International Linear Accelerator Conference 2022
28th August –2nd September 2022

MOPORI22 (SUPCRI07)

High-Power Test of an APF IH-DTL Prototype for the Muon Linac

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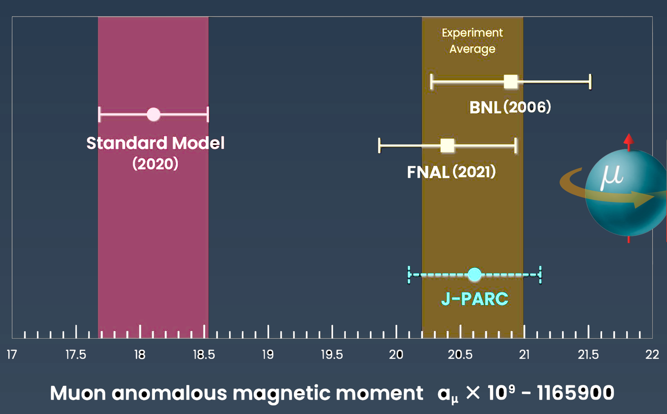
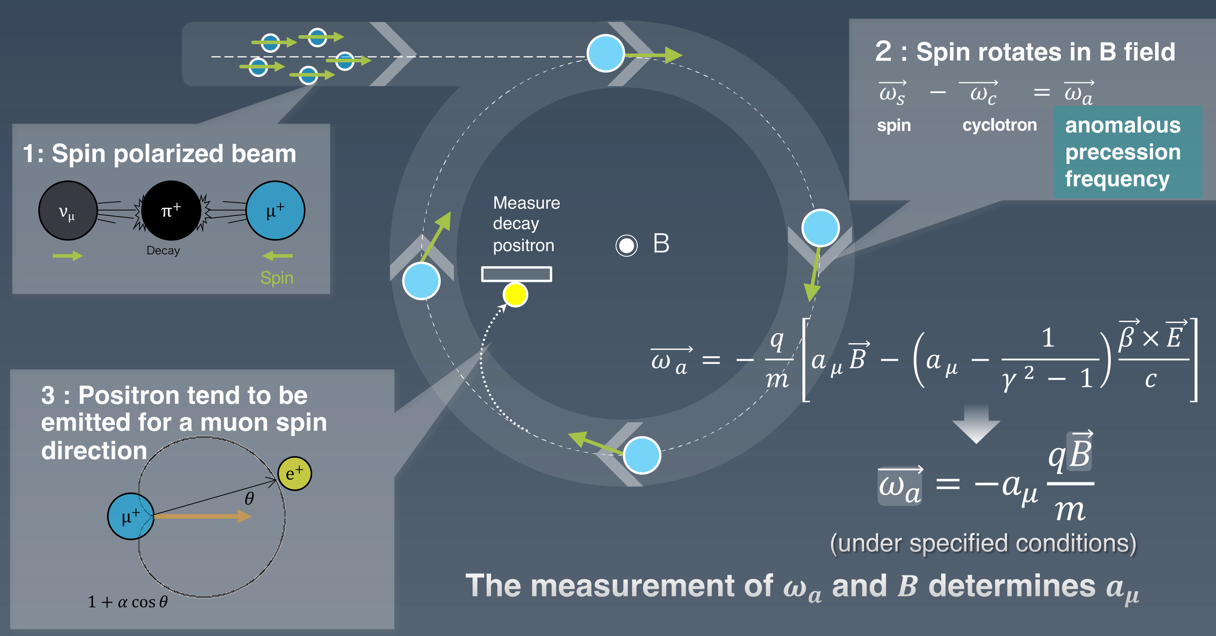
Background

Muon anomalous magnetic moment (g-2)

The Fermi National Accelerator Laboratory (FNAL) measured muon g-2 with an accuracy of 0.46 ppm, which is consistent with the previous experiment BNL-E821, and these results showed a discrepancy of 4.2 standard deviations from the SM prediction.



Experimental method



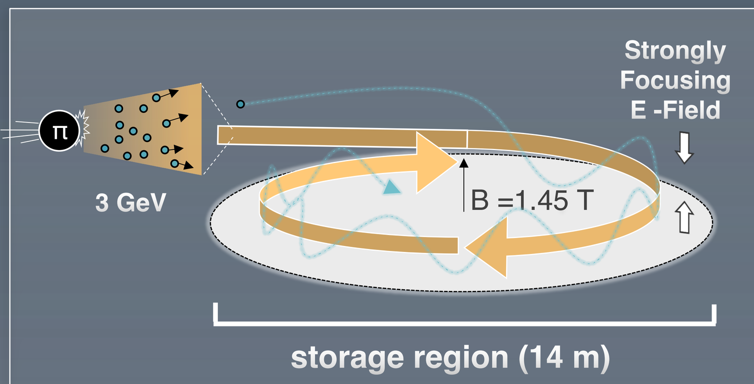
$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

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

(under specified conditions)

The measurement of ω_a and B determines a_μ

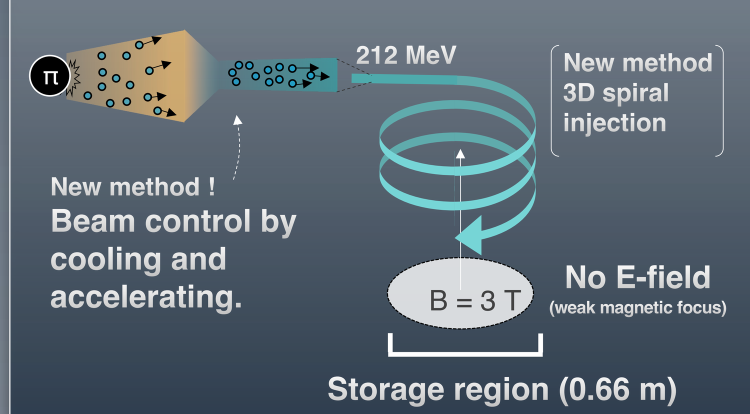
BNL / FNAL method



$$a_\mu - \frac{1}{\gamma^2-1} = 0$$

- Large emittance
- Strong focusing by E-field

J-PARC method

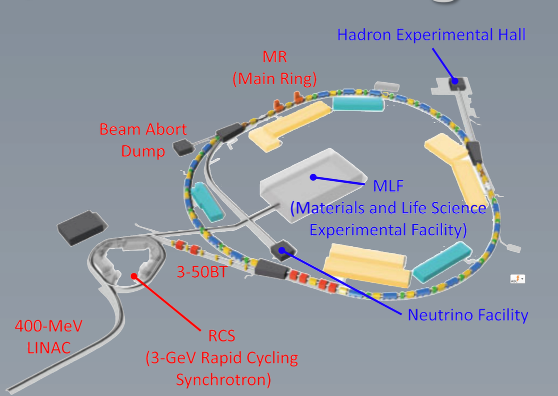


$\vec{E} = 0$ at any γ

- Reduction of beam-derived systematic error (ω_a)
- a_μ and EDM can be measured simultaneously.

Low-emittance muon beam is needed.

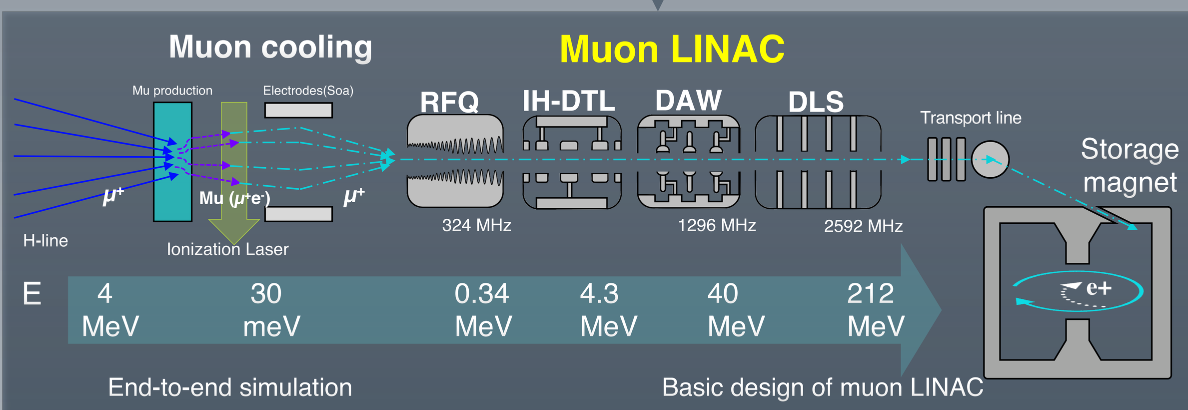
J-PARC muon g-2/EDM experiment (E34)



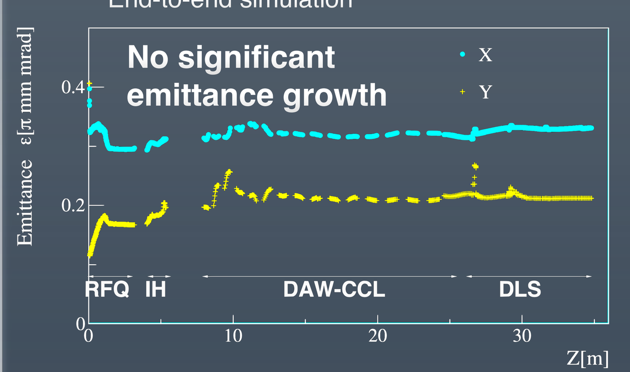
Japan Proton Accelerator Research complex

MLF (Materials and Life Science Experimental Facility)
- 3 GeV proton beam
- μ target and n target
- Beam power 1MW (First half of 2022 : 830 kW)
- Double pulses, 25 Hz

New beamline will be constructed at MLF H-line.



End-to-end simulation



Basic design of muon LINAC

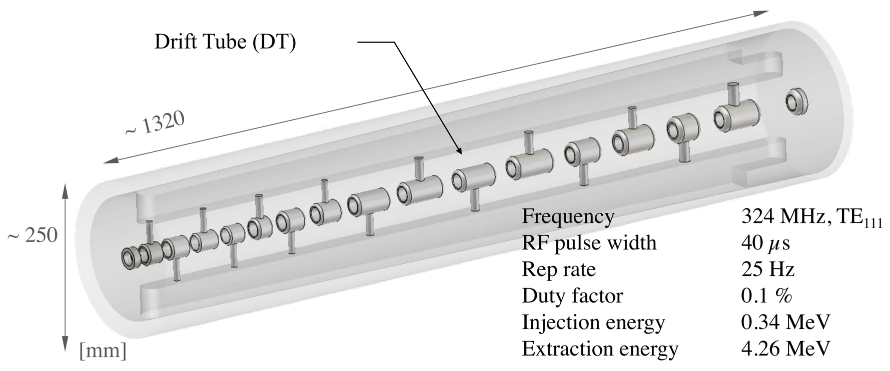
Frequency	324MHz, 1296MHz, 2592 MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

Need to develop a new muon linac and demonstrate acceleration.

2016	: Basic design & cavity design
2017	: World's first muon acceleration with RFQ. [R. Kitamura, LINAC2018]
2018 ~ 2019	: Bunch measurement of accelerated muon
2020 ~	**: Development of IH-DTL**

1. IH-DTL (Inter-digital H-mode DTL)

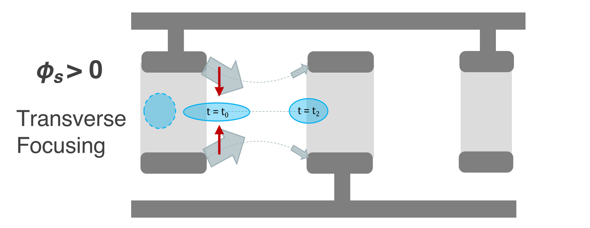
High efficiency and short-range acceleration are necessary to suppress decay loss during acceleration in the low-β region.



Alternating Phase focusing (APF) method was adopted for transverse focusing.

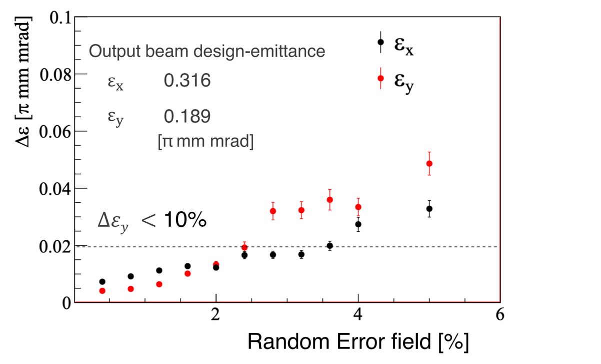
Transverse focusing is possible only RF E-field by adjusting the synchronous phase (ϕ_s) of each cell.

☺ **No focusing magnets→ Simplified DT**



The monolithic DT structure can be applied.
- DT alignment procedure is not required.
- Cost saving

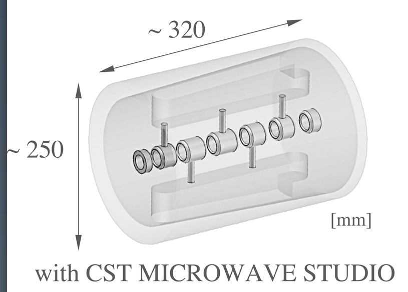
☹ **Field error affect the dynamics.**



First time that the monolithic DT structure is being applied to a 324 MHz IH-DTL for muon acceleration.
→ we developed a short-length IH-DTL ("short- IH") as a prototype.

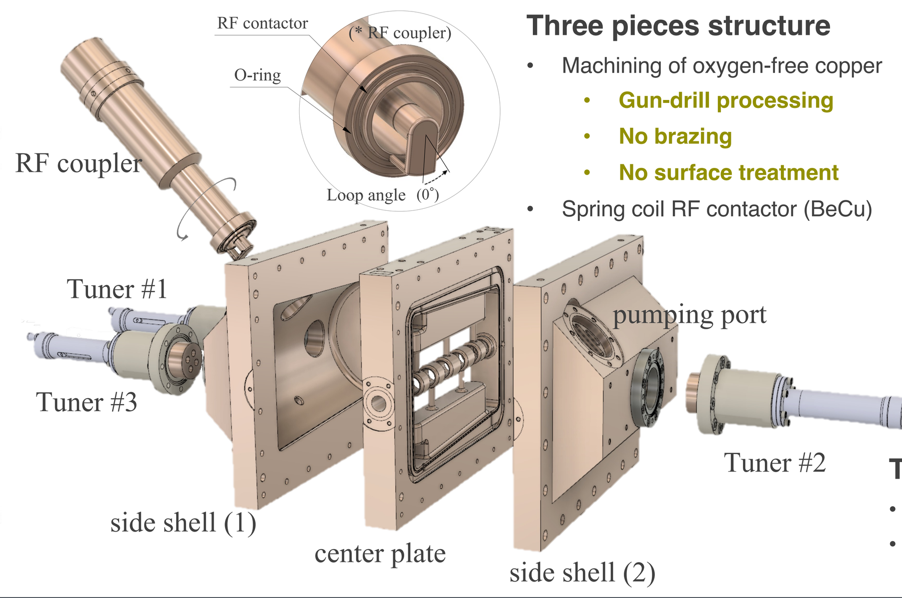
2. Short-IH design

The short-IH corresponds to the upstream one-third of the full-length IH-DTL (full-IH).



Parameters	Full-IH	Short-IH
Number of the cells	16	6
Extraction energy (MeV)	4.26	1.30
Cavity length (m)	1.45	0.45
Averaged accelerating field (MV/m)	3.6	3.0
Maximum surface field (MV/m)	35.4 (2.0 E_k[a])	34.7 (1.9 E_k[a])
Nominal peak power (kW)	310[b]	65[b]
Horizontal emittance growth (%)	7.5	4.5
Vertical emittance growth (%)	13.8	6.3
Transmission (%)	99.97	99.85
Transient time (ns)	25	13
Survival rate (%)	98.9	99.4
Total transmission (%)	98.9	99.3

[a] Kilpatrick limit
[b] Calculated from a simulated Q_0 value



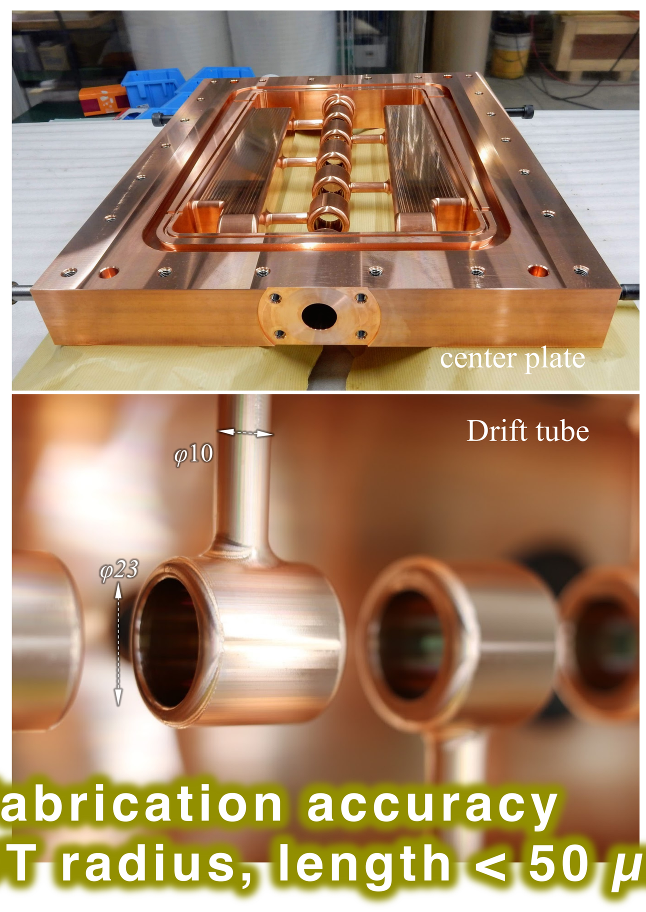
Three pieces structure
- Machining of oxygen-free copper
  - Gun-drill processing
  - No brazing
  - No surface treatment
- Spring coil RF contactor (BeCu)

No water-cooling
Although the outer cavity wall of the full-IH will be water-cooled, it is difficult to cool the monolithic DT structure directly.

RF coupler
- Coaxial loop antenna
- RF window : Alumina Ceramics
- Spring Coil RF contactor (BeCu)

Tuner ×3
- 50 mm stroke
- No RF contactor

3. Fabrication / Low-power tuning



Fabrication accuracy DT radius, length < 50 μm

Low-power tuning

1. bare cavity w/o tuners and coupler

Parameters	Meas.	Sim.
Resonant frequency (MHz)	321.36	321.88
Unloaded Q	7800	8600

2. w/ tuners and coupler
   - The frequency was roughly adjusted
   - The coupling coefficient ($\beta_{coupler}$) of the coupler was adjusted to critical coupling by rotating the loop angle (θ = 50 deg.)
3. fine-tuning
   - The frequency was tuned to 324.00 MHz. (L_{tuner}#1, #2, #3 = 45.2 ,43.3, 45.8 mm)
   - $\beta_{coupler}$ = 1.01

Parameters	Meas.	Sim.
Resonant frequency (MHz)	324.00	324.00
Unloaded Q	7100	8300

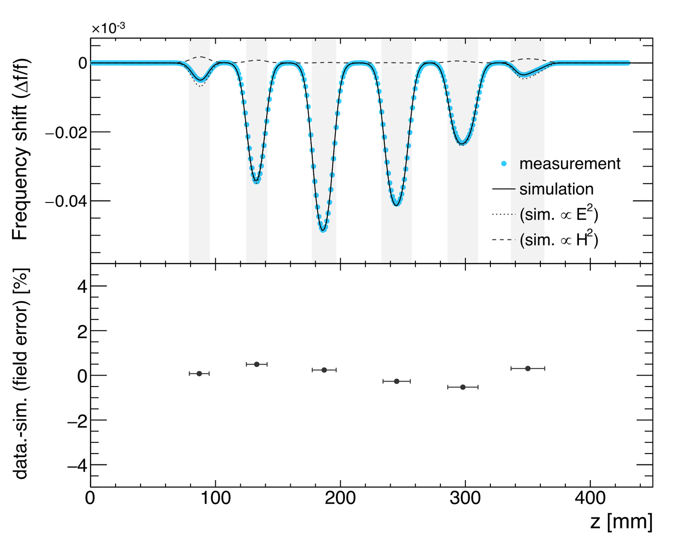
$Q_{0\,meas.} = 86\ \%\ Q_{0\,sim}$

Field measurement

- After low-power tuning, the electro-magnetic field distribution of the cavity was measured using the bead-pull method.

$$\frac{f_p - f_0}{f_0} = -\frac{\pi r^3}{U}\left[\varepsilon_0 E_0^2 - \frac{\mu_0}{2}H_0^2\right]$$

f_0 : unperturbed frequency
f_p : perturbed frequency



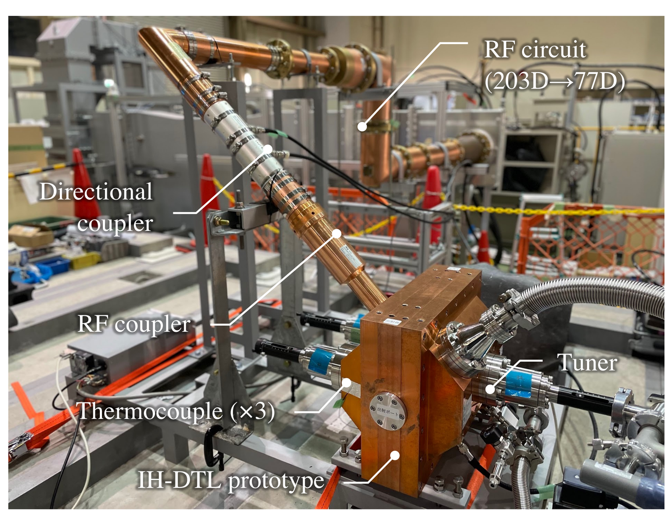
Field error < ± 2 %

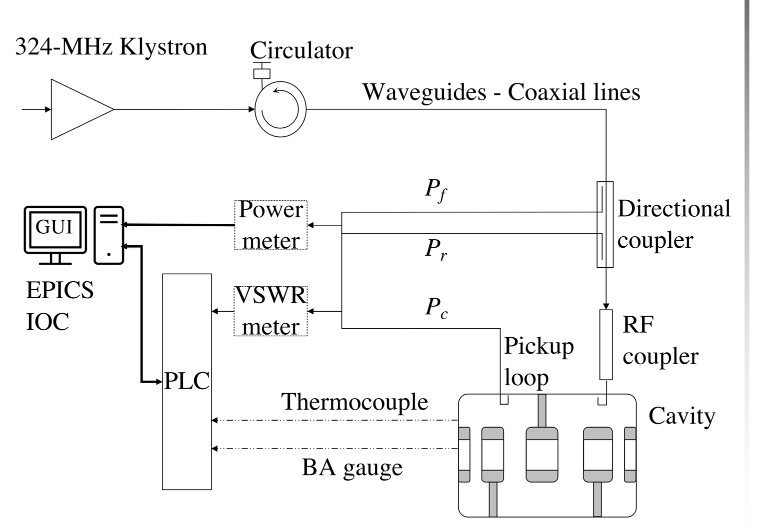
The fabrication accuracy of the drift tube with a monolithic structure fulfills the requirement.

4. High-power test

Experimental setup

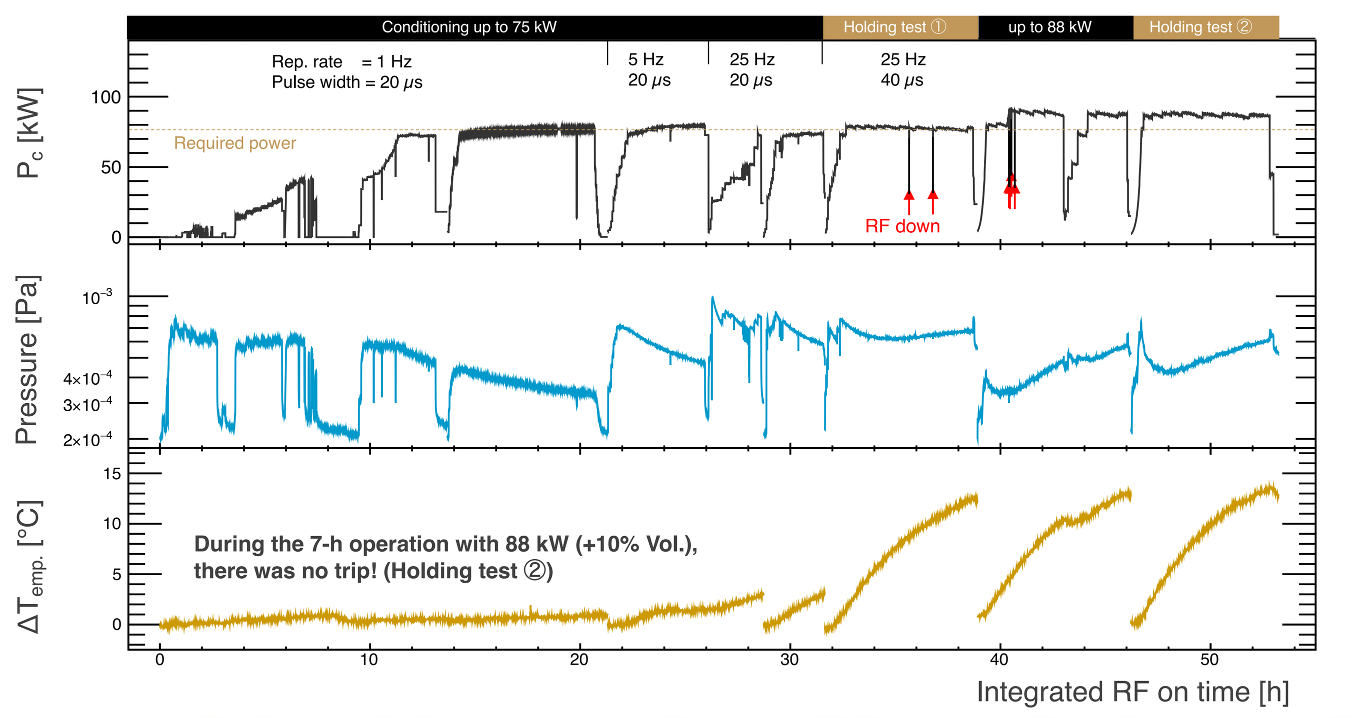
- RF source : 324-MHz klystron (Canon E3740A)
- Vacuum pumping : 240-L/s TMP.
- The data from the power meters were directly recorded by an EPICS IOC.
- Inter-lock
  - Vacuum pressure [Bayard-Alpert gauge]
  - Temperature rise [thermocouple]
  - Reflection voltage [VSWR meter]





Conditioning / Holding test

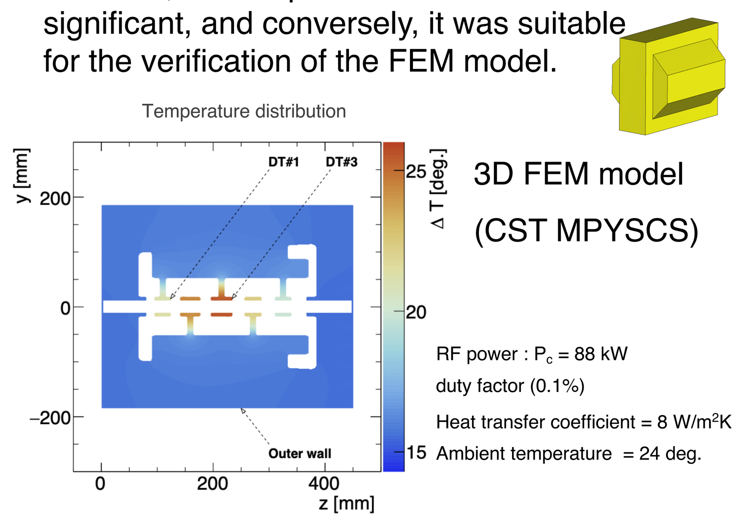
Date. 2022/4/1 ~ 4/27 @J-PARC LINAC Klystron test stand



Successful stable operation with nominal power!

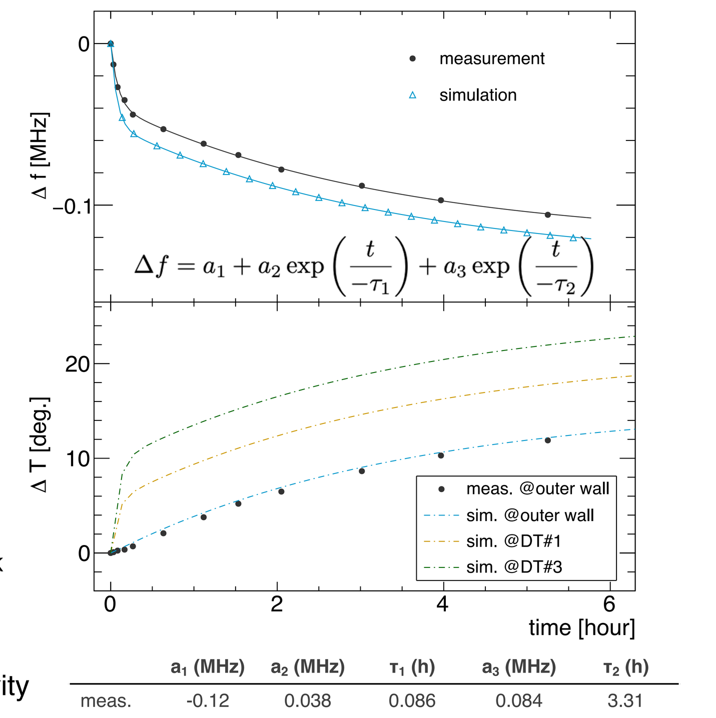
Thermal characteristics

Because the short-IH has no water-cooling structure, the temperature rise was significant, and conversely, it was suitable for the verification of the FEM model.



3D FEM model (CST MPYSCS)

τ1 : Local deformation of DT + expansion of whole cavity
τ2 : expansion of whole cavity



$$\Delta f = a_1 + a_2 \exp\left(\frac{t}{-\tau_1}\right) + a_3 \exp\left(\frac{t}{-\tau_2}\right)$$

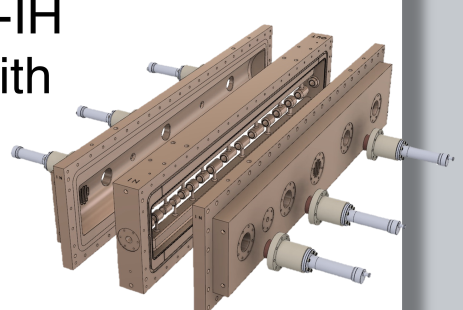
	a_1 (MHz)	a_2 (MHz)	τ_1 (h)	a_3 (MHz)	τ_2 (h)
meas.	-0.12	0.038	0.086	0.084	3.31
sim.	-0.14	0.051	0.074	0.086	3.37

Measurements were consistent with the simulation results.

These studies prove that the design and fabrication methodology established by the short-IH can be applied to the full-IH.

5. Summary / Prospects

- We demonstrated that the short-IH could be operated very stably with high-power.
- Full-IH was already fabricated.
- We plan to conduct an acceleration test with Full-IH in 2024.



These work were supported by JSPS KAKENHI grant numbers 25800164, JP15H03666, JP16H03987, JP16J07784, JP18H03707, 18H05226 , JP20J21440, S18J22129, 19J21763, JP20H05625, JP21K18630, JP21H05088, JP22H00141; the JST FOREST Program (grant number JPMJFR212O); and the natural science grant of the Mitsubishi Foundation. These studies were based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).