Development of a Muon Linac for the g-2/EDM Experiment at J-PARC

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[4]Kyoto University
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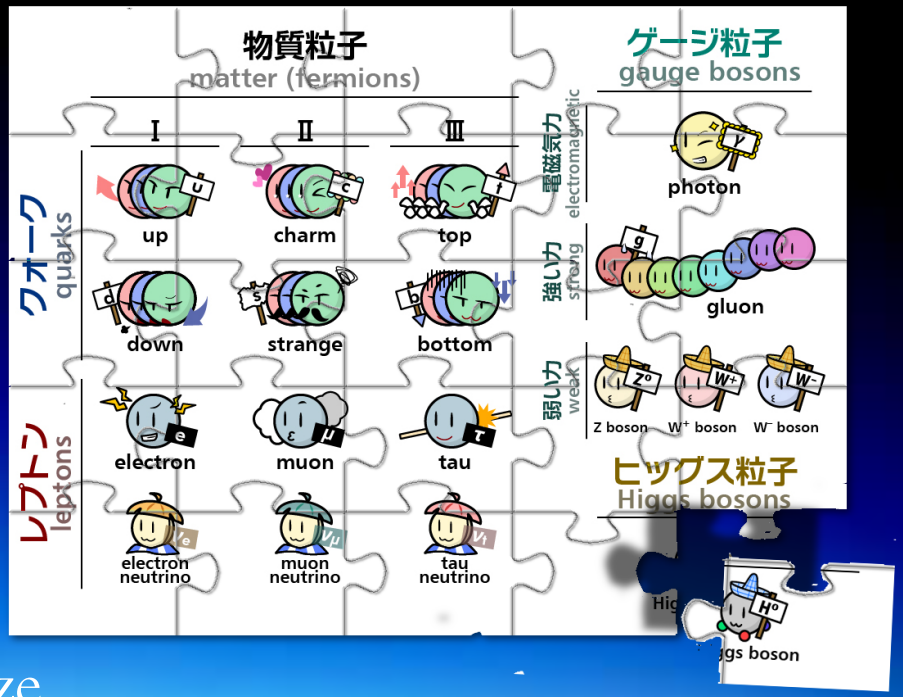
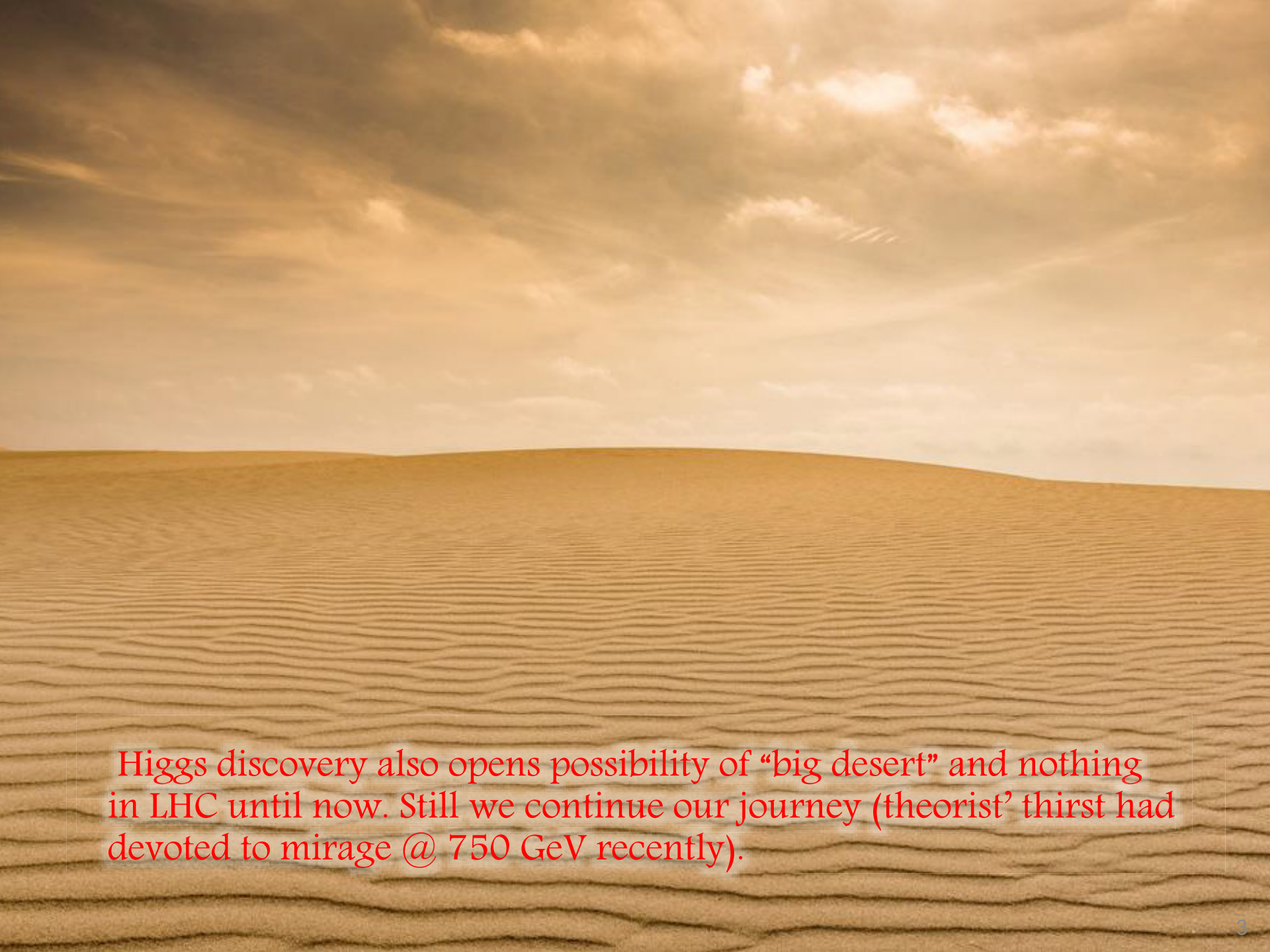
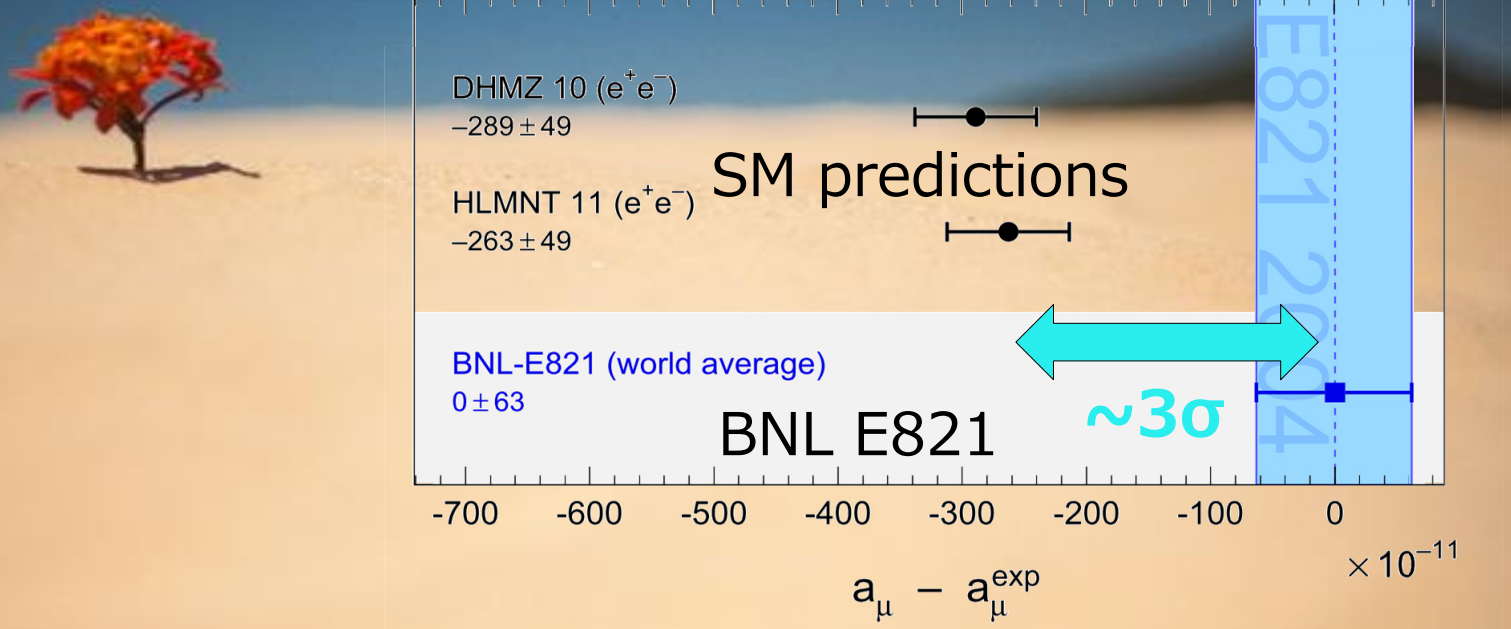
2013 Novel Prize



Higgs discovery completed particles in Standard Model and stimulated our hope to beyond SM.


Higgs discovery also opens possibility of “big desert” and nothing in LHC until now. Still we continue our journey (theorist’ thirst had devoted to mirage @ 750 GeV recently).

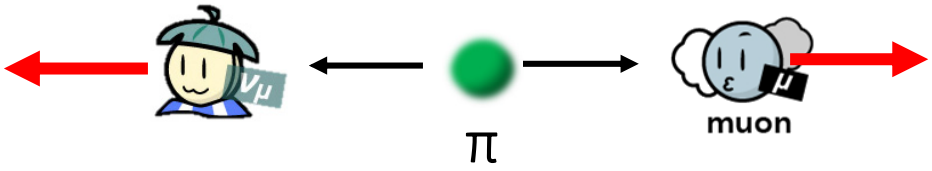
Muon g-2 [$a_\mu=(g-2)/2$]



- 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 ($a_\mu^{EW} \sim 15 \times 10^{-10}$)

Hope of new landscape near us.

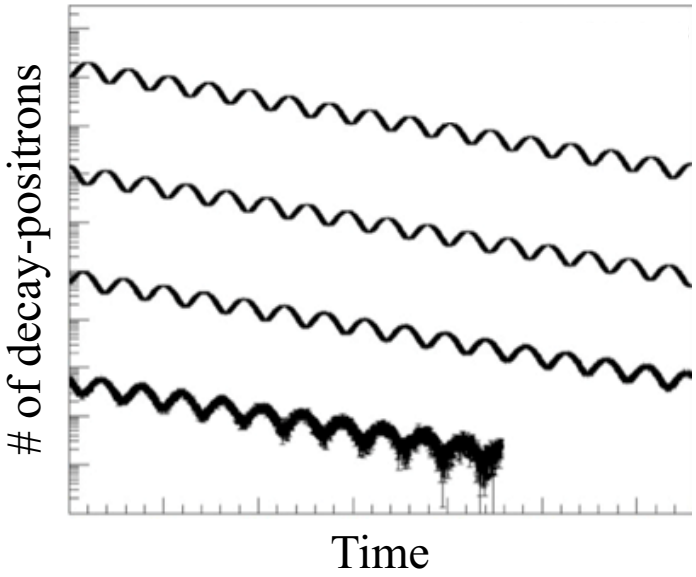
g-2 [$a_\mu=(g-2)/2$] Measurements



$\otimes$
$\vec{B}$

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

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



Measurements @ BNL & FNAL

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

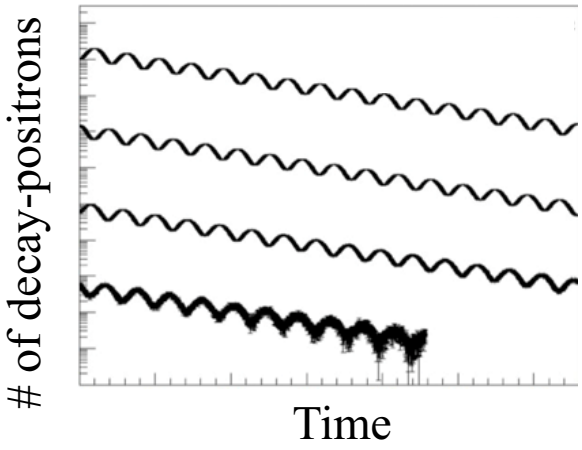
EDM

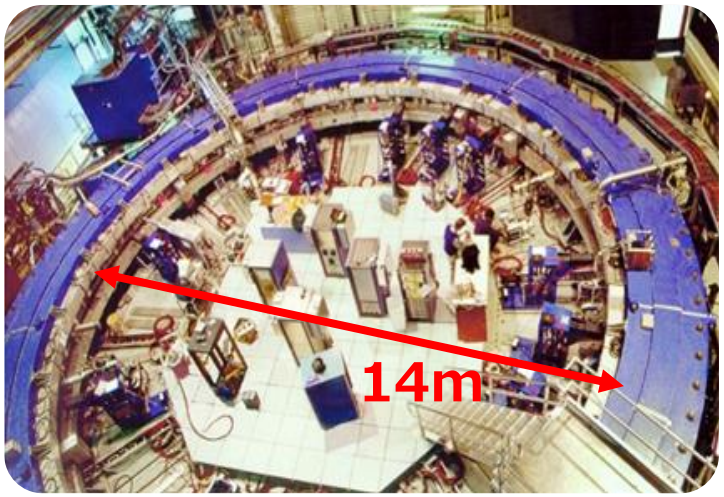
$\vec{B}$ by relativistic motion $\vec{E}$

"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





PHYSICAL REVIEW D 73, 072003 (2006)

Final report of the E821 muon anomalous magnetic moment measurement at BNL

G. W. Bennett,[2] B. Bousquet,[10] H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[10] G. T. Danby,[2] P. T. Debevec,[8] M. Deile,[13] H. Deng,[13] W. Deninger,[8] S. K. Dhawan,[13] V. P. Druzhinin,[3] L. Duong,[10] E. Efstathiadis,[1] F. J. M. Farley,[13] G. V. Fedotovich,[3] S. Giron,[10] F. E. Gray,[8] D. Grigoriev,[3] M. Grosse-Perdekamp,[13] A. Grossmann,[7] M. F. Hare,[1] D. W. Hertzog,[8] X. Huang,[1] V. W. Hughes,[13,*] M. Iwasaki,[12] K. Jungmann,[6,7] D. Kawall,[13] M. Kawamura,[12] B. I. Khazin,[3] J. Kindem,[10] F. Krienen,[1] I. Kronkvist,[10] A. Lam,[1] R. Larsen,[2] Y. Y. Lee,[2] I. Logashenko,[1,3] R. McNabb,[10,8] W. Meng,[2] J. Mi,[2] J. P. Miller,[1] Y. Mizumachi,[11] W. M. Morse,[2] D. Nikas,[2] C. J. G. Onderwater,[8,6] Y. Orlov,[4] C. S. Özben,[2,8] J. M. Paley,[1] Q. Peng,[1] C. C. Polly,[8] J. Pretz,[13] R. Prigl,[2] G. zu Putlitz,[7] T. Qian,[10] S. I. Redin,[3,13] O. Rind,[1] B. L. Roberts,[1] N. Ryskulov,[3] S. Sedykh,[8] Y. K. Semertzidis,[2] P. Shagin,[10] Yu. M. Shatunov,[3] E. P. Sichtermann,[13] E. Solodov,[3] M. Sossong,[8] A. Steinmetz,[13] L. R. Sulak,[1] C. Timmermans,[10] A. Trofimov,[1] D. Urner,[8] P. von Walter,[7] D. Warburton,[2] D. Winn,[5] A. Yamamoto,[9] and D. Zimmerman[10]

(Muon ($g-2$) Collaboration)

BNL E821 achieved 0.5 ppm.

Measurements @ BNL & FNAL

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

EDM

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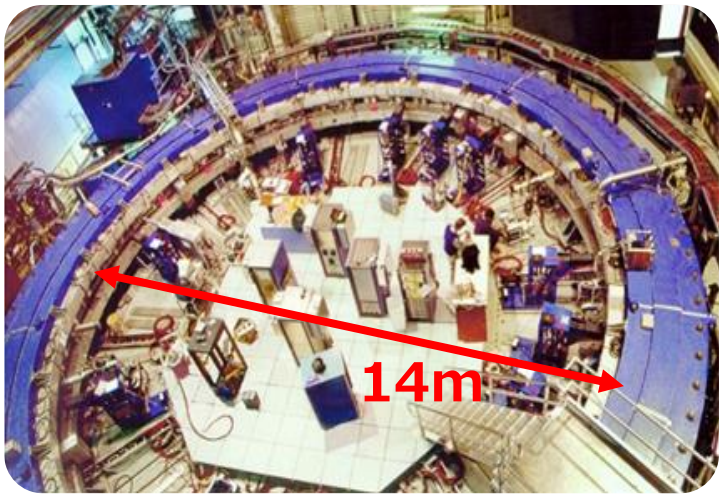
negligible



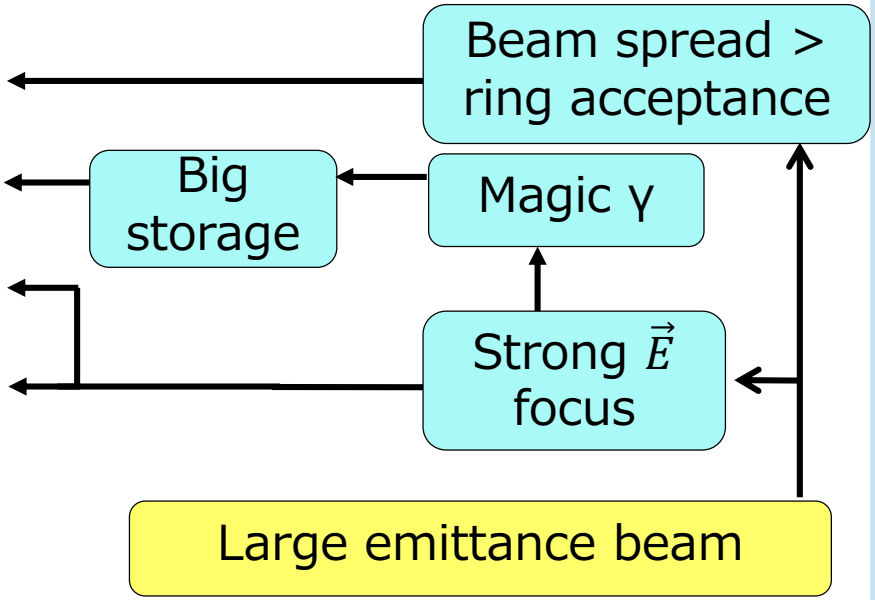
ICHEP2016,
C. Polly & E. Swanson

FNAL E989 will start 2017, aiming 0.1 ppm

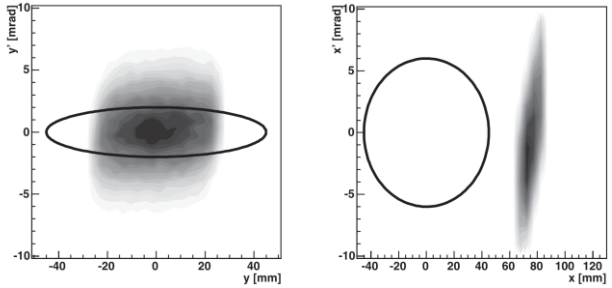
Uncertainties Breakdown

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



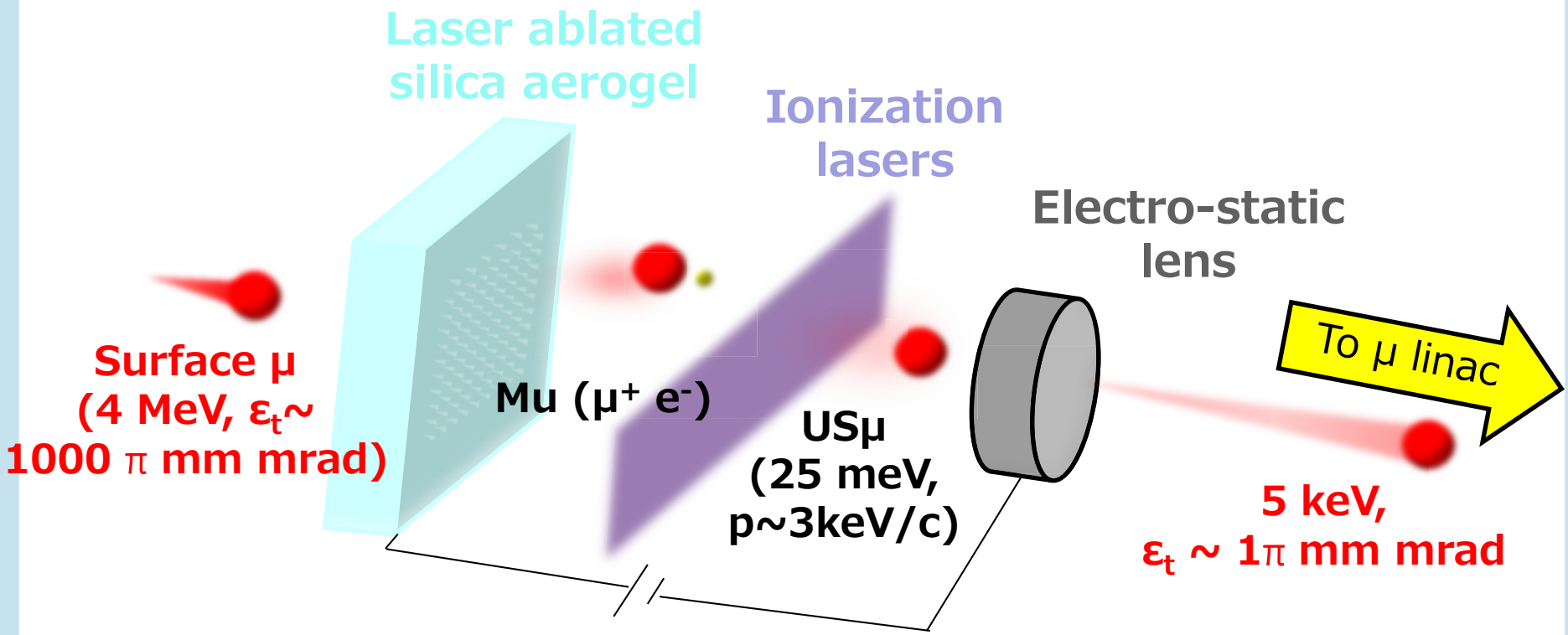
BNL μ beam at the inflector exit



Low emittance beam offers independent & precise measurement.

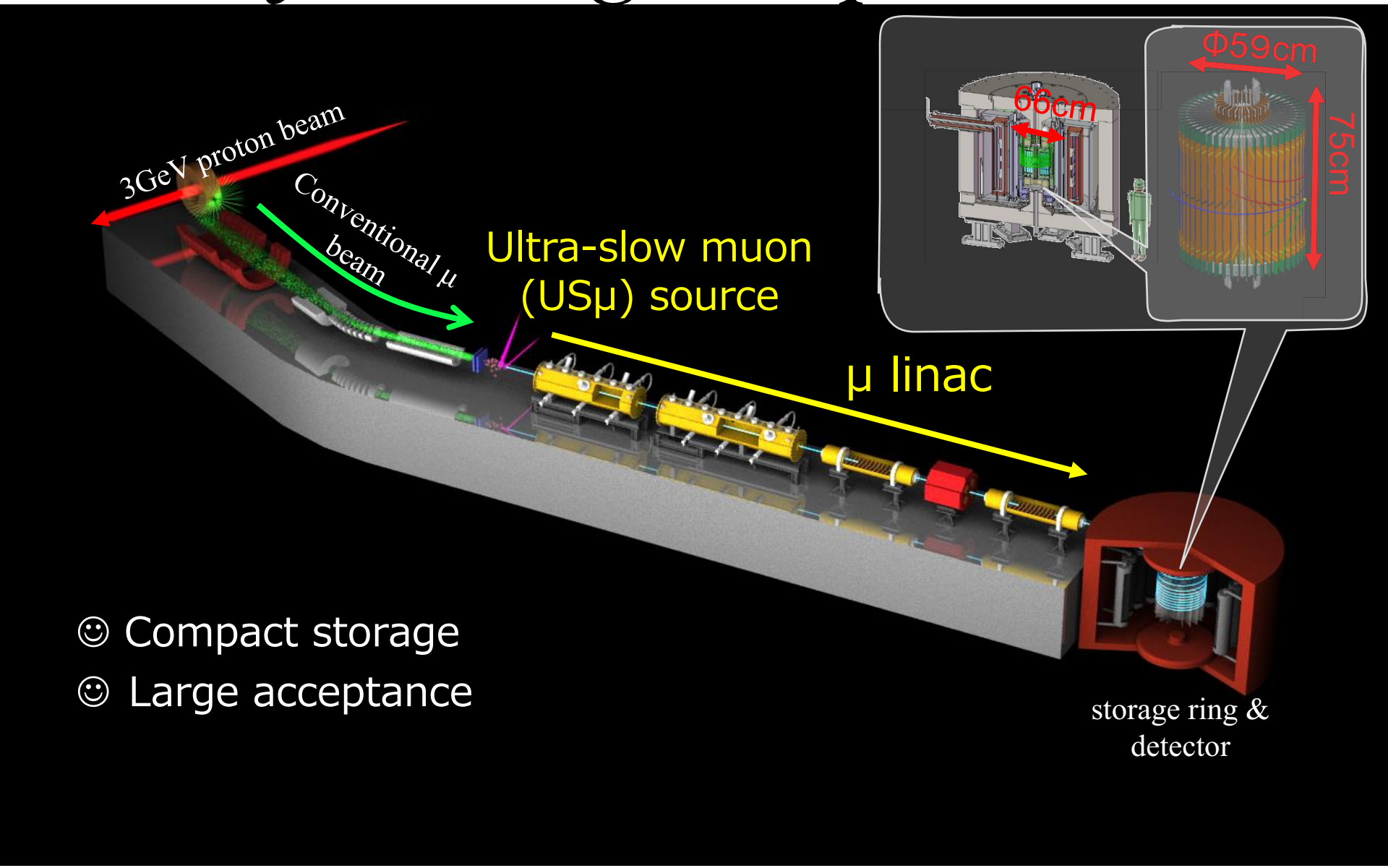
Cited from Phys. Rev. D. 73, 072003, 2006.

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

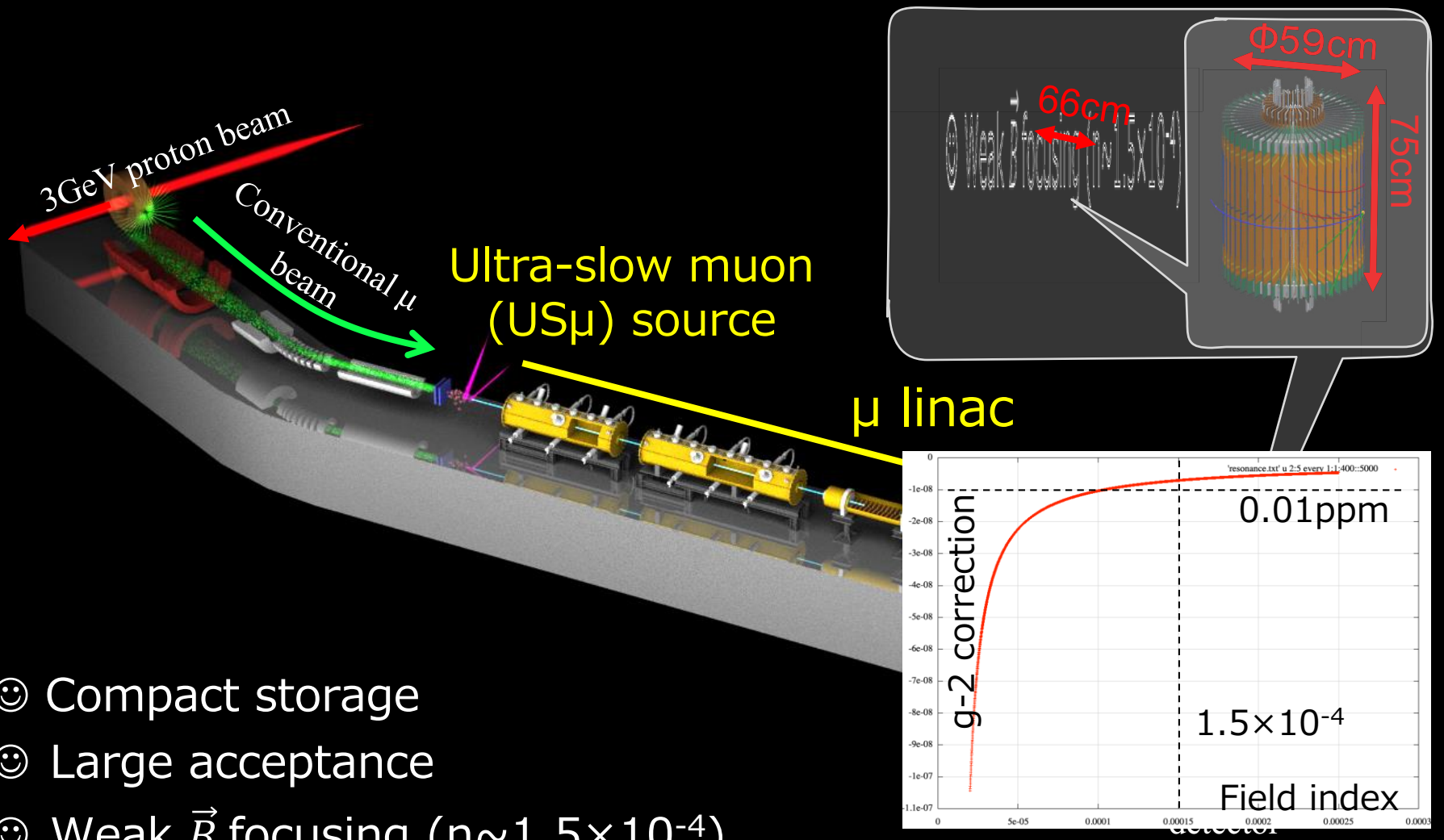


☺ Compact storage

☺ Large acceptance

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

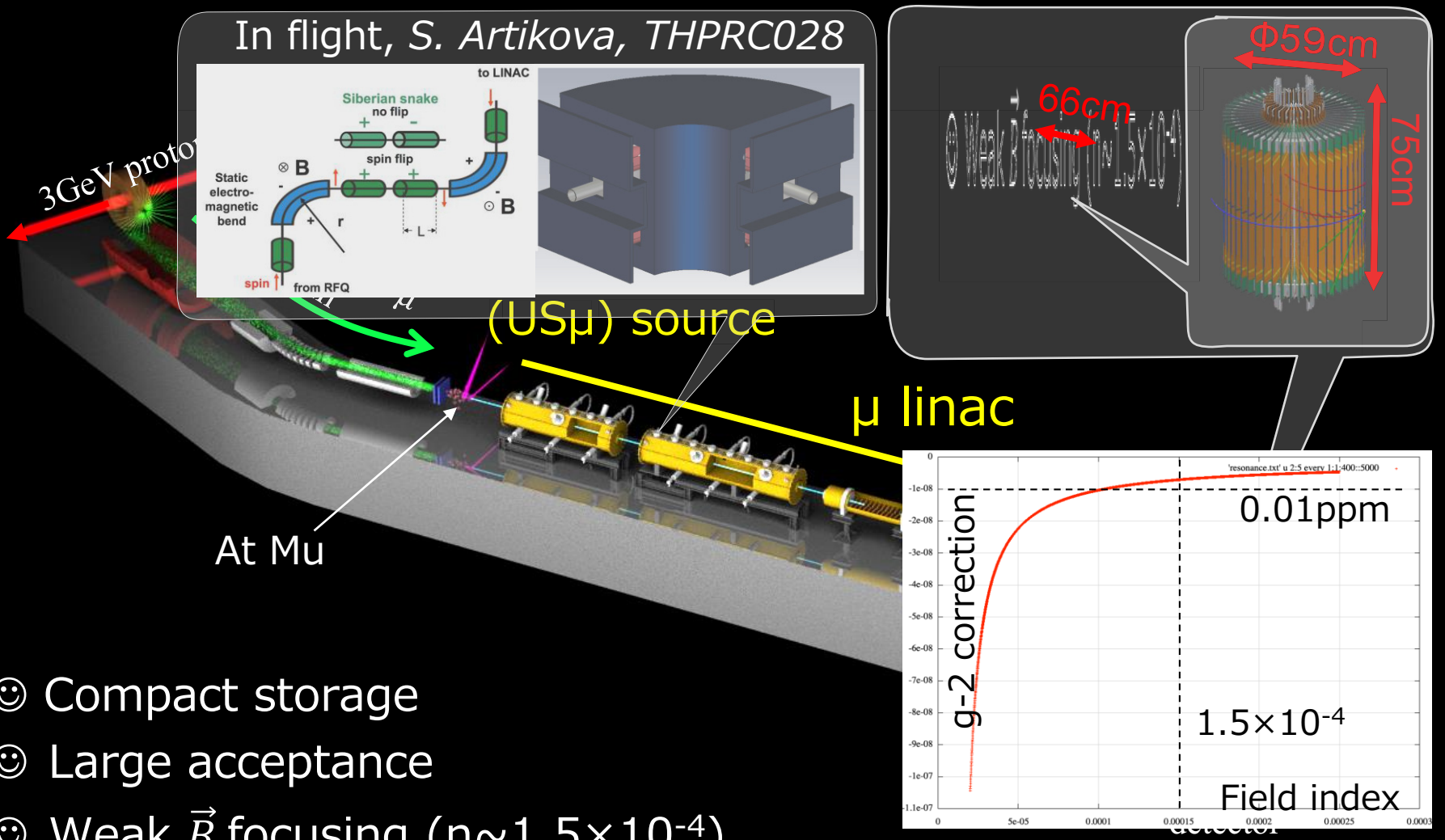
J-PARC g-2 Experiment



- ☺ 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

J-PARC g-2 Experiment



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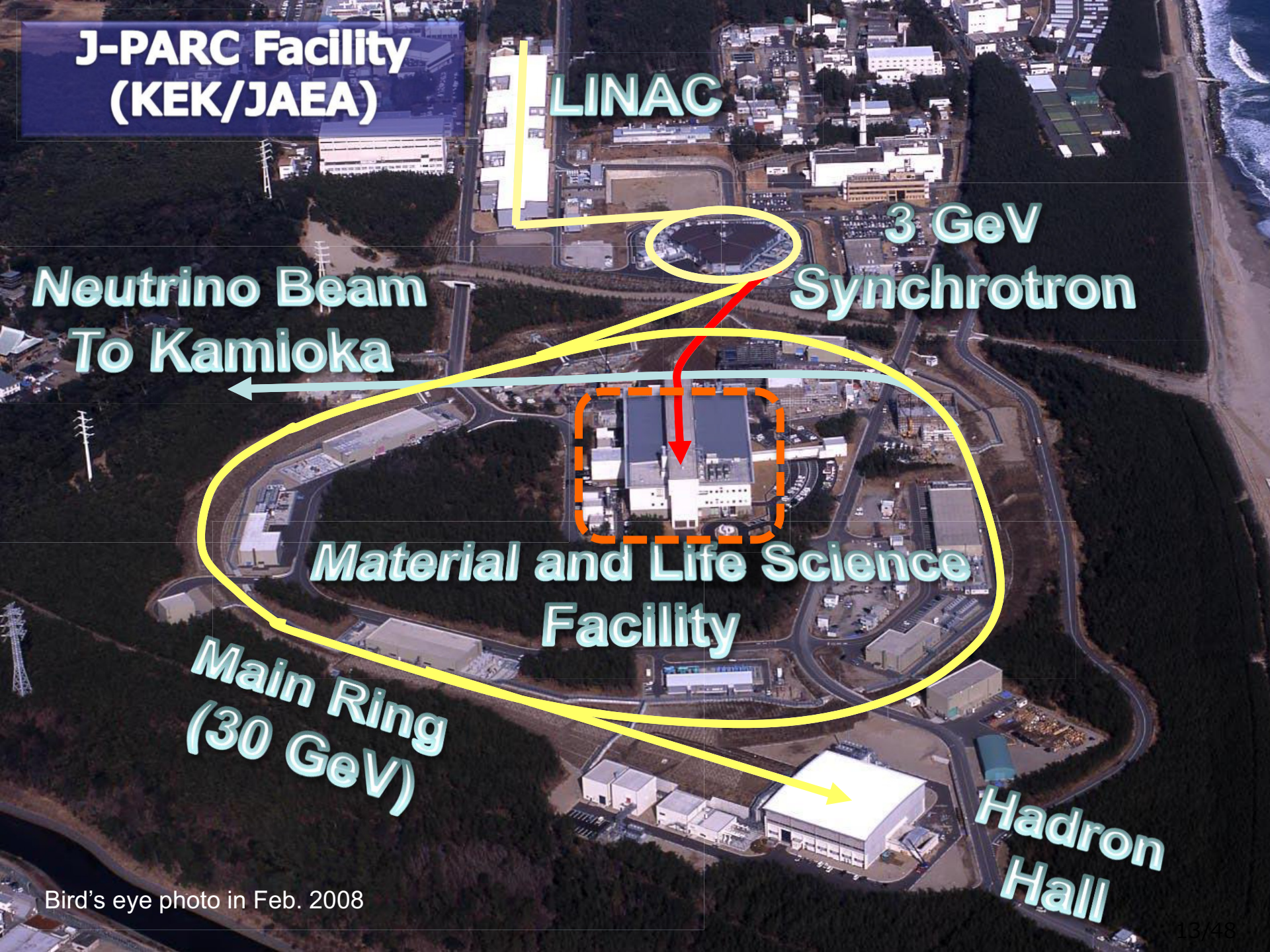
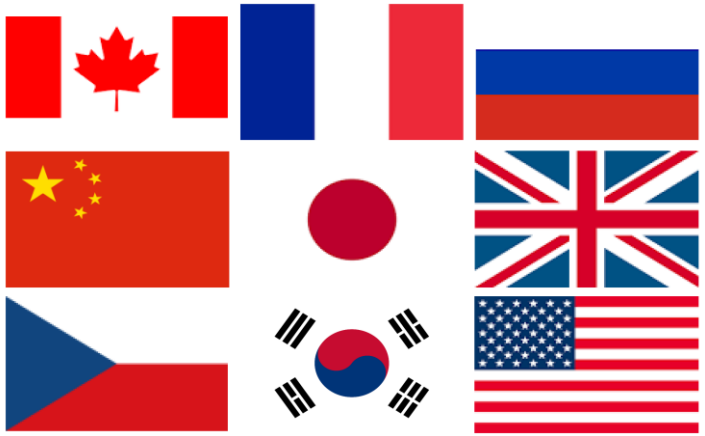


Bird's eye photo in Feb. 2008

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.

Start experiment 3 years after budget approval

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

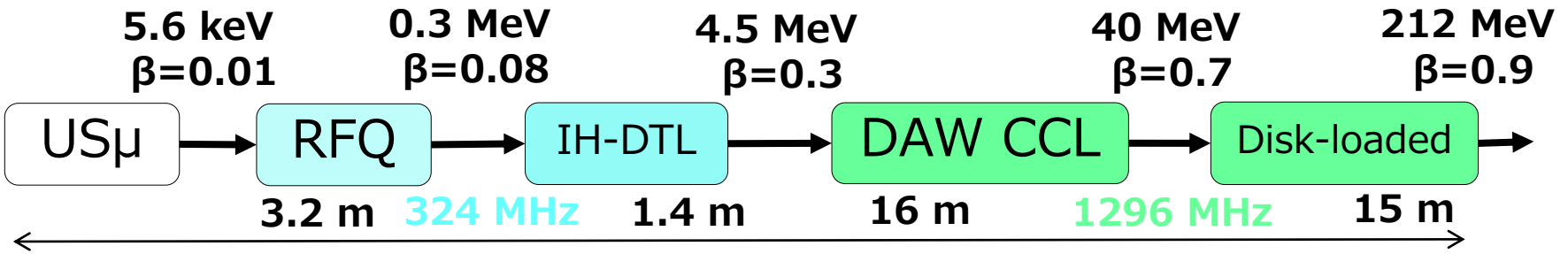
- Timely manner to FNAL g-2.
- Bigger impact in LHC era.

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

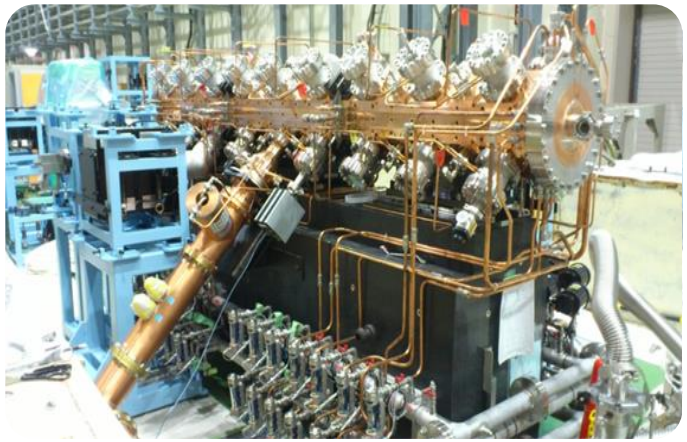


Total ~ 40m

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

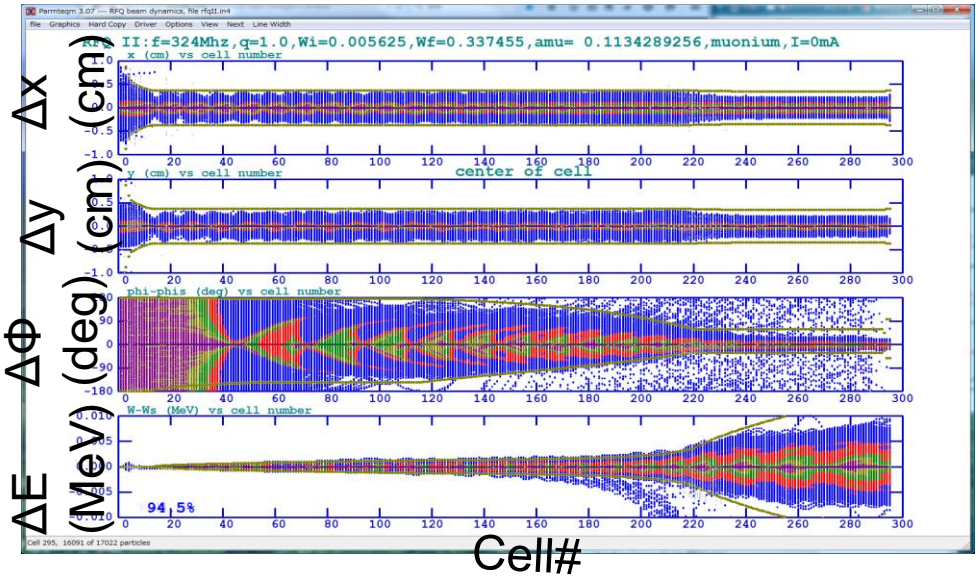
- Several structures to cover wide β
  - Rapid β evolution due to small mass
- Low current, low duty.
- Needs fast acceleration to avoid decay loss.
  - τ_μ = 2.2 usec

RFQ



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

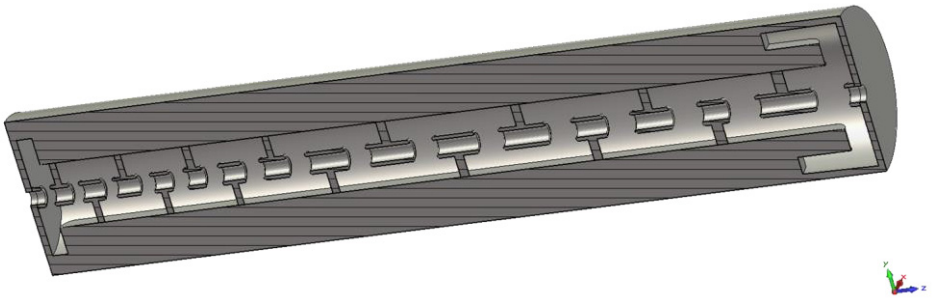
f [MHz]		324
Length [m]		3.2
Energy [keV]	In	5.6
	Out	340
Inter-vane V [kV]		9.3
Power [kW]		4.2



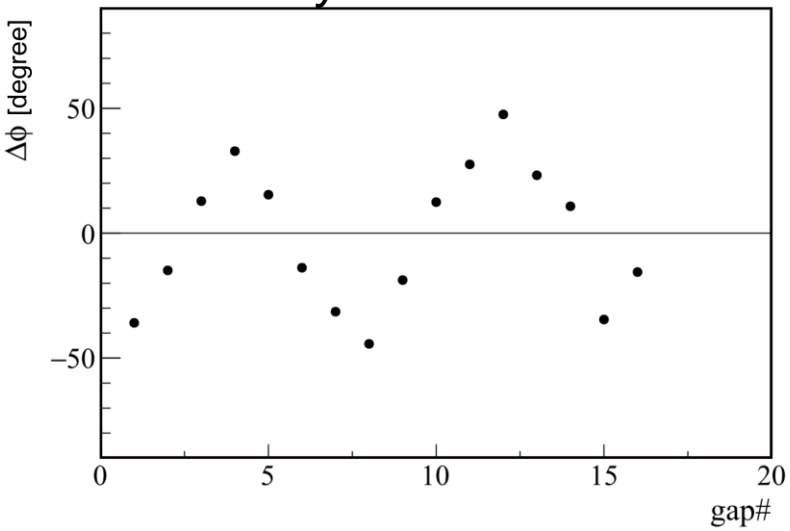
Good transmission (95%).

Interdigital H-DTL

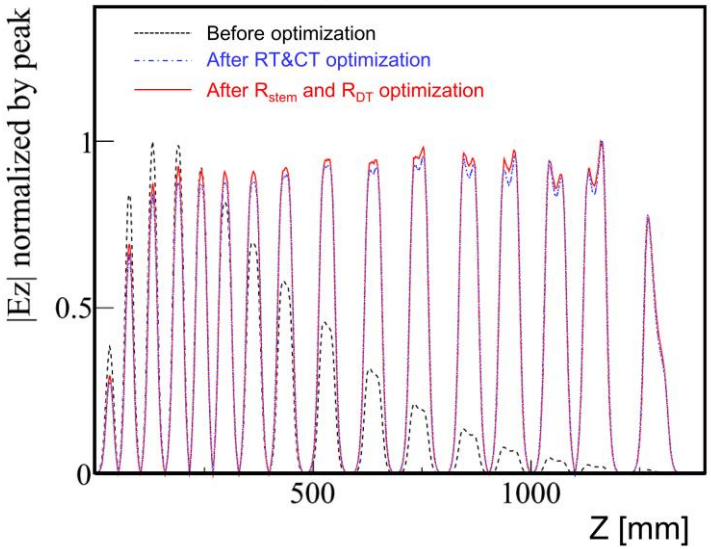
- H-mode + alternative phase focusing (APF) for high-efficiency.
- Rapid velocity evolution
  → Optimization of Φ_s and cavity for ideal APF are essential.



Φ_s optimization by annalytical calculation

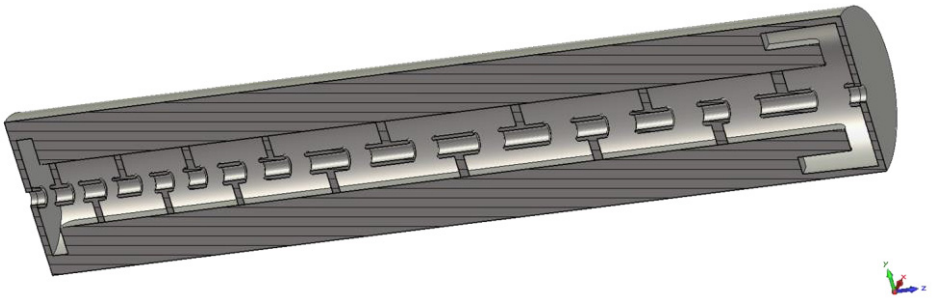


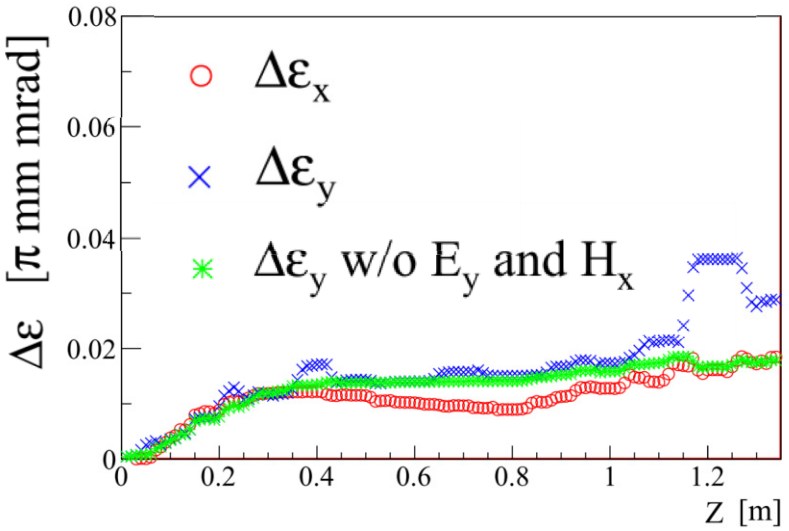
On-axis field before/after IH cavity optimization



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

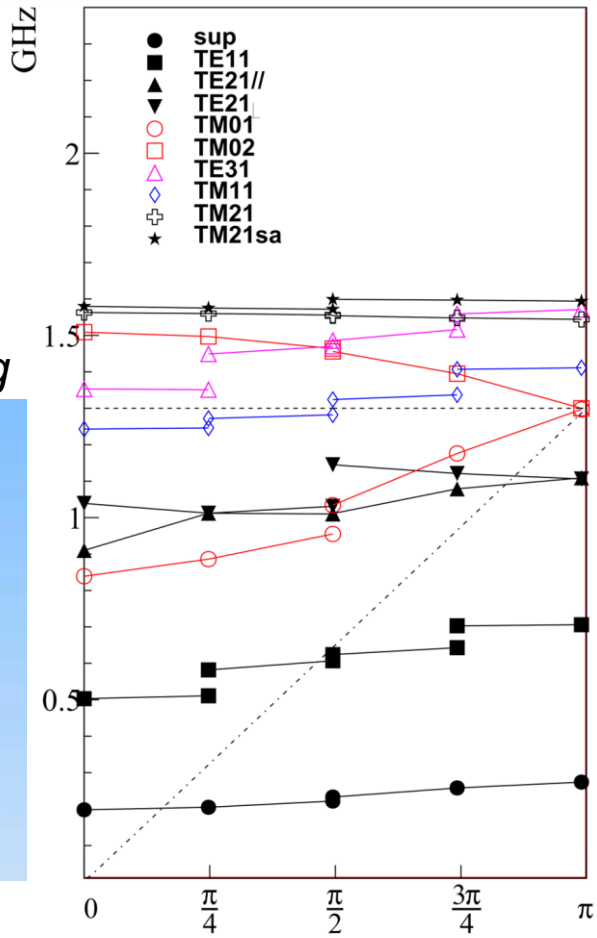
M. Otani et al., PRAB19, 040101, 2016.

Finish beam dynamics design.

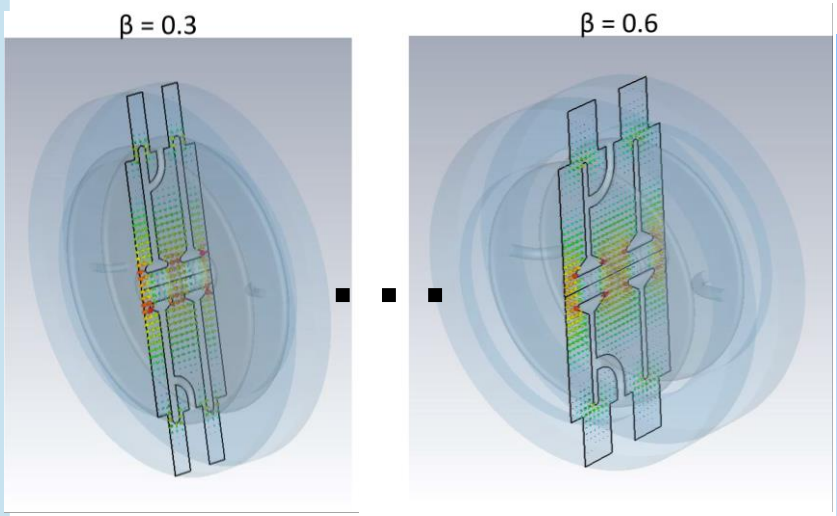
Disk And Washer CCL

- 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.

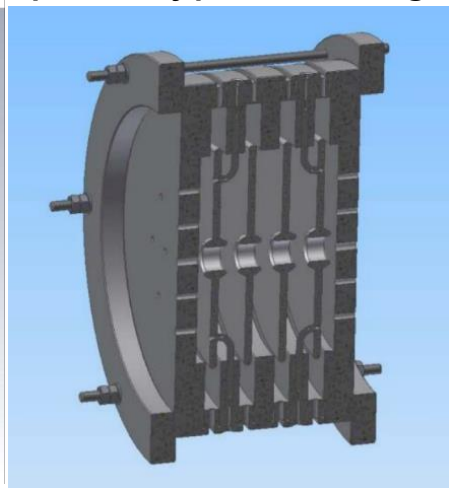
dispersion (β=0.3 model)



CST models



proto-type drawing

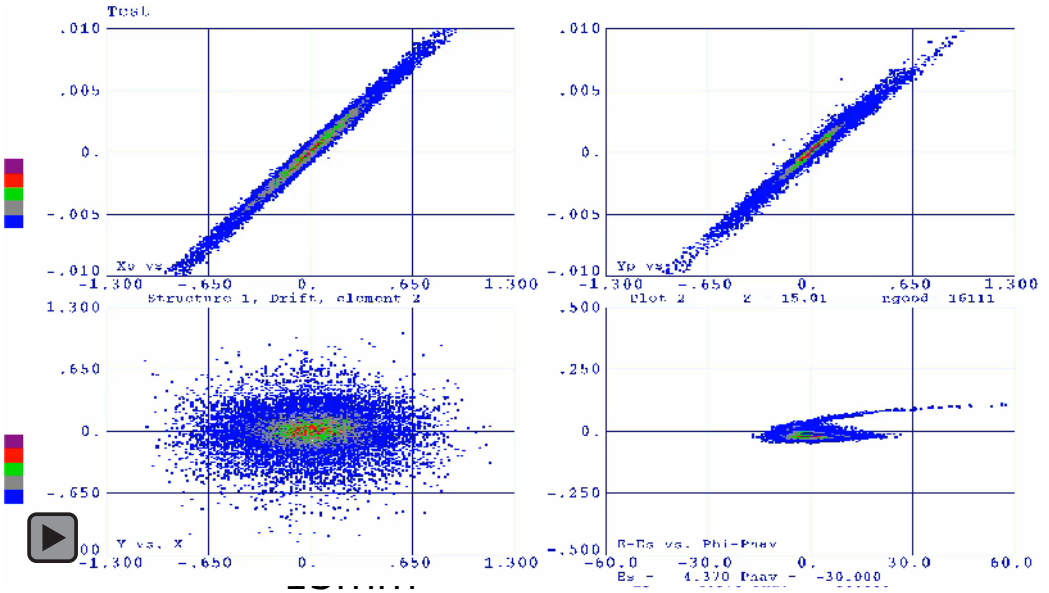


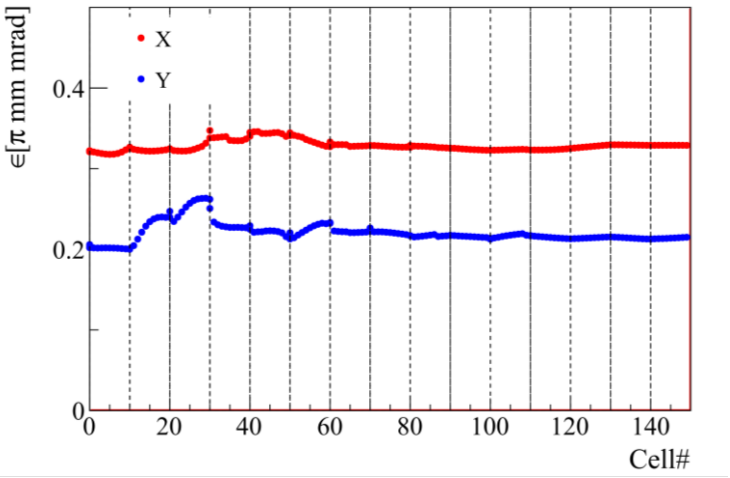
Under proto-type evaluation.

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

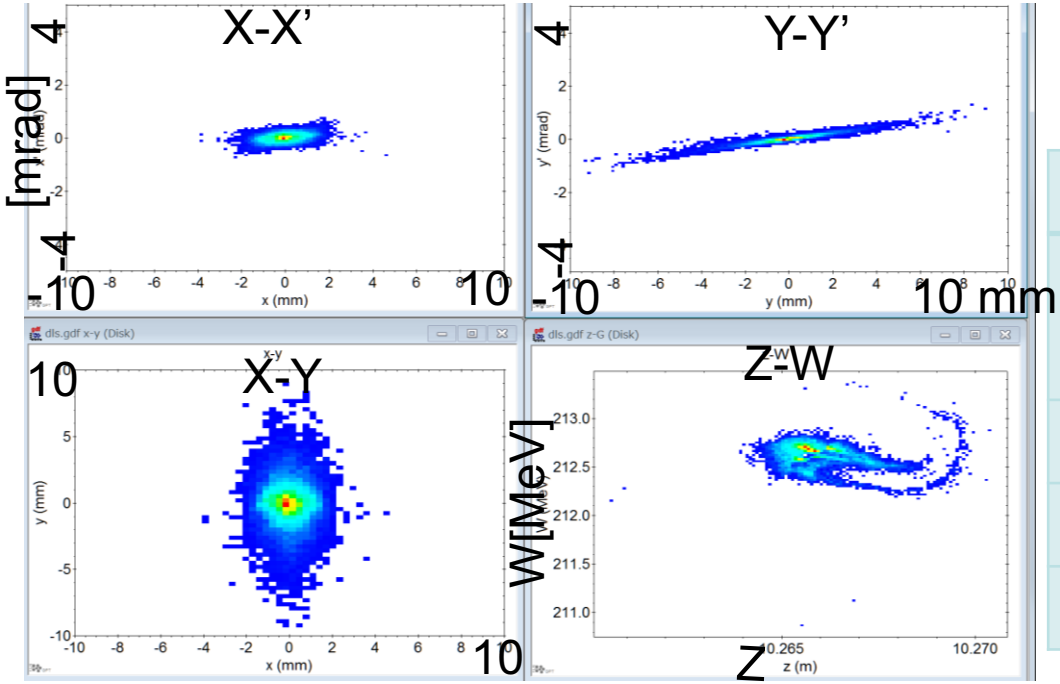


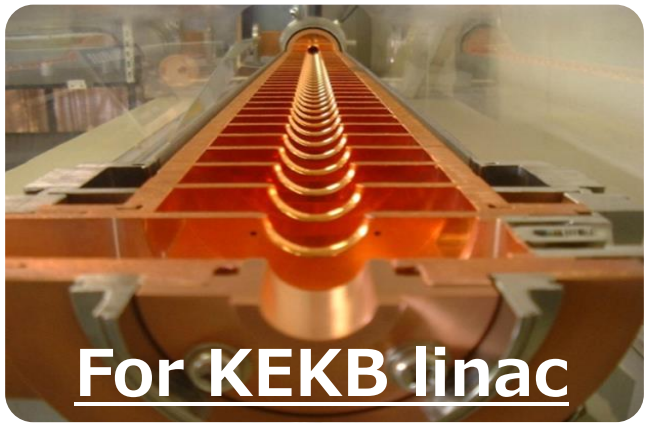


Finish dynamics design.

Disk-loaded

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



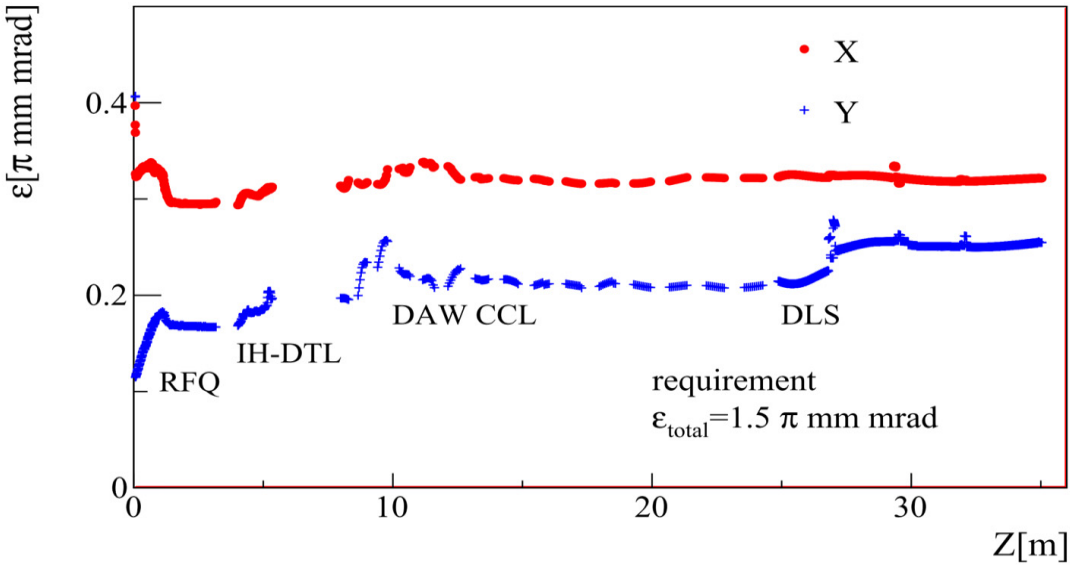


f [MHz]		1296
Energy [MeV]	In	40
	Out	212
E_0 [MV/m]		20
Φ_s [deg.]		-10
# modules		4

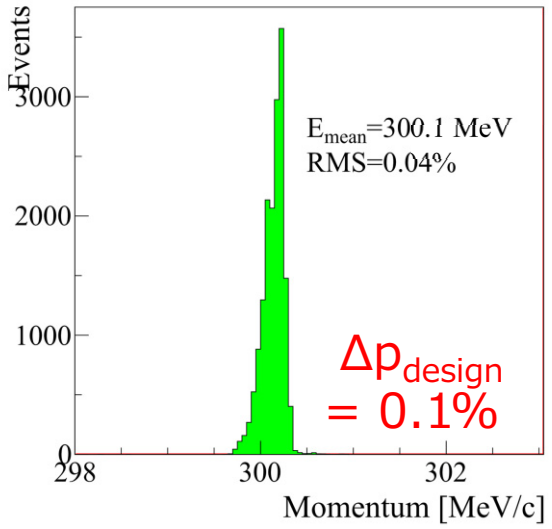
Finish reference design.

Design Summary

Emittance evolution



Momentum spread

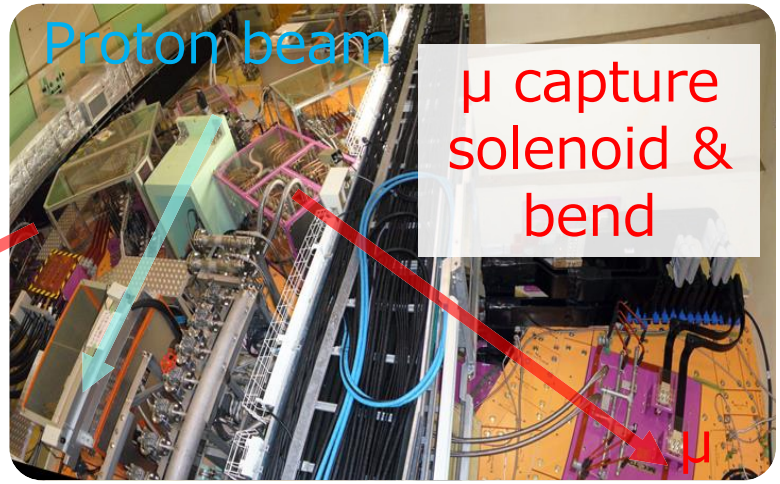


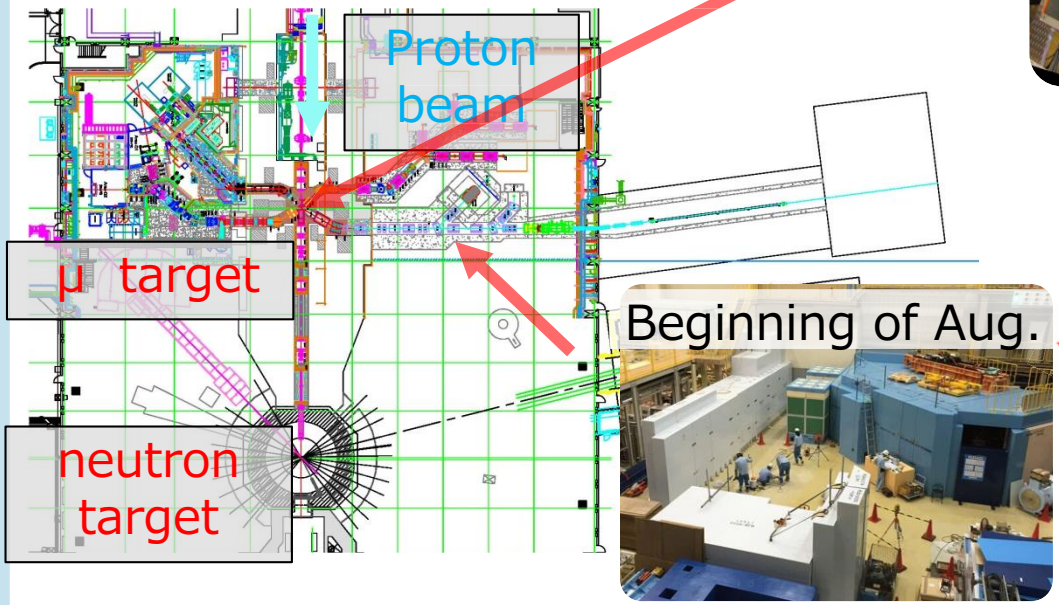
	Init.	RFQ	IH	DAW	DLS
Decay survival [%]	83	81	98	96	99
Transmission [%]	87	95	99.9	99.5	99.9

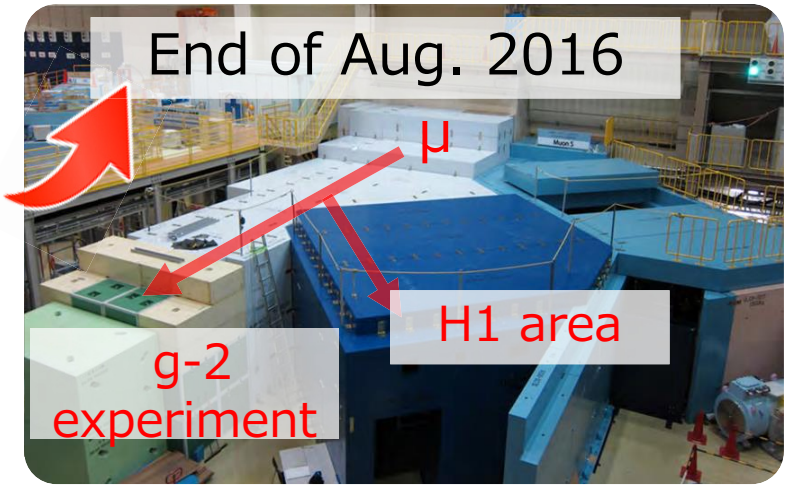
Comparable to the requirement.

Muon Source (New μ Beamline)

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

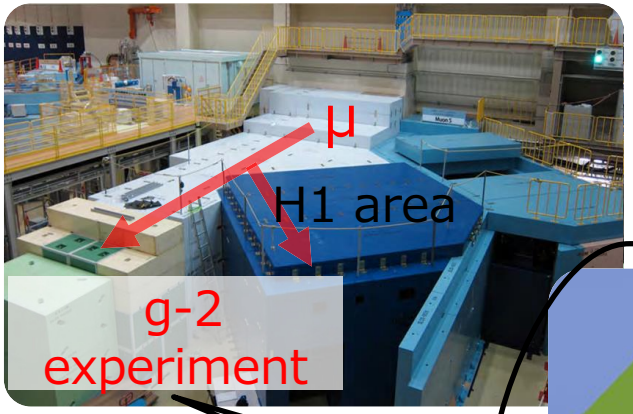


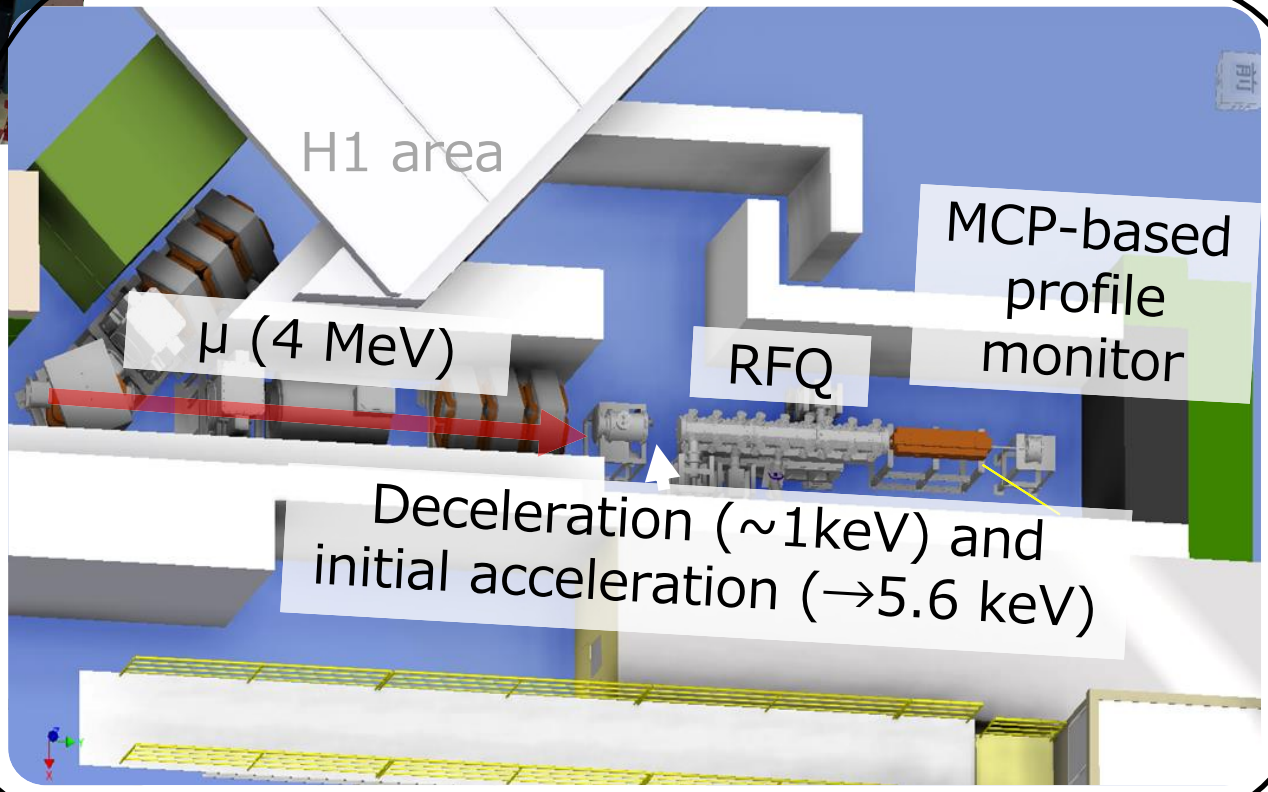




Primary muon beam will be available soon.

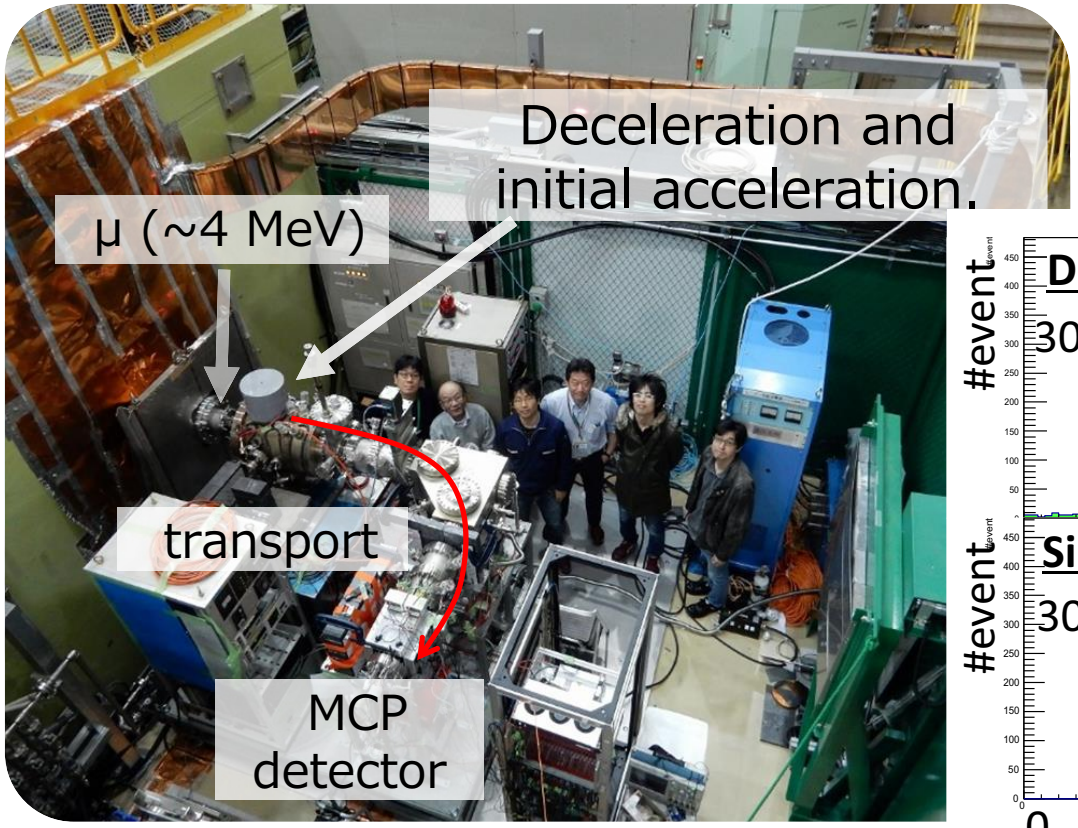
First Commissioning Setup

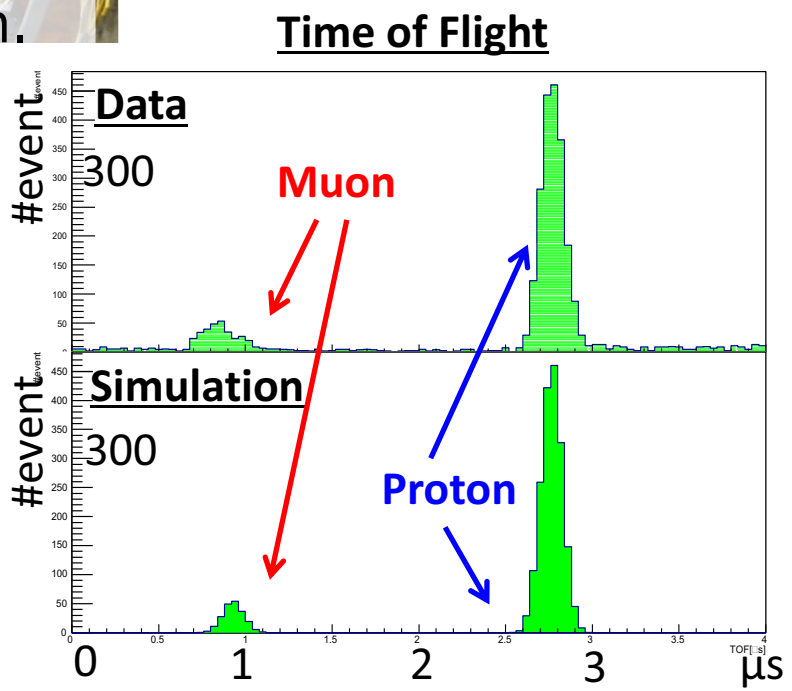




Demonstration of Deceleration and Initial Acc.

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





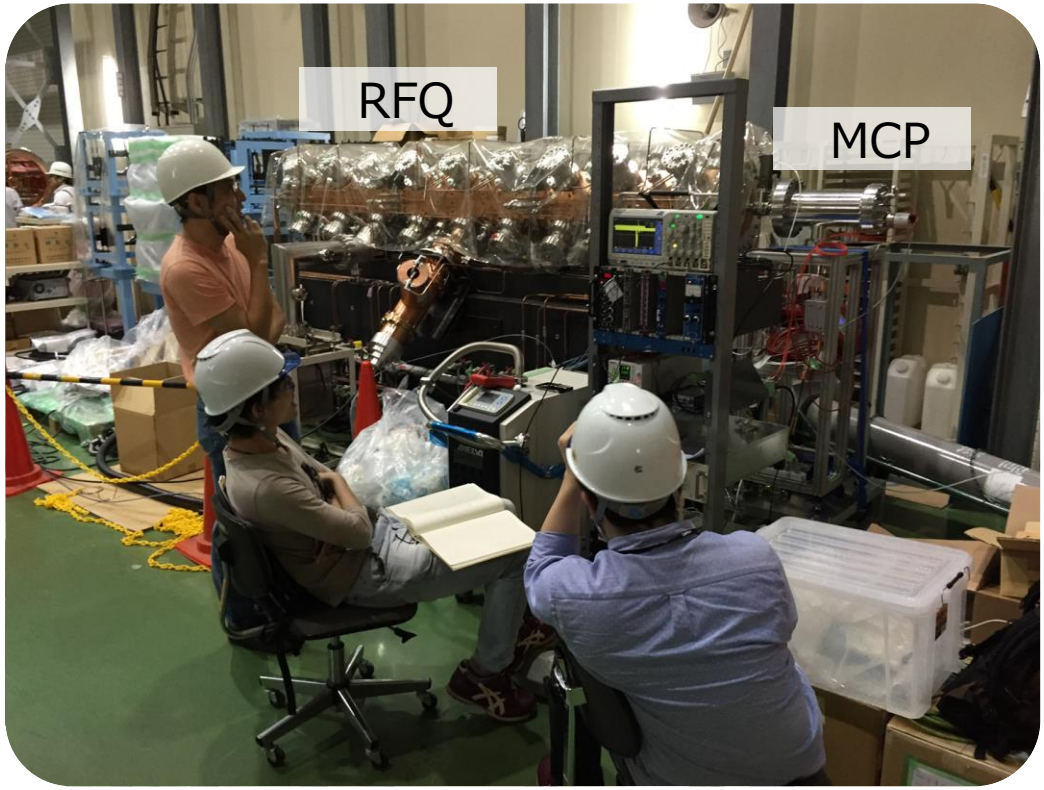
Slow muon source is ready.

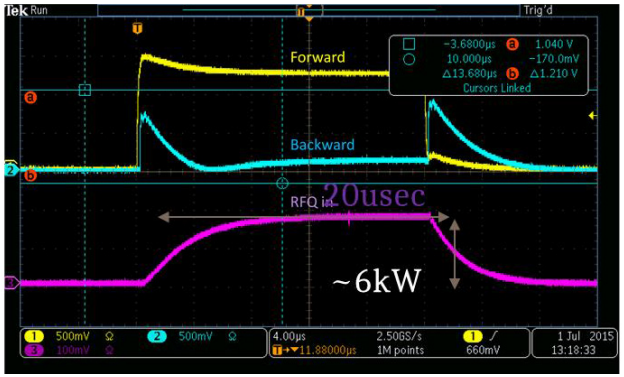
RFQ Offline Operation

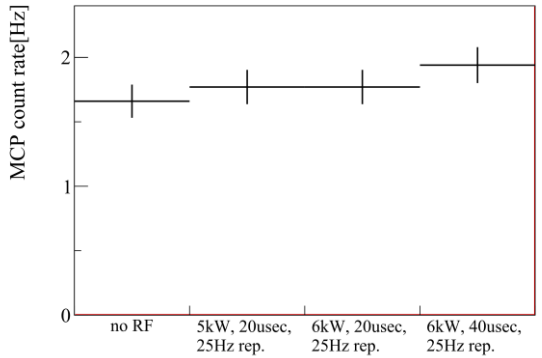
@ J-PARC LINAC facility, Jun. 2015.

☑ 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.