the 14th workshop on breakdown science and high gradient technology – HG2022

Design of disk-loaded traveling wave structure for the muon linac

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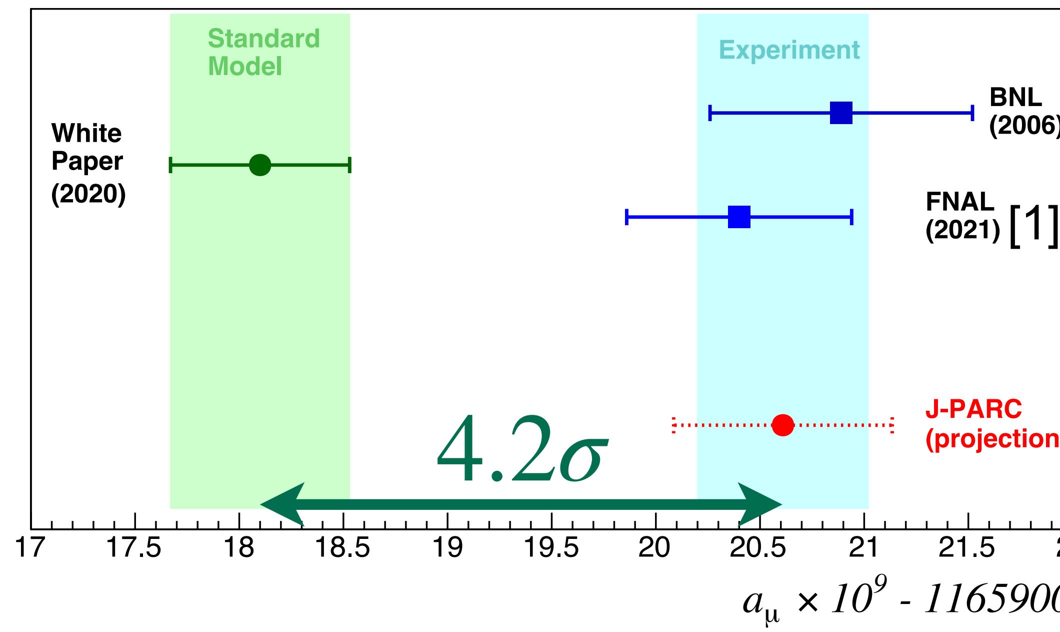
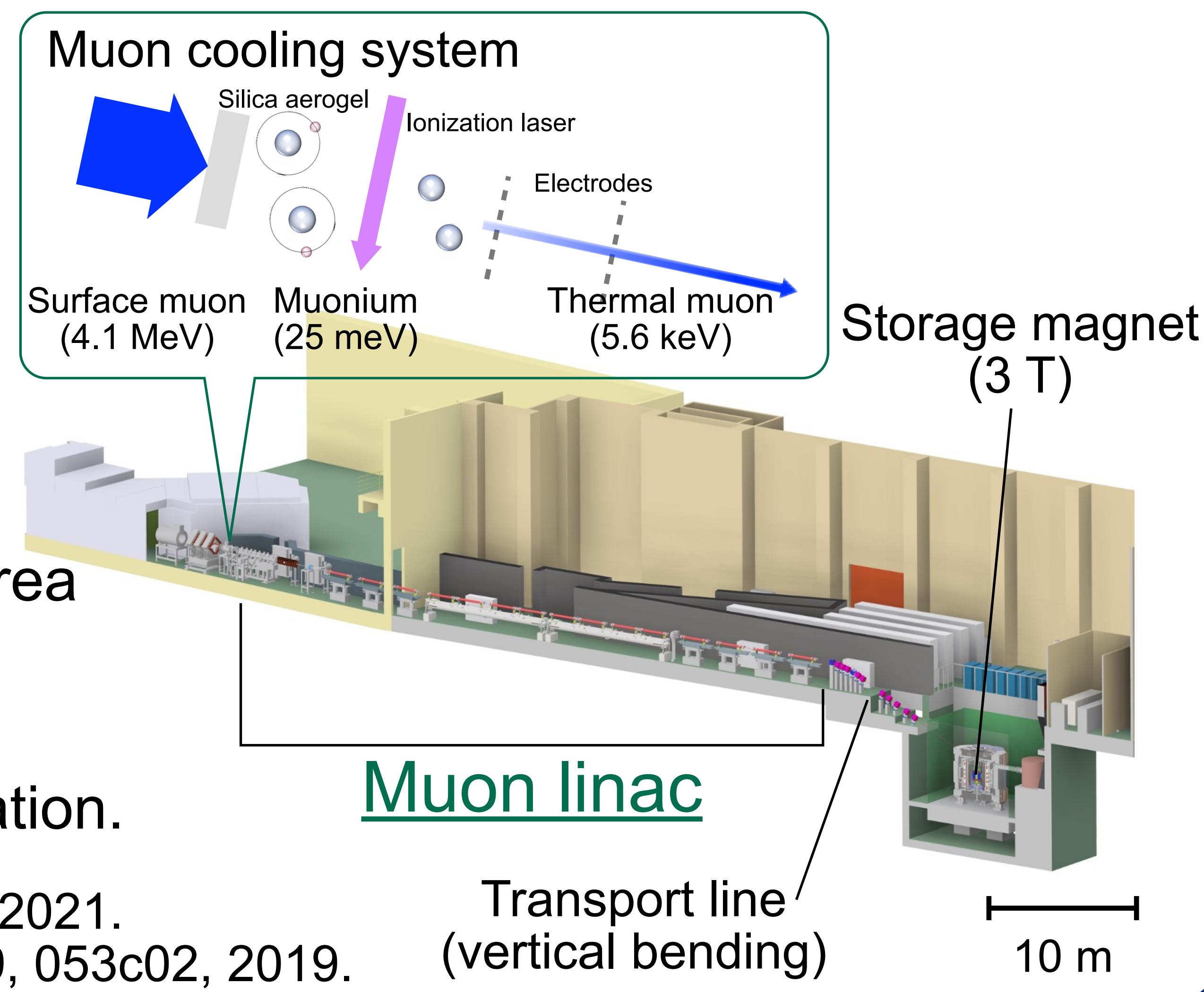
Introduction

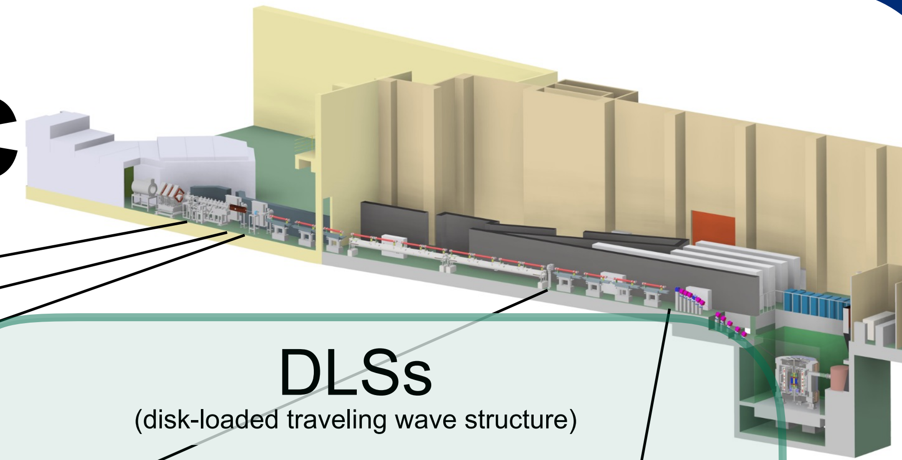
- The experimental average value of muon anomalous magnetic moment ($a_\mu = (g_\mu - 2)/2$) deviates from the standard model prediction by 4.2σ [1].
  → It may be a sign of physics beyond the standard model.
- The experiment plans in J-PARC to validate this discrepancy with the novel method [2].
  - Low emittance muon beam with cooling & acceleration (~ 1pi mm mrad (normalized))
  - Compact storage magnet (orbit radius 333 mm)
  - No electrostatic focusing in storage area
  - Three-dimensional spiral injection
- There is no precedent for muon acceleration.





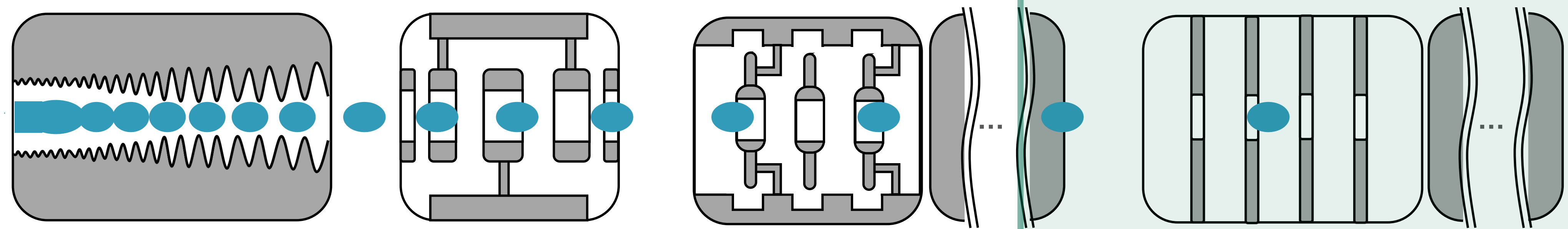
[1] B. Abi *et al.*, Phys. Rev. Lett., vol. 126, 141801, 2021.
[2] M. Abe *et al.*, Prog. Theor. Exp. Phys., vol. 2019, 053c02, 2019.

Muon linac



Y. Nakazawa
(Talk in May 19 [link])

	RFQ (radio frequency quadrupole)	IH-DTL (inter-digital H-mode drift-tube linac)	DAW-CCLs (disk and washer coupled cavity linac)	DLSs (disk-loaded traveling wave structure)
Frequency:	324 MHz	324 MHz	1296 MHz	2592 MHz



$\beta = v/c$: 0.01 → 0.08 → 0.3 → 0.7 → 0.94

Kinetic: 5.6 keV → 0.3 MeV → 4 MeV → 40 MeV → 212 MeV

	RFQ	IH-DTL	DAW-CCLs	DLSs
Length:	3.2 m	1.4 m	16 m	10 m

- Muon linac consists of four structures for short*-time acceleration to obtain a low emittance & small momentum spread beam without decay loss.

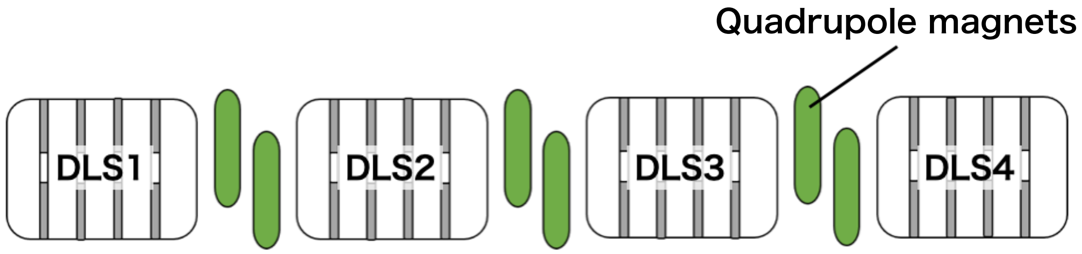
  * sufficiently shorter than the muon lifetime of 2.2 us

- Features of each structure
  - RFQ: Bunching (bunch width 10 ns → 3 ns x 3 bunches)

    (intensity = ~1e6 muons/pulse x 3 pulses x 25 Hz)
  - IH-DTL:
    High effective shunt impedance of 58 MOhm/m, alternating phase focusing
  - DAW-CCLs: Widest velocity range, strong coupling between cells
  - DLSs: Highest accelerating gradient of 20 MV/m, varying disk spaces

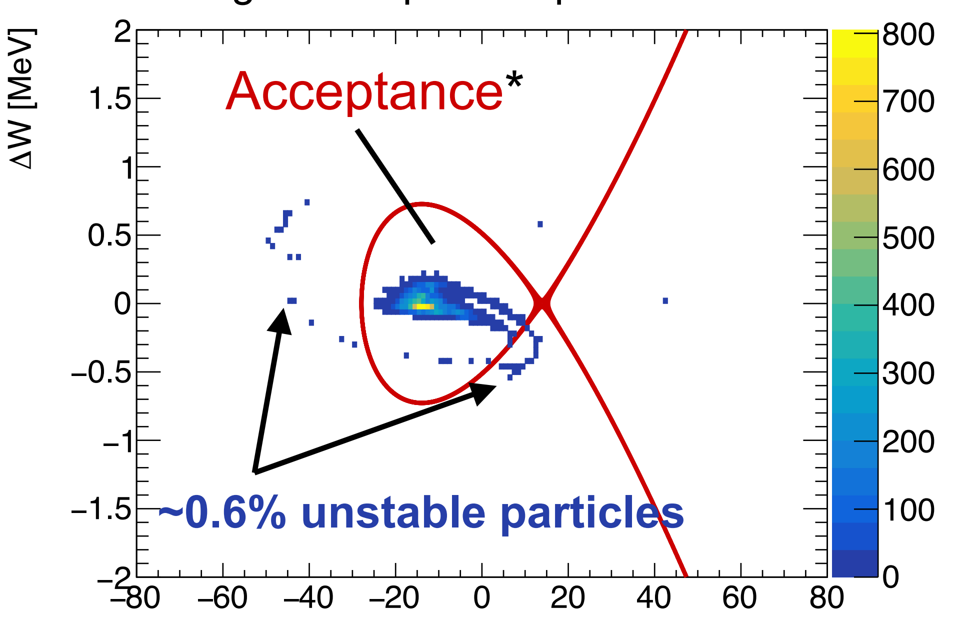
Disk-loaded structures

- The high-velocity section consists of four DLSs, each ~2 m long with ~60 regular cells.
- Three transport lines, each ~0.4 m long, connecting the DLSs contain two quadrupole magnets, each with a gradient of ~20 T/m.
- TM01-2pi/3 mode is selected as the accelerating mode for high shunt impedance.
- Velocity varies drastically during acceleration, muon DLSs have to choose off-crest acceleration to obtain longitudinal acceptance.
- Synchronous phase (ϕ_s) is chosen as −13 deg by considering
  - longitudinal phase acceptance $\approx 3|\phi_s|$
  - momentum spread at the exit of DLS section
  - energy gain $\propto \cos\phi_s$
  - RF defocusing force $\propto \sin\phi_s/\beta\gamma^2$
- The RF pulse length is ~1 us including a filling time of ~0.5 us.



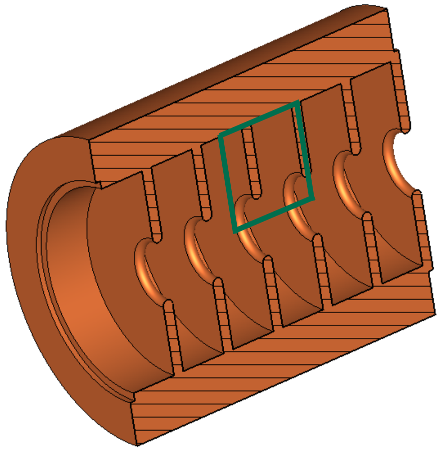
Structure type	disk-loaded traveling wave quasi-constant gradient type
Frequency	2592 MHz (324 MHz x 8)
Resonant mode	TM01-2pi/3
Synchronous phase	−13 deg
Accelerating gradient	~20 MV/m @ 40 MW
Structure length	2.0 m(DLS1) - 2.3 m(DLS4)
Filling time	0.50 us(DLS1) - 0.55 us(DLS4)

Simulated longitudinal phase-space at DLS1 entrance



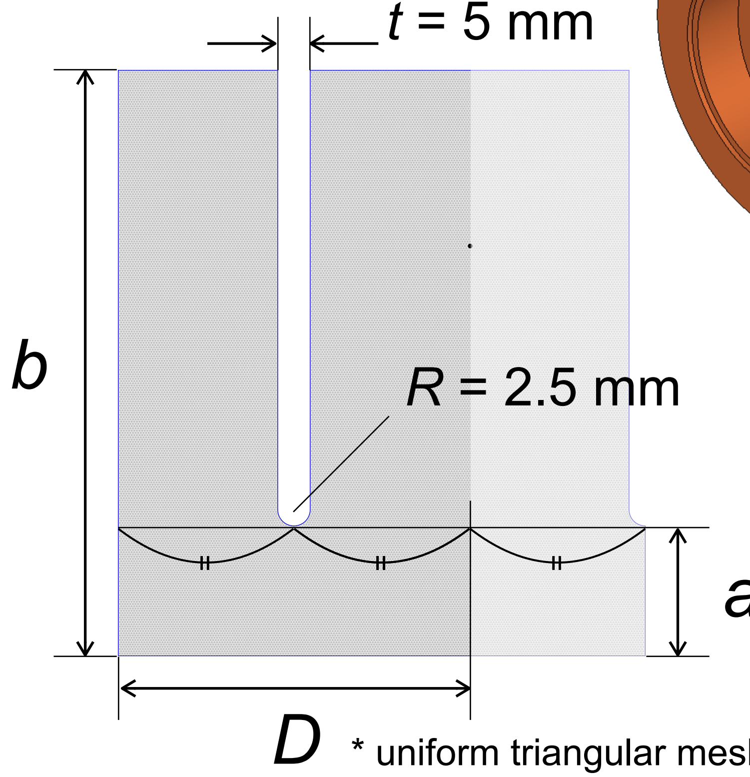
* excluding beta change effect

Structure design 1

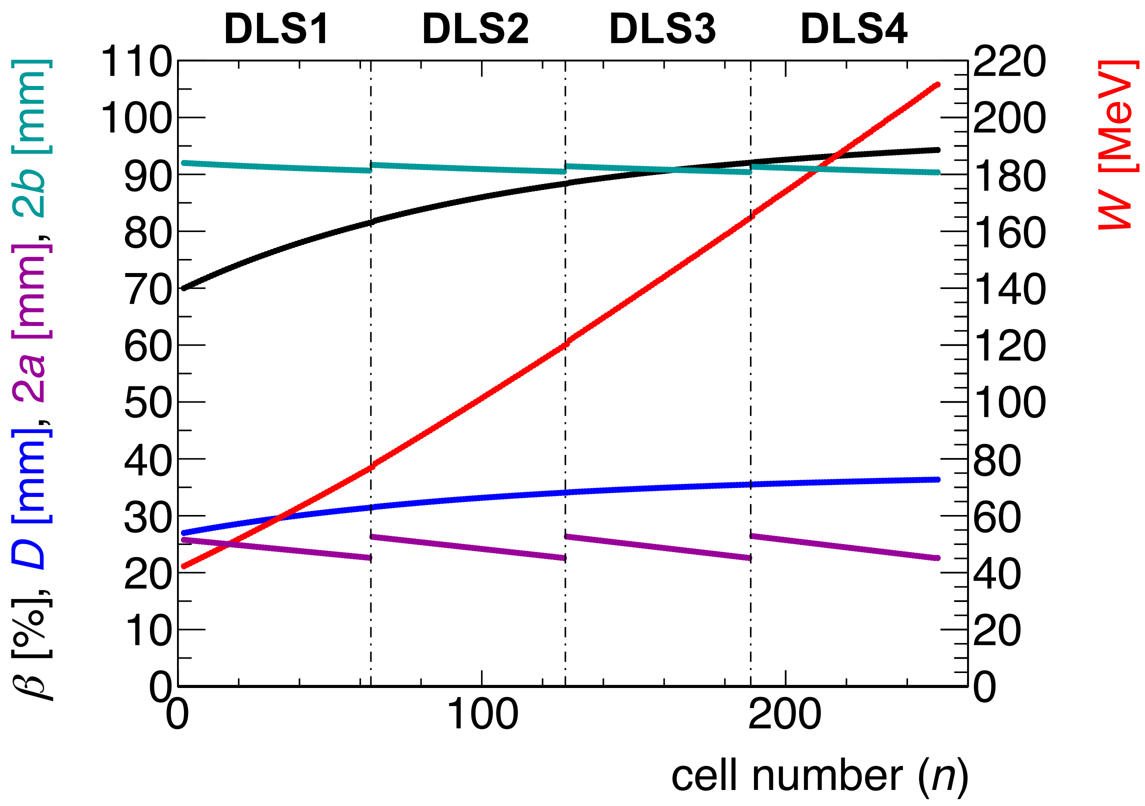


【 Cell design with SUPERFISH 】

- Kinetic energy (W) varies with the (average) accelerating gradient (Eacc) [3].
  $W_n \simeq W_{n-1} + \overline{E_{\rm acc}} D_n \cos\phi_s$
  Synchronous phase: $\phi_s = -13$ deg
- Cell length (D) is proportional to beta (= muon velocity / speed of light) [3].
  $D_n = \beta_n(W_n)\lambda/3$ $\lambda \approx 115.661$ mm
- Iris diameters (2a) are tapered to maintain a quasi-constant accelerating gradient distribution in each DLS.
- Cylinder diameter (2b) of each cell is adjusted to have a resonant frequency of 2592 MHz.
- The cumulative phase slip due to mismatch between beam velocity and phase velocity is less than 2%, which is smaller than that due to machining uncertainty.



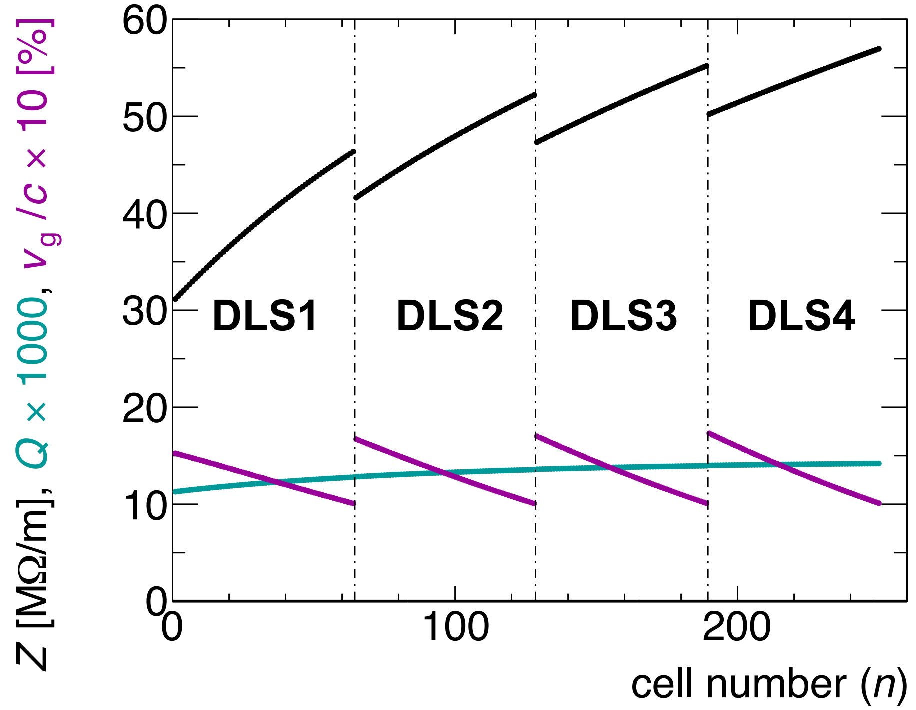
* uniform triangular mesh with a size of 0.2 mm



[3] Y. Kondo *et al*., J. Phys.: Conf. Ser., vol. 874, 012054, 2017.

Structure design 2

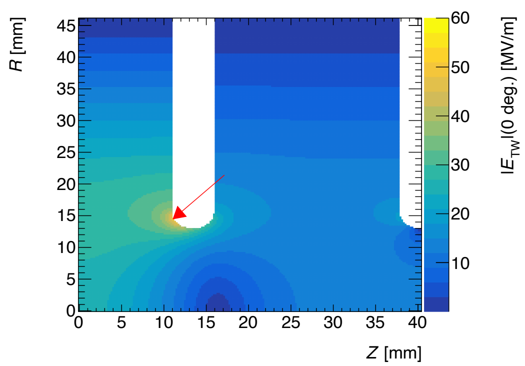
- RF parameters
  - Shunt impedance (Z):
    Depends mainly on cell length, with a maximum value is ~57 MOhm/m.
  - Quality factor (Q):
    Depends on cell length.
  - Group velocity / speed of light (vg/c):
    Depends on iris aperture, should be at least 1%c to account for permissive frequency error.

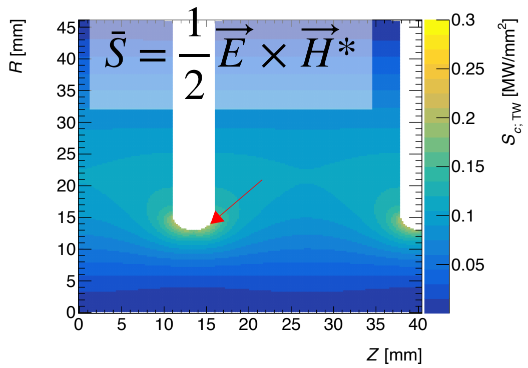


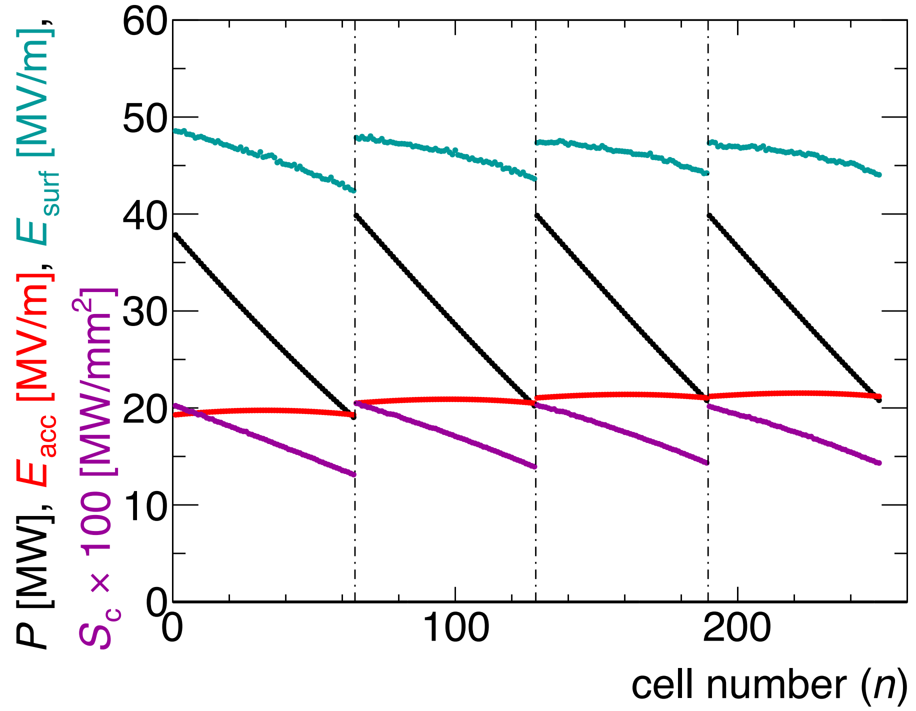
- Quantities for breakdown rate
  - Peak surface electric field (Esurf):
    Kilpatrick limit at 2592 MHz is 43.8 MV/m [4].
    → The bravery factor is approximately 0.97 to 1.11.
  - Modified Poynting vector [5]:

$$S_c = \|\Re(\bar{S})\| + \frac{\|\Im(\bar{S})\|}{6}$$

The safety threshold is 5 MW/mm²
at a pulse length of 200 ns [5].
→ Sufficiently below.







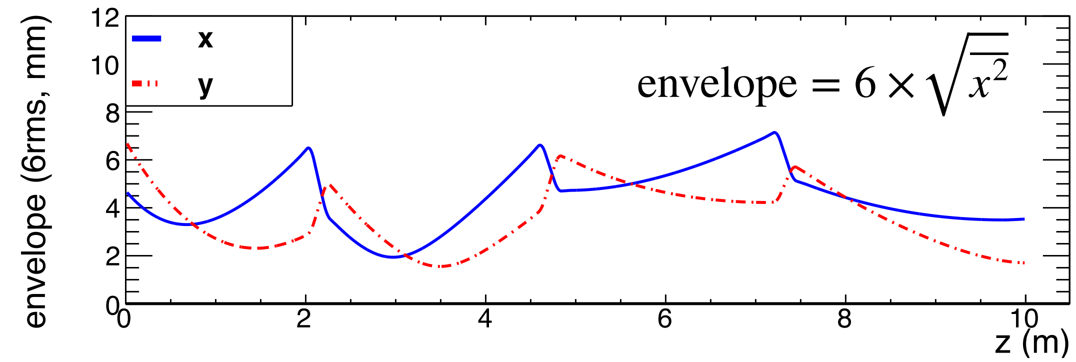
* a 3% deterioration of Q taken into account for power dissipation.

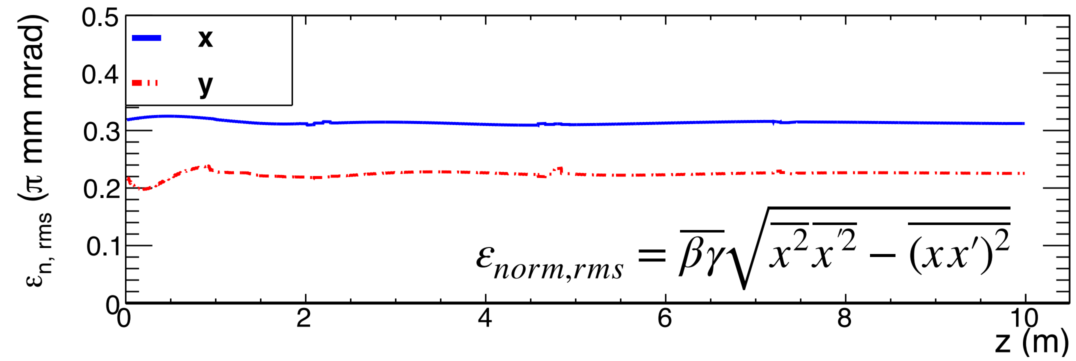
[4] W. D. Kilpatrick, University of California Radiation Laboratory Report No. UCRL-2321, 1953.
[5] A. Grudiev *et al.*, Phys. Rev. Spec. Top. Accel. Beams, vol. 12, 102001, 2009.

Beam dynamics simulation

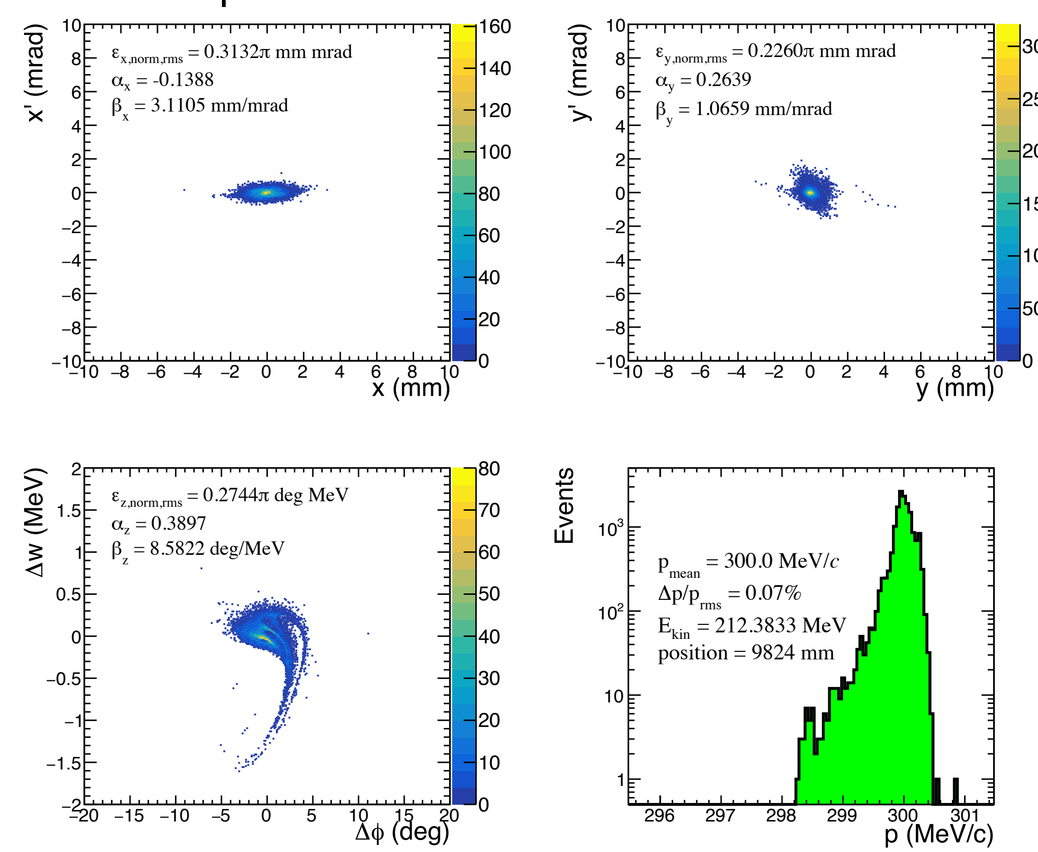
【 Particle tracking simulation with GPT 】

- The lattice of the transport line between DLS1 and DLS2 is adjusted by applying periodic boundary conditions for Twiss-beta at the DLS1 and DLS2 entrances.
- The beam phase advance from the DLS1 entrance to the DLS2 entrance is limited to less than 80 degrees.
- The beam envelope is evaluated as 6 times x(horizontal)- and y(vertical)-RMS, assuming almost the full width of the beam.
→ Sufficiently smaller than the iris radius of about 11.3 to 13.2.
- Normalized transverse RMS emittance does not increase through the DLS section.
→ Satisfies the requirement of 1.5pi mm mrad.
- Momentum spread at the exit of the DLS section is 0.07% in RMS.
→ Satisfies the requirement of 0.1%.
- Transmission: 15976/16074 ~ 99.4%





Phase-space distribution at the exit of DLS section



* low static simulation

Summary & Prospect

- The muon linac for the muon g−2 experiment is under development.
- S-band DLSs, with varying cell lengths, are designed for muon acceleration above 70% of the speed of light.
- The accelerating gradient of ~20 MV/m, estimated breakdown rate is sufficiently small, and simulated beam quality satisfies the requirement.
- The factors which limit accelerating gradient are the lower limit of the iris aperture, the RF defocusing force, and the RF system.
- We plan to fabricate a prototype of DLS1 to evaluate the real RF parameters of a few cells and attempt tuning for regular and coupler cells.

Acknowledgments

This work is supported by JSPS KAKENHI Grant Numbers JP18H03707, JP18H05226, JP20H05625, 21K18630, 21H05088, and 22H00141, JST FOREST Program (Grant Number JPMJFR212O), and the natural science grant of the Mitsubishi Foundation. This paper is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

References

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[3] Y. Kondo et al., J. Phys.: Conf. Ser., vol. 874, 012054, 2017.

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