J-PARC Linac and RCS

-operational status and upgrade plan to 2 MW-

ICANS XXIV

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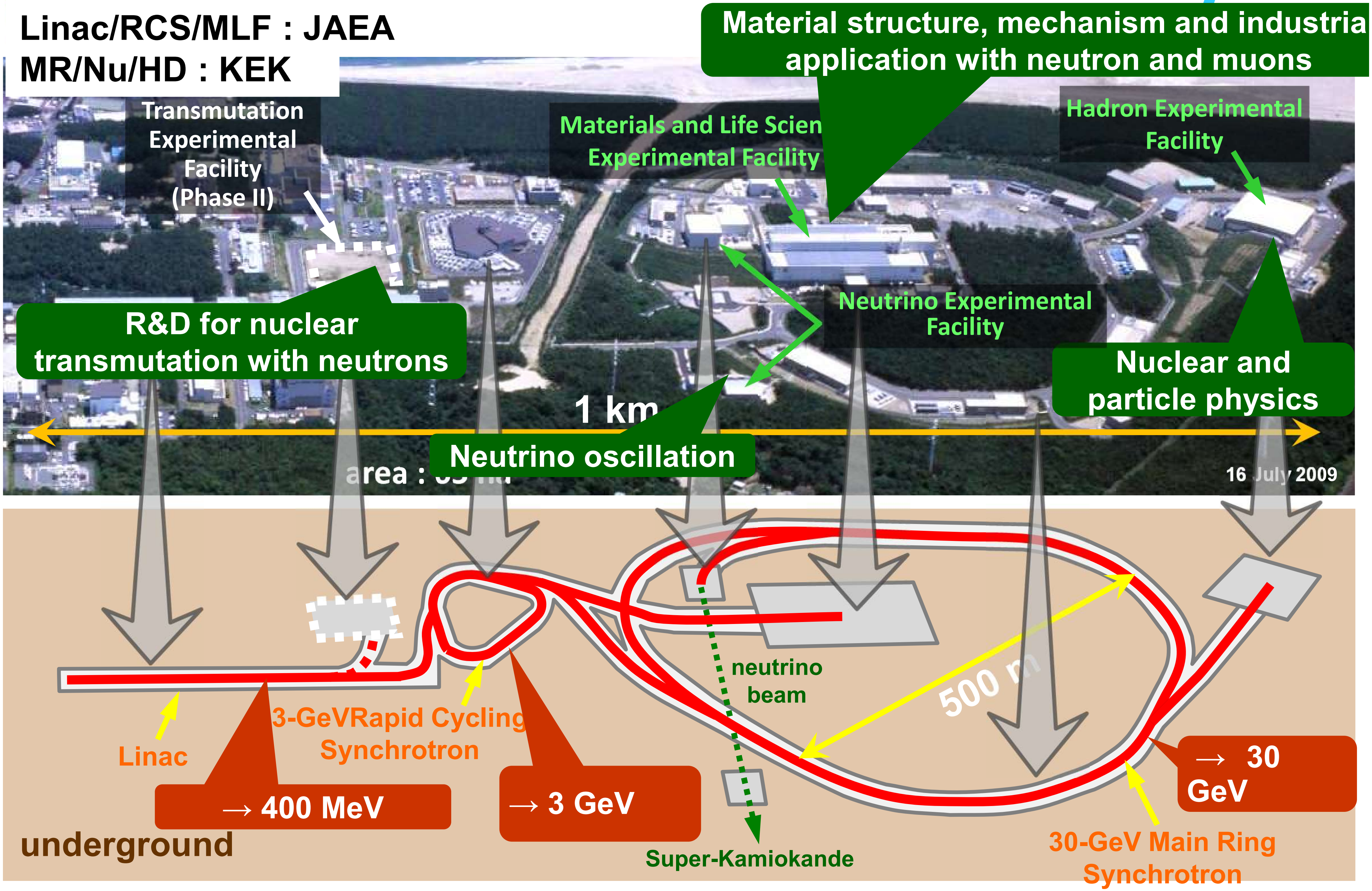
- Outline of the J-PARC Linac and RCS
- Recent beam commissioning results
- Upgrade to 2 MW
- Summary

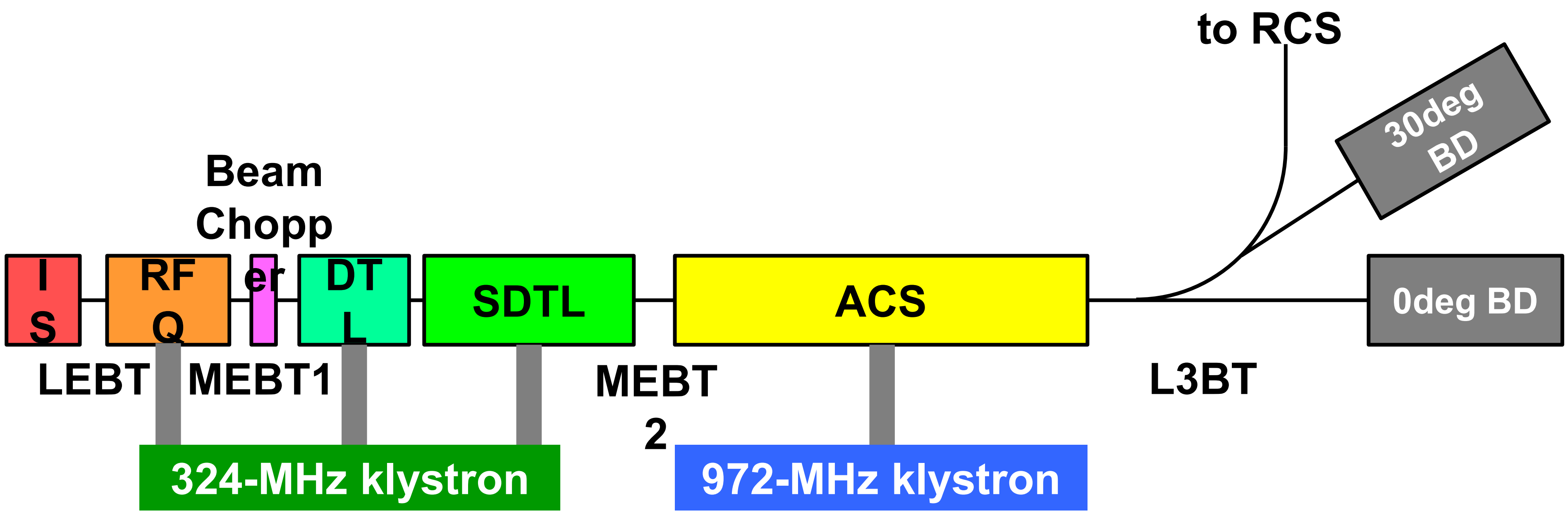
Japan Proton Accelerator Research Complex



3 proton accelerators and (3+1) experimental facilities

J-PARC Linac

Acceleration particle:	Negative hydrogen ion (H^-)
Energy:	400 MeV
Peak current:	50 mA
Pulse width/ repetition:	0.5 msec/ 25 Hz



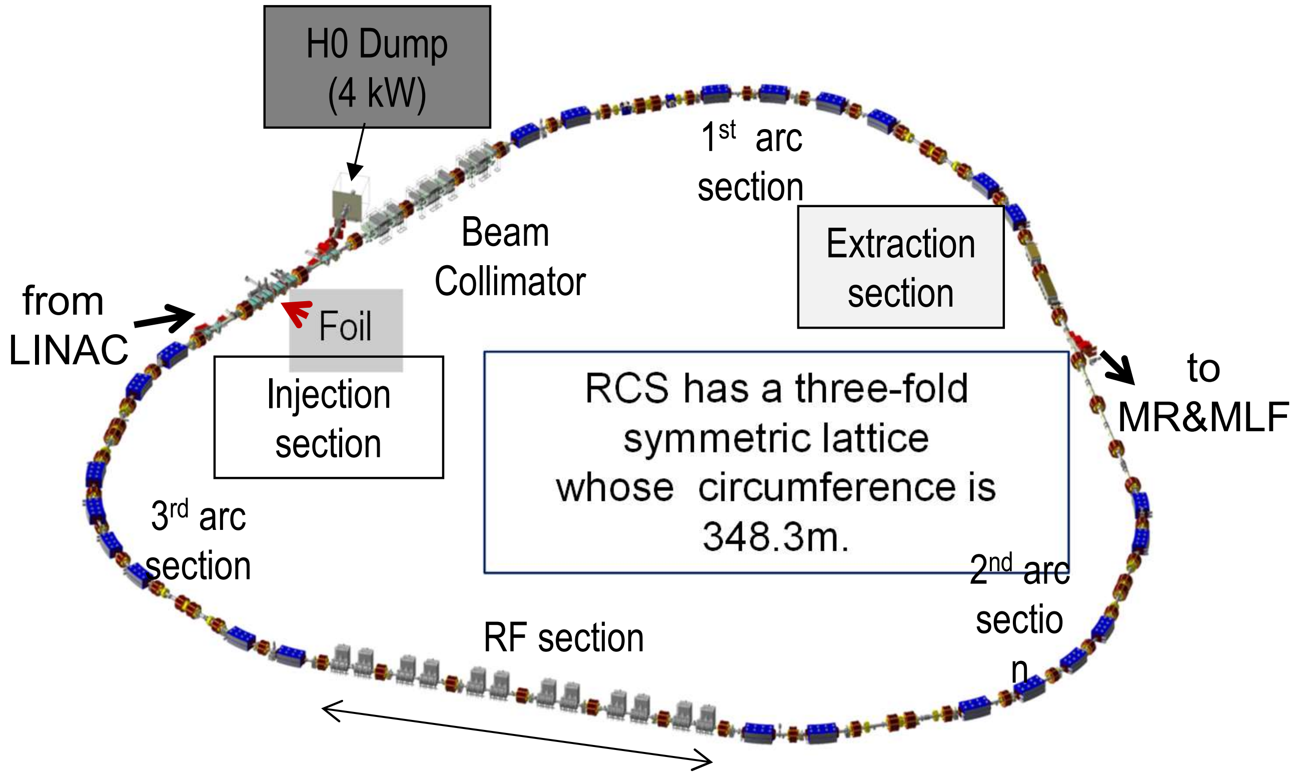
Schematic of the linac

3GeV-RCS in J-PARC

Design parameters

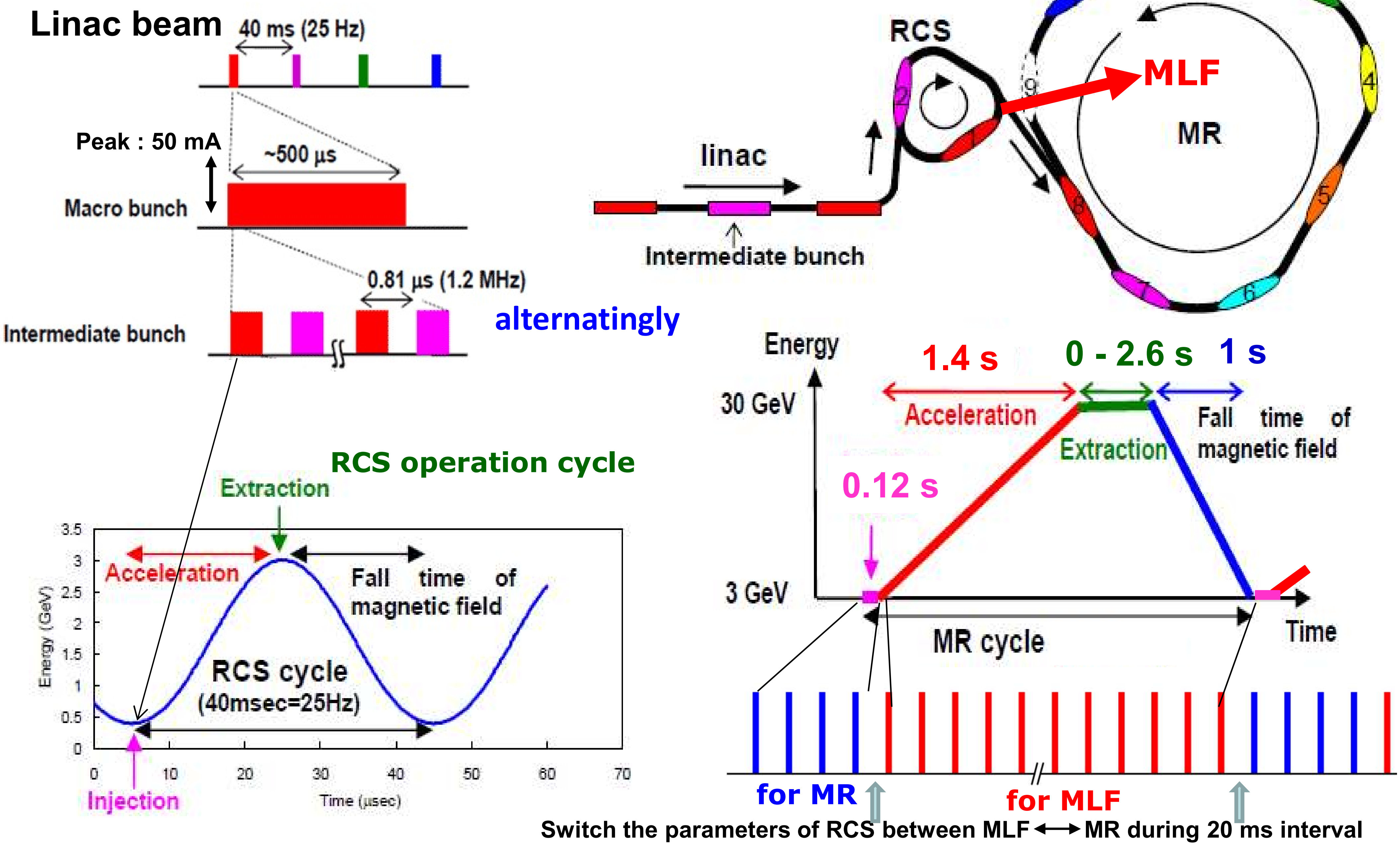
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
F_{rev}	0.61-0.84 MHz
F_{rf}	1.23-1.67 MHz
Injection energy	400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	8.3e13 with 1 MW
Output beam power	0.5 MW (1 MW)
Transition gamma	9.14
Number of dipoles	24
quadrupoles	60 (7 families)
sextupoles	18 (3 families)
steerings	52
RF cavities	12

The H0 dump is used to dump unstripped beams at the stripping foil. The capacity is 4kW.



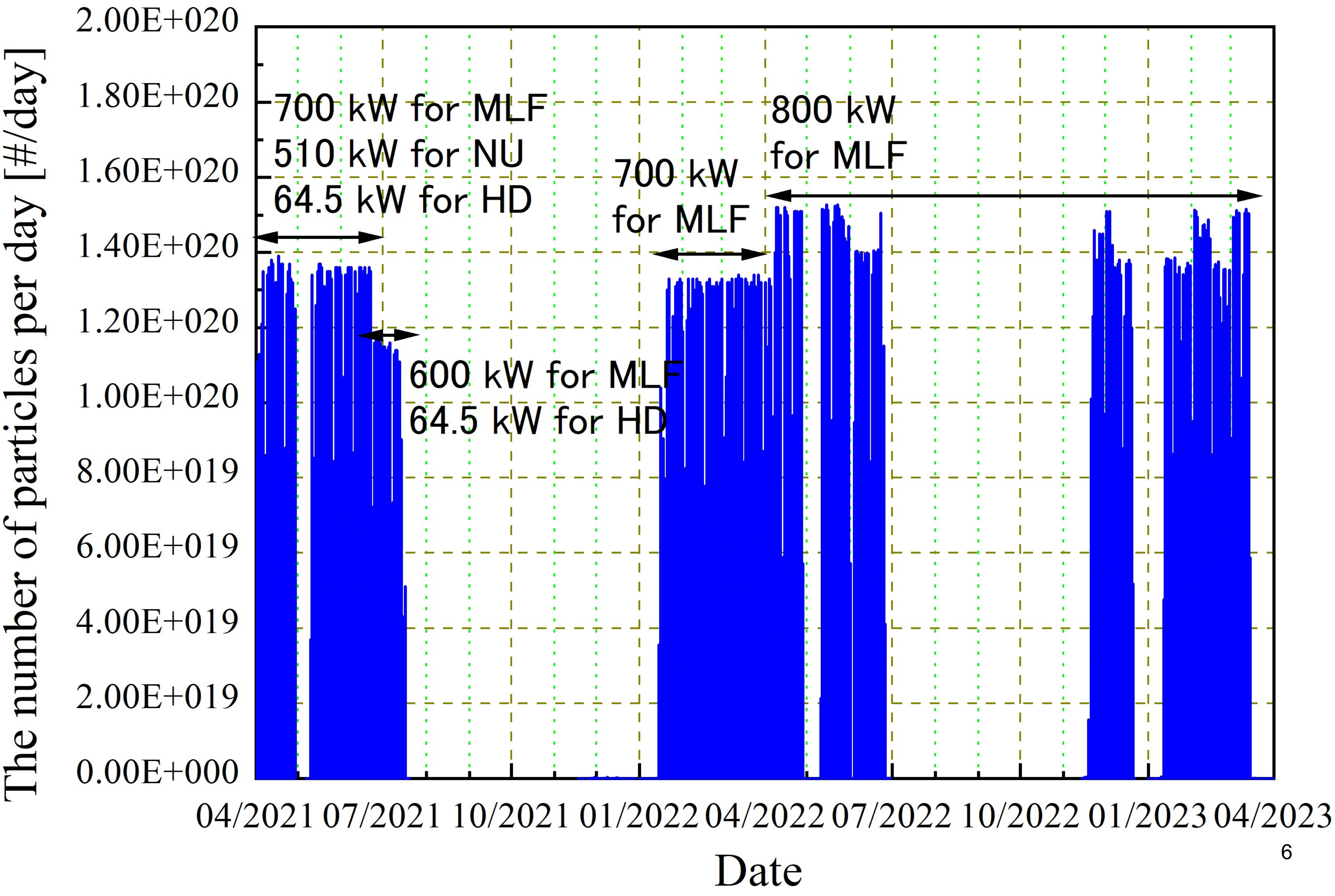
One of the three-fold symmetric lattice comprises two arc modules and a long straight insertion.

Time Structure of accelerator operation

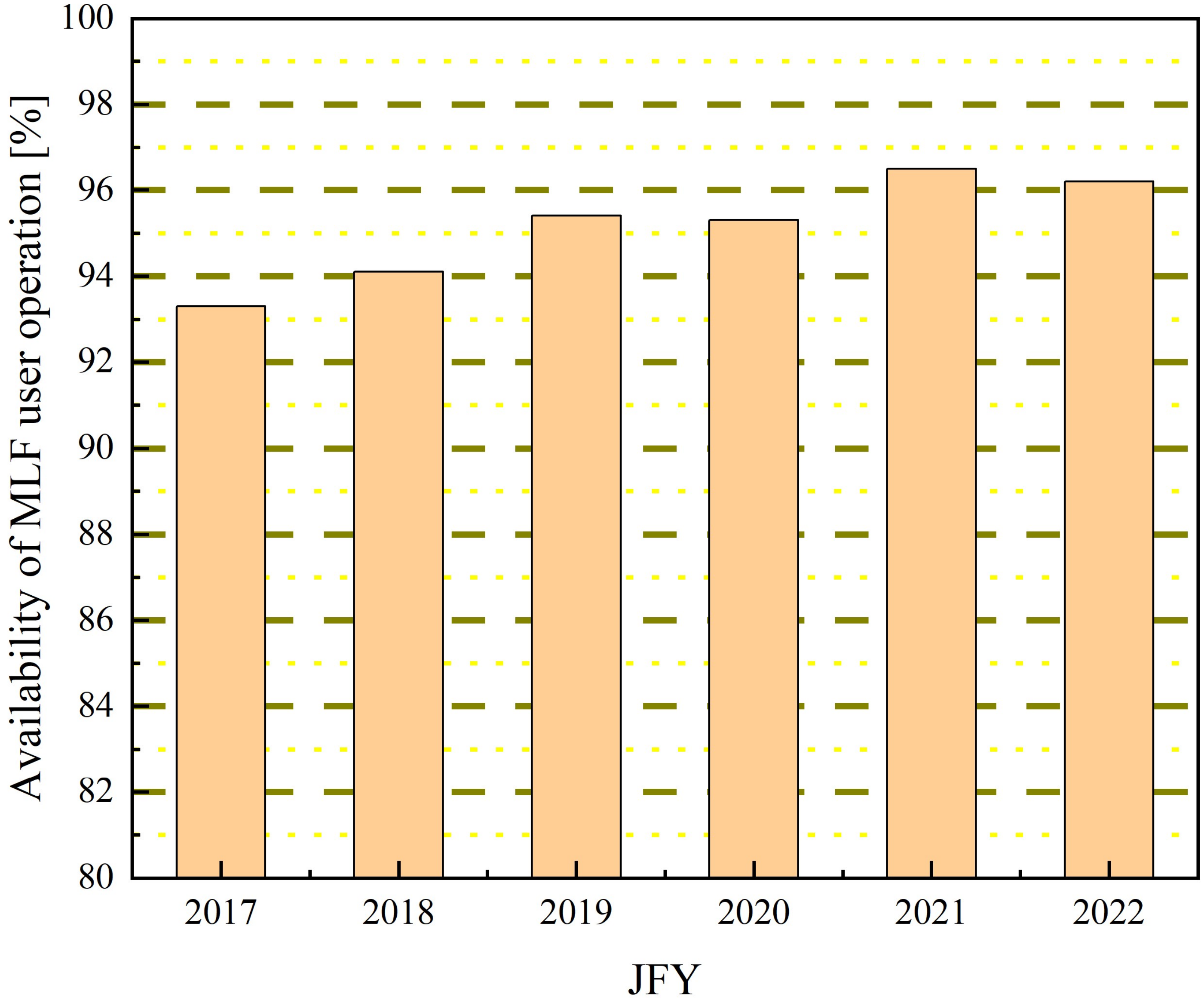


MR operation cycle was shorten!
FX:2.48 s -> 1.36 s (MLF Duty 93.5%->88.2%)

User operation of RCS



Reliability



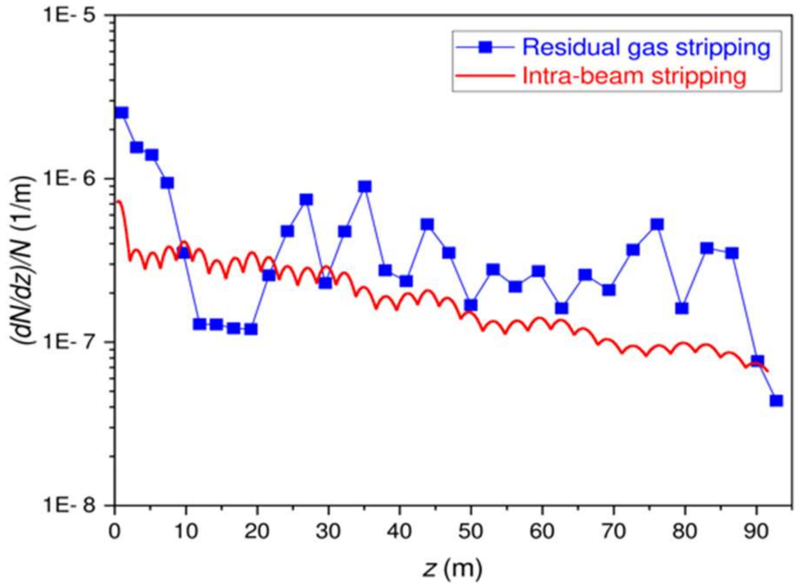
For neutron and muon users, there is no serious trouble in recent five years. (LI, RCS and MLF)

Recent beam commissioning results

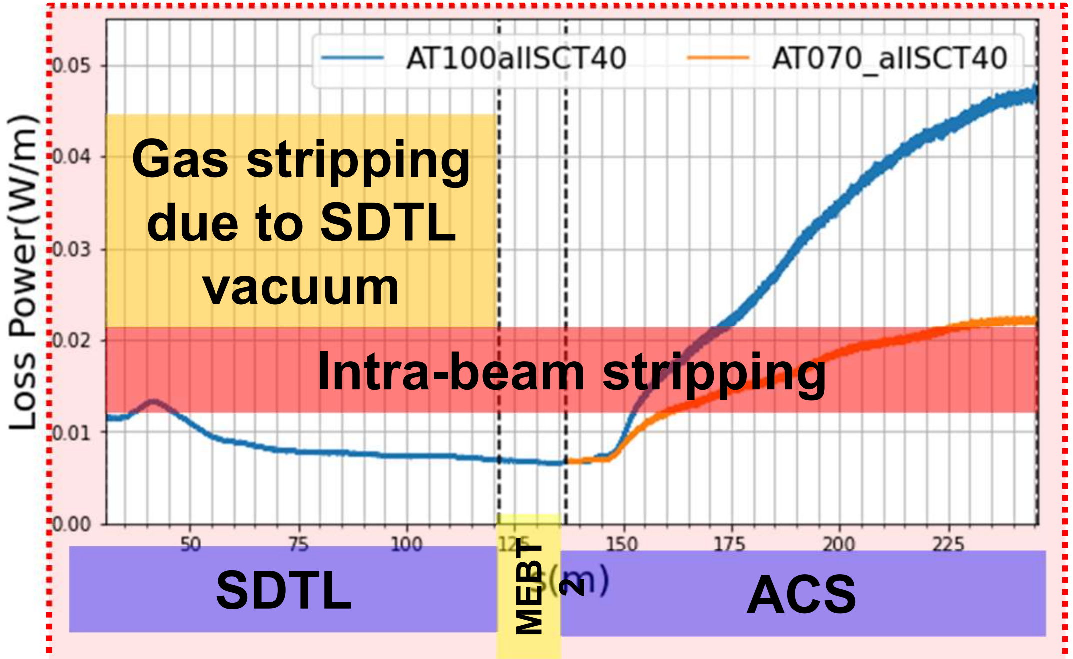
- We already demonstrated a 1-MW beam operation.
- Now we tried further reduction of the beam loss in Linac and RCS.

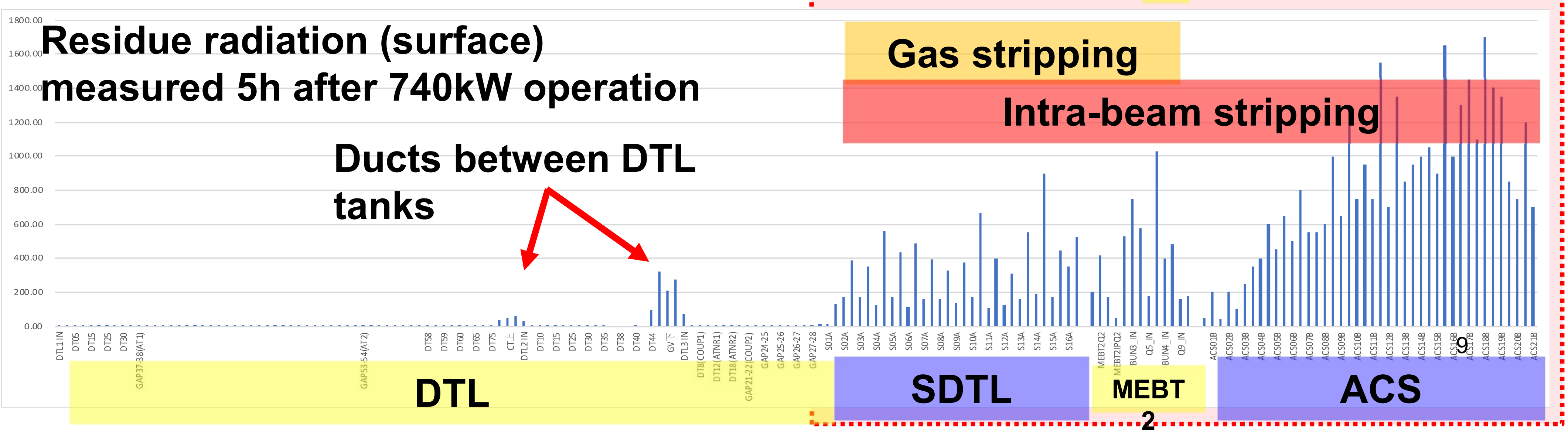
Beam Loss Pattern Simulation vs. Measure Residue

Gas stripping estimated in SDTL



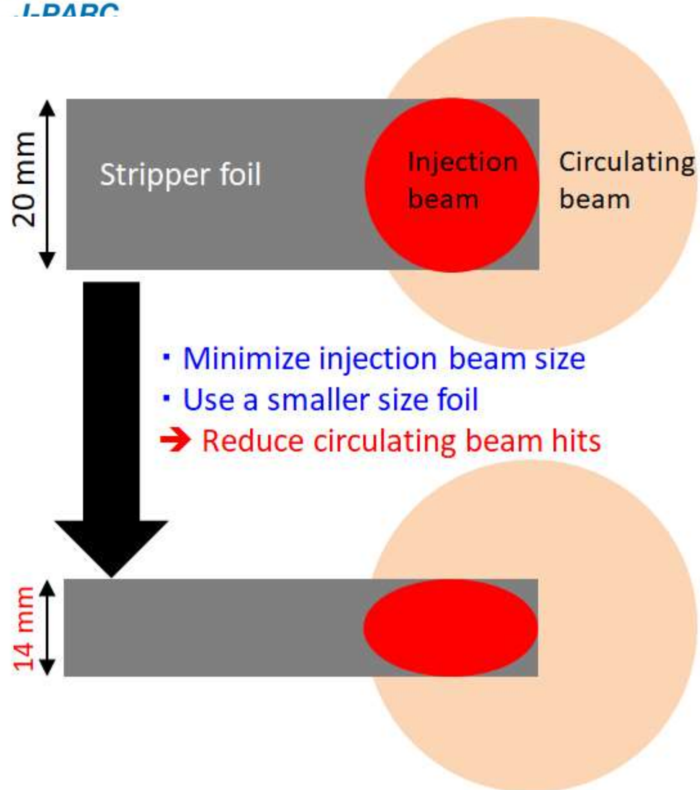
Simulation of loss location

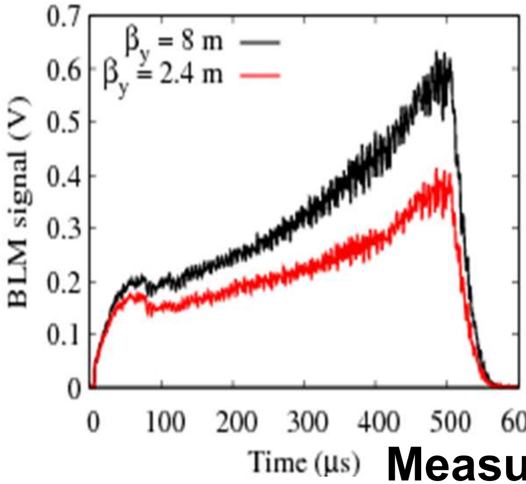


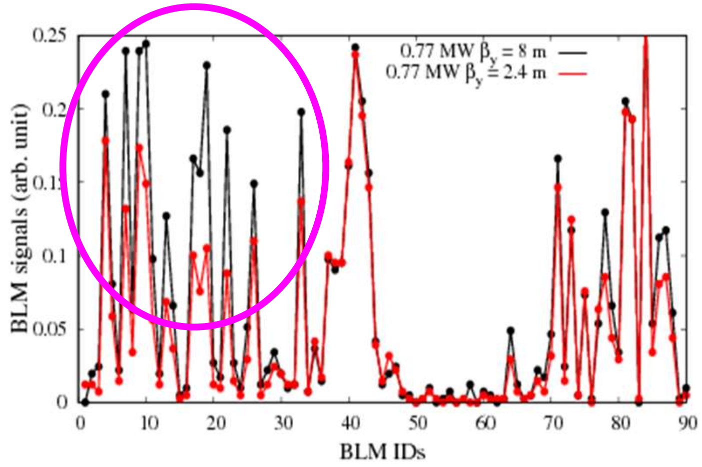


Acctivation related loss mechanism is quantitatively understood

Improvement of RCS beam losses

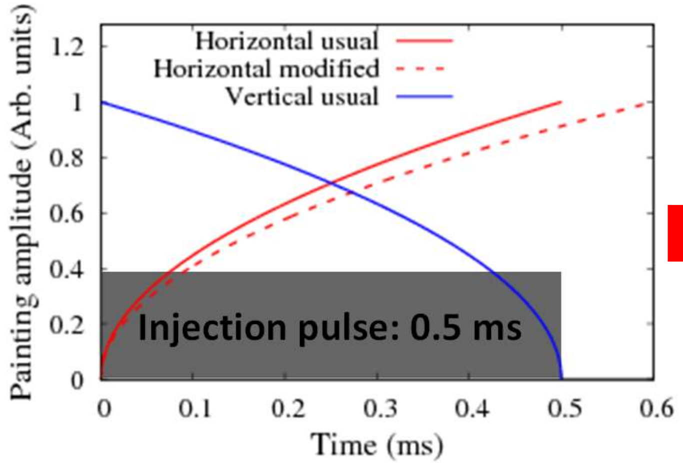


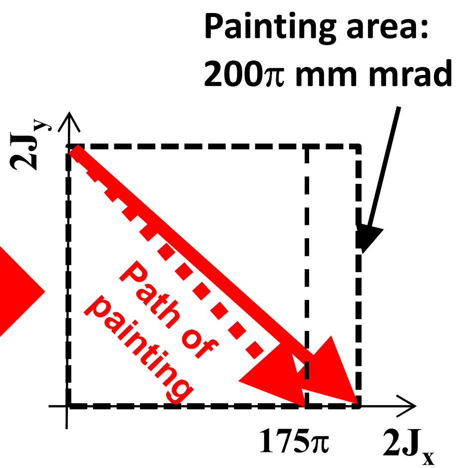




Measured foil hits:

30% reduced, loss also reduced same level

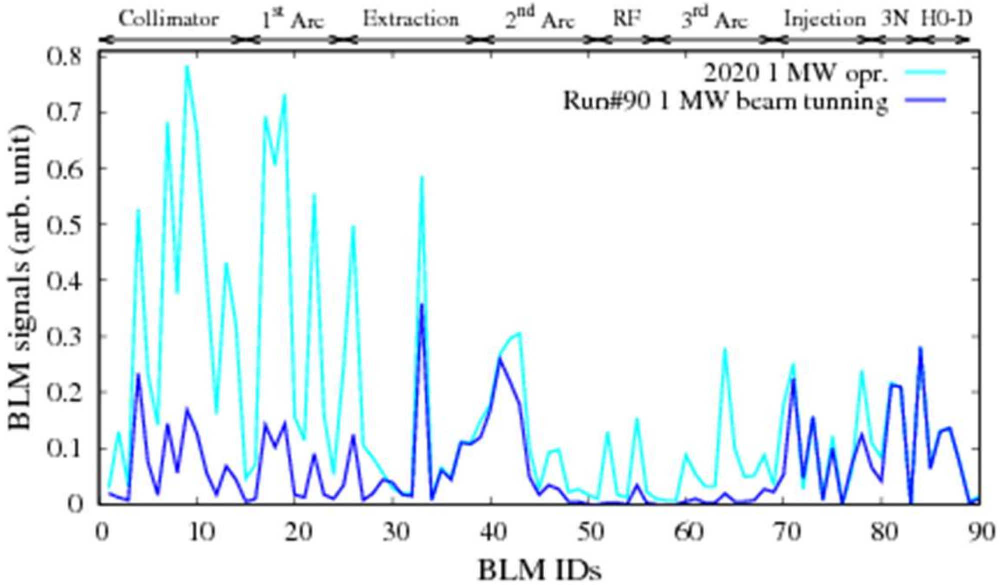




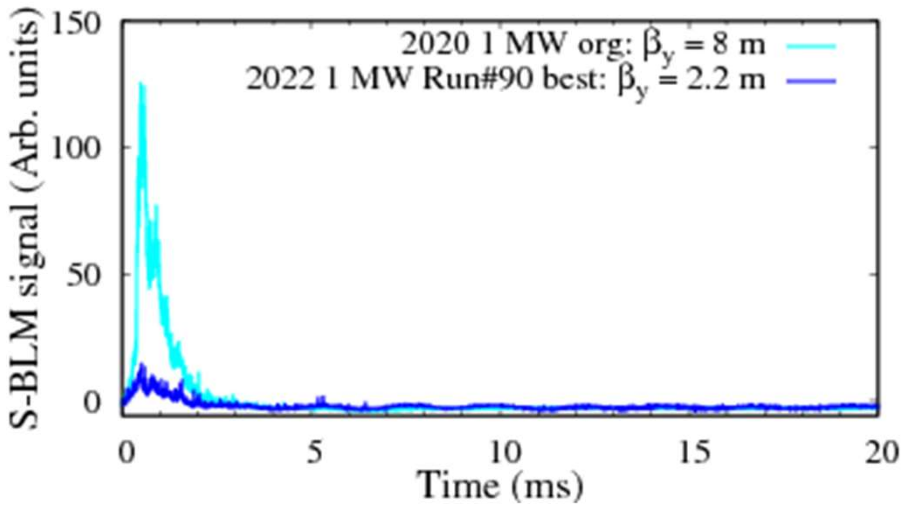
- ✓ **Minimized injection beam and the foil size.**
- ✓ **Optimized transverse and longitudinal paintings.**
- ✓ **Optimized betatron tunes.**
- ✓ **Reduced $3\nu_x = 19$ effect due to intrinsic sextupole of SB by reducing ×0.8 field.**

The unpainted region is filled by the space charge.

Summary of latest beam loss mitigation at 1 MW



Time structure of the beam loss



We have achieved more than 80% beam loss mitigation at 1 MW as compared the trail operation in 2020.

- **The residual beam loss is < 0.05%. Dominated by the foil scattering.**
- **We will try to further reduce the foil size.**

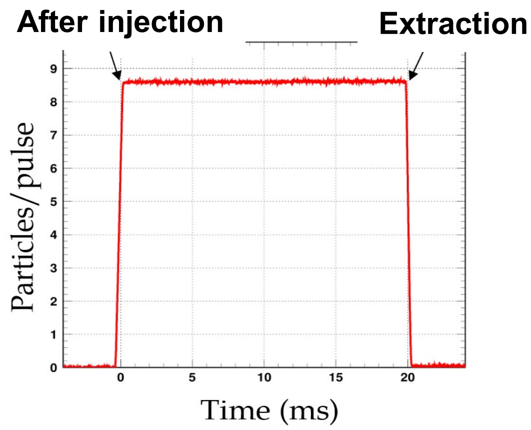
→ We expect 1 MW operation with a minimum beam loss in the RCS!

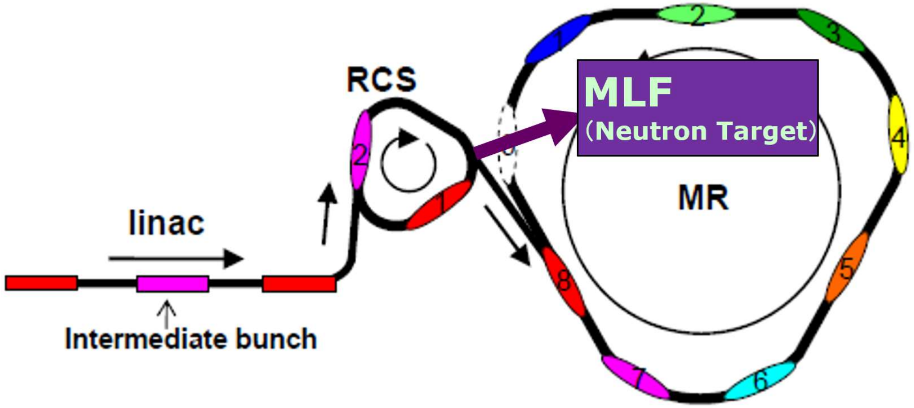
Upgrade to 2 MW

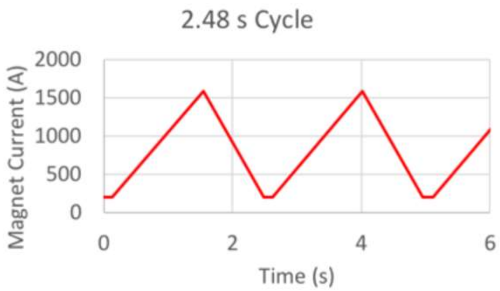
Motivation

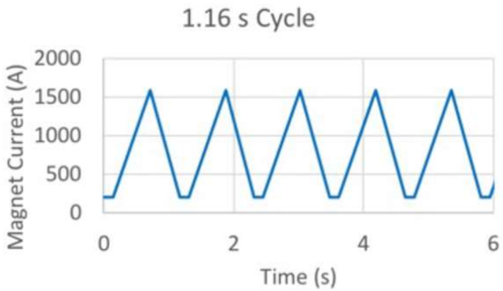
- The J-PARC Rapid Cycling Synchrotron (RCS) successfully demonstrated 1-MW beam acceleration with quite low loss condition. Now Main Ring(MR) cycle is shortened to increase its beam power. Shorter MR cycle affects the effective beam power on the neutron target. (MR duty Before:0.16/2.48~6% After:0.16/1.16~14%)

Beam current@1 MW

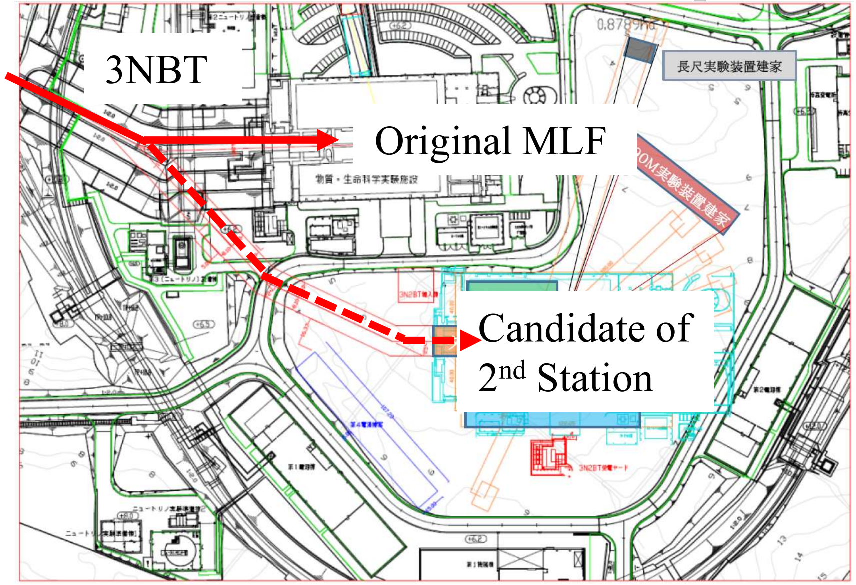








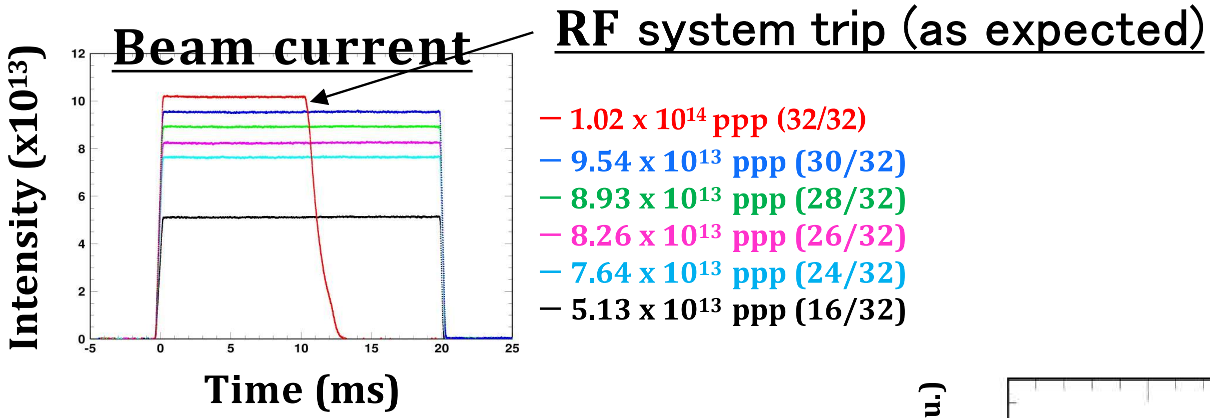
- We also have a plan to construct a second-target station for the neutron and muon experiments.



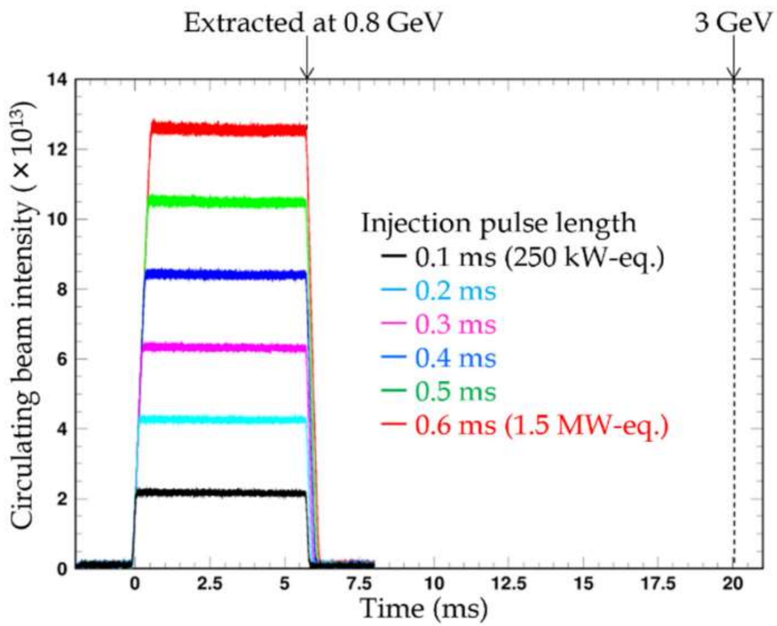
It is critical to evaluate the maximum beam power of the RCS to consider the upgrade path of J-PARC!

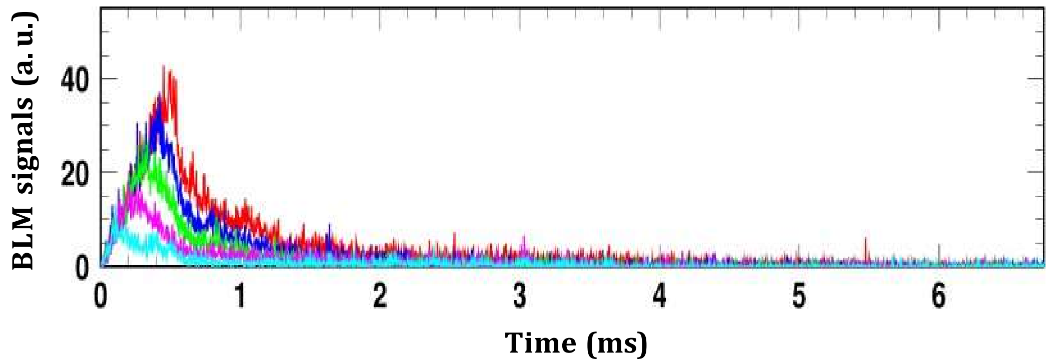
Demonstration beyond 1 MW (Cont'd)

Currently, the capacity of the anode power supply of the RF system limits the maximum number of particles that can be accelerated. The RF bucket is distorted due to the wake voltage caused by the high beam current of more than 1-MW, and all beams are lost at the middle stage of acceleration.



Courtesy : H. Hotchi





✓ Beam loss were proportional to the beam current.→well controlled!

The study results demonstrate the potential of the RCS beyond 1-MW power.

Scenario Beyond 1-MW

Requirement for the linac

Courtesy : T. Morishita

Relationship between the rapid-cycling synchrotron (RCS) output power, the linac peak current, and macro-pulse length

RCS output power[MW]		Peak current [mA]					
		50	60	70	80	90	100
Macro-pulse length [ms]	0.5	1.05	1.26	1.47	1.68	1.89	2.10
	0.55	1.15	1.38	1.62	1.85	2.08	2.31
	0.6	1.26	1.51	1.76	2.01	2.27	2.52
	0.65	1.36	1.64	1.91	2.18	2.45	2.73
	0.7	1.47	1.76	2.06	2.35	2.64	2.94
	0.75	1.57	1.89	2.20	2.52	2.83	3.15
	0.8	1.68	2.01	2.35	2.69	3.02	3.36

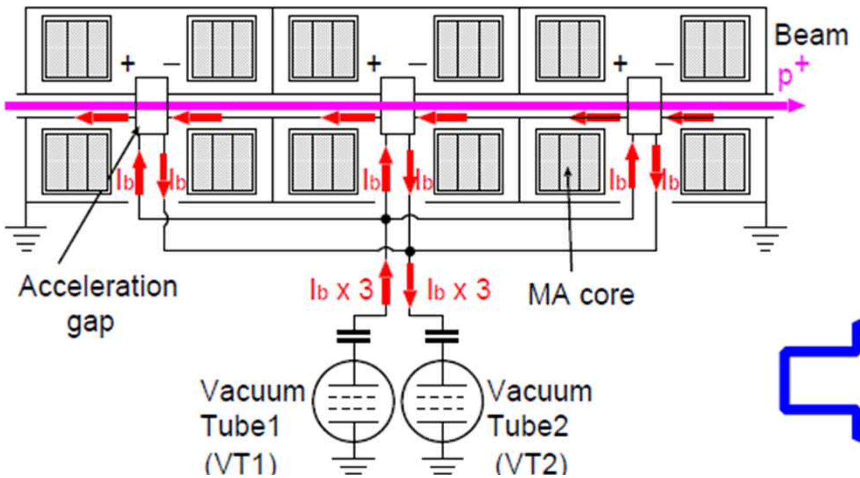
- **Some parameter choices exist in the linac to achieve more than a 1-MW beam power in the RCS.**

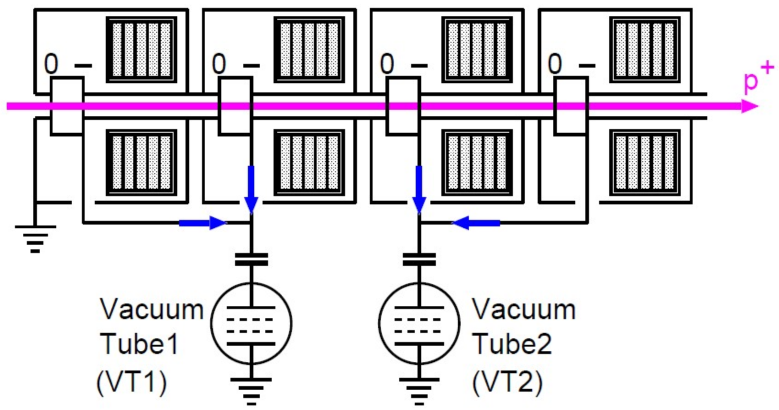
- **A higher peak current is better for the RCS for mitigation of the injection loss due to the foil scattering. However, then beam control in the linac becomes challenging in the higher peak current beam.**
- **In the longer macro-pulse case, we demonstrated the beam dynamics with the peak current of up to 60 mA in the linac. However, we must reinforce the linac RF system to extend the macro-pulse length.**
- **So far, 80 mA and 0.75 ms are the targets for future linac upgrades.**
- **Optimizing these parameters, we will try up to 2-MW beam acceleration.**

RCS Upgrade Items -New RF cavity-

The priority in the RCS upgrade is replacing the RF cavity

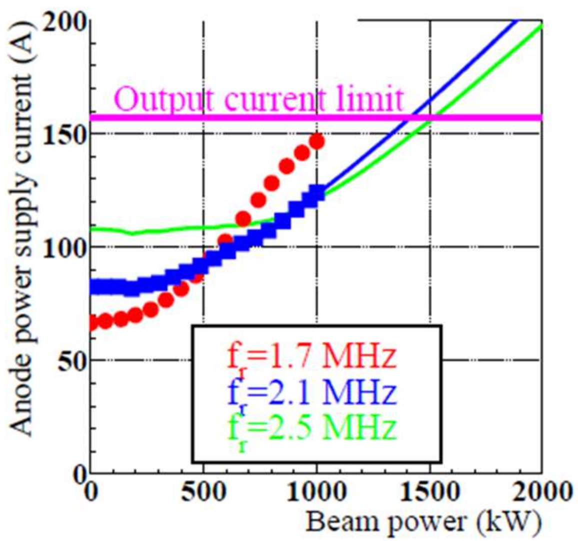
- Negative sign cavity

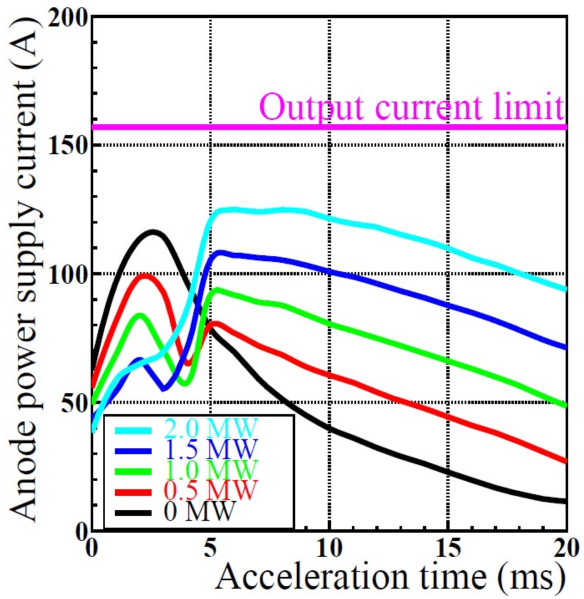




Not enough margin for 1-MW acceleration

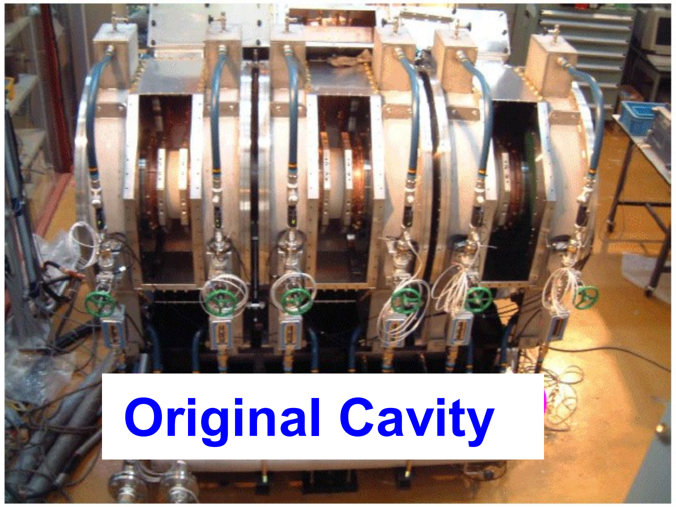
Develop the new cavity for high power acceleration!



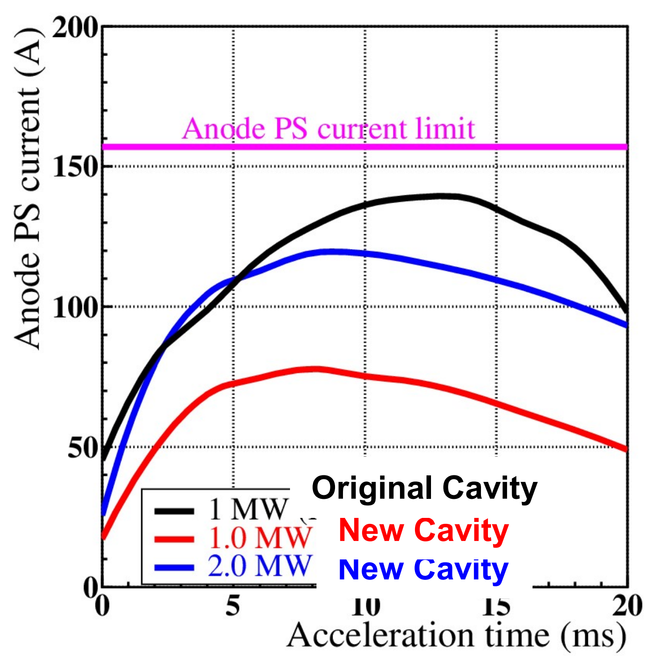


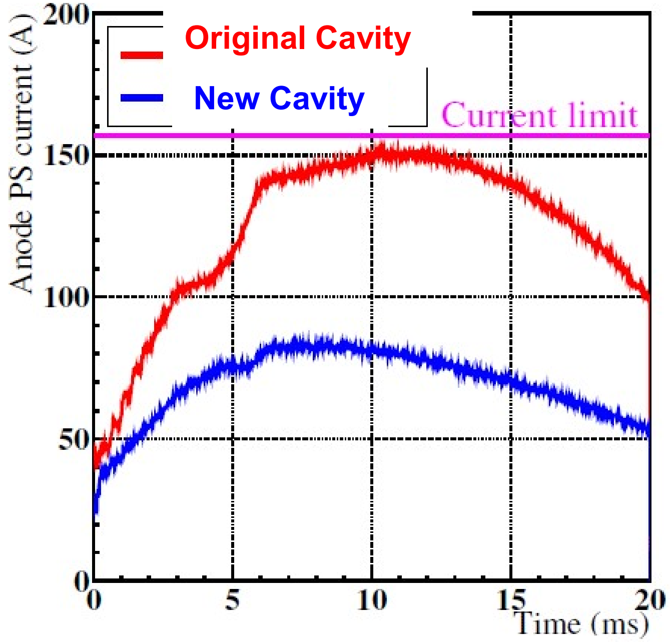
Detail :M. Yamamoto et al., "Development of a single-ended magnetic alloy loaded cavity in the Japan Proton Accelerator Research Complex rapid cycling synchrotron", *Prog. Theor. Exp. Phys*,073G01, 2023. doi: 10.1093/ptep/ptad085

Result of New cavity test



We replaced 1 of 12 cavities with new one.





(left)Simulation (right)actual result

Anode current during the acceleration

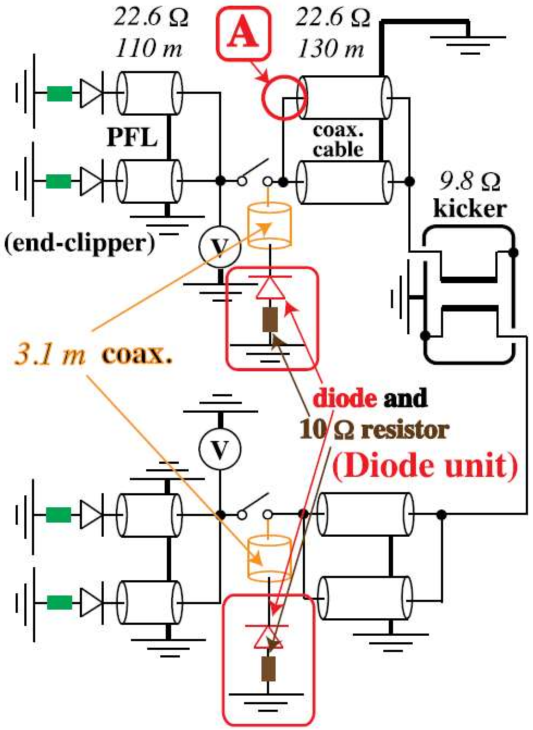
Reduced to 60% !

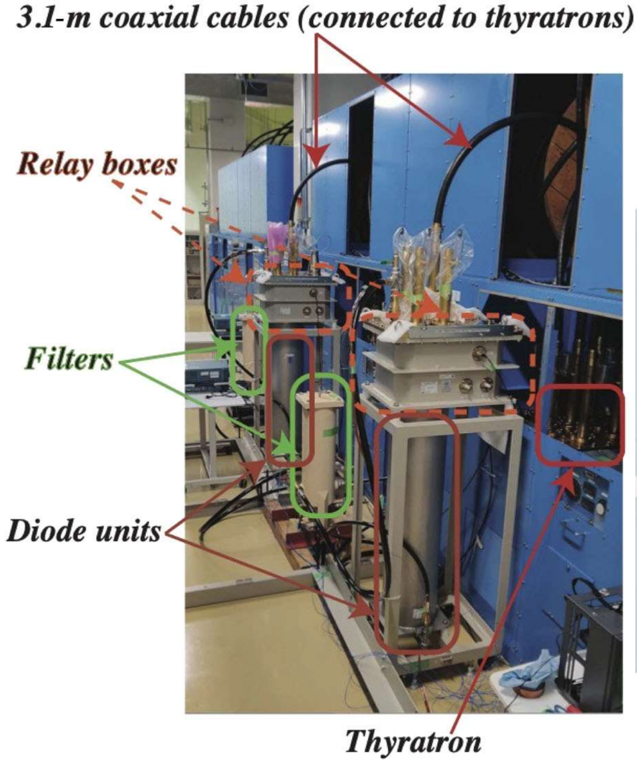
We have started mass-production.

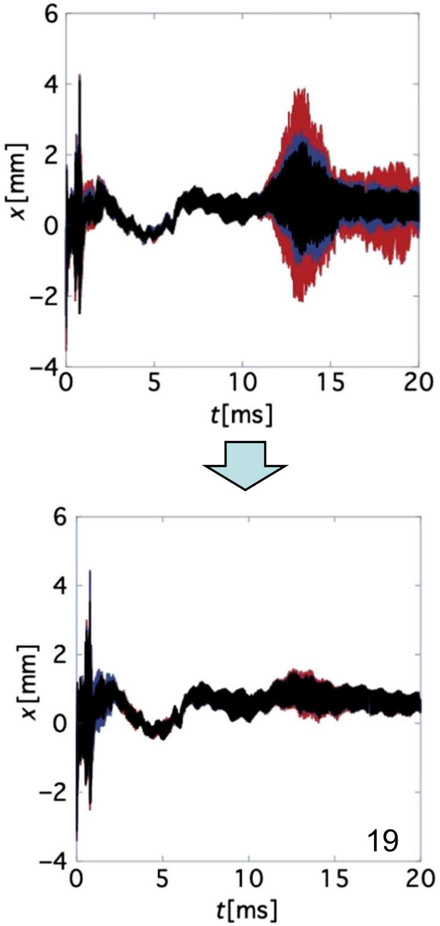
The replacement will be completed by 2028. After replacement, the new RF system can accelerate more than a 1-MW beam in the RCS.

RCS Upgrade Items
-Impedance reduction damper-

- Even with a beam current of 1 MW, the poor choice of some parameters (e.g., betatron tune, chromaticity correction pattern) can lead to beam instability.
- In the RCS, the primary source of the instability is the transverse impedance of the extraction kicker magnets.
- A new damping system was developed to suppress the instability.
- Our simulation indicated that four damping modules are needed to achieve a 1.5-MW full acceleration. We plan to install four damping modules; one module was already implemented with another one being installed this autumn, while the others are under construction.
- For 2 MW, possibly all 8 kicker would need this dumper. We will add rest four damping modules if needed.





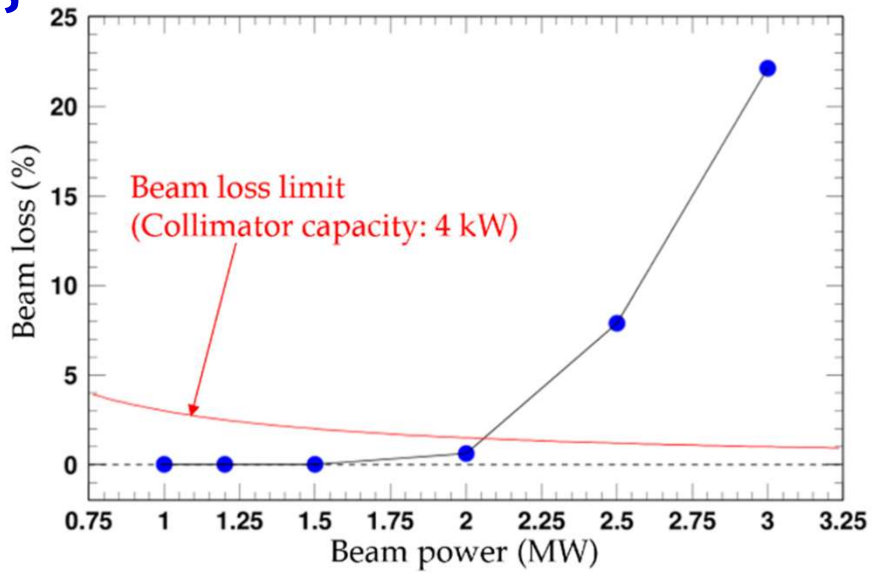


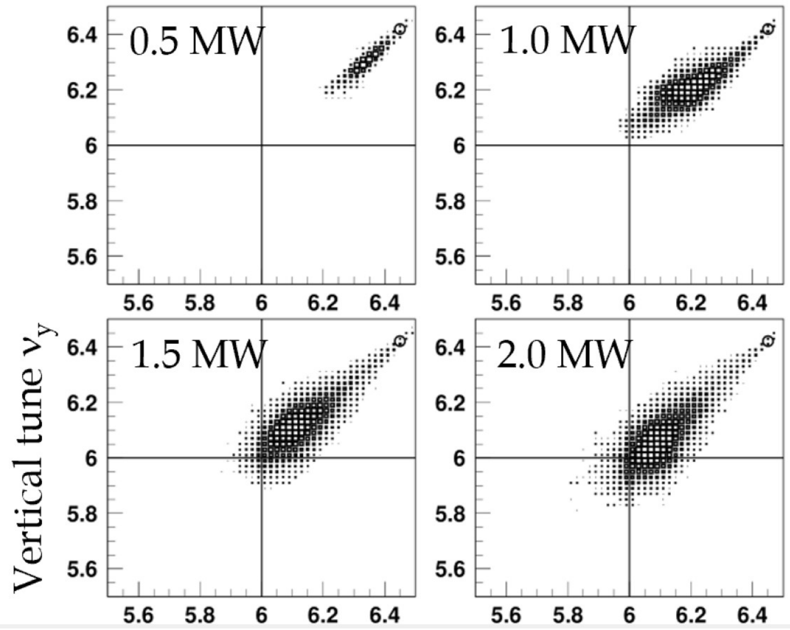
Courtesy : Y. Shobuda

Perspective of the beam manipulation beyond a 1-MW beam intensity

J-PARC

Courtesy : H. Hotchi

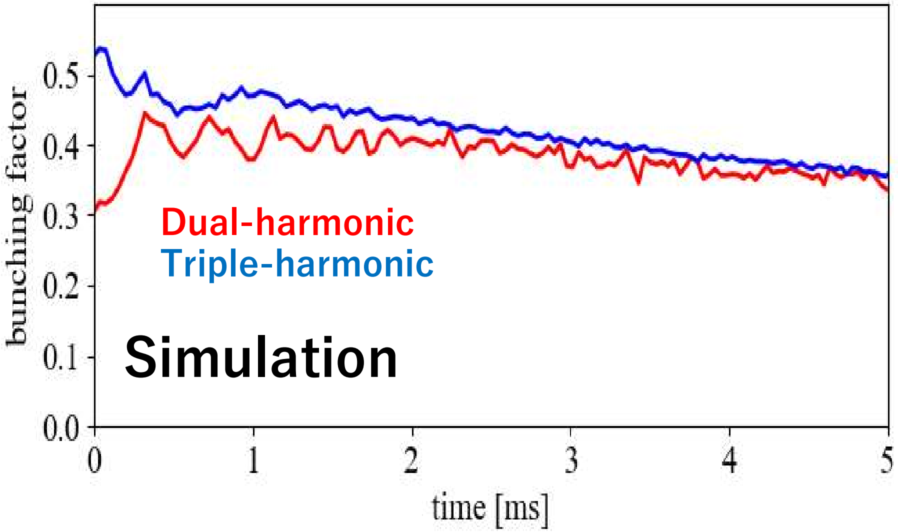


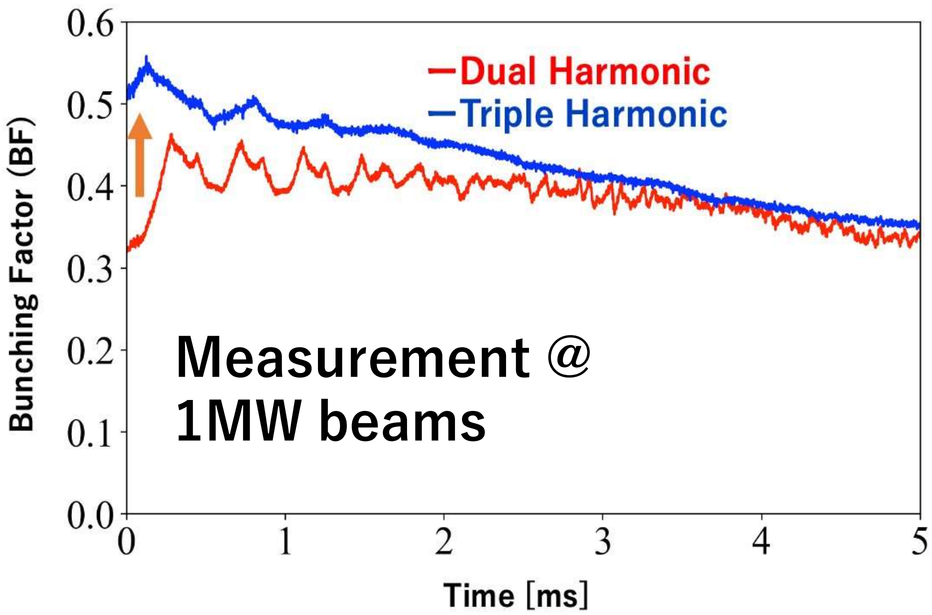


- Previous simulations indicated that the number of particles in the RCS would be limited to less than a 2 MW equivalent.
- Thanks to the space charge effect caused by the high-intensity beam of more than 2-MW, an excessive tune shift occurs and causes a large amount of beam loss.
- Flattening the beam distribution and reducing the high-density portions mitigate the space charge effect. We have been applying the dual-harmonic RF operation for the longitudinal beam manipulation.
- This scheme enables us to accelerate a 1-MW beam with enough low-loss conditions but not enough for more than a 1.5-MW beam.
- Recently, we have started to study the triple-harmonic RF operation applied for high-intensity beam acceleration.

Triple-harmonic RF operation

Courtesy : H. Okita





- Upper figure shows the bunching factor (BF) simulation results with the dual and triple-harmonic schemes.

$$BF = \frac{I_{average}}{I_{peak}}$$

- Lower figure is a beam test results.
- Higher BF means more flat and low peak density beams.
- Simulation results reproduced the actual beam behavior well.
- Promising for >1MW beam with small beam loss!

Summary

- We achieved stable user operation with up to 800 kW.
- We have demonstrated the potential of the RCS beyond 1-MW beam power.
- We will complete the replacement of all cavities with new ones by 2028.
- A list of items that are required beyond 1 MW beam acceleration is being developed in Linac and RCS.
- Finally, we will prepare to conduct beam acceleration tests at the highest intensity possible in 2028.
- Combining the increase of the linac peak current and the extension of the injection pulse length for the RCS, we will try up to 2-MW beam acceleration.