ミュオンビームライン２

－ ＯＨＯ’２３－

高エネルギー加速器研究機構（ＫＥＫ）

大強度陽子加速器施設（Ｊ－ＰＡＲＣ）

河村　成肇

Muon Facility in MLF, MUSE

S-line μ^+

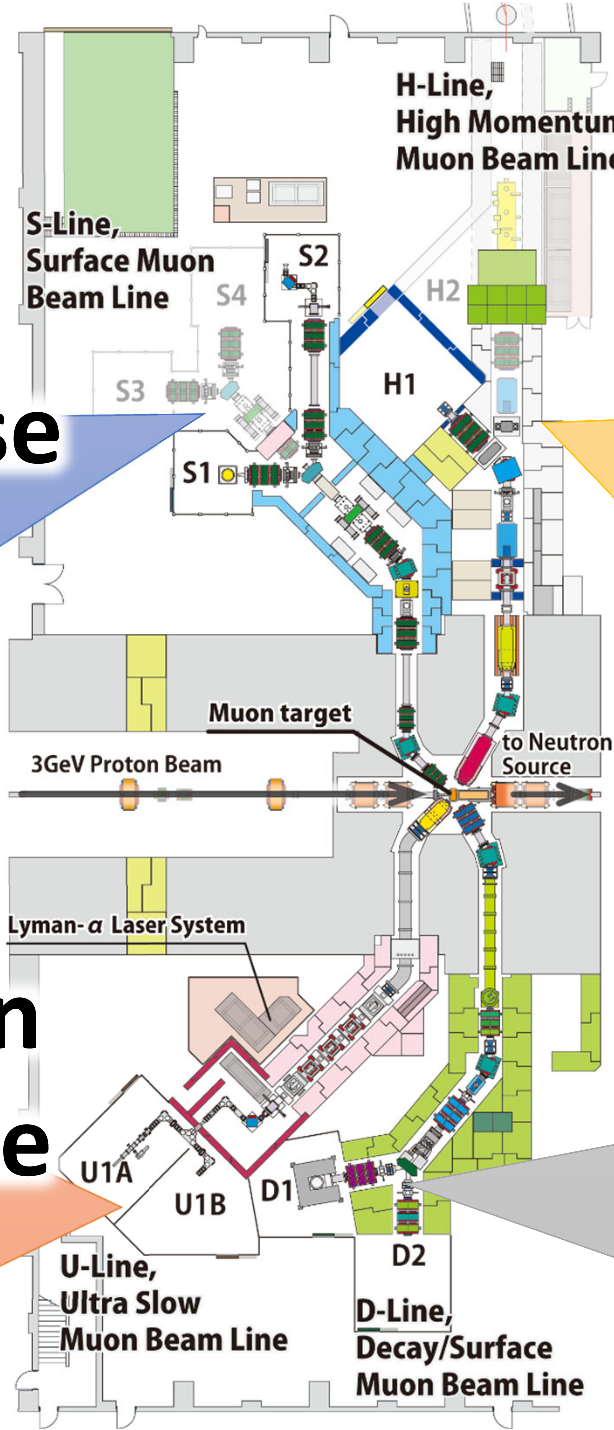
Surface muon (4 MeV)
dedicated to bulk μSR
in 4 experimental areas
w/ various sample env.
- ultra-low temperature
- high magnetic field
- pulsed excitations *etc.*

4 areas
Simultaneous use

H-line μ^+/μ^-

High-intensity surface
muon (<4 - 50 MeV)
"fundamental physics"
- requiring high precision,
- high sensitivity

High Intensity
General Use



U-line μ^+

(0.1 - 30 keV)
/interface sciences (U1A)
Test-bench for TμM
(U1B)

Ultra Slow Muon
Surface/Interface

D-line μ^+/μ^-

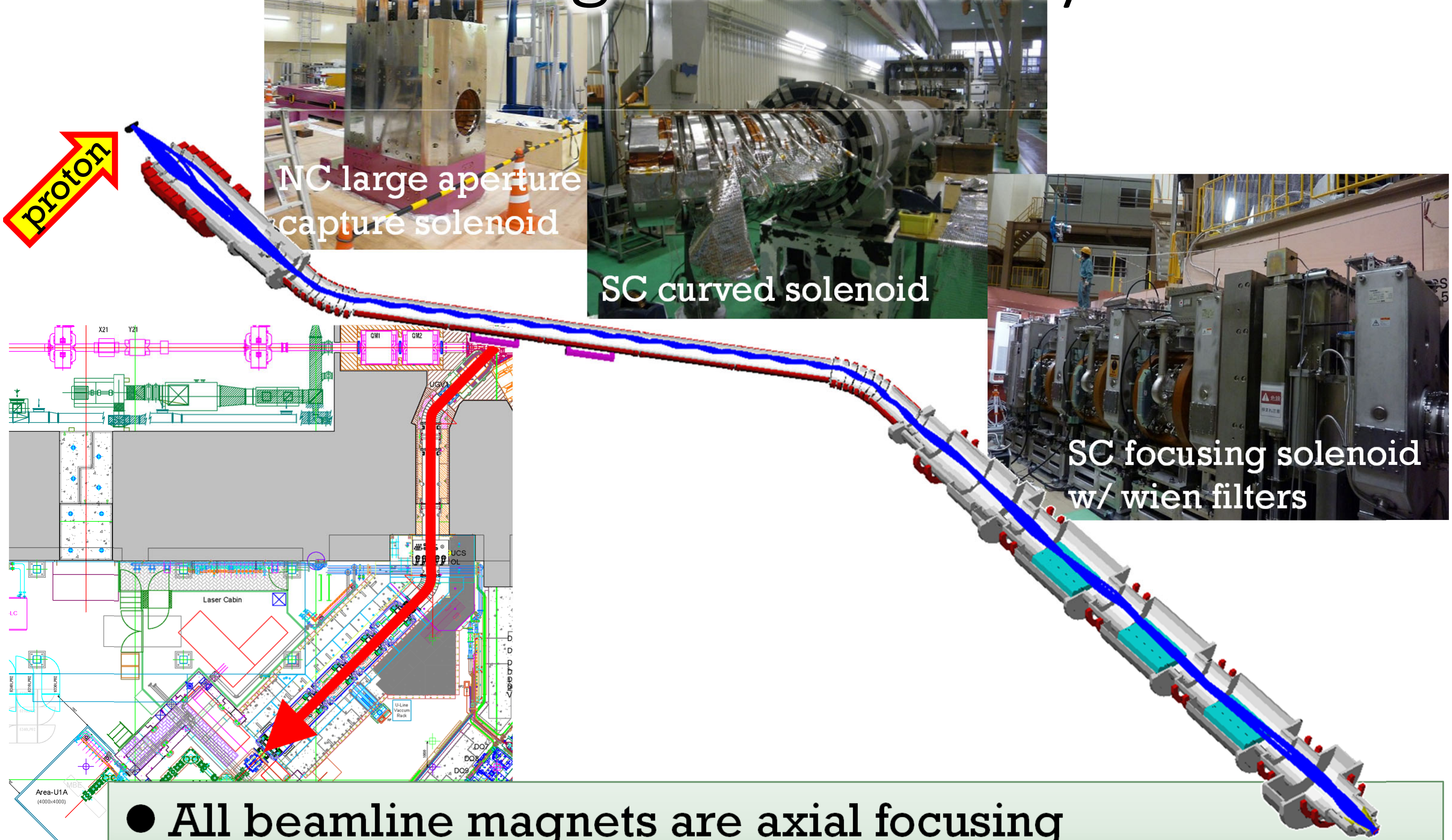
Decay and surface muon
to answer a variety of
users' demands with
μSR spectrometer (D1)
general purpose (D2)

General Use

新しいビームライン

より大強度に
MUSE UラインとHライン

U-line: The highest intensity beamline



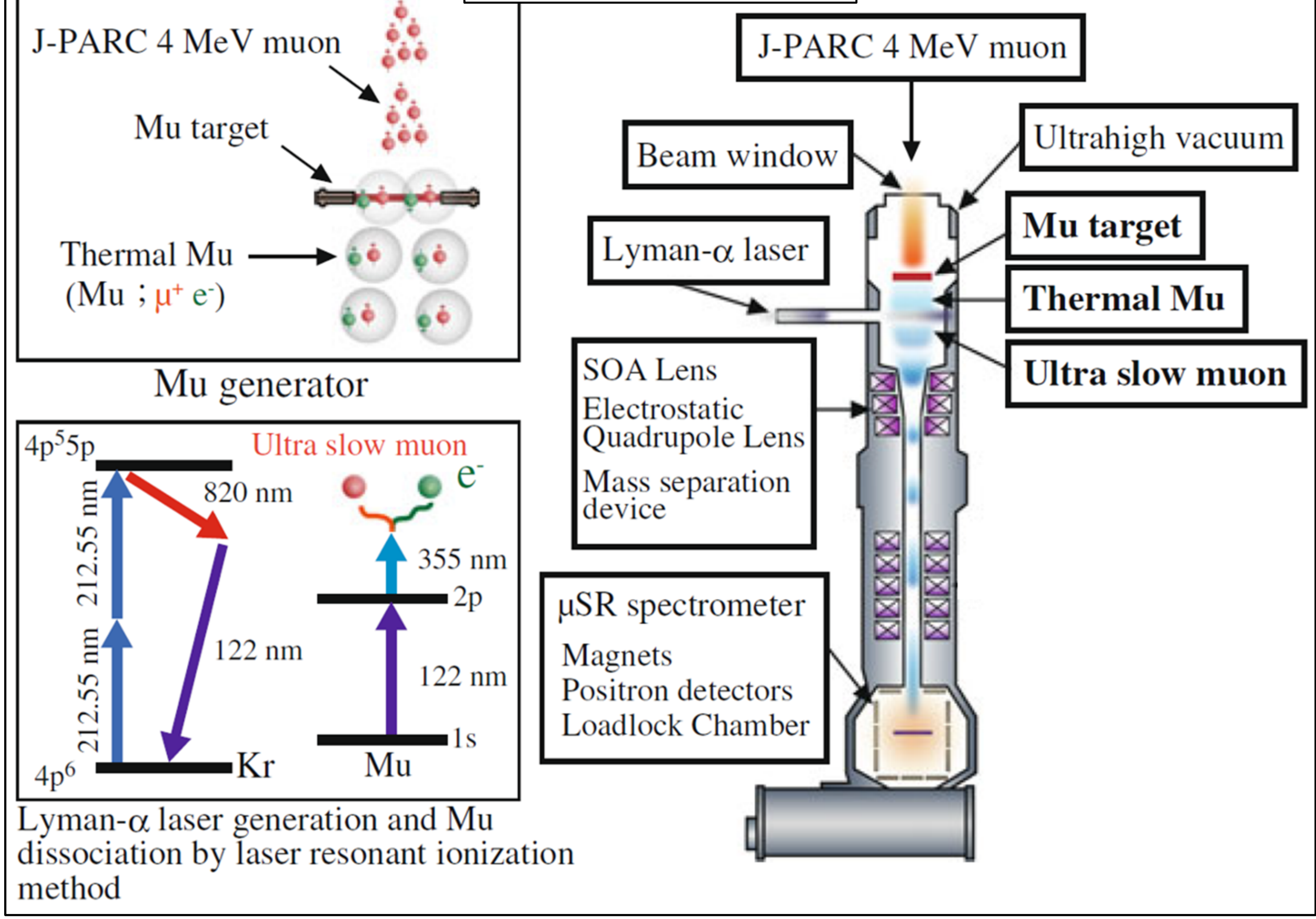
- All beamline magnets are axial focusing
- The world strongest pulsed muon: $2\times10^{8}\ \mu^{+}/s$, $1\times10^{7}\ \mu^{-}/s$

Ultra Slow Muon beam

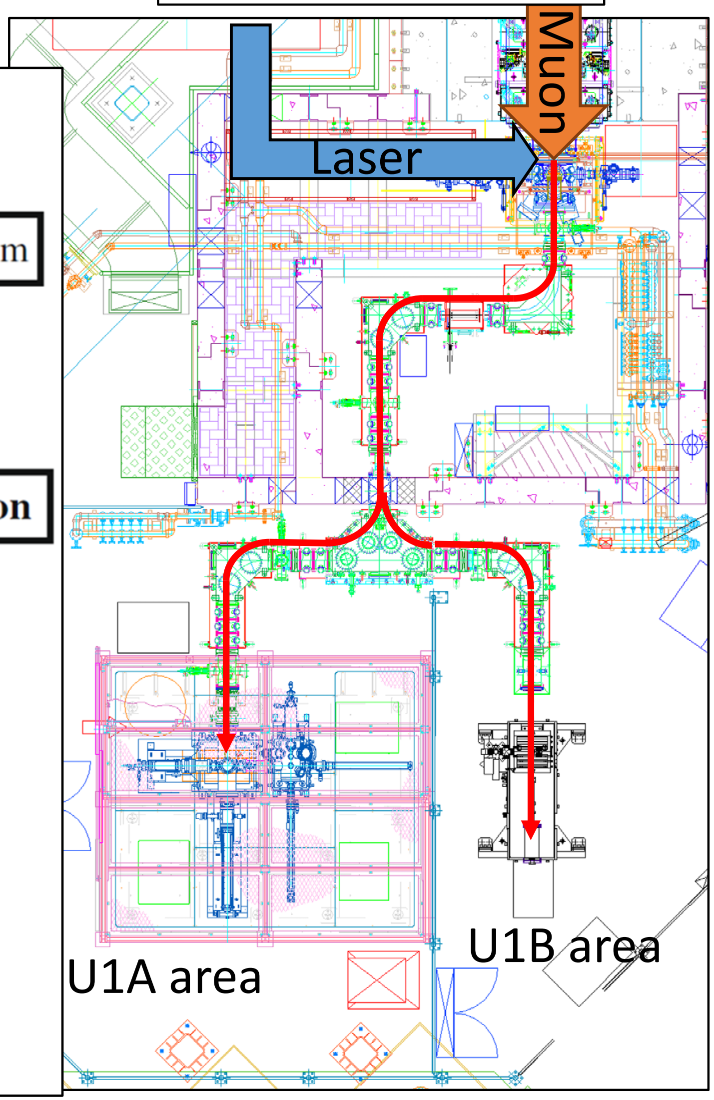
Ultra Slow Muon (USM) beam has a small emittance

- Controllable low energy (50 eV ~ 30 keV) with a small energy spread (~50 eV)
- Small beam size ~ 1 mm
- Pulse beam with a short time width of ~ 2 ns

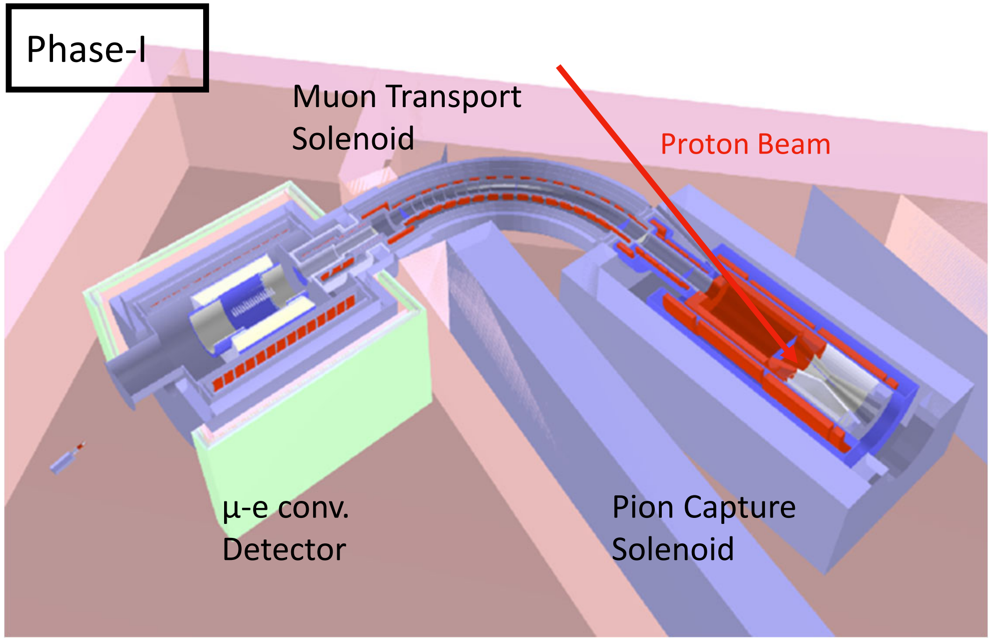
Scheme of U-line



Top view of USM



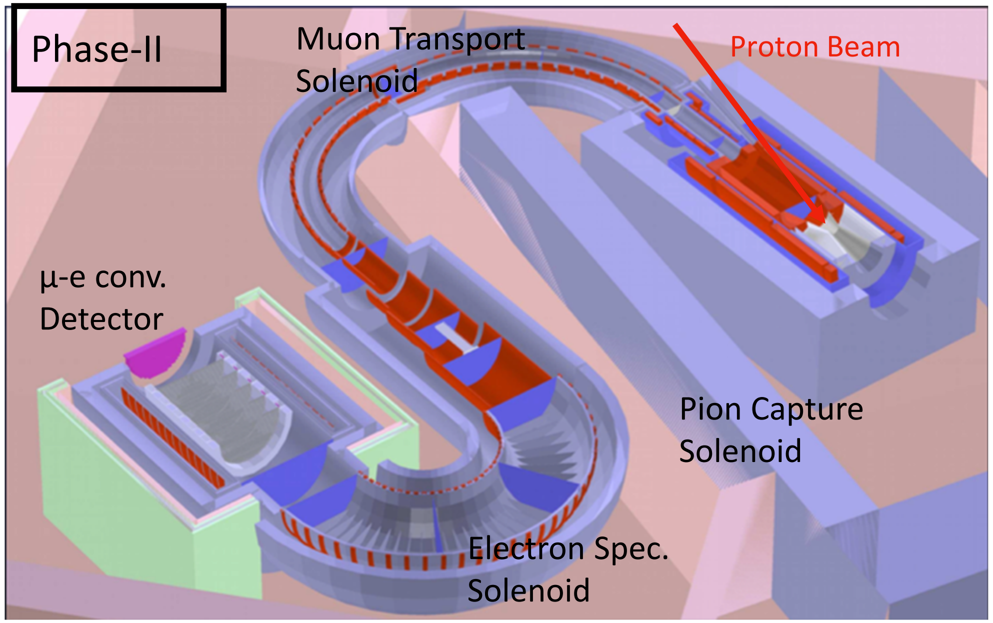
COMET in J-PARC Hadron Facility



Target Sensitivity <10^{-14} with 3.2kW beam

- **Proton beam line** construction in progress to be completed in **FY2021**
- **Graphite** as a pion production target
- Pion Capture Solenoid construction is in the 2nd year of multi-year construction contract (FY2020-2022)
- Physics Detector
  - CDC and hodoscope in a solenoid
  - Muon stopping target (Al) at the center of the solenoid

Beam engineering run in FY2022 and physics in FY2023.



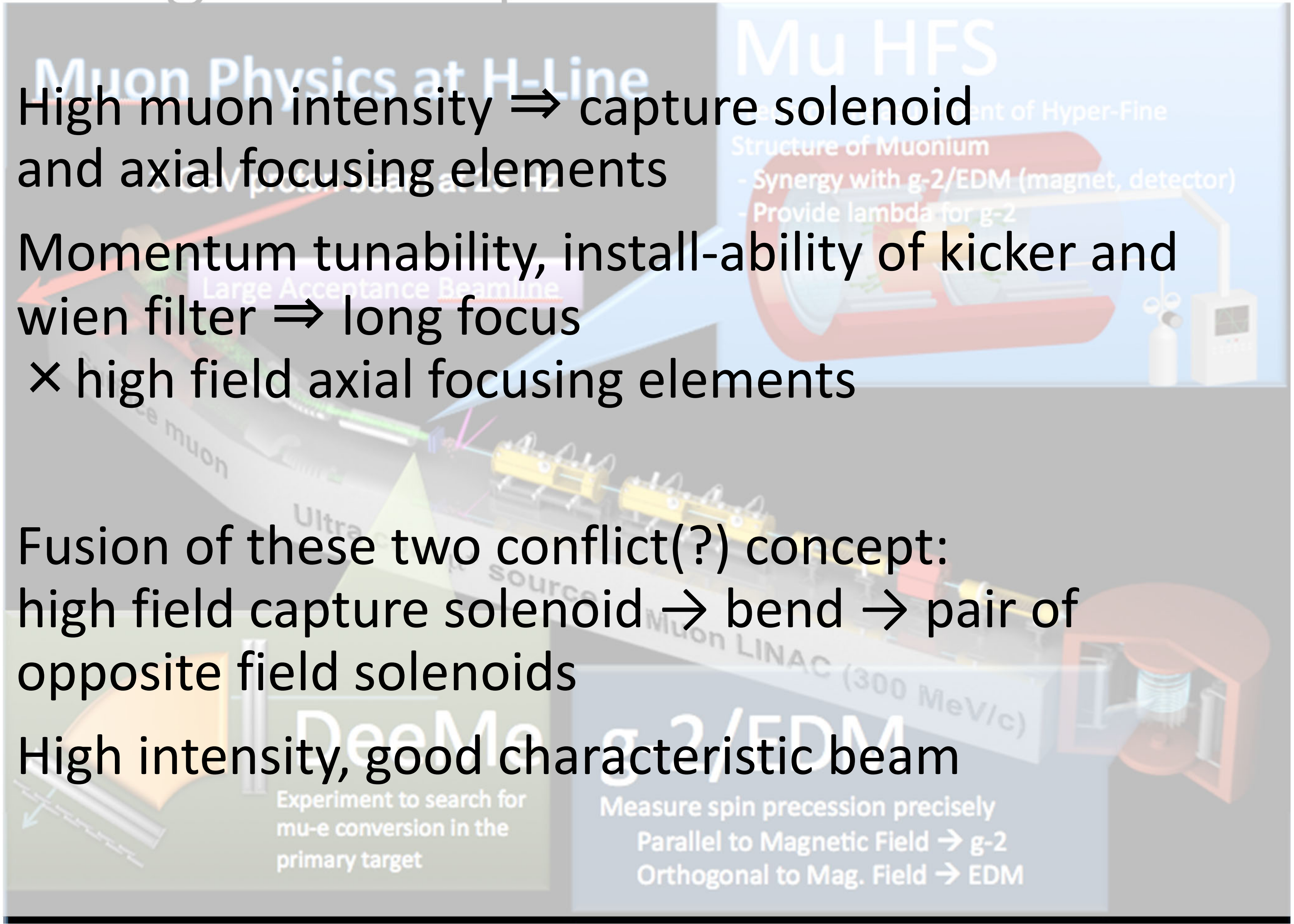
Target Sensitivity <10^{-16} with 56 kW beam

- **Extension of muon transport solenoid** to **cope with higher proton beam power**
  - More efficient beam background suppression
  - Pions decay to muons in longer transport
- **Tungsten alloy** as a pion production target
- **Electron spectrometer solenoid** to suppress the detector counting rate
- Physics detector
  - Straw-tube tracker and LYSO calorimeter
  - Muon stopping target (Al + others) in a gradient magnetic field for the purpose of signal electron collection with a magnetic lens

軸収束型ビームラインの問題点

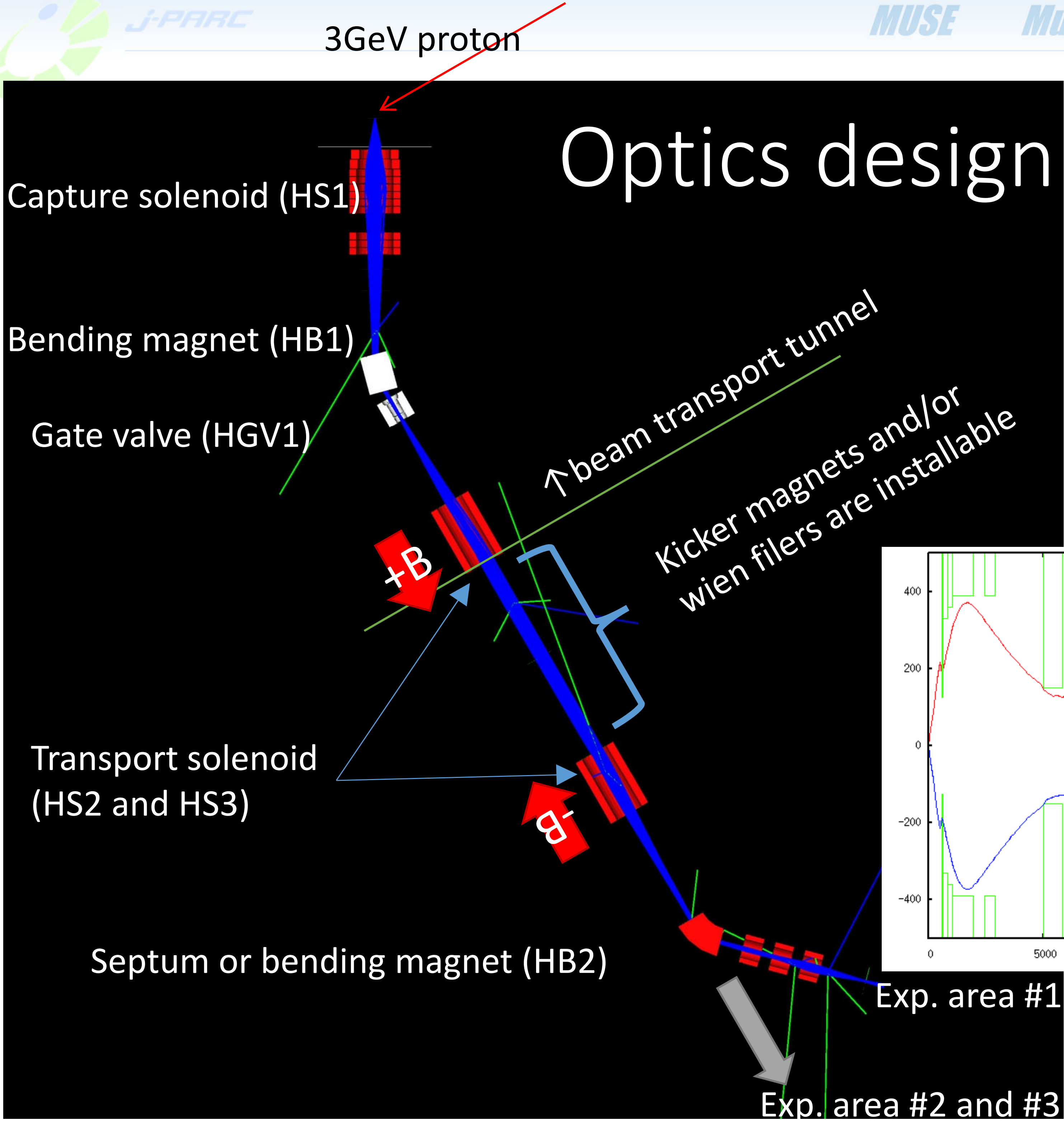
- 確かにビーム強度（ミュオン数）の観点では良い
  COMETのようにインライン標的を用いると理想的
- ただし、軸収束磁場から出た瞬間にビームが発散してしまうので、磁場内（COMET）か磁場から出てすぐ（Uライン）にビームを停止させる試料を配置
- それに特化した実験なら問題ないが、様々な実験装置を駆使する汎用的な使い方には向かない
  ミュオン科学では汎用性が大事
- 強度を落とさず、汎用性のあるビームラインを！

Design concept of H line



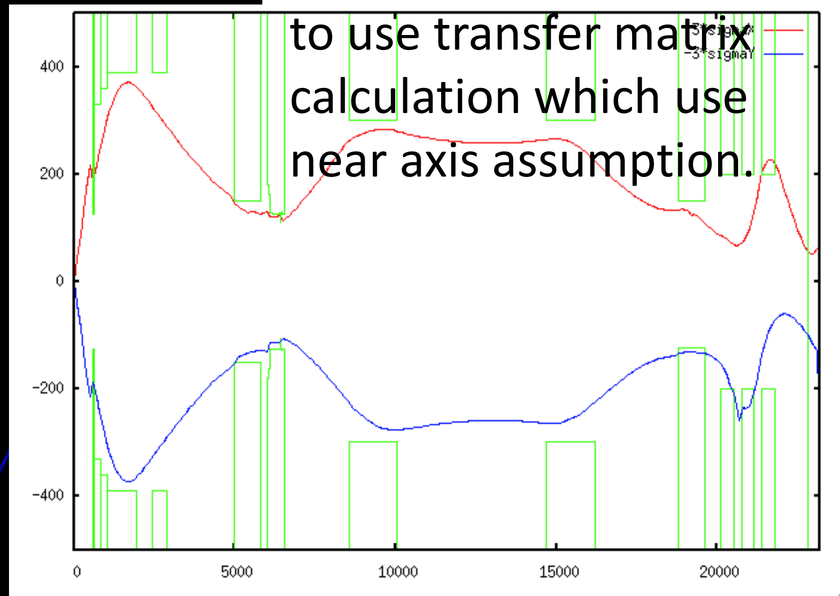
- High muon intensity ⇒ capture solenoid and axial focusing elements
- Momentum tunability, install-ability of kicker and wien filter ⇒ long focus
  ✕ high field axial focusing elements
- Fusion of these two conflict(?) concept:
  high field capture solenoid → bend → pair of opposite field solenoids
- High intensity, good characteristic beam

Optics design for H line

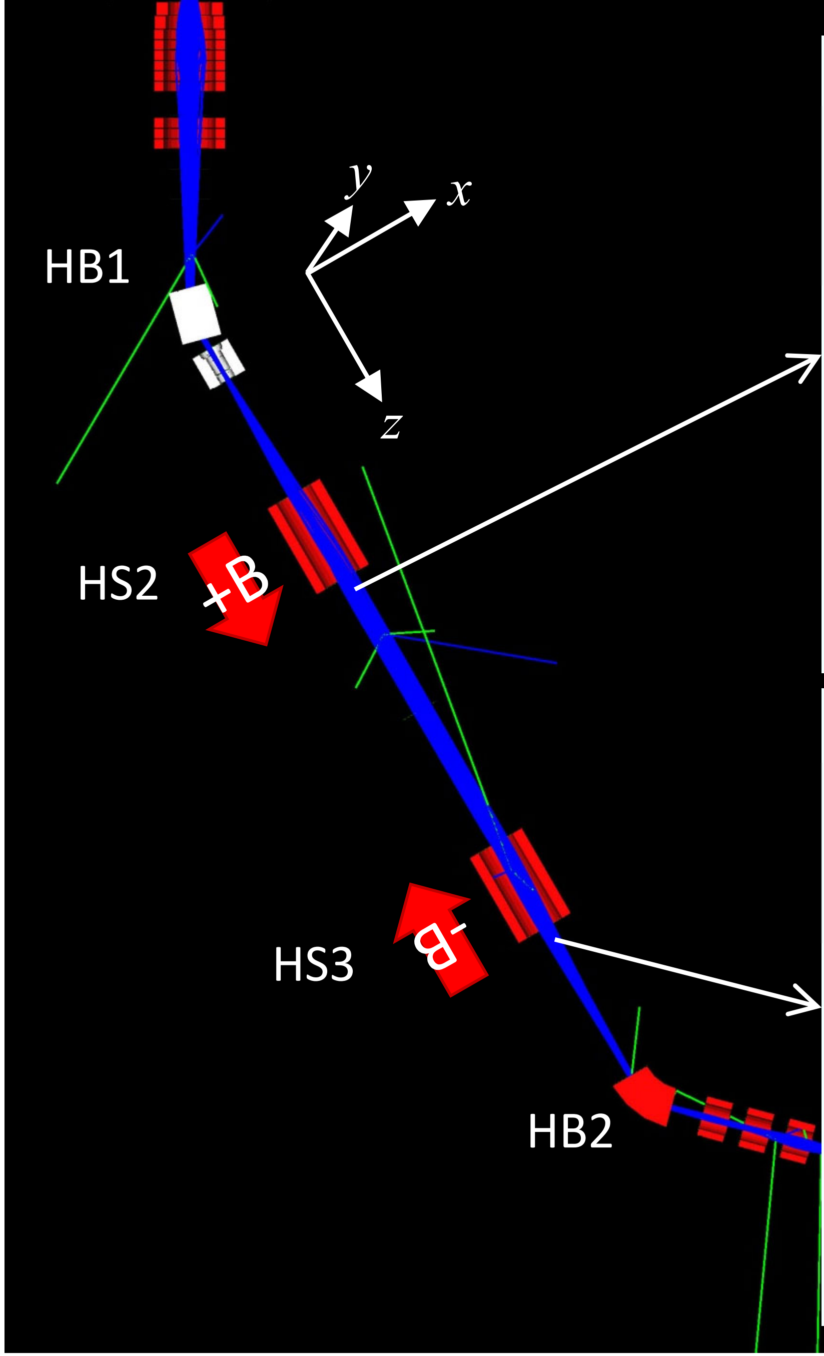


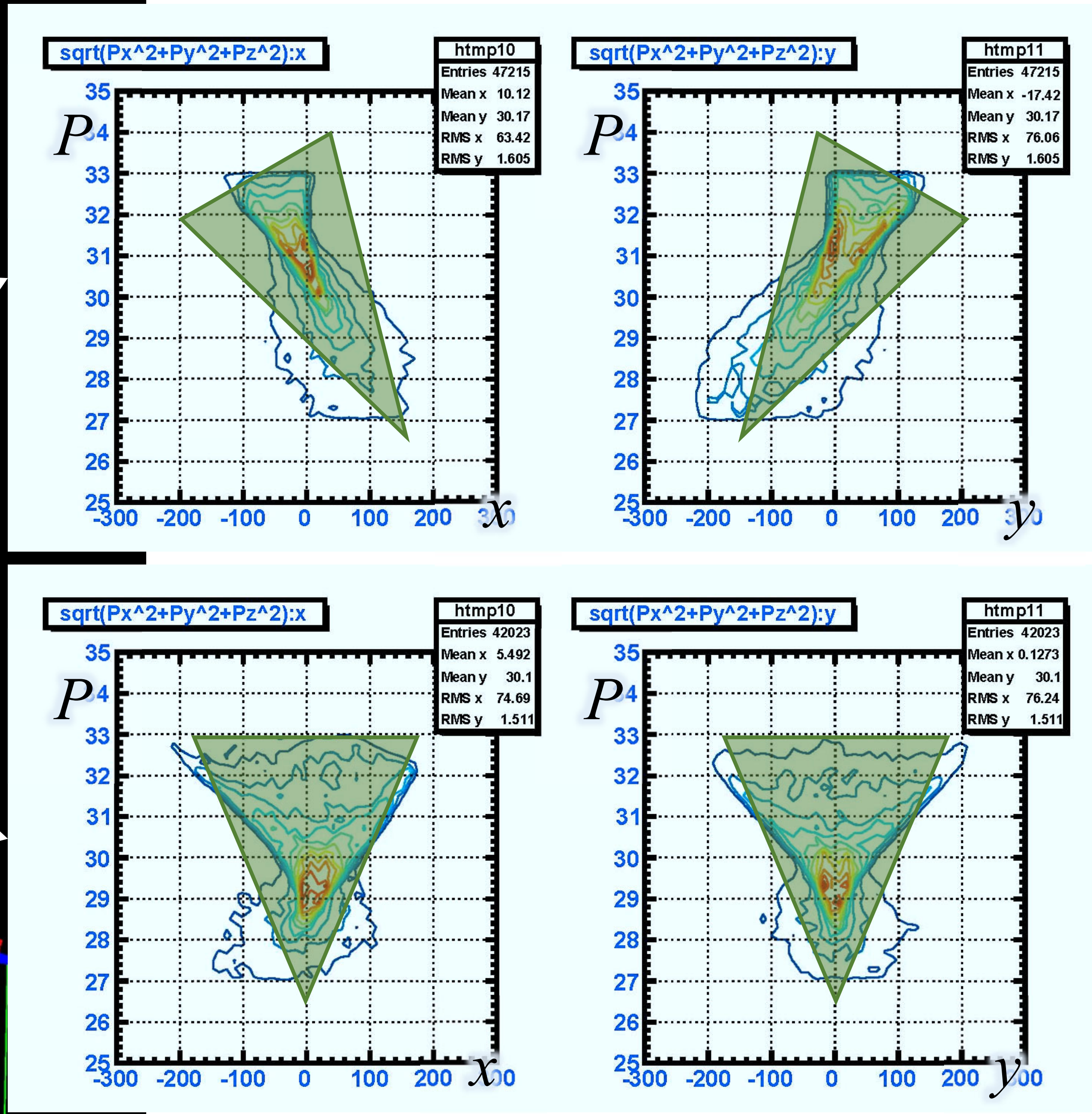
30 MeV/c mono-chromatic beam calc. performed by a MC-code (G4beamline)

Large aperture short solenoids do not allow us to use transfer matrix calculation which use near axis assumption.

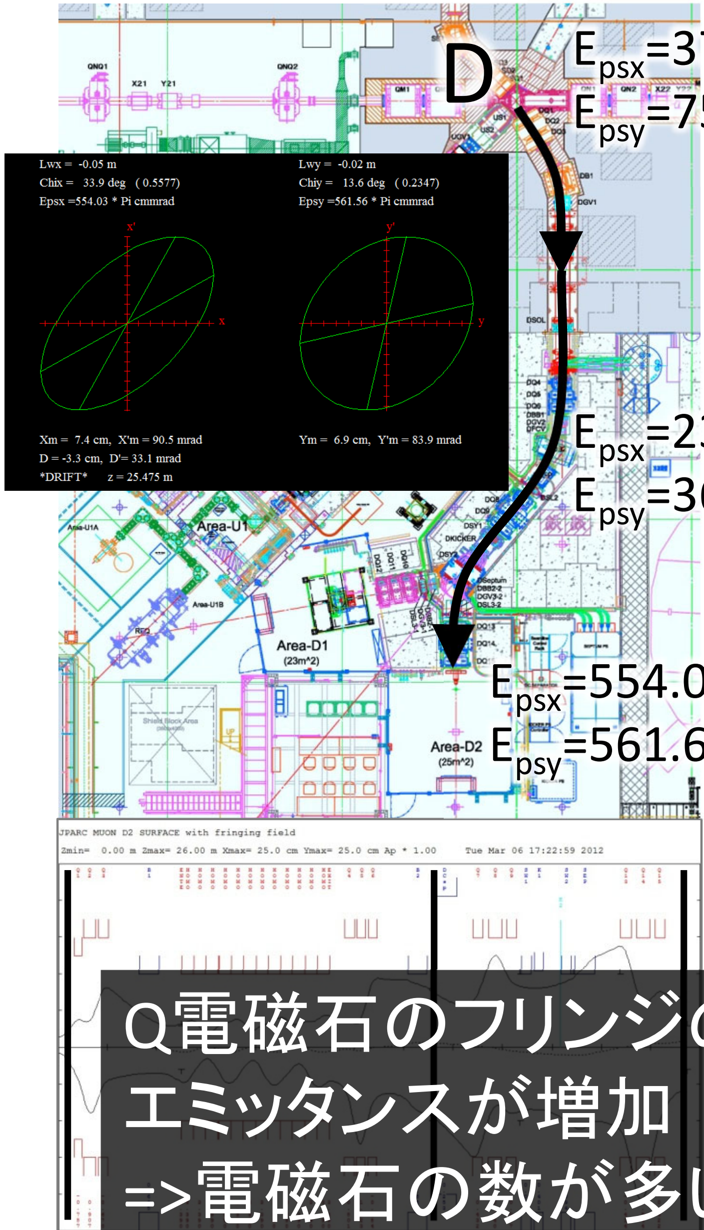


Merit of opposite field solenoid





Merit of opposite field solenoid



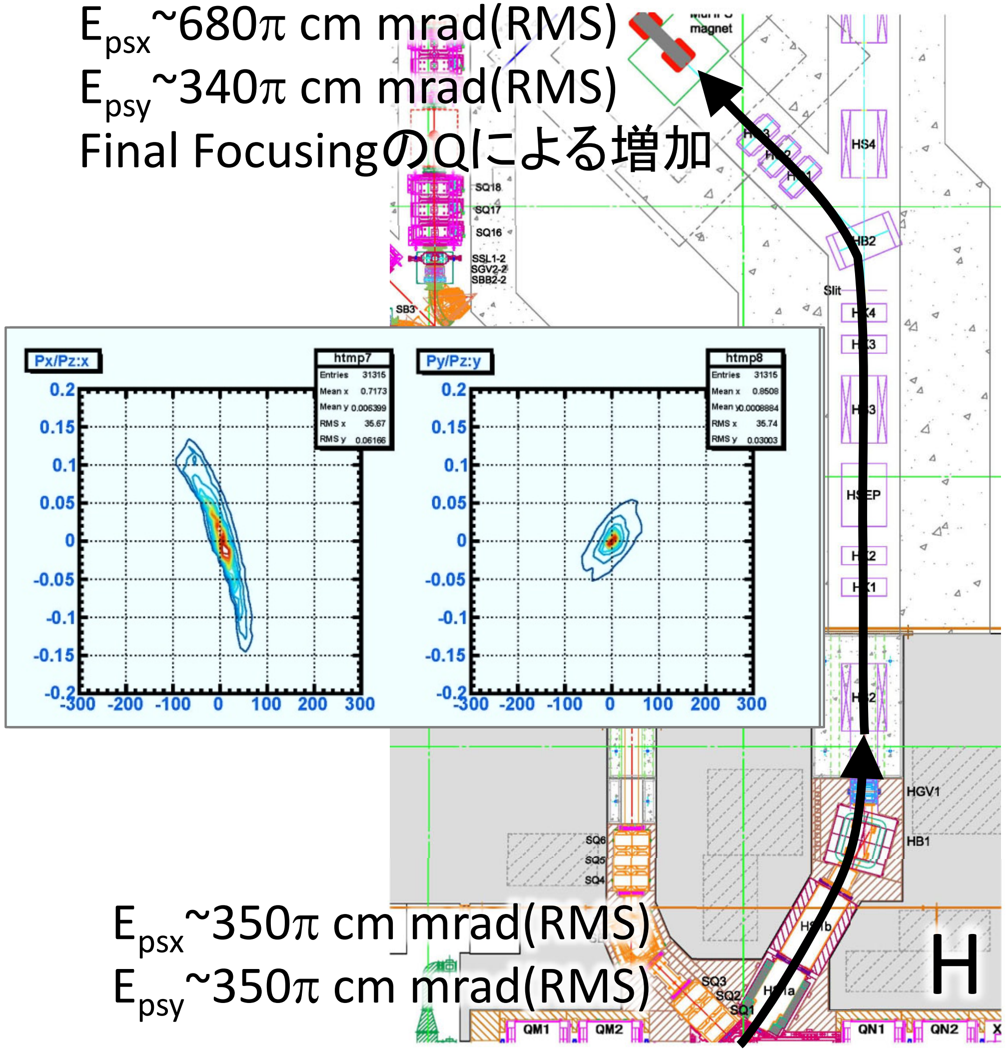
E_{psx}=37.5π cm mrad
E_{psy}=75.0π cm mrad

E_{psx}=235.2π cm mrad
E_{psy}=368.9π cm mrad

E_{psx}=554.0π cm mrad
E_{psy}=561.6π cm mrad

Q電磁石のフリンジの効果でエミッタンスが増加
=>電磁石の数が多い：×

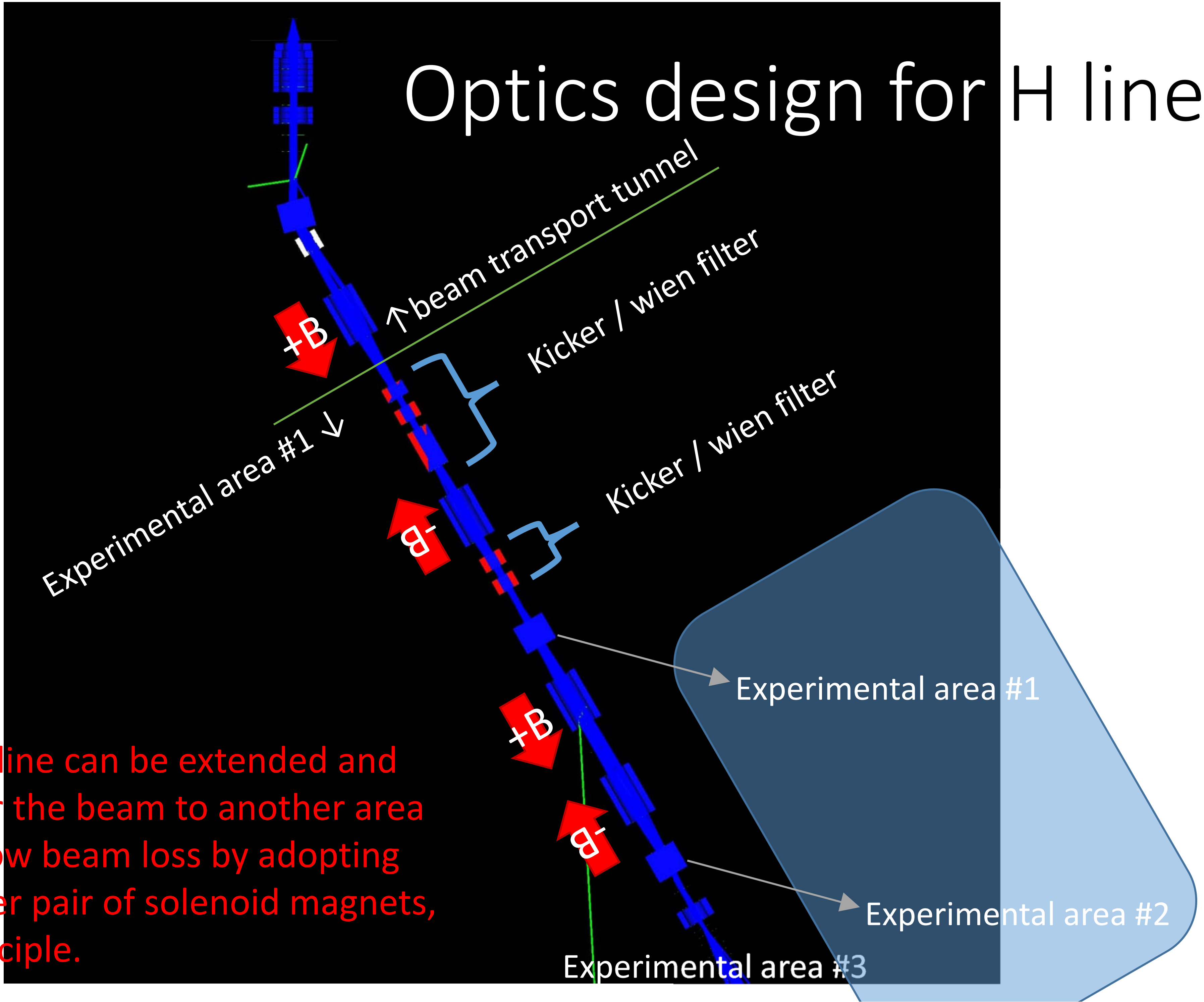
E_{psx}~680π cm mrad(RMS)
E_{psy}~340π cm mrad(RMS)
Final FocusingのQによる増加



E_{psx}~350π cm mrad(RMS)
E_{psy}~350π cm mrad(RMS)

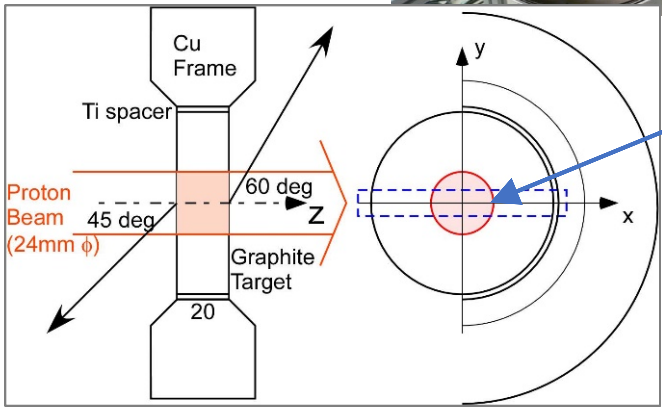
少ないQ電磁石でエミッタンスの増加：小

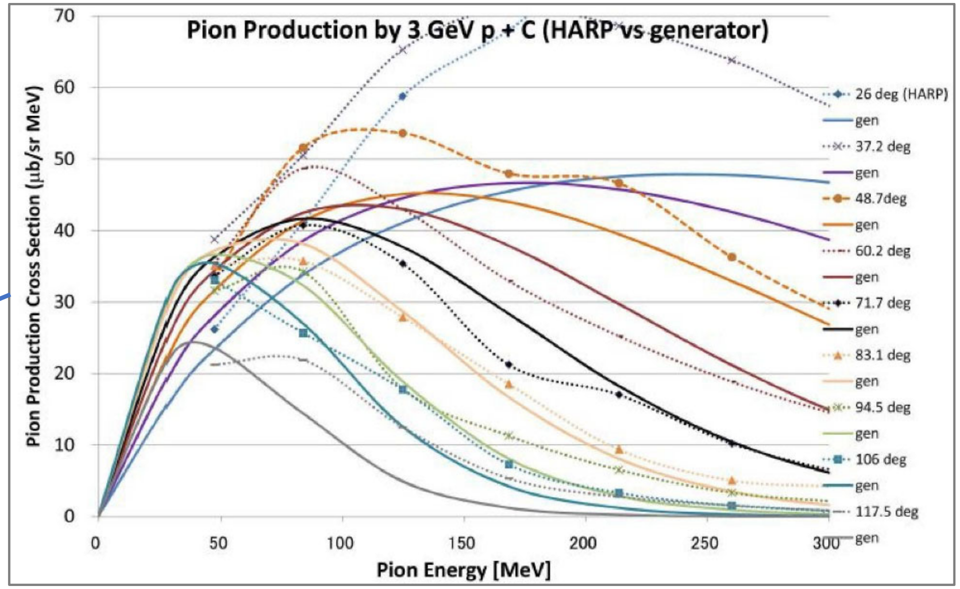
Optics design for H line



The H line can be extended and deliver the beam to another area with low beam loss by adopting another pair of solenoid magnets, in principle.

Yield evaluation - Pion production





muon production target: ^{t}2cm graphite (~2014: fixed, 2014~: rotating)

Empirical formula of pion production by 3GeV proton

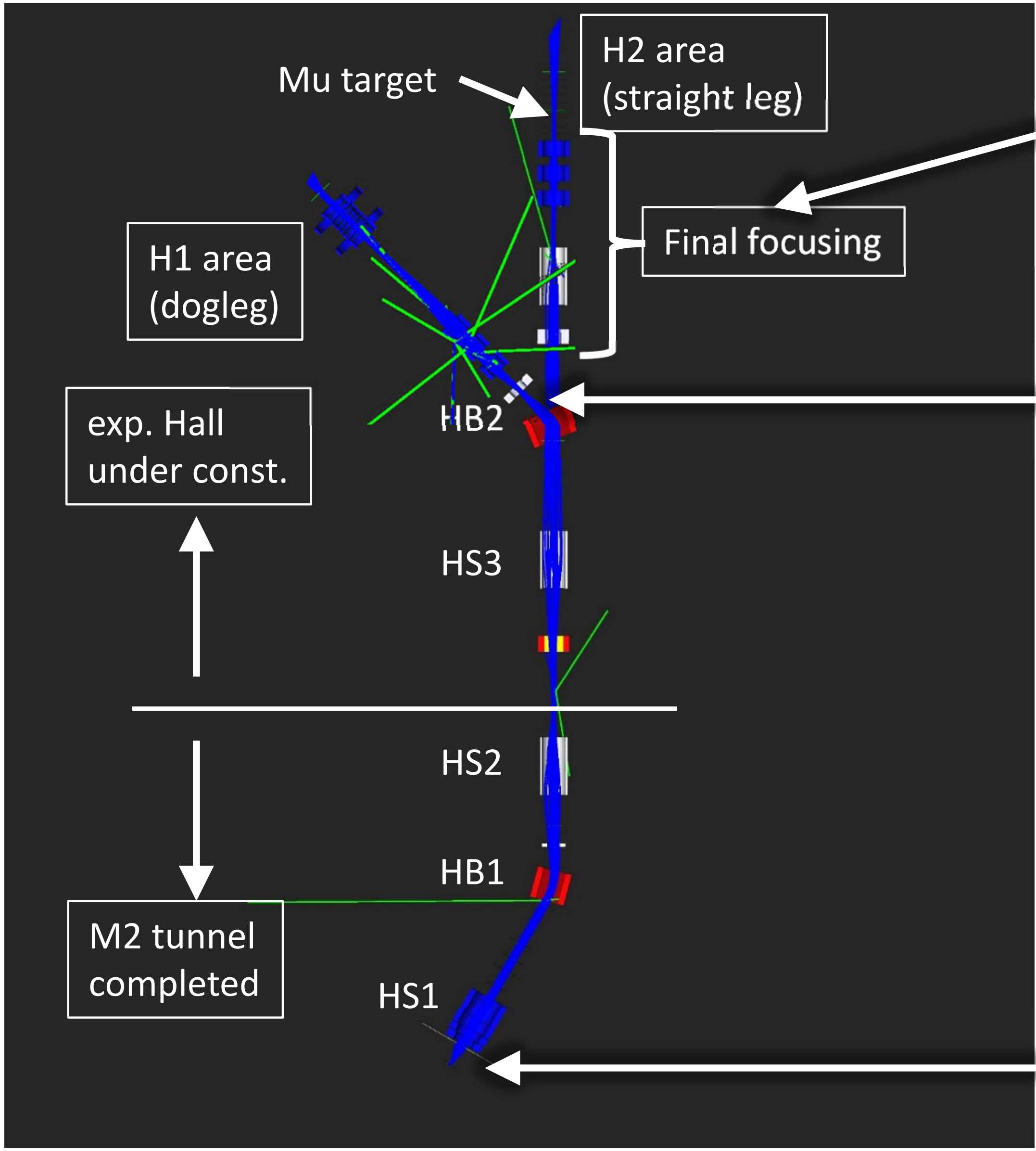
$$d\sigma^2/dE\ d\Omega = \frac{80\times 40aE}{[33+1200a+40aE][1+\exp(40aE/60-2)[1+\exp((E-1000)/200)]]}$$

$$a = 0.001 + 0.02\tan\theta_1$$

$$\theta_1 = \theta/1.5\ \ (\theta < 90°), = 0.32(\theta - 90) + 60\ (\theta > 90°)$$

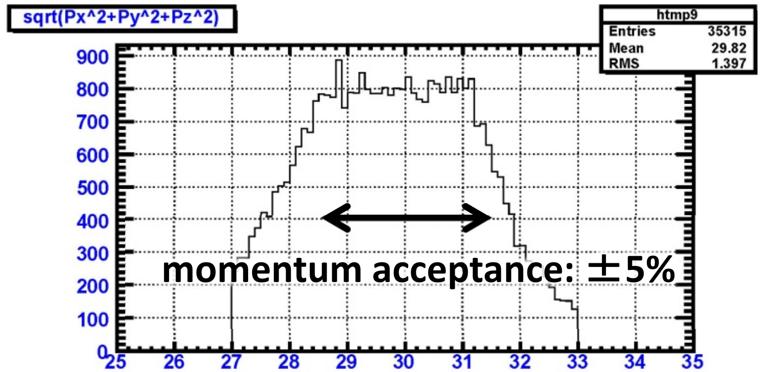
Consistent with Geant/GHEISHA, Geant/FLUKA

Yield evaluation - Beam transmission



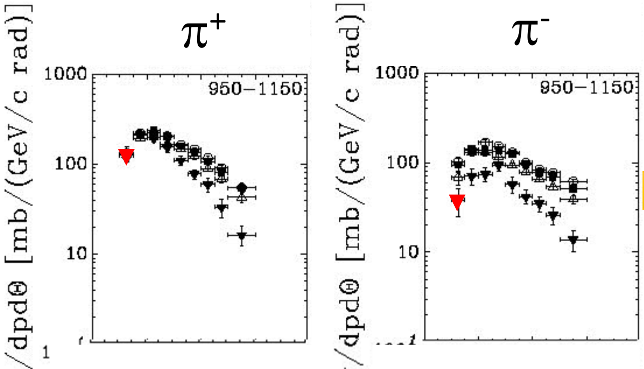
Typical Transmission efficiency in Final focusing part: > 80%

Transmission efficiency from the entrance of HS1 to the exit of HB2
⇒ 81% (geom. acceptance: 109 mstr)

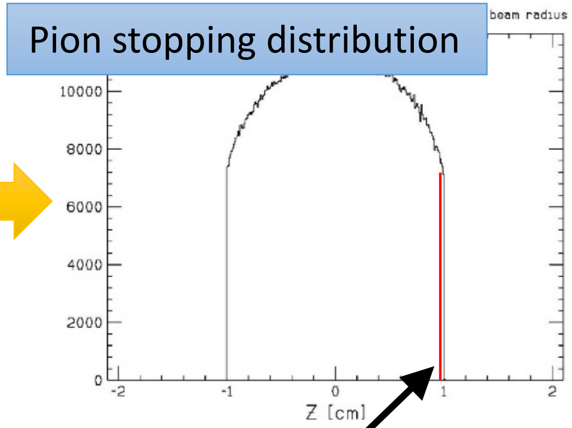


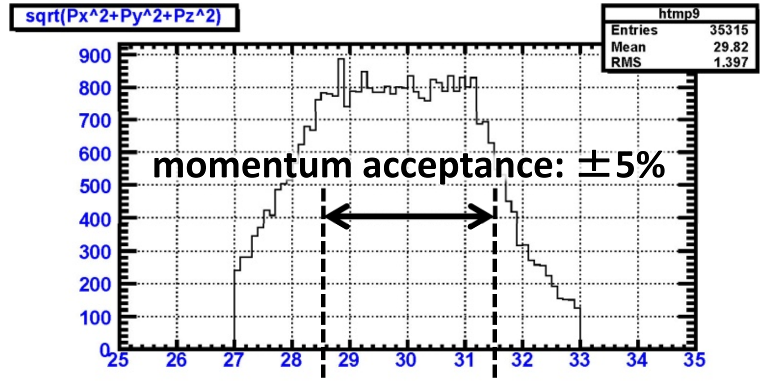
Aperture of the entrance of H line
∅250 mm @ 60 cm apart from the target
⇒ 136 mstr

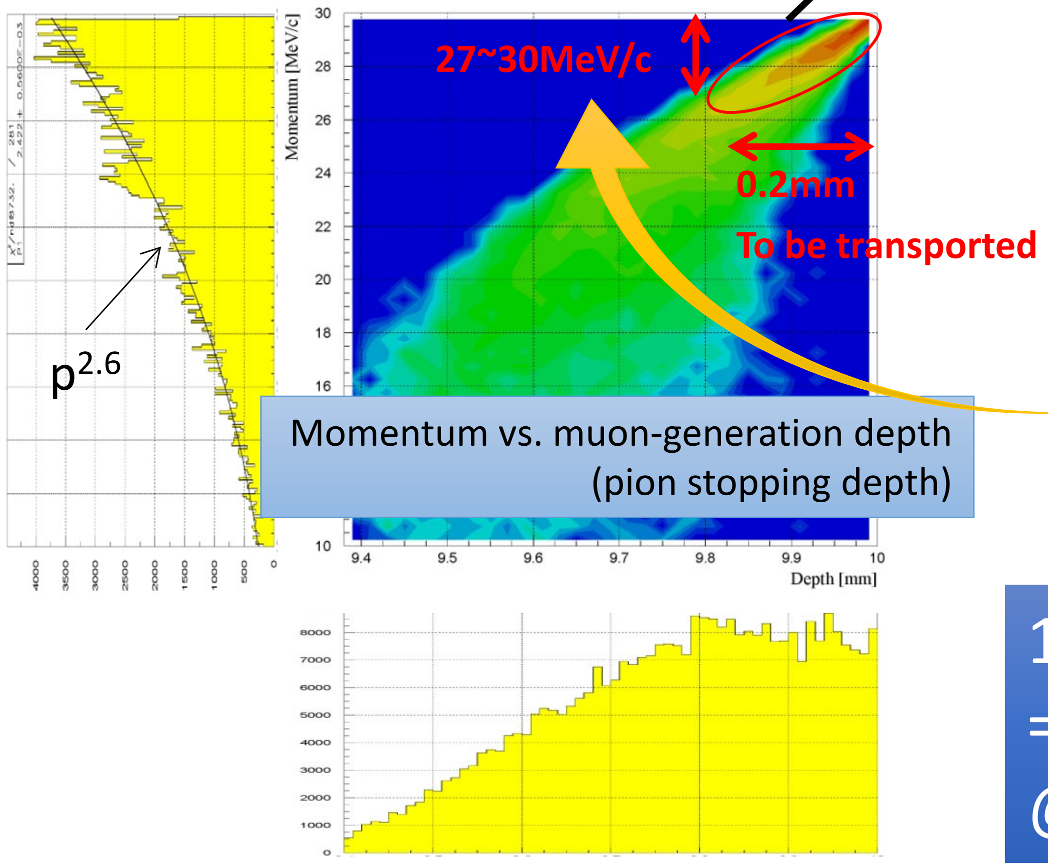
Beam intensity evaluation

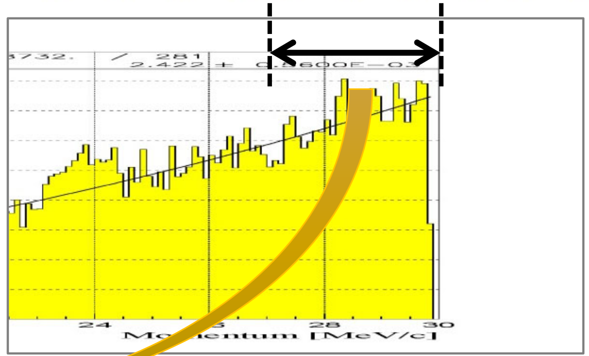


HARP Eur. Phys. J. C 53 177 (2008)









$15{,}000\text{M} \times 0.109/4\pi \times 0.8$

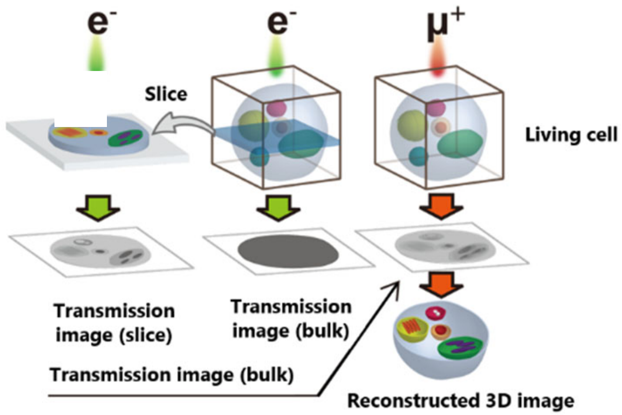
= 100M/s surface muon

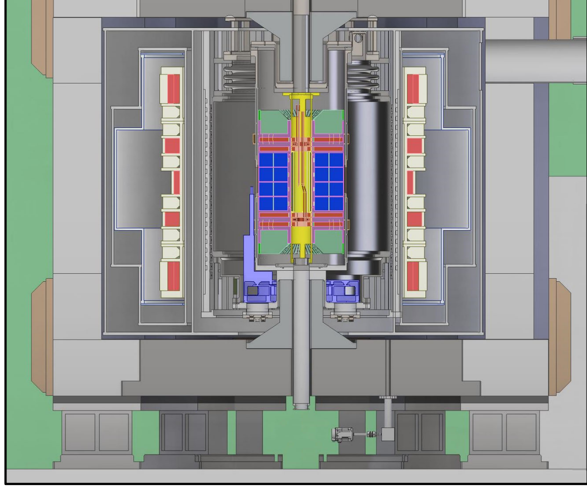
@ exp. area

Hラインの延長計画

透過型ミュオン顕微鏡

ミュオンの高い
透過能力により
電子顕微鏡では
不可能だった
生きた細胞の
丸ごと顕微観察



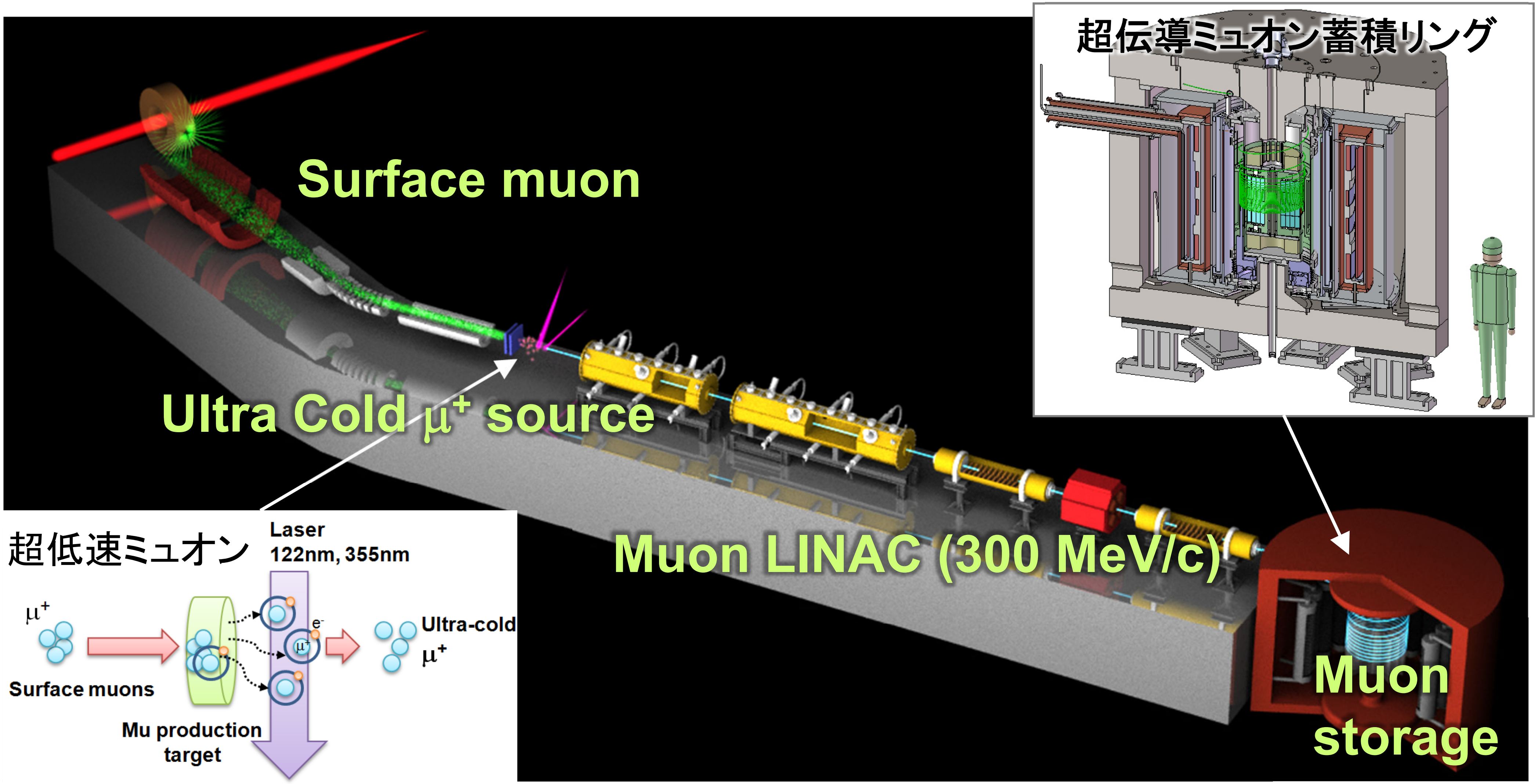


g-2/EDM実験

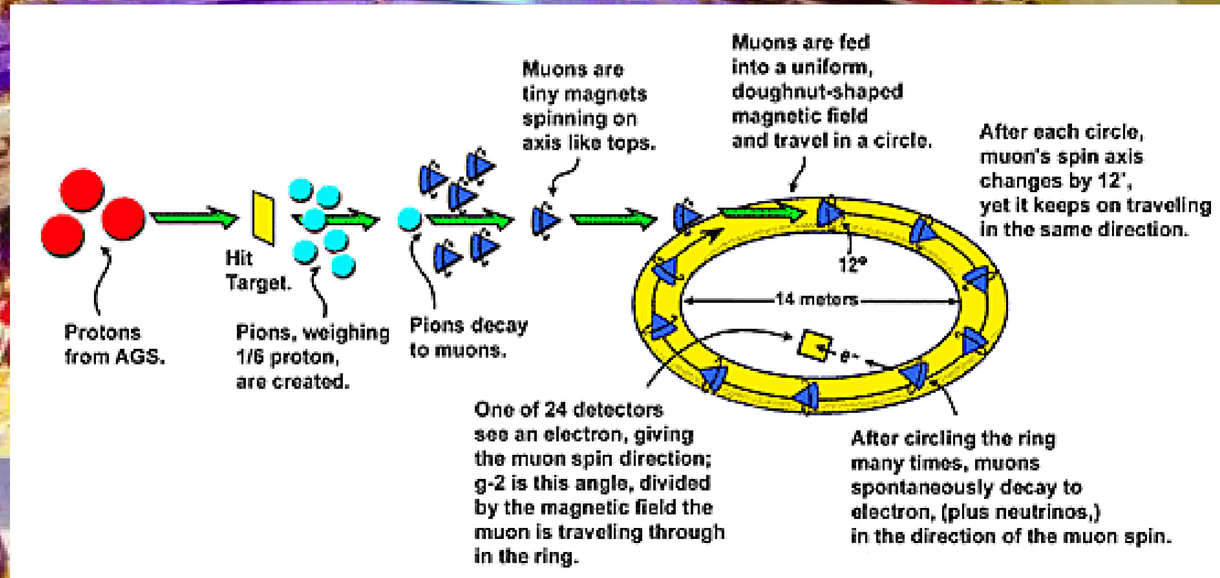
素粒子標準模型を
超える新物理探索

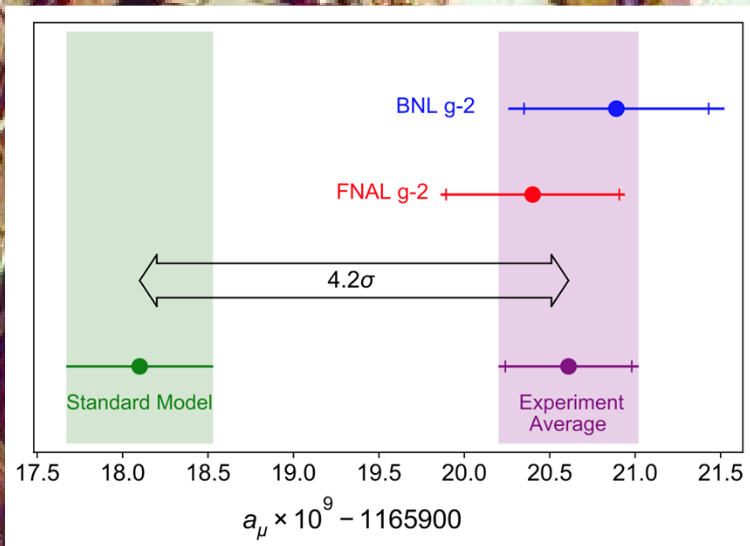
J-PARC E34(g-2/EDM)実験

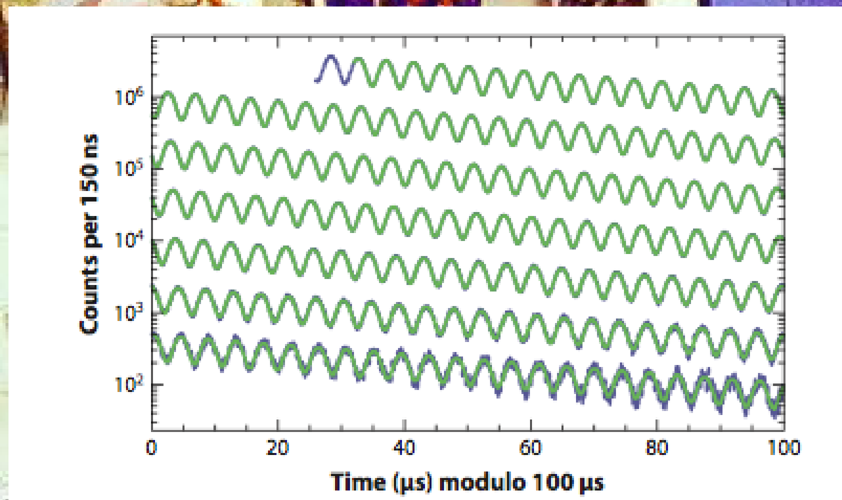
- 収束電場を使わない
  - 低エミッタンスのミュオンビーム（超低速ミュオン）を再加速



Muon g-2 experiment at BNL







Fermi lab E989実験

- BNLからミュオン蓄積リングを移築
- より高統計(より多くの崩壊電子を検出すること)で $\Delta a_\mu \leq \pm 16 \times 10^{-11}$ (0.14ppm) を目指す

2013年に直径15mのリングをNYからイリノイ州に輸送

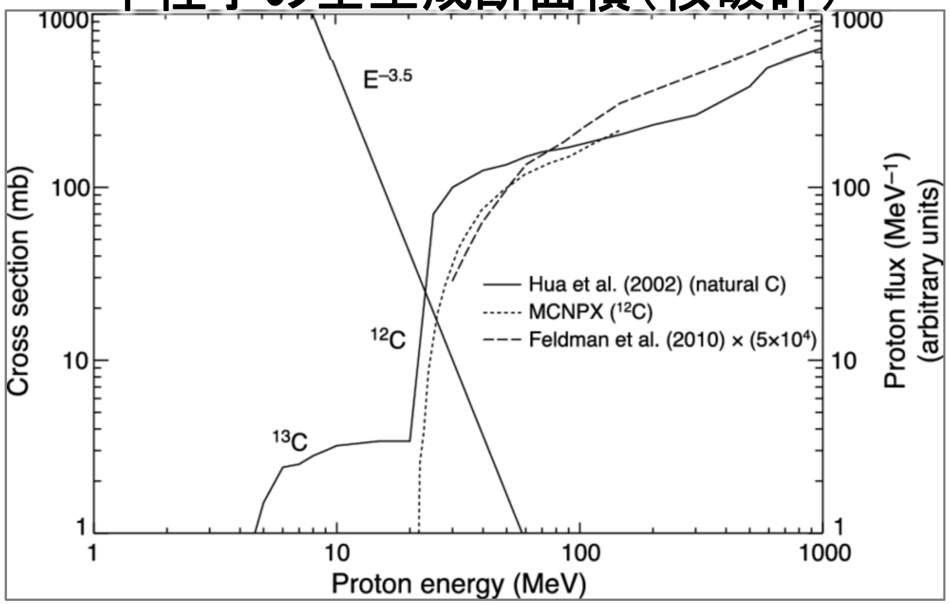
大強度ビームの問題点

高放射線環境下で安定して動くビームライン

放射線対策

- 陽子と標的（炭素原子核）との反応はπ中間子の生成だけではない
  - ミュオン標的では約5%（50kW）の陽子を消費
    - π^+生成断面積（50mb）≪中性子生成断面積（1000mb）
      毎秒10^{14}個の中性子が生成（周囲の放射化等、様々な反応）
  - ２次粒子生成に使われるのは高々数100W
    - π中間子生成: $(300+100)\ \mathrm{MeV}\times 5\cdot 10^{12}\ \mathrm{s}^{-1} \sim 300\ \mathrm{W}$
- 放射線対策が必須
  - （吸収）線量率評価
    - 放射線遮蔽
    - 耐放性材料選定
  - 放射能生成量評価（機器、空気、冷却水）
    - 運転・保守シナリオ

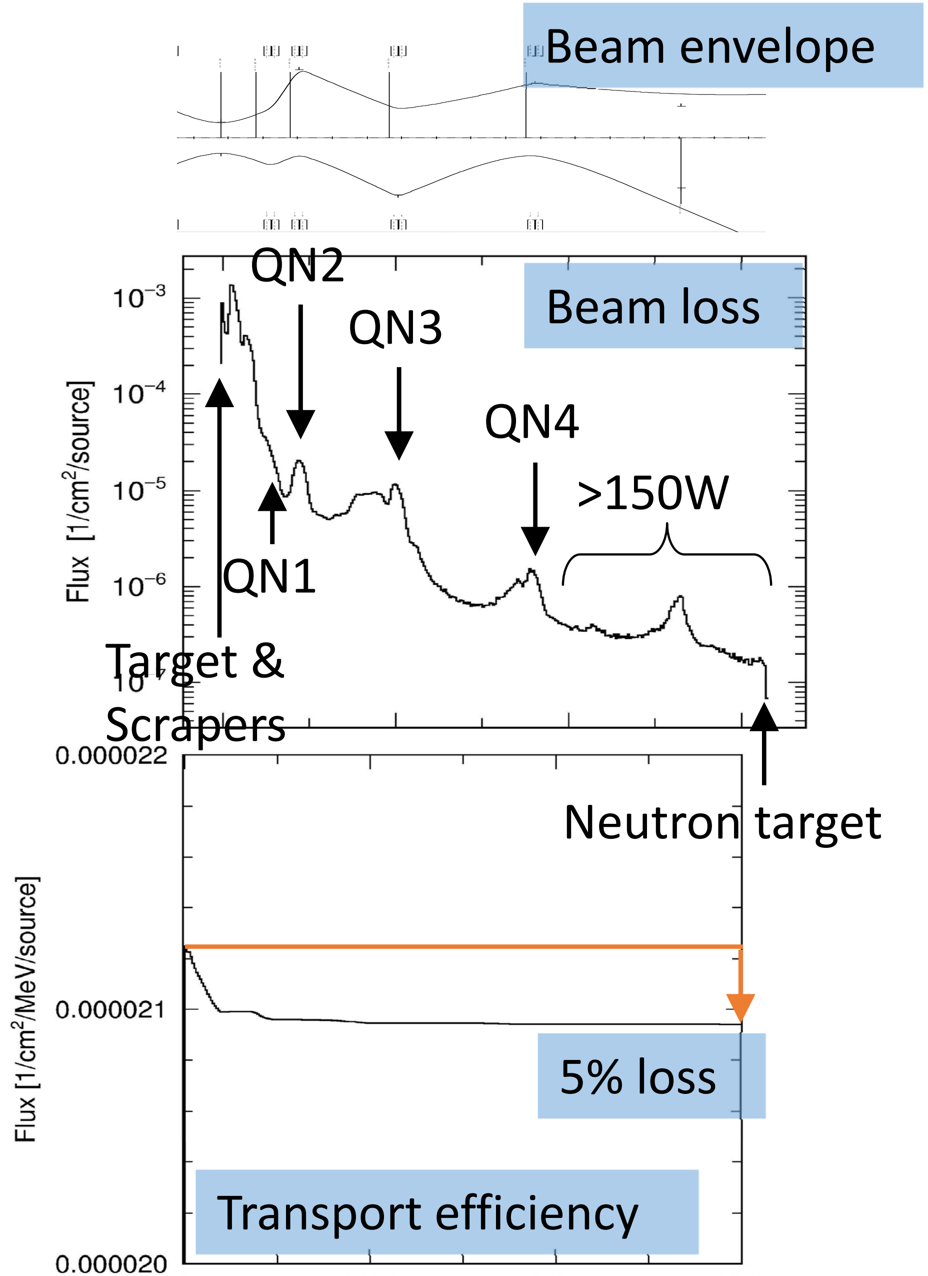
中性子の全生成断面積（核破砕）



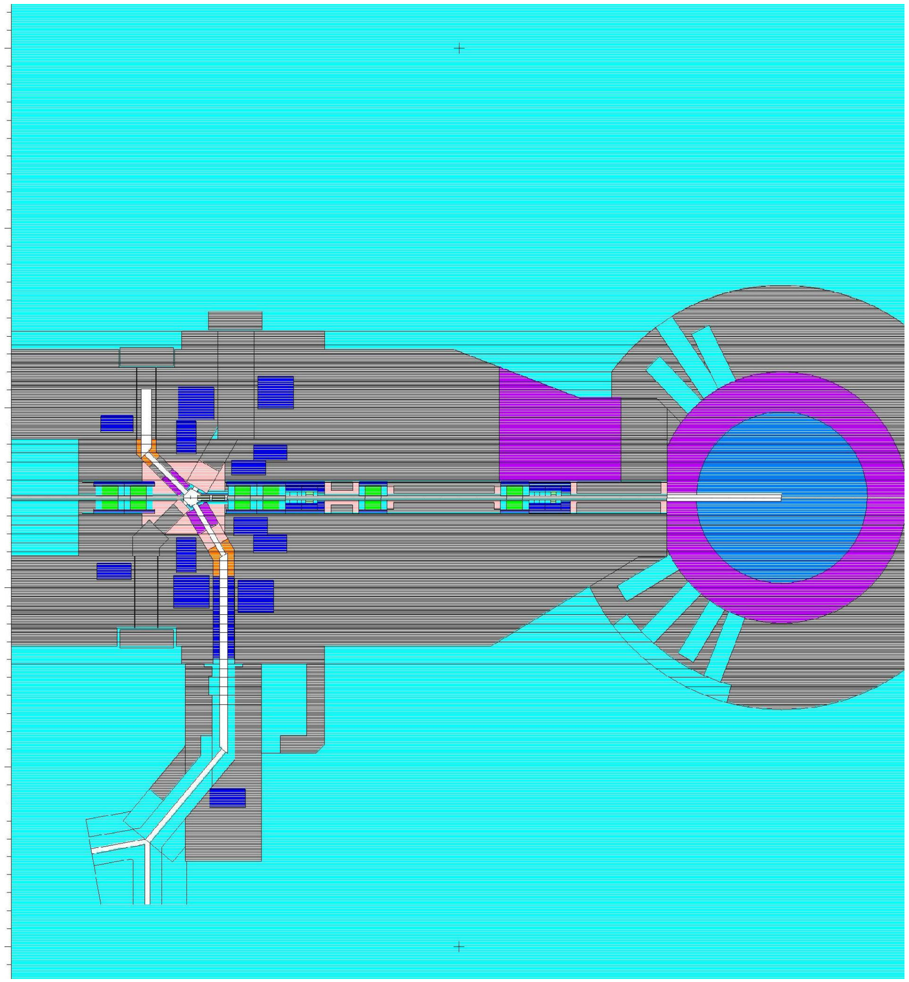
Beam loss

- The 2-cm graphite target causes a 5% (50 kW of 1MW) beam loss mainly at target and scrapers.
  - The effect of the scattered particles and secondary particles reaches whole M2 tunnel and its surroundings.

- The effect of radiation and the related things are serious problem for MLF, J-PARC.

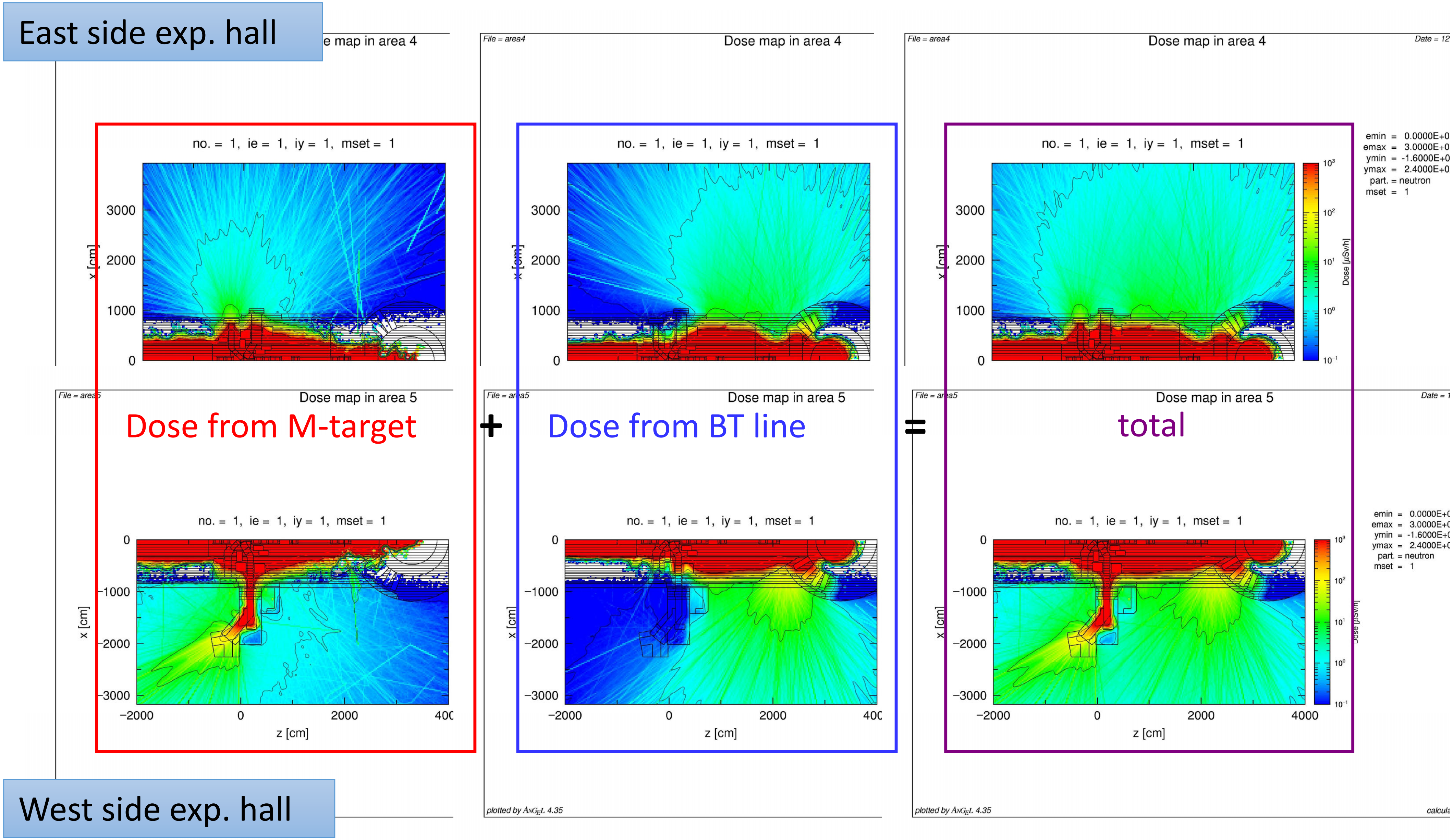


Evaluation of radiation dose



- Several MC (MCNPX, NMTC/JAM, PHITS) were used.
- Beam loss around the muon target:
  3-GeV proton beam with an emittance of 81π mm･mrad is injected into the muon target.
- Beam loss at downstream:
  Evaluation is performed with some margin due to miss-alignment and so on.

Simulation result

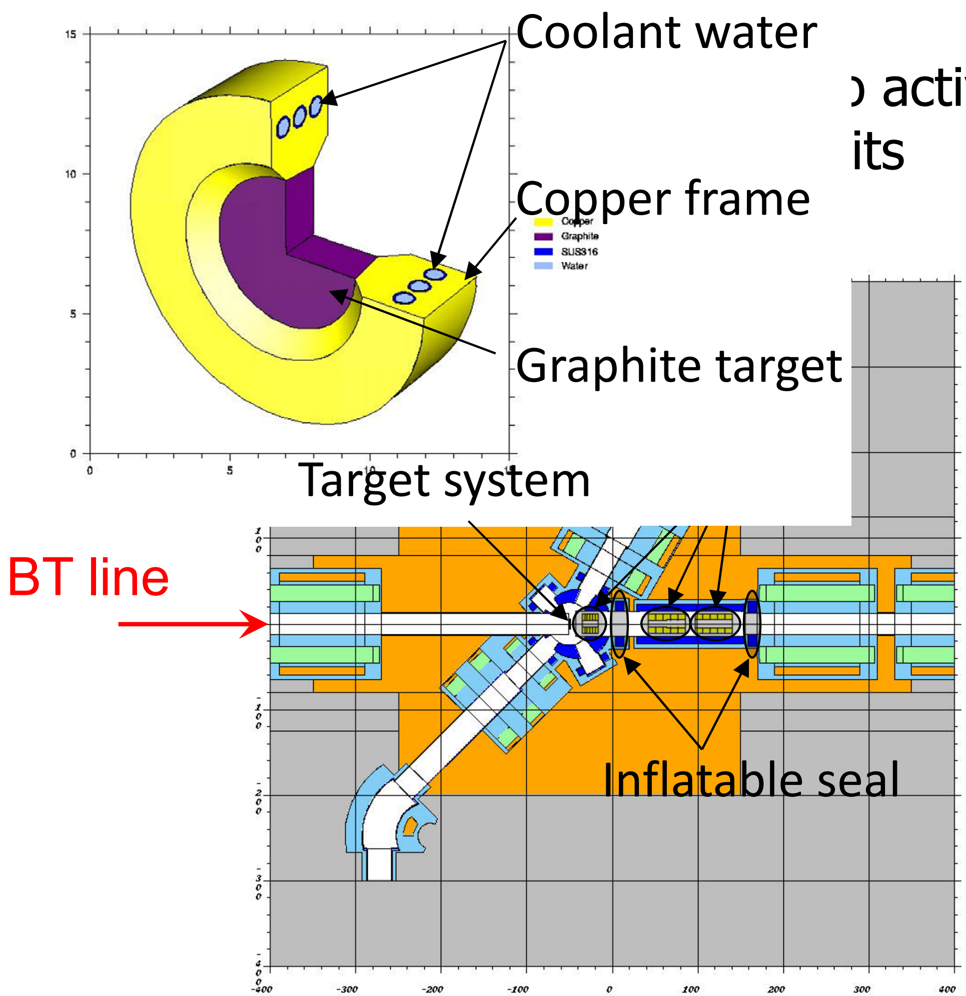


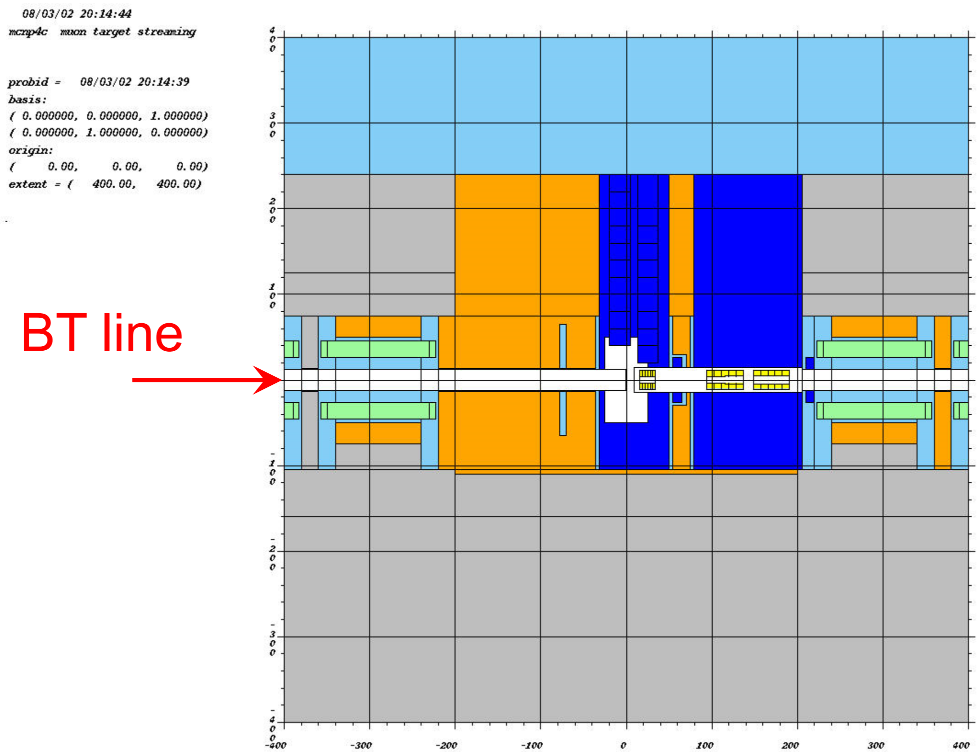
Evaluation model

Evaluation of:

ɔ activity production
its

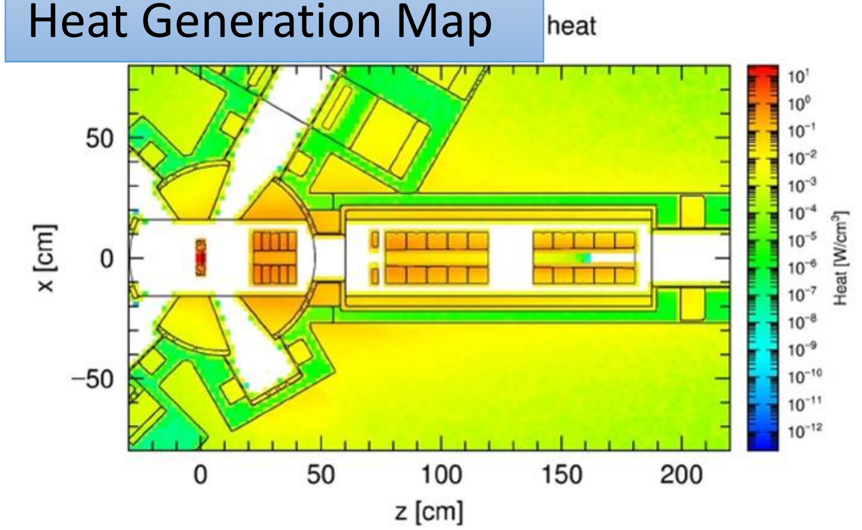
Decay-TURTLE
PHITS and/or MCNP
DCHAIN-SP and MCNP

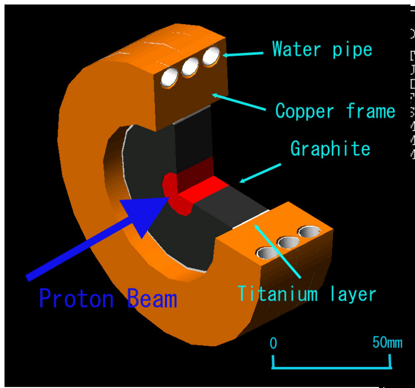


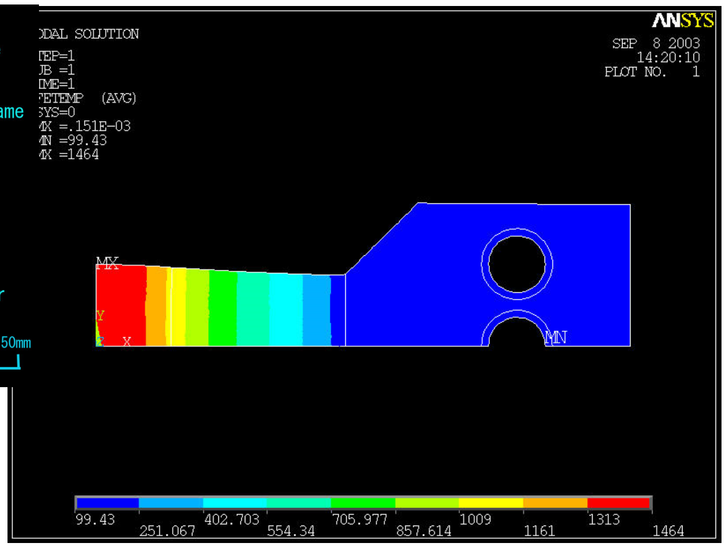


Evaluated results

Heat Generation Map





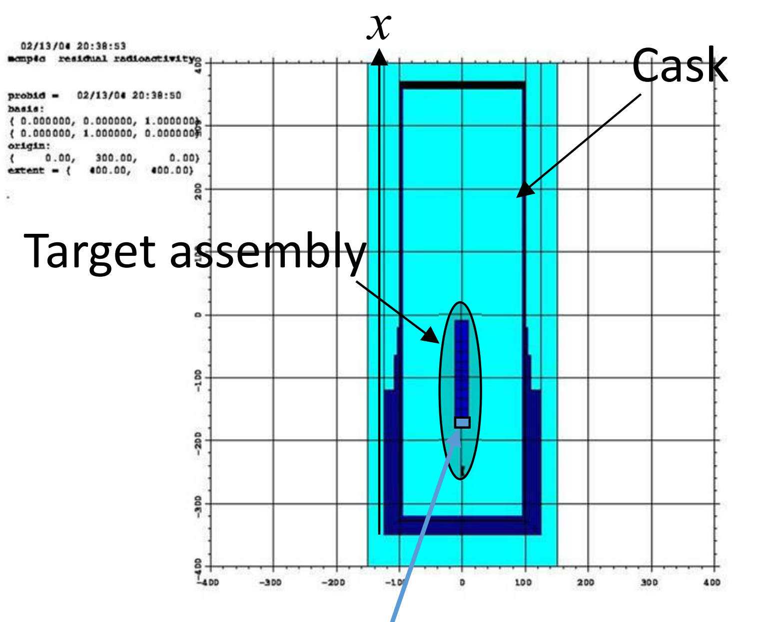


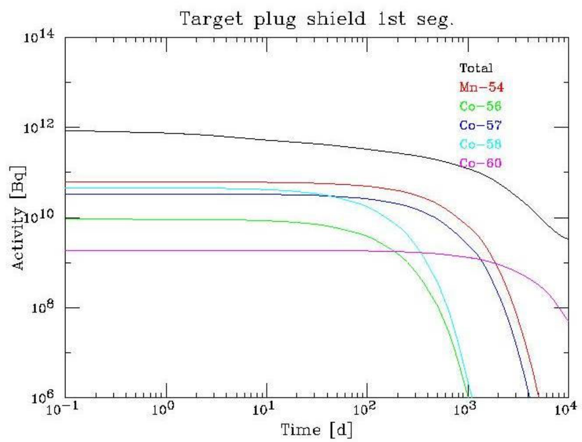
Heat generation ⇒ Temperature distribution
(PHITS) (ANSYS)

Heat Generation [kW]		
Target		3.3
Scraper #1		5.7
Scraper #2		5.0
Scraper #3		1.8
Dose [MGy/40y]		
BT line	QM1	2.0
	QM2	11.8
	QN1	905.0
	QN2	3490.4
	QN3	805.4
	QN4	174.8
M Line	DQ1	4270.0
	DB1	2.0
	SQ1	427.4
	SB1	0.8

QM1, QM2, QN4, DB1, SB1: polyimide
QN1, QN2, QN3, DQ1, SQ1: MIC

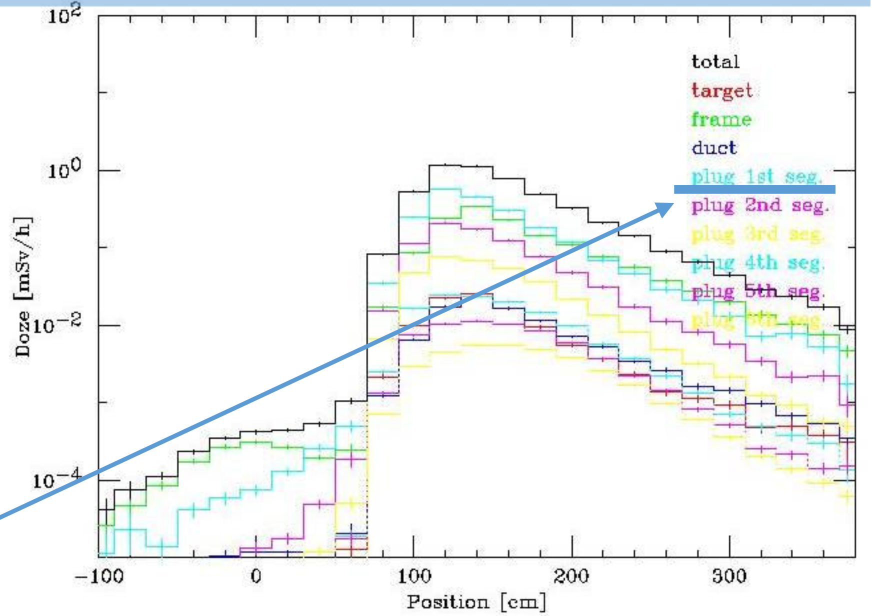
Effect of residual activity





Residual activity in the 1st segment of the target plug

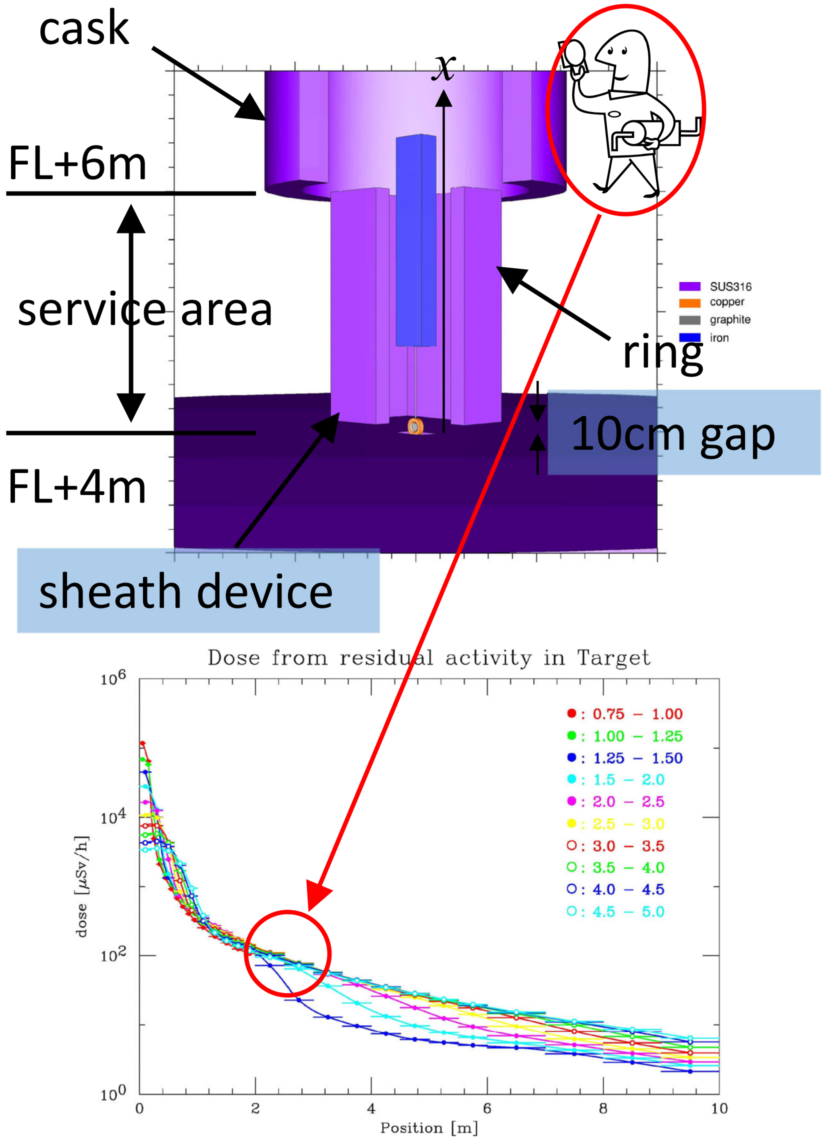
Dose on the cask surface
10-year irradiation and 1-day cooling



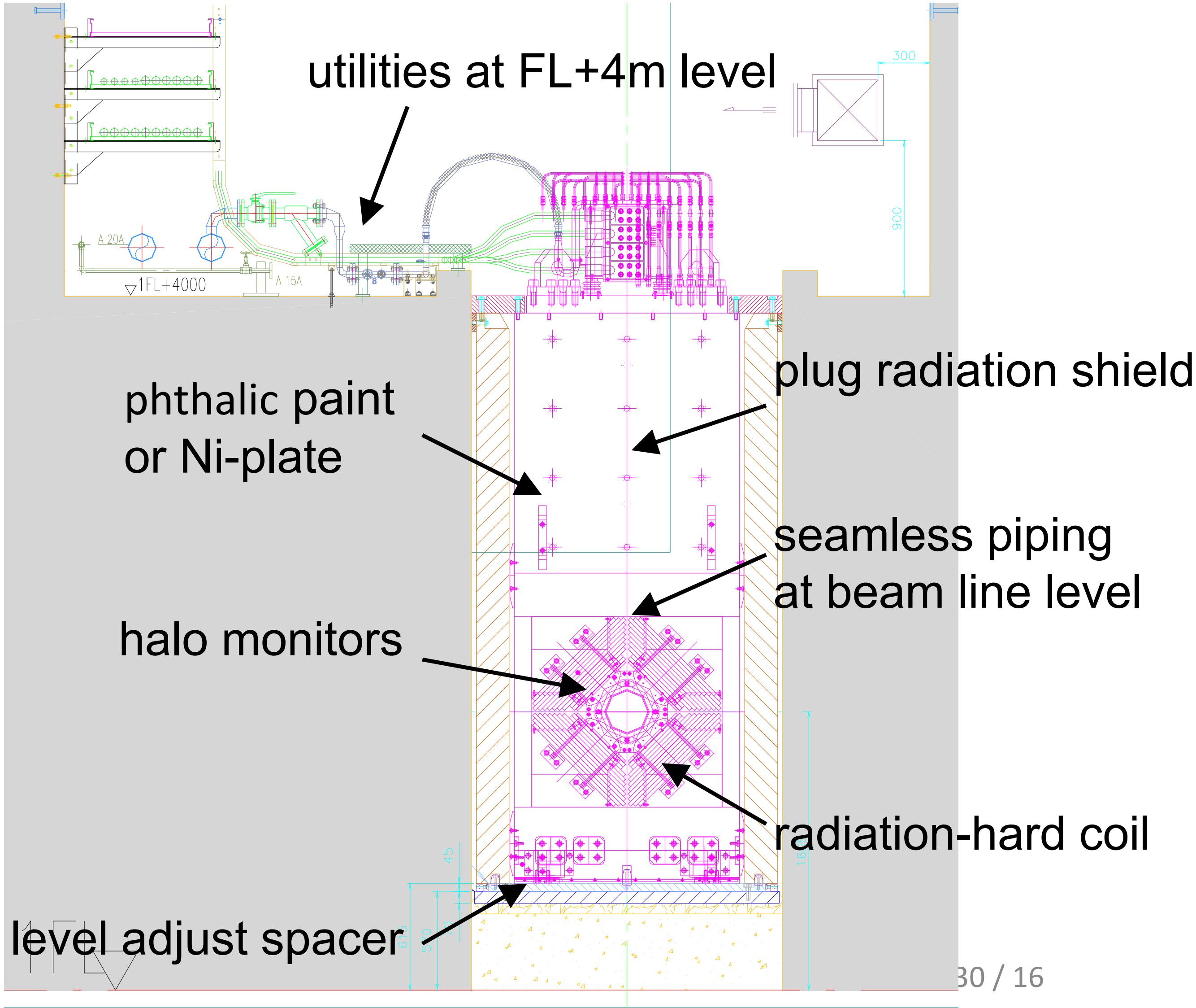
Reality of the maintenance scenario is examined.

Dose during target maintenance

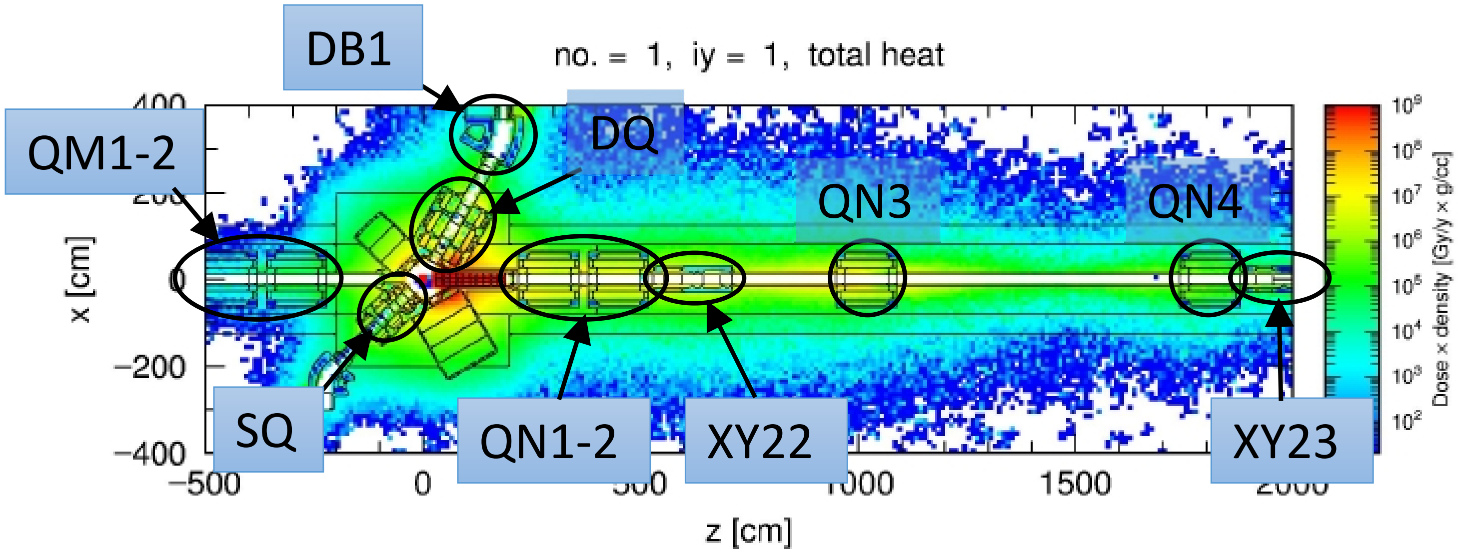
- In principle, target maintenance can be controlled remotely.
  - Accumulated dose is negligible.
- In trouble, one can work
  - for several hours at FL+6m
  - for a few minutes at FL+4m
- A sheath device has to be prepared in several years.



Basic design of M2-tunnel magnets

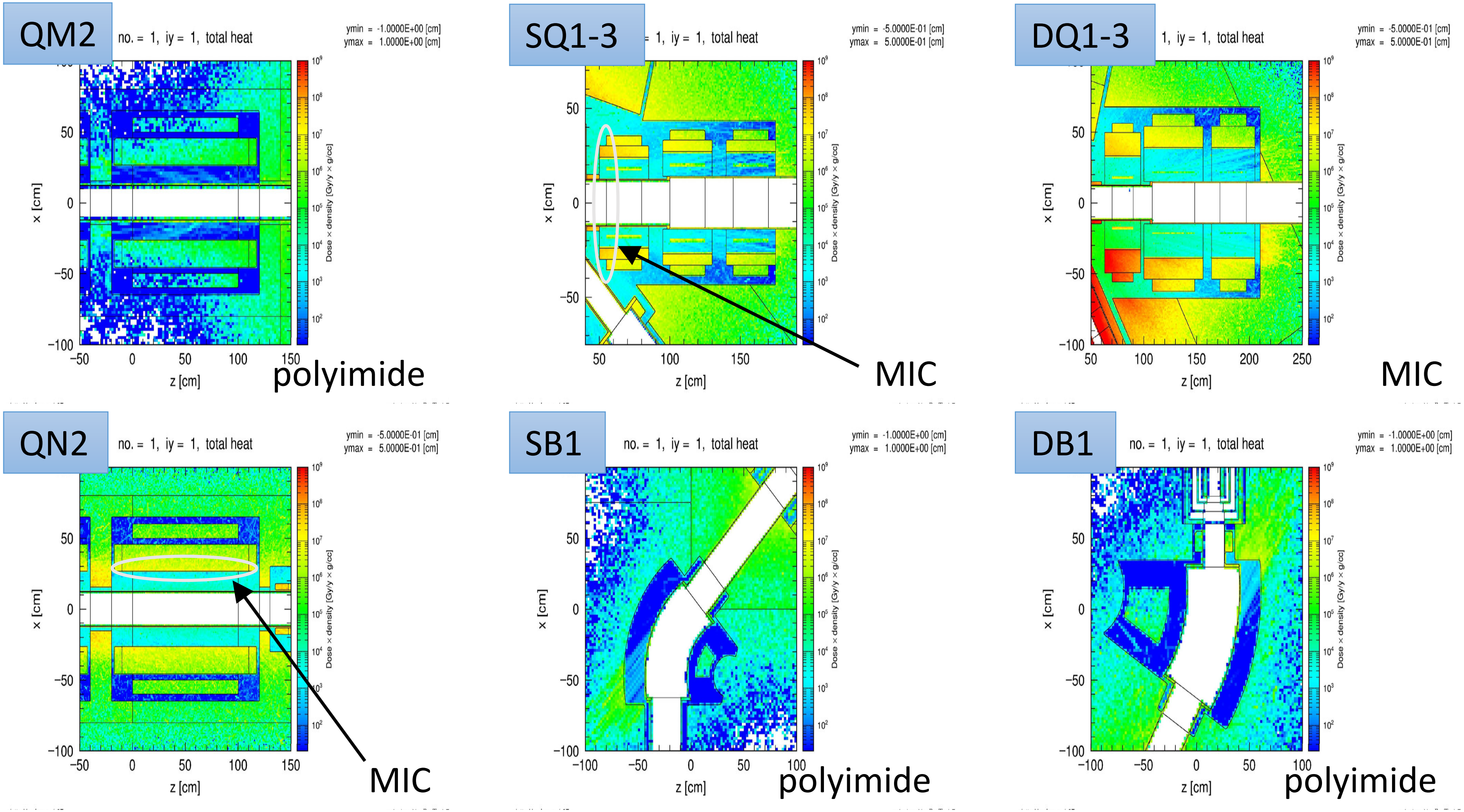


Material determination



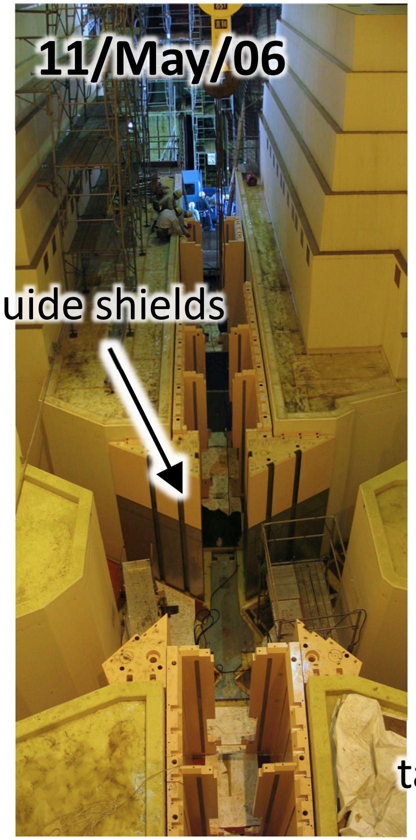
MGy/40y	Yoke	Coil	Pole/Duct	Cable mat.
QM2	0.1	0.7	10.1	Polyimide
QN2	21.3	65.7	2574.9	MIC
X22	202.5	414.7	349.3	MIC
X23	4.4	15.1	19.5	Polyimide
SQ1	75.8	207.8	114.2	MIC
DQ1	271.1	900.4	559.8	MIC
DB1	0.4	2.2	2.0	Polyimide

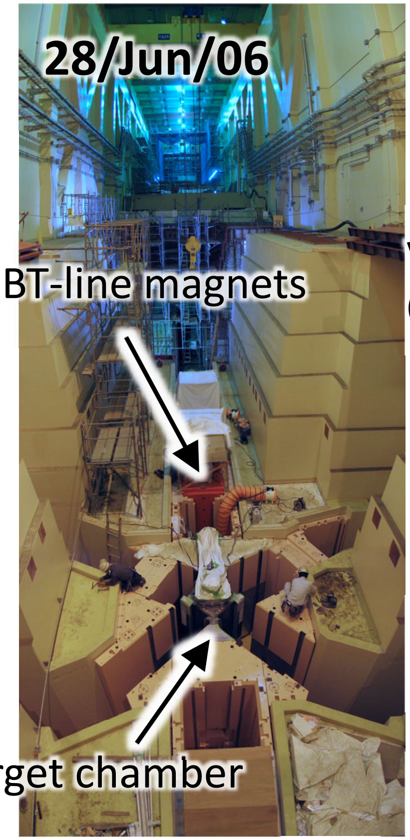
Material determination

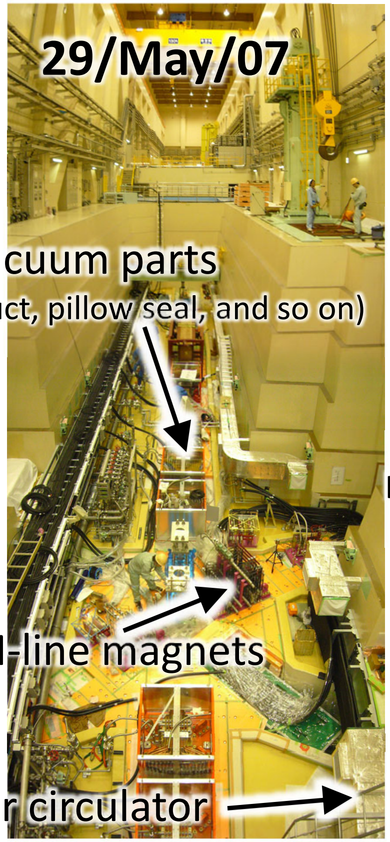


Detailed evaluation: polyimide (average) ⇒ MIC (hottest point)

M2 tunnel construction status

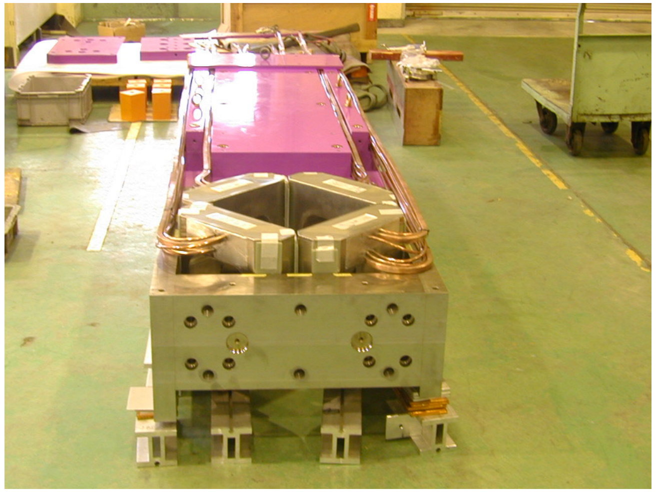


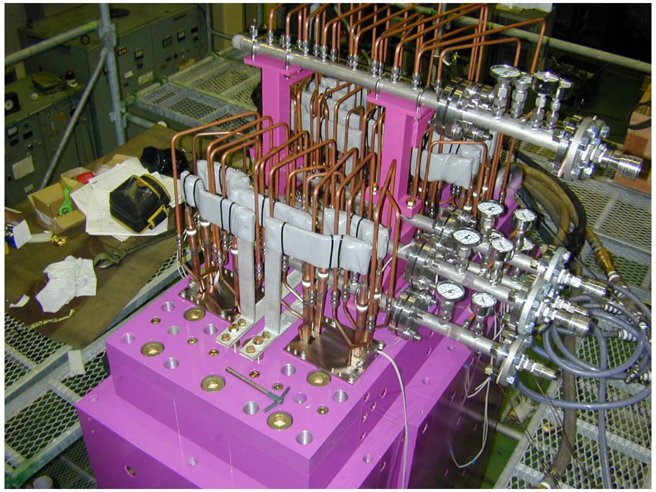


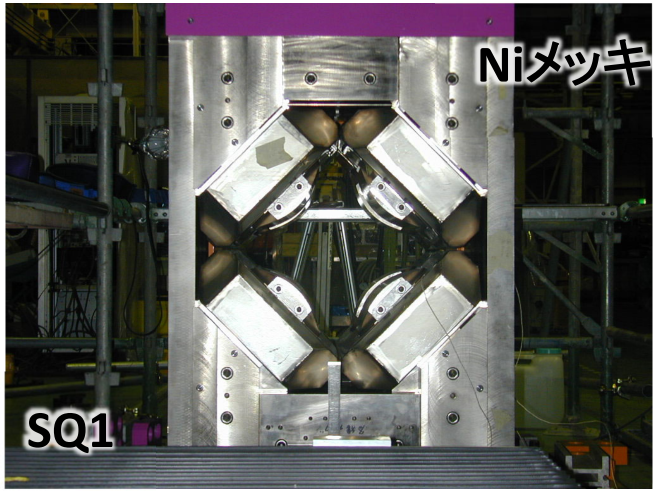


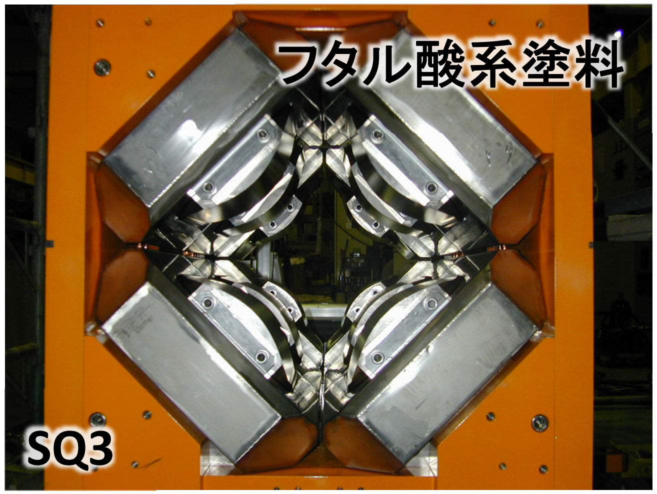
FY2004	FY2005	FY2006	FY2007
buried iron block	base plate	BT magnet M magnet	CW pipe, cabling
	alignment plate	air circulator	cask
	guide shield	BT shield	roof shield hatch
	target chamber	vacuum parts	system commissioning

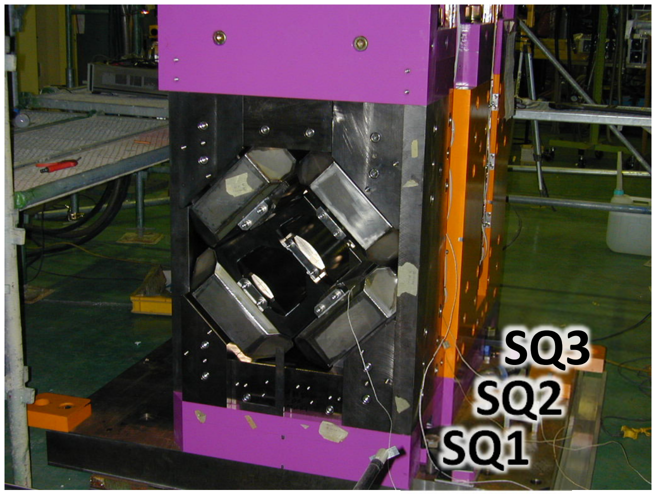
電磁石の製造







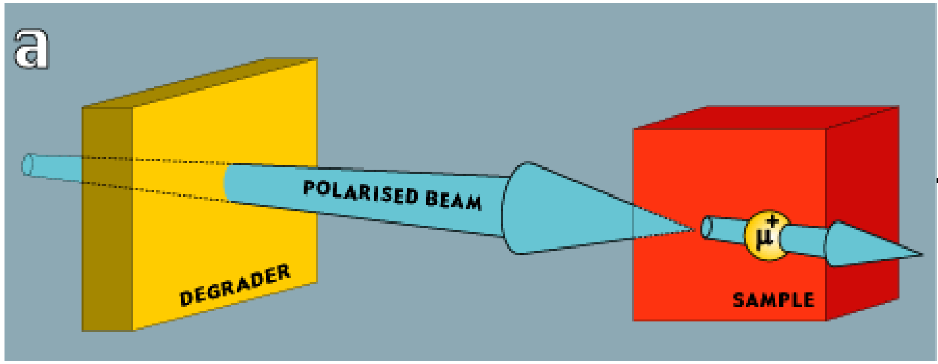




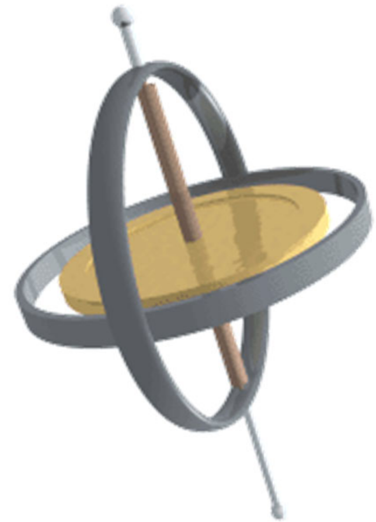
ミュオン科学

少しだけ紹介

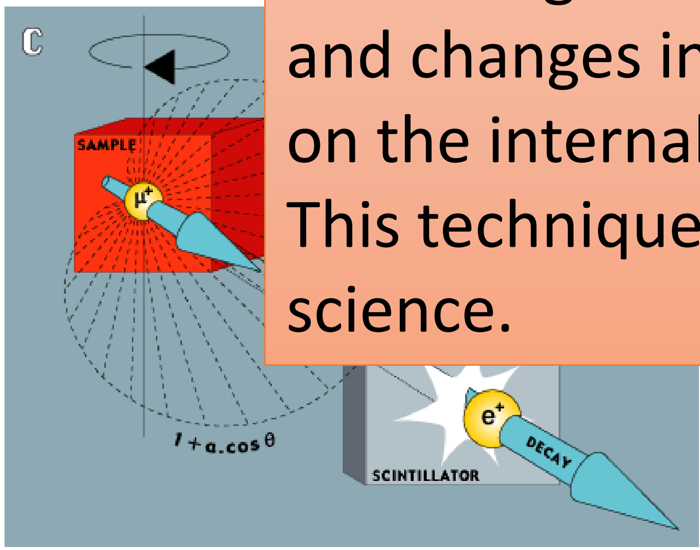
μSR (muon spin Rotation, Relaxation, Resonance)



a) Almost 100% spin-polarized muon beam is transported from the muon production target to the sample through the beamline



Observing the muon's precession frequency and changes in amplitude gives information on the internal magnetic field of the specimen. This technique is mainly used for material science.



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magetic Field.

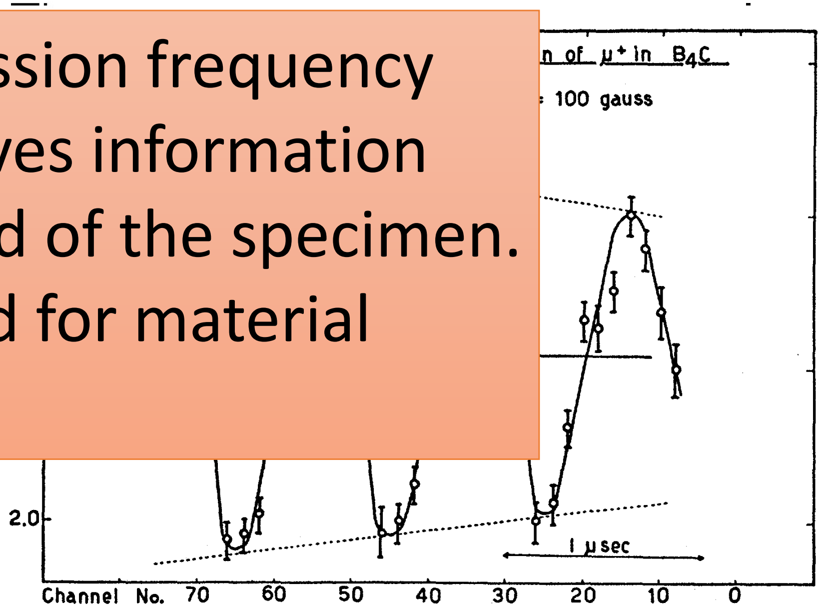
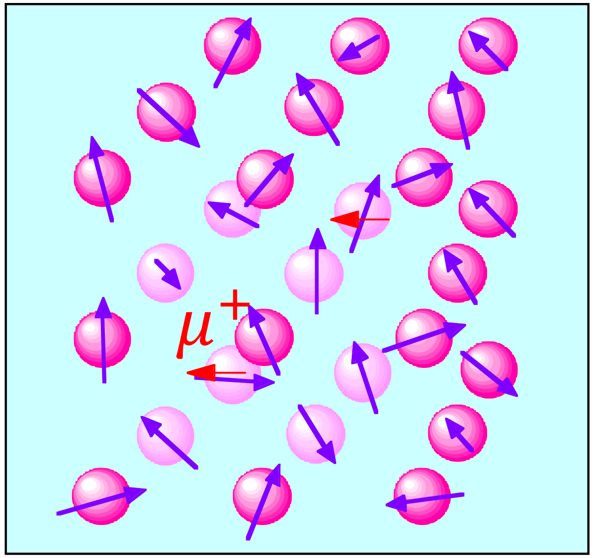


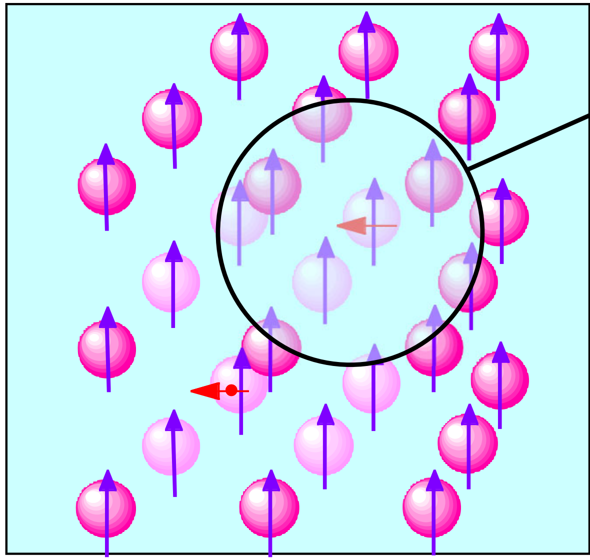
FIG. 7. Muon precession in boron carbide after decay and background correction.

μSRによる磁性研究

磁気秩序がない状態

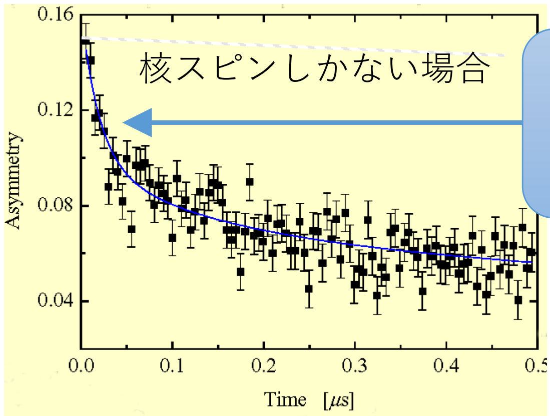


磁気秩序(強磁性)状態



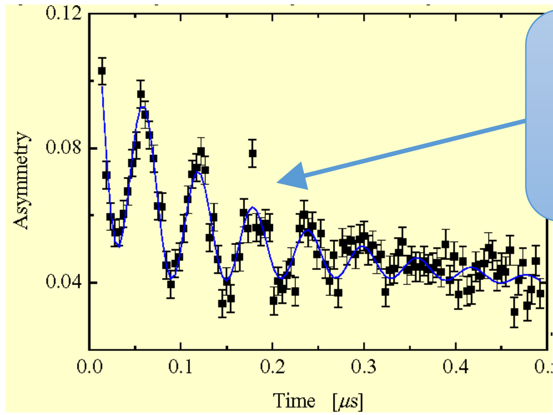
最隣接の磁気モーメントからの双極子磁場にのみ敏感

内部磁場はサイトに依存、ミュオンの偏極率も時間とともに減少



緩和の速さから核磁気モーメントの大きさを推定可能

内部磁場はサイト毎に一定、ミュオンスピンは同じ周期で回転

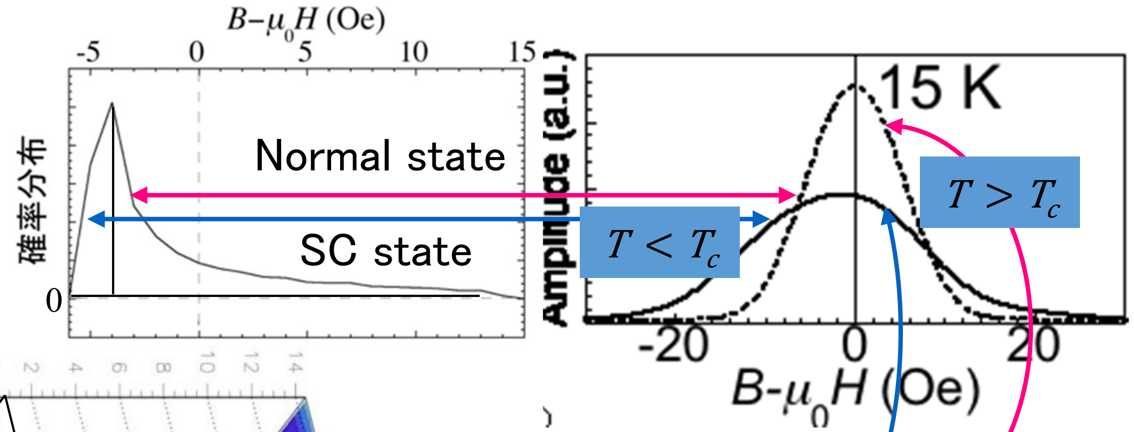


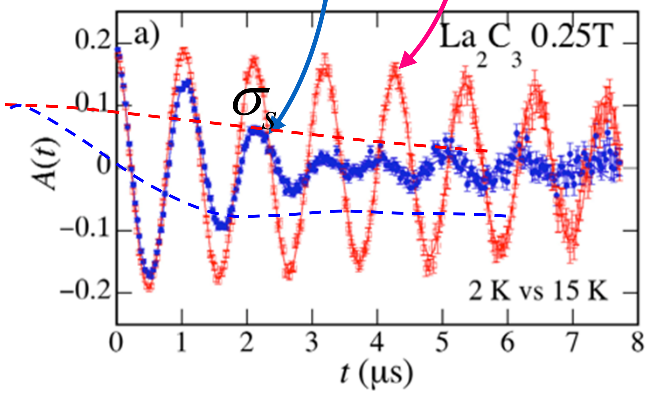
脈動する信号
- 周波数
- 緩和率
- 振幅

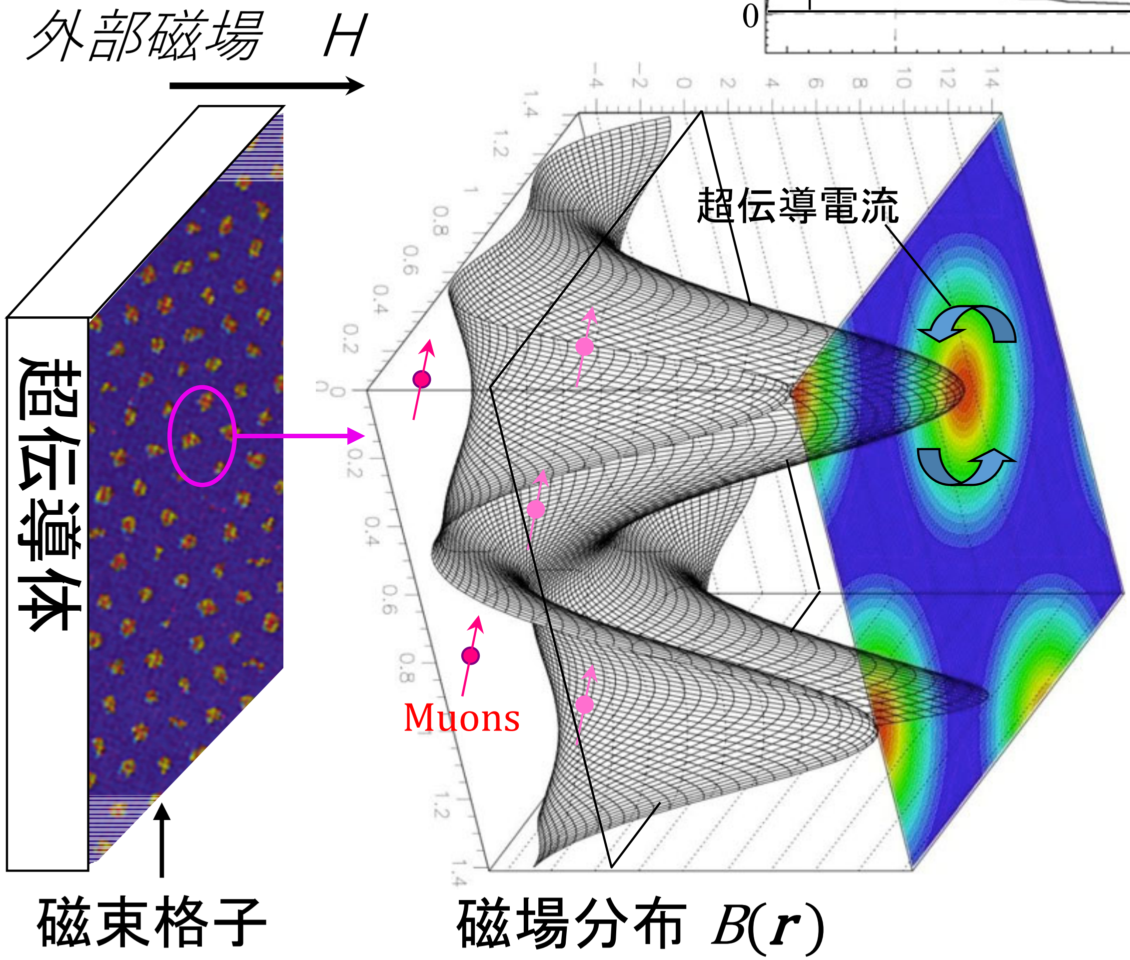
ミュオンの停止位置は空間的に分布があり、磁気構造の違いには必ずしも敏感でない

μSRで超伝導を見る

第二種超伝導体の磁束格子状態
超伝導体中では磁束が規則的に並んだ状態⇄磁場分布が空間的に不均一







$B(\boldsymbol{r})$ の分布幅は超伝導電流密度で決まる.

$$\sigma_s \propto \frac{1}{\lambda^2} = \frac{n_s e^2}{m^* c^2}$$

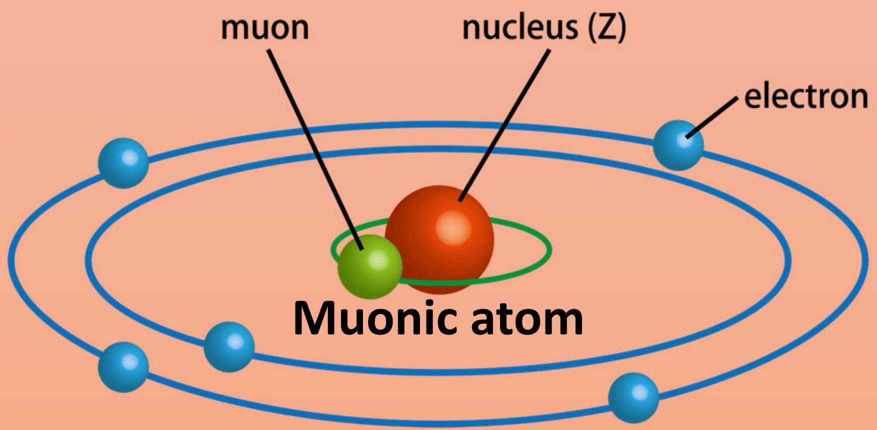
ミュオンは$B(\boldsymbol{r})$をランダムにサンプリング

Muonic X-ray measurements

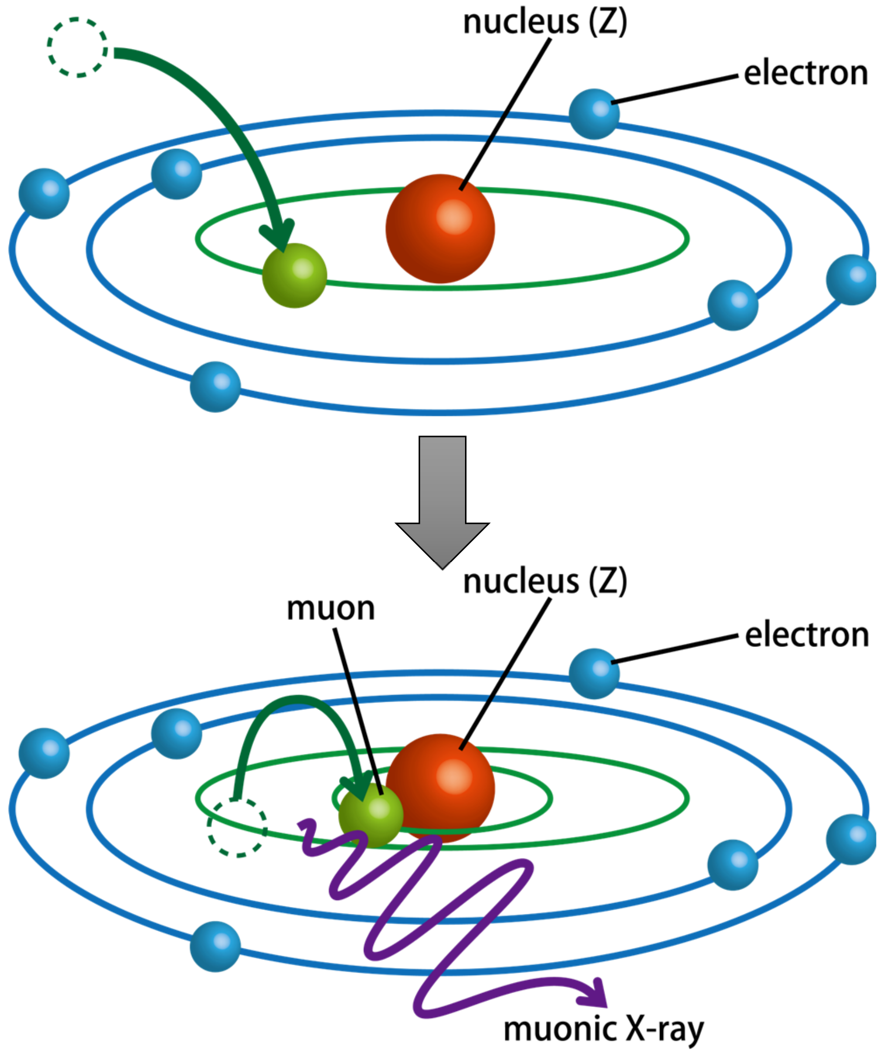
A muon is 200 times heavier than an electron

↓

The orbital of a muonic atom is 200 times smaller



The chrematistic X-ray energy is 200 time higher.



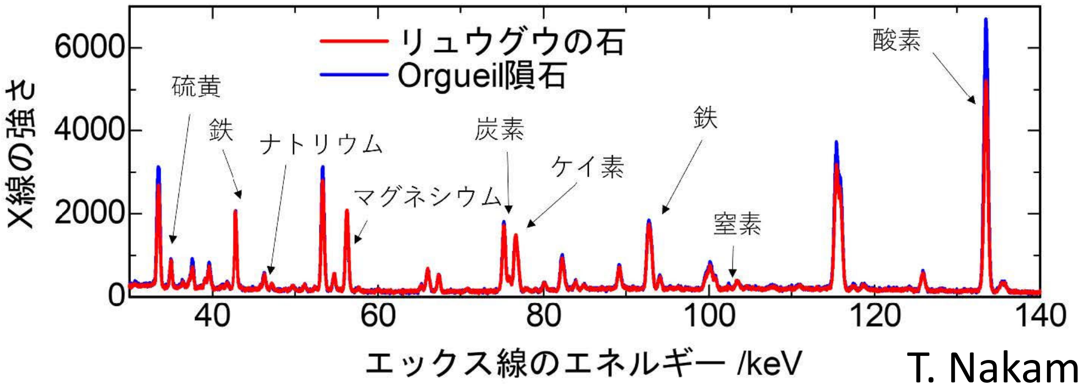
A negative muon captured by an atom loses its energy down to the ground state by emitting X-rays.

小惑星リュウグウの石を元素分析

中間子科学の地球惑星科学への展開

炭素が多いC型小惑星リュウグウの石の分析では炭素や窒素などの軽元素を含む元素比を定量する必要がある。**大気暴露せずに分析する必要がある**

多くの分野の研究者が集結、議論しながら実験を実施



リュウグウの石は、太陽系の固体物質の化学組成の基準であるCIコンドライトという種類の隕石と似た組成だが、酸素含有量が少なく、リュウグウの石の方が代表物質に相応しい可能性が示唆された

T. Nakamura *et al.*, *Science*, 10.1126/science.abn8671 (2022).

あなたはミュオンを知っている？

YES → 研究対象を探るツール（プローブ）

ミュオンの分かっている性質を応用して

物質・生命の未知の部分を探る

μSR：$\gamma_\mu / 2\pi = 135.54\ [\mathrm{MHz/T}]$

非破壊元素分析：$m_\mu = 105.6\ [\mathrm{MeV}/c^2]$

NO → ミュオン自体が研究対象

知っている事実（素粒子標準理論）で

説明できない部分がミュオンにはあるはず

それを暴き、素粒子標準理論を超える

Particle Boys

ILC学園3年生

好奇心旺盛で、遺跡や古代ロマンが好き。

ミューオンニュートリノと仲良しで、だいたい一緒にいる。

いつもニコニコしていていまいち掴みどころがない。

なぜミュオン？

素粒子標準理論を超える新物理はミュオンだけに働くわけではない。では、なぜミュオン？

【技術的な理由】

- 作りやすい
  - 重心系で140MeV（Lab系で290MeV）が生成閾値
    中程度のエネルギーの大強度マシンで大量生産
- 見やすい
  - ほどほどの測りやすい寿命（2.2μs）で、検出しやすい（陽）電子を出して崩壊
    スピン偏極したビームが得られ、崩壊で出る（陽）電子はその向きを反映→ミクロな状態を知りやすい

なぜミュオン？

【学術的な理由】

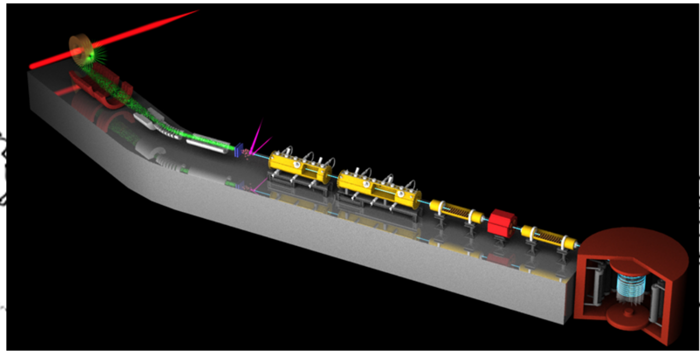
- 内部構造を持たない点状粒子（と考えられている）
  - 理論計算の精度を上げやすい
- 電弱相互作用のみ（強い相互作用が働かない）
  - 強い相互作用の効果を直接的には受けない
    （高次の補正でしか効かない）
  - ミュオニウム（μ^+e^-）は理想的な“水素”
- 新物理の質量スケール
  - 標準理論を超えた物理の感度（現れやすさ）は質量の２乗に比例する。はず
    電子は作りやすさではミュオンを圧倒するが、感度は1/42,000（=1/205.6^2）

だからミュオン！

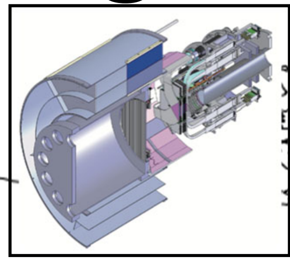
- Higgs粒子の発見により、素粒子標準理論は完成、でも…
- 標準理論が不十分なのは明白
- 大量のミュオンの中に「標準理論から外れるもの」、「説明できない性質」を探し出す
- ミュオンを用いた新物理探索では観測精度が大事
  - 系統誤差：技術開発で小さくできる
  - 統計誤差：観測するミュオンの数を増やすしかない

  だから、大強度フロンティアのミュオン施設！

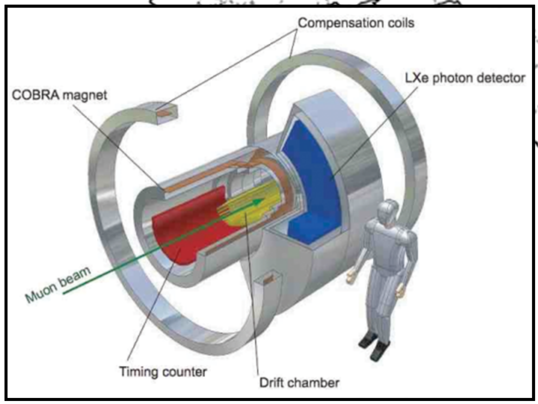
Fundamental Physics using muon



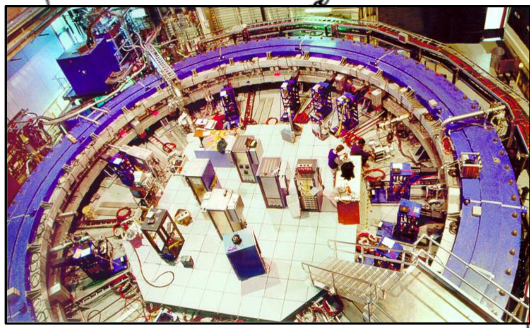
J-PARC: μ g-2 < 0.1 ppm



TRIUMF: PiENu



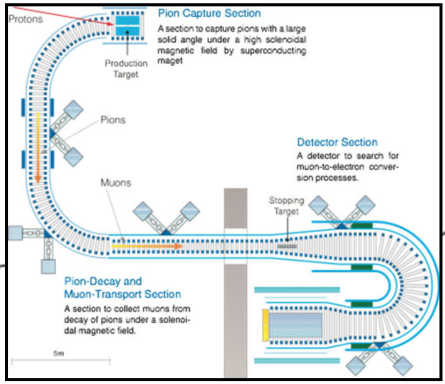
PSI/MEG: BR($\mu \rightarrow e\gamma$) < 10^{-13}

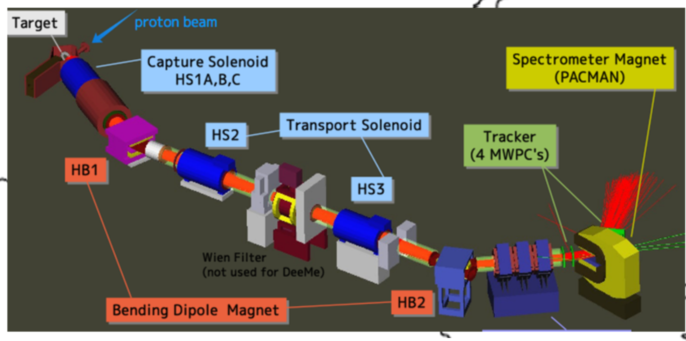


FNAL: μ g-2 < 0.1 ppm

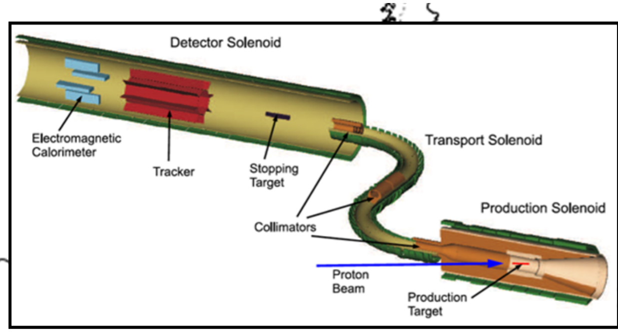
BNL: μ g-2 < 0.5 ppm

>3-σ off from SM



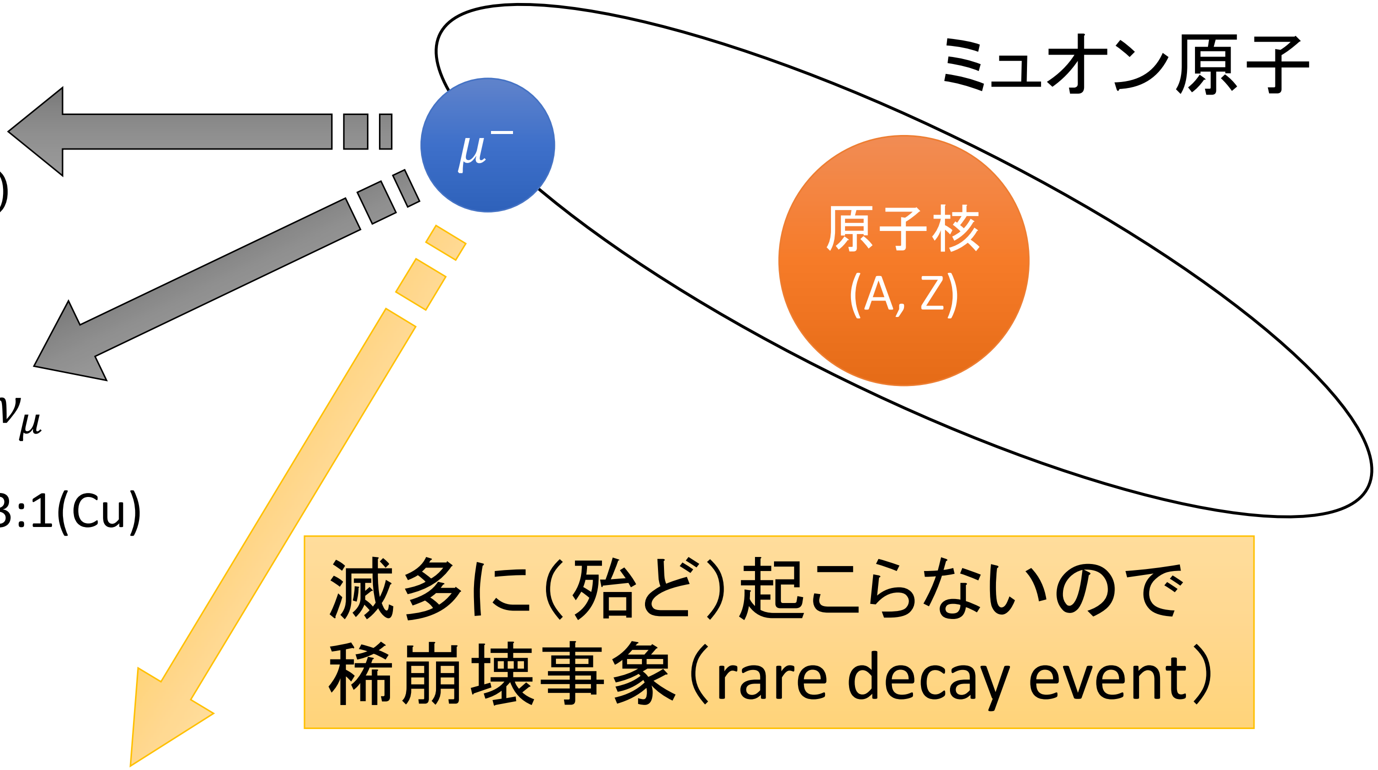


J-PARC: BR(μ^- N → e^- N) < 10^{-14}, 10^{-16}



FNAL: BR(μ^- N → e^- N) < 10^{-16}

ミュオン電子転換過程



ミュオン捕獲（MC）
$\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$

ミュオン崩壊（MDO）
$\mu^- \to e^- + \overline{\nu_e} + \nu_\mu$

MC:MDO=1:1000(H), 2:1(Si), 13:1(Cu)
Free decay: $\tau_0 = 2.2\ [\mu s]$
μ⁻ in Si: $\tau_{\mathrm{eff}} = 0.76\ [\mu s]$

滅多に（殆ど）起こらないので
稀崩壊事象（rare decay event）

ミュオン電子転換過程（μ-e Conversion）
$$\mu^- + (A, Z) \to e^- + (A, Z)$$
荷電レプトン混合によるプロセス

$$\mathrm{BR}[\mu^- + (A, Z) \to e^- + (A, Z)] \equiv \frac{\Gamma[\mu^- + (A, Z) \to e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)]}$$

どの程度起こらない？

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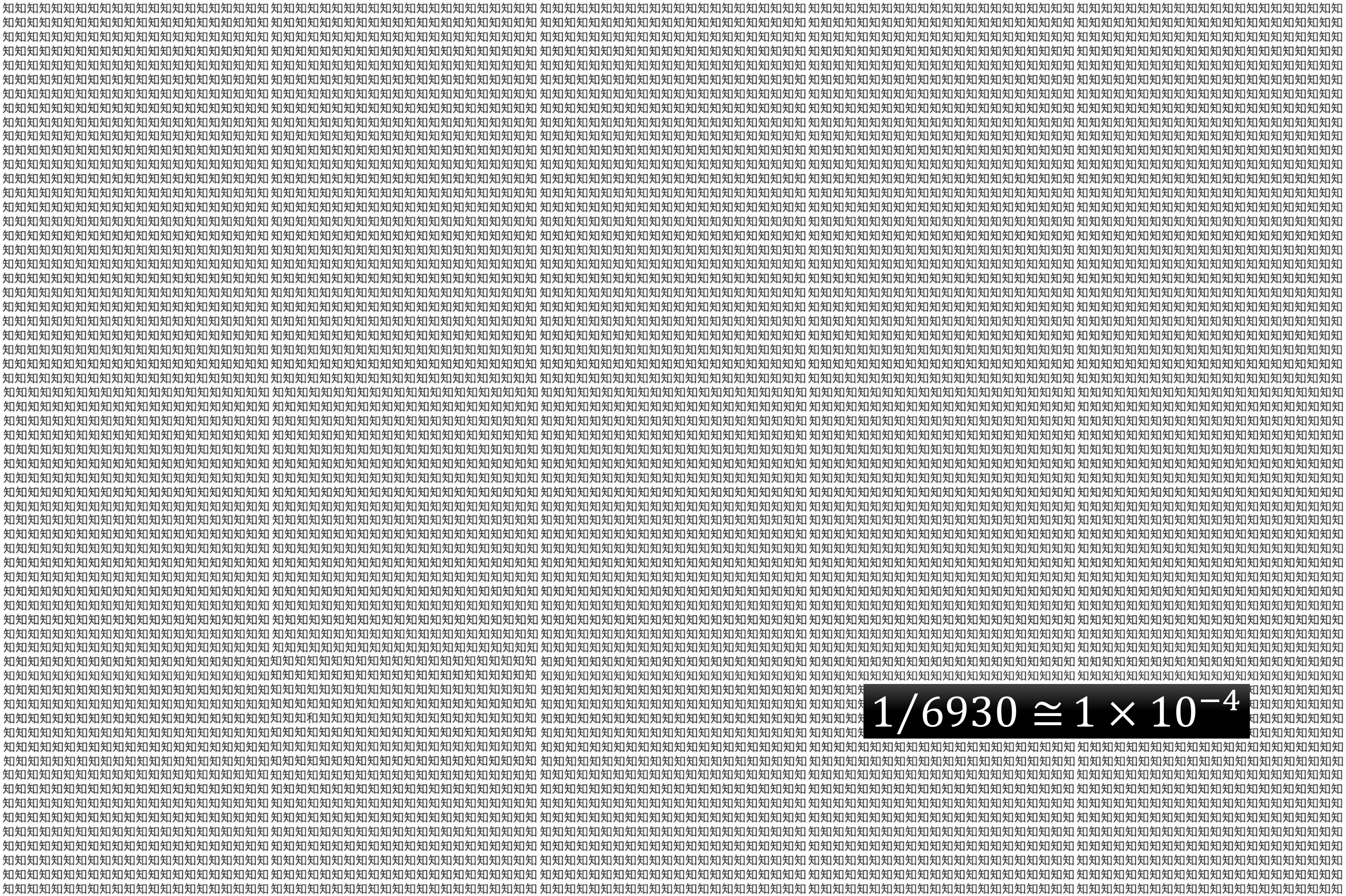
$1/198 \cong 5 \times 10^{-3}$



$$1/6930 \cong 1 \times 10^{-4}$$

実際には

- 必要なイベント数は10^{12}～10^{14}
- A4に25nm角の大きさで「知」を書くと10^{14}個になる
- 10^{14}個のミュオンを作るのも大変（J-PARCで最強のビームラインでも100日以上）
その中の1個を探すのも大変（何か工夫）

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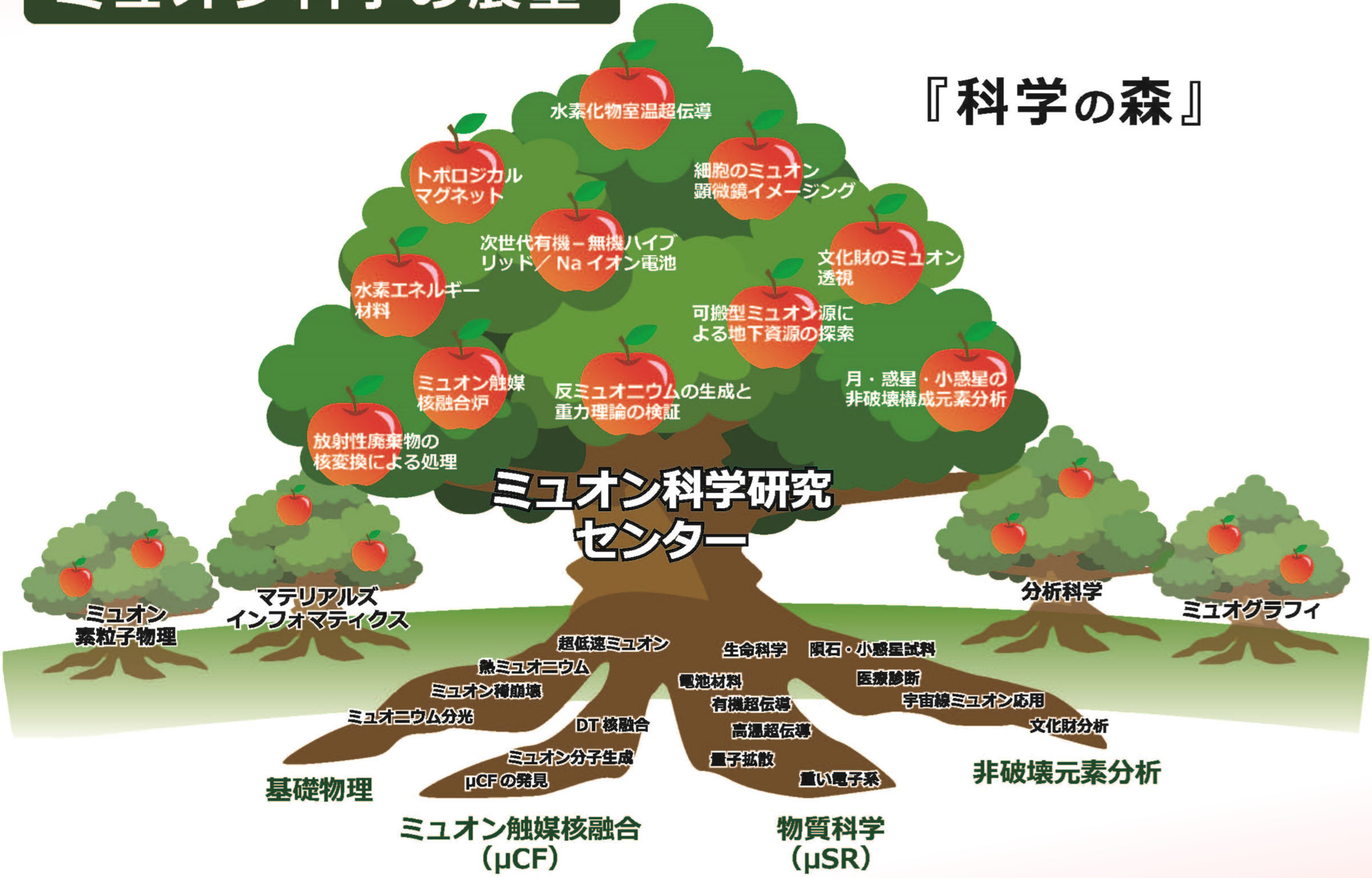
JMMS

日本中間子科学会が「学術の中長期研究戦略」において提案したビジョン

ミュオン科学の展望



ちょっと宣伝

- 大強度施設の標的などに関する国際ワークショップ開催
  理研和光キャンパス
  11/6 - 11/10
- Registration
  9/10 - 10/15
- https://indico2.riken.jp/event/3102/

SCOPE:

The HPT Workshop brings together scientists and engineers from the international community for particle accelerator targetry. Applications include neutrino facilities, neutron facilities, radioactive ion beam facilities, material irradiation facilities, accelerator driven systems and precision experiments for rare processes.

Themes for the workshop include:

1. R&D to support concepts
2. Radiation damage in target material and related simulations
3. Post-irradiation examination
4. Target design, analysis and validation of concepts
5. Target facility challenges
6. Construction, fabrication, inspection, quality assurance
7. Operation of targets and beam dumps
8. Multipurpose use of targets and beam dumps

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