Basic Design Study for Disk-Loaded Structure in Muon LINAC

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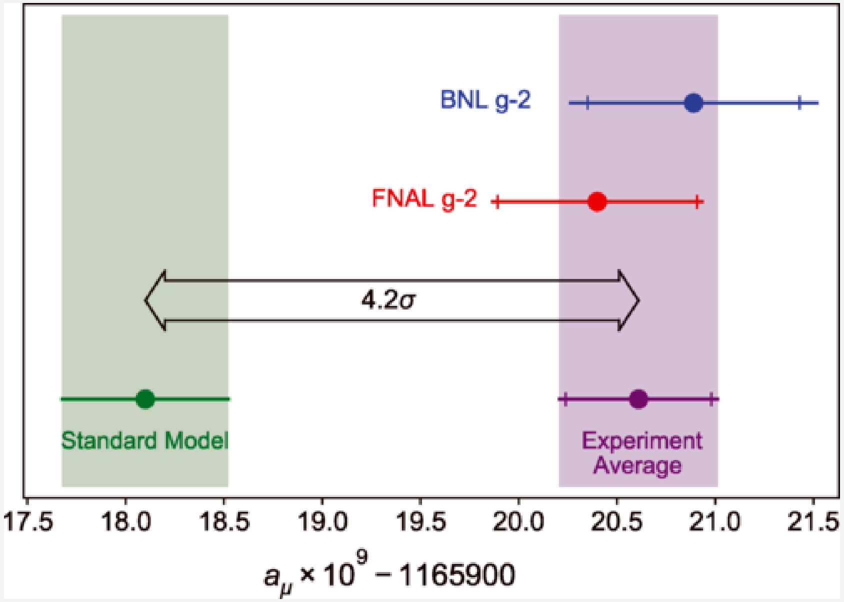
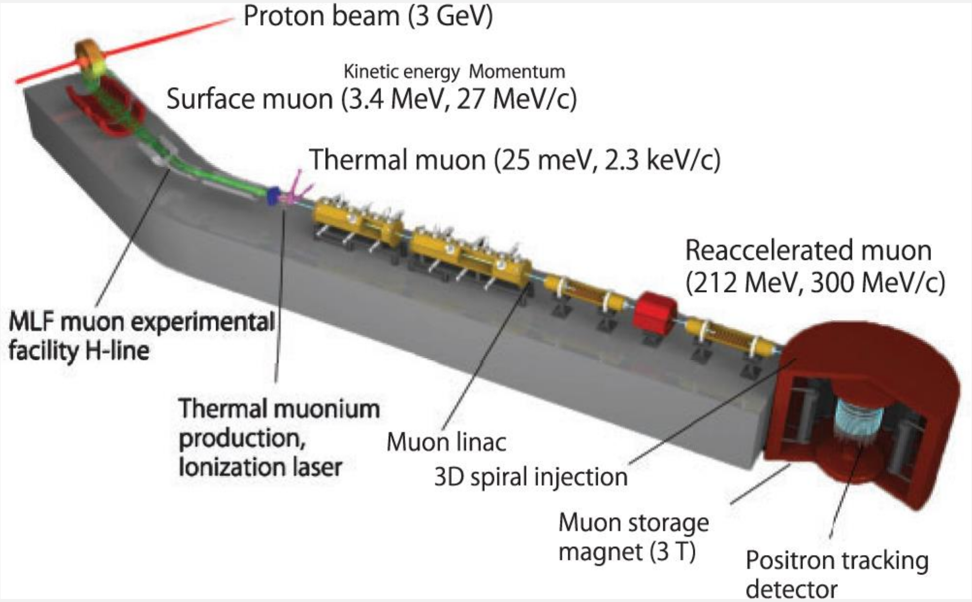
Introduction

- The $(g-2)_\mu$ anomaly from the average of two experiments [1][2] has 4.2σ discrepancy from the Standard Model prediction [3]. The contribution of New Physics is expected.
- A novel method measurement for the $(g-2)_\mu$ and the EDMμ using muon acceleration is under development at J-PARC [4].

$(g-2)_\mu$: the muon anomalous magnetic moment
EDM$_\mu$: the muon electric dipole moment



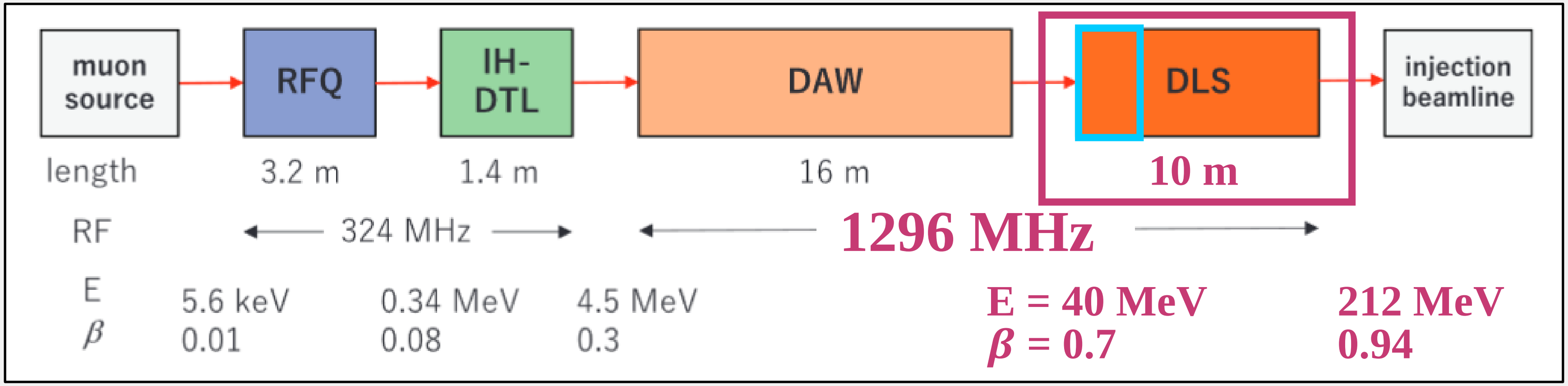
The values of $a_\mu = (g-2)_\mu/2$ [2].



Schematic view of the experiment at J-PARC [4].

Muon LINAC Overview

➢ The disk-loaded structures (DLS) take charge acceleration from 40 MeV (β = 0.7) to 212 MeV (β = 0.94) in the high-β section.



Schematic configuration of the muon LINAC [4].

➢ The requirements for the DLS section

- **An accelerating gradient of 20 MV/m**.
  (to acquire 172 MeV energy gain in about 10 m section)
- **A low normalized transverse emittance of 1.5π mm mrad or less** & **a small momentum spread of 0.1 % or less**.
  (for spiral injection & storage in the compact and weak focusing magnet)

※ In this poster, I'll consider a part of the DLS (40 MeV (β = 0.7) to **80 MeV (β ~ 0.8)**).

The First Design

- The length of each cell in the DLS (D) is determined as

$$D = \beta\lambda/3$$

λ: the wavelength of a 1296 MHz wave
※ $2\pi/3$ mode

to synchronize the beam velocity β & the phase velocity of RF.

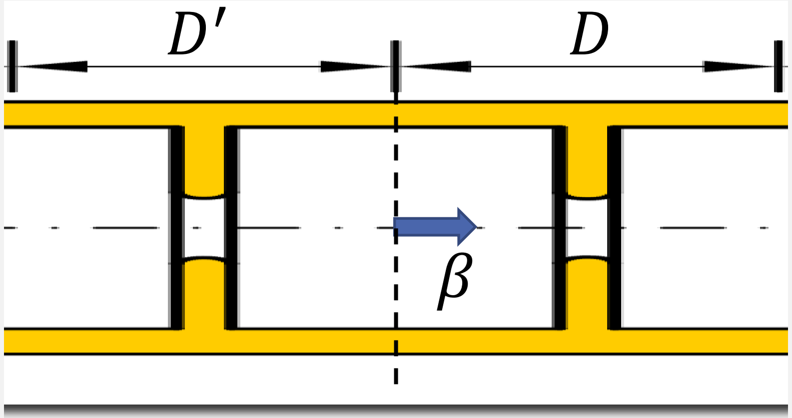
- β is calculated in terms of the energy gain **assuming a constant accelerating gradient (20 MV/m)** as

$$\text{Energy Gain} = 20\ \text{MV/m} \times \cos(-10\ \text{deg}) \times D'$$

-10 deg: the beam-synchronous phase yield a sufficient longitudinal acceptance
D': the length of the adjacent cell on the upstream

- This design requires an input RF power of 80 MW for an accelerating gradient of 20 MV/m.

- The first design (CI type) was estimated to meet the requirements [5], however, we need more consideration about the gradient and the phase slip.



Schematic diagram of the cross-section of 2 cells.

- I'll show
  - the calculation method of the RF properties of the traveling wave in the DLS.
  - the status of the cell designs for the **quasi-CG type muon DLS**.

Calculation of Traveling Wave

- The traveling wave is obtained by the superposition of the standing waves in two different boundary conditions:
  Neuman boundaries ($E_T = 0$) & Dirichlet boundaries ($H_T = 0$)
  calculated by using Autofish solver in SUPERFISH [6].
- In $2\pi/3$ mode, the solver calculates the same boundaries for every 1.5 cells.
- Other parameters are calculated as
  - Quality factor:

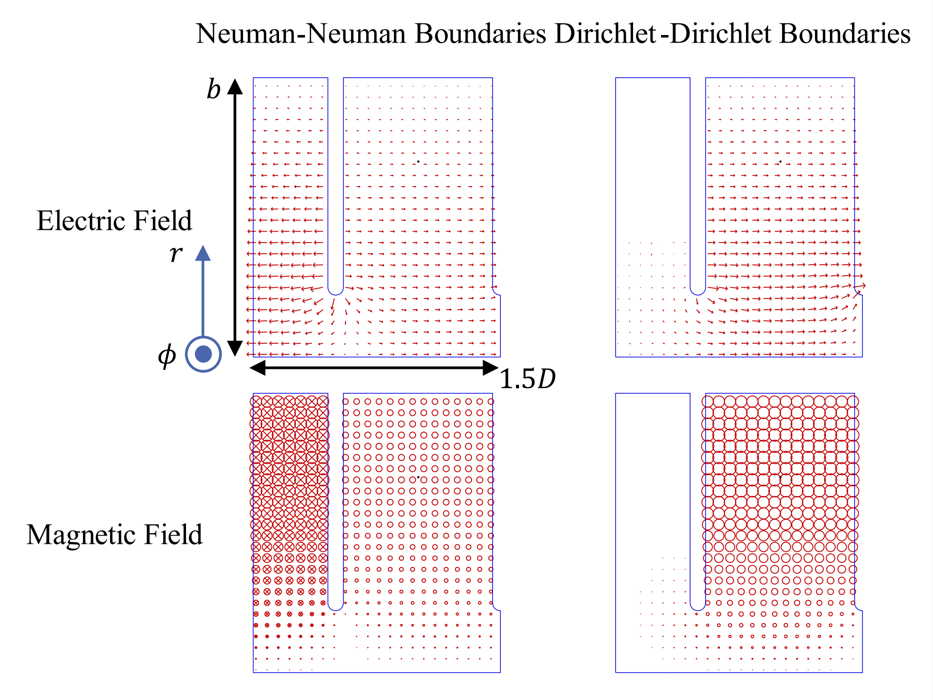
$$Q = \frac{2\pi f U}{P}$$

  - Shunt impedance per unit length:

$$Z = \frac{|E_0'|^2}{P/1.5D}$$

  - Group velocity at the left side [7][8]:

$$v_g = \frac{\frac{1}{2}\int_0^b E_{r,\mathrm{Dirichret}}(r) H_{\phi,\mathrm{Neuman}}(r) 2\pi r dr}{2\ \mathrm{Joules}/1.5D}$$



Standing-wave fields in half of 1.5 cells.

[definitions]
f: frequency = 1296 MHz,
U: the stored energy in 1.5 cells, P: the power dissipation in 1.5 cells,
$|E_0'|$: the accelerating gradient averaged over 1.5 cells,
E_r, H_ϕ: the electric/magnetic fields of each boundaries normalized to U = 1 Joule at the left side of the cell.

Cell Design for CG Type DLS

Four kinds of structures were designed under the following conditions.

- The iris aperture ($2a$) of the first cell is fixed to 40 mm.
- $2a$ of the last cell ($2a_{\text{last}}$) is set to 37 mm, 38 mm, 39 mm, or 40 mm (CI type).
- $2a$ of the other cells is determined as the function of the cell number (n):

$$2a(n)\ [\text{mm}] = 40 + \frac{2a_{\text{last}} - 40}{32} \times n$$

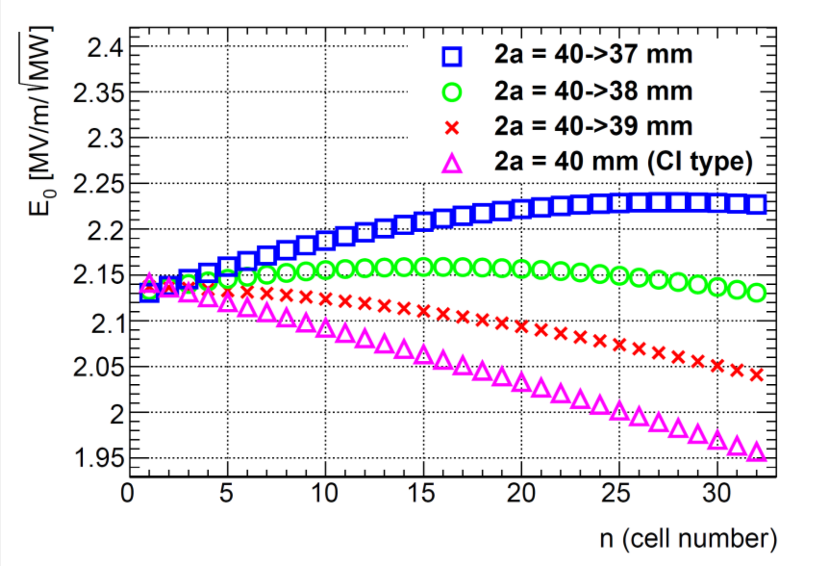
The average & normalized accelerating gradient per cell (E_0) is given as

$$E_0(n) = \sqrt{\Delta P(n) Z(n) / D(n)}$$

where $\Delta P(n)$ is the power dissipation per cell:

$$\Delta P(n) = P_{\text{in}} e^{-2\sum_{i=1}^{n-1} \alpha(i) D(i)} \left(1 - e^{-2\alpha(n) D(n)}\right)$$

P_{in}: the input RF power = 1 MW
α: the field attenuation factor = $\pi f / v_g(n) Q(n)$



The structure with $2a_{\text{last}}$ = 38 mm (green) has the most uniform gradient.
→ evaluate the phase slip & E_0 in detail as the quasi-CG type.

Evaluation of Phase Slip & Gradient

- The phase and the gradient are calculated in General Particle Tracer [9].
- One muon with an initial kinetic energy of 42.7 MeV is traced.
- The phase slip at the middle of a cavity of each cell is calculated as

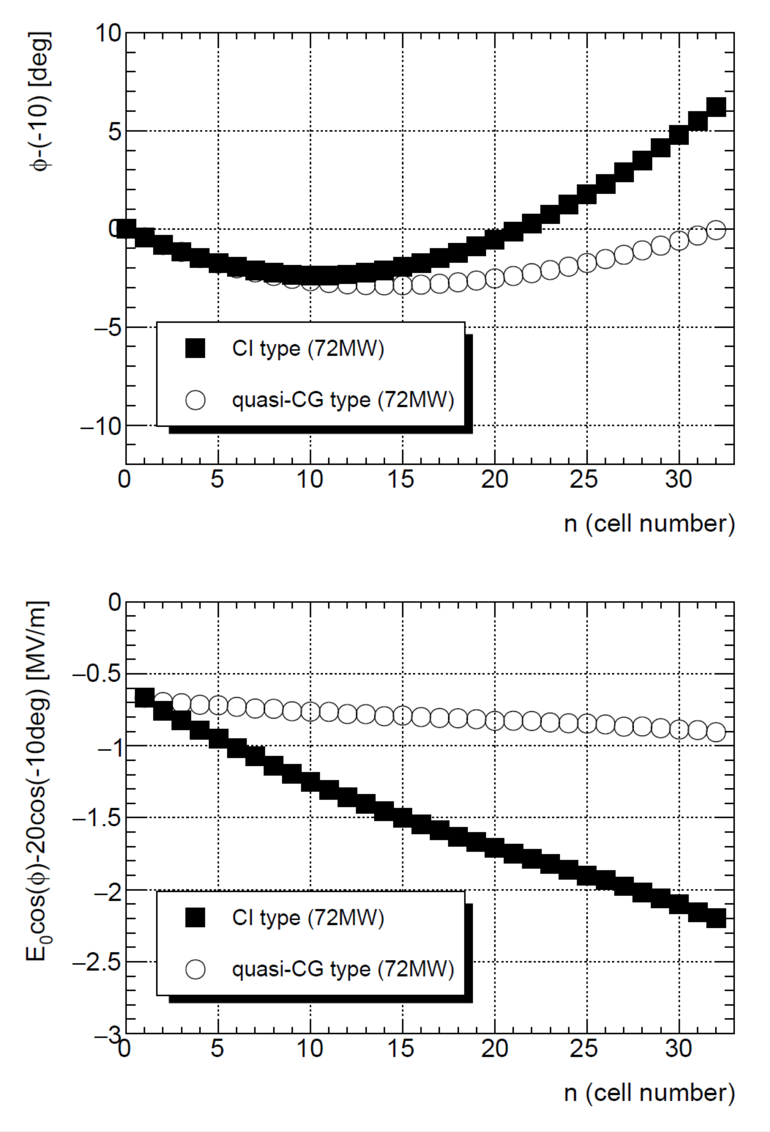
$$\phi(n) - (-10) = 360 f\, t_{\mathrm{beam}}(n) - 120n$$

- The accelerating gradient is calculated as

$$E_0(n)\cos\phi = \frac{1}{D(n)}\int_{D(n)} E_z(z)\, dz$$

$t_{\mathrm{beam}}(n)$: the arrival time of the muon to the end of the n-th cell
$E_z(z)$: the longitudinal electric field

- The input RF power of 72 MW is chosen to be $\phi_{\mathrm{quasi-CG}}(32) \simeq -10$ deg.
- **The quasi-CG type has a smaller phase slip and a more uniform accelerating gradient than those of the CI type.**



Summary and Prospect

Summary

- We got the better solution with the quasi-CG type DLS:
  - the **smaller phase split**.
  - the **more uniform accelerating gradient**.

  with the **same input RF power**.
- The accelerating gradient of about 19 MV/m is lower than 20 MV/m.

Summary of simulated parameters of the quasi-CG type

Input beam energy	42.7 MeV ($\beta = 0.702$)
Output beam energy	78.5 MeV ($\beta = 0.819$)
Operating frequency (f)	1296 MHz
Accelerating mode	TM01-$2\pi/3$
Synchronous phase	−10 deg
Number of regular cells	32
Input RF power (P_{in})	72 MW
Accelerating gradient (E_0)	~19 MV/m
Cell length (D)	54–63 mm
Disk thickness	5 mm
Iris aperture ($2a(n)$)	38–40 mm
Cylinder diameter ($2b(n)$)	179.5–180.3 mm
Quality factor ($Q(n)$)	17 000–19 000
Shunt impedance ($Z(n)$)	28–36 MΩ/m
Group velocity/speed of light	0.82–0.96 %
Filling time	0.69 μs
Field attenuation factor ($\alpha(n)$)	0.083–0.086

Prospect

To get solutions with less energy deviation from the design, the more rigorous simulations will be needed.

Acknowledgements

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References

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