ミューオンg-2精密測定にむけた ミューオン線型加速器の開発

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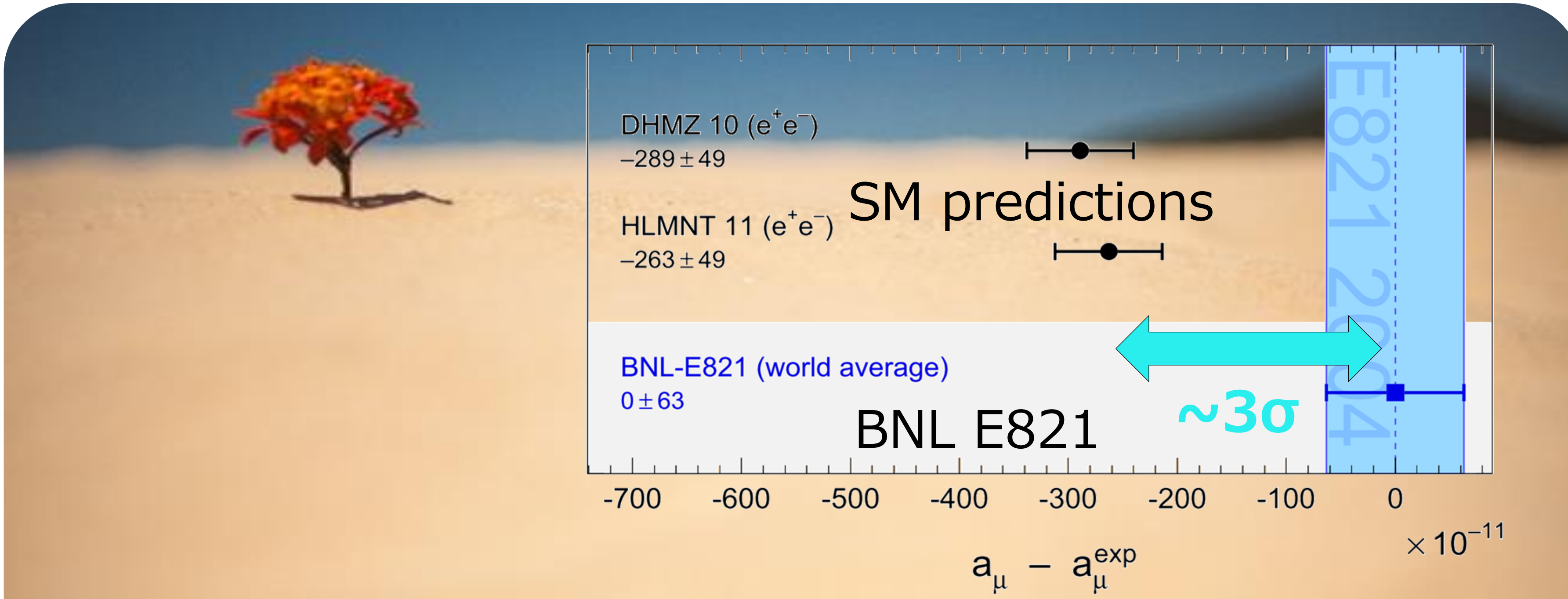
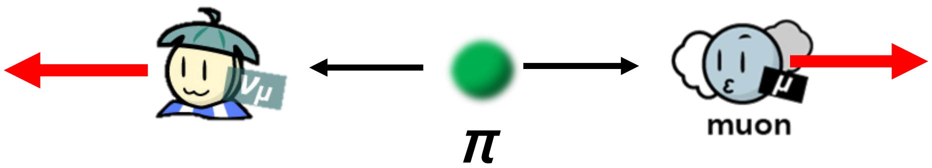
Muon g-2 [$a_\mu=(g-2)/2$]



- BNL E821 reported g-2 with a precision of 0.5 ppm in 2006.
- Discrepancy $\Delta a_\mu \sim 26 \times 10^{-10} \sim 3\sigma$ has not been resolved yet.
- Indicates new physics in electroweak scale ($a_\mu^{EW} \sim 15 \times 10^{-10}$)

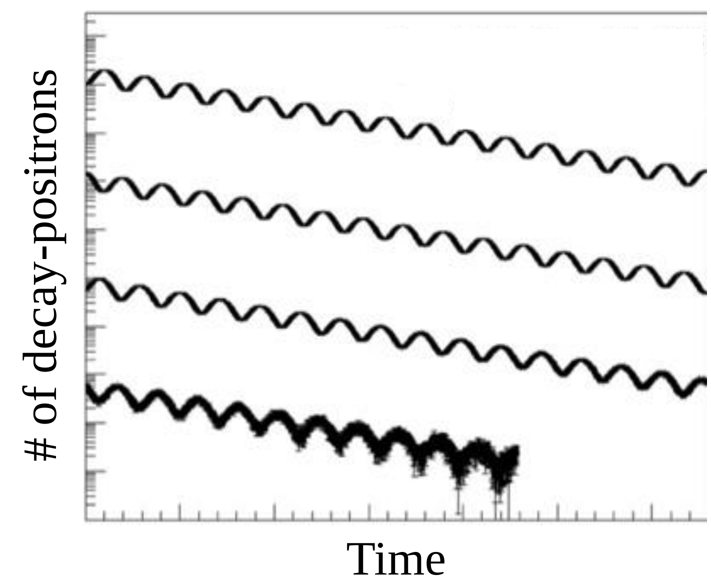
g-2 [a_μ=(g-2)/2] Measurements



$\otimes$ $\vec{B}$

$$\vec{\omega} \sim -\frac{e}{m} a_\mu \vec{B}$$

1. Polarized muon beam injection.
2. Muon spin precession relative to momentum ~ a_μ
3. High energy decay-electron ~ spin direction.



Measurements @ BNL & FNAL

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

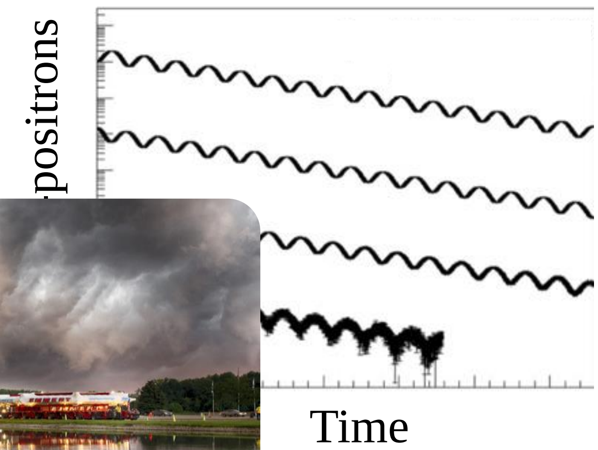
$\vec{B}$ by relativistic motion $\vec{E}$

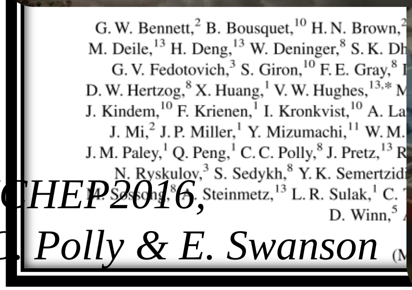
EDM

“magic” γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

negligible




G. W. Bennett,[2] B. Bousquet,[10] H. N. Brown,
M. Deile,[13] H. Deng,[13] W. Deninger,[8] S. K. Dh
G. V. Fedotovich,[3] S. Giron,[10] F. E. Gray,[8]
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J. M. Paley,[1] Q. Peng,[1] C. C. Polly,[8] J. Pretz,[13] R
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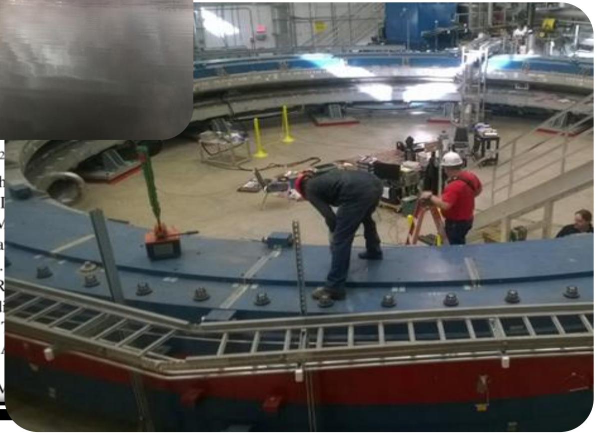
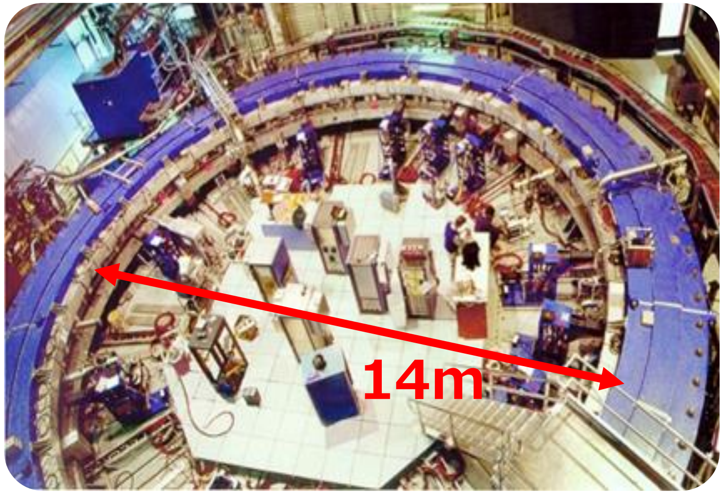
ICHEP2016, C. Polly & E. Swanson





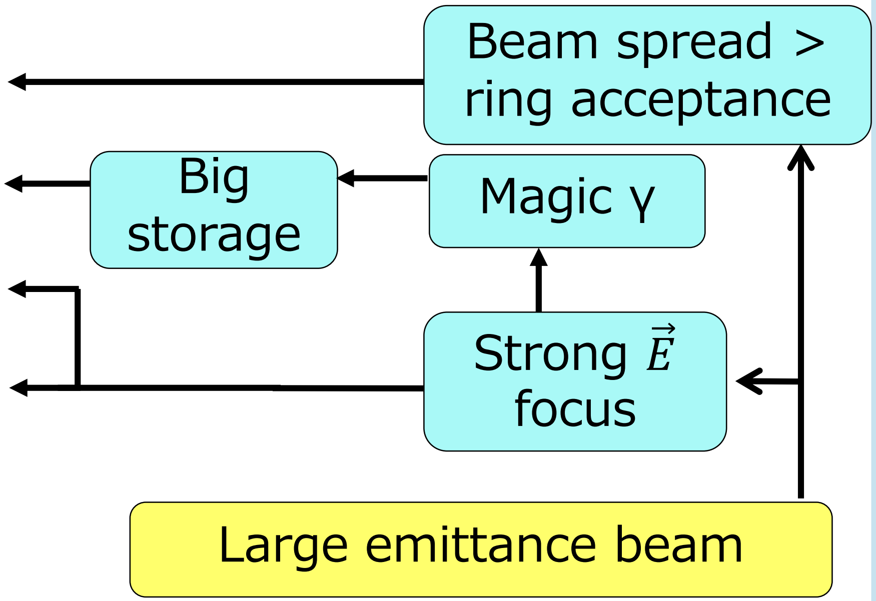
BNL E821 achieved 0.5 ppm.

FNAL E989 will start 2017, aiming 0.1 ppm

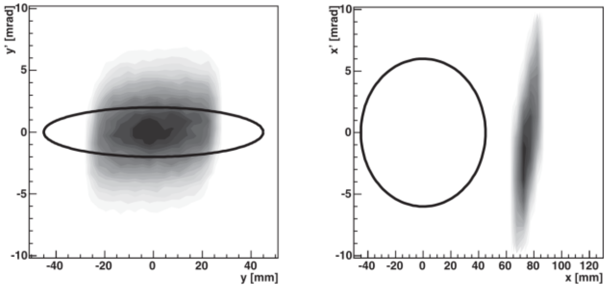
Uncertainties Breakdown

Cited from E989 TDR.

Error [ppb]	BNL result	FNAL goal
Lost muons	90	20
B field	170	70
CBO	70	<30
E and pitch	50	30
Gain changes	120	20
Pileup	80	40



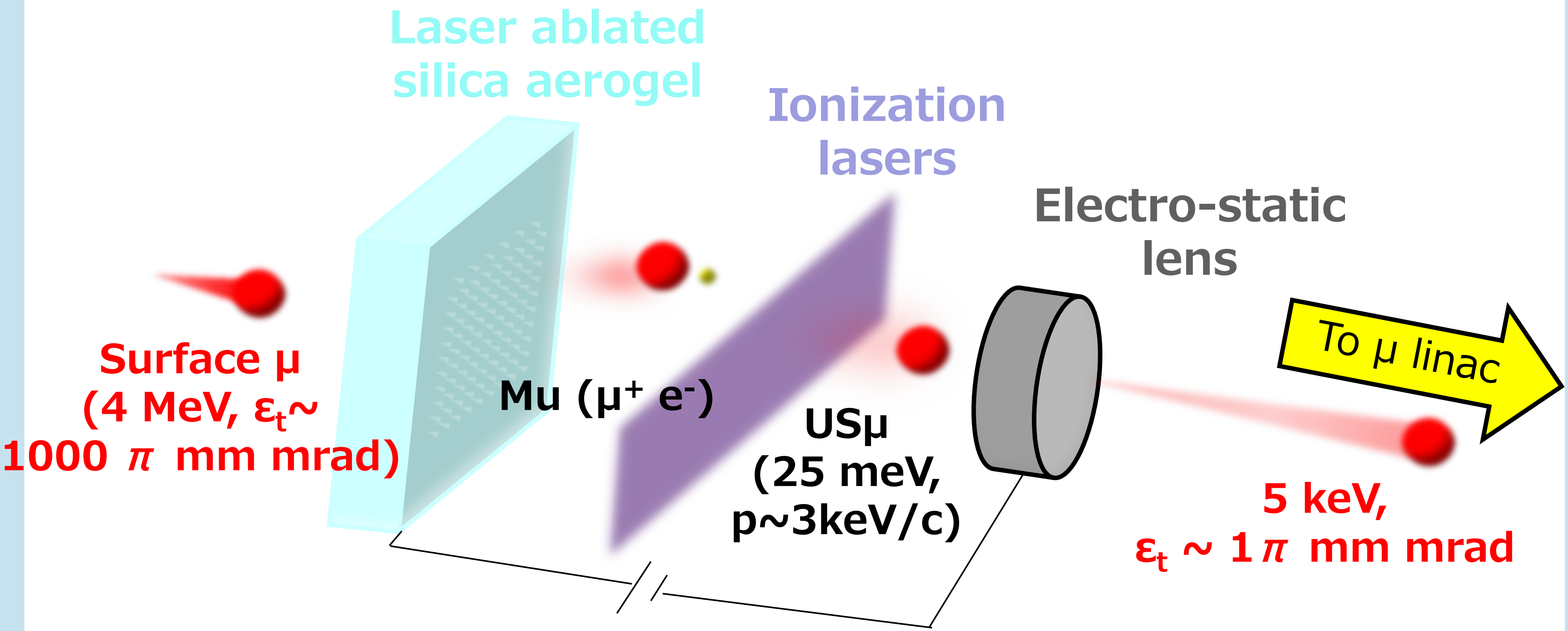
BNL μ beam at the inflector exit



Cited from Phys. Rev. D. 73, 072003, 2006.

Low emittance beam offers independent & precise measurement.

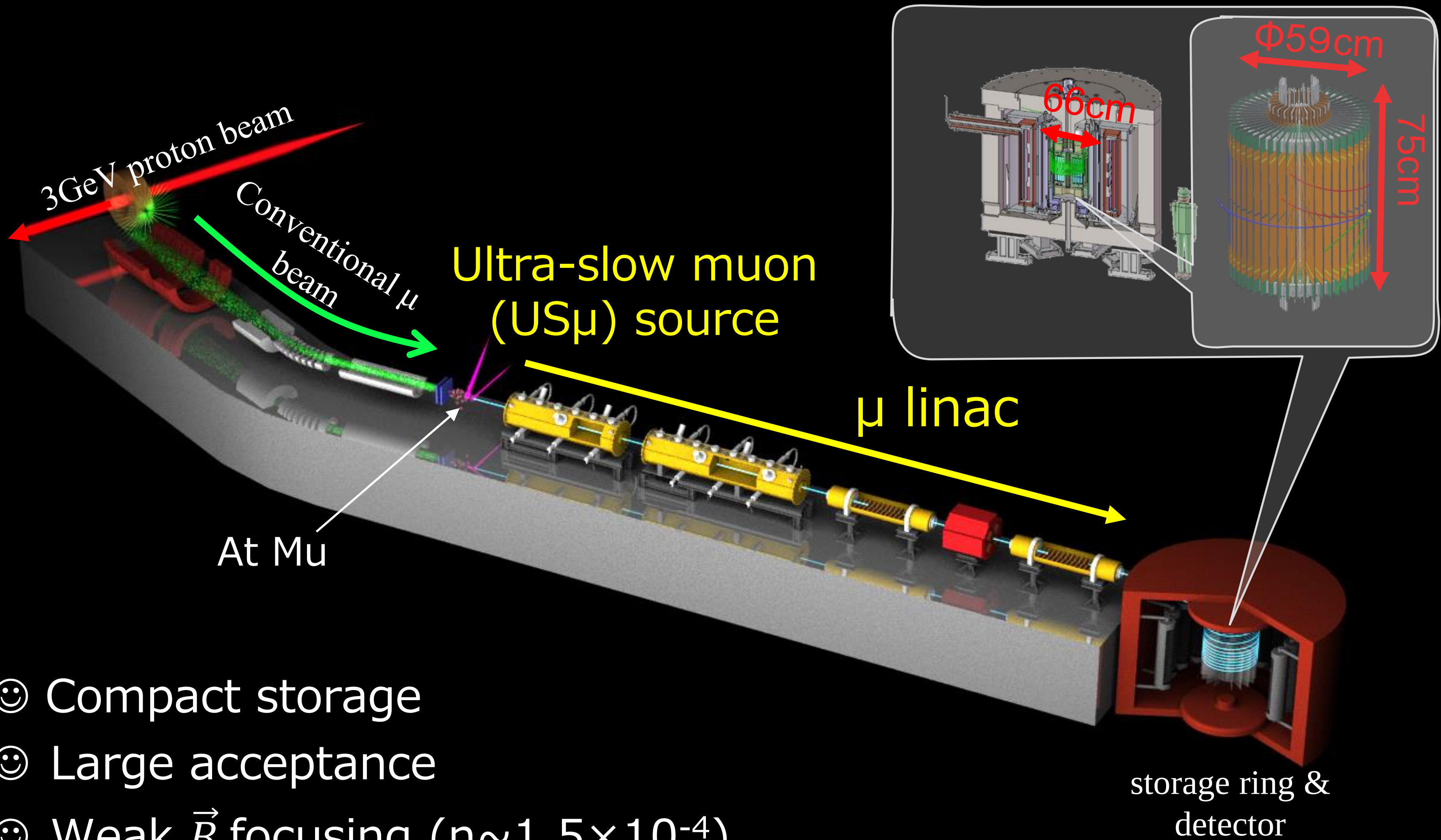
Ultra-Slow Muon (USμ) Source



USμ brief History

1986.	Thermal Mu in vacuum [PRL.56.1463. 1986.]
1988.	Mu resonant ionization via 1s-2s [PRL.60.101.1988]
1995-2008.	USμ@ KEK & RAL[RRL.74.4811.1995, NIMB.266.335.2008.]
2014.	High-efficiency Mu target [PTEP.091.C01.2014]

J-PARC g-2 Experiment



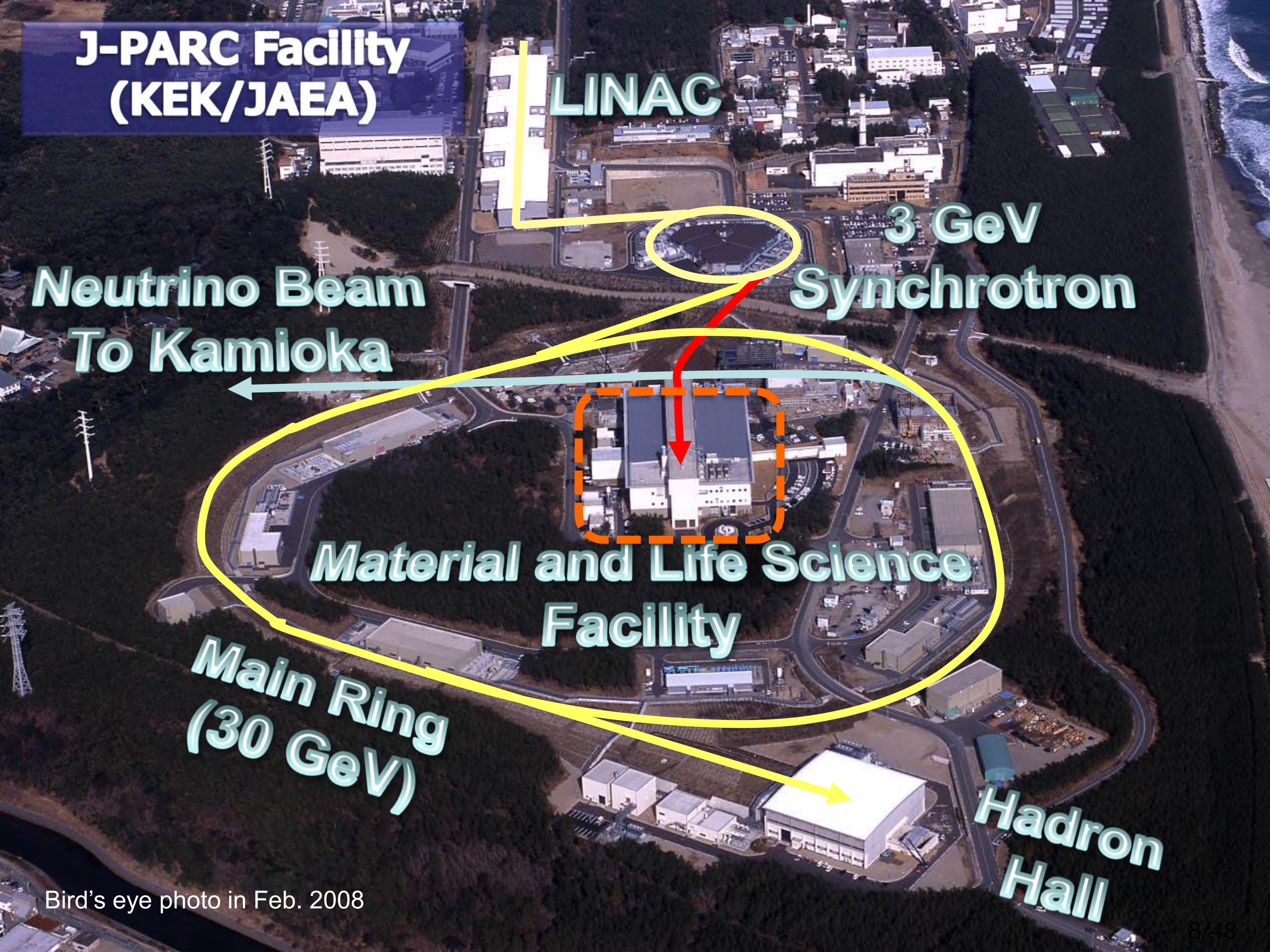
☺ Compact storage

☺ Large acceptance

☺ Weak $\vec{B}$ focusing (n~1.5×10^{-4})

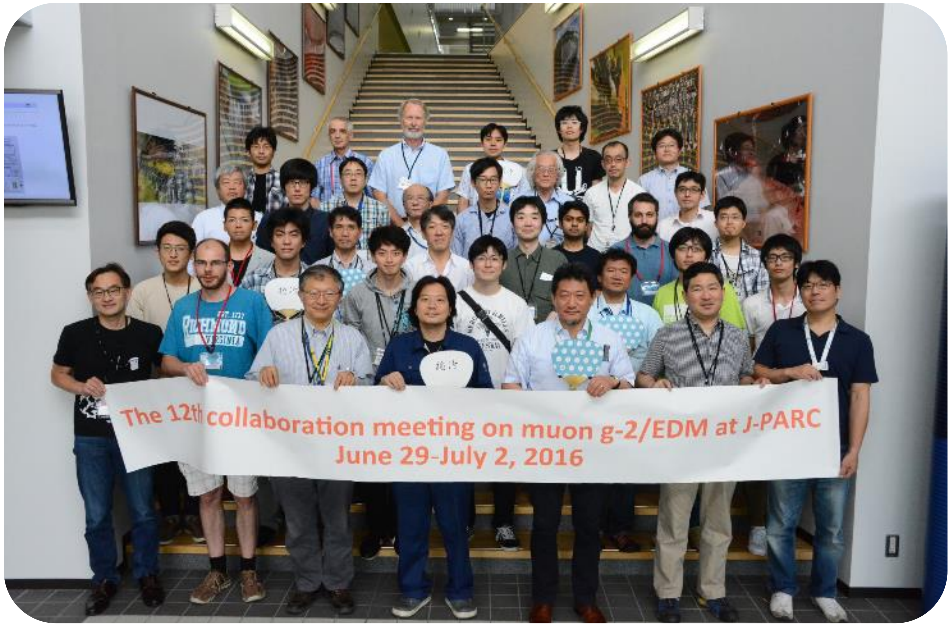
☺ Polarity control

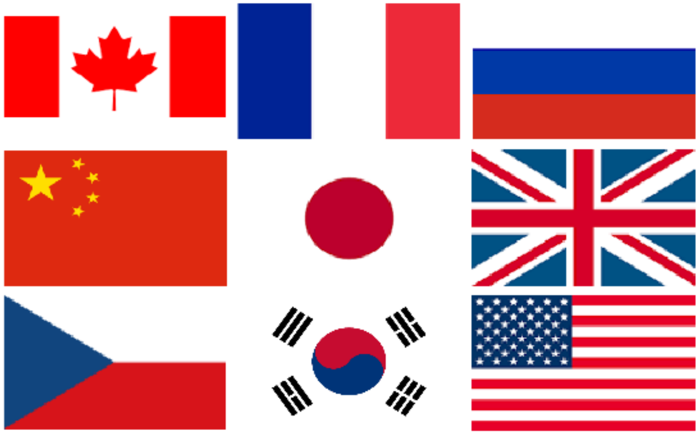
Goal: g-2 with 0.1 ppm and EDM up to 10^{-21} e·cm



Bird’s eye photo in Feb. 2008

Collaboration Status





137 members from 9 countries, 49 institutions.

- Submitted Technical Design Report.
  - aims 0.4 ppm as stage 1.
- High priority in KEK Project Implementation Plan.
- Detailed review to move construction stage is organized in this year.

<u>Start experiment 3 years after budget approval</u>

Prospects for Muon Acceleration

- Fundamental Science
  - G-2/EDM
  - Fixed target exp. with high energy muon ($\mu \to \tau$ conversion, dark photon)
  - Neutrino factory, muon collider
  - ($\mathrm{Mu} - \overline{\mathrm{Mu}}$ conversion)
  - …
- Applied Science
  - Transmission μ microscope
  - Muon tomography
  - …
- **Welcome new ideas.**

Muon Linac Conceptual Design

NC proton- & electron-like linac with 324 & 1296 MHz.

40 MW L-band klystron, originally developed for KEKB linac, is available.

pasj2011, TUPS158

High quality

- 300 MeV/c with small emittance growth

Fast

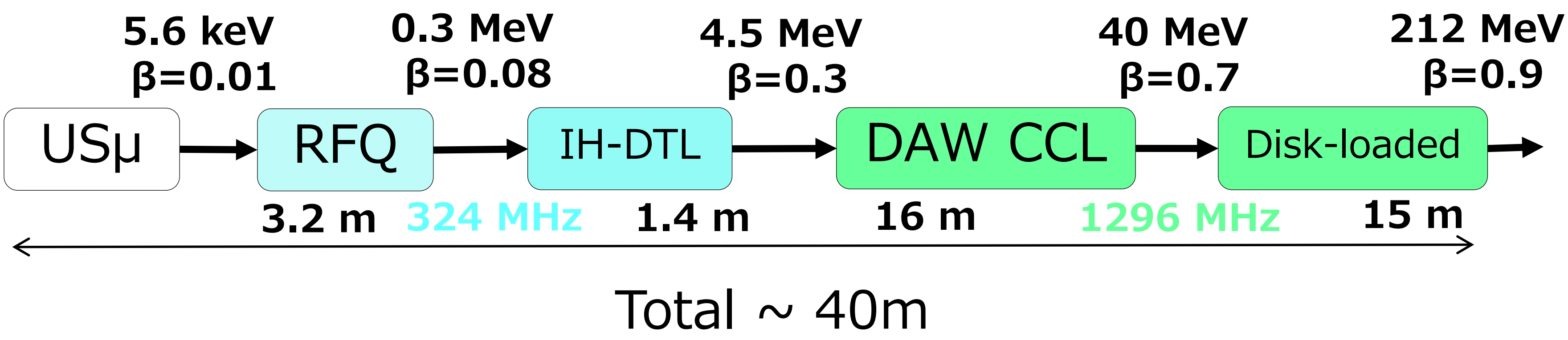
- Timely manner to FNAL g-2.
- Bigger impact in LHC era.

Cost effective

- Cheaper is better, of course.
- Two big facilities Japan soon: J-PARC and SuperKEKB

Plenty resources and experiences for 324 MHz linac @ J-PARC

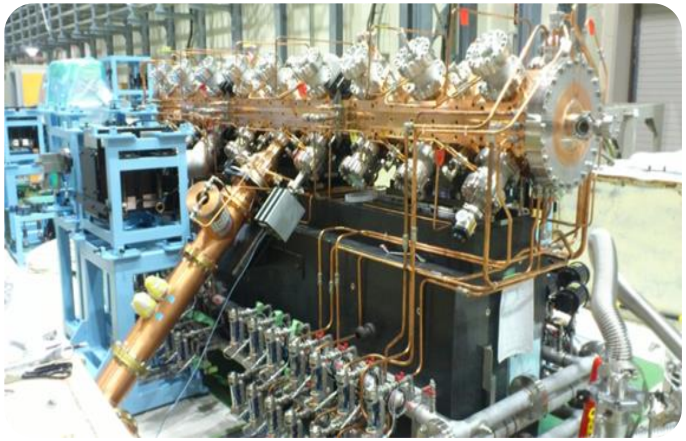
Configuration



Energy [MeV]	212
Intensity [/s]	10^6
Repetition [Hz]	25
Pulse length [nsec]	10
Normalized ε_t [π mm mrad]	1.5
Δp [%]	0.1

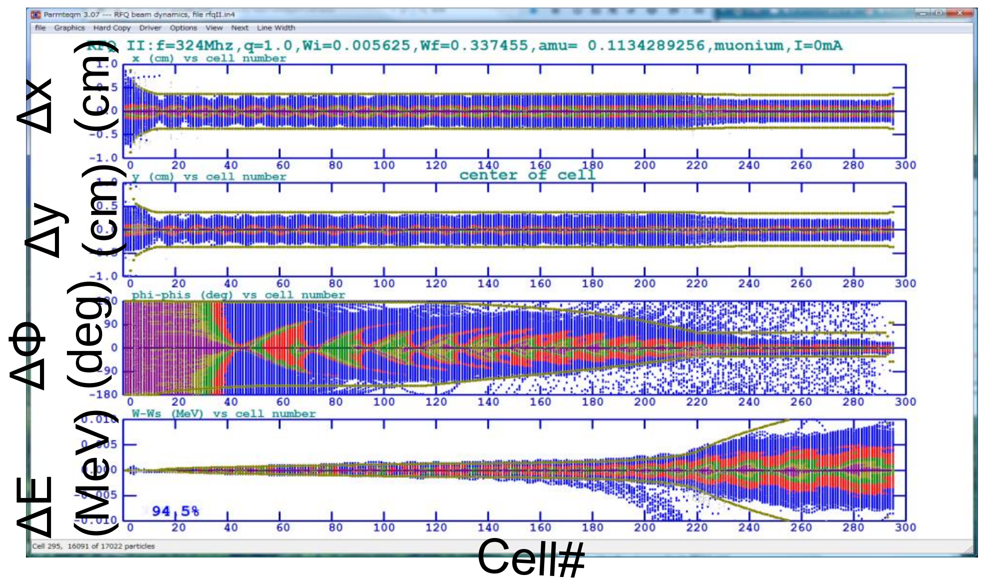
- Several structures to cover wide β
  - Rapid β evolution due to small mass
- Low current, low duty.
- Needs fast acceleration to avoid decay loss.
  - τ_μ = 2.2 usec

RFQ



- J-PARC H⁻ spare is used.
  - Inter-vane voltage is scaled by mass
- Simulation shows good transmission to muon.

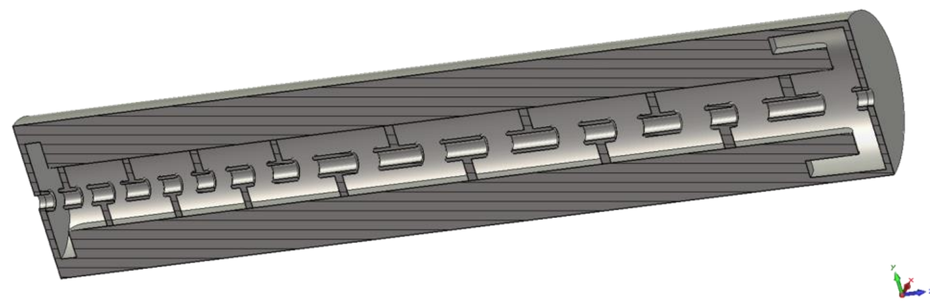
f [MHz]		324
Length [m]		3.2
Energy [keV]	In	5.6
	Out	340
Inter-vane V [kV]		9.3
Power [kW]		4.2



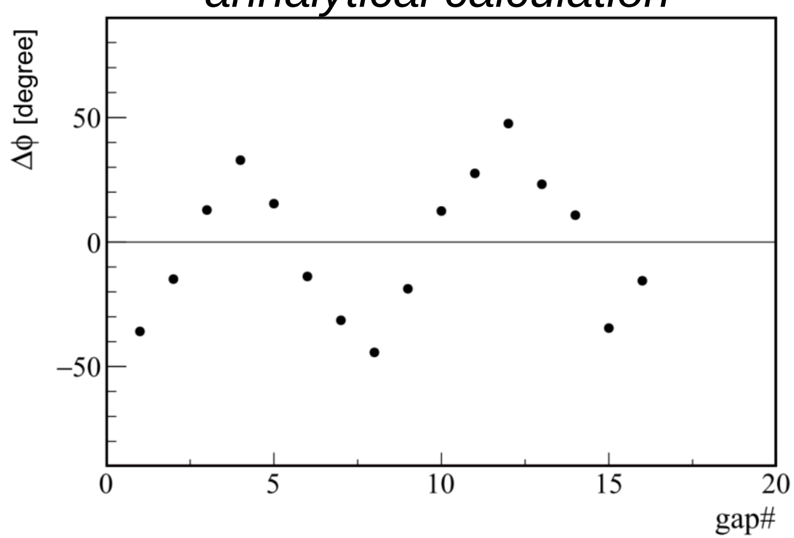
Good transmission (95%).

Interdigital H-DTL

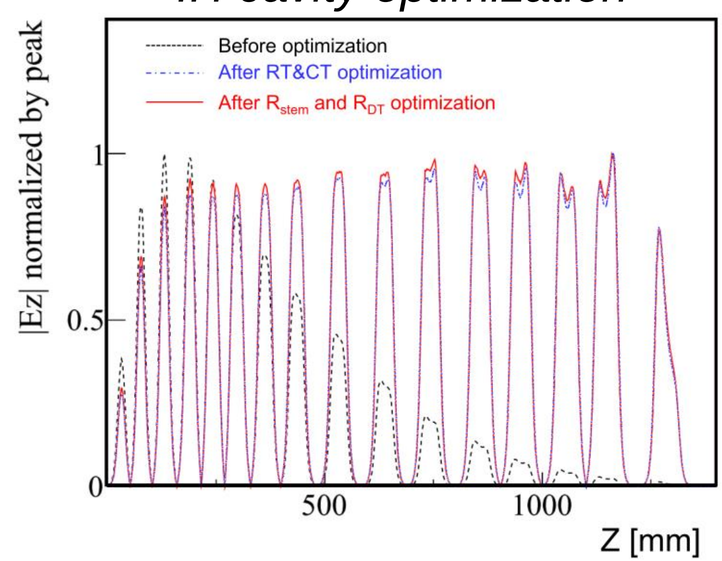
- H-mode + alternative phase focusing (APF) for high-efficiency.
- Rapid velocity evolution
  → Optimization of Φ_s and cavity for ideal APF are essential.



Φ_s optimization by annalytical calculation

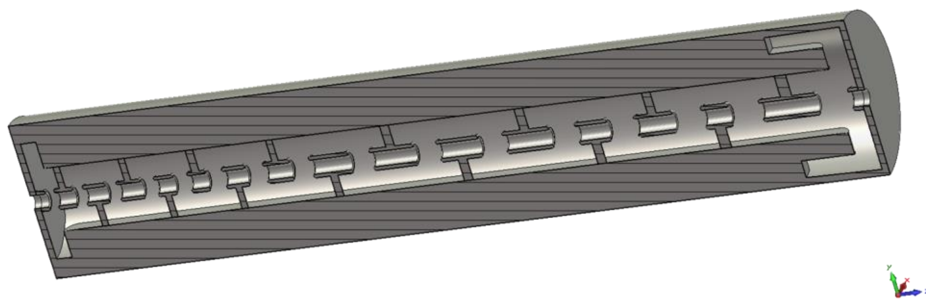


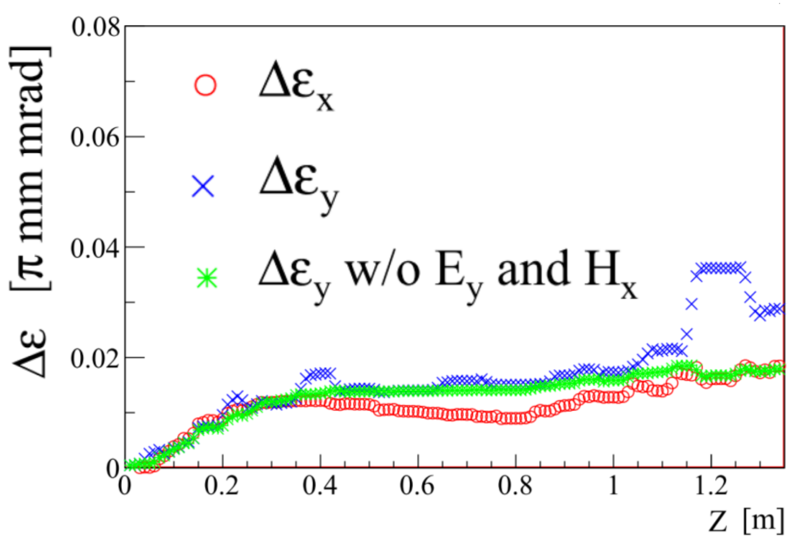
On-axis field before/after IH cavity optimization



Interdigital H-DTL

- H-mode + alternative phase focusing (APF) for high-efficiency.
- Beam dynamics evaluated by numerical calculation → ε growth is small enough.





f [MHz]		324
Length [m]		1.3
Energy [MeV] & β	In	0.34 (0.08)
	Out	4.5 (0.28)
# of cells		16
Φ_s [deg.]		-44 ~ 48

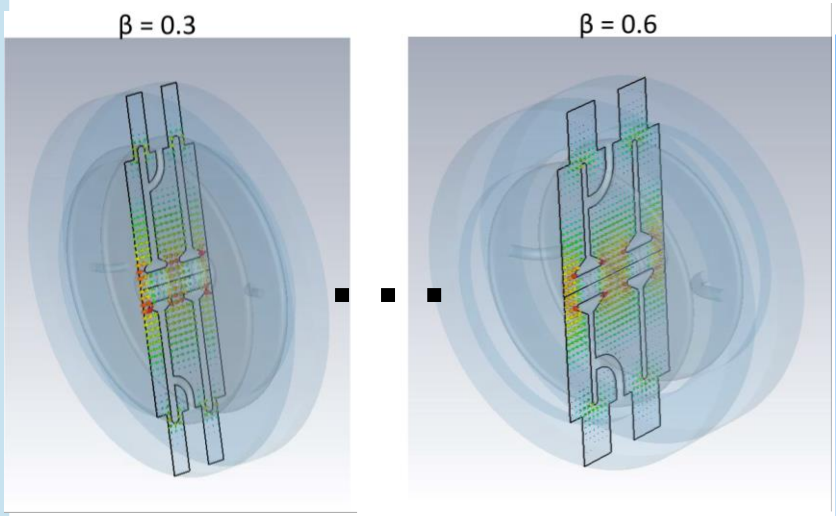
M. Otani et al., Phys. Rev. AB19, 040101, 2016.

Finish beam dynamics design.

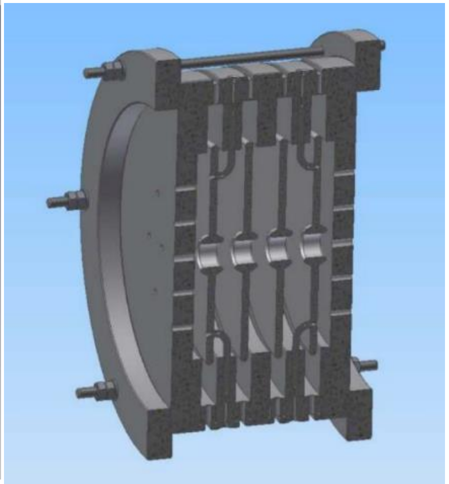
Disk And Washer CCL

- CCL with simple structure and high coupling constant.
- Needs design for wide β (0.3~0.7) → semi-automatic algorithm for cavity optimization was constructed.

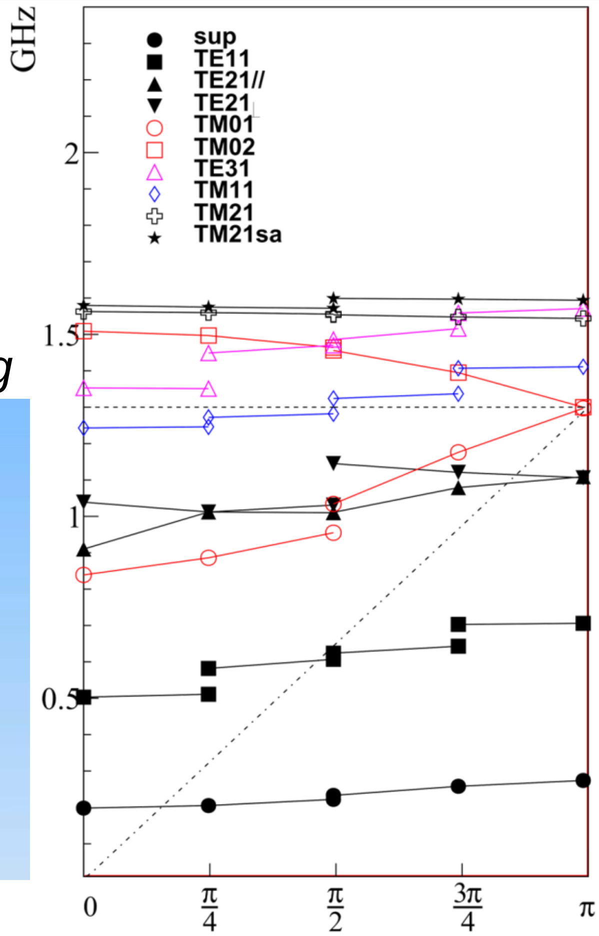
CST models



proto-type drawing



dispersion (β=0.3 model)

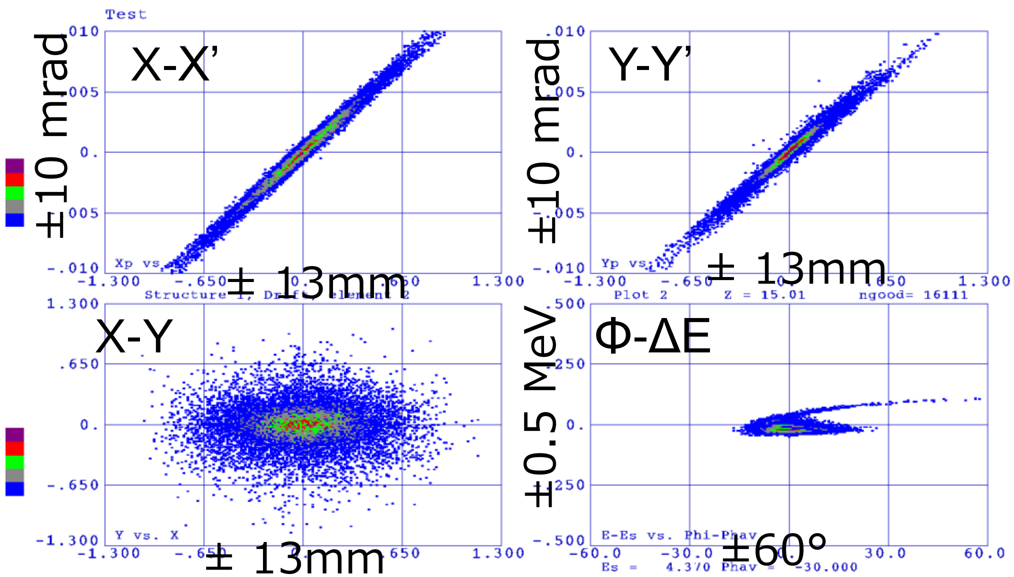


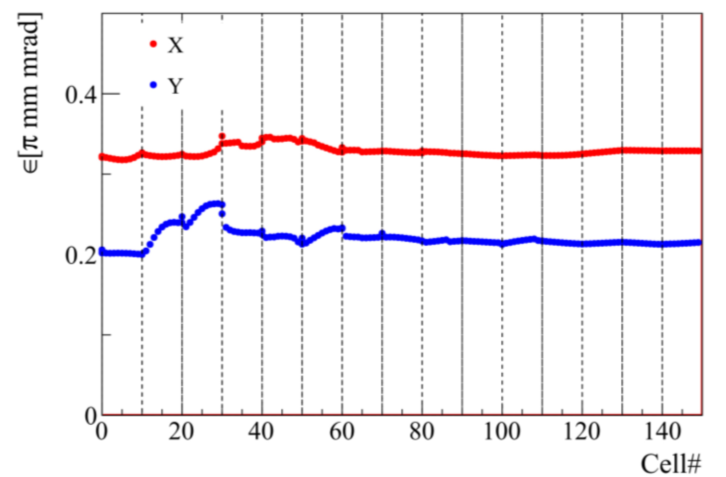
Under proto-type evaluation.

Dynamics Design

- Because DAW starts from low-β region, RF-defocusing is dominant.
- Design with σ_0<90° to achieve stable beam dynamics.

f [MHz]	1296
Length [m]	16
E_0 [MV/m]	5.6
Φ_s [deg.]	-30
Power [MW]	4.5

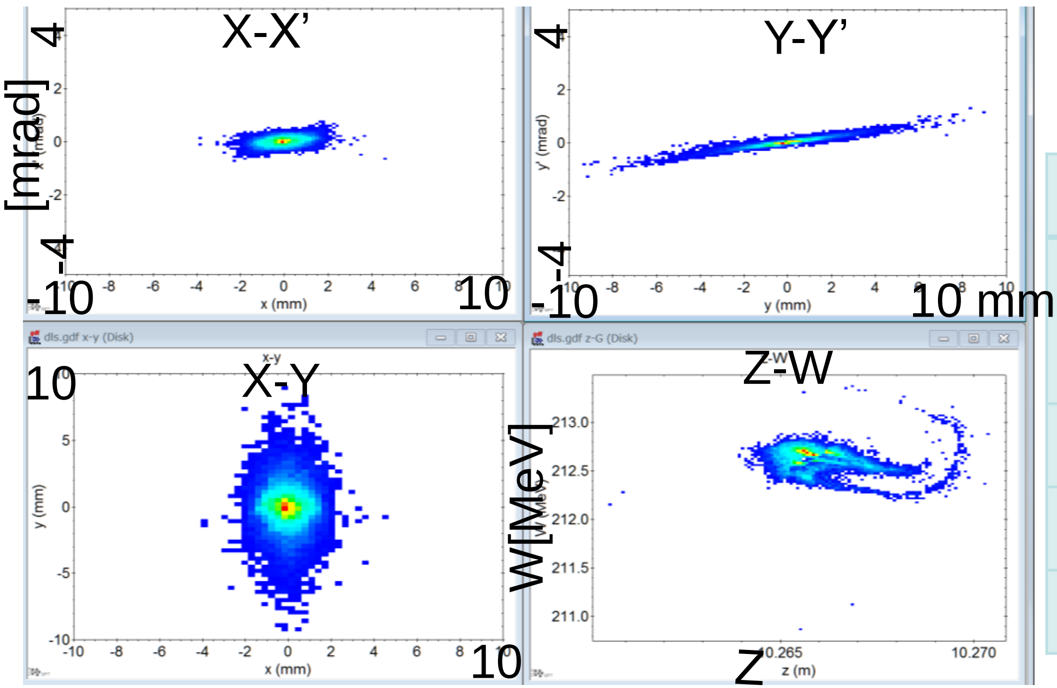


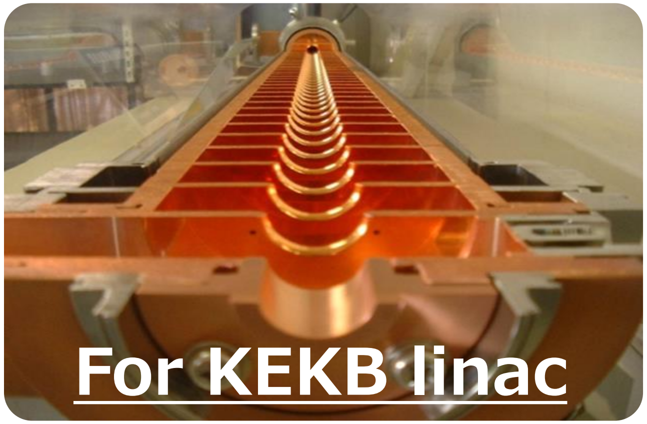


Finish dynamics design.

Disk-loaded

- High-gradient acceleration.
- Due to β≠1, synchronized β cell design is conducted.



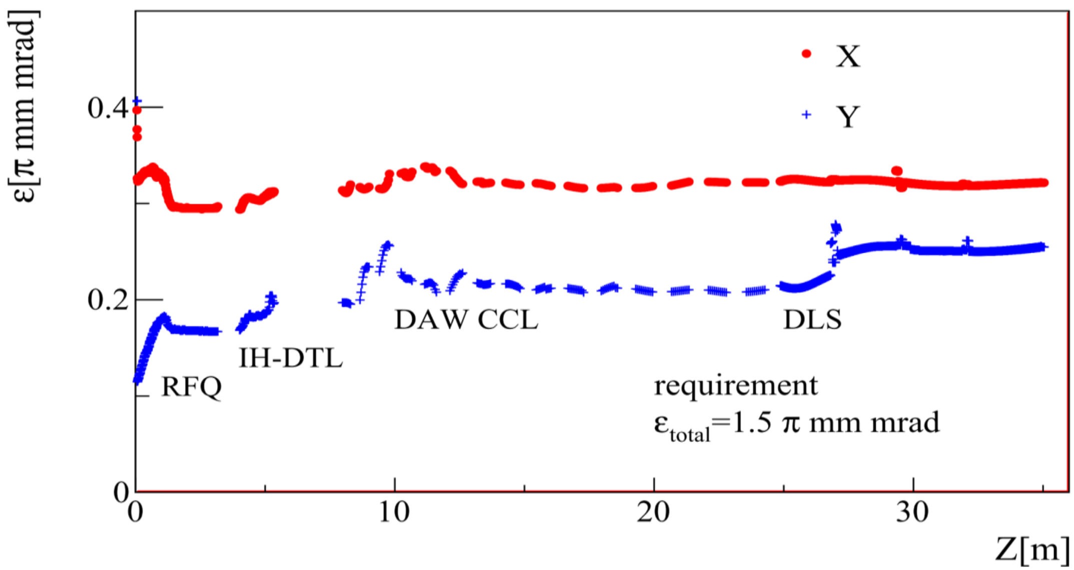


f [MHz]		1296
Energy [MeV]	In	40
	Out	212
E_0 [MV/m]		20
Φ_s [deg.]		-10
# modules		4

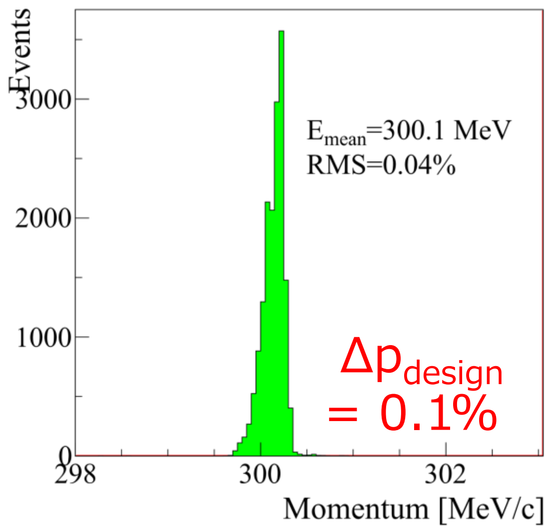
Finish reference design.

Design Summary

Emittance evolution



Momentum spread

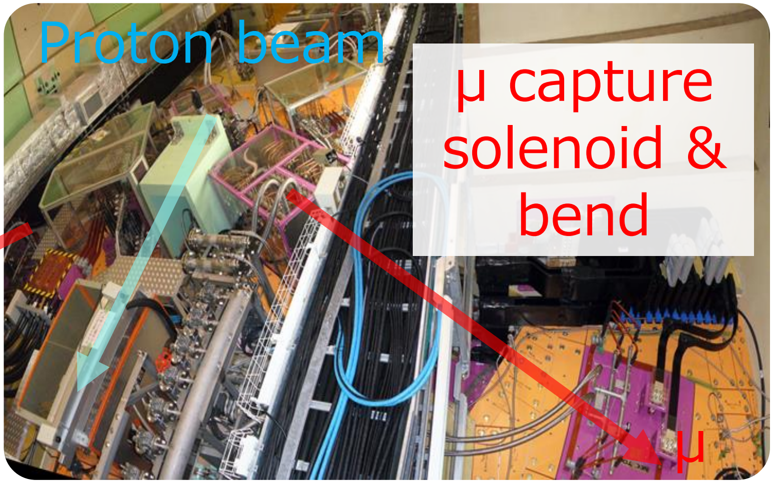


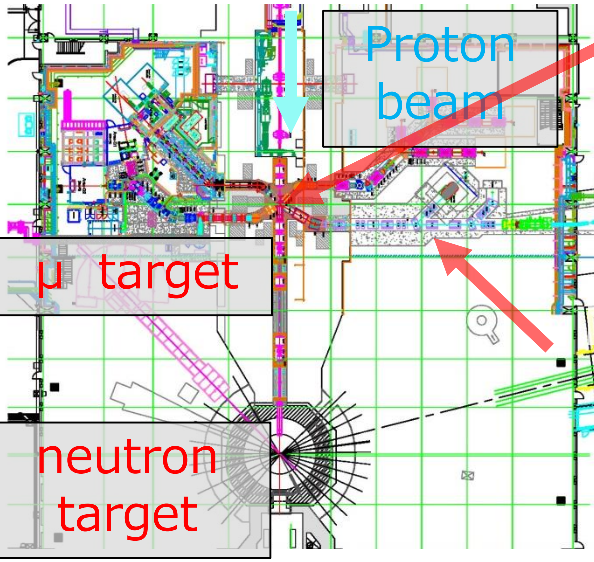
	Init.	RFQ	IH	DAW	DLS
Decay survival [%]	83	81	98	96	99
Transmission [%]	87	95	99.9	99.5	99.9

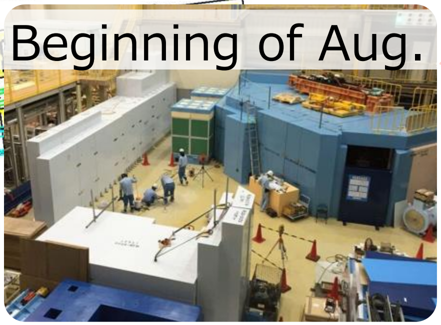
Comparable to the requirement.

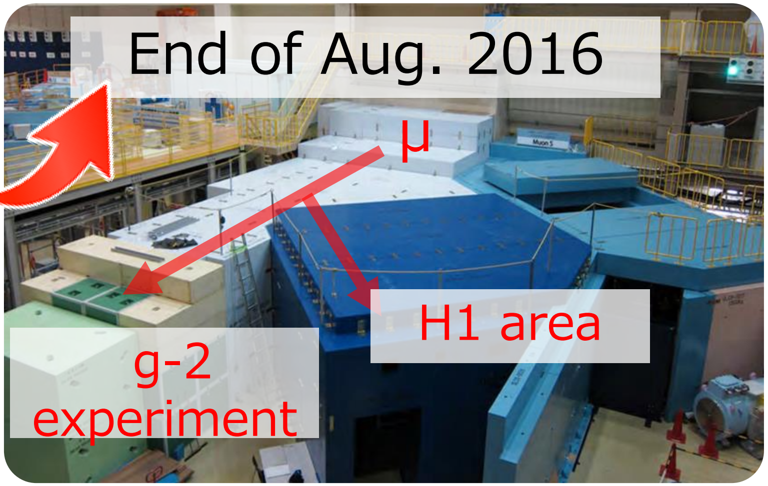
Muon Source (New μ Beamline)

- Front-end solenoid was ready.
- Part of the transport line constructions is conducted in this Summer.



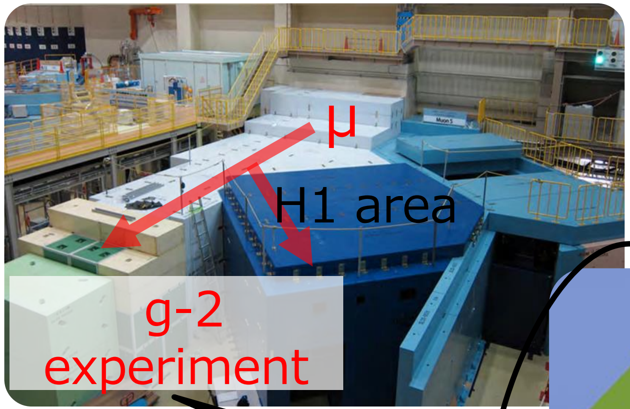


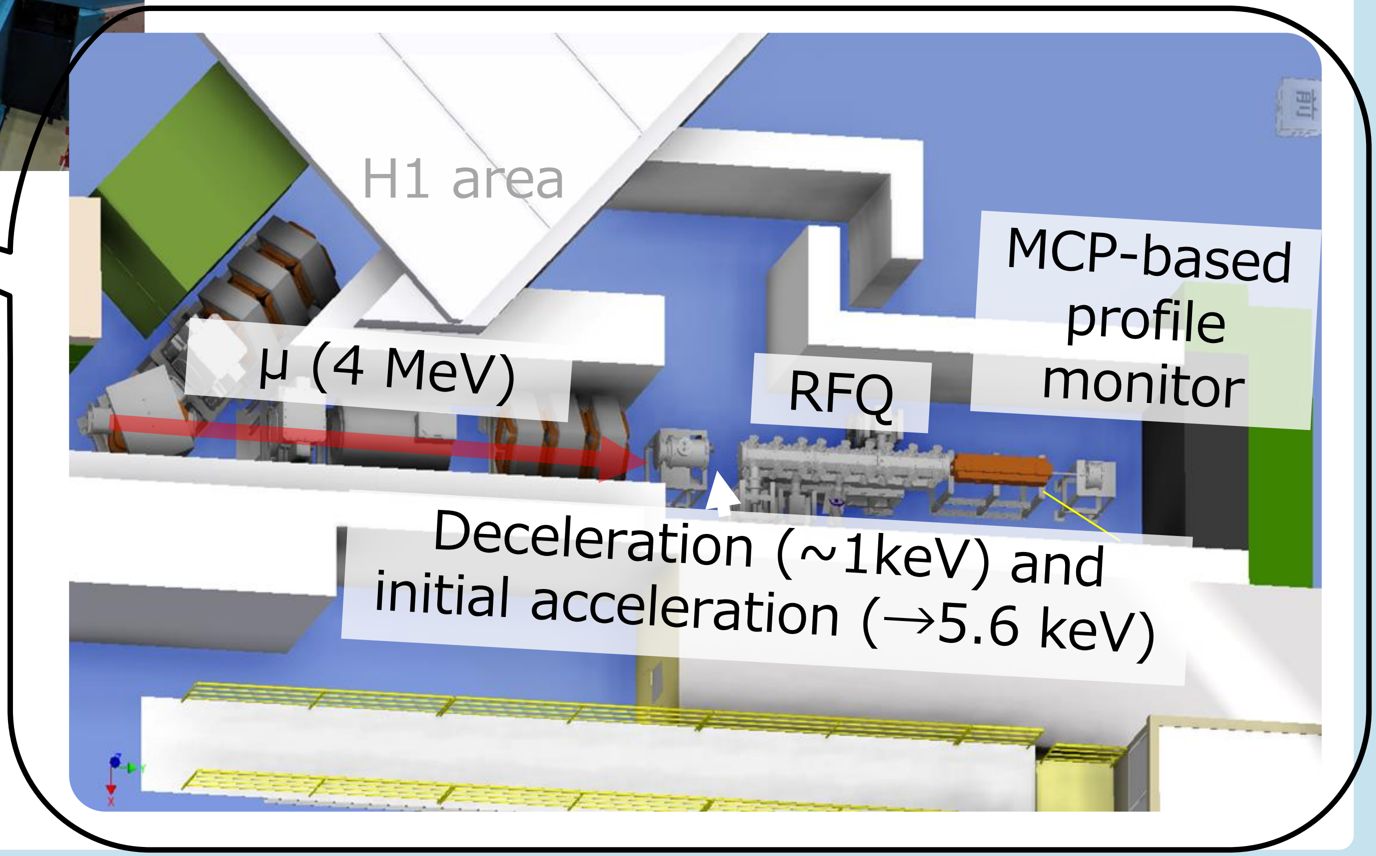




Primary muon beam will be available soon.

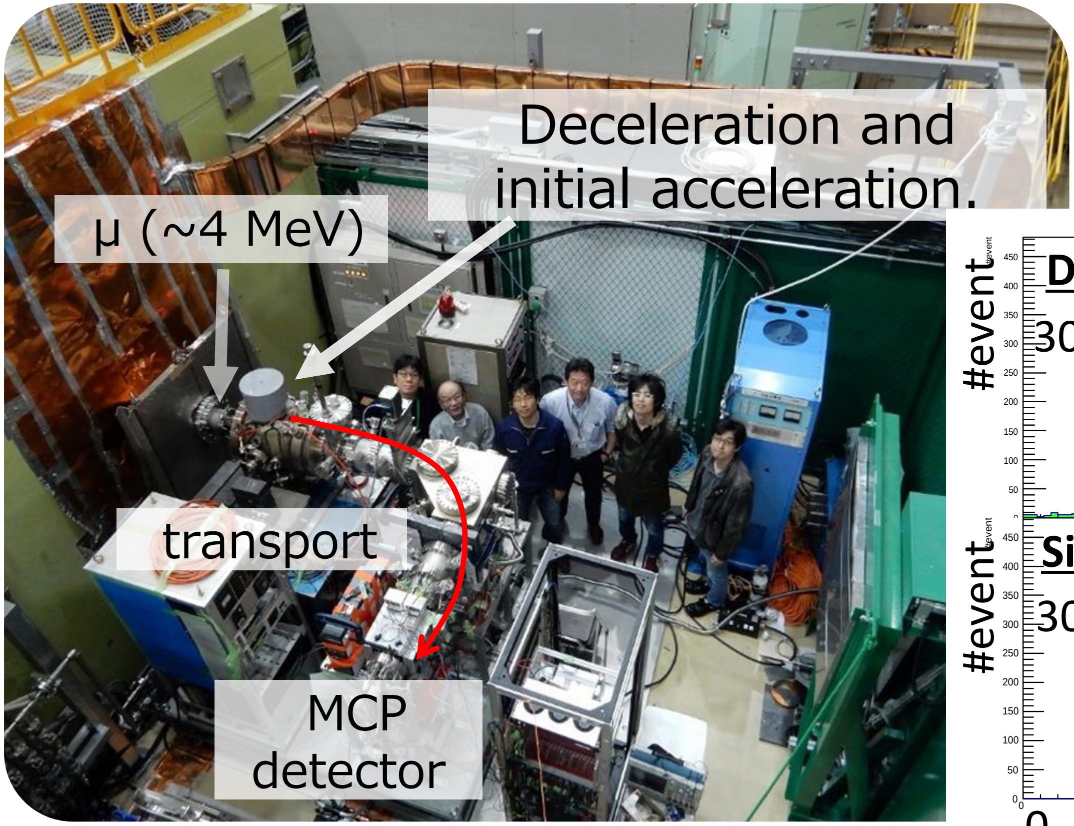
First Commissioning Setup

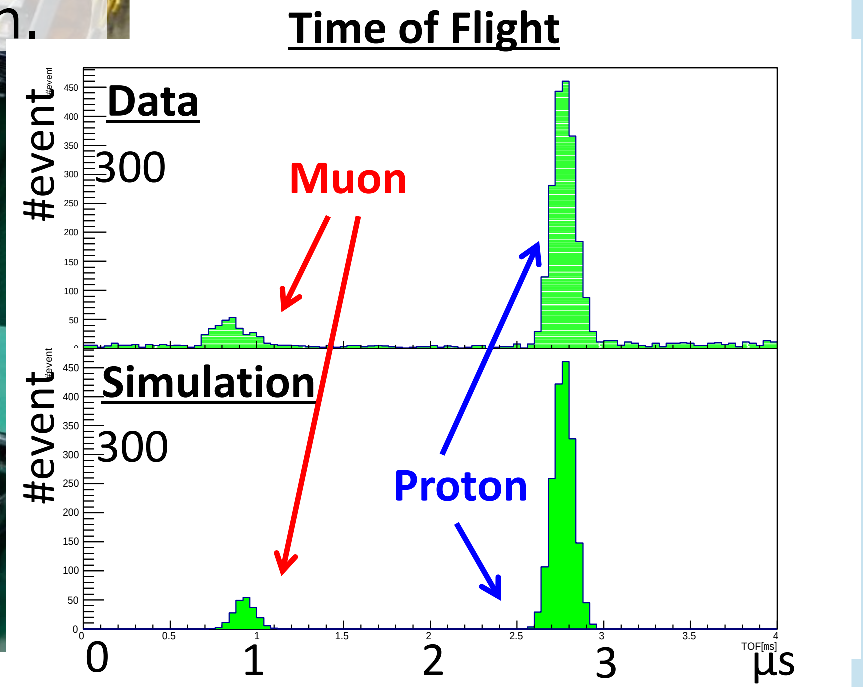




Demonstration of Deceleration and Initial Acc.

@ J-PARC MLF test muon beamline, Feb. 2016.





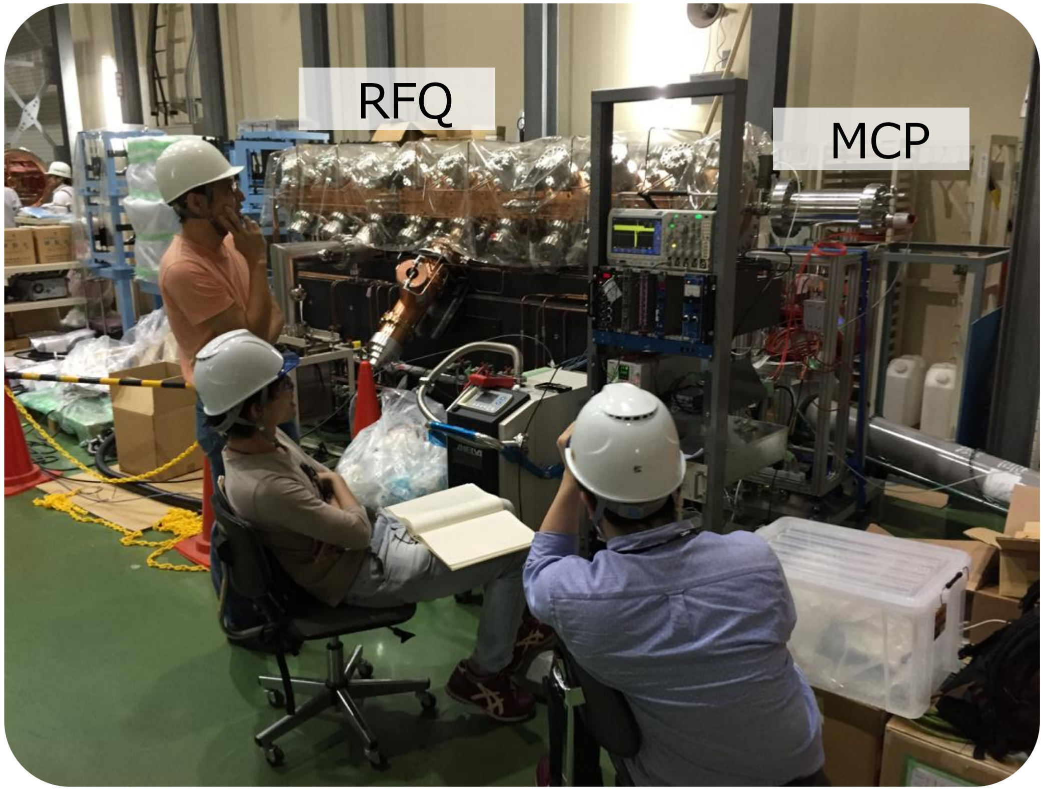
Slow muon source is ready.

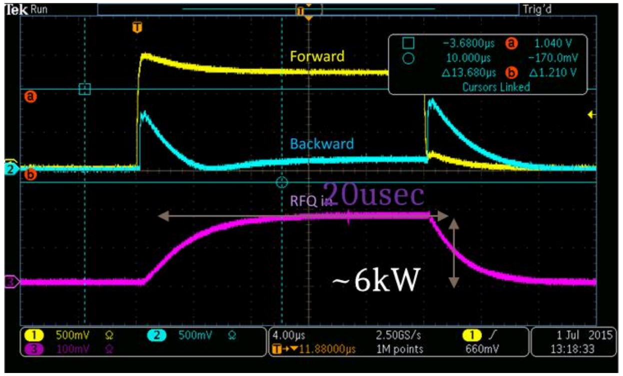
RFQ Offline Operation

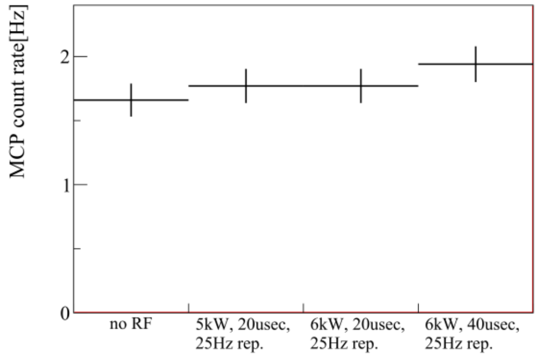
@ J-PARC LINAC facility, Jun. 2015.

☑ Nominal power (4.6 kW) and duty operation.

☑ No RF-related background with MCP.







RFQ is ready.

Summary

- **Muon linac is being developed for new g-2 experiment at J-PARC.**
  - 3σ discrepancy between SM and measurement in g-2.
- **Reference design for the muon linac has completed.**
  - Finish IH dynamics design [PRAB19, 040101, 2016]
  - Finish DAW design and test proto-type.
- **Muon acceleration with RFQ is planned, which will be first case in the world.**
  - Primary μ beamline is being constructed.
  - Slow μ and RFQ are ready.

Thank you for your attention.

Backup