缪子科技与应用

CSNS缪子源实验站工程介绍

鲍煜
On Behalf of MELODY Collaboration

Outlines

- 缪子的诞生和历史
- 国际缪子研究装置
  - 分类
  - 研究领域
- 缪子源实验站MELODY设计进展
  - 靶站
  - 束线
  - 谱仪
- MELODY未来应用与发展
- Summary

Birth of muon

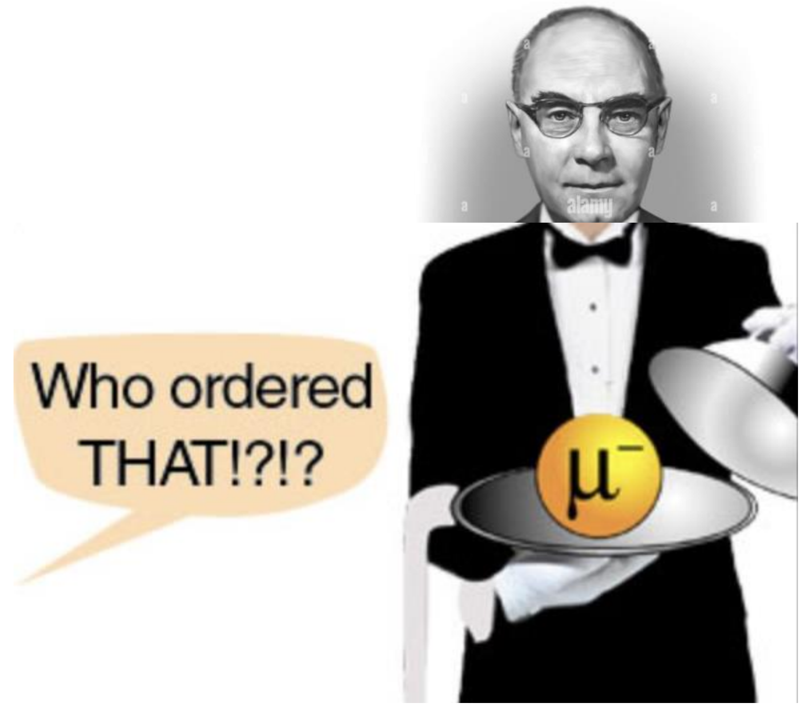

Science & Technology

Who Ordered the Muon?

THE HUNTING OF THE QUARK

By Marcia Bartusiak

I. I. Rabi
Nobel Price 1944

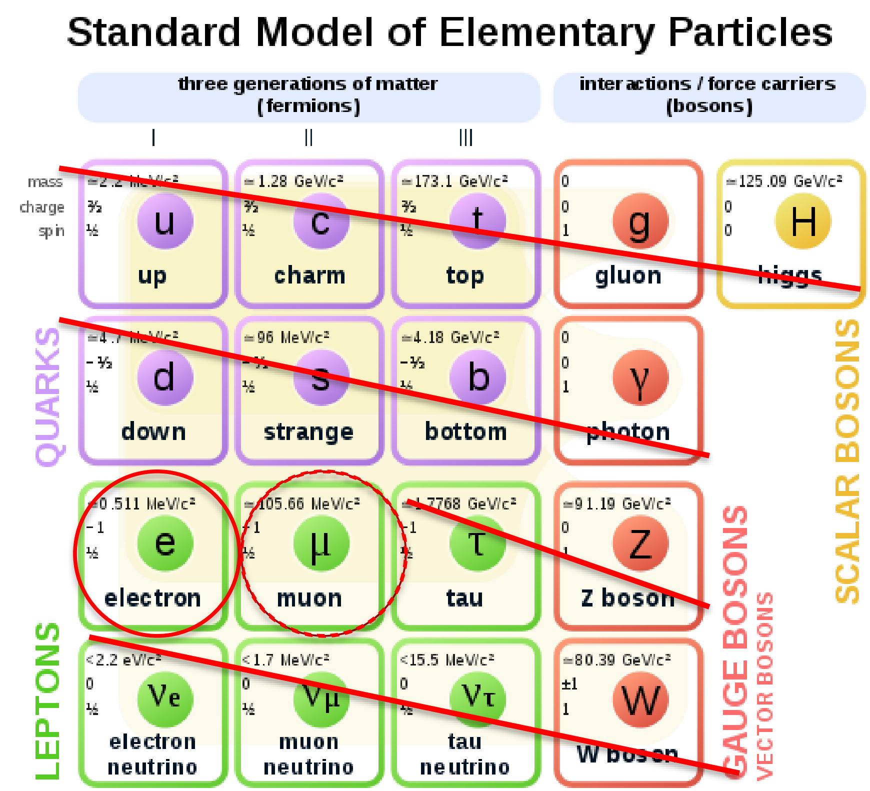


Carl Anderson
Nobel Price 1936

缪子带来的混乱

“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.” – ***Kelvin, 1900***

“Physics as we know it will be over in six months.” – ***Max Born, 1930***

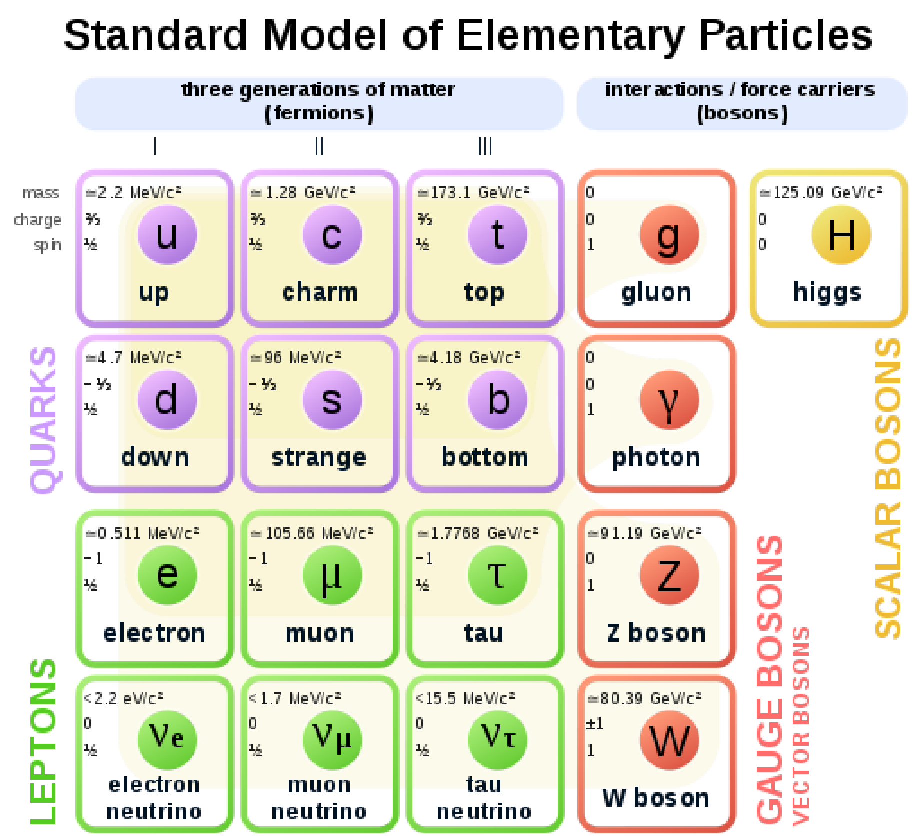


Muon

- 1956: Lee & Yang postulate **P-violation** in weak interactions
- 1957: Wu confirms *P*-violation in *β* decay;

Friedman & Telegdi confirm *P*-violation in *π*-*μ*-*e* decay;

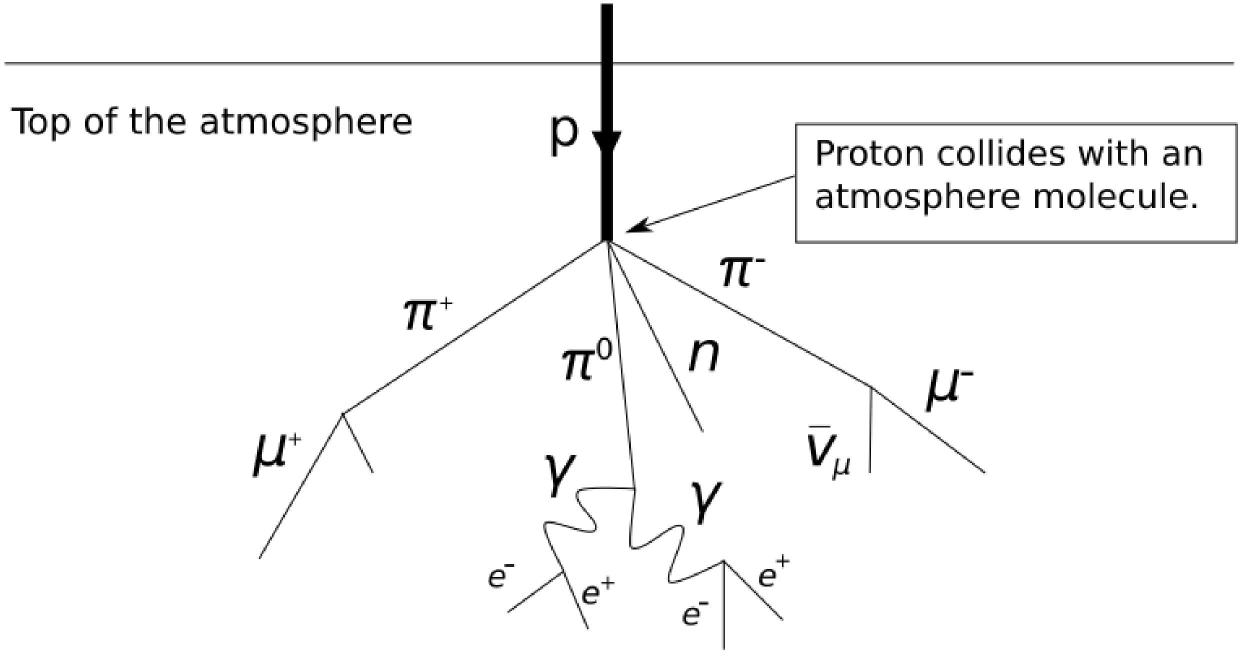
so do Garwin, Lederman & Weinrich, using a prototype ***μSR*** technique.



- Mass: 106MeV/c2
- Charge: mu-、mu+
- Life: 2.2us

缪子从哪里来？

野生缪子



Top of the atmosphere
p
Proton collides with an atmosphere molecule.
π^+
π^-
π^0
n
μ^+
μ^-
$\bar{\nu}_\mu$
γ
γ
e^-
e^+
e^-
e^+

如何驯服野生缪子

如何驯服野生缪子

为我所用的野生缪子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NATURE | NEWS

E-alert

Cosmic-ray particles reveal secret chamber in Egypt's Great Pyramid

Researchers have used muon detectors to discover a mysterious, 30-metre-long space — which could help to reveal how the 4,500-year-old monument was built.

Jo Marchant

02 November 2017

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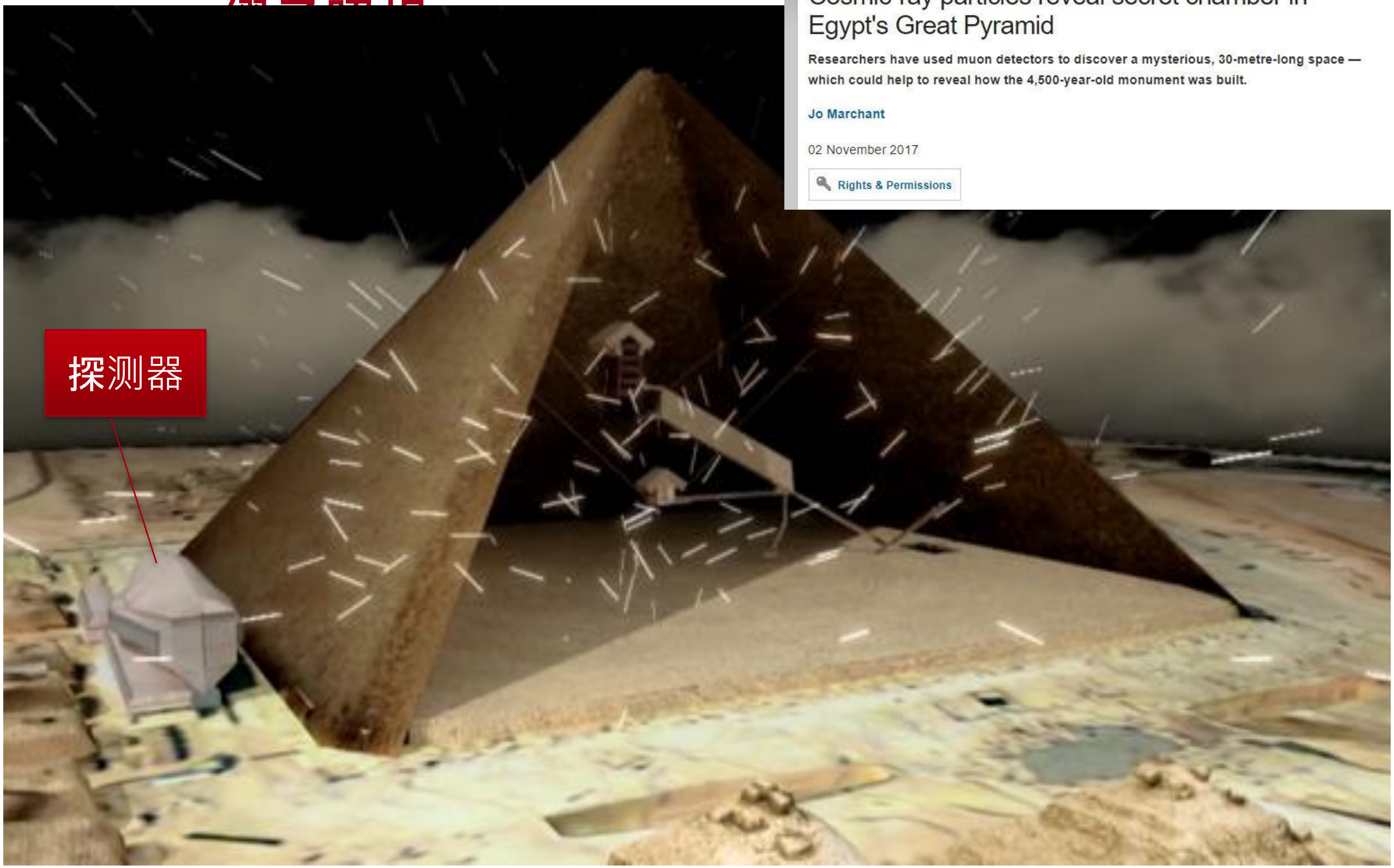
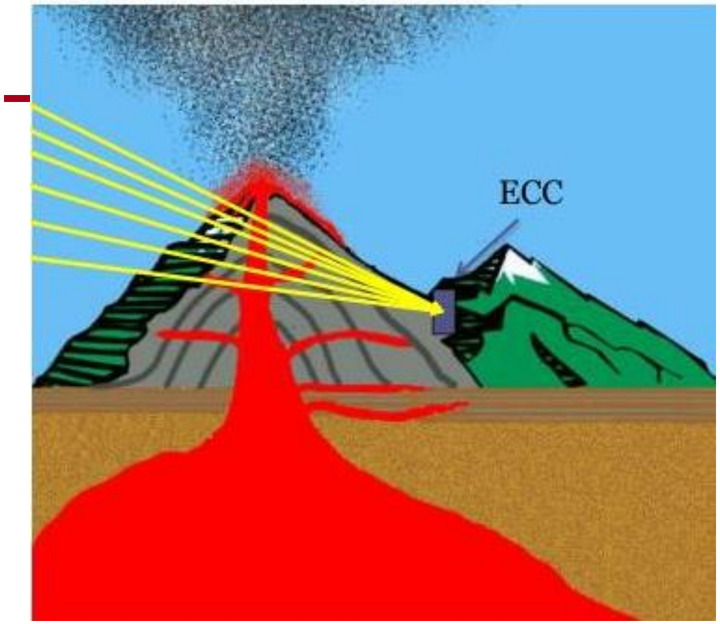
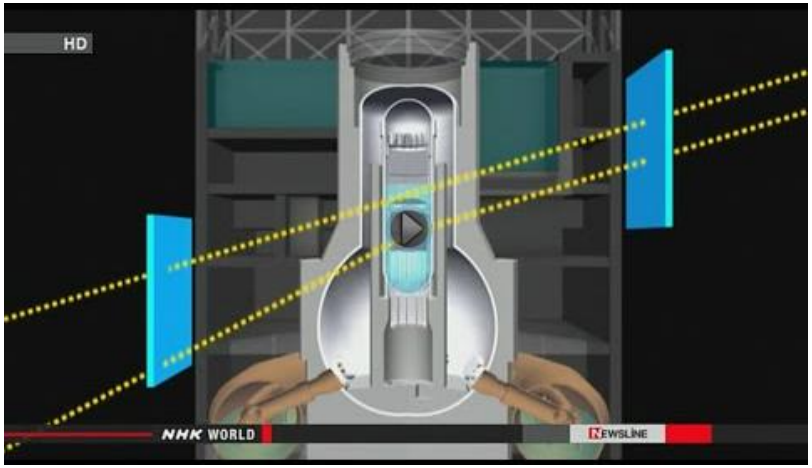


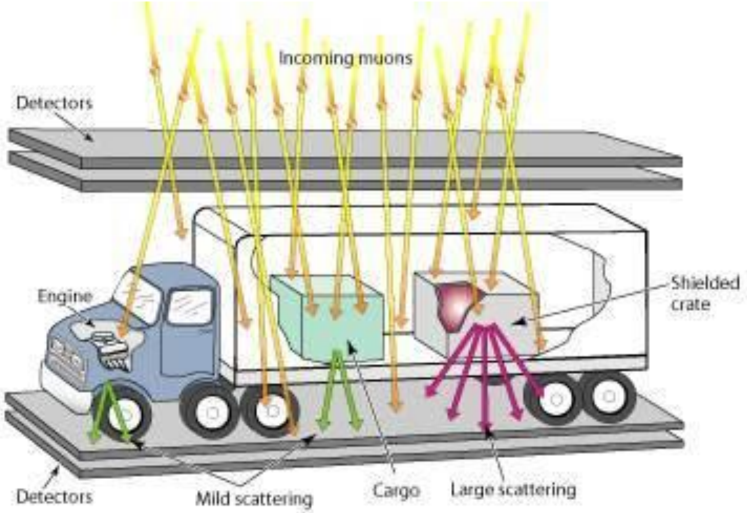
为我所用的野生缪子



火山活动监控



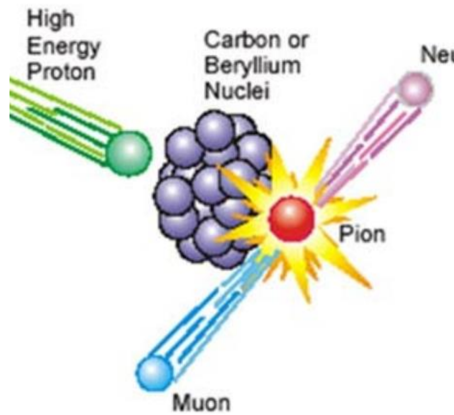
反应堆燃料监控

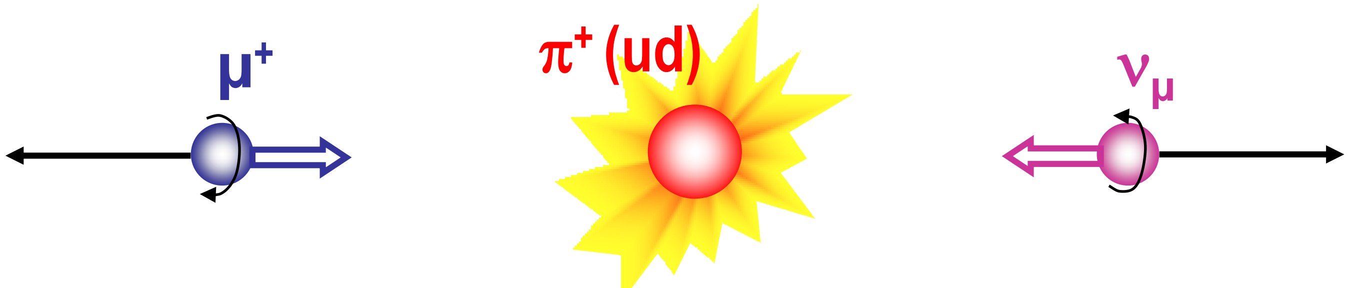


集装箱检查

强度所限，照一张相通常需要几天到几个月😭

如何圈养缪子





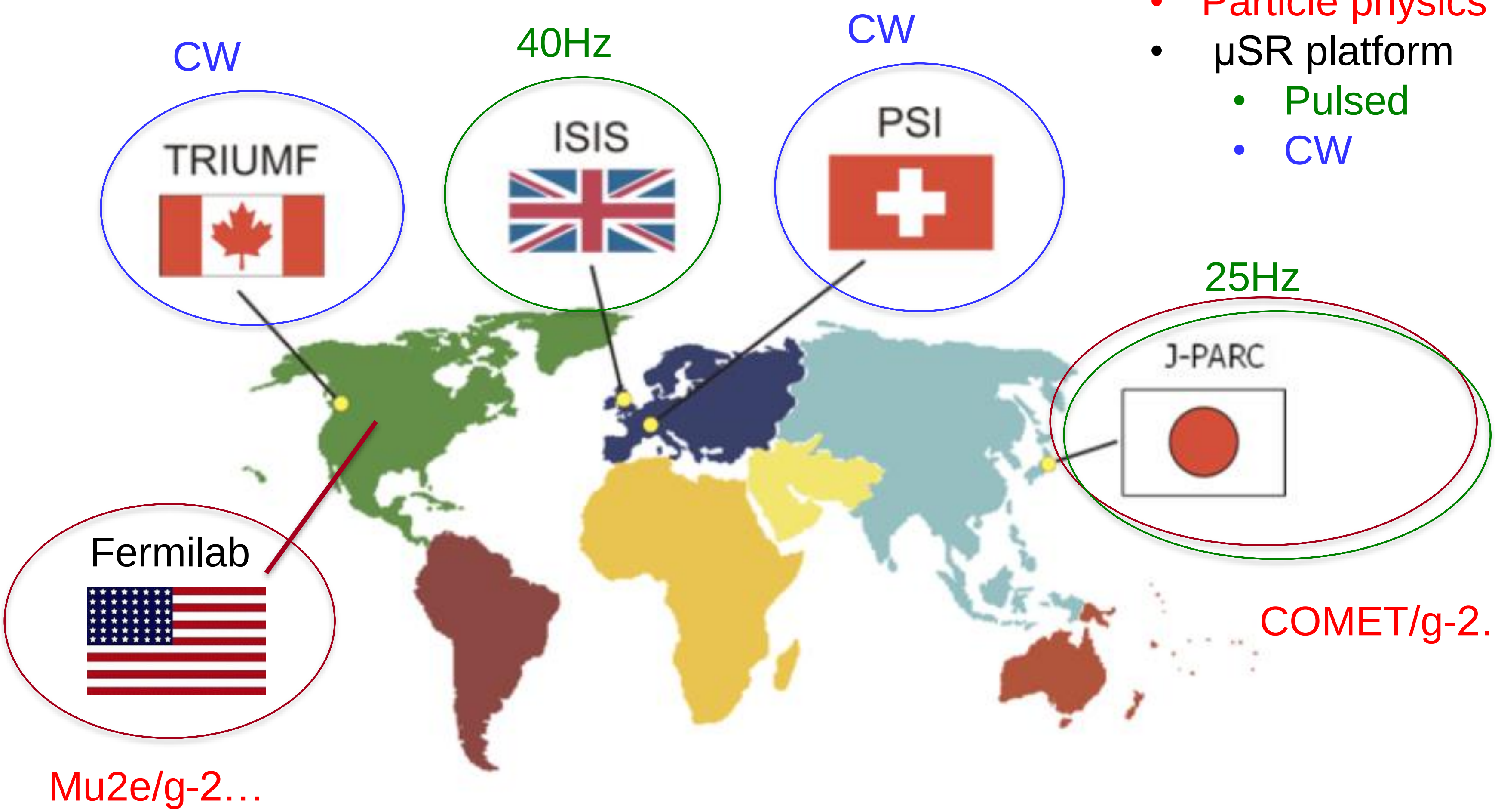
S = 0 (τ_π = 26ns)

Two-body decay ▶ muon has always the energy 4.1 MeV in the reference frame of the pion (assuming m_ν = 0)

Spin pion = 0 ▶ Muon has a spin 1/2 and is 100% polarized (as only left-handed neutrinos are produced)

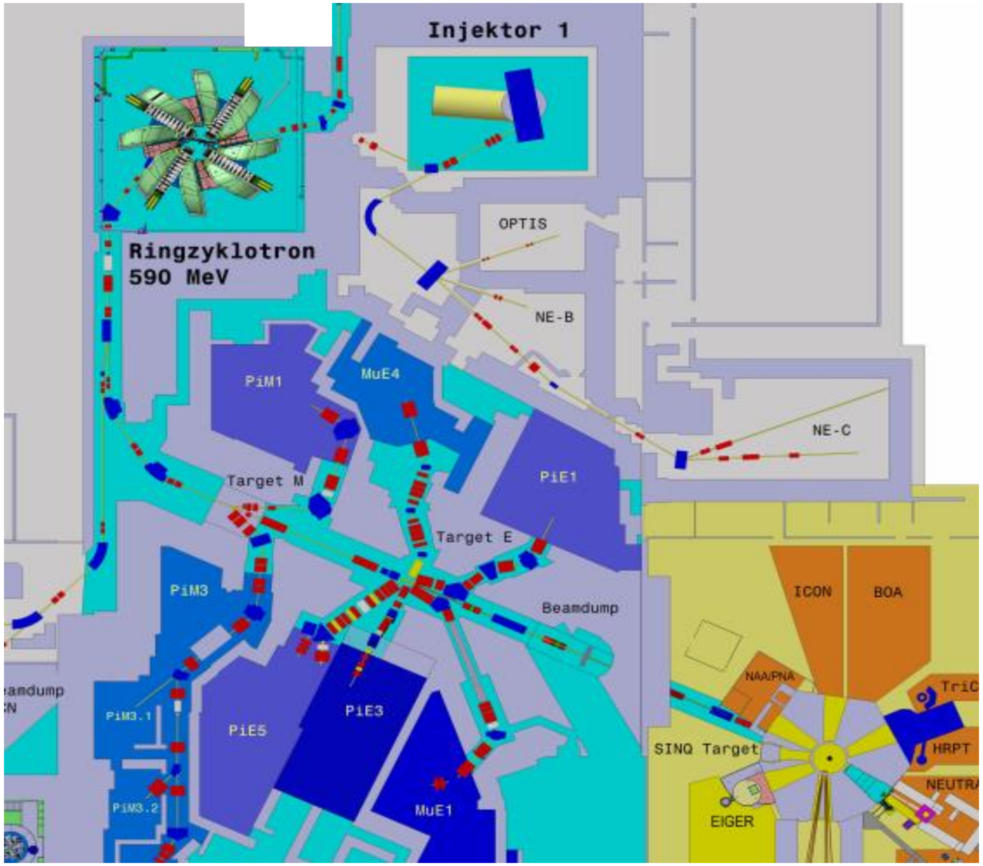
国际缪子源装置

- Particle physics
- μSR platform
  - Pulsed
  - CW



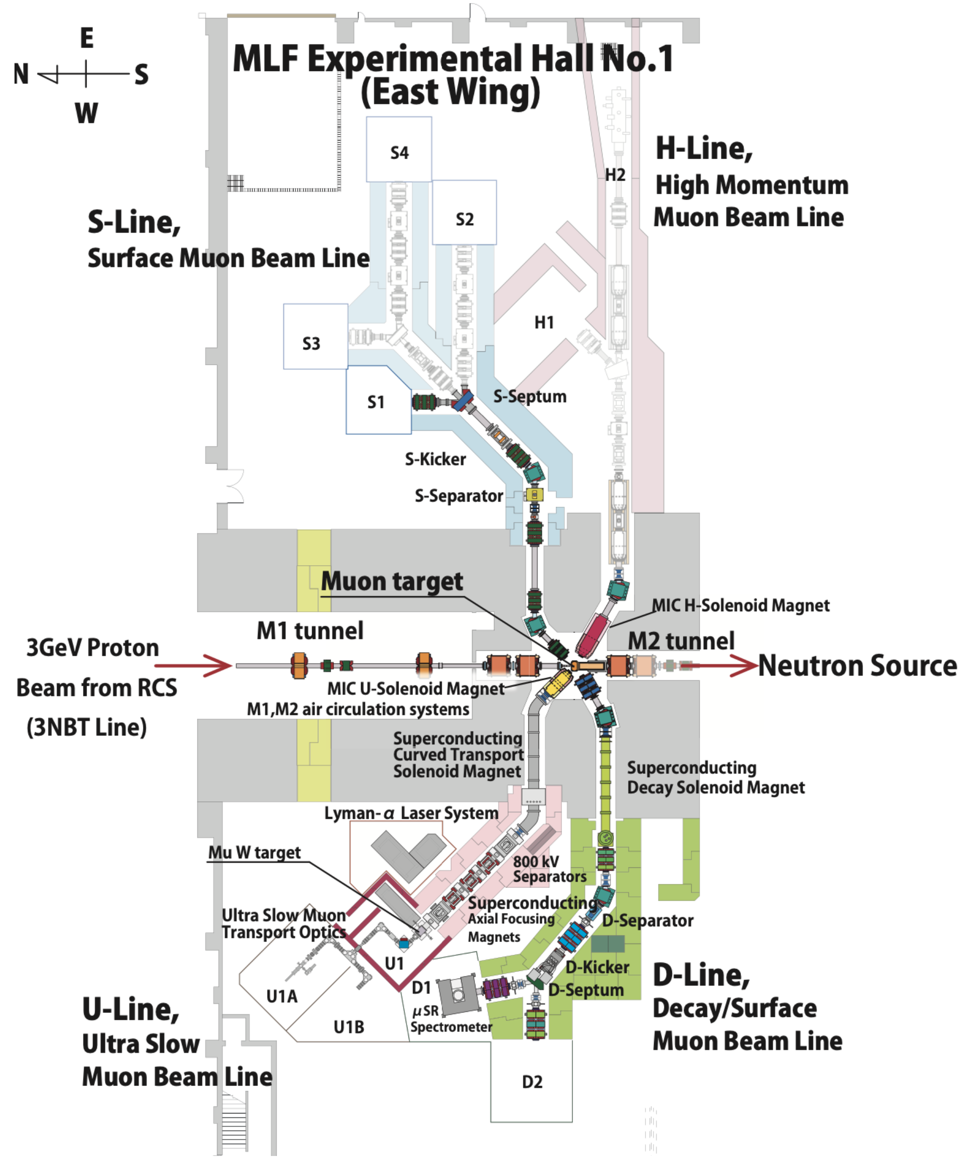
PSI (SμS Swiss Muon Source)

- Continuous Beam
- 590 MeV, 2mA
- 1.2 MW, 30% to muon
- Two graphite targets
- 7 Beamlines
  - 4 μSR
  - 2 particle physics
  - 1 test instrument



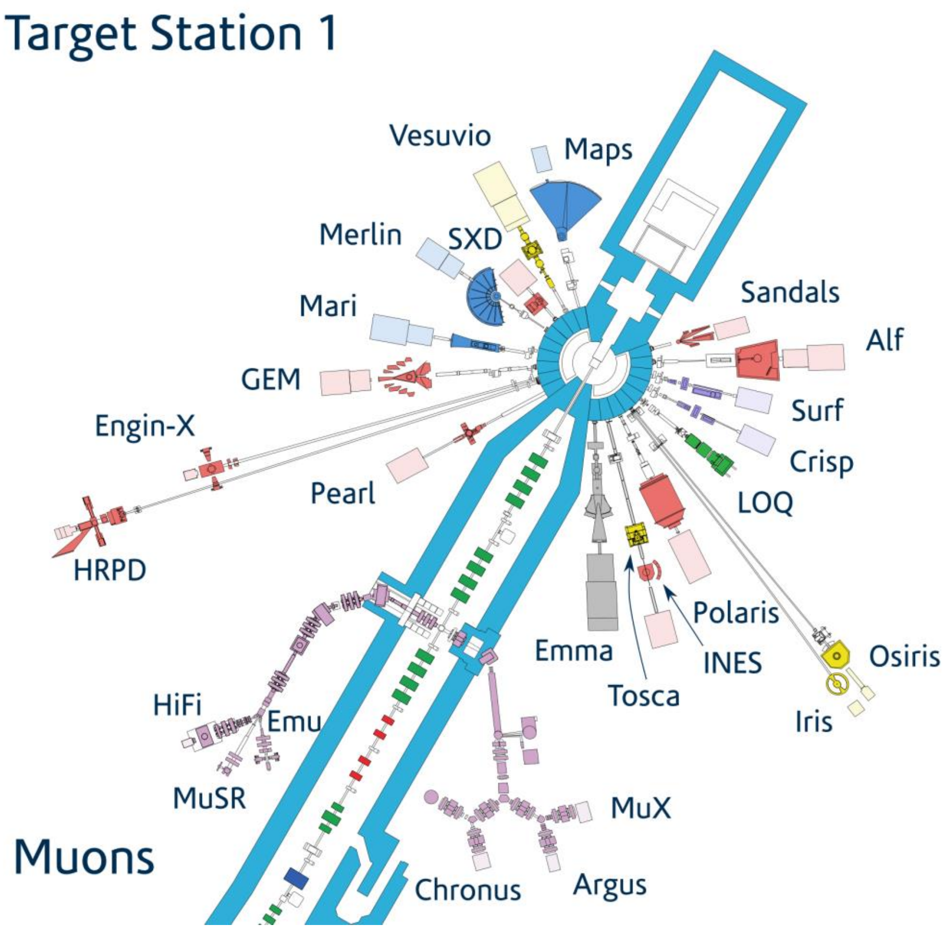
J-PARC

- 25 Hz Pulsed Beam
- 3GeV proton beam
- 1 MW, 5% to muon
- 5 Beamlines
  - 3 μSR
  - 1 particle physics
  - 1 test instrument



ISIS RIKEN-RAL Muon Facility (RμF)

- Owned and Operated by RIKEN
- 40 Hz 800 MeV proton
- 140 kW, 4% to muon
- Graphite target
- Muon Ionization Cooling Experiment (MICE)
- 2 beamlines
- 7 instruments
  - 5 μSR
  - 2 test

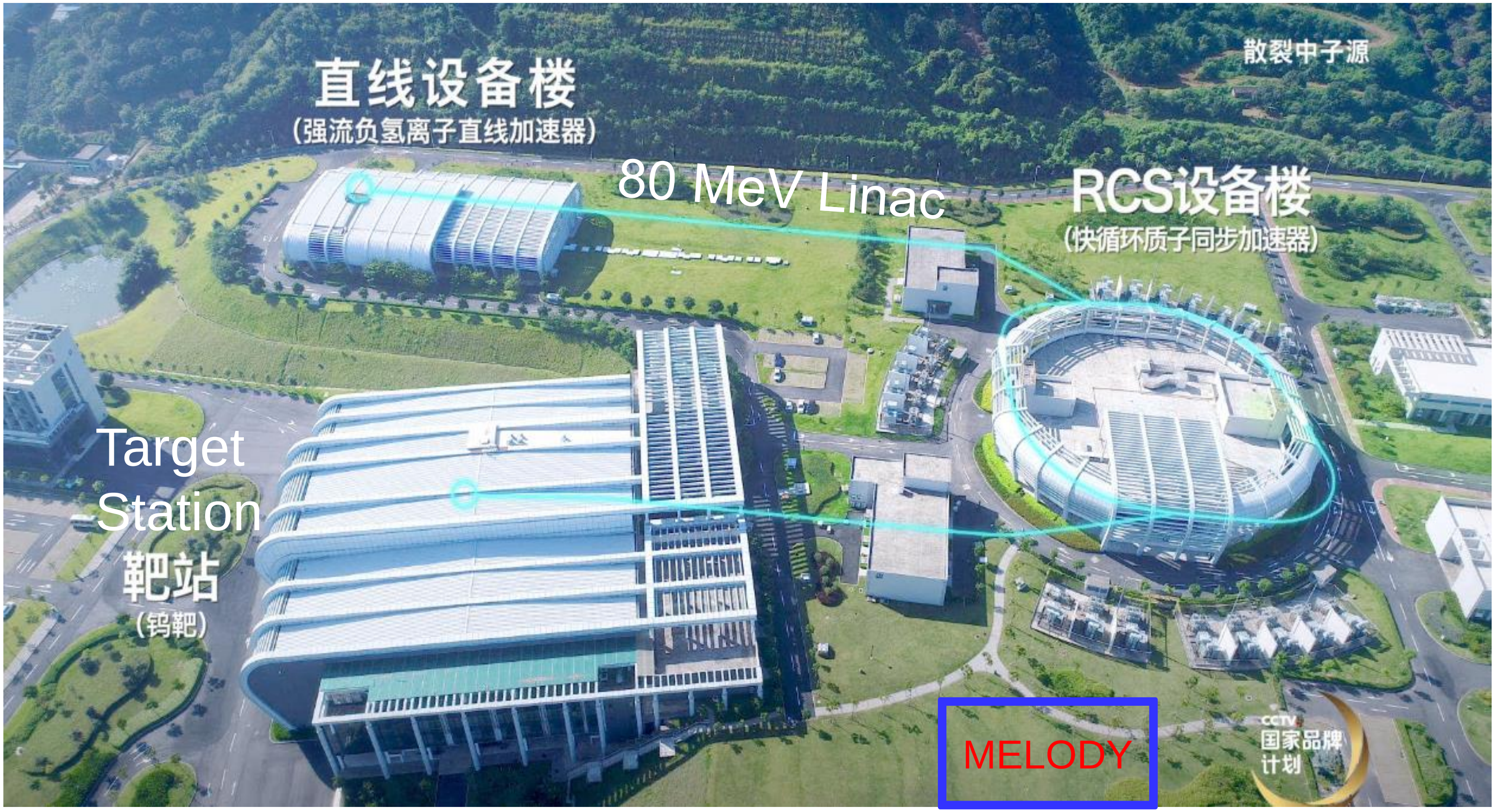


国际上主流粒子物理实验

Experiment	Muon rate used	DC / pulsed	Momentum	Polarization
MuLan	1E7/s	DC	30MeV/c	100%
TWIST	2500/s	DC	30MeV/c	100%
ePolar	1E7/s	DC	30MeV/c	100%
Mu2e+	mu-, 1E7/s	DC	100MeV/c	0
MEG	1E8/s	DC	30MeV/c	100%
Mu3e	1E8/s, 1E10/s	DC	30MeV/c	100%
Mu2e	mu-, 1E10/s	Pulsed	75MeV/c	0
g-2	1E4/s	Pulsed	300MeV/c or 3GeV/c	50% or 100%
Mu - antiMu	1E7/s	DC	30MeV/c	0
Mu 1s-2s	3000/s	Pulsed/DC	30MeV/c	0
Mu hyperfine	1E8/s	DC	30MeV/c	0

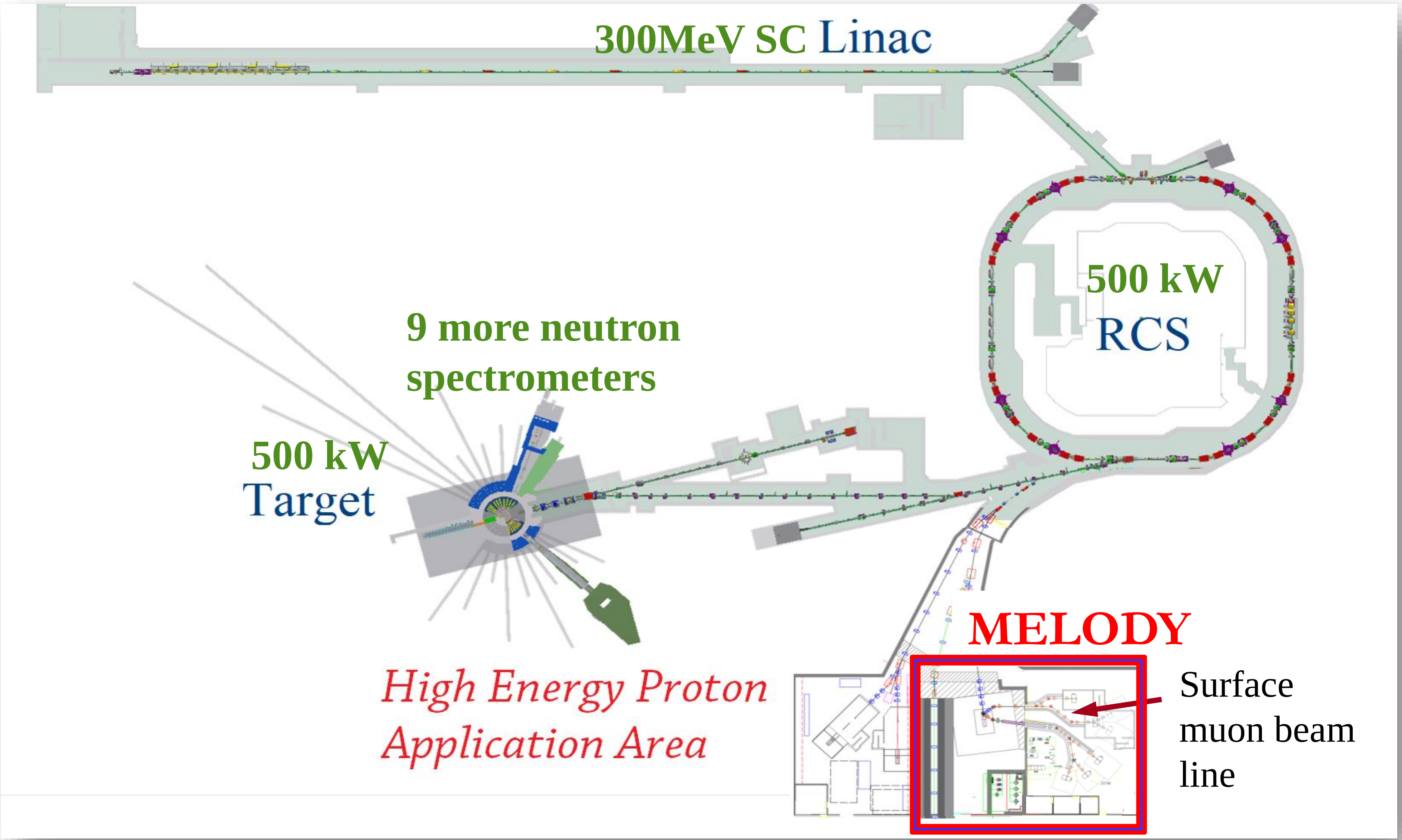
China Spallation Neutron Source

China Spallation Neutron Source（CSNS)



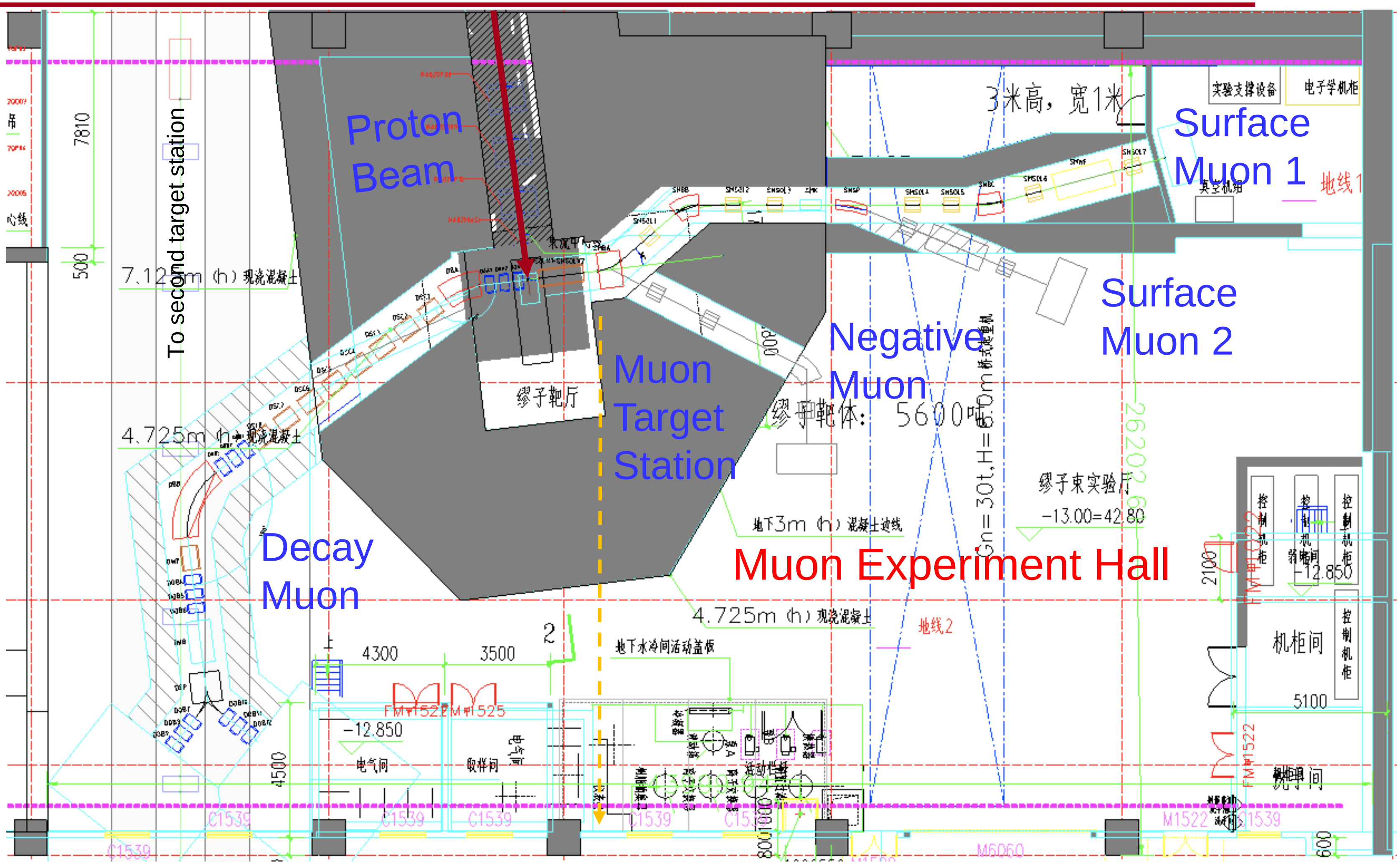
Accelerator: 100kW 25Hz 1.6GeV proton beam
Neutron Spectrometers: 7 built and 3 under construction

CSNS II Project



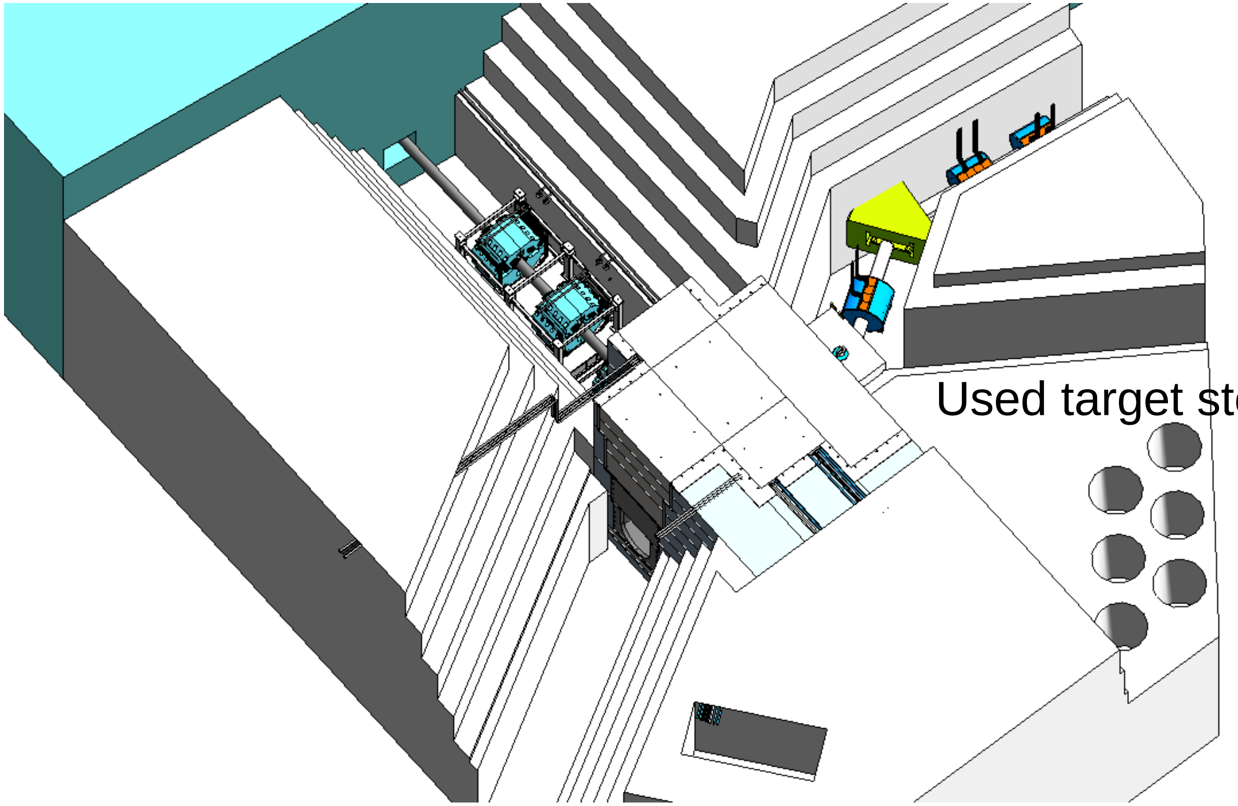
Architectural Design of MELODY

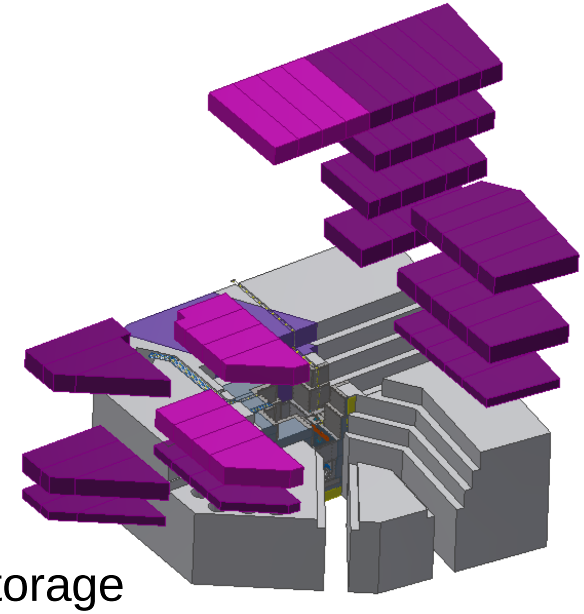
MELODY Design



- Protons: 1.6GeV, 1 Hz (up to 5Hz), 130ns double pulses
- Muon beamlines: one **surface muon** and one decay muon beam
- Spectrometers: **1 μSR spectrometer** and more…

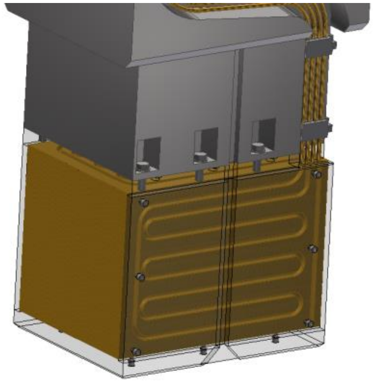
Muon Target Station

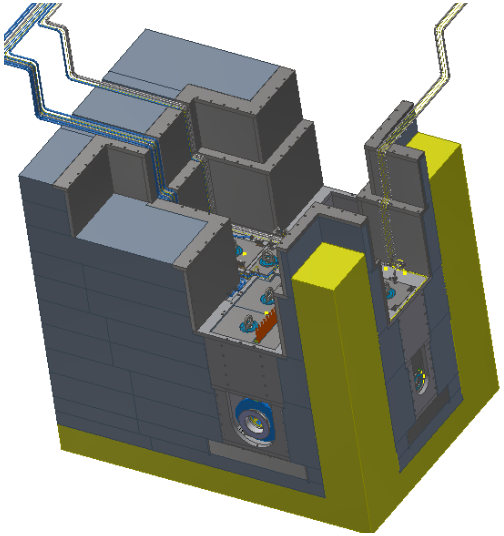




Shielding: Iron 5m*4m*4m
Concrete 5.5*5.5m*1m

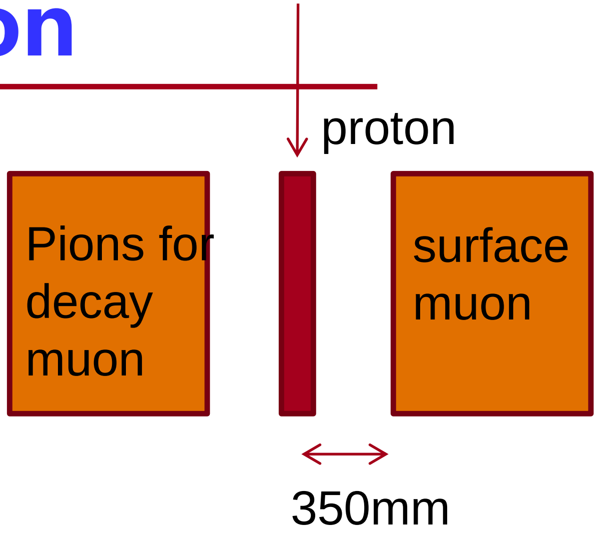
Beam absorber: Copper

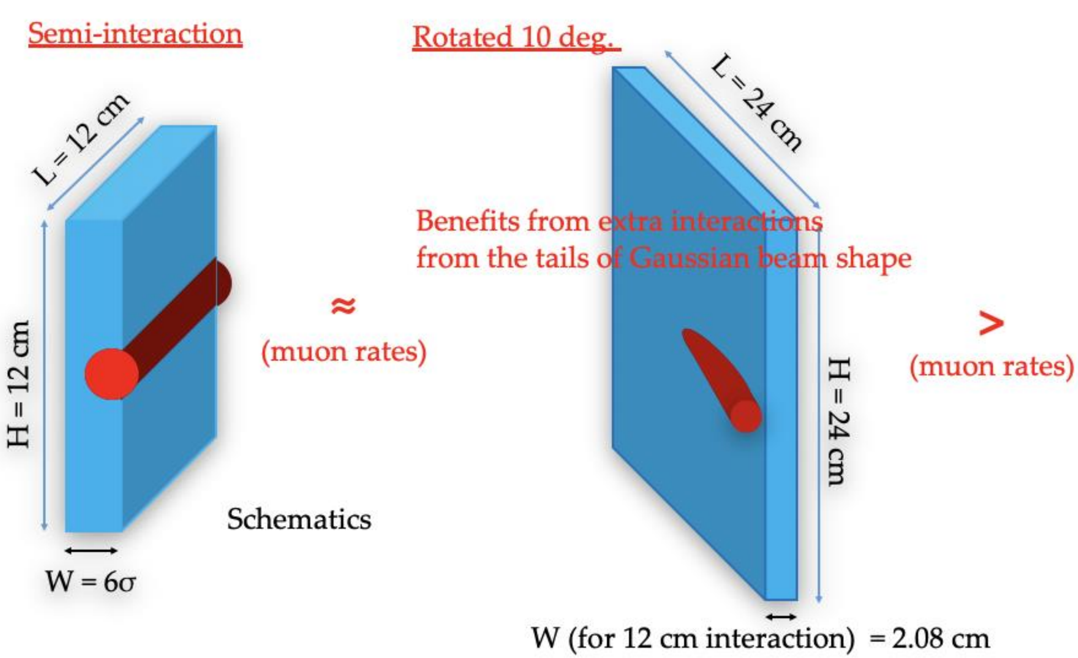


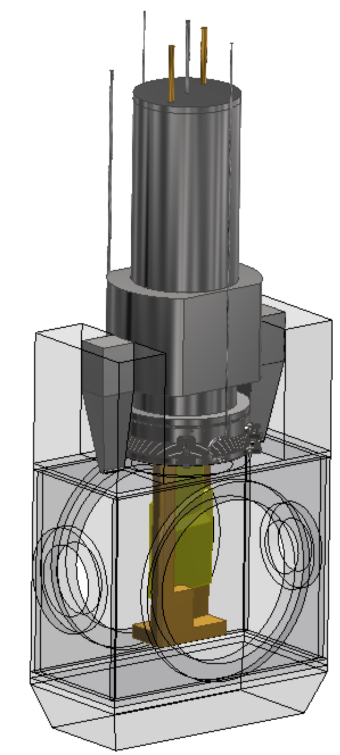


Muon Target Optimization

- Use Copper/Graphite as target
- Optimize the surface muon production with rotation of 11°
- Optimum: 240*240*11 mm for Cu
  240*240*14 mm for C

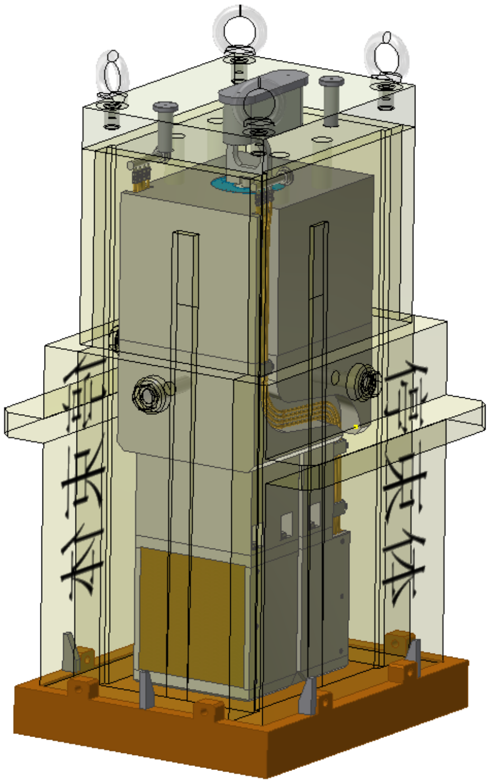




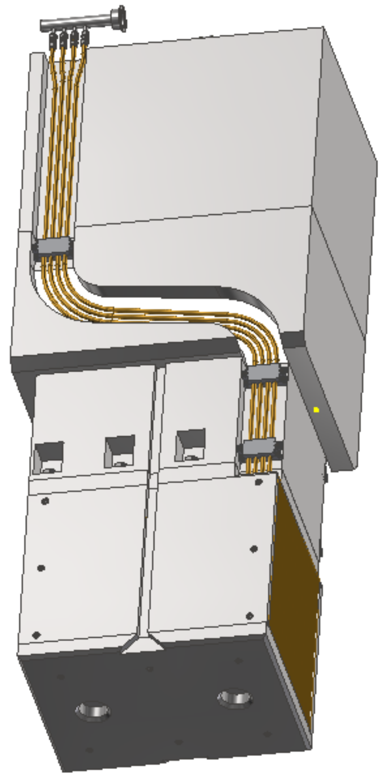


Maintenance

Target flask



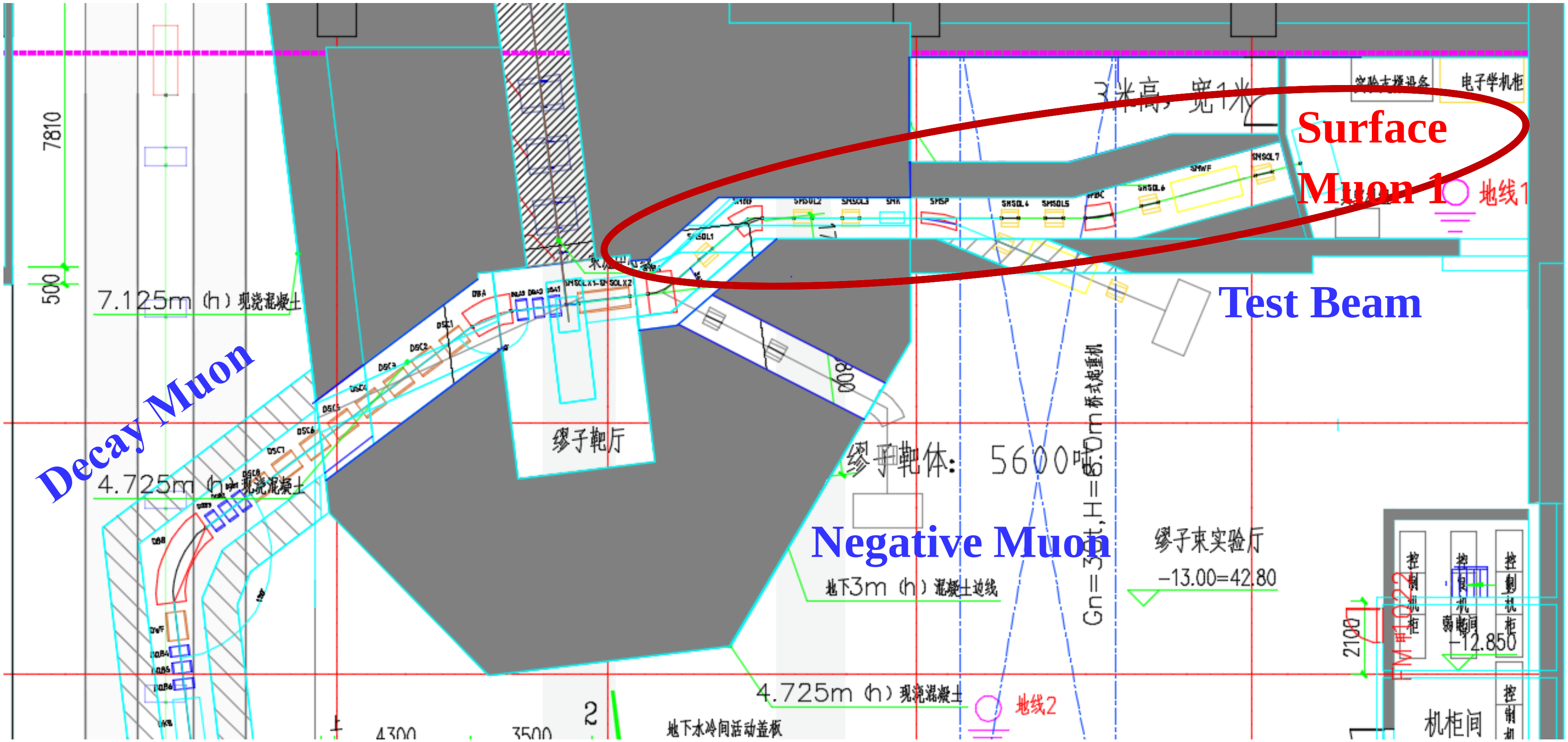
Beam dump



First solenoid

- Remote maintain from the top
- Target/magnets/absorber/flange
- Water cooling system

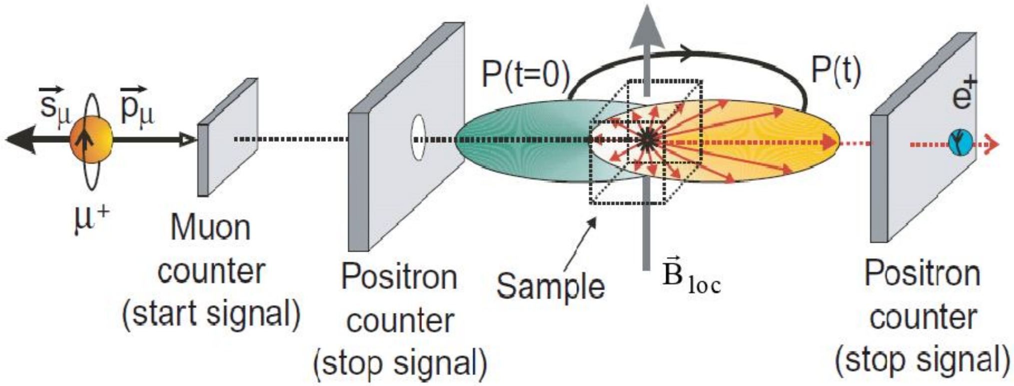
Surface Muon Beam

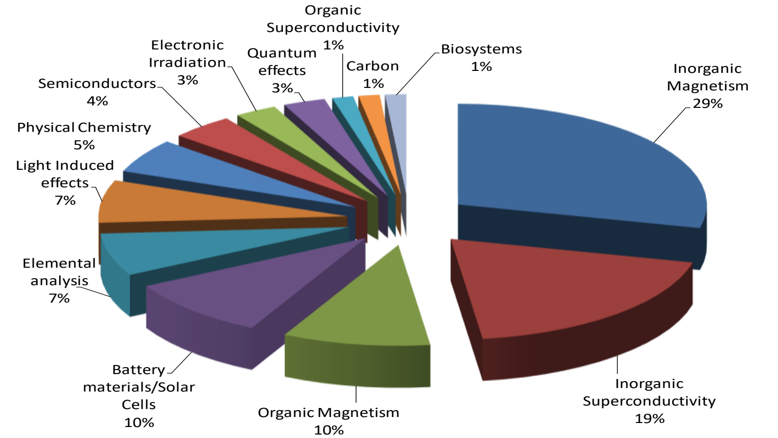


- Energy：4 MeV
- Polarization: >95%
- Intensity：$10^5 \sim 10^7 \mu^+/s$
- Time Resolution: 120ns

Surface Muon application

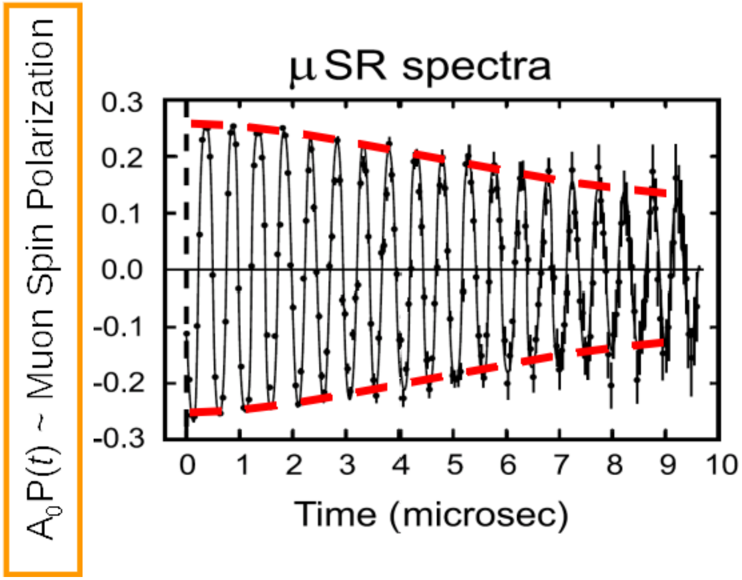
Principle of MuSR





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

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



$A_0P(t)$ contains the physics:

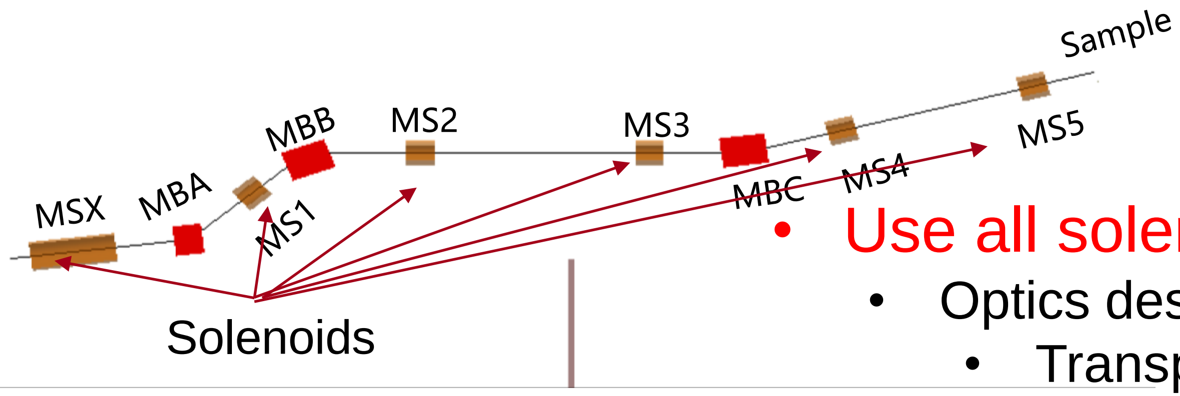
frequency: $\omega_L = \gamma_\mu B_{loc}$, value of field at muon site

damping: width of field distribution, fluctuations

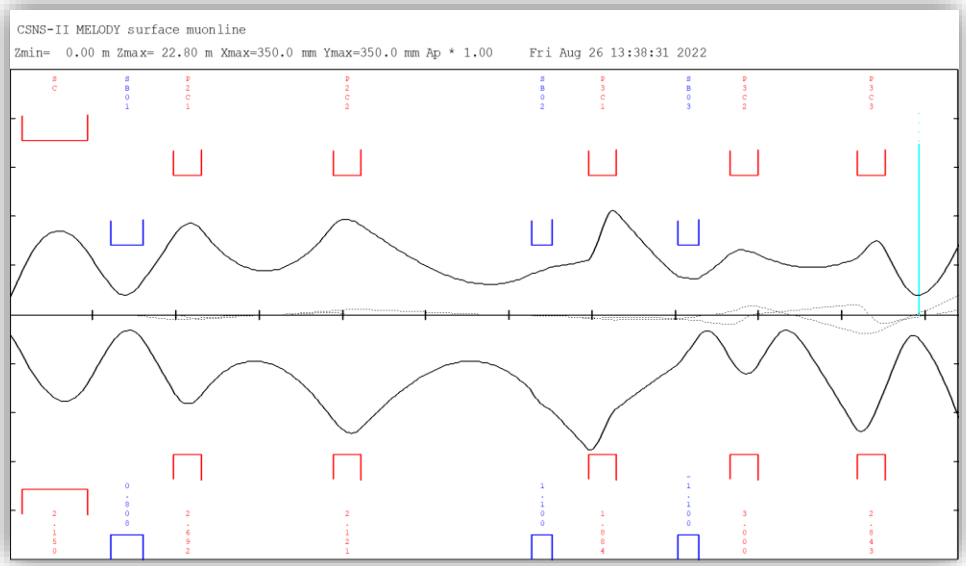
amplitude: magnetic/non-magnetic volume fraction, or Mu fraction

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

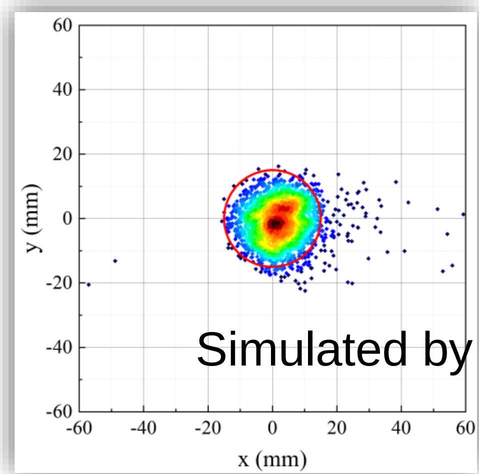
Surface Muon Beamline Design



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



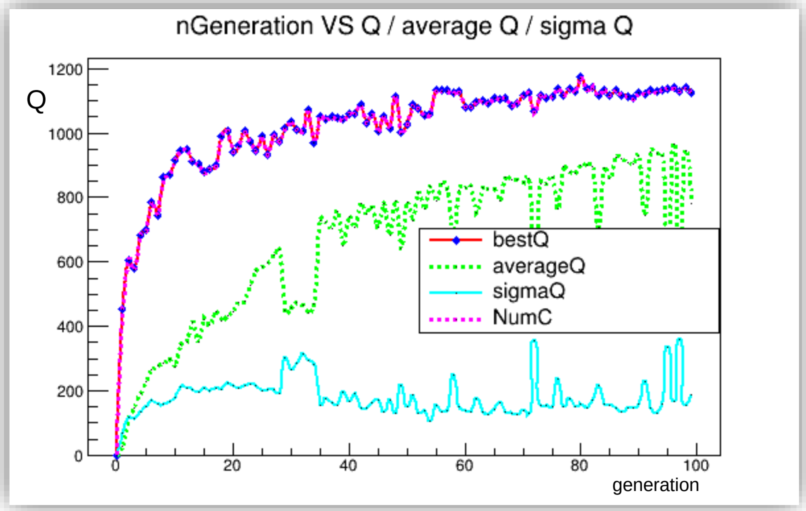
Designed by Transport

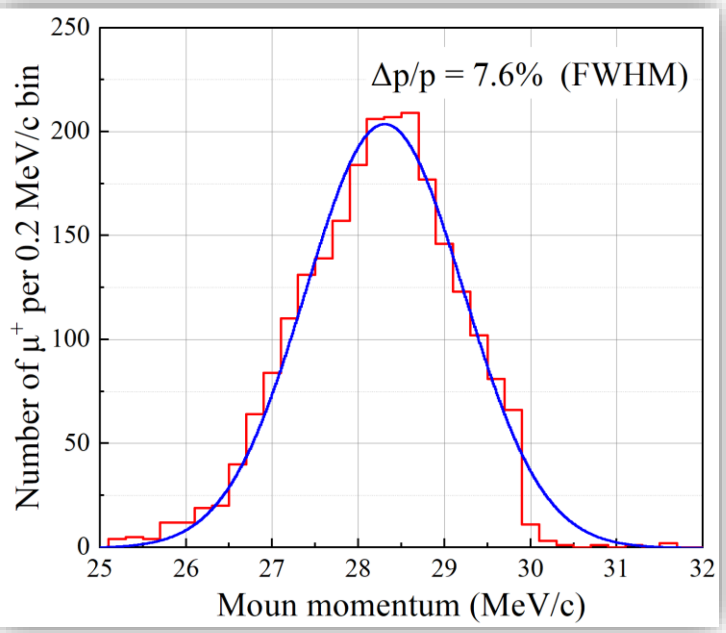


Simulated by G4beamline

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

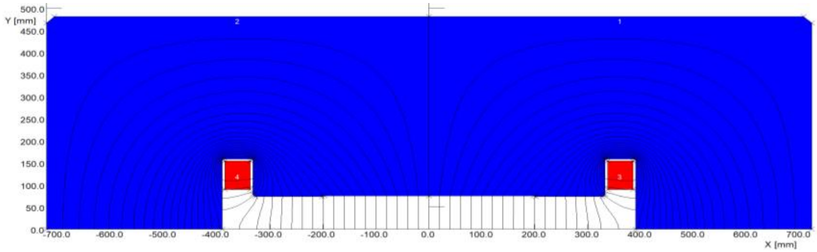




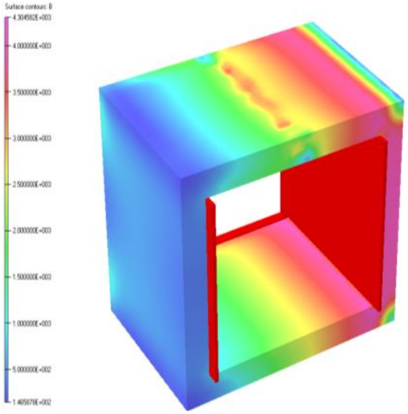
Parameters	G4bl simulation
x (FWHM)	1.64 cm
y (FWHM)	1.84 cm
$\Delta p/p$ (FWHM)	~ 7.6%
μ+ rate	18.2×10^5 μ^+/s
μ+ rate on ϕ30 mm	**15.7×10^5 μ^+/s**
Core ratio	91.24%
Polarization	**~ 95%**
e^+/μ^+	<0.01

Technique design of the magnets

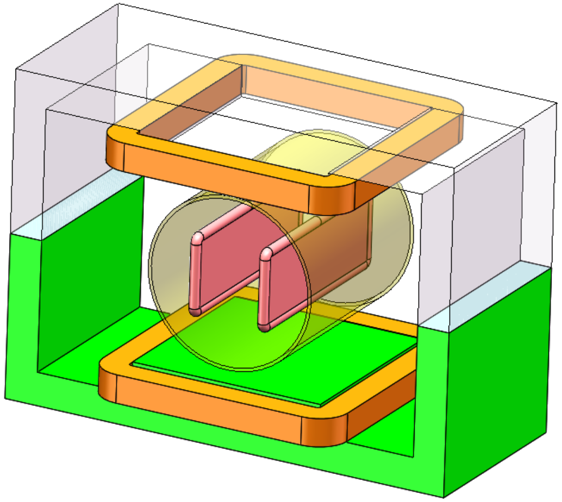
Dipole

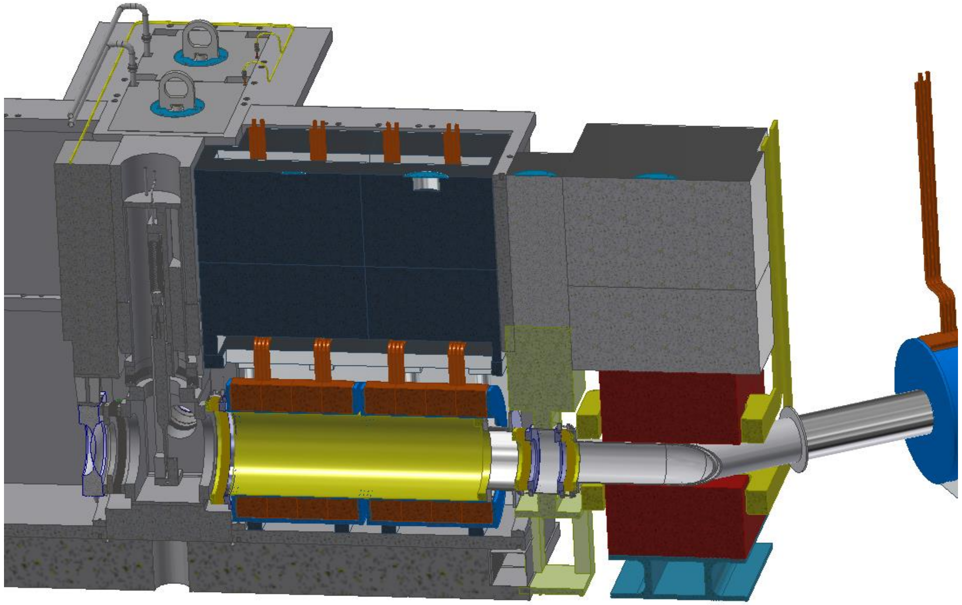


Kicker



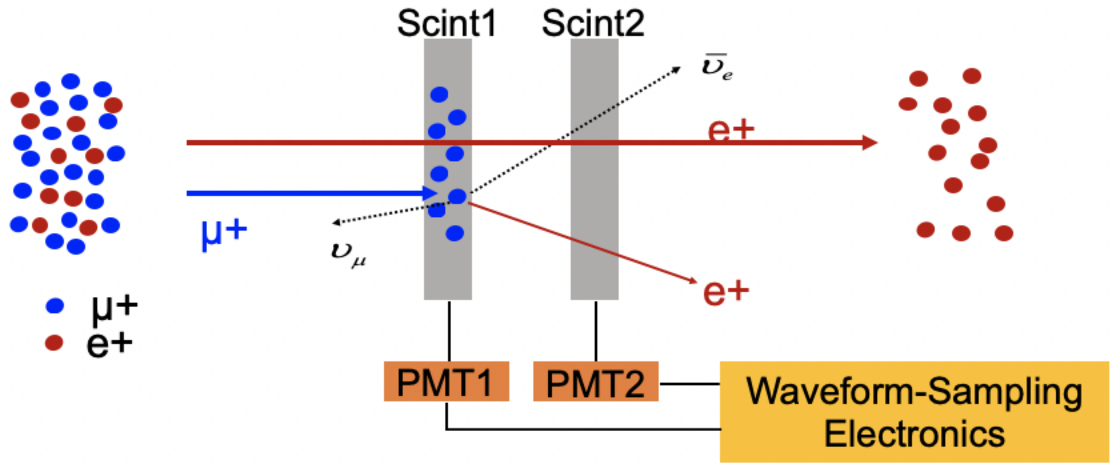
Wein fielter



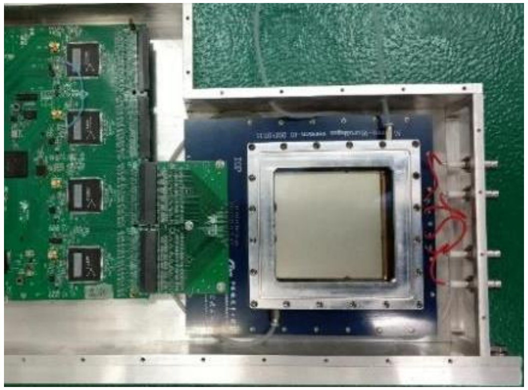


Mechanical design of the magnets

Beam measurement

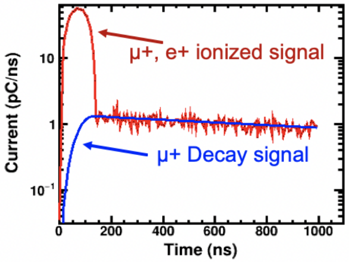


Beam intensity measurment

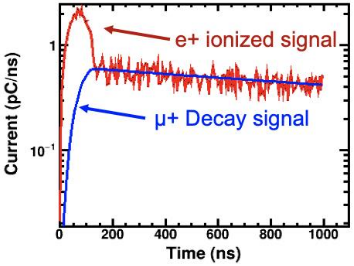


Beam spot monitor

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



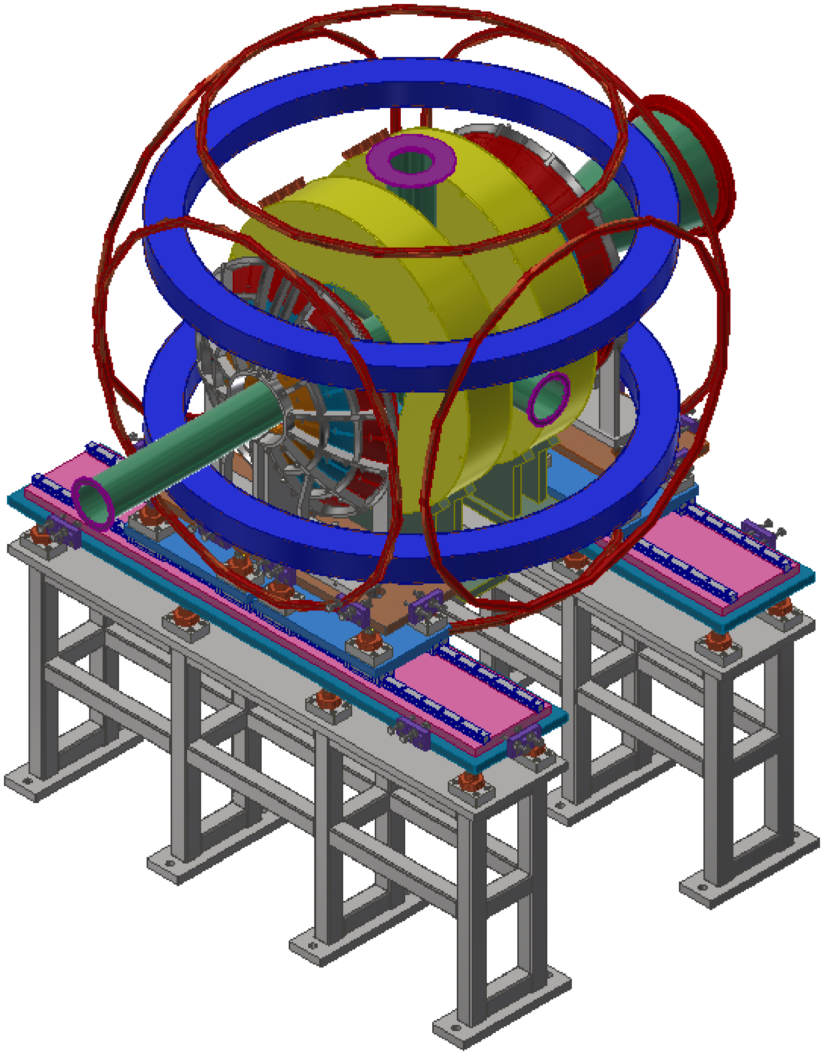
- Measure beam spot size with a MicroMegas detector



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

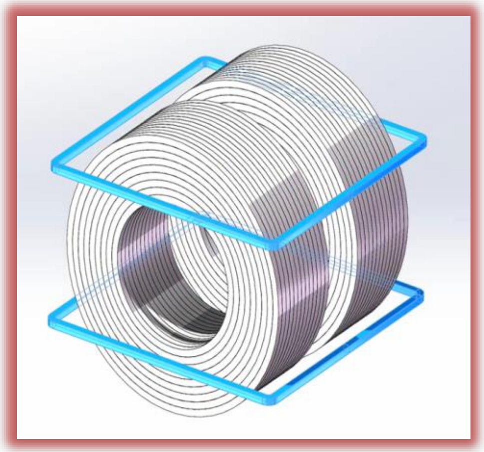
μSR Spectrometer

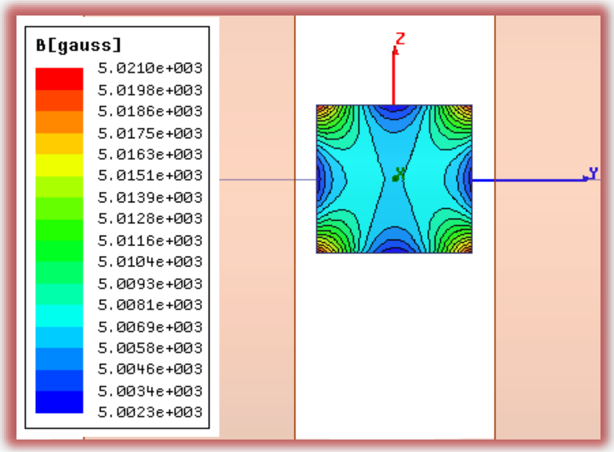
- **Feature:** High single-pulse intensity
- **Detector unit**: ~ 3000 detectors (scintillator+SiPM) pointed to sample
- **Electronics**: ASIC based FEE + multi-stop TDC
- **Fly-pass structure**

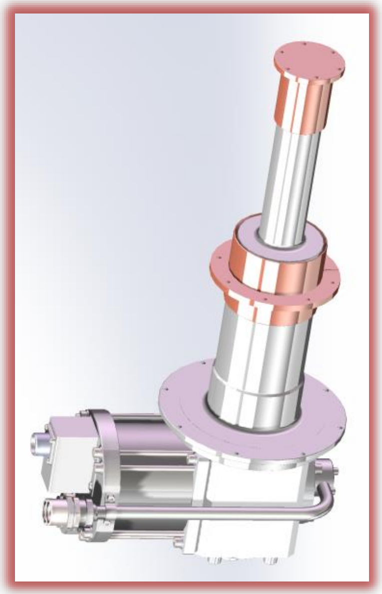


Sample Environment

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

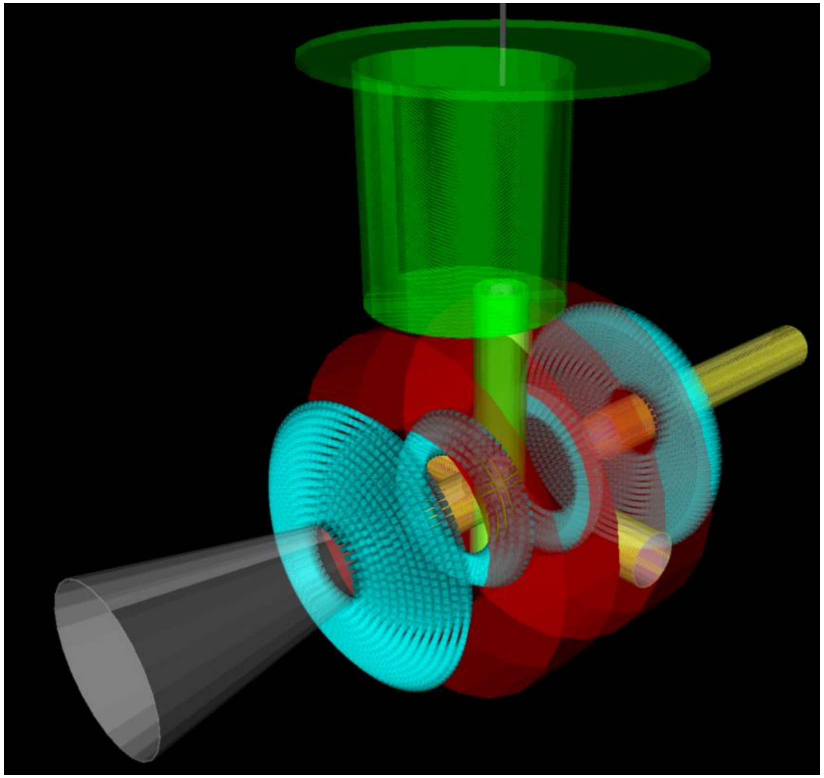


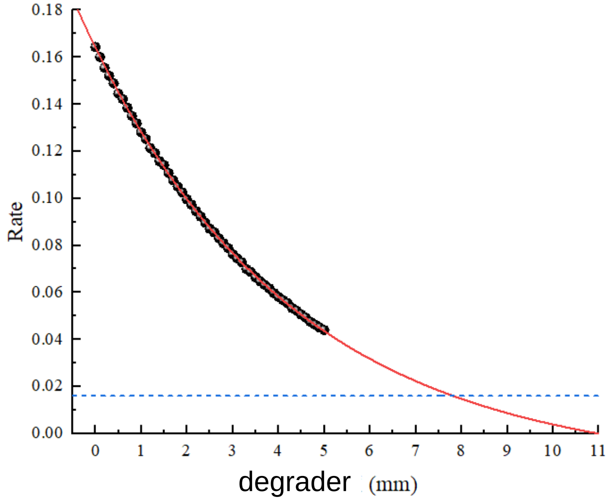


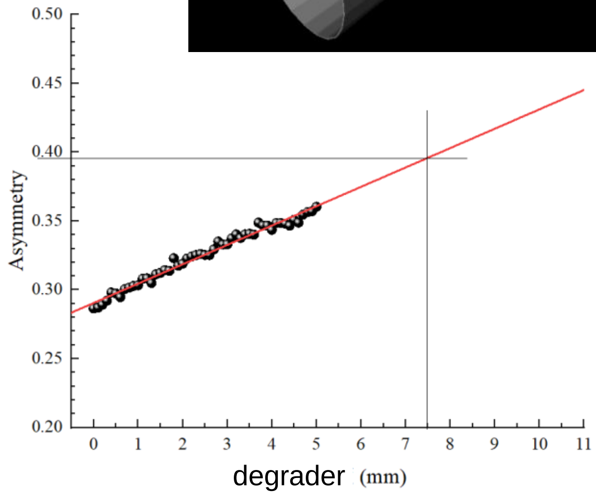


Simulation

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



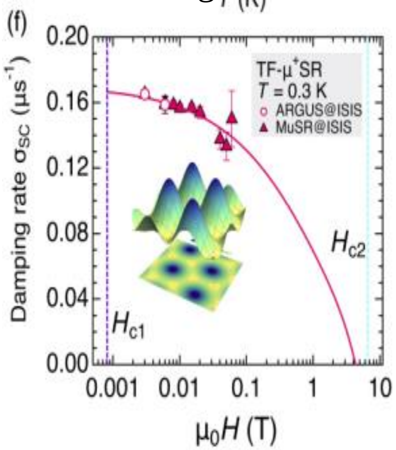




Pros and cons

- 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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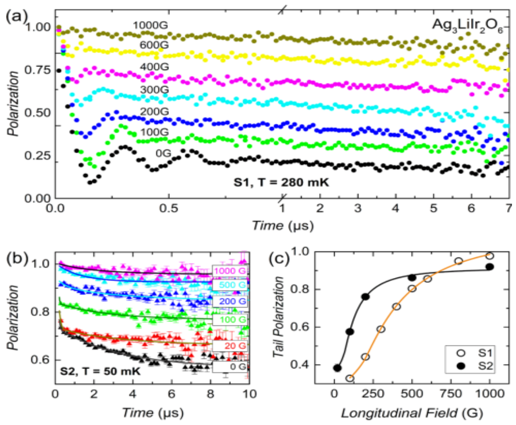
- Low repetition rate：
  - Low counting rate
    - ➢ More detectors
- Large pulse width：
  - Low time resolution
    - ➢ Beam slicing

Spin Liquid



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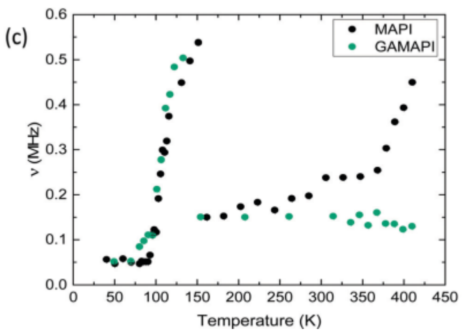
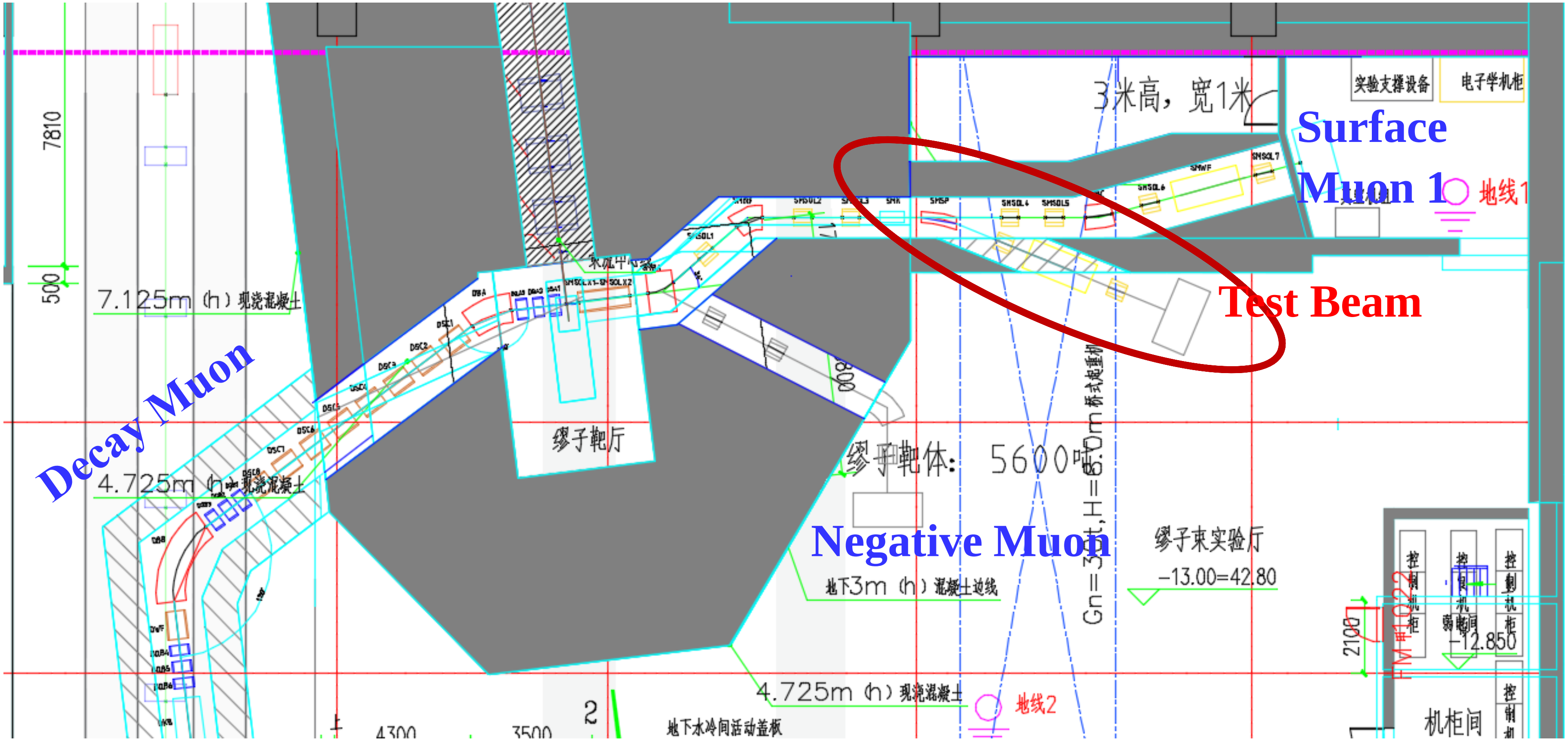
Batteries



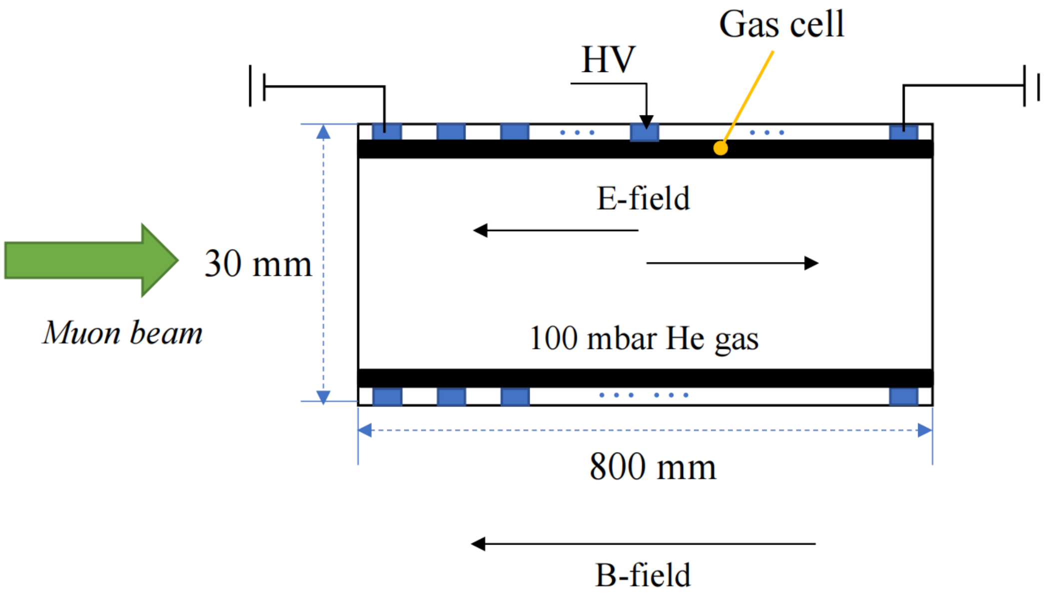
Energy Environ. Sci. **12**, (2019) 2264

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: $\phi 10$ mm
- Energy degrader: 0.78 mm–thick carbon foil
- He gas: 100 mbar, 293 K
- Gas cell: $\phi 30$ 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

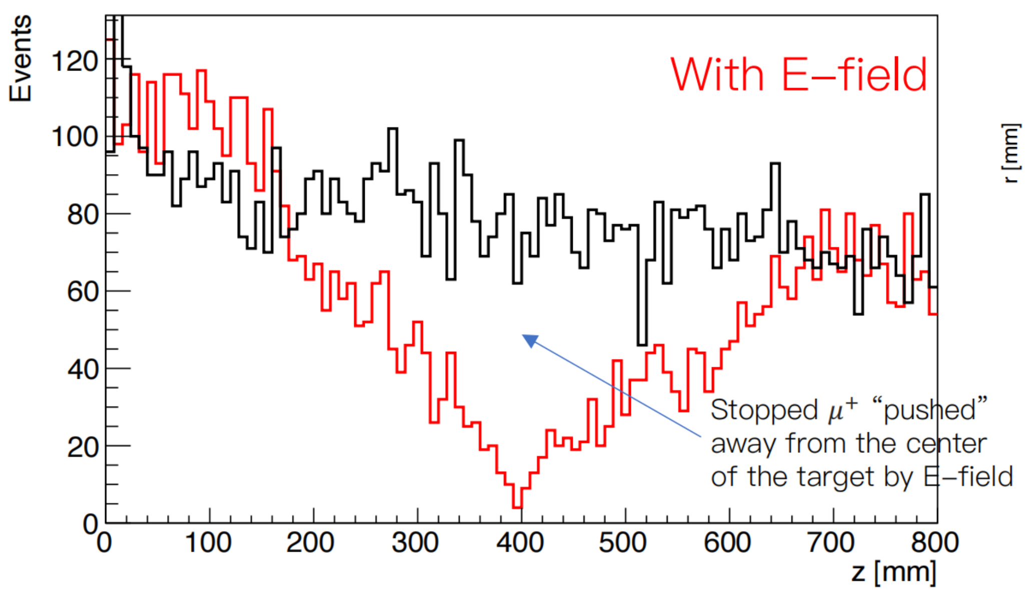
- Use helium gas to stop muons
- Use electric field to steer muon out of the gas cell
- Bring 0.1% muons to 300 eV

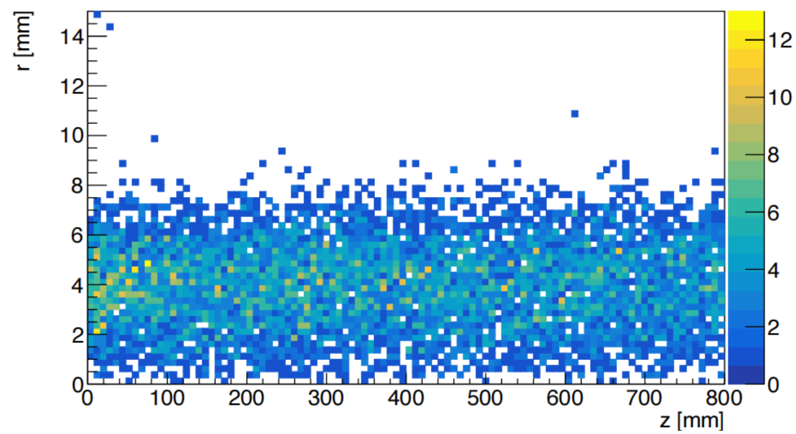
Key: use ESD material to remove the charge and to avoid breakdown in helium gas

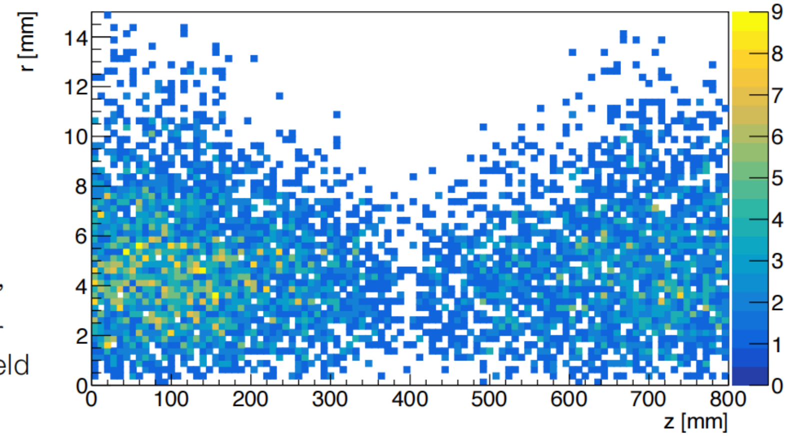
Muon moderation technology

Simulation

μ^+ stopped in He gas





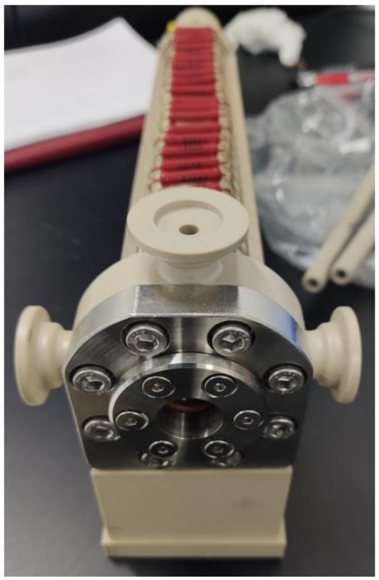


Going to be tested at ISIS...

Muon moderation technology

FCD Experiment

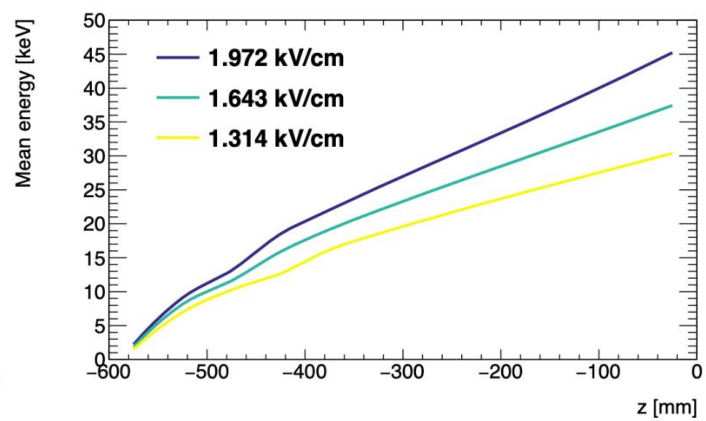
Gas cell



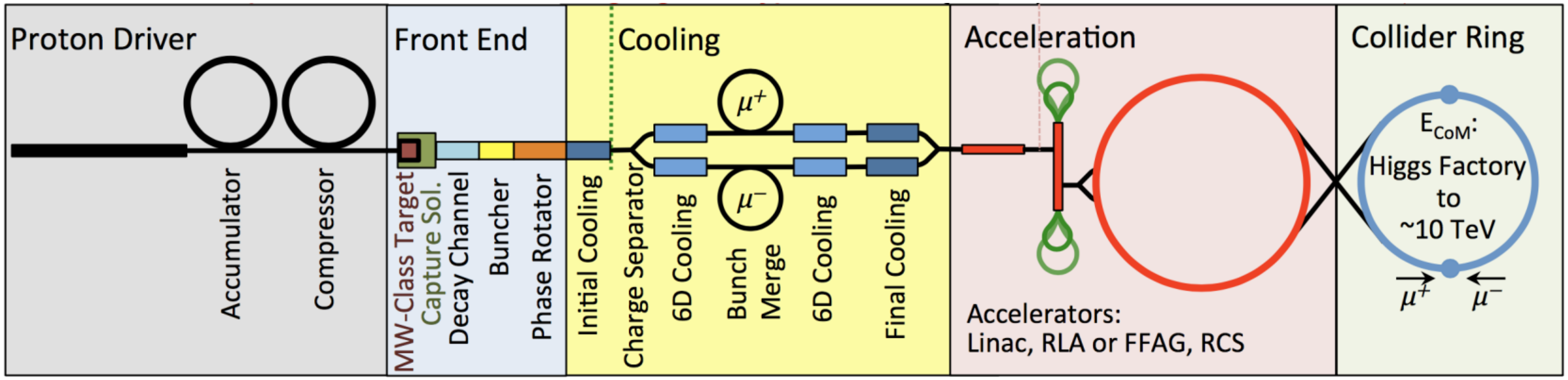
Proton source:
Am−241 + Mylar foil

Frictional cooling demonstration experiment with proton

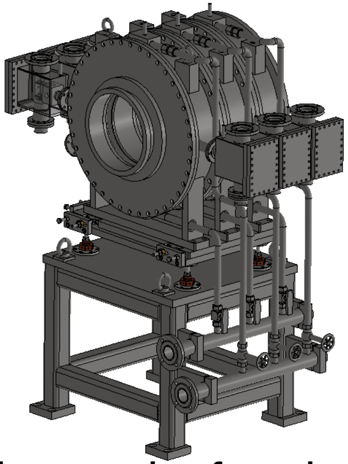
G4bl simulation
He gas: 1 mbar, 293 K
Proton initial energy: 1 eV
Proton initial z ~ −600 mm



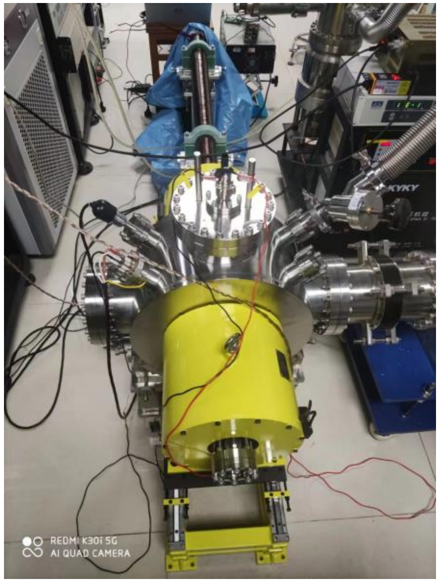
Muon de/acceleration/cooling



- Develop technologies for Muon Collider/Neutrino factory
  - Muon cooling
  - Phase rotation
  - Muon acceleration



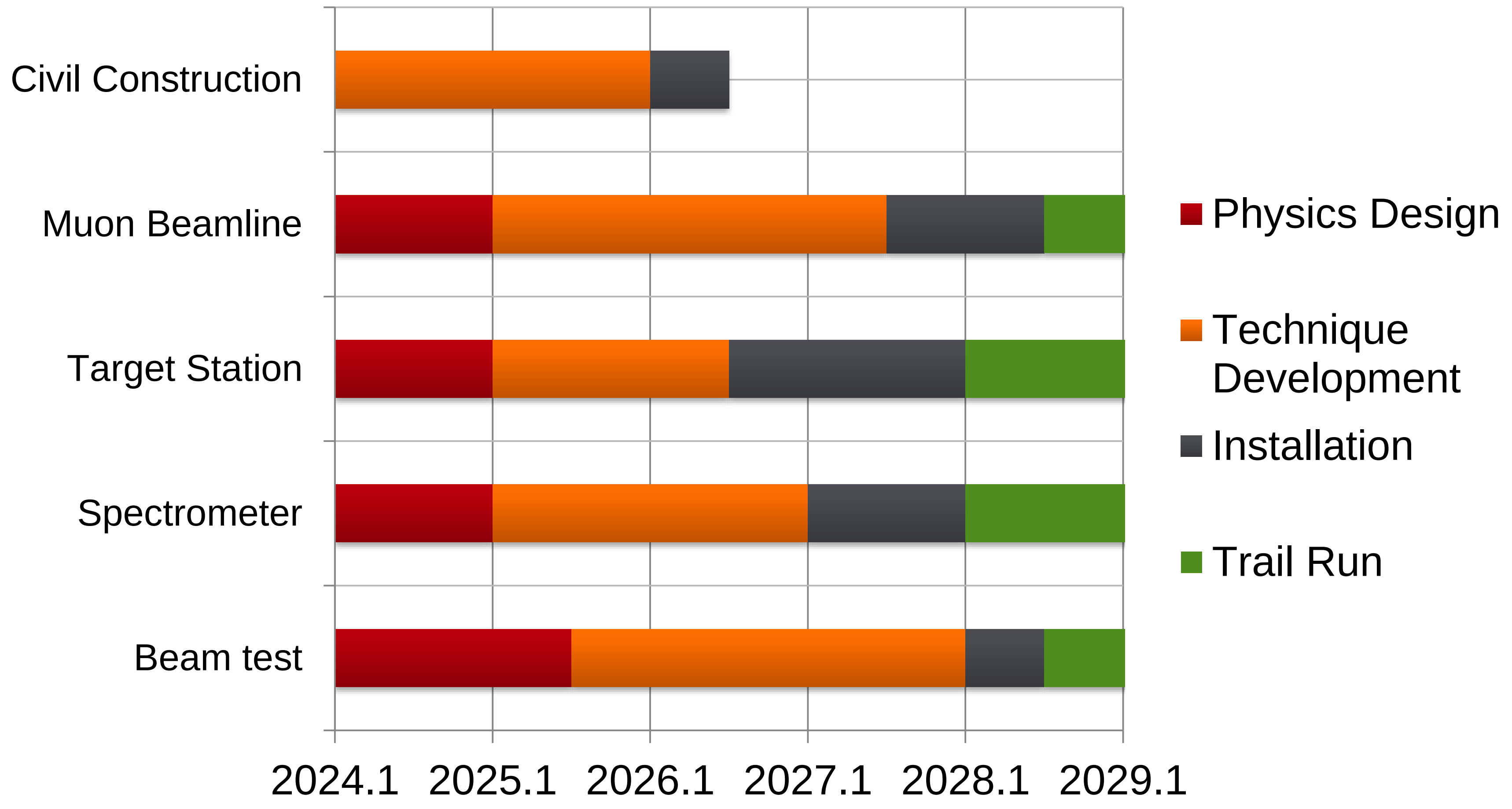
Induction cavity for phase rotation



Magnetic mirror for muonium physics

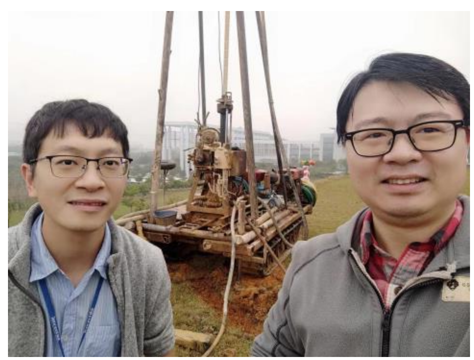
Timeline of MELODY

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

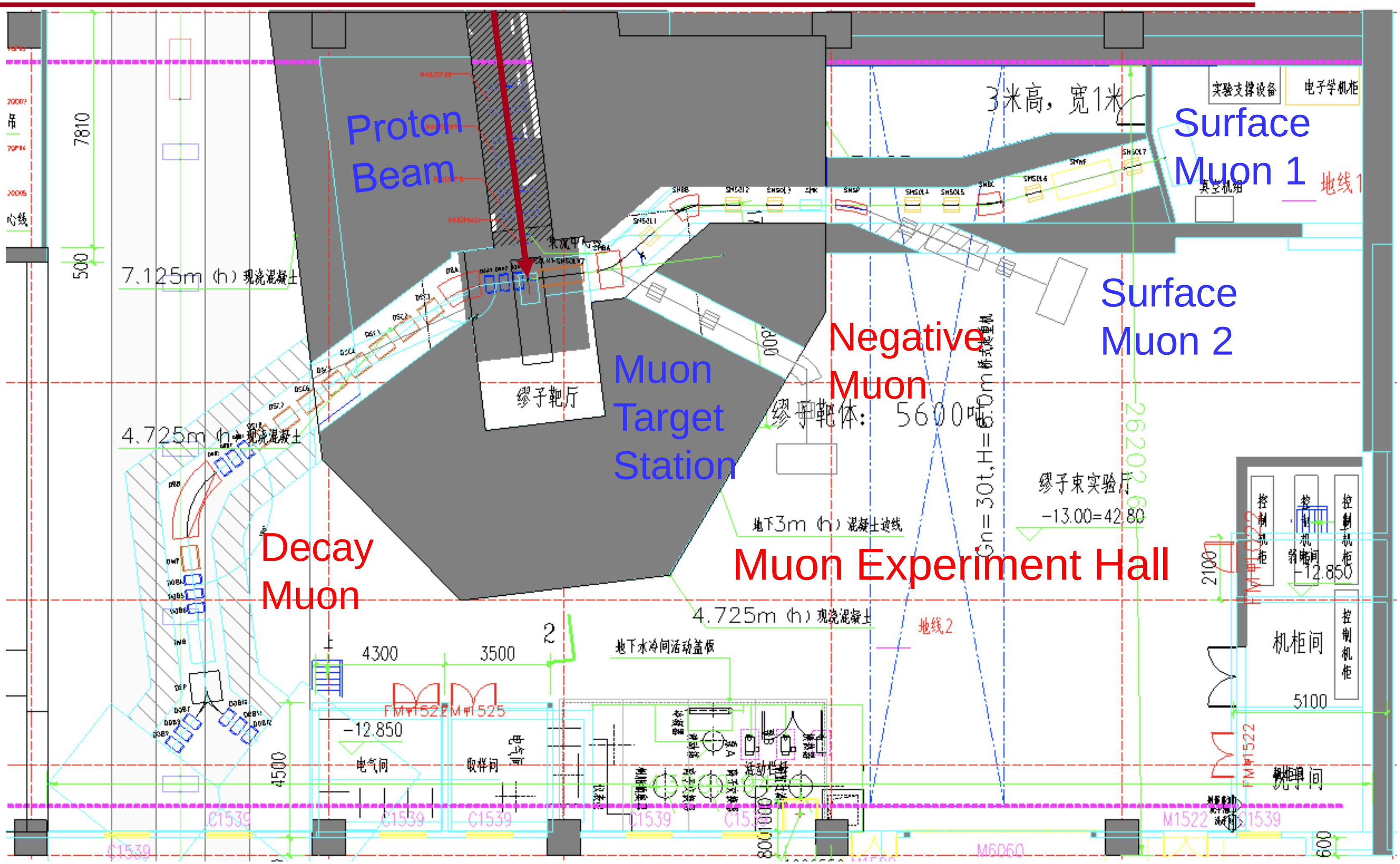


First Geosurvey

First Geosurvey has been carried out at the muon hall



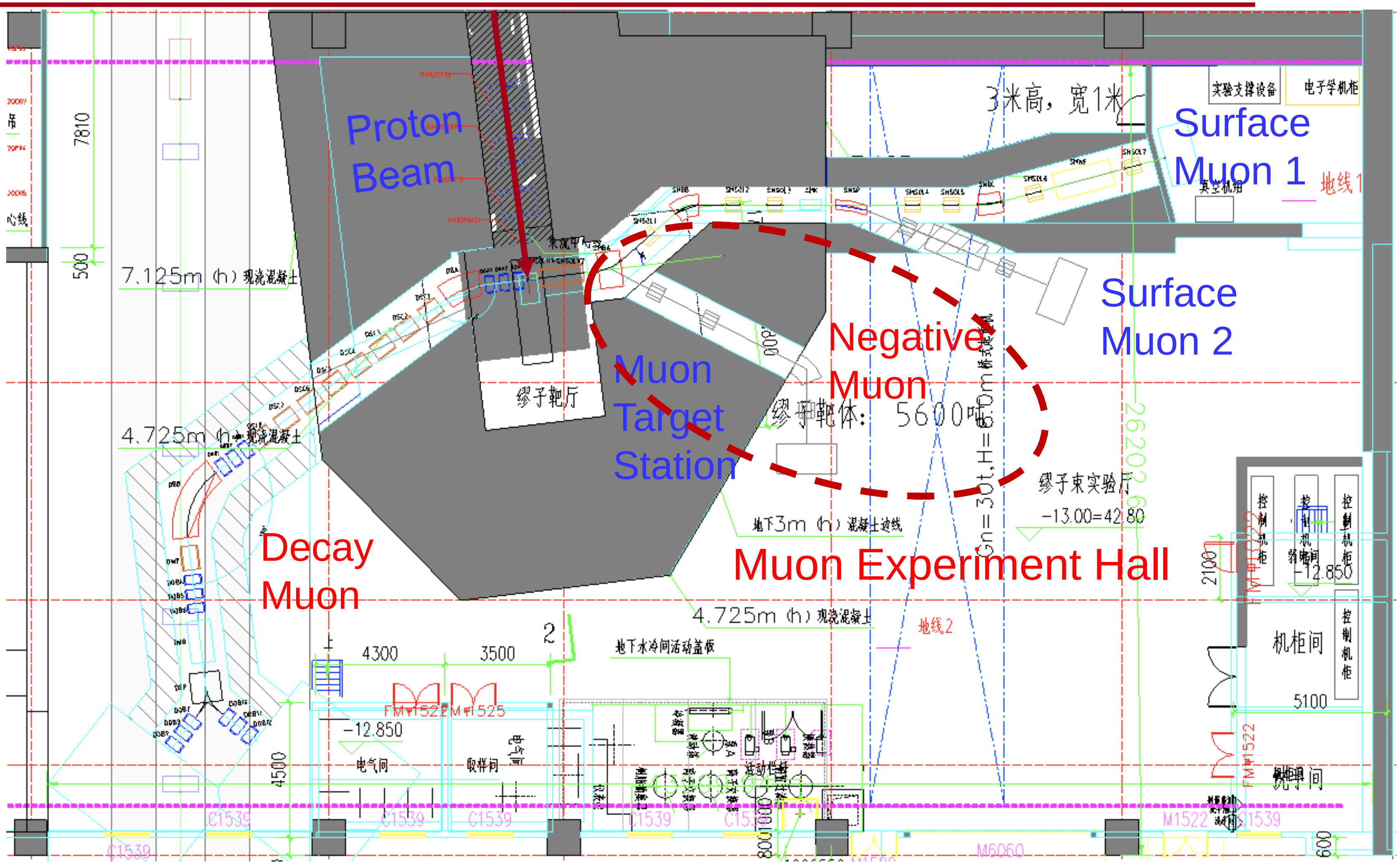
Prospect with MELODY II



- 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



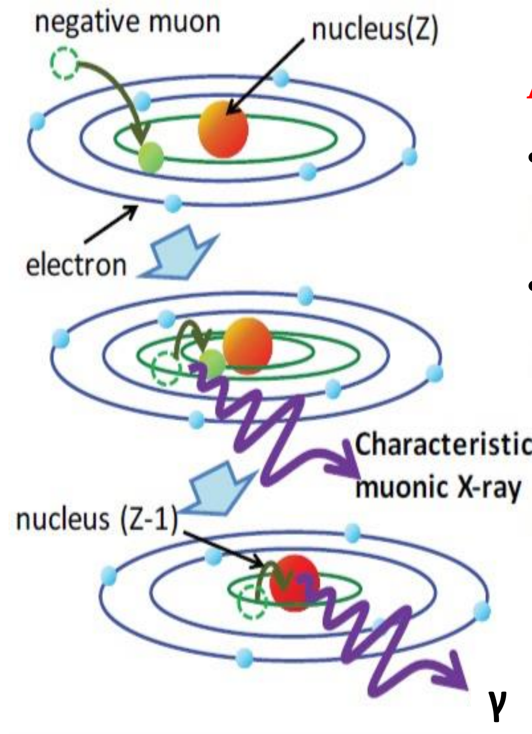
- Negative muon beam:
    - Momentum: 30MeV/c
- More terminals：
    - Various spectrometers
    - Muon imaging
    - Muonic X-ray

Muon Induced X-ray Emission

μ^- capture in the atom（Muonic atom）

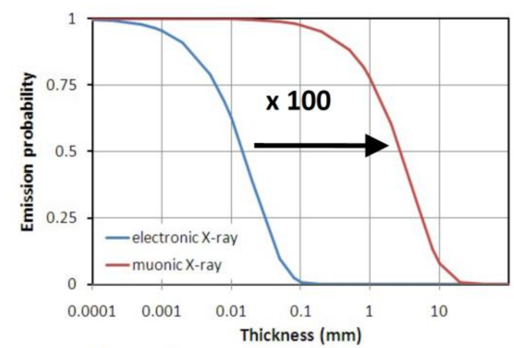
μ^- induce the X-ray to the ground state

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 $K\alpha$

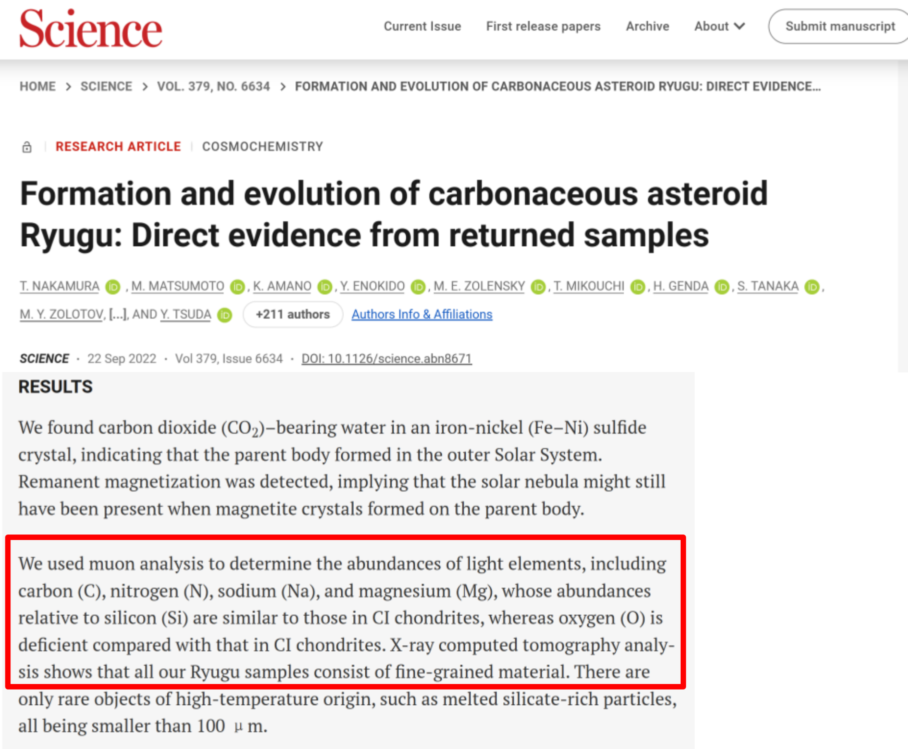
元素	Fluorescence $K\alpha$ [keV]	Muonic $K\alpha$ [keV]
Li	0.052	18.7
C	0.3	75
Cu	8	1500

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)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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

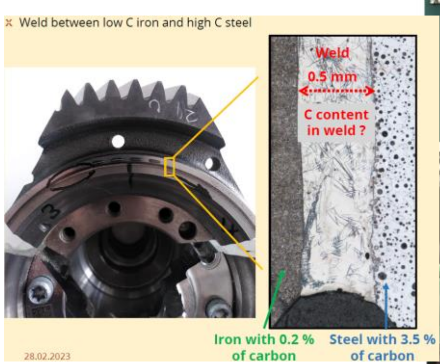
T. NAKAMURA, M. MATSUMOTO, K. AMANO, Y. ENOKIDO, M. E. ZOLENSKY, T. MIKOUCHI, H. GENDA, S. TANAKA, M. Y. ZOLOTOV, [...], AND Y. TSUDA +211 authors Authors Info & Affiliations

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.

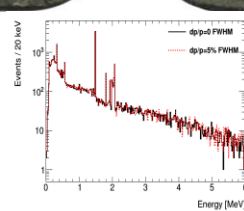
We used muon analysis to determine the abundances of light elements, including carbon (C), nitrogen (N), sodium (Na), and magnesium (Mg), whose abundances relative to silicon (Si) are similar to those in CI chondrites, whereas oxygen (O) is deficient compared with that in CI chondrites. X-ray computed 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

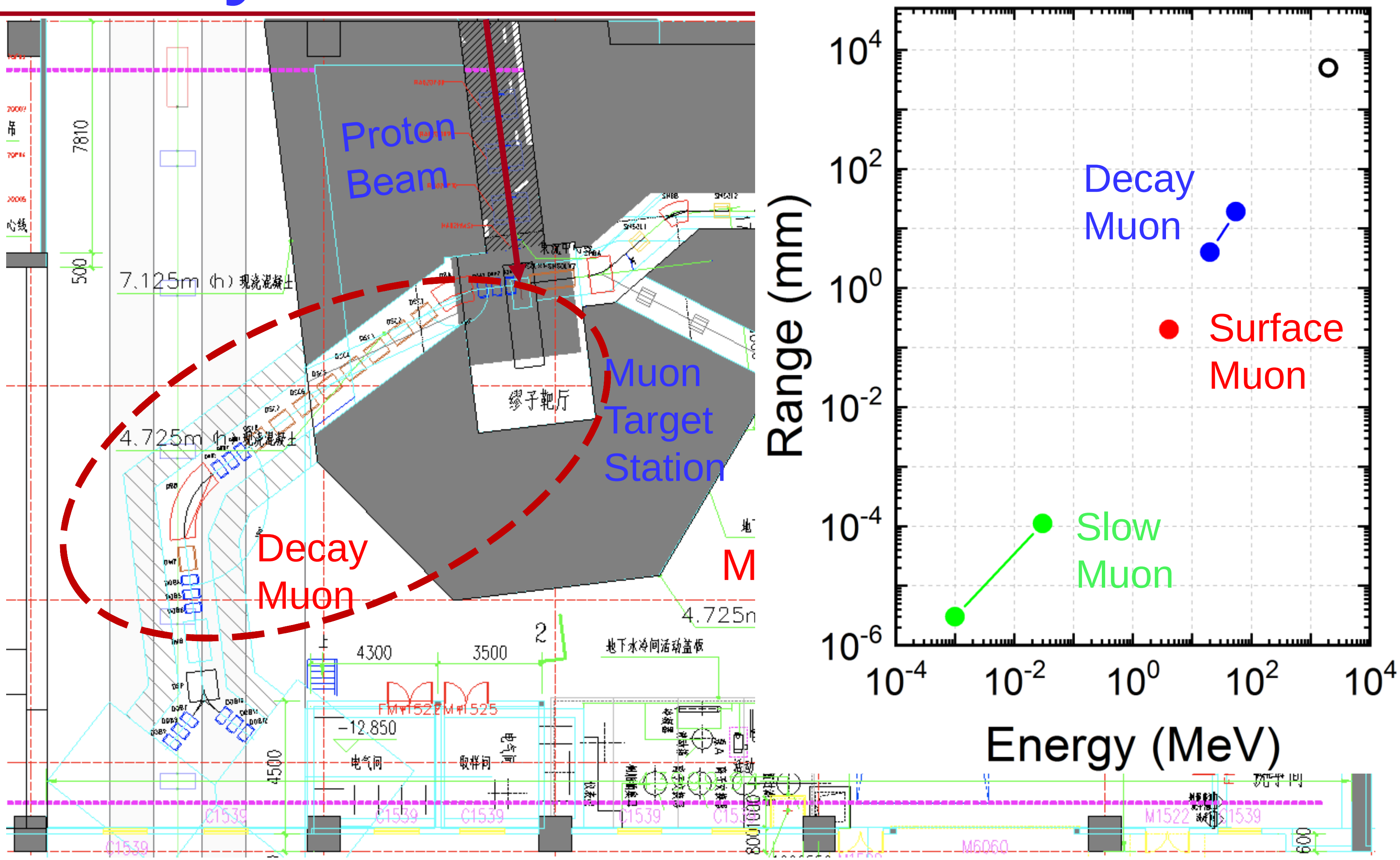
JPARC on Lithium batteries

ISIS MIXE on ancient ROME coin



JPARC MIXE on ancient Chinese Mirror

Decay Muon Beam



- Momentum: 20 ~ 120 MeV/c
- Charge: + or -
- Intensity: $10^5 \sim 10^7$ 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
- Baterries

Muon Imaging
- Thick samples

Single Particle Effect
Large capture cross section of μ^-

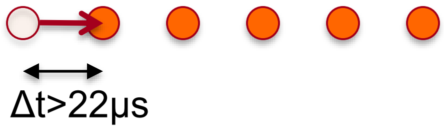
Muon Beam Parameters

	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 ~ 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

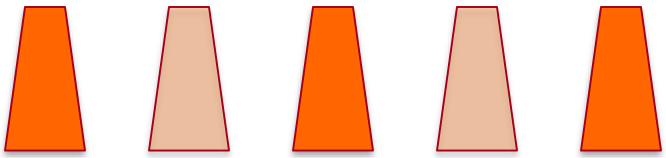
重复频率

$\tau = 2.2\ \mu sec$

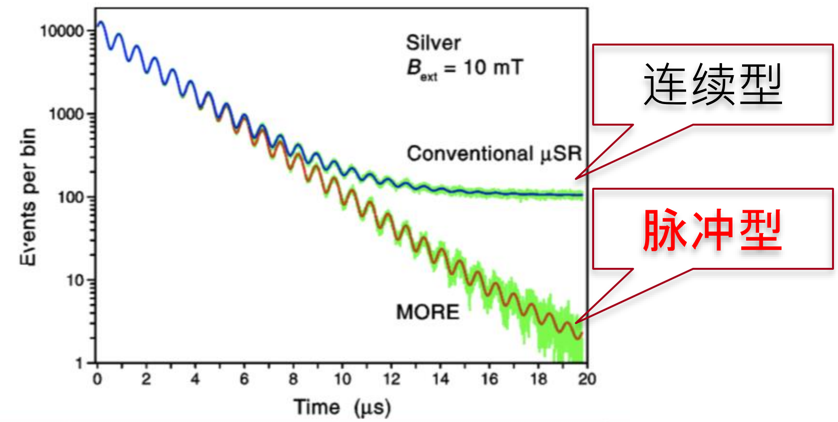
连续型



脉冲型



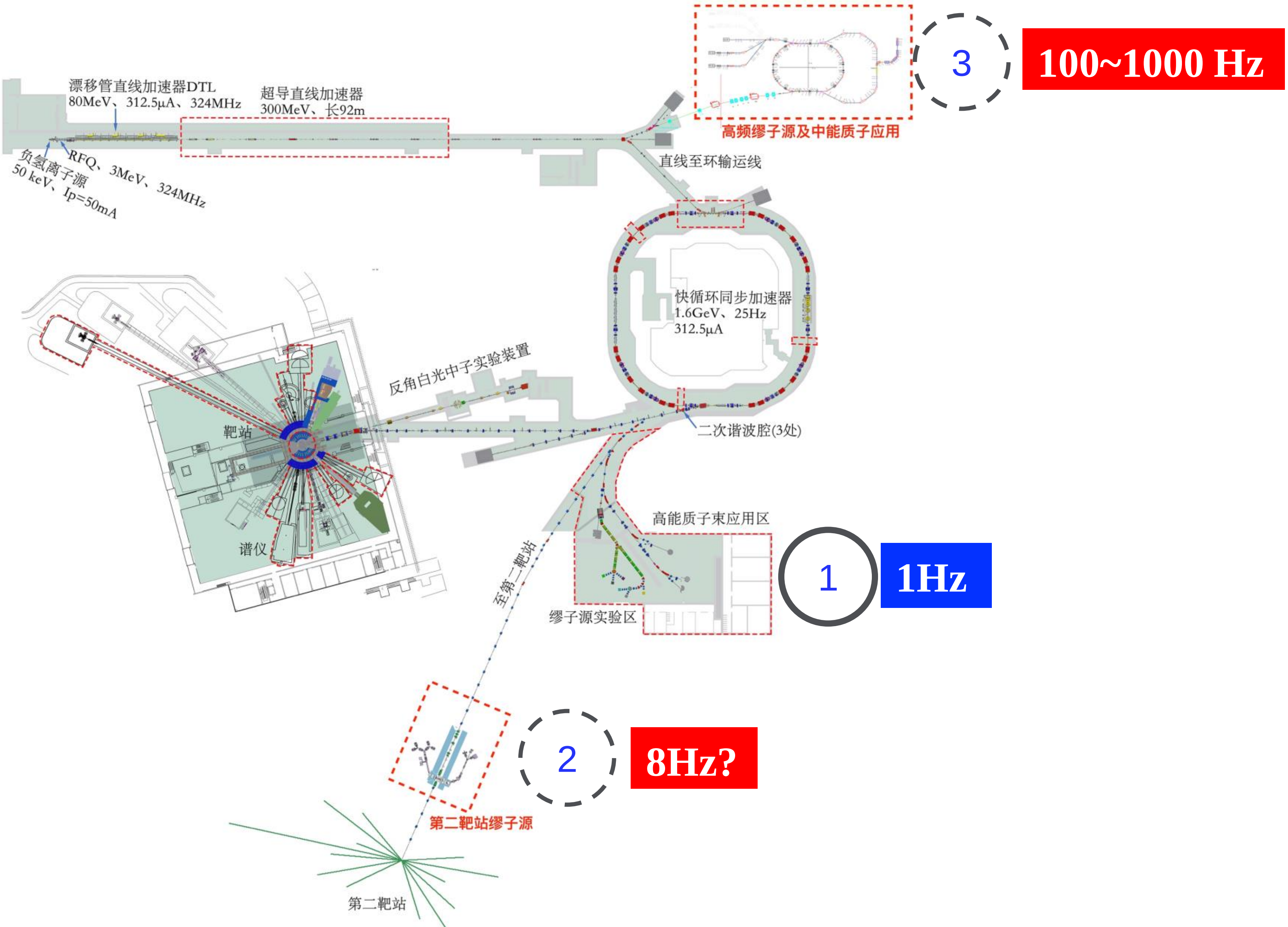
两种μSR信号对比



	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

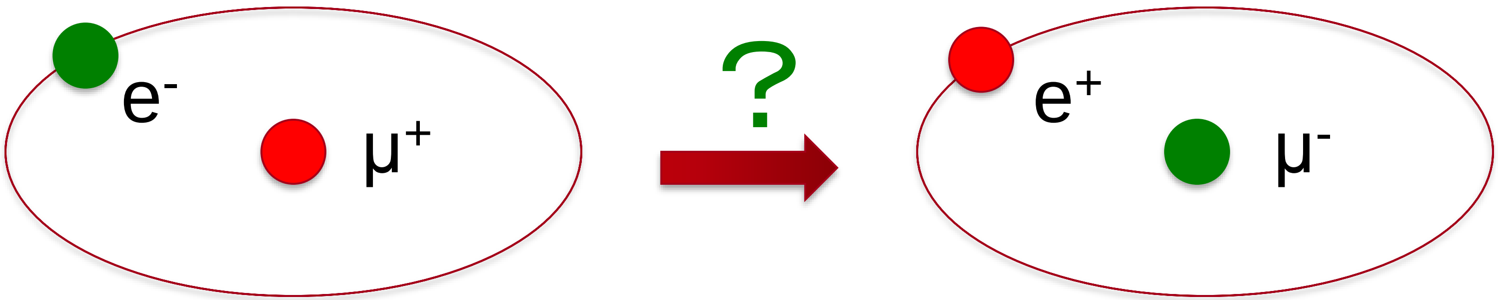
* 探测器结构一定的情况下

High rEpetition Muon Source (HEMS)

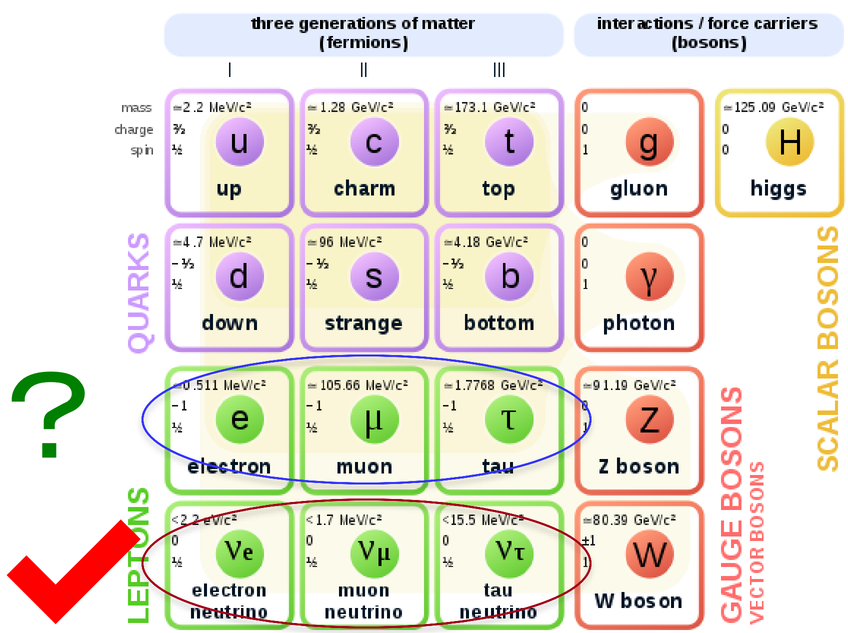


高重复频率缪子源应用之MuMubar

Muonium (Mu) Anti-muonium ($\overline{Mu}$)



Standard Model of Elementary Particles



获得院从0到1原始创新项目支持

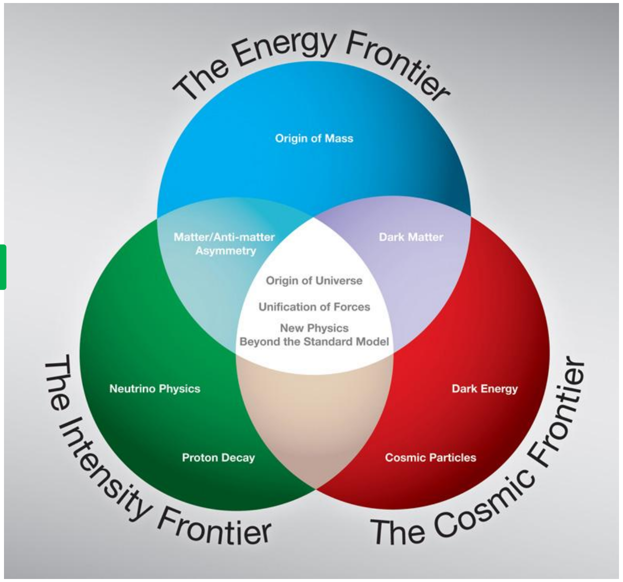
已完成初步概念设计

研究背景- 探索超出标准模型新物理

强度前沿物理：

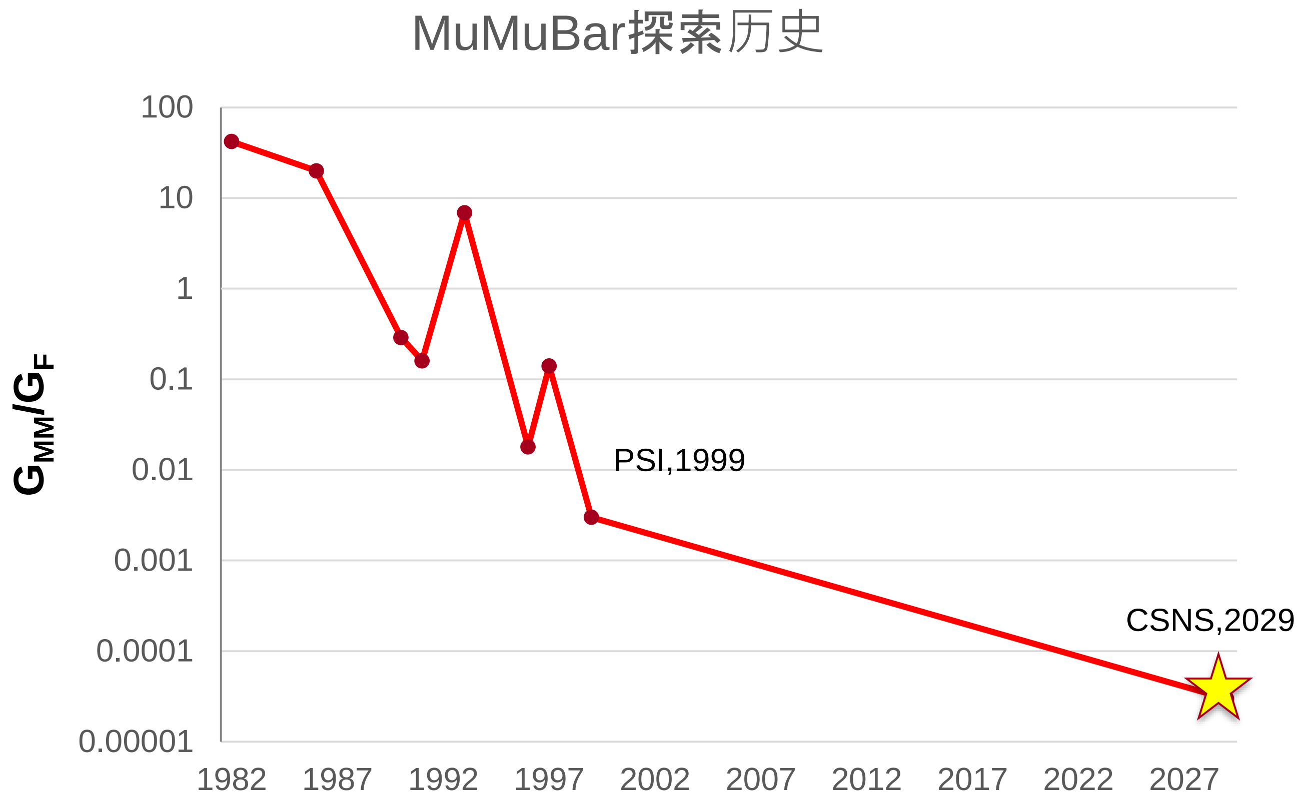
- 中微子实验
- 中子/缪子EDM
- 带电轻子味道破坏实验 cLFV：
  - Mu2e/COMET
    - $\mu^- + Al \rightarrow e^- + Al$
  - MEG
    - $\mu^+ \rightarrow e^+ + \gamma$
  - Mu3e
    - $\mu^+ \rightarrow e^+ e^- e^+$
  - **MuMuBar:**
    - $\mu^+ e^- \rightarrow \mu^- e^+$

粒子物理三个前沿方向



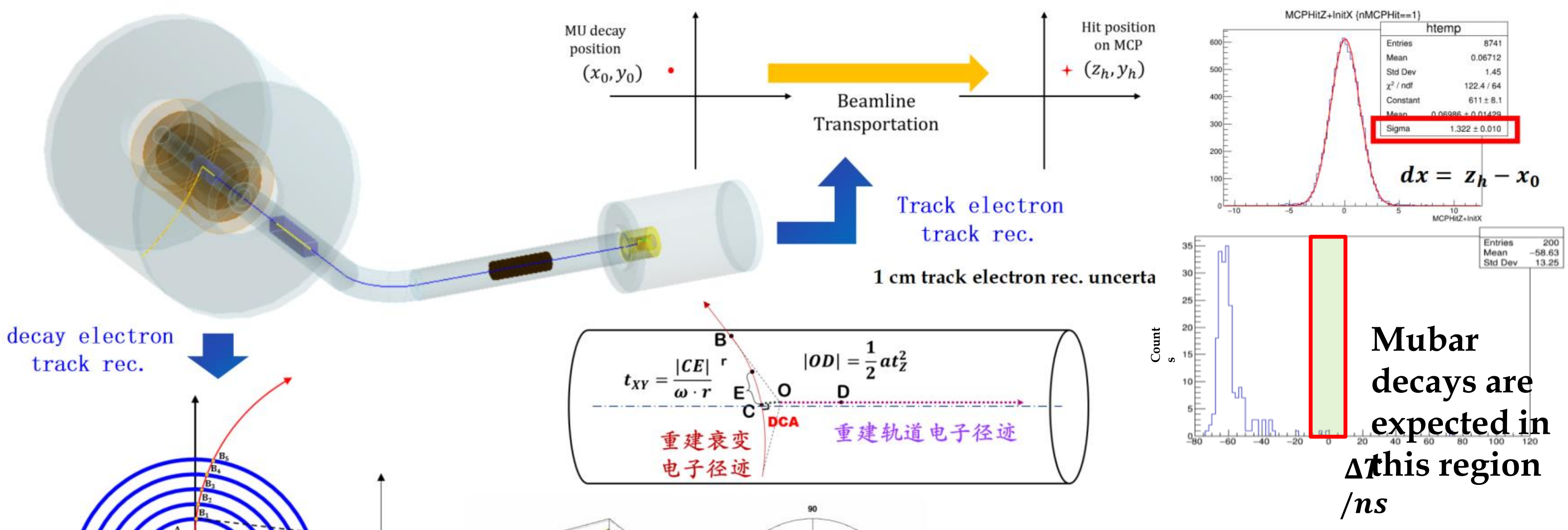
- **标准模型强烈压低（<10^{-54}）**
- **违反轻子味道数守恒两个单位**

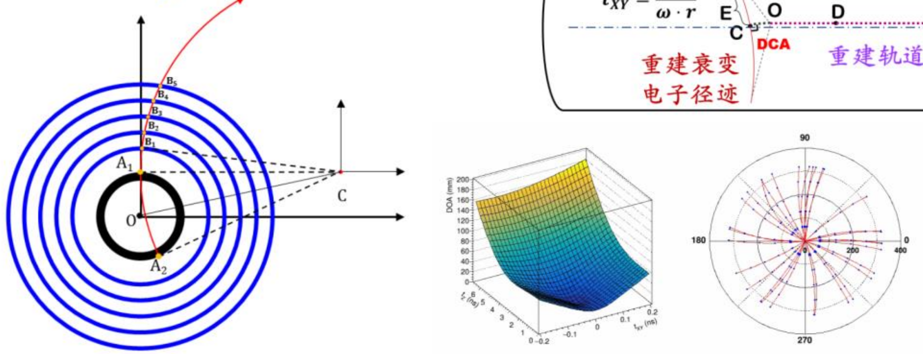
历史上的MuMuBar



- 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





- 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 …

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

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

总结

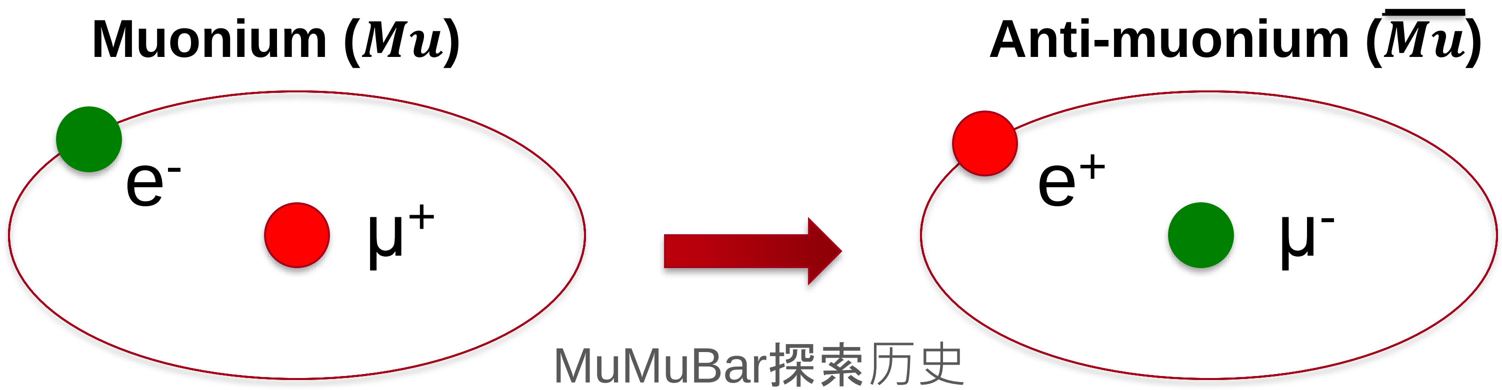
- 缪子束流在凝聚态物理、磁性材料、电池材料、文物元素分析、电子元件单粒子效应等领域具有广泛而独特的应用
- 散裂二期将建设国内首个缪子源应用平台，将初步建设缪子靶站、表面缪子束线及MuSR应用终端和测试终端
- 基于缪子源平台将可发展负缪子束线、高能衰变缪子束线等多束线终端
- 未来将发展高重复频率缪子源，发展粒子物理实验

本人微信

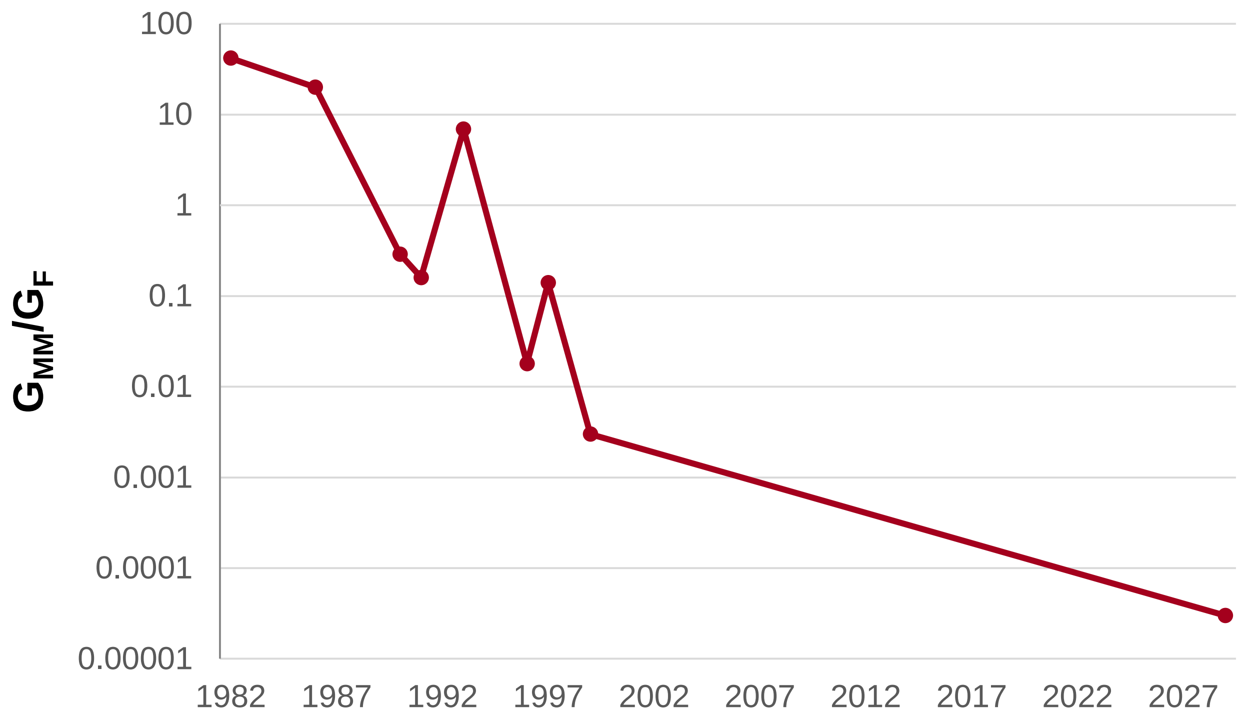
欢迎合作研讨！ 谢谢！

backups

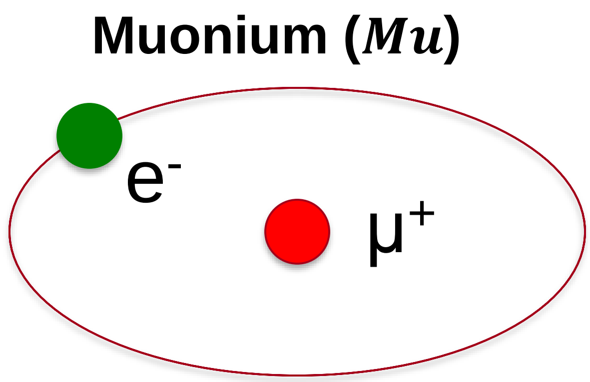
Potential muon physics - MuMuBar?



MuMuBar探索历史



MuMuBar requires High Repetition Muons



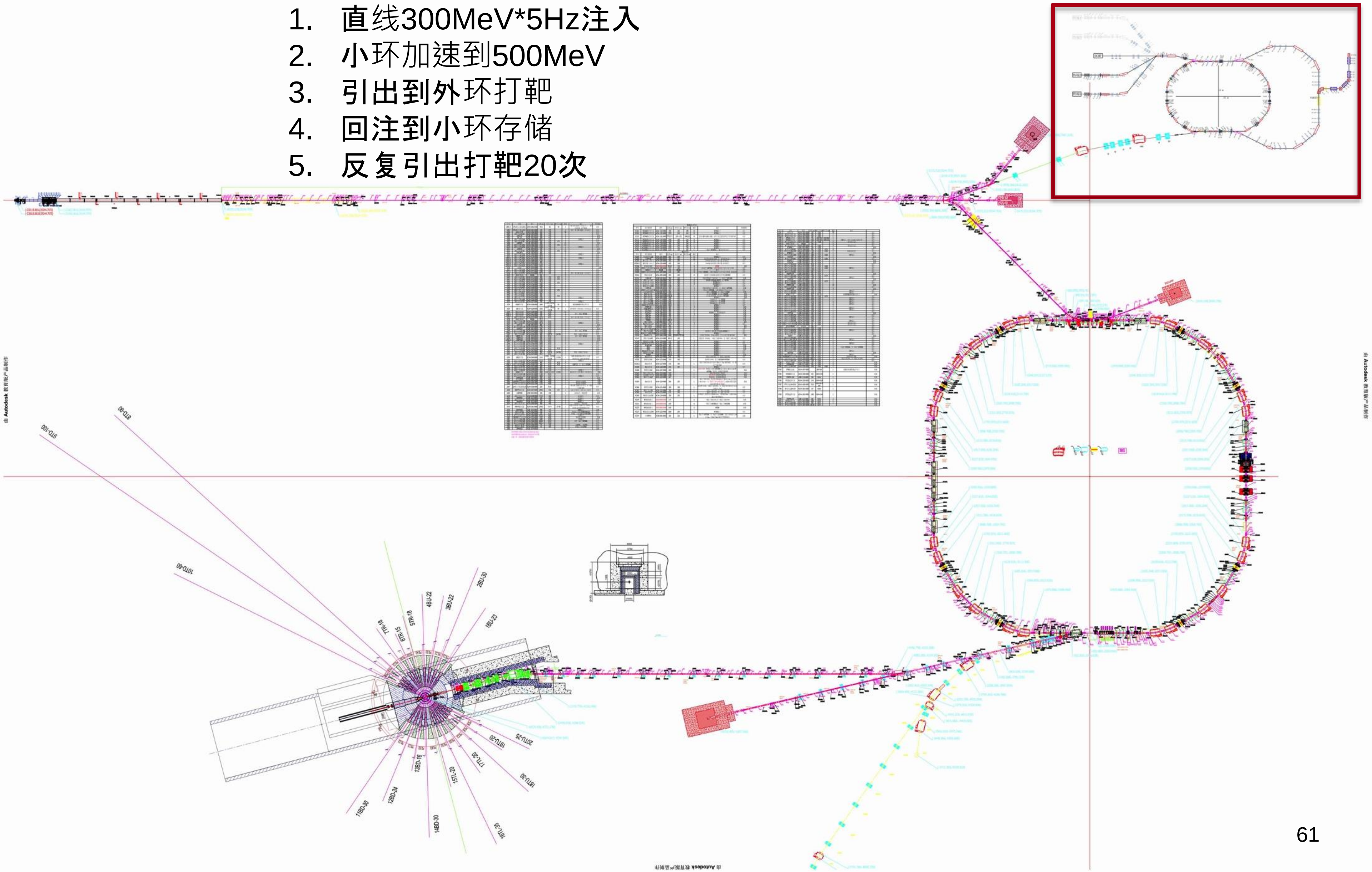
Total intensity : > $2*10^8$ μ^+/s

Single Pulse intensity : < $5*10^6$

→ Repetition>40Hz

High rEpetition Muon Soure - HEMS

1. 直线300MeV*5Hz注入
2. 小环加速到500MeV
3. 引出到外环打靶
4. 回注到小环存储
5. 反复引出打靶20次

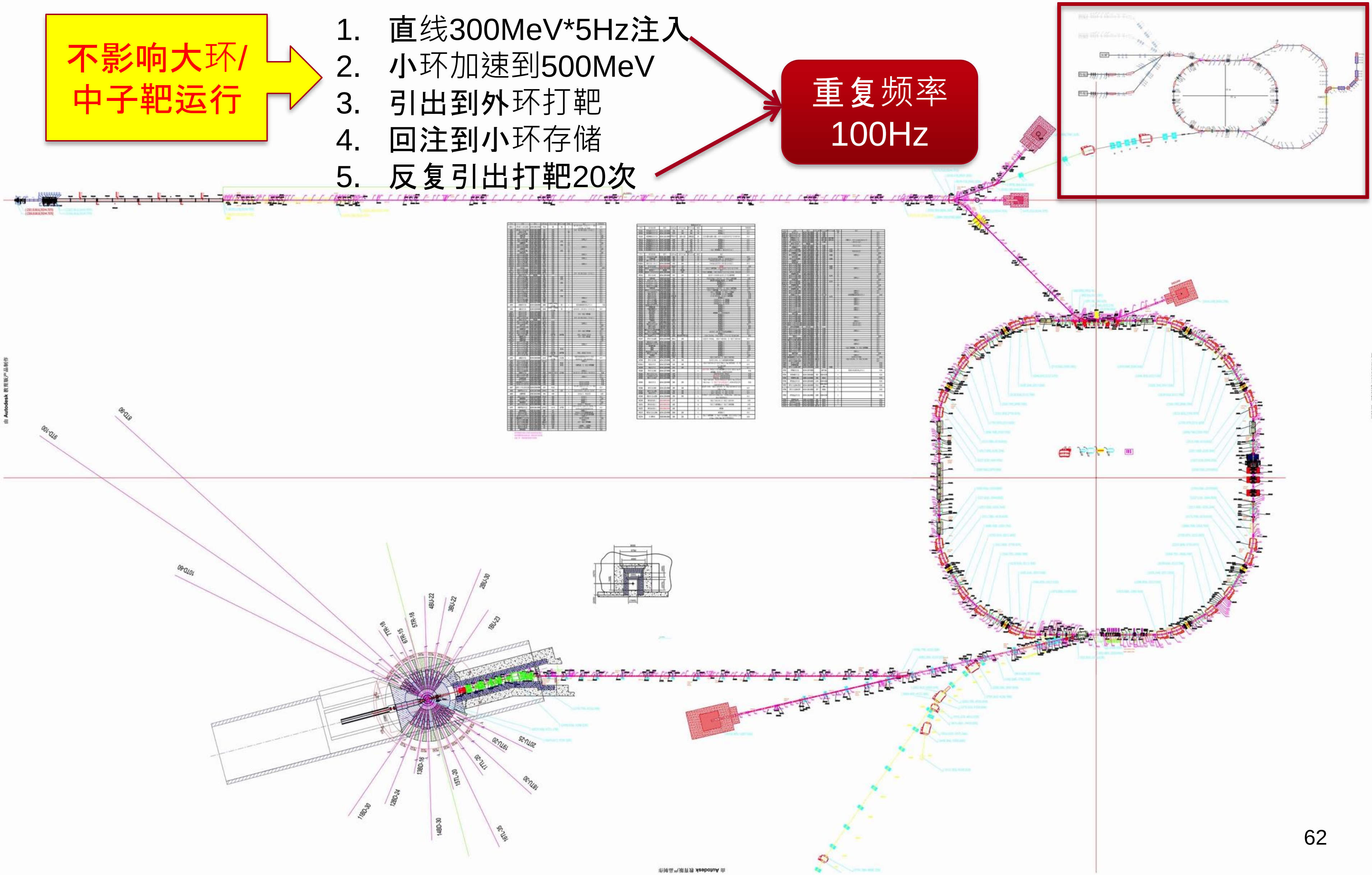


High rEpetition Muon Soure - HEMS

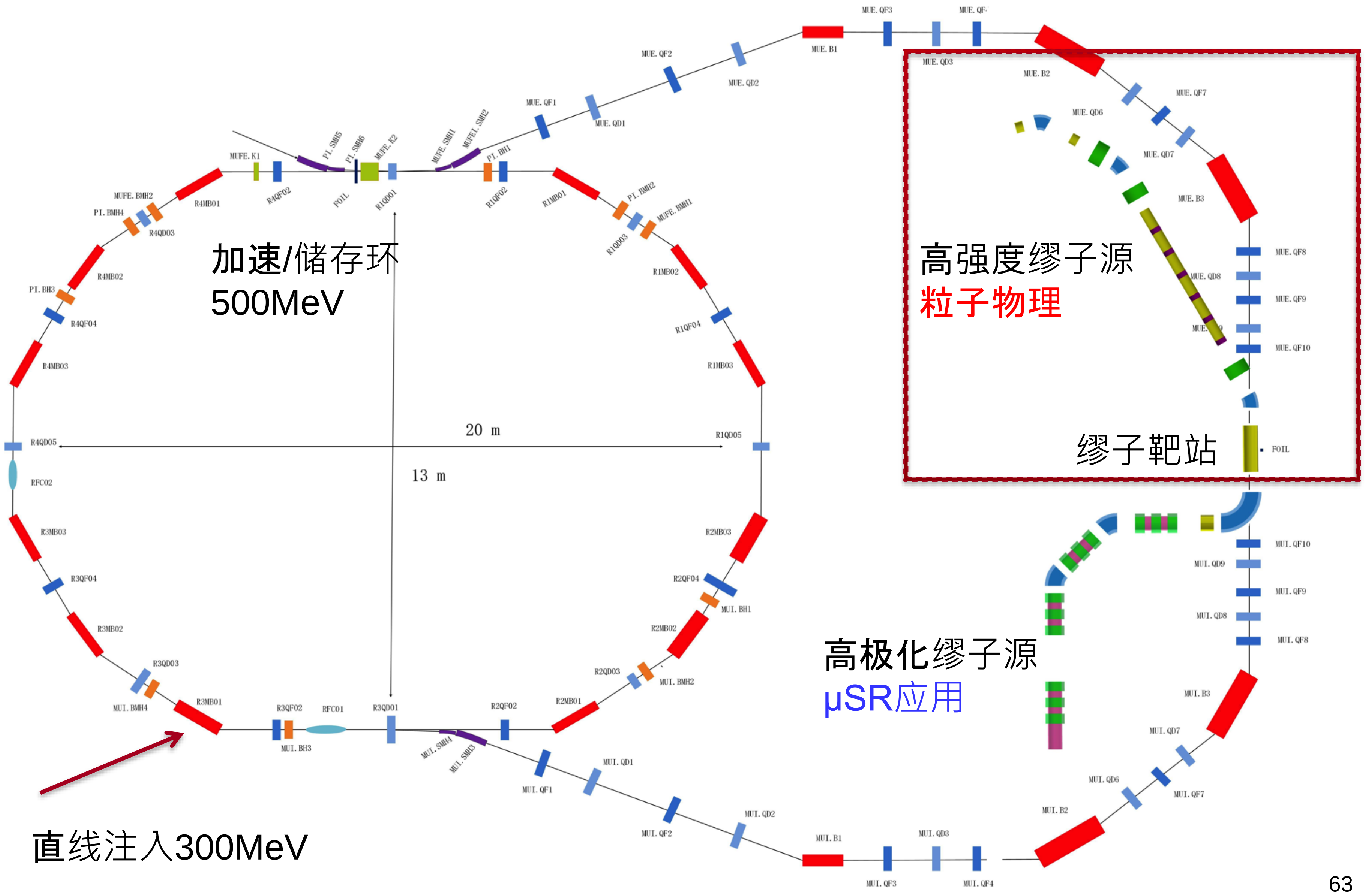
不影响大环/中子靶运行

1. 直线300MeV*5Hz注入
2. 小环加速到500MeV
3. 引出到外环打靶
4. 回注到小环存储
5. 反复引出打靶20次

重复频率 100Hz



HEMS 高强度缪子束线



HEMS parameters

参数	HEMS	PSI	ISIS	JPARC
μSR应用				
重复频率[Hz]	100	CW	40	25
μ+强度[μ+/s]	5E6	1.5E7~4E8	5E5	3E6
动量范围[MeV/c]	20-200	10-350	20-200	20-300
计数率[MEvent/h]	Up to 800	~20	20-200	180
粒子物理实验				
MuMuBar	3E8 μ^+/s	8E6 μ^+/s	NA	NA
μ-EDM	$5*10^6$ μ^+/s	<$5*10^4$ μ^+/s	NA	

in the far future, but who knows...

Summary

yubao@ihep.ac.cn

- MELODY has been approved！
- Now: We are going to build a surface muon beam and a muSR spectrometer.
- Future: We reserve the space for more applications in the future.
- Far future: We expect muon physics and HEMS
- We welcome all kinds of suggestions and collaborations.

Thank you!

backups

CSNS II Project