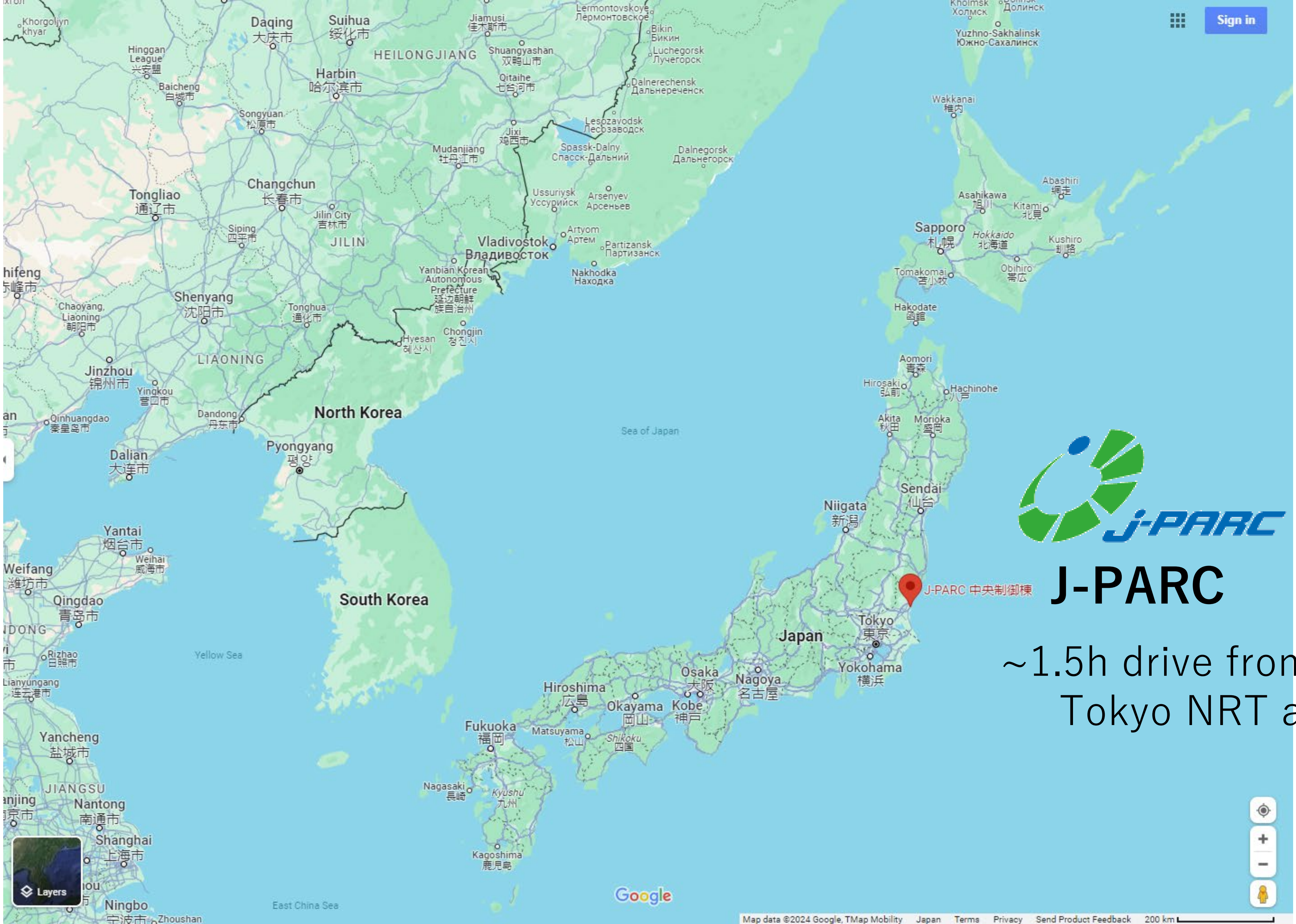
Current Status of Slow Extraction at J-PARC Main Ring

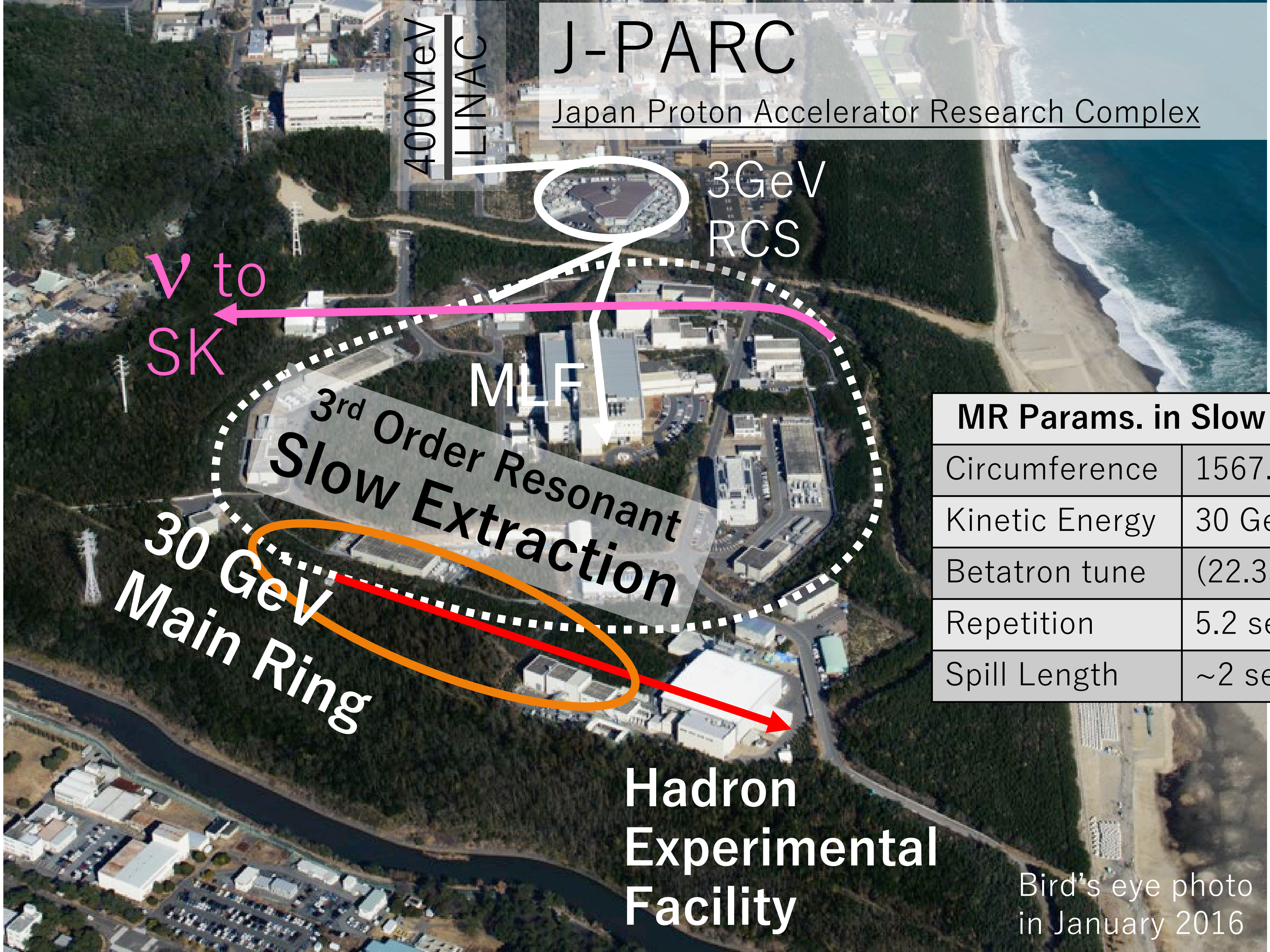
Ryotaro Muto
J-PARC/KEK

2024-Feb
Slow Extraction Workshop 2024



J-PARC

~1.5h drive from Tokyo NRT airport



MR Params. in Slow Extraction	
Circumference	1567.5 m
Kinetic Energy	30 GeV
Betatron tune	(22.333, 20.78)
Repetition	5.2 sec
Spill Length	~2 sec

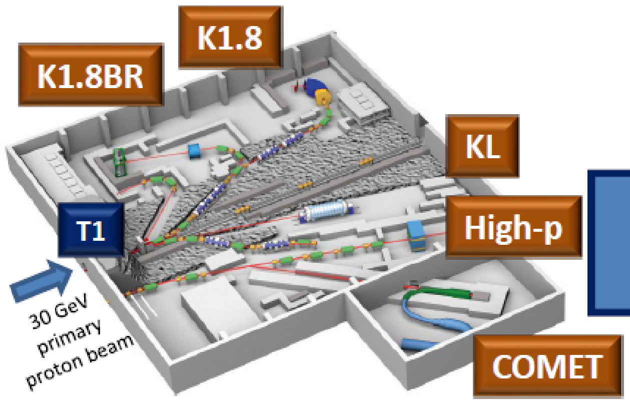
Bird's eye photo in January 2016

Hadron Hall and Its Extension Project

Hadron Experimental Facility eXtension (HEF-ex) Project

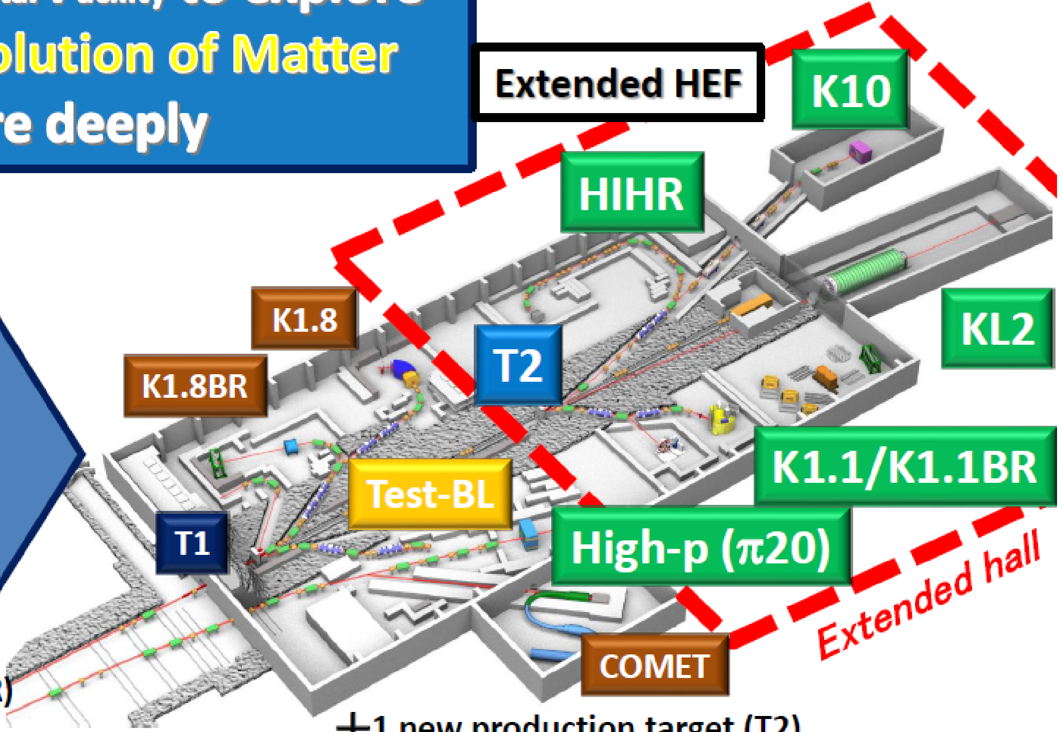
Expand research programs at the Hadron Experimental Facility to explore Origin & Evolution of Matter more deeply

Present HEF (2009～)



1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

Extended HEF

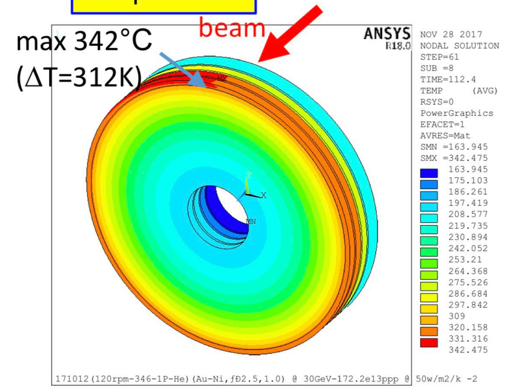


＋1 new production target (T2)
＋4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
＋ 2 updated beamlines (High-p (π20), Test-BL)

New Production Target (under development)

He gas cooled (assuming 50 W/m²/K)

temperature



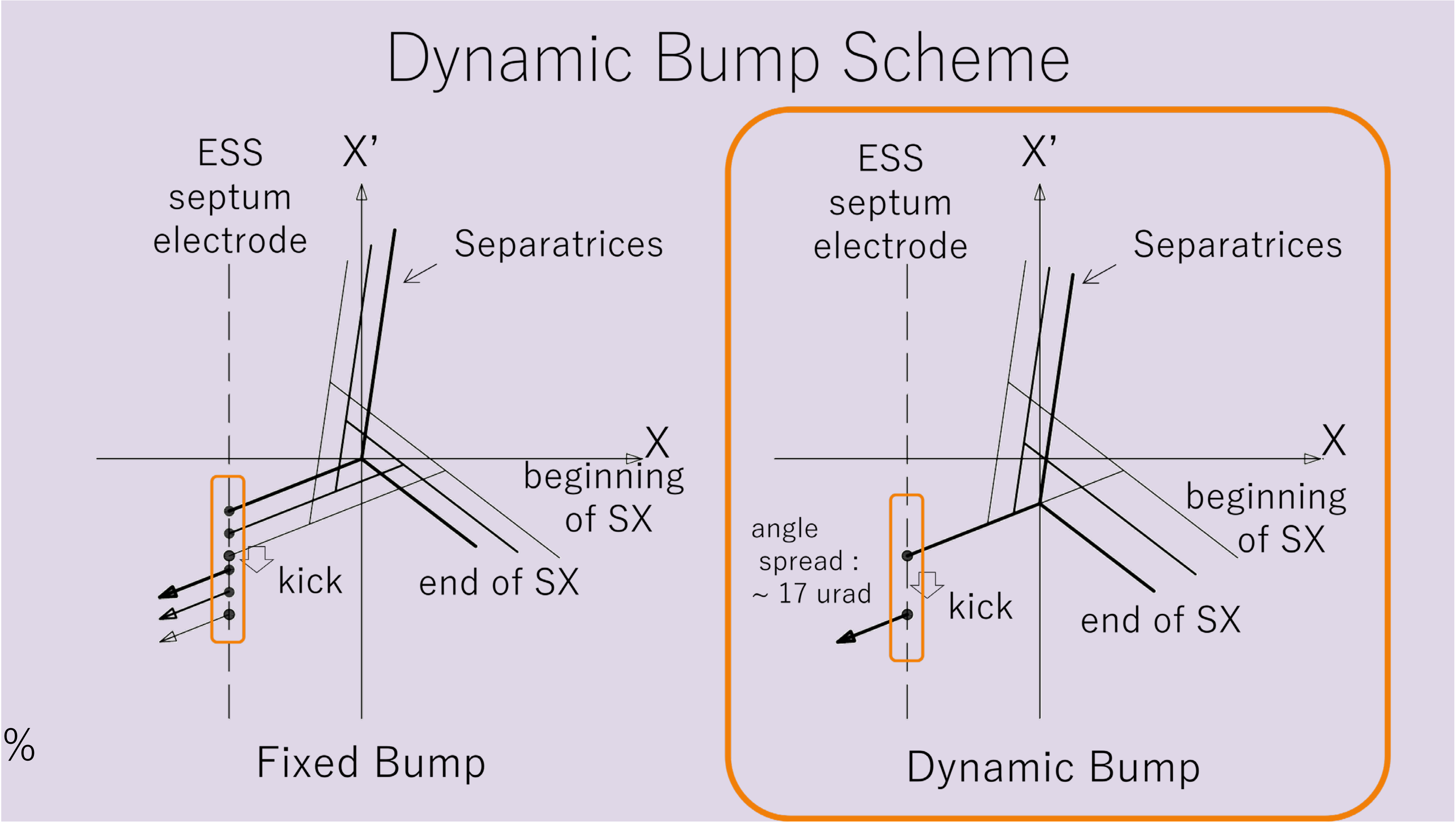
Acceptable Beam Power: >**150 kW**

→ Feb. 13 (Tue) A. Toyada, "Position and beam size measurements for unbunched beams in transfer lines"

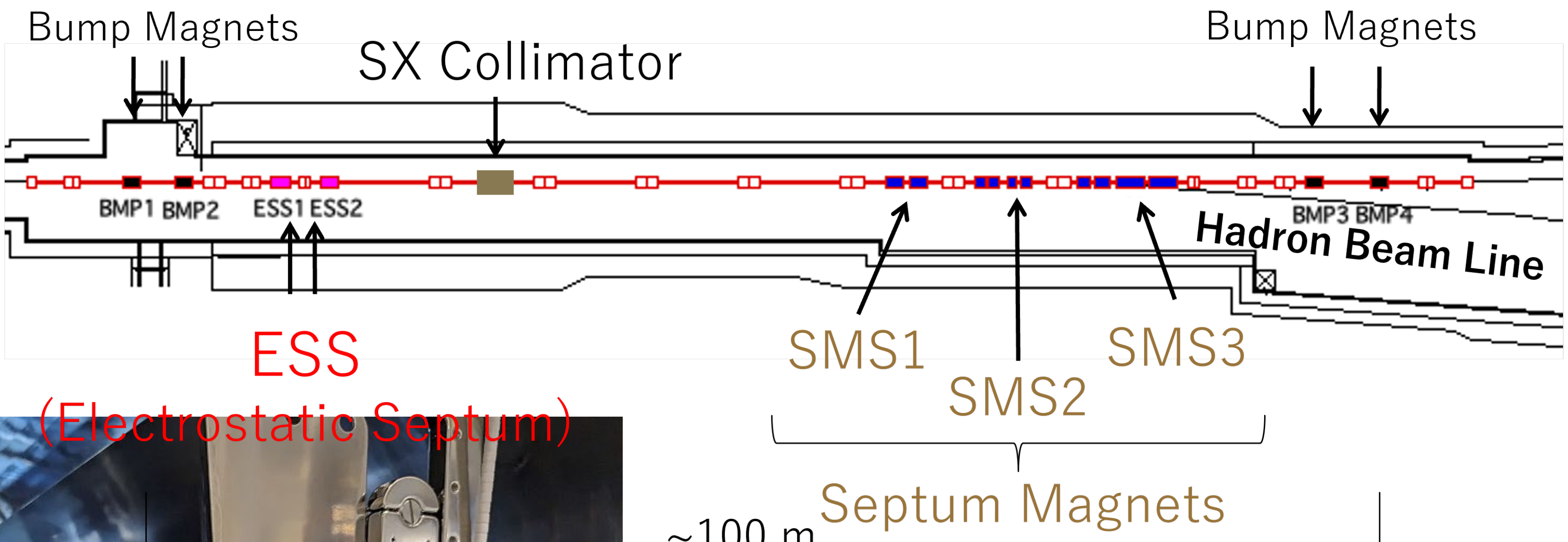
Slow Extraction at J-PARC MR

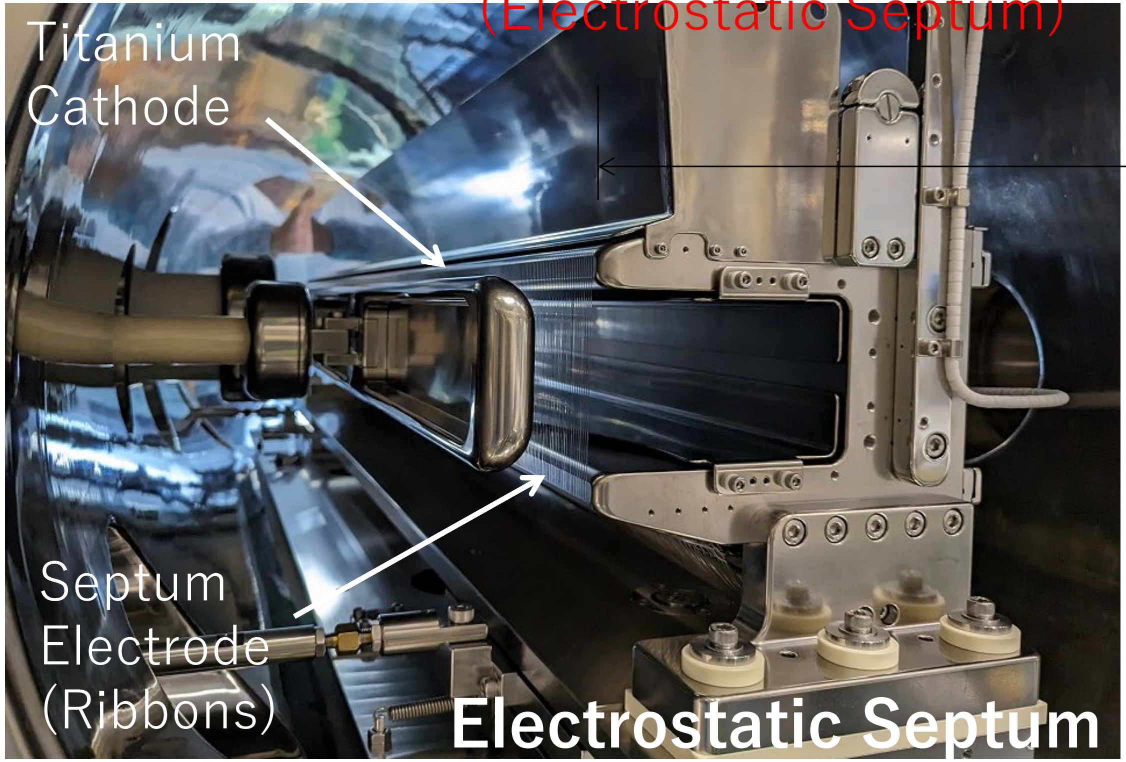
- 3rd-order Resonant Slow Extraction
- Horizontal betatron tune is ramped by Q mags in arcs

- Designed Step Size: 20 mm
- Septum thickness: 60 um
- Dispersion in Straight Section: ~0
- Chromaticity: ~0
- Dynamic Bump Scheme
  → High Extraction Eff. ~99.5%

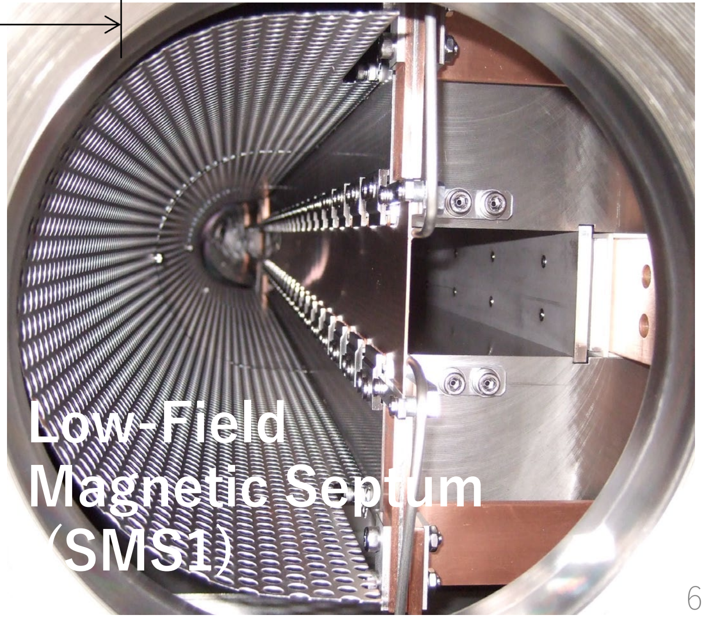


Slow Extraction at J-PARC MR

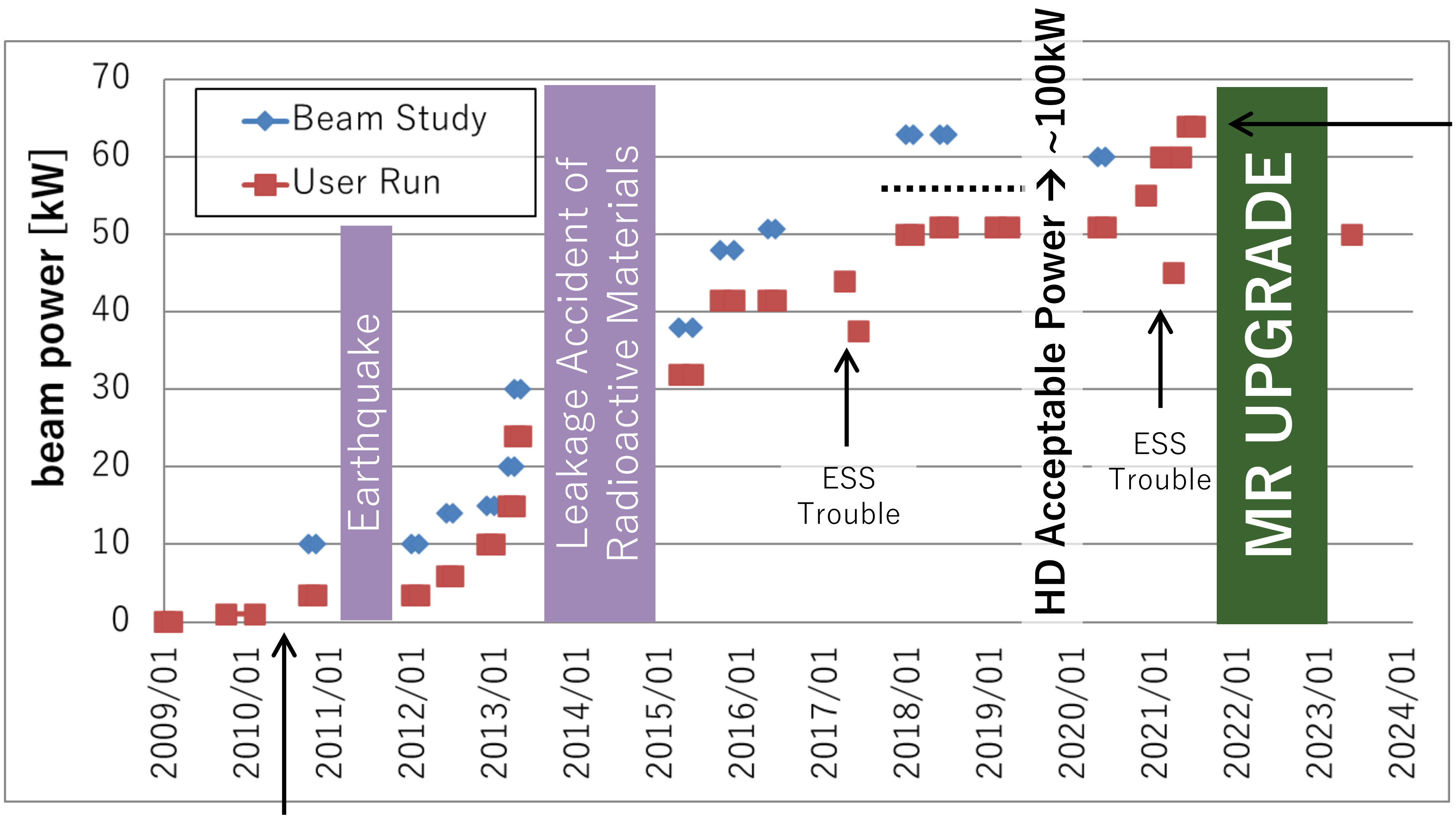




	ESS1,2
Voltage / Gap	104 kV / 25 mm = 4.2 MV/m
Deflection Angle	- 0.2 mrad
Longitudinal Length	1.5 m
Ribbon Material	W-26 Re
Ribbon Thickness	30 μm
Ribbon Width	1 mm
Ribbon Interval	3 mm
# of Ribbons	495



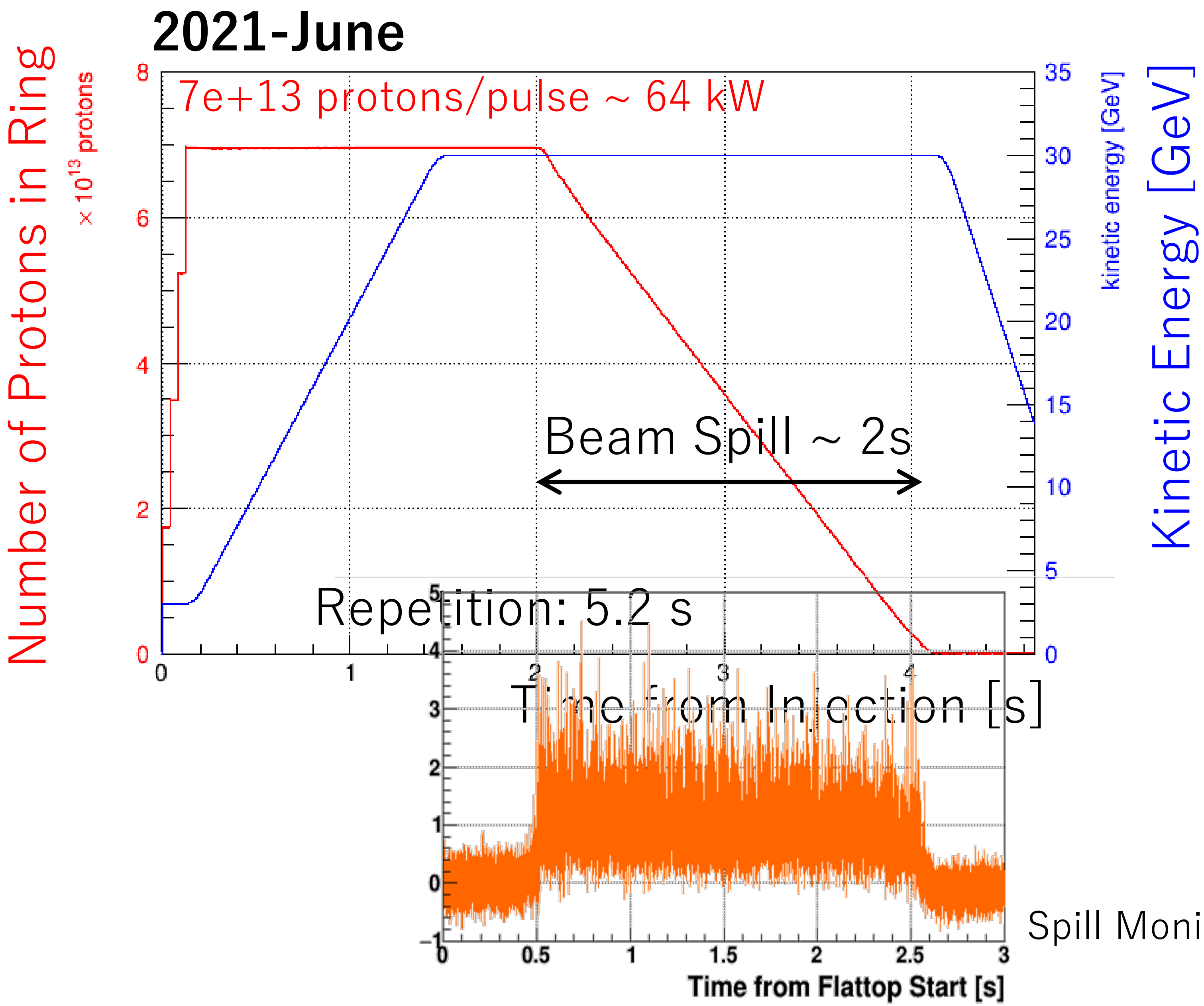
Slow Extraction Beam Power Trend



Achieve 99.5% Extraction Efficiency

Before MR upgrade
Beam power: 64kW
(5.2 s repetition)
Ext. efficiency: 99.5%
Spill duty: ~60%
for user operation
(2021-Jun)

Slow Extraction before MR Upgrade



Spill Monitor Signal

Beam Power: 64 kW

Extraction Efficiency: ~99.5%

Spill Duty Factor: ~60%

$$\text{Spill duty factor} \equiv \frac{\langle I \rangle^2}{\langle I^2 \rangle}$$

I : beam current

$\langle \rangle$: time average

J-PARC MR Upgrade

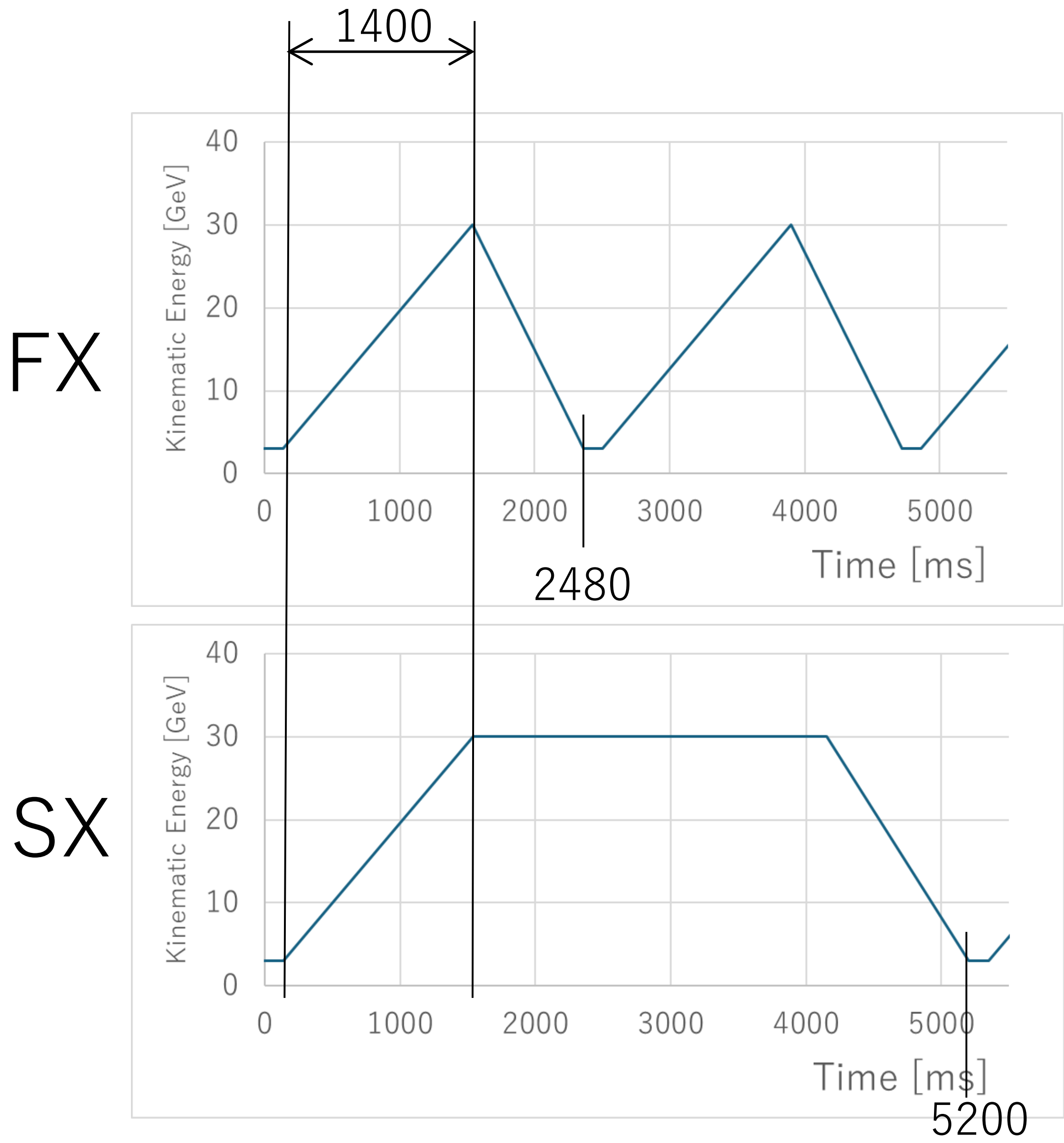
Main purpose: shorten acceleration time to increase the repetition rate

Upgrades of Main Magnet Power Supplies, RF cavities, and Injection and Fast Extraction Devices

ACC time : 1.4 s → 0.65 s

FX repetition: 2.48 s → 1.36 s

SX repetition: 5.20 s → 4.24 s
with the same flattop length of 2.61 s
Beam power with the same particle number will increase by a factor of 1.23



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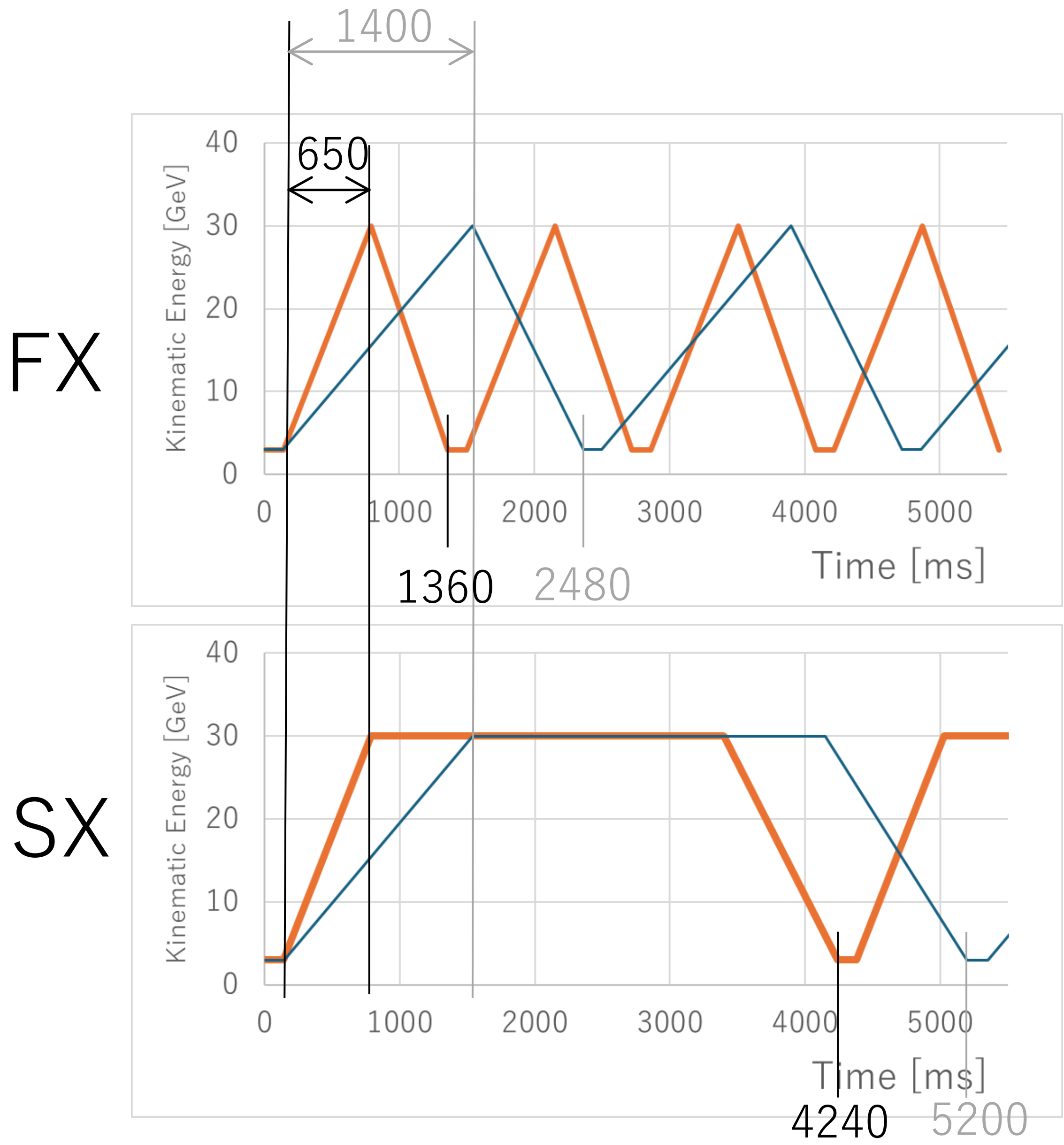


Beam operation after the MR upgrade

2022									2023											
Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.

PS test

Beam study **3 GeV**

Maintenance / PS test

FX study with **8 GeV** ext.

SX **8GeV** for COMET phase-α

FX **30 GeV** study

Recovery

SX **30 GeV** study & User Op. (50 kW)

Recovery / Maintenance

FX

New PS failure (BM6)

EM contactor was broken due to poor assembling

2W for recovery

New PS failure (QFN,QDN)

Many fuses were blown triggered by the lost of 12 MHz timing signal

2W for recovery

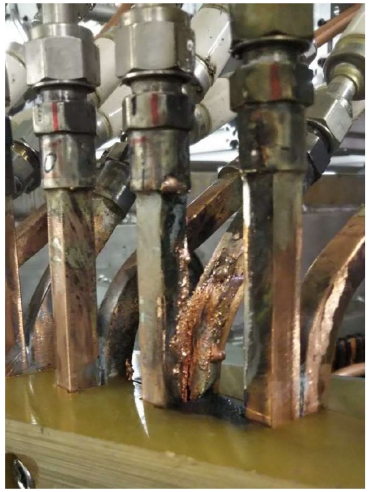
New PS failure (BM4)

IGBTs failed. The cause is still under investigation

~1 month for recovery

FX septum magnet failure

→ **Ext. energy is limited to 8 GeV**

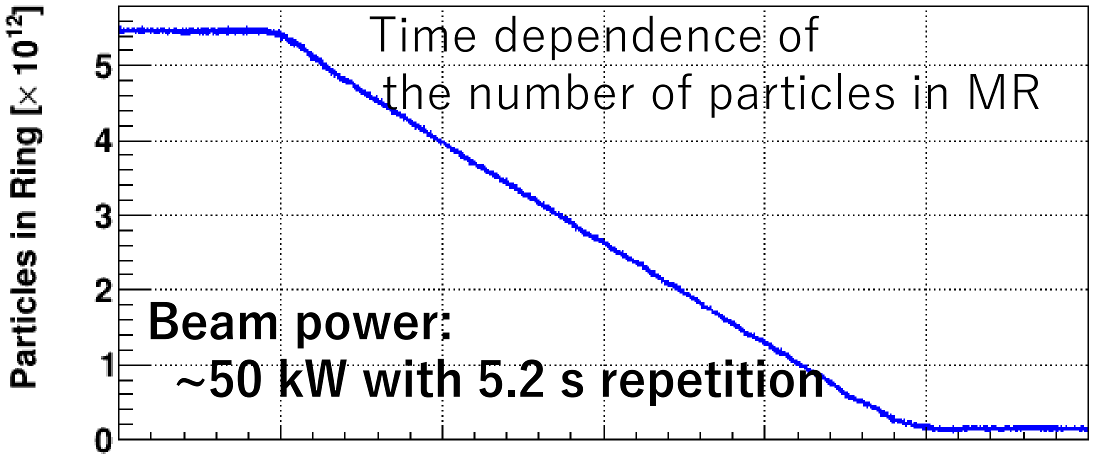


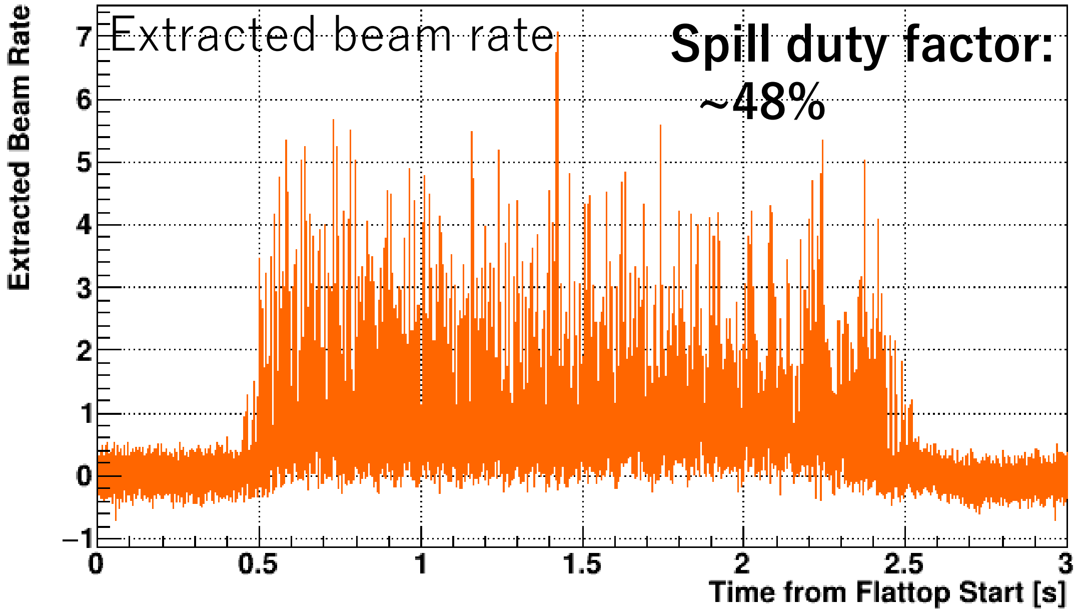
New PS failure (fire on QDN charging transformer)

Fire on old mag. PS in HD

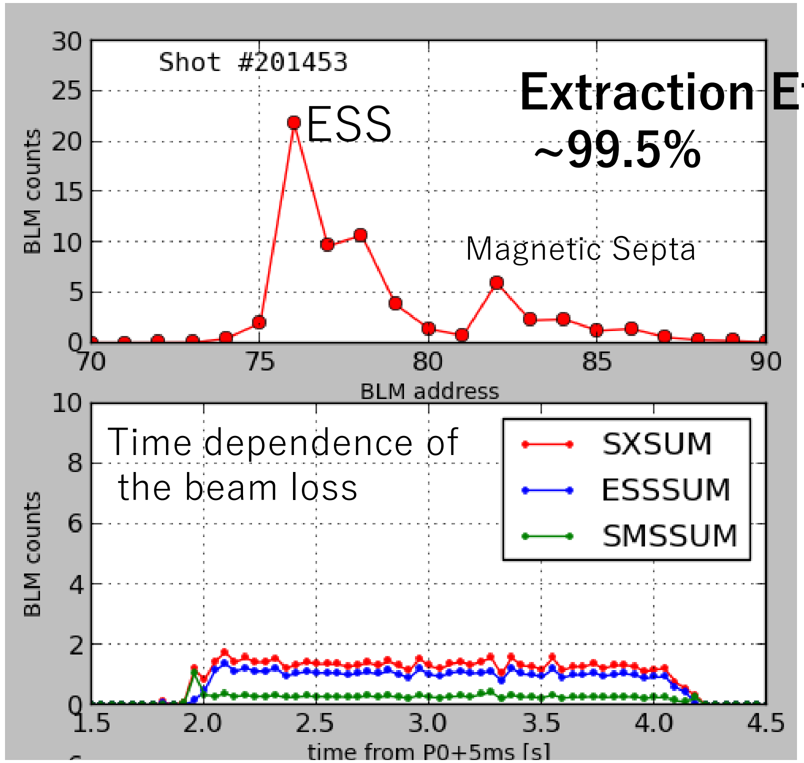
Slow Extraction after MR Upgrade

2023-Jun





Beam loss distribution in SX straight section



Extraction Efficiency:
~99.5%

The extraction efficiency of 99.5% before the main power supply upgrade was well reproduced.

Next Step

Next March:

・Beam acceleration and debunch test
with shortened repetition time of 4.24 s (without slow extraction)

Next April – May:

・Slow extraction tuning with 4.24 s repetition time
aiming at beam power increase
・User operation

Major Challenges in J-PARC Slow Extraction

Beam Power Upgrade

- Beam Loss Reduction
  - Diffusers → Feb. 13 (Tue) "Beam diffusers for beam loss reduction"
  - Bent Silicon Crystal
- Mitigation of Beam Instability at Debunch Timing
  - RF Manipulation at Inj. and Flattop
  - Large Slippage Optics
  - VHF cavity

Spill Structure Improvement

→ Feb. 12 (Mon) "Spill structure with newly upgraded main magnet power supplies in J-PARC Main Ring"

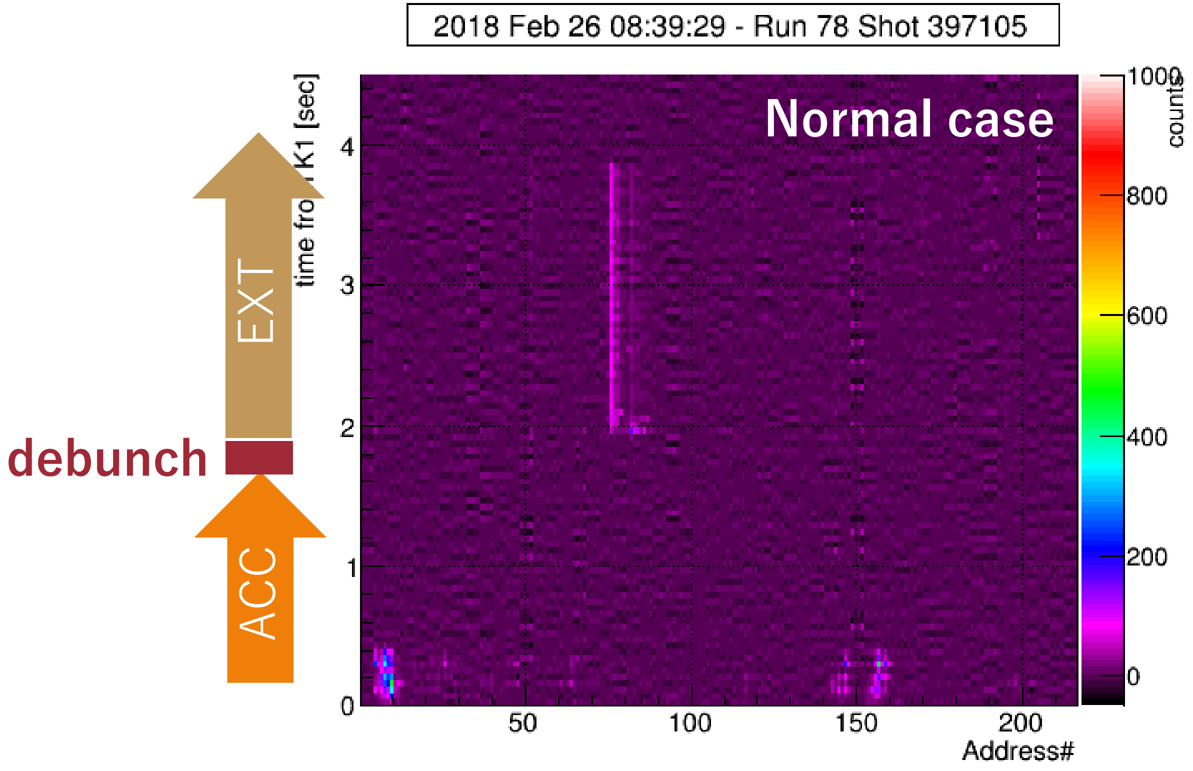
Machine Protection System

→ Feb. 13 (Tue) M. Tomizawa, "Machine protection measures for malfunctions of accelerator devices in J-PARC Main Ring"

Beam Instability at Debunch Timing

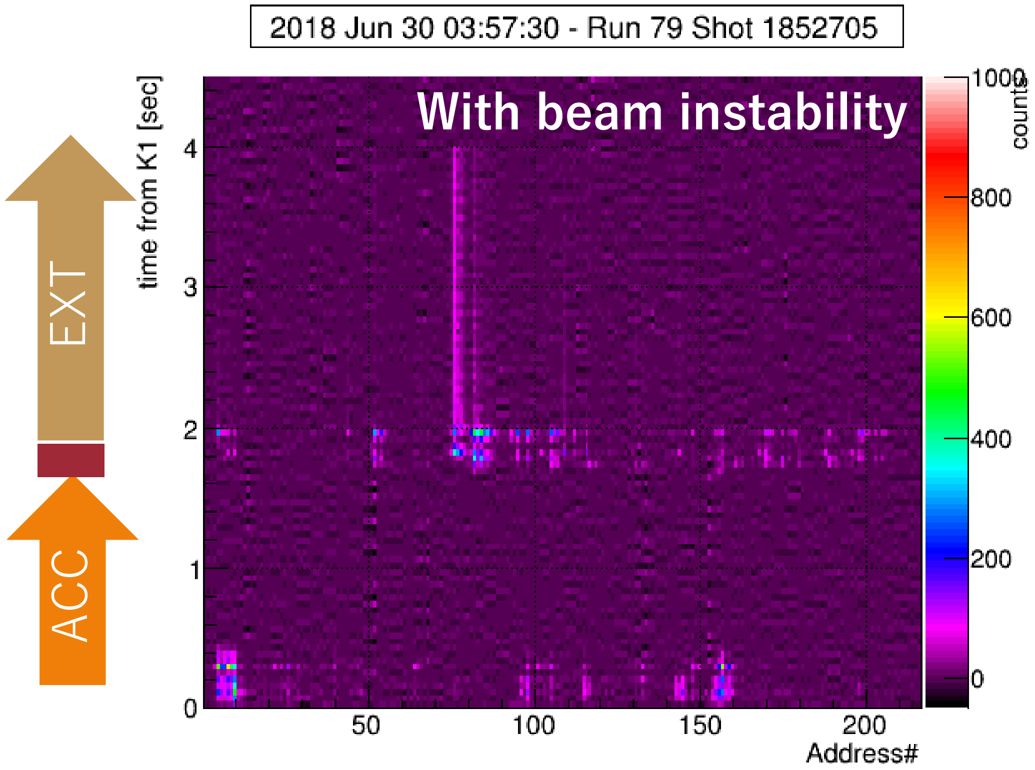
RUN78 (Feb-2018) 63 kW

Ext. Efficiency 99.472% with phase offset of 50°



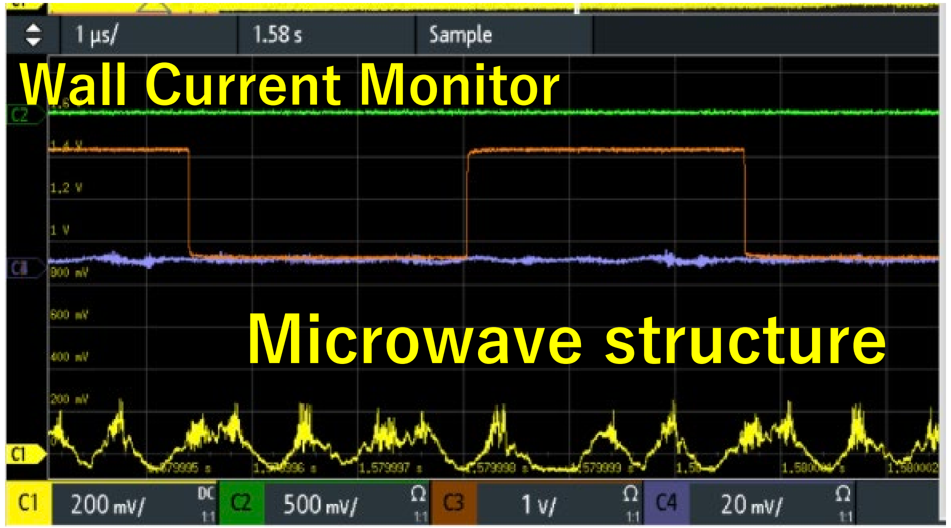
RUN79 (Jun-2018) 63 kW

Ext. Efficiency 98.666% with phase offset of 60°

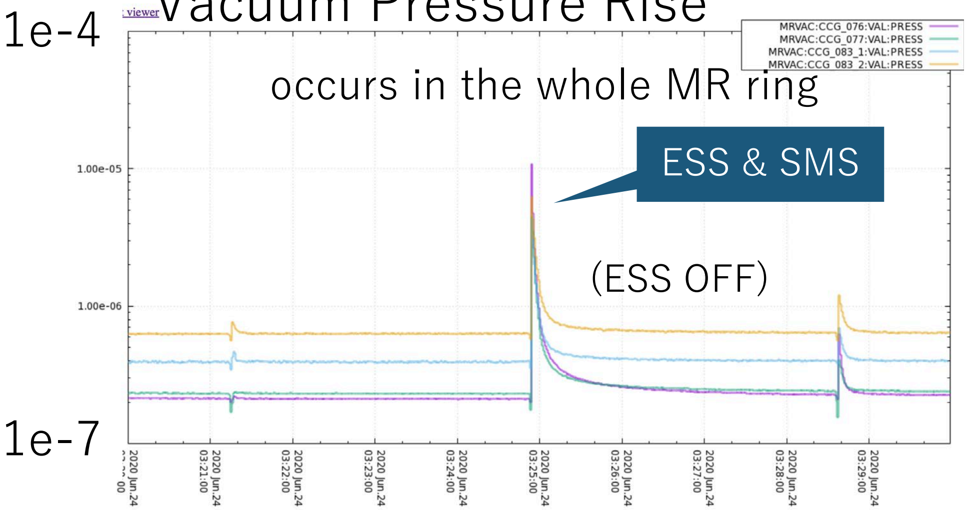


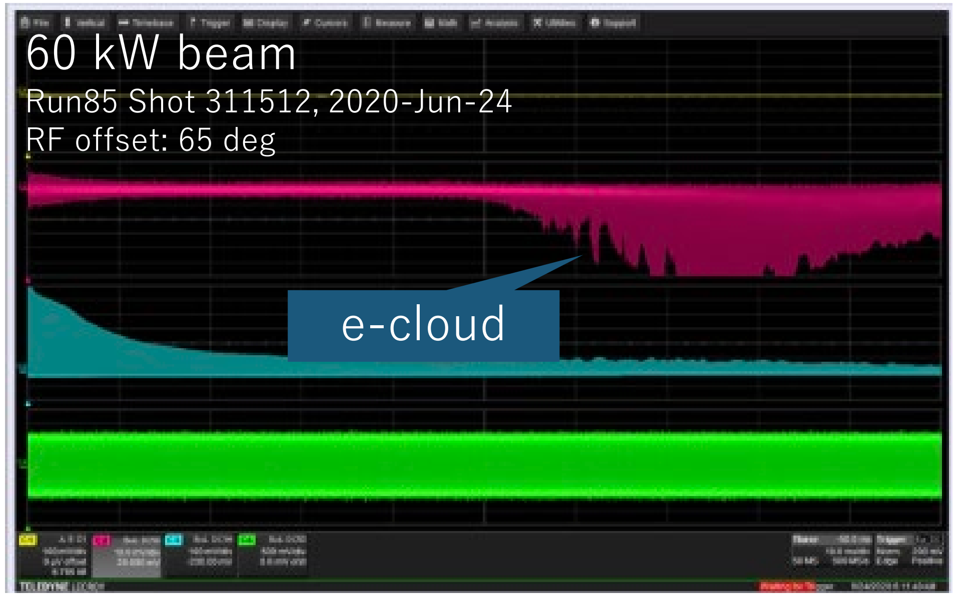
Beam losses were observed in the whole ring at debunch timing

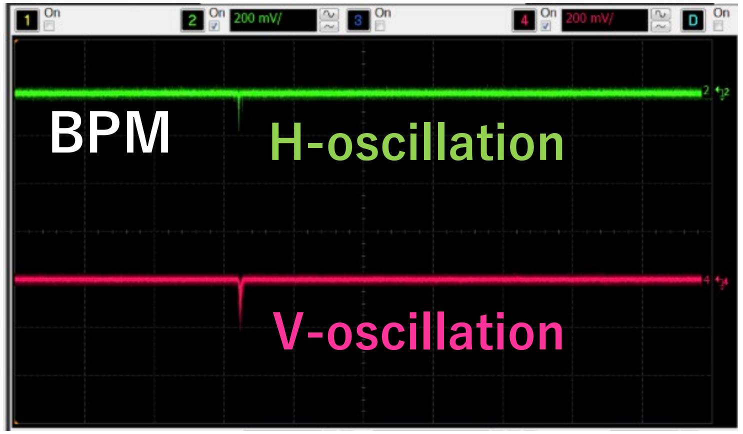
Beam Instability at Debunch Timing



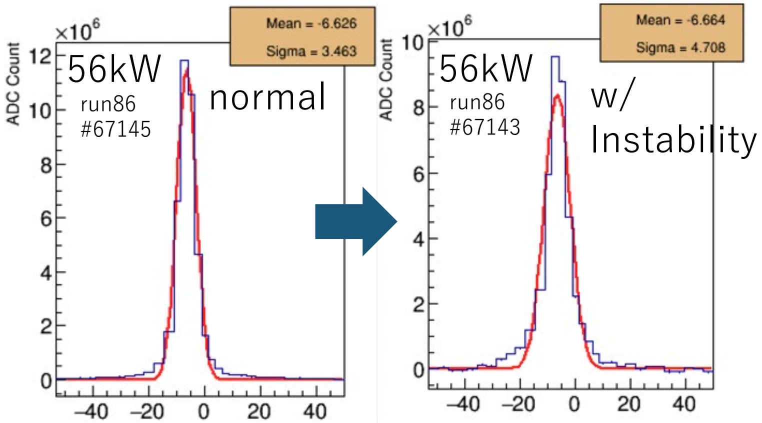
Vacuum Pressure Rise







Transverse Beam Size Growth



Beam instability occurs ~60ms after RF OFF

Suppression of beam instability during debunching

Keil-Schnell criterion

Slippage

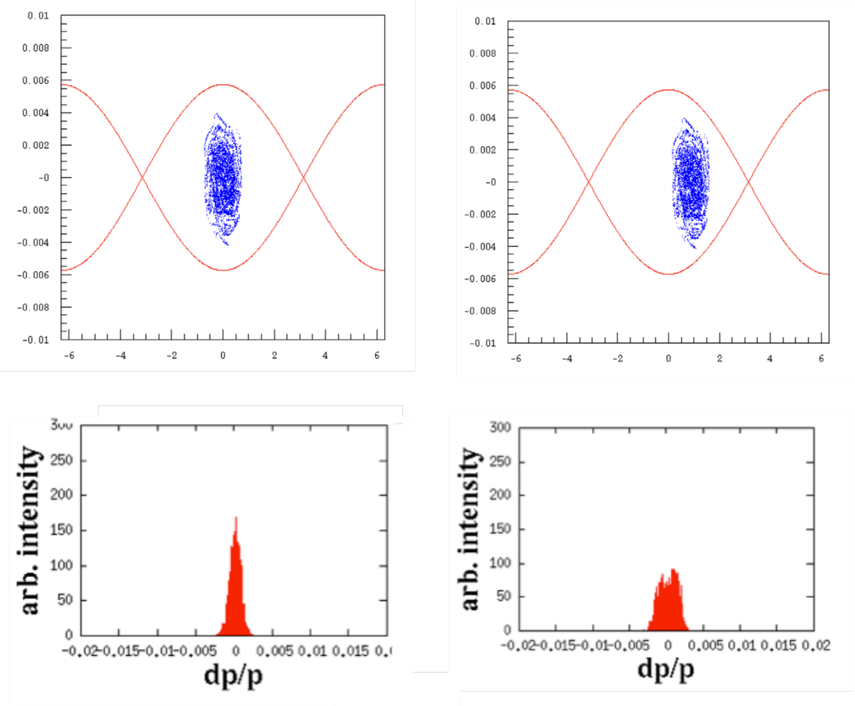
$$\left|\frac{Z_L(n\omega_0)}{n}\right| < F\cdot\frac{|\eta|\beta^2 E_0/e}{I_p}\left(\frac{\Delta p}{p}\right)^2_{FWHM}$$

Impedance

Longitudinal Emittance

Phase offset 0°

Phase offset 50°



In the beam test after MR upgrade, we were able to suppress the instability

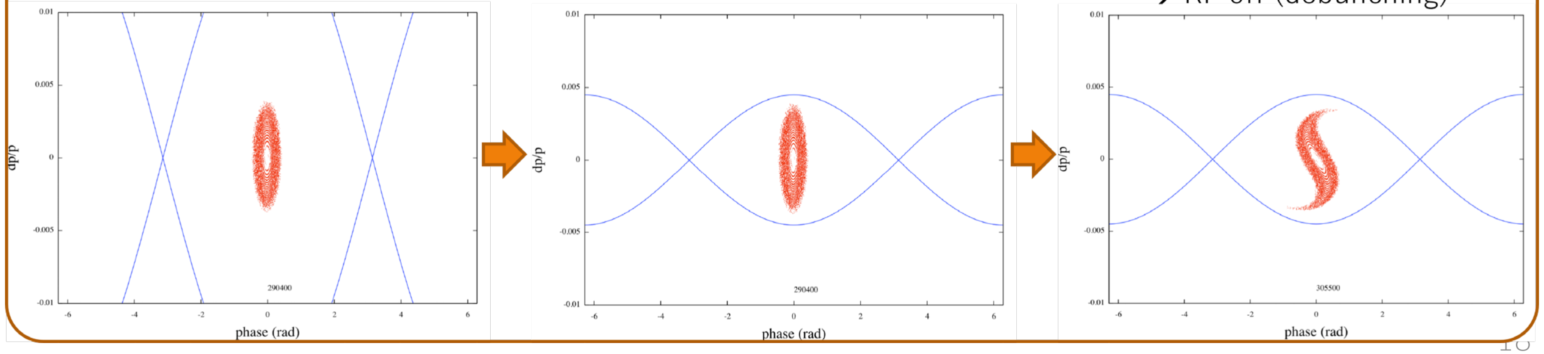
up to 70.8 kW (7.6 e+13 protons/pulse with 5.2 s repetition).

We will further optimize RF manipulation based on simulation and beam study.

After acceleration : RF 256 kV

RF 17 kV

After 80 ms with RF 17 kV
→ RF off (debunching)



Large Slippage Optics

Keil-Schnell criterion

$$\left|\frac{Z_L(n\omega_0)}{n}\right| < F \cdot \frac{|\boldsymbol{\eta}|\beta^2 E_0/e}{\boldsymbol{I_p}}\left(\frac{\boldsymbol{\Delta p}}{\boldsymbol{p}}\right)^{\mathbf{2}}_{\boldsymbol{FWHM}}$$

Slippage

Impedance

Longitudinal Emittance

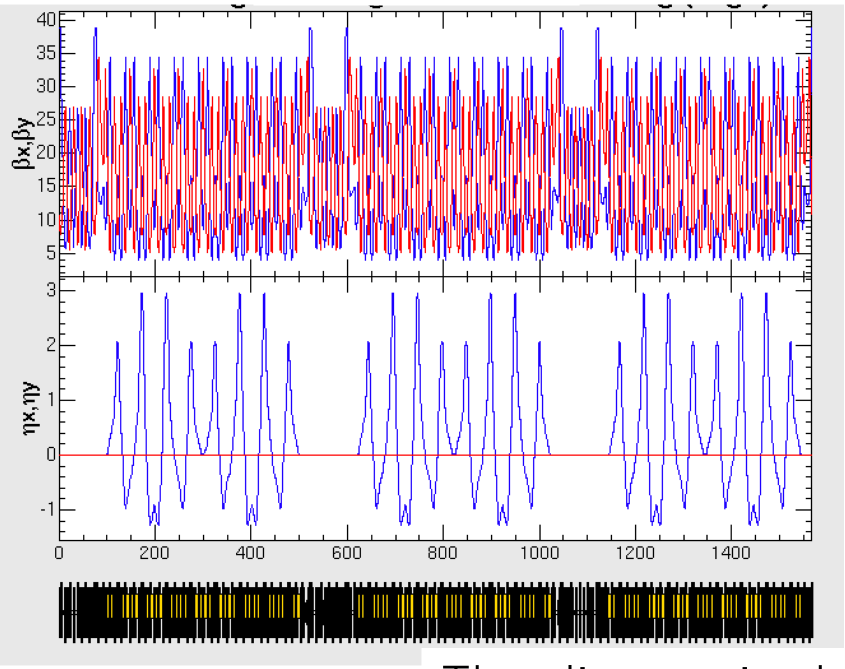
MR Lattice: imaginary γ_t → flexible momentum compaction

Optics with a larger slippage |η| is a promising candidate for suppressing the instability at a higher beam power

η =-.001920 (current optics)

Tune (22.286, 20.788)

mrsx_021_009

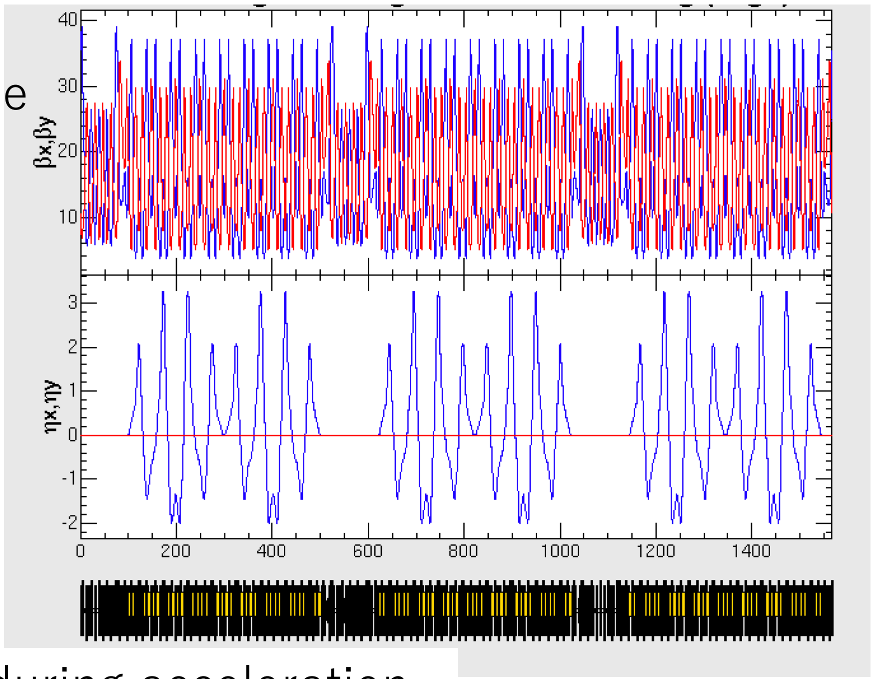


Slippage x 1.5

η =-.00291

Tune (22.286, 20.788)

mrsx_021_011_1



Reported in ATAC2021

The slippage is changed during acceleration

VHF Cavity for Longitudinal Emittance Growth

Keil-Schnell criterion

Slippage

$$\left|\frac{Z_L(n\omega_0)}{n}\right| < F \cdot \frac{|\boldsymbol{\eta}|\beta^2 E_0/e}{\boldsymbol{I_p}} \left(\frac{\Delta \boldsymbol{p}}{\boldsymbol{p}}\right)^2_{FWHM}$$

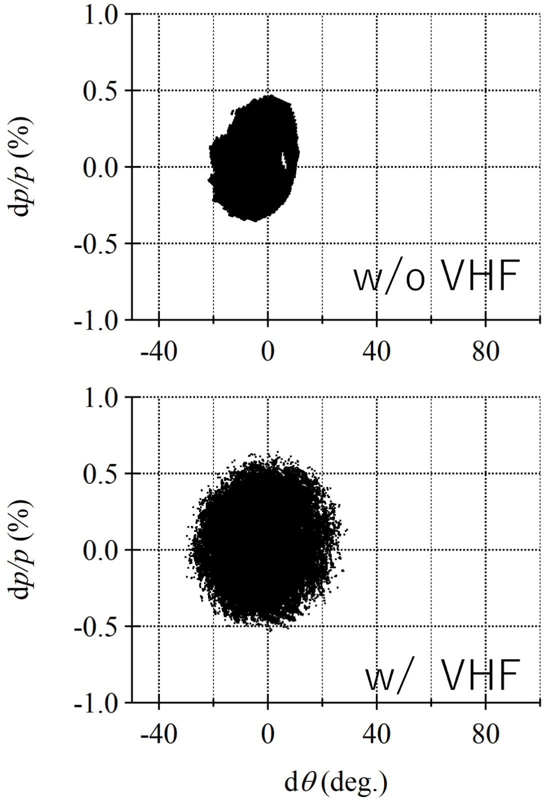
Impedance

Longitudinal Emittance

Longitudinal emittance growth by VHF cavity phase modulation

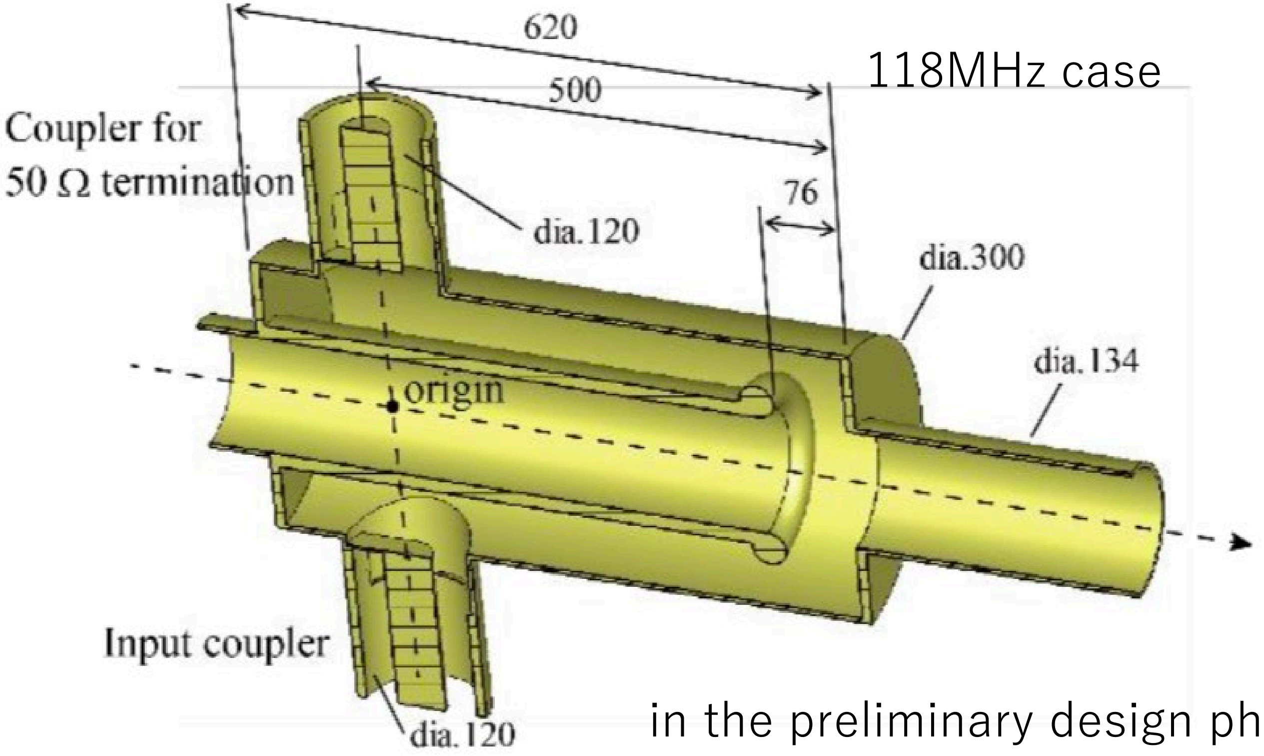
$$V_{total}(t) = V_0 \sin 2\pi f_0 t + V_b \sin(2\pi f_b t + \psi(t)),$$
$$\psi(t) = \Delta\phi_m \sin 2\pi f_m t$$

Simulation example



by Y. Morita

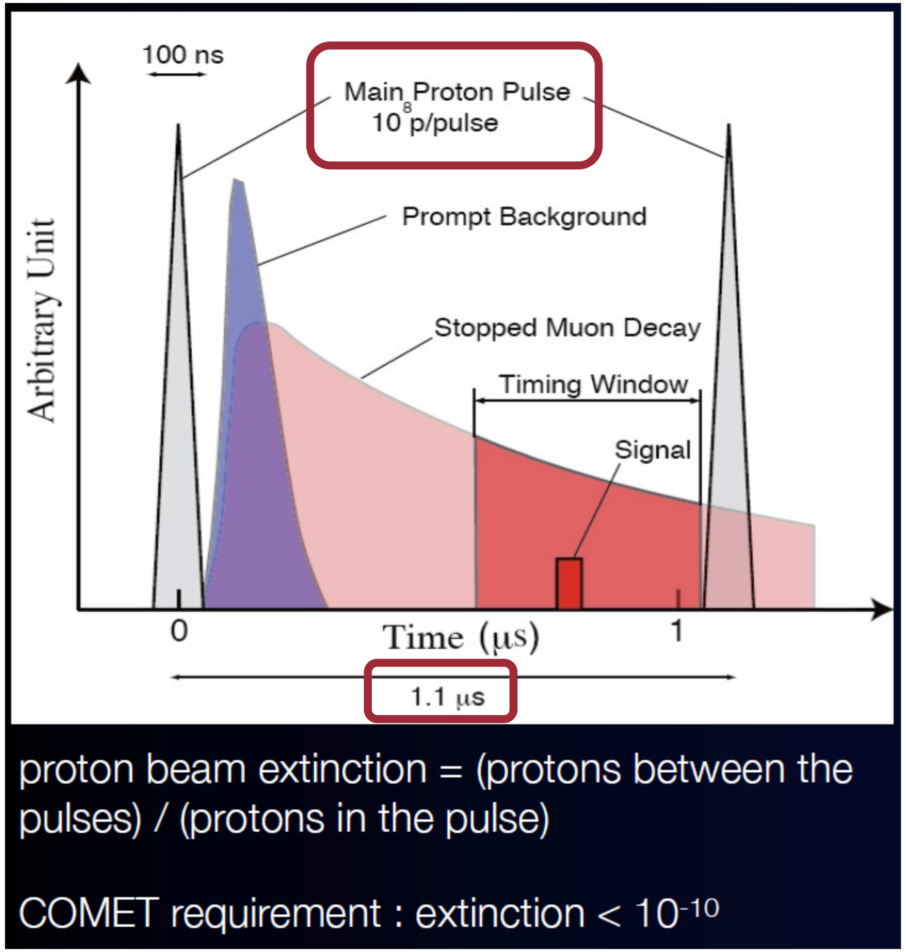
$\lambda/4$-coaxial cavity



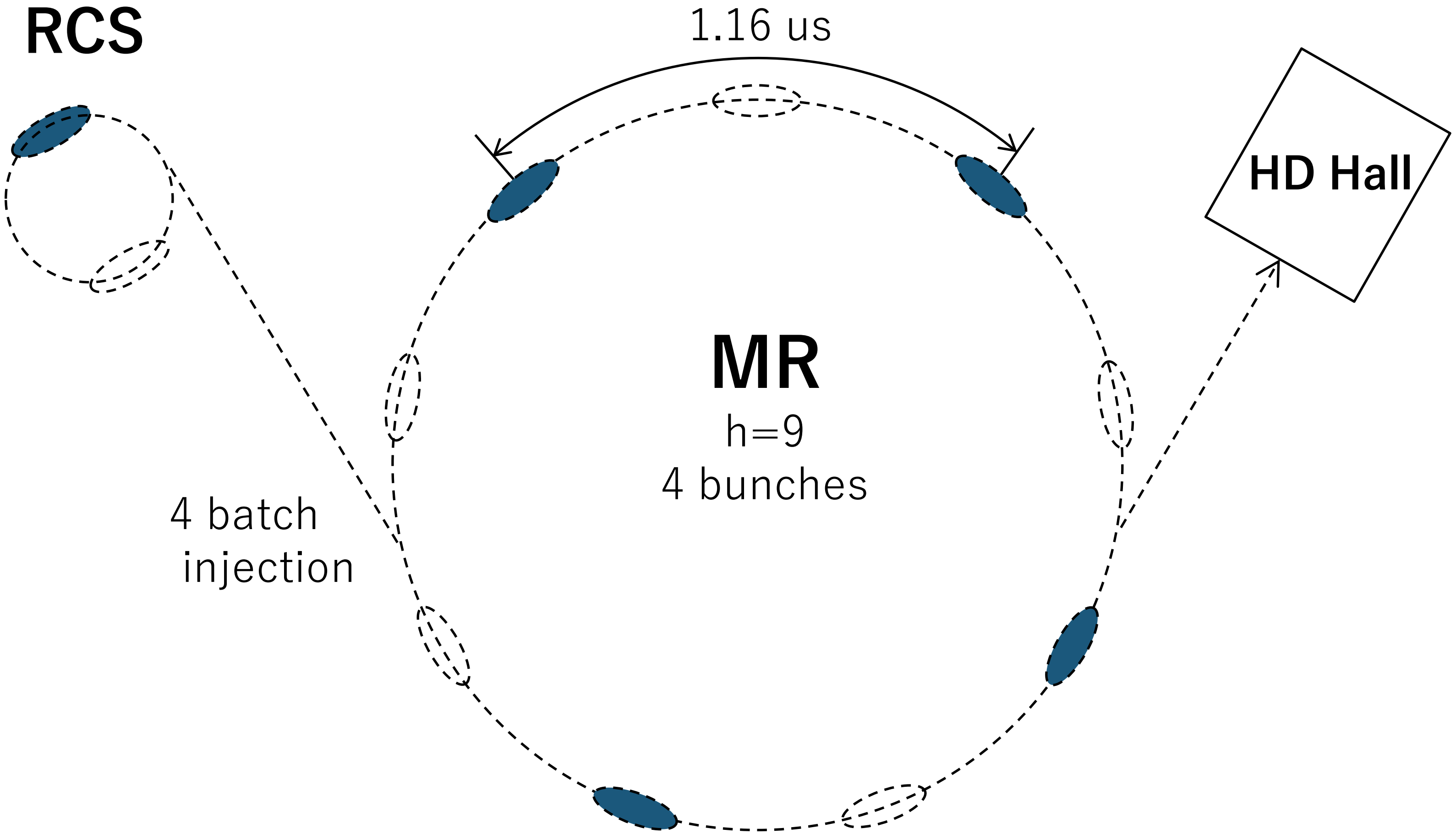
118MHz case

in the preliminary design phase

Slow Extraction Beam for COMET



From Kuno-san's slide for 26th J-PARC PAC



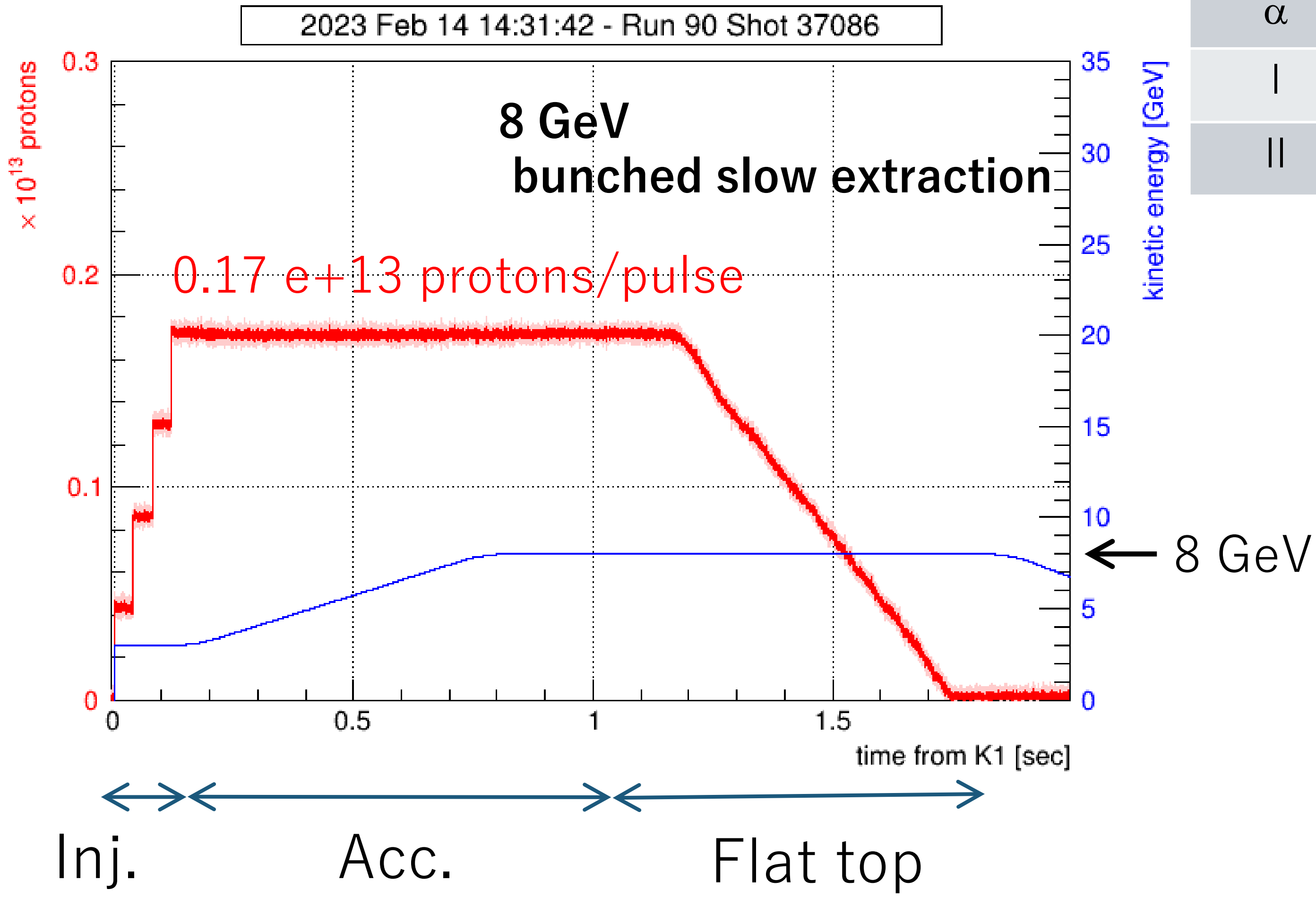
8 GeV operation for COMET

- Beam energy : 8 GeV
- ~1 MHz pulsed beam
- < 10^{-10} proton beam extinction → slow extracted bunched beam

Operation for COMET phase- α

Phase	Power [kW]	Cycle [s]	#Proton [TP/pulse]	#Proton [TP/bunch]	Acc. Status
α	0.22	9.2	1.6	0.4	**Done**
I	3.2	2.48	6.2	1.6	**Ready**
II	56	1.2	52.5	13.1	

2023-Feb



Acceleration up to 8 GeV and slow extraction operation were successfully performed with the requested beam intensity (~0.2 kW)

0.14 s   0.9 s   0.8 s (Spill length: ~0.6 s)   Repetition: 9.6 s