Muon g-2 & EDM @ J-PARC

Gerco Onderwater

on behalf of the J-PARC E34 Collaboration

Muon4Future Workshop, Venezia, IT, 20 May 2023

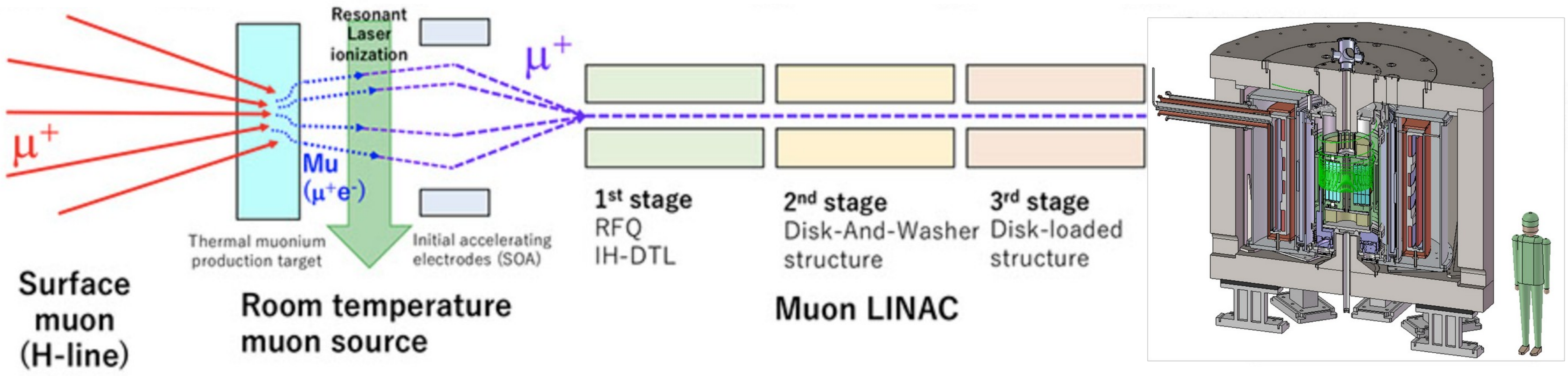
MAASTRICHT SCIENCE PROGRAMME

Maastricht University

Experiment E34 @ J-PARC

See also talk Takayuki Yamazaki

Part of a wide-range muon physics programme

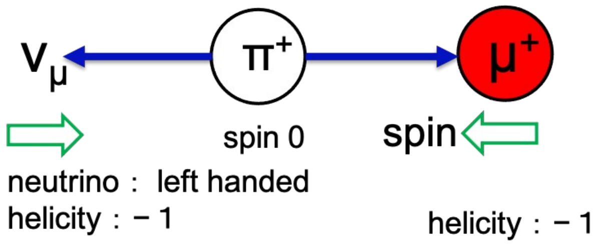


Aim: competitive measurement of muon g-2 and EDM

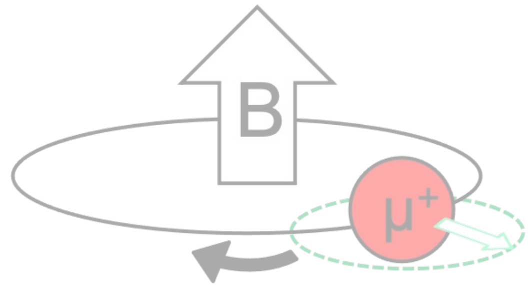
https://g-2.kek.jp/portal/index.html

Elements of an MDM or EDM Expt

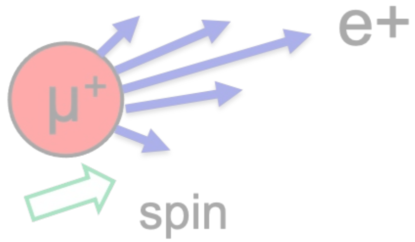
Polarized Muon Production



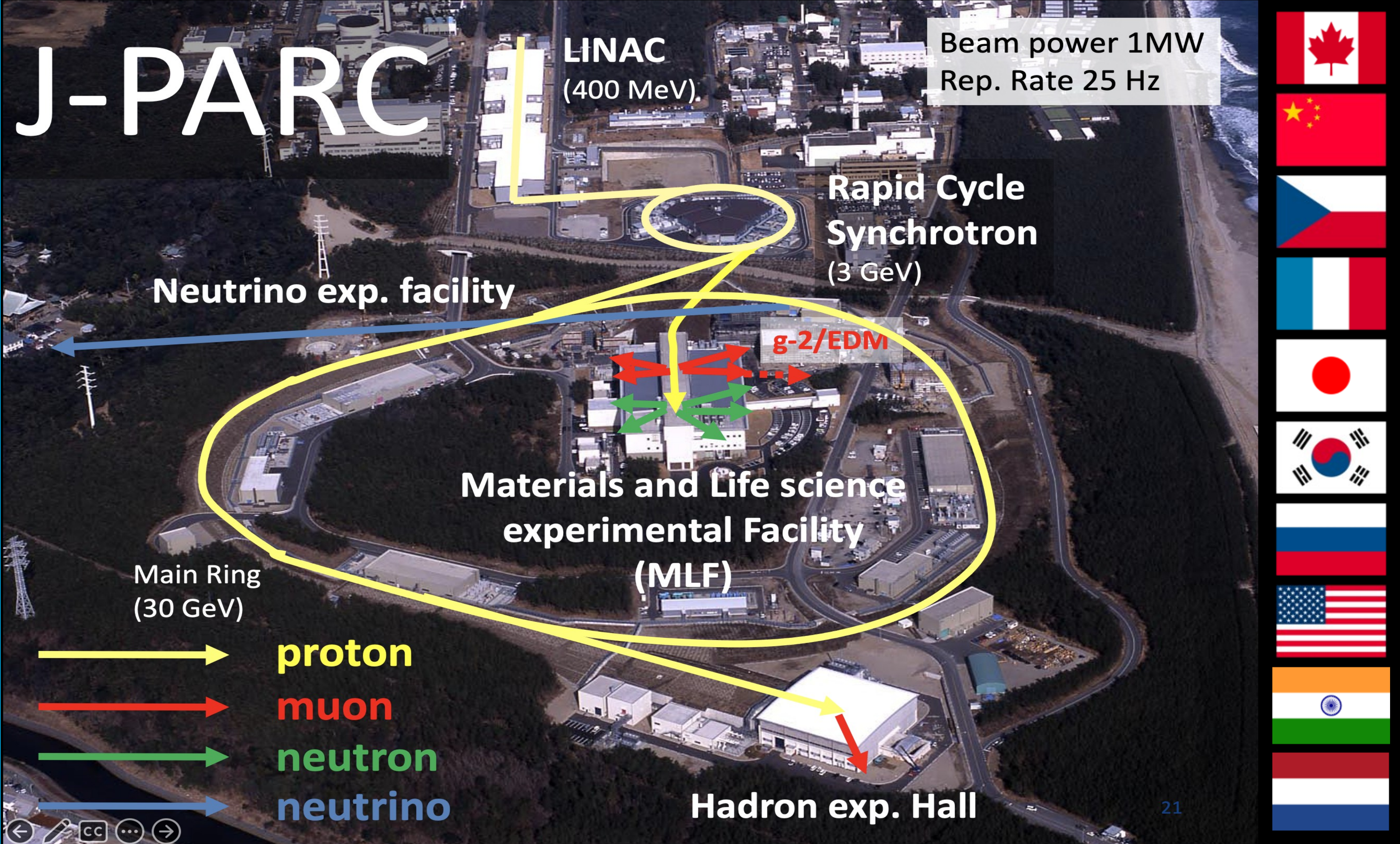
Storage & Spin Precession



Detection of Spin Orientation

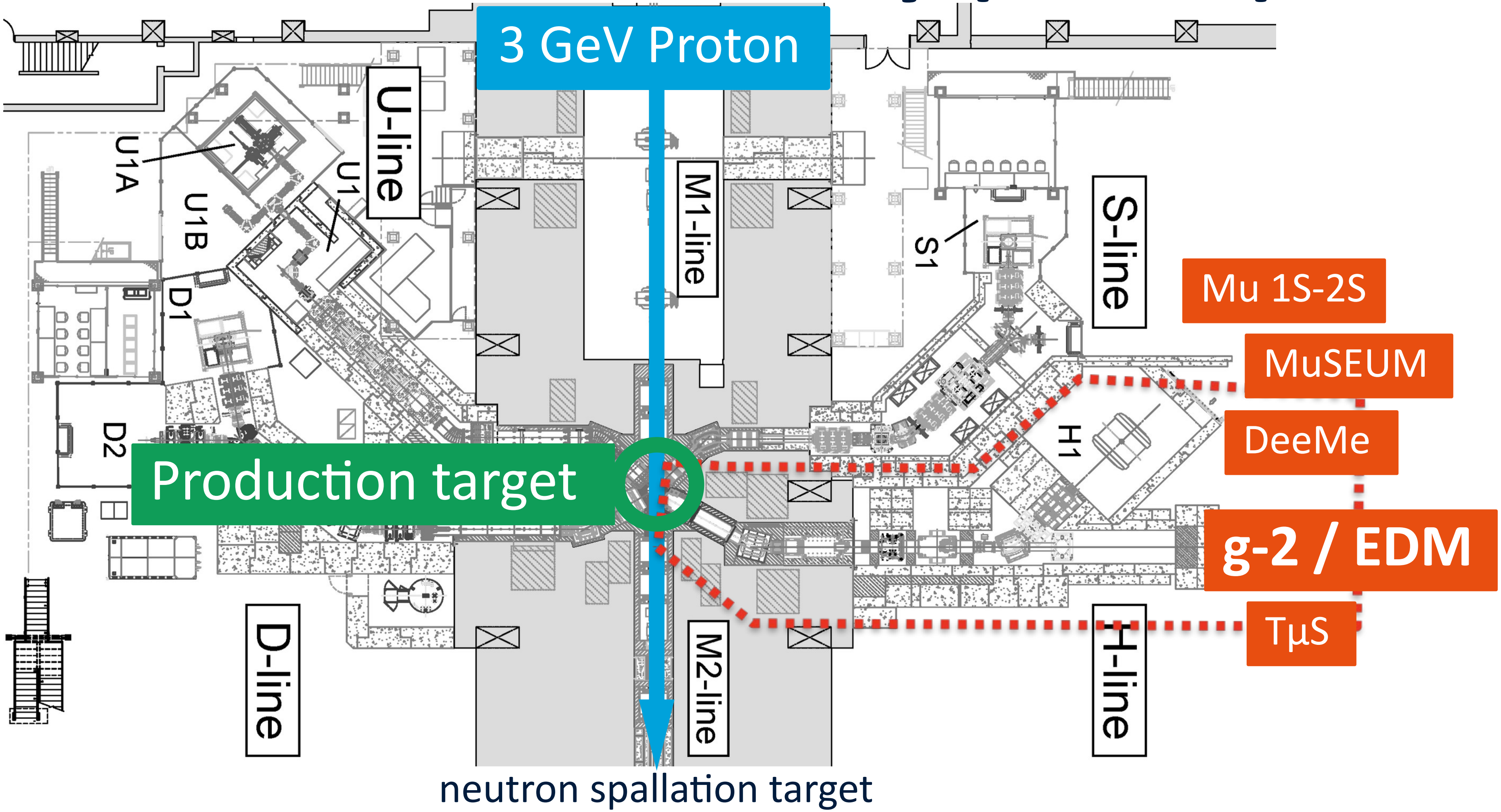


J-PARC



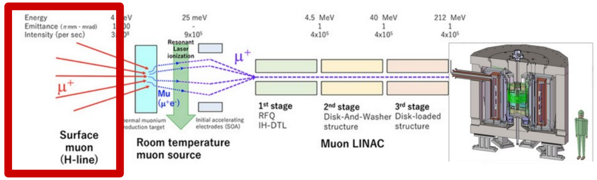
LINAC
(400 MeV)
Beam power 1MW
Rep. Rate 25 Hz
Rapid Cycle
Synchrotron
(3 GeV)
Neutrino exp. facility
g-2/EDM
Materials and Life science
experimental Facility
(MLF)
Main Ring
(30 GeV)
proton
muon
neutron
neutrino
Hadron exp. Hall

Muon Science Facility (MUSE)

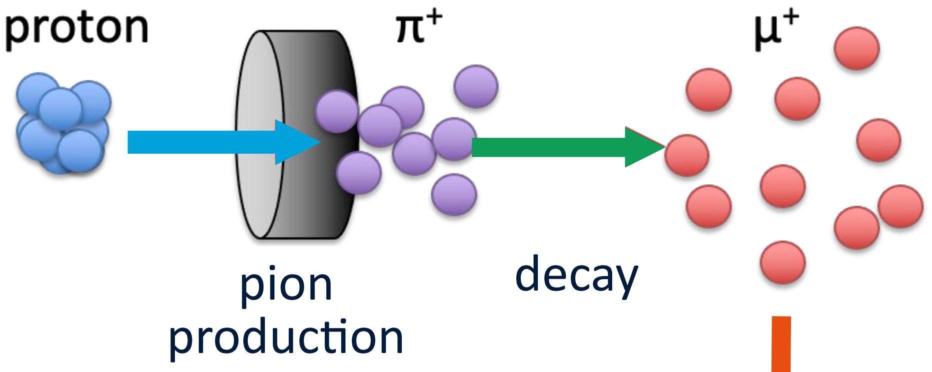


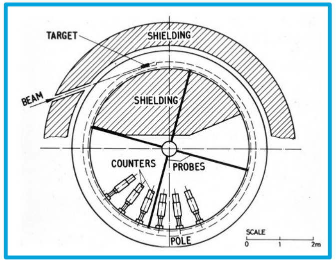
Production

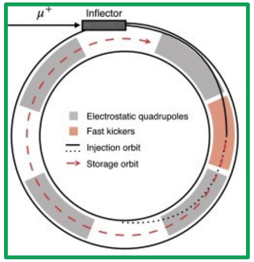
See also talk
Shusei Kamioka

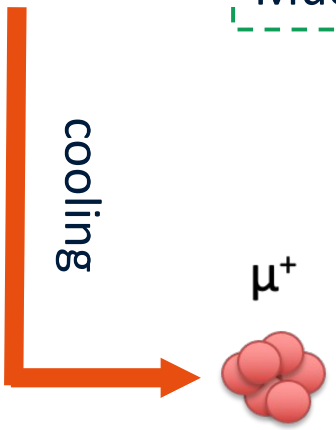


↦ CERN









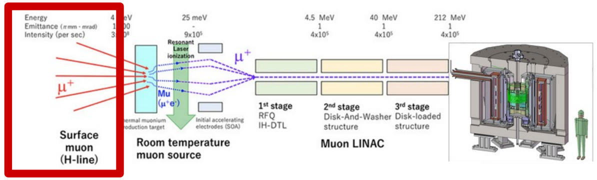
↦ BNL FNAL

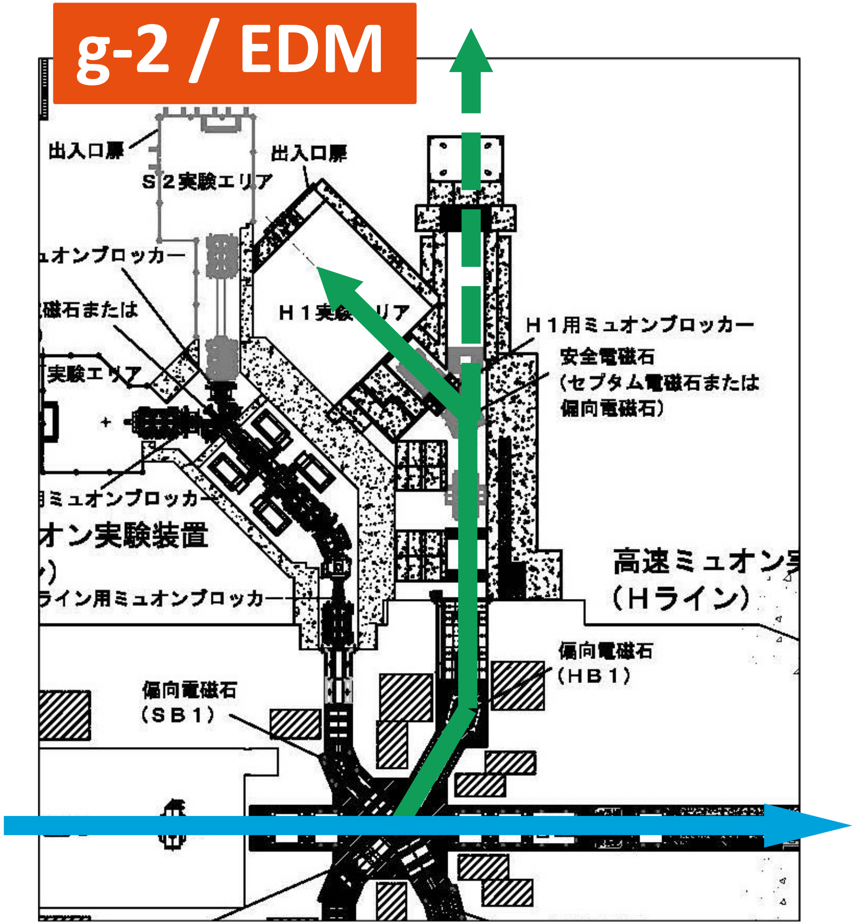
Emittance ~ 1000π mm·mrad
Proton and pion contamination
Need strong (electric) focussing
Need 'magic' $\gamma = \sqrt{(1/a_\mu+1)} = 29$
Muon loss

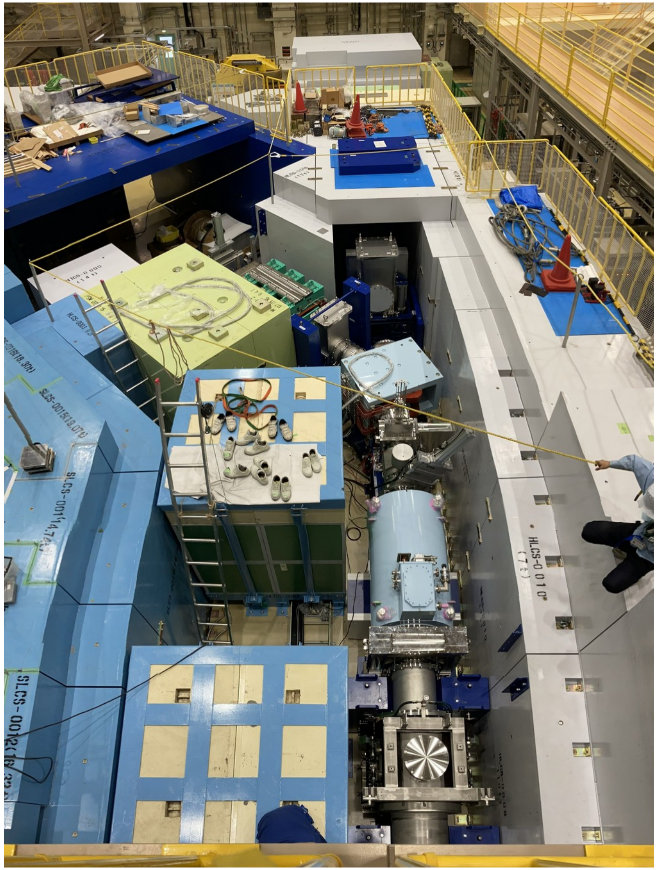
↦ JPARC

Emittance ~ 1π mm·mrad
(after reacceleration)
little/no need for focussing
Can run at any γ
Allows a compact setup

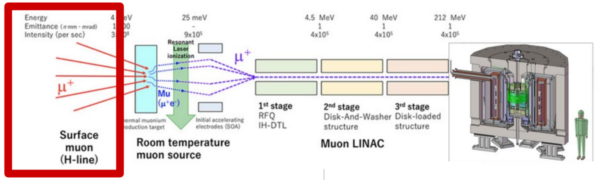
H1-Beamlines



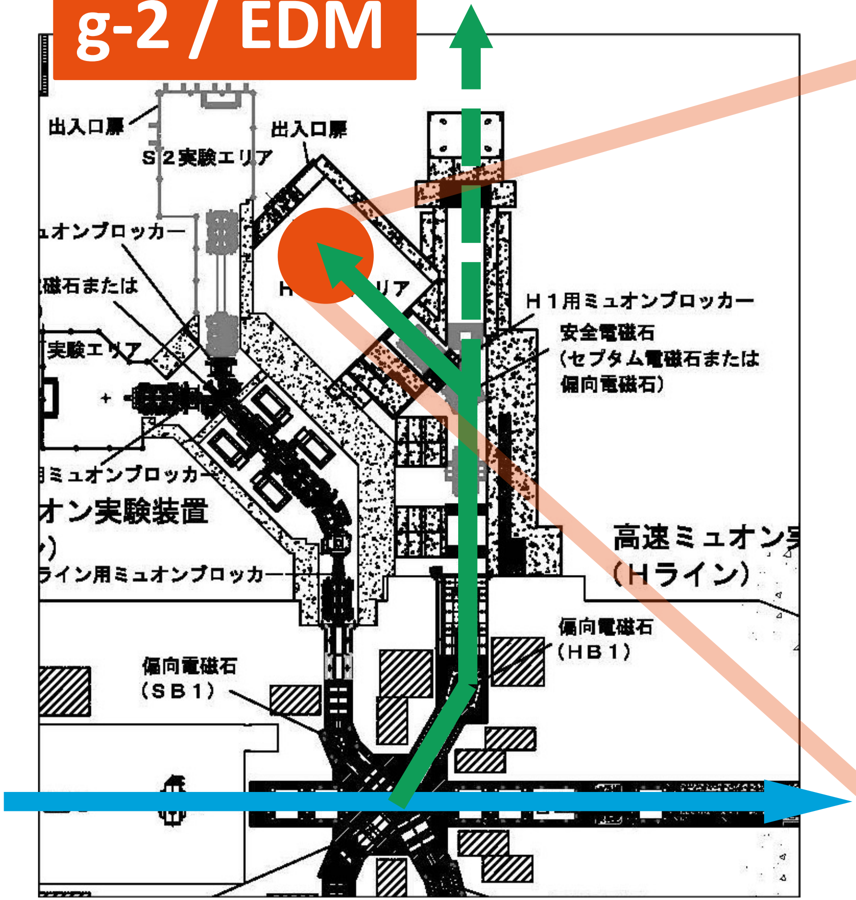


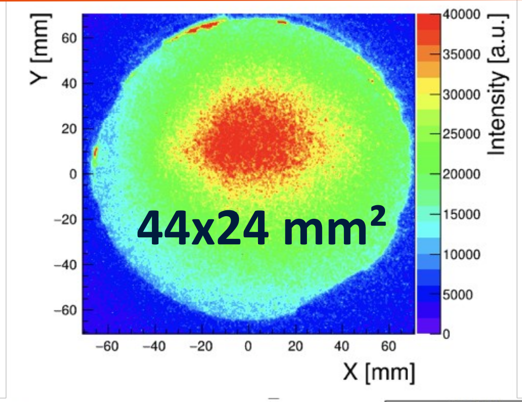


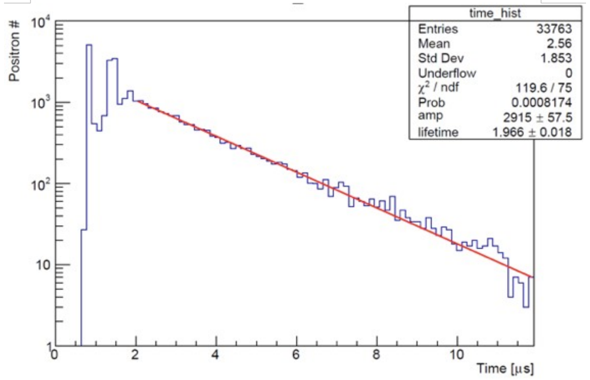
First beam (Jan. 2022)



g-2 / EDM

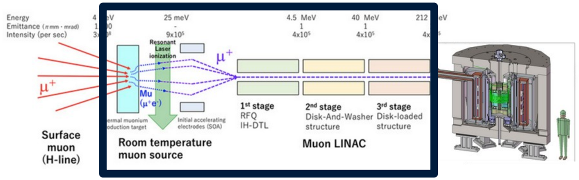






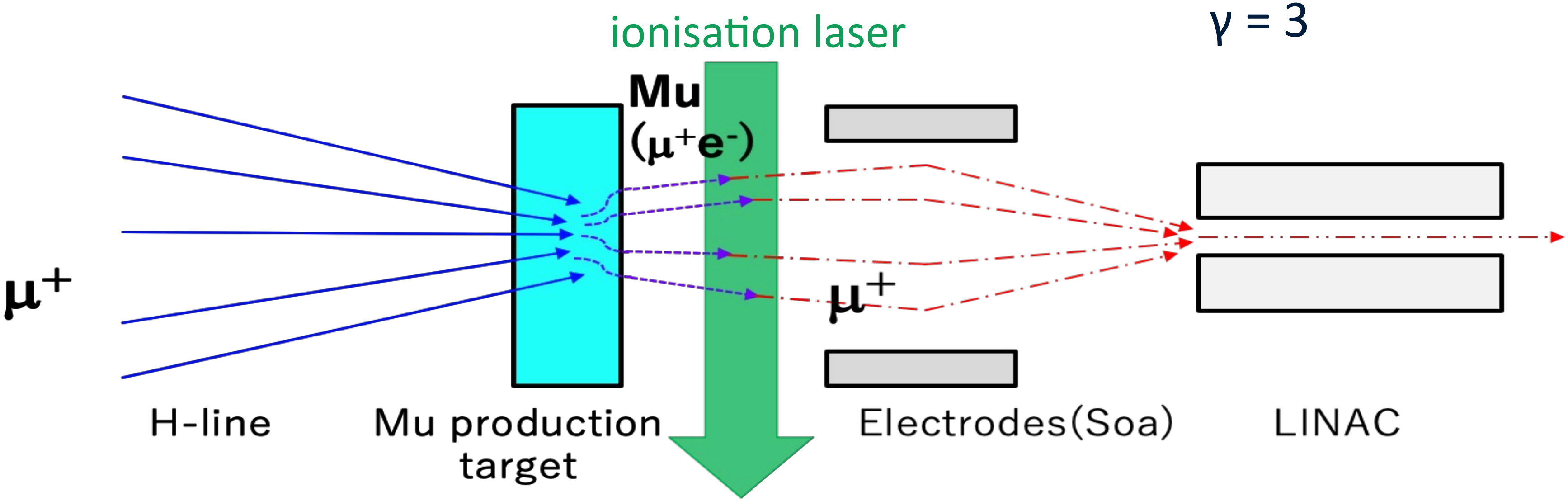
7×10^{7}/s @ 28 MeV/*c*, 730 kW

Muon Cooling



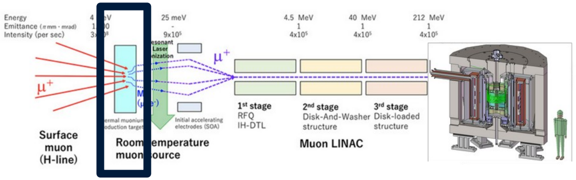
	surface muons	thermal muons	accelerated muons
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/*c*	2.3 keV/*c*	300 MeV/*c*
Δp/p	0.05	0.4	0.0004

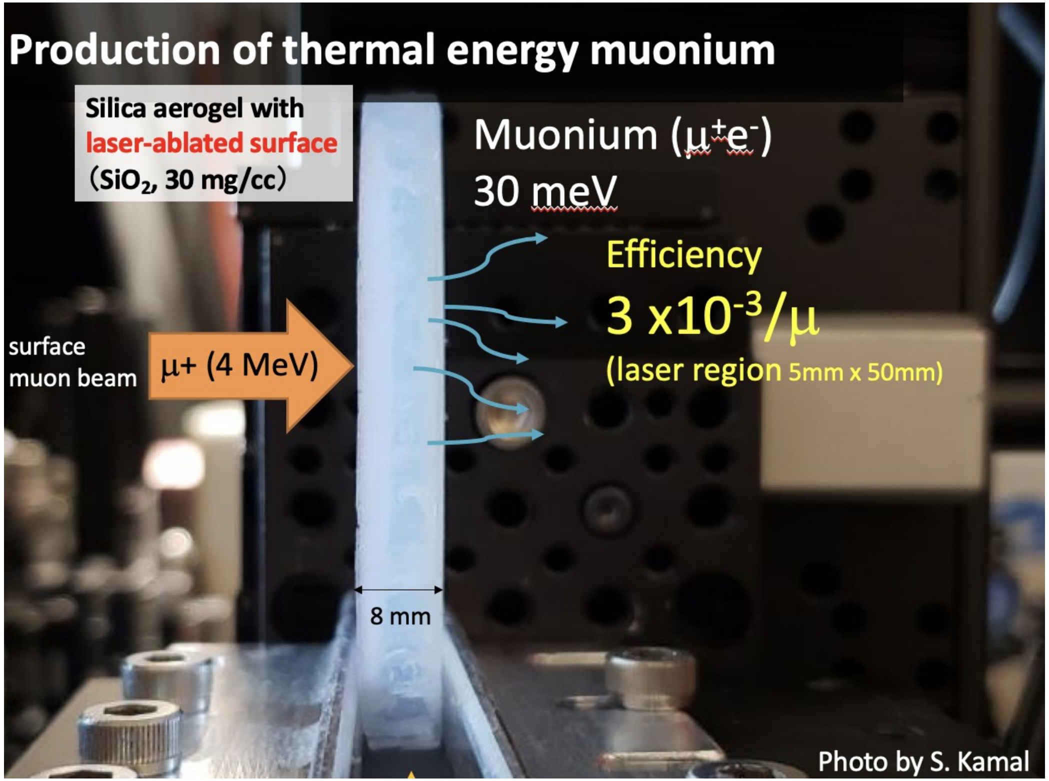
γ = 3



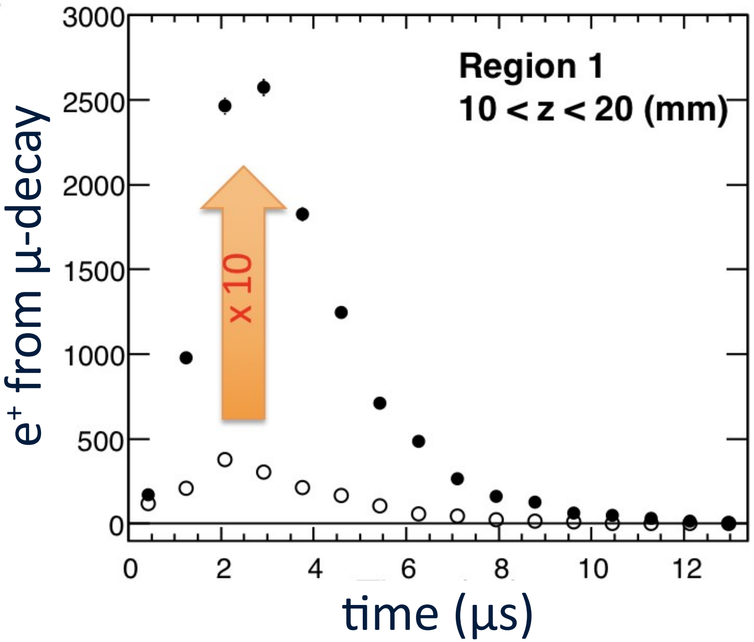
Cooling + LINAC : world's first muon accelerator

Muonium Production



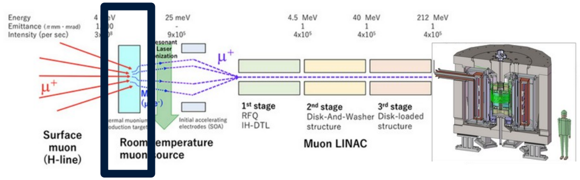


Muonium yield measured @ TRIUMF

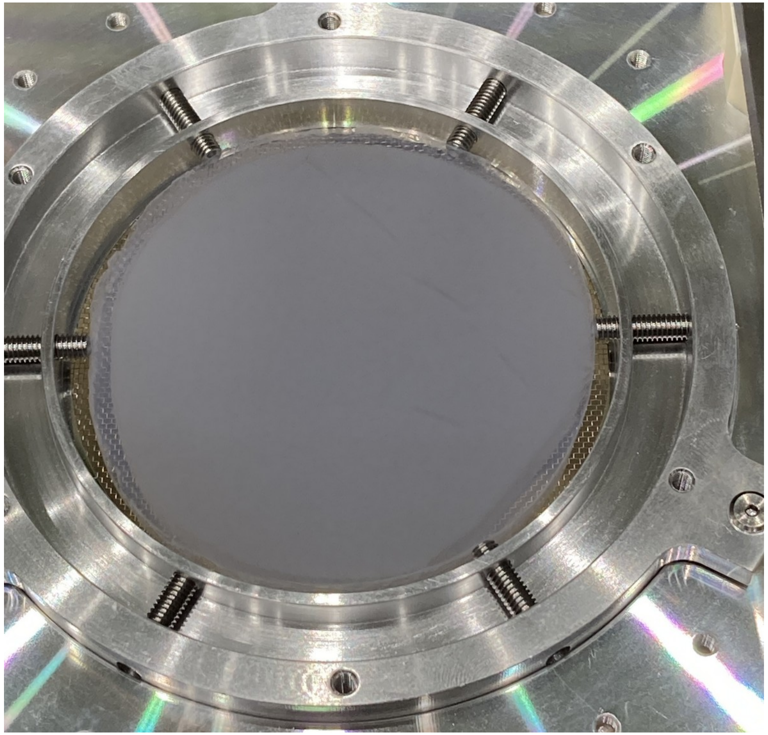


Sufficient to reach Δa_μ ~ 450 ppb

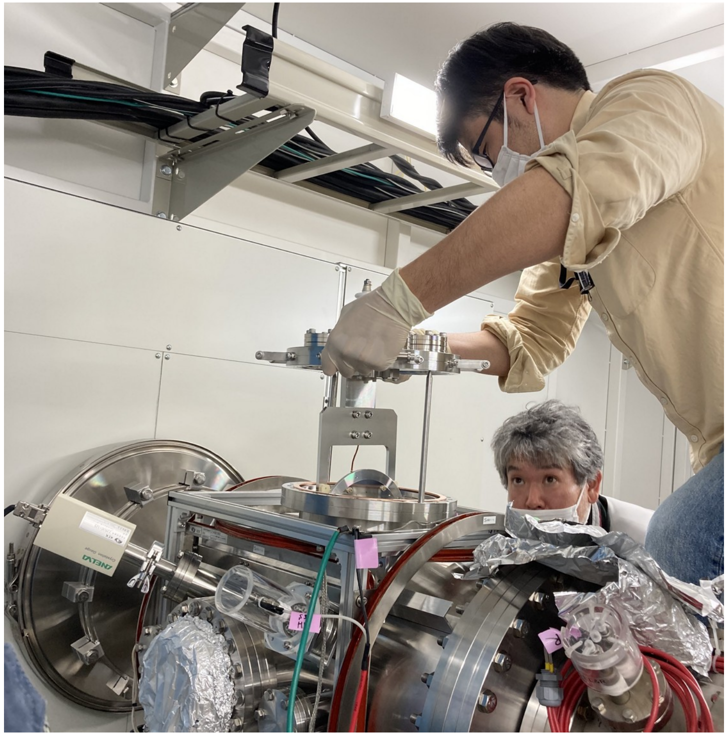
Muonium Production



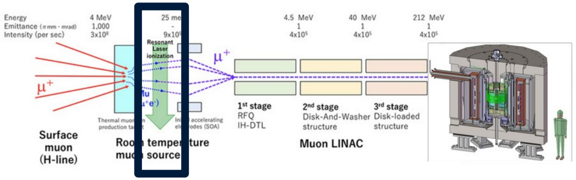
Laser ablated silica aerogel

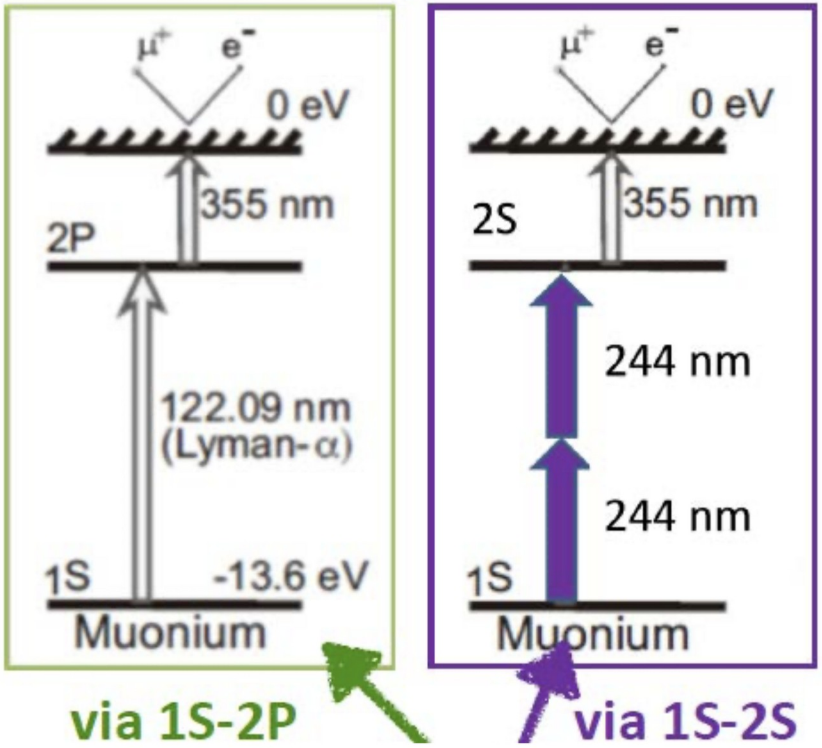


J-PARC S2 area (Feb. 2023)

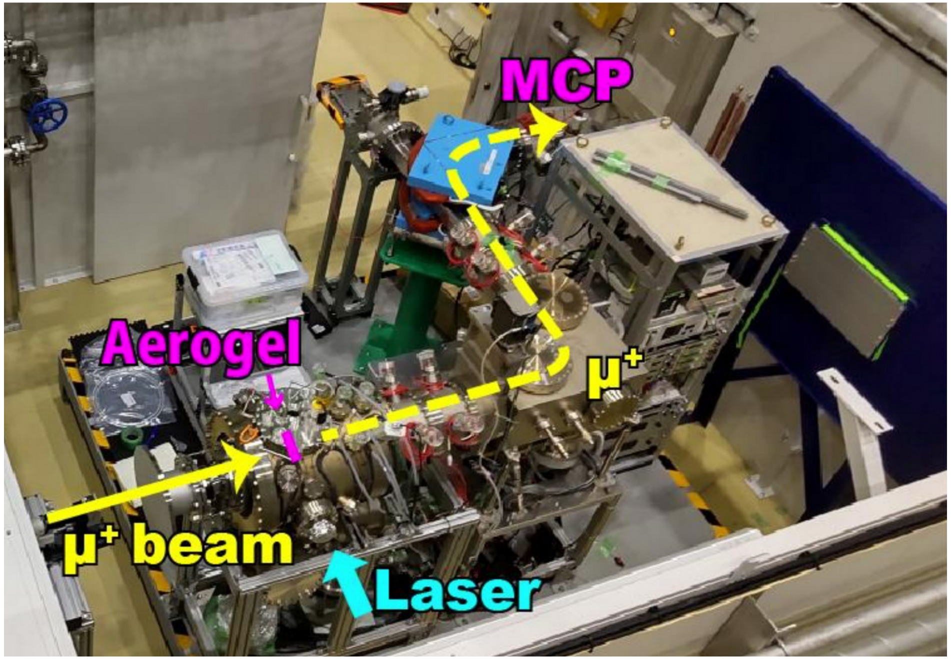


Muonium Ionisation



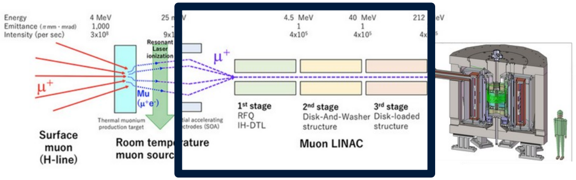


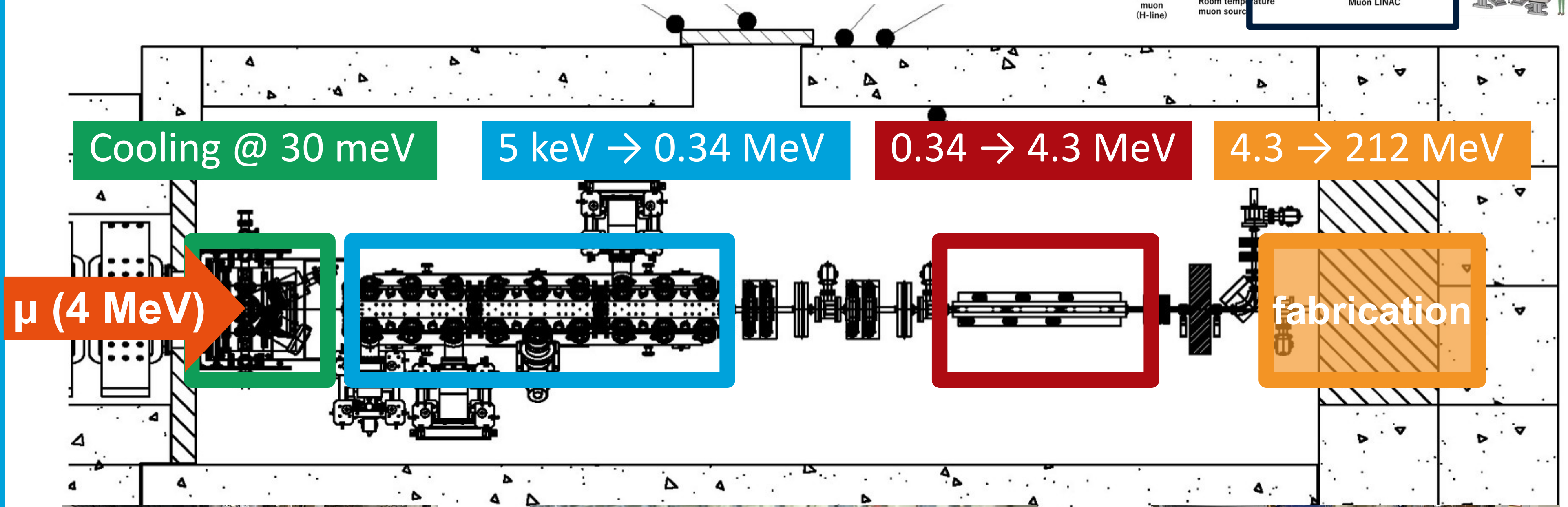
Ionisation test via 1S-2S

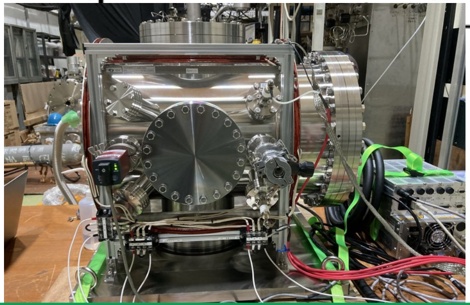


In collaboration w/ Okayama University (Uetake *et al.*)

Muon Acceleration





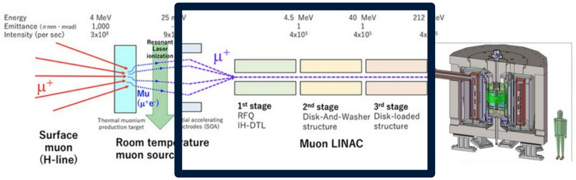


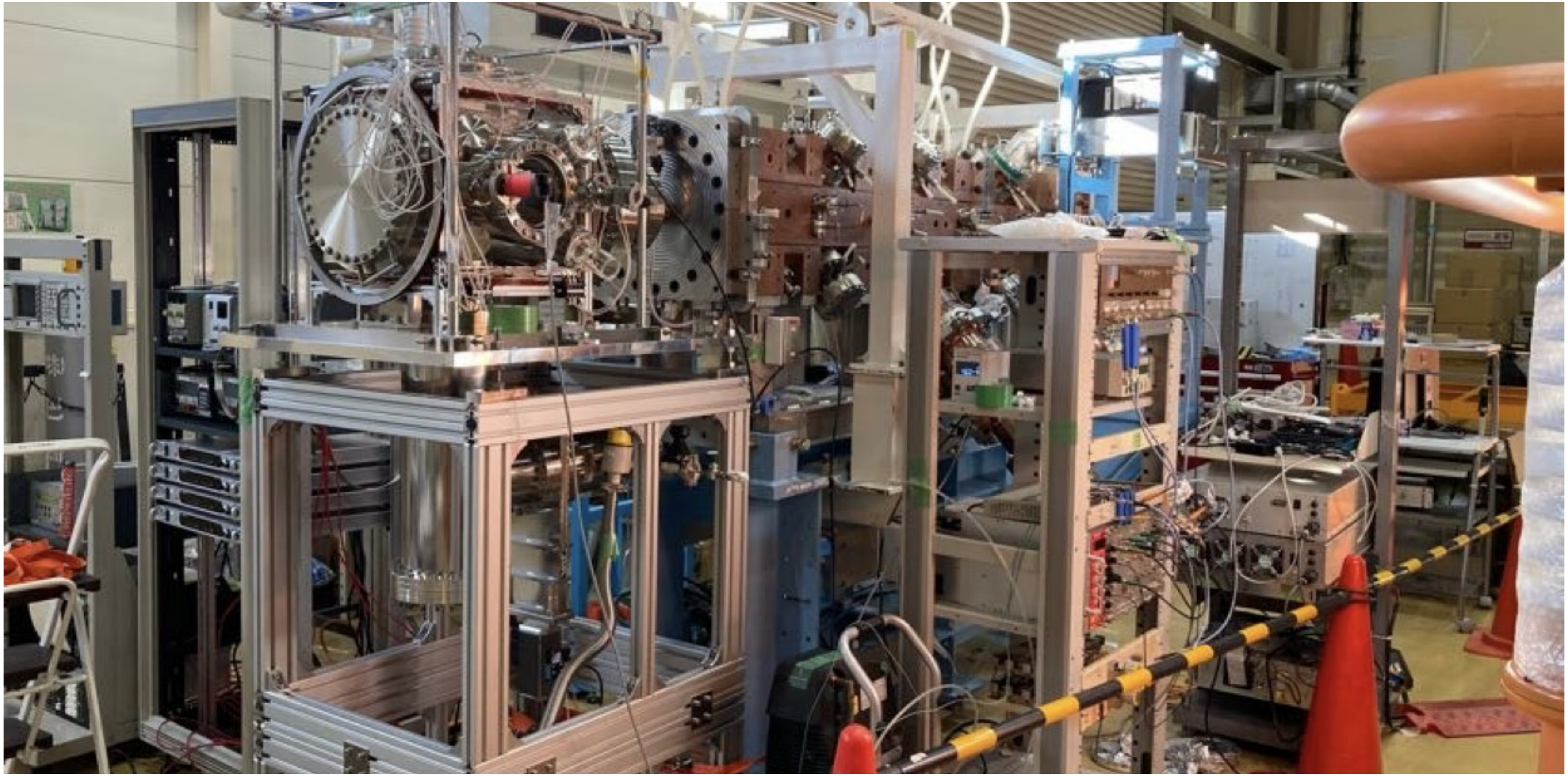
Mu chamber (available)

J-PARC Linac RFQ (available)

IH-DTL (fabricated & tested)

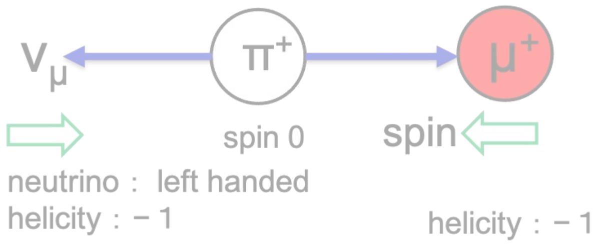
Assembly for Test ('23)



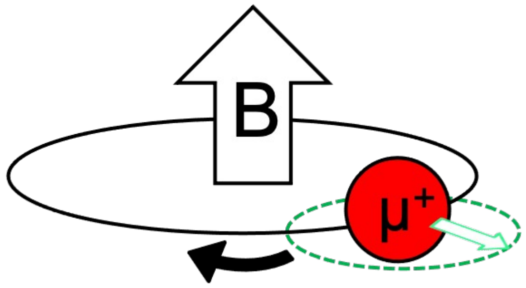


Elements of an MDM or EDM Expt

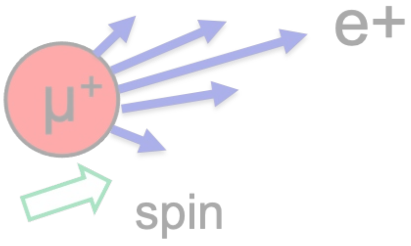
Polarized Muon Production



Storage & Spin Precession



Detection of Spin Orientation



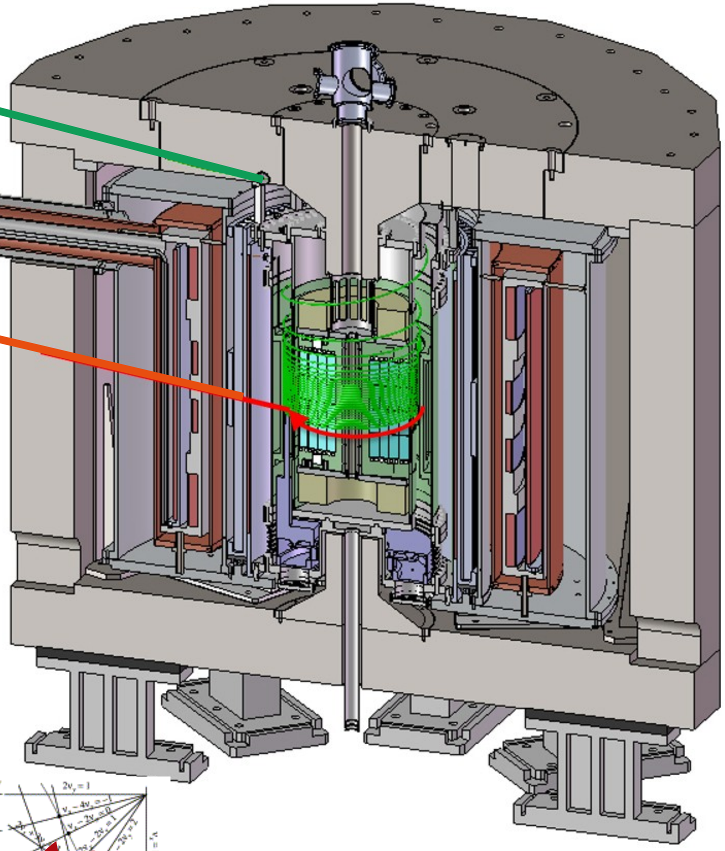
Storage

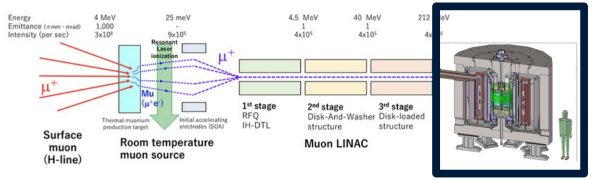
Vertical injection
Efficiency **η = 85%**
(*c.f.* Horizontal 5%)

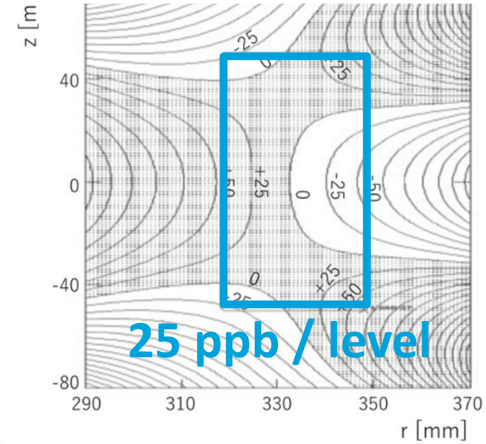
Muon orbit
radius **R = 33** cm
(*c.f.* R = 711 cm)

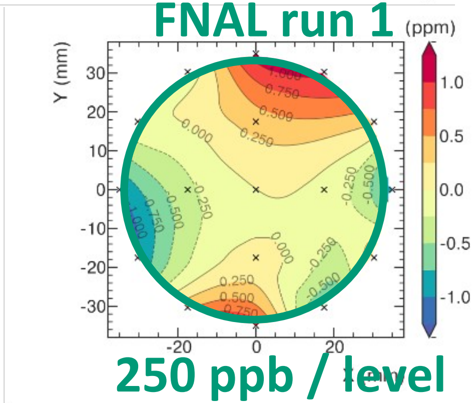
Magnetic field
strength **B = 3 T**
(*c.f.* 1.45 T)

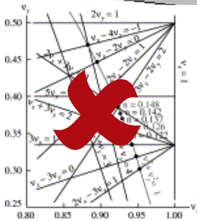
Electric quad-field
strength $Q_E = 0$
(*c.f.* Q_E = 1 kV/cm²)





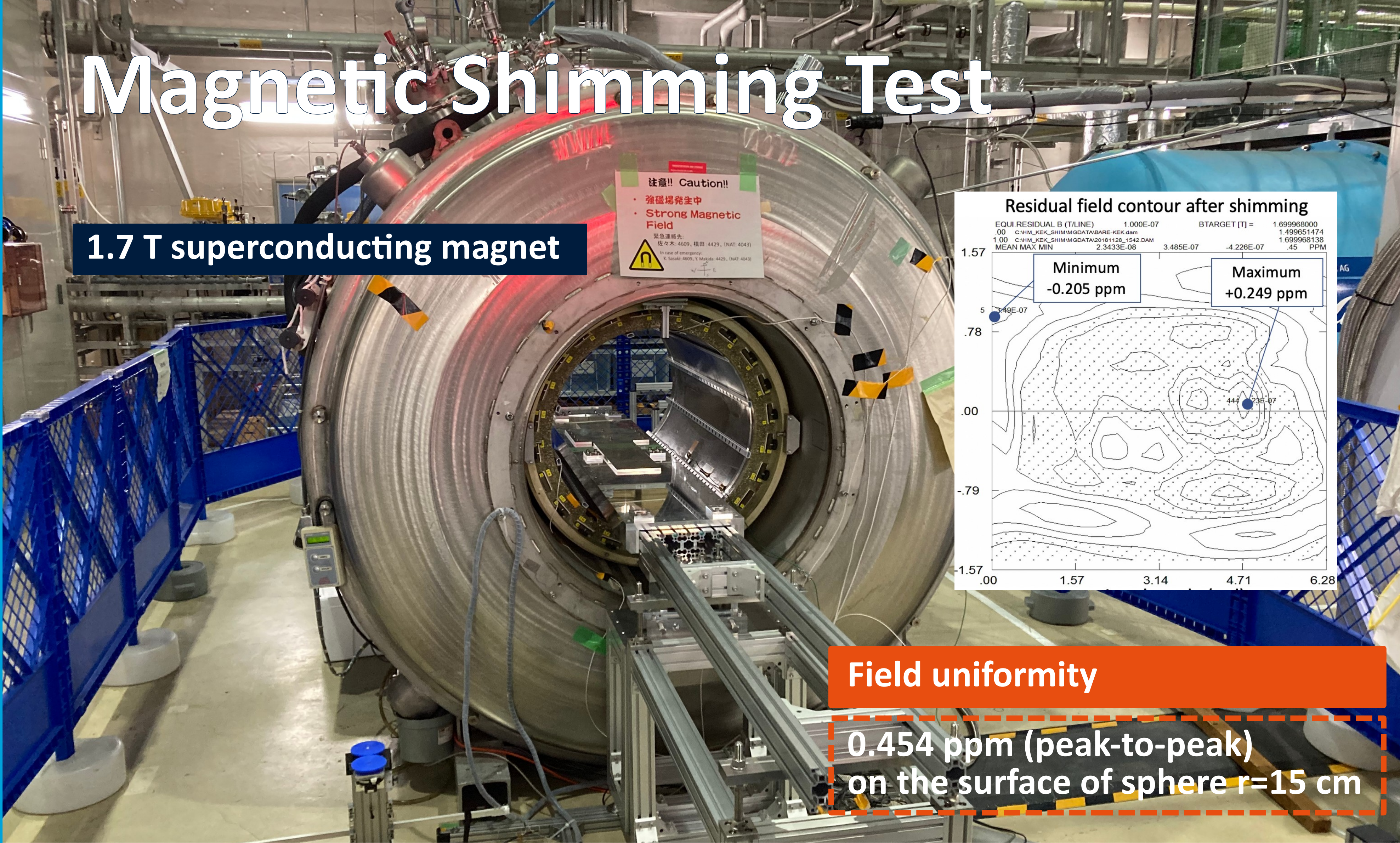






Abe *et al.*, DOI: 10.1016/j.nima.2018.01.026 (2018)
Albahri *et al.*, DOI: 10.1103/PhysRevA.103.042208 (2021)
Semertzidis *et al.*, DOI: 10.1016/S0168-9002(03)00999-9 (2003)

Magnetic Shimming Test

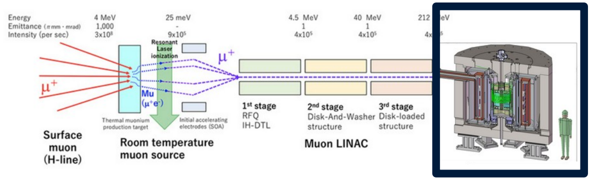


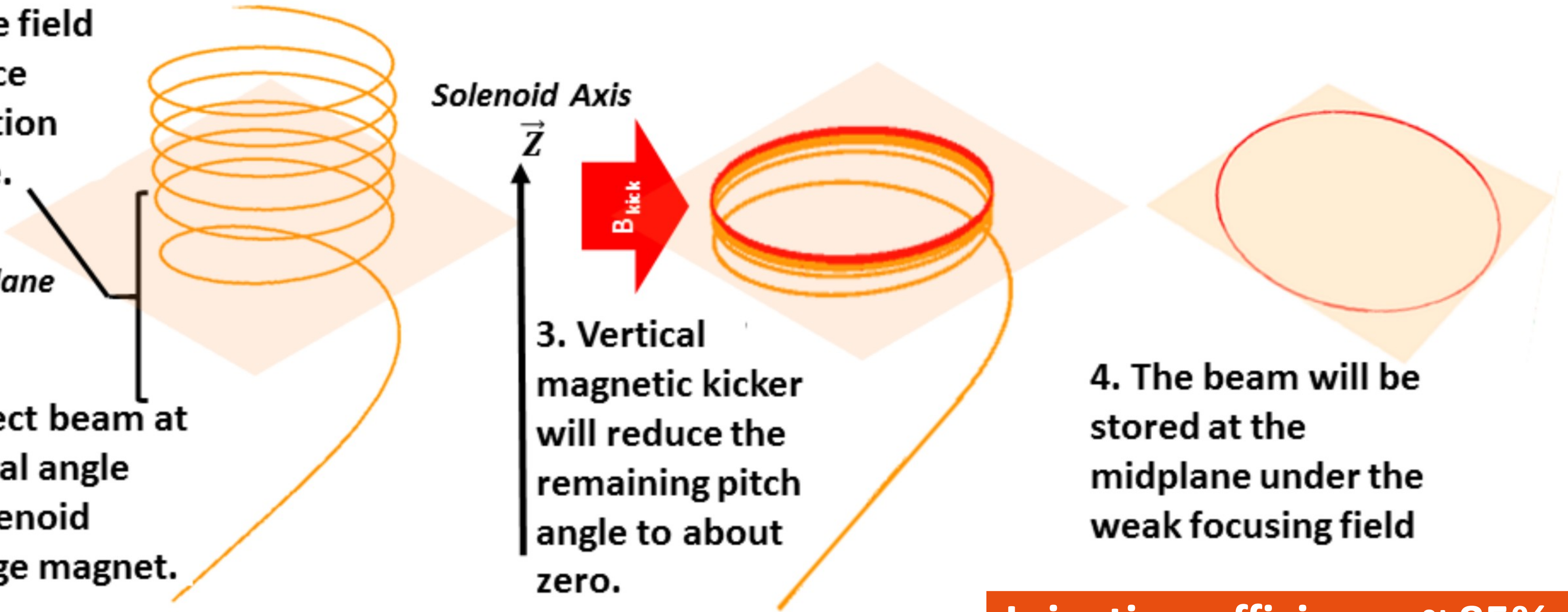
1.7 T superconducting magnet

Field uniformity

0.454 ppm (peak-to-peak) on the surface of sphere r=15 cm

Spiral Injection





2. Radial fringe field reduce injection angle.

1. Inject beam at vertical angle in solenoid storage magnet.

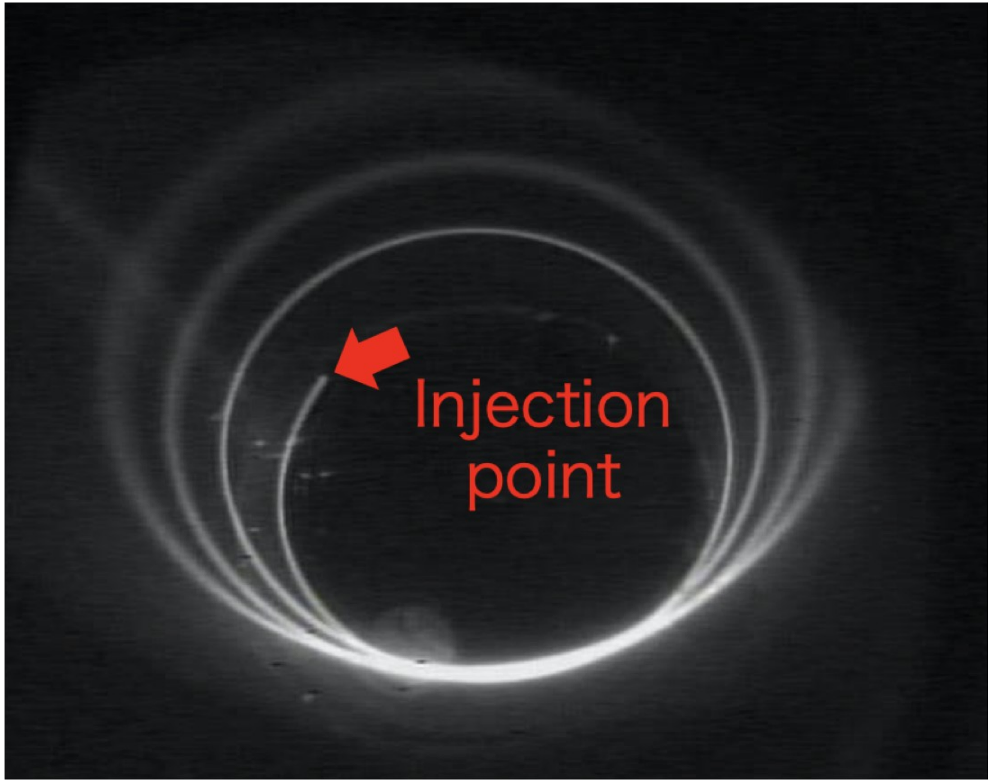
3. Vertical magnetic kicker will reduce the remaining pitch angle to about zero.

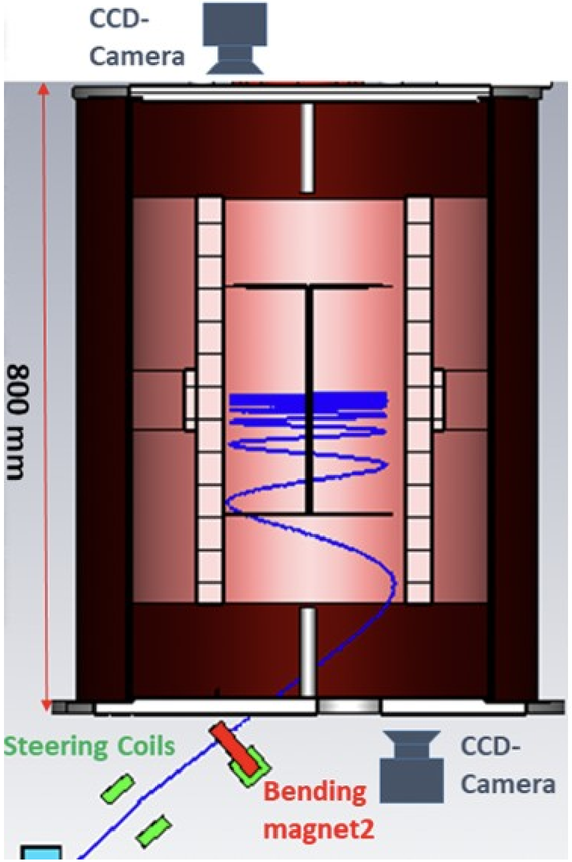
4. The beam will be stored at the midplane under the weak focusing field

Injection efficiency ~ 85%

Iinuma *et al.*, DOI: 10.1016/j.nima.2016.05.126 (2016)
Rehman et al., DOI: 10.18429/JACoW-LINAC2018-THPO017 (2017)
Oda *et al.*, DOI: 10.1109/TASC.2022.3164996 (2022)

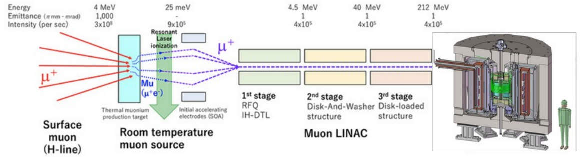
Test w/ Electrons

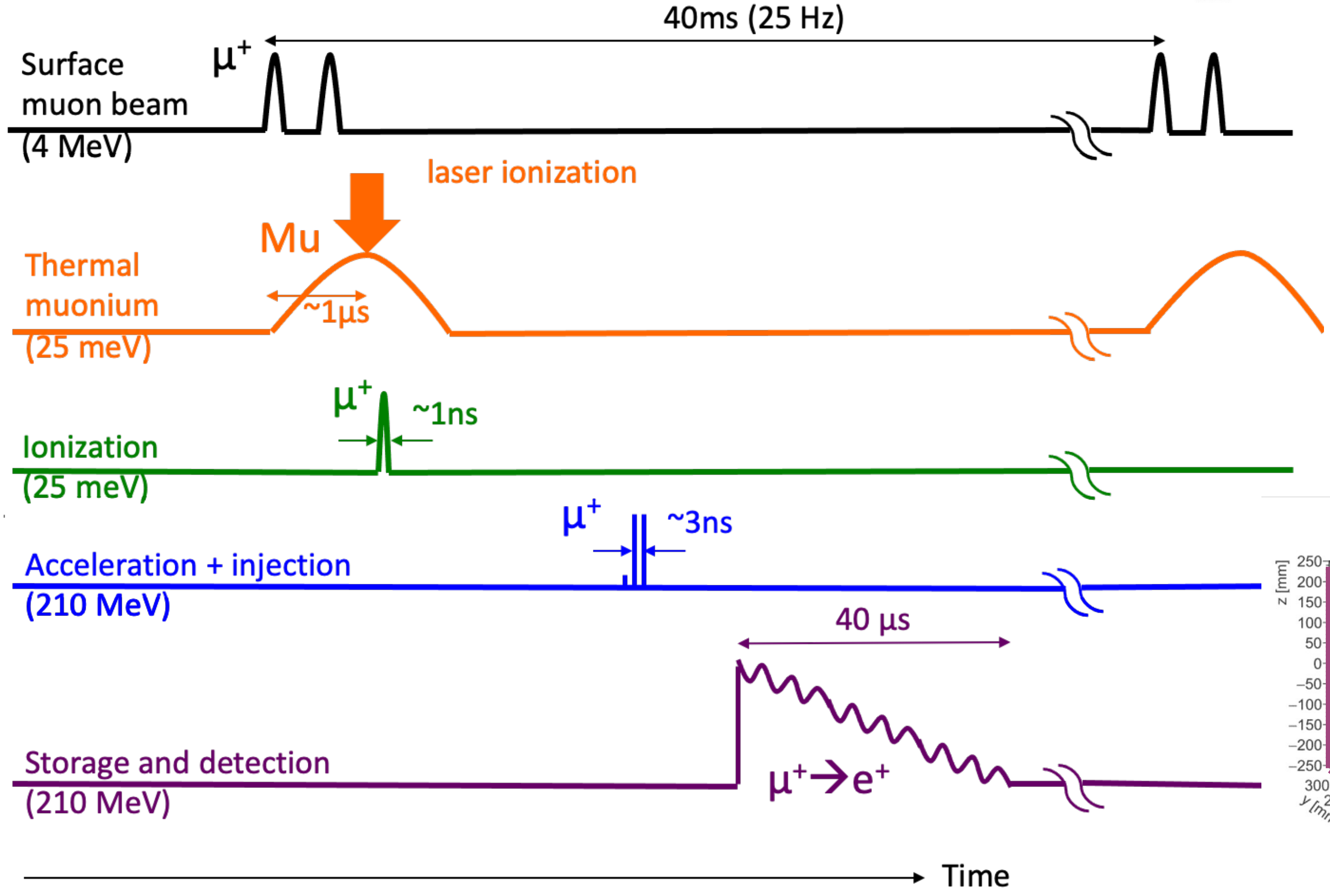


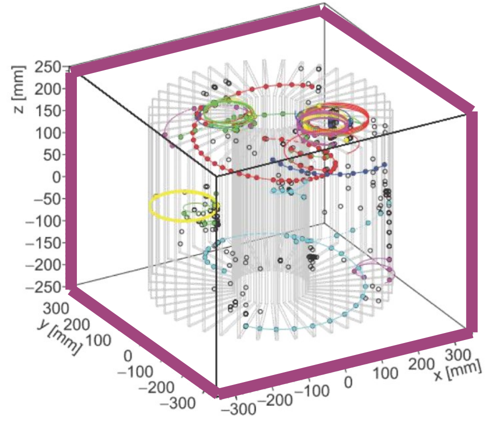


Iinuma *et al.*, Publication forthcoming

Experimental Cycle







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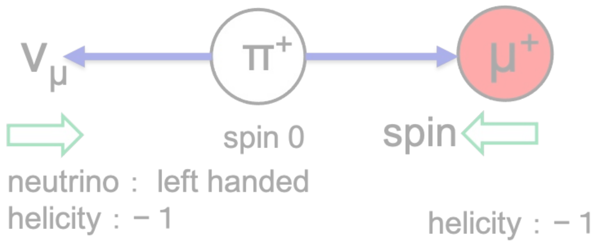
Polarized Muon Production



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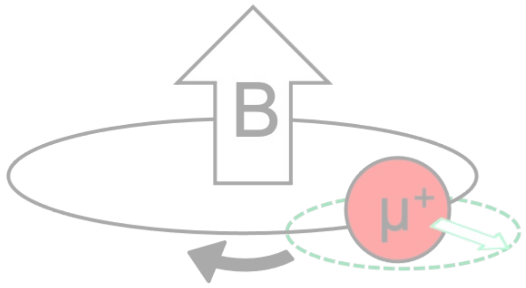

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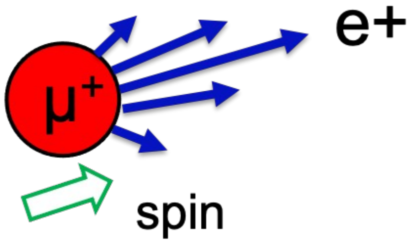


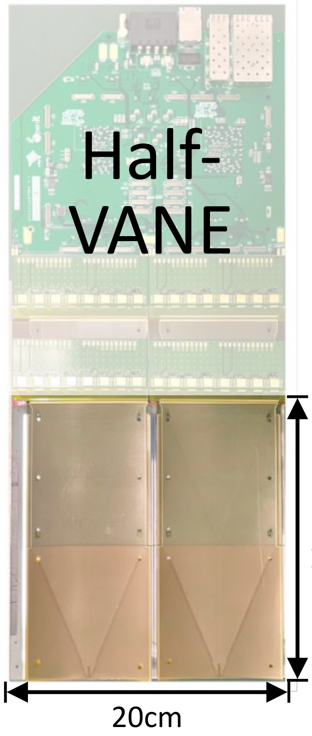
Detection

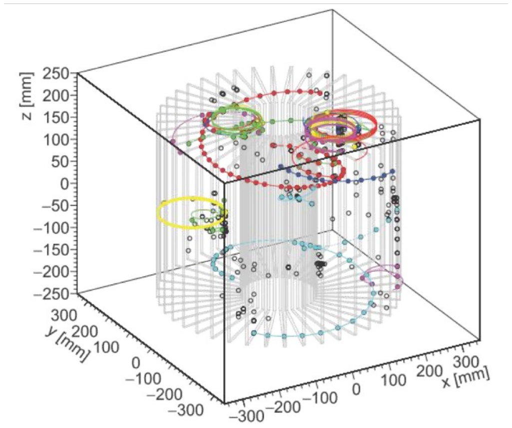
In-field Si-strip Tracker

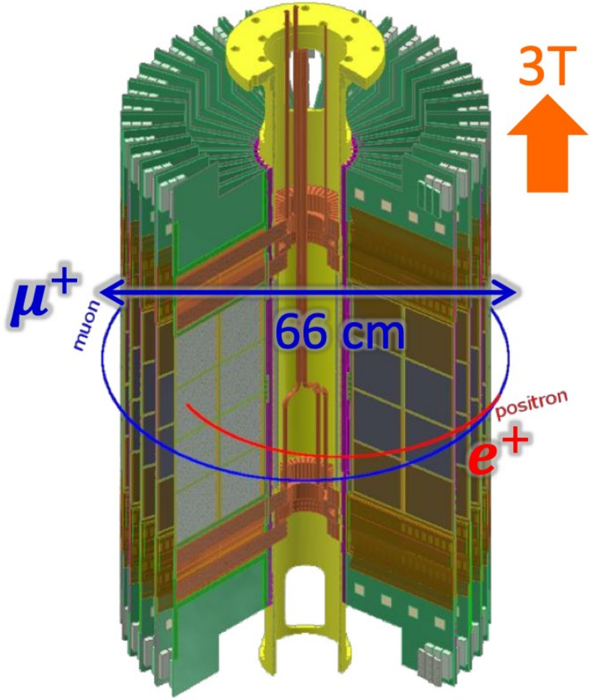
40 vanes
@ 4 x 4 x (H+V) sensors / vane
@ 1024 strips / sensor
@ 5 cm x 190 μm / strip
@ 250 kreads / s (1 frame / 5 ns)
→ (0.5 Tbits/s) → zero-suppress

Spectrometer Specs

Expected max. #e⁺'s 6/ns, 30/frame
Max. hit rate: 150 kHz / mm²
$p > 200$ MeV/c
$dp/p = 8 \times 10^{-4}$

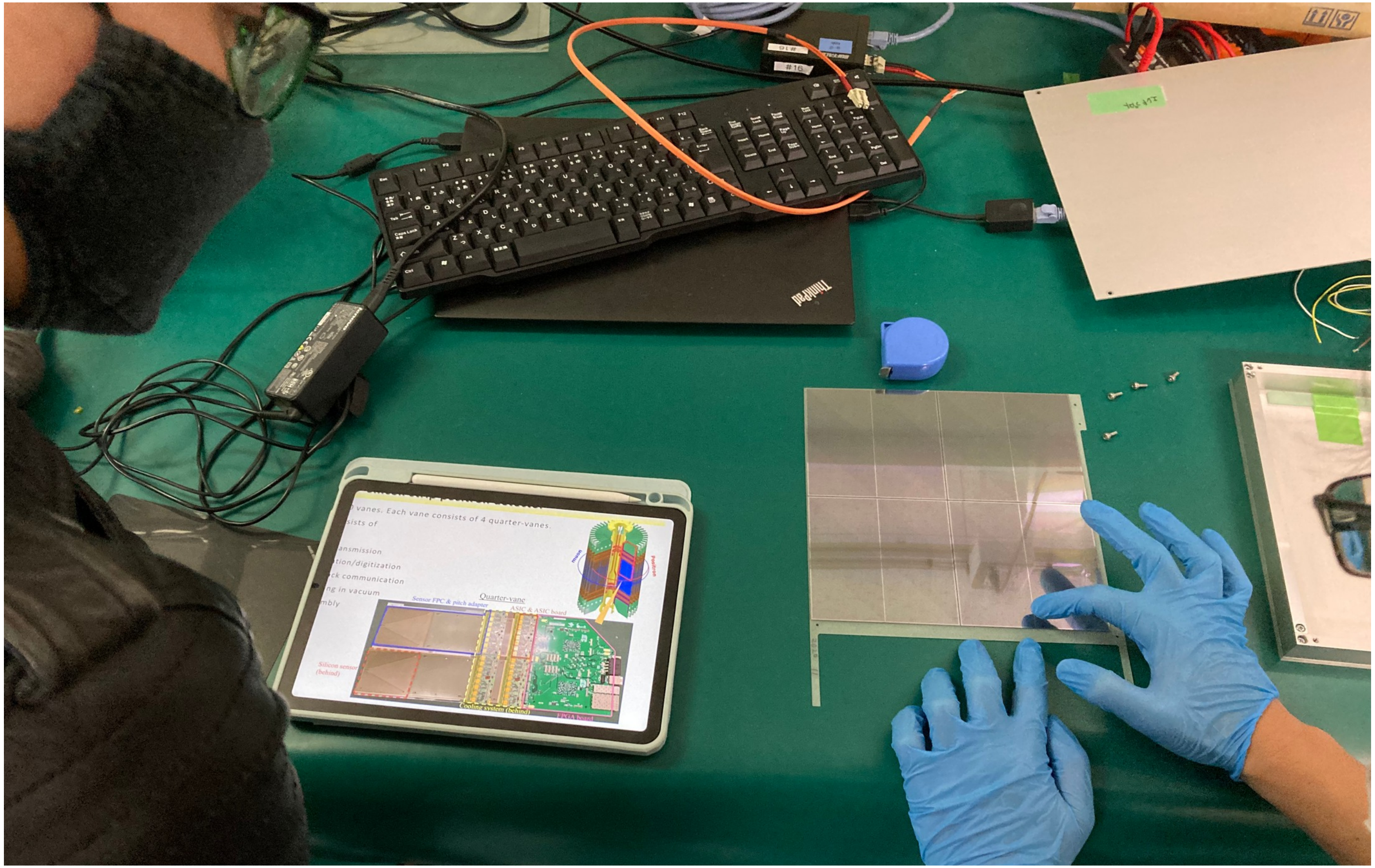






Aoyagi *et al.*, DOI: 10.1088/1748-0221/15/04/P04027 (2020)

Vane Production



EDM sensitivity

Electron

Internal E in molecule: **HfF^+** → E_{eff} = 2300 GV/m

$|d_e| < 4.1 \times 10^{-30}$ *e*·cm (90% C.L.)

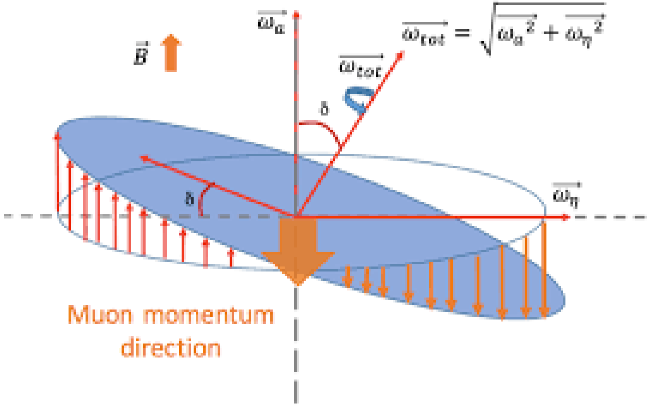
Muon

Relativistic E: **g-2** → $E_{eff} = v \times B$ = 0.5 GV/m

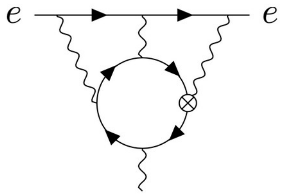
$|d_\mu| < 1.8 \times 10^{-19}$ *e*·cm (95% C.L.)

Indirect from ^{199}Hg and ThO

$|d_\mu|_{Hg} < 6 \times 10^{-20}$ *e*·cm, $|d_\mu|_{ThO} < 2 \times 10^{-20}$ *e*·cm



tilt ~ ηβ/2a



Aim: $|d_\mu| < 1.5 \times 10^{-21}$ *e*·cm (95% C.L.)

Roussy *et al.*, DOI: https://doi.org/10.48550/arXiv.2212.11841 (2022)
Bennett et al., DOI: 10.1103/PhysRevD.80.052008 (2009)
Ema, Gao, and Pospelov, arXiv:2108.05398 (2021)

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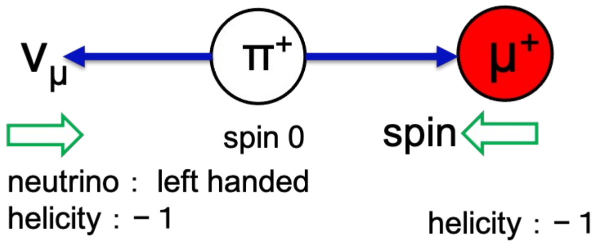

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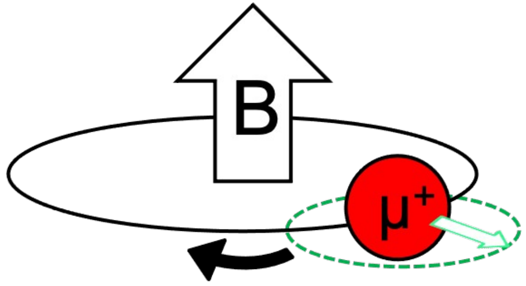

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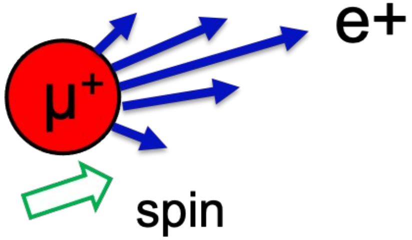


Comparison of Specs

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e\cdot$cm	–	1.5×10^{-21} $e\cdot$cm
(syst.)	0.9×10^{-19} $e\cdot$cm	–	0.36×10^{-21} $e\cdot$cm

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)

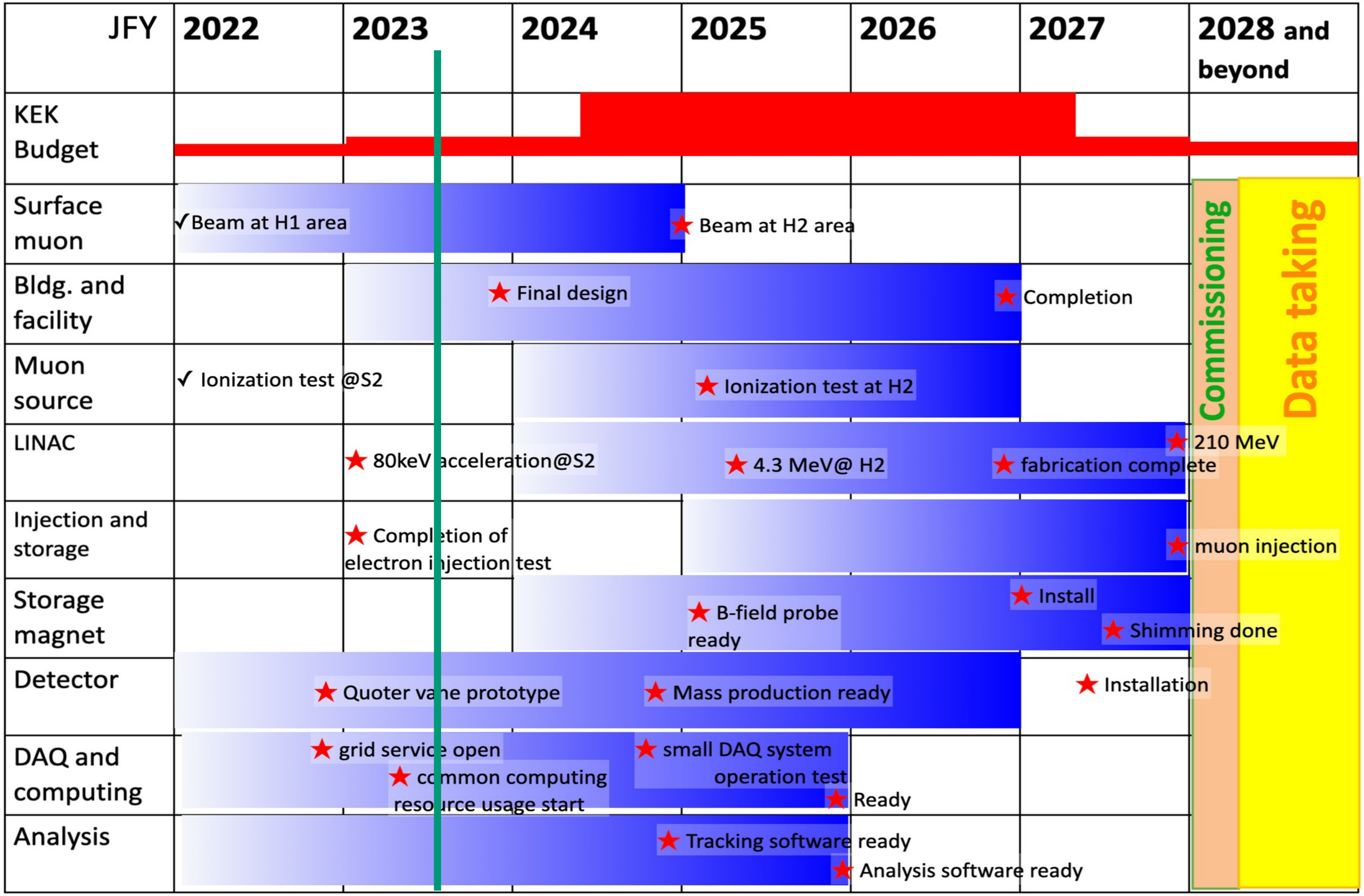
Systematics

TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ correction terms in Eq. (4), and uncertainties due to the constants in Eq. (2) for a_μ. Positive C_i increase a_μ and positive B_i decrease a_μ.

Quantity	Correction terms (ppb)	Uncertainty (ppb)		
ω_a^m (statistical)	⋯	434		
ω_a^m (systematic)	⋯	56	↦ <36	: Pileup, (gain, CBO)
C_e	~~489~~	53	↦ 10	: residual E-fields (no Quads)
C_p	~~180~~	13	↦ 13	: pitch correction
C_{ml}	~~−11~~	5	↦ 2	: differential decay & (muon losses)
C_{pa}	~~−158~~	75	↦ 0	: transverse muon distribution
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	⋯	56	↦ 49	: probe positioning & calibration
B_k	~~−27~~	37	↦ <10	: kicker transients
B_q	~~−17~~	92		
$\mu'_p(34.7°)/\mu_e$	⋯	10		
m_μ/m_e	⋯	22		
$g_e/2$	⋯	0		
Total systematic	⋯	157	↦ <64	
Total fundamental factors	⋯	25		
Totals	~~544~~	462		

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)
Abi *et al.*, DOI: 10.1103/PhysRevLett.126.141801 (2021)

Schedule & Milestones



Gerco Onderwater, Muon4Future, Venice, 30-5-2023

Muon g-2 & EDM @ JPARC

Conclusion - I

Leptons excellent testing ground for flavour physics

Rich palette of observables
Ultra-precise predictions
Extremely sensitive measurements

Long standing ~3σ anomaly in muon g-2

Experimental and theoretical uncertainty @ sub-ppm level **!!**
New experimental results expected from FNAL ↦ **100 ppb ?!**
Experiments consistent ↦ but (somewhat) correlated
Steady progress in theory improvement
Tension in (hadronic) theory ↦ complicates interpretation

Conclusion - II

New J-PARC g-2/EDM experiment

Alternative experimental method

- pencil beam : cooled & re-accelerated positive muons
- compact ring : stable & homogeneous magnetic field
- in-field spectrometer : reliable & precise positron detection
- **Complementary systematic sensitivities**

Many components of the experiments ready or being tested

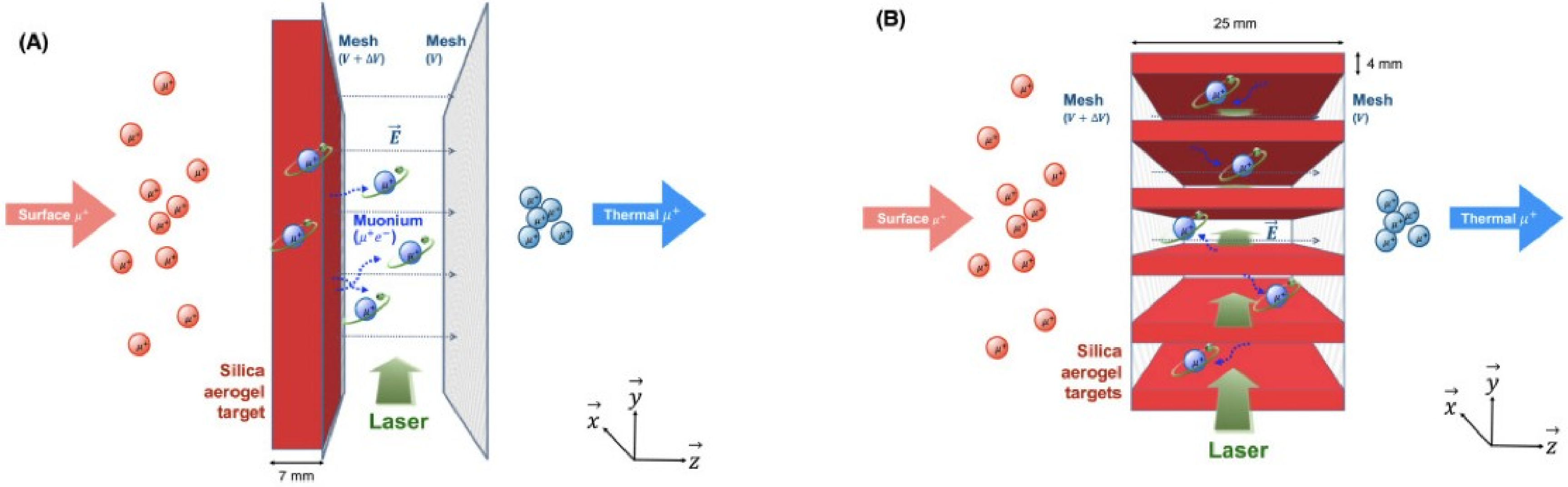
Expected data taking starting in 2028

Thank you for your attention

Comparison of Specs

	BNL-E821	Fermilab-E989	Our experiment	PSI
Muon momentum	3.09 GeV/c		300 MeV/c	125 MeV/c
Lorentz γ	29.3		3	1.57
Polarization	100%		50%	90%
Storage field	$B = 1.45$ T		$B = 3.0$ T	B=3.0 T, E=2MV/m
Focusing field	Electric quadrupole		Very weak magnetic	weak magnetic
Cyclotron period	149 ns		7.4 ns	3.8 ns
Spin precession period	4.37 μs		2.11 μs	∞
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}	3.2×10^{11}
Number of detected e^-	3.6×10^9	–	–	-
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb	-
(syst.)	280 ppb	100 ppb	<70 ppb	-
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	–	1.5×10^{-21} $e \cdot$ cm	1×10^{-23} e·cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm	?
	R = 280" (7112 mm)		R = 333 mm	R = 140 mm

Future source upgrade



Intensity x 3.5

@ somewhat increased phase space

Zhang *et al.*, DOI: https://doi.org/10.1016/j.nima.2022.167443 (2022)

Civil Engineering : MLM extension