The world's first muon linac towards the muon g-2/EDM experiment at J-PARC

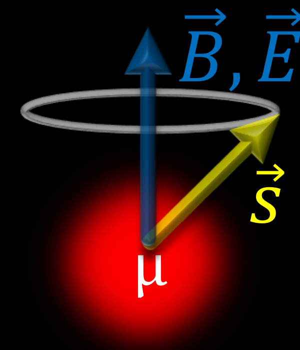
M. Otani (KEK)

2016/2/2

1. Introduction
2. Muon linac Design
3. Current Status
4. Summary

Dipole Moments

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$



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

Electric $\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$

$$g = 2(1+a)$$

QED tree level

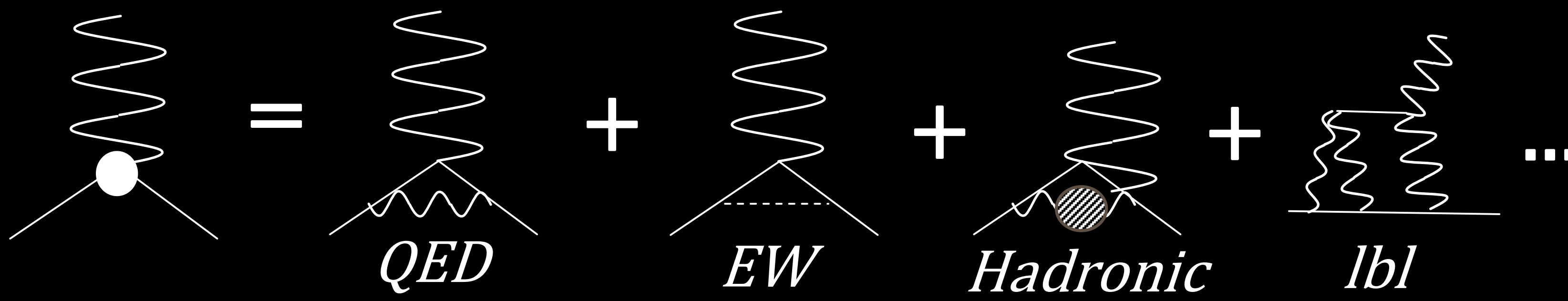
SM, and beyond

- Contains plenty of physics including beyond SM

- T violated and highly suppressed in SM ($d \sim 10^{-38}$ e・cm)
- Current direct limit is $< 1.9 \times 10^{-19}$ e・cm

Beyond SM can be surveyed via dipole moments.

Measurement and SM Prediction



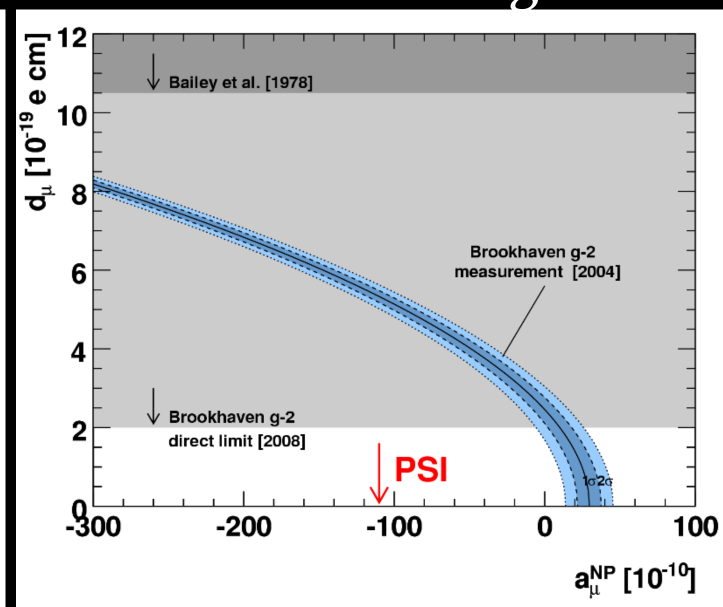
Muon g-2, SM prediction and measurement

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

D. Nomura, tau2012

contour at d & g-2

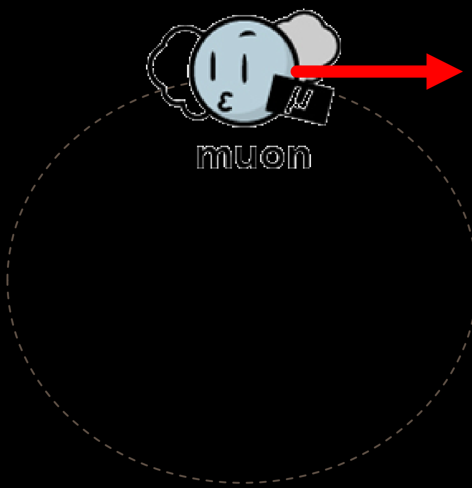


Nucl. Phys. B613, 366 (2001)

Needs more precise meas. for g-2 and search for EDM $< 10^{-19}$

Measurement Method

- In uniform magnetic field, muon spin rotes ahead of momentum due to g-2≠0
  - And spin direction is reconstructed by decay-e



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

Magic momentum (p=3.1GeV/c)

$\vec{E}=0$

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

BNL & FNAL

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

J-PARC (new method)

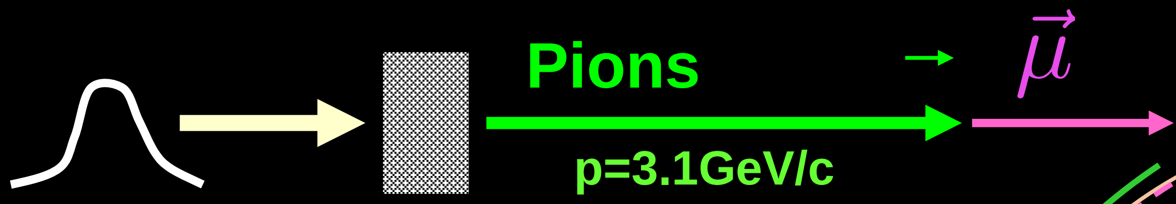
Experimental Technique

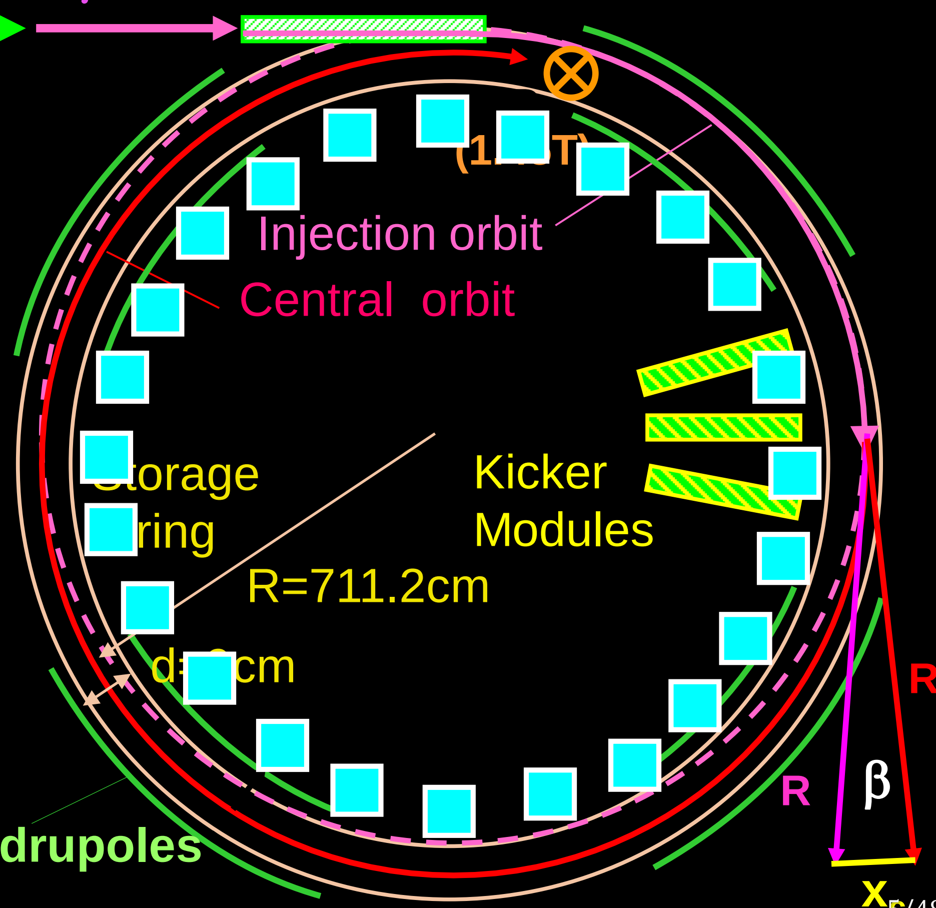
narrow bunch of protons

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm



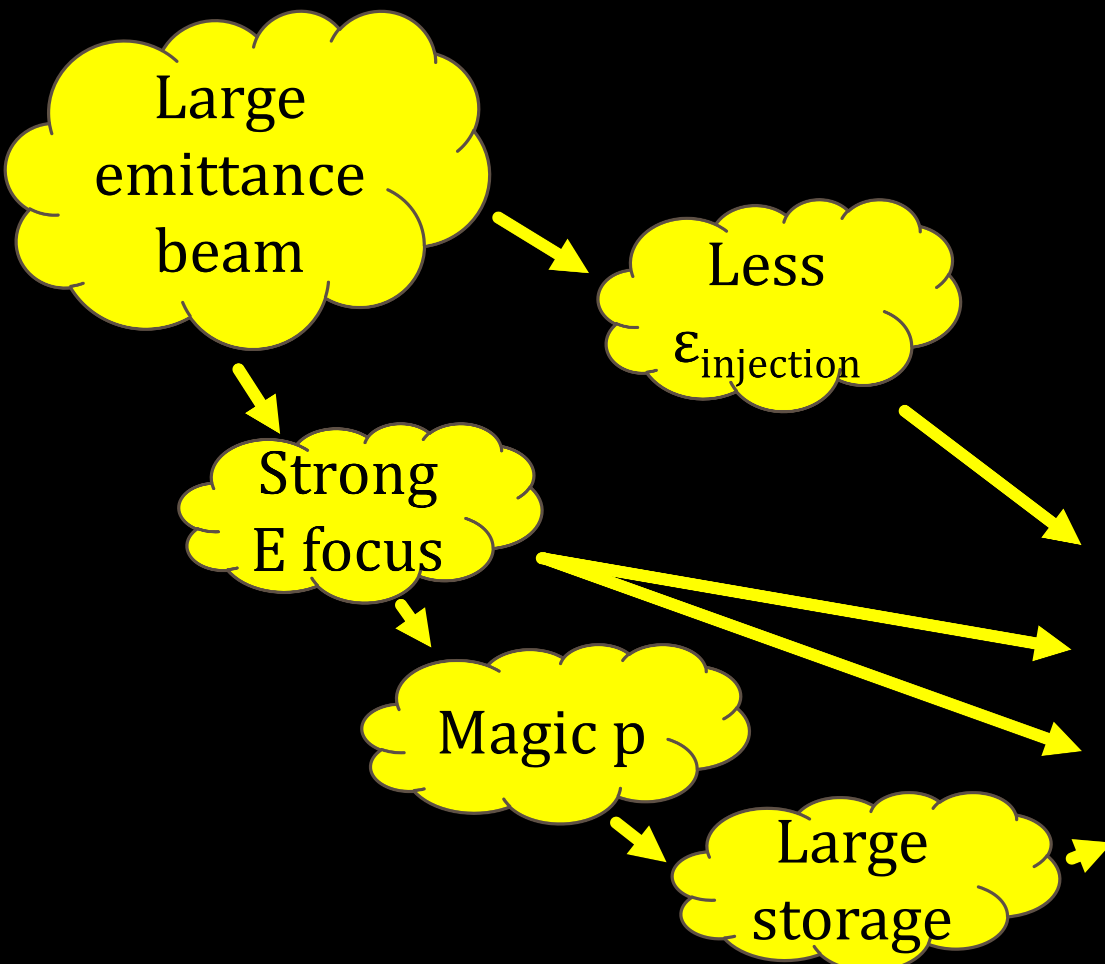


- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$

Slide by Lee Roberts

Uncertainties



Error	ppb
Gain changes	120
Pileup	80
Lost muons	90
CBO	70
E and pitch	50
B field	170

Cited from Fermilab-FN-0992-E

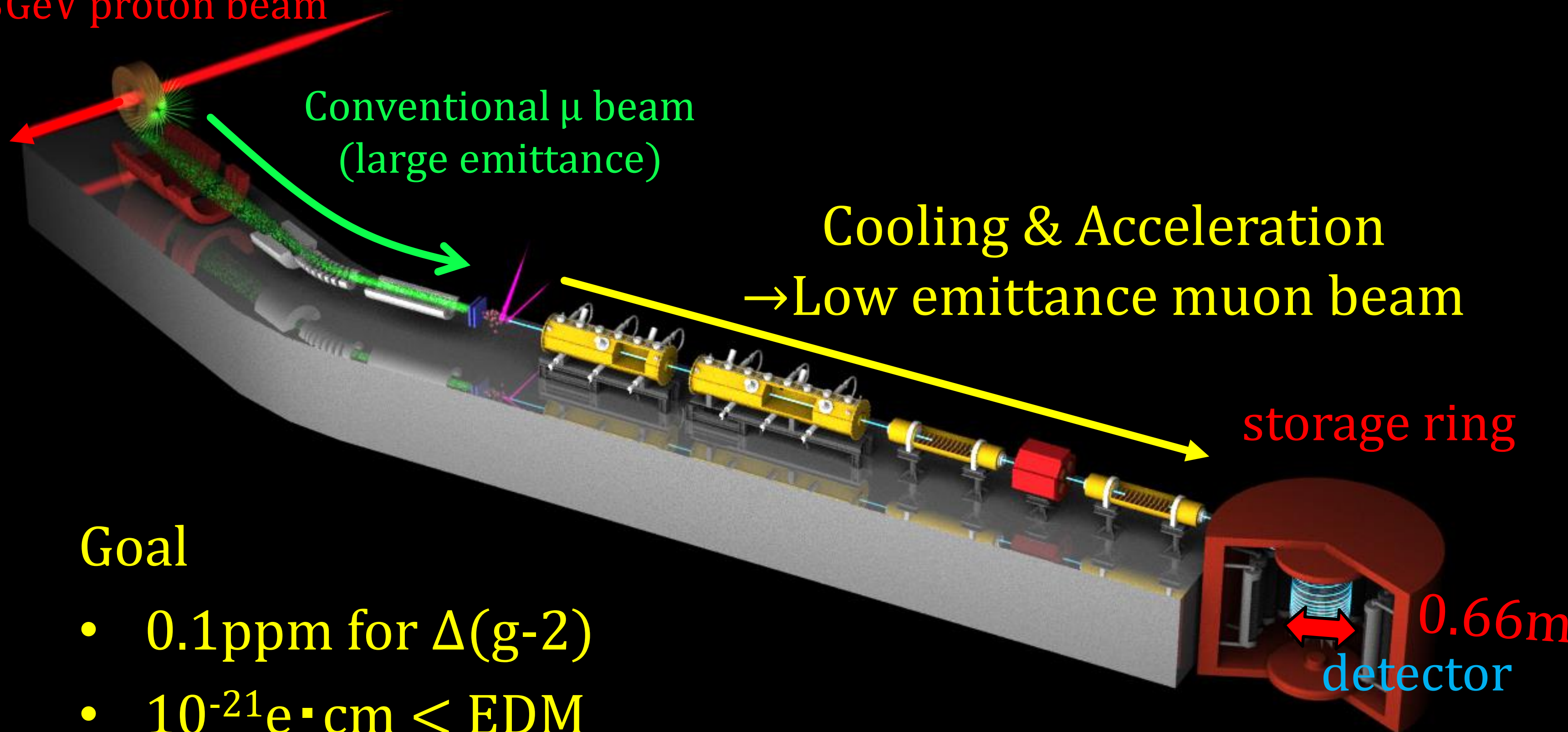
Low emittance muon beam offers better precision

Experiment @ J-PARC (E34)

- Measurement of g-2 and EDM with low emittance muon beam

w/o E focusing at storage

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

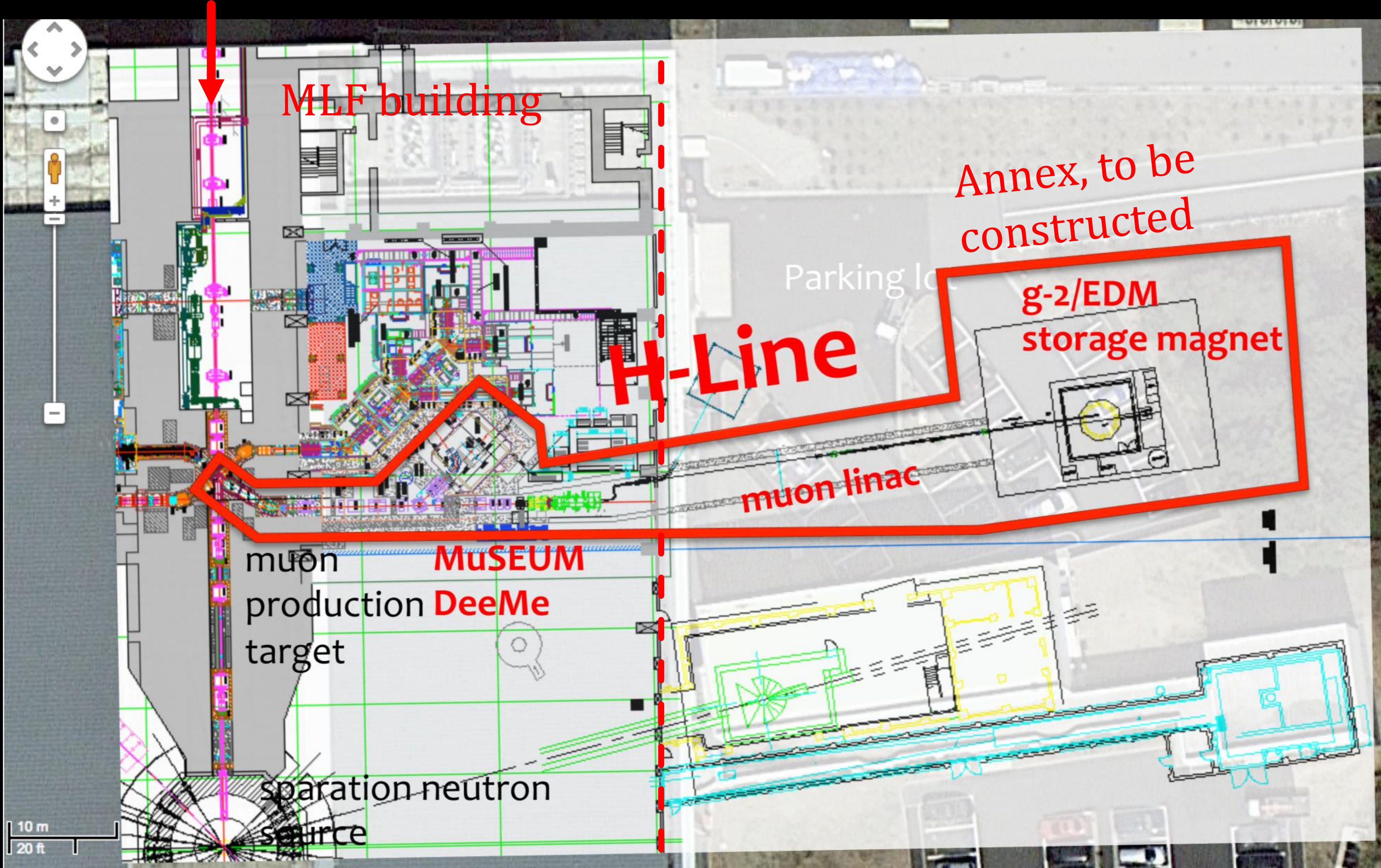


Goal

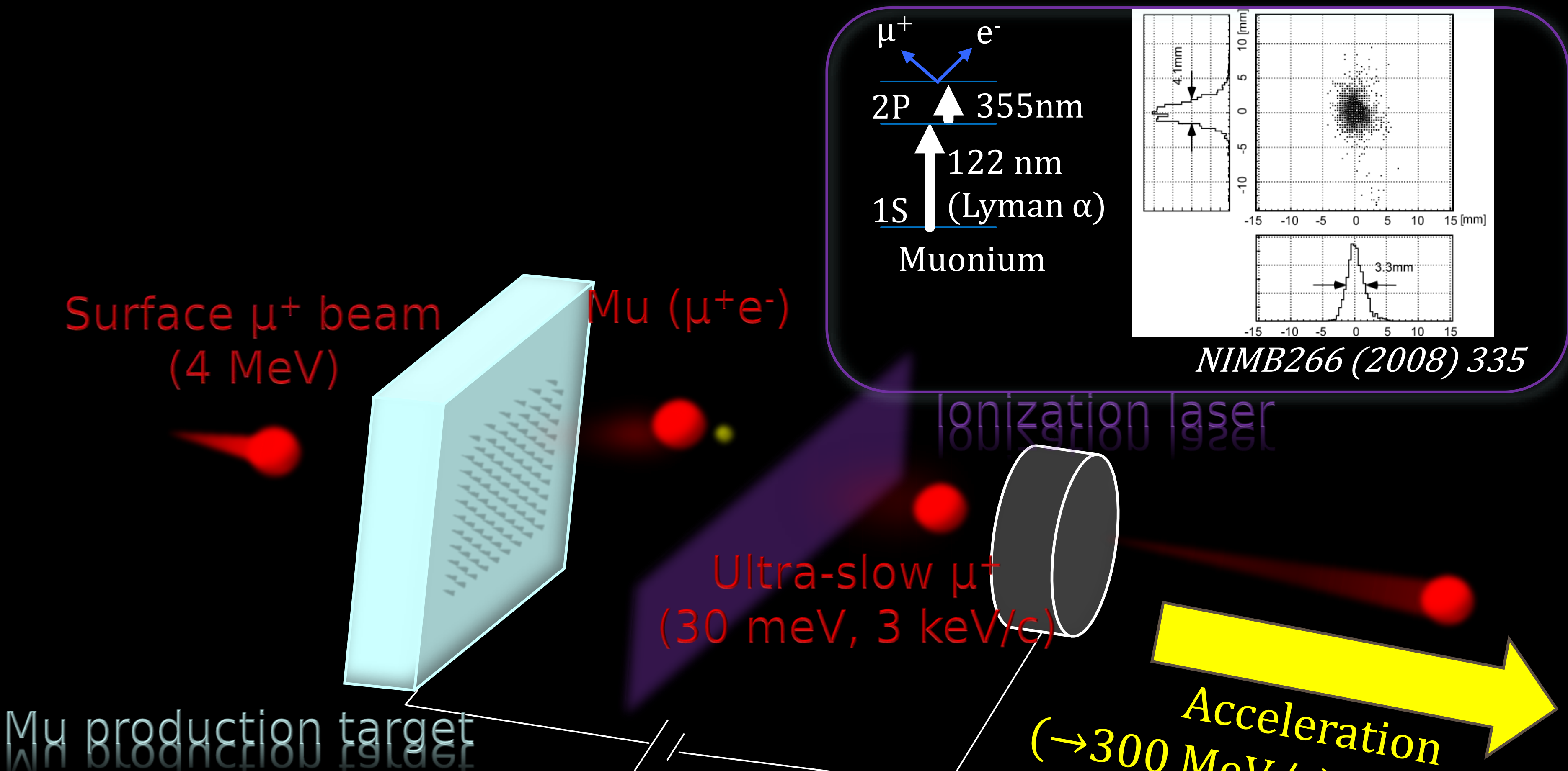
- 0.1ppm for Δ(g-2)
- 10^{-21}e･cm < EDM

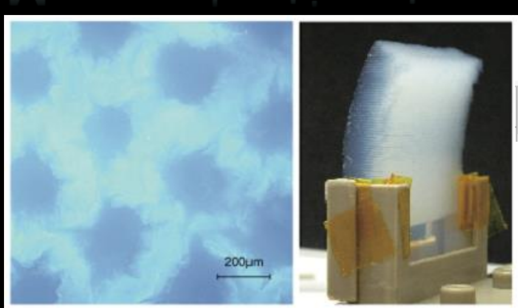

J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in Feb. 2008

3 GeV proton beam



Low Emittance Muon Beam





[PTEP **2014**, 091C01]

第５回　奨励賞受賞者が決定しました。　(2016/1/6)

西川賞

三部　勉氏（高エネルギー加速器研究機構）

石田　勝彦氏（理化学研究所岩崎先端中間子研究室）

「極冷ミューオンビーム実現のためのミュオニウム標的開発」

Summary of Introduction

- The world's first muon linac cast light on beyond SM via precise measurement of g-2/EDM

2016 New Year's Address

January 14, 2016

Thank you all for your tremendous support in 2015 and many wishes for a productive and fruitful new year.

At the start of 2016 I would like to consider the reasons why the research conducted at KEK must be at global forefront.

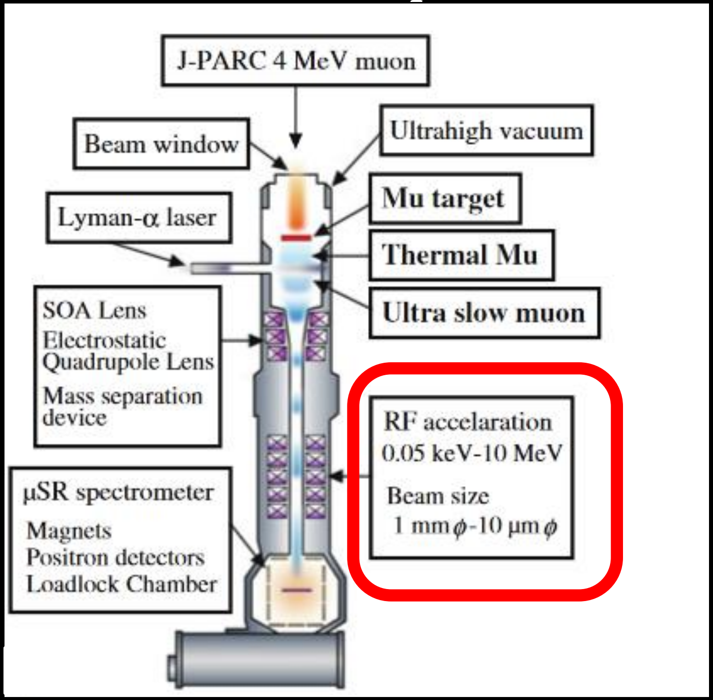
In the research of physics, especially fundamental physics, being the first to discover new, previously unknown phenomena or theories is accorded the highest value. Acquiring and broadly sharing new knowledge prompts new discoveries, progressively expanding the limits of our understanding. As knowledge broadens, fundamental laws of nature emerge. Humanity has furthered its understanding of the natural world in this way ever since the days of Aristotle. The supreme value placed on becoming the first to know the unknown

So, how does one come to know the unknown? Methodology varies widely by research field, but in the field of which KEK is a part, accelerators, which accomplish previously impossible feats in the demonstration of phenomena, play an indispensable role. In concrete terms, this means that KEK's contribution to science lies in the creation of accelerators with world-leading performance, delivering higher levels of energy or intensity than ever before to reveal as-yet-unknown universal natural laws.

Summary of Introduction

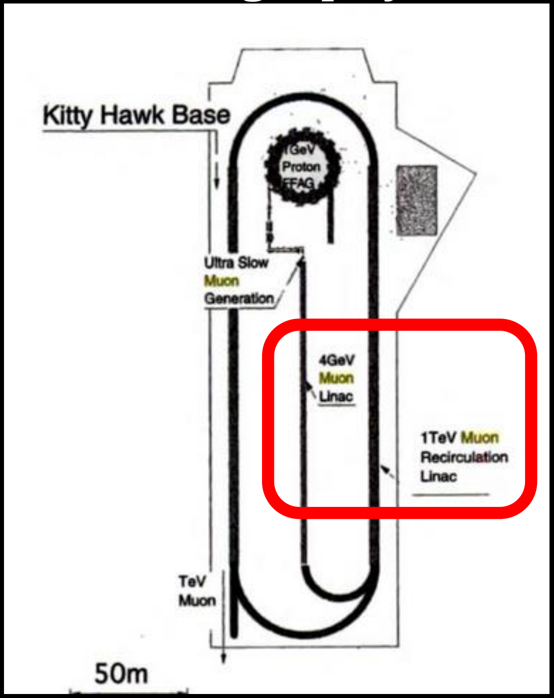
- The muon linac will promote other science fields.

Ultra slow muon microscope



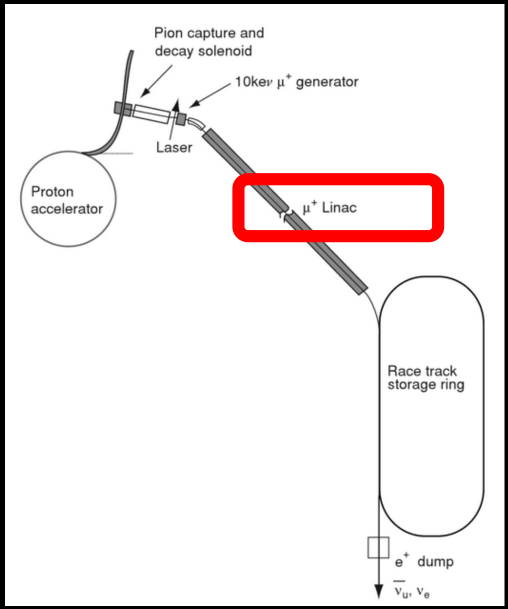
DOI 10.1007/s10751-012-0759-4

Mobile TeV muon source for muon tomography



Proc. Of New Initiative on Lepton Flavor Violation and Neutrino Oscillation (2002)

ν factory



Muon linac Design

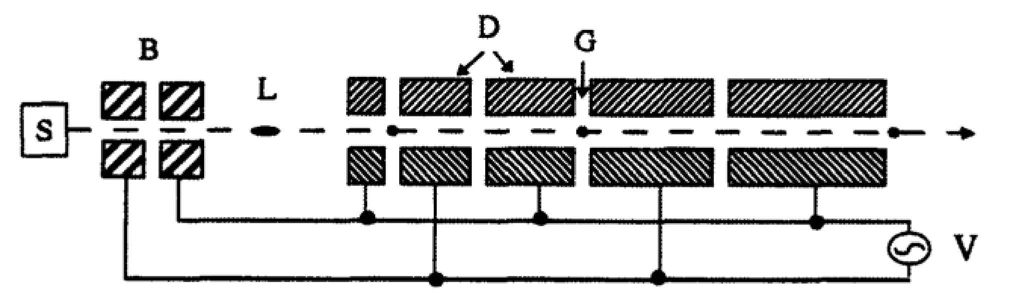


Figure 1.1 Concept of the Wideröe drift-tube linac.

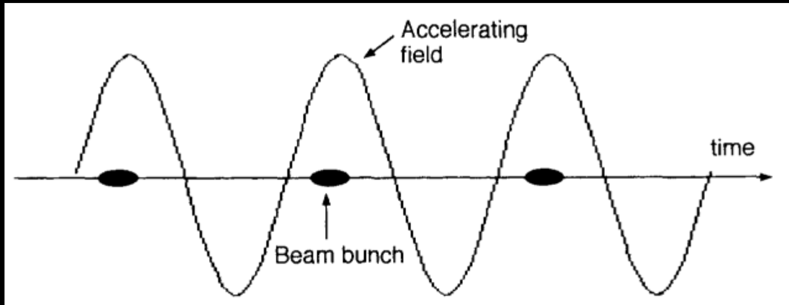
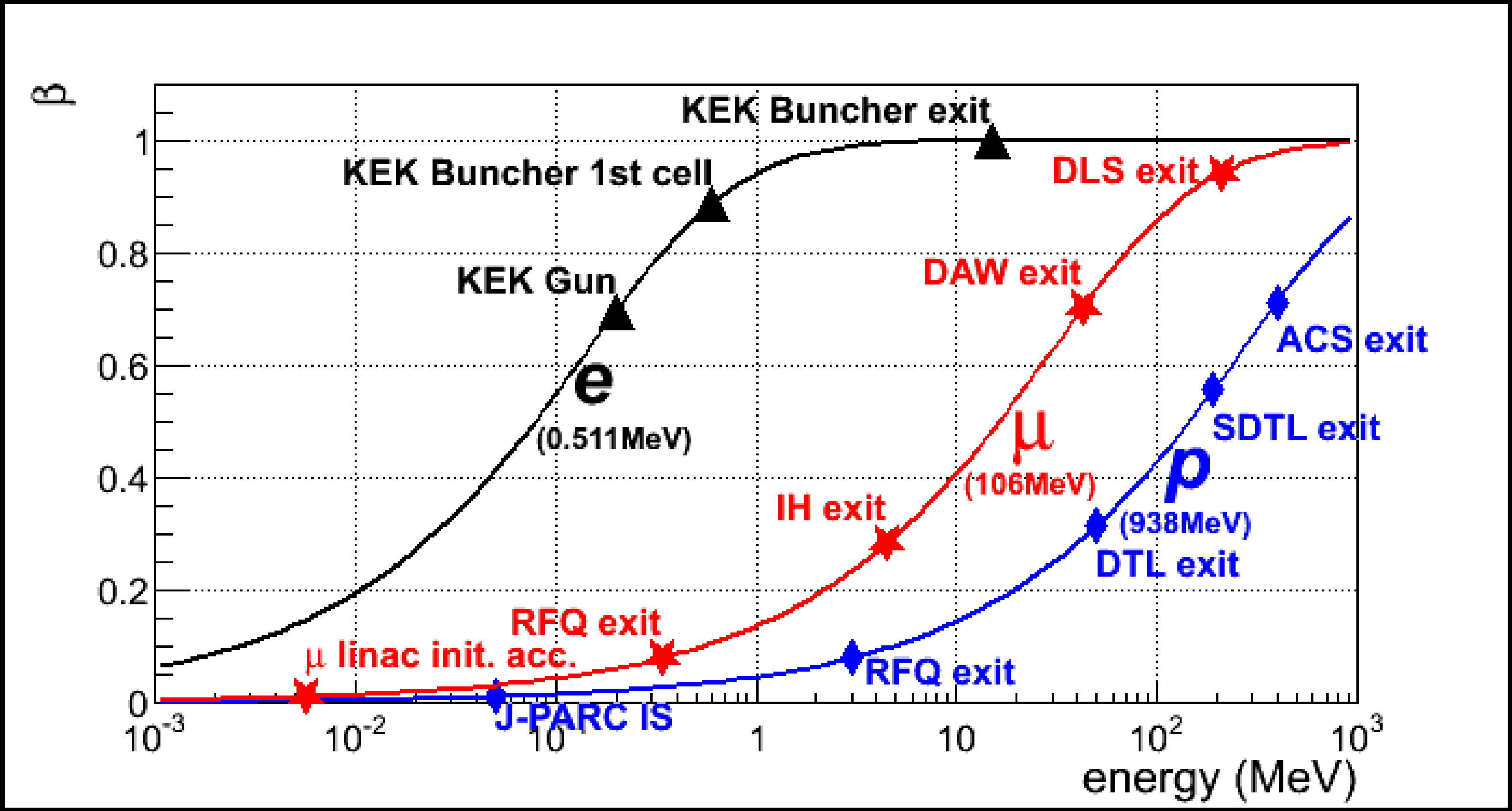


Figure 1.3 Beam bunches in an RF linac.

Thomas P. Wangler, "RF Linear Accelerators", WILEY-VCH

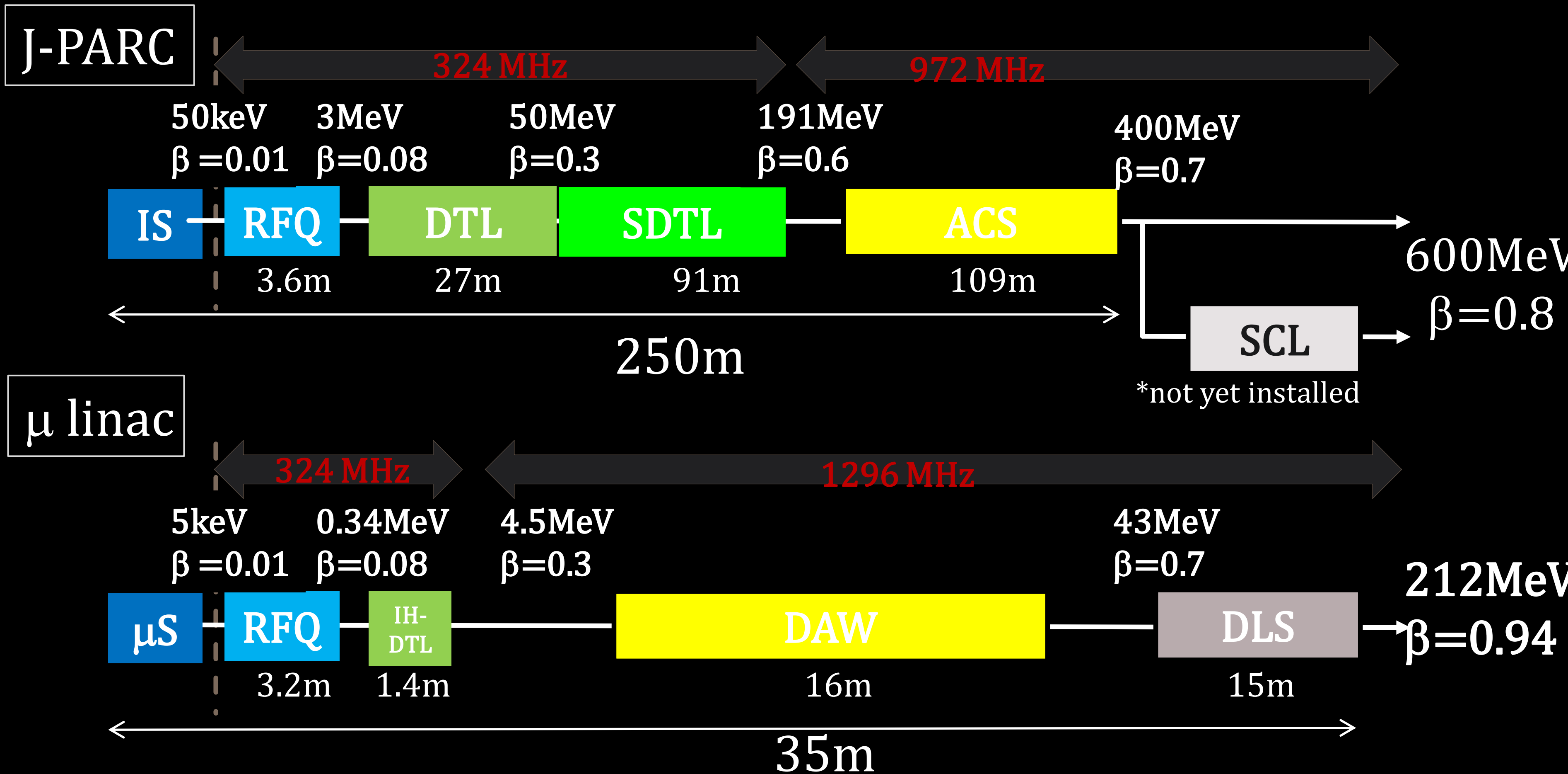
Velocity Evolution

- Muon LINAC is first case in the world → need design
- Velocity is a guide for the design (b/c cell length = $\beta\lambda$ or $\beta\lambda/2$)



- Employ a hybrid design between proton's and electron's.

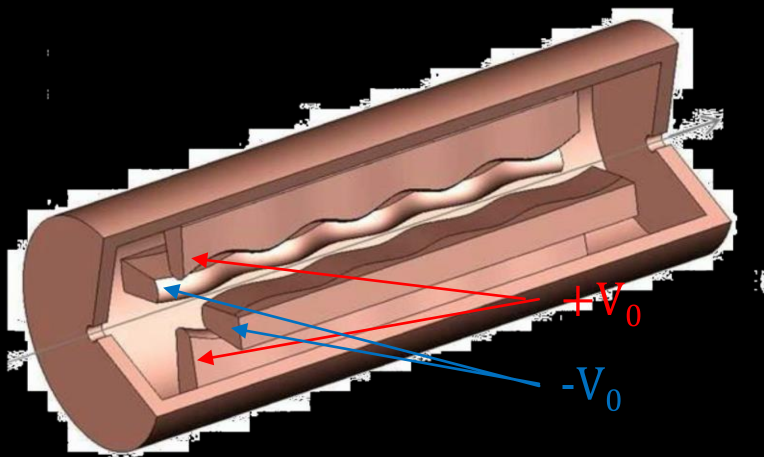
Configuration



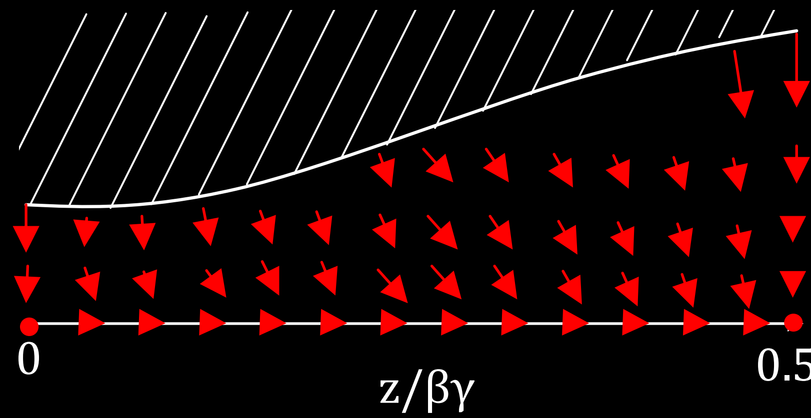
- Similar configuration to J-PARC except
  - Disk Loaded Structure (travelling-wave) ⇔ SCL
  - Shorter length
  - Zero current ($\sim 10^4\ \mu^+$/pulse)

Radio Frequency Quadrupole (RFQ)

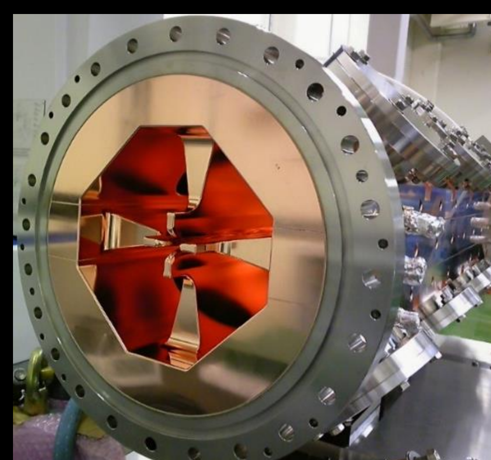
Schematic view



Electrode modulation for longitudinal field



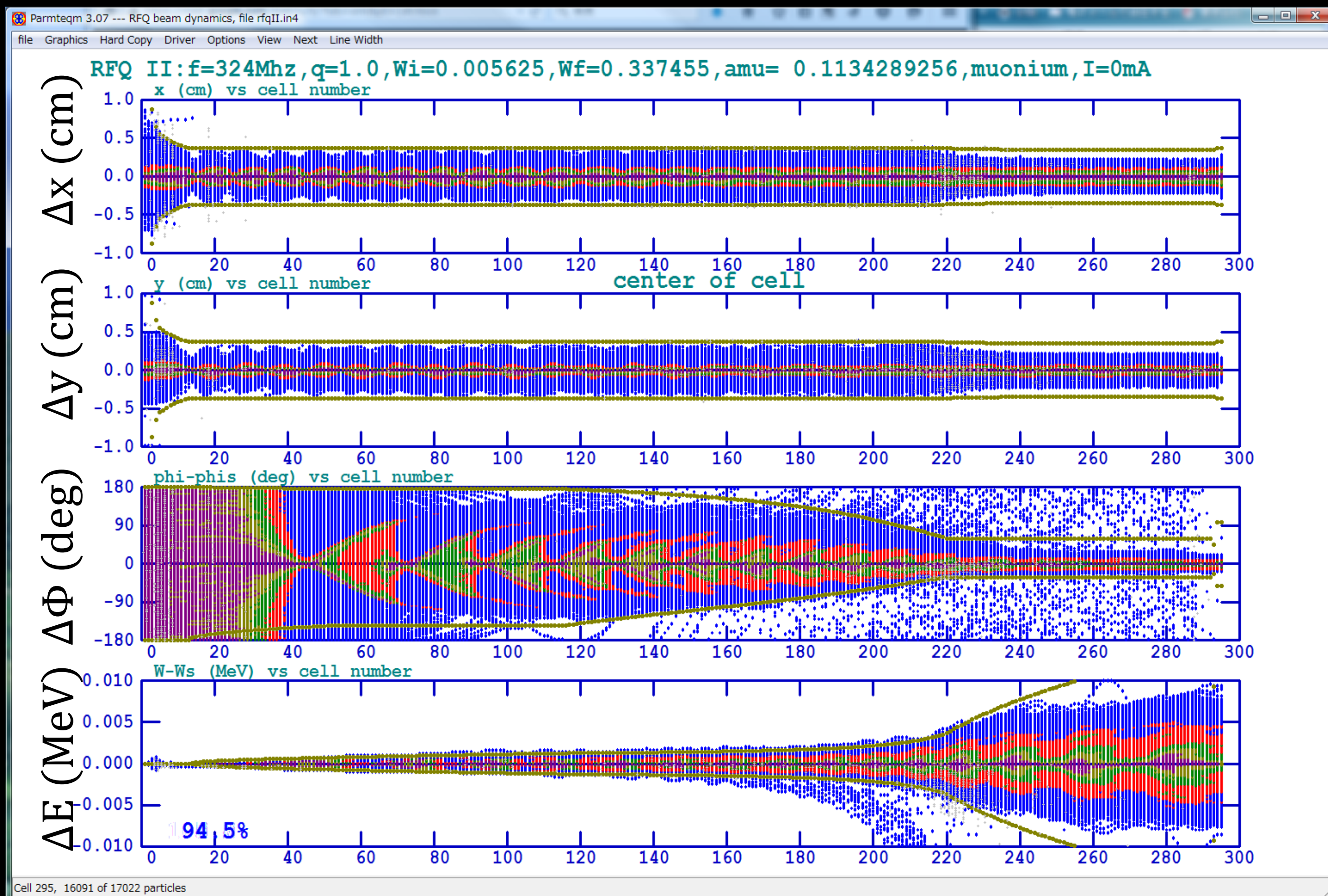
- ✓ Longitudinal bunching
- ✓ RFQ originally developed for J-PARC LINAC is available



Beam species	H^-	μ
Mass (MeV/c^2)	939.302	105.658
Injection β	0.010318	
Injection energy (keV)	50.000	5.625
Extraction β	0.079732	
Extraction energy (MeV)	3.000	0.337
Inter vane voltage (V)	82.879	9.324
Nominal power (kW)	330	4.177

Simulation Results

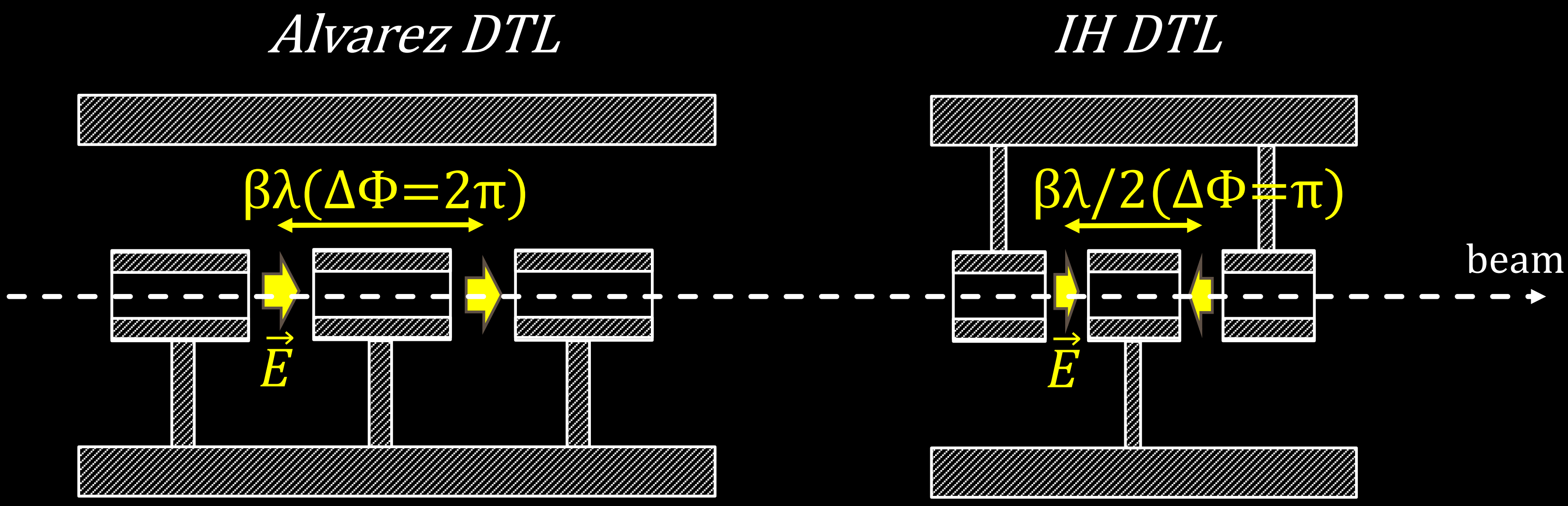
- Transverse (x,y) and longitudinal (Φ, E) dynamics are evaluated by PERMTEQM



Good transmission (95%)

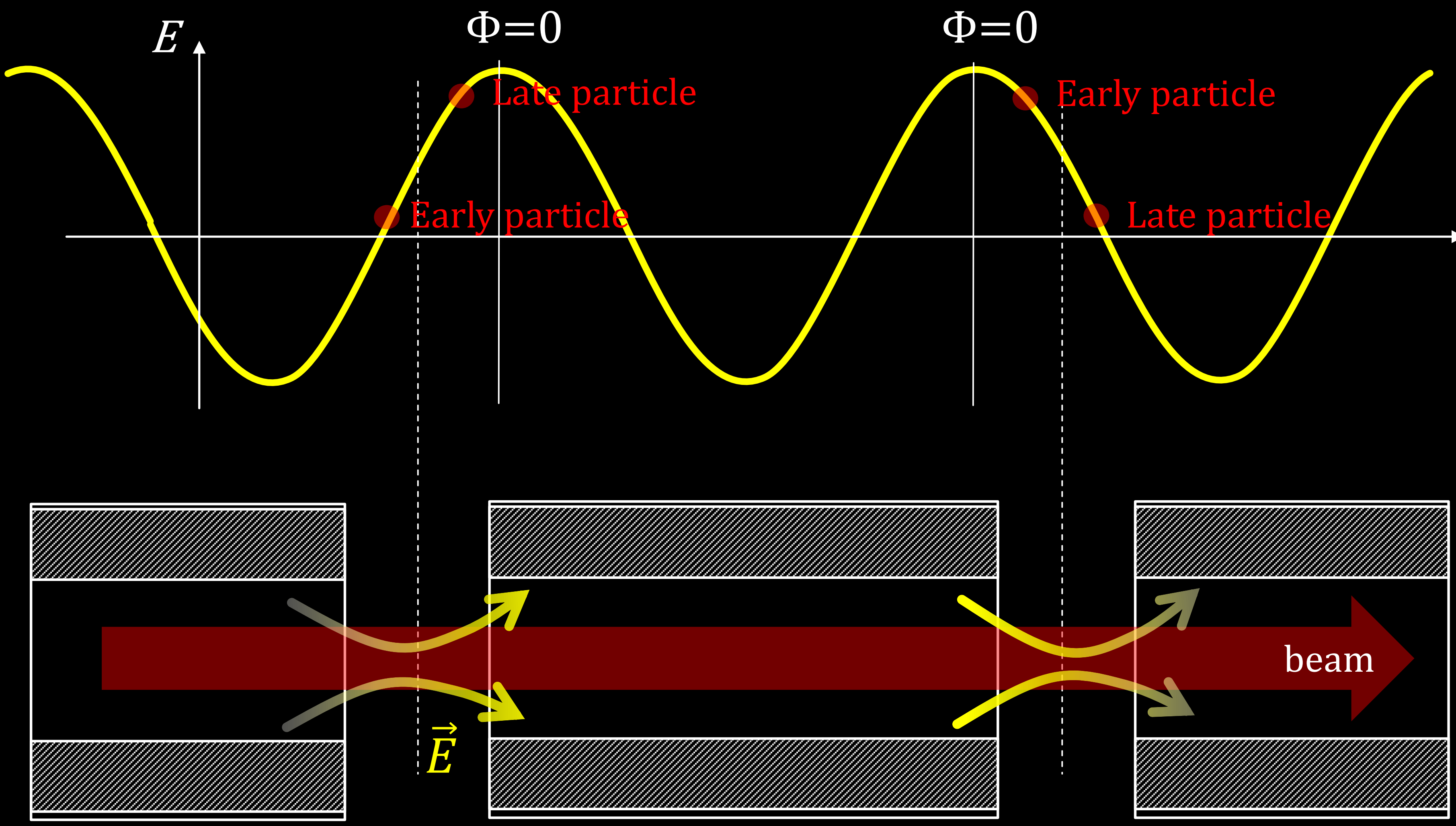
Alvarez and IH DTL

- Because the RFQ acceleration efficiency decreases with β^{-2}, other structure is necessary.



- Acceleration with short period is important to avoid decay loss (τ_μ=2.2 usec) → IH DTL is adopted

Longitudinal & Transverse Motion



Φ<0
longitudinal: focus
transverse: defocus

Φ>0
longitudinal: defocus
transverse: focus

Alternative Phase Focusing (APF)

- $\Phi n < 0$ in conventional LINAC and the transverse focusing is done with additional structures
  → longer length / higher cost ☹

Cf. J-PARC LINAC SDTL

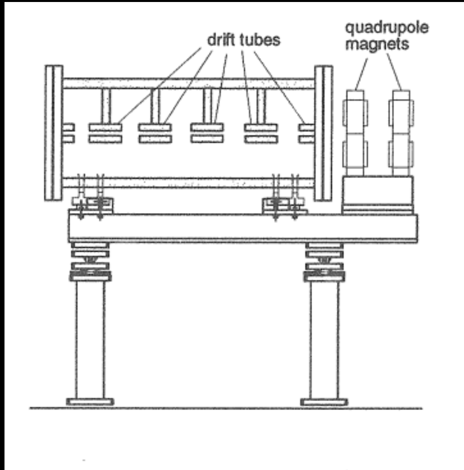


Figure 7: SDTL のレイアウト

OHO 2001, Ikegami

- Φn are changed periodically so that alternating-focusing forces are applied in transverse and longitudinal directions → APF

  ☺ No additional structure for focusing
  → shorter length / lower cost

  ☹ limited to lower current beam
  → does not matter in the muon linac (∵zero current)

APF IH-DTL Design

- {Φn} for APF
- Cavity design

Entangled problem:
Dynamics → {Φn} → cavity → RF field → Dynamics…

- To solve it, procedures are divided into three steps:
  1. {Φn} optimization with the analytical calculation of the beam dynamics
  2. IH cavity design
  3. Numerical calculation of the beam dynamics

Beam Dynamics & Φn optimization

- Dynamics are calculated by approximating the gap fields as rectangular profile.

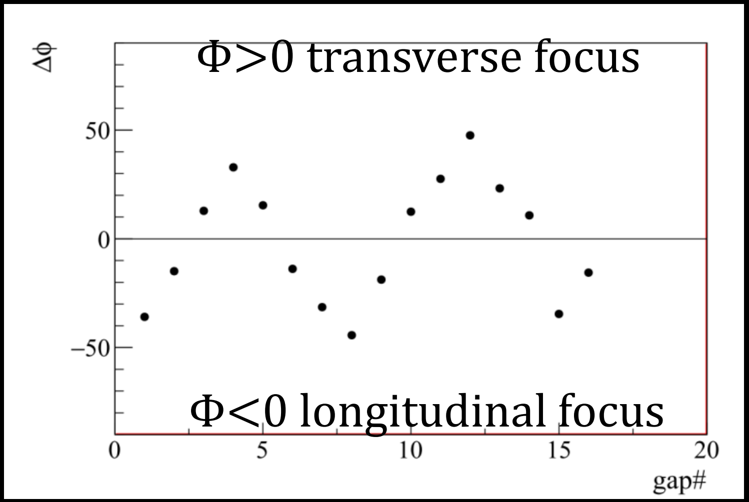
$$\Delta W = qV_0 T\cos\varphi \qquad cf.\ \Delta W = qV_0 \text{ in DC field}$$

$$\Delta\gamma\beta r' = \left(-\frac{\pi q E_0 T sin\varphi L}{mc^2\gamma^2\beta^2\lambda}r\right)\times\left[1+\frac{\Delta\beta}{\beta}\frac{\cos(\pi g/\beta\lambda+\varphi)}{2\sin(\pi g/\beta\lambda)\sin(\varphi)}\right]$$

T :Transit Time Factor, represents time variation of the field.

- {Φn} is optimized by a subroutines for function minimization (NPSOL).
  - Minimization function is constructed with $\Delta\varepsilon \times \Delta E \times N_{loss}$

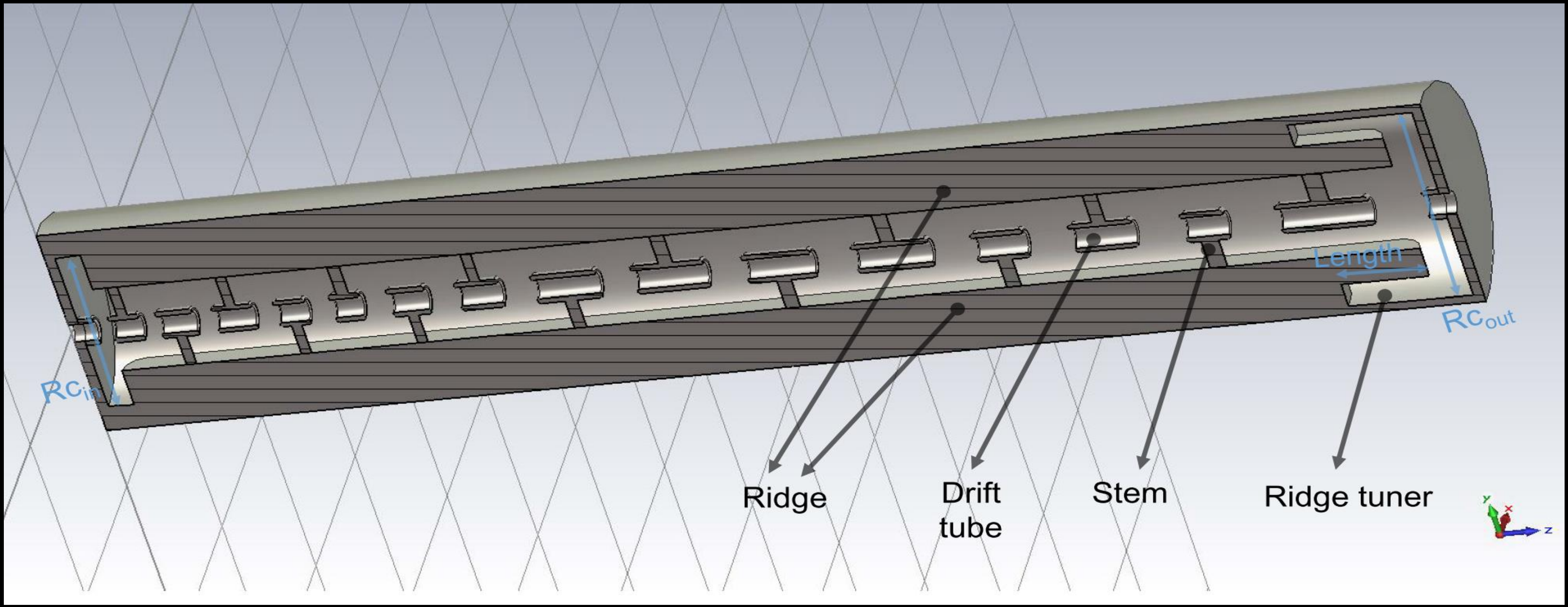
Optimized Φn



Cavity Design

⟐ Overall structure is necessary for the cavity evaluation

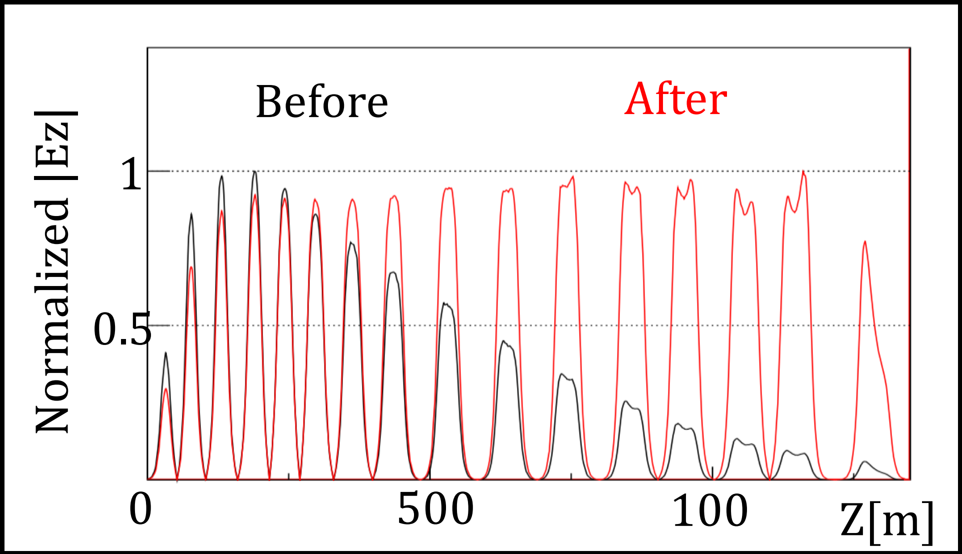
→ Three dimensional model is constructed in CST MW Studio



⟐ Some dimensions are optimized so that the acceleration fields are smooth along the gaps.

- ⟐ Cavity radius, cavity taper, ridge tuner…

Before/After Optimization



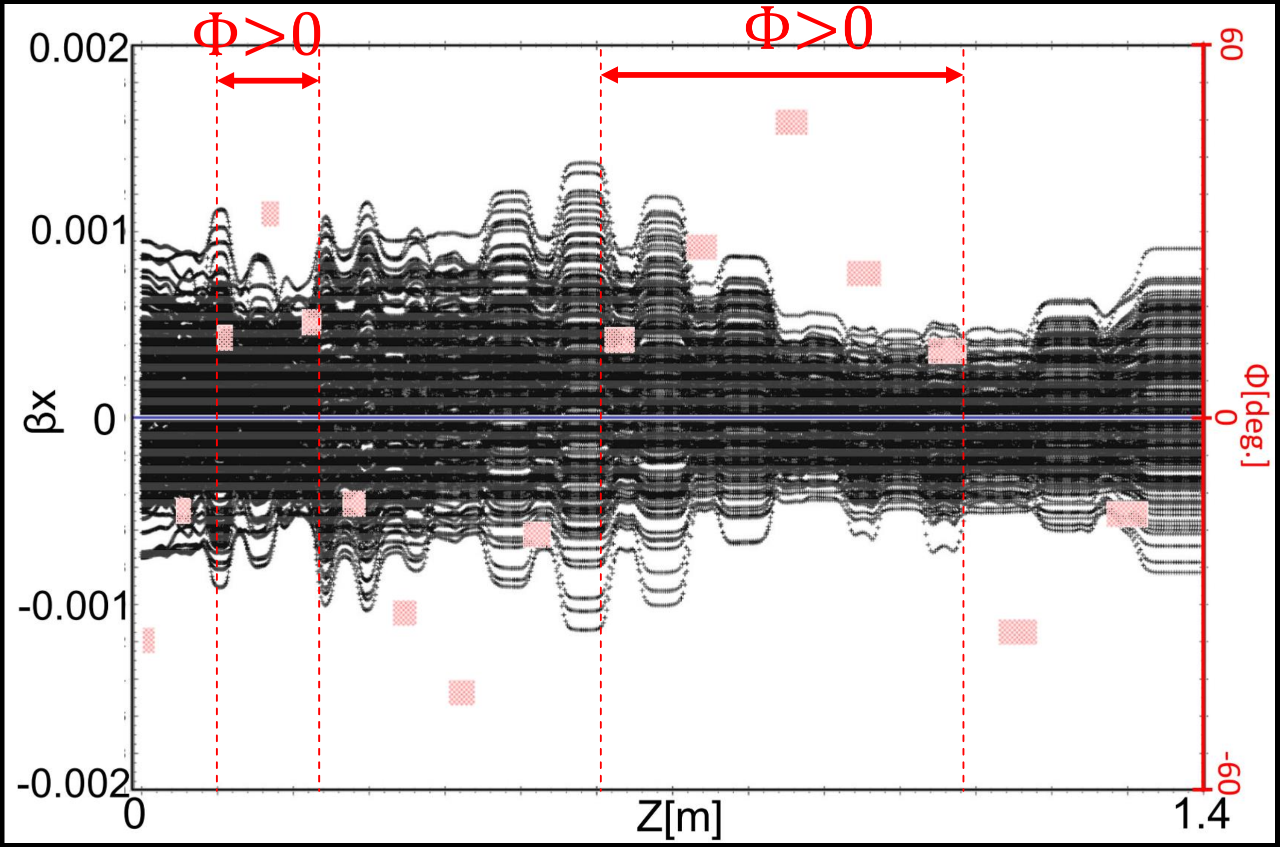
Frequency	**323.1 ***
Length	1.44m
Q0	1.07×10^4
ZTT [MW/m]	92
Power [kW]	250
Emax	1.9 Kilpatrick

* For room by tuners

Optimized well

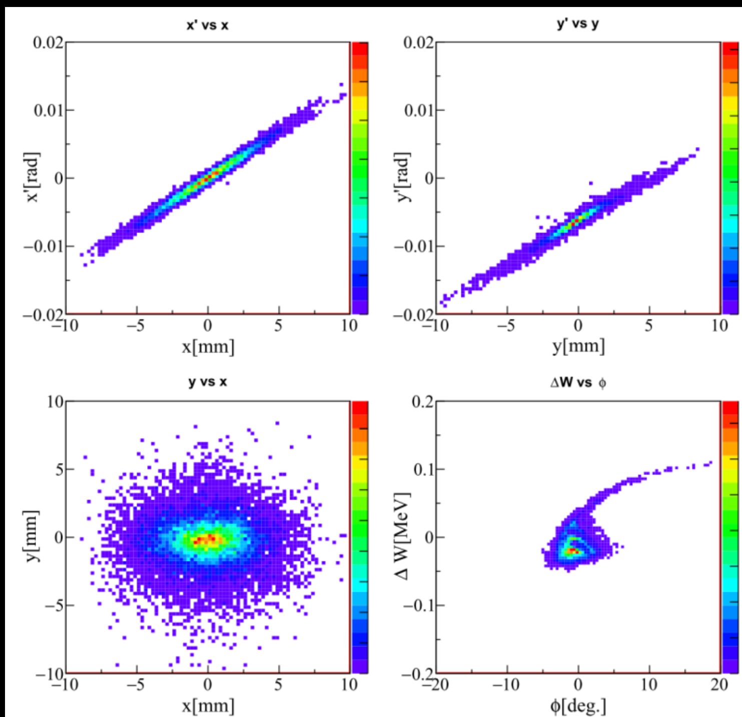
Tracking Result

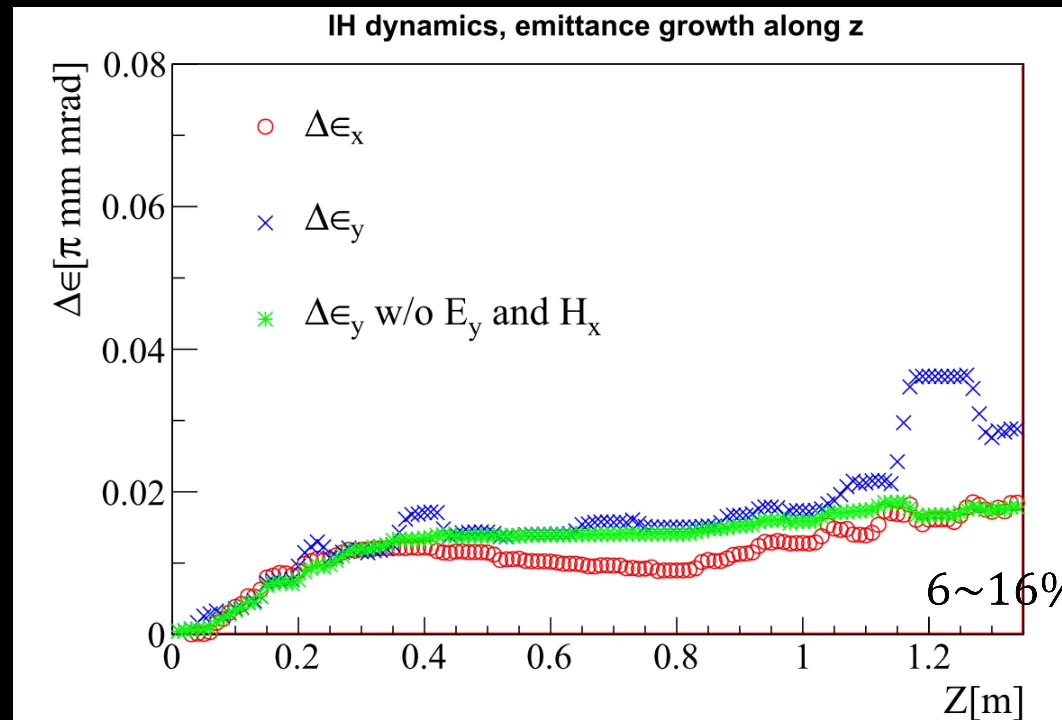
- Finally the dynamics in the RF field are calculated with GPT
  - General Particle Tracer, 5th order embedded Runge-Kutta



Succeeded to focus transversely by APF

Phase Spaces & Emittance



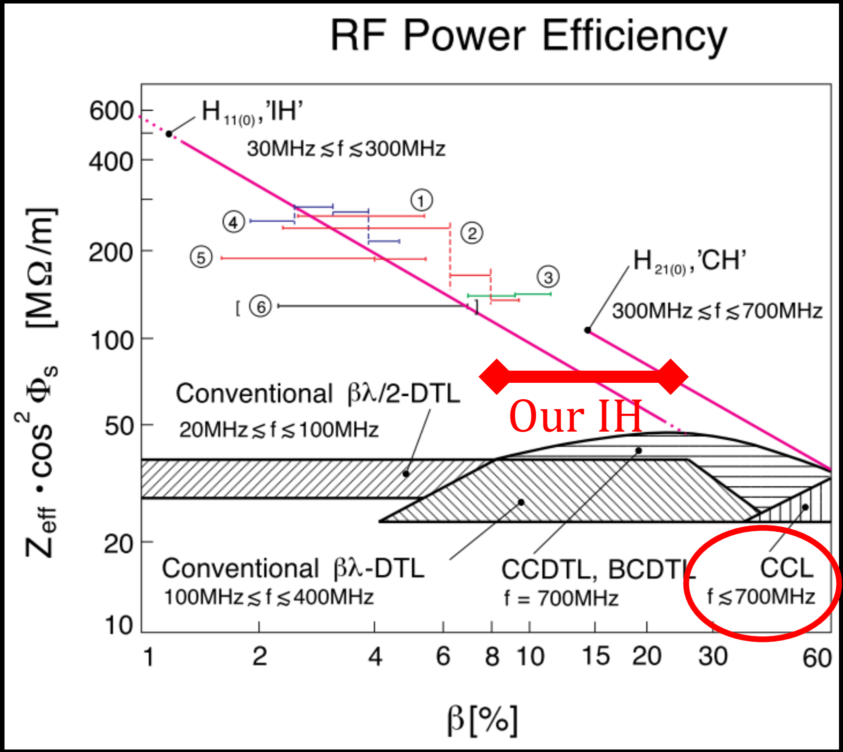


Emittance growth is sufficiently small

will submit paper to Phys.Rev.STAB soon

Accelerator for $\beta > 0.28$

- Acceleration efficiency become smaller → need to change the structure from $\beta > 0.28$



U. Ratzinger, CERN Yellow Report No. 2005-003

Various Coupled Cavity Linac

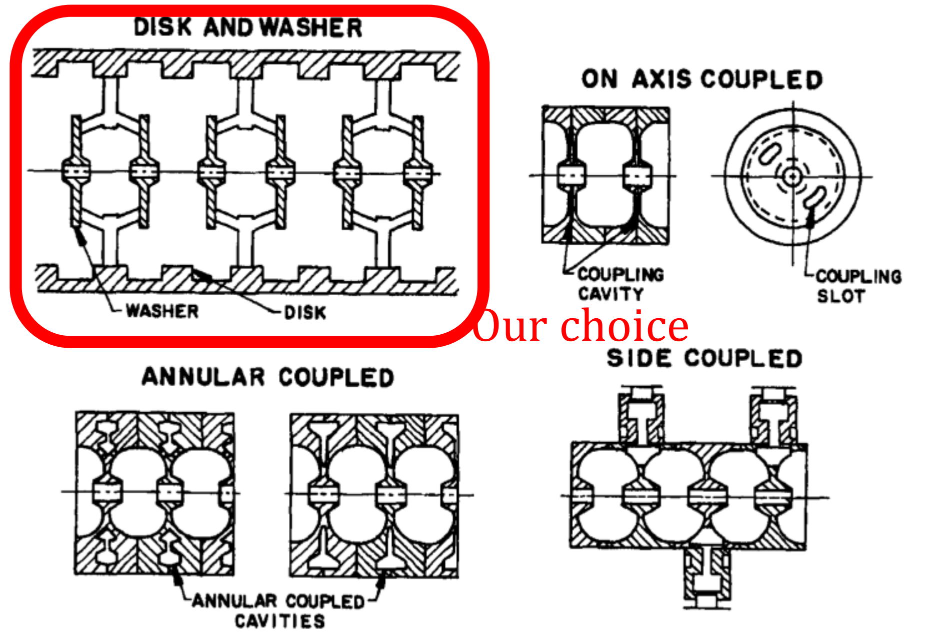


Figure 4.17 Four examples of coupled-cavity linacs.

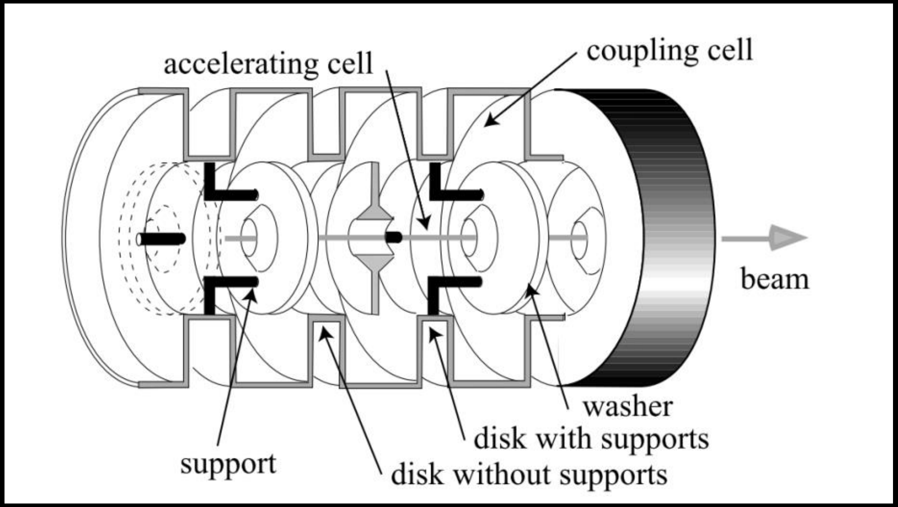
☺ Strong coupling → may reduce production cost

☺ Experiences at INR (Russia), KSR (Kyoto) etc.

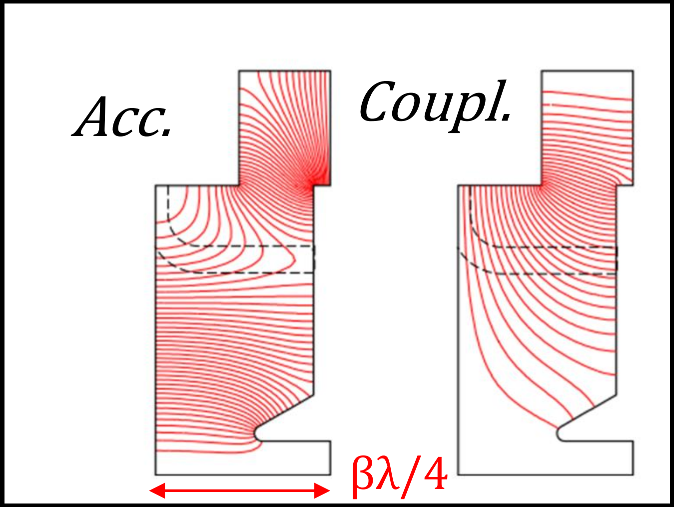
☹ First time to apply $\beta < 0.4$ → need design

DAW

DAW with bi-periodic L-support



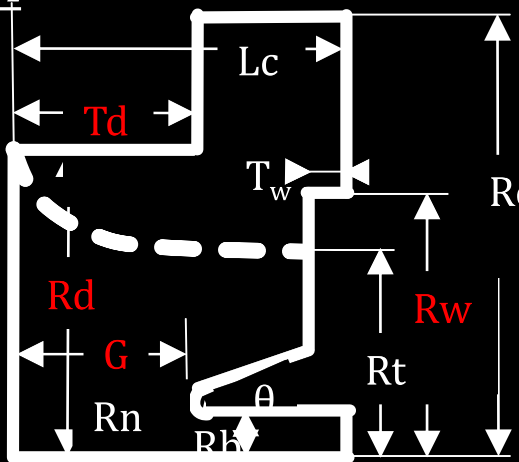
Acc./coupling mode (TM02π/TM01π) in ½ cell



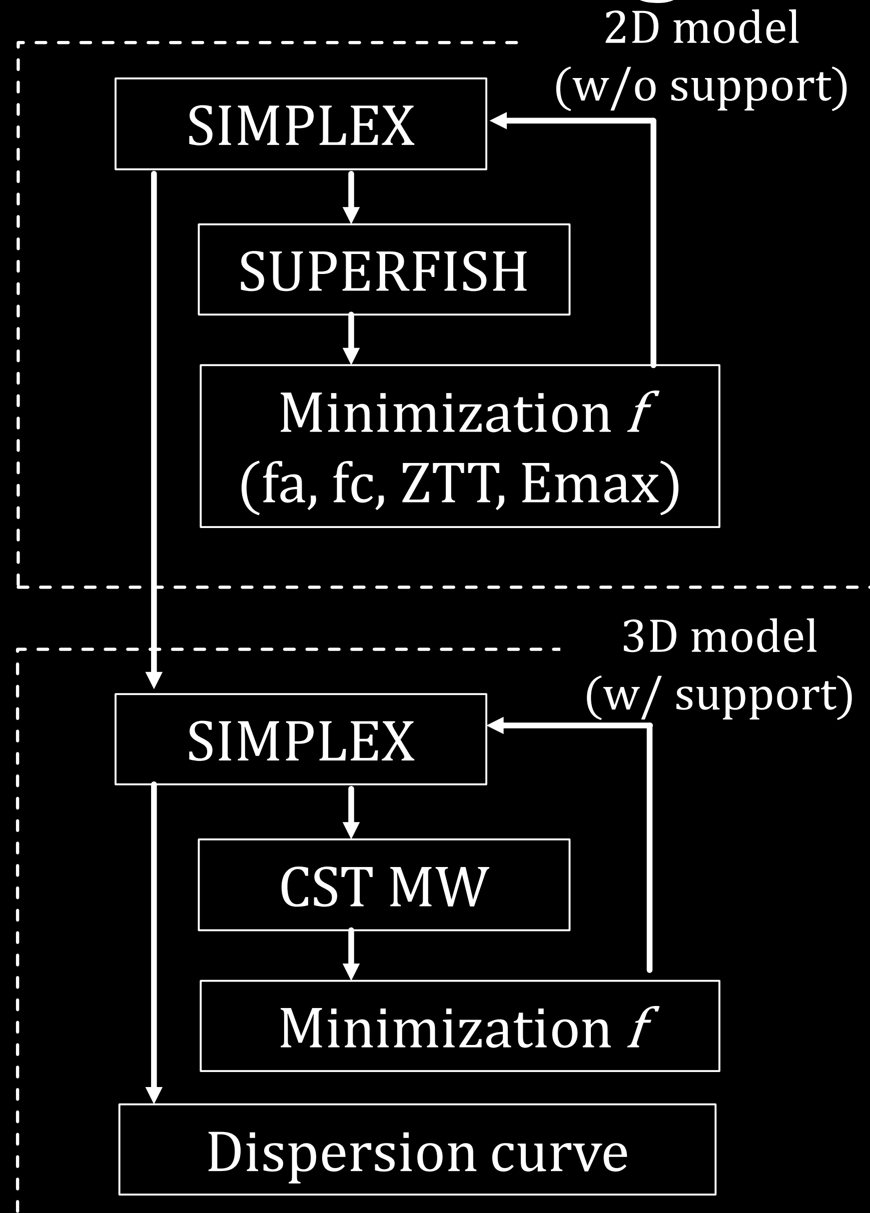
- Requirement for the cell design
  - Confluence ($f_{acc.} = f_{coup.}$)at 1.3 GHz
  - No other mode at 1.3 GHz
  - Higher efficiency (ZTT) and Eav./Emax
  - Design for several β

Procedures for the cell design

model

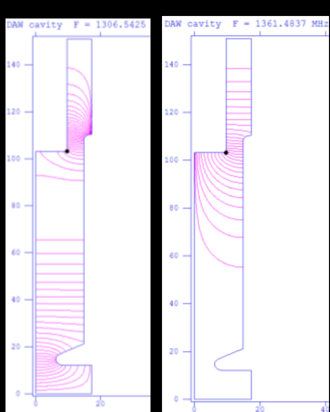


Td, Rd, Rw, G: fitting parameters

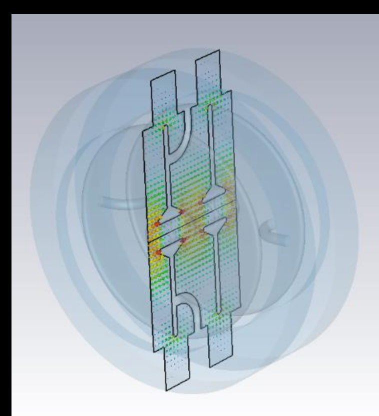


Calculation example

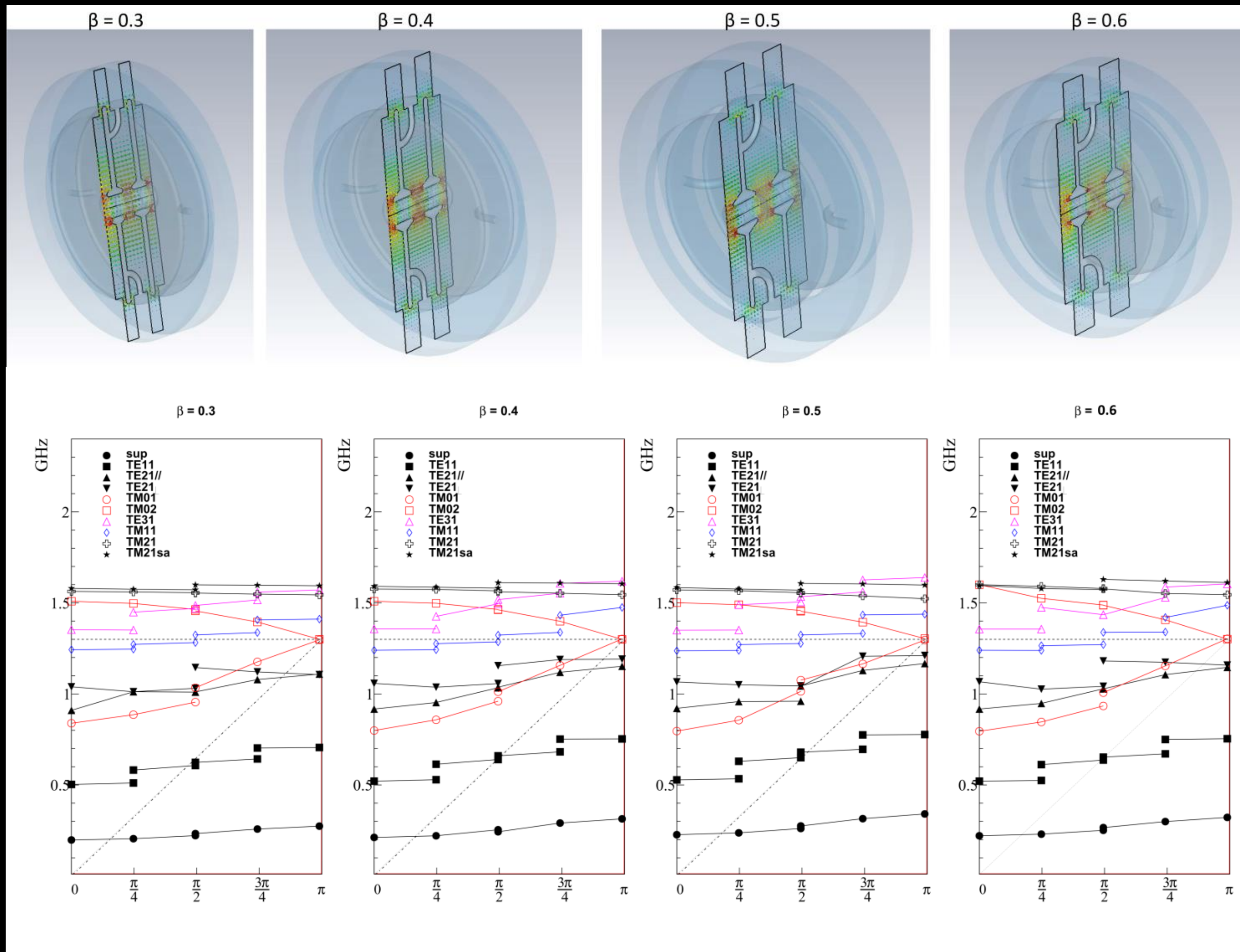
SF



CST MW



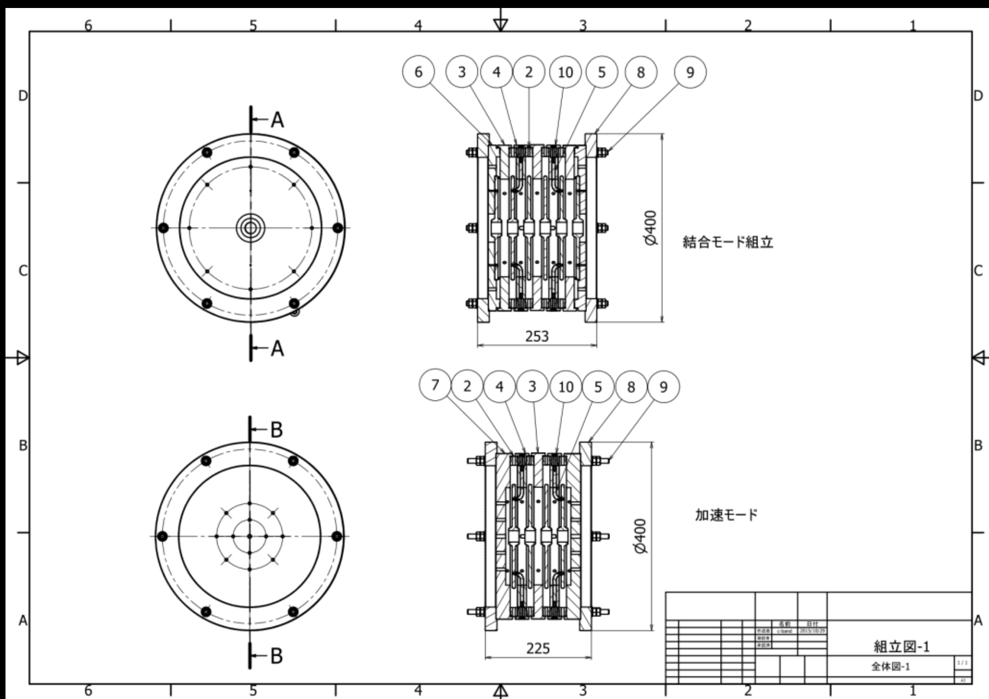
Results

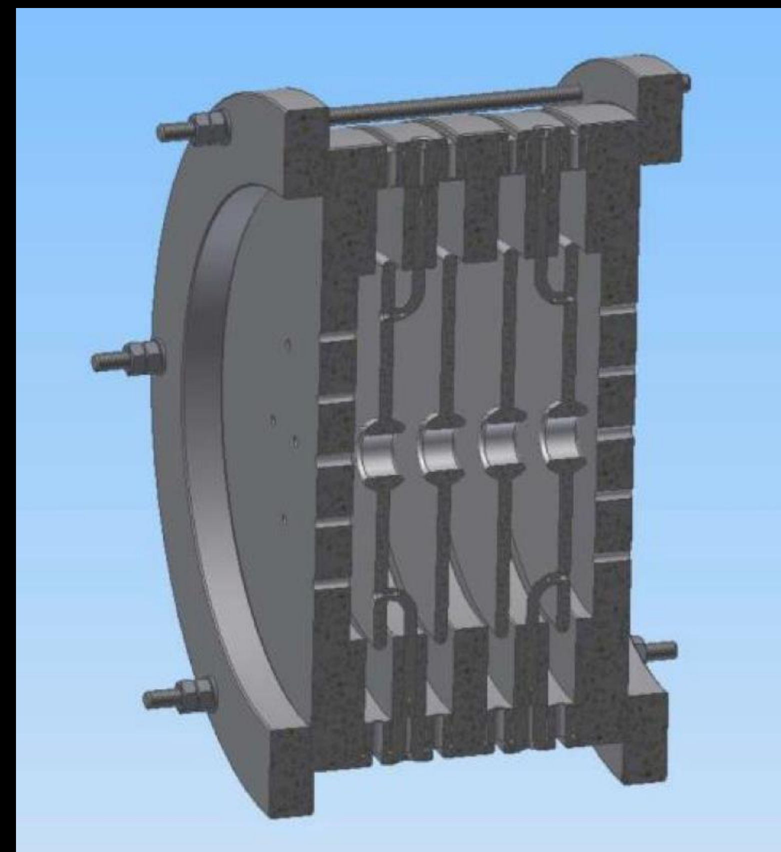


cell design was finished in all the β region

Prototype

- Al cold model for the filed measurement etc is being fabricated.
  - Kiban(B) by Otani

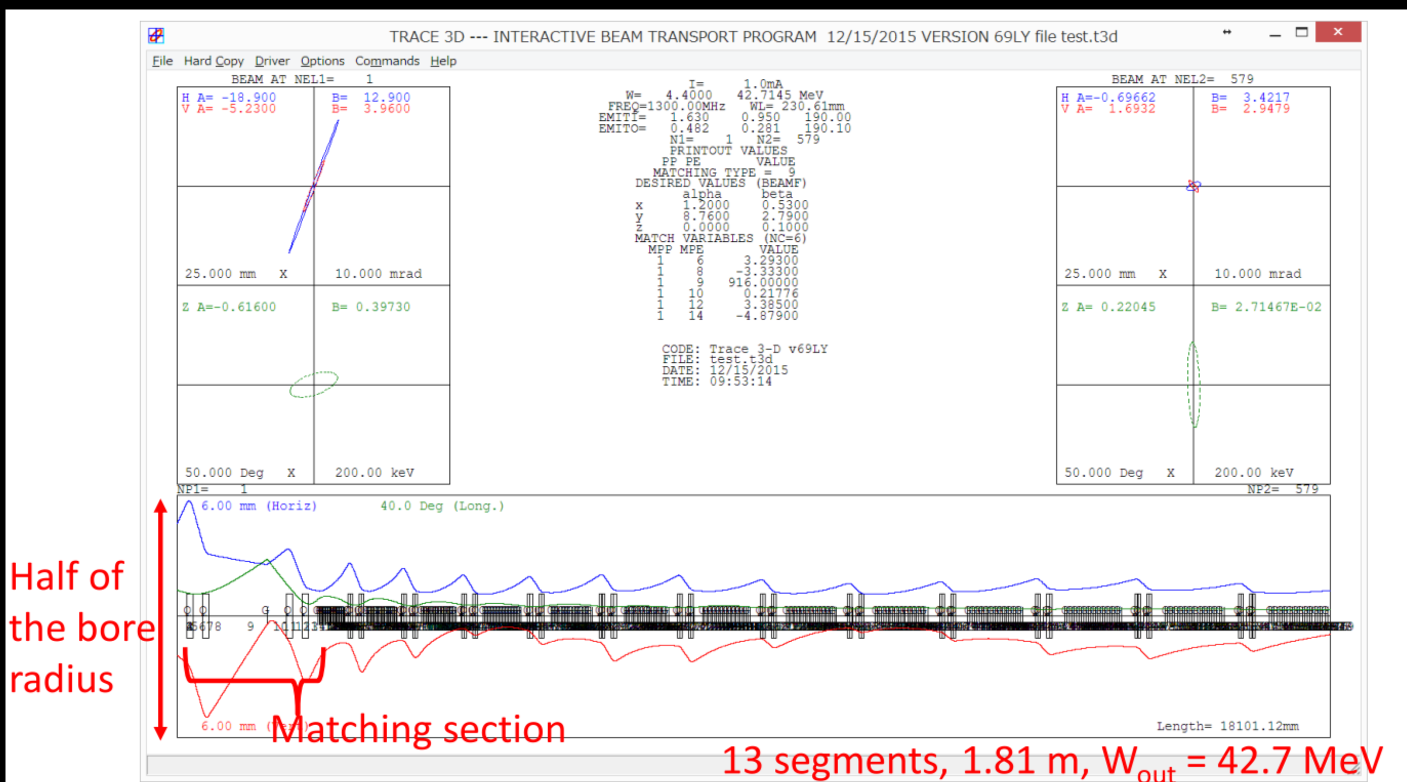




Prototype is ready by Mar. and tested soon.

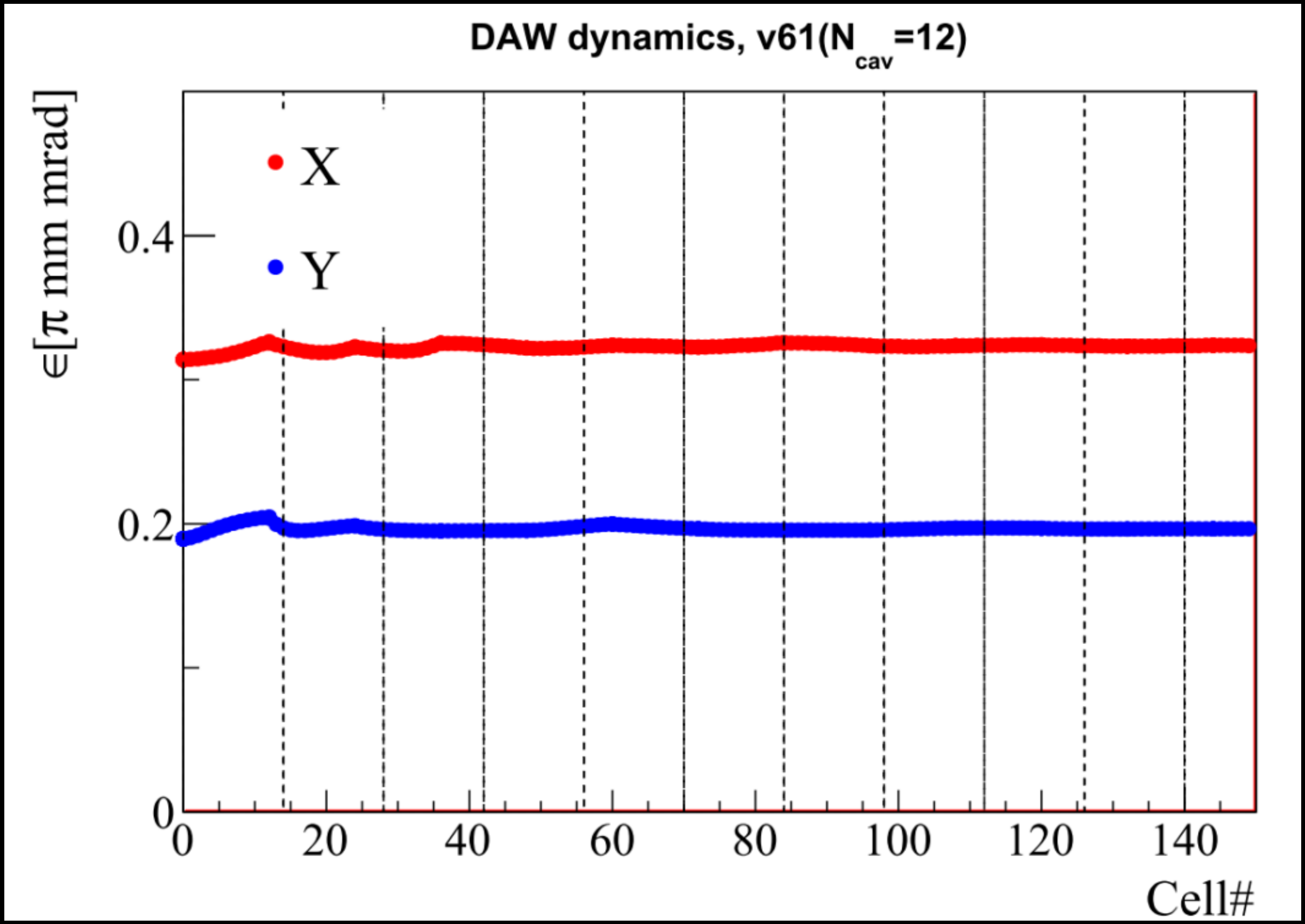
Beam dynamics design

- Dynamics is designed based on the optimized cell design with TRACE3D and PARMILA
  - Cell design → parameters required for dynamics design (shunt impedance, transit time factor etc.)



Result

- Emittance growth is evaluated along the cell

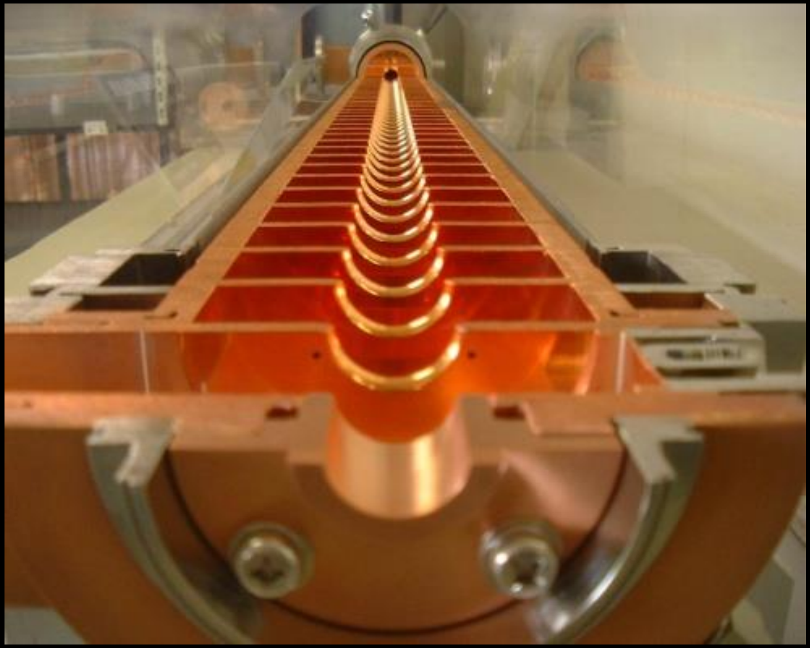


Growth is sufficiently small (few %)

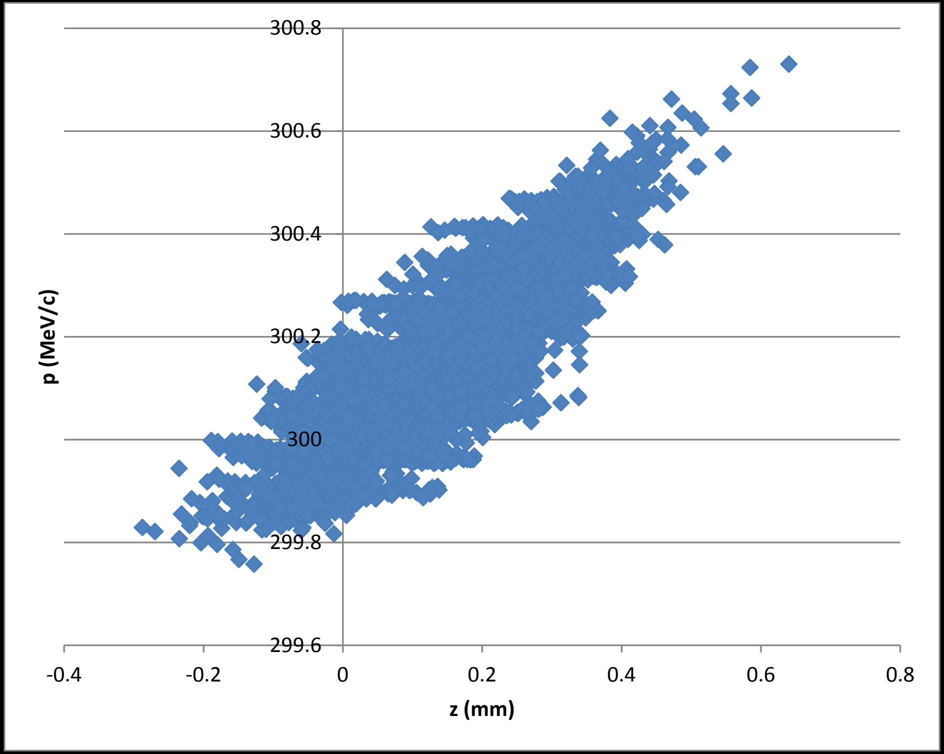
Disk-loaded Structure

- To achieve sufficient acceleration gradient and then accelerate muons, the disk loaded structure is used.

Disk loaded for e LINAC



Transverse Phase Space of output beam



Good transportation in longitudinal direction

transverse dynamics is being evaluated

Summary of the LINAC design

- Almost all the components were designed.
  - ☑ RFQ
  - ☑ IH-DTL with APF (μ dedicated NEW!)
  - ☑ DAW (μ dedicated NEW!, β<0.4 NEW!)
  - ► DLS

	β	Trans.	ε_x [π mm mrad]	ε_y
RFQ	0.08	77%	0.297	0.168
IH	0.28	99%	0.315	0.195
DAW	0.70	95%	0.33	0.21
Disk-loaded	0.95	-	-	-

Sufficiently small compared to the requirement of <1.5 π mm mrad

Current Status

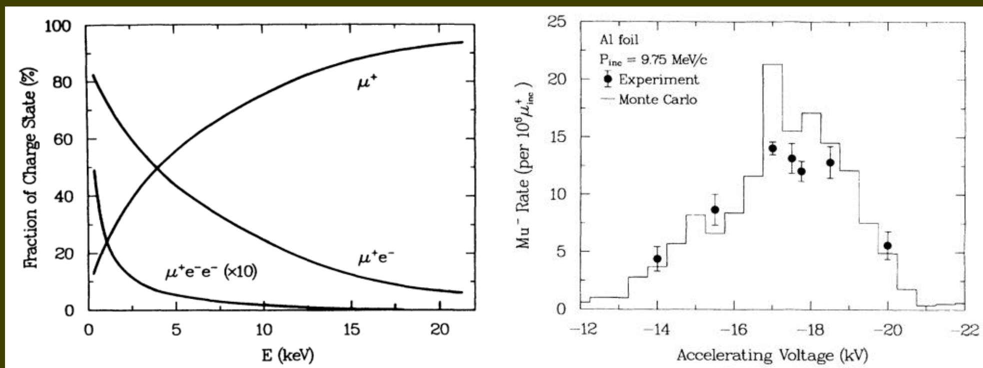
Acceleration up to IH

Muon acceleration is first case in the world and one of milestones of our experiment.

- ☑ Space up to IH is available w/o annex
- ☑ Already have RFQ and the IH proto-type
- □ Mu ionization laser
- □ Initial acceleration (source → RFQ) apparatus (SOA lens)
- □ Offsite commissioning

Slow Muon Source w/o laser

Deceleration (Mu^-/μ^+) with thin metal foil ($E \sim$keV, $\varepsilon \sim 10^{-4}$)

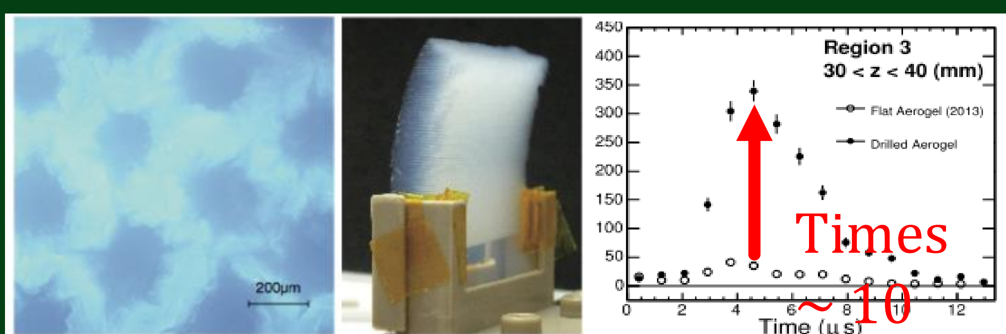


Phys. Rev. A. 39.6109 (1989)

<5.6 keV $= E_{RFQin}$ with low cost and simple apparatuses

Cf. for actual g-2/EDM experiment

Thermal Mu (μ^+e^-) + laser dissipation ($E \sim 30$ meV, $\varepsilon \sim 10^{-3}$)

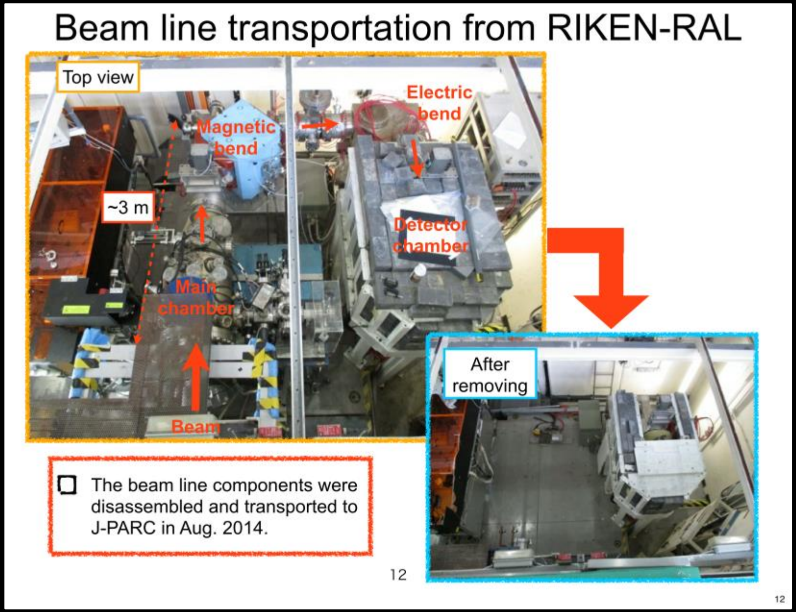


G. A. Beer et al. PTEP 091 (2014) C01

Can reach comparable statistics to BNL E821 (0.34 ppm)

SOA lens and slow muon beamline

- The apparatuses came from RIKEN-RAL



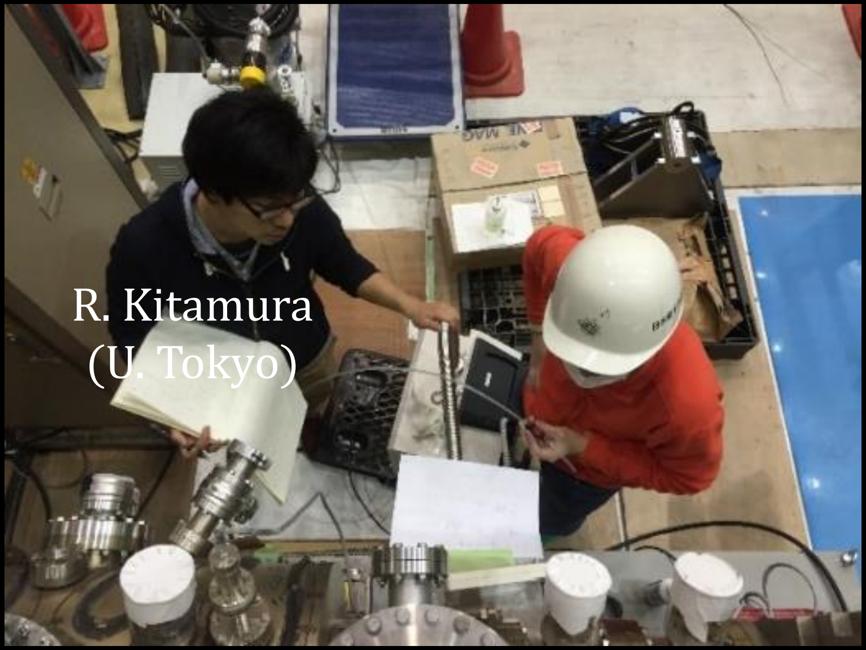
@ RIKEN-RAL, Aug. 2014

2014/8-11	Transport from RIKEN-RAL to J-PARC
2014/12	Start assembling @ J-PARC MLF
2015/1-3	Interruption due to the fire accident at MLF
2015/4-5	Resume assembling and finish commissioning

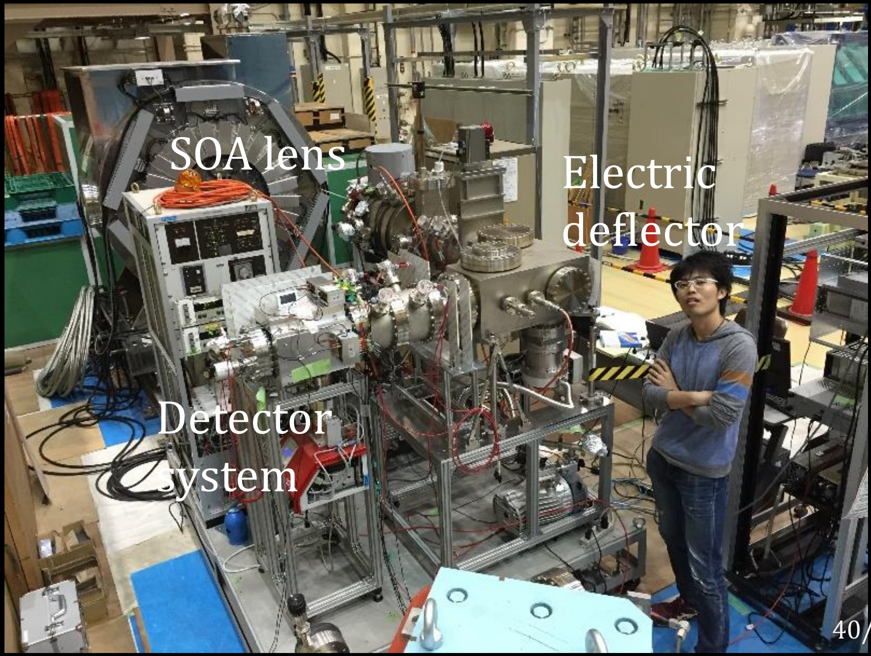
Assembling

Alignment

Leak check



Finish!!



Slow Muon Measurement @ J-PARC

- □ Verify deceleration with thin metal foil
- □ Commissioning of the apparatuses with the muon beam

Surface muon beam

- $8 \times 10^4\ \mu^+ /s @ 10 MeV/c$

Al foil

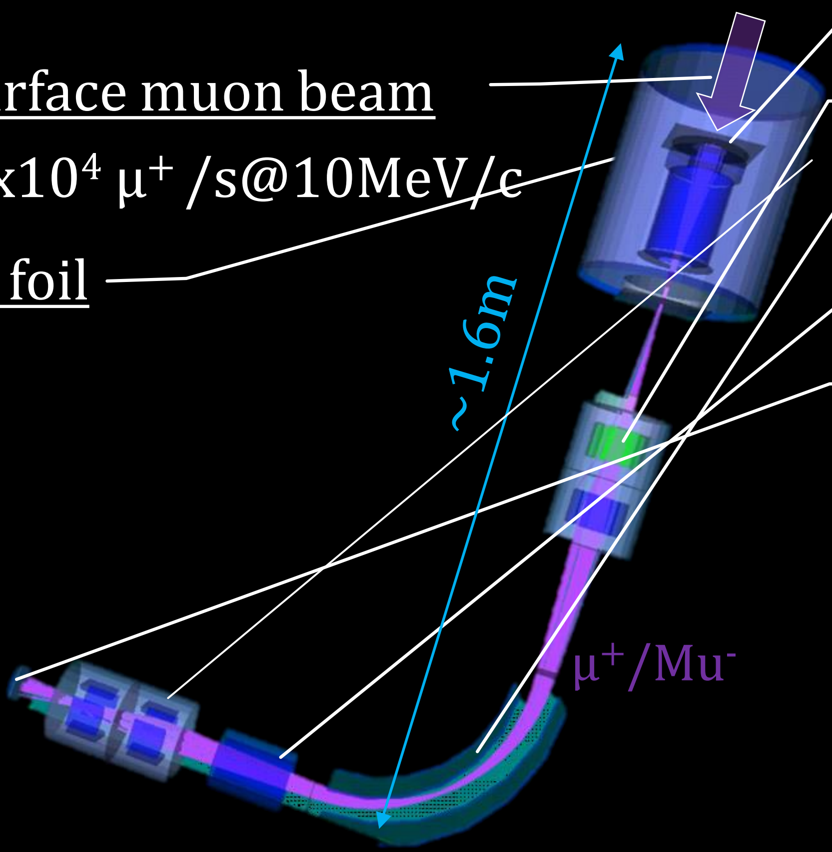
SOA lens

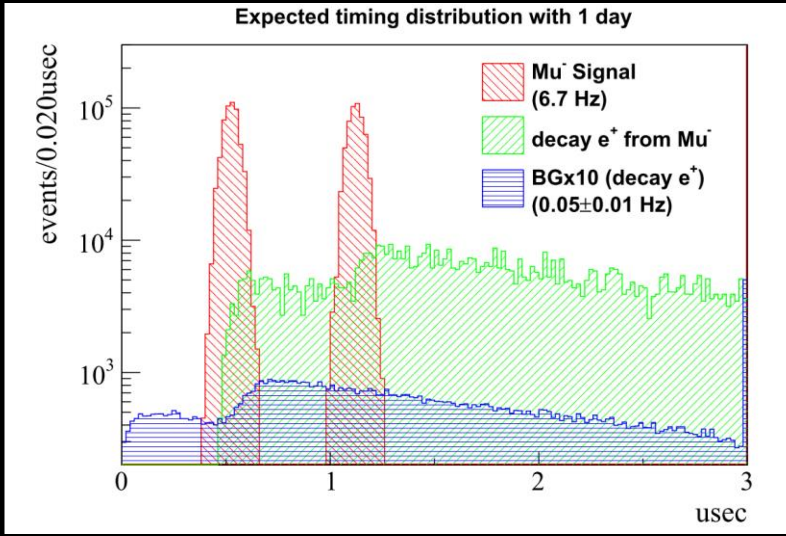
Electric Qudrupoles

Electric Deflector

collimater

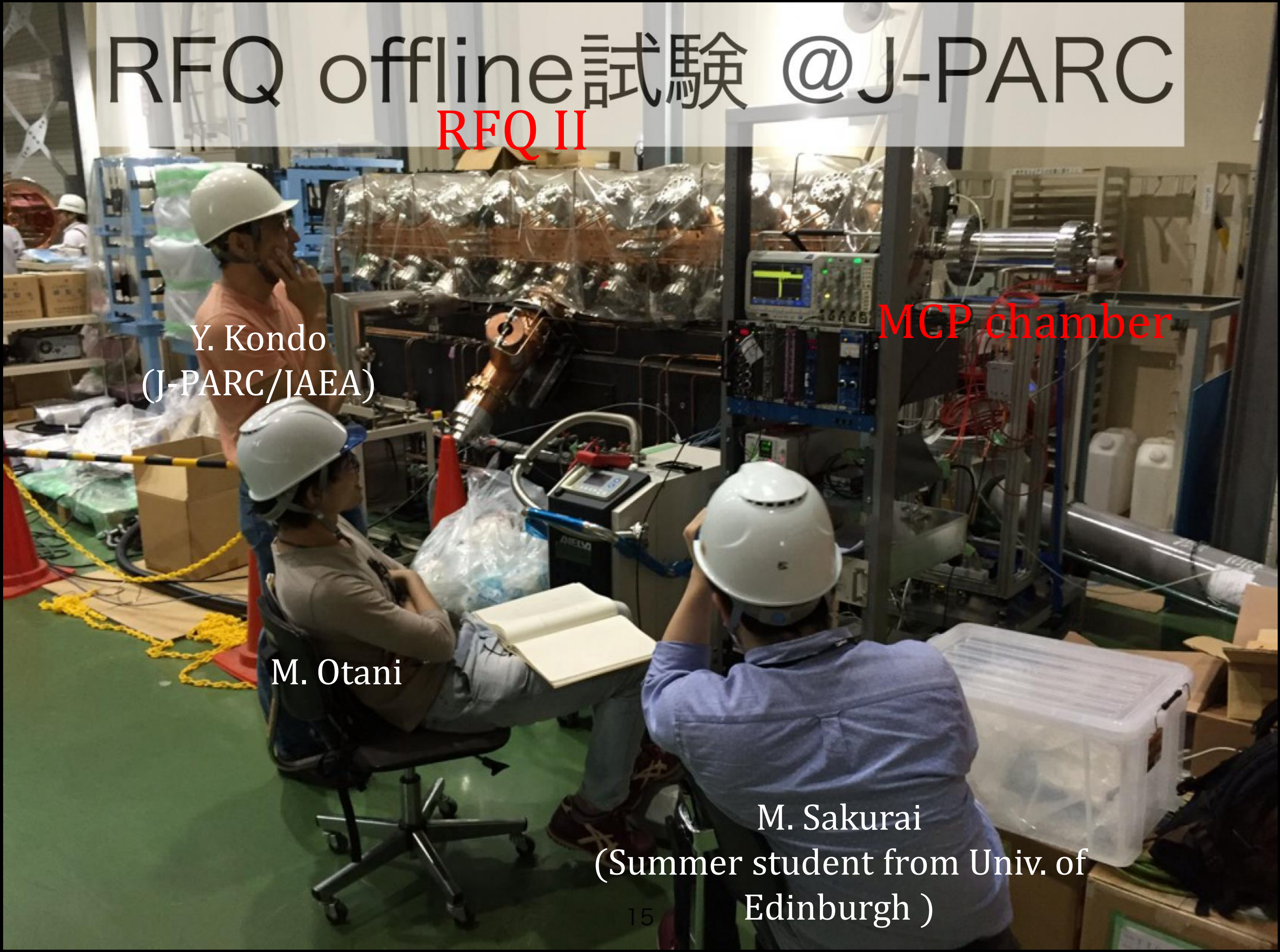
Detector system





scheduled in the end of Feb.

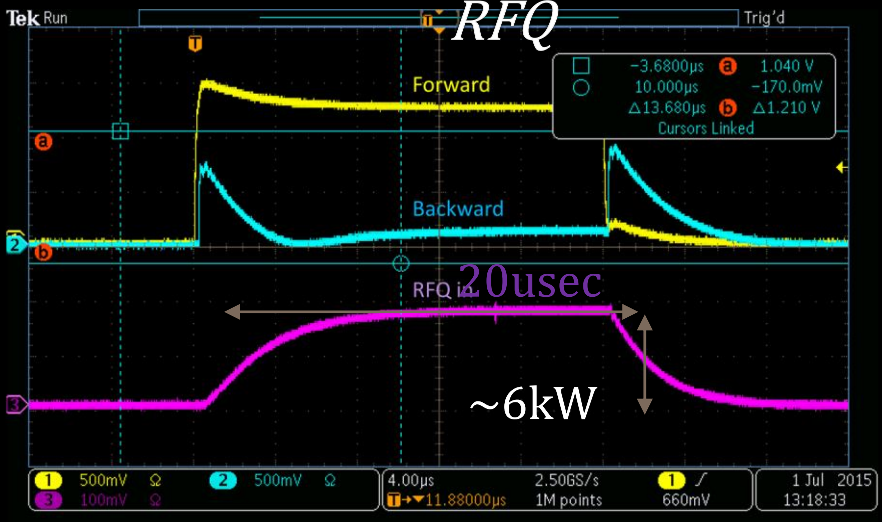
RFQ offline試験 @J-PARC



- Nominal power (>4.2kW) operation?
- No RF-related background?

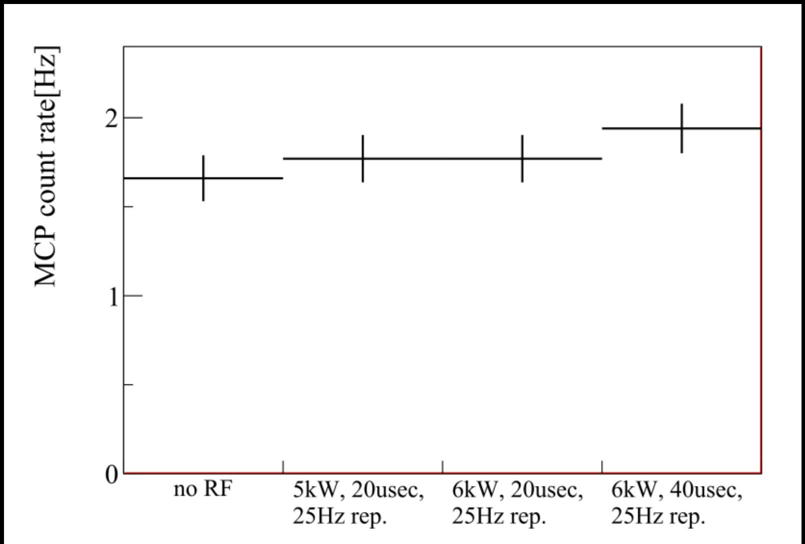
Results

Forward, reflection and pick-up in RFQ



Succeeded to operate with ~6kW

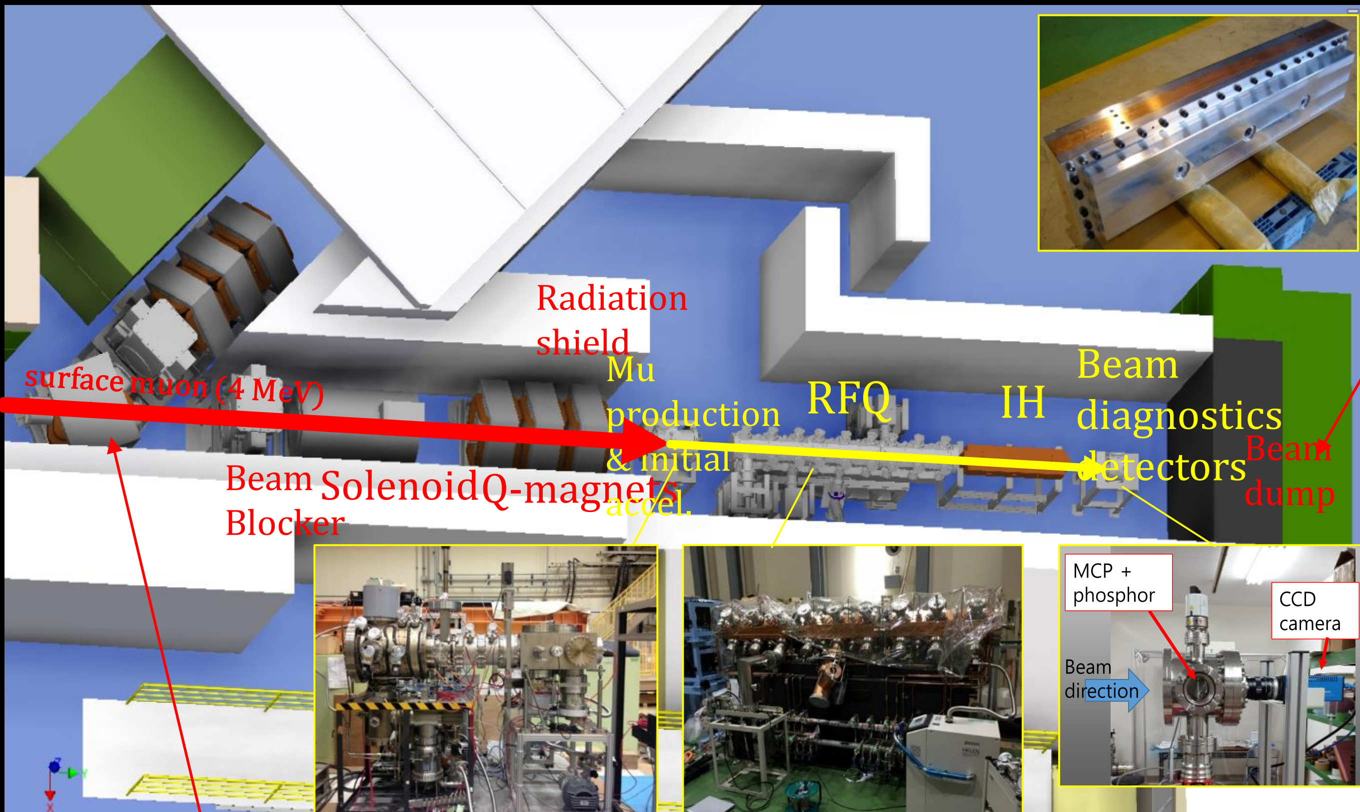
BG measurement



No BG

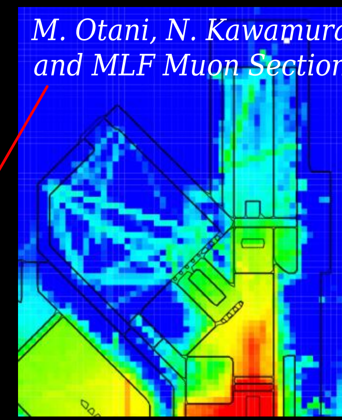
RFQ is ready for the μ acceleration

Preparation for onsite commissioning



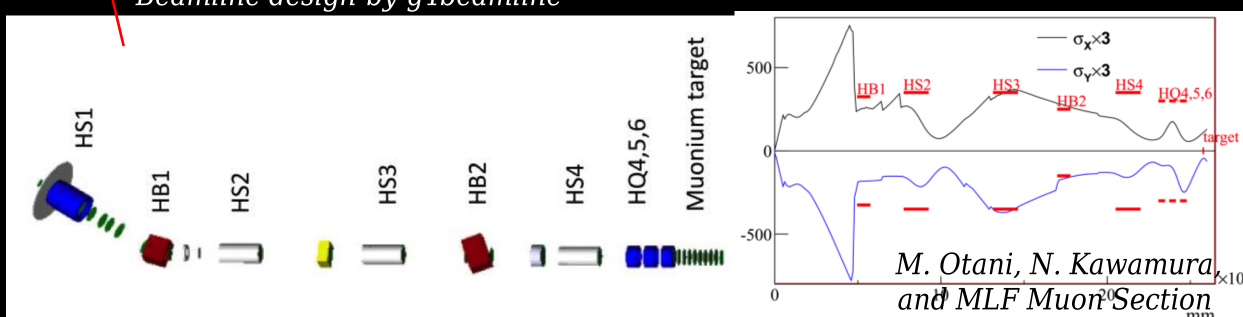
Ready Ready Ready

Radiation shield design by PHITS



Reay for design

Beamline design by g4beamline



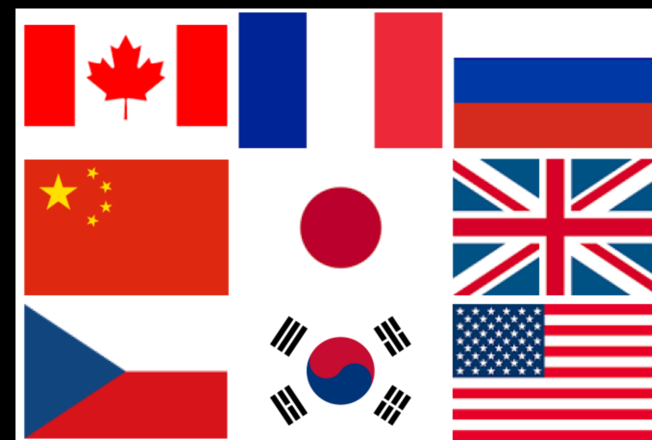
Summary of This Talk

- Basic designs of the world's first moun linac were finished.
- We are ready for muon acceleration after getting H-line.

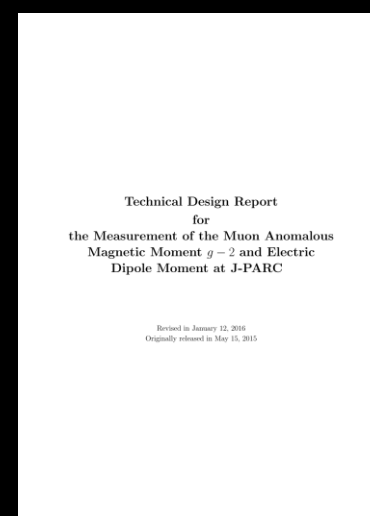
E34 Collaboration

- 137 members from 9 countries, 49 institutions
- TDR was submitted and review will start for stage-2 approval

Nov. 2015, J-PARC



Nov. 2014, KAIST(Korea)


Technical Design Report
for
the Measurement of the Muon Anomalous
Magnetic Moment $g-2$ and Electric
Dipole Moment at J-PARC

Revised in January 12, 2016
Originally released in May 15, 2015

For muon LINAC

Working members

- **M. Otani**, R. Kitamura (U. Tokyo), K. Hasegawa (J-PARC/JAEA), M. Yoshida (KEK), T. Mibe (KEK), Y. Kondo (J-PARC/JAEA)

Adversary members

- N. Hayashizaki (TITech), Y. Iwata (NIRS), Y. Iwashita (Kyoto), H. Ao (FRIB), A. Sayyora (J-PARC/JAEA), F. Naito (KEK), N. Toge (KEK), S. Kurokawa (KEK)

JFY2015-2016 budget request

☑ Kiban (B) by M. Otani

☐ Kiban (S) by K. Hasegawa, Kiban (B) by Y. Kondo, Houga by M. Otani

☐ Shingakuzyutu

☐ 山田科学，笹川, by M. Otani

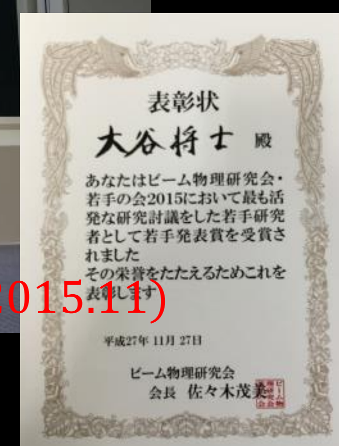

多摩六都科学館 (2015.8)


Korea (2014.11)

Thank you for your attention.


NuFact@Brazil (2015.8)


ビーム物理研究会(2015.11)


表彰状

大谷将士 殿

あなたはビーム物理研究会・若手の会2015において最も活発な研究討議をした若手研究者として若手発表賞を受賞されました
その栄誉をたたえるためこれを表彰します

平成27年11月27日

ビーム物理研究会
会長 佐々木茂美

BACKUP