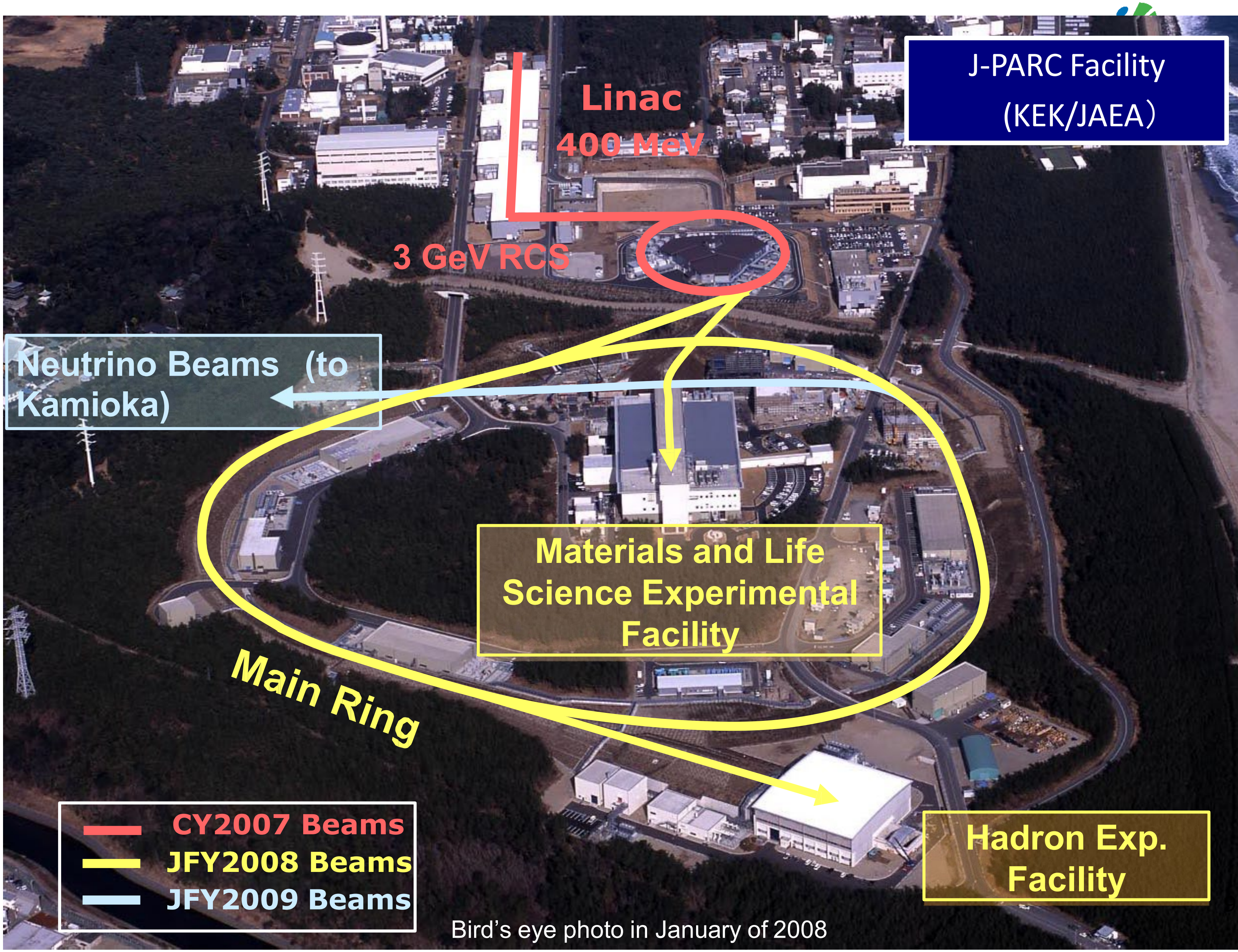
High intensity operations of J-PARC accelerators

Michikazu Kinsho

J-PARC Center
Japan Atomic Energy Agency (JAEA)



J-PARC Facility
(KEK/JAEA)
Linac
400 MeV
3 GeV RCS
Neutrino Beams (to Kamioka)
Materials and Life Science Experimental Facility
Main Ring
Hadron Exp. Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC Accelerators

High-intensity proton accelerators

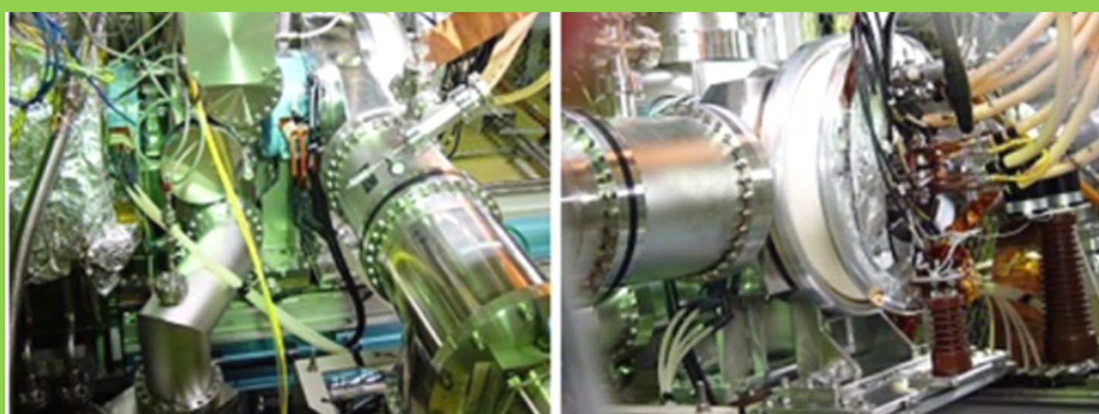
- **Linac**
  - length: 249 m
  - energy: 181MeV (- 2013), 400 MeV (2014 -)
  - beam extracted to RCS

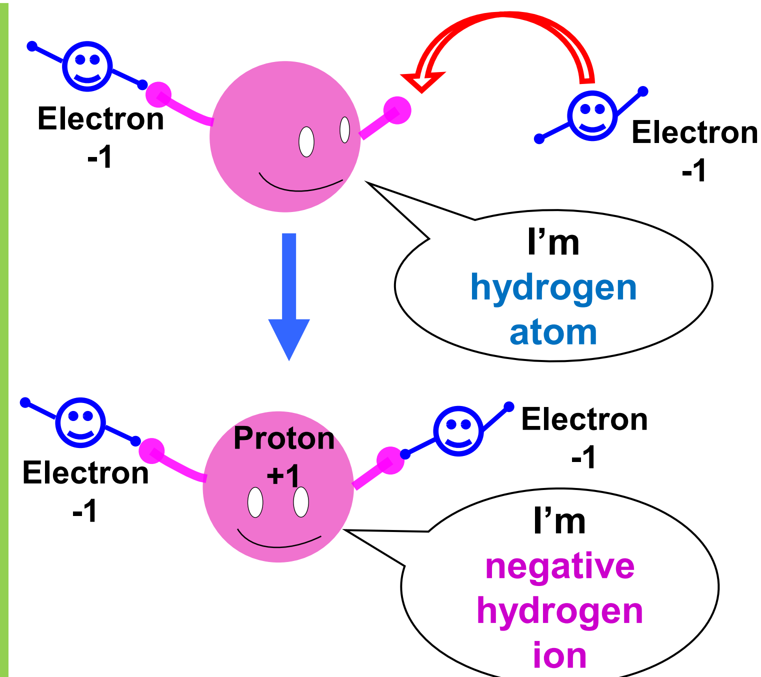
- **Rapid-Cycling Synchrotron (RCS)**
  - circumference: 348 m
  - energy: 3 GeV
  - design beam power: 1 MW
  - beam extracted to MR
    and Materials and Life Science Experimental Facil

- **Main Ring (MR)**
  - circumference: 1,568 m
  - energy: 30 GeV
  - design beam power:
    750 kW at 1st stage , 1300kW at 2nd stage for **Nu**
    100kW for **HD**
  - beam extracted to Neutrino Facility (Nu), or Hadron Facility (HD)

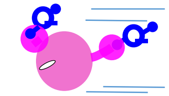
400 MeV linear accelerator

Ion source



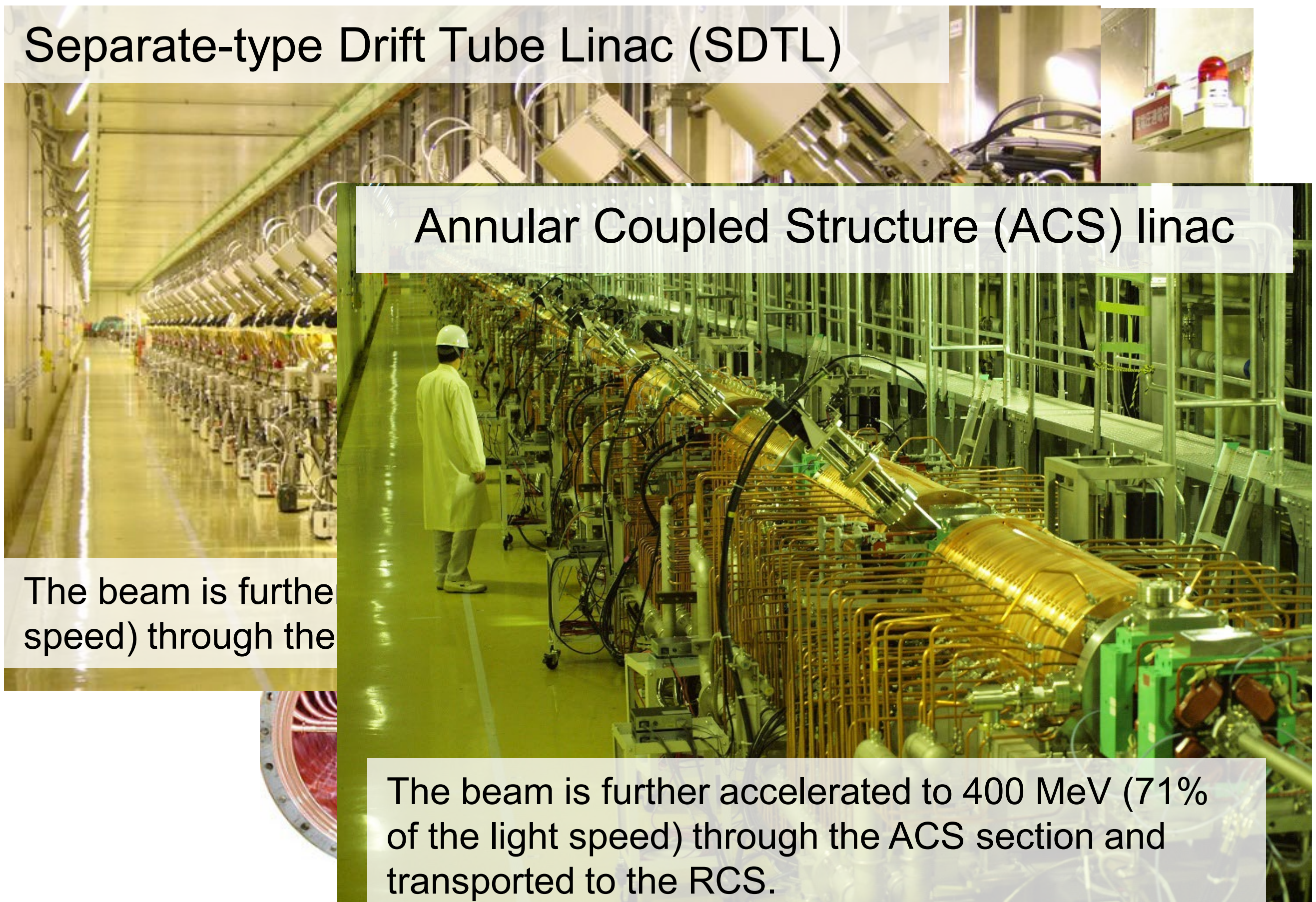


A negative hydrogen ion is produced by addition of an electron to a hydrogen atom



To 3 GeV synchrotron ← **ACS** — **SDTL** — **DTL** — **RFQ** — **Ion source**

400MeV	191MeV	50MeV	3MeV	50KeV	Energy



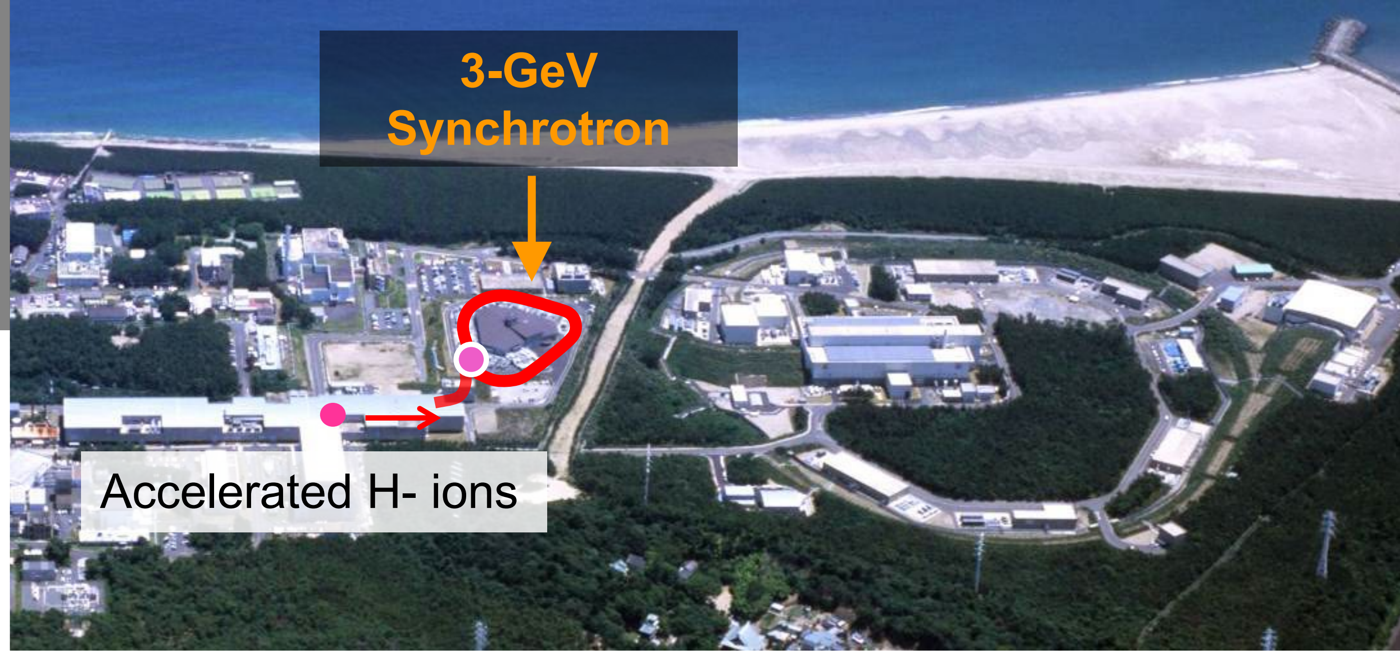
Separate-type Drift Tube Linac (SDTL)

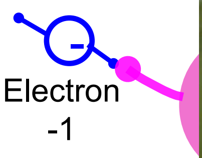
The beam is furthe
speed) through the

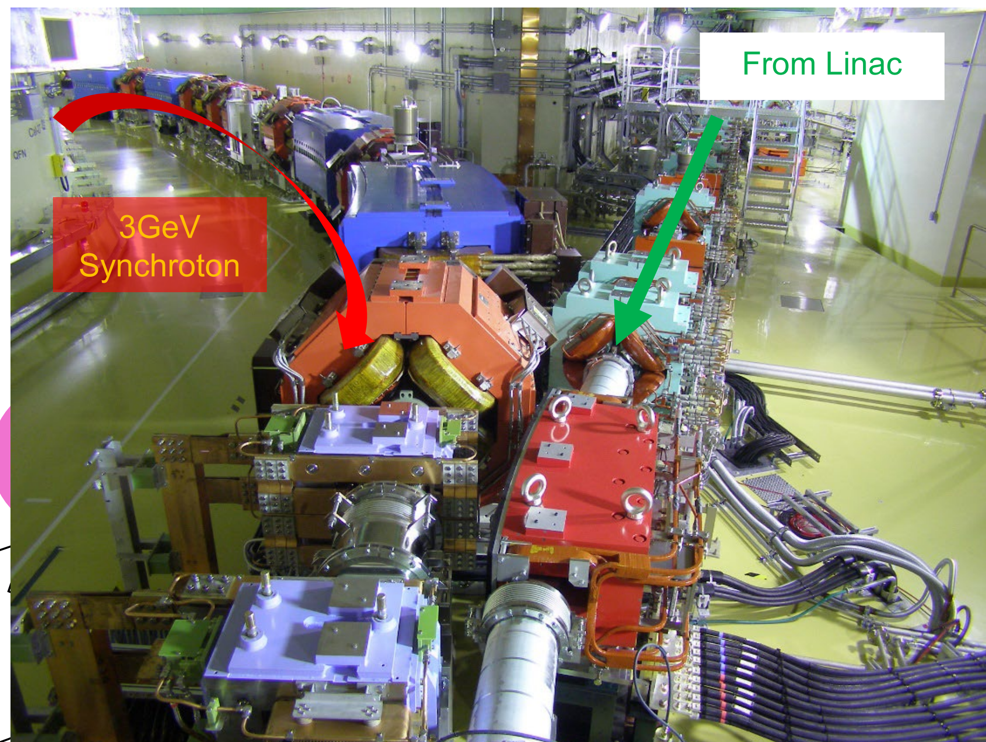
Annular Coupled Structure (ACS) linac

The beam is further accelerated to 400 MeV (71% of the light speed) through the ACS section and transported to the RCS.

3 GeV Rapid-Cycling Synchrotron (RCS)



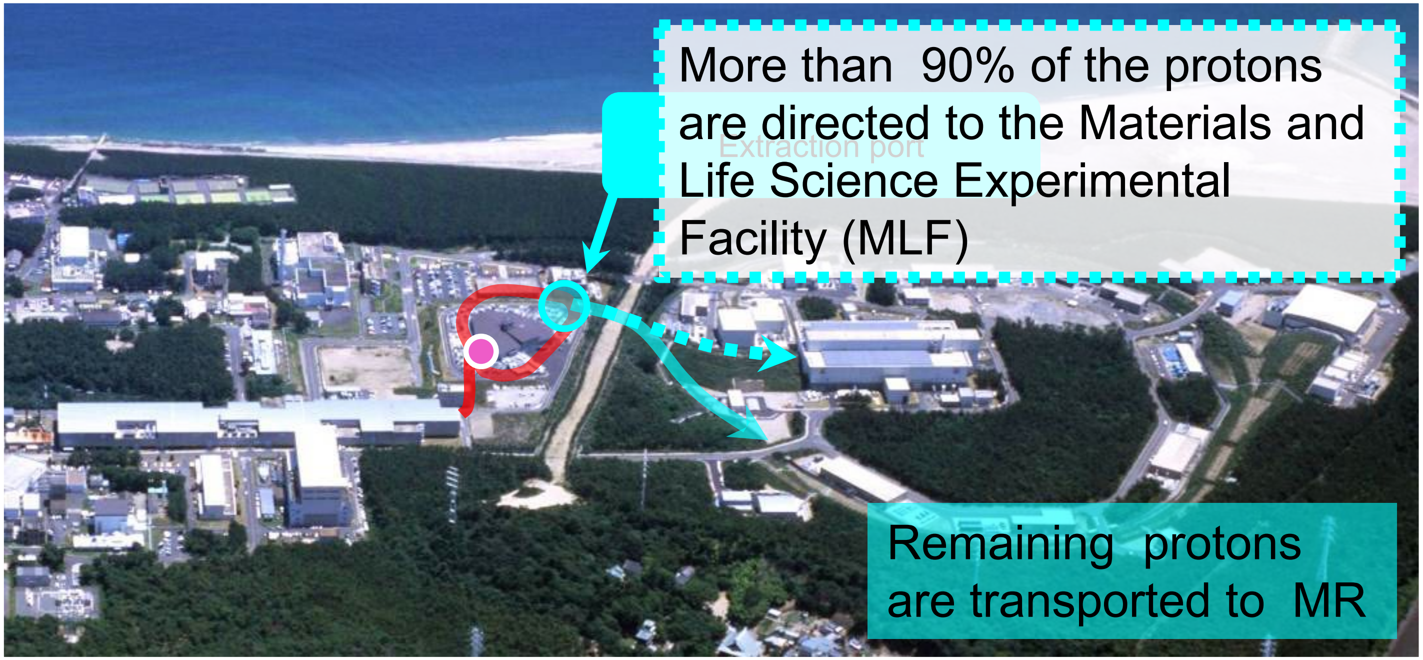


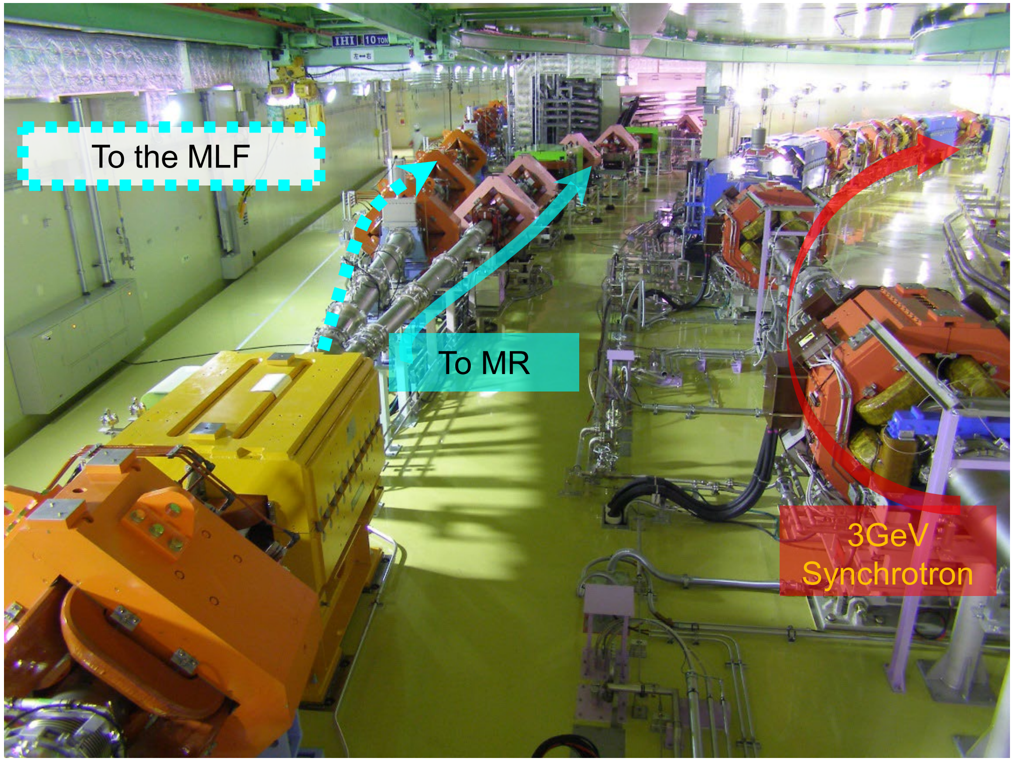


I'm Negative hydrogen ion

I'm Proton!

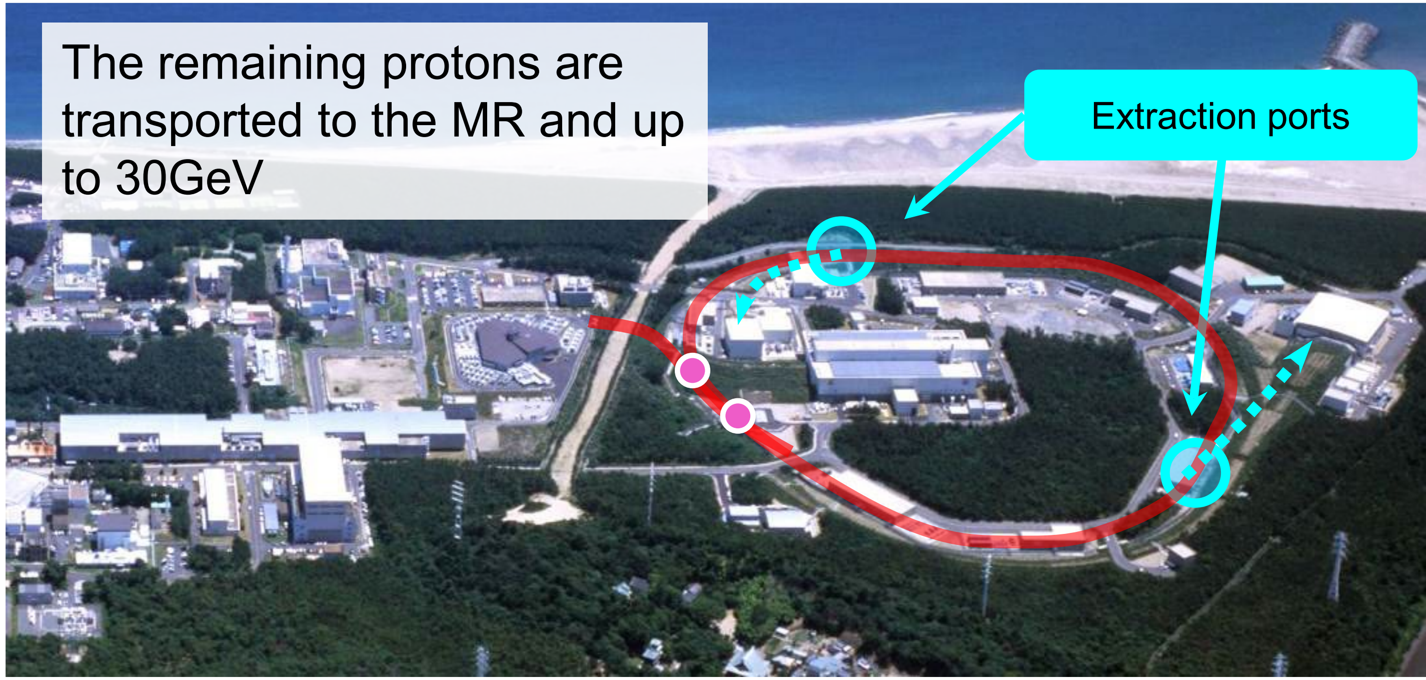
3 GeV Rapid-Cycling Synchrotron (RCS)

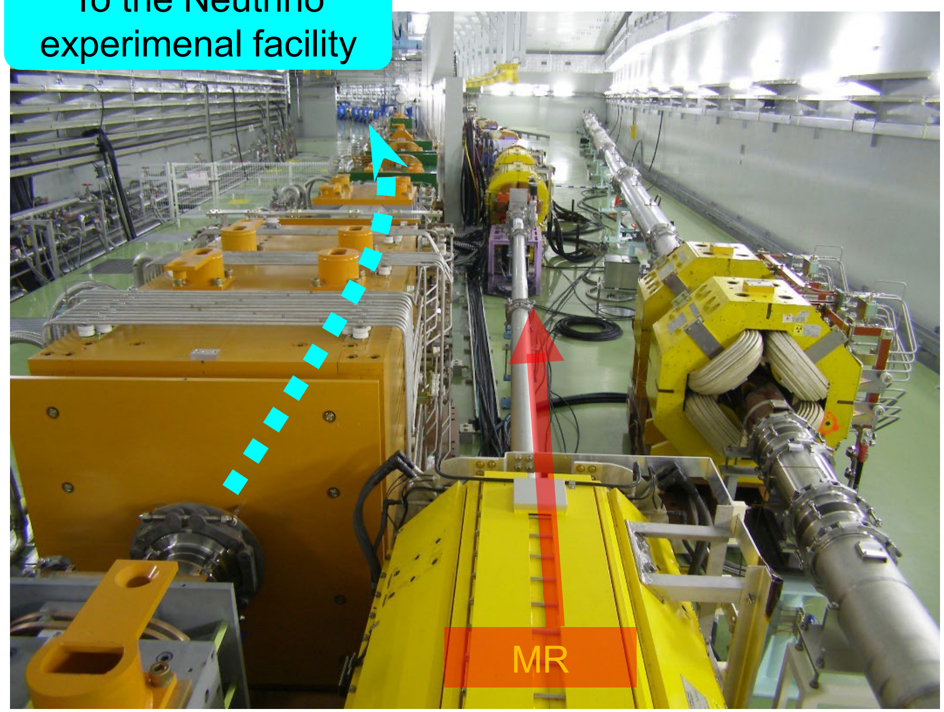


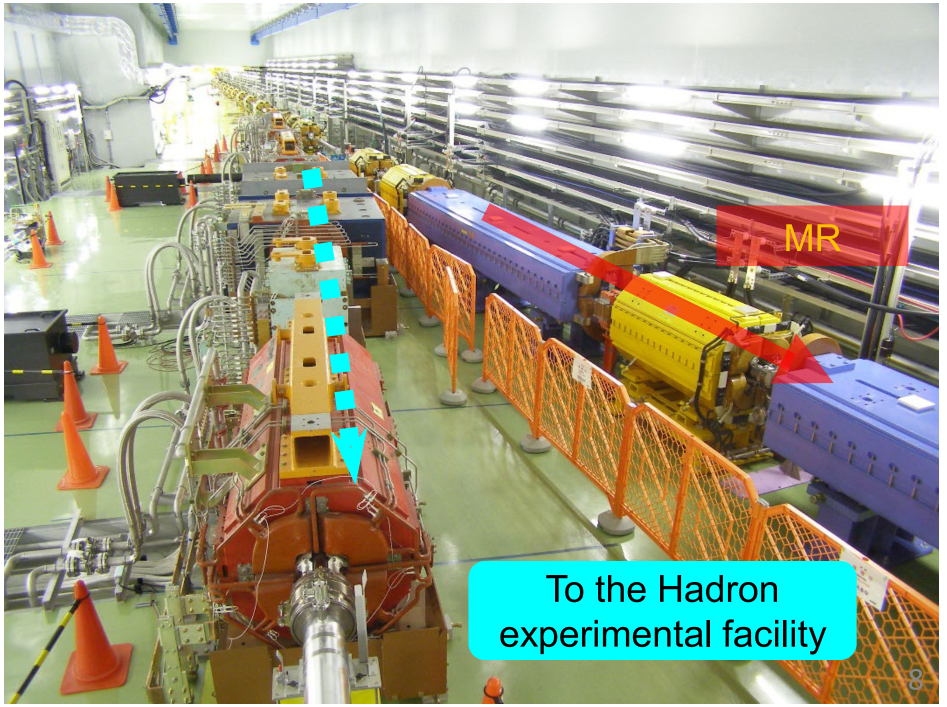


Main Ring (MR)

The remaining protons are transported to the MR and up to 30GeV







History of beam delivery from Accelerators to Users

2007

- The **linac** accelerated the beam to a design value of **181 MeV** at that time on January 24th, 2007.

- The **RCS** accelerated the beam to a design value of **3 GeV** on October 31st, 2007.

2008

- The beam extracted from the RCS was transported to **the Neutron production target** on May 30th, 2008.

- The beam extracted from the RCS was transported to the **muon production target** on September 26th, 2008.

- The **MR** accelerated the beam to a design value of **30 GeV** on December 23rd, 2008.

2009

- Beam extracted from the MR by slow extraction and transported to the **Hadron Experimental Hall** on January 27th, 2009.

- Beam extracted from the MR by fast extraction and transported to the **Neutrino Experimental Hall** on April 23rd, 2009.

The linac accelerated the beam to a design value of 181 MeV at that time on January 24th, 2007.

2007

- The **linac** accelerated the beam to a design value of **181 MeV** at that time on January 24th, 2007.

- The **RCS** accelerated the beam to a design value of **3 GeV** on October 31st, 2007.

2008

- The beam extracted from the RCS was transported to **the Neutron production target** on May 30th, 2008.

- The beam extracted from the RCS was transported to the **muon production target** on September 26th, 2008.

- The **MR** accelerated the beam to a design value of **30 GeV** on December 23rd, 2008.

2009

- Beam extracted from the MR by slow extraction and transported to the **Hadron Experimental Hall** on January 27th, 2009.

- Beam extracted from the MR by fast extraction and transported to the **Neutrino Experimental Hall** on April 23rd, 2009.

The RCS accelerated the beam to a design value of 3 GeV on October 31st, 2007.

2007

- The **linac** accelerated the beam to a design value of **181 MeV** at that time on January 24^{th}, 2007.

- The **RCS** accelerated the beam to a design value of **3 GeV** on October 31^{st}, 2007.

2008

- The beam extracted from the RCS was transported to **the Neutron production target** on May 30^{th}, 2008.

- The beam extracted from the RCS was transported to the **muon production target** on September 26^{th}, 2008.

- The **MR** accelerated the beam to a design value of **30 GeV** on December 23^{rd}, 2008.

2009

- Beam extracted from the MR by slow extraction and transported to the **Hadron Experimental Hall** on January 27^{th}, 2009.

- Beam extracted from the MR by fast extraction and transported to the **Neutrino Experimental Hall** on April 23^{rd}, 2009.

The MR accelerated the beam to a design value of 30 GeV on December 23rd , 2008.

2007

- The **linac** accelerated the beam to a design value of **181 MeV** at that time on January 24th, 2007.

- The **RCS** accelerated the beam to a design value of **3 GeV** on October 31st, 2007.

2008

- The beam extracted from the RCS was transported to **the Neutron production target** on May 30th, 2008.

- The beam extracted from the RCS was transported to the **muon production target** on September 26th, 2008.

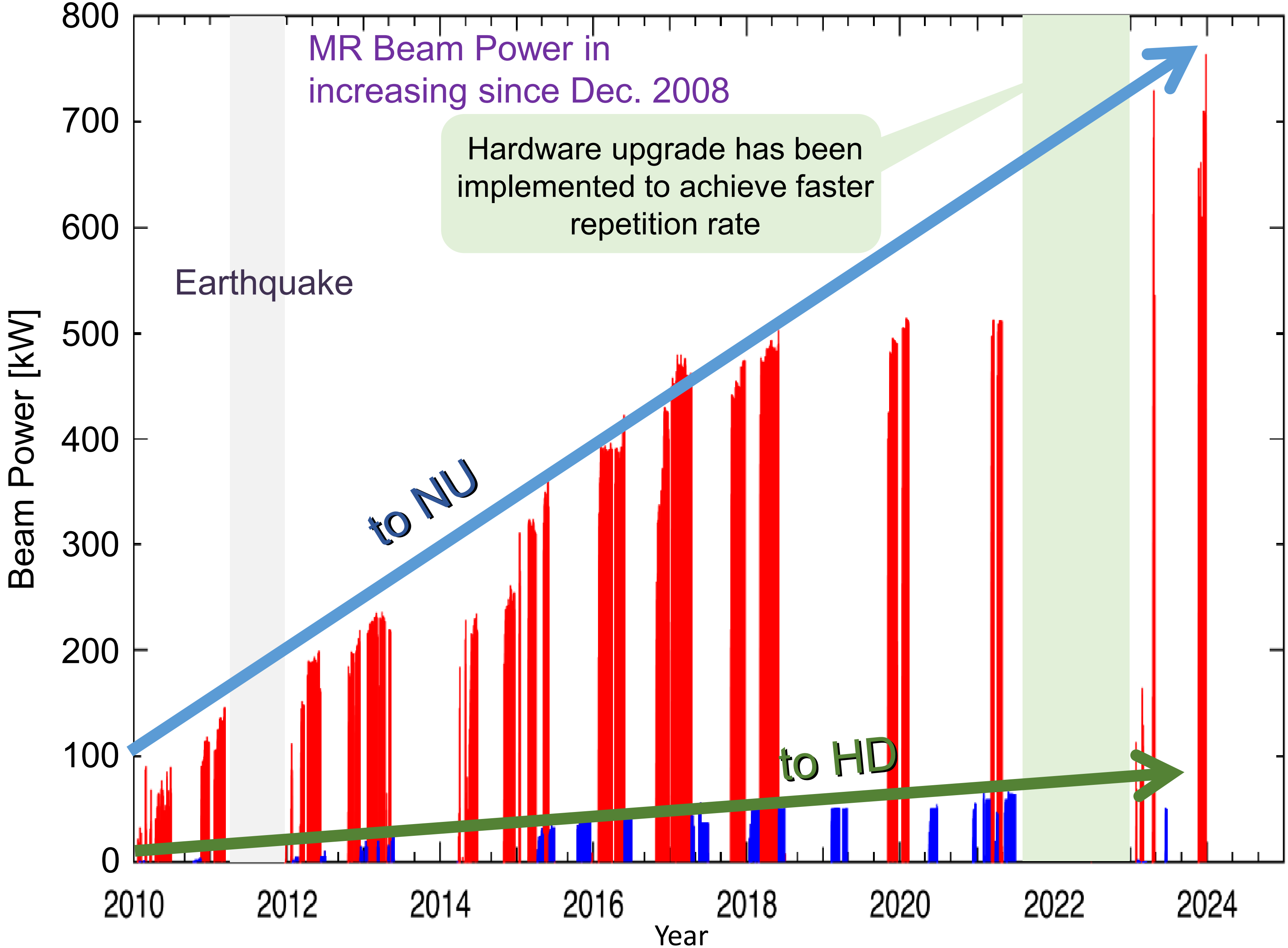
- The **MR** accelerated the beam to a design value of **30 GeV** on December 23rd, 2008.

2009

- Beam extracted from the MR by slow extraction could be transported to the **Hadron Experimental Hall** on January 27th, 2009.

- Beam extracted from the MR by fast extraction could be transported to the **Neutrino Experimental Hall** on April 23rd, 2009.

History of MR beam power

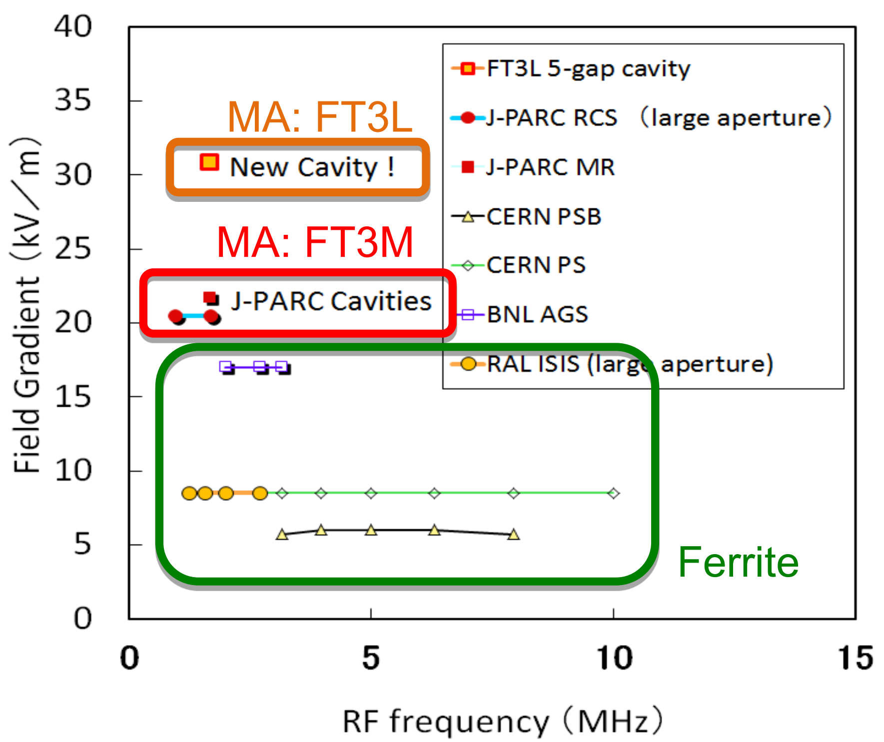


MR

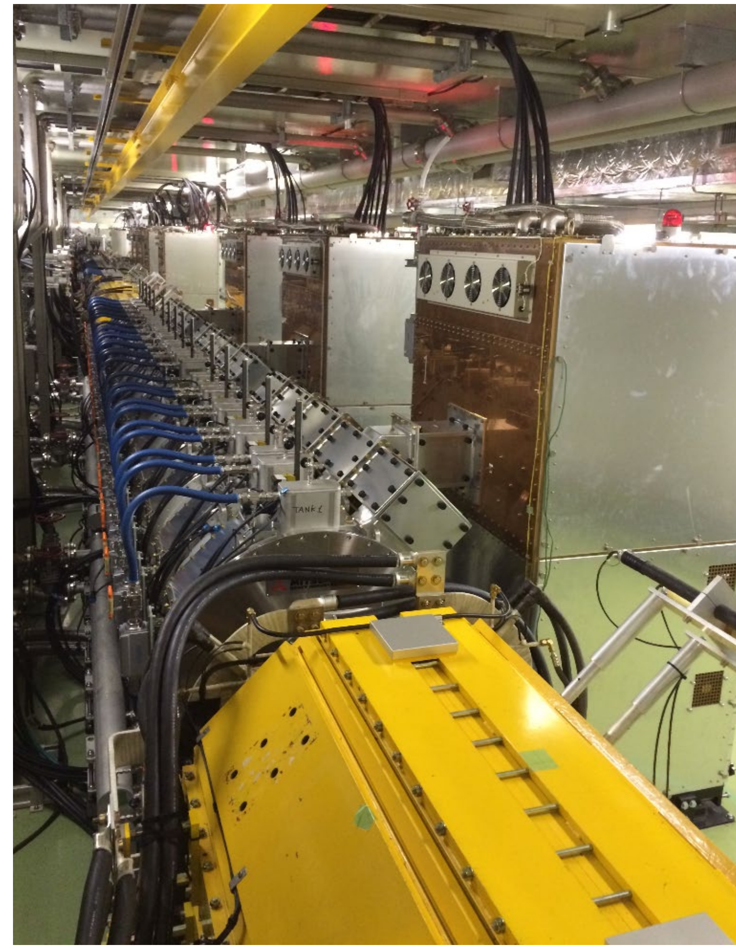
high repetition rate upgrade

High impedance rf system

A new type of the magnetic alloy (MA) core, FT3L(made by Hitachi Metal), was developed and adopted to increase shunt impedance of the rf cavity.



Comparison of field gradient of rf cavities for proton synchrotron.



The rf cavities installed in the MR tunnel.

- Performance of cavities depends on core materials: **ferrite** and MA.

➢ Our rf cavity achieved very high field gradient.

Much Higher intensity proton could be accelerated in J-PARC synchrotrons.

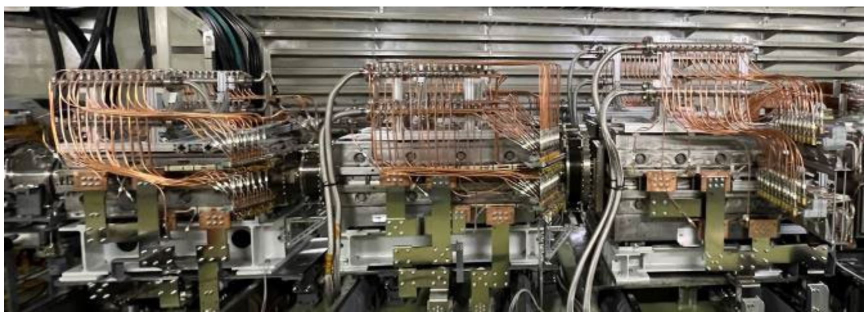
Large-scale hardware upgrades for faster repetition rate & higher beam intensity

New main magnet p.s. QDN

Installation of new trans.

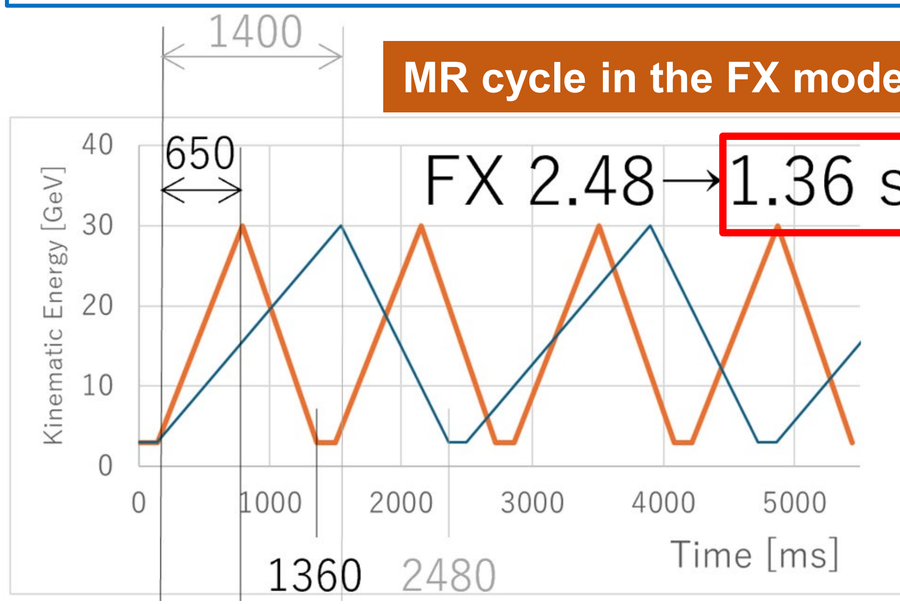
- MR had major hardware upgrades for
  - Main magnet power supplies
  - RF system
  - Inj/FX system
  - Collimators, etc.

  with one-year long shutdown period of July 2021- June 2022.



New high field FX septum magnets SM30-32

MR cycle in the FX mode



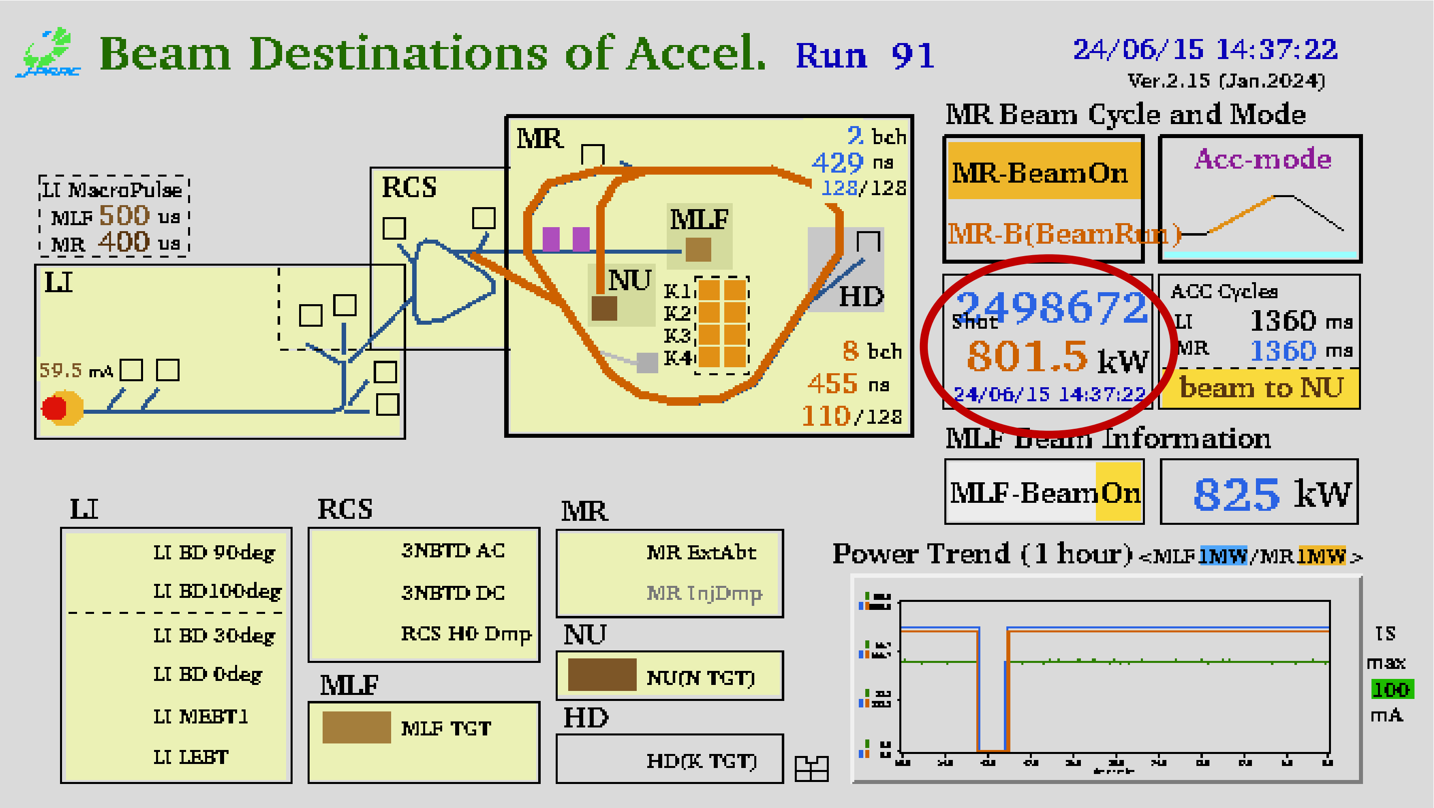
New power amp. for cav#12

New collimator D

Beam commissioning at the operation cycle of 1.36 s is in progress in parallel to the user operation.

Achieved stable operation of MR at 800kW for NU

- During the initial machine tuning and operation, various troubles occurred for the updated devices.
- But we accommodated these troubles each time, and **reached** several important milestones after the high-repetition rate upgrade.
  - Started beam operation for users in earnest from the April of 2023.
  - Achieved **760 kW** beam operation in December 2023,
    - ➢ exceeding the original design performance of **750 kW**
  - Achieved **800 kW stable user operation** in June 2024
    with continuous efforts in both beam tuning & hardware tuning

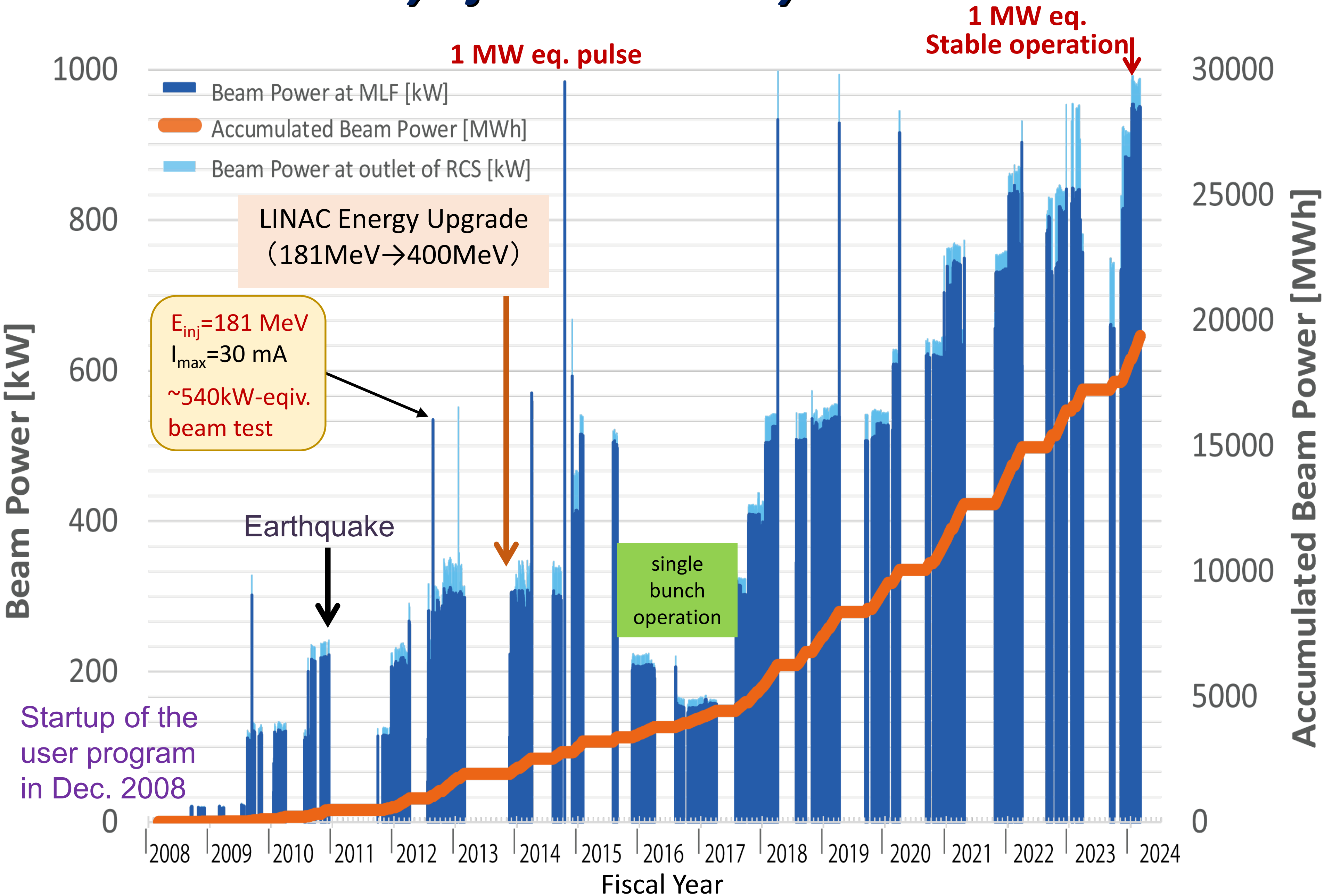


Achieved stable operation of MR at 80kW by slow extraction for HD

- We preformed:
  - Optics tuning
  - Dynamic RF manipulation to suppress beam instability during the de-bunching process at flattop
  - Introduction of a diffuser to reduce beam loss at ESS during SX
  - Spill feedback tuning …

Extraction efficiency 99.6%
Spill duty factor 72%

History of beam delivery to the MLF

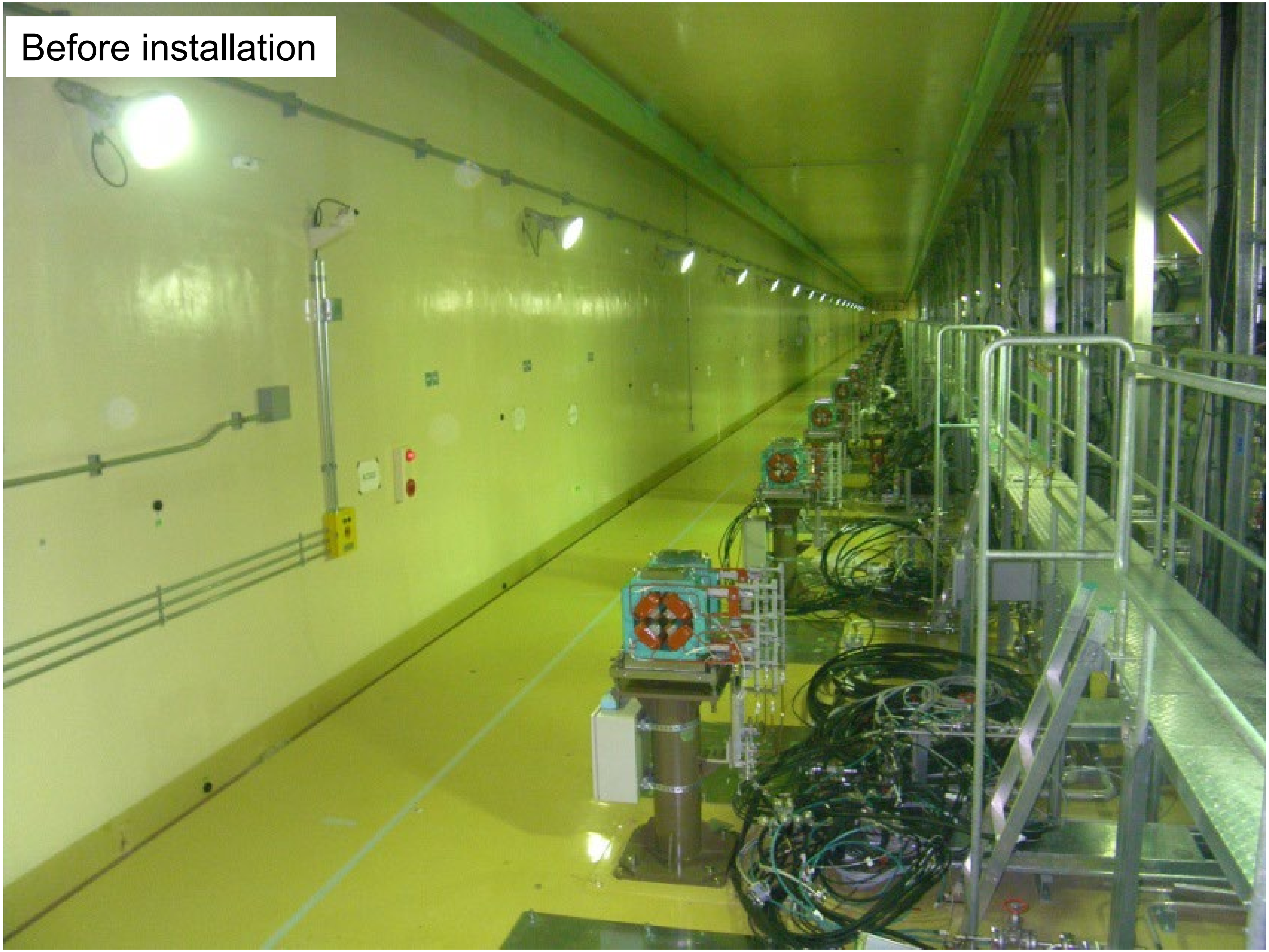


Linac Upgrade

energy and peak current

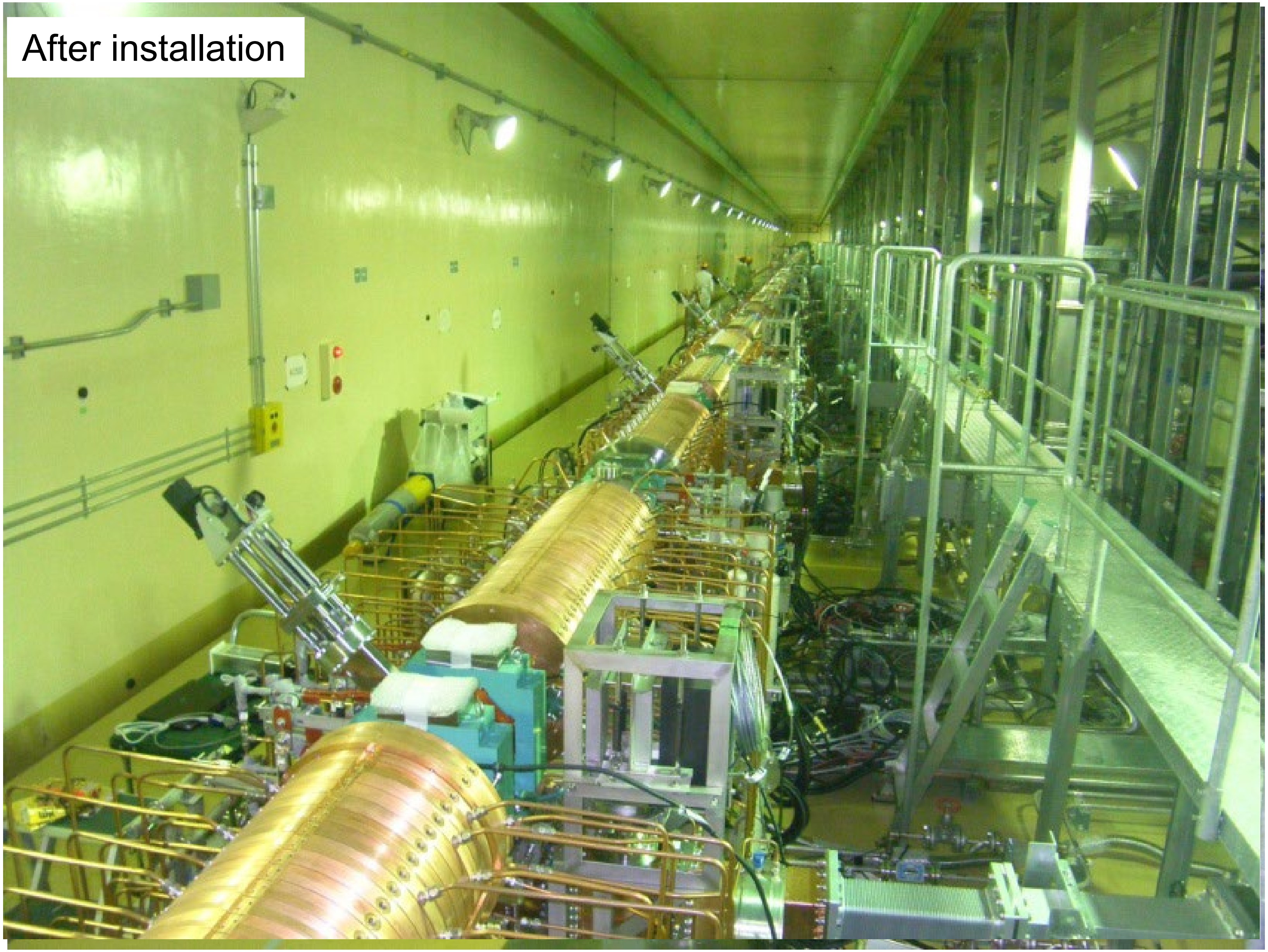
Linac energy upgrade

Energy upgrade (from 181 MeV to 400 MeV) by installing ACS in 2013.



Linac energy upgrade

Energy upgrade (from 181 MeV to 400 MeV) by installing ACS in 2013.

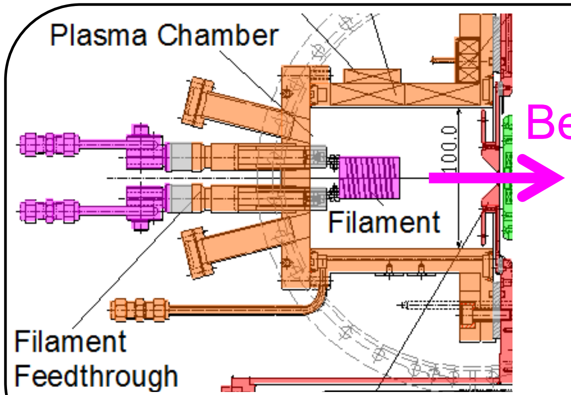


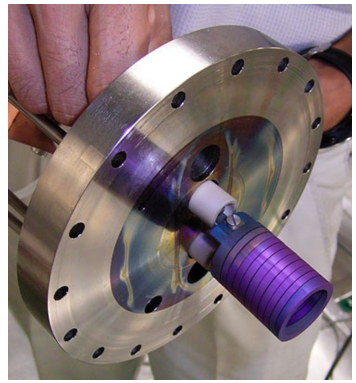
The linac accelerated the beam to a design value of 400 MeV on January 17th, 2014.

Linac peak current upgrade

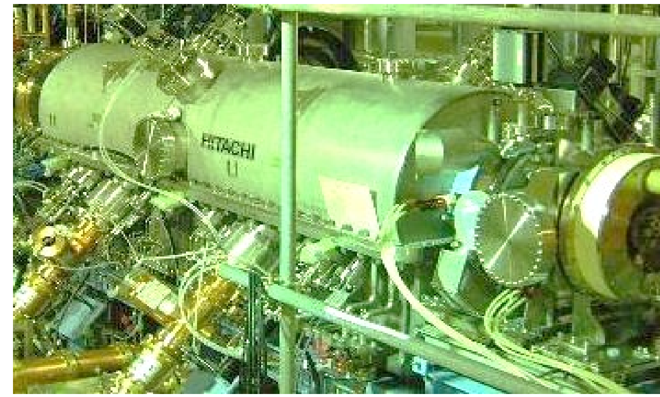
Ion Source and RFQ were replaced in 2014

Ion source



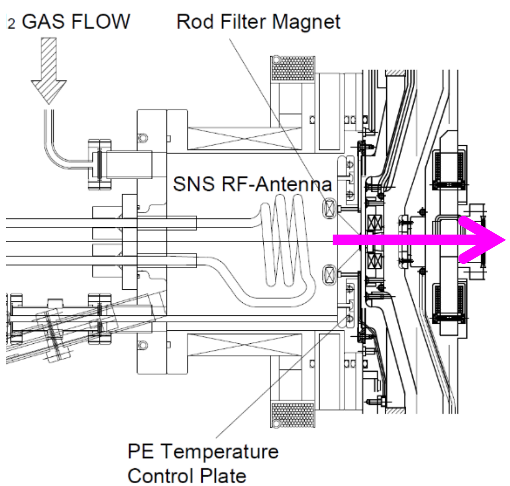


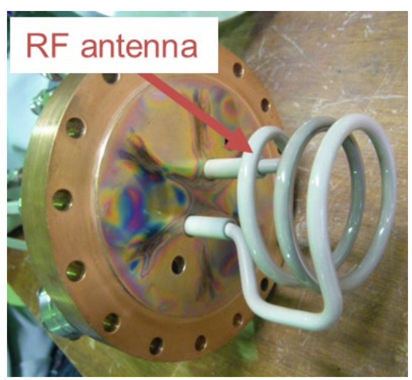
RFQ



New

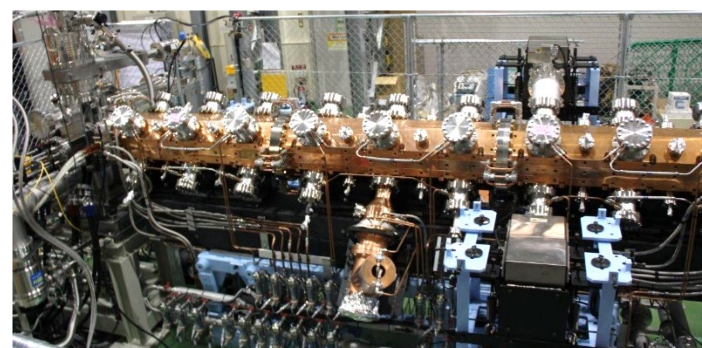
- Filament -> RF-driven
- Cs free -> Cs seeded





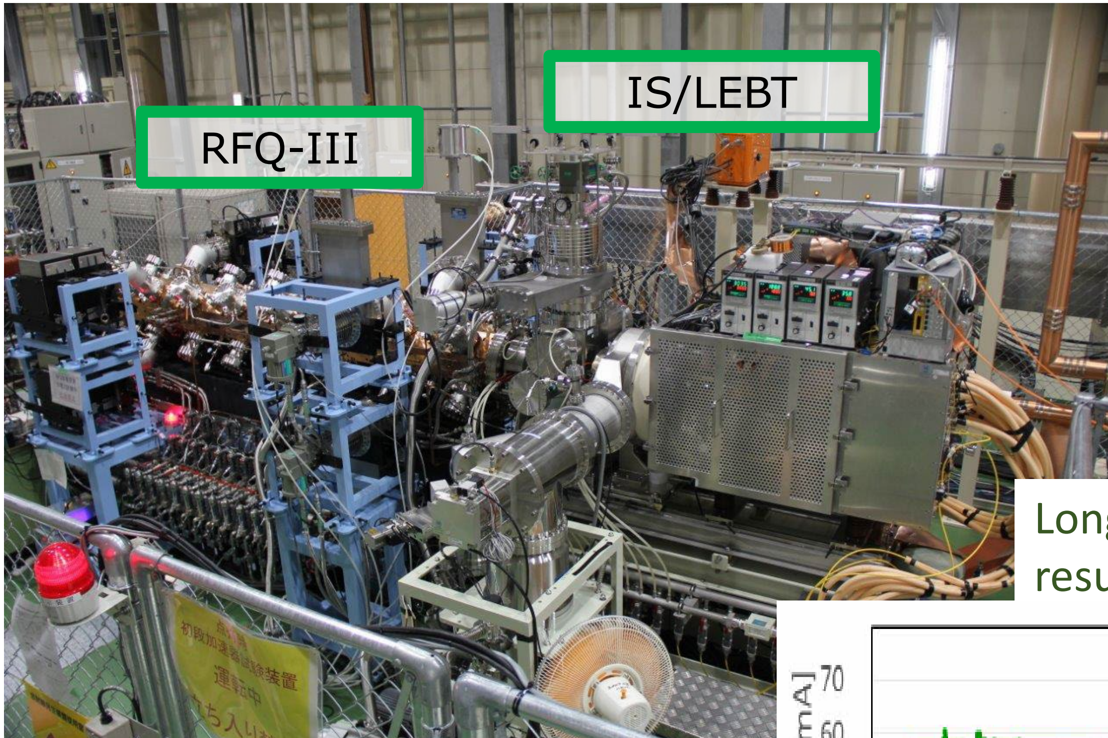
- Modified RFQ with beam dynamics design for higher beam current

New

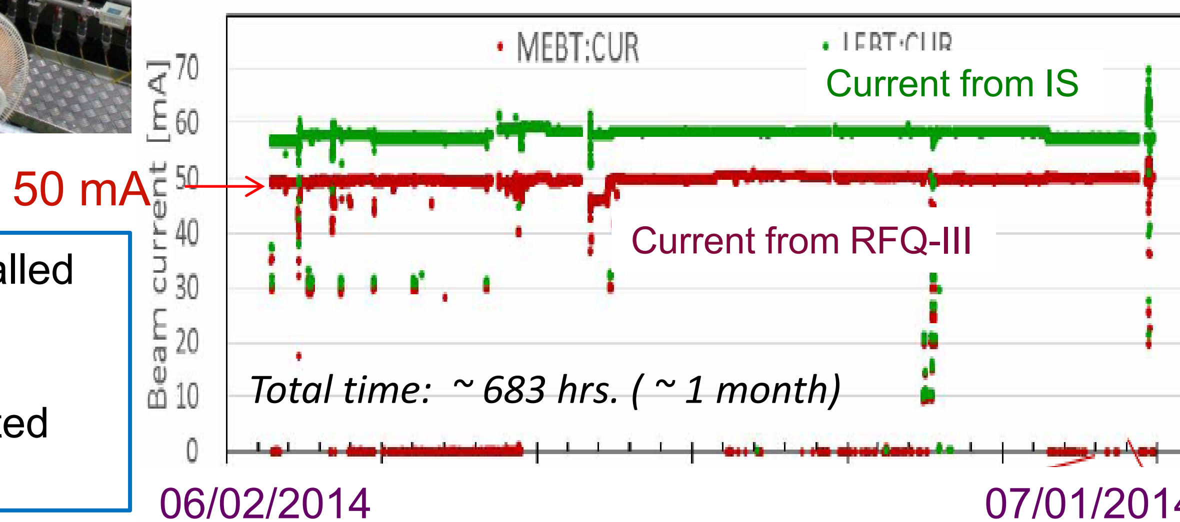


New front-end system for peak current upgrade

An rf-driven H^- ion source and RFQ-III for the peak current of 50 mA were tested in a test bench, which was constructed in the linac building, before installed in the tunnel.

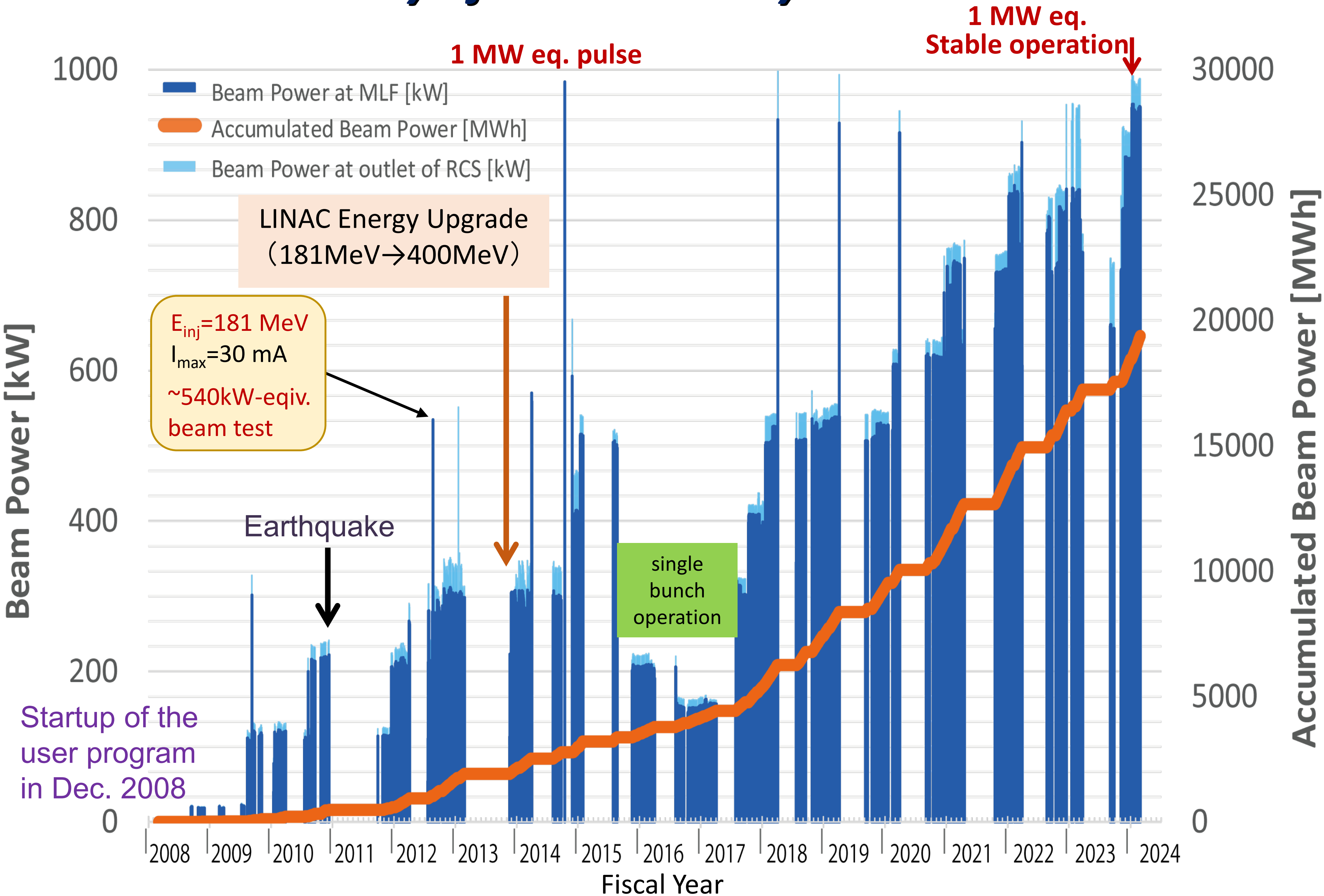


Long-term continuous operation results of the new front-end system

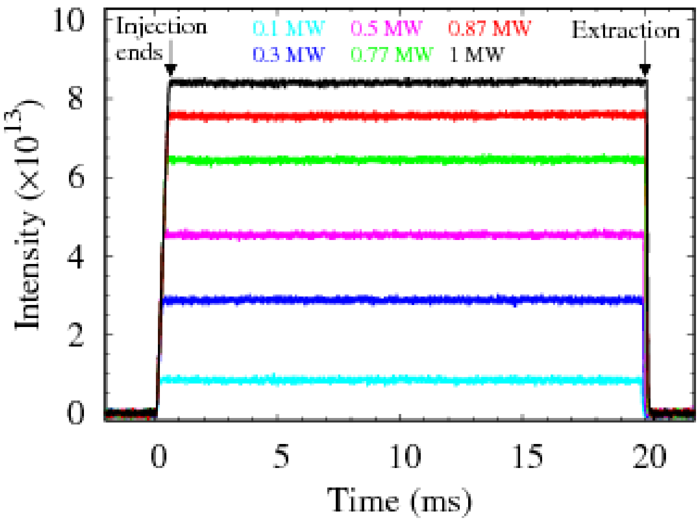


- ✓ The front-end system was installed in the linac tunnel in summer shutdown of 2014.
- ➢ Beam commissioning was started from October 1st, 2014.

History of beam delivery to the MLF

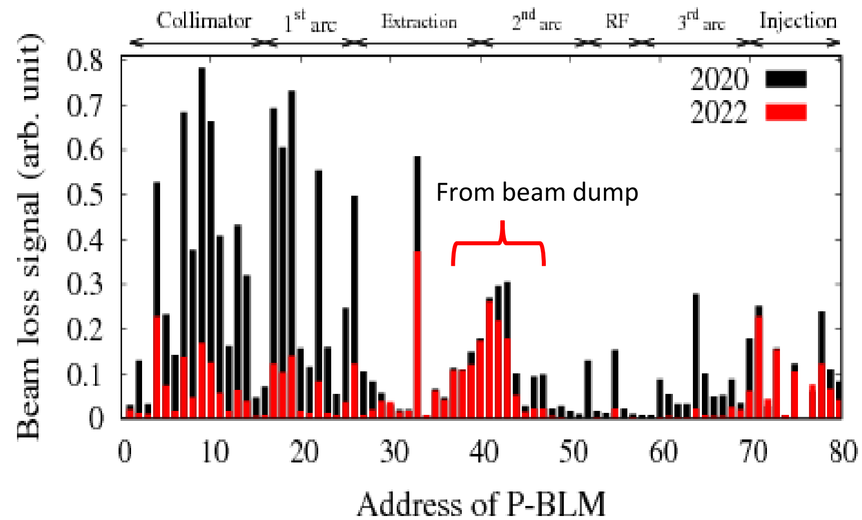


Latest beam loss mitigation at 1 MW operation in the RCS

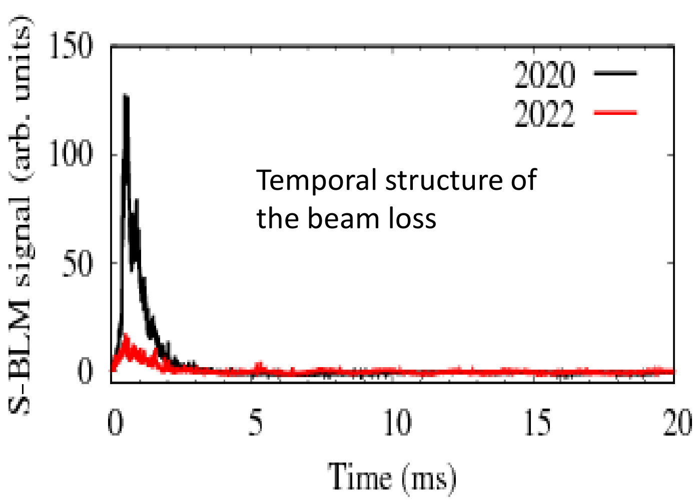


Circulating beam intensity measured by the SCT

➢ No beam intensity loss can be seen.



Beam loss distribution whole the RCS



Beam loss signal measured by S-BLM

➢ The beam loss occurs only around during injection.

- Measured beam loss in the RCS at 1 MW integrated from injection to extraction.

✓ The beam loss is **80% reduced** from that of 2020 by optimizing stripper foil size, resonance correction, optimizing longitudinal and transverse paintings including and betatron tunes.

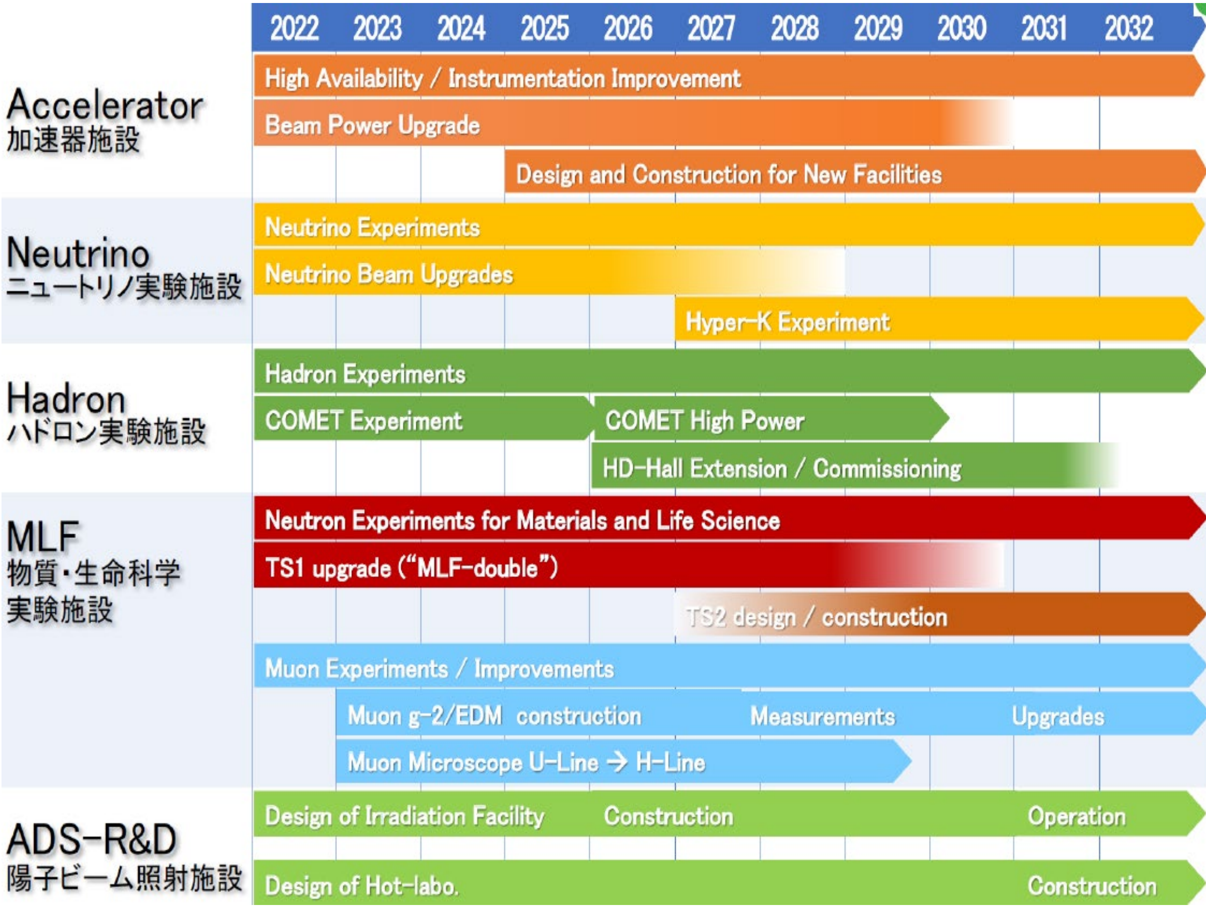
✓ Estimated beam loss is dominated by the foil scattering beam loss of the circulating beam during injection.

➢ Corresponds beam loss power is **~0.1 kW**

  ✓ **Very small** value compered to the collimator capacity of 4 kW.

J-PARC future plan

J-PARC future plan



- **Neutrino facility**

  Hyper-Kamiokande experiment will be start form 2027,with high power beam from MR. The goal of beam power is 1.3MW.

- **Hadron facility**
  - **Hadron hall expansion** will be planed from 2026. We have to realize the beam power of 100kW as soon as possible for hadron experiments.
  - **The COMET experiment** with 8GeV bunched beam extracted from MR will be planed in the Hadron Experimental facility.

- **MLF**

  has plan to build a **2nd target station** in 2030s.
  - The beam power of more than 1.5MW has to be realize at energy of 3GeV with 25Hz in the RCS.

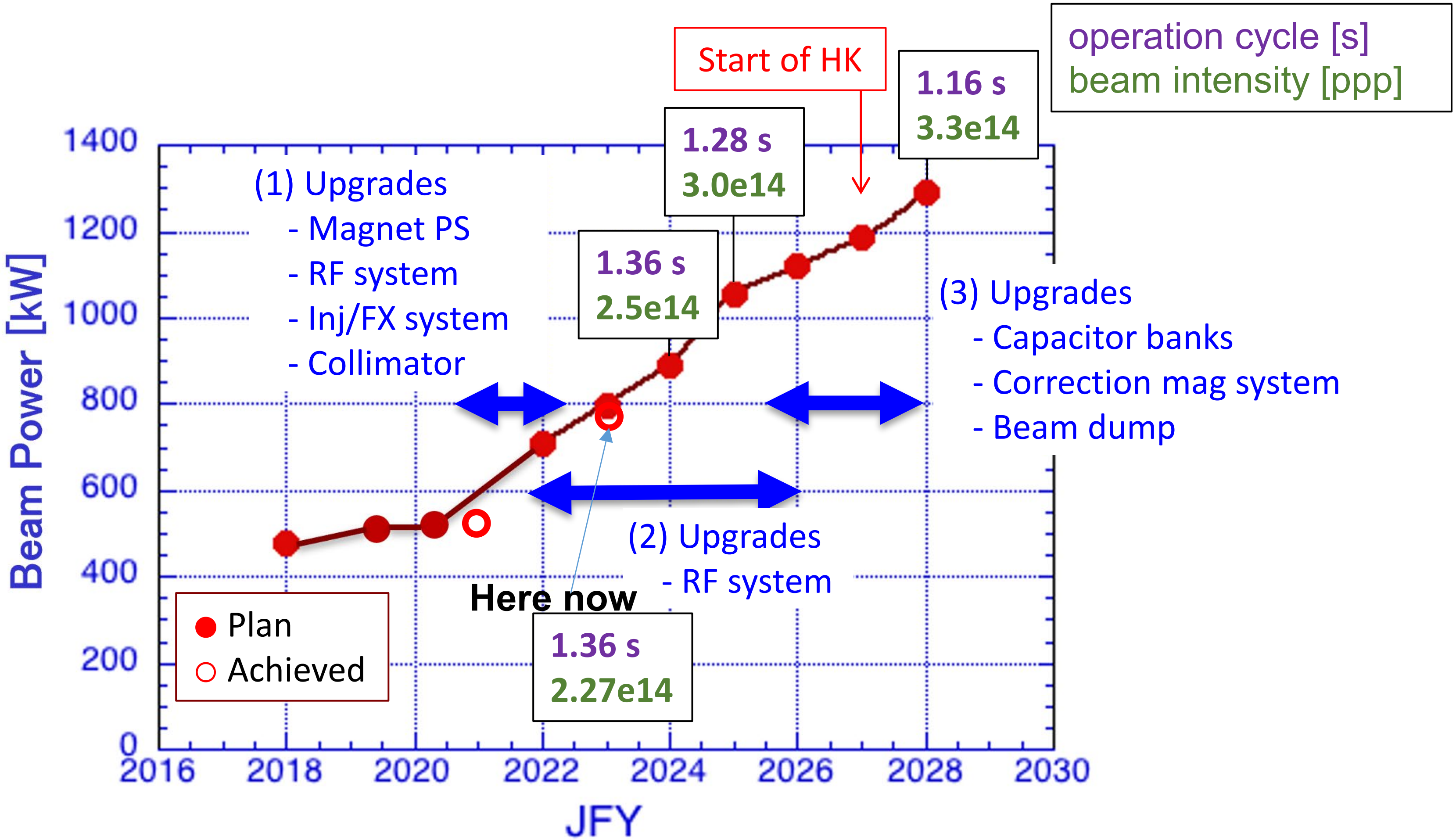
- **Irradiation facility** for accelerator driven transmutation experiment.

  Beam power of 250kW at the energy of 400MeV with 25Hz are requested from this facility to the linac.

MR developments

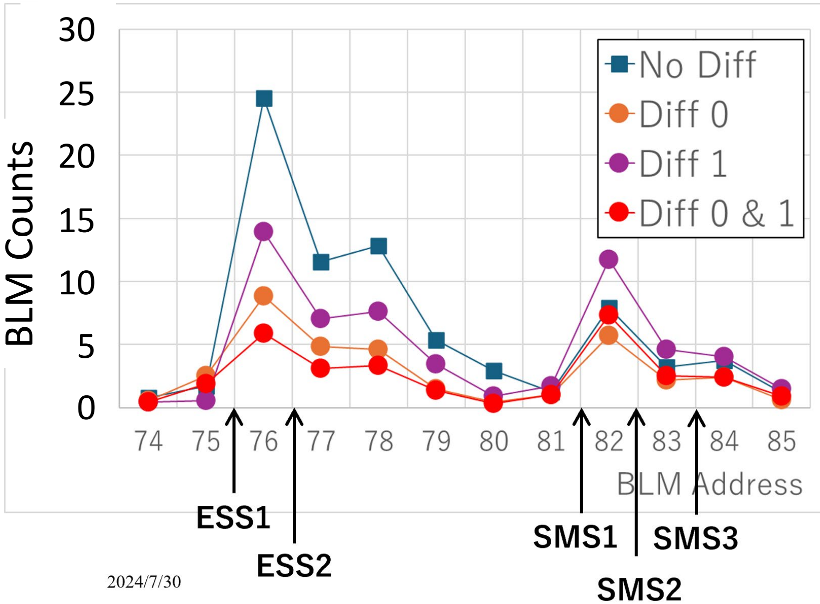
Beam intensity 1.3 MW for Nu / 100kW for HD

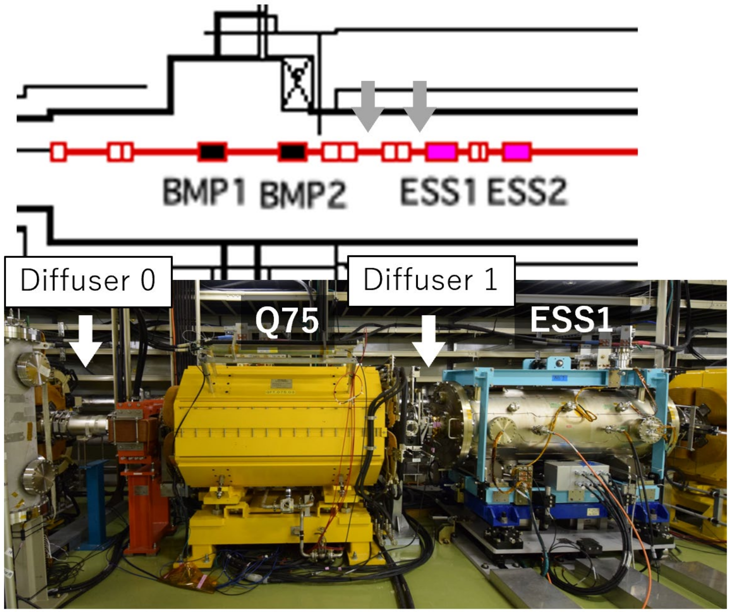
FX beam power projection through 2028



- The beam power will be increased step by step with hardware upgrades,
  - while gradually reducing the **operation cycle**
  - while gradually increasing the **beam intensity**
  - while continuing beam dynamins tuning for **beam loss reduction**.
- We aim to achieve **1.3 MW in 2028** in line with the startup of Hyper-Kamiokande.

Perspective of the SX operation





Beam study results with two sets of diffusers
for low intensity beam (11 kW)

- It was found that installation of diffuses in slow extraction area is effective to reduce beam loss.

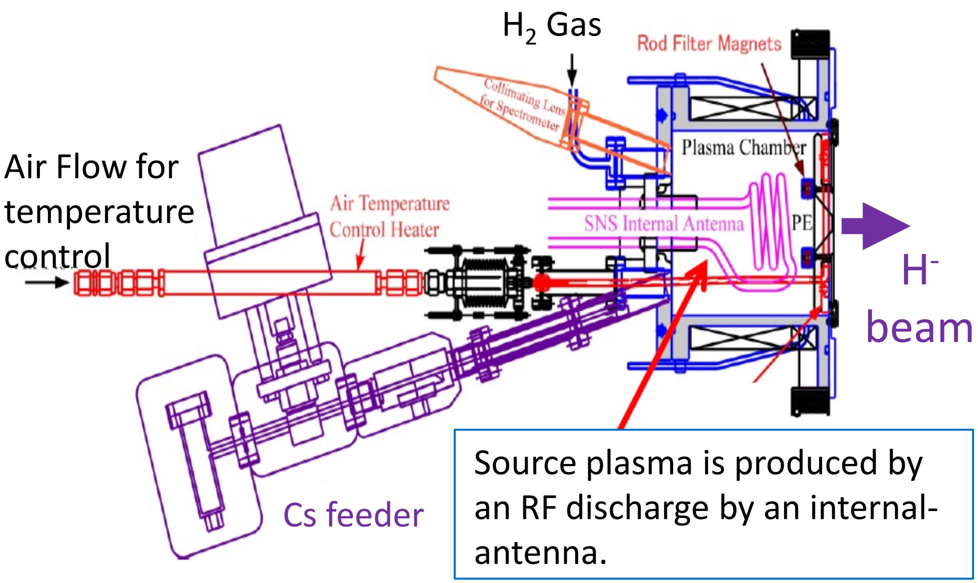
- The beam power will be increased to**100 kW** in stages
  - while further **reducing beam loss**, - while further **improving spill duty factor**

  by
  - improving configuration of diffusers, - introducing new optics with large slippage factor
  - improving spill feedback system, - reducing current ripple of main magnet PS
  - introducing VHF cavity, etc.
- We aim to achieve this by 2026.

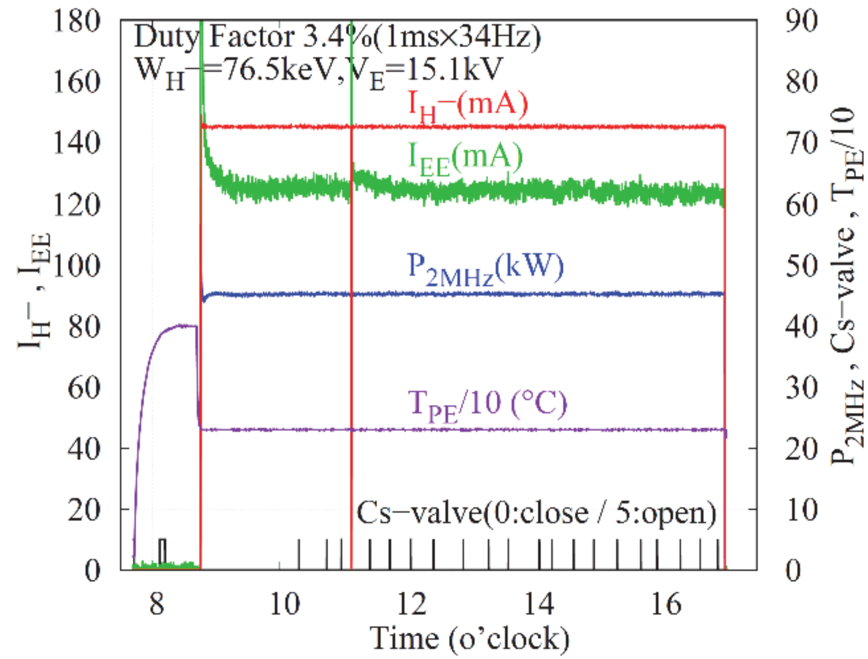
Developments of Linac and RCS for high intensity beam operation

Beam intensity ~1.5 MW is a next goal

Development of high intensity ion source



Schematic of the RF-driven H^- ion source

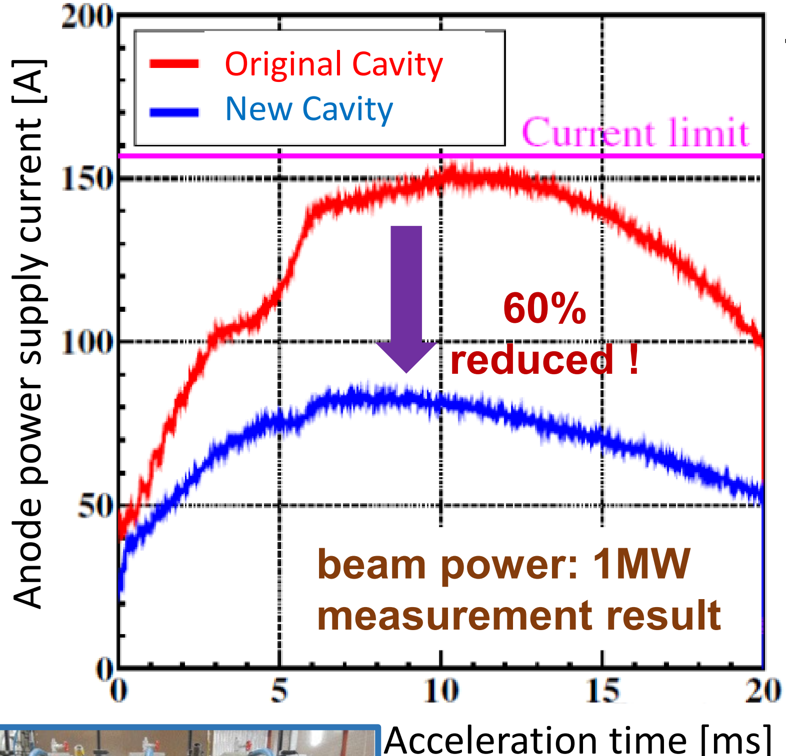


Trend graph of I_{H-} , I_{EE} , P_{2MHz} , and Cs-valve during 8 hours operation

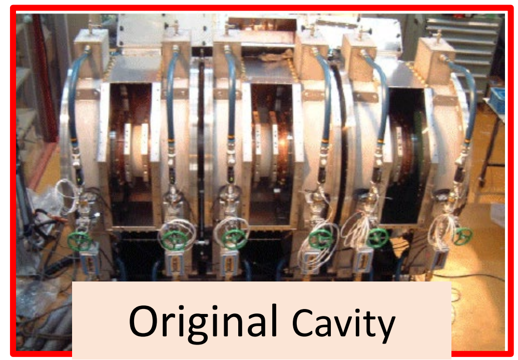
- We have developed cesiated RF-driven H^- ion source to realize high intensity.
- The stable operation with 145 mA and duty factor of 3.4% has been performed for 8 hours.
- This beam has particle distributions in horizontal and vertical phase planes comparable to that used in typical RFQ designs.
- This beam intensity will realize the next generation benchmark H^- ion source for high intensity and high energy H^- LINACs.

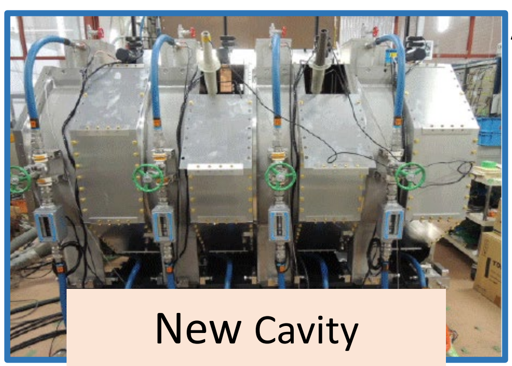
Ref. : A. Ueno, "Innovative cesiation deriving incredible 145 mA beam from J-PARC cesiated RF-driven H^- ion source", J. Phys. Conf. Series, 2743, 012001 (2024).

New cavity for the RCS

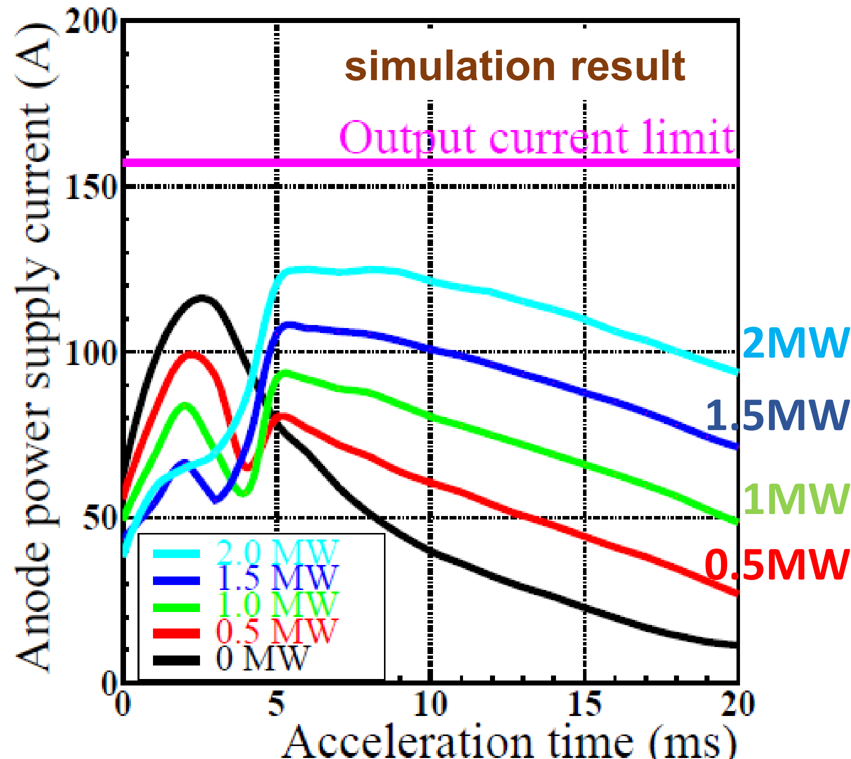


The beam power of the RCS had been limited by the cavity anode power supply current.





The new cavity solved this issue.



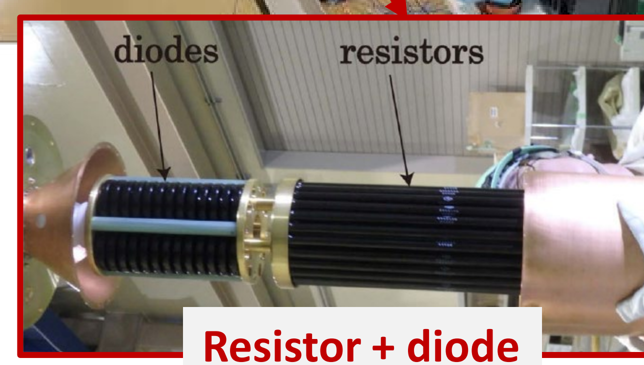
The new cavity has the capability to realize 2 MW beam power in the RCS.

Reduction of RCS kicker magnet impedance effect

We proposed a scheme for suppressing the kicker impedance by using diodes and resistors, thereby demonstrating the effect on the kicker impedance reduction, because simulations have shown that reducing the impedance of the kicker magnets is necessary for stable acceleration of particles with high intensities more than 1 MW in the RCS.

- We have demonstrated that the special diodes with resistors **can suppress the beam instability** by reducing the kicker impedance.
  - ➢ This system makes it possible to stably accelerate more than 1MW beam in the RCS.
- This system have a negligible effect on the extracted beam from the RCS.

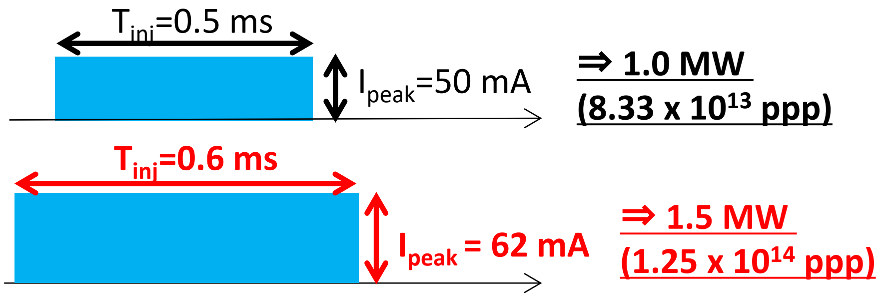
- The J-PARC RCS must be operated with a repetition rate of 25 Hz, which urged us to consider special diodes that are tolerant to heating.
  - ➢ Enhanced durability of the prototype diodes and resistors for the 25Hz operation was also realized.



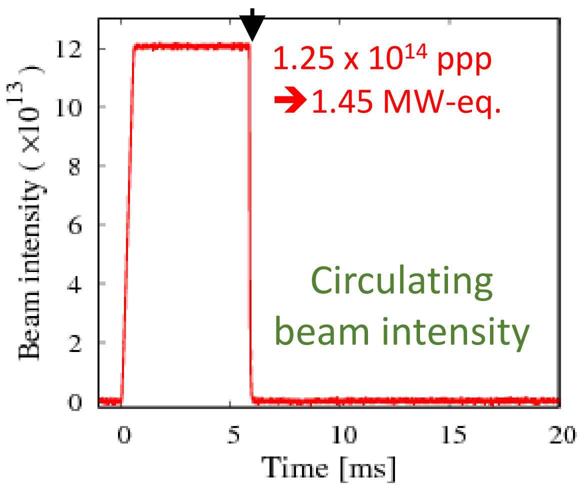
Ref. : Y. Shobuda et al., Demonstration of a kicker impedance reduction scheme with diode stack and resistors by operating the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, *Phys. Rev. Accel. Beams 26, 053501 (2023)*

Beam study for 1.5 MW beam power

Injection pulse (from linac)

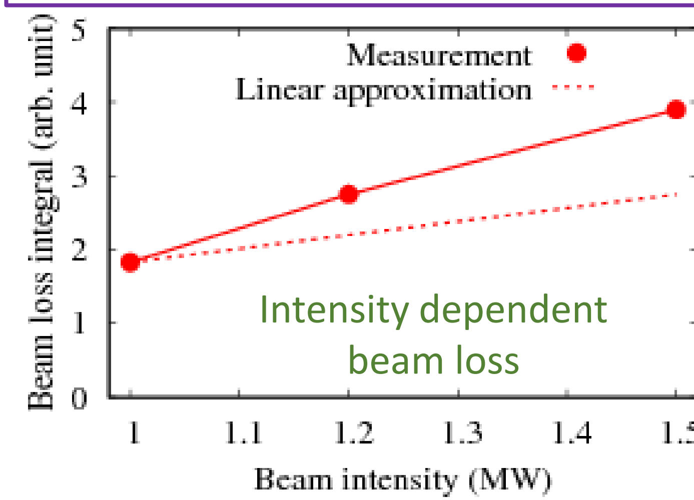


Extraction at 0.8 GeV



Acceleration up to 0.8 GeV:

- ✓ Due to limitation of the RF system for acceleration up to 1 GeV,
  - ✓ because the RF cavities are not yet fully replaced to new ones.
- ➢ we extracted the beam at 0.8 GeV (~6 ms) to avoid any RF trips.
- ✓ Enough to check the beam loss as occurring at lower energy



- The beam loss occurs only around injection energy localizing at the collimator area.
- The beam loss power is **only 0.2 kW**
  - ➢ very small value compared to the collimator capacity of 4 kW.
- We can't confirm it at **1.5 MW** now as acceleration was done up to 0.8 GeV.

✓ Simulation results shows **that no beam instability occurs** at **1.5 MW** with impedance reduced to half by diodes installed at the extraction kicker magnets.

Summary

- Since its operation, the J-PARC accelerator facility has increased beam intensity through the development of various components and careful beam tuning.
- This is the great effort of the accelerator team members, so I would like to pay tribute to them.
- I would also like to thank all of users for the tremendous support and encouragement for us.

Mission of J-PARC

- **J-PARC will continue to evolve and become a facility that can continuously produce research results, and to be an internationally attractive, state-of-the-art facility.**
  - As a global common facility, we will constantly pursue **the world's highest intensity and highest quality quantum beams**, supply them to all users and make them a source of new breakthroughs.
    - ✓ New technologies have expanded mankind's knowledge and created new breakthroughs.
- **And contribute to the welfare and prosperity of human society through research and development results**
  - We develop those world-leading tools ourselves, take advantage of the benefits we have, use them ourselves, and create new breakthroughs.

The J-PARC accelerator facility will continue to evolve to satisfy the requirements of all users.