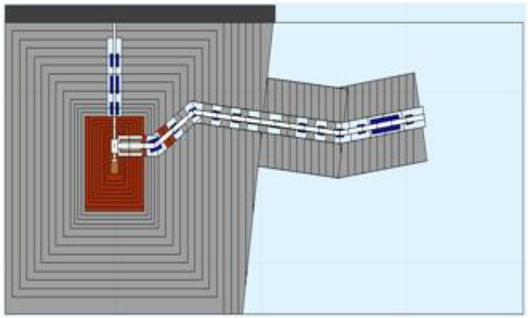
target and vacuum chamber

- **Fixed target，Cu,24cm*24cm*10mm，tilt by 7degree**
- **Edge water cooling， < 200°**
- **Inflatable bellows connection**

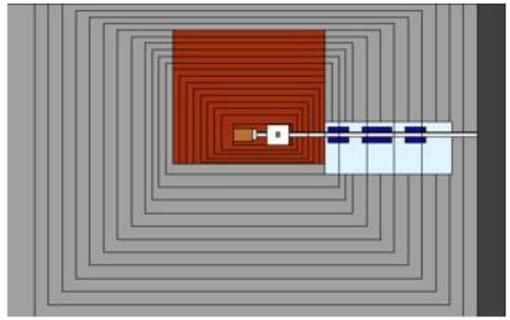
Radiation Shield

Two layers:

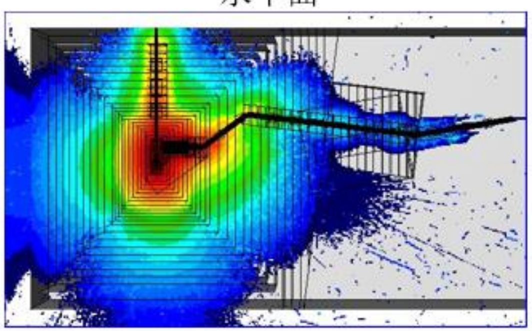
1. Mild steel
2. Concrete



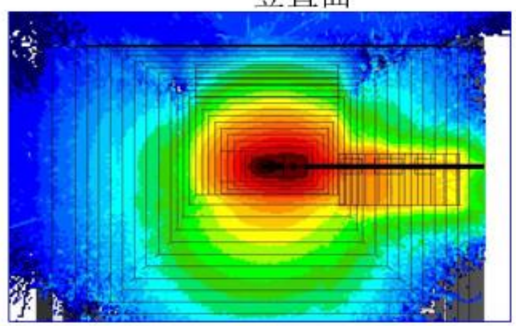
水平面



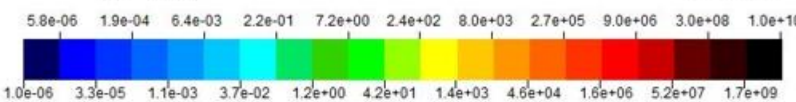
竖直面



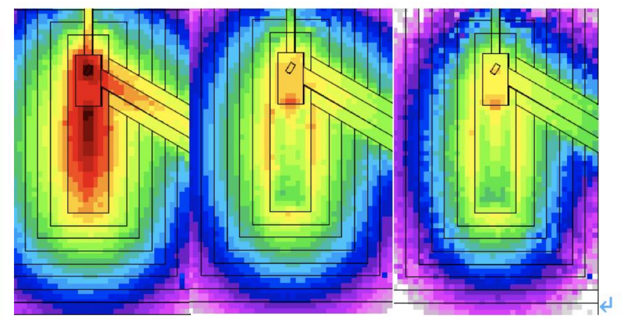
水平面



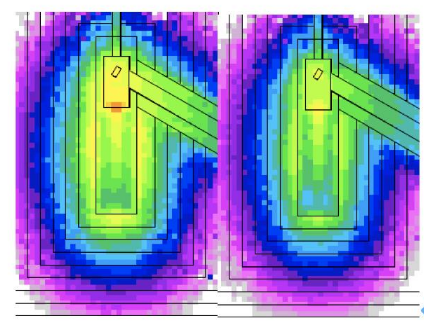
竖直面



瞬发辐射剂量率（mSv/h）

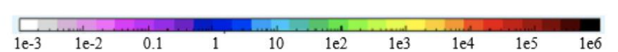


刚停机 停机 4 小时 停机 1 天



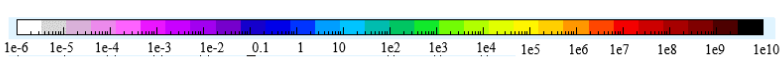
停机 1 周 停机 2 月

Residual dose

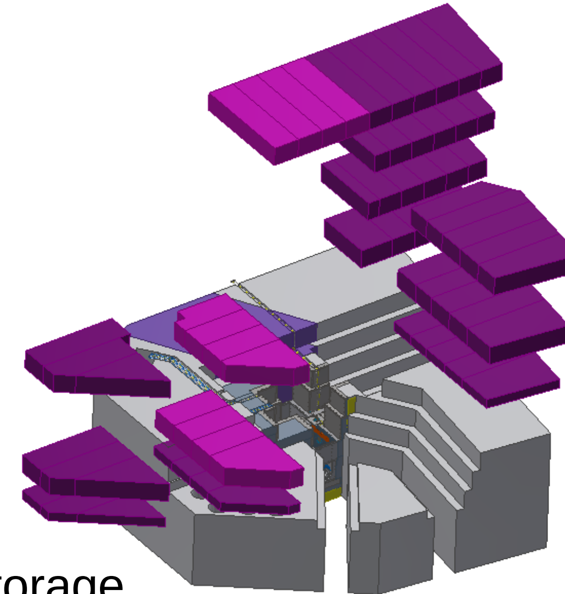


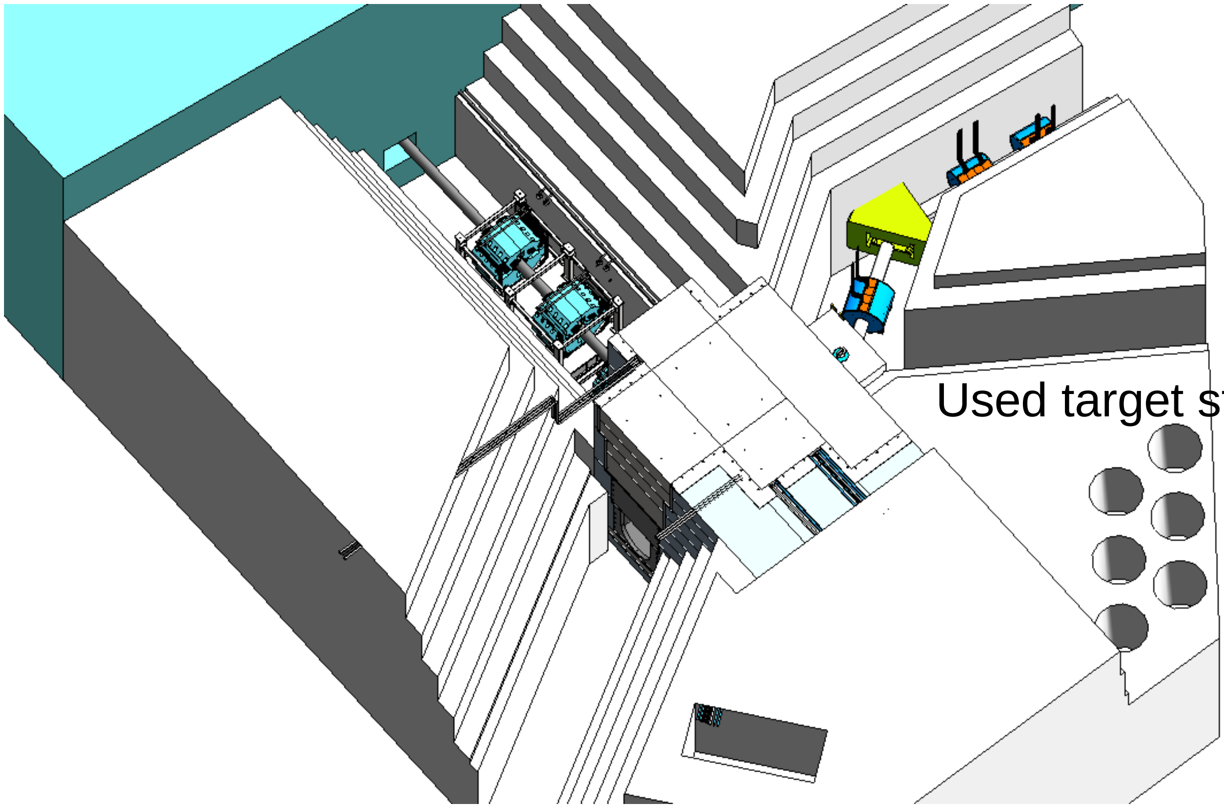
(单位：mSv/h)

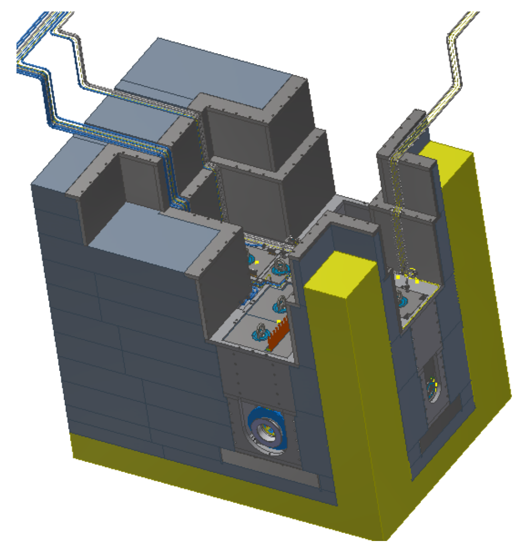
Prompt dose



Muon Target Station



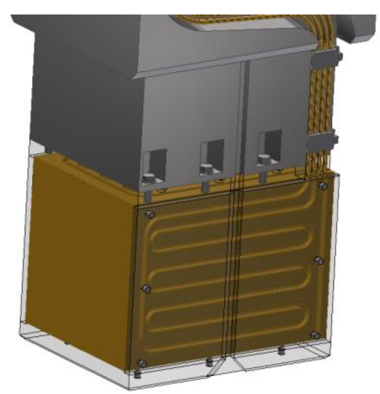




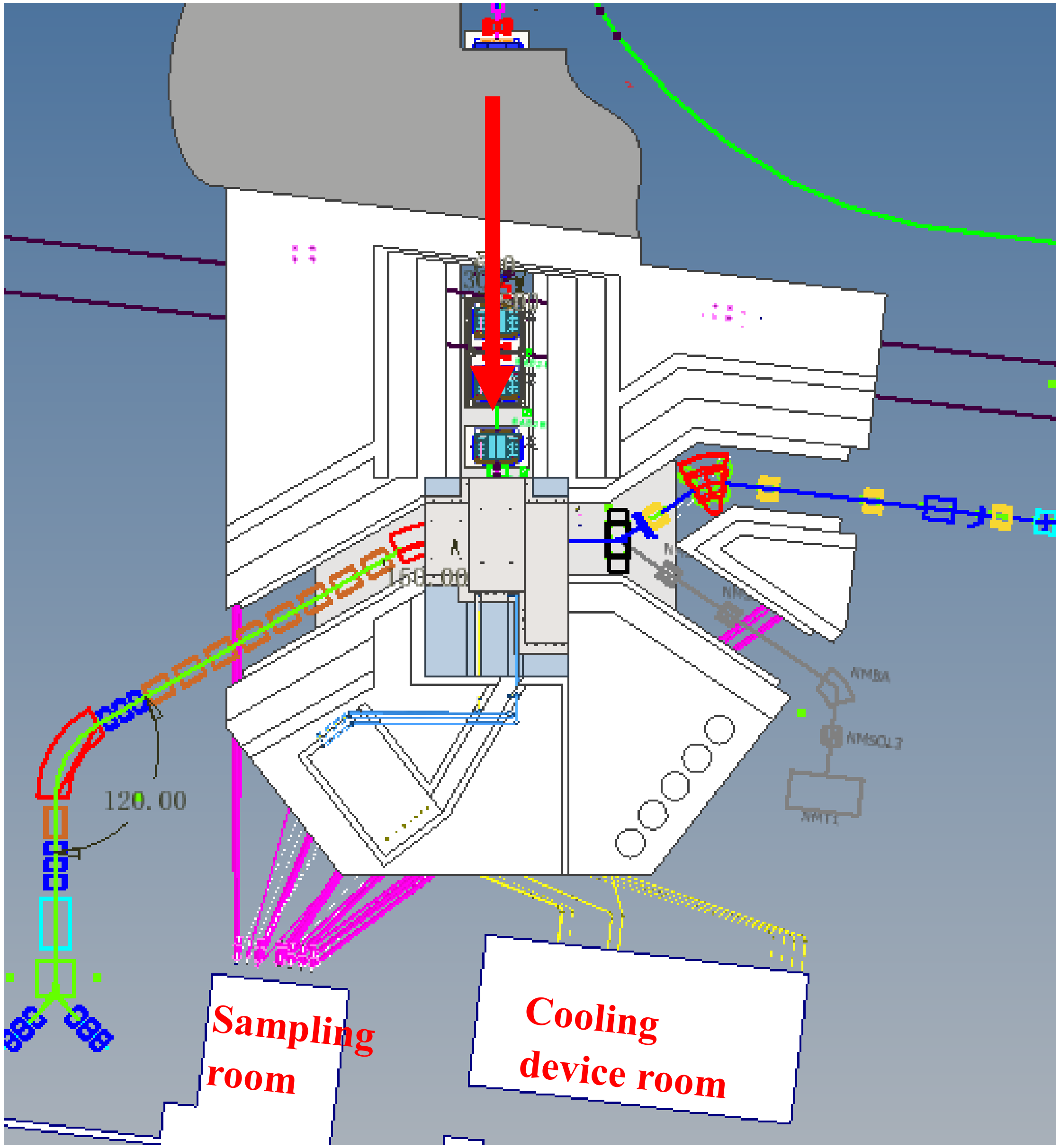
Shielding: Iron 5m*4m*4m

Concrete 5.5*5.5m*1m

Beam absorber: Copper



Target station

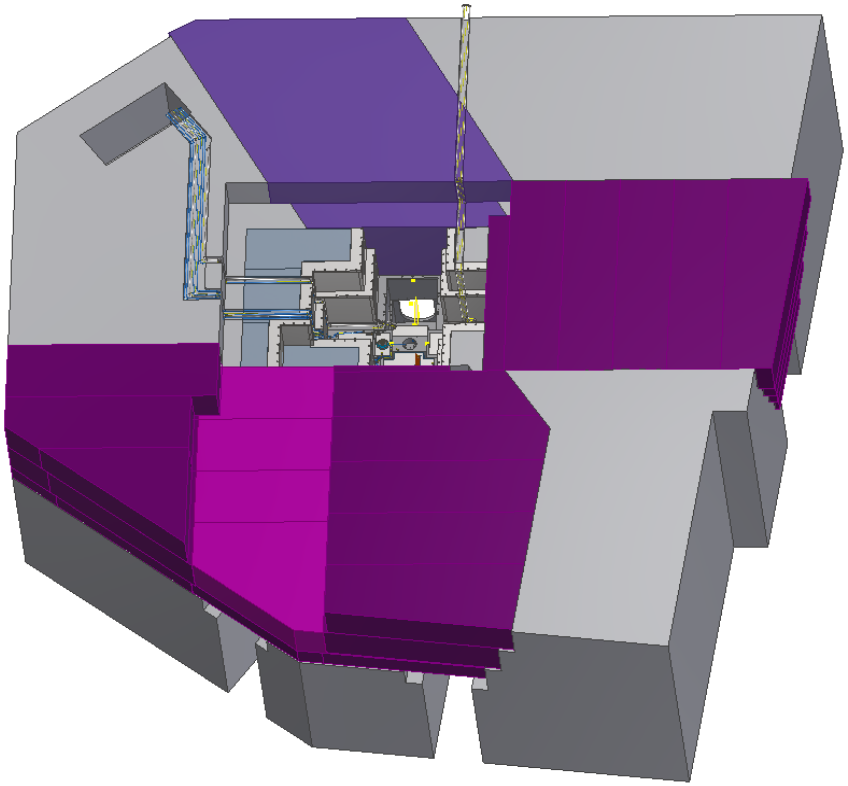


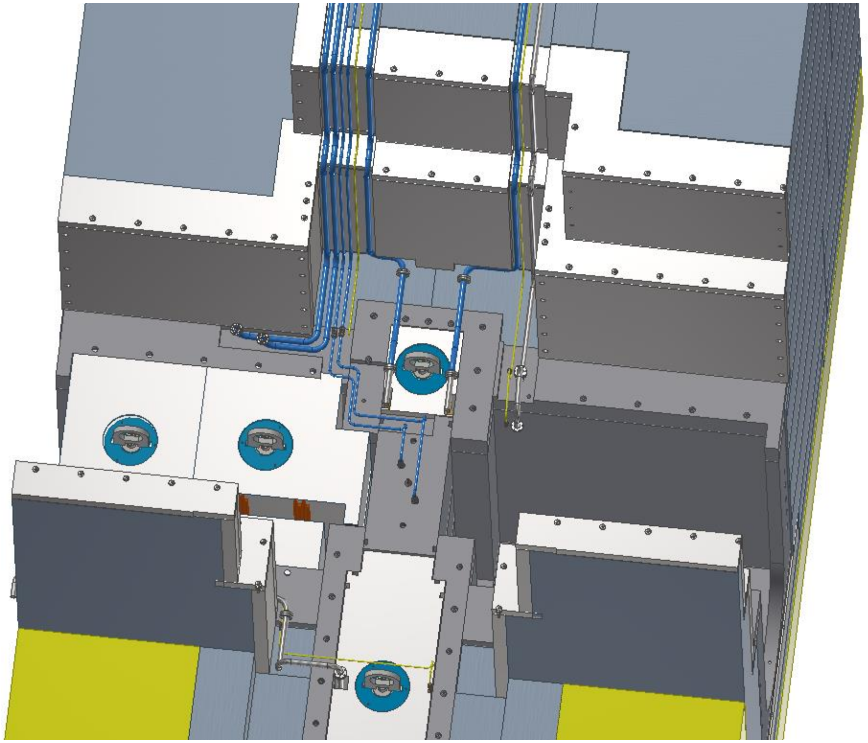
- Proton beam
- Iron shielding
- Concrete shielding
- Muon tunnels
- Delay tank
- Used target storage

- Cooling device rooms (underground)
- sampling room

Gas and water Pipes/Cables

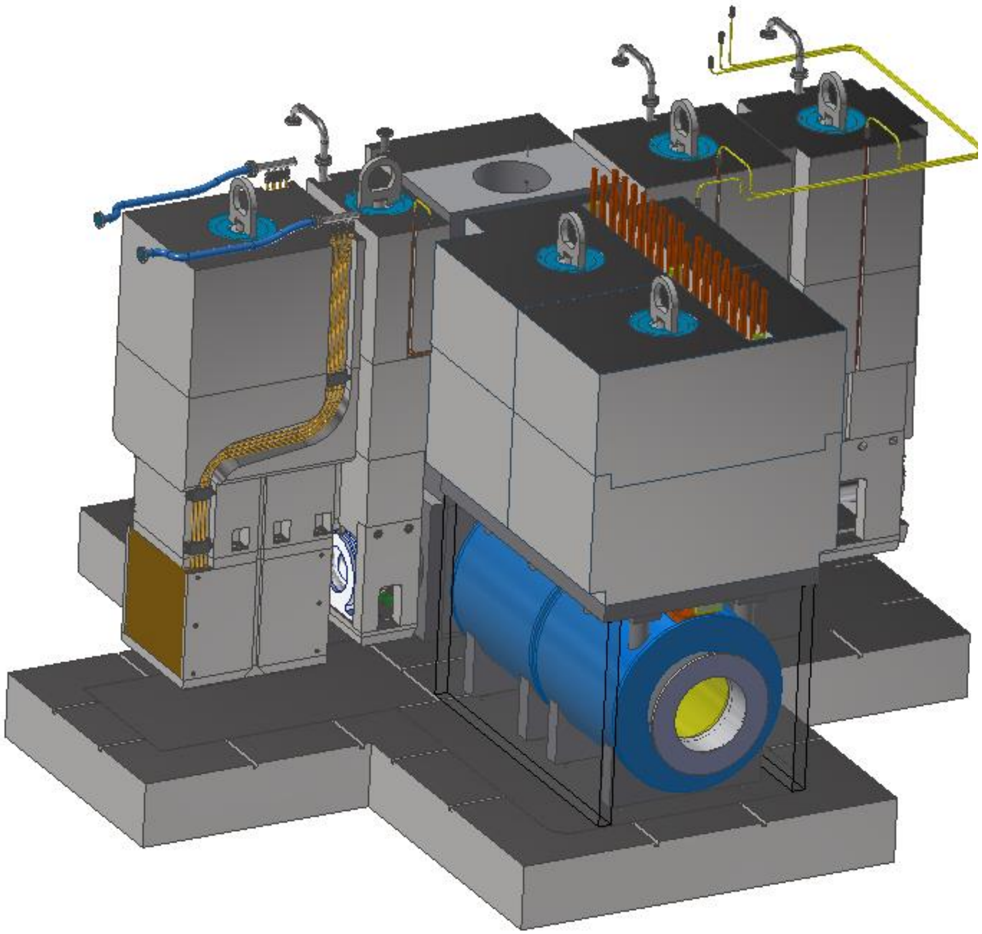
All connections are on top of the shielding, 2.2m above the beamline, radiation dose below 1 mSv/h

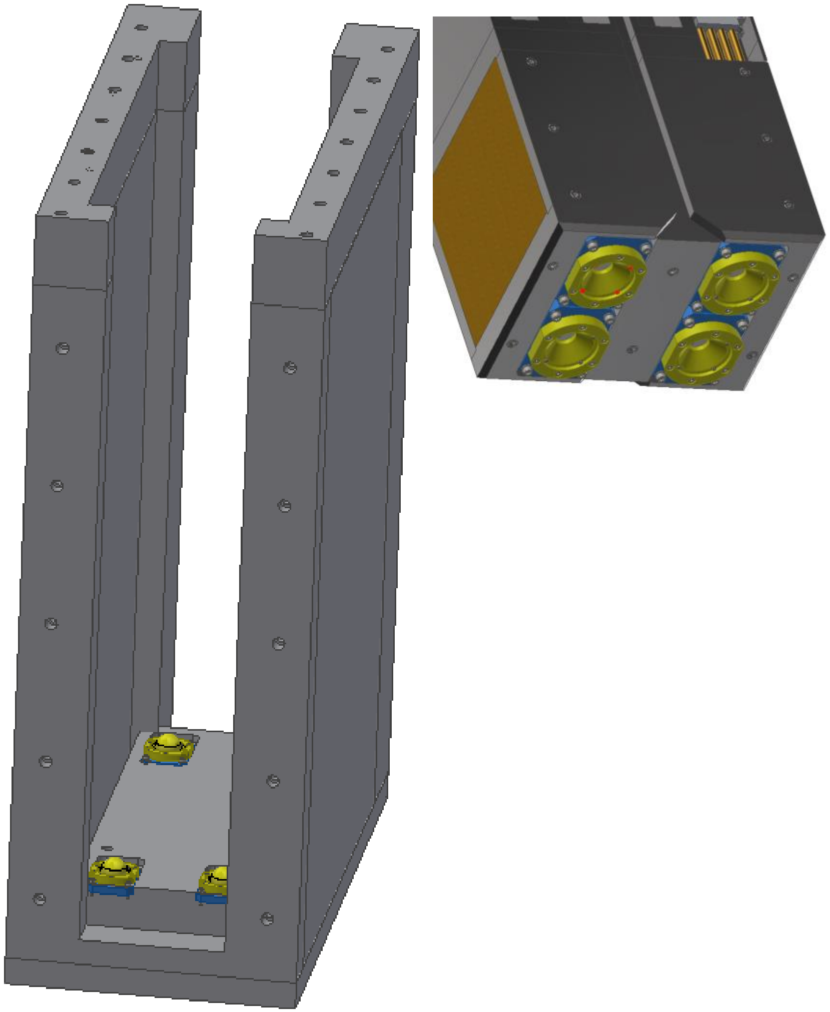




Positioning of magnets

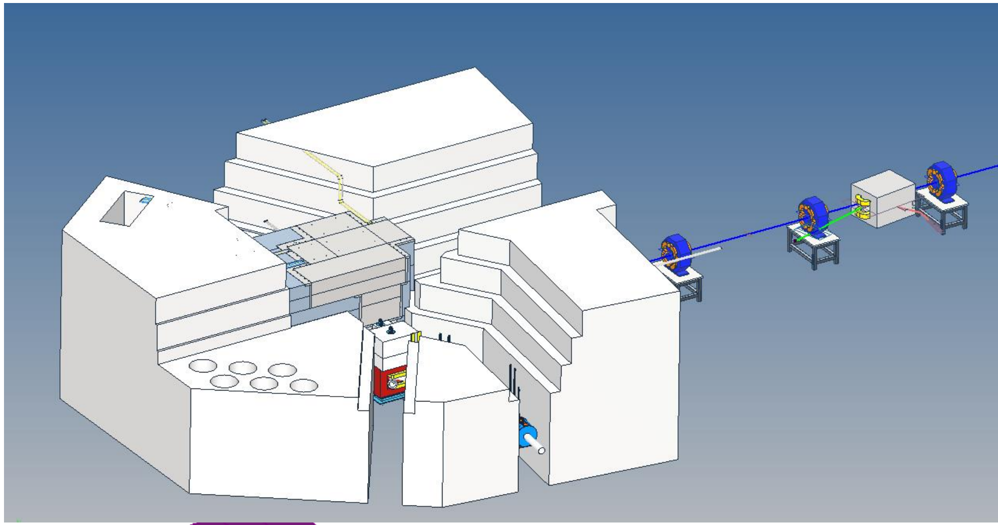
Sockets on the floor

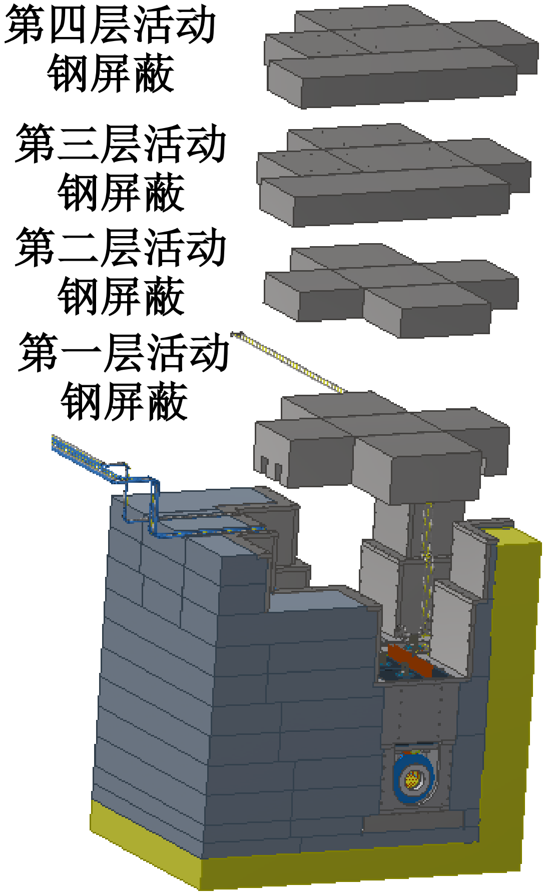


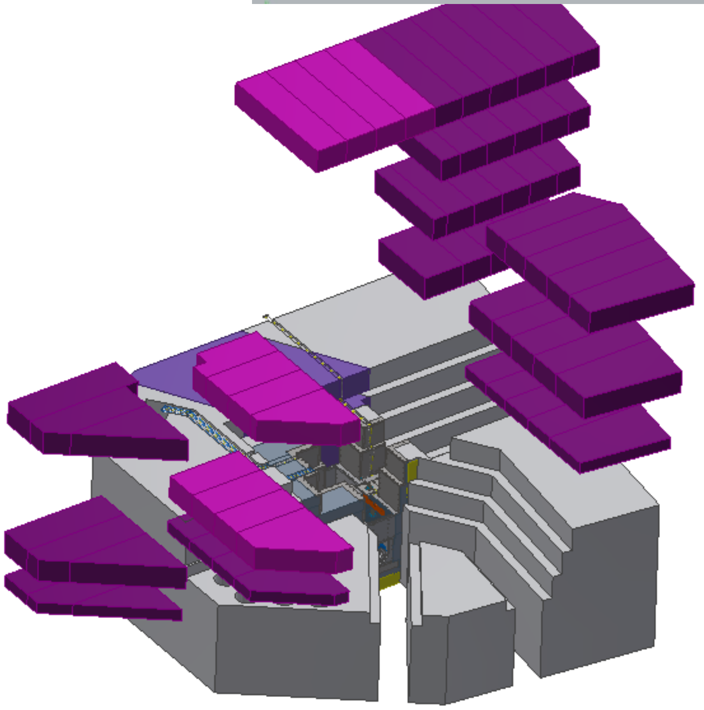


Removable shielding

NEED TO BE SEELED for air tight!

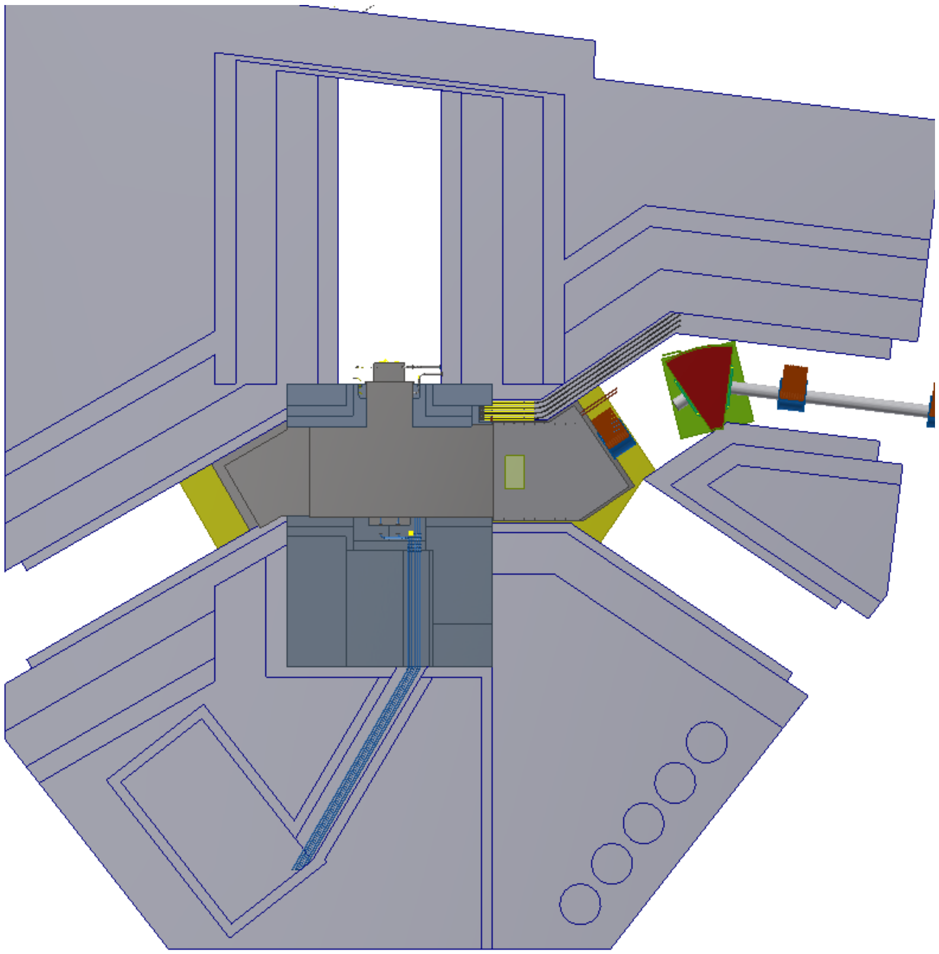


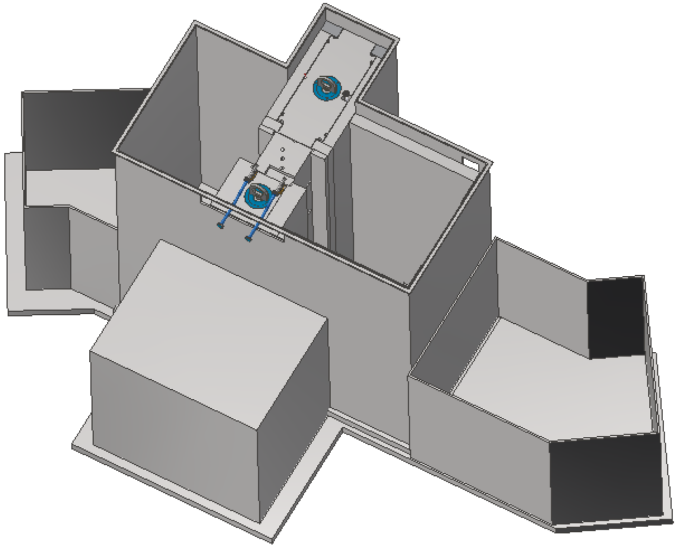




solution for gas tight

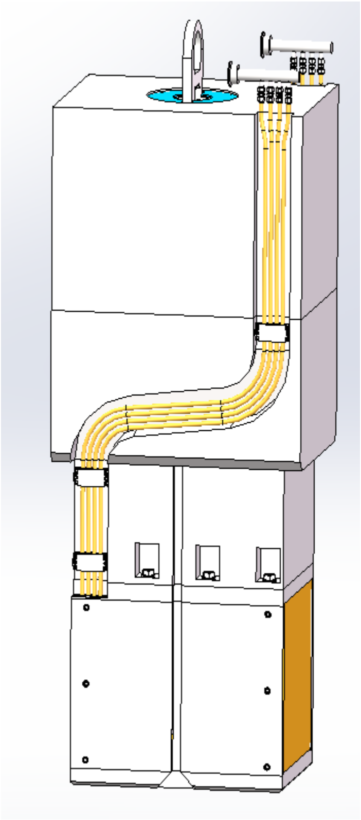
- Use a gas tank to Wrap the radiated air up
- Problem: increasing the difficulty of maintenance



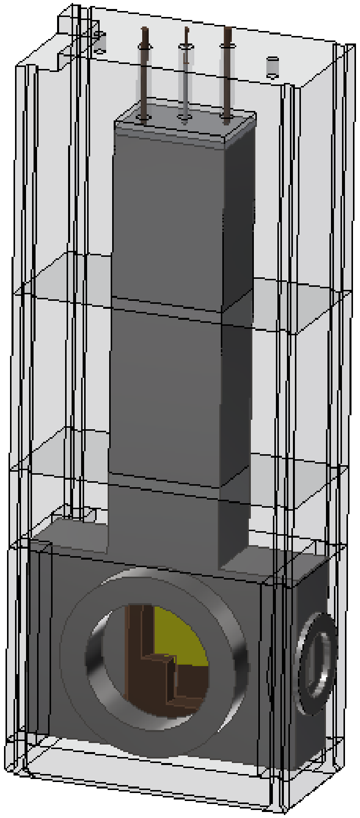


Remote maintenance

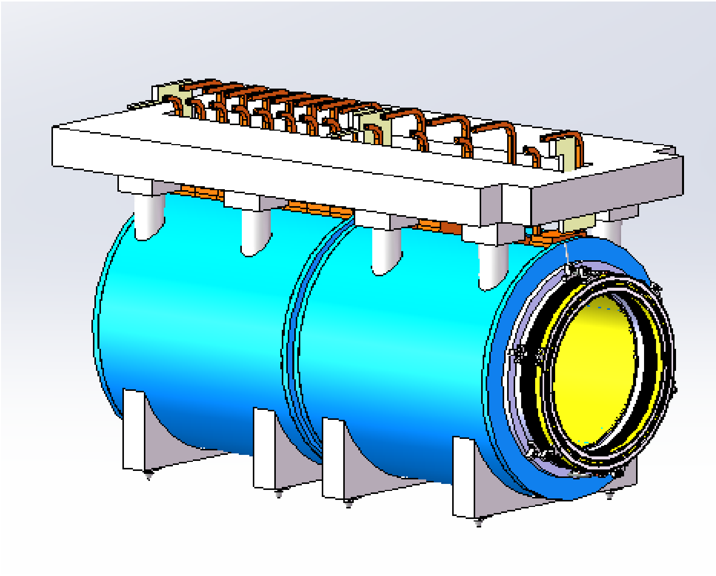
- 4 equipment to be maintained 。
- All from the top of the shielding, cut connections from 2.2m above the beamline



Proton dump

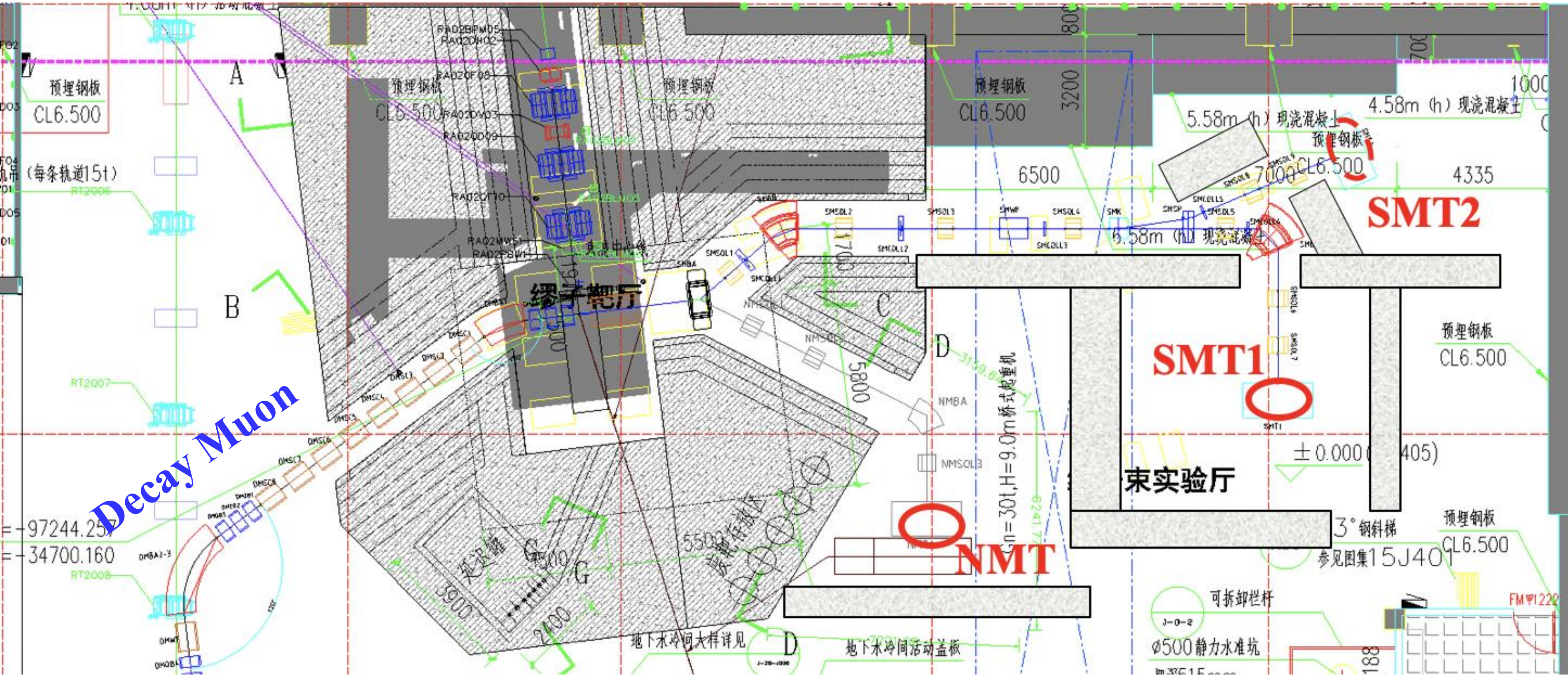


Target chamber



magnet

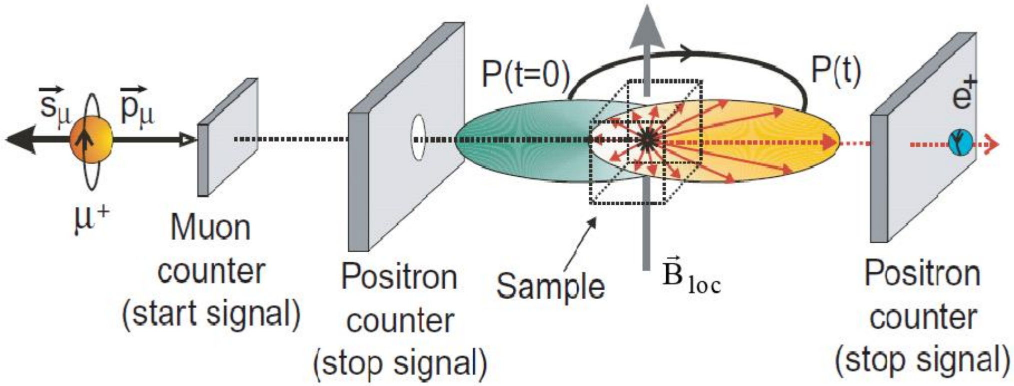
Surface Muon Beam

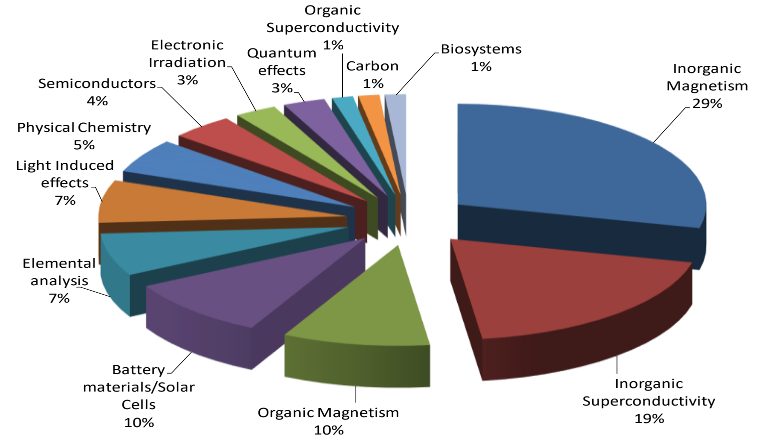


- **Energy：4 MeV**
- **Polarization: >95%**
- **Intensity：10^5~10^7 μ^+/s**
- **Time Resolution: 120ns**

Surface Muon application

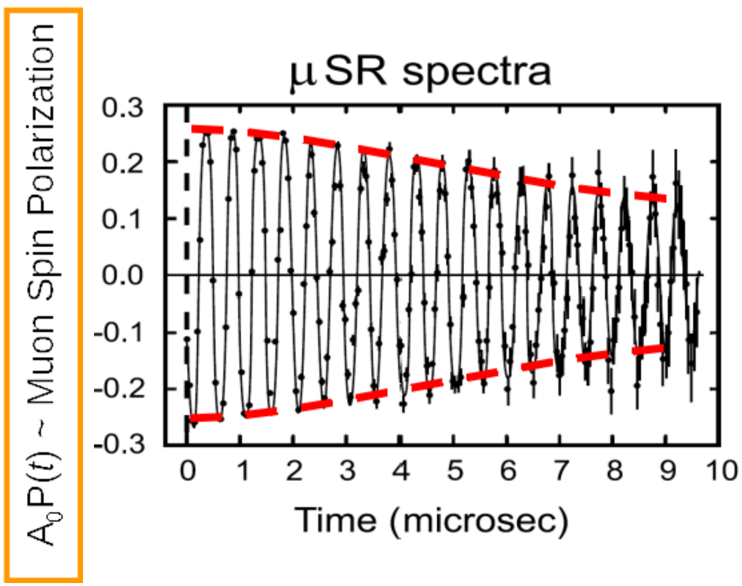
Principle of MuSR





MuSR： **Magnetic material, superconductivity, battery, semiconductor**

Advantage： **high magnetic sensitivity, short range magnetic order, all element**



$A_0P(t)$ contains the physics:

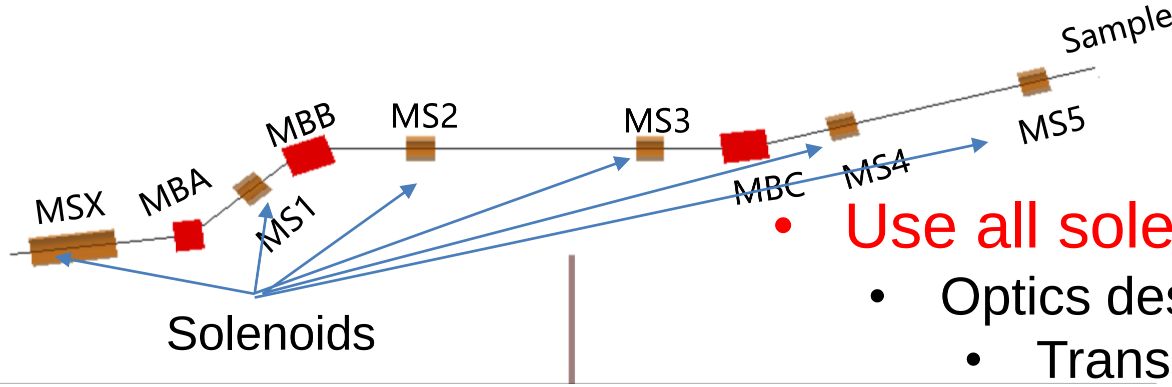
frequency: $\omega_L = \gamma_\mu B_{loc}$, value of field at muon site

damping: width of field distribution, fluctuations

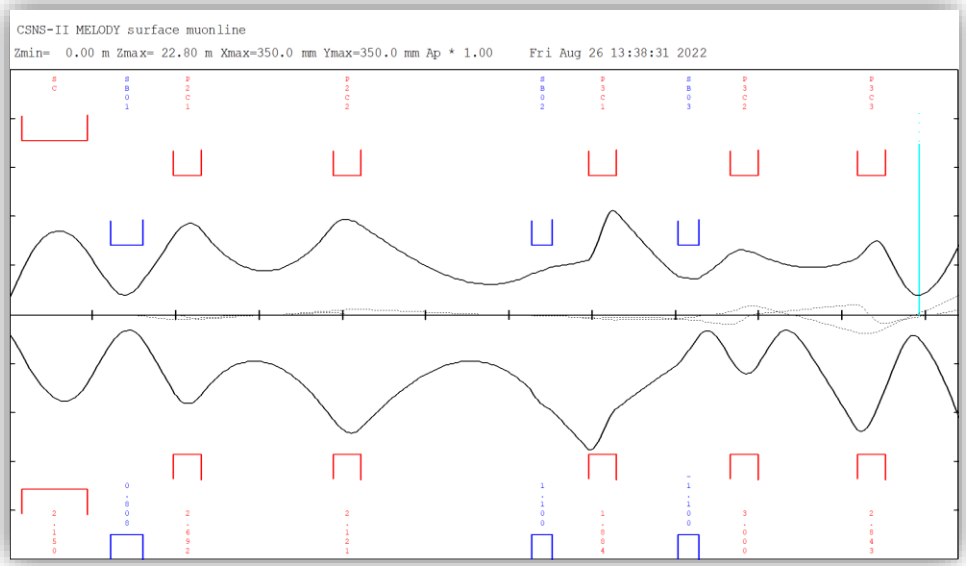
amplitude: magnetic/non-magnetic volume fraction, or Mu fraction

$A_0P(t) = [F(t) - B(t)] / [F(t) + B(t)]$

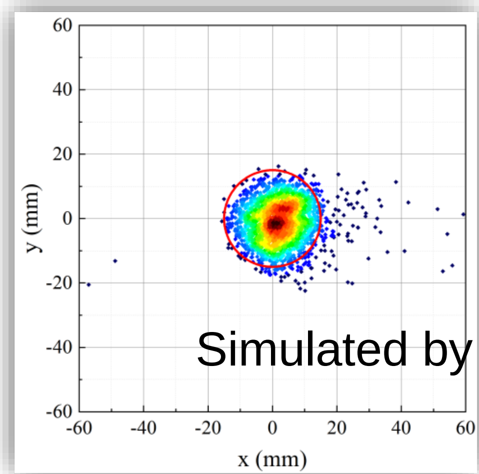
Surface Muon Beamline Design



- Use all solenoids for focusing
  - Optics design :
    - Transport
  - Simulation:
    - G4beamline with 10^{11} POT
  - Fringe field shielding:
    - Reduce the fringe field at sample position



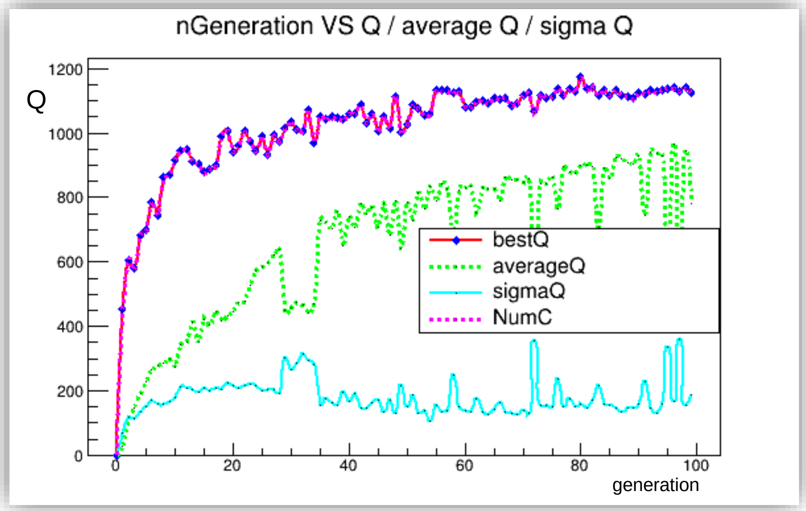
Designed by Transport

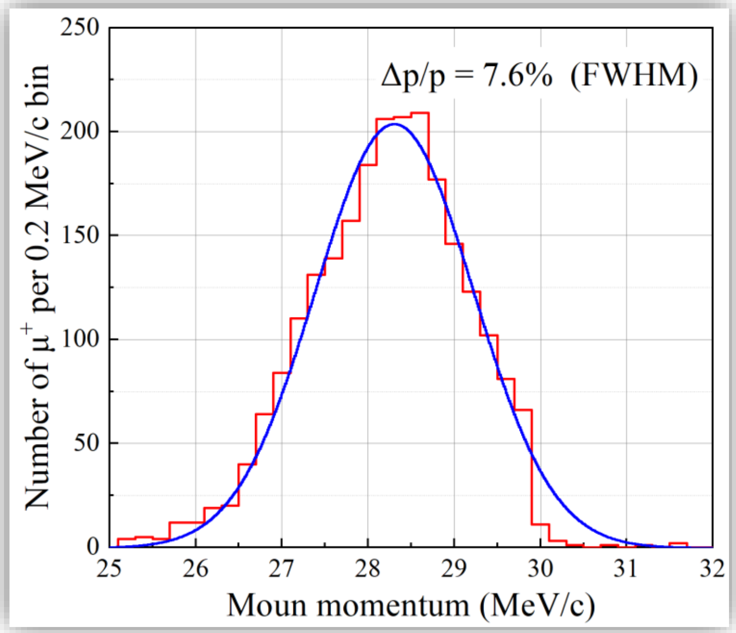


Simulated by G4beamline

Optimization by A.I.

- Maximize the number of muons in the Φ=30mm sample area
- Set the strength and positions of the 6 solenoids as tune parameters
- Start from a set of random parameters

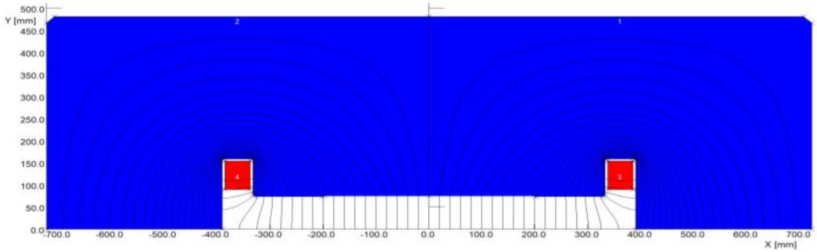




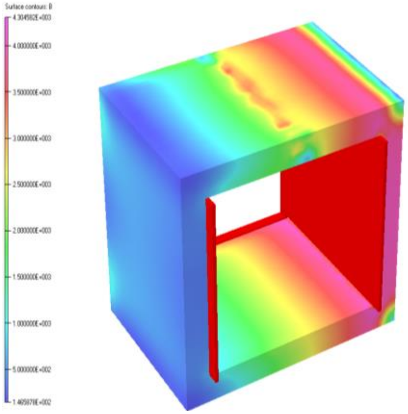
Parameters	G4bl simulation
x (FWHM)	1.64 cm
y (FWHM)	1.84 cm
$\Delta p/p$ (FWHM)	~ 7.6%
μ+ rate	$18.2 \times 10^5\ \mu^+/s$
μ+ rate on ϕ30 mm	**$15.7 \times 10^5\ \mu^+/s$**
Core ratio	91.24%
Polarization	**~ 95%**
e^+/μ^+	<0.01

Technique design of the magnets

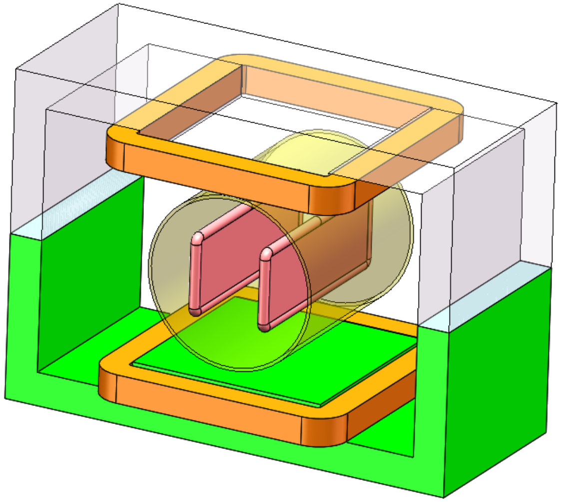
Dipole

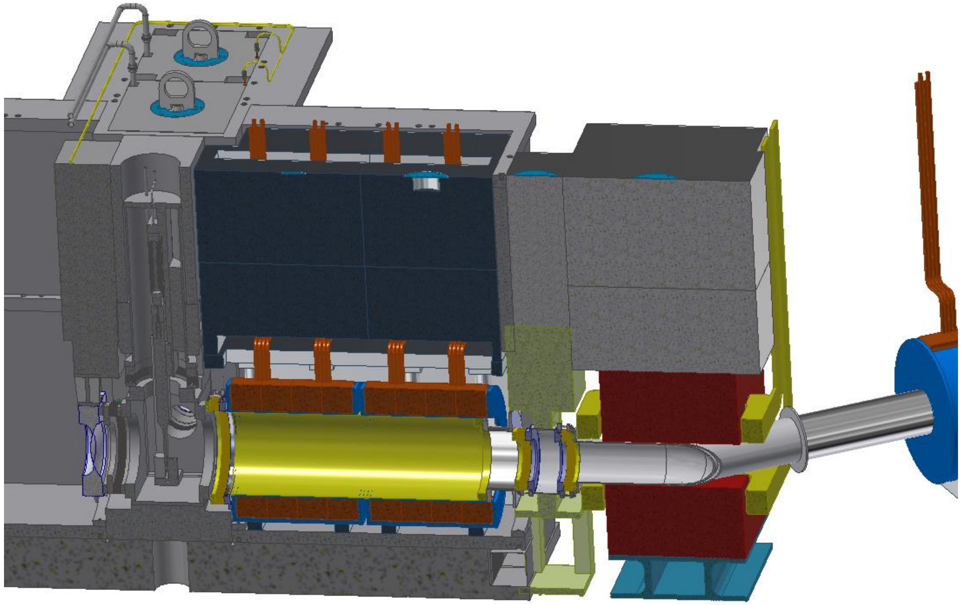


Kicker



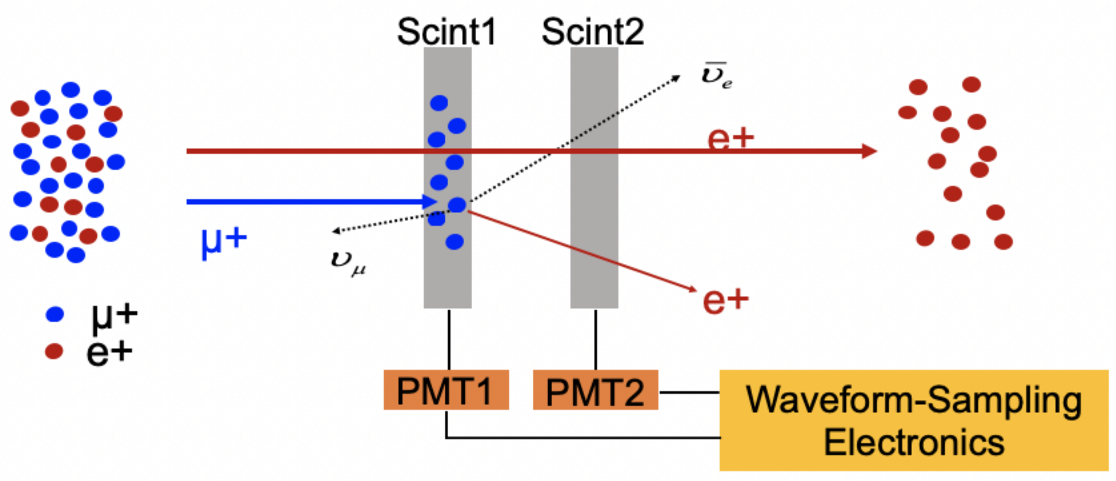
Wein fielter

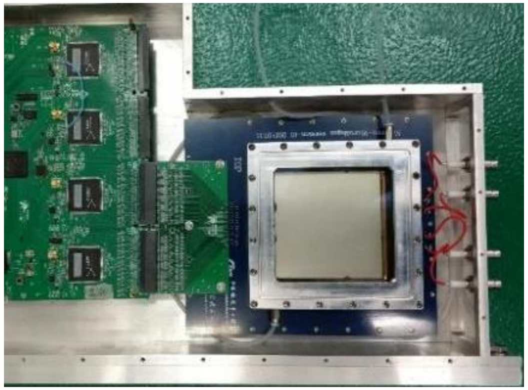




Mechanical design of the magnets

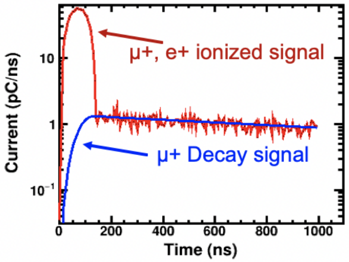
Beam measurement

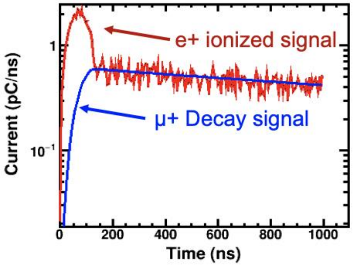




Beam spot monitor

Beam intensity measurment





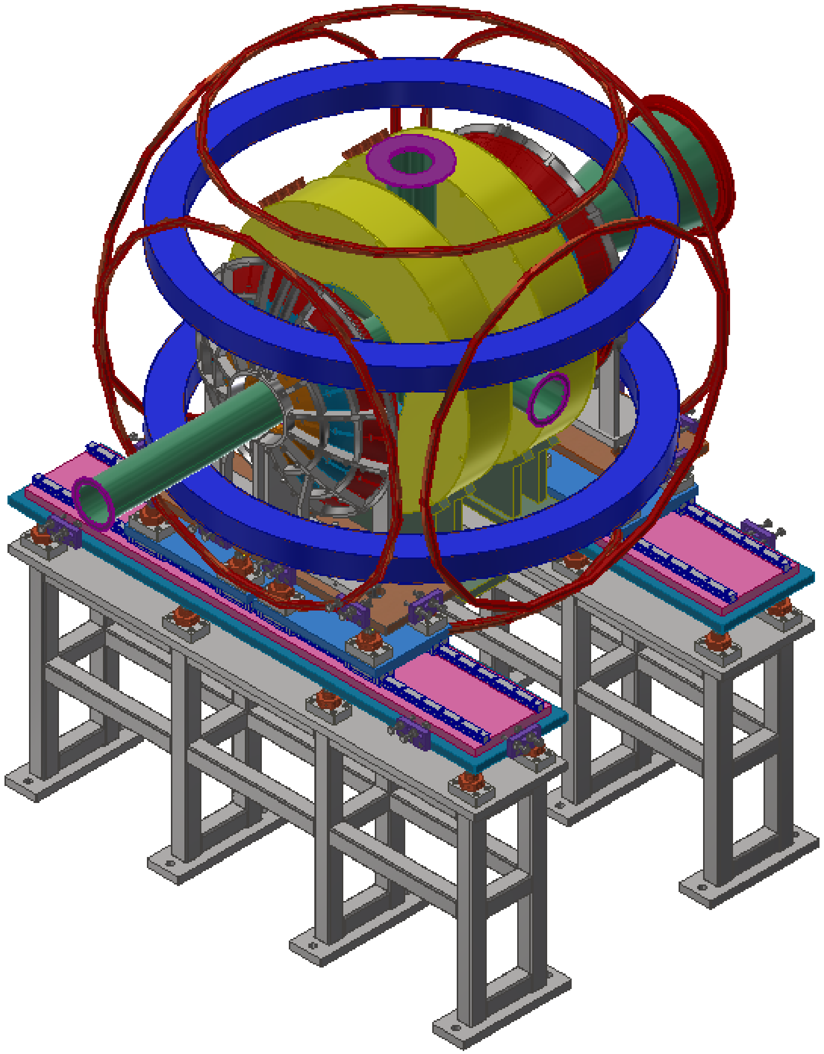
- Measure muon beam intensity by double scintillators
  - Distinguish positron content

- Measure beam spot size with a MicroMegas detector

- Challenge: high intensity in one pulse
  - Need more online tests

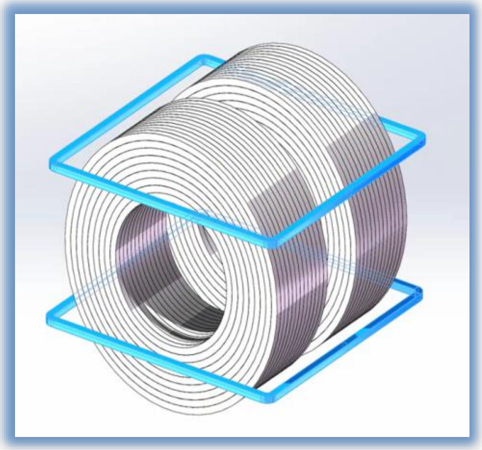
μSR Spectrometer

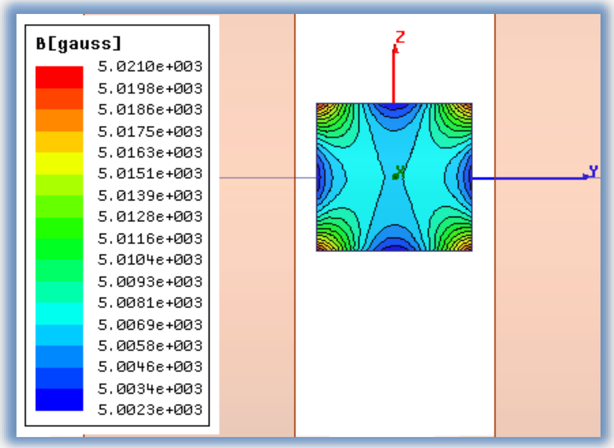
- **Feature:** High single-pulse intensity
- **Detector unit**: ~ 3000 detectors (scintillator+SiPM) pointed to sample
- **Electronics**: ASIC based FEE + multi-stop TDC
- **Fly-pass structure**

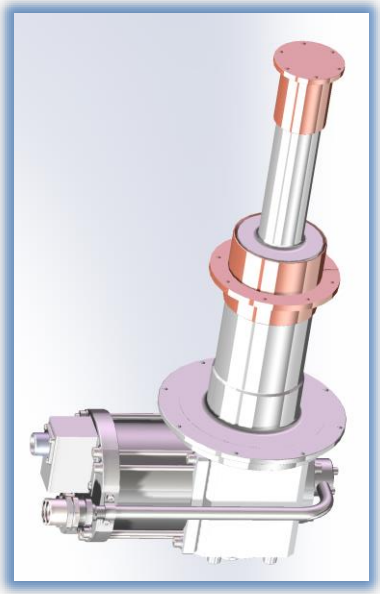


Sample Environment

- Magnetic field：
  - LF:5000G，TF:400G
  - Homogeneity < 100ppm @ 40*40*10mm sample area
- Low temperature：
  - Cryostat: 2 K ~ 300K (Start-up)
  - CCR: 10 K ~ 600K (Future)
  - Upgrade to 300mK (Future)

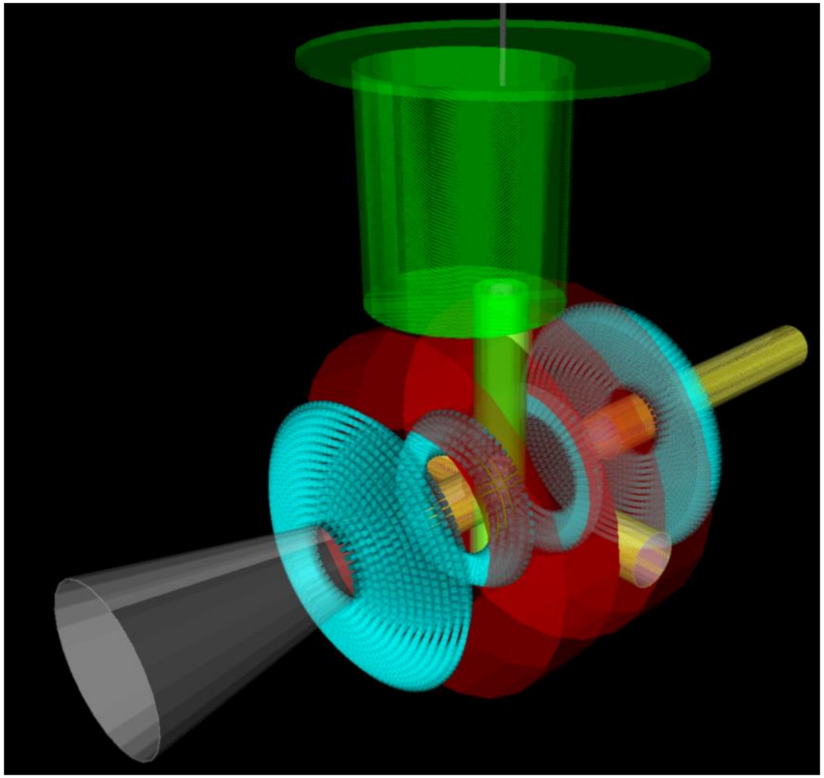


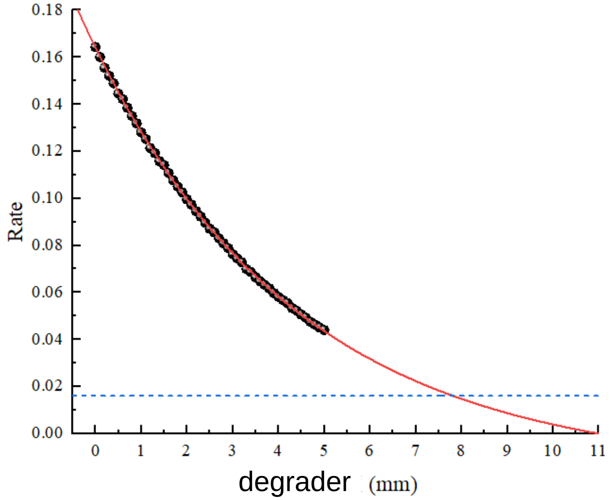


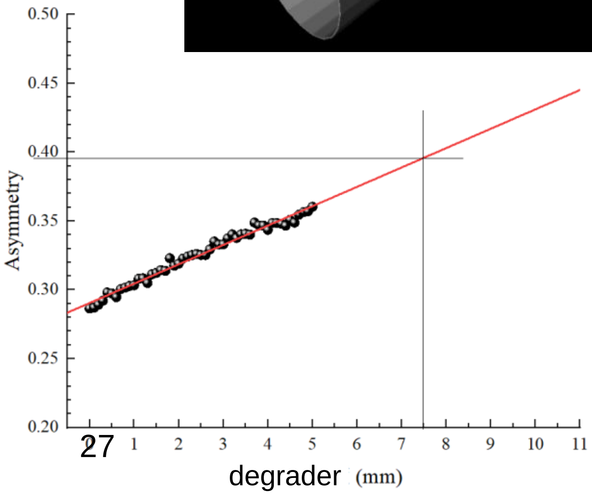


Simulation

- Investigated the boundary conditions:
- Use thick degrader to increase the Asymmetry
- Simulated results:
  - Counting rate: 80 Mevents/h
  - Asymmetry: 0.31





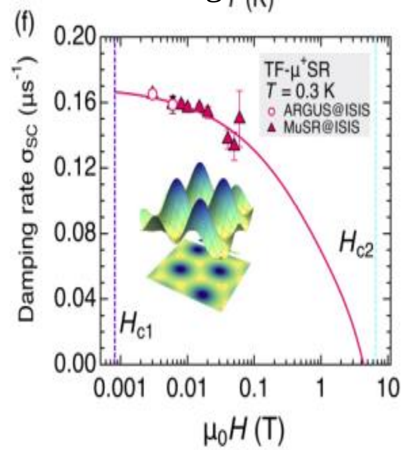


Pros and cons

- High single pulse intensity：
  - Weak relaxing signal detection
  - Small beam spot
  - Beam slice to 10ns

- High asymmetry：
  - High precision

Organic SC



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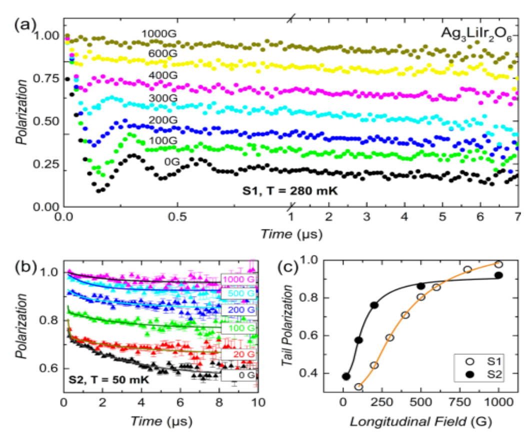
- Low repetition rate：
  - Low counting rate
    - ➢ More detectors

- Large pulse width：
  - Low time resolution
    - ➢ Beam slicing

Spin Liquid



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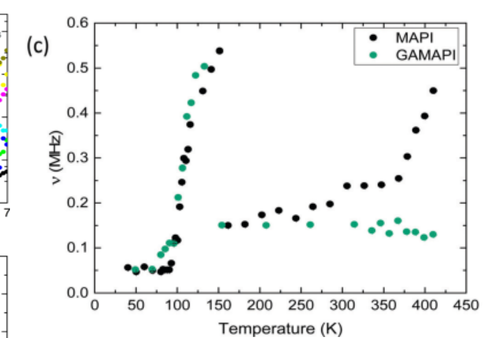
Batteries



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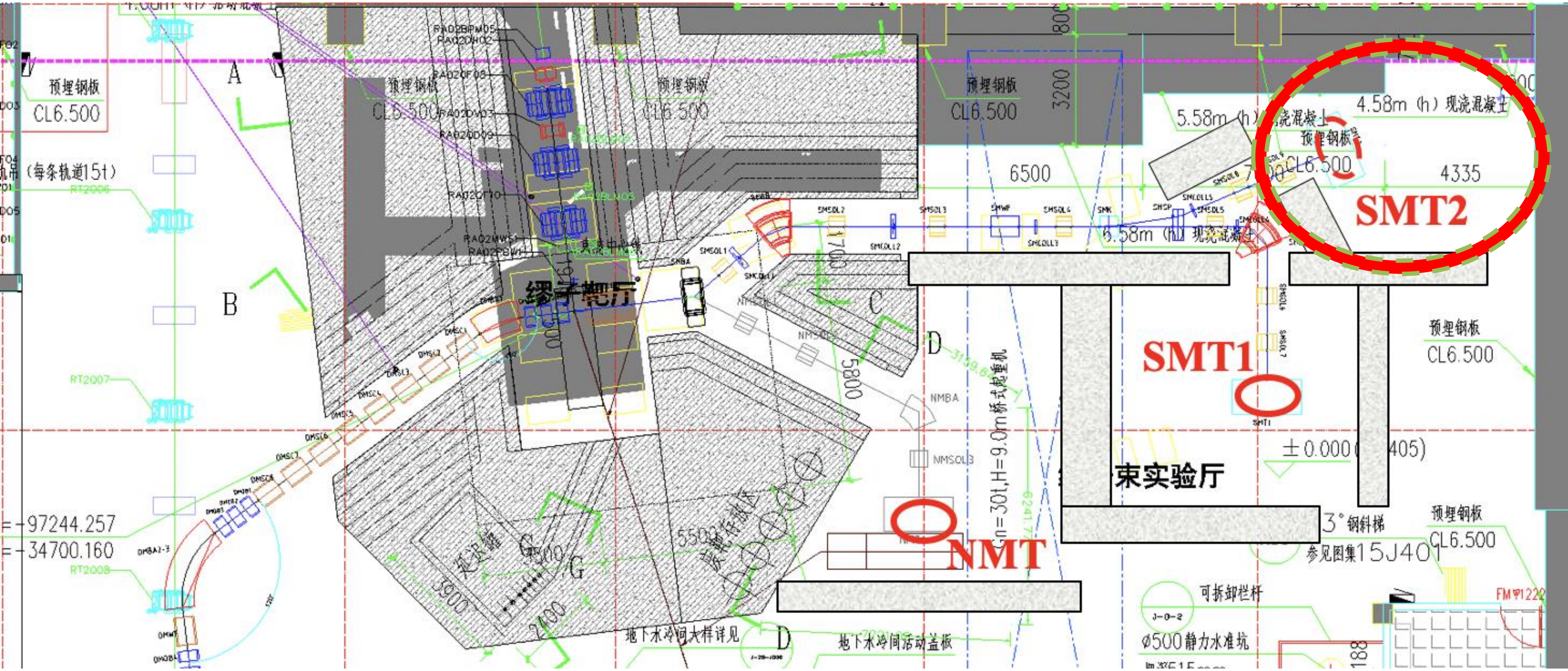
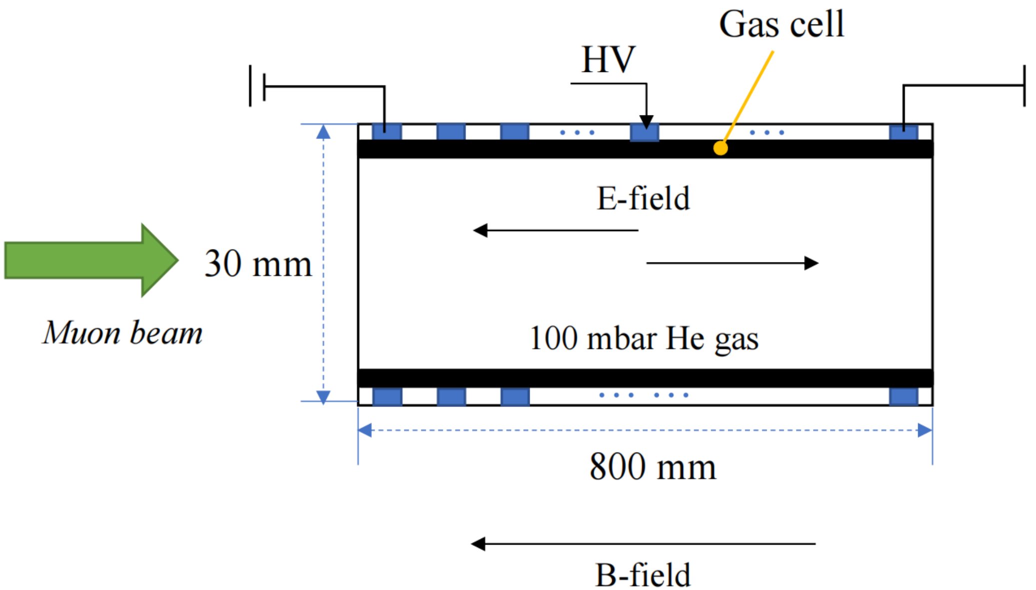
Test Beam Port



- **Energy：4 MeV**
- **Polarization: >95%**
- **Intensity：10^5~$10^7 \mu^+$/s**
- **Time Resolution: 120ns**

Muon moderation technology



- μ^+ beam: 28 MeV/c, $\frac{\Delta p}{p} = 8\%$ (FHWM), $10^6\ \mu^+$
- Beam spot size: ϕ10 mm
- Energy degrader: 0.78 mm–thick carbon foil
- He gas: 100 mbar, 293 K
- Gas cell: ϕ30 mm, length 800 mm
- Electric field: ~ 0.11 kV/mm; HV applied at the center of the gas cell, i.e., decelerating (accelerating) E–field for the first (second) half
- Magnetic field: 5 T

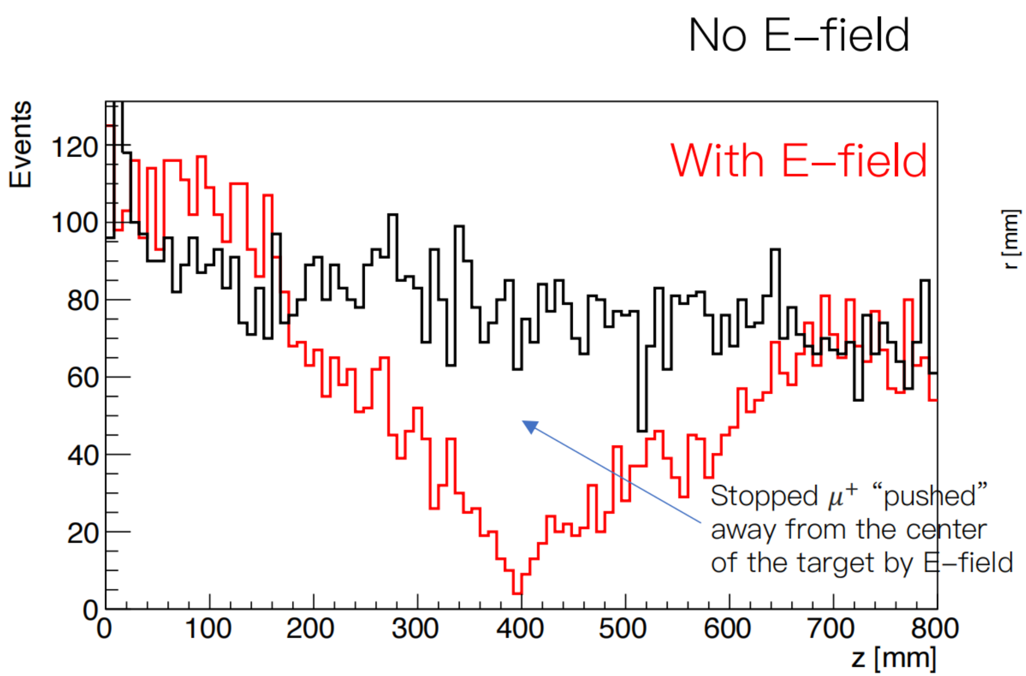
- Use helium gas to stop muons
- Use electric field to steer muon out of the gas cell
- Bring 0.1% muons to 300 eV

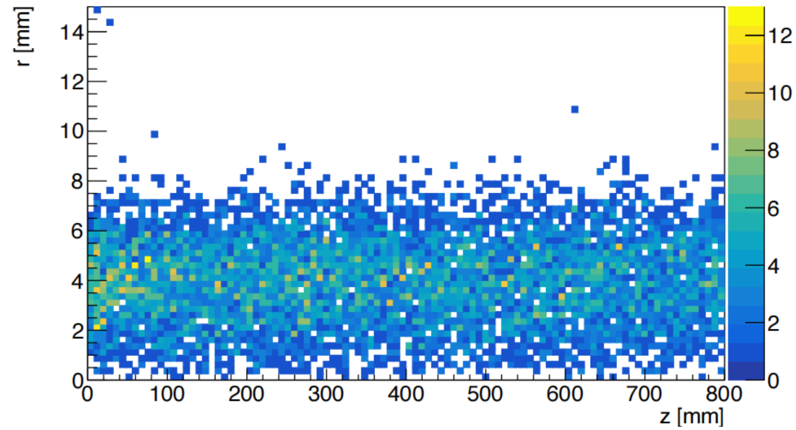
Key: use ESD material to remove the charge and to avoid breakdown in helium gas

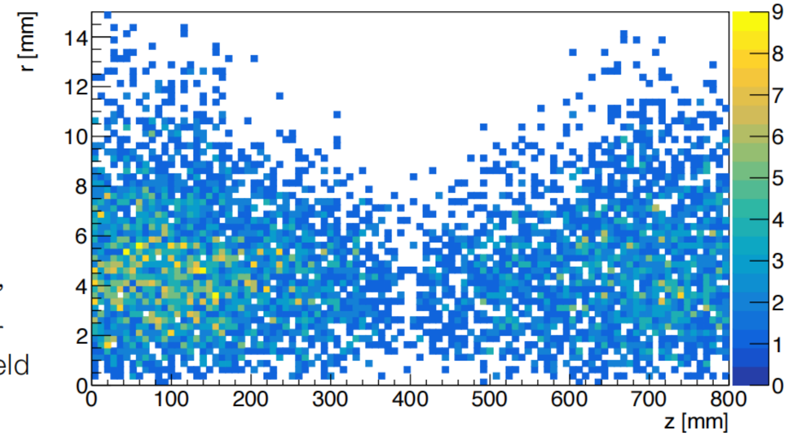
Muon moderation technology

Simulation

μ^+ stopped in He gas





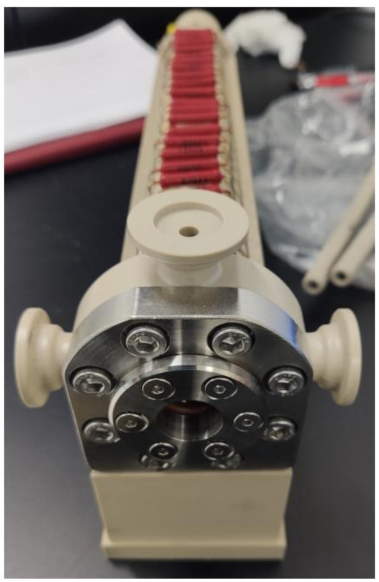


Going to be tested at ISIS...

Muon moderation technology

FCD Experiment

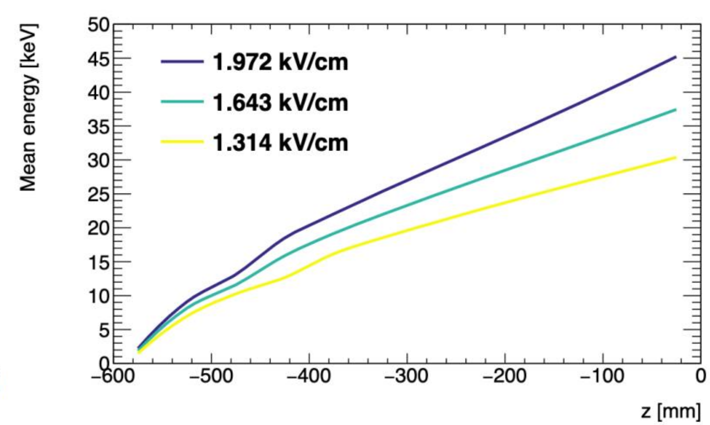
Gas cell



Proton source:
Am–241 + Mylar foil

Frictional cooling demonstration experiment with proton

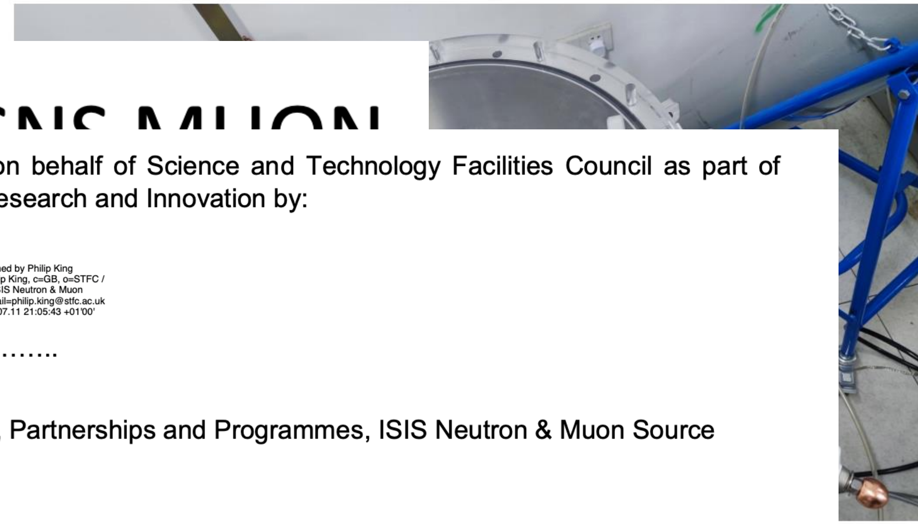
G4bl simulation
He gas: 1 mbar, 293 K
Proton initial energy: 1 eV
Proton initial z ~ –600 mm



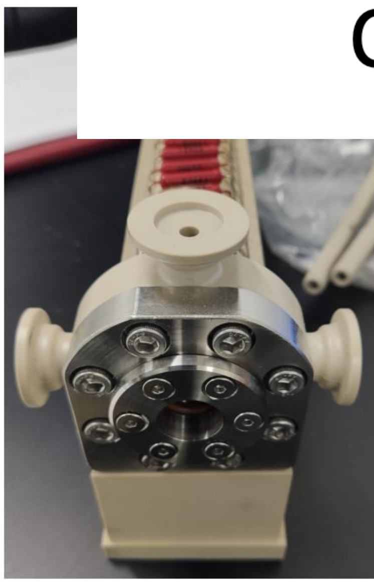
Muon moderation technology

FCD Experiment

Frictional cooling demonstration experiment with proton



MOU FOR IS... CSNS MUON COLLA...



Proton s...

Am–241 ...

SIGNED for and on behalf of Science and Technology Facilities Council as part of United Kingdom Research and Innovation by:

Philip King Digitally signed by Philip King DN: cn=Philip King, c=GB, o=STFC / UKRI, ou=ISIS Neutron & Muon Source, email=philip.king@stfc.ac.uk Date: 2023.07.11 21:05:43 +01'00'

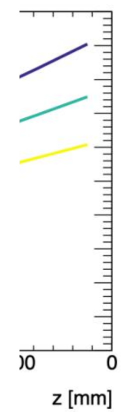
……………………………

Philip King
Associate Director, Partnerships and Programmes, ISIS Neutron & Muon Source

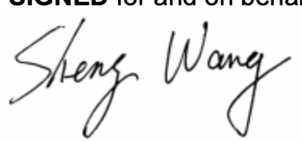
11 July 2023

……………………………

Date



SIGNED for and on behalf of the China Spallation Neutron Source by:



……………………………

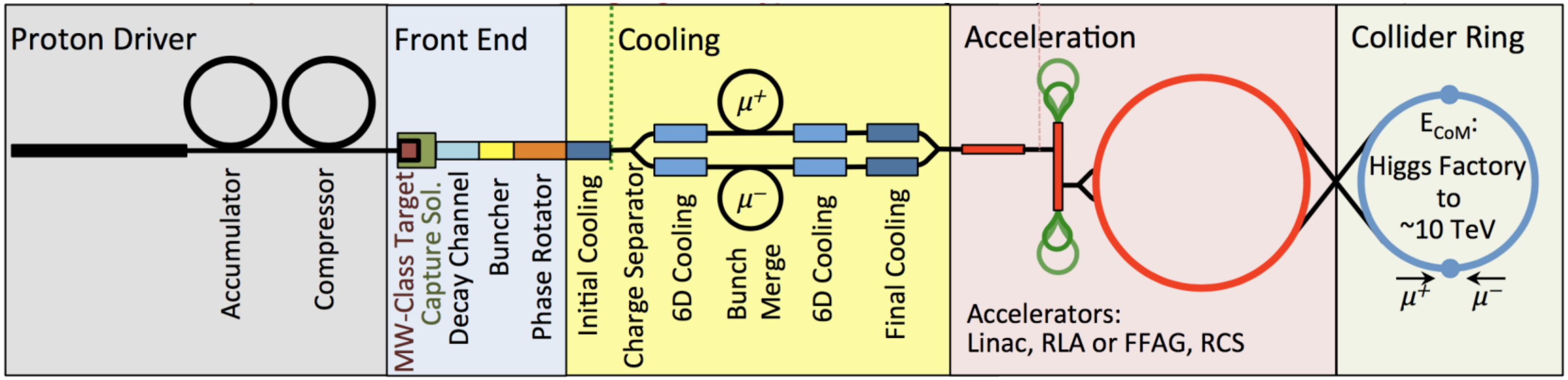
Professor Sheng Wang
Director, China Spallation Neutron Source

18 July 2023

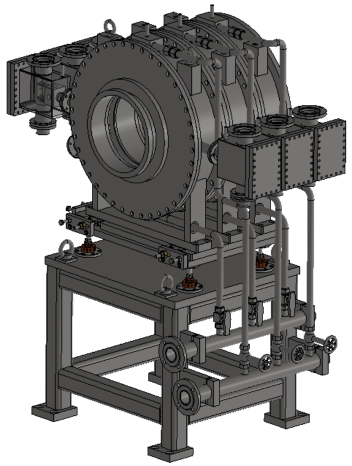
……………………………

Date

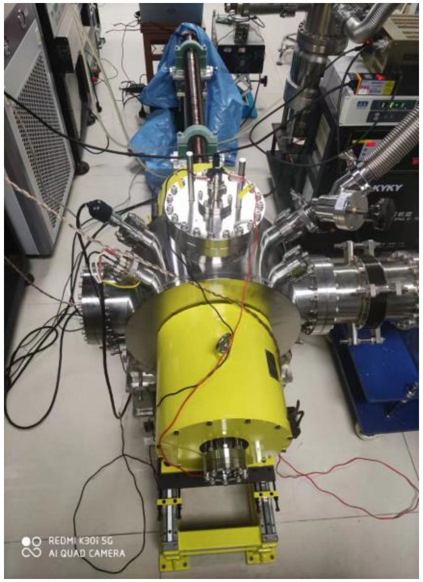
Muon acceleration/ Muonium/ PKMuon



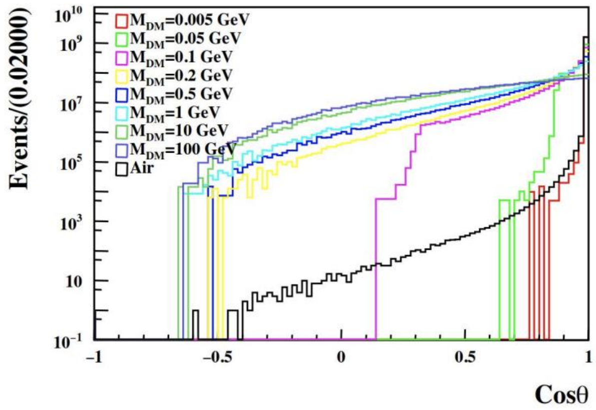
- Develop technologies for future muon experiments



Induction cavity for phase rotation



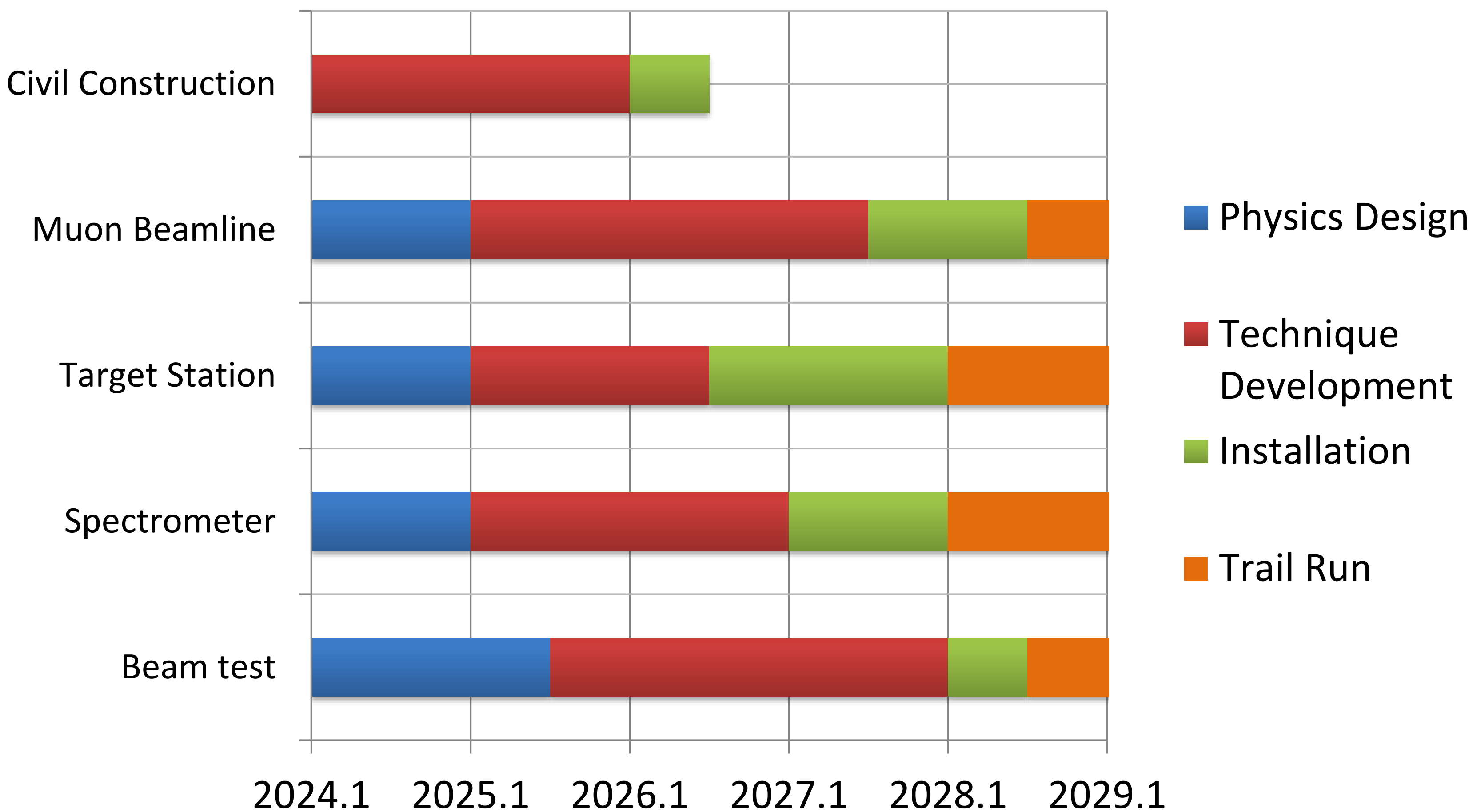
Magnetic mirror for muonium physics



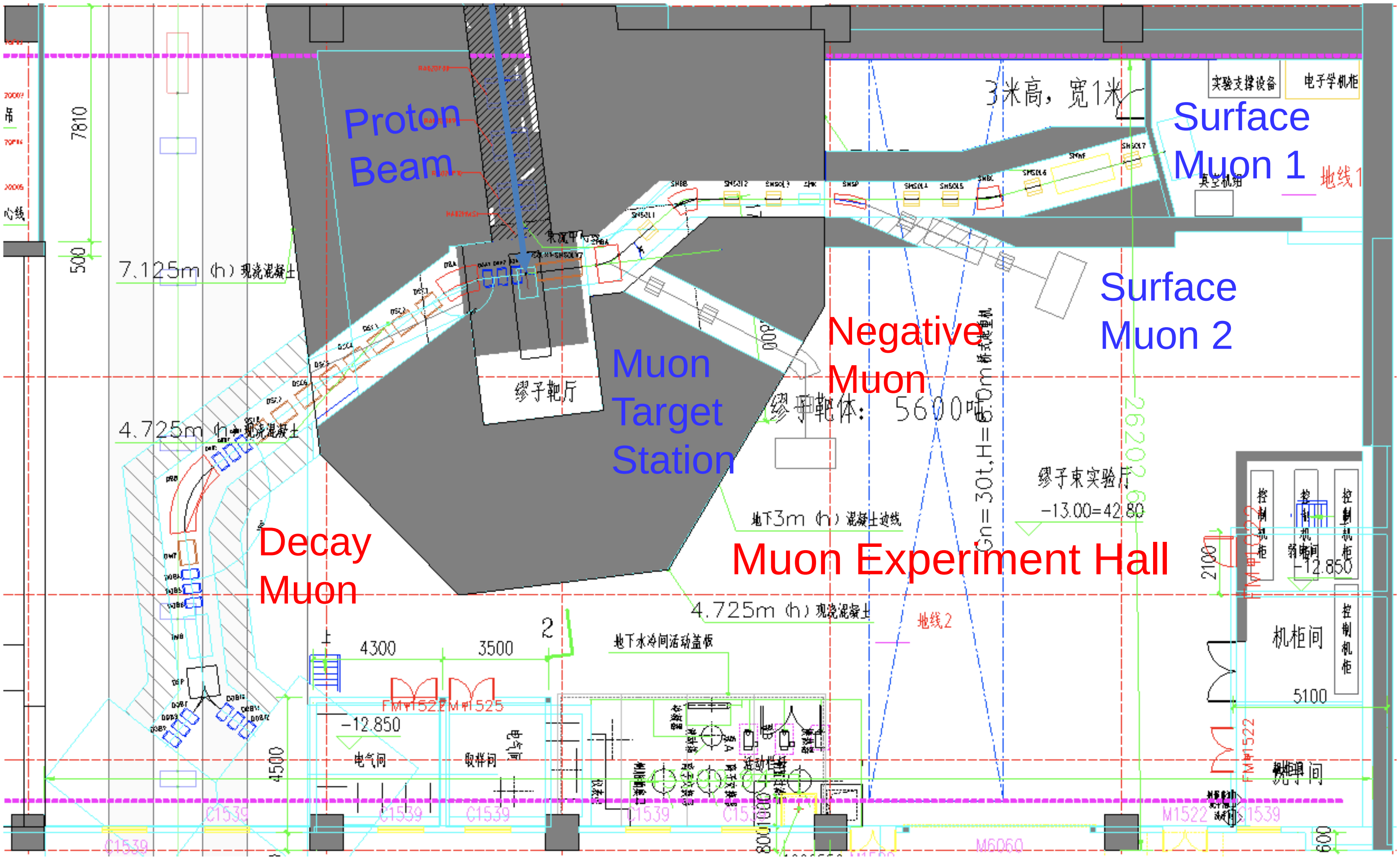
PKMuon

Timeline of MELODY

Project has been approved and will be built in 5years.



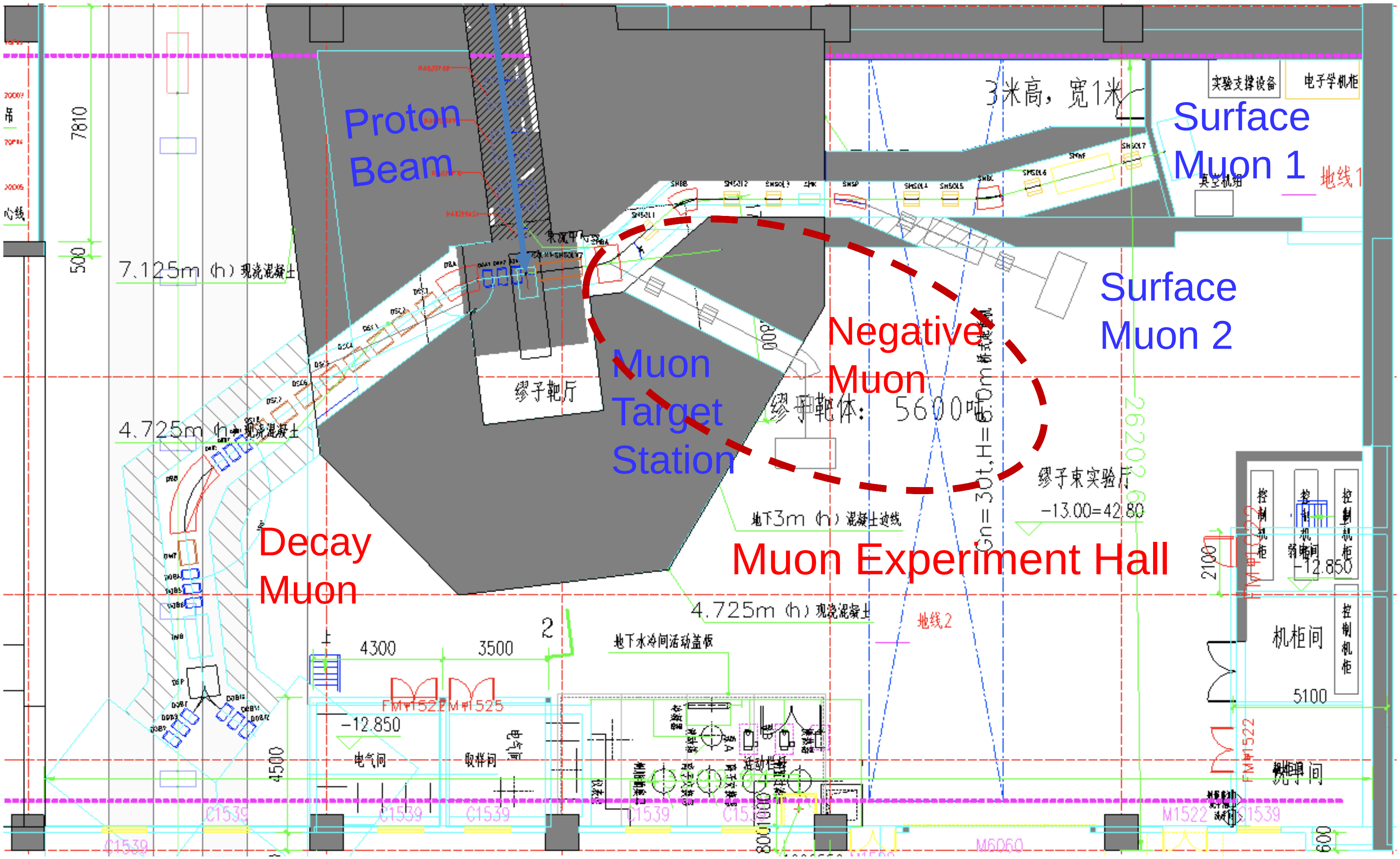
Prospect with MELODY II



- Pion/Decay muon beam：120MeV/c
- Negative muon beam: 30MeV/c
- Higher repetition rate: up to 5 Hz

- More terminals：
  - Various spectrometers
  - Muon imaging
  - Muonic X-ray

μ⁻ for MIXE



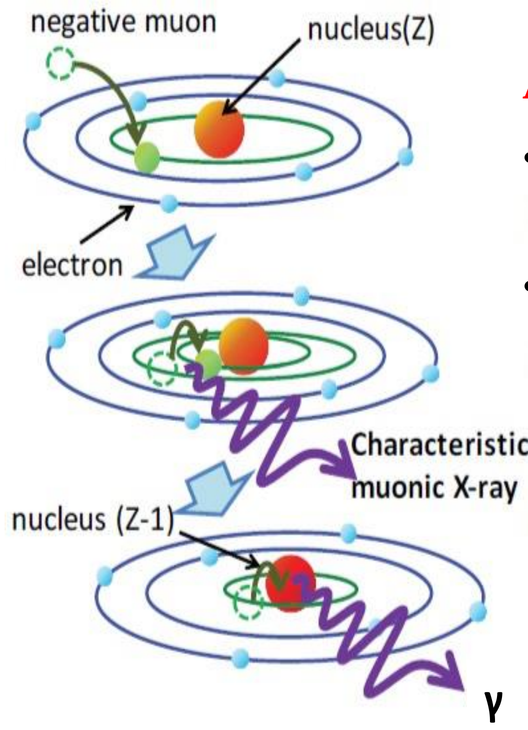
- Negative muon beam:
  - Momentum: 30MeV/c
- More terminals：
  - Various spectrometers
  - Muon imaging
  - Muonic X-ray

Muon Induced X-ray Emission

μ^- capture in the atom（Muonic atom）

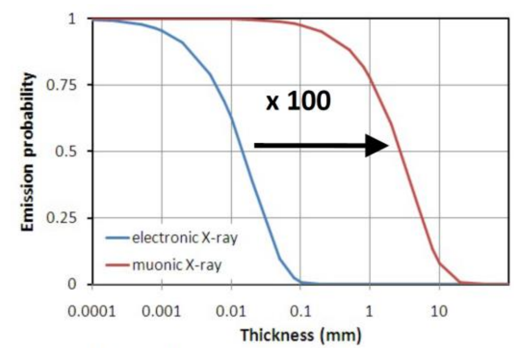
μ^- induce the X-ray to the ground state

μ^- decays or captured by the nuclei, and emits an gamma ray



Advantage of MIXE:

- **Un-destructive analysis for all elements**
- **Sensitive to C, N, O, which are not easy to detector in other methods**



X ray absorption efficiency in Cu

Fluorescence of Li, C, Cu and Muonic X-ray $K\alpha$

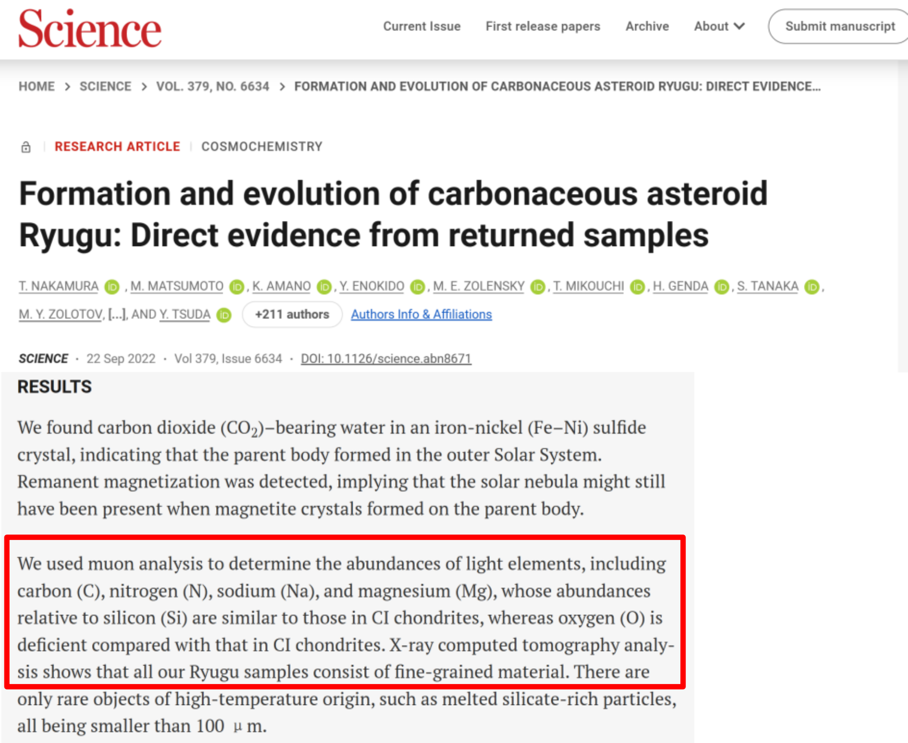
元素	Fluorescence $K\alpha$ [keV]	Muonic $K\alpha$ [keV]
Li	0.052	18.7
C	0.3	75
Cu	8	1500

Prompt Gamma Neutron Activation Analysis

Element	Molar mass A	Peak energy (keV)	Detector relative efficiency	Partial gamma emission cross section ($\times 10^{-24}$ cm)	Cps/mg
C	12.0107	4945	0.2674	0.00261	5.225 E−03
H	1.00794	2223	0.5785	0.3326	1.716 E+01
N	14.0067	10,828	0.0772	0.0113	5.603 E−03
Cl	35.453	786.3	1.1402	3.42	9.890 E+00
Cl	35.453	788.4	1.1383	5.42	1.565 E+01

MIXE Applications

1. **Asteroid or Moon samples**
   - Organic elements analysis（C、N、O）
   - Key method for
2. Archaeology
   - Ancient Rome coin（ISIS）
   - Ancient Chinese Mirror（JPARC）
3. Batteries
   - Li-ion battery（JPARC）
4. Carbon in car bearings
   - Welding of car bearing (PSI)



Science | Current Issue | First release papers | Archive | About | Submit manuscript

HOME > SCIENCE > VOL. 379, NO. 6634 > FORMATION AND EVOLUTION OF CARBONACEOUS ASTEROID RYUGU: DIRECT EVIDENCE...

RESEARCH ARTICLE | COSMOCHEMISTRY

Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned samples

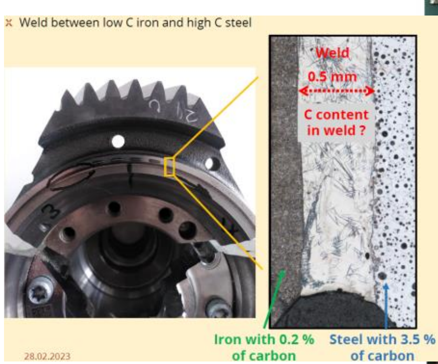
T. NAKAMURA, M. MATSUMOTO, K. AMANO, Y. ENOKIDO, M. E. ZOLENSKY, T. MIKOUCHI, H. GENDA, S. TANAKA, M. Y. ZOLOTOV, [...], AND Y. TSUDA +211 authors Authors Info & Affiliations

SCIENCE • 22 Sep 2022 • Vol 379, Issue 6634 • DOI: 10.1126/science.abn8671

RESULTS

We found carbon dioxide (CO_2)–bearing water in an iron-nickel (Fe–Ni) sulfide crystal, indicating that the parent body formed in the outer Solar System. Remanent magnetization was detected, implying that the solar nebula might still have been present when magnetite crystals formed on the parent body.

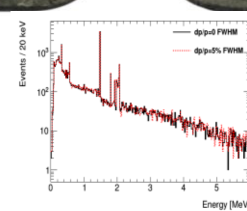
We used muon analysis to determine the abundances of light elements, including carbon (C), nitrogen (N), sodium (Na), and magnesium (Mg), whose abundances relative to silicon (Si) are similar to those in CI chondrites, whereas oxygen (O) is deficient compared with that in CI chondrites. X-ray computed tomography analysis shows that all our Ryugu samples consist of fine-grained material. There are only rare objects of high-temperature origin, such as melted silicate-rich particles, all being smaller than 100 μm.



PSI MIXE on car bearing

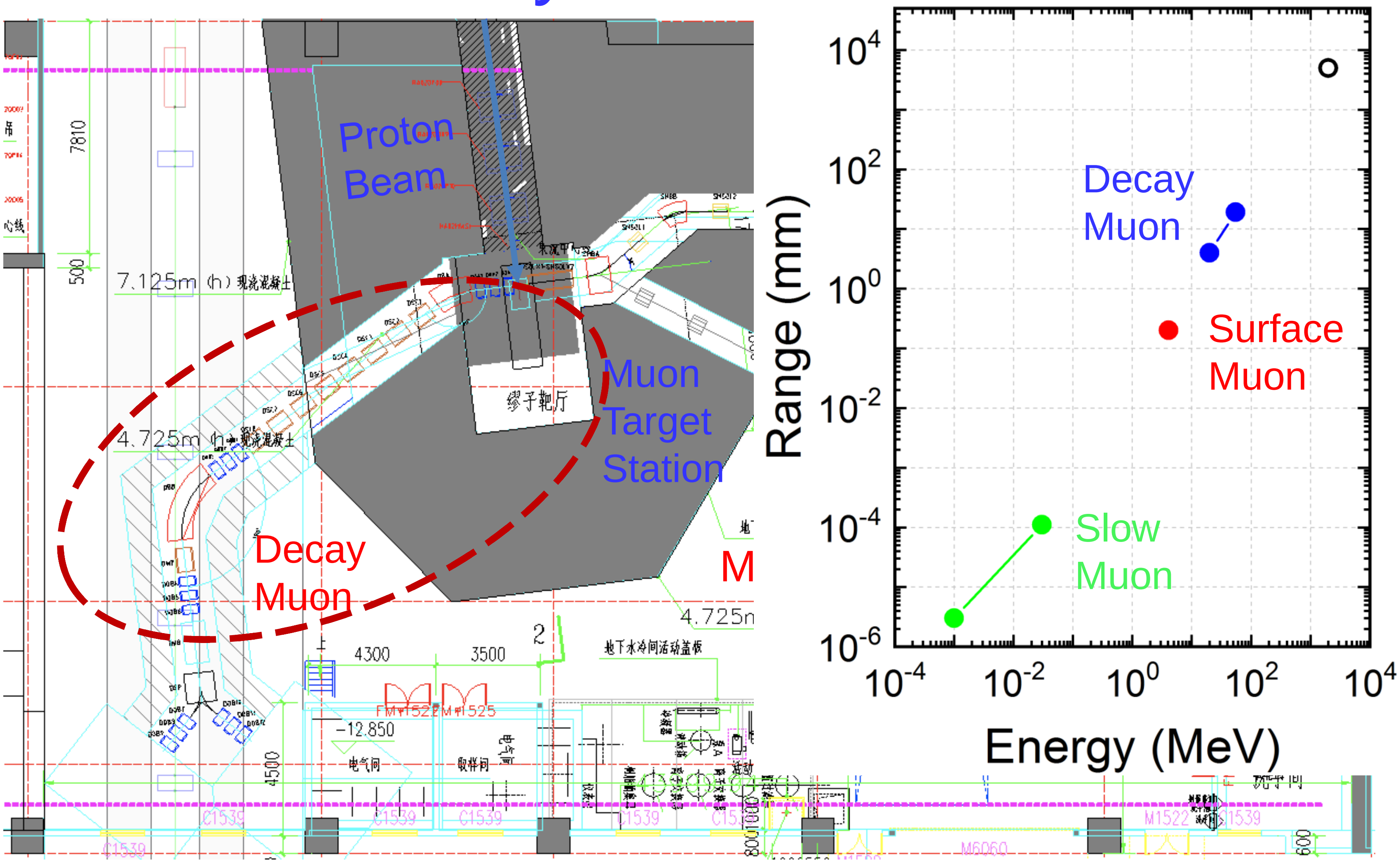
JPARC on Lithium batteries

ISIS MIXE on ancient ROME coin



JPARC MIXE on ancient Chinese Mirror

Decay Muon Beam



- Momentum: 20 ~ 120 MeV/c
- Charge: + or -
- Intensity: 10^5~10^7 muon/s
- Penetration in Cu: 1 ~ 50 mm
- Polarization: 50% ~ 99%

Decay Muon Applications

High-energy MuSR

- Thick Samples
- Samples in container
- High field

Depth scan MIXE

- Depth scan for archaeology
- Thick moon rock
- Batterries

Muon Imaging

- Thick samples

Single Particle Effect

- Large capture cross section of μ^-

Muon Beam Parameters

	Surface Muon	Negative Muon	Decay Muon
Proton Power（kW）	20	Up to 100	Up to 100
Pulse width (ns)	130 to 10	500	130 to 10
Muon intensity（/s）	$10^5 \sim 10^6$	Up to $5*10^6$	Up to $5*10^6$
Polarization（%）	>95	>95	50~95
Positron（%）	<1%	NA	<1%
Repetition（Hz）	1	Up to 5	Up to 5
Terminals	2	1~2	2
Muon Momentum（MeV/c）	30	30	10 to 120
Full Beam Spot（mm）	10 ~ 30	10 ~ 30	10~30

MELODY团队及国际合作

缪子源团队：

- 靶站：刘磊、张刚、贺华艳、何宁、李治多、Nikos Vasiloploss、陈佳鑫、谭志新
- 束线：吕游、陈聪、邓昌东、齐欣、张文庆、王鹏程、张玉亮、何泳成、刘光东
- 谱仪及探测：李强、潘子文、李样、吕游、樊瑞睿、杜海燕、郭宇航、梁昊、杨天意、叶邦角

国际合作：

日本理化所/JPARC：Isao Watanabe, Yasuhiro Miyake …

英国ISIS：Adrian Hillier, James Lord, Rhea Stewart，合作实验

瑞士PSI： Thomas Prokscha，Alex Amato，派遣学生学习负缪子束流应用

First workshop of MELODY

Summary

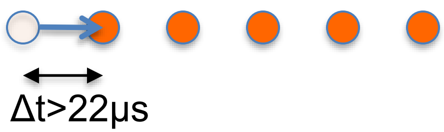
- **MELODY has officially started construction !**
- **MELODY will be built in 6 years !**
- **Surface muon beam will be built in phase I and a negative muon beam and decay muon beam will be build in future**

All collaborations are welcome!

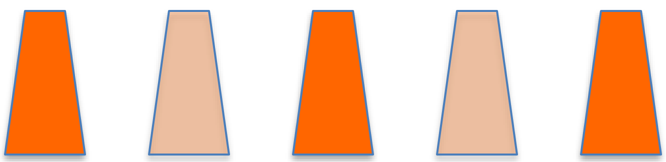
重复频率

$$\tau = 2.2\ \mu sec$$

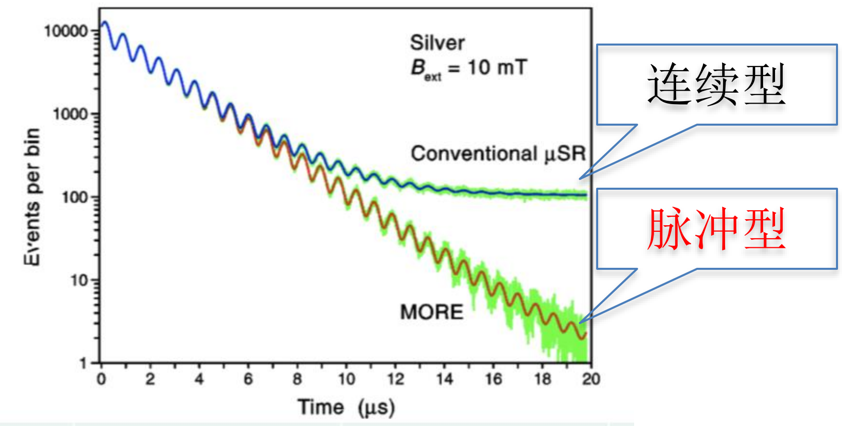
连续型



脉冲型



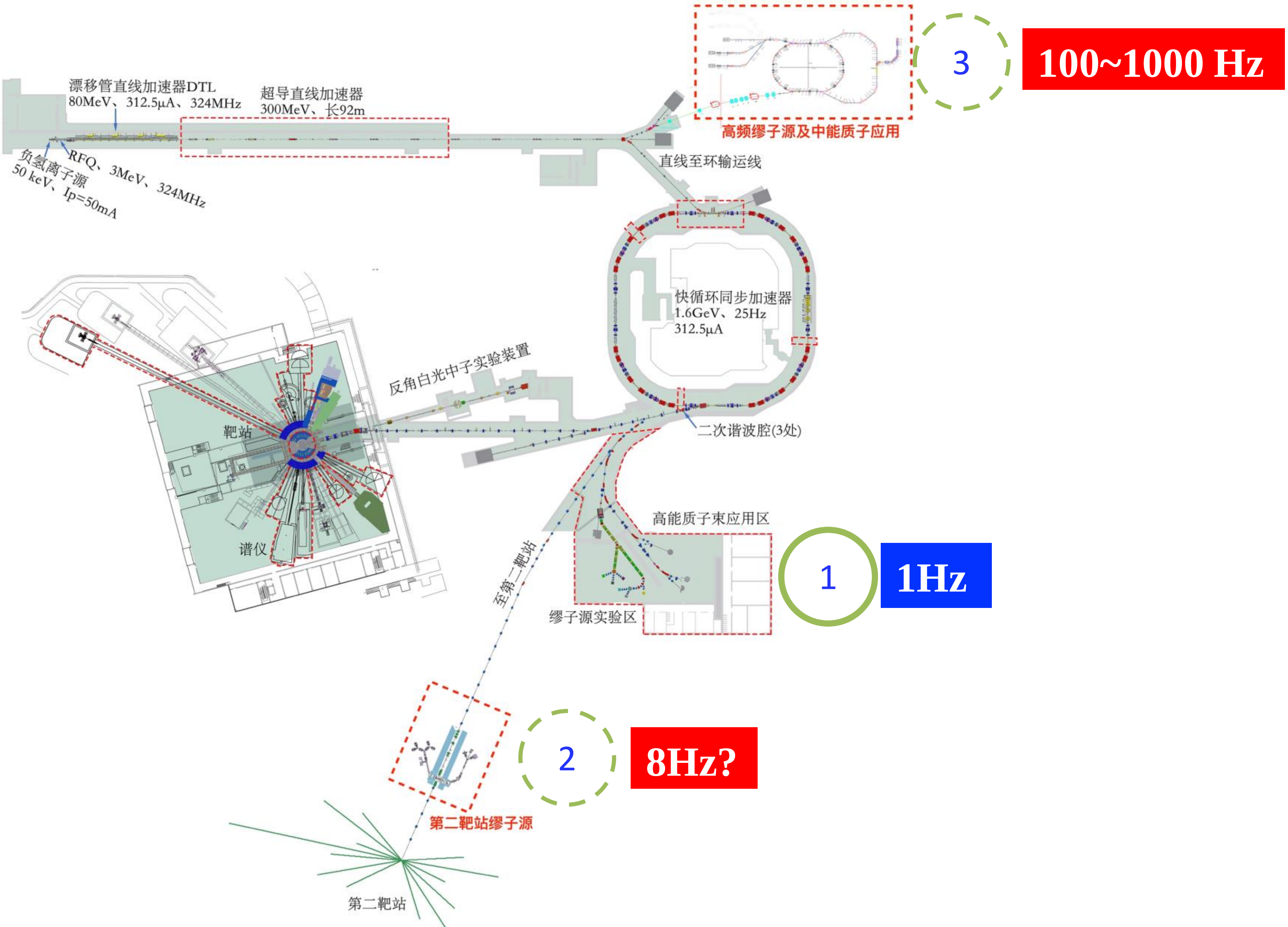
两种μSR信号对比



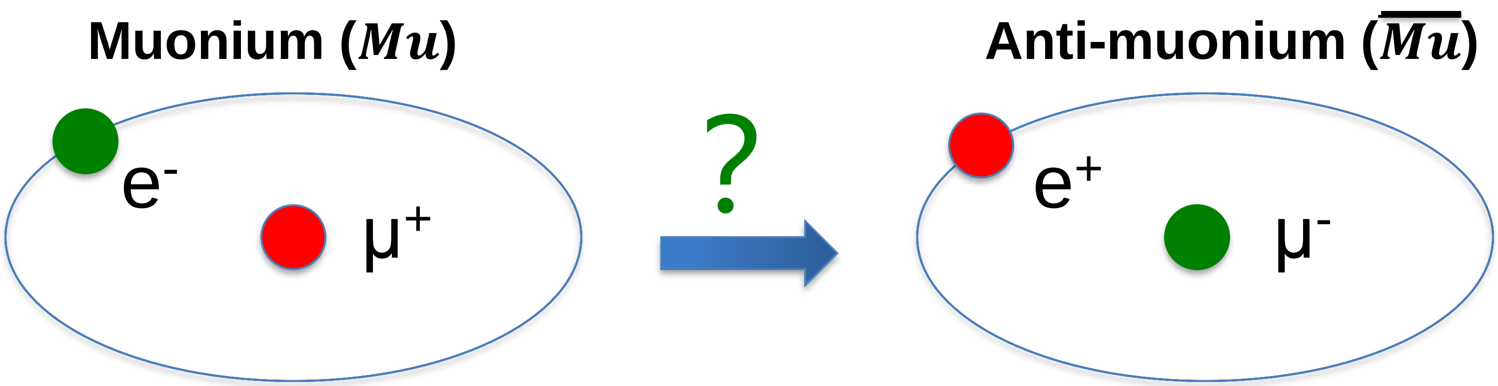
	连续型	脉冲型
计数率	$< 5*10^4\ \mu^+/s$	仅受重复频率限制*
背景噪音	大	小
时间分辨率	1 ns	80 ns

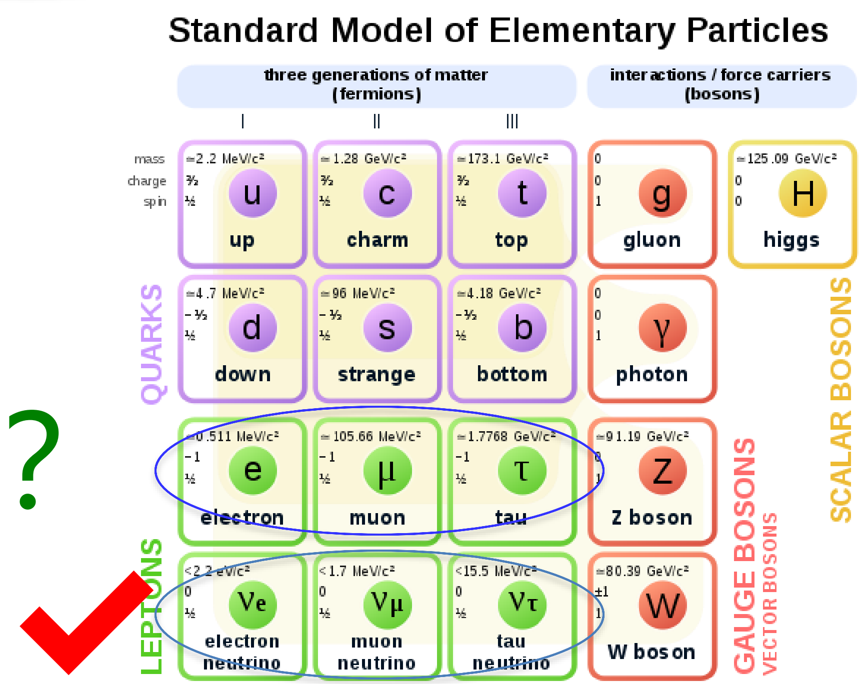
* 探测器结构一定的情况下

High rEpetition Muon Source (HEMS)



高重复频率缪子源应用之MuMubar



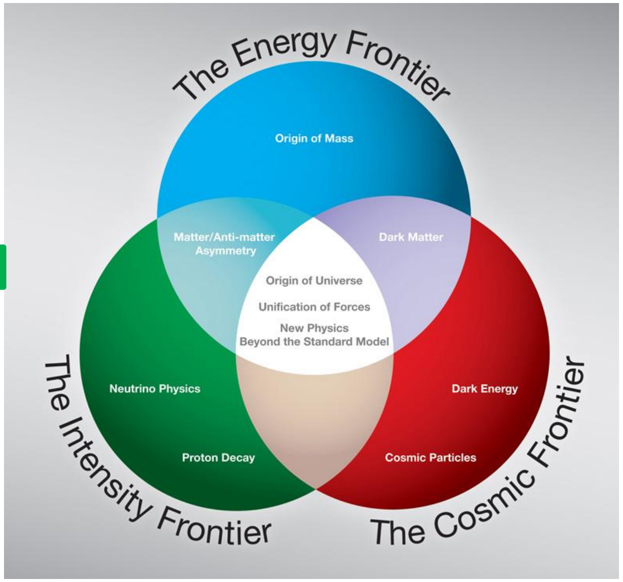


获得院从0到1原始创新项目支持

已完成初步概念设计

研究背景- 探索超出标准模型新物理

粒子物理三个前沿方向

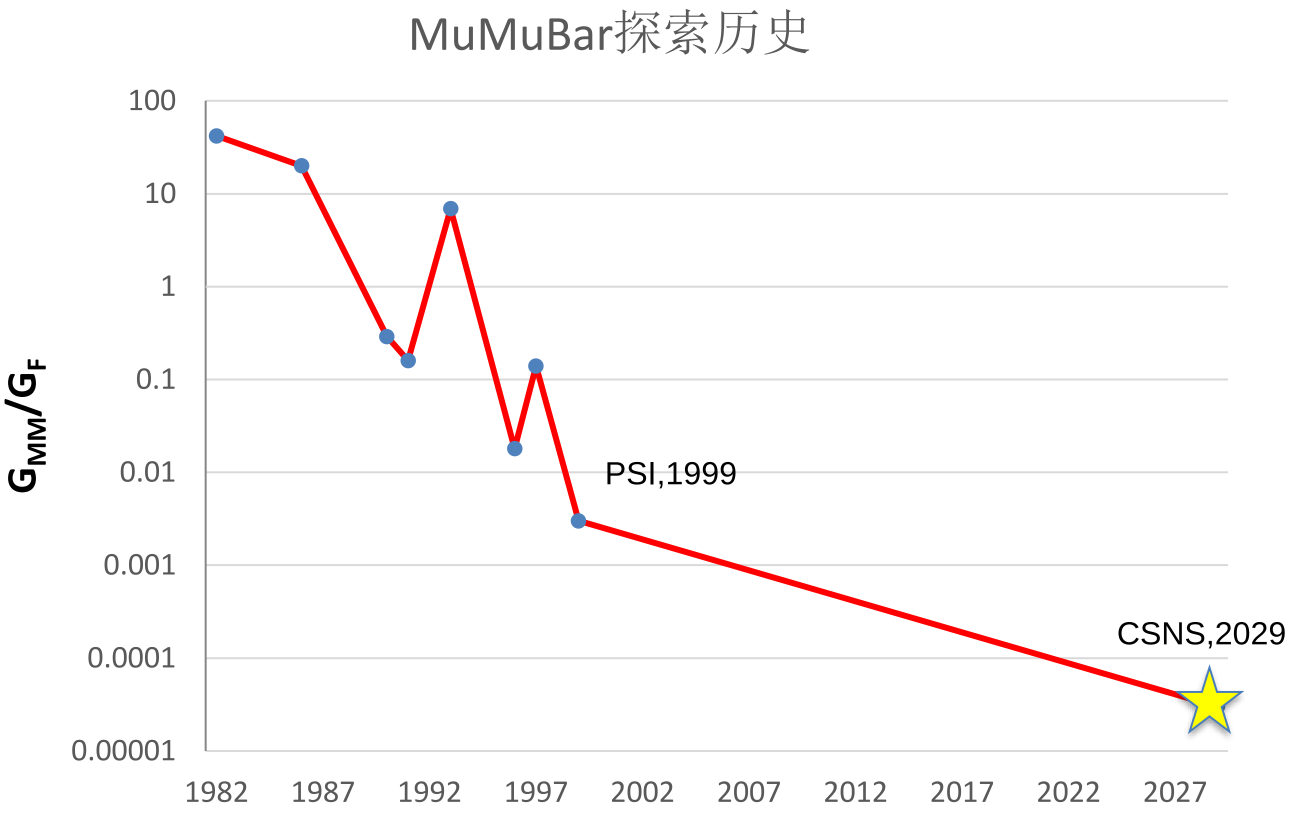


强度前沿物理：

- 中微子实验
- 中子/缪子EDM
- 带电轻子味道破坏实验 cLFV：
  - Mu2e/COMET
    - $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$
  - MEG
    - $\mu^+ \to e^+ + \gamma$
  - Mu3e
    $\mu^+ \to e^+ e^- e^+$
  - **MuMuBar:**
    - $\mu^+ e^- \to \mu^- e^+$

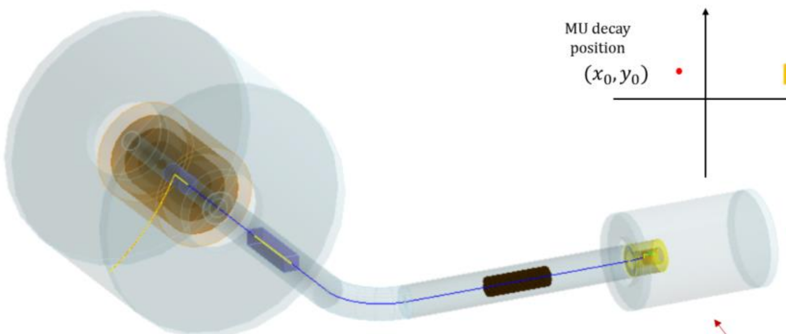
- **标准模型强烈压低（<10^{-54}）**
- **违反轻子味道数守恒两个单位**

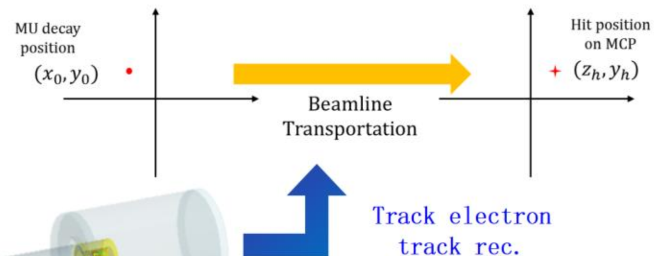
历史上的MuMuBar



- 最近一次探索是20年前在PSI开展。
- 我们将从多个技术手段改进该实验，将实验精度提高两个数量级
- 目前国际上没有正在进行的相关实验，我国有望在该领域实现“0到1”的突破。

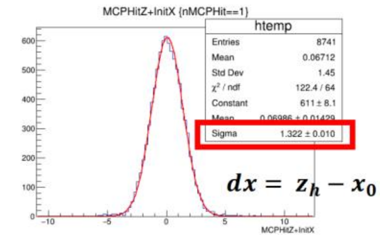
MuMuBar @ HEMS



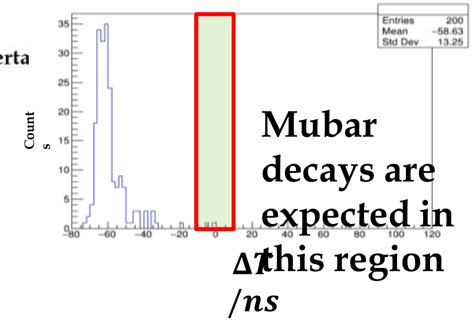


Track electron track rec.

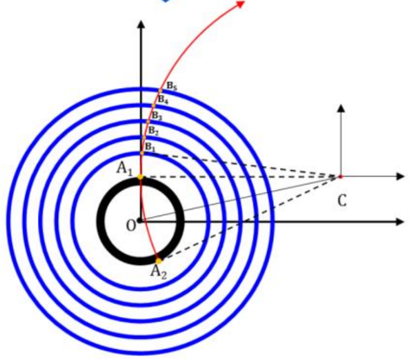
1 cm track electron rec. uncerta

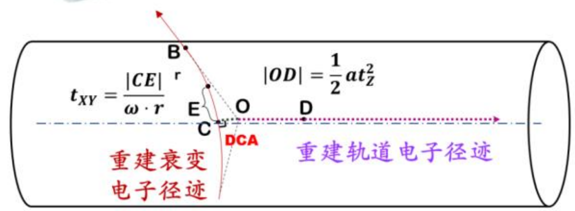


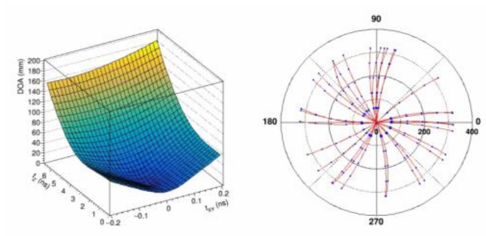
decay electron track rec.



Mubar decays are expected in this region







- DCA (Distance of Closest Approach) is calculated according to the rec tracks.
- ΔT (bias to the expected TOF of track electron) is also acquired from track rec.

- We have reconstructed the PSI experiment
- We are developing the data analysis software and detector system for MuMuBar
- More detailed simulation is on going …