Muon g-2 & EDM @ J-PARC

Gerco Onderwater

on behalf of the J-PARC E34 Collaboration

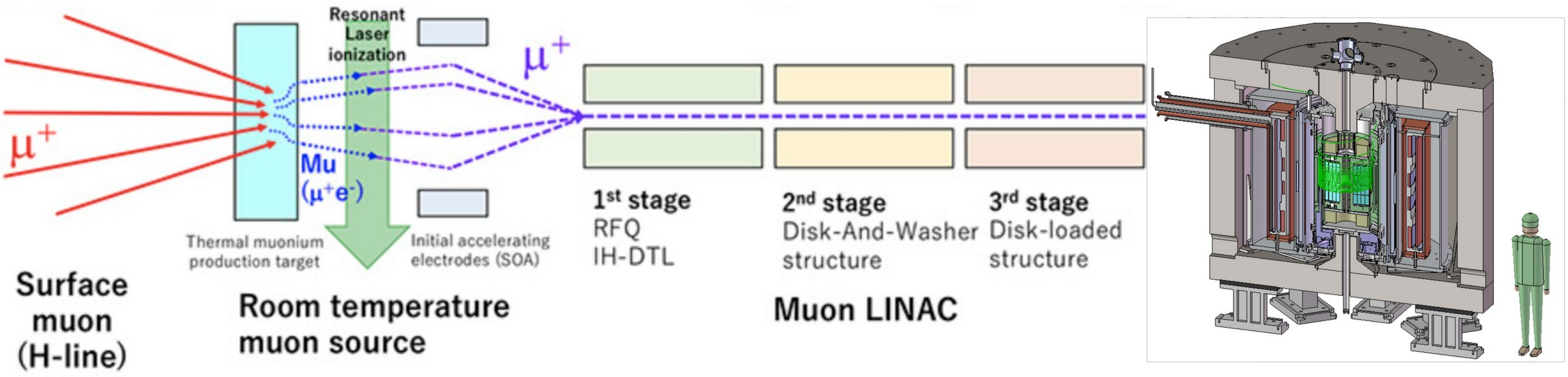
Workshop on Precision Muon Physics, Liverpool, UK, 8 Nov 2023

MAASTRICHT SCIENCE PROGRAMME

Maastricht University

Experiment E34 @ J-PARC

Part of a wide-range muon physics programme

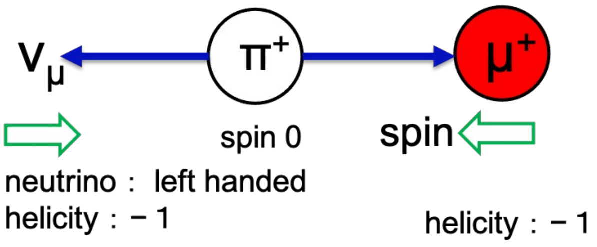


Aim: competitive measurement of muon g-2 and EDM

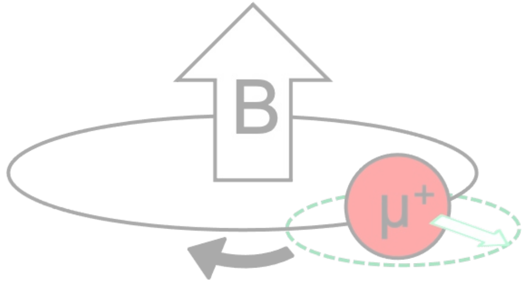
https://g-2.kek.jp/portal/index.html

Elements of an MDM or EDM Expt

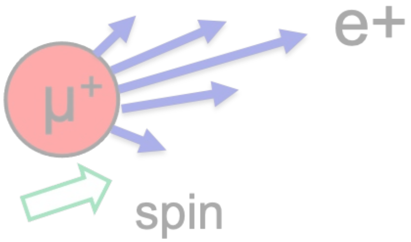
Polarized Muon Production



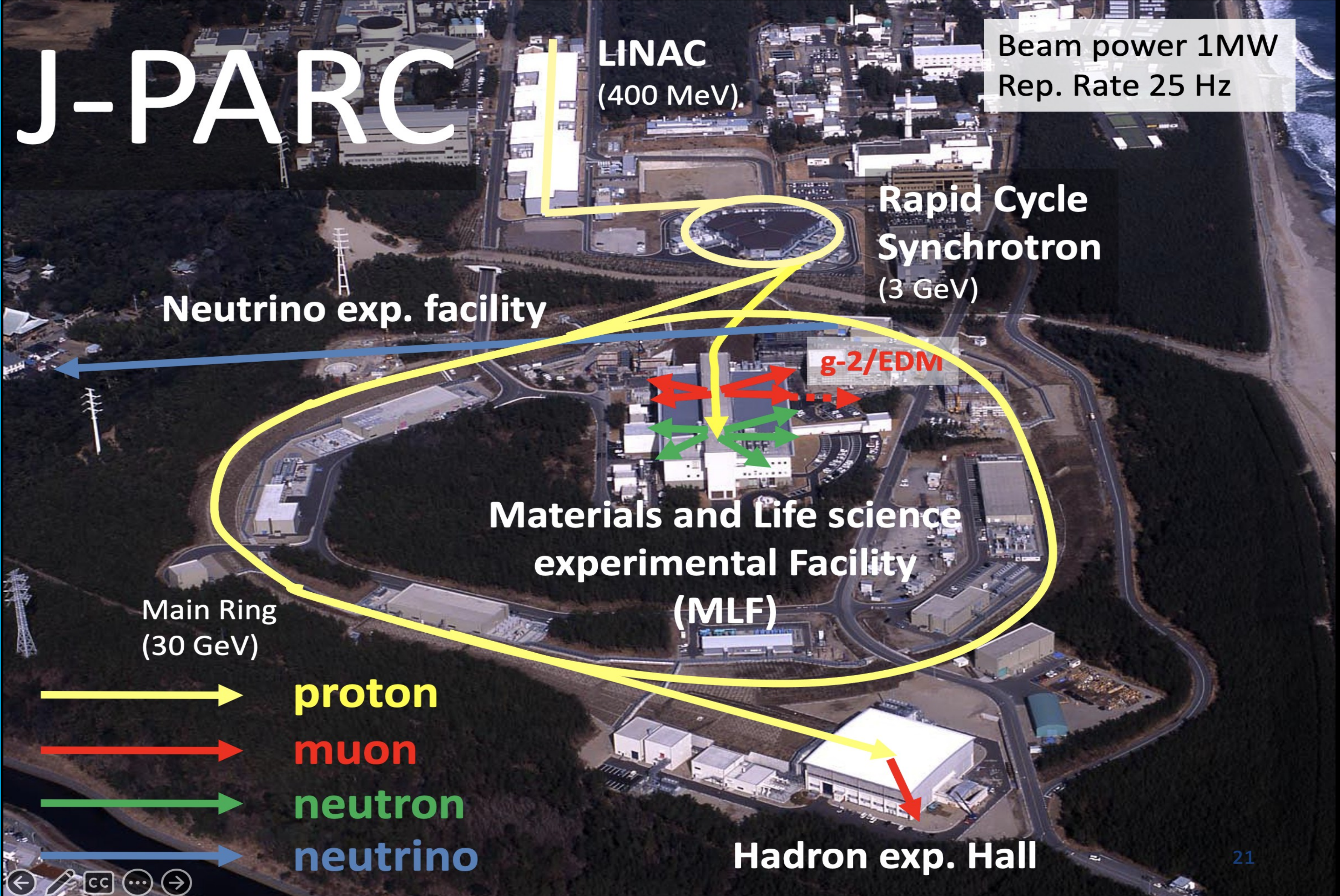
Storage & Spin Precession



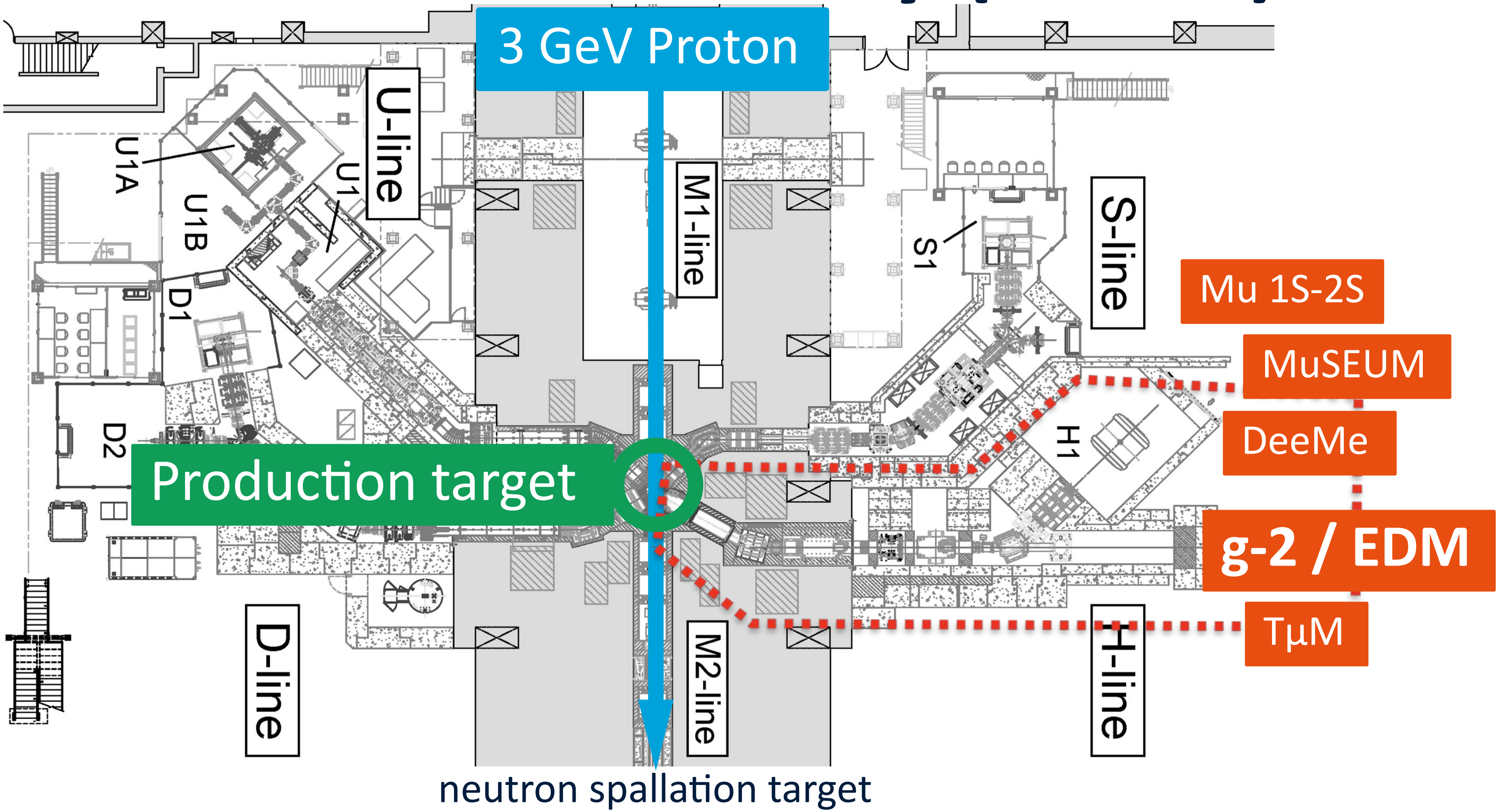
Detection of Spin Orientation



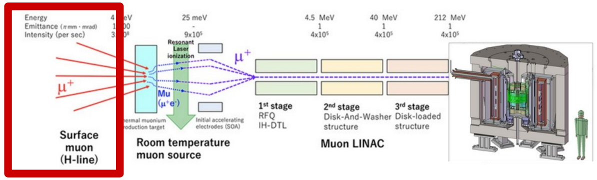
J-PARC


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)

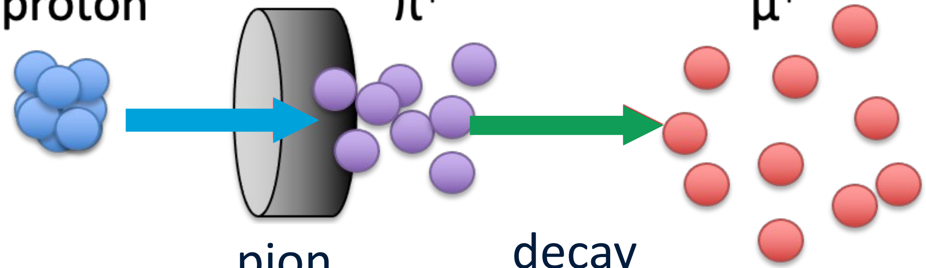


Production



↦ CERN

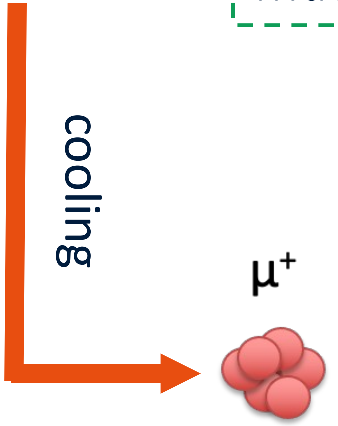
proton π^+ μ^+



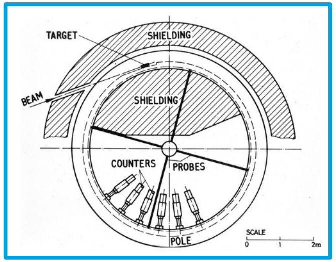
pion production

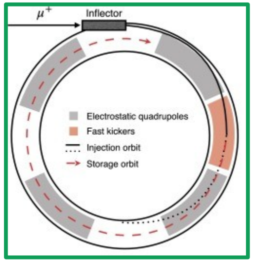
decay

cooling



μ^+





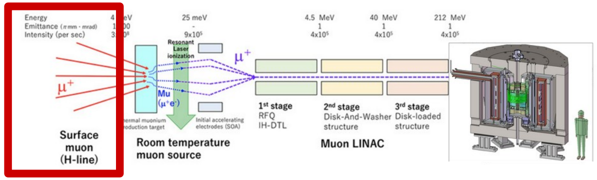
↦ BNL FNAL

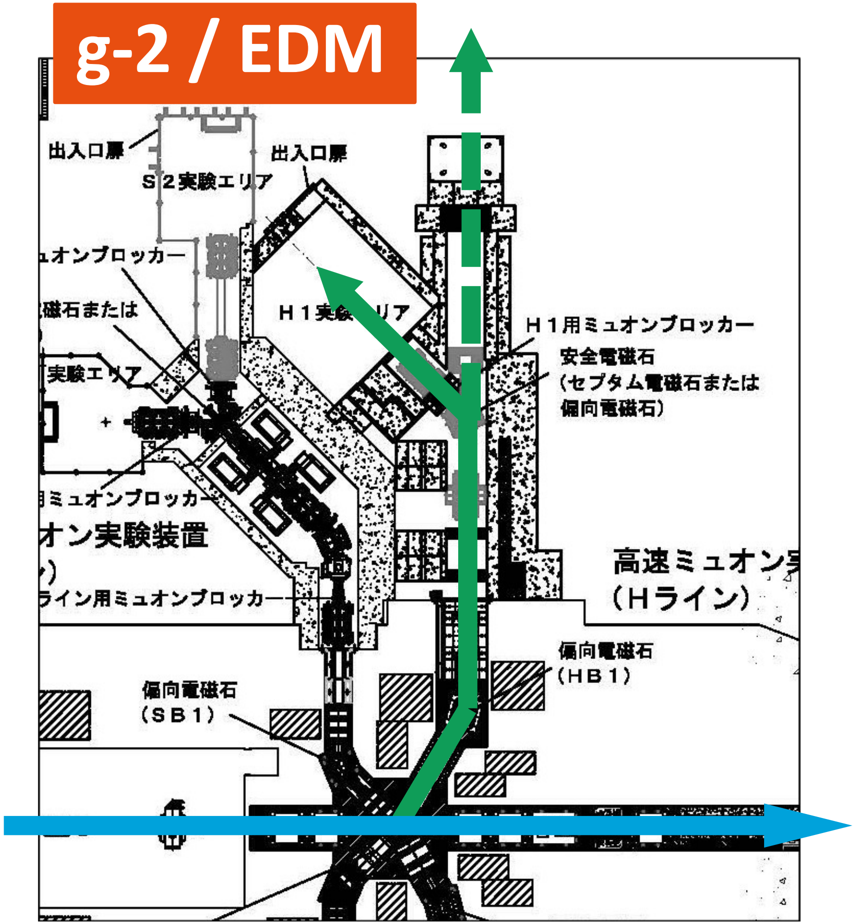
Emittance ~ 1000π mm·mrad
Proton and pion contamination
Need strong (electric) focussing
Need 'magic' $\gamma = \sqrt{(1/a_\mu+1)} = 29$
Muon loss

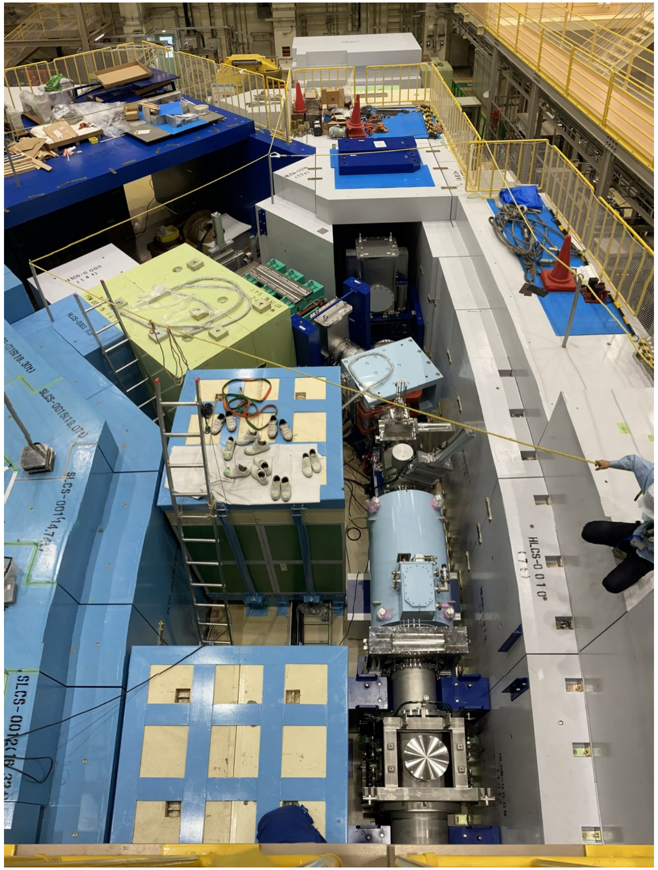
↦ JPARC

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

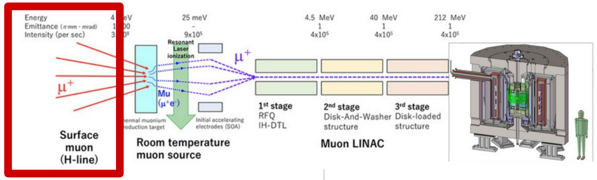
H1-Beamlines

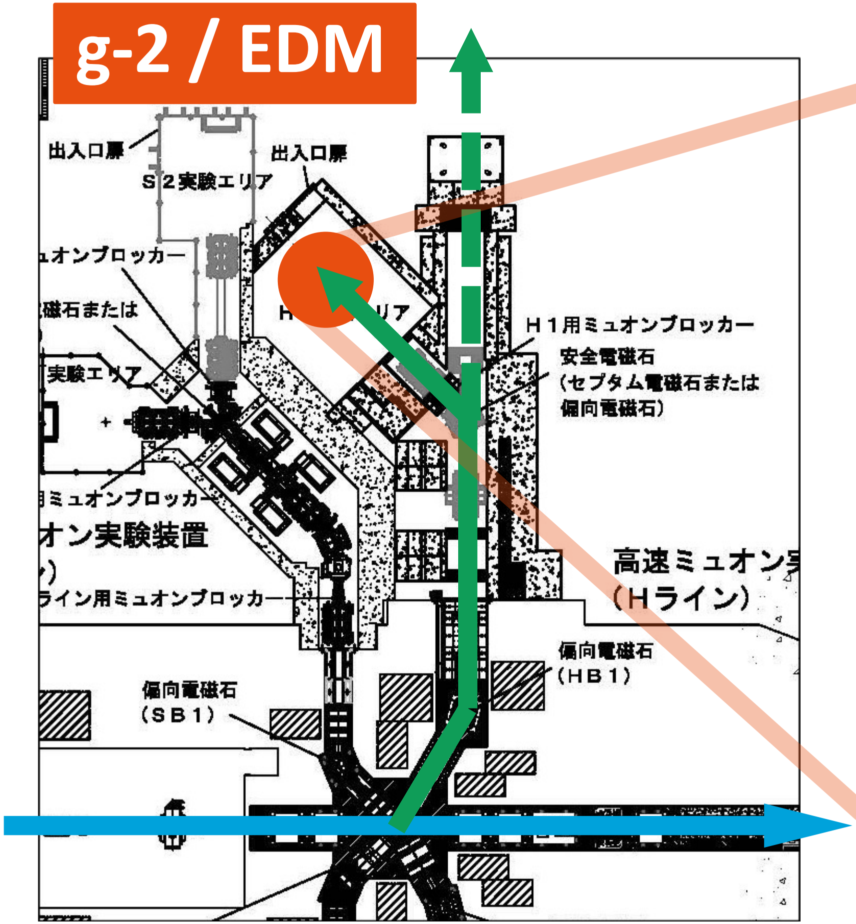


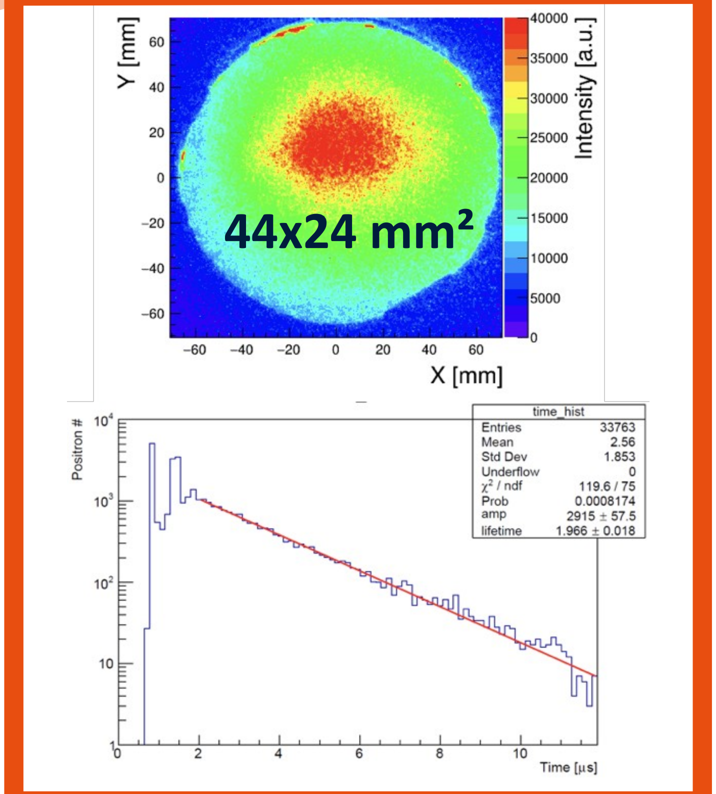




First beam (Jan. 2022)

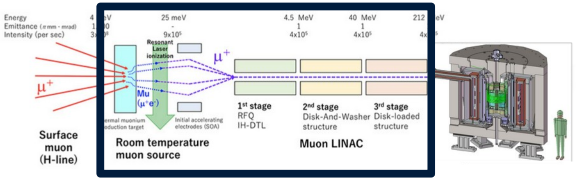






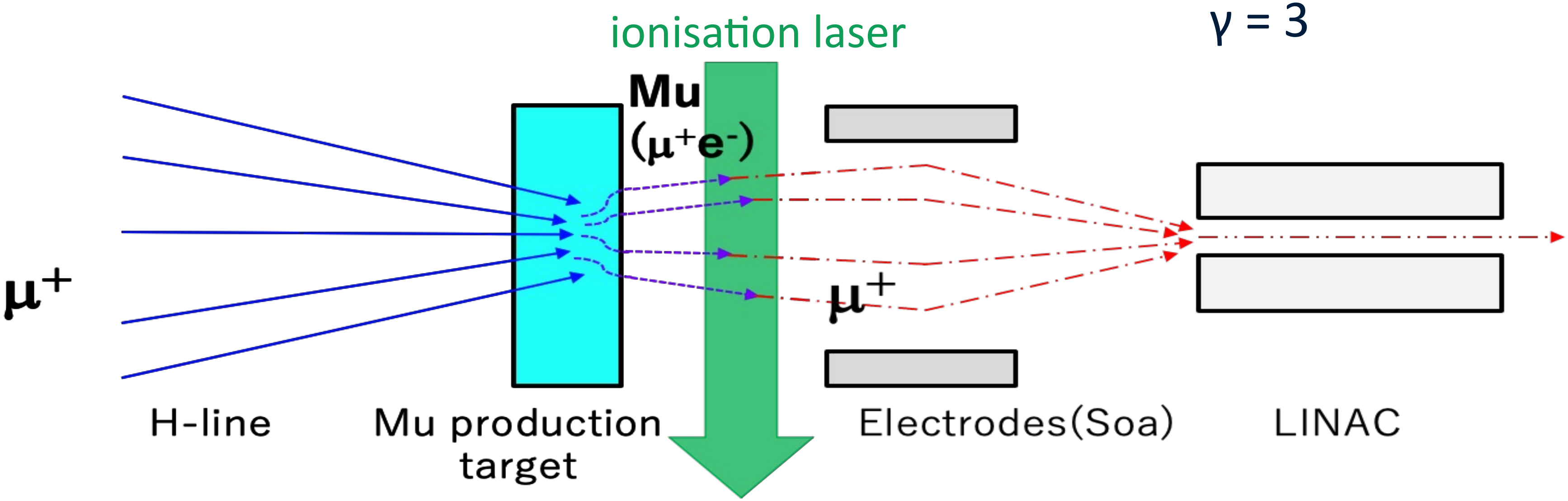
7×10^7/s @ 28 MeV/*c*, 730 kW

Muon Cooling



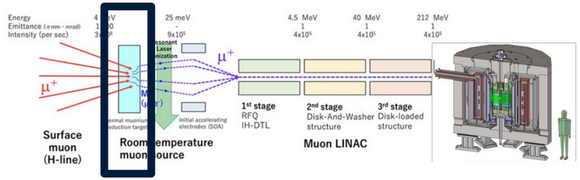
	surface muons	thermal muons	accelerated muons
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/*c*	2.3 keV/*c*	300 MeV/*c*
Δp/p	0.05	0.4	0.0004

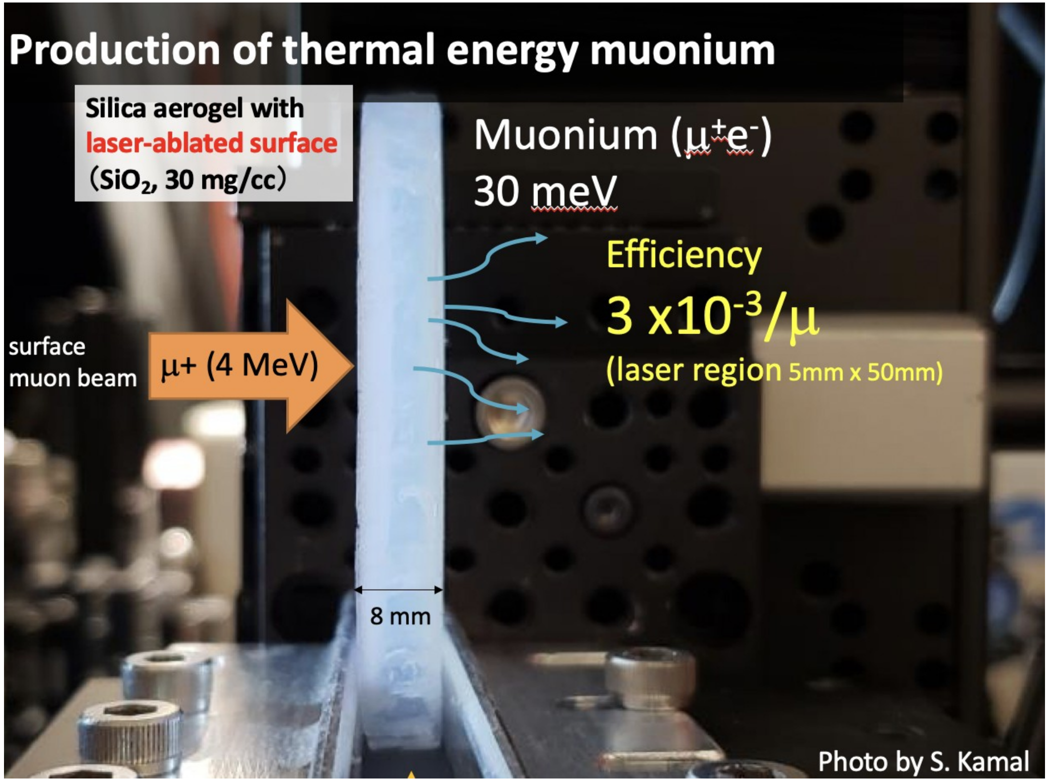
$\gamma = 3$



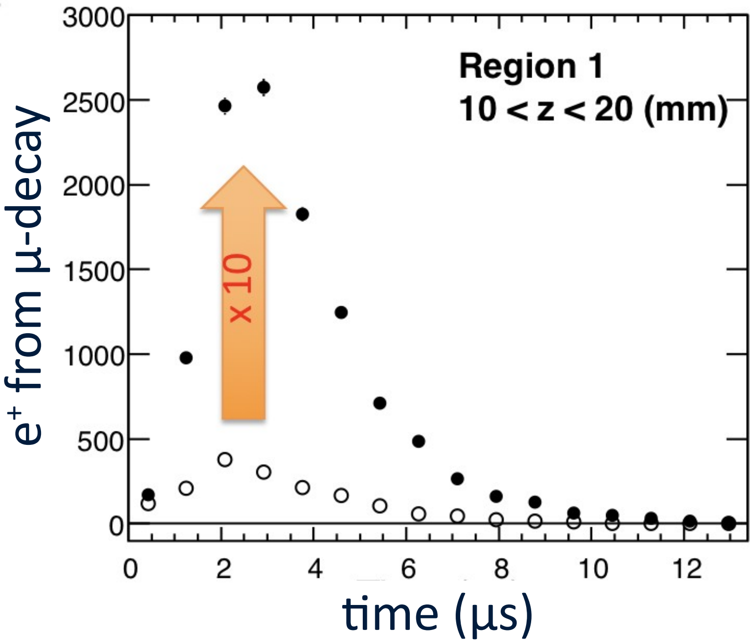
Cooling + LINAC : world's first muon accelerator

Muonium Production



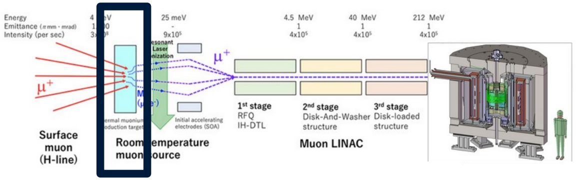


Muonium yield measured @ TRIUMF

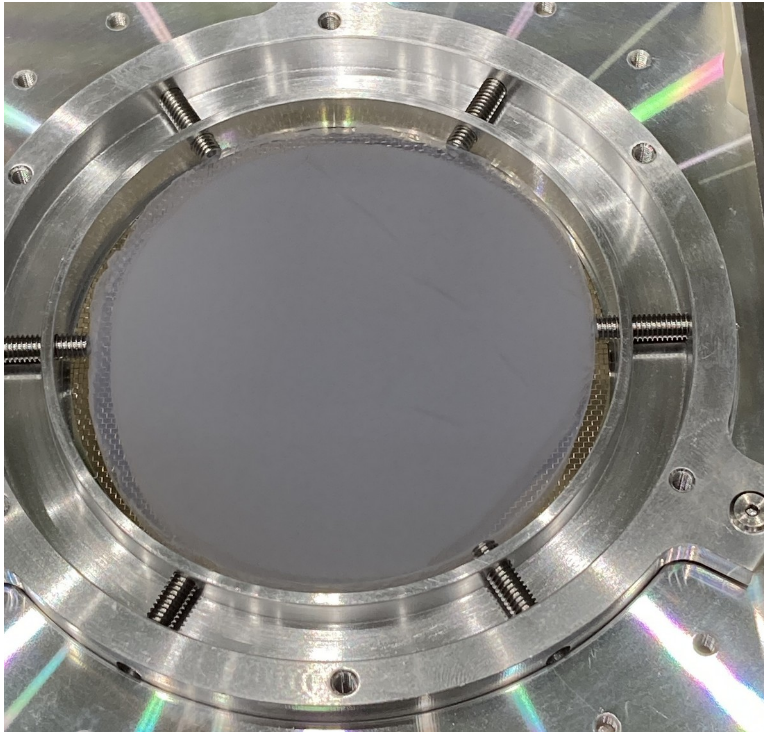


Sufficient to reach Δa_μ ~ 450 ppb

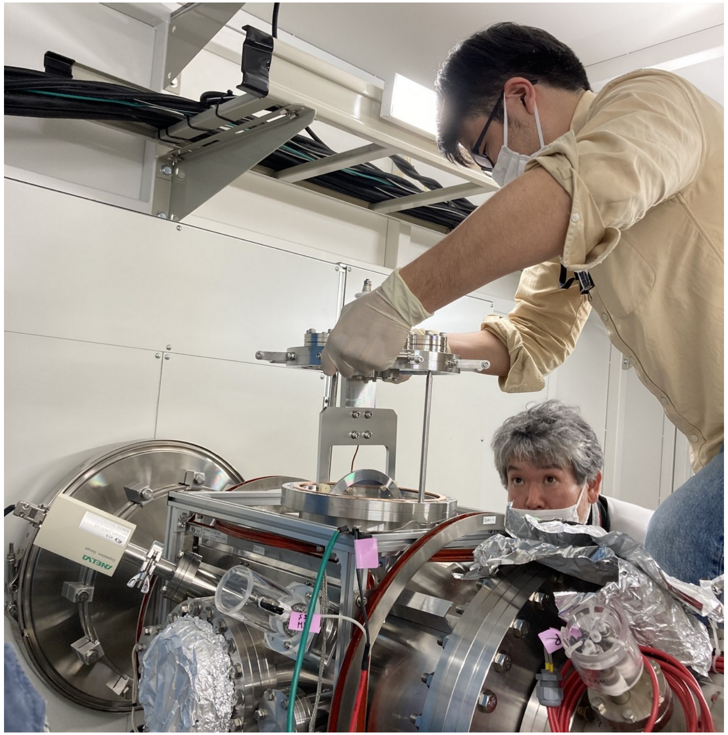
Muonium Production



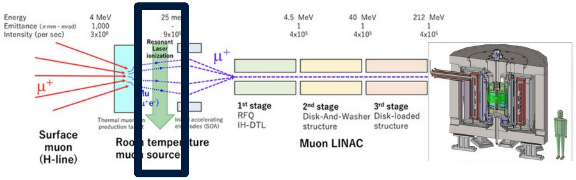
Laser ablated silica aerogel

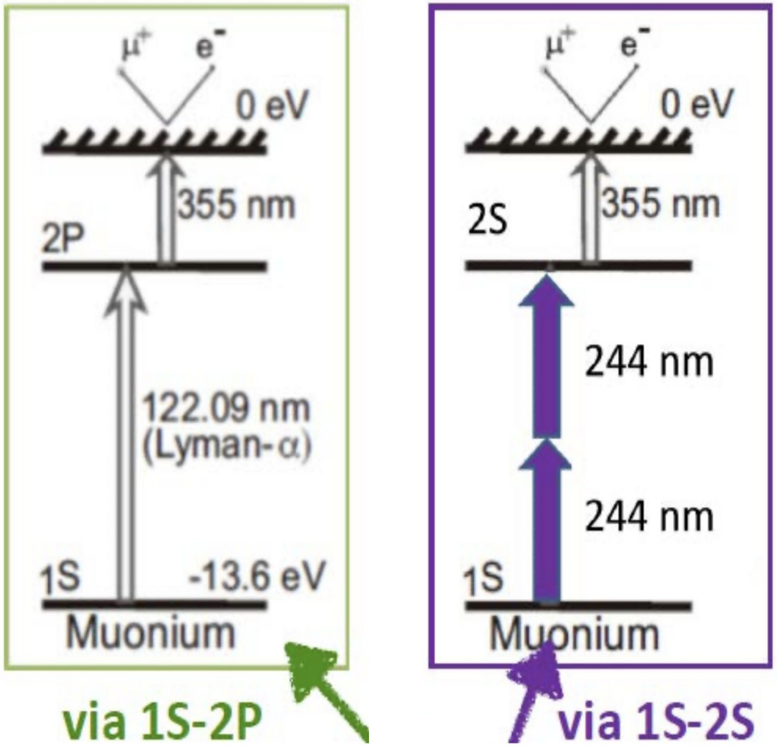


J-PARC S2 area (Feb. 2023)

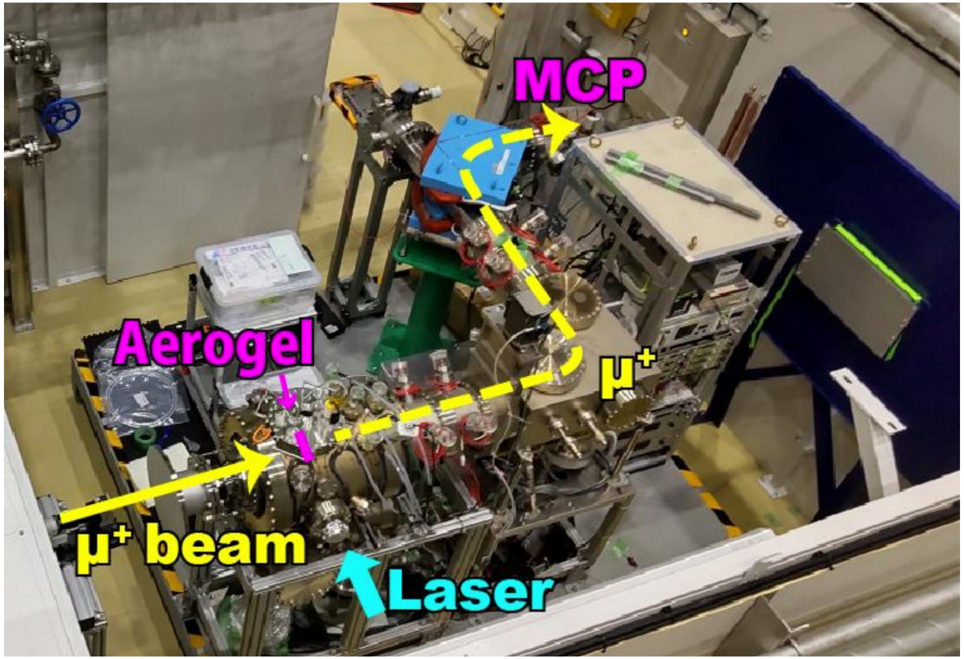


Muonium Ionisation



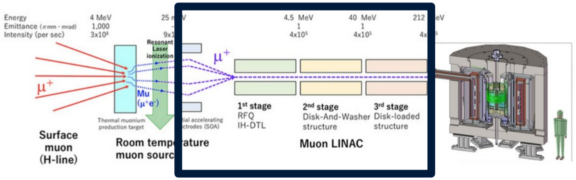


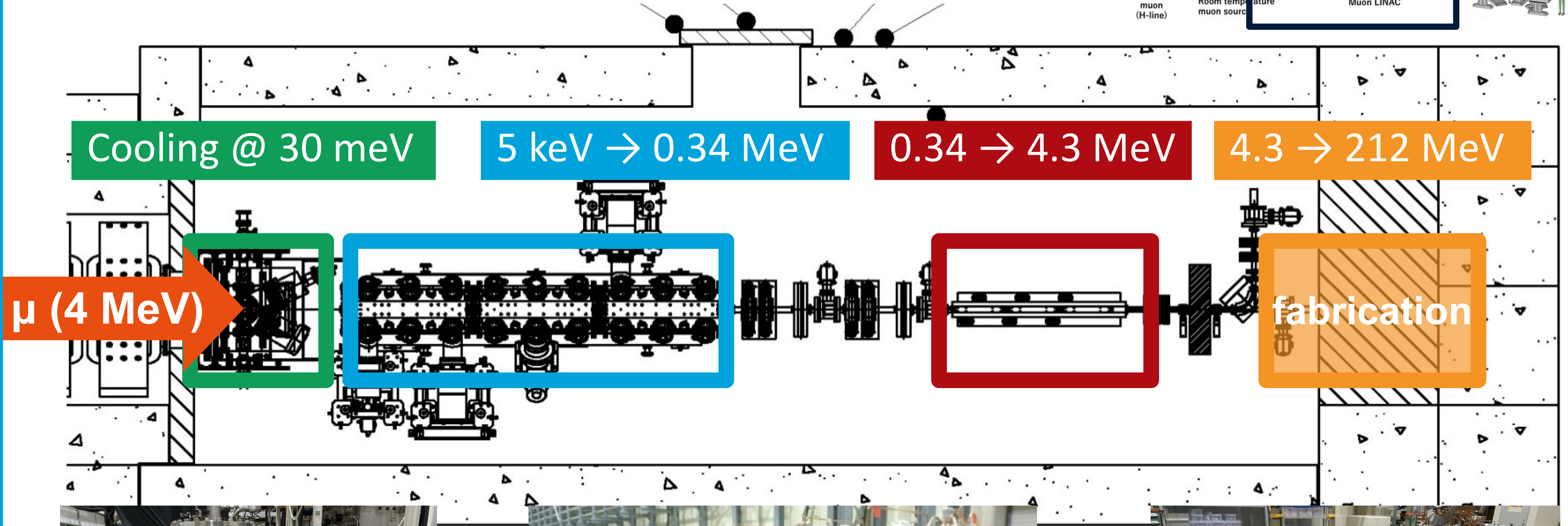
Ionisation test via 1S-2S

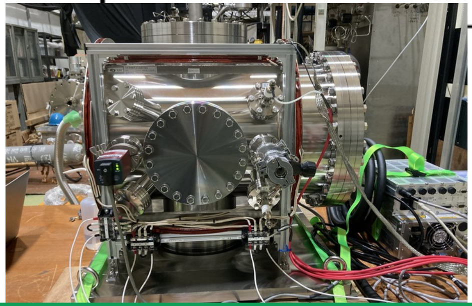


In collaboration w/ Okayama University (Uetake *et al.*)

Muon Acceleration



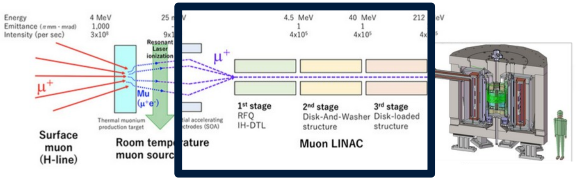


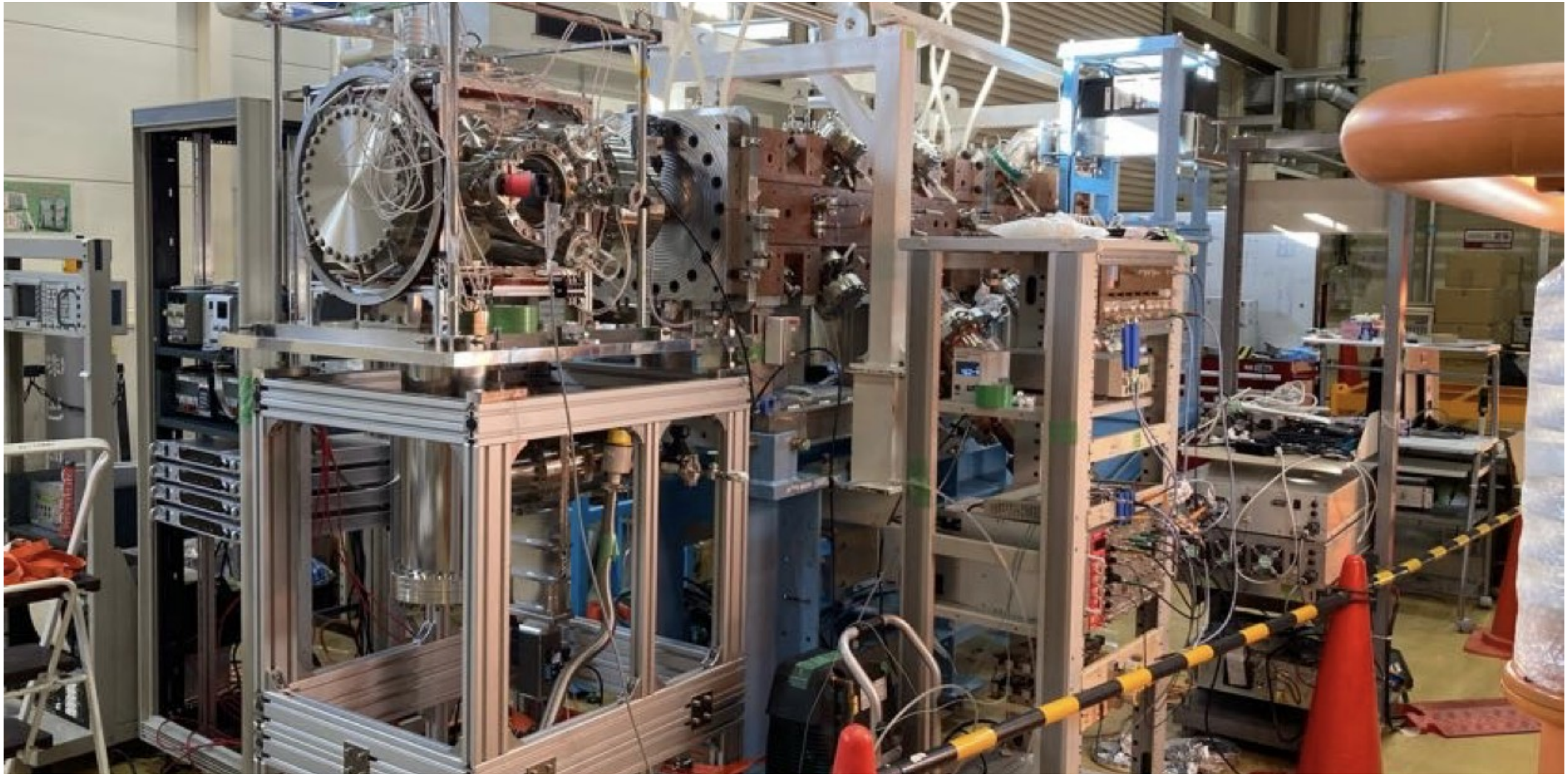

Mu chamber (available)


J-PARC Linac RFQ (available)


IH-DTL (fabricated & tested)

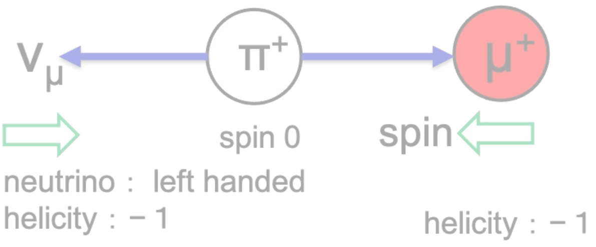
Assembly for Test ('23)



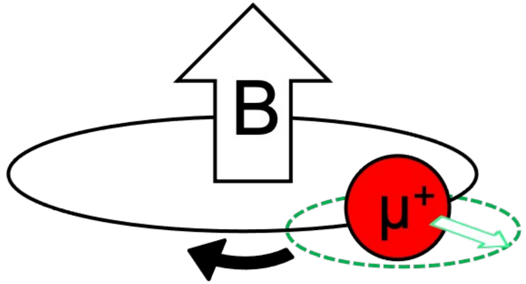


Elements of an MDM or EDM Expt

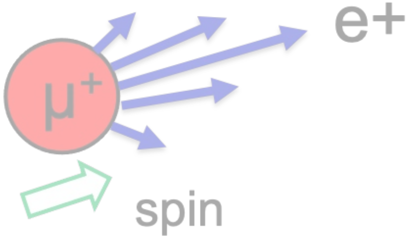
Polarized Muon Production



Storage & Spin Precession



Detection of Spin Orientation



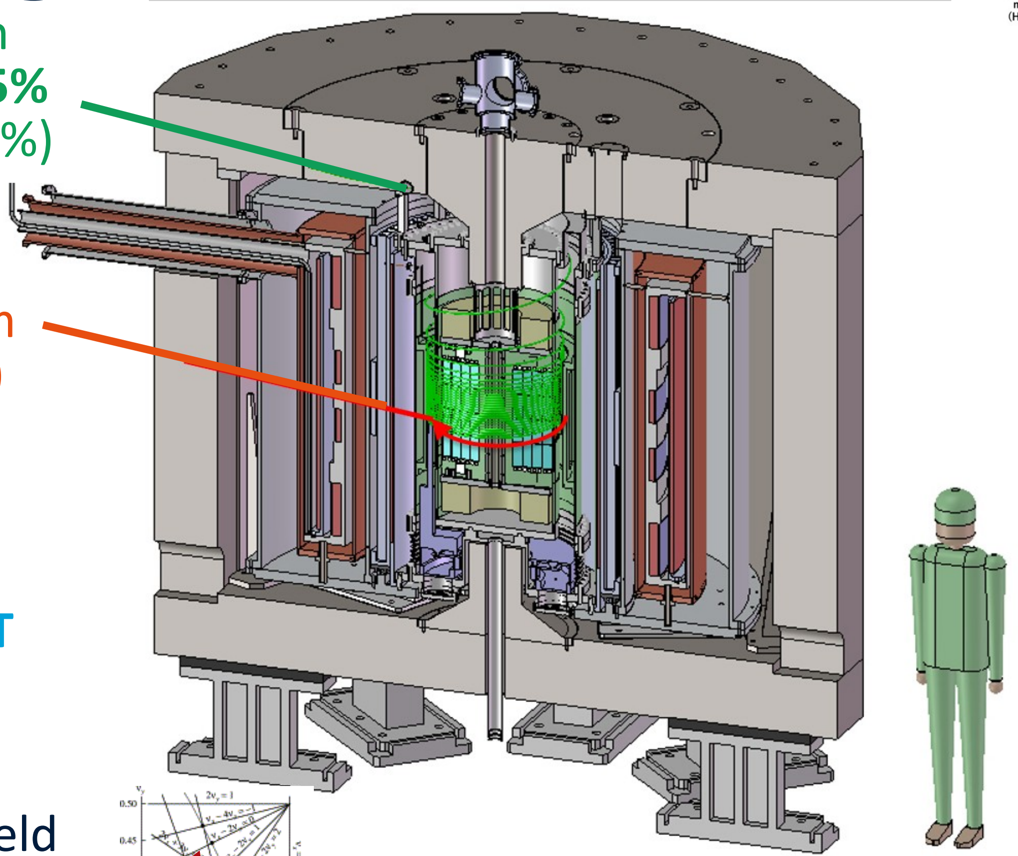
Storage

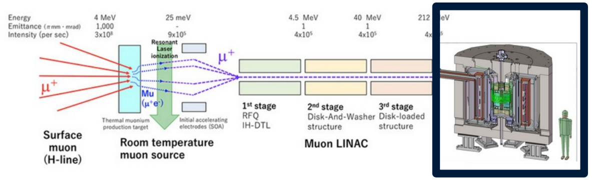
Vertical injection
Efficiency **η = 85%**
(*c.f.* Horizontal 5%)

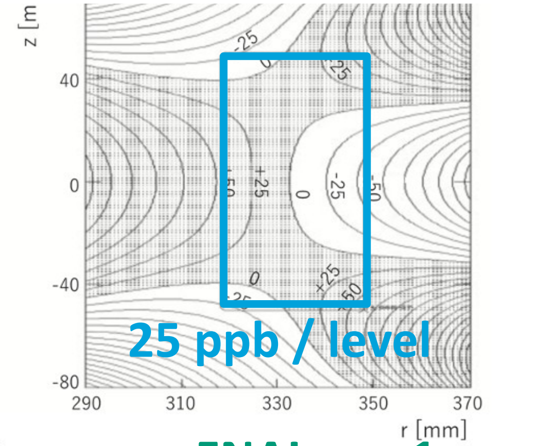
Muon orbit
radius **R = 33** cm
(*c.f.* R = 711 cm)

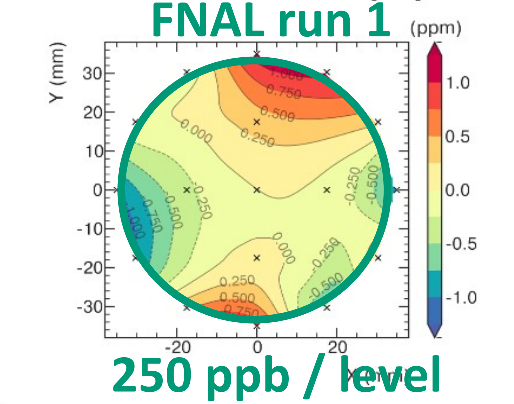
Magnetic field
strength **B = 3 T**
(*c.f.* 1.45 T)

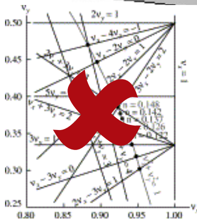
Electric quad-field
strength $Q_E = 0$
(*c.f.* Q_E = 1 kV/cm²)





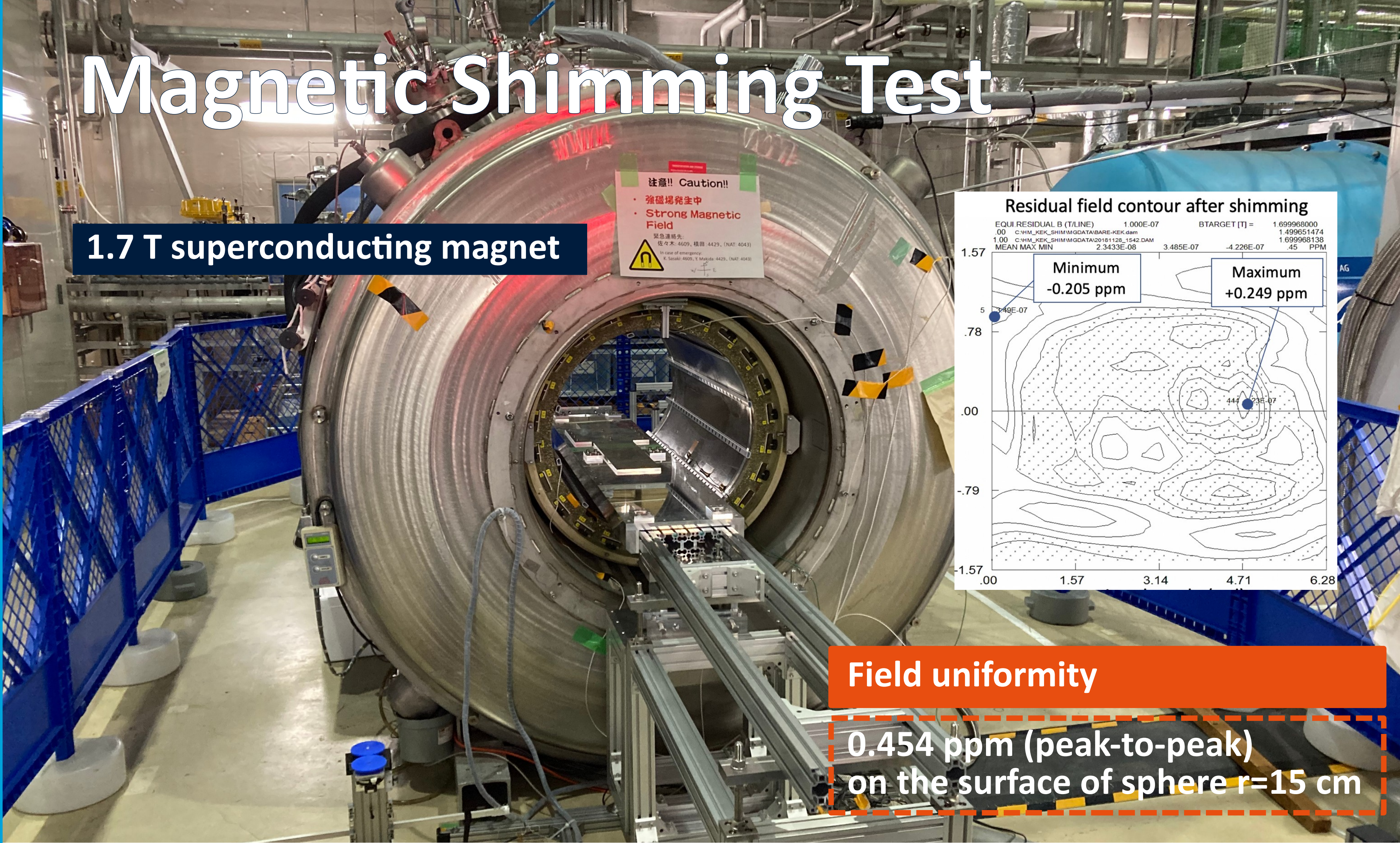






Abe *et al.*, DOI: 10.1016/j.nima.2018.01.026 (2018)
Albahri *et al.*, DOI: 10.1103/PhysRevA.103.042208 (2021)
Semertzidis *et al.*, DOI: 10.1016/S0168-9002(03)00999-9 (2003)

Magnetic Shimming Test

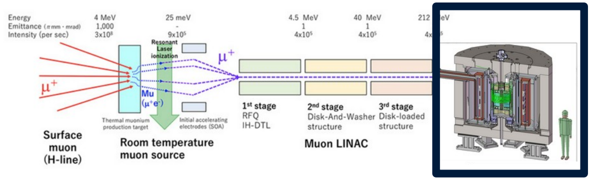


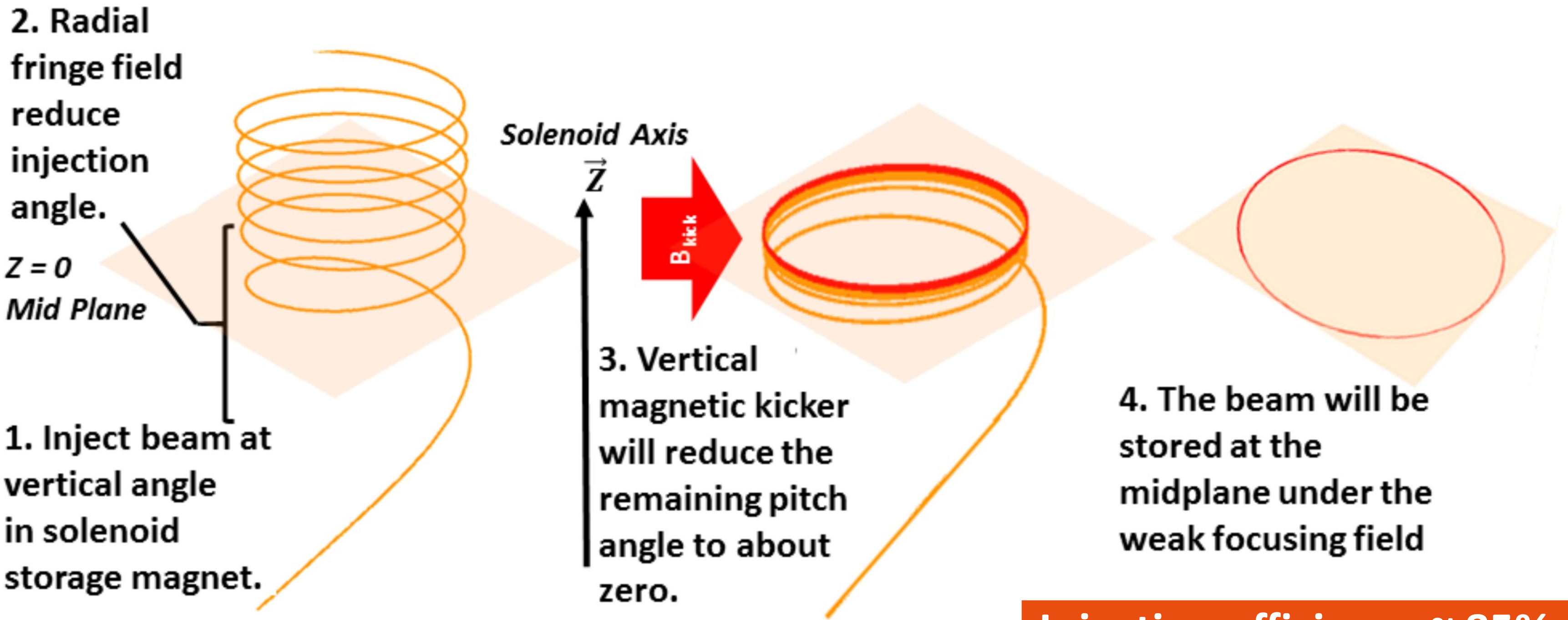
1.7 T superconducting magnet

Field uniformity

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

Spiral Injection

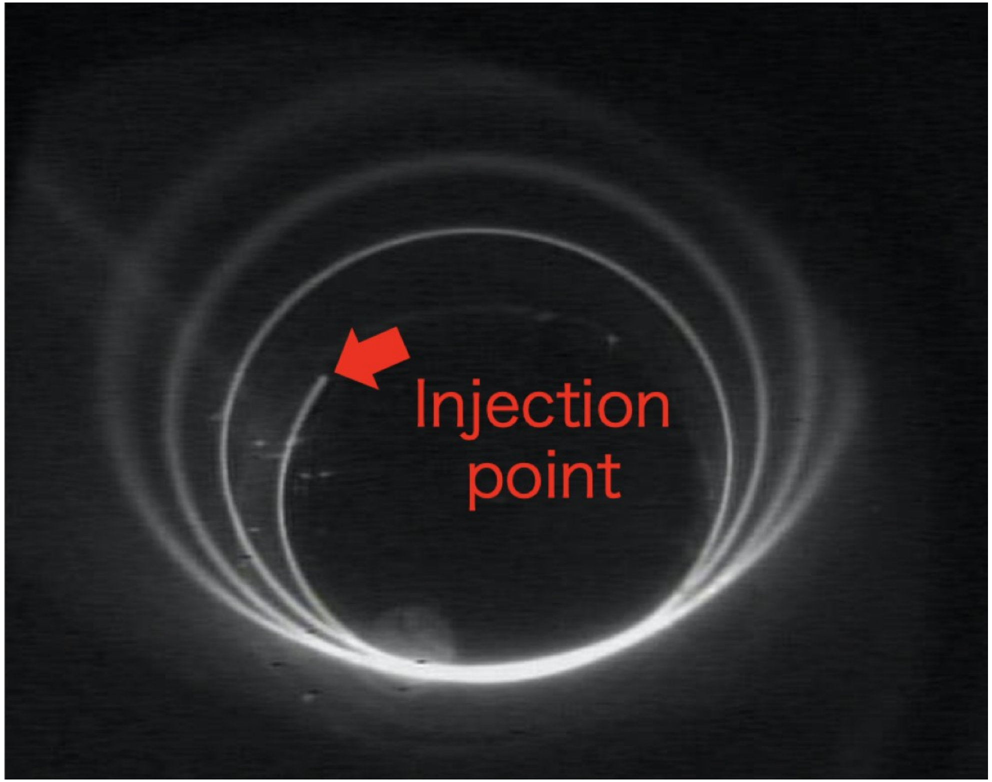


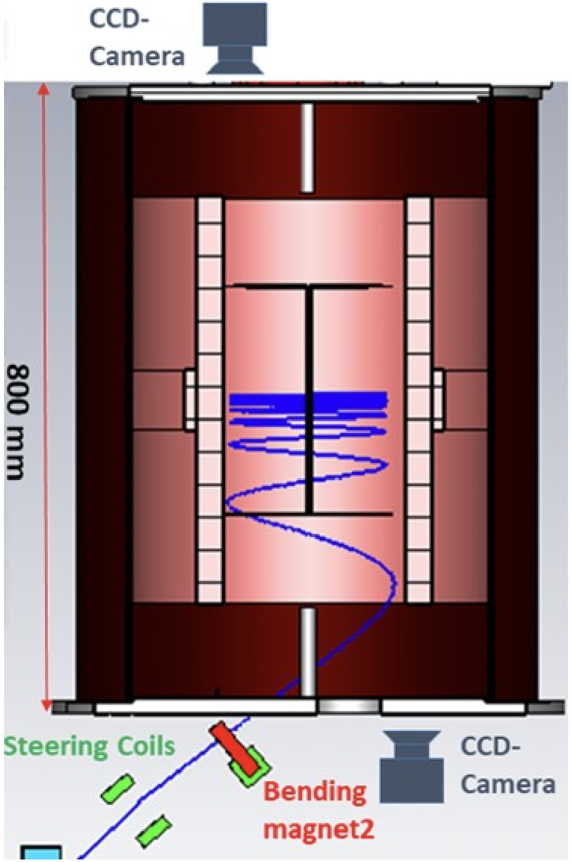


Injection efficiency ~ 85%

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)

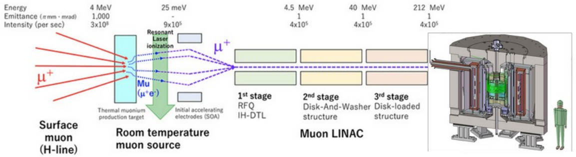
Test w/ Electrons

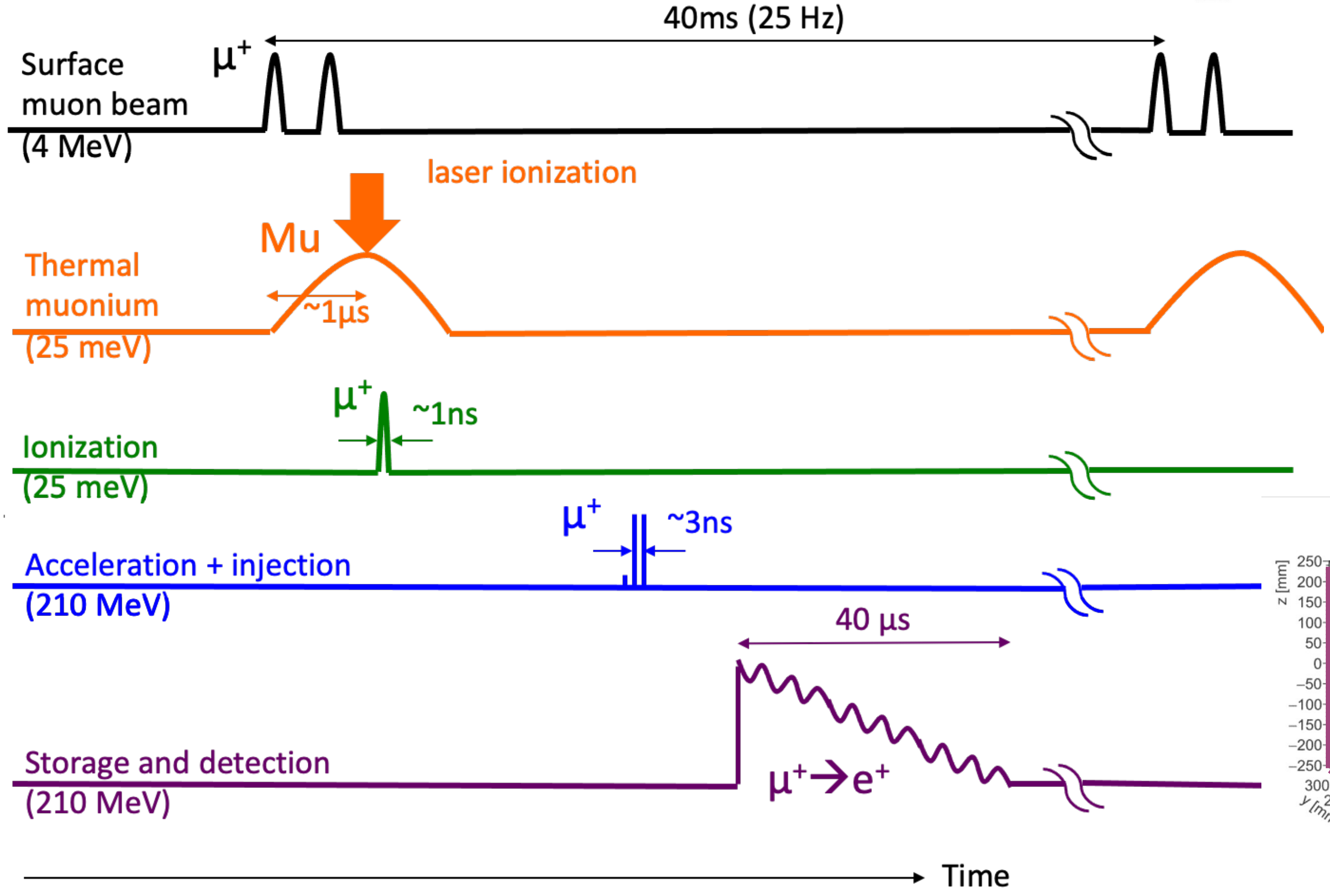


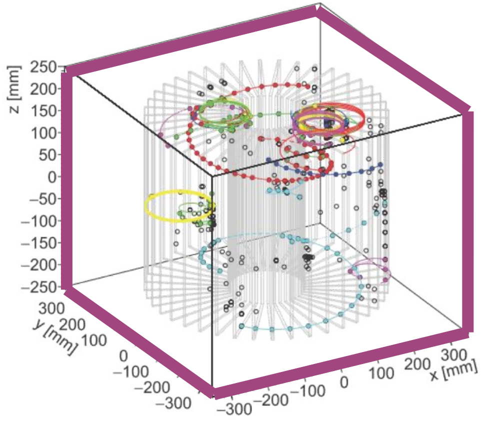


Iinuma *et al.*, Publication forthcoming

Experimental Cycle

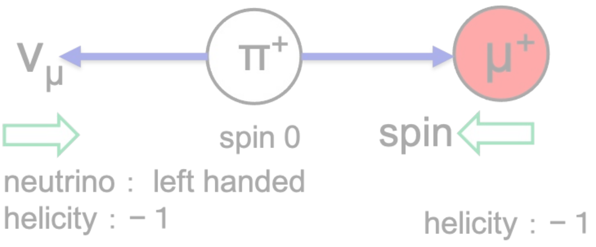




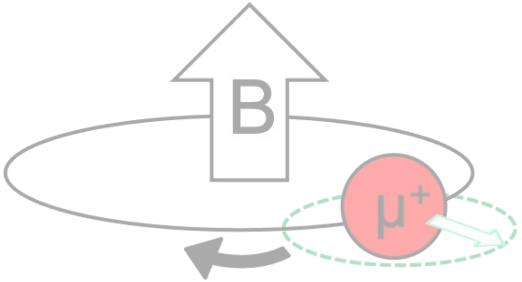


Elements of an MDM or EDM Expt

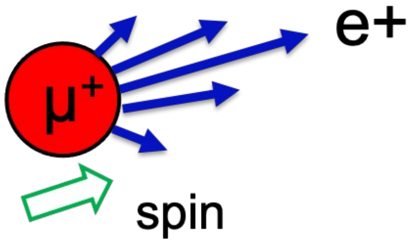
Polarized Muon Production



Storage & Spin Precession



Detection of Spin Orientation



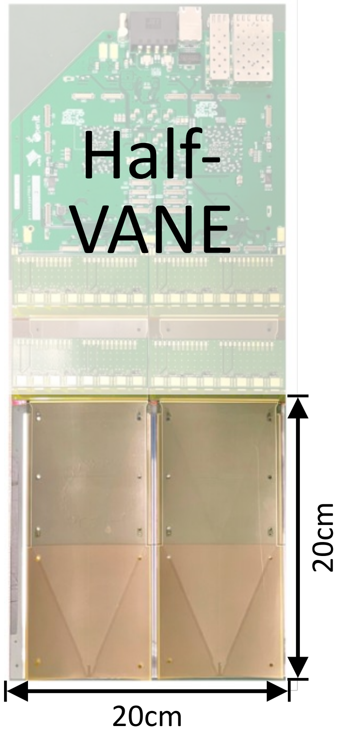
Detection

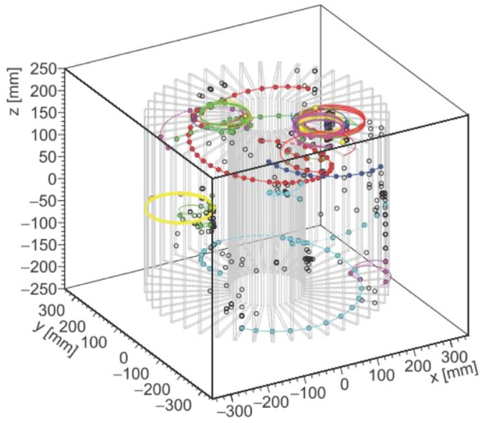
In-field Si-strip Tracker

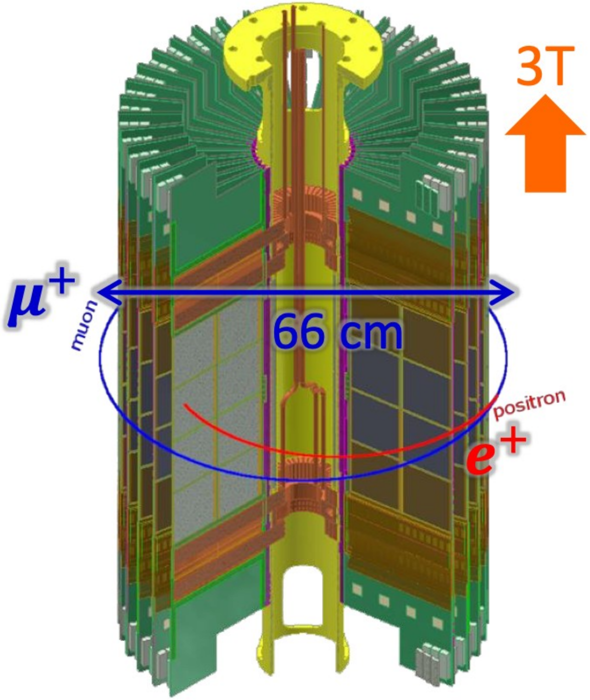
40 vanes
@ 4 x 4 x (H+V) sensors / vane
@ 1024 strips / sensor
@ 5 cm x 190 μm / strip
@ 250 kreads / s (1 frame / 5 ns)
→ (0.5 Tbits/s) → zero-suppress

Spectrometer Specs

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

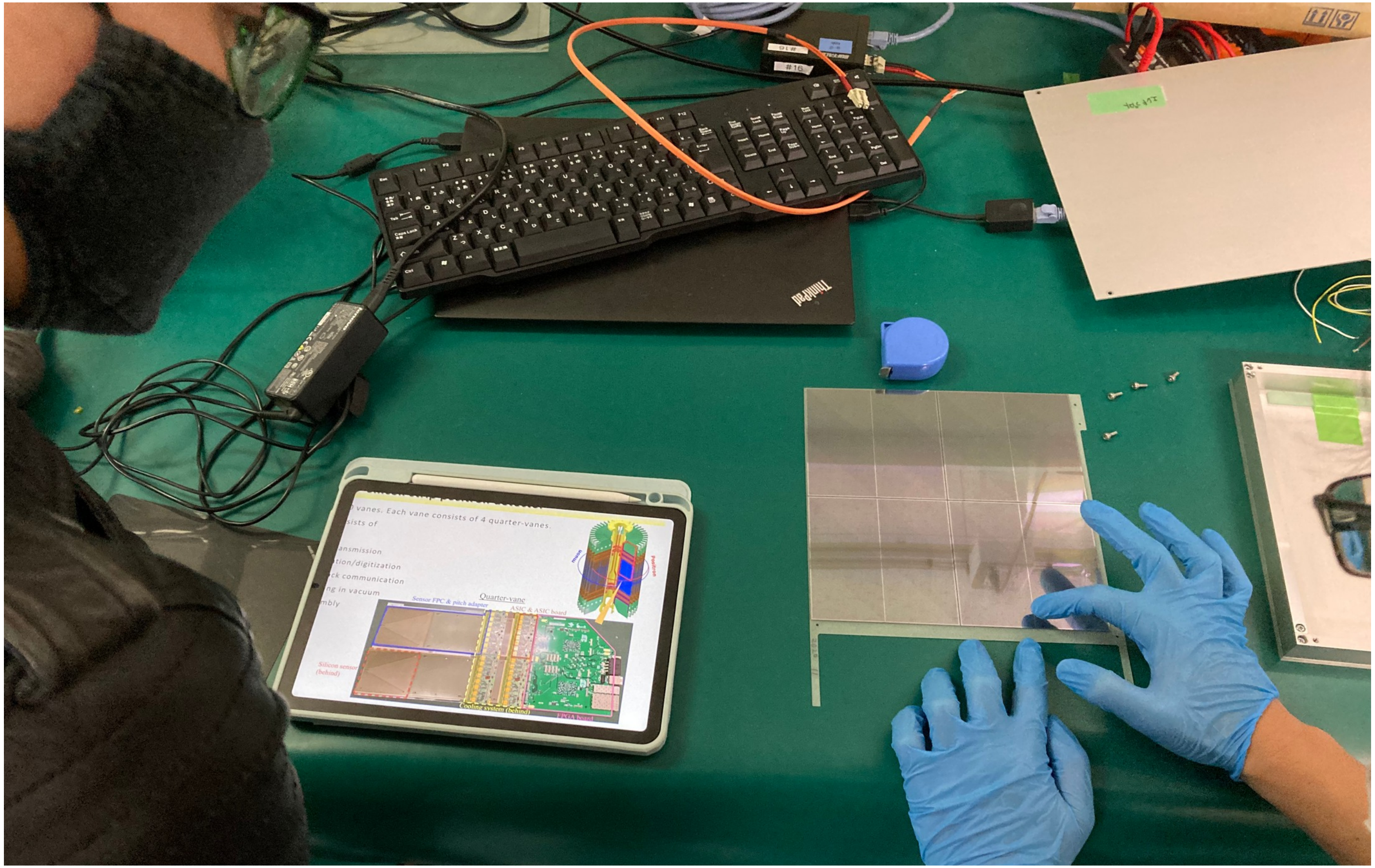






Aoyagi *et al.*, DOI: 10.1088/1748-0221/15/04/P04027 (2020)

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.)

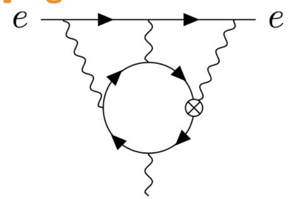
Muon

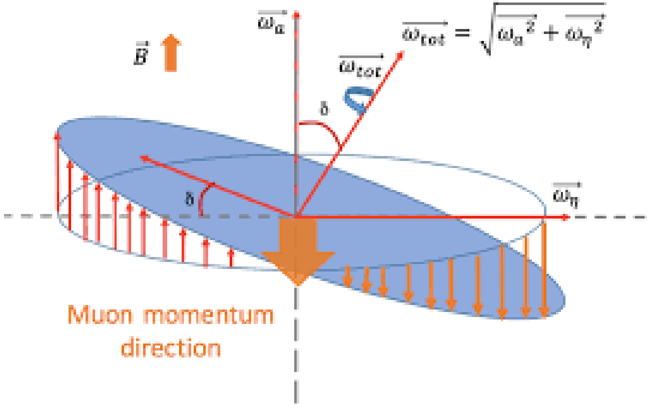
Relativistic E: **g-2** → E_{eff} = v x B = 0.5 GV/m

$|d_\mu| < 1.8 \times 10^{-19}$ *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





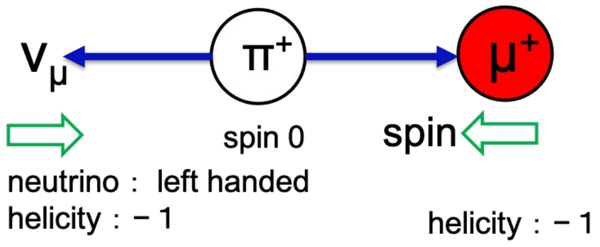
tilt ~ ηβ/2a

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

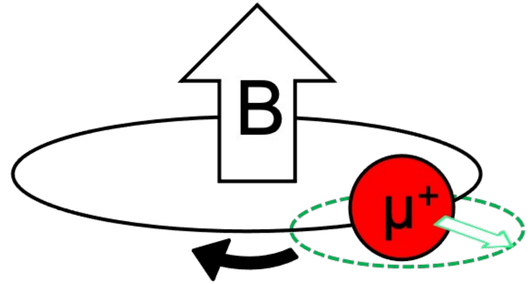
Roussy *et al.*, DOI: https://doi.org/10.48550/arXiv.2212.11841 (2022)
Bennett et al., DOI: 10.1103/PhysRevD.80.052008 (2009)
Ema, Gao, and Pospelov, arXiv:2108.05398 (2021)

Elements of an MDM or EDM Expt

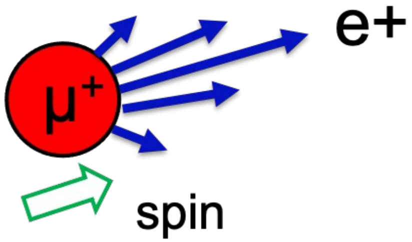
Polarized Muon Production



Storage & Spin Precession



Detection of Spin Orientation



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)

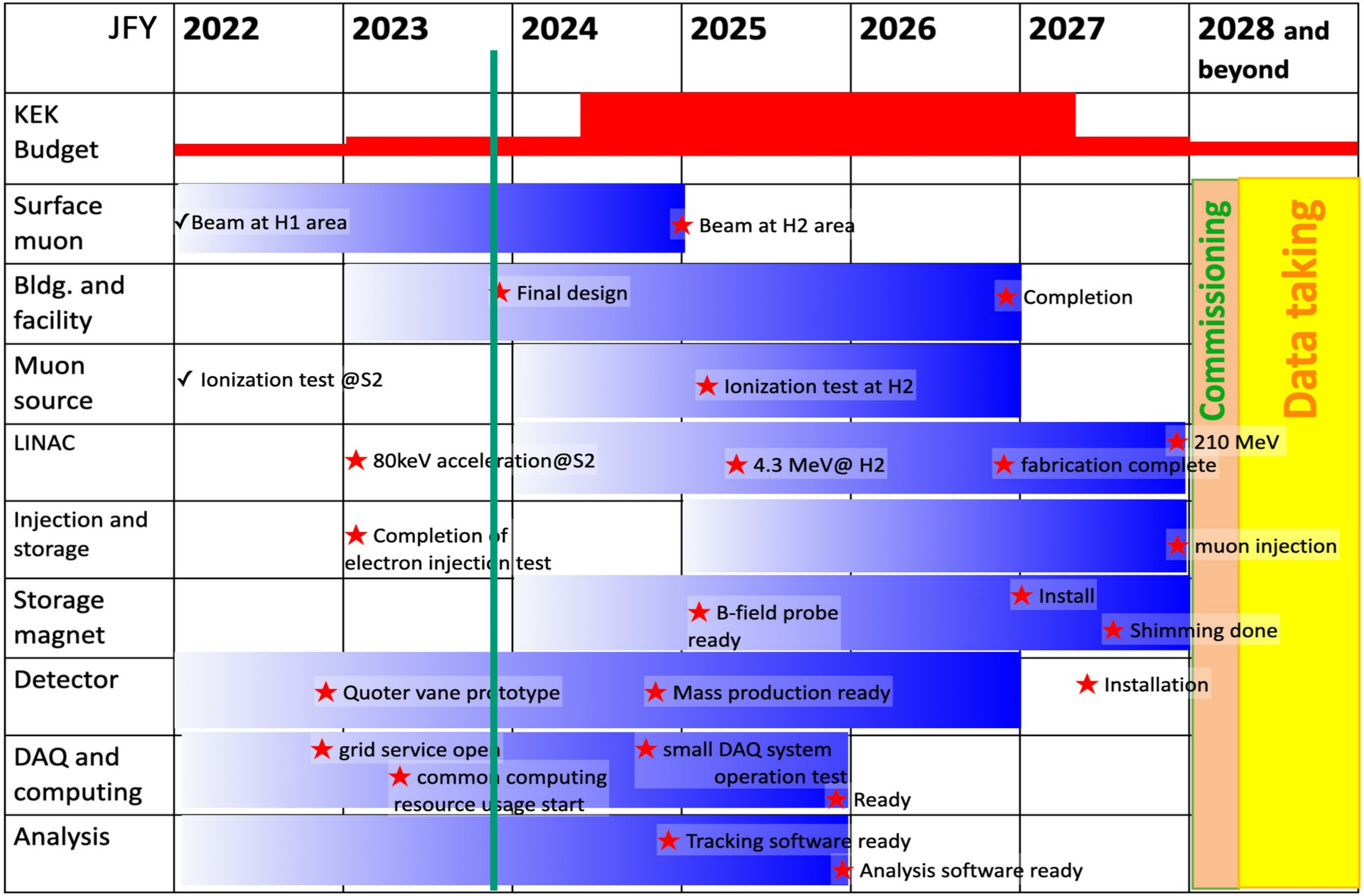
Systematics

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



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

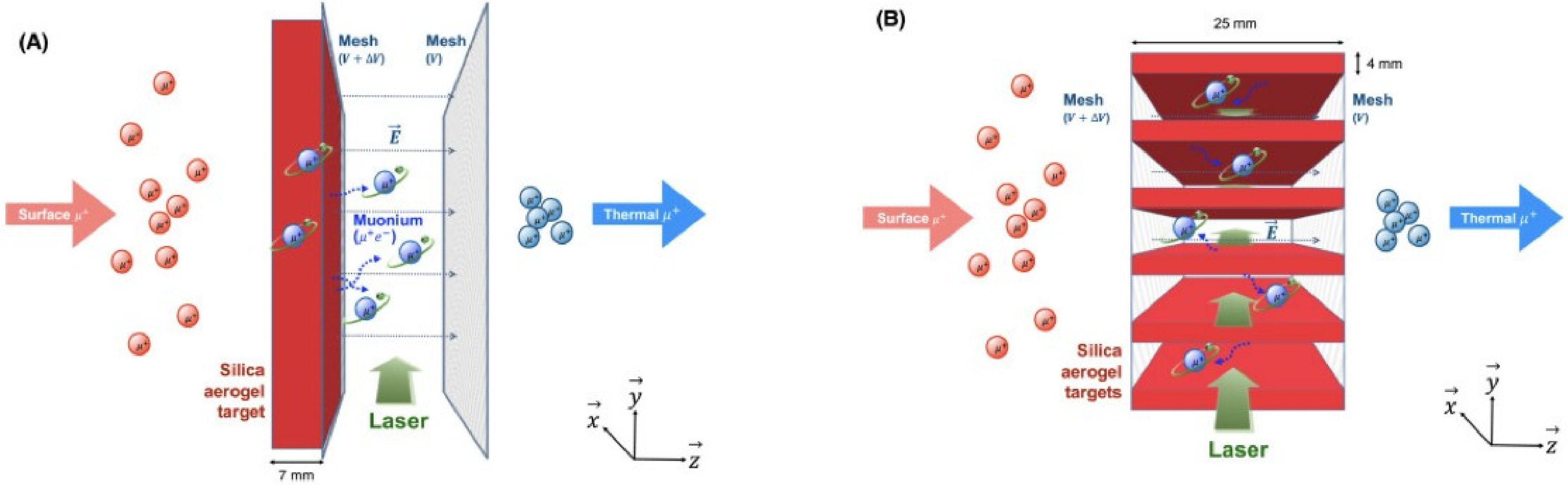
Expected data taking starting in 2028

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