

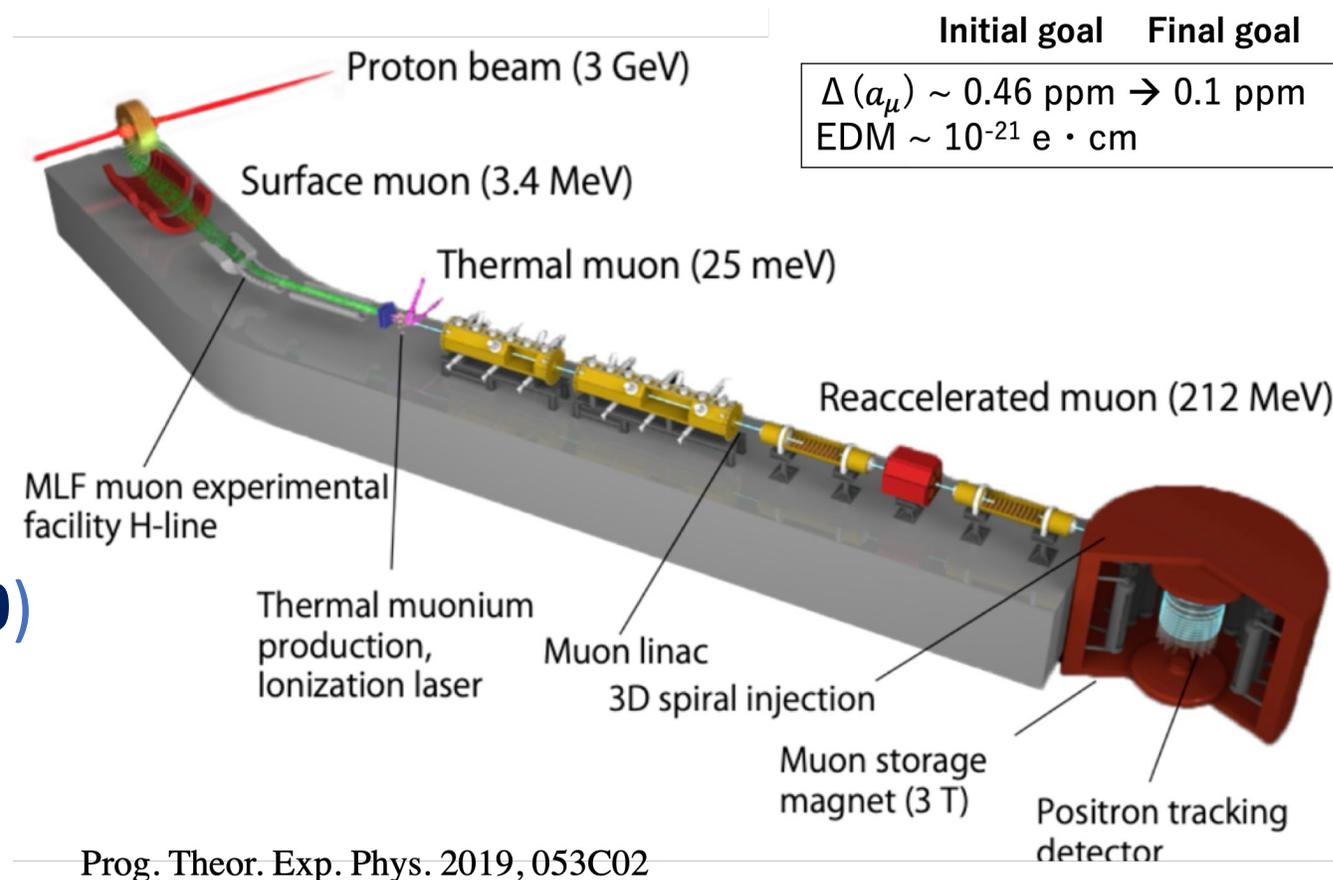
# Muon Linac towards 600 MeV

E. Bottalico  
Muon Group Meeting  
9<sup>th</sup> March 2026



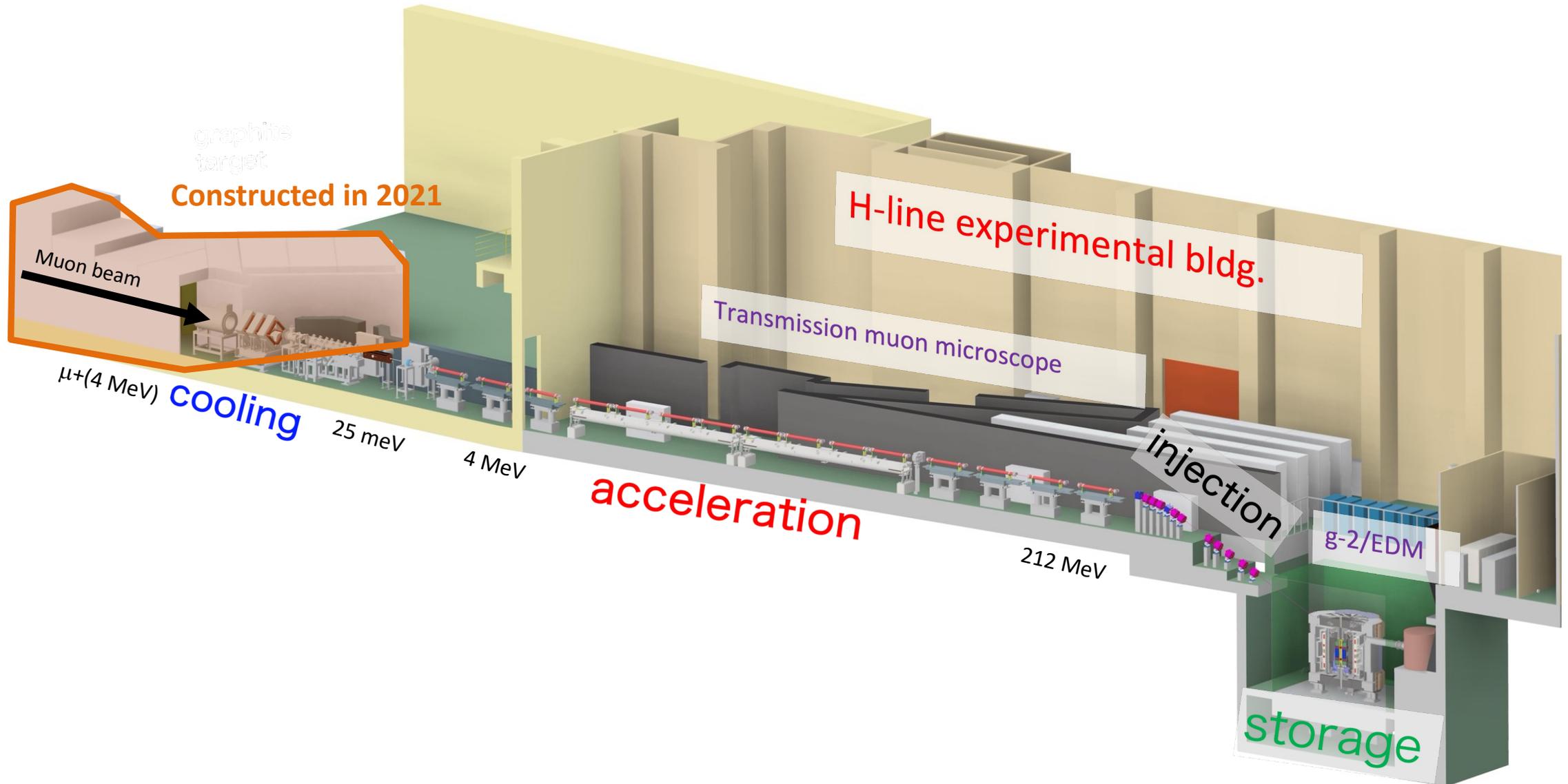
# New features of E34

- Low emittance muon beam (**1/1000**)
- Muon acceleration -> **212 MeV**
- **No strong** focusing
- 3D spiral injection:
  - Large kick in few ns
  - Good injection efficiency (**x10**)
- Compact storage ring (**1/20**)
- Tracking detector
- Excellent sensitivity to **muon EDM** about **100 times** better than the previous limit



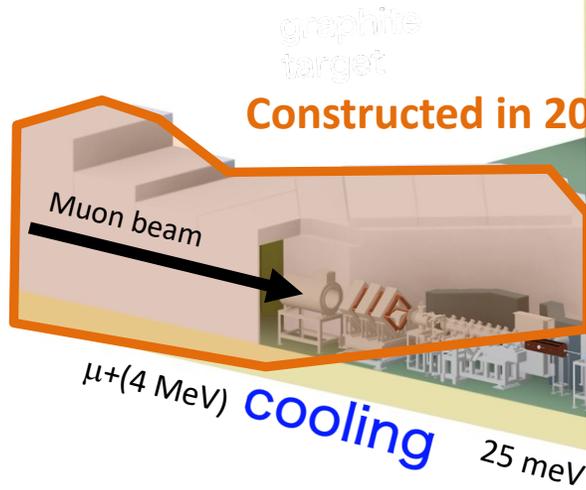


# Experimental hall





# Muon cooling





# Muon cooling



- **A conventional muon beam:**

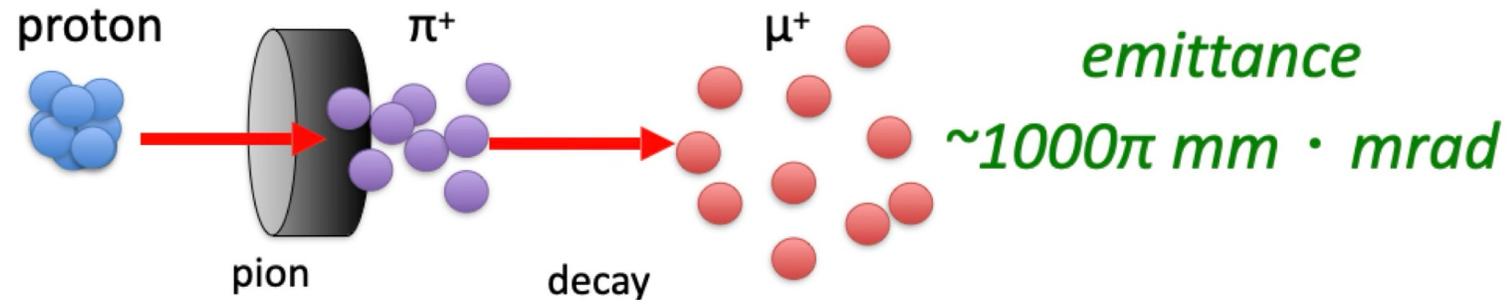
- can not be injected without a strong focusing  $\rightarrow$  electric field;
- This leads to muon losses and background contamination from  $\pi$ .

- **Desired beam:**

- The muon must be compact and non-divergent;
- Typically, with an RMS of  $\sim$ mm  $\rightarrow$  never achieved before.

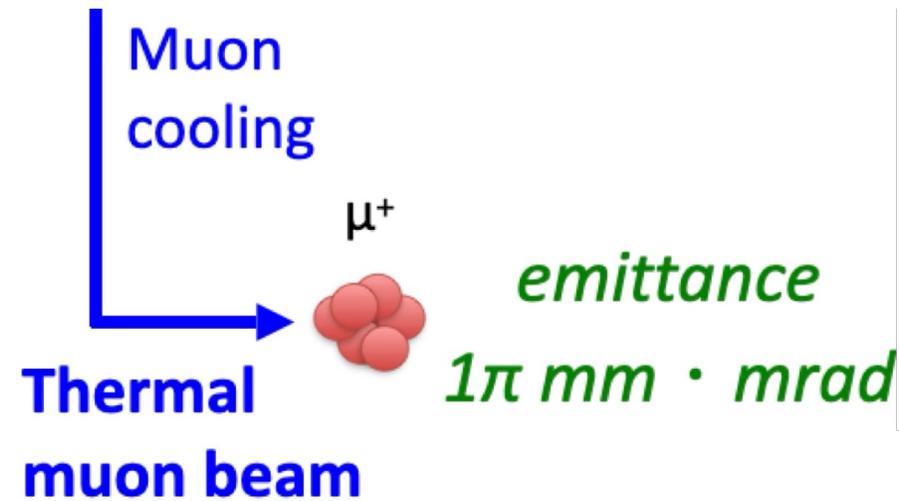
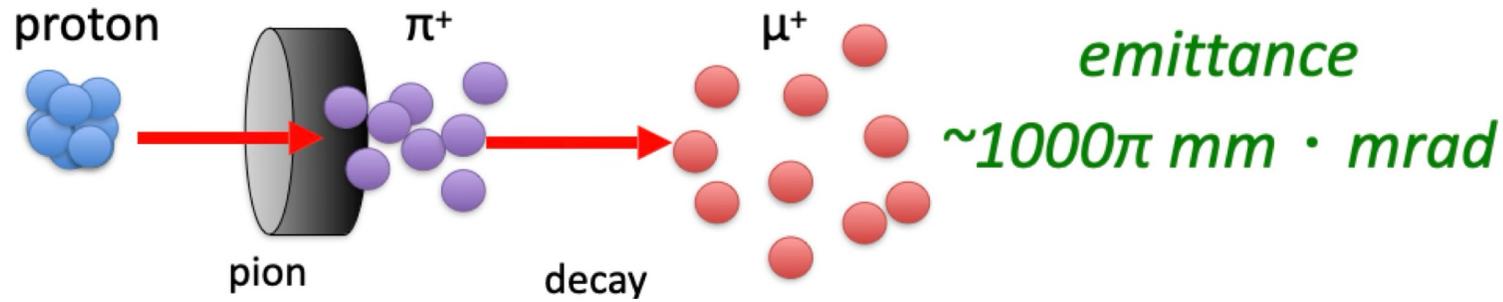


# Muon cooling





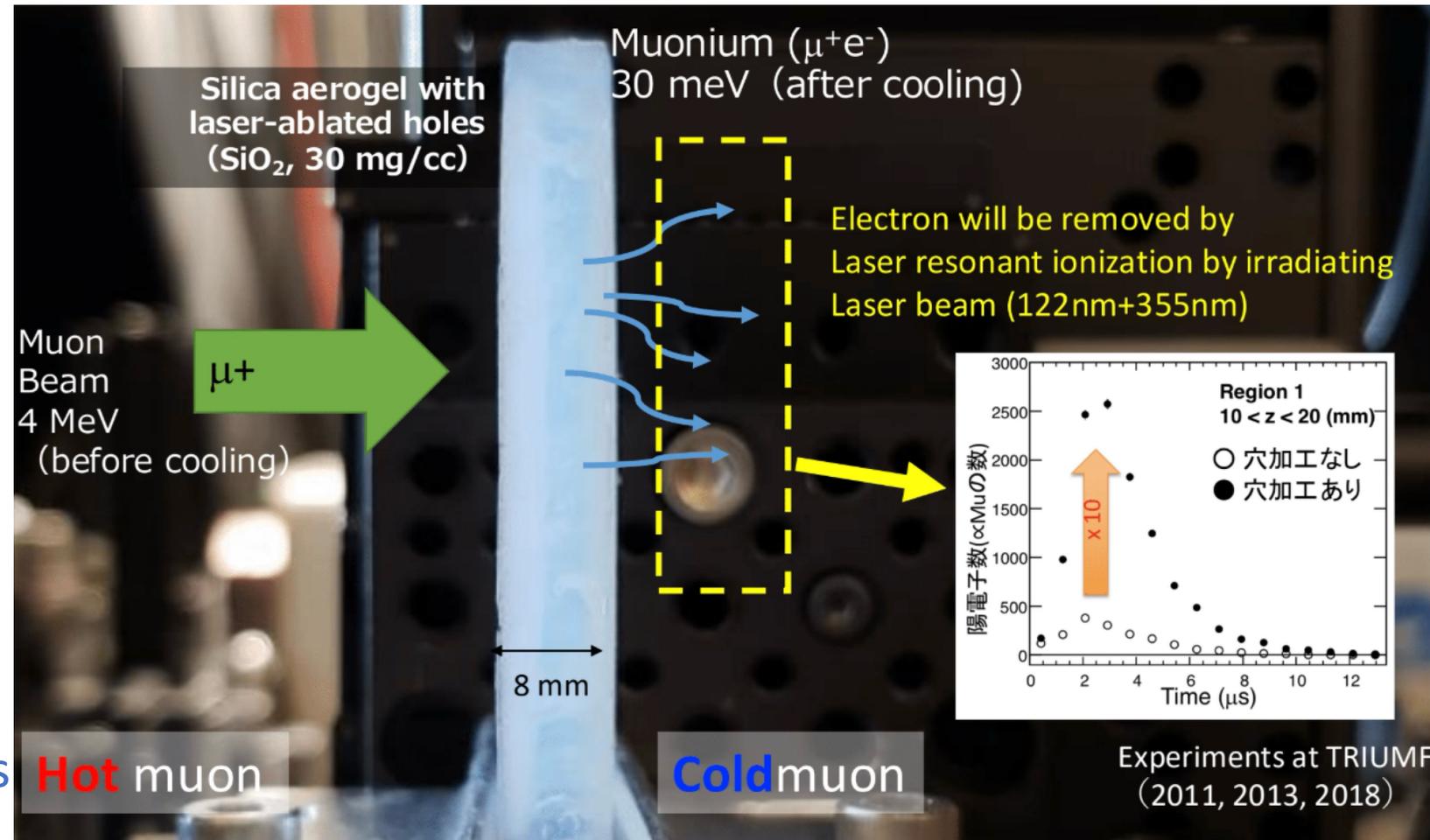
# Muon cooling





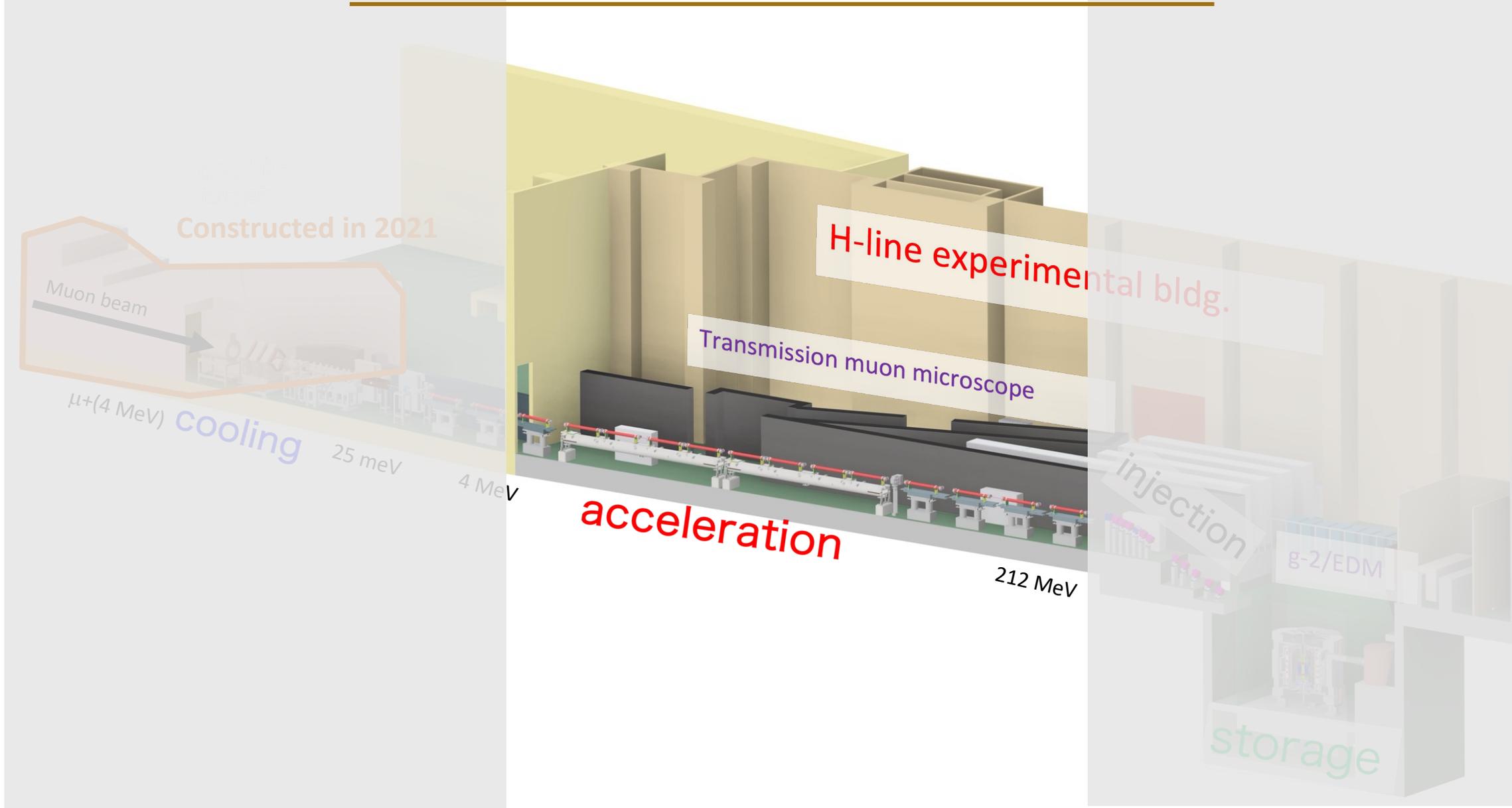
# Ultra-cold muons

- Surface  $\mu^+$
- Stop in (laser ablated surface) Aerogel
- Diffuse Muonium ( $\mu^+ e^-$ ) atoms into vacuum
- Ionize:
  - $1S \rightarrow 2P \rightarrow \text{unbound}$
  - **Max Polarization 50%**
- Accelerate:
  - E field, RFQ, linear structures
  - $E = 212 \text{ MeV}$  ( $p = 300 \text{ MeV}/c$ )





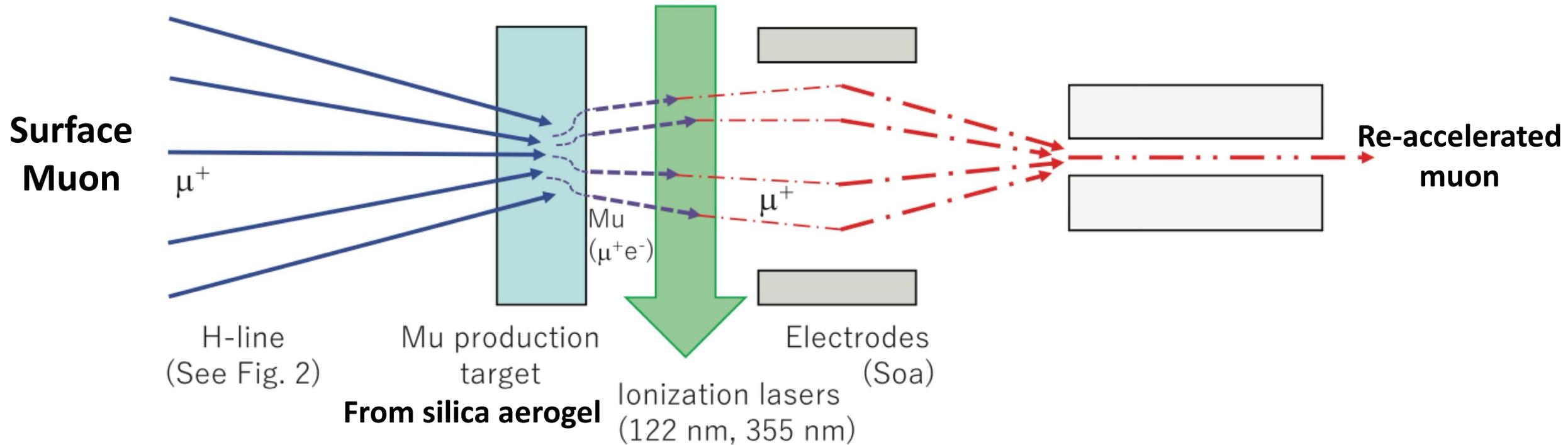
# Re-accelerated thermal muon





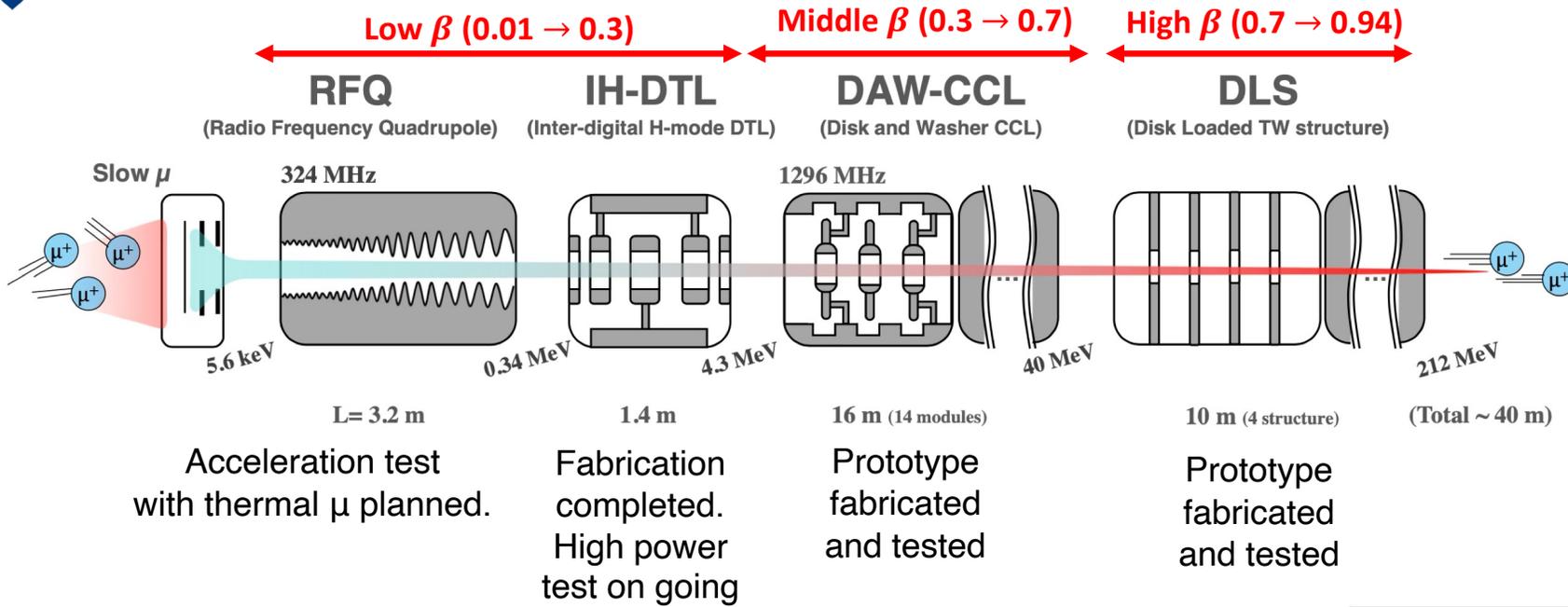
# Re-accelerated thermal muon

	Surface muon	Thermal muon	Accelerated Muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	$4 \times 10^{-4}$





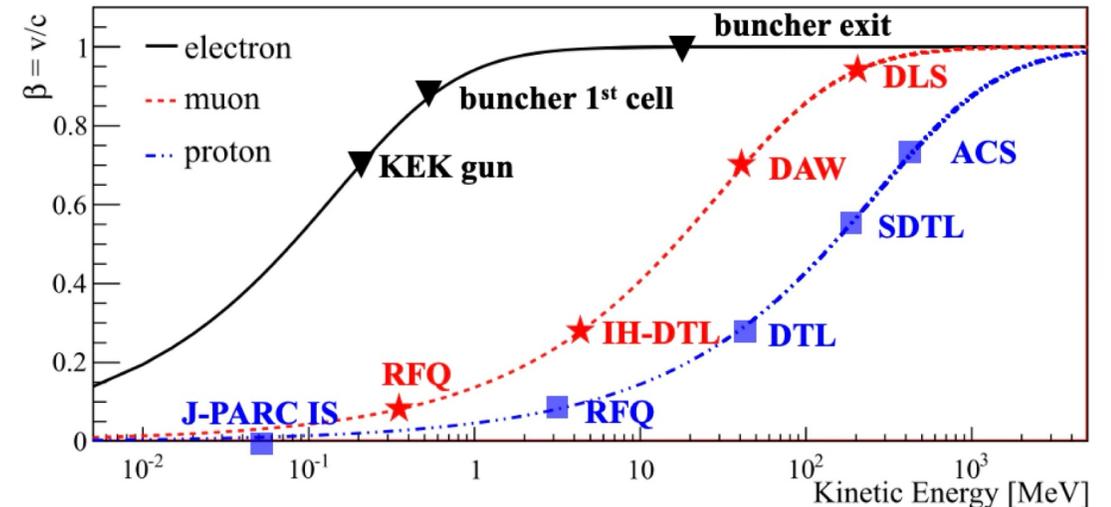
# Re-accelerated thermal muon



Muon LINAC parameters

Frequency (2-stage)	324MHz, 1296MHz
Intensity	$1 \times 10^6$ /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	$1.5 \pi$ mm mrad
Momentum spread	0.1 %

- The first muon-dedicated linac in the world!
- Muon Acceleration to 212 MeV
- 4 steps acceleration depending on  $\beta$  -> total length 40 m





# Towards high sensitivity

- The statistical precision on the anomalous precession frequency  $\omega_a$  is:

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P} \sqrt{\frac{2}{NA^2}}$$

**Increasing** the **momentum** improves measurement precision linearly.

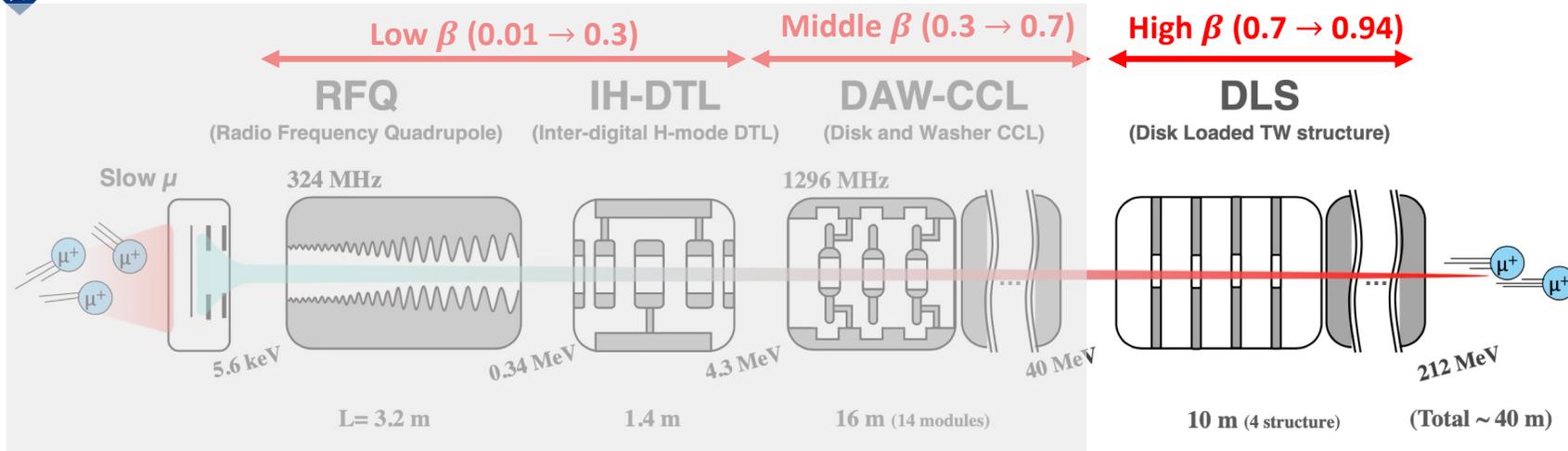
- Magnetic Field Adjustment:**
  - Higher momentum requires a proportional increase in the magnetic field to maintain experiment size.
- Effect on Anomalous Precession ( $\omega_a$ ):**
  - A stronger magnetic field **increases** the **anomalous precession frequency**.

→ Doubling both momentum and field ⇒ **x4** improvement in  $\omega_a$

precision.



# Towards high sensitivity



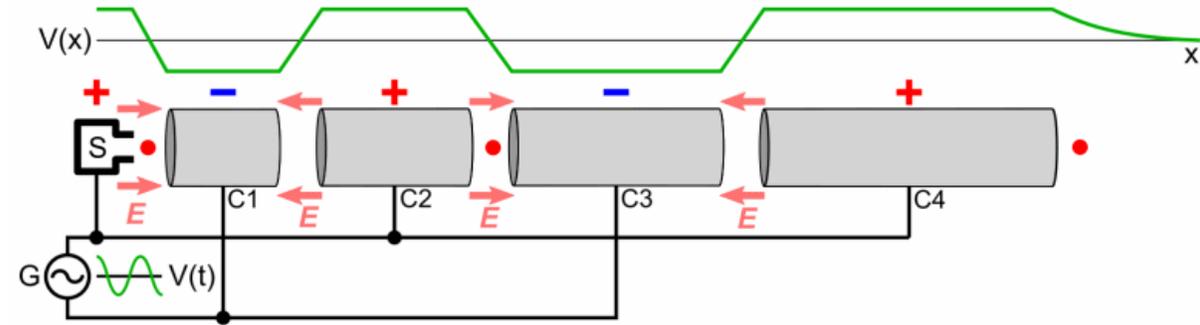
- The last section of the acceleration brings muon from 40 MeV to the final energy of 212 MeV (300MeV/c)
- This is the section where the largest improvement in the final energy can be reached.



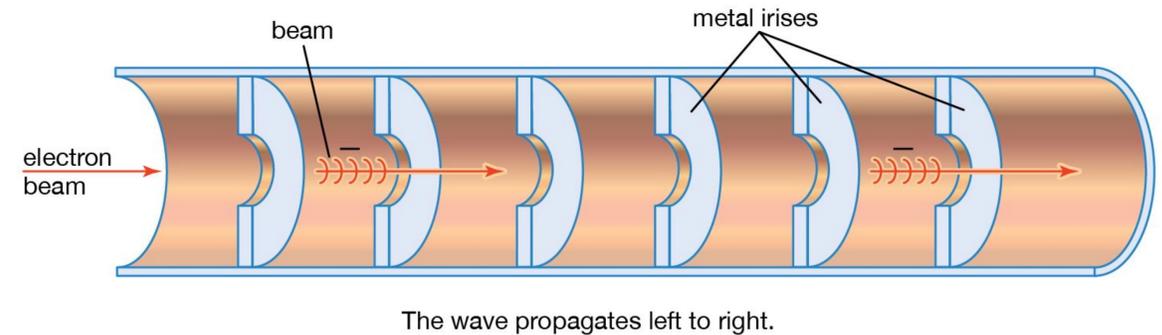
# DLS design

- DLS is a type of Linac accelerator.
- **DLS** stands for: **D**isk-**L**oaded traveling-wave **S**tructure;
- Cylindrical waveguide used in RF acceleration made of periodic metal disks mounted along the waveguide interior;
- Disk geometry shapes the electromagnetic fields and controls phase velocity;

## Linac concept



## DLS concept

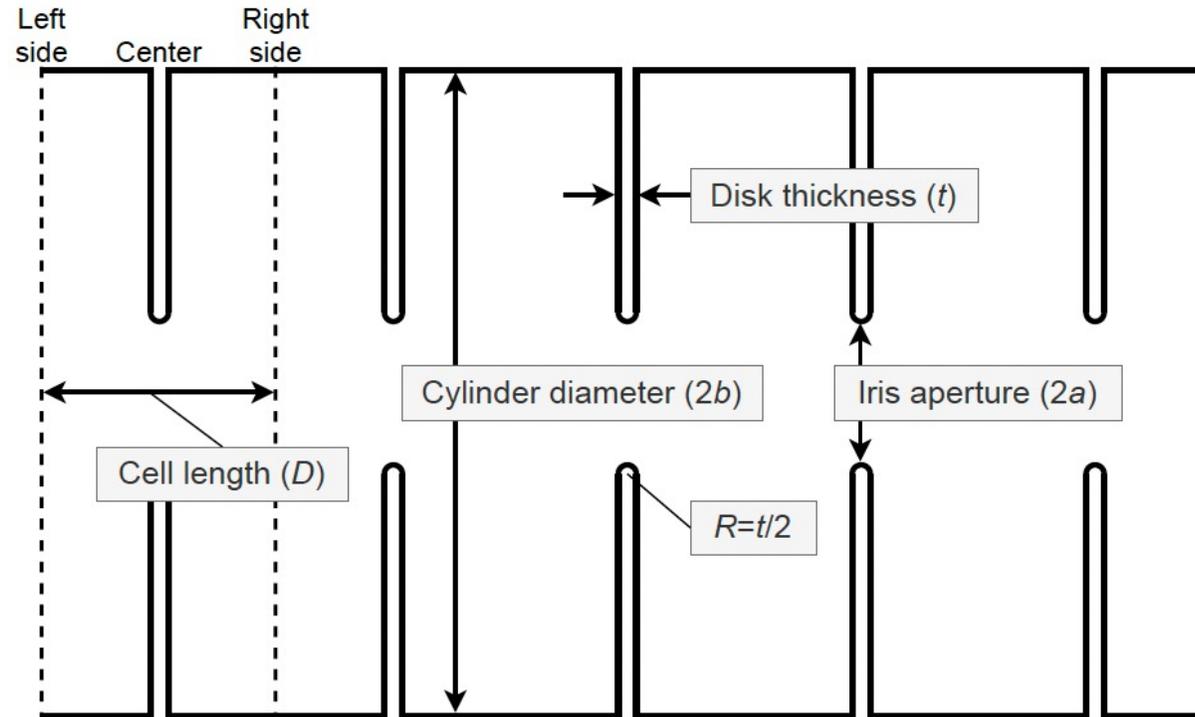


- The operating frequency should be selected as a multiple of **324 MHz** in the muon linac, for **S-band** is **2592 MHz**.



# DLS design

- The main geometrical parameters for a DLS design are:

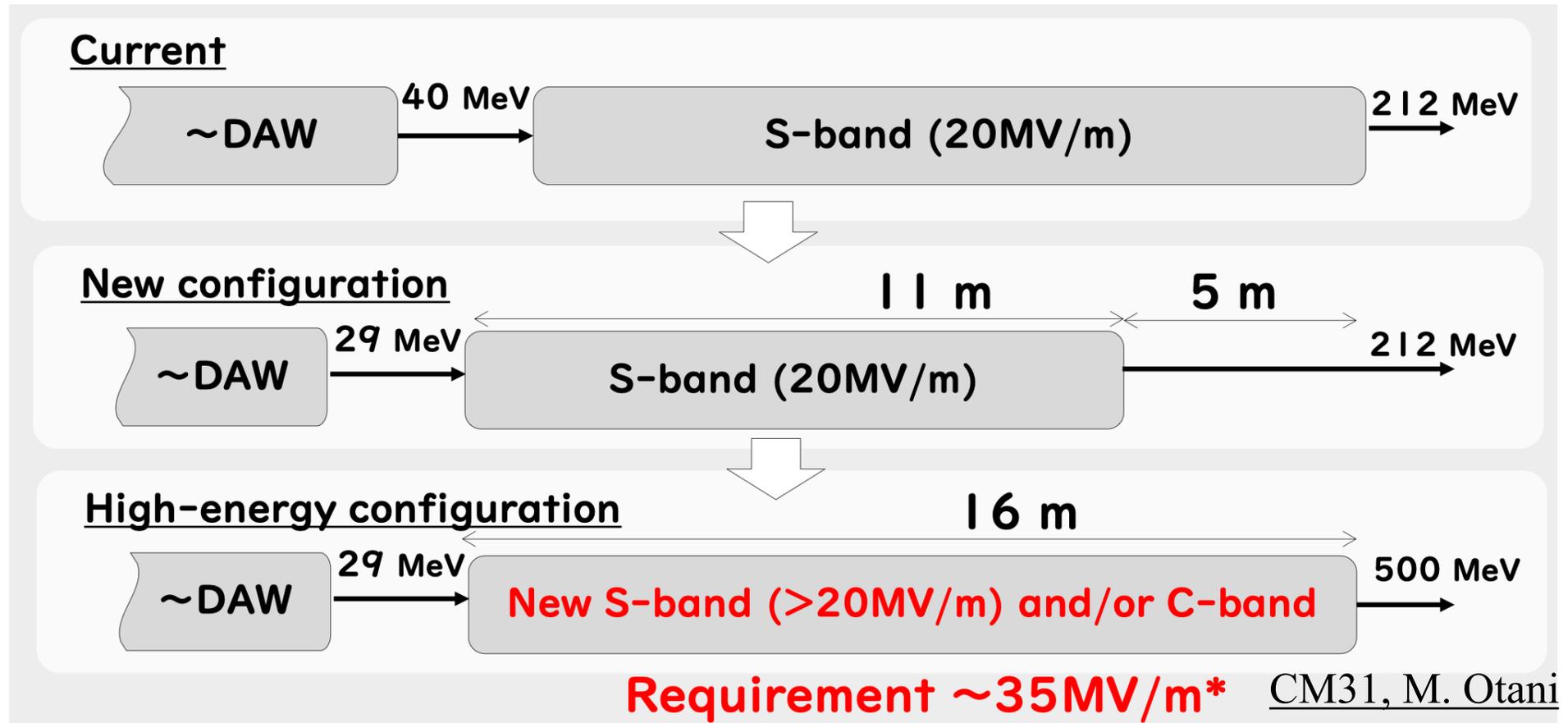


- The gain in energy per cell is  $\propto E_0 \cdot D$  where  $E_0$  is the electric field gradient.



# New design simulation

- As shown at the CM31 the current design has changed:



- From an email exchange with experts, looks like that C-band (**double frequency**) option is more expensive and less investigated than higher S-band option



# New Design

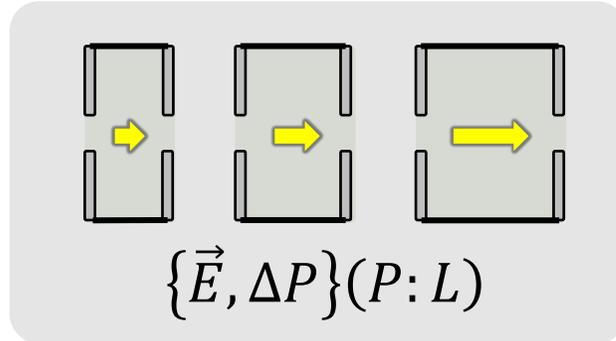
- The final energy from the **DAW** is 29 MeV w.r.t. initial 41 MeV.
- We want to break up the design of the DLS in two parts, a first section which include 2 DLS tanks with the **S-band** cavity type, with 2 different gradient:
  - **20 MeV/m** (current design)
  - **35 MeV/m** (higher gradient design) -> feasible discussed with Ego-san.
- Then design the following tanks (~16m available) both considering S-band higher gradient **or** C-band cavity types:
  - We need to demonstrate the coupling between S-BAND and C-BAND.



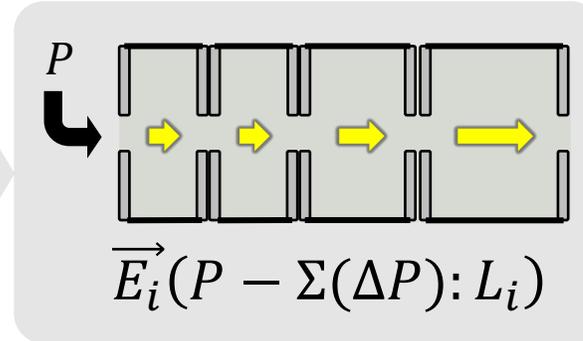
# Work flow

- The overall flowchart is:

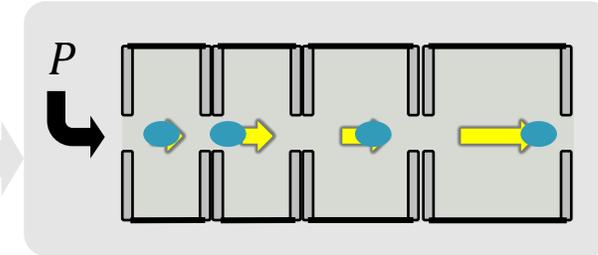
## 1. RF design of a cell



## 2. Design accelerator



## 3. Beam simulation



## 4. Check beam quality

## 5. Design including beam matching

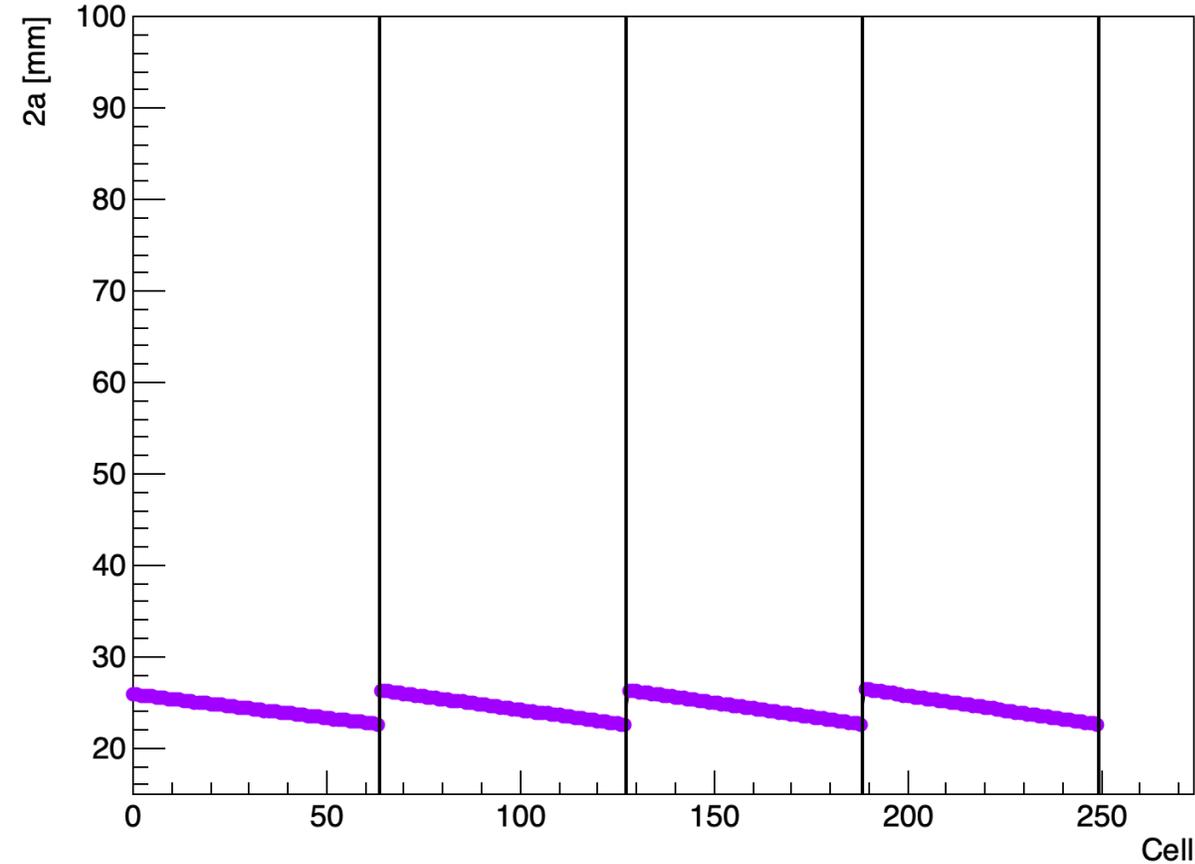
- We need to re-design the entire DLS to include the **new initial energy** and **higher gradient** accelerating section **S-band 35 MeV/m** and understand the coupling with **C-band** section.



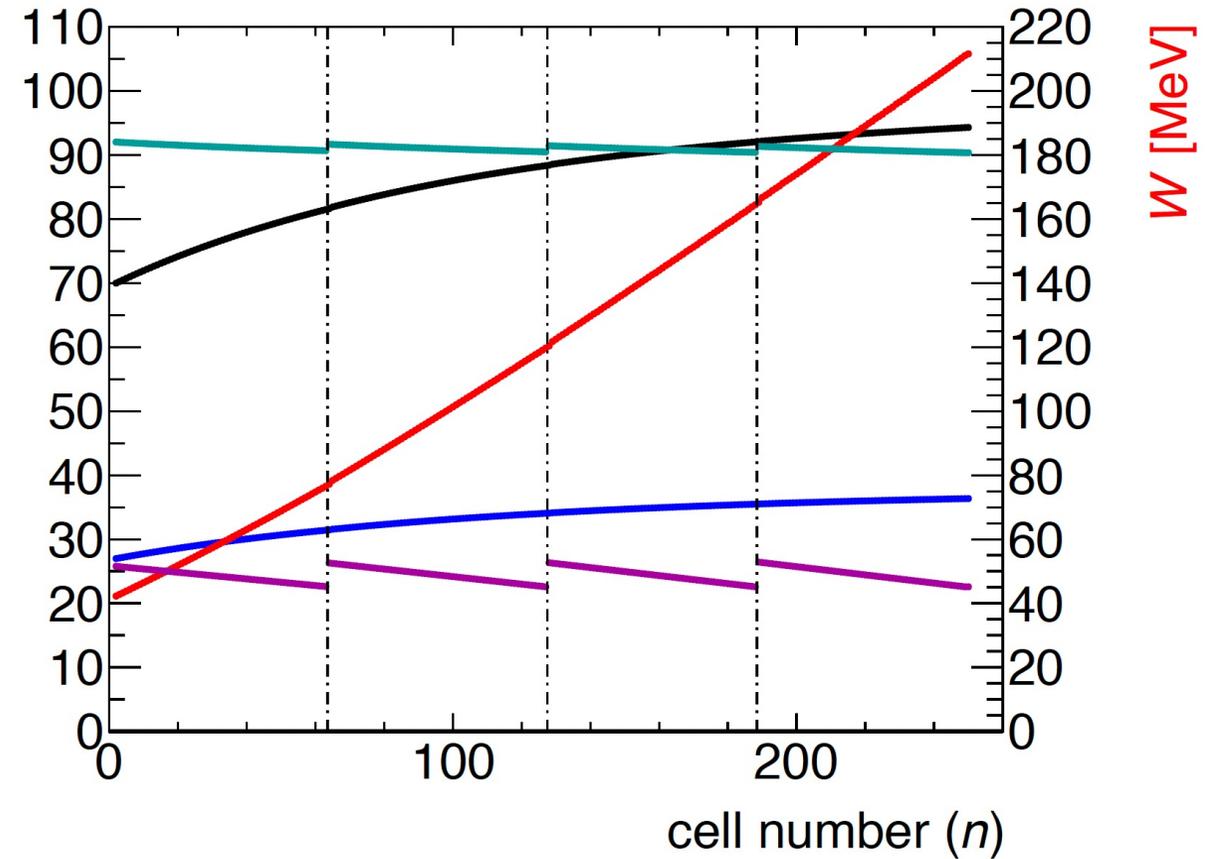
# First look at the simulation – DLS design

- From the injected RF at **2592 MHz** the initial design of the DLS is:

Iris aperture (2a) vs cell



$\beta$  [%],  $D$  [mm],  $2a$  [mm],  $2b$  [mm]



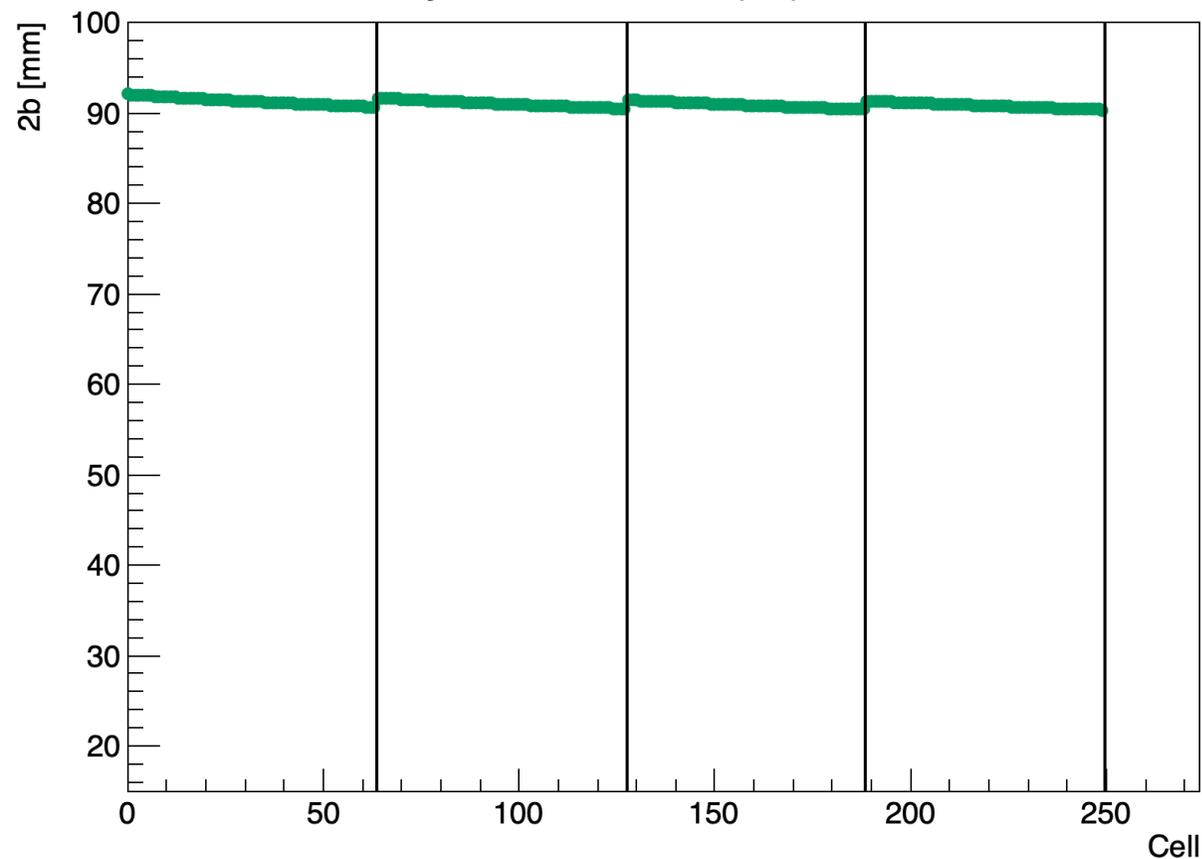
[K. Sumi, Ph.D. thesis, Nagoya University, 2025](#)



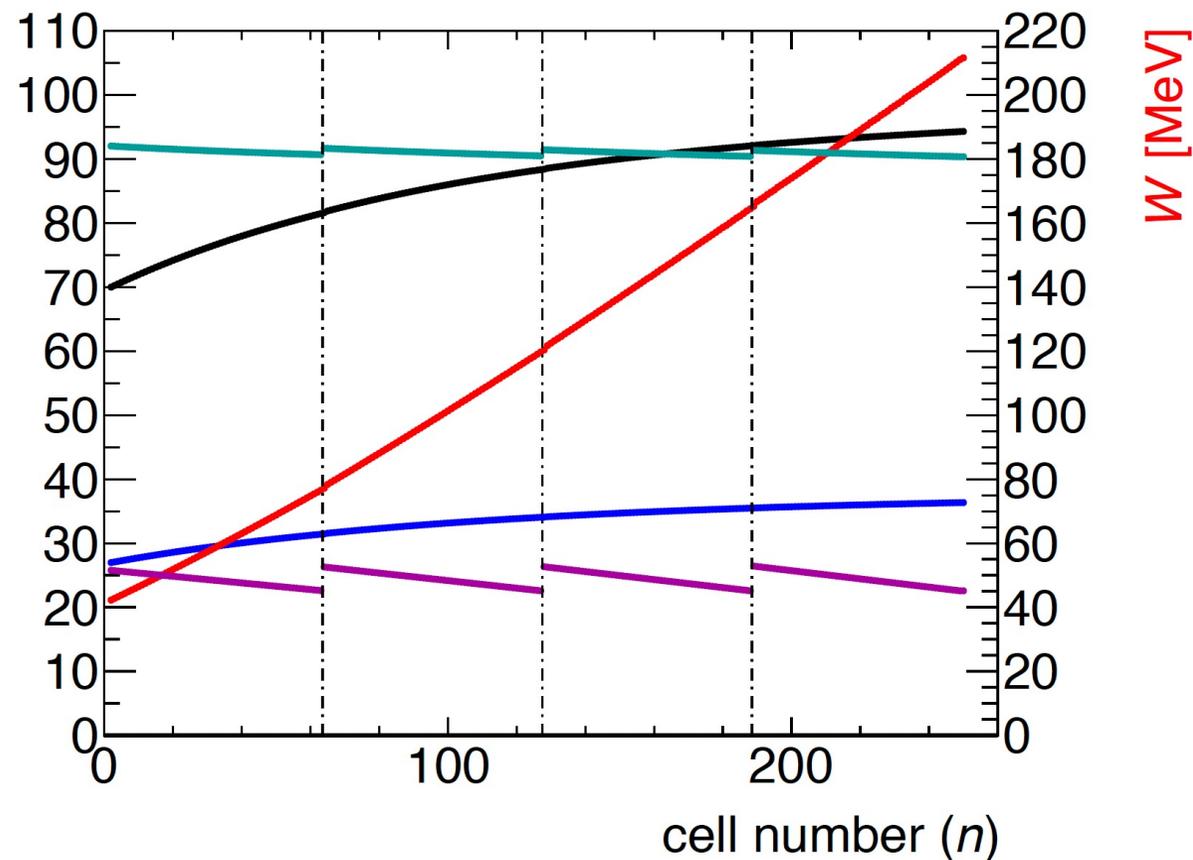
# First look at the simulation – DLS design

- From the injected RF at **2592 MHz** the initial design of the DLS is:

Cylinder diameter (2b) vs cell



$\beta$  [%],  $D$  [mm],  $2a$  [mm],  $2b$  [mm]

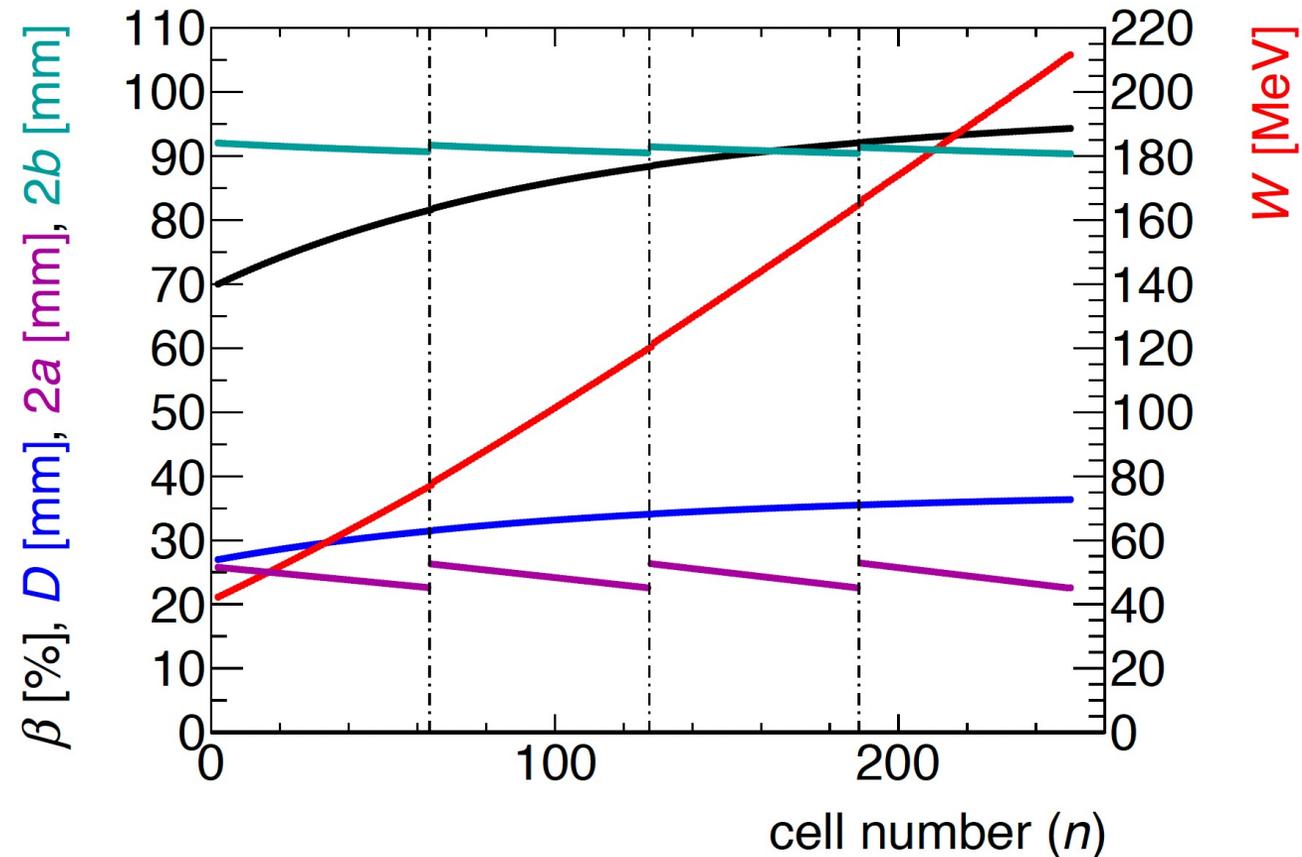
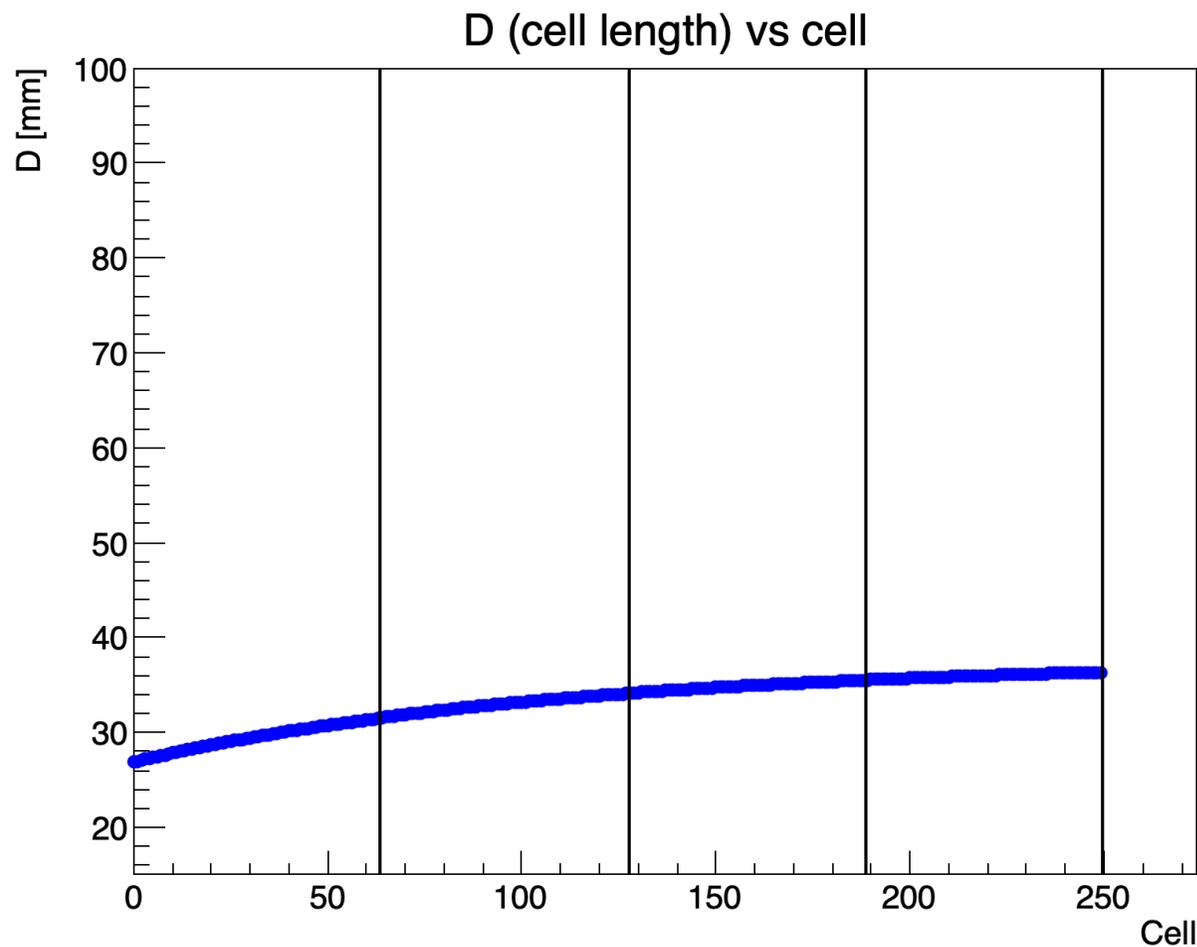


[K. Sumi, Ph.D. thesis, Nagoya University, 2025](#)



# First look at the simulation – DLS design

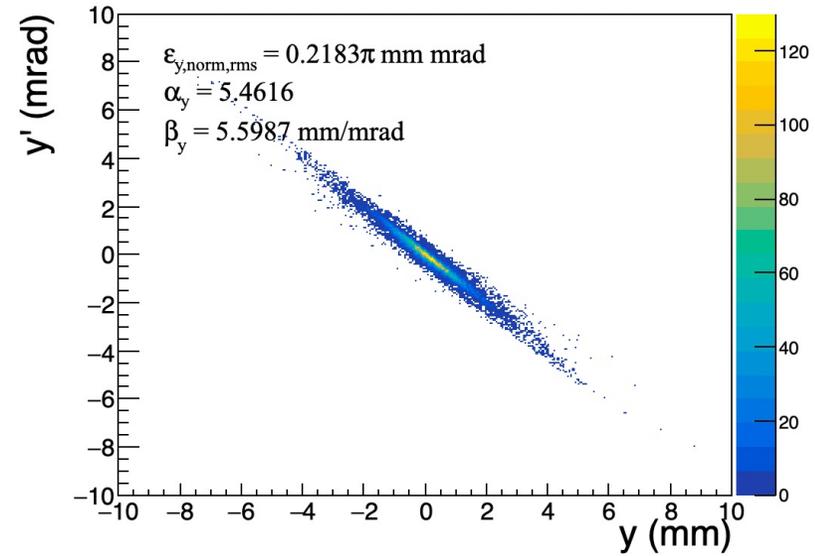
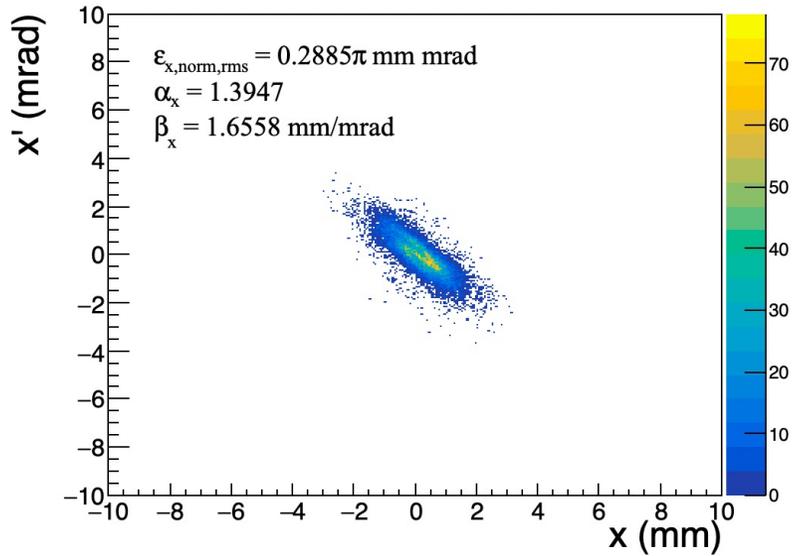
- From the injected RF at **2592 MHz** the initial design of the DLS is:



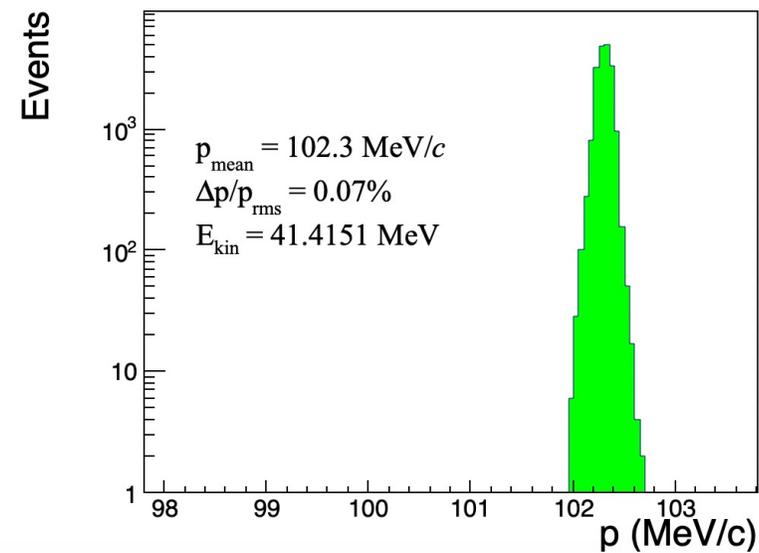
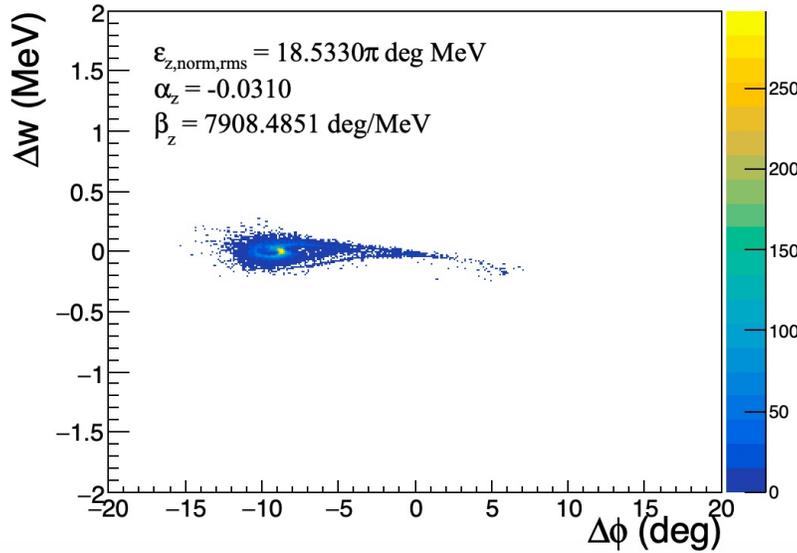
[K. Sumi, Ph.D. thesis, Nagoya University, 2025](#)



# Current design simulation



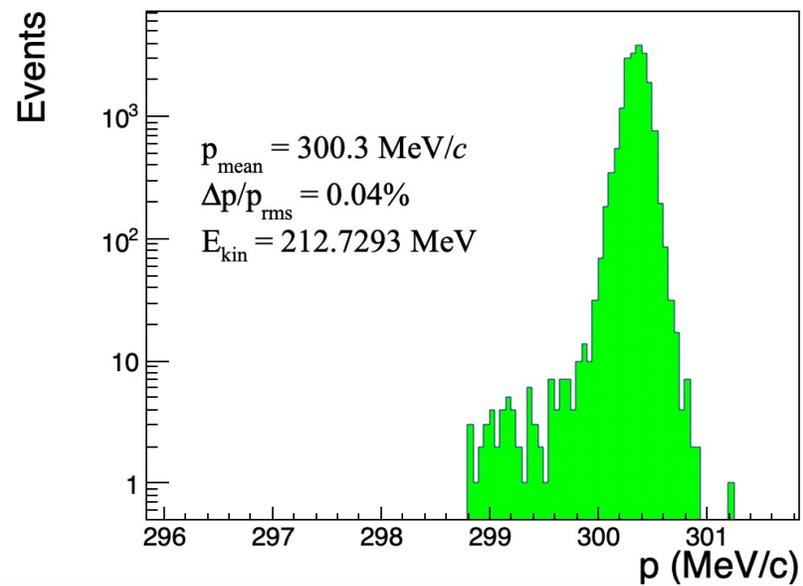
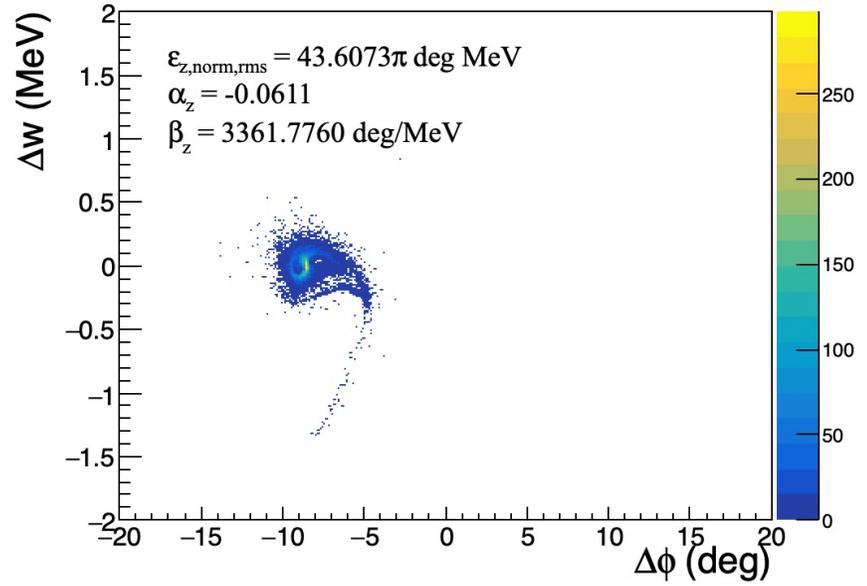
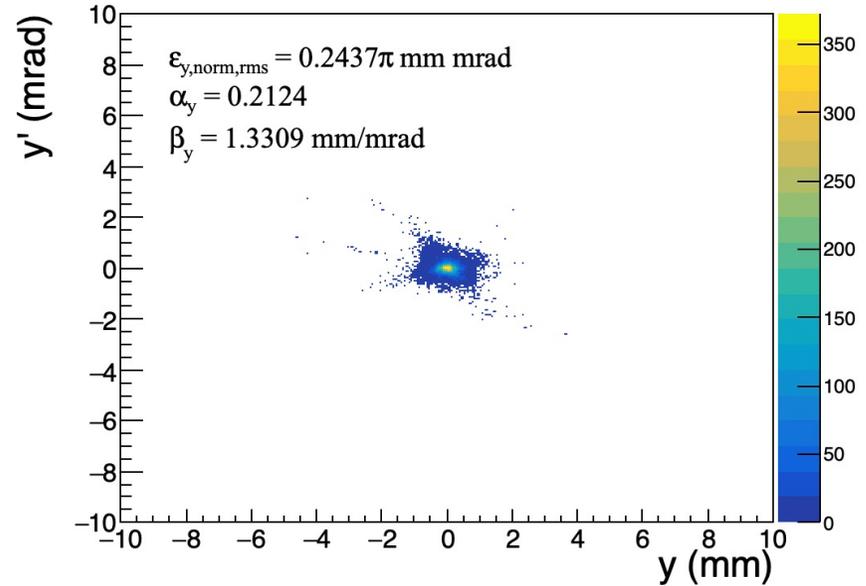
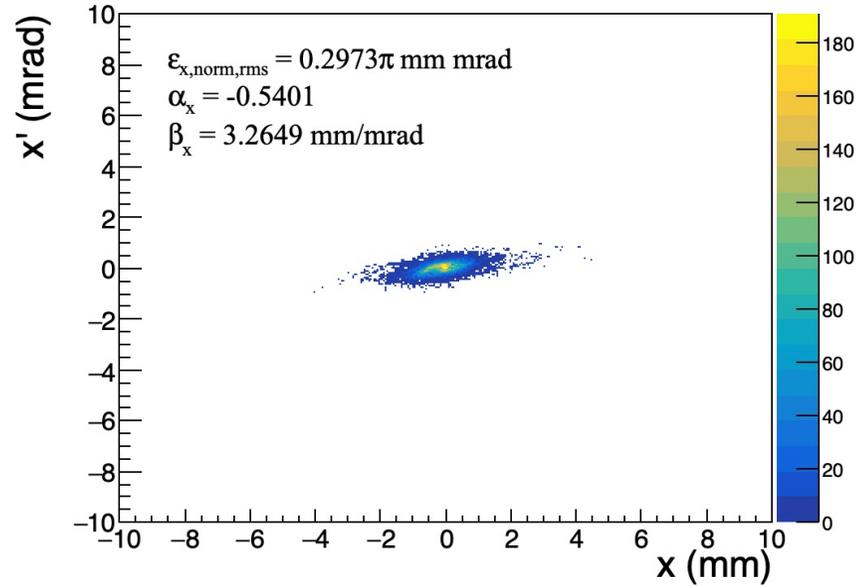
At DAW exit  
41.4 MeV





# Current design simulation

At DLS4 exit  
212.7 MeV

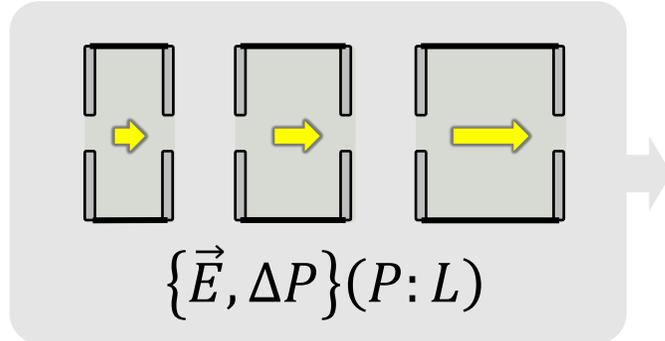




# New RF design

- As first step we redesign the cell RF for the new initial and final energy:

## 1. RF design of a cell



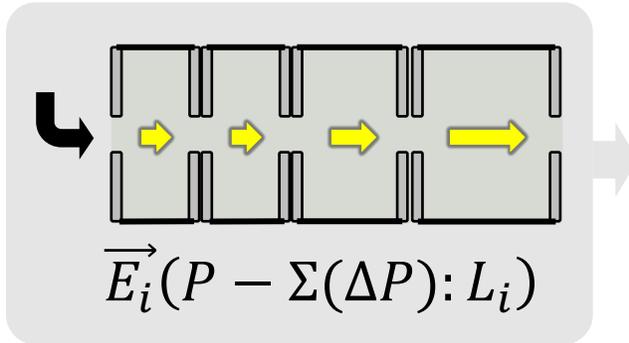
- We moved from:
  - Initial 41 MeV -> 29 MeV
  - Final 212 MeV -> 500 MeV
- This will be the input to the next step.



# Accelerator design

- We used the new input RF and the new parameters to design the first part of the DLS

## 2. Design accelerator



- In the following the accelerator design for the two gradients:
  - 20 MeV/m;
  - 35 MeV/m.

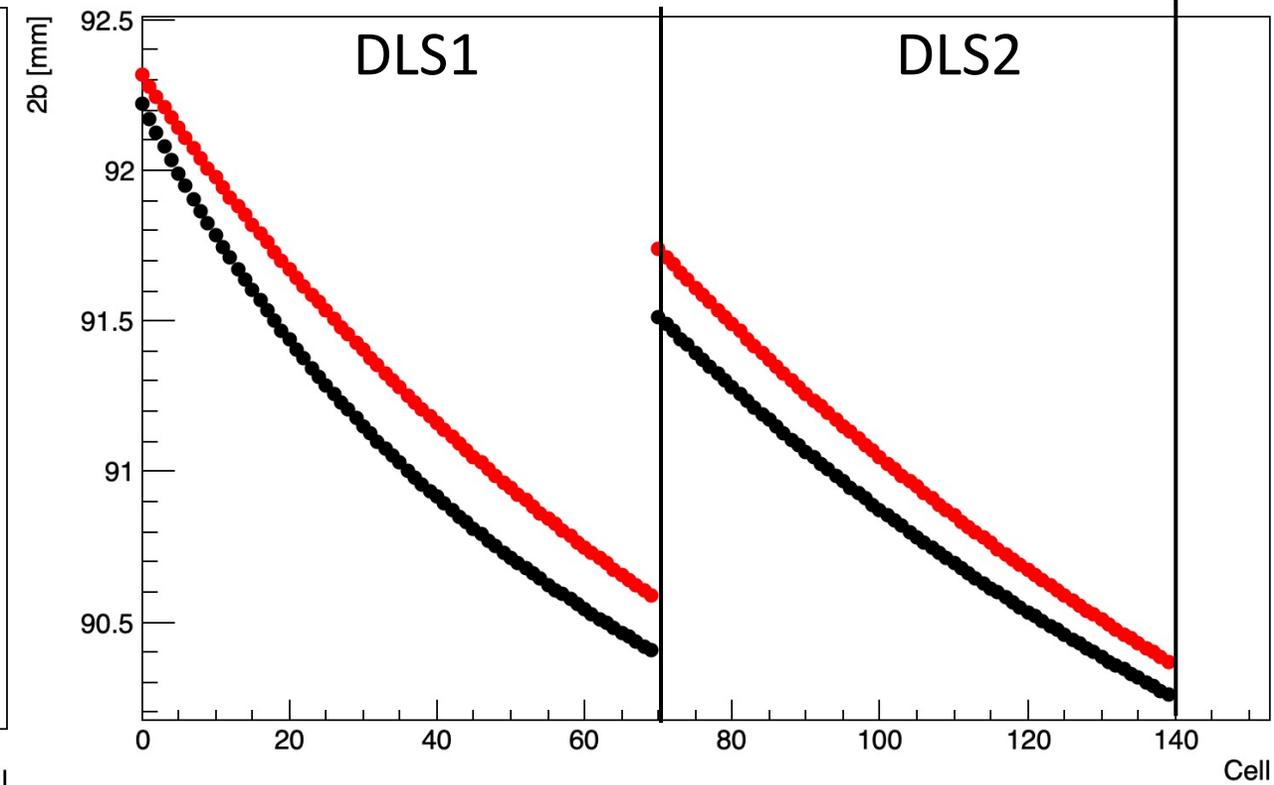
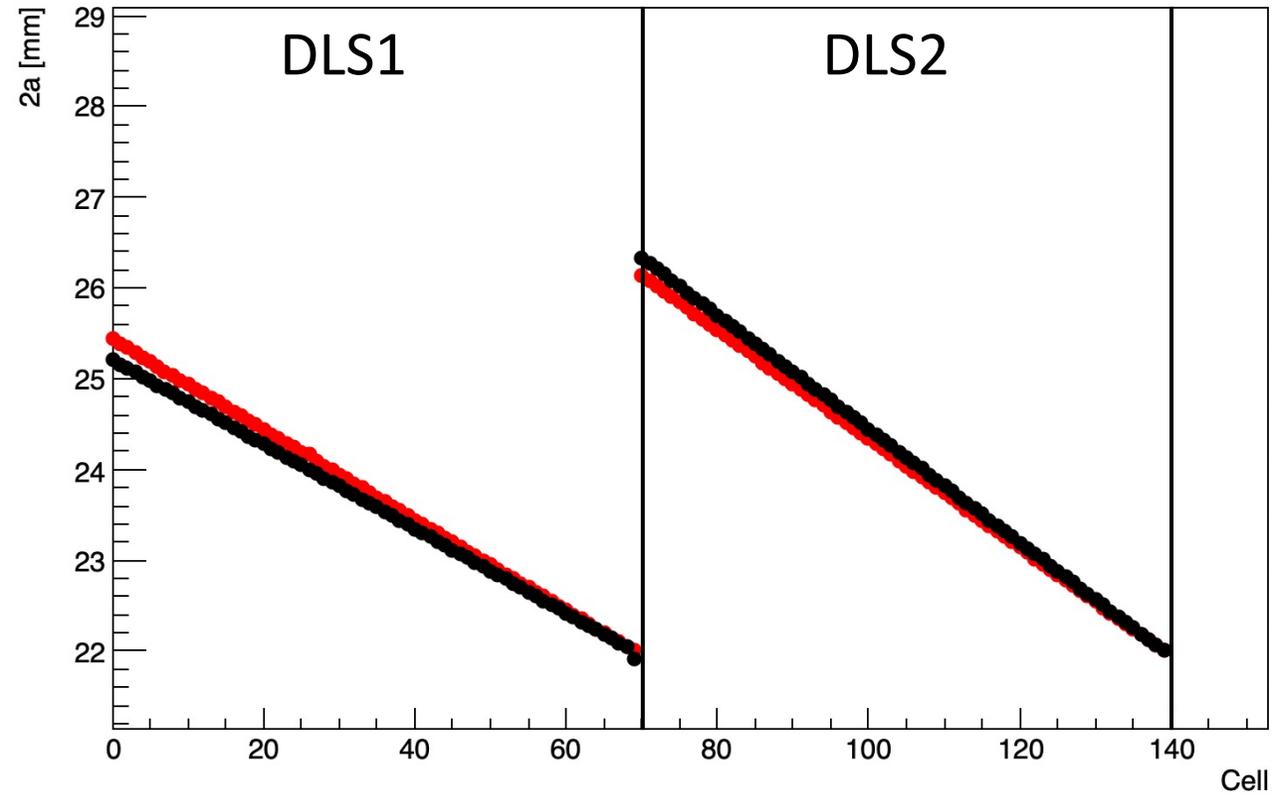


# Accelerator design

- 20 MV/m
- 35 MV/m

2a vs cell

2b vs cell



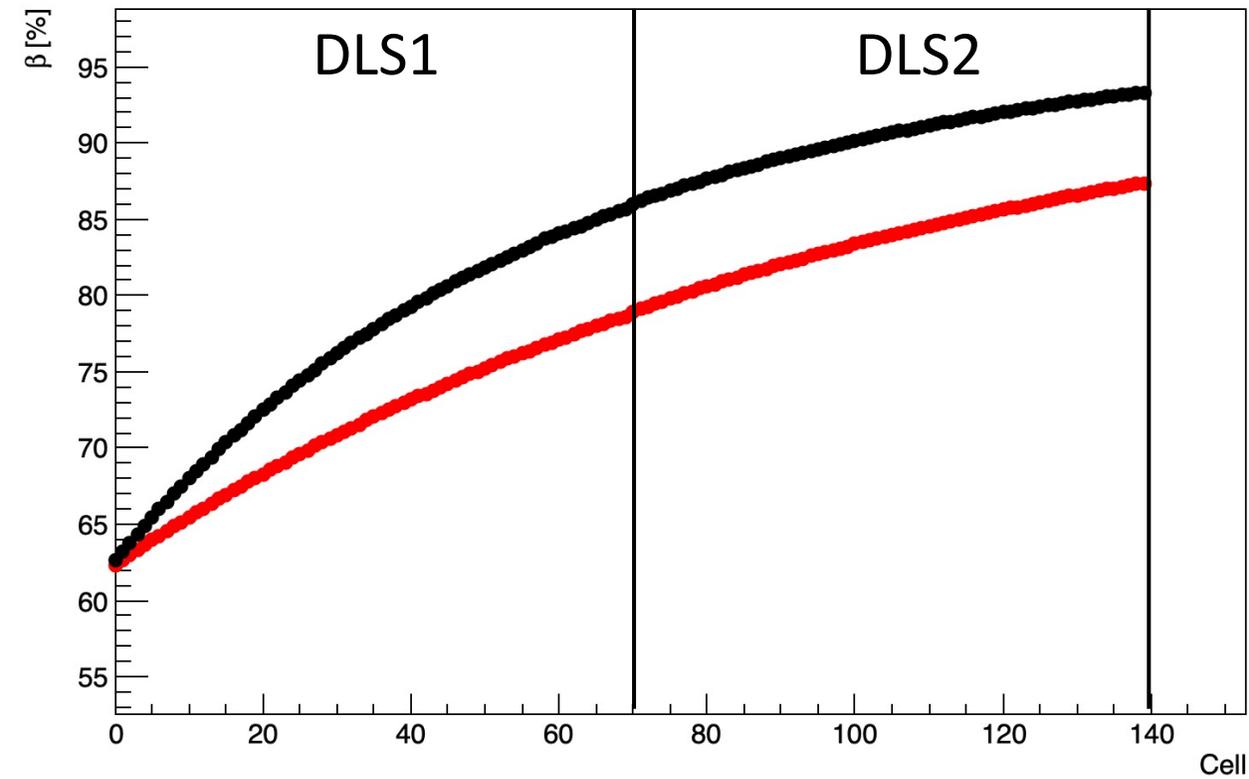
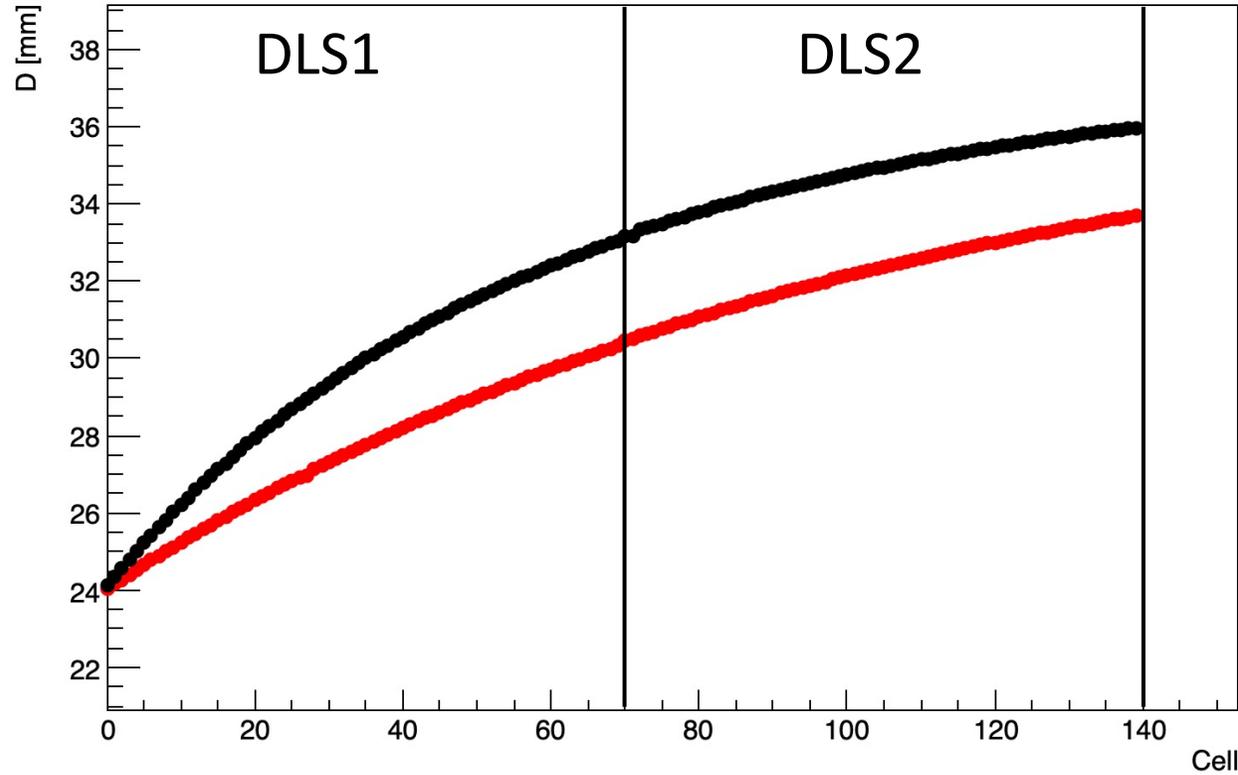


# Accelerator design

- 20 MV/m
- 35 MV/m

D vs cell

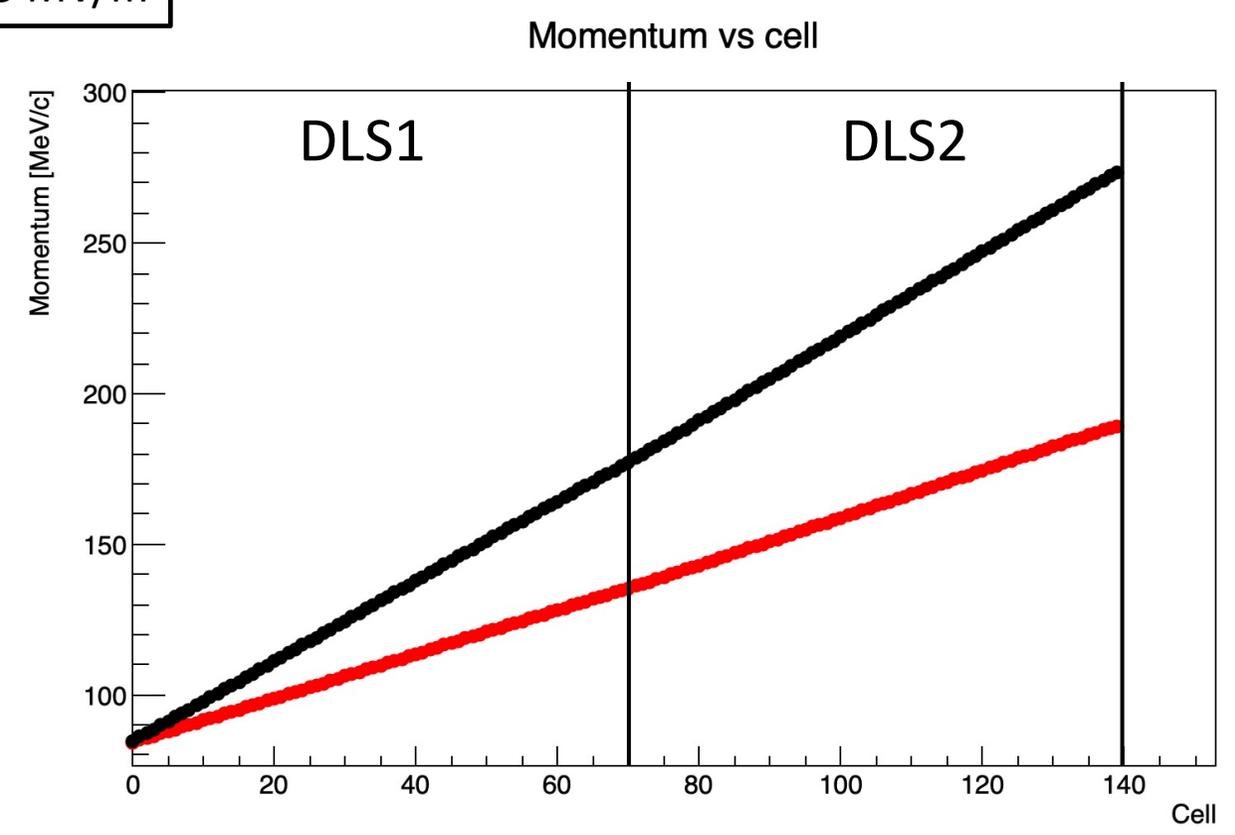
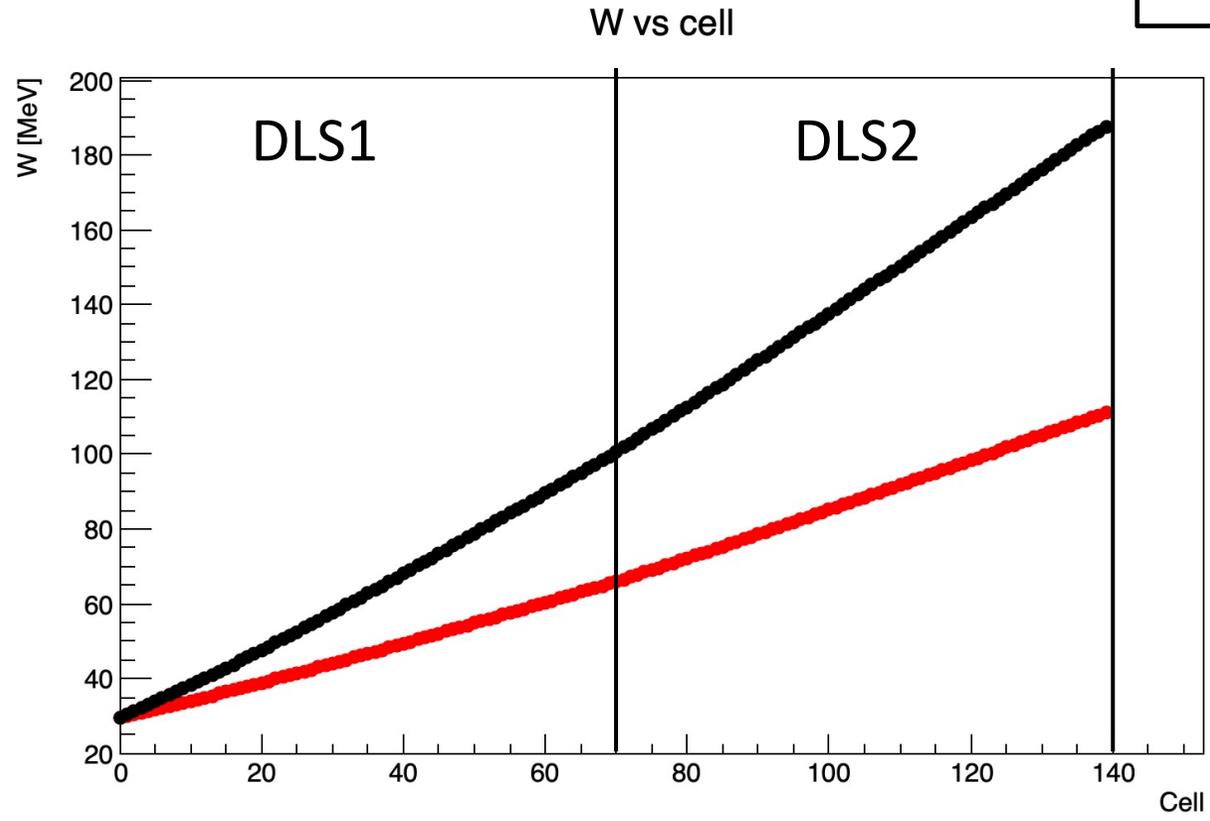
$\beta$  vs cell





# Accelerator design

- 20 MV/m
- 35 MV/m

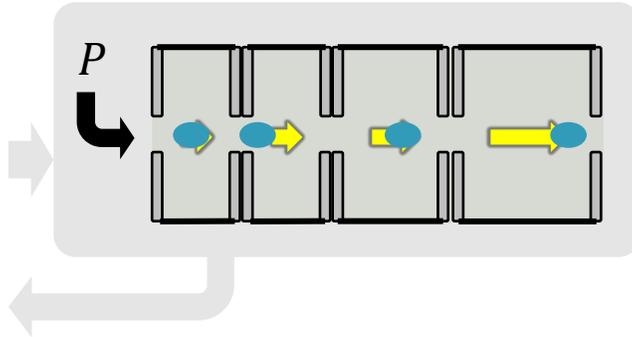




# EM calculation and beam simulation

- With the input from the previous step we ran SUPER-FISH to compute the EM field on the new cavity design.

## 3. Beam simulation

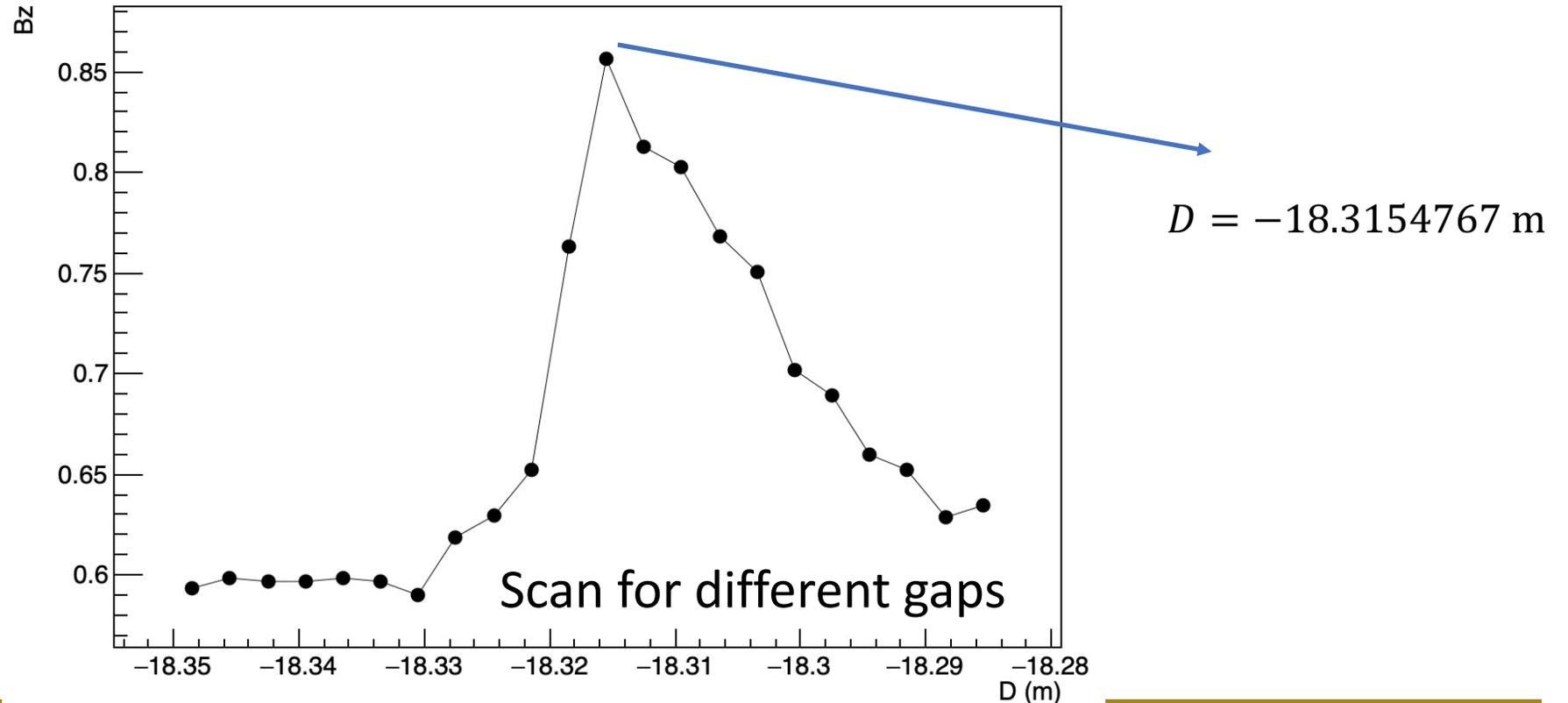


- This output will be used for track the particle and define the beam quality, covering the step 3 and 4.



# Design optimization for Particle propagation

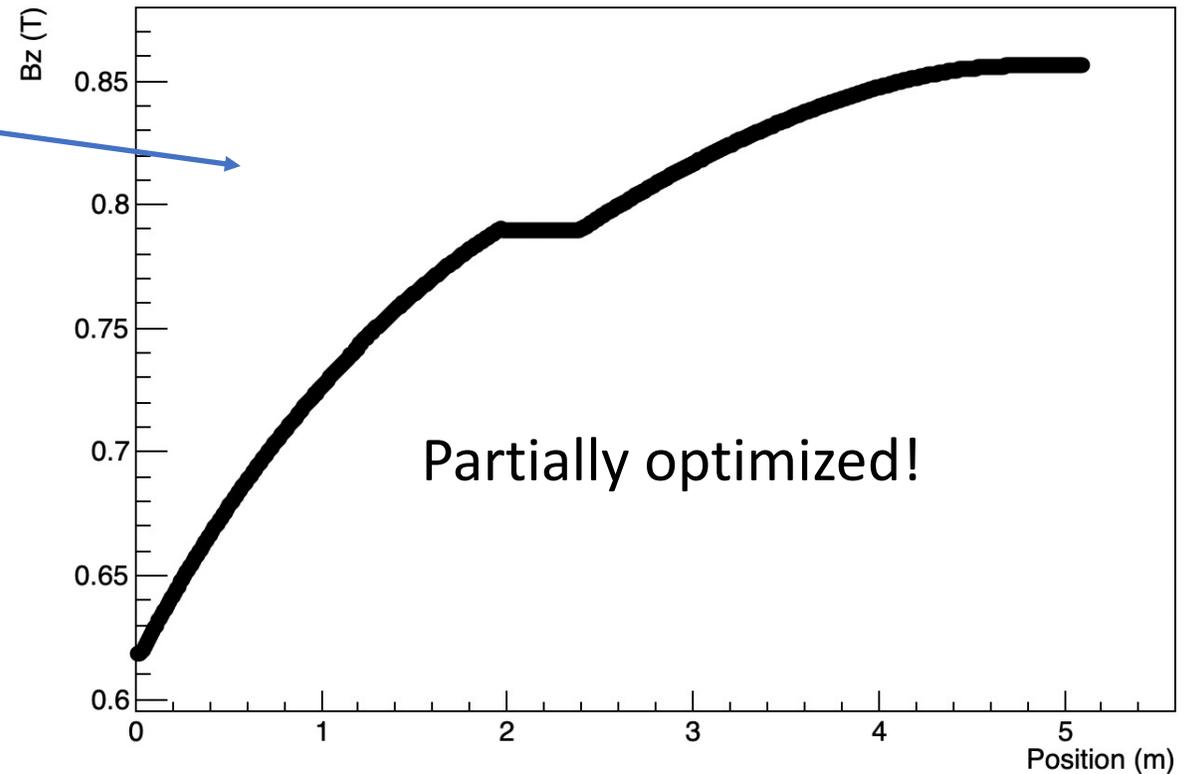
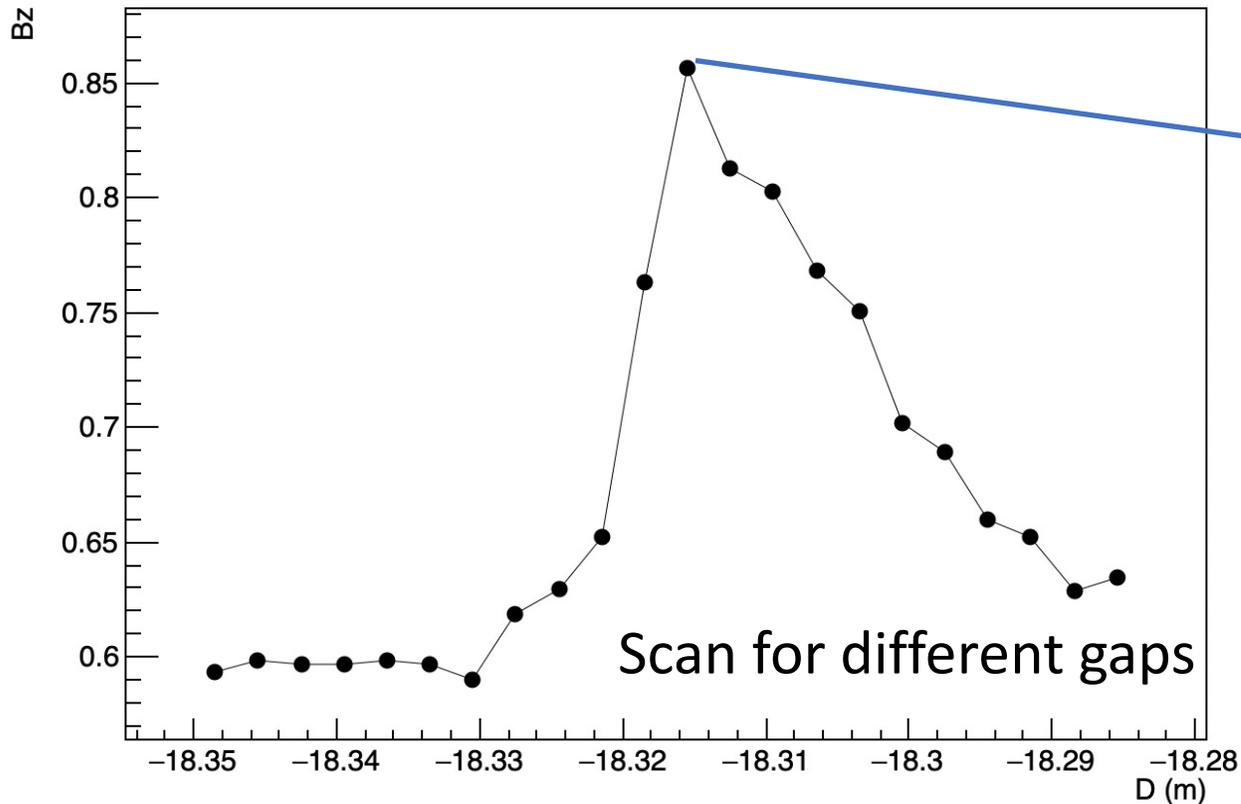
- In order to get the particle accelerated correctly we have to optimize the DLS design by propagating the particles through the DLS with computed EM fields.
- One parameter to tune is the gap between the DAW and the DLS:





# Design optimization for Particle propagation

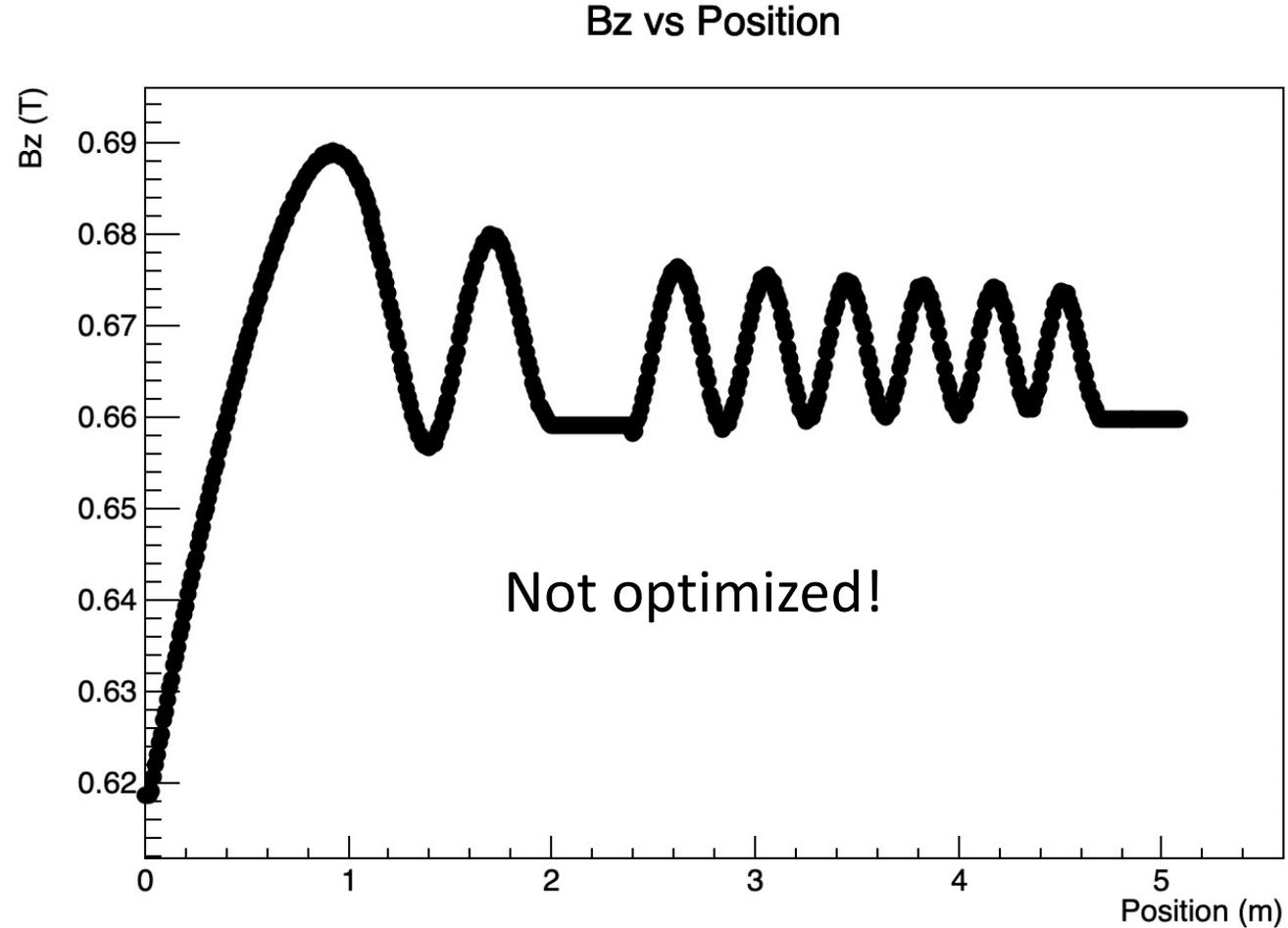
- In order to get the particle accelerated correctly we have to optimize the DLS design by propagating the particles through the DLS with computed EM fields.
- One parameter to tune is the gap between the DAW and the DLS:  
Bz vs Position





# Design optimization for Particle propagation

- When not optimal the  $\beta$  of the particle as function of the position inside the DLS looks like that:





# Conclusion

- During these few months of work on the DLS design we familiarized with the code and start producing the old design.
- We start producing the simulation for the higher energy case;
- We figured out 3 main solution which can bring to the final energy:
  - **2 S-band** DLS tanks (20 MeV/m) + **2 C-band** DLS tanks (40 MeV/m);
  - **2 S-band** DLS tanks (35 MeV/m) + **2 C-band** DLS tanks (40 MeV/m);
  - **4 S-band** DLS tanks (35 MeV/m).
- Check the beam quality;
- Check the longitudinal acceptance -> fundamental for the C-band coupling;
- Determine the solution that best fits our requirements.

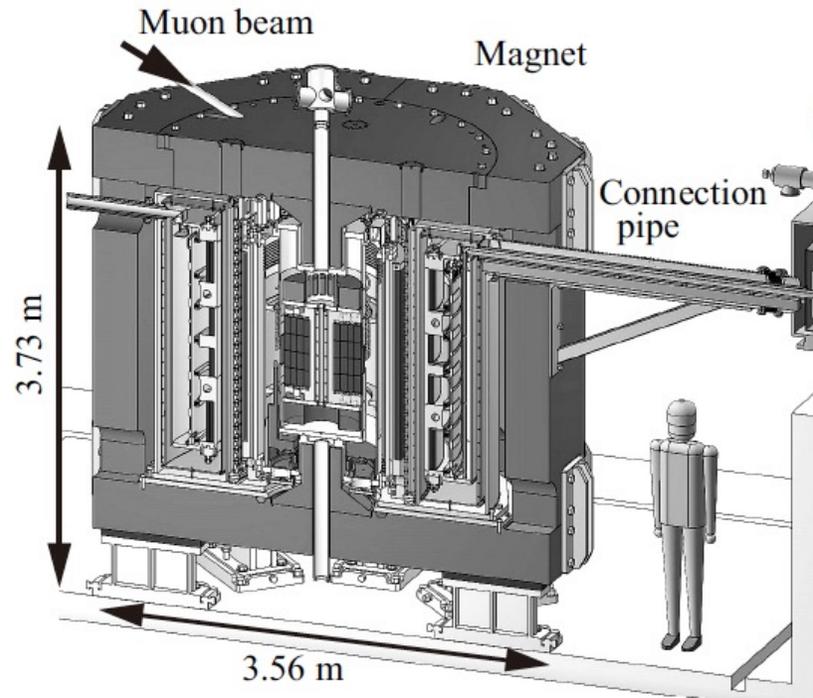


# BACK UP

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# Measurement principle – J-PARC



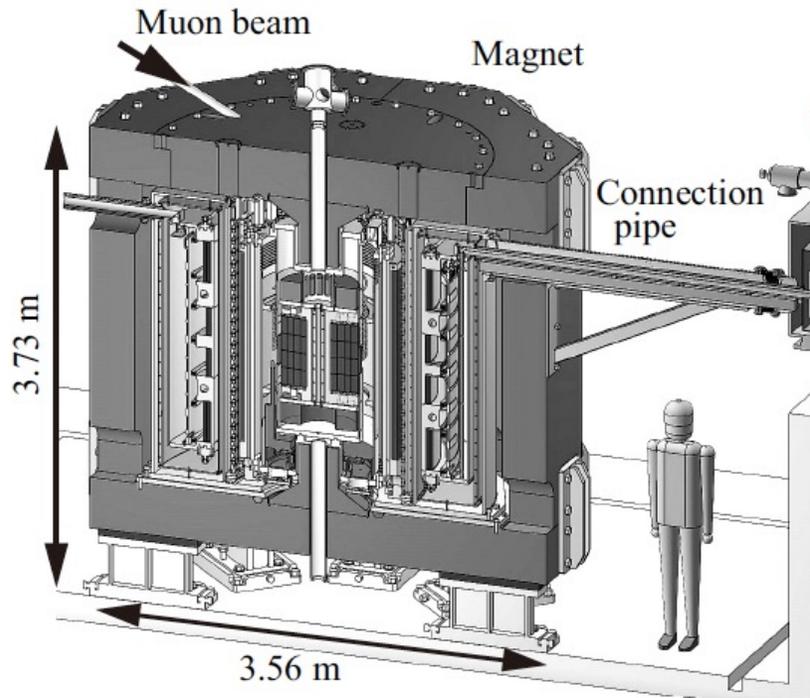
$$\vec{\omega}_a = \frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) (\vec{\beta} \times \vec{E}) \right]$$

- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$



# Measurement principle – J-PARC



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

- 300 MeV/c momentum
- 0.66 m ring diameter ( $B = 3 \text{ T}$ )
- No electric field ( $E=0$ )

Both the experiment can extract  $a_\mu$  very precisely measuring  $\vec{B}$  and  $\vec{\omega}_a$

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$