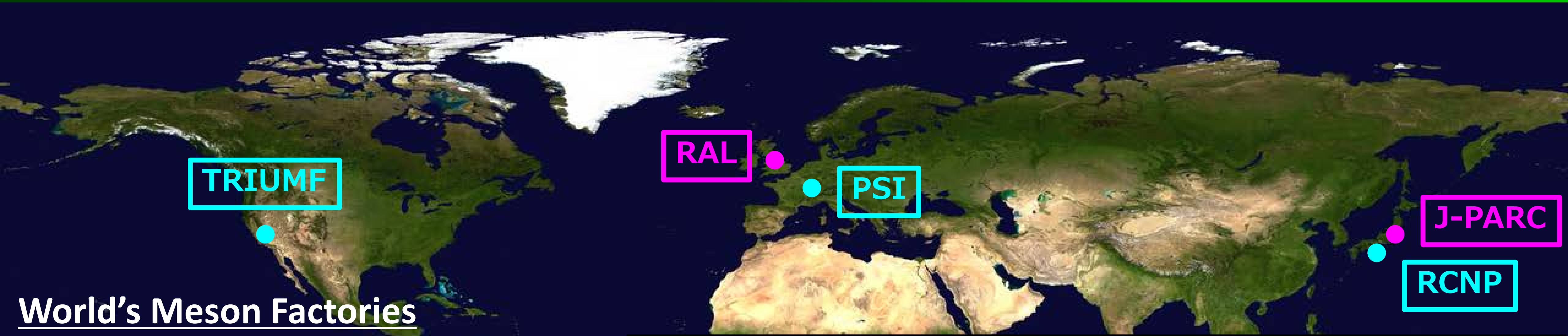
Negative muon beamline and applications

High Energy Accelerator Research Organization (KEK)
Institute of Materials Structure Science (IMSS)
Muon Science Division

J-PARC Materials and Life Science Division (MLF)
Muon Section

Soshi Takeshita
竹下 聡史

World’s Meson Factories



World’s Meson Factories

Pulse

- J-PARC(MLF) : Japan
- RAL(ISIS) : United Kingdom

DC

- PSI(SμS) : Switzerland
- TRIUMF : Canada
- RCNP(MuSIC) : Japan

Facility	Type	Power (W)	Energy (eV)	Current (A)	Freq. (Hz)	Width (s)	Day1
J-PARC	Pulse	1.00M	3G	333μ	25	100n	2008
RAL	Pulse	160k	800M	200μ	50	80n	1984
PSI	DC	1.4M	590M	2.4m	50M	-	1989
TRIUMF	DC	88k	520M	170μ	23M	-	1974
RCNP	DC	0.4k	400M	1μ	19M	-	2010

https://en.wikipedia.org/wiki/World_map#/media/File:Blue_Marble_2002.png

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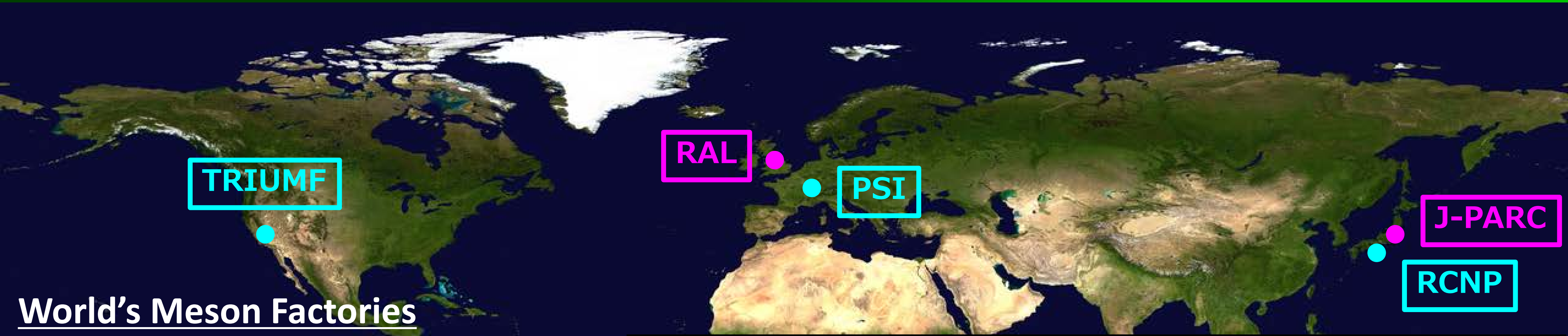

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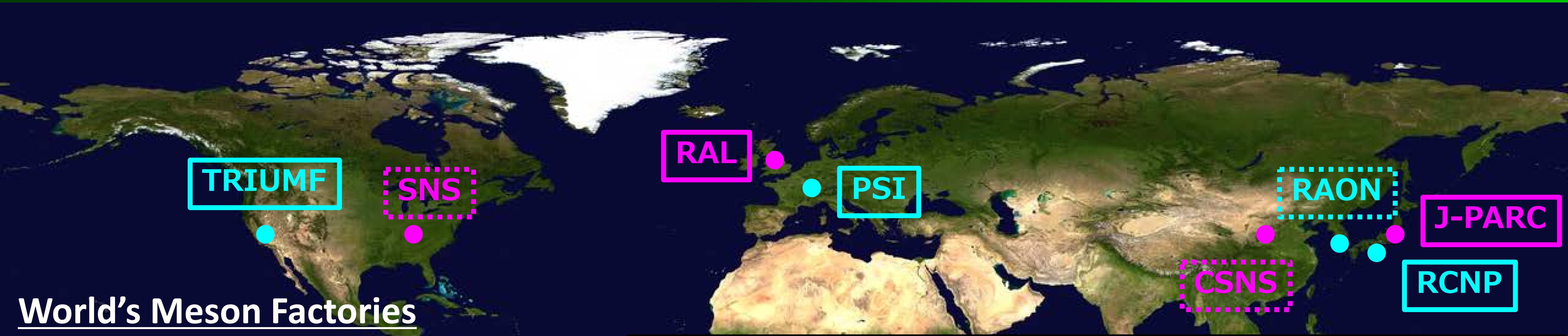

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Facility	Type	Power (W)	Energy (eV)	Current (A)	Freq. (Hz)	Width (s)	Day1
SNS	**Pulse**	**2.47M**	**1.3G**	**1.5m**	**60**	**30n?**	**?**
J-PARC	Pulse	1.00M	3G	333μ	25	100n	2008
CSNS	**Pulse**	**500k**	**1.6G**	**313μ**	**1**	**150n**	**2028**
RAL	Pulse	160k	800M	200μ	50	80n	1984
PSI	DC	1.4M	590M	2.4m	50M	-	1989
RAON	**DC**	**400k**	**600M**	**666μ**	**81M**	**-**	**?**
TRIUMF	DC	88k	520M	170μ	23M	-	1974
RCNP	DC	0.4k	400M	1μ	19M	-	2010

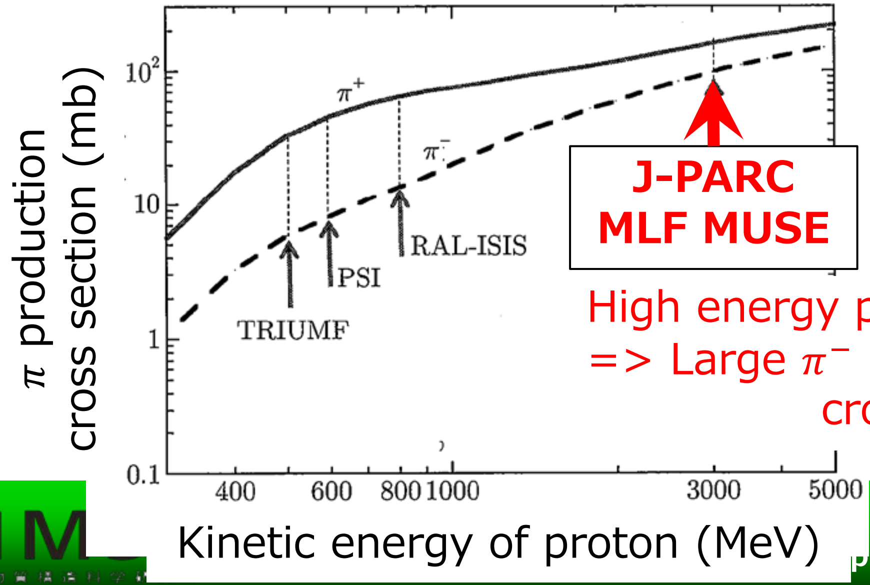
https://en.wikipedia.org/wiki/World_map#
/media/File:Blue_Marble_2002.png

The Position of the D-Line in Muon Facilities Worldwide

- Proton Energy and Pion Production Cross Section
  - **The world's highest intensity pulsed muon source**

R. Kadono (2016), Muon spin rotation method, Kyoritsu Shuppan.

Facility	Energy	Current	π^- cross section	Potential efficiency	Target loss	Effective efficiency
J-PARC	**3 GeV**	**333 μA**	**100 mb**	**33.3 μAb**	**5 %**	**1.66 μAb**
RAL	800 MeV	200 μA	10 mb	2.0 μAb	5 %	0.1 μAb
PSI	**590 MeV**	**2.4 mA**	**8 mb**	**19.2 μAb**	**18 %**	**3.46 μAb**
TRIUMF	520 MeV	400 μA	6 mb	0.9 μAb	—	—
RCNP	400 MeV	1uA	3 mb	0.003 μAb	—	—



High energy proton beam
=> Large π^- production cross section

Variable momentum: D, U, H, (S)

BL	Area	μ+	μ-	Variable Pμ
D-Line	**D1/D2**	○	○	○
U-Line	U1A/U1B	○	×	○
S-Line	S1/S2	○	△	△
H-Line	H1	○	○	○

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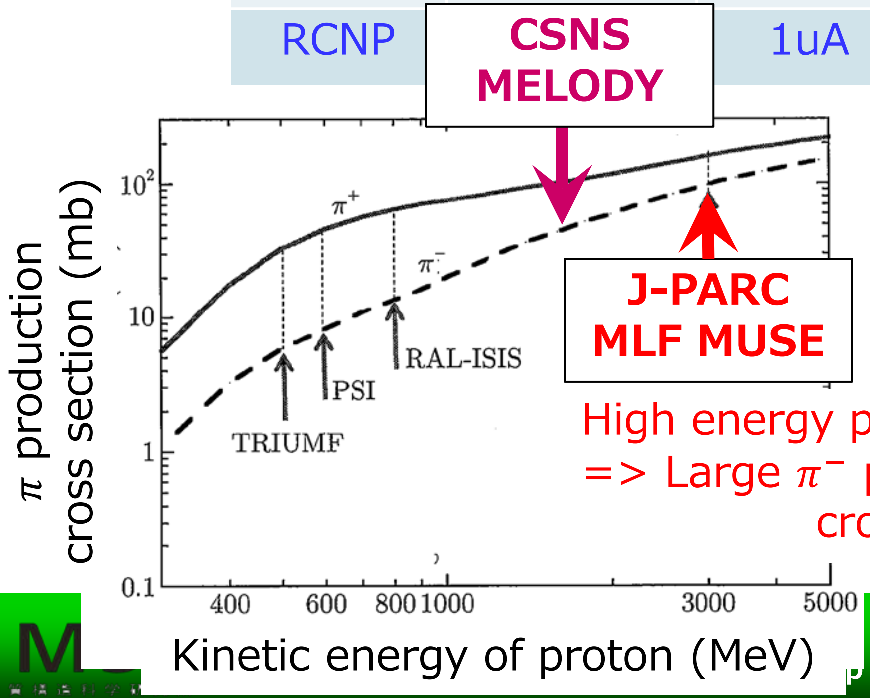

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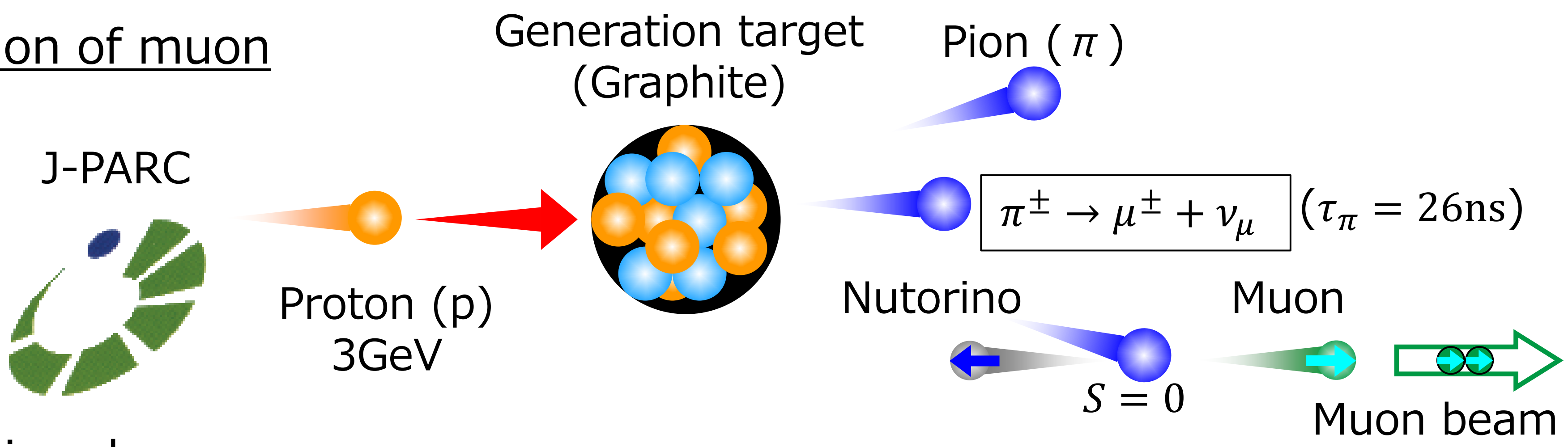
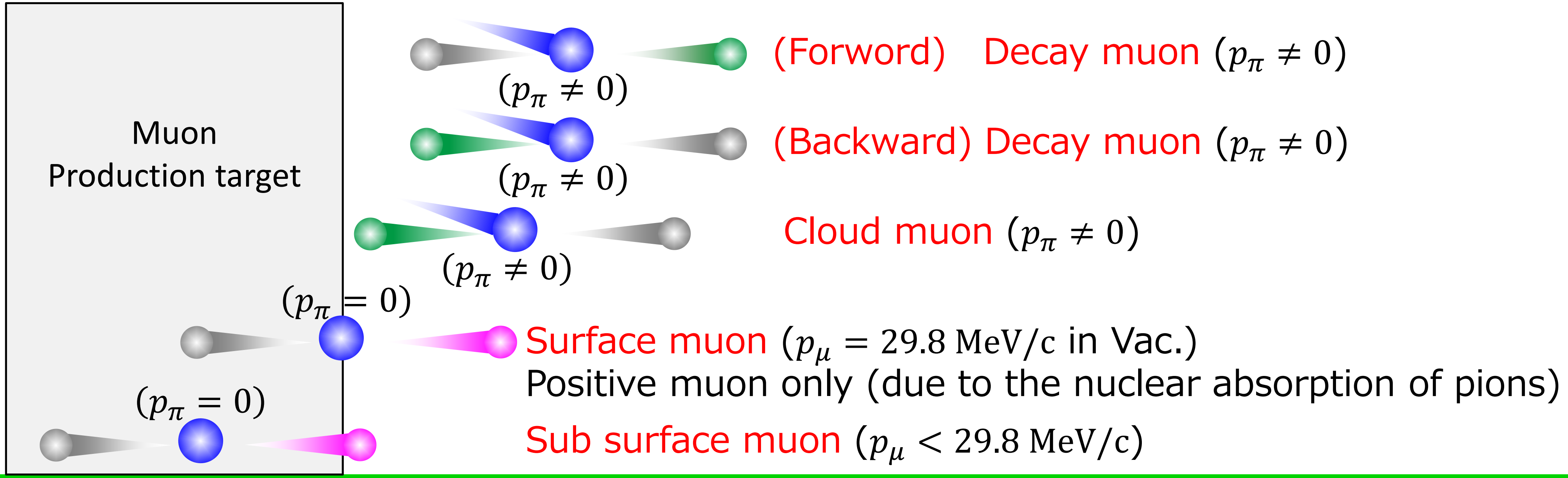
H-Line	H1	○	○	○

MLF Muon Science Establishment (MUSE)

- Generation of muon



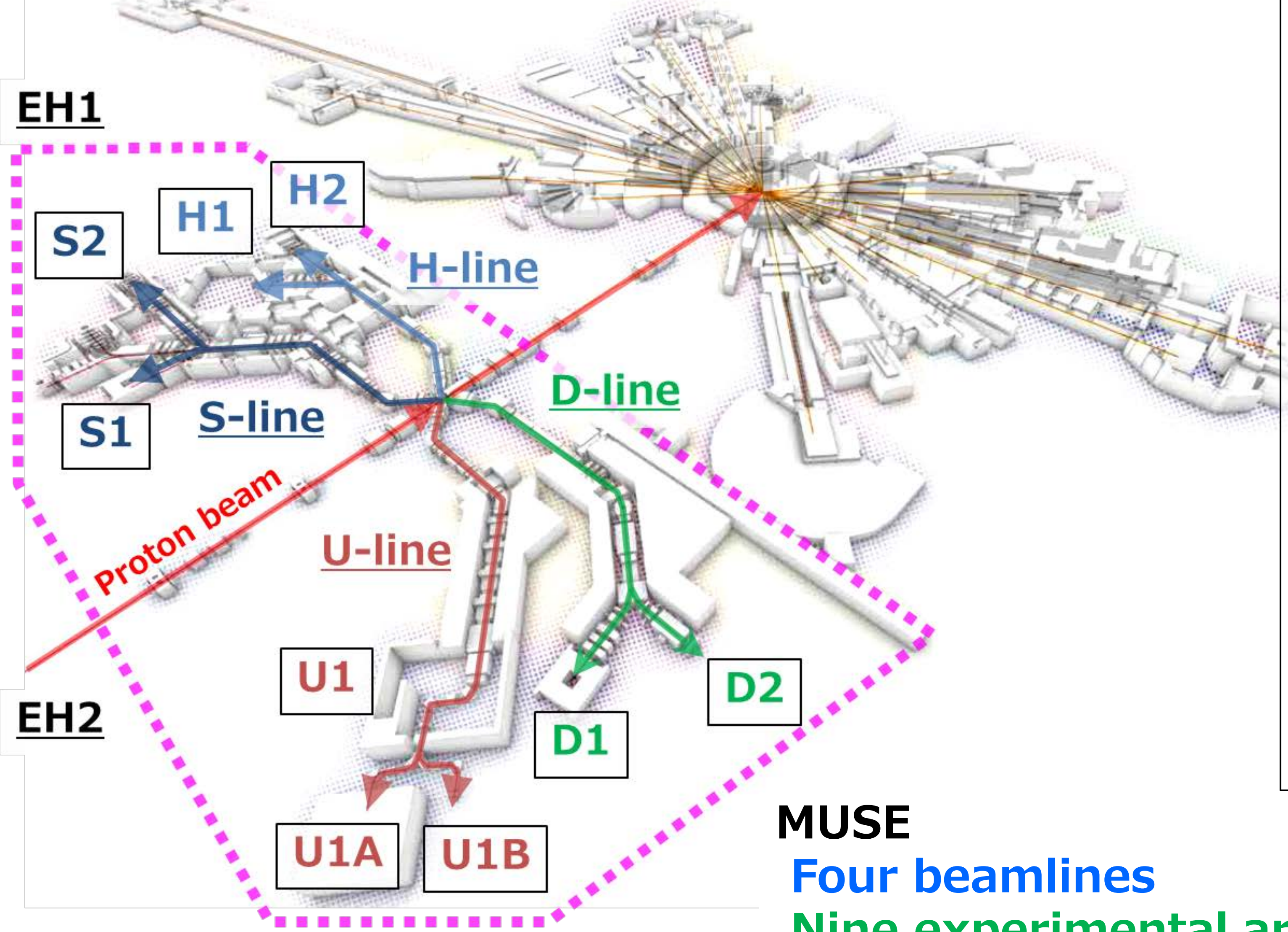
- Where pion decays



MLF Muon Science Establishment（MUSE)

- **Muon Science Establishment (MUSE)**

From MLF brochure

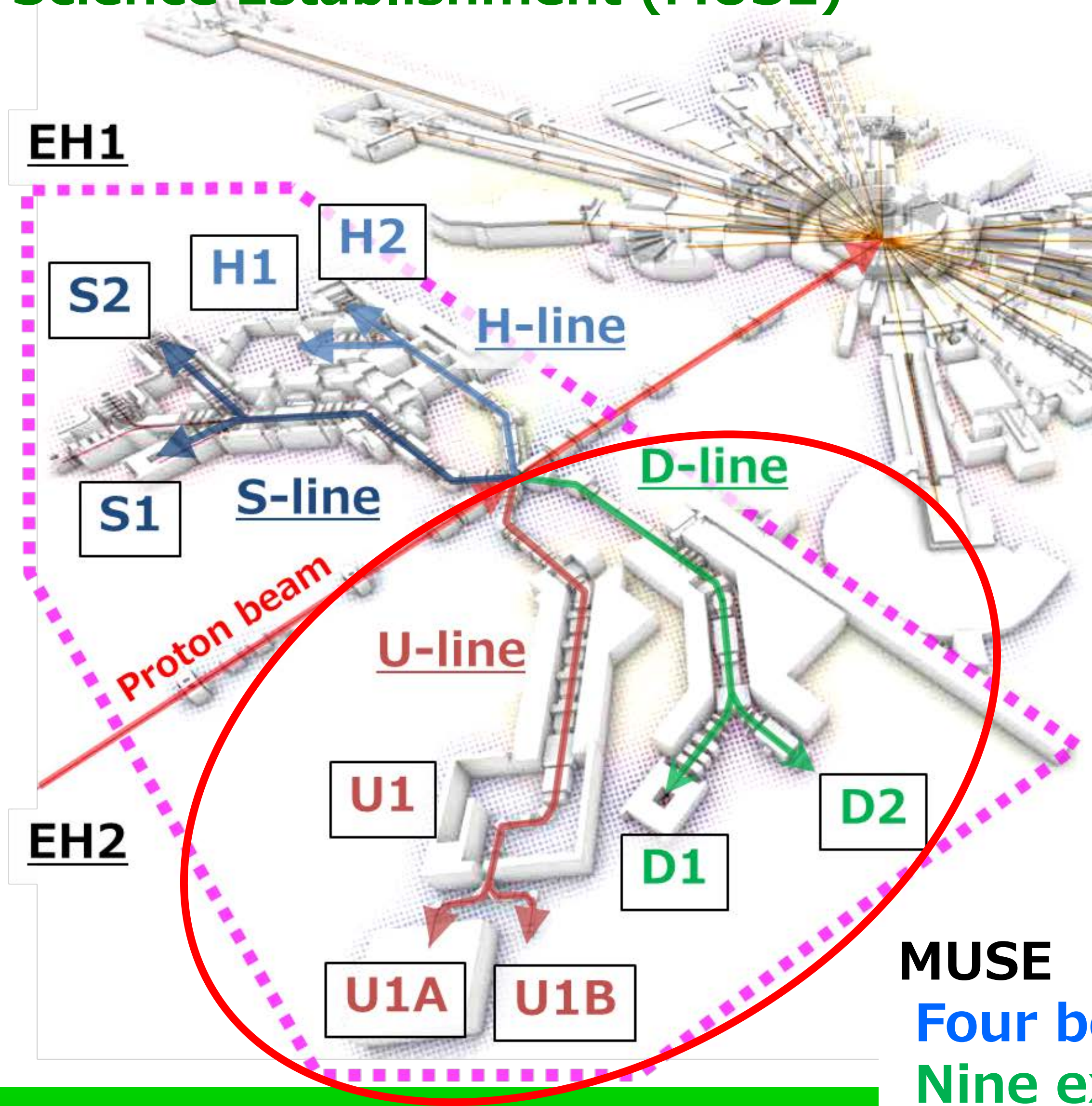


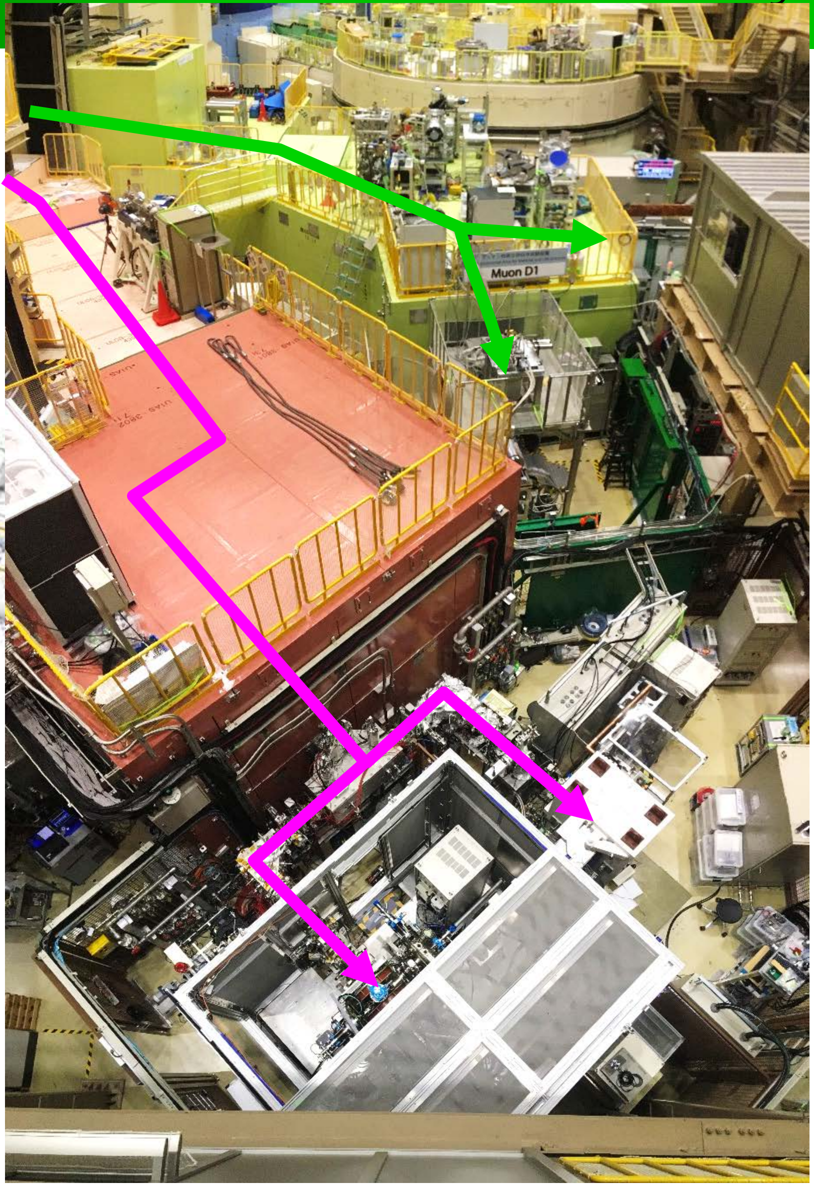
- **Exp. Hall #1 (EH1)**
  - **S-line**
    - S1 area
    - S2 area
  - **H-line**
    - H1 area
    - H2 area
- **Exp. Hall #2 (EH2)**
  - **D-line**
    - D1 area
    - D2 area
  - **U-line**
    - U1 area
      - U1A
      - U1B

MUSE
Four beamlines
Nine experimental area

MLF Muon Science Establishment（MUSE)

- Muon Science Establishment (MUSE)

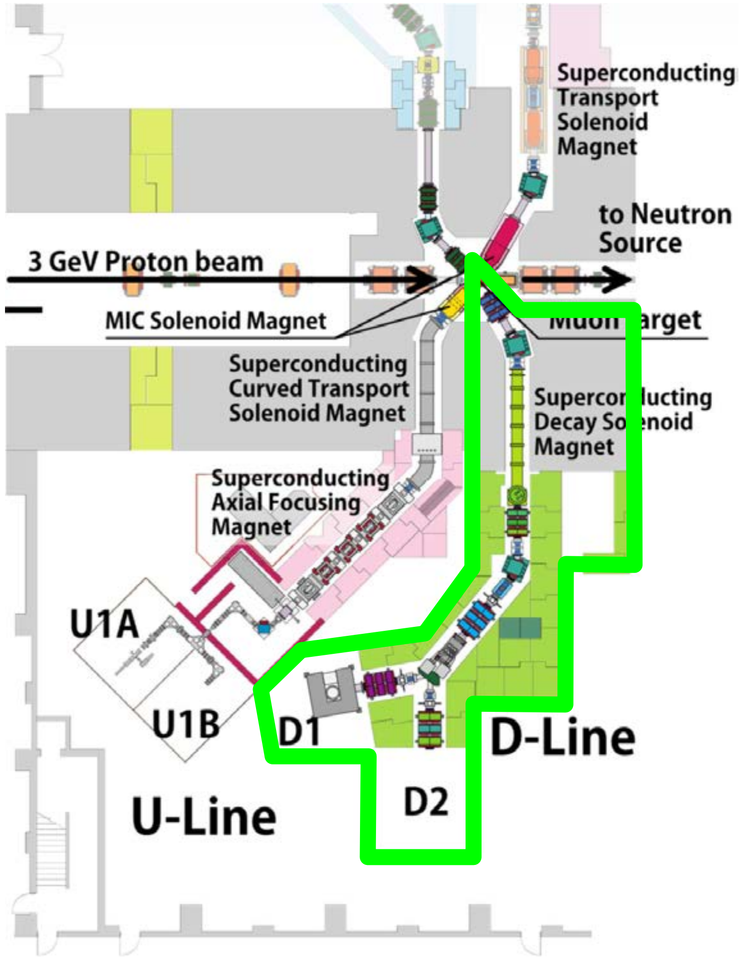




MUSE
Four beamlines
Nine experimental area

The secondary beamline for transporting decay and surface muons

- **D-line overview**

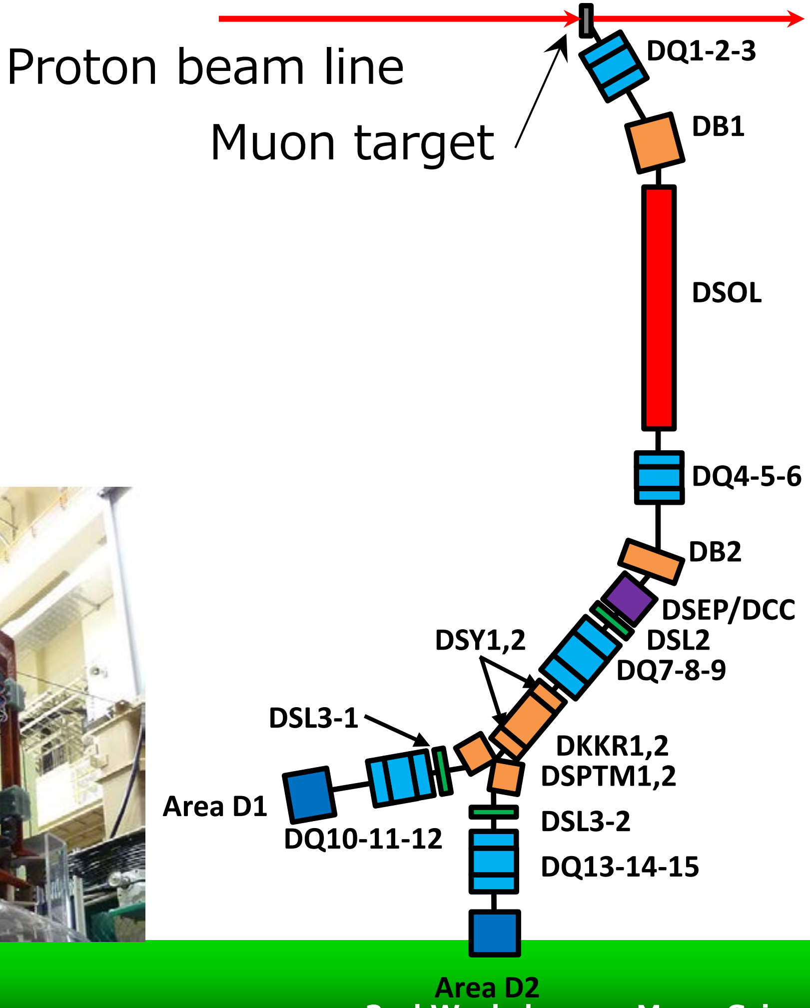


Instrument specifications (as of 2022)

- **Beamline**
  - D-line was constructed at 2008.
  - Magnetic kicker system (as of 2013)
  - Warm bore long solenoid magnet (as of 2015)
  - High power magnet for beam transport (Ongoing)
- **Beam**
  - (sub) Surface, cloud and decay muons are available.
  - Positive and negative muons are available.
  - Variable momentum beam from 3 to 120 MeV/c
  - Single and double pulse beam
- **Experimental areas**
  - D1: μSR (Spectrometer)
  - D2: General purpose (Open geometry)
- **Staff**
  - Permanent staff: **DL**:ST, PS, **D1**:AK, WH, **D2**:IU, (PS)
  - Contracted staff: SD, SS, AH **Total:8 persons**

D-Line Components

- D-Line
  - Warm bore superconducting long solenoid (Pion decaying section)
  - The only beamline to use decay muon in MLF at the moment.

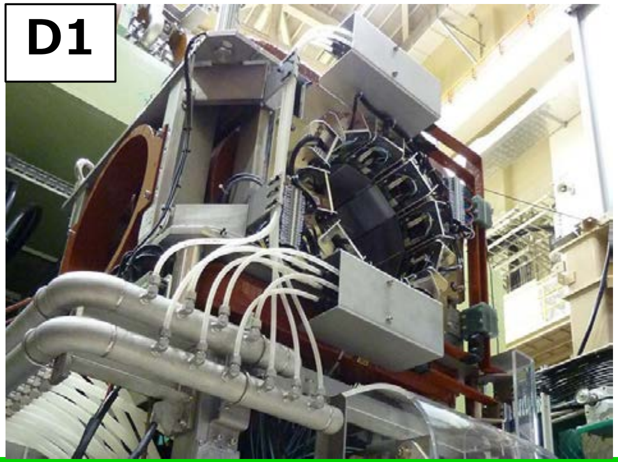


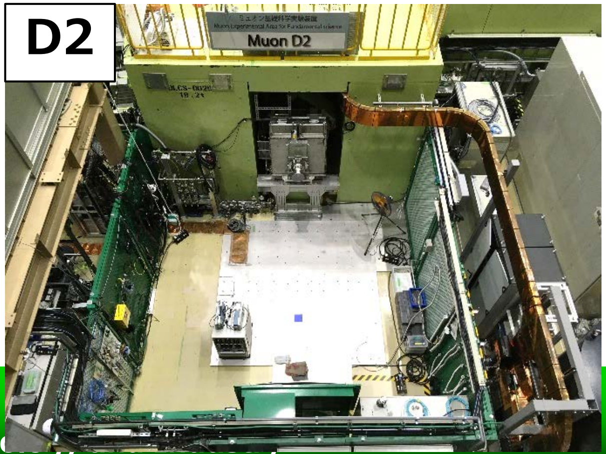
Negative and positive muon beam
Variable momentum muon beam
are available.

Area

D1: μSR spectrometer dedicated for
> dilution refrigerator (DR)
> μ^-SR

D2: Open area dedicated for
user experimental apparatus





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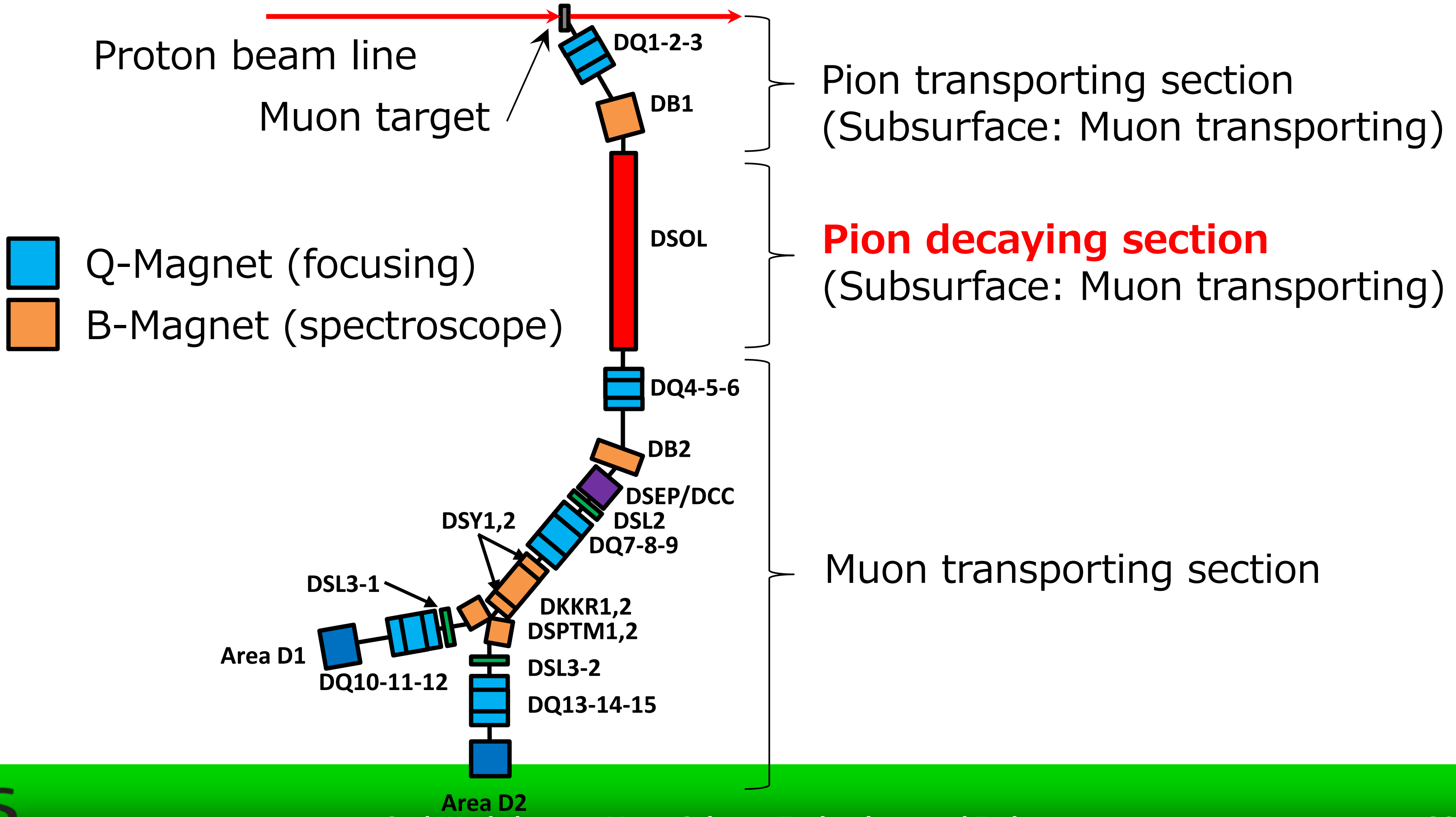
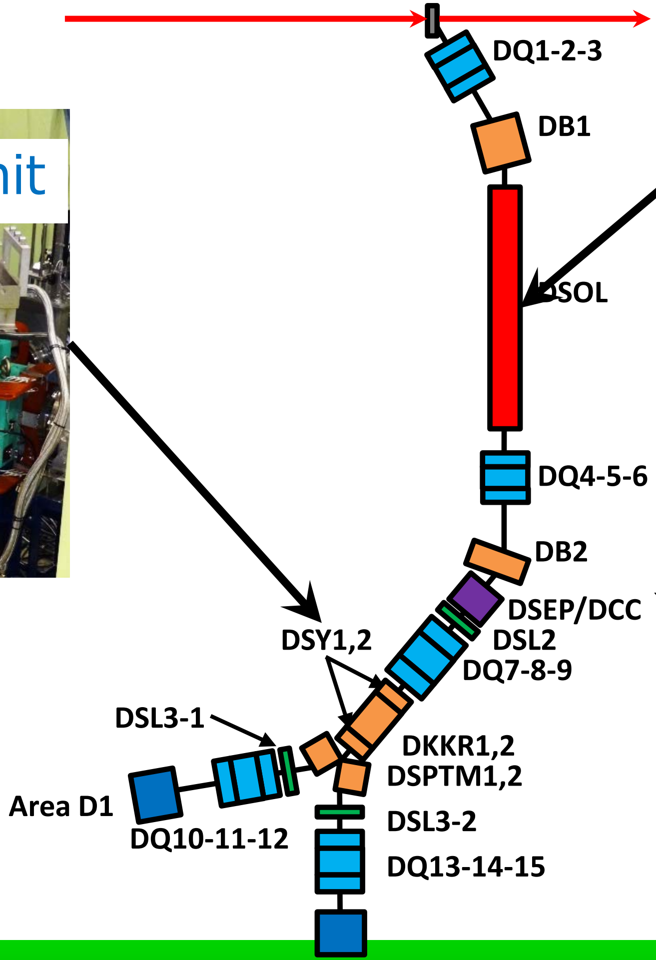


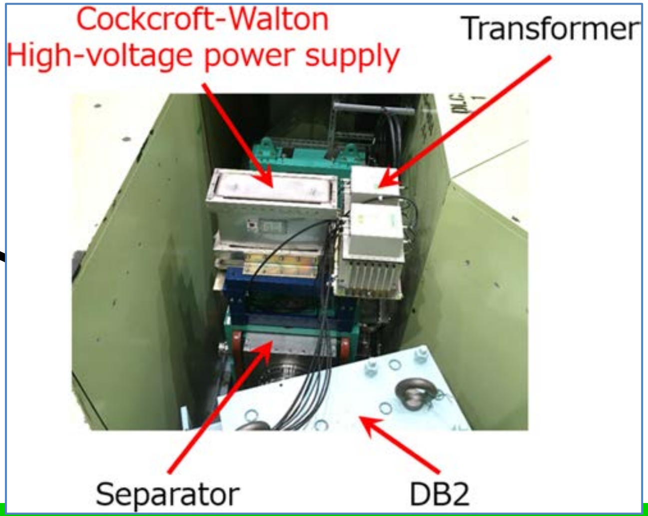
D-Line Components

- D-Line
  - Warm bore superconducting long solenoid (Pion decaying section)
  - The only beamline to use decay muon in M SC Solenoid nent.

(Magnetic) Kicker Unit



Refrigerator (TCF50)

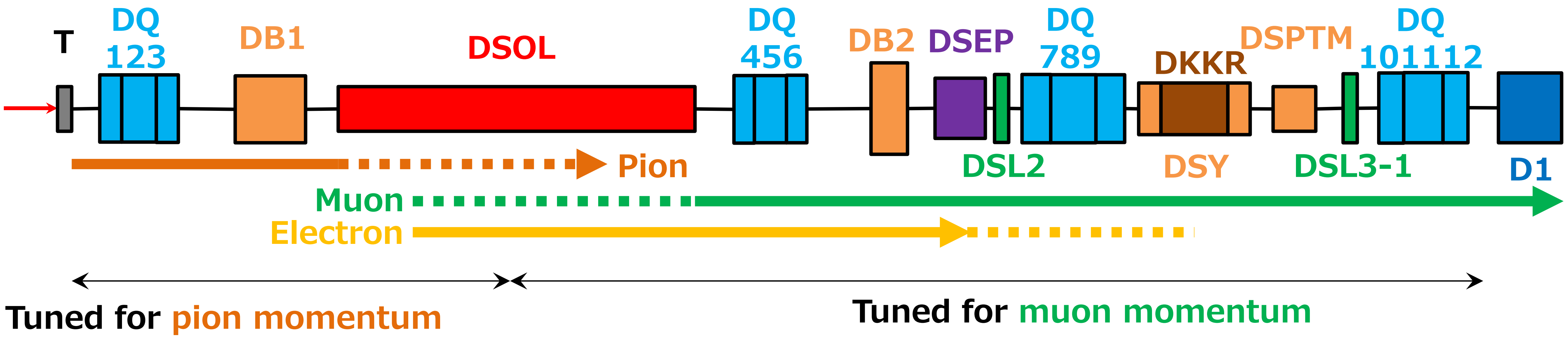


DC Separator

https://journals.jps.jp/doi/pdf/10.7566/JPSCP.2.010103

D-Line Components

- Beamline

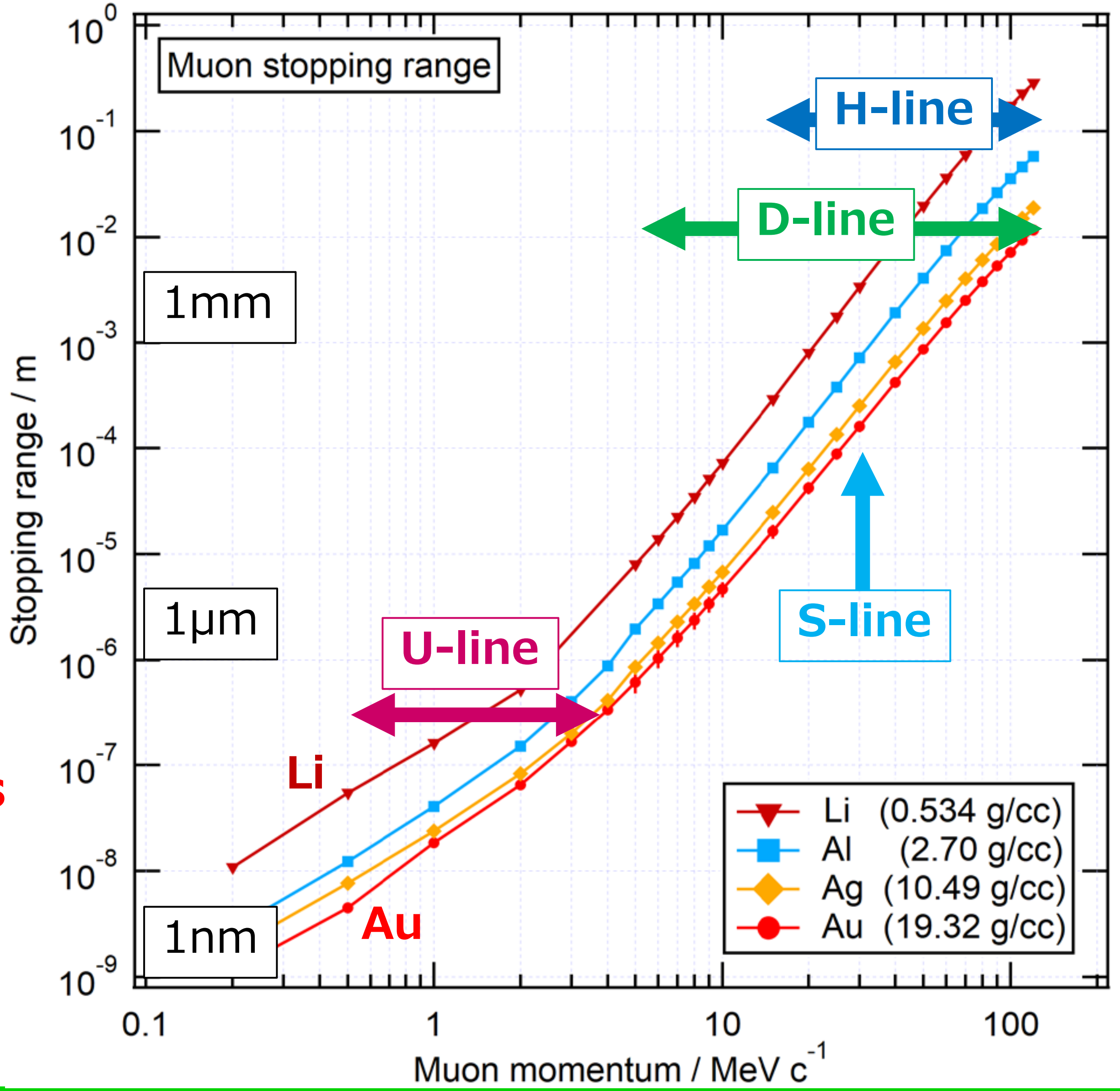


- Merit
  - **Pions** decay within the solenoid (pions are filtered).
    - Change of transport mode
  - **Electrons** are filtered at the separator (Wien filter).

    - Reducing background components

D-Line Components

- Application of negative muon at D-line
  - Variable momentum,
    i.e. Variable stopping range
    - =>**Depth resolved analysis**
  - Different muon lifetime
    for different elements
    - =>**Elemental analysis**
  - Nuclear capture
    - Muonic X-rays=>**Elemental analysis**
    - **Soft-error in semiconductors**
    - **Clear muon site (no self diffusion)**



Non-destructive elemental analysis of a medicine bottle that cannot be opened

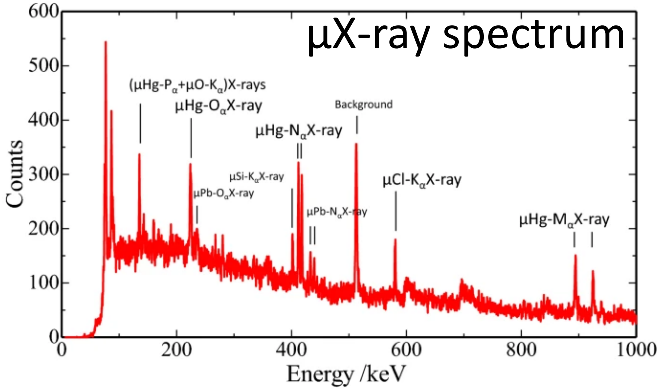
- ✓ The lid is stuck and impossible to open.
- ✓ Possibility of chemically unstable in the atmosphere

Muonic X-ray elemental analysis non-destructively revealed that the material inside the bottle is Hg_2Cl_2.

Kōan's Drug box

OGATA Kōan (緒方 洪庵)
1810~1863 (Edo period)
Doctor, *Rangaku* scholar

The medicine bottle



Significant impact on the public


朝日新聞 DIGITAL

北京五輪 速報 朝刊 夕刊 連載 特集 ランキング コメント

トップ 社会 経済 政治 国際 スポーツ オピニオン IT・科学 文化・芸能

朝日新聞デジタル > 記事

緒方洪庵の「開かずの薬瓶」、中身は…？ 素粒子で透視

小川裕介 2021年3月19日 15時00分

シェア ツイート ブックマーク メール 印刷

緒方洪庵が晩年に使用していたとされる薬箱。中に薬瓶などが入っている＝大阪大学総合学術博物館の高橋京子・招へい教授提供

大阪大学 などの研究チームが、幕末の蘭（らん）医学者である緒方洪庵（1810～1863）が往診などで使ったとされる薬瓶の中身を突き止めた。瓶が古くフタが開けられないままになっていたが、素粒子 の一種「ミュー粒子」を使った「透視」に成功した。

緒方洪庵は幕末、阪大医学部の源流とされる蘭学塾「適塾」を開き、医療や教育に力を注いだ。研究チームによると、阪大は洪庵が愛用した薬箱二つを所蔵。このうち

Newspapers (5 major National newspapers etc.)

- *The Asahi Shimbun* (‘21/3/19)
- *The Yomiuyri Shimbun* (‘21/4/30)
- *The Mainichi Shimbun* (‘21/5/12)
- *Nihon Keizai Shimbun* (‘21/5/13)
- *The Sankei Shimbun* (‘21/5/25)
- *etc.*

TV news

- *NHK General TV* (‘21/6/8)
- *etc.*

K. Shimada-Takaura, et al., J. of Natural Medicines 75, (2021) 532.

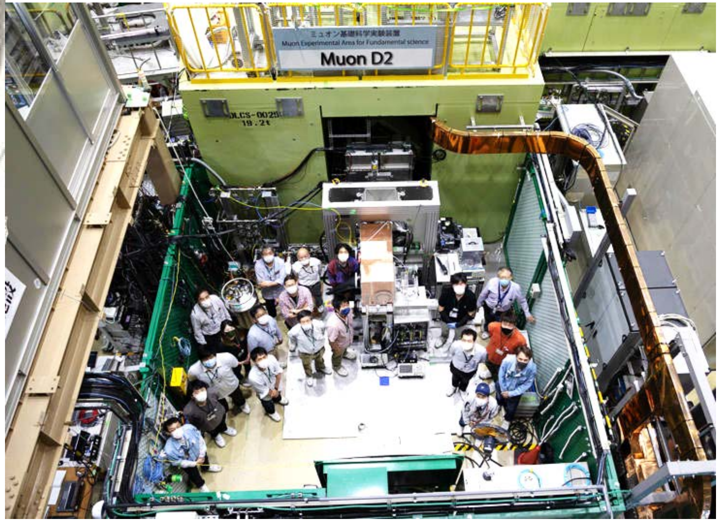
Research highlights

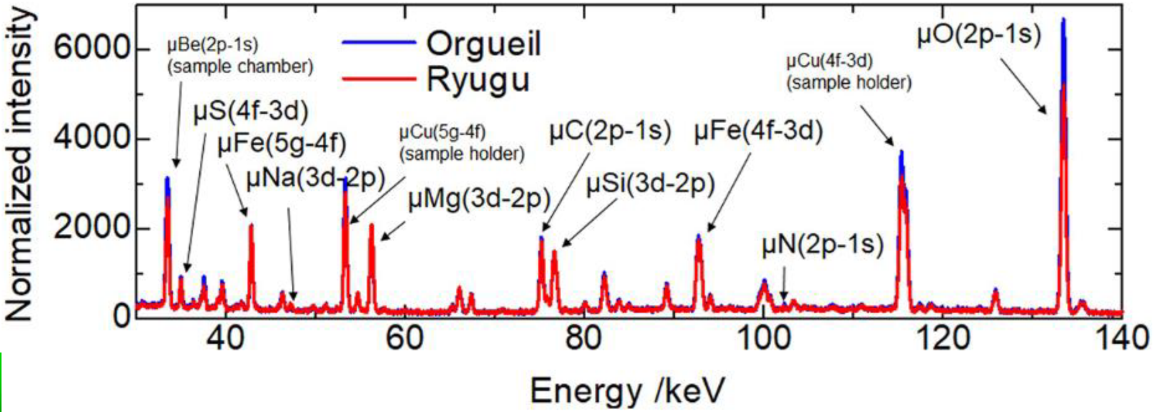
2019MS01

Non-destructive elemental analysis of return samples from asteroid *Ryugu*

- ✓ Need to know the elemental composition of the entire stone, including light elements such as C.
- ✓ Possibility of chemically unstable in the atmosphere

Muonic X-ray elemental analysis was employed as an initial analysis of Ryugu samples.



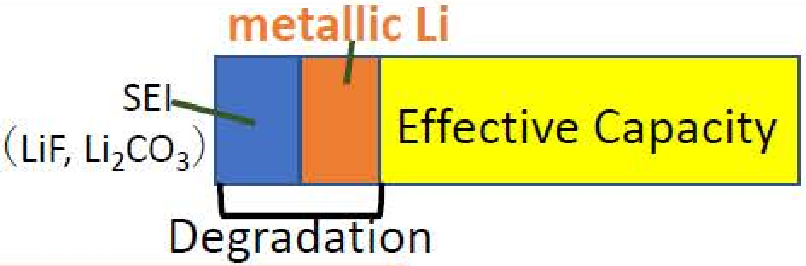


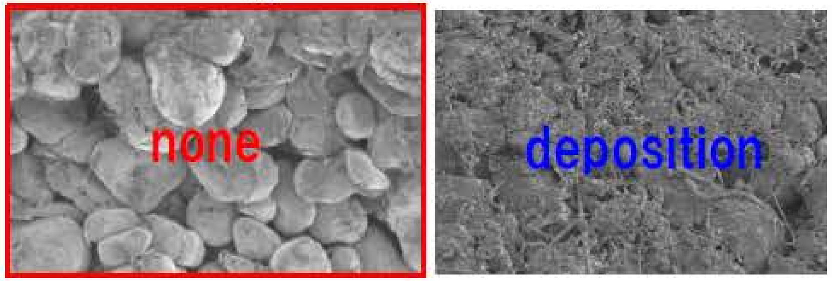
T. Nakamura et al., Science379, eabn8671(2023).
DOI:10.1126/science.abn8671

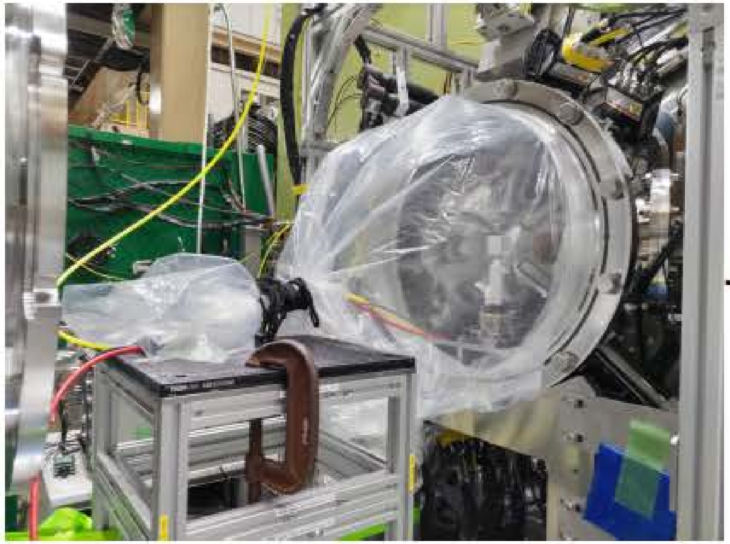
Technique to detect Li metal deposition in a Li-ion battery by muonic x-rays

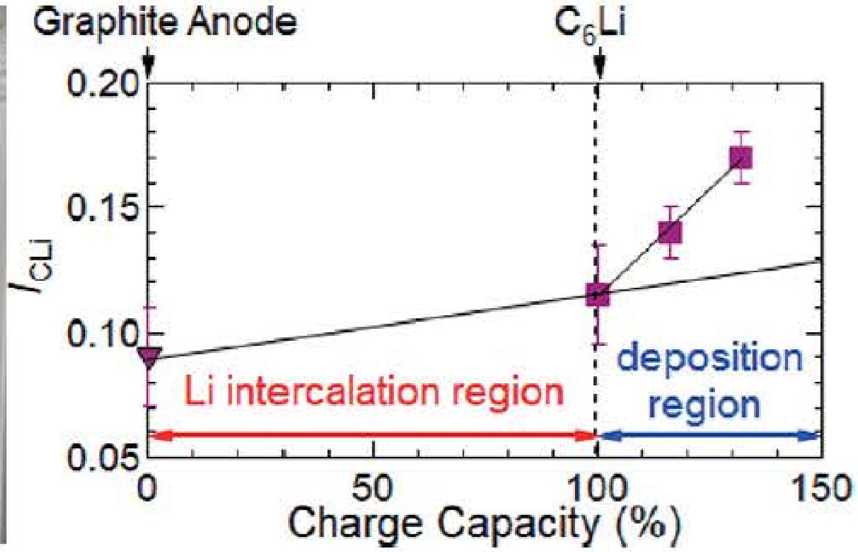
Purpose

Development technique to detect metallic Li, avoiding collection and recovery, in a Li-ion battery using muonic x-rays

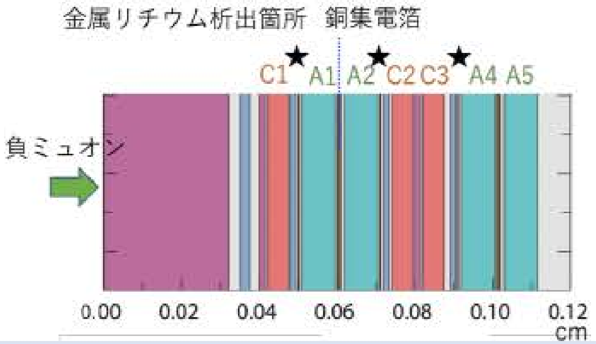








cell for
digital camera



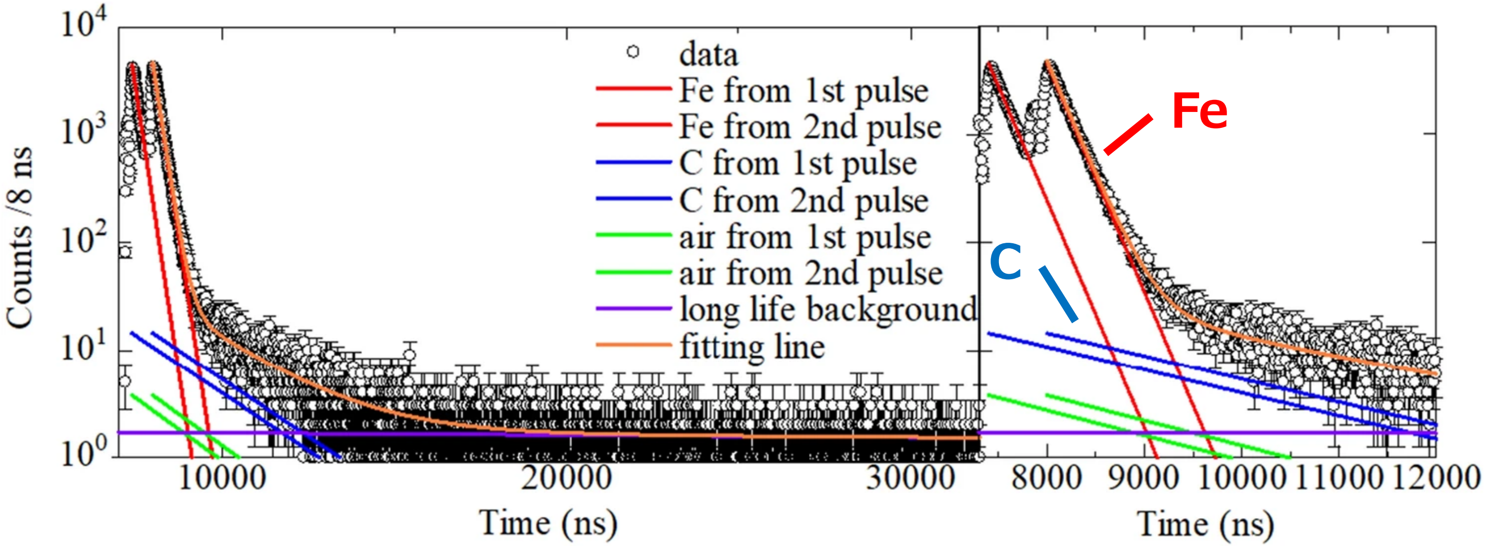
We have already confirmed that we can apply this technique to detect metallic Li.
Recently we have started to apply this technique to a cell with multiple pairs of electrode.

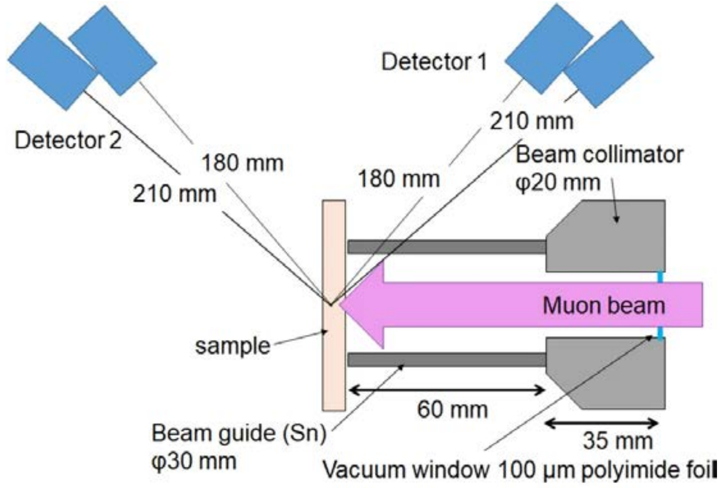
Research highlights

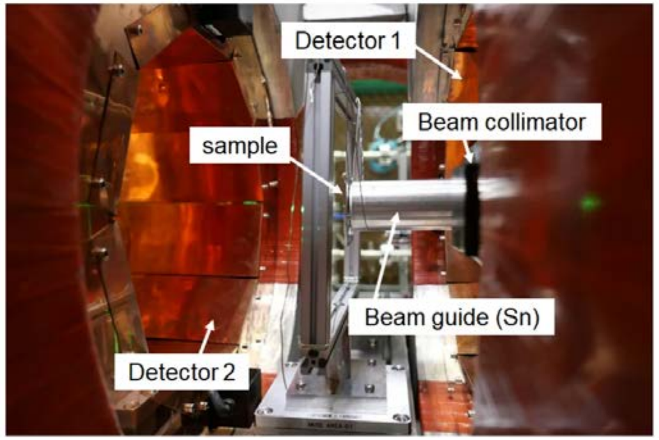
Non-destructive depth-selective quantification method for sub-percent carbon contents in steel

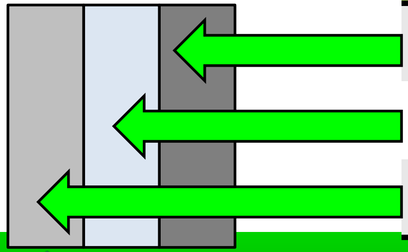
✓ There were no Non-destructive elementary analysis of trace carbon in steel

Succeeded in development of a method for the identification of trace elements in steel.









Muon Energy	Carbon content by destructive analysis	Carbon content by this method
4.9 MeV	1.03 %	1.12+-0.03 %
7.3 MeV	0.20 %	0.19+-0.01 %
9.8 MeV	0.51 %	0.50+-0.02 %

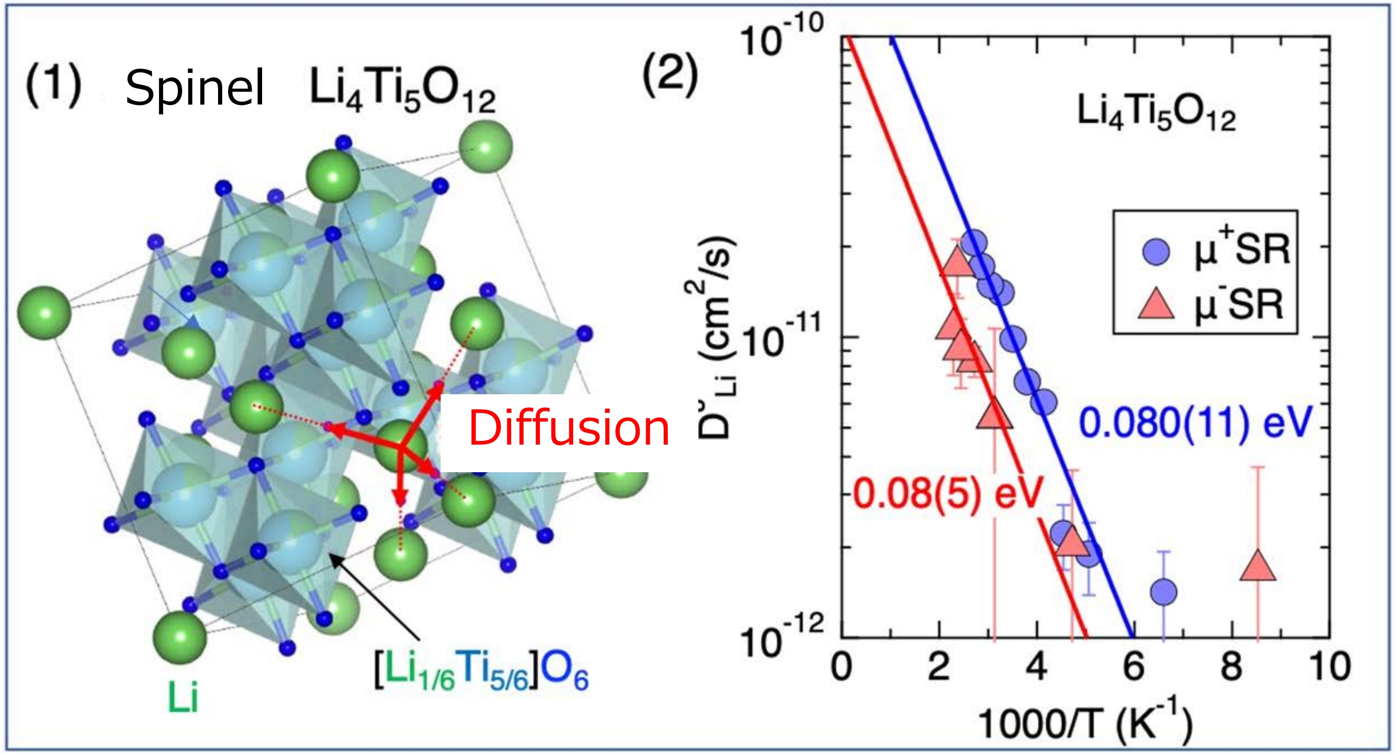
K. Ninomiya et al., Sci Rep 14, 1797 (2024).
https://doi.org/10.1038/s41598-024-52255-5

Research highlights

Lithium transfer phenomena in all-solid-state lithium battery anode materials by positive and negative muons.

✓ When we probe diffusion of atom by muon, there is a possibility of self-diffusion in case of positive muon.

Succeeded in measure the Li diffusion constant by negative muon spin relaxation measurement.



The results obtained with positive and negative muons are both consistent.

To solve the possibility of positive muon diffusion, using negative muon spin relaxation is a good technique.

'. Umegaki et al., J. Phys. Chem. C 126, 25, 10506 (2022).
https://doi.org/10.1021/acs.jpcc.2c02055

Summary

- D line
  - Both negative and positive muons are available.
  - (sub) Surface, cloud and decay muons are available.
  - Variable momentum beam from 3 to 120 MeV/c
  - Single and double pulse beam

- Research highlights
  - Non-destructive analysis of cultural heritages (which must not be broken)
  - Non-destructive analysis of the return samples from asteroid Ryugu (as an initial analysis)
  - Non-destructive analysis on Li ion batteries
  - Soft errors in SRAM due to negative muons
  - Non-destructive analysis for identification of trace elements in steels
  - Diffusion constant measurement using Negative and positive muons