Re-acceleration of Ultra Cold Muon in J-PARC Muon Facility

Y. Kondo*, K. Hasegawa, T. Morishita (JAEA) M. Otani, Y. Fukao, K. Futatsukawa, N. Kawamura, T. Mibe, Y. Miyake, K. Shimomura, T. Yamazaki, M. Yoshida (KEK) R. Kitamura, S. Li (Univ. of Tokyo) Y. Nakazawa, H. Iinuma (Ibaraki Univ.) Y. Sue, T. Iijima (Nagoya Univ.) K. Ishida (RIKEN) N. Hayashizaki (Tokyo Institute of Technology) Y. Iwashita (Kyoto Univ.) Y. Iwata (NIRS) N. Saito (J-PARC center) S Bae, H. Choi, S. Choi, B Kim, H. S. Ko (SNU) E. Won (Korea Univ.) G. P. Razuvaev (BINP)

* yasuhiro.kondo@j-parc.jp

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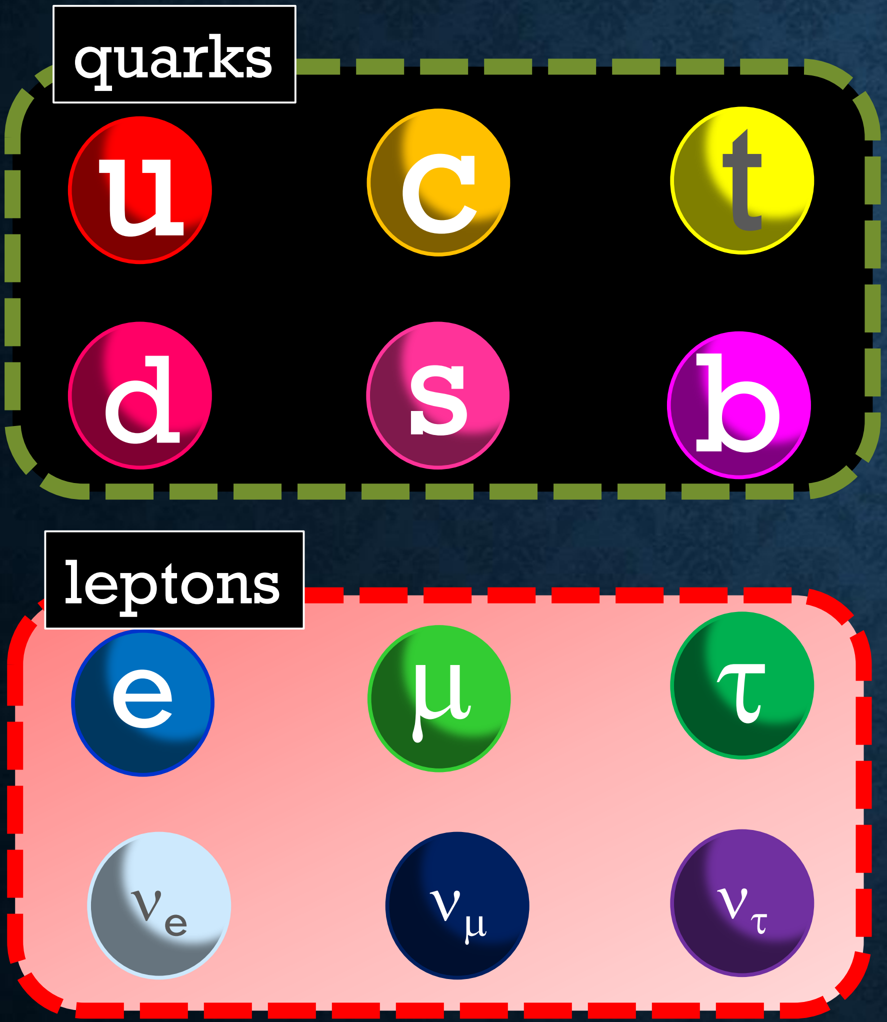
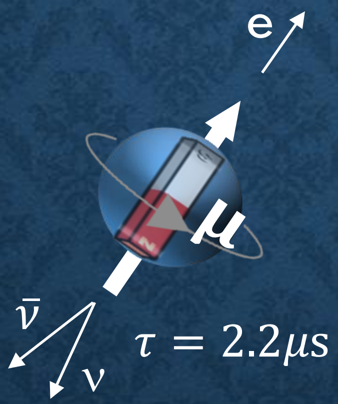
1. Muon science at J-PARC

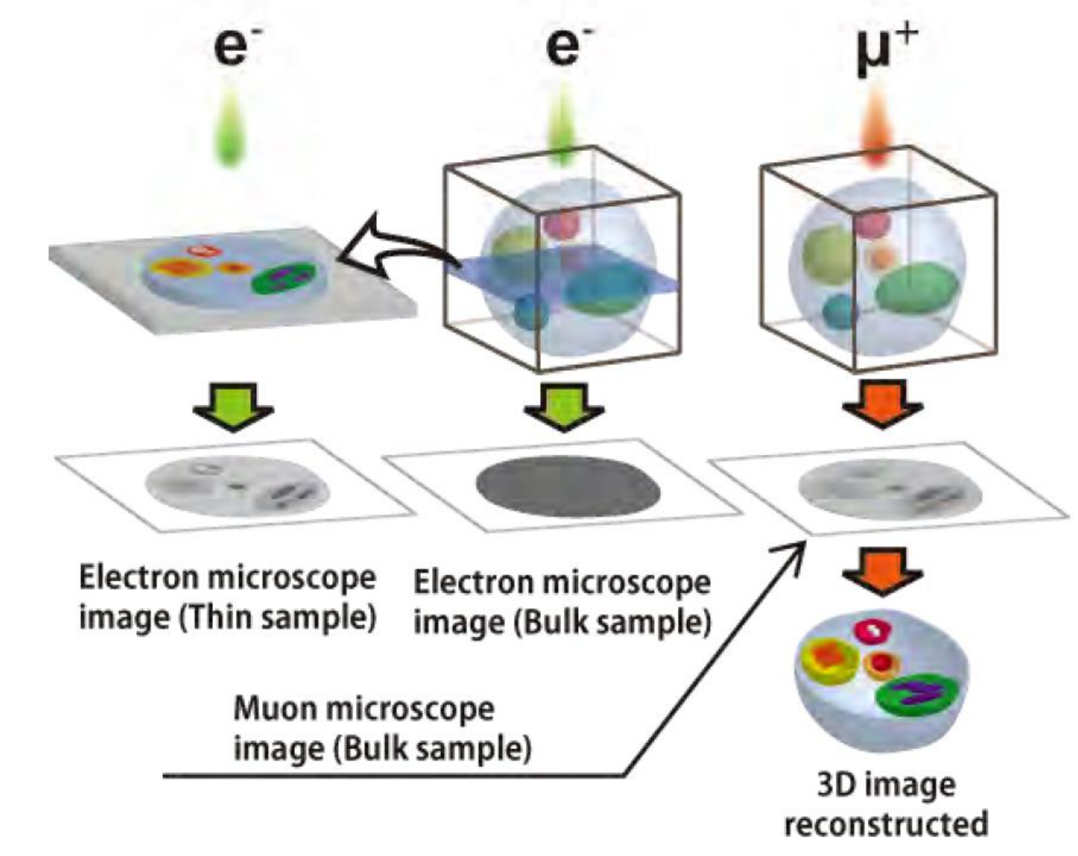




Courtesy of S. Kondo

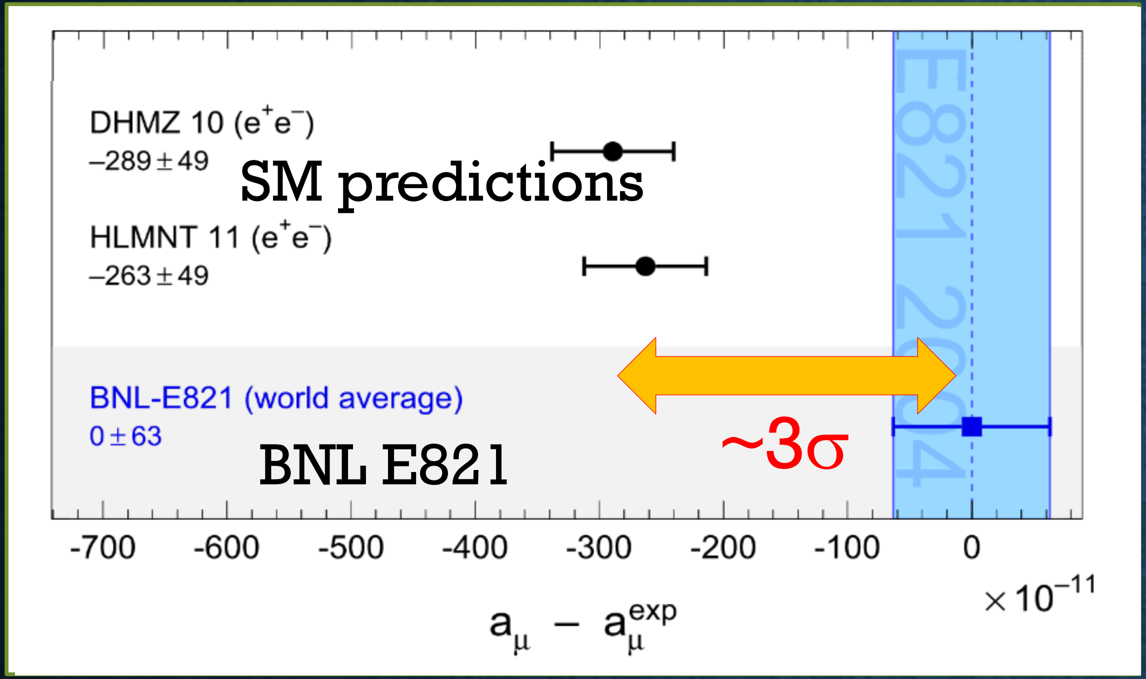
- 2^{nd} generation charged lepton like electron.
- spin $\frac{1}{2}$, direction is easily measured by decay products → good magnetic probe.
- $m_\mu \sim 200 \times m_e$
  - High penetration
  - Sensitive to unknown particles

Transmission muon microscopy



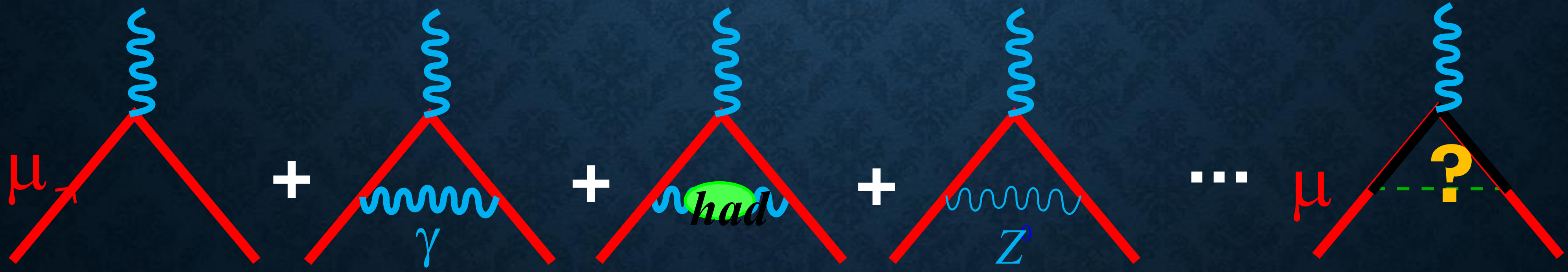
- 3D imaging of living cells using deep penetration.
- Require extremely small emittance muon beam ~10 MeV.

Beyond the Standard Model? – muon g-2



$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{S}$$

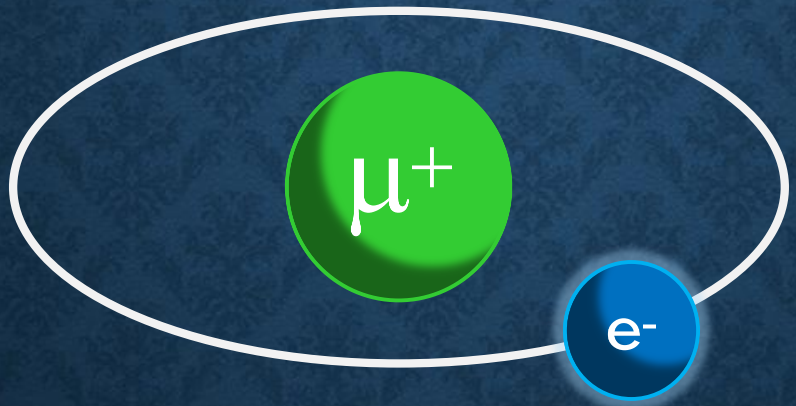
$$a_\mu = \frac{g-2}{2}$$



$g = 2$ QED Hadronic Weak Beyond SM?

THE CHARACTERS

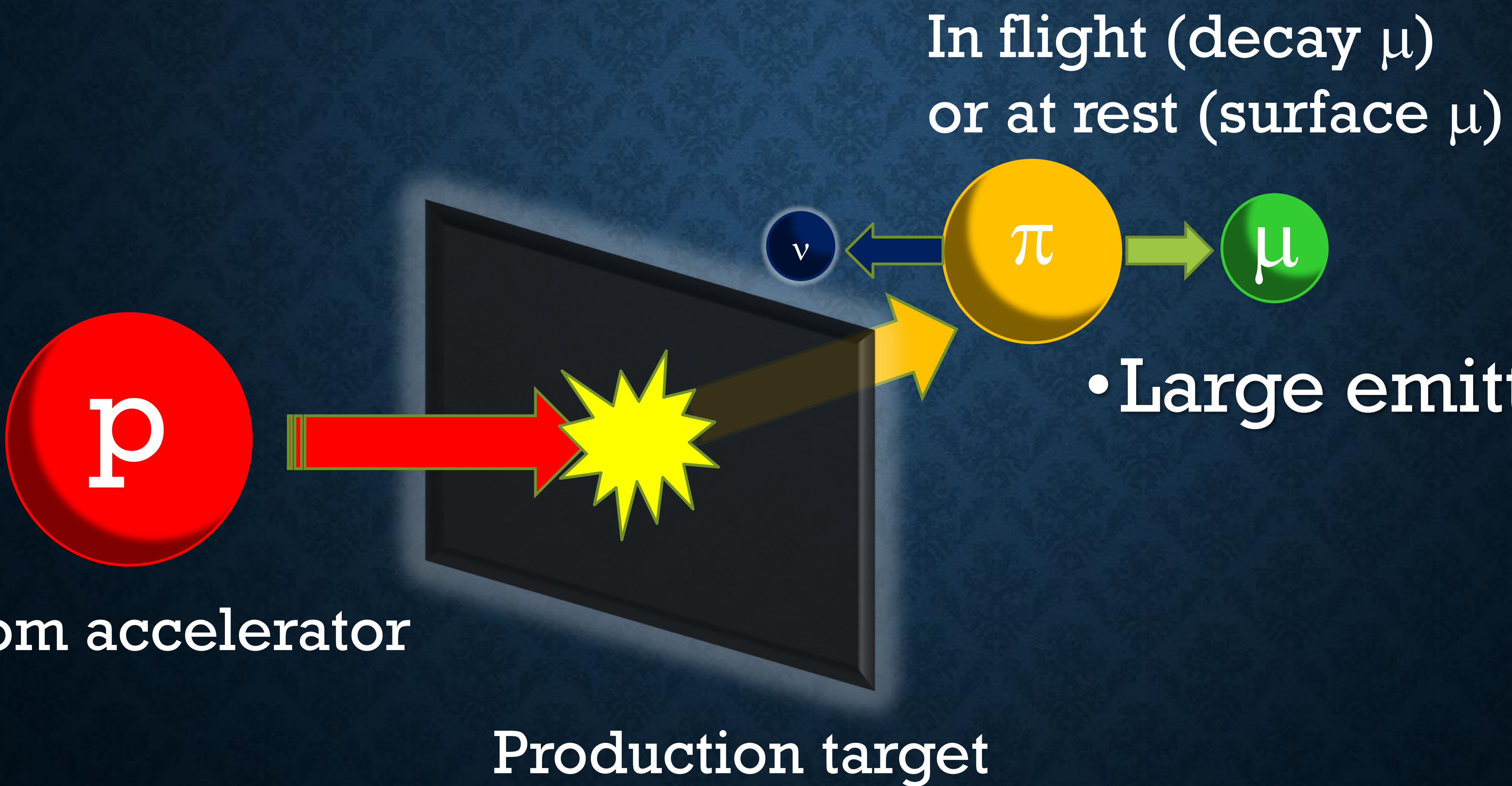
positive muon



neutral Muonium
(Mu: μ^+e^-)

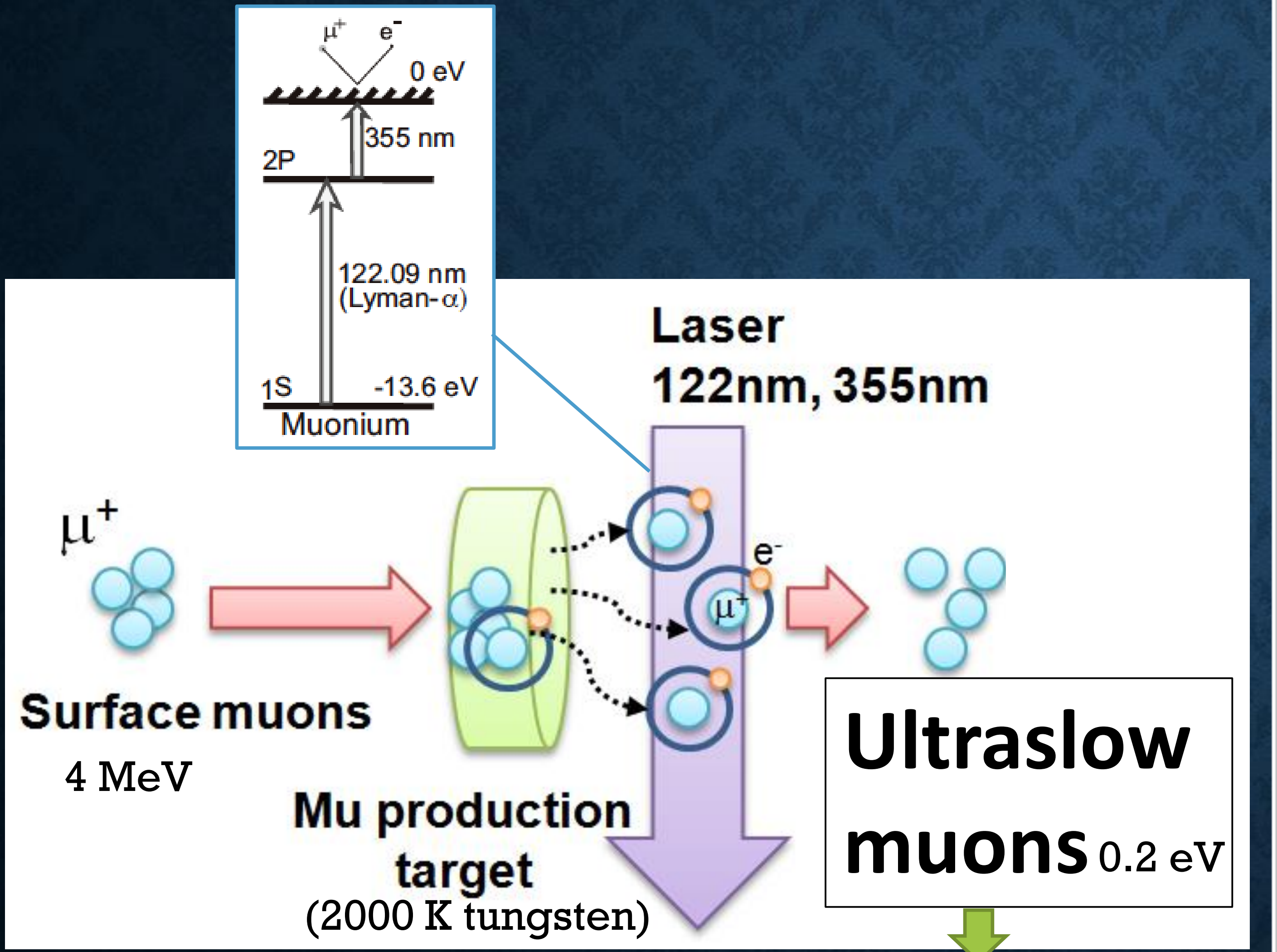
negative Muonium
(Mu^-: $\mu^+e^-e^-$)

Conventional muon production process



- Large emittance!

Ultra Slow Muon (USM) developed at KEK



Re-accelerate
→ Ultra Cold Muon beam

1985
Generation of thermal muoium
Mills, Imazato, Nagamine et al.,
Phys. Rev. Let. **56**, 14, p1463 (1986)

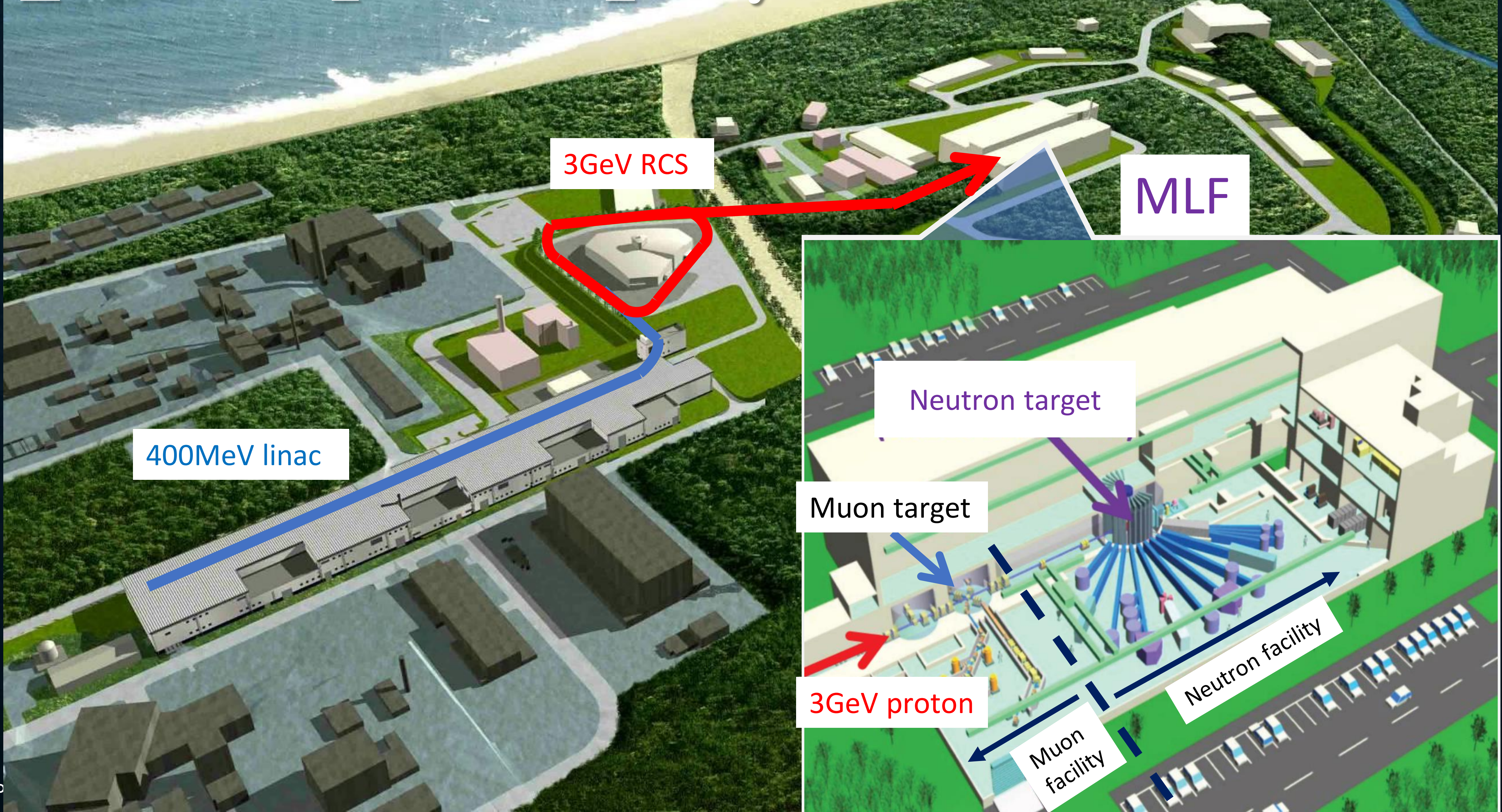
1987
Laser excitation fo muoium
Chu, Mills, Kuga, Yodh, Miyake, Nagamine et al.,
Phys. Rev. Let. **60**, 2, p101 (1988)

1990
USM @ KEK
Nagamine, Miyake, Shimomura et al.,
Phys. Rev. Let. **74**, 24, p4811 (1995)

1999
USM @ RIKEN-RAL
Bakule, Matusuda, Miyake, Nagamine, Shimomura et al.,
NIM B **266**, p335 (2008)

2010
USM @ J-PARC

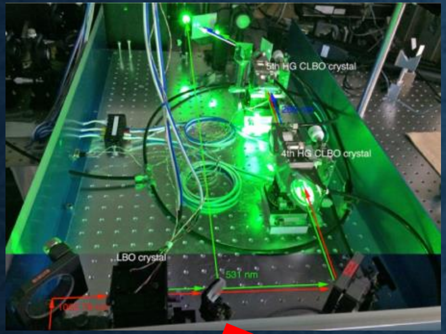
J-PARC MLF
Materials and Life science Facility



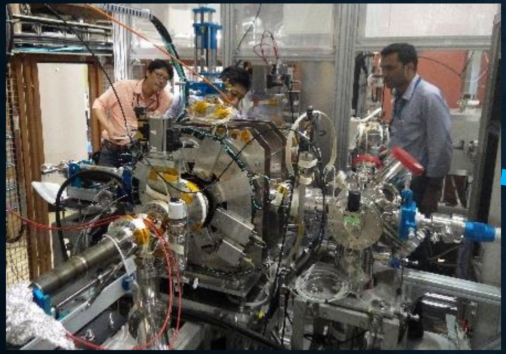
J-PARC MUSE

MUon Science Establishment

Laser system
for U-line



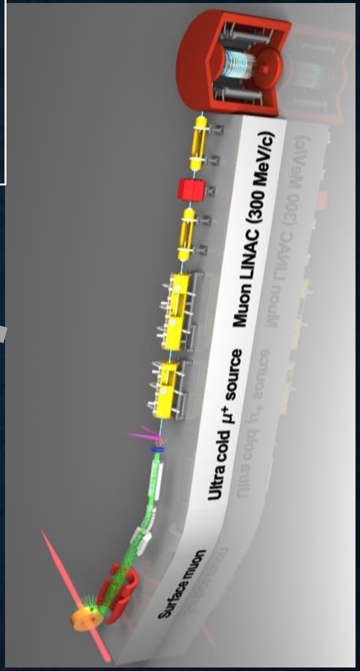
U1A
μSR spectrometer



Shielding only

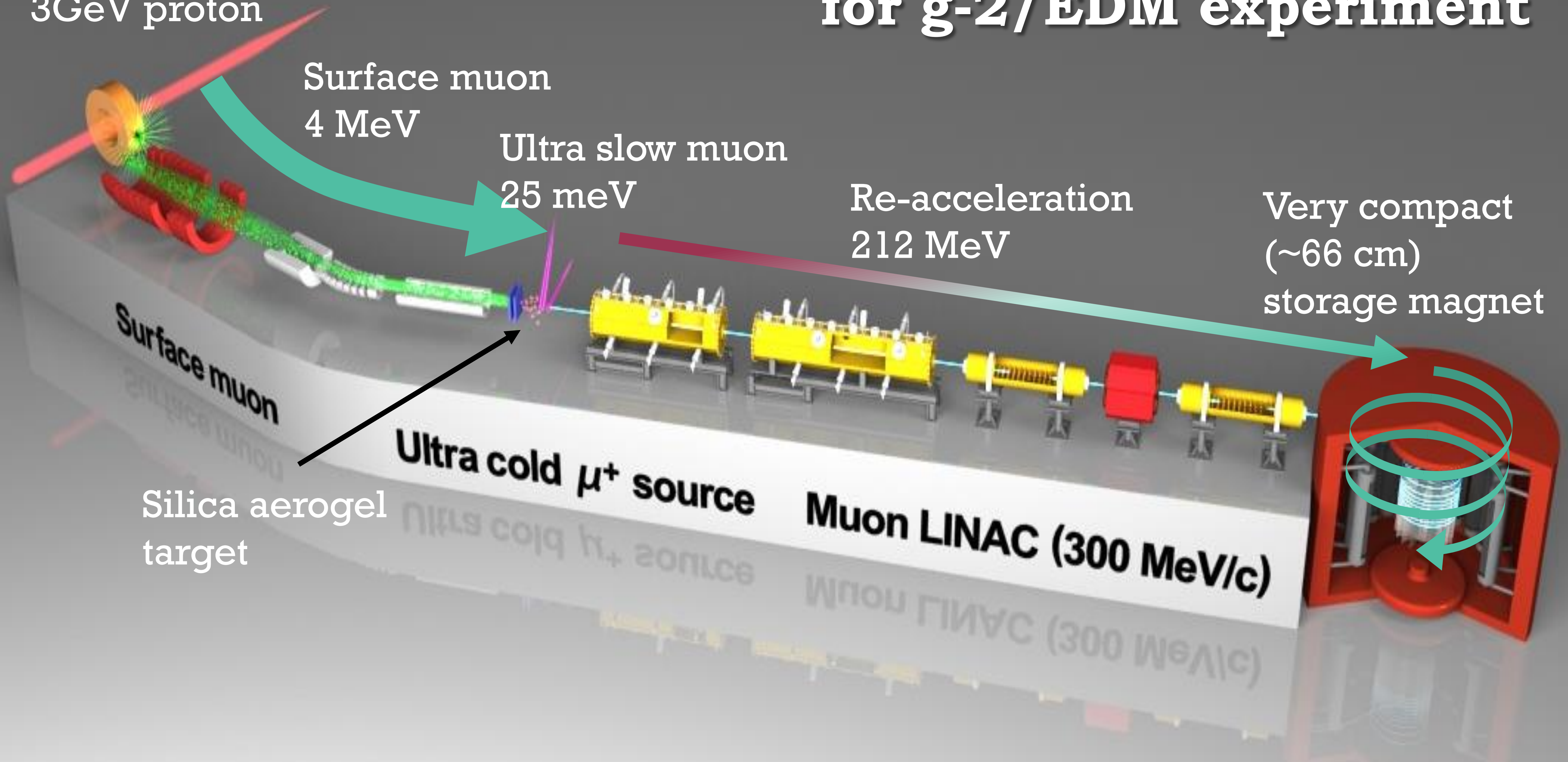
U-line
USM beamline

H-line
Transmission muon
microscope
& g-2/EDM

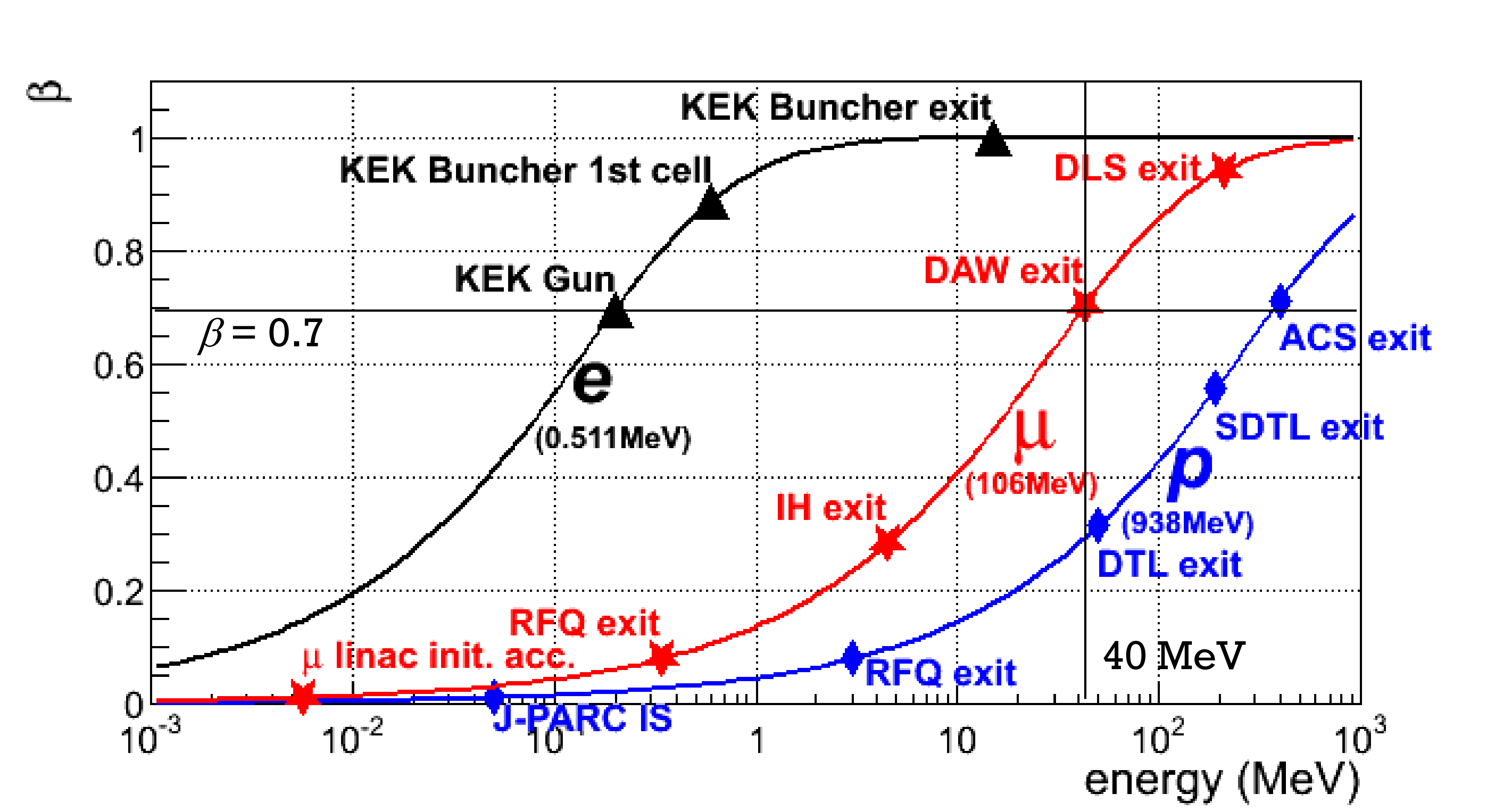


U1B
Development of
transmission muon
microscope

2. Muon linac (μ linac) for g-2/EDM experiment

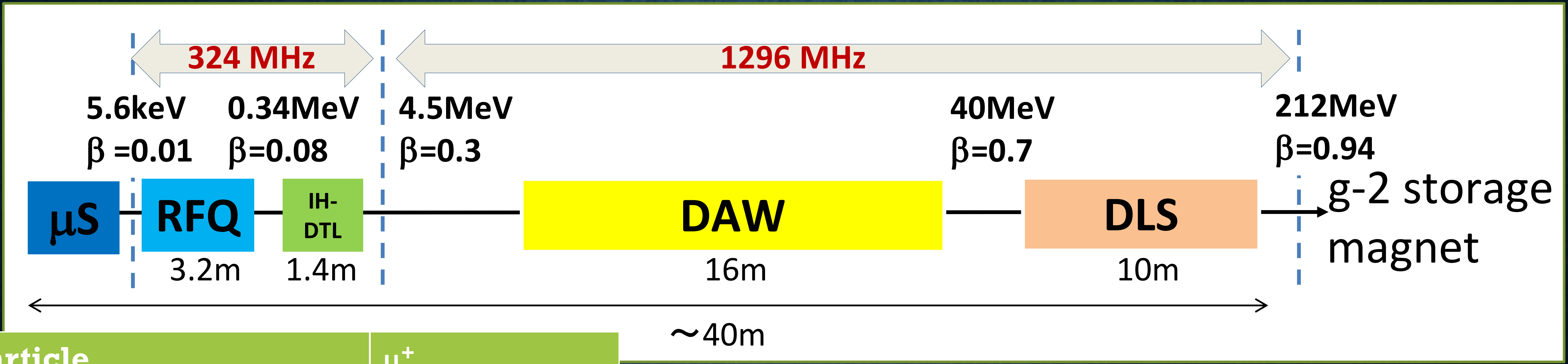


Comparison e, μ, p linac



- 200 x $m_e \sim m_\mu$ (105.7 MeV) $\sim m_p/9$

Configuration of μ LINAC

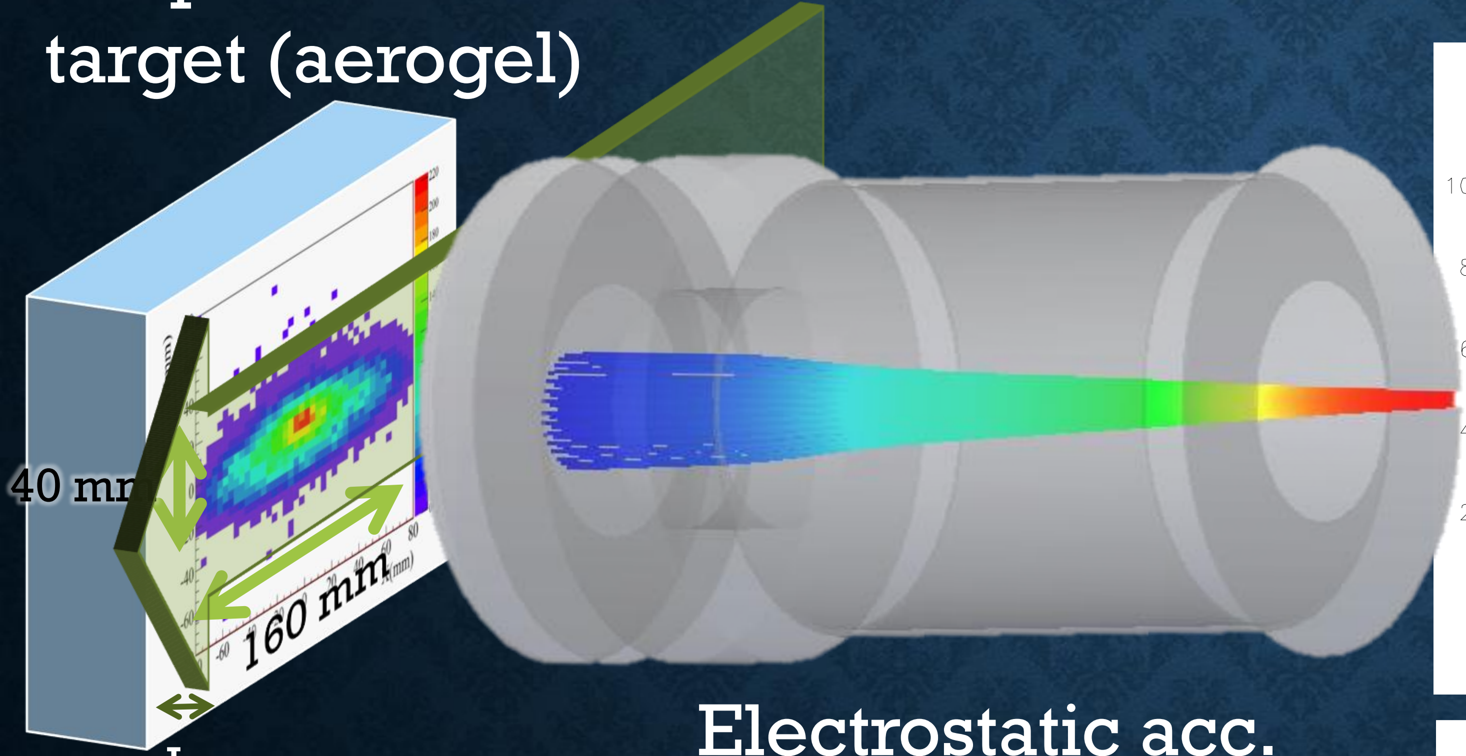


Particle	μ^+
Energy	212 MeV
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Normalized rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- 2-stage frequency, 4-structures.
- Comparable emittance to p linac, but very low intensity.
- p-e linac hybrid.

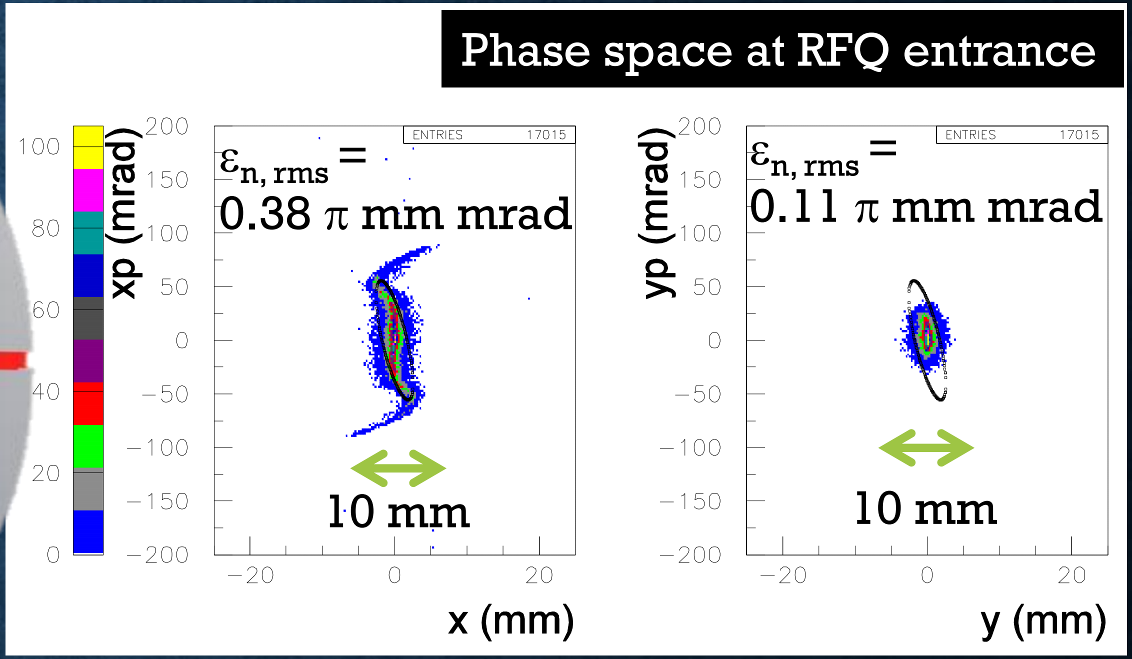
Initial acceleration to 5.6 keV

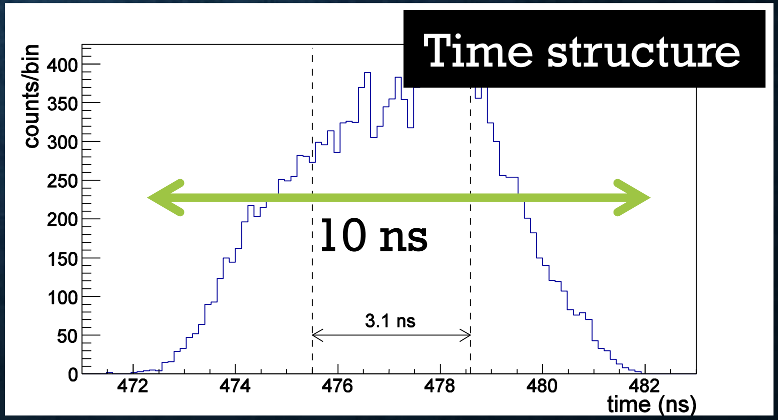
Mu production target (aerogel)



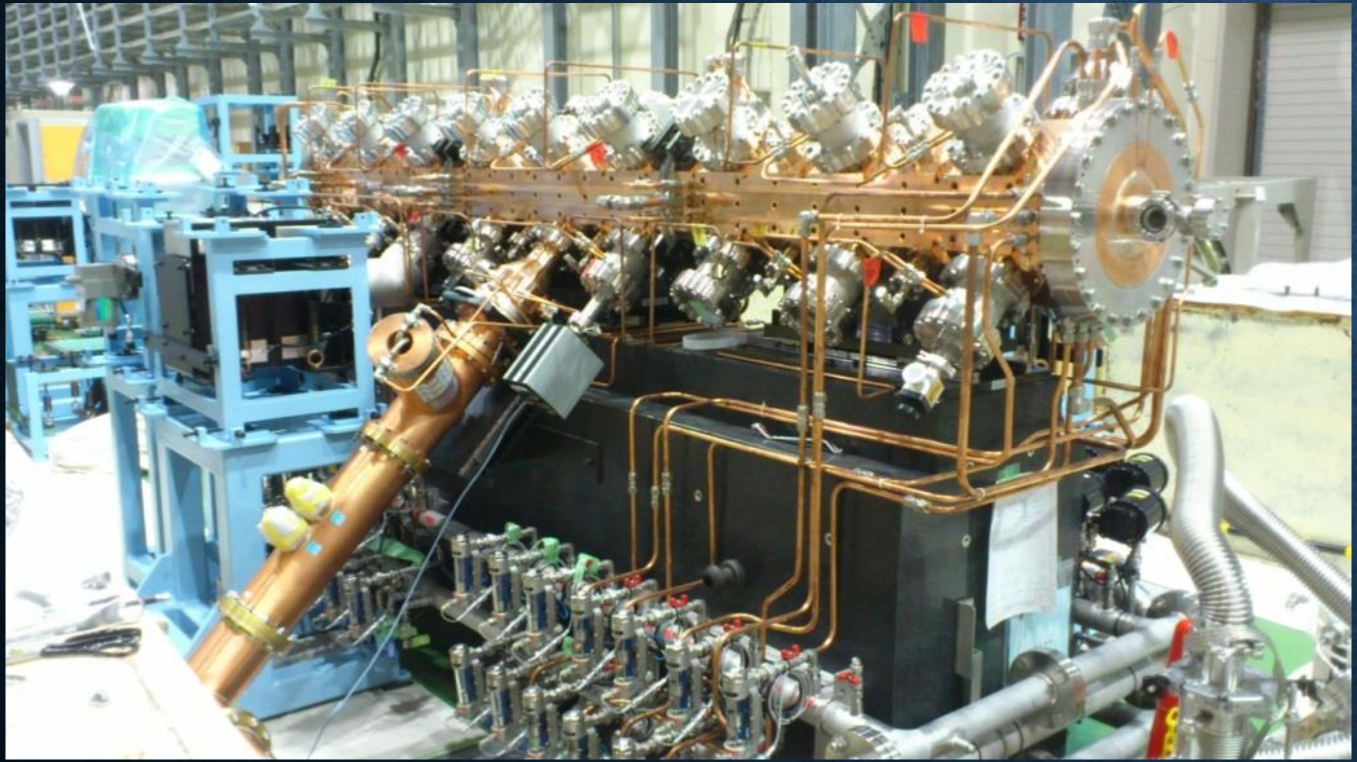
Laser
Spot width 6 mm
Pulse length 1 ns

Electrostatic acc.
And focus





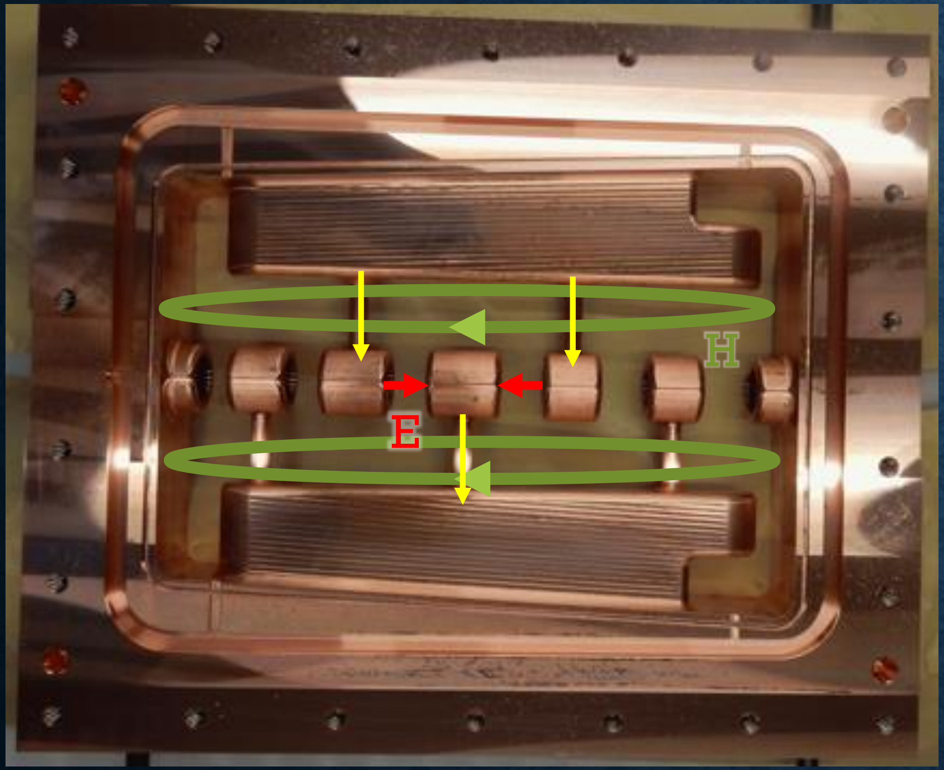
324-MHz structure 1. RFQ 0.056 to 0.34 MeV



	H^-	μ
Particle mass (MeV/c^2)	939.3	105.7
Intervane voltage (kV)	83	9.3
Power dissipation (kW)	330	4.2
Input energy (keV)	50	5.6
Output energy (MeV)	3	0.34

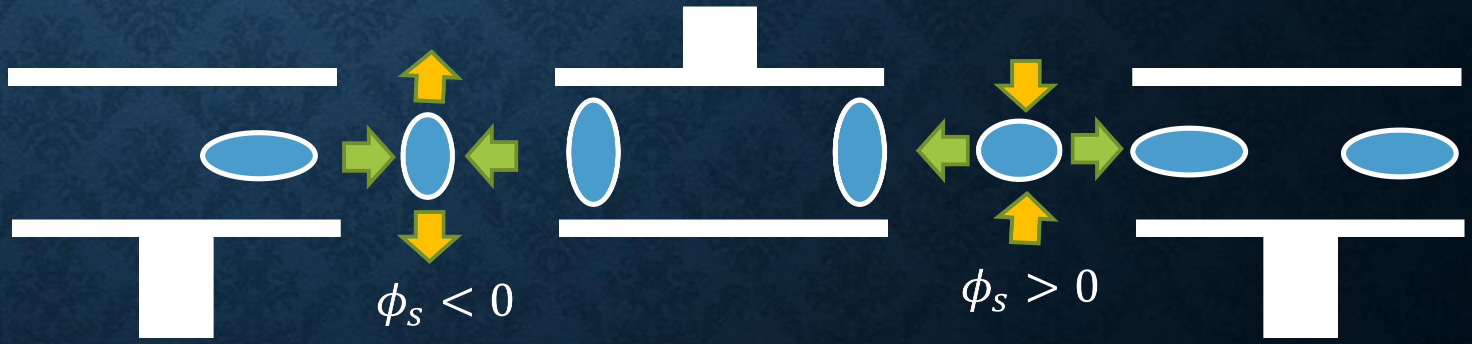
- J-PARC RFQ II (A spare of 30mA RFQ)

324-MHz structure 2. APF IH-DTL - 0.34 MeV to 4.5 MeV



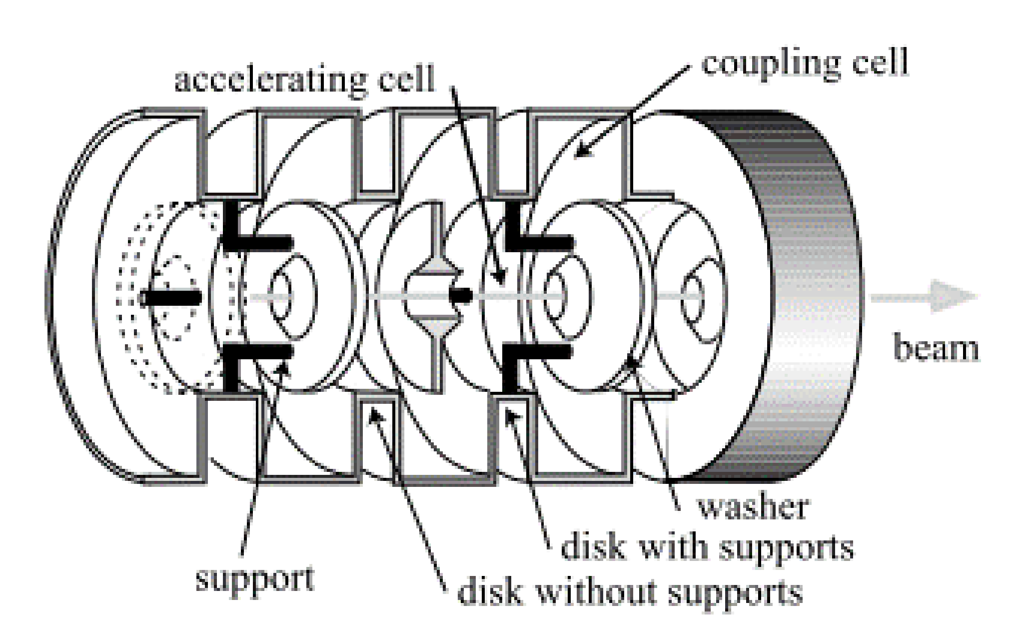
6-cell prototype cavity
(final version is 16-cell 1.3 m)

- TE110 mode (H mode) cavity
- π mode operation $\left(l_c = \frac{\beta\lambda}{2}\right)$
- Alternative Phase Focusing (APF)

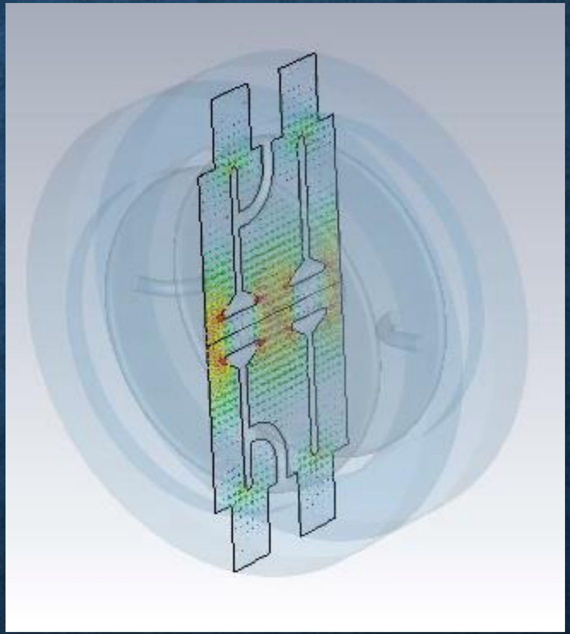


Transverse: defocus | focus
longitudinal: focus | defocus

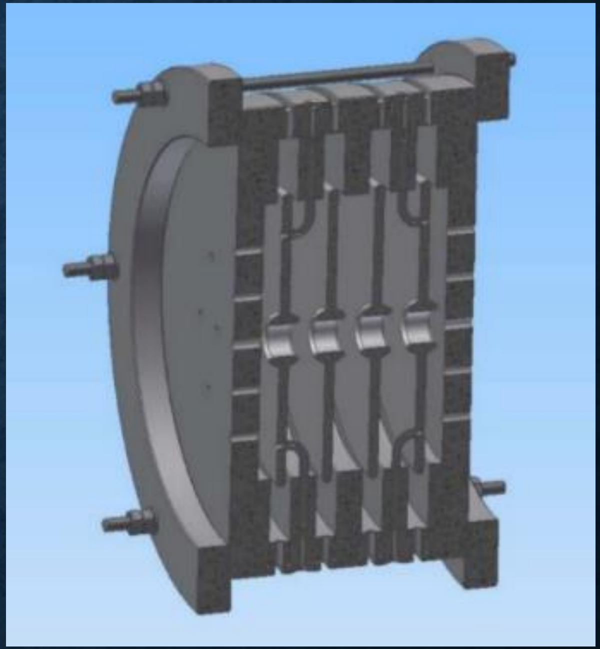
1296-MHz structure 1. DAW CCL - 4.5 to 40 MeV



Disk and Washer (DAW) structure



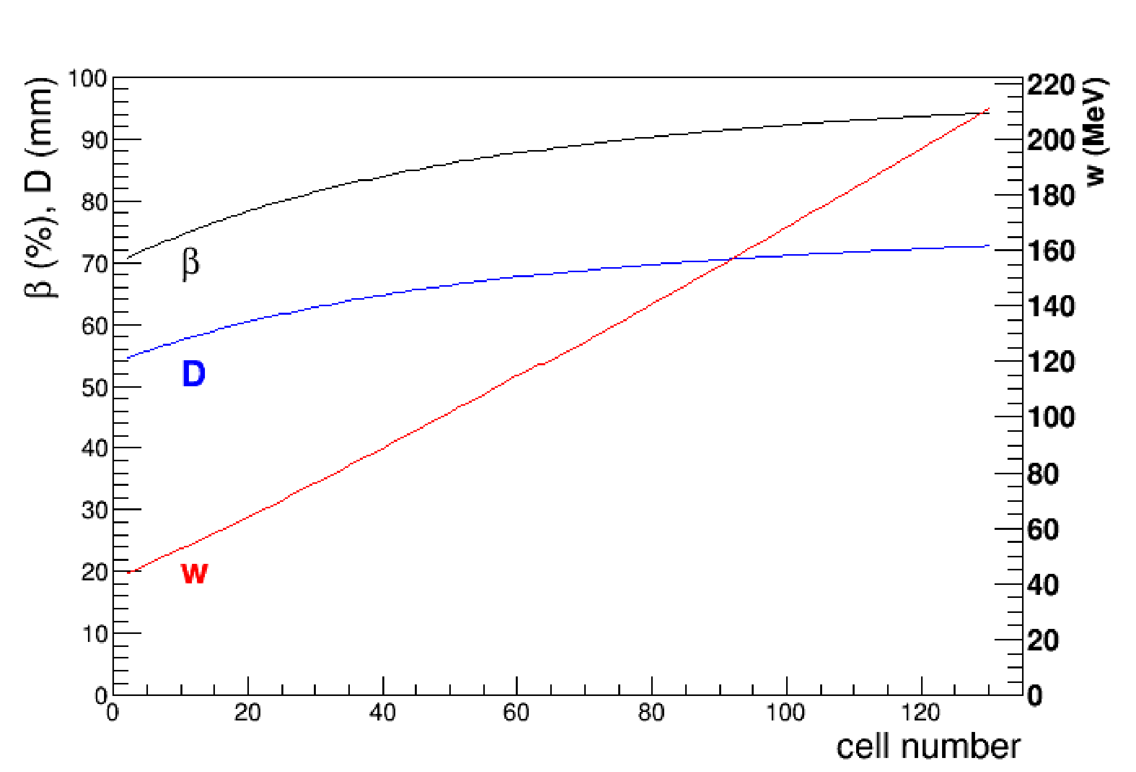
CST model
E_0 = 5.6 MV/m



Cold model

- Section total (15 modules, 16m) 4.5 MW

1296-MHz structure 2.
Disk loaded travelling wave structure – 40 to 212 MeV

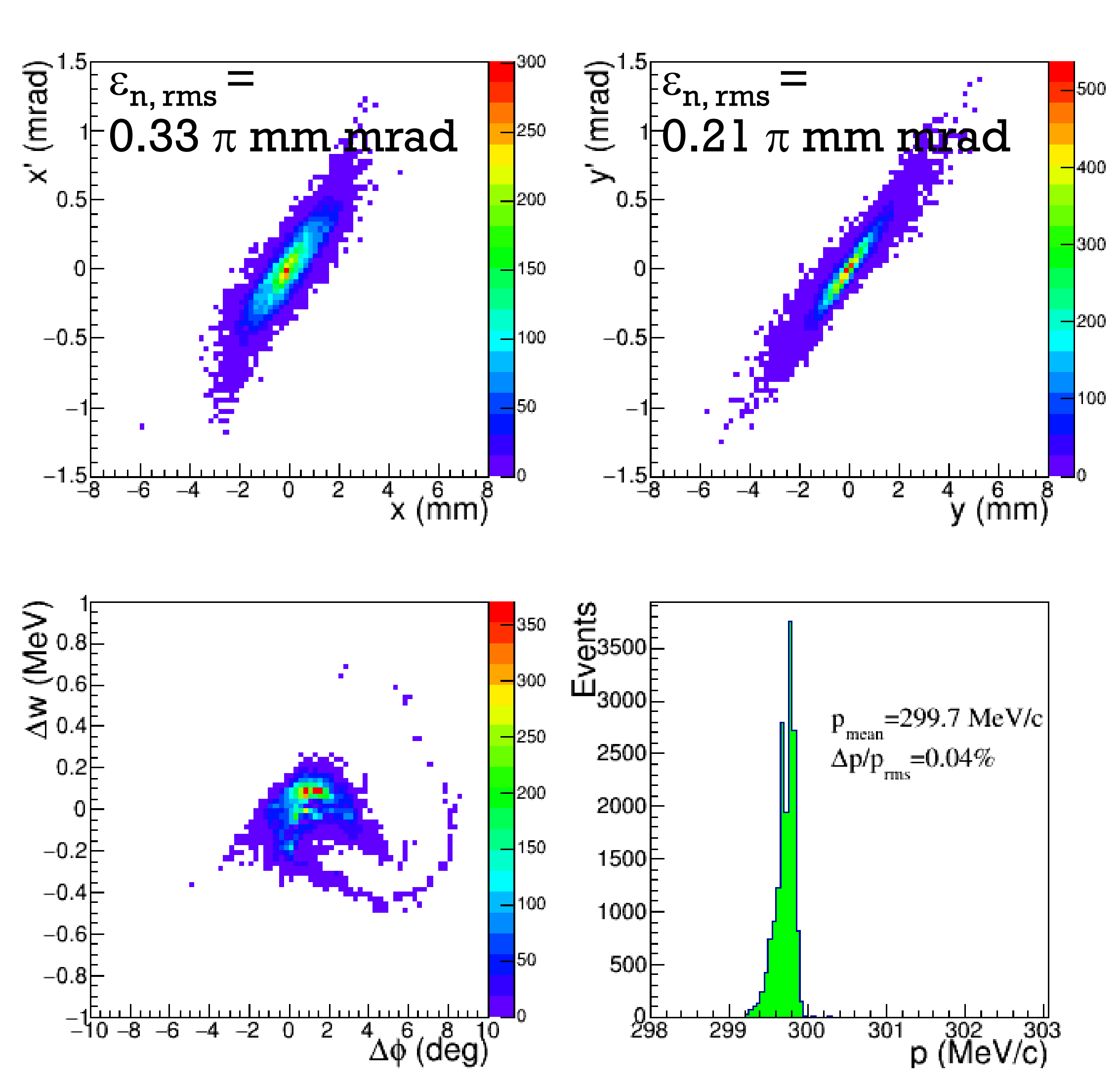


$$D = \frac{\beta\lambda}{3} \left(\frac{2\pi}{3} \text{ mode}\right)$$

D cell length
β synchronous velocity

Main parameters of DLS section	
Acceleration gradient	20 MV/m
Synchronous phase	-10°
Number of acc. tubes	4

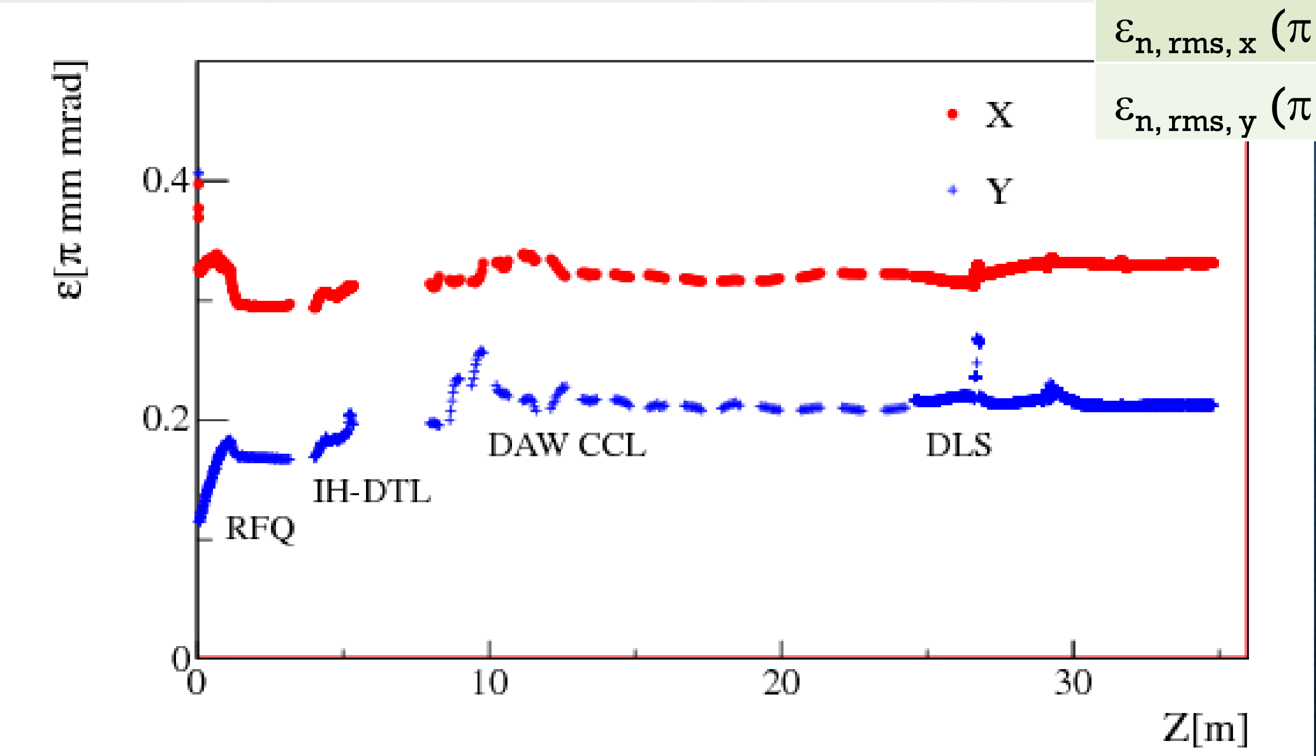
Simulated phase-space distribution @ μ linac exit



E2E simulation summary

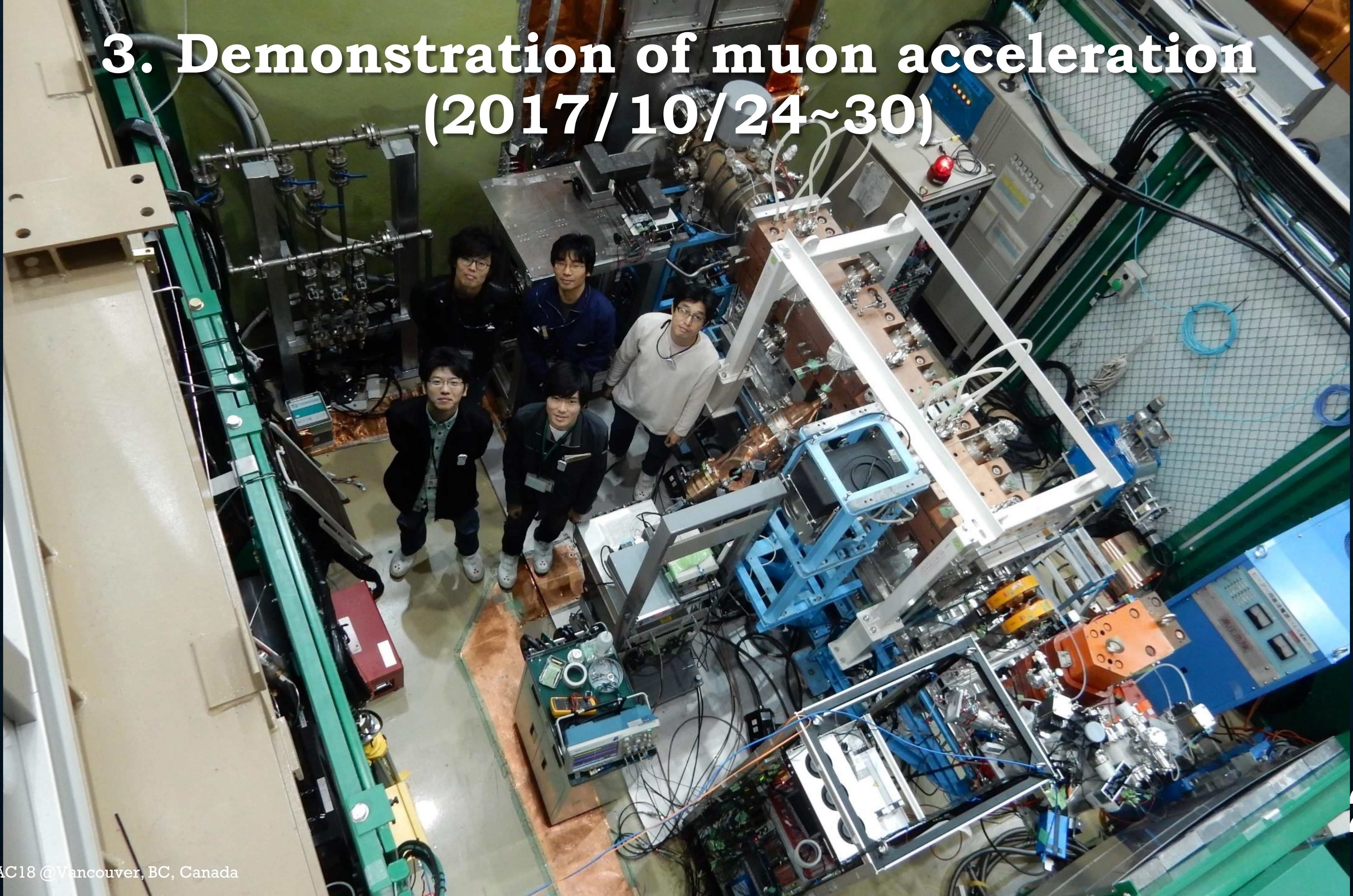
	Initial	RFQ	IH	DAW	DLS
transmission (%)	87	94.7	100	100	100
Decay loss (%)	17	19	1	4	1
$\varepsilon_{n,\,rms,\,x}$ (π mm mrad)	0.38	0.30	0.32	0.32	0.33
$\varepsilon_{n,\,rms,\,y}$ (π mm mrad)	0.11	0.17	0.20	0.21	0.21

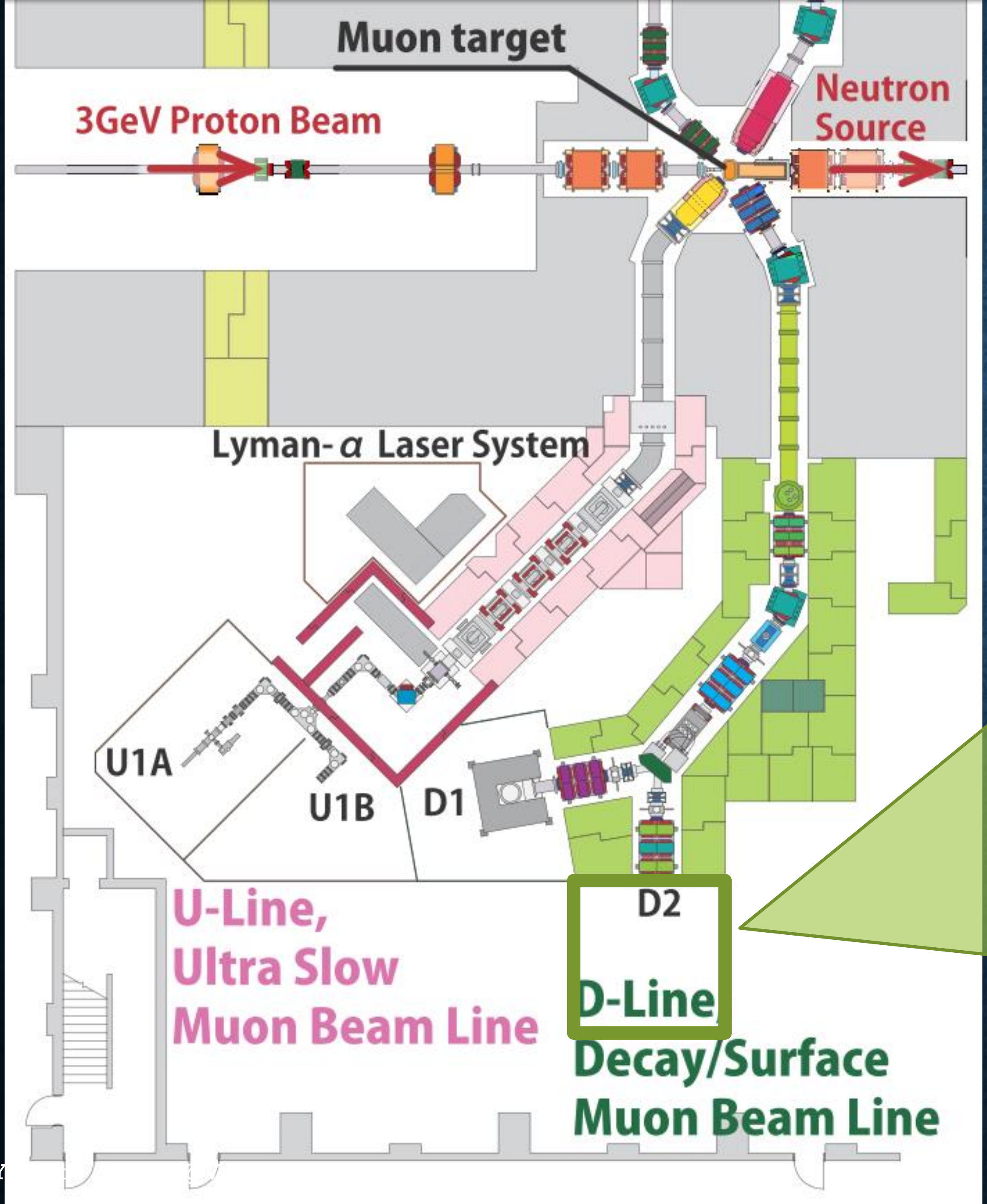
Emittance evolution from the RFQ

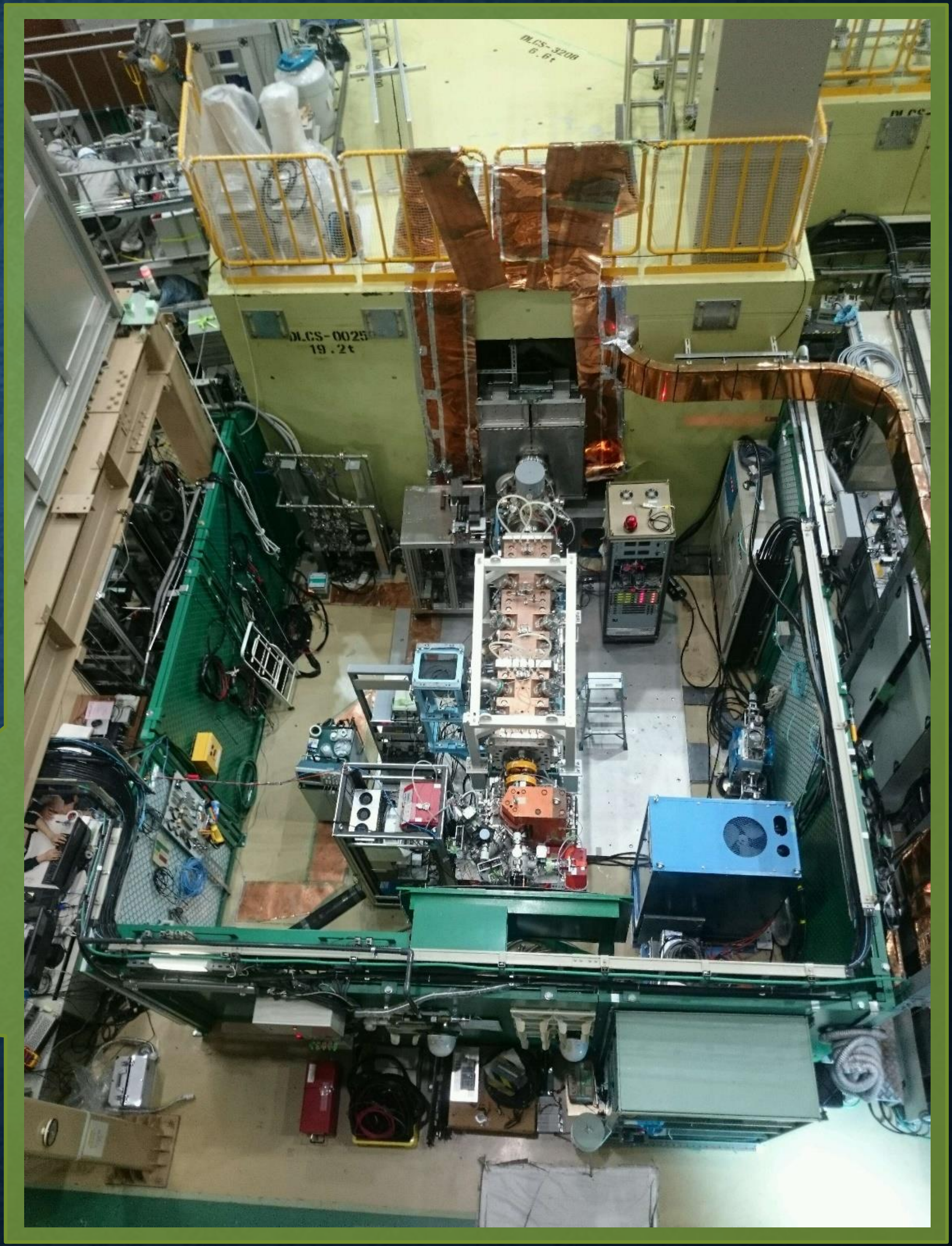


- Good transmission.
- Minimum delay loss and emittance growth.

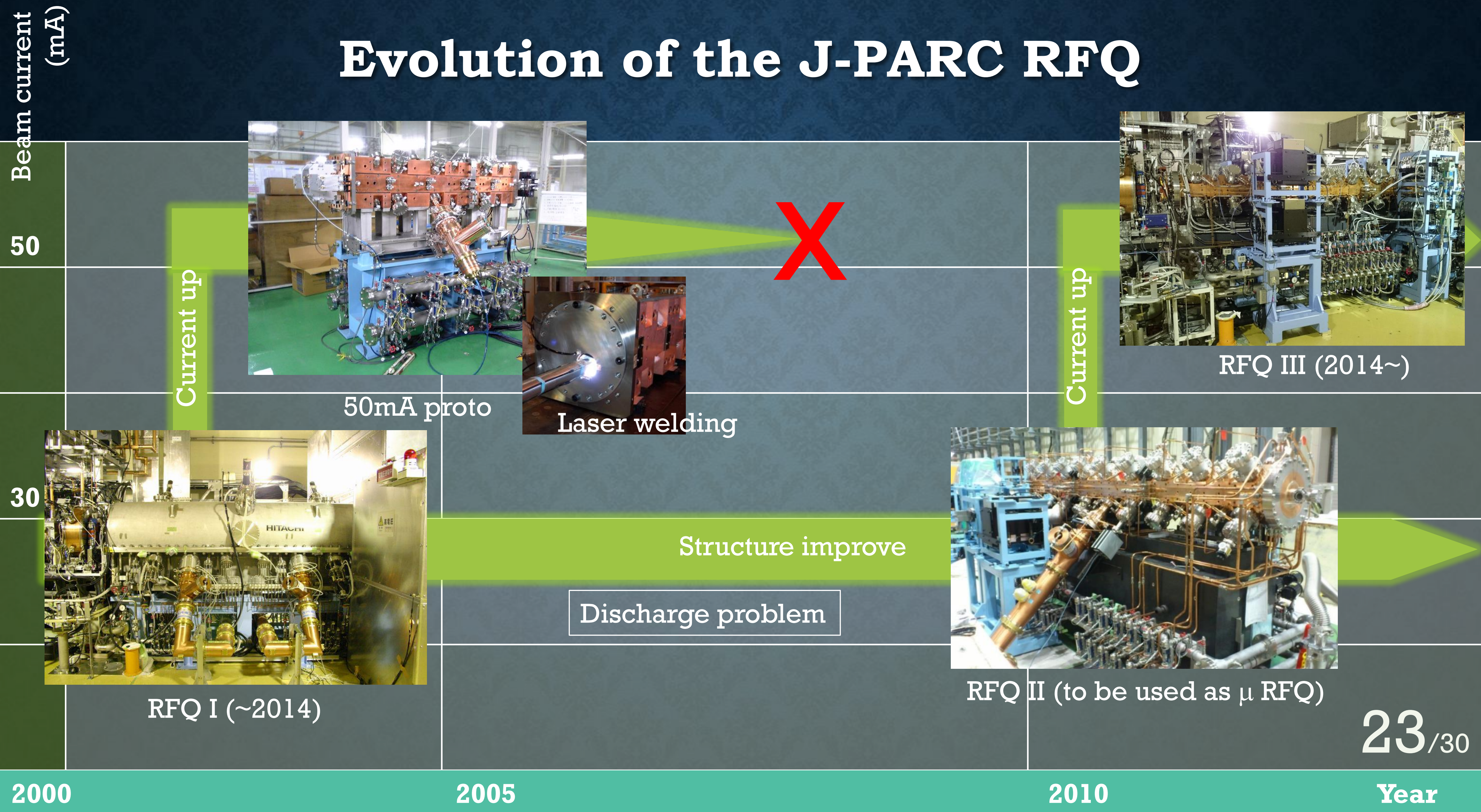
3. Demonstration of muon acceleration (2017/10/24~30)



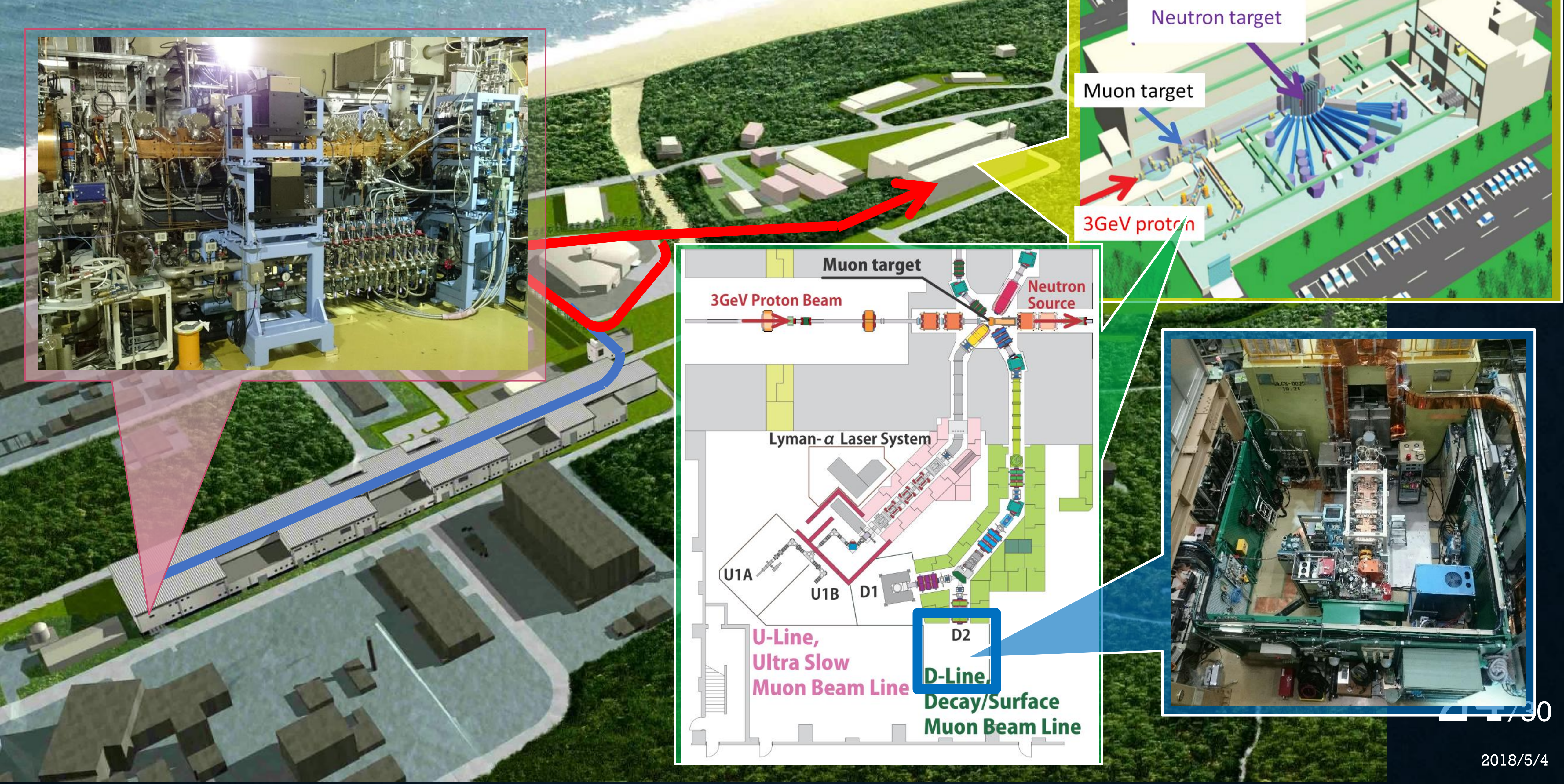

Muon target
3GeV Proton Beam
Neutron Source
Lyman-α Laser System
U1A
U1B
D1
D2
U-Line, Ultra Slow Muon Beam Line
D-Line, Decay/Surface Muon Beam Line



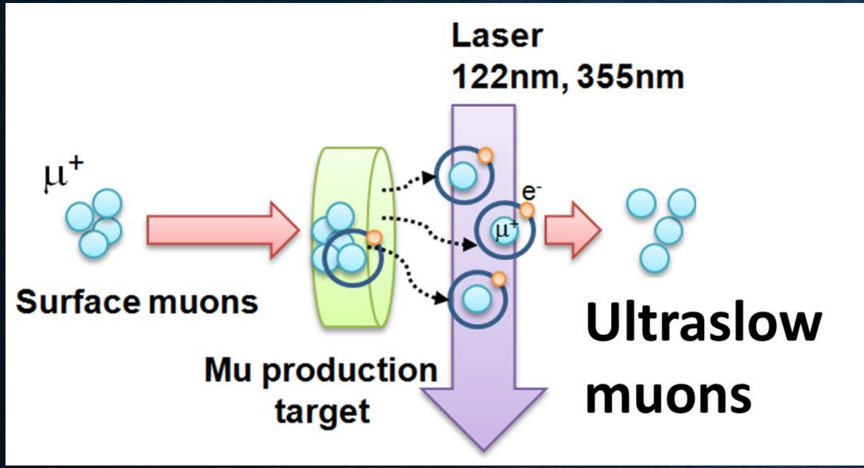
Evolution of the J-PARC RFQ



RFQs at both ends

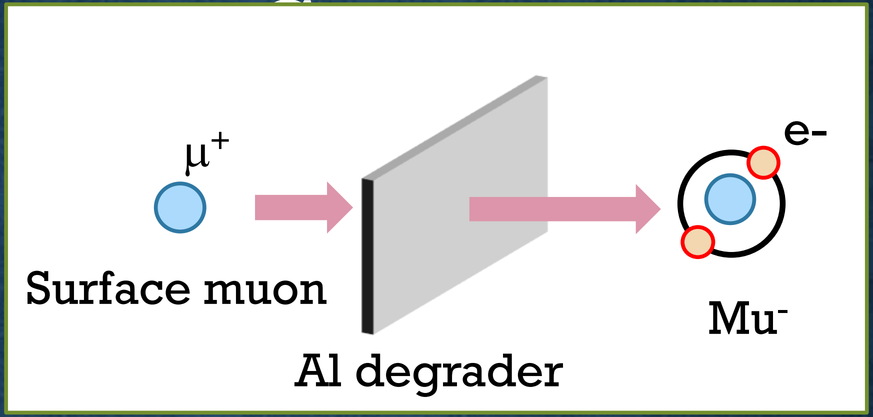


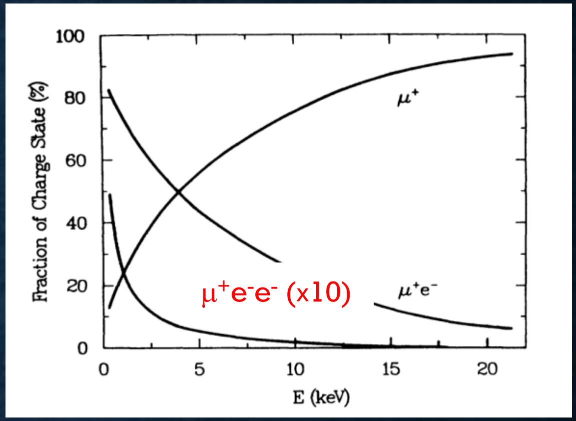
Ultra Slow Muon



Best quality,
but complicated.

Slow (~keV) muon source





Y. Kuang et al., Phys.Rev.A, 39, 6109

- Portable. ⤴
- No laser. ⤴
- No hard-to-handle target. ⤴
- Lower efficiency, larger emittance than USM ⤵

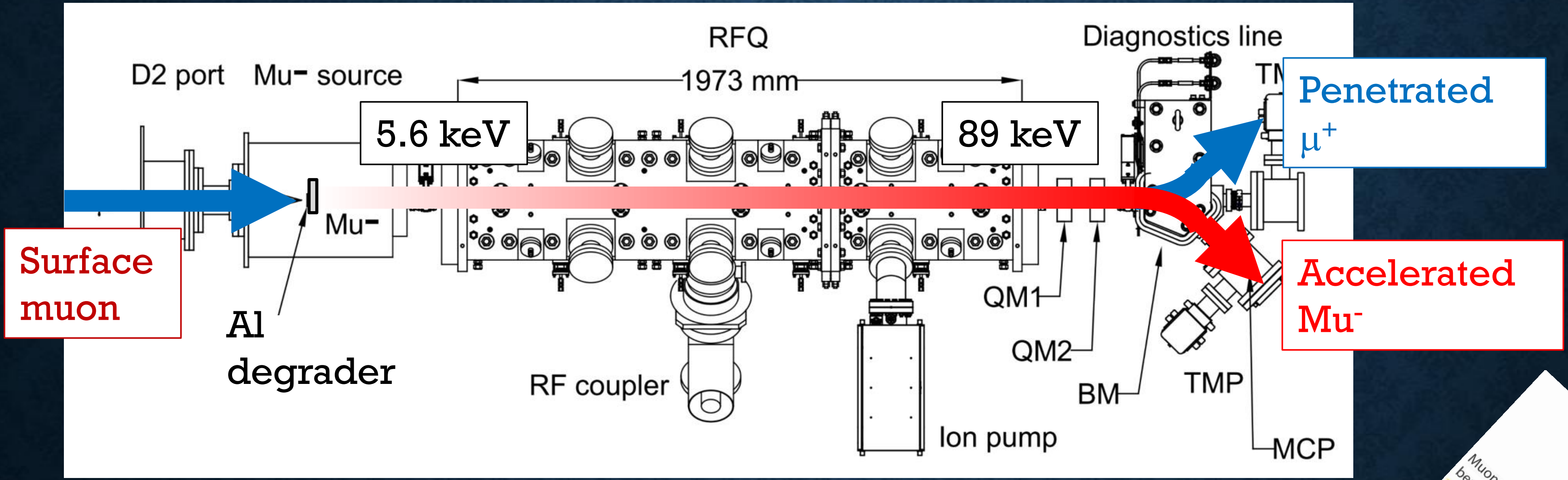
How to identify accelerated Mu⁻ ?

Initial acc
307 ns
GEANT4

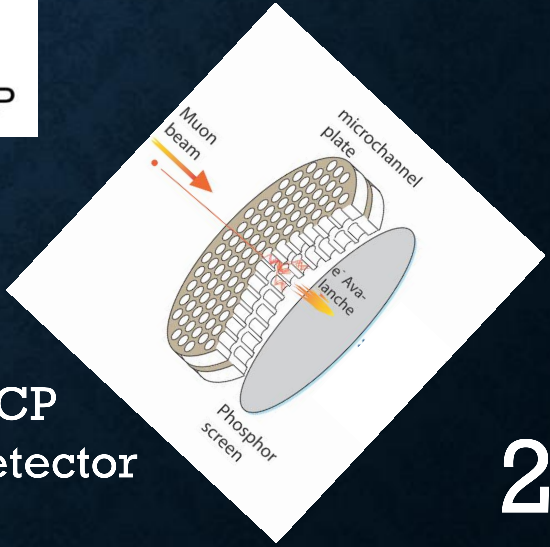
RFQ
$$\frac{297 \text{ cells}}{2\times 324 \text{ MHz}} = 458 \text{ ns}$$

Diag.
89 keV = β 0.041
L = 0.91m
74 ns

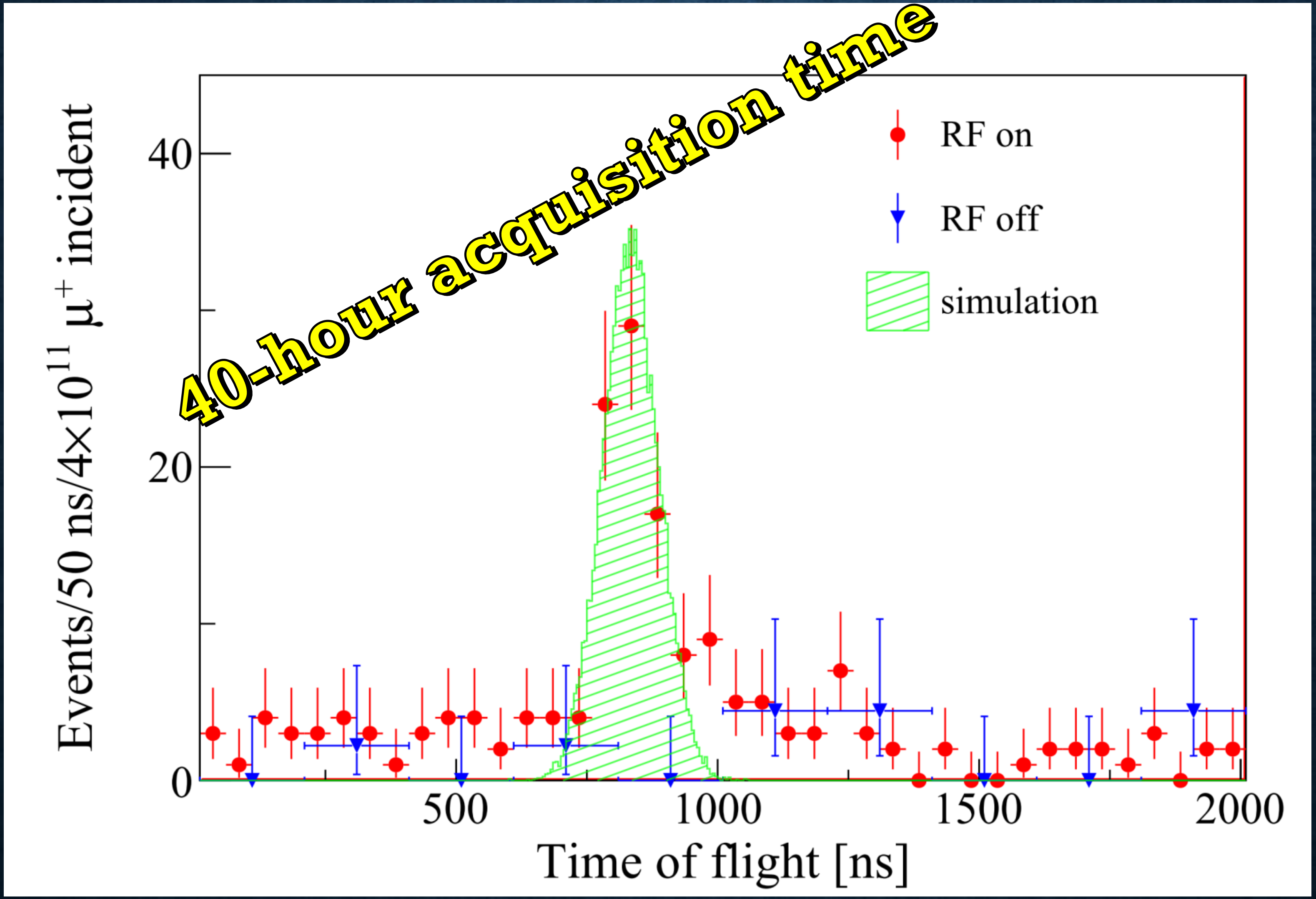
TOF total
839 ns



MCP detector



The world's first RF accelerated muons !



To be published in Phys. Rev. AB
arXiv:1803.07891

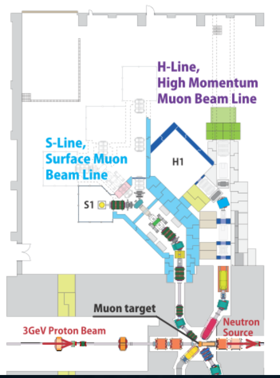
Next step…

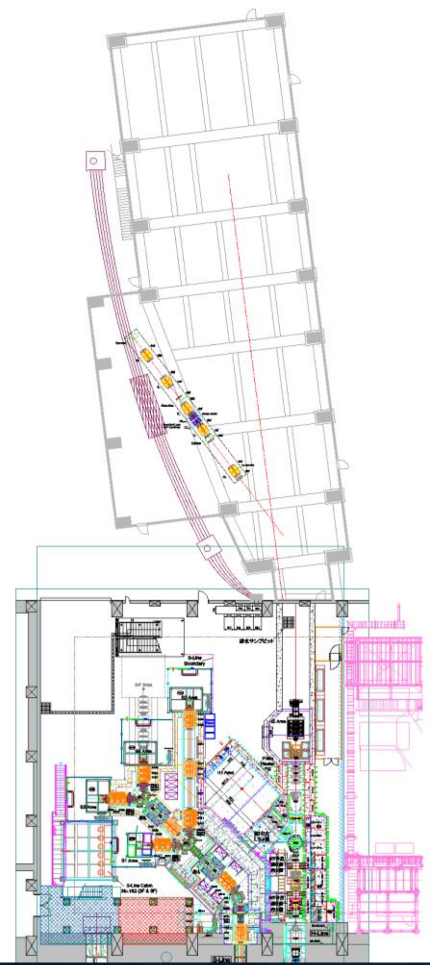
- Considering feasibility
  RFQ II + IH proto @ H1 area
- Then toward H-line extension

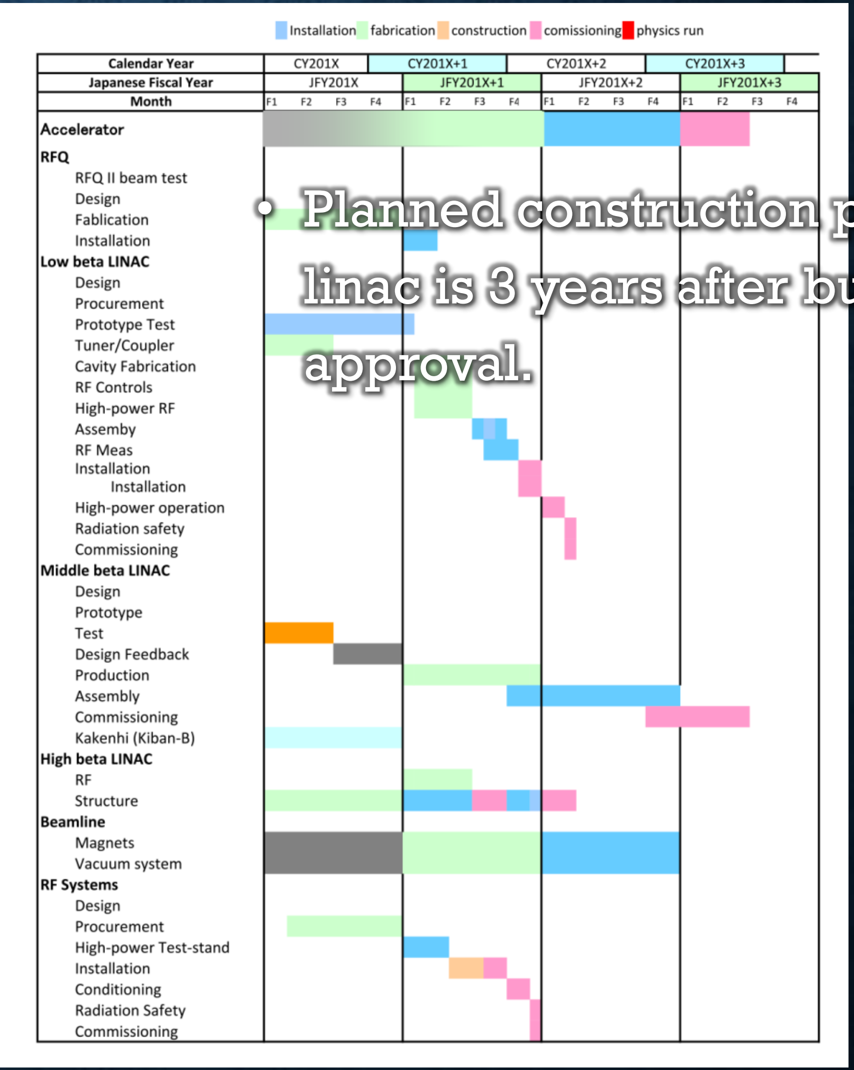
Schedule

- H1 are will be constructed as the 1st step.
- Then the building is expanded.

2020 ?







- Planned construction period of μ linac is 3 years after budget approval.

SUMMARY

- USM re-acceleration programs are underway at J-PARC muon facility.
- Reference design of μ linac for g-2/EDM experiment has been established.
- Demonstrated the world's first muon acceleration using RF linac.

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