BEYOND 1-MW SCENARIO IN J-PARC RAPID-CYCLING SYNCHROTRON

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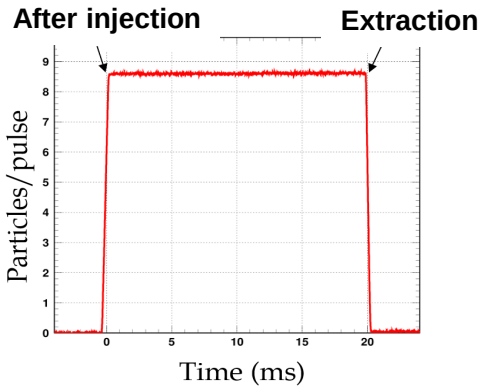
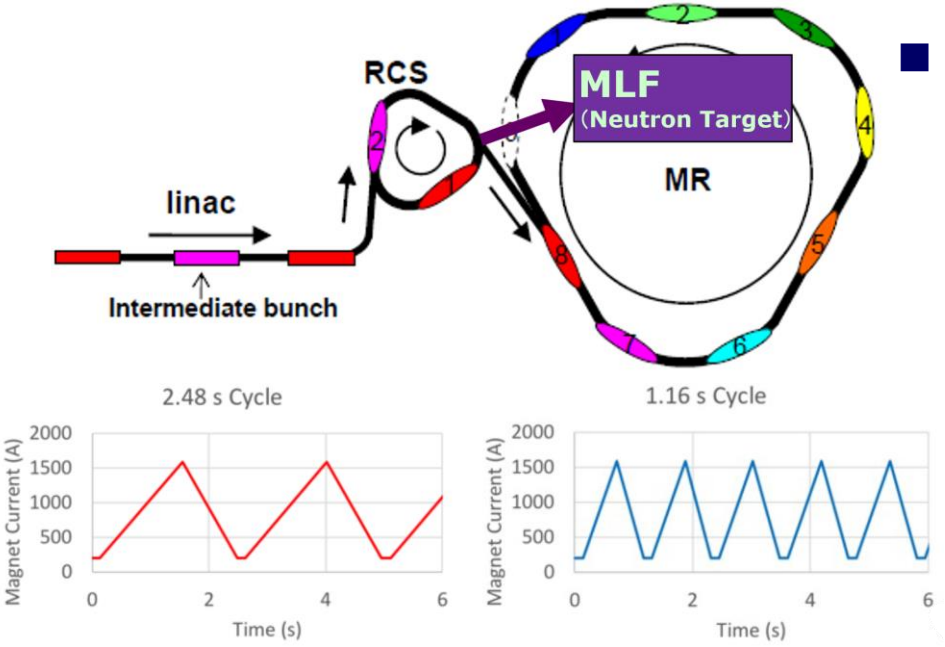
- Summary

Motivation

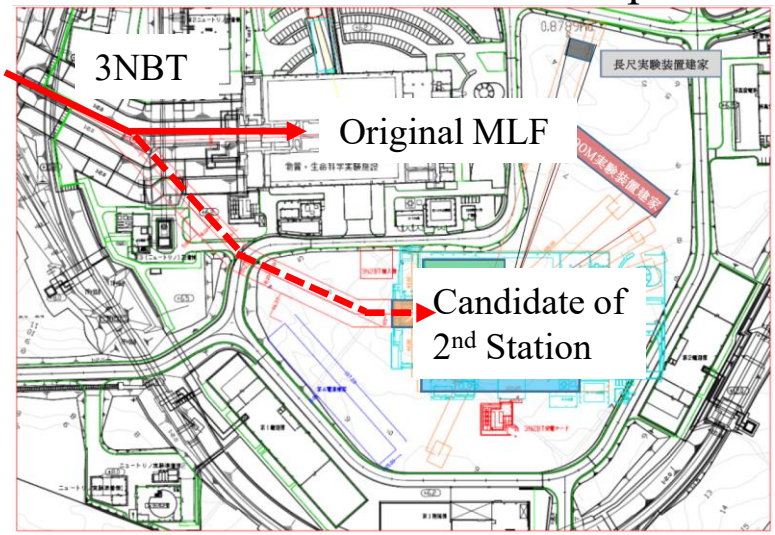
- The J-PARC Rapid Cycling Synchrotron (RCS) successfully demonstrated 1-MW beam acceleration with quite low loss condition. (Saha's presentation, TUA4l2)
- Now Main Ring(MR) cycle is shortened to increase its beam power. (Yoichi's presentation "Beam commissioning of the J-PARC MR after its high-repetition rate upgrade")
- 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.

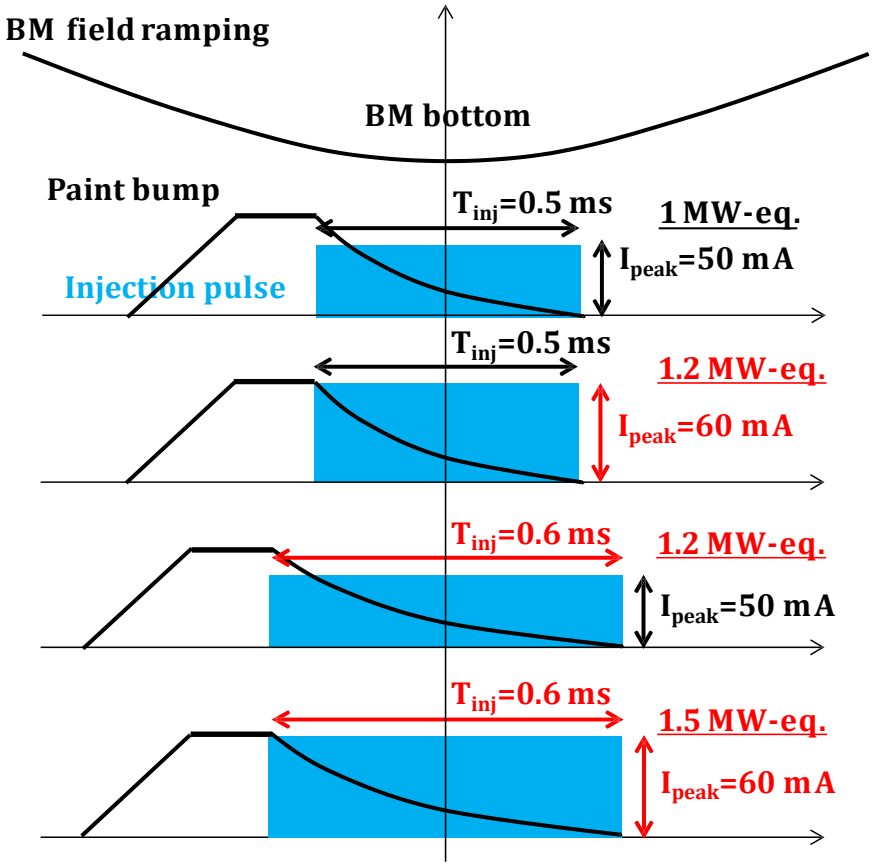


It is critical to evaluate the maximum beam power of the RCS to consider the upgrade path of J-PARC!

Demonstration Results Beyond a 1-MW Beam

Demonstration beyond 1-MW

We studied the potential of the RCS beyond a 1-MW power.



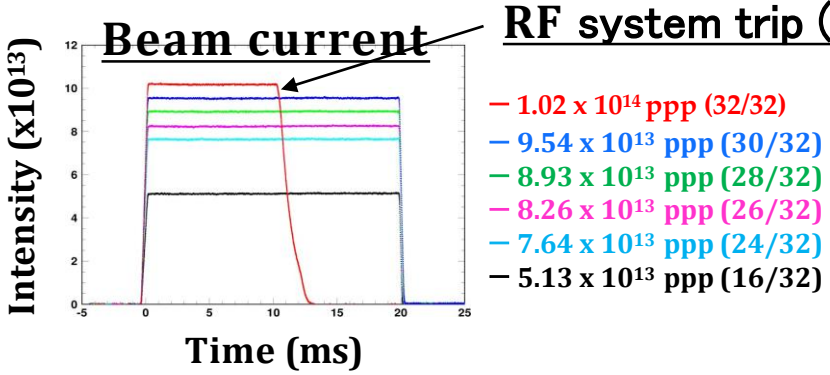
Original 1 MW acceleration scheme

- ✓ **1.2 MW-eq. Particle injection**
- ✓ **1.2 MW-eq. Particle injection**
- ✓ **1.5 MW-eq. Particle injection**

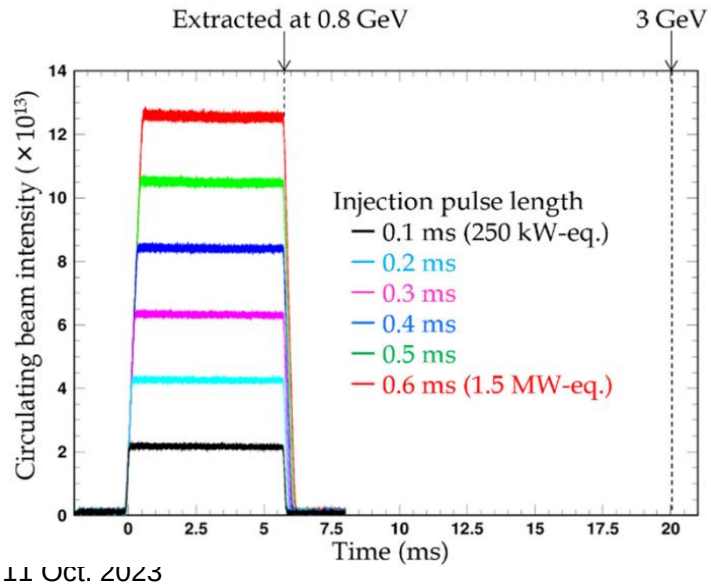
Injection Beam Parameters

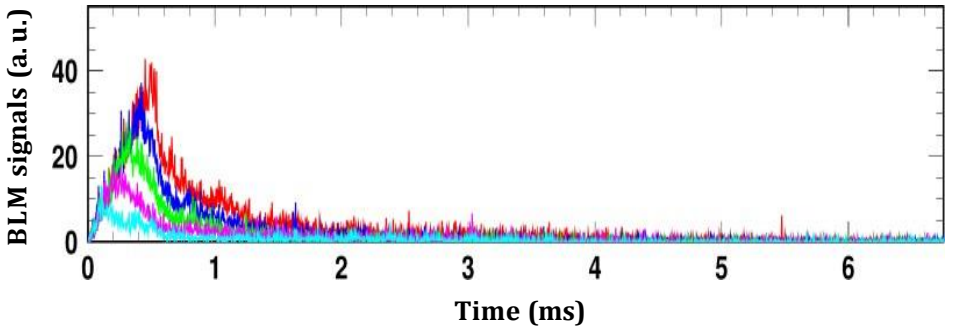
Demonstration beyond 1 MW (Cont'd)

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.**

Requirement for the linac (Cont'd)

Courtesy : T. Morishita

List of the study items

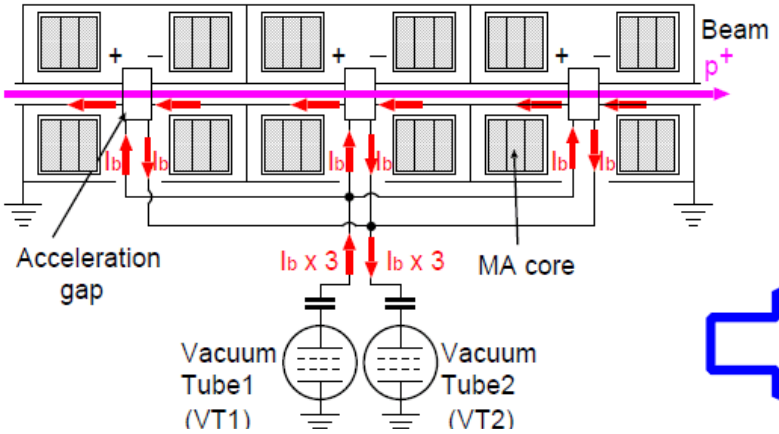
- Beam commissioning
  - Further study for the beam loss reduction
  - Especially the longitudinal beam parameters
- IS
  - Study in the test-stand with higher peak current and longer lifetime
- RF source
  - Development of the pulsed power supply
  - High efficiency High power Klystron
  - LLRF_FF improvement
- Cavity
  - DTL coupler and RF window replacement
  - Inproement of SDTL Vacuum level
  - DTQ pulse operation
  - Reinforcement of the cooling water system
- MEBT1
  - Study for low loss condition
  - Octupole magnet study for "Halo" control
  - Alternative chopper for longer lifetime

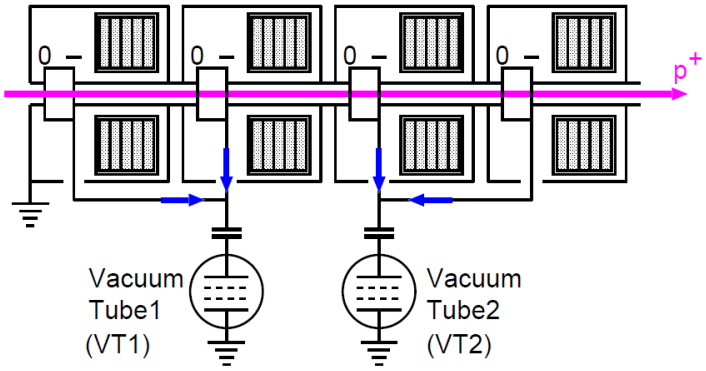
We have started these studies.

RCS Upgrade Items -New RF cavity-

The priority in the RCS upgrade is replacing the RF cavity

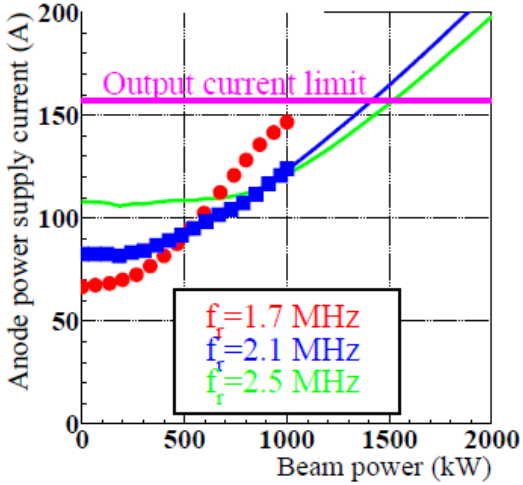
- Negative sign cavity

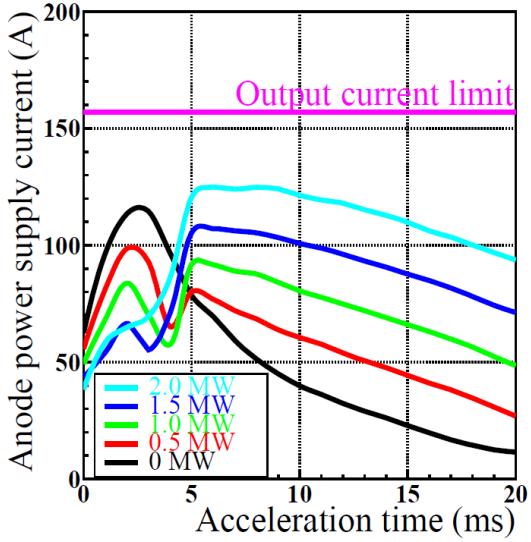




Not enough margin for 1-MW acceleration

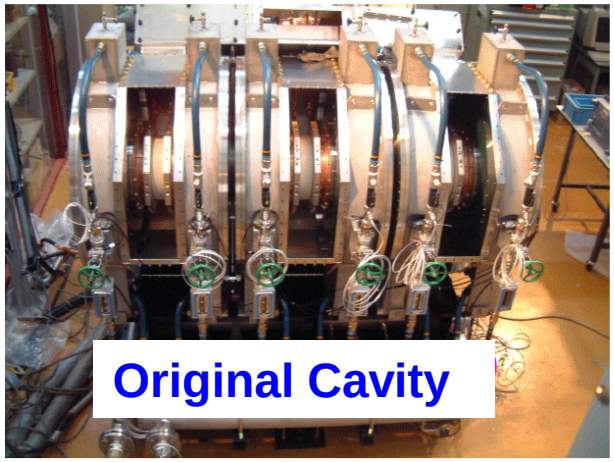
Develop the new cavity for high power acceleration!



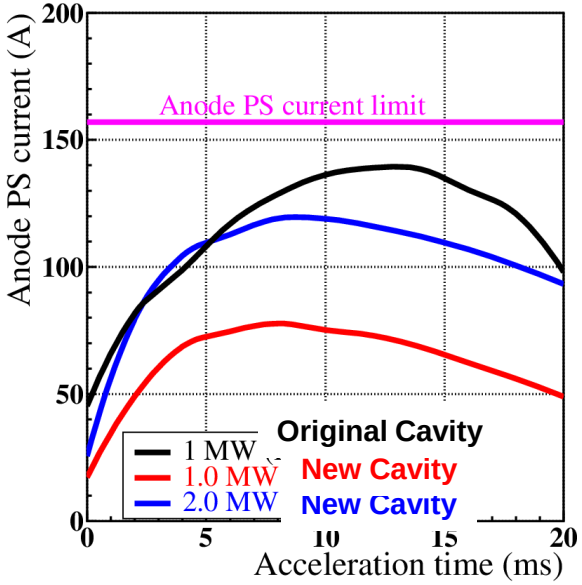


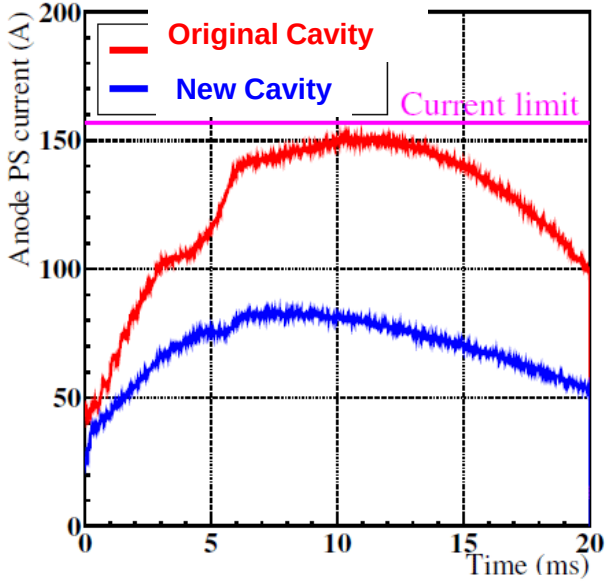
Detail :M. Yamamoto et al., "Development of a single-ended magnetic alloy loaded cavity in the Japan Proton Accelerator Research Complex rapid cycling synchrotron", *Prog. Theor. Exp. Phys*,073G01, 2023. doi: 10.1093/ptep/ptad085

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% !

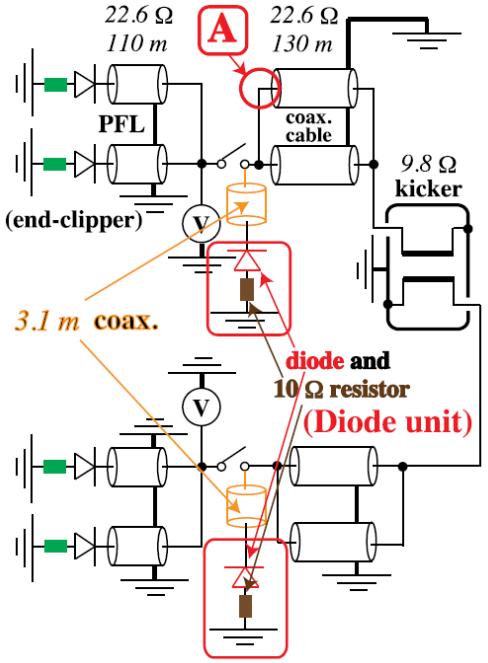
We have started mass-production.

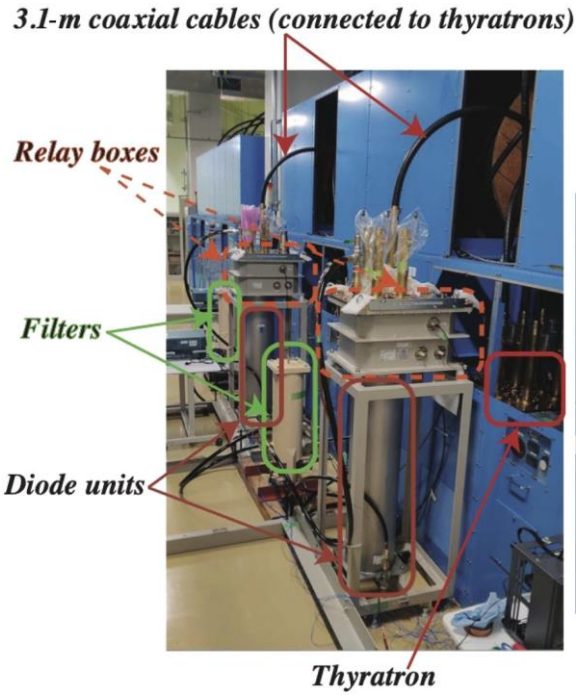
The replacement will be completed by 2028. After replacement, the new RF system can accelerate more than a 1-MW beam in the RCS.

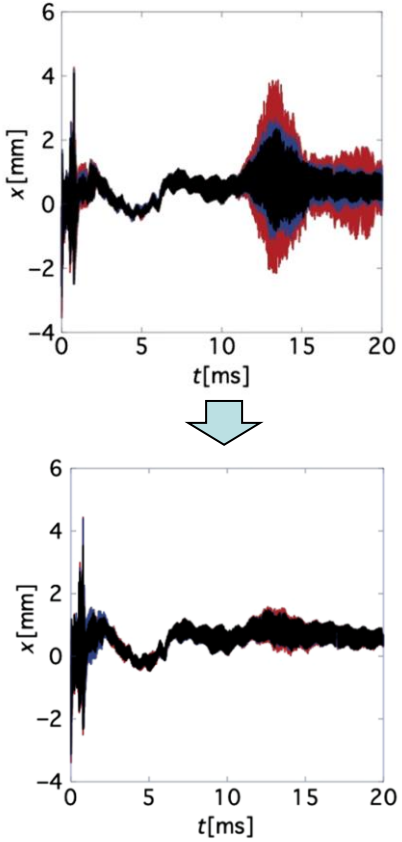
Detail:Fumihiko Tamura's presentation, WEC4l1

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.







Yoshi Shobuda's presentation, TUC4l1

Other study items in RCS

- In the ring RF system, not only cavity replacement but reinforcement of the amplifier chain is also required for more than 1-MW beam acceleration.

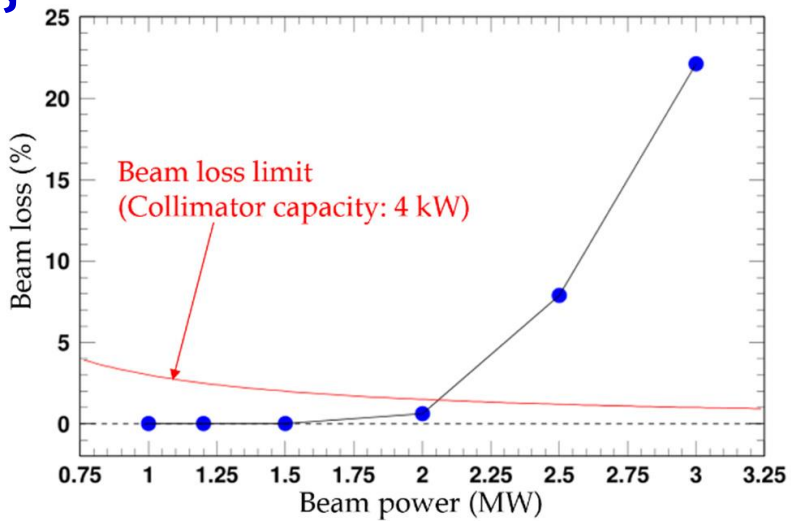
- The duration of the field patterns of the injection magnets must also be extended. The sift bump magnets, which make a bump orbit to merge the injection and circulating orbit, can extend the duration of the flat field to 0.7 ms with the present system. The requirements for the paint bump magnets, which make the particle distributions in the phase space, depend on the required paint pattern.

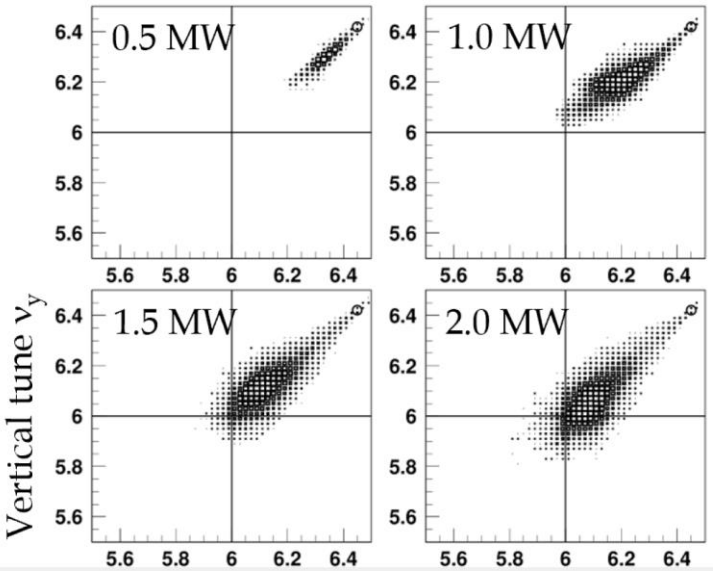
- We evaluated the dynamic range of each beam monitor and found that the beam current exceeds the measurement limit of the direct current (DC) current transformer. Thus, we are considering replacing it.

- In the RCS, a hybrid-type thick boron-doped carbon (HBC) foil was used for the charge exchange injection. Recently, we have developed pure carbon foil instead of HBC. It shows a similar performance to the HBC. We will evaluate the performance of the HBC and pure carbon foils for higher power operation.

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

Courtesy : H. Hotchi



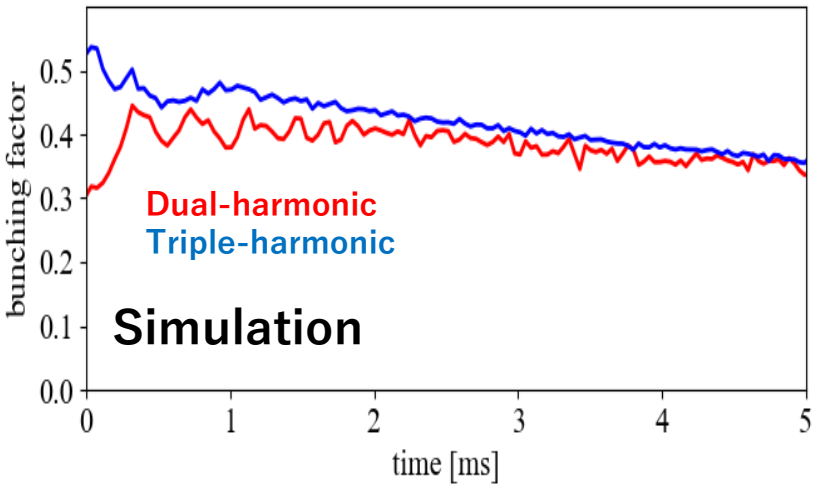


- Previous simulations indicated that the number of particles in the RCS would be limited to less than a 2 MW equivalent.
- Thanks to the space charge effect caused by the high-intensity beam of more than 2-MW, an excessive tune shift occurs and causes a large amount of beam loss.
- Flattening the beam 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.

  Detail:Fumihiko Tamura's presentation, WEC4l1
- 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.

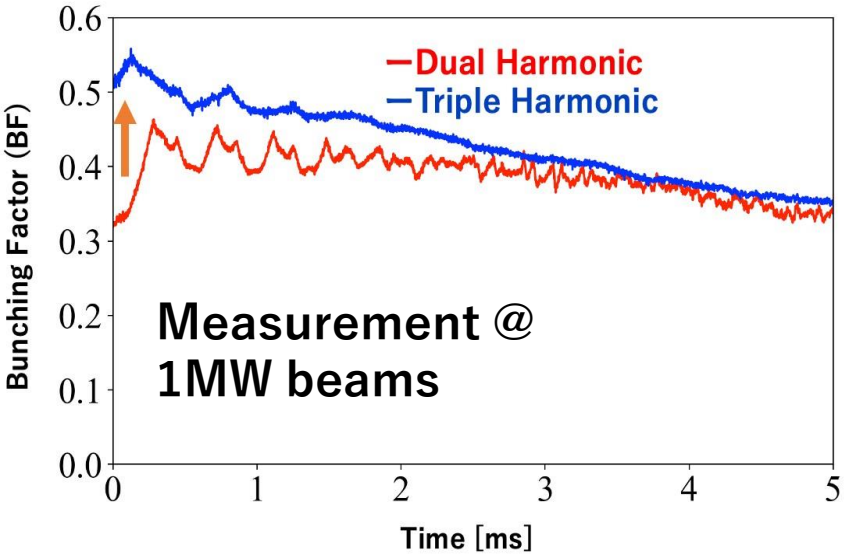
Triple-harmonic RF operation

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.
- Promissing for >1MW beam with small beam loss!

Summary

- **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.**