Status and future upgrade Plan of J-PARC Accelerators

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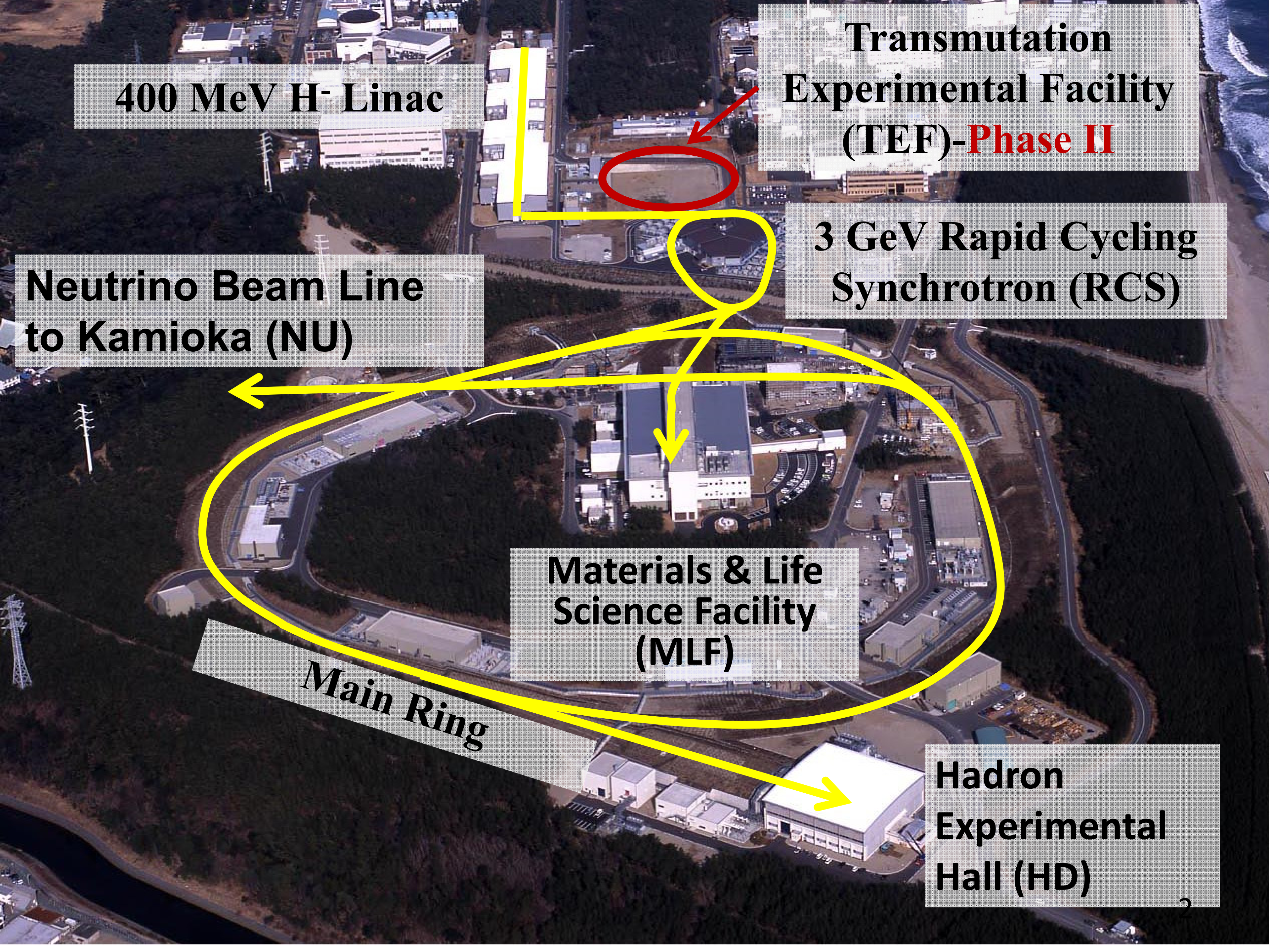
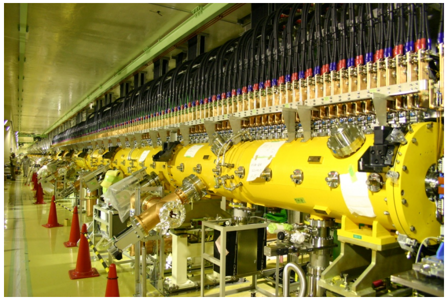


400 MeV H- Linac
Transmutation Experimental Facility (TEF)-Phase II
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino Beam Line to Kamioka (NU)
Materials & Life Science Facility (MLF)
Main Ring
Hadron Experimental Hall (HD)

J-PARC Accelerators

High-intensity proton accelerators

- **Linac**
  - length: 249 m
  - energy: 400 MeV
  - beam extracted to RCS
    and (Transmutation Experimental Facility)



- **Rapid-Cycling Synchrotron (RCS)**
  - circumference: 348 m
  - energy: 3 GeV
  - beam power: 1 MW (0.5 MW)
  - beam extracted to MR
    and Materials and Life Science Experimental Facility

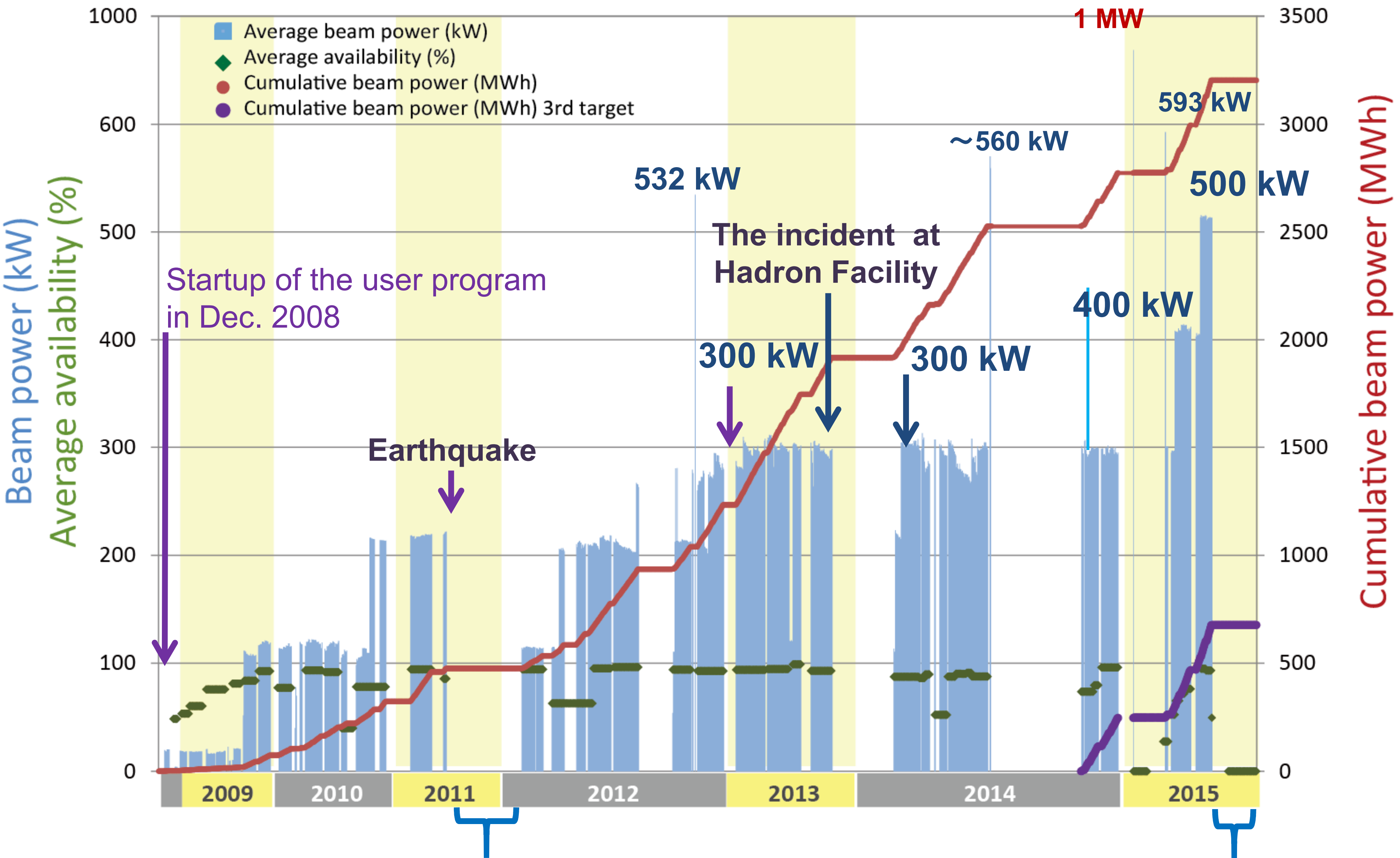
- **Main Ring (MR)**
  - circumference: 1,568 m
  - energy: 30 GeV
  - beam power: 750 kW/100kW (395 kW/ 42kW)
  - beam extracted to Neutrino Facility, or Hadron Facility

numbers in parentheses are current operation parameters

History of beam delivery from Accelerators to Users

History of beam delivery to the MLF

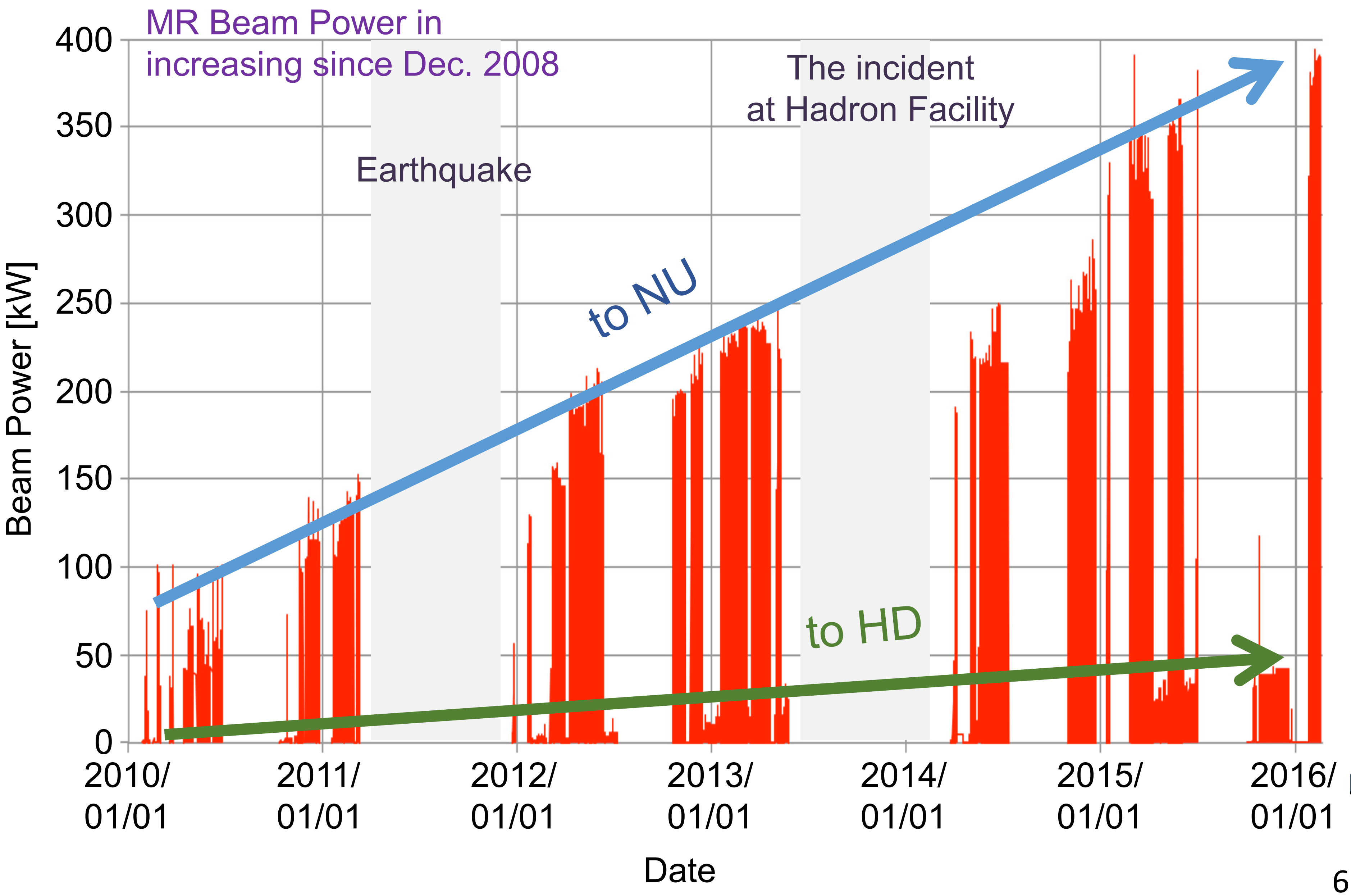
- as of 3rd of June 2015



~10 months interruption due to the earthquake

Interruption due to a trouble of Hg-target

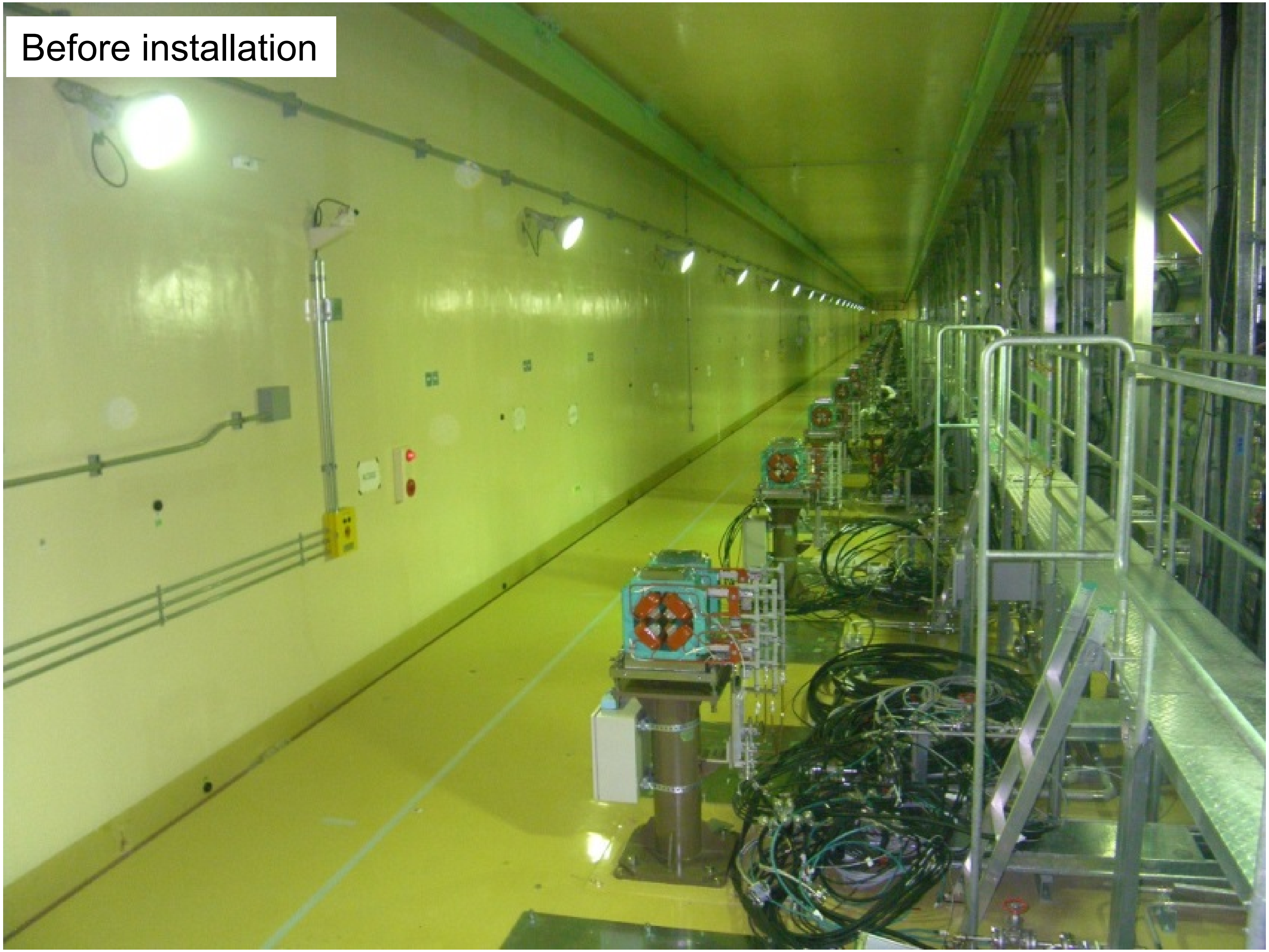
History of MR beam power



Linac Status

Linac energy upgrade

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



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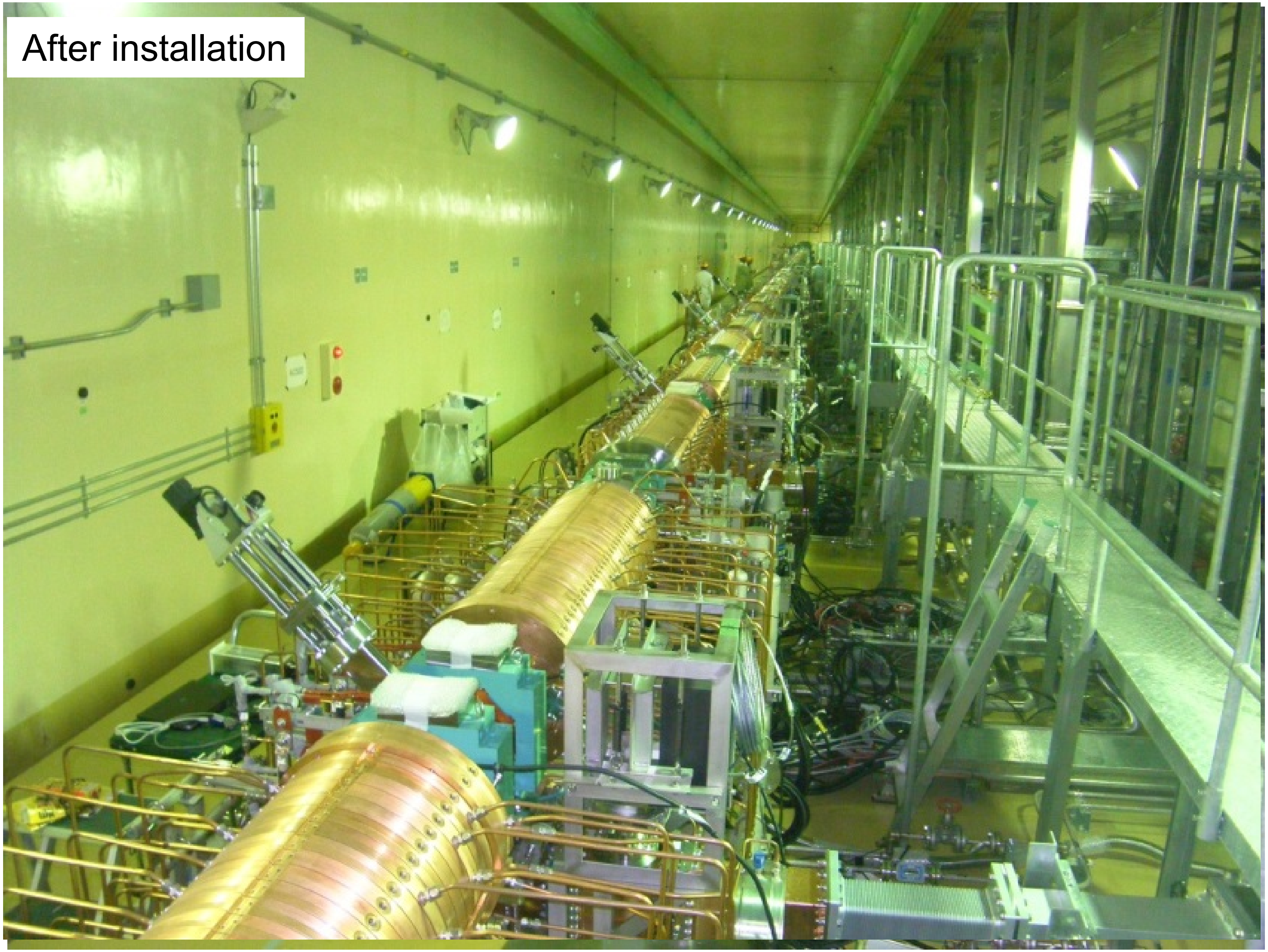
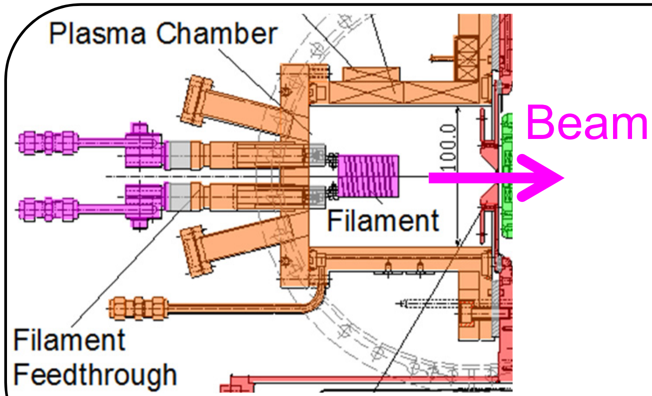
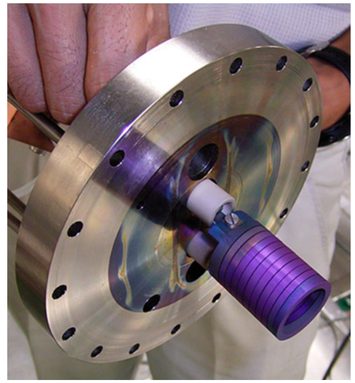


Linac peak current upgrade

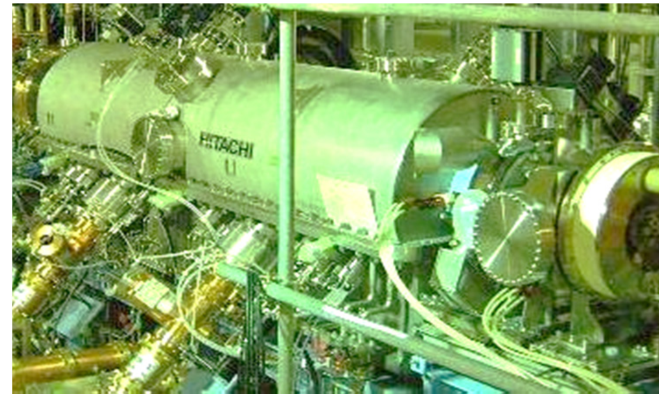
Ion Source and RFQ has been replaced in 2014

Ion source



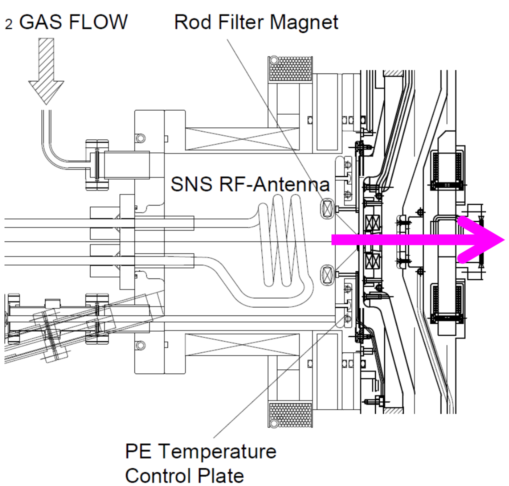


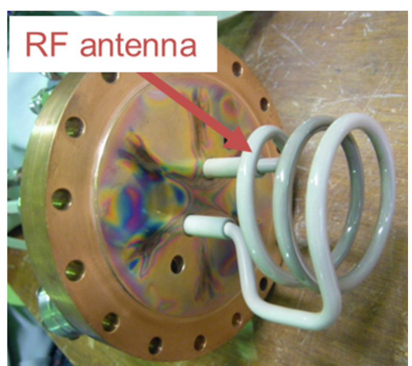
RFQ



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

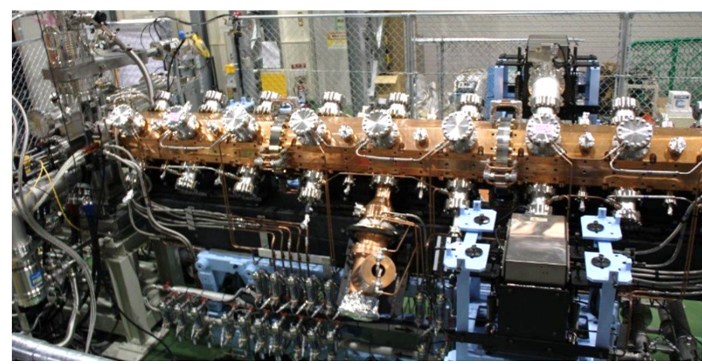
New



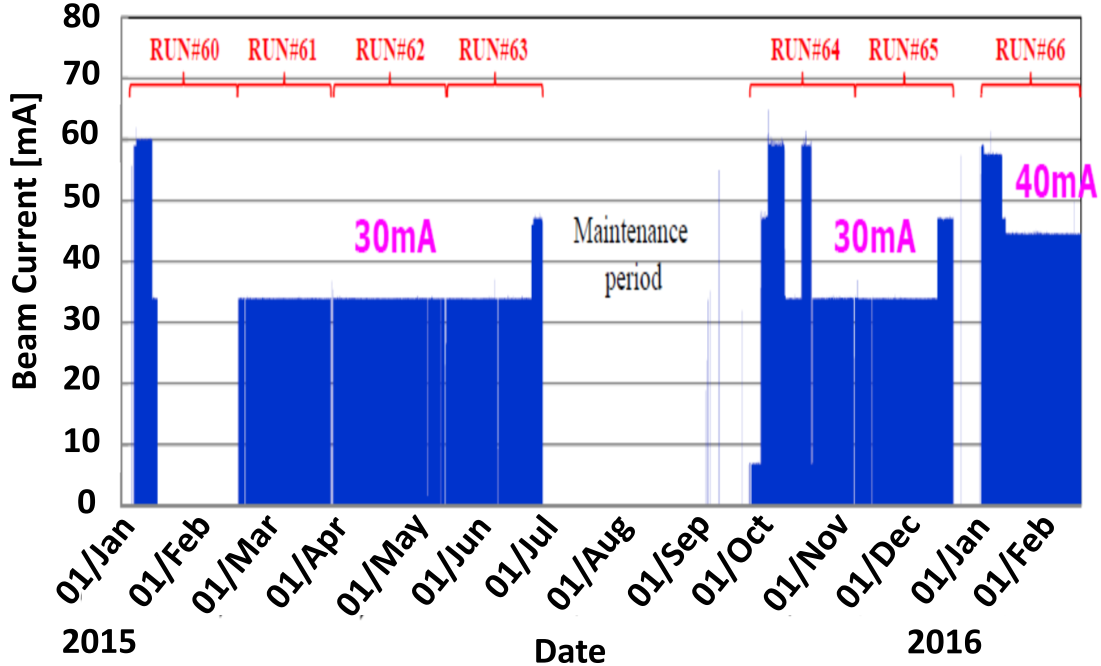


- Structure: Bolt -> Brazed
- Beam dynamics design for higher beam current

New

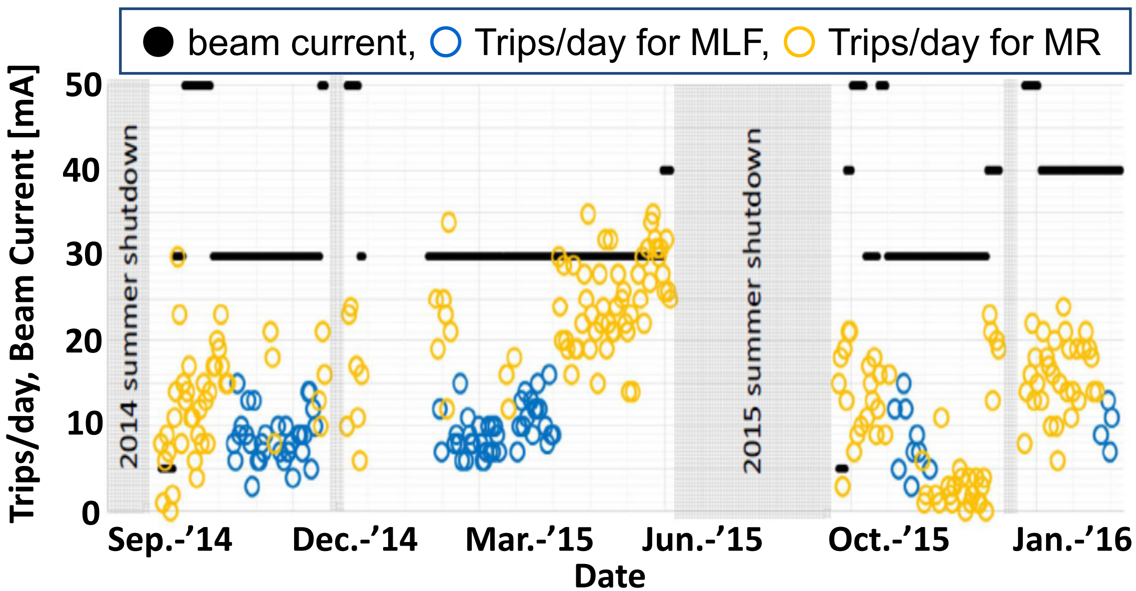


Status of the Ion Source and RFQ



- Continuous operation
  - 1,100 hrs. with 33 mA
  - 1,004 hrs. with 45 mA
- Peak current : 60 mA

has been achieved.



- Currently, the number of trips
  - 10 times/day for MLF, 30mA
  - 16 times/day for MR, 40mA
- Beam operation resumed < 1minitus

RCS Status

1-MW trial at RCS

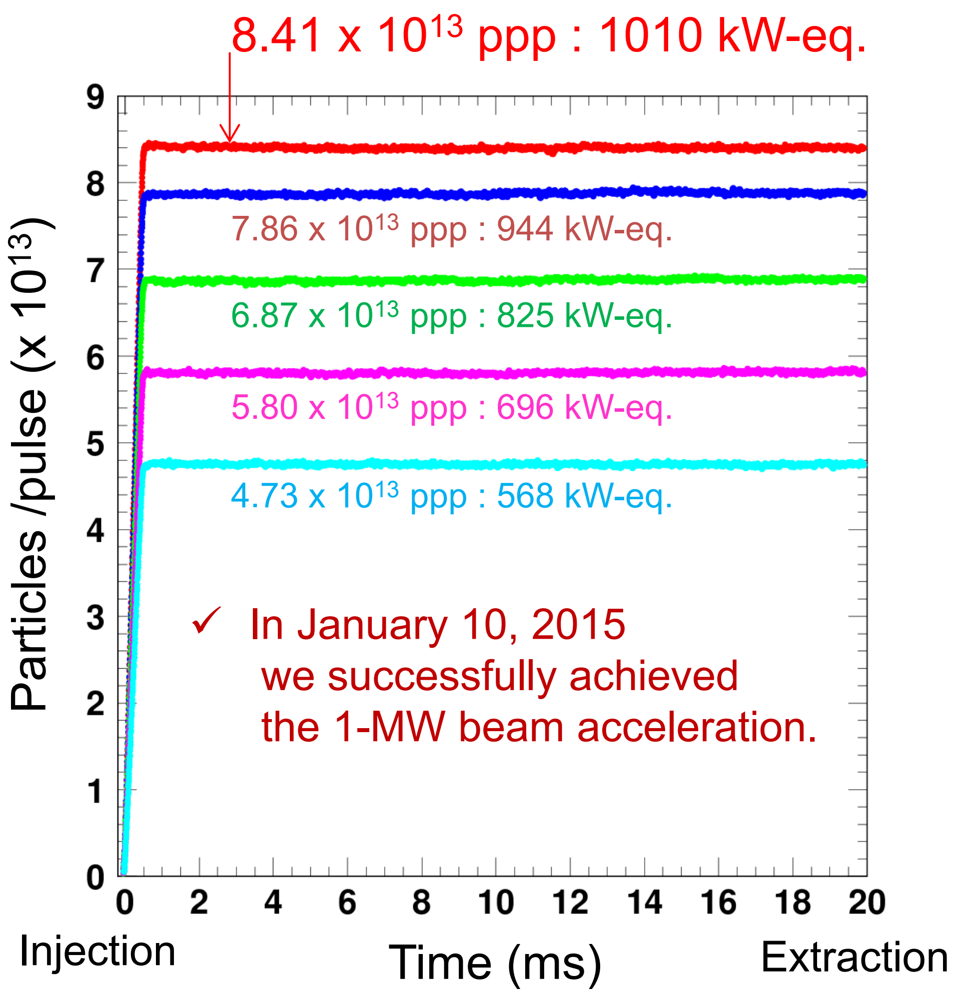
Experimental condition

- Injection beam condition
  - Injection energy : 400 MeV
  - Peak current : **45.0 mA**
    @ the entrance of RCS
  - Pulse length : 0.5 ms
  - Chopper beam-on duty factor : 60%
    - ➢ 8.41 x 10^{13} particles/pulse, corresponding to **1010 kW** at 3 GeV

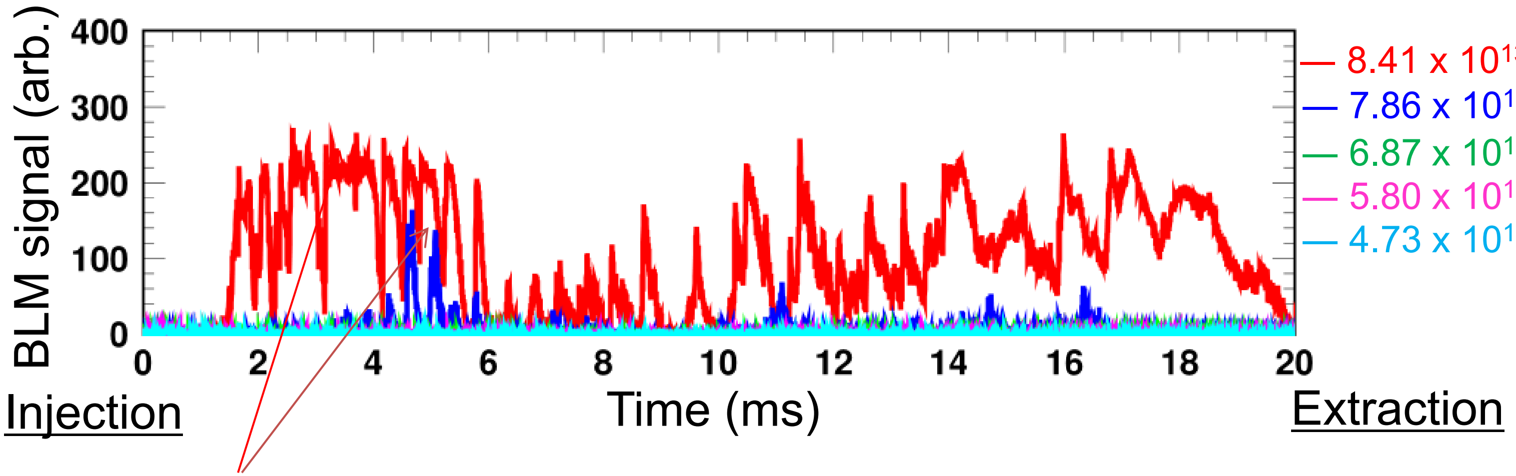
- Injection painting parameter;
  100π transverse painting
  + full longitudinal painting

There is no terrible beam loss, but some unnecessary beam losses was detected at the arc sections.

Circulating beam intensity over the 20 ms from injection to extraction measured by CT



Beam loss in the high dispersion area (arc sections)



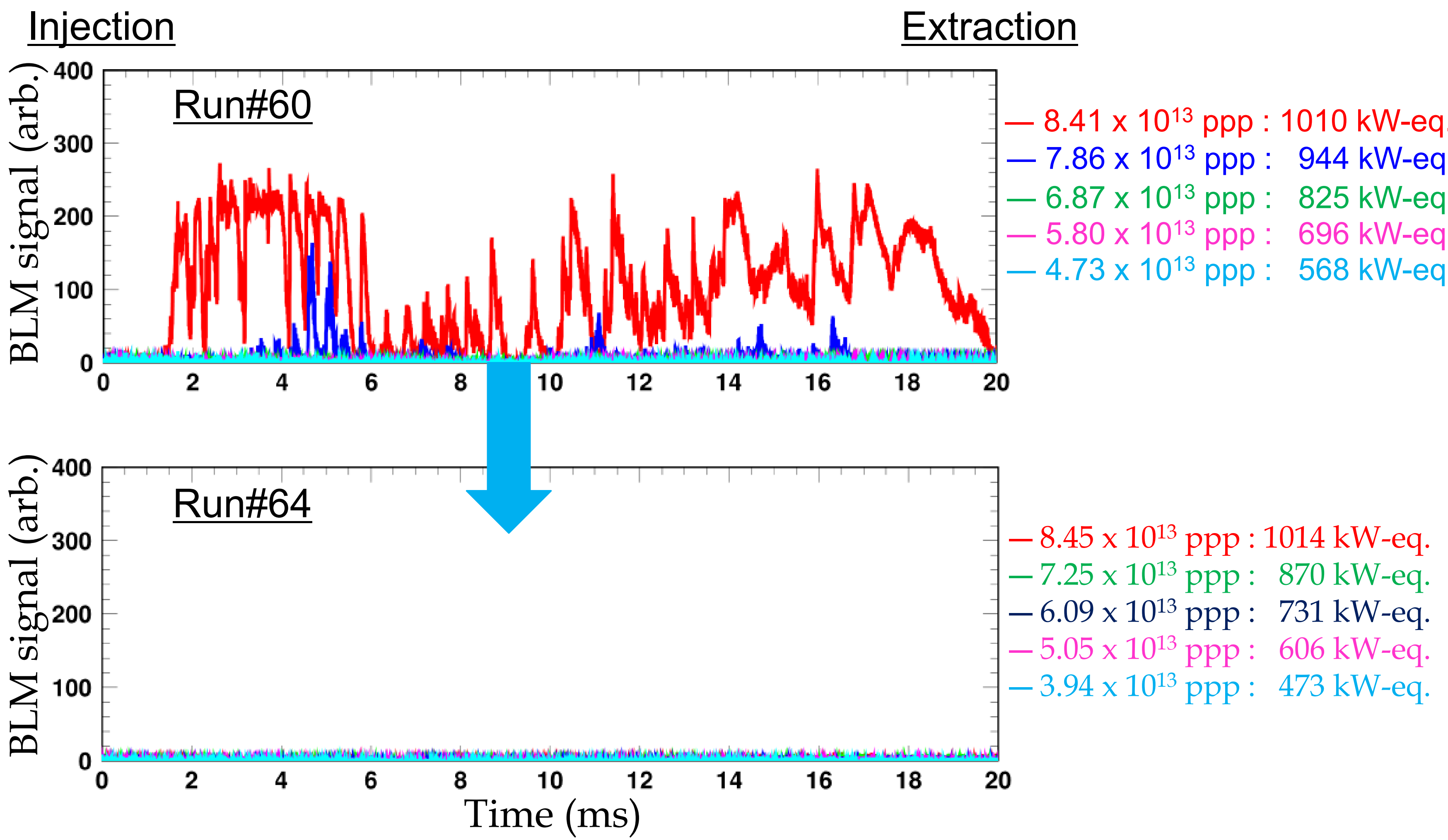
- ✓ The beam losses observed for the **944-kW (blue)** and **1010 kW (red)** beams can be interpreted as ***longitudinal beam loss arising from a distortion of the RF bucket caused by the beam loading effect***.
- ✓ Such beam particles suffer from large momentum excursion and most of them are lost in the high dispersion area, not at the collimator section located in the dispersion-free section.
- ✓ This type of longitudinal beam loss has to be cured by beam loading compensation. ***But then the anode power supply in the RF system had no enough margin to complete sufficient beam loading compensation for the 1-MW beam.***

We carried out the anode power supply upgrade using the 2015 summer maintenance period.

1MW beam test again in October 2015

Result of the 1-MW trial in Oct. 2015

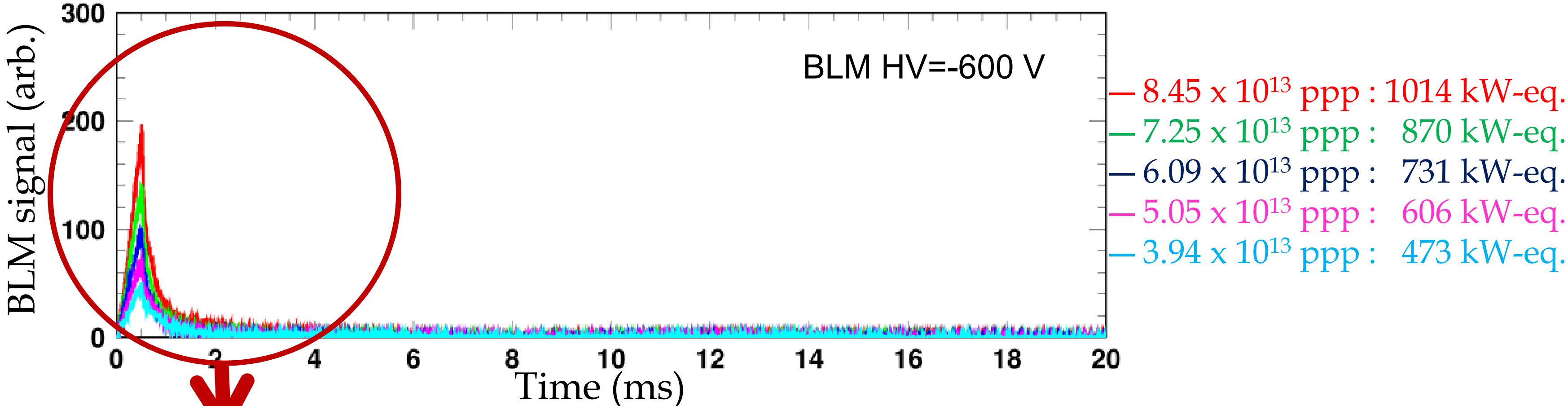
BLM signals at the high dispersion area (arc sections)

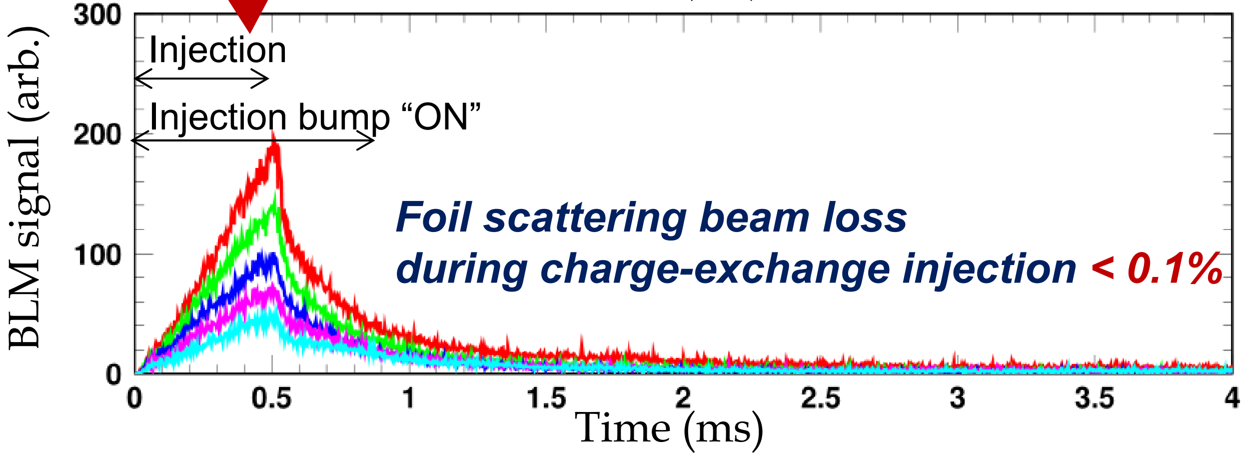


Longitudinal beam loss was well mitigated as expected by sufficient beam loading compensation after the RF power supply upgrade.

Beam loss at the collimator

BLM signals at the collimator section (dispersion-free straight section)



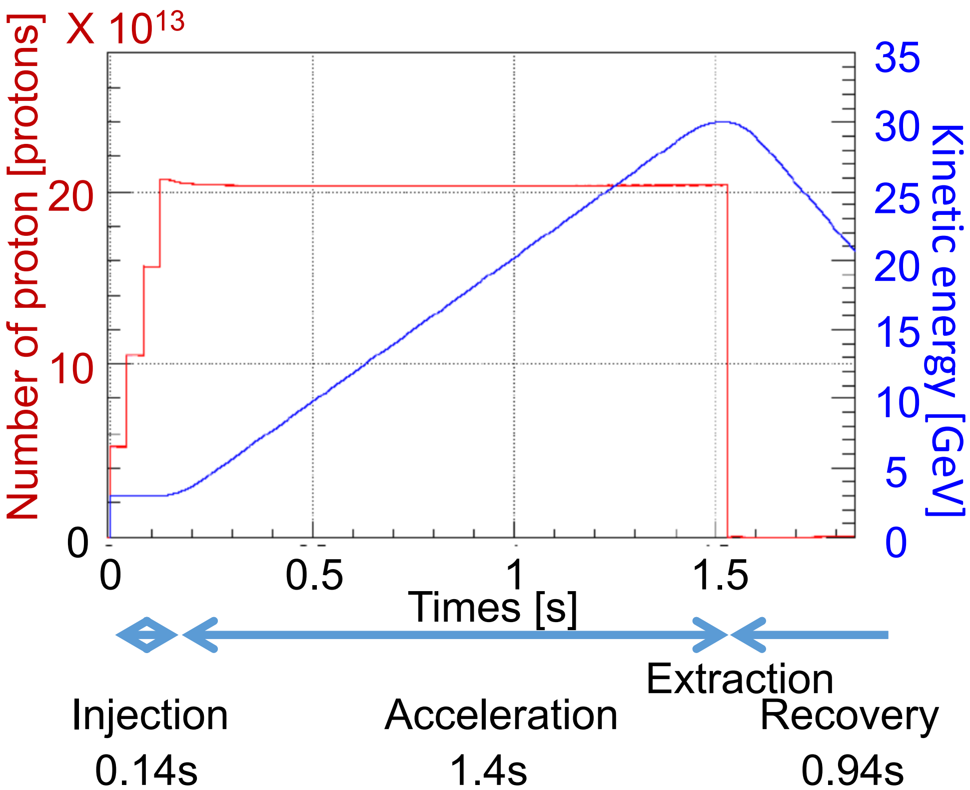


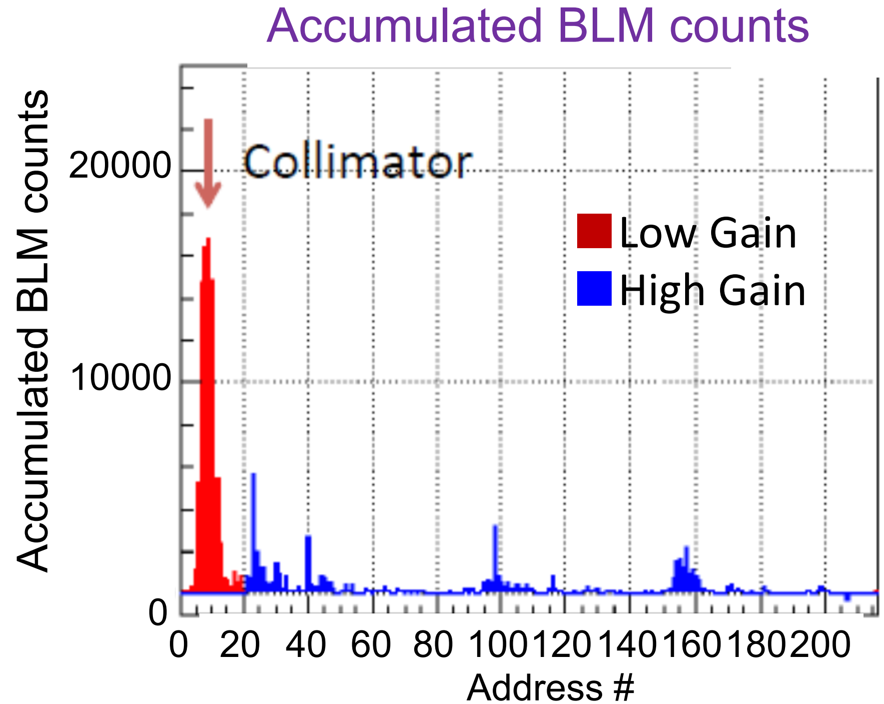
- ✓ The beam loss at the collimator section mainly arises from ***foil scattering during injection.***
- ✓ The other beam loss, such as space-charge induced beam loss, was well minimized by injection painting even for the 1-MW beam.
- ✓ The remaining beam loss for the 1-MW beam was estimated to be < 0.1% (< 133 W in power) << Collimator limit of 4 kW.
- ✓ RCS beam commissioning made big progresses in this beam test.

➢ 1MW operation is still ready !

MR Status

Typical Operation Status for Fast Extraction





Power	395 kW
Repetition	2.48 sec
Loss	Total ~940 W (Collimator limit : 2kW)
	during injection : 191 W
	beginning of acceleration : 746 W

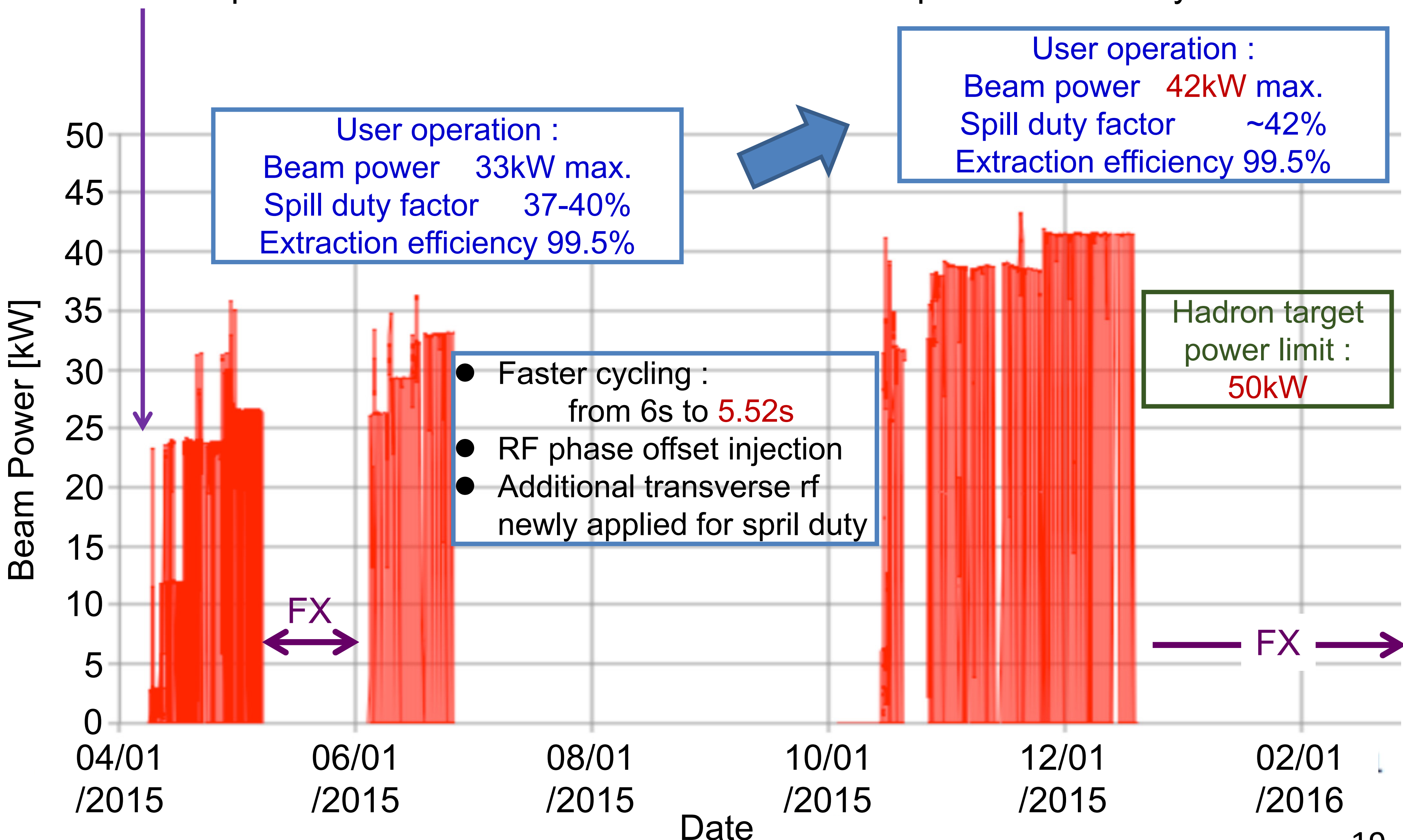
Beam losses
: localized at collimator area

- Collimator aperture :
  H : 60π-70π, V : 60π-70π

When the cycle time is 1.3 sec
beam power : 750 kW

Slow extraction

After the long shutdown for 1 year and 11 months,
beam operation resumed for users in the hadron experimental facility.



Mid –term plan of MR

- ***FX***

The high repetition rate scheme is adopted to achieve the design beam intensity, ***750 kW***.

  - Cycle time will be increased from 2.48 s to 1.3 s by replacing PS's for main magnet (B, Q, S), RF cavities and some injection and extraction devices.

- ***SX***

The beam power will be gradually increased toward ***100 kW*** watching the residual activity.

  - Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose.

Upgrade scenario

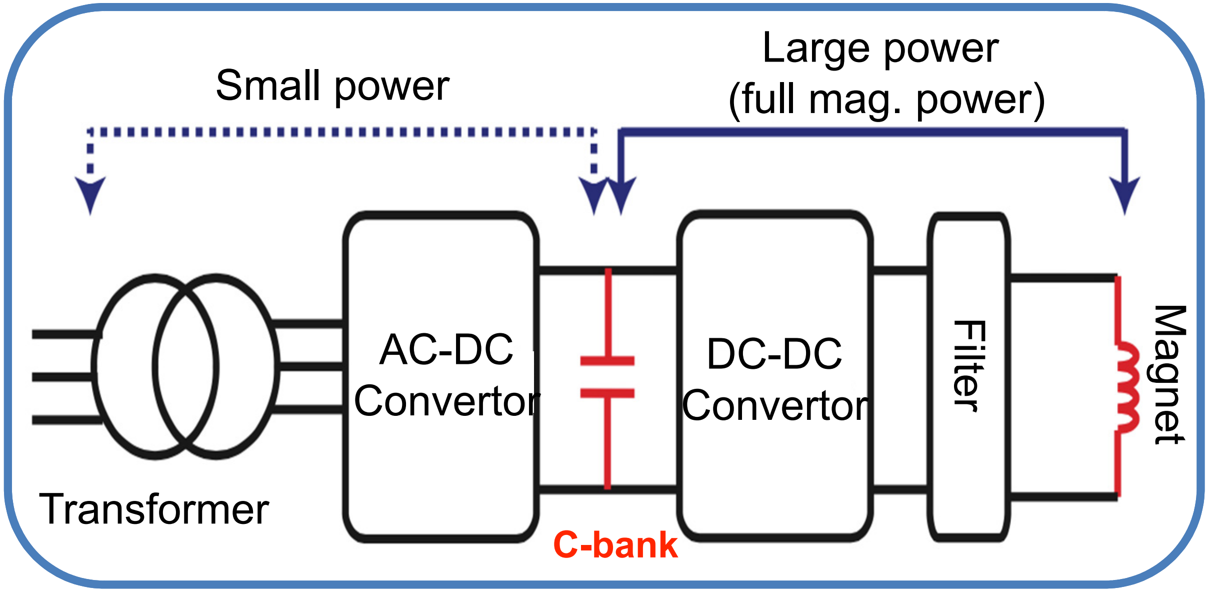
JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX [kW] (study/trial)	240-320	> 360	400	450	700	800	900
SX [kW] (study/trial)	-	30-40	50	50-70	50-70	~100	~100
Cycle time PS	2.48 s				1.3 s	1.3 s	1.25 s
New magnet PS	R&D	Large scale prototype		Mass production installation/test			
High gradient rf system	Manufacture, installation/test						
2nd harmonic rf system							
VHF cavity							
Ring collimators		Add.collimators (2 kW)		Add.collimators (3.5kW)			
Injection system	Kicker PS improvement, Septa manufacture /test						
FX system							
Large aperture QDT							
SX Local shields			Local shields				
Ti ducts Ti chamber	Beam ducts		ESS				

Requirements for New power supplies

- High repetition rate : 1.3 sec. cycle
  - ✓ Issue : large power variation @ AC main grid
    - ✓ Not allowed by Electric Power Company
      - ➢ Energy recovery with Bank capacitor

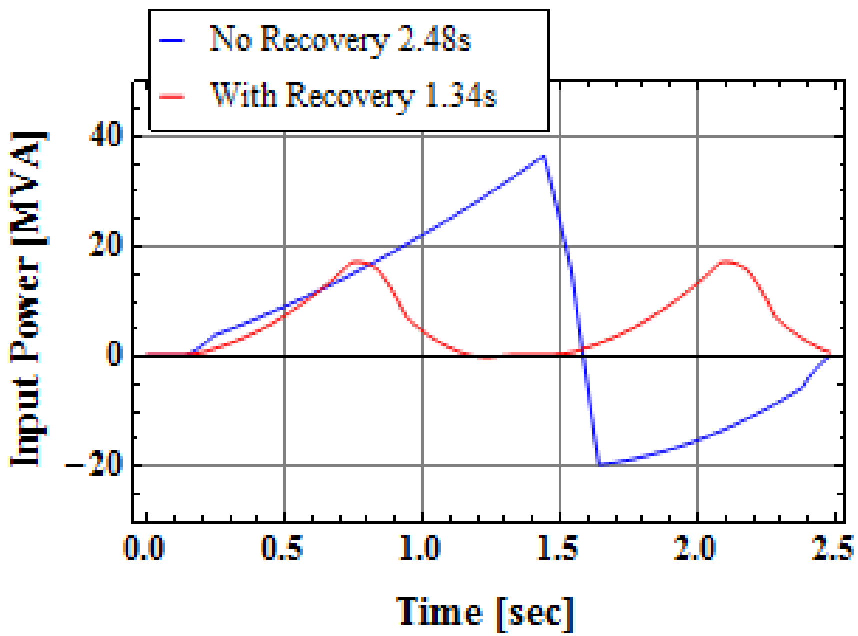
- Precise output current
  - ➢ Issue : Noise in current measurement, Switching ripple
      - ➢ Low noise current measurement and digital control system
      - ➢ High switching frequency (> kHz)

New power supplies for 1.3 s cycle



- Energy recovery with Bank capacitor
  - Two large converters and large capacitance for energy recovery, symmetric power module circuit

Effect on the Energy Consumption

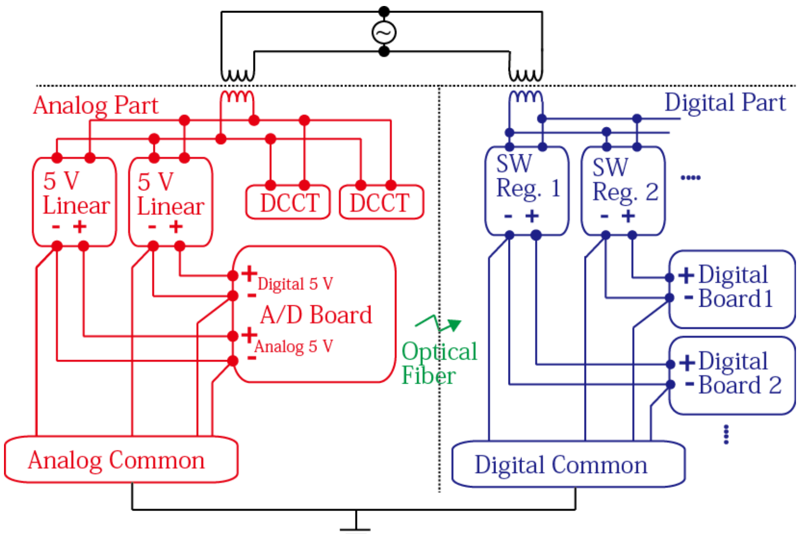


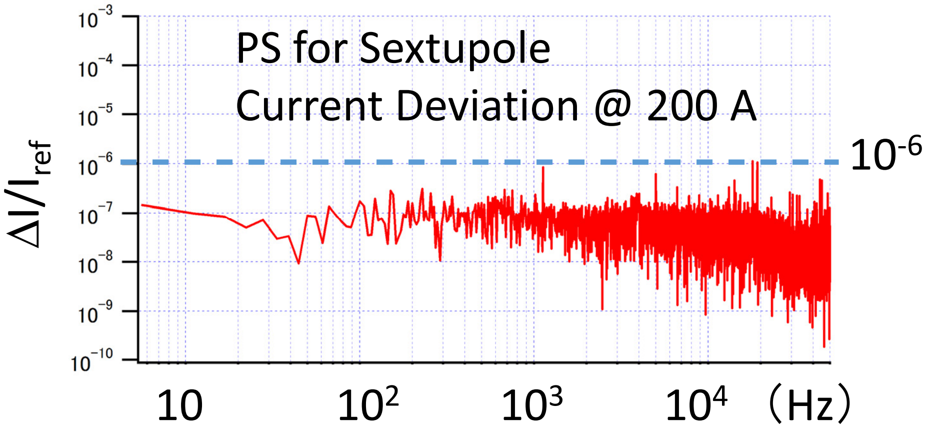
Energy transfer control between the capacitor bank and magnet has been succeeded.

R&D of new power supplies for 1.3 s sycle

Y. Kurimoto et. al. IEEE. TNS

24 bit A/D board and Isolation between analog and digital components





➢ Succeed to measure current at ppm level

Low noise current measurement and digital control system

- 24 bit A/D board and Isolation between analog and digital components
  - ➢ Succeed to measure current at ppm level
- Digital control board for tracking error correction
  - ➢ Tracking error can be reduced down to 10^{-5}

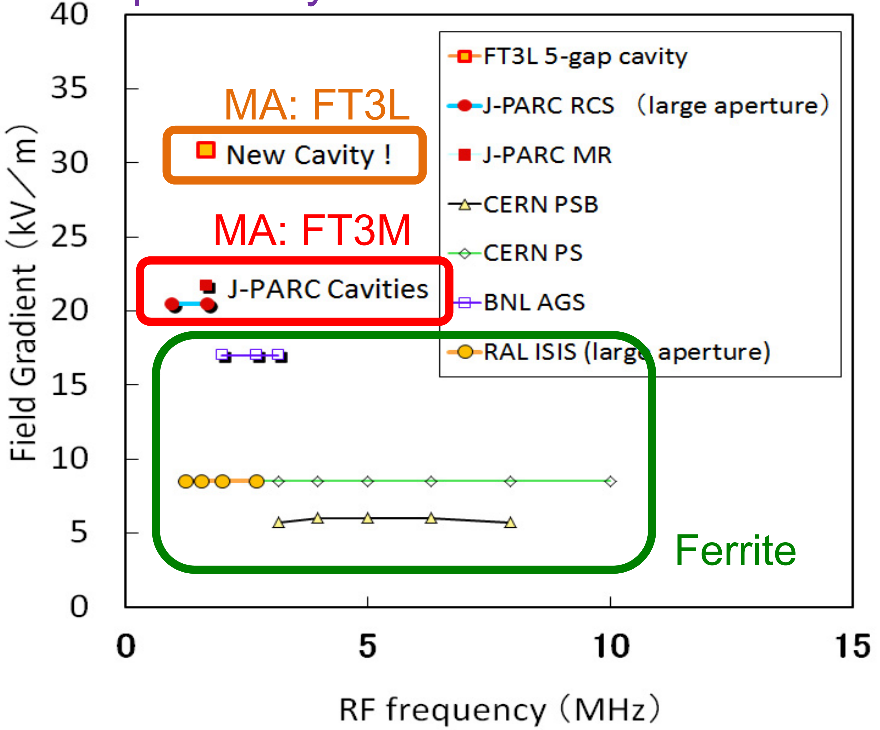
The test have enabled the manufacture to produce all components of new PSs

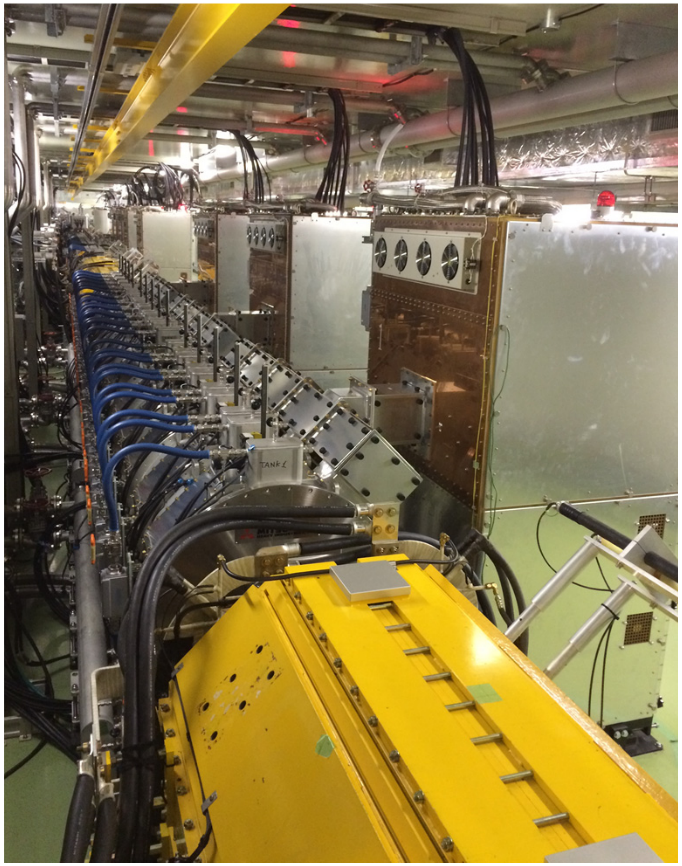
Mass production has been started.

High impedance rf system

A new type of the magnetic alloy (MA) core, FT3L(made by Hitachi Metal), is adopted to increase shunt impedance of the rf cavity. The core is processed by annealing with magnetic field.

Comparison of field gradient of rf cavities for proton synchrotron.





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

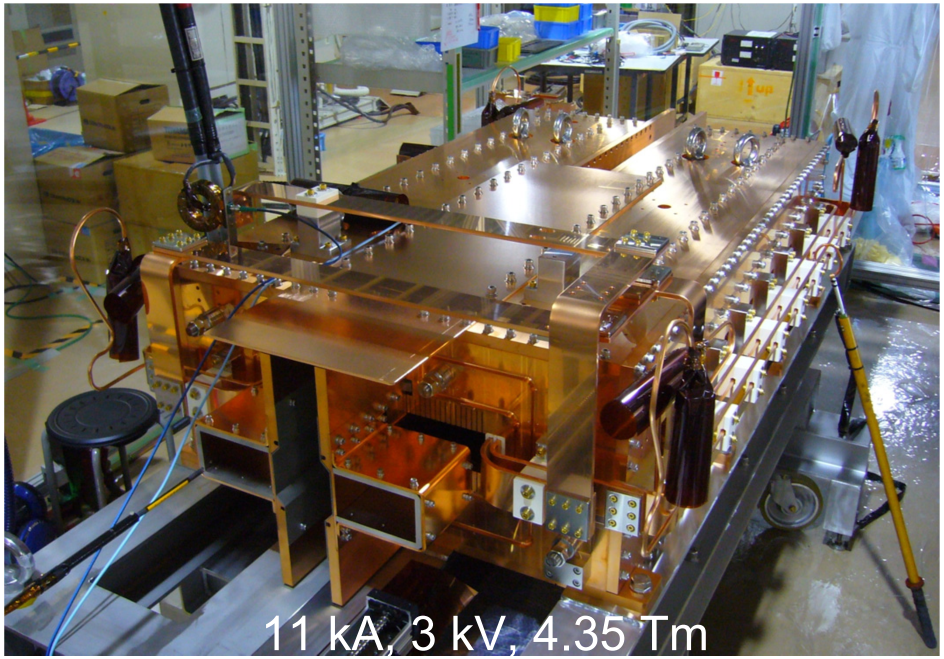
➢ J-PARC already achieved very high field gradient.

- The first **FT3L** cavity has been operated stably for 20 month in the MR.
- Four new FT3L cavities was installed in the 2015 summer shutdown.

Injection and FX septum systems

New injection septum magnet I and FX low field septum for the high repetition rate operation have been manufactured and now tested.

Injection septum magnet



FX low field septum magnet

To realize 1.3 sec. cycle operation, improvements of devices (PSs, RF cavity, Injection septum, …) have been performed on schedule according to the upgrade scenario

Long-term upgrade plan

- ***Linac***

  for TEF
  - ✓ Repetition : 50Hz for TEF

  for higher power operation of RCS
  - ✓ Peak current : >60mA
  - ✓ Pulse length : >0.6ms

- ***RCS***

  Beam power : > 1MW

- ***MR***

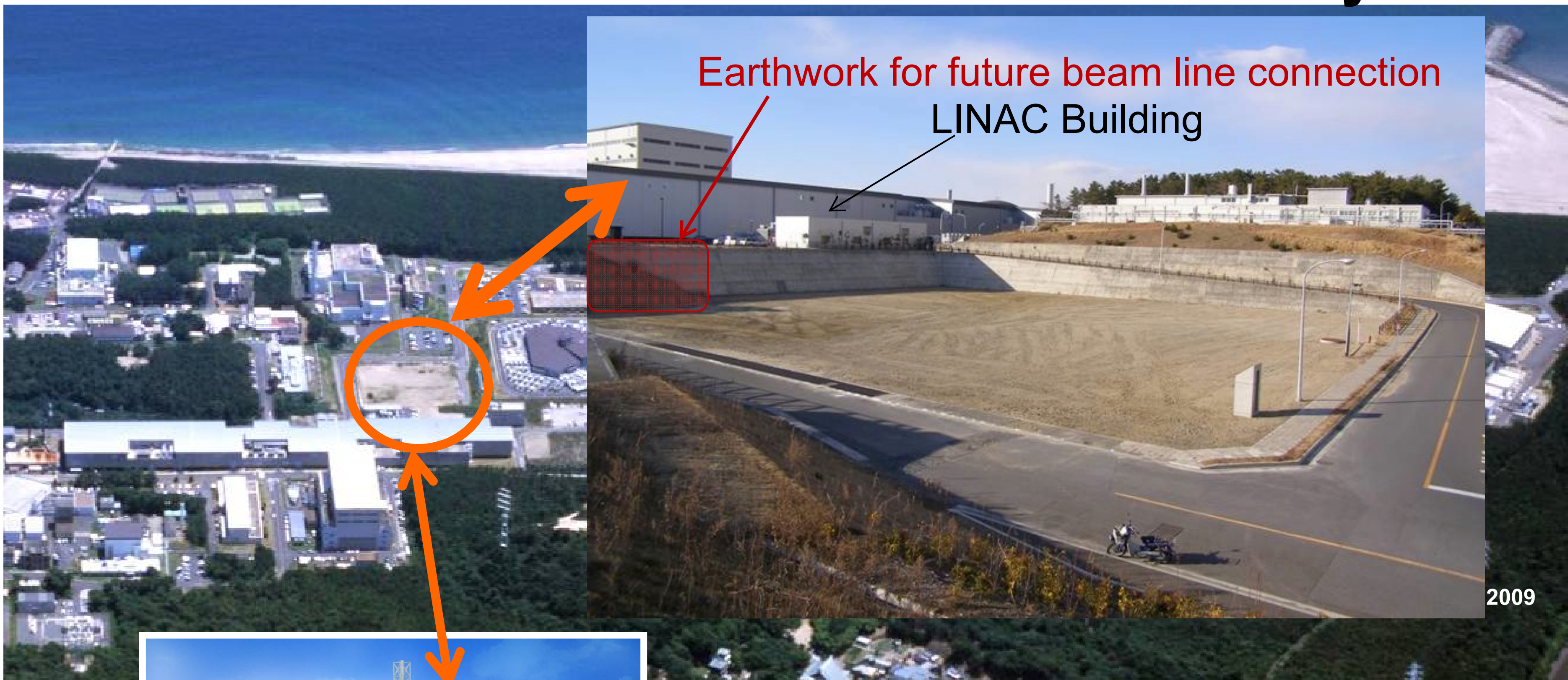
  Beam power for neutrino : > 1MW

Transmutation Experimental Facility (TEF)

- R&D for technology to reduce the environmental impact of radioactive waste with neutrons
- Experimental facility of Accelerator Driven System (ADS) is now being designed with great efforts

Transmutation Experimental Facility (TEF)

Current Condition of Facility Site



- R&D for technology to reduce the environmental impact of radioactive waste with neutrons
- Experimental facility of Accelerator Driven System (ADS) is now being designed with great efforts

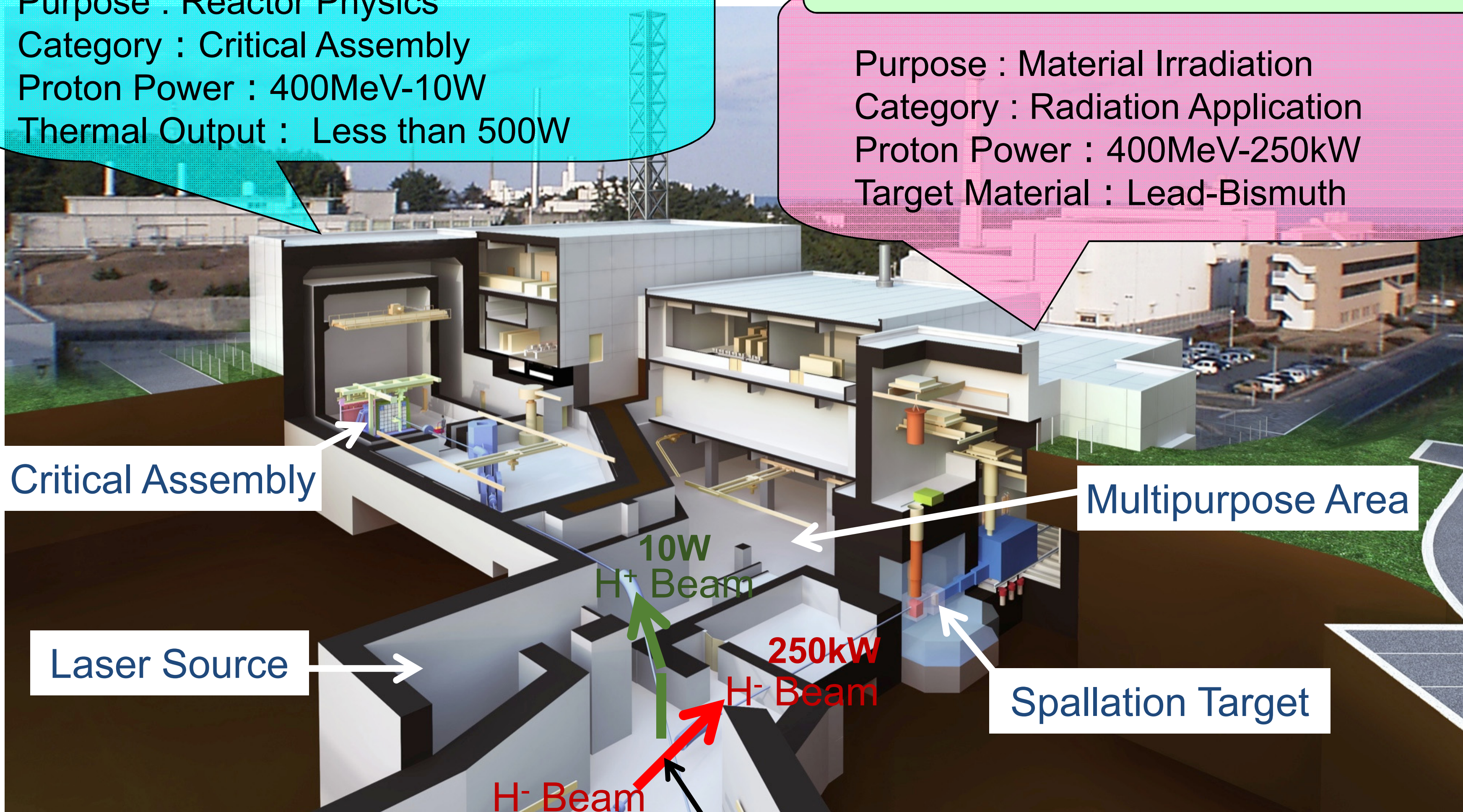
Transmutation Experimental Facility (TEF)

TEF-P: Transmutation Physics Experimental Facility

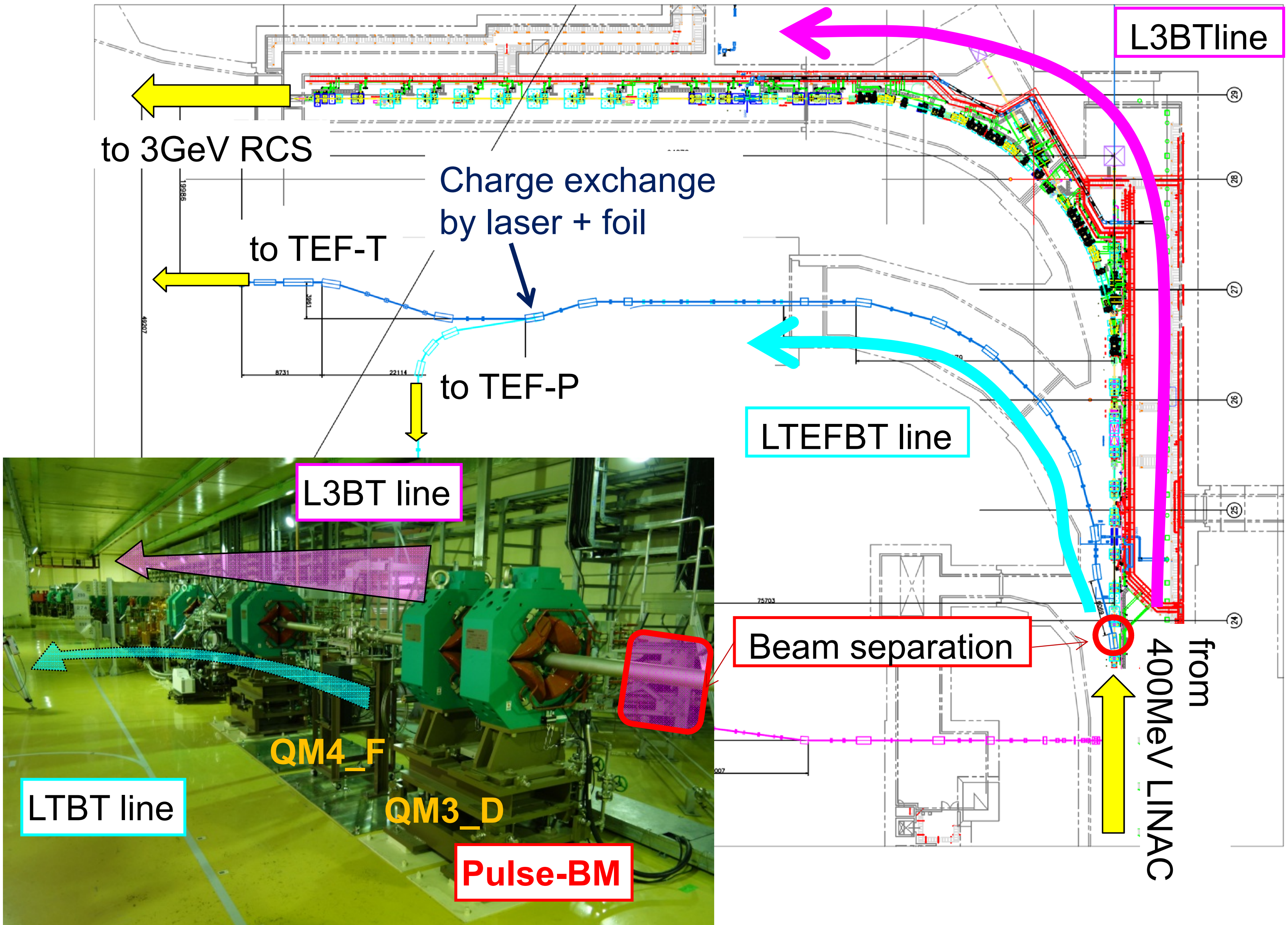
Purpose : Reactor Physics
Category：Critical Assembly
Proton Power：400MeV-10W
Thermal Output： Less than 500W

TEF-T: ADS Target Test Facility

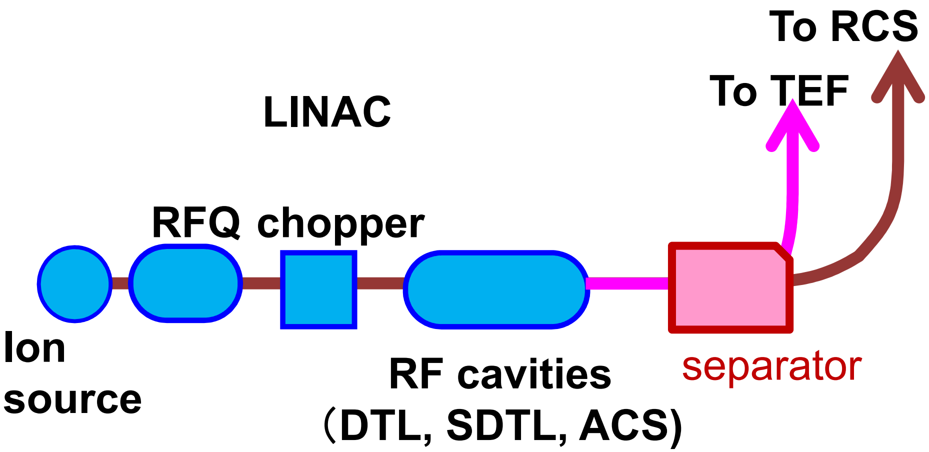
Purpose : Material Irradiation
Category : Radiation Application
Proton Power：400MeV-250kW
Target Material：Lead-Bismuth

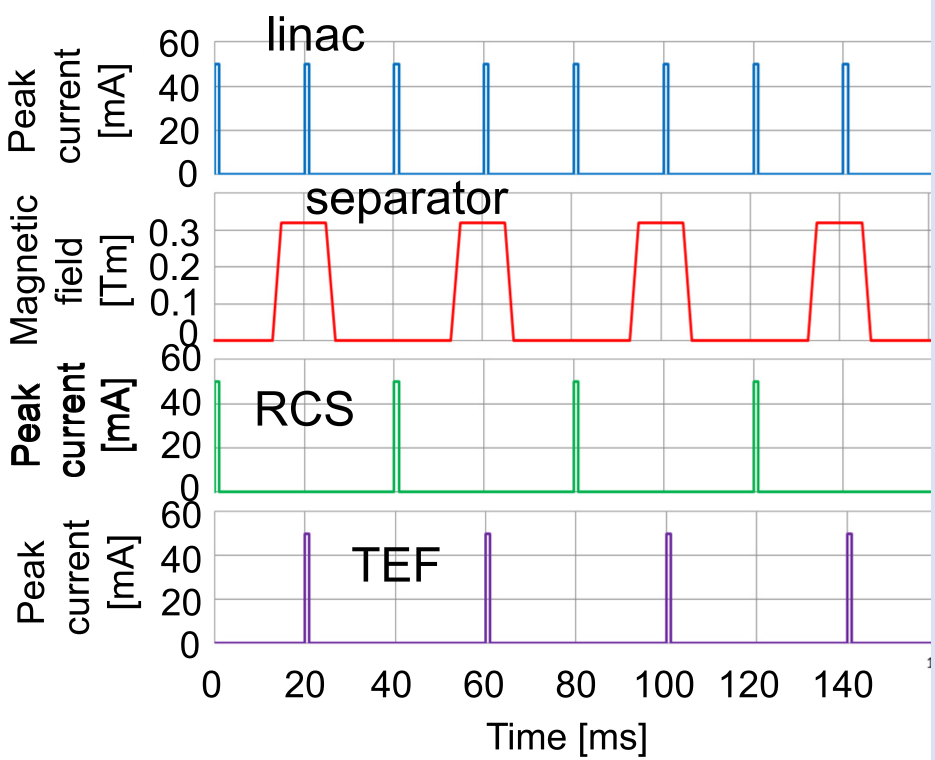


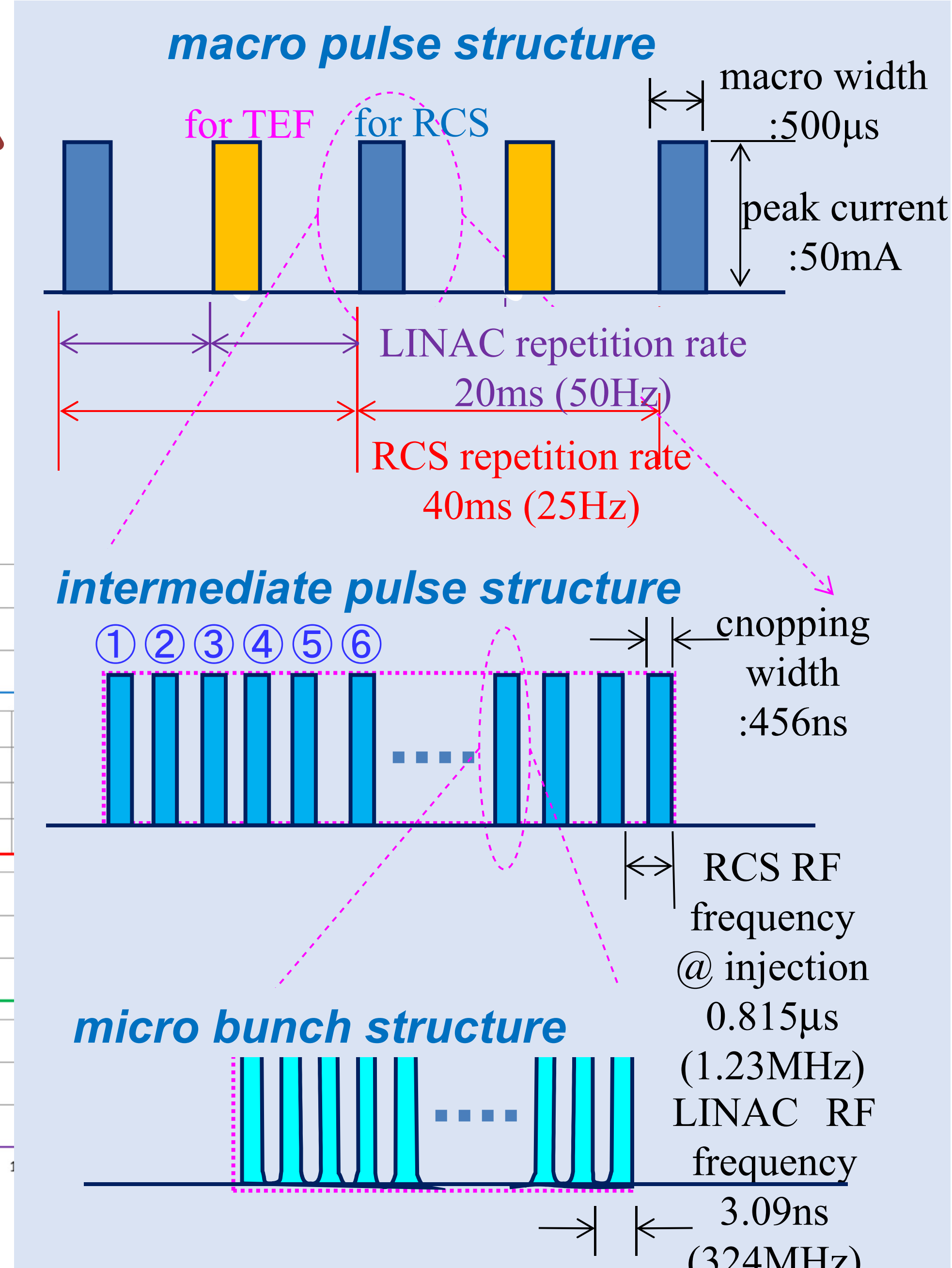
Layout plan of L-TEFBT and L3BT line



Beam structure







LINAC status and Upgrade for TEF

TEF : Transmutation Experimental Facility

	status	design	plan
peak current	30mA	50mA	complete
energy	400MeV	400MeV	complete
repetition	25Hz	50Hz	1st stage : Upgrade of cooling water system ➢ Beam power limits ~133kW with beam chop 2nd stage : Upgrade of power supply of klystron ➢ Beam power up to 250kW without beam chop
beam separation			Installation of New devices ➢ R&D started

Long-term upgrade plan

- ***Linac***

  for TEF

  ✓ Repetition : 50Hz for TEF

  for higher power operation of RCS

  ✓ Peak current : >60mA

  ✓ Pulse length : >0.6ms

- ***RCS***

  Beam power : > 1MW

- ***MR***

  Beam power for neutrino : > 1MW

Operation with beam intensity > 1MW in the RCS

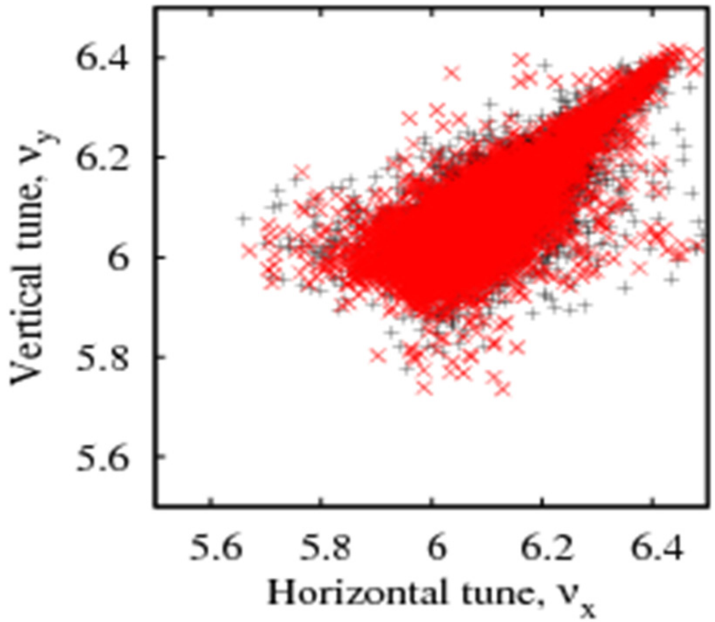
Space charge

Laslett tune shift at injection energy:

$$\Delta \nu = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon B_f}$$

r_p: classical radius of proton
n_t: no. of protons in the ring
β, γ: relativistic parameters
ε: transverse painting emittance (100π mm mrad)
B_f : Bunching factor (0.4)

Tune footprint simulated by ORBIT



Black:
181 MeV inj., 540 kW-eq.

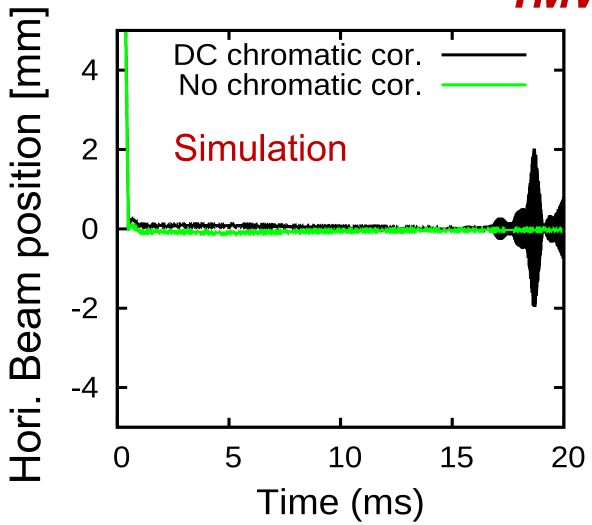
Red:
400 MeV inj., 1.5 MW-eq.

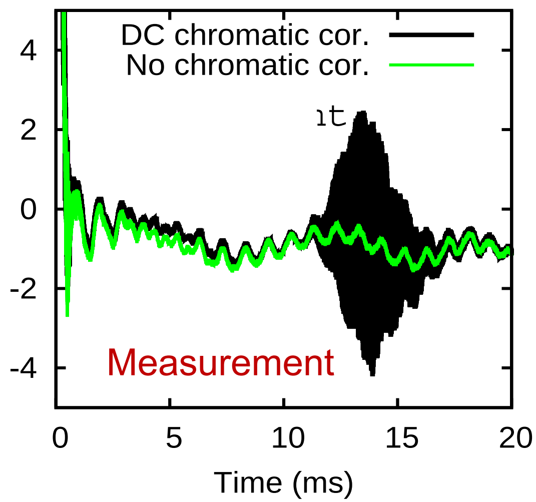
E_{inj} (MeV)	ppp ($\times 10^{13}$)	Beam power at E_{ext} (MW)	$\Delta\nu$	Comment
181	4.5	0.54	-0.53	Achieved
400	8.33	1	-0.33	Achieved
400	10.8	1.3	-0.43	Reasonable
400	13.3	1.6	-0.53	Reasonable

Beam instability issue for high power operation

Source: Transverse impedance of the RCS extraction kicker magnets

1MW case



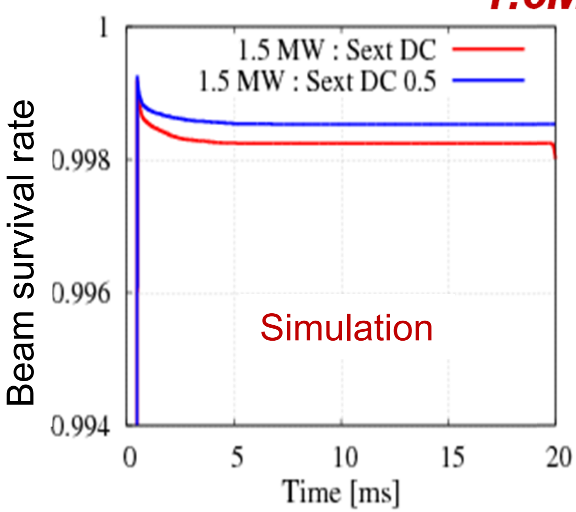


Simulation set condition for 1 MW

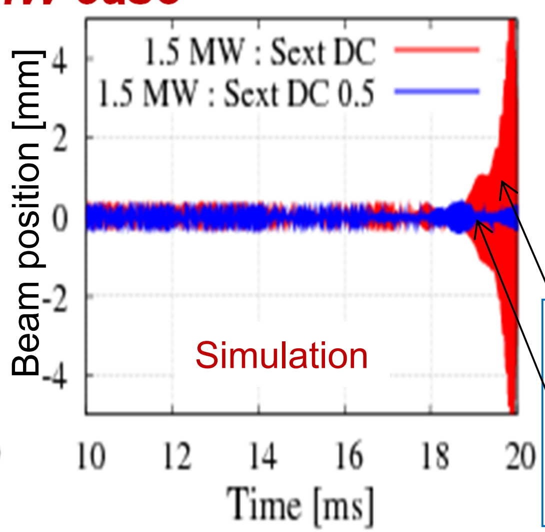
- ✓ Tune tracking (6.45, 6.42) →(6.40, 6.40) at ext.
- ✓ Reduce even degree of DC chromatic cor. (1/2)
- ✓ $\Delta p/p < 0.1\%$

Successfully accomplished 1 MW!

1.5MW case



No significant beam loss except foil scattering at inj.



Slight beam growth occurs even for $\Delta p/p$ = 0.09% and Sext DC 1/2

Conditions

Ipeak: 75 mA, $\Delta p/p$: 0.09%

Injection: 0.5ms

ε_{tp}: 100π mm mrad, Longitudinal: Full

Foil scattering, KM impedance included

- Beam instability occurs for DC chromatic correction.
- Suppressed when degree of DC chromatic correction reduced to half.

Operation with beam intensity exceeding 1MW in RCS

Beam intensity ~1.5 MW is a next goal

- Second neutron production target station is also under discussion.

Challenges:

- ***Linac***

  Peak current : >60mA

  Macropulse width : > 0.6ms

- ***RCS***

  Reinforcement of RF system using the FT3L cavity

  Charge stripping and instability due to kicker impedance will be issues but within reach.

Long-term upgrade plan

- ***Linac***

  for TEF

  - ✓ Repetition : 50Hz for TEF

  for higher power operation of RCS

  - ✓ Peak current : >60mA
  - ✓ Pulse length : >0.6ms

- ***RCS***

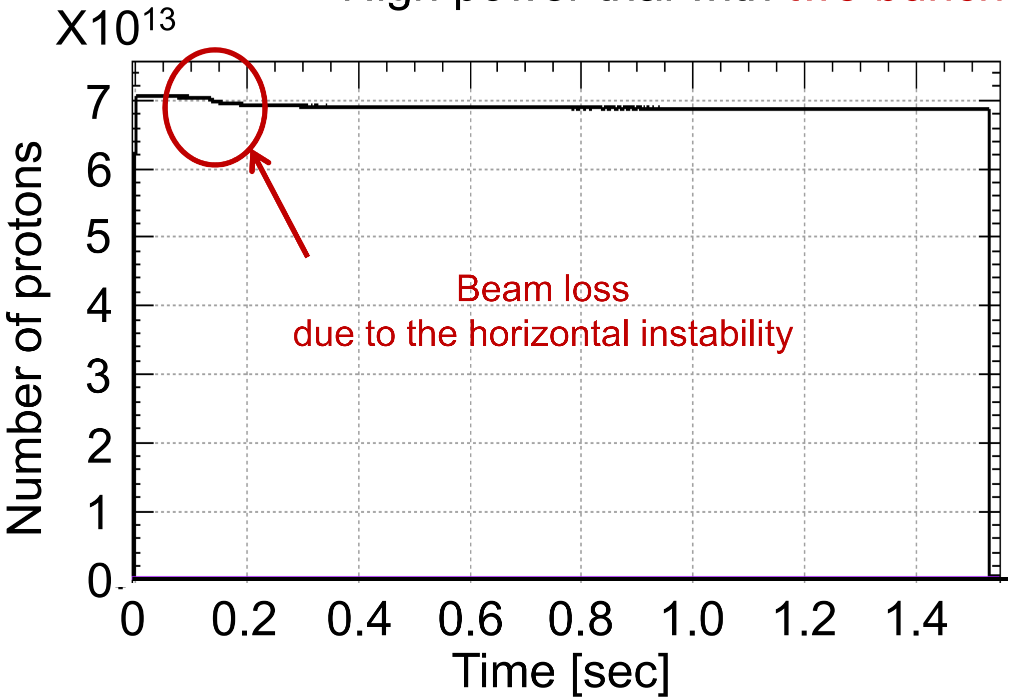
  Beam power : > 1MW

- ***MR***

  Beam power for neutrino : > 1MW

High Intensity beam study of MR

High power trial with two bunches at the new betatron tune



(21.24, 21.31)

- Extracted beam : 6.82×10^{13} ppp
  - (132 kW eq. ,2 bunches)
- Total beam loss : ~ 420 W

Near future tunable knobs to reduce the beam loss:

Injection kicker, BxB feed-back,
2nd harmonic cavity,
VHF cavity, etc.

Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
2	2.48	132	0.42	achieved
8	2.48	530	1.7	estimation
8	1.3	1000	3.2	estimation

The MR has capability to reach 1MW with the high repetition rate operation

Summary

- ***Status and operation***
  - Achieved beam power in user operation :
    500 kW for the MLF users
    395 kW and 42 kW for the T2K experiment and HD users, respectively.
  - High power demonstration :
    1 MW eq. beam was achieved in the RCS
    132 kw eq. beam with two bunches in the MR
    - ➢ The MR has a capability to reach beam power ~ 1 MW with faster cycle operation (1.3 sec.).

- ***Mid-term upgrade plan***
  - The design power of 750 kW for the FX, and 100 kW for the SX will be achieved after the replacement of main magnet power supplies.

- ***Lon-term upgrade plan***
  - Linac : repition 50Hz for TEF, peak current > 60mA, pulse length > 0.6msec
  - RCS : beam power : ~ 1.5MW
  - MR : beam power for the FX : > 1MW