Challenges to Higher Beam Power in J-PARC: Achieved Performance and Future Prospects

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MOYPLM1

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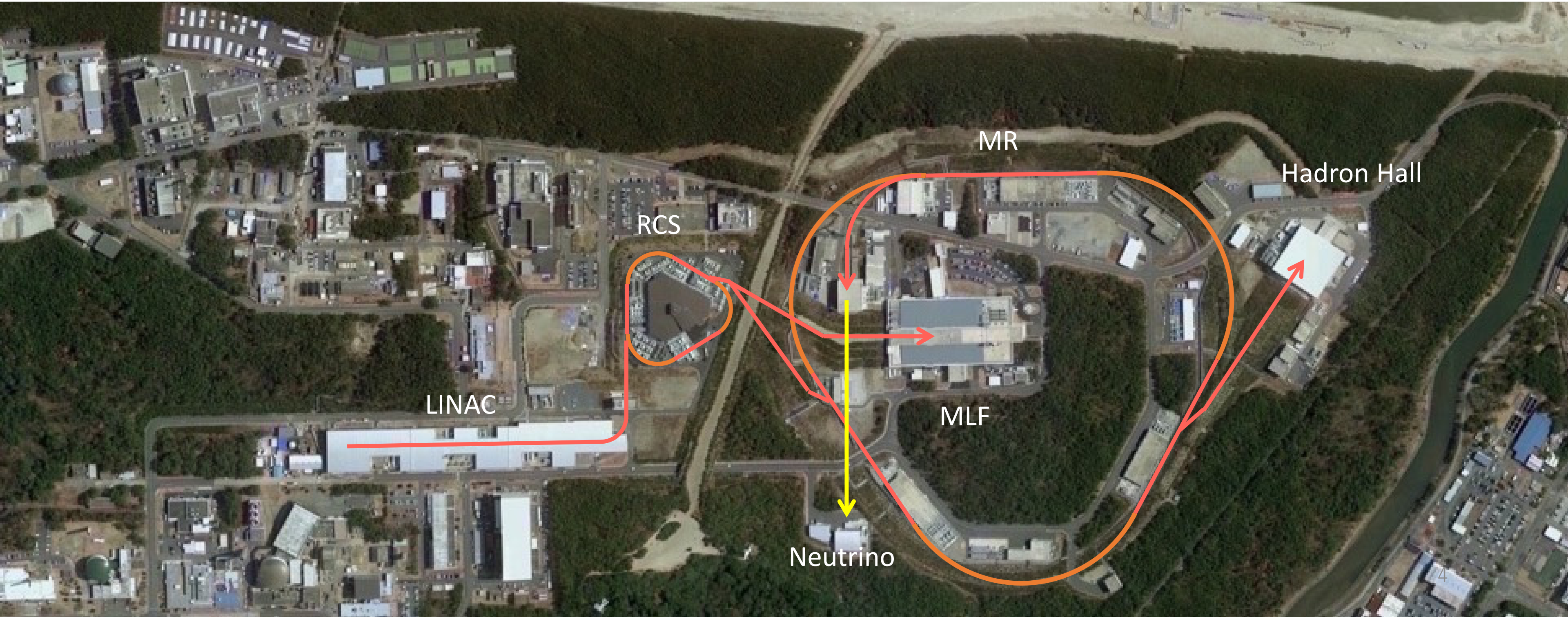
Japan Proton Accelerator Research Complex

- High Intensity Proton Accelerators
- Facilities to use the secondary beams
- Operated by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK)

- LINAC (400 MeV)
- Rapid Cycling Synchrotron (RCS) (3 GeV)
  - Materials and Life Science Experimental Facility (MLF)

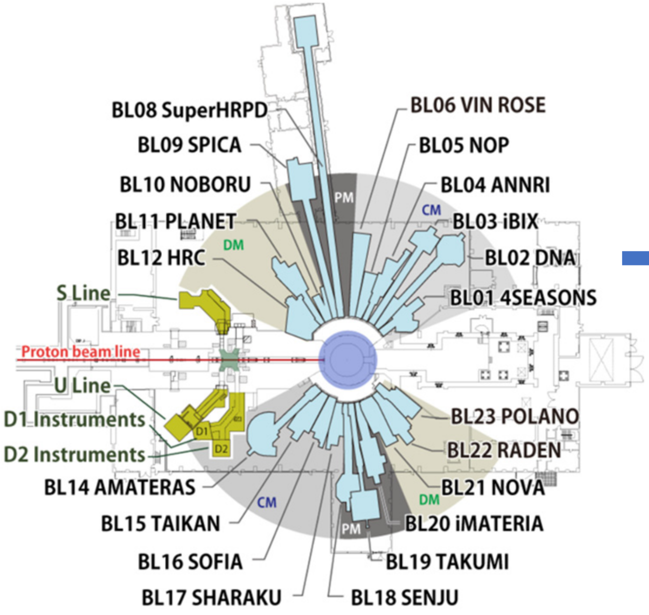
- Main Ring (MR) (30 GeV)
  - Hadron Hall
  - Neutrino Facility



High Power Beams to Users

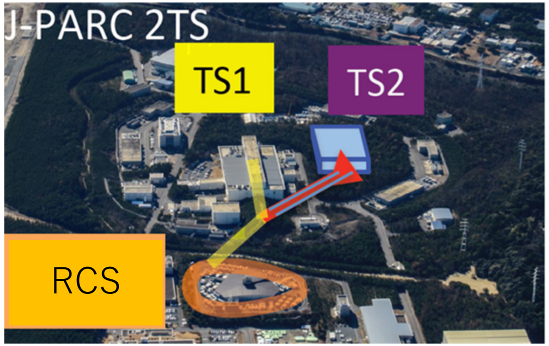
Materials and Life Science Experimental Facility (MLF) (2008−)

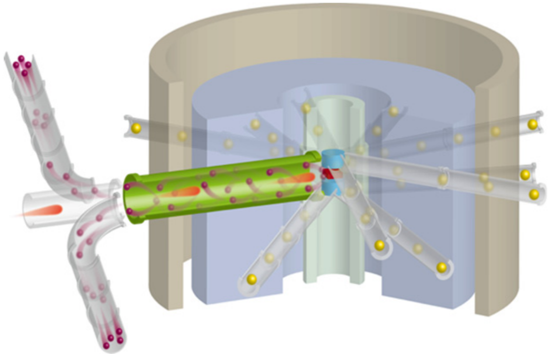
- 21 Neutron beam lines
- 3 Muon beam lines
- RCS Design Beam Power : 1 MW



Future Plan of the MLF Second Target Station

- New design of target, moderators, reflectors
- Neutron Brightness : > 20 times
- Muon Intensity : > 50 times
- RCS Beam Power : 1.5 MW

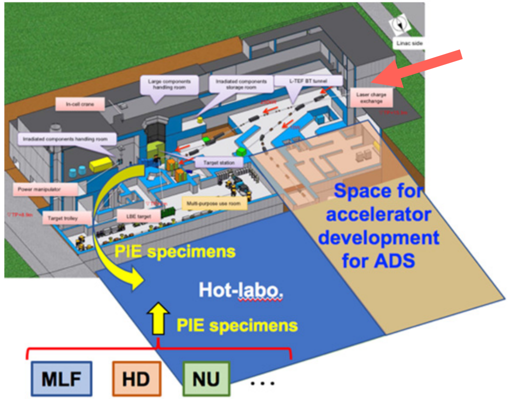




Future Program with the Linac Beam : Proton Irradiation Facility

with laboratories of

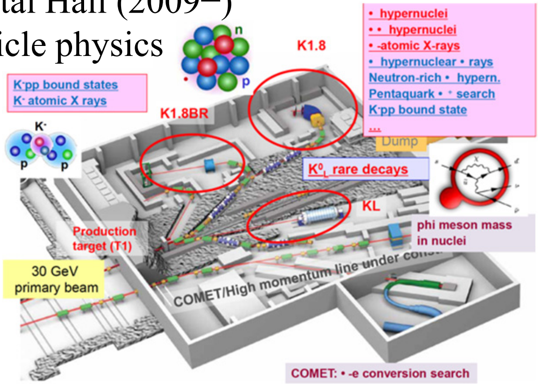
- Post irradiation examination
- Accelerator development for ADS
- 400 MeV, 250 kW



High Power Beams to Users

Hadron Experimental Hall (2009–)

- Nuclear and particle physics



Future Plan for the extension of the Hadron hall

- More intensity of secondary particles
- Purity
- $\Delta p/p$

Neutrino Facility (2009–)

- Long baseline neutrino oscillation experiment (T2K)

+
J-PARC Main Ring Beam Power Upgrade

- Upgrade Plan for the Neutrino Experiment
- Far Detector
  - 50 kton → 260 kton Water Cerenkov detector
- MR Beam Power
  - 750 kW → 1.3 MW

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- MR: Slow extraction operation status and upgrade plan
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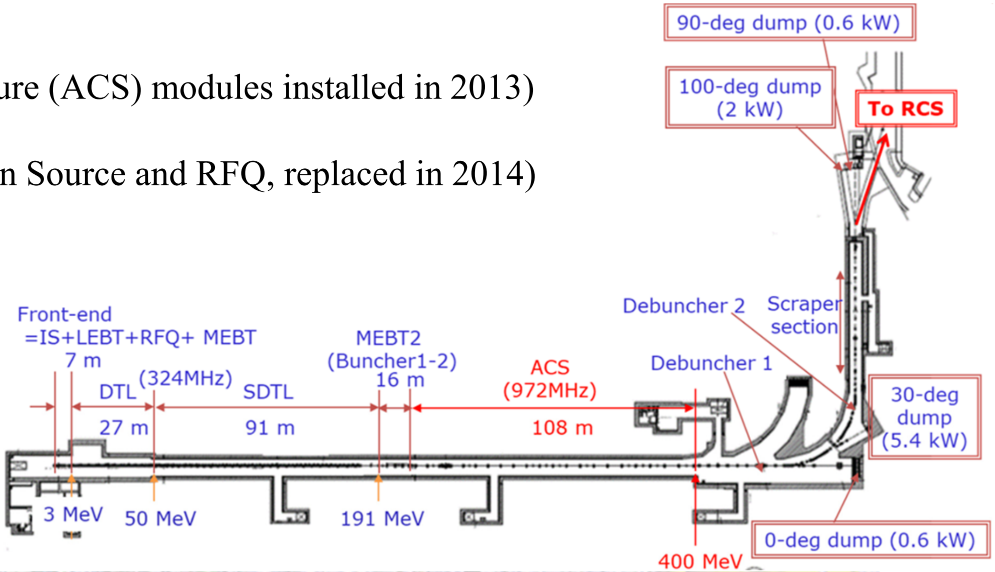
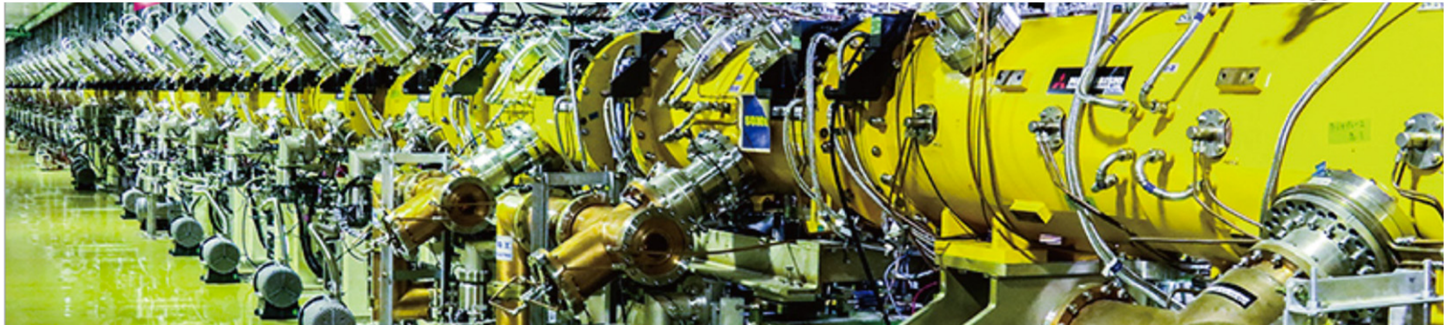
Linac: Operation Status

Y. Liu TUPTS027
Y. Kondo MOPTS046

Particle: H^-
Energy: 181 MeV
→ 400 MeV (Annular Coupled Structure (ACS) modules installed in 2013)
Peak Current: 30 mA
→ 50 mA (Front-end system, Ion Source and RFQ, replaced in 2014)
→ 60 mA for beam study
Macro Pulse Width: 0.5 ms
→ 0.6 ms for beam study
Repetition Rate: 25 Hz





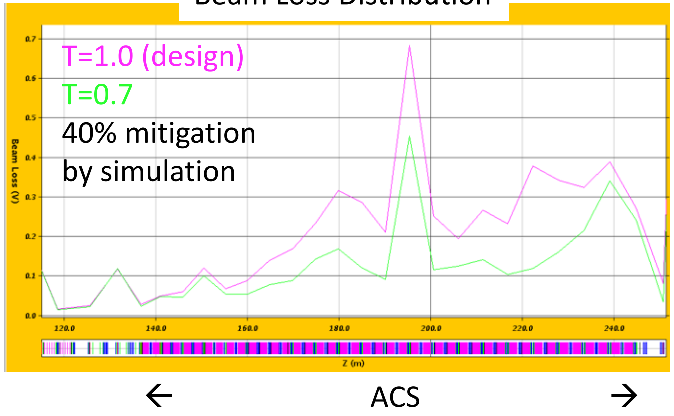
Y. Liu TUPTS027
M. Otani MOPTS048

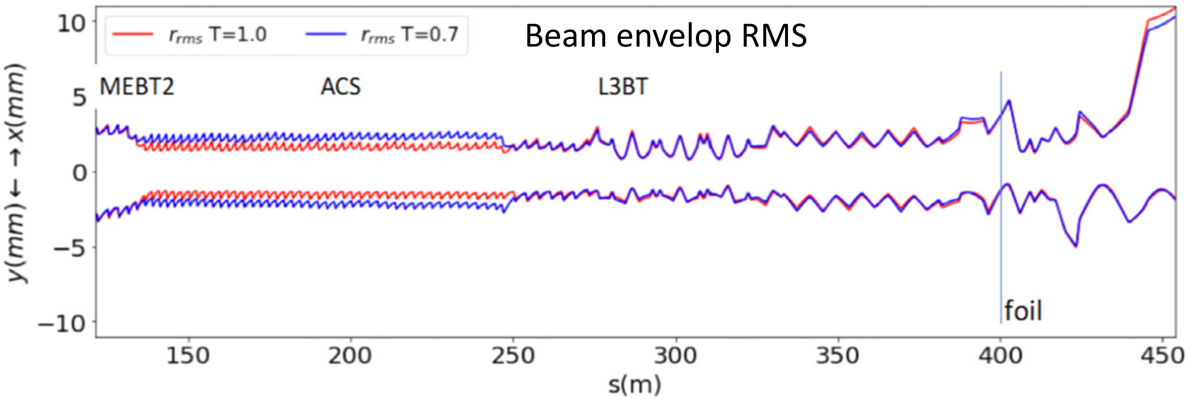
Linac: Tuning for the Beam Loss Reduction

- Tuning of the ion source, LEBT, RFQ and chopper
- Transverse optic matching at MEBT1, MEBT2 and L3BT
- RF phase scan of DTL, SDTL and ACS.

- The intra-beam stripping of H^- causes serious beam losses in ACS.
- The new lattice has been demonstrated for ACS with Txy/Tz = 0.7 from the original equipartitioned lattice.
- Meanwhile the transverse and longitudinal coupling instability by the space charge effect was not observed.

Beam Loss Distribution



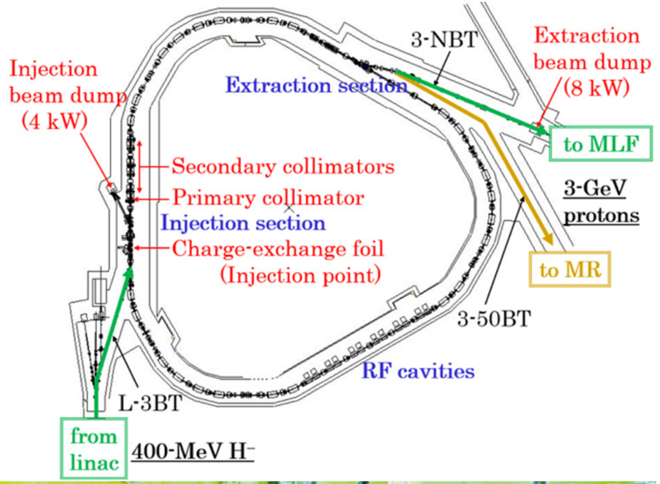


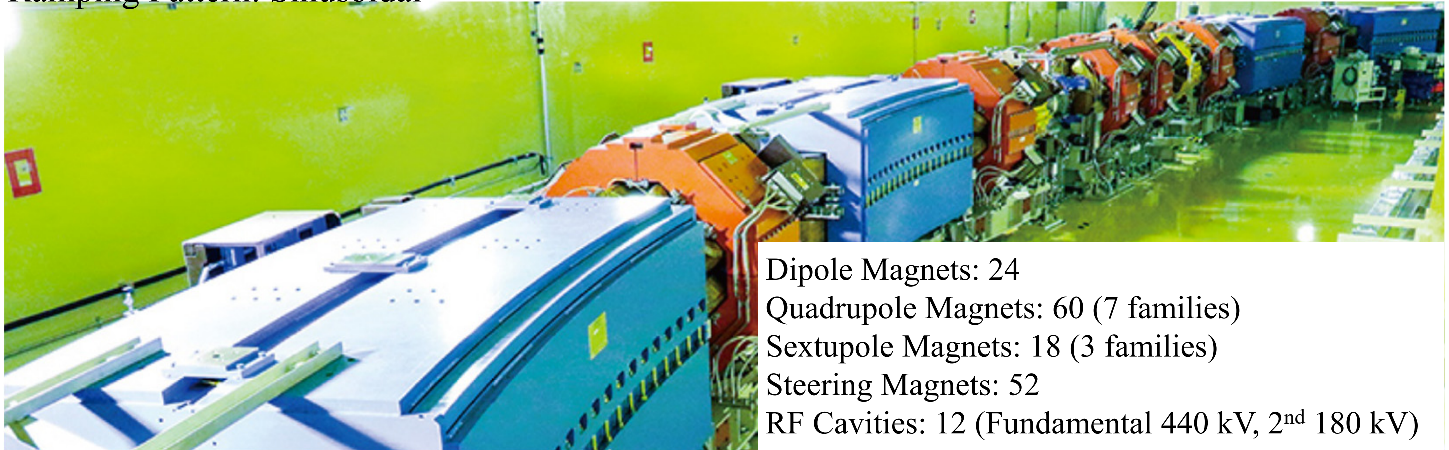
Rapid Cycling Synchrotron: Parameters

Circumference: 348.333 m
Super-periodicity: 3
Harmonic number: 2
Injection Energy: 400 MeV
Extraction Energy: 3 GeV
Original Design Beam Power: 1 MW

- Large Aperture: 486π mmmrad
    - Painting injection during 0.5 ms (307 turns)
- Beam Loss Localization with Collimators
- Lattice for high transition γ: 9.14

Repetition Rate: 25 Hz
Ramping Pattern: Sinusoidal

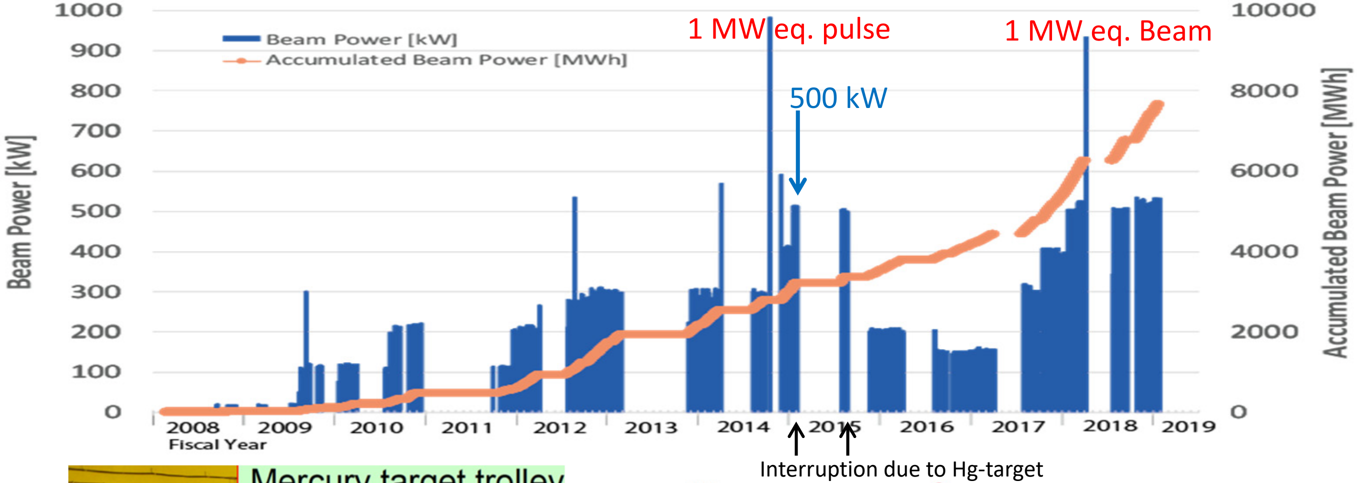


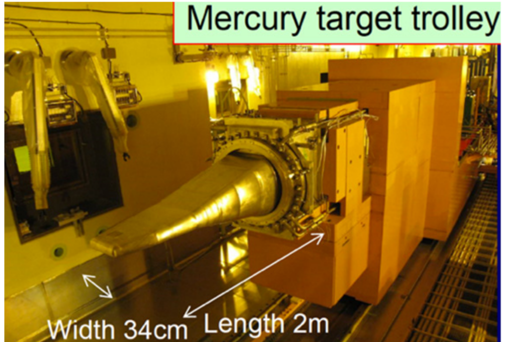


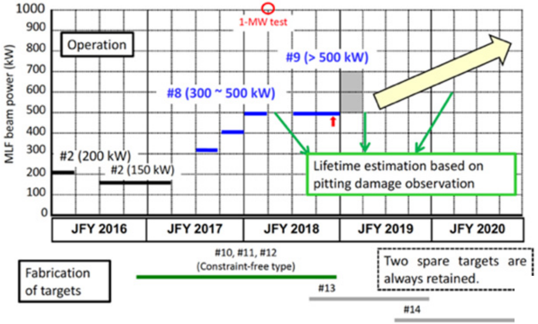
Dipole Magnets: 24
Quadrupole Magnets: 60 (7 families)
Sextupole Magnets: 18 (3 families)
Steering Magnets: 52
RF Cavities: 12 (Fundamental 440 kV, 2nd 180 kV)

Beam Power History at MLF

- The beam power of the recent user operation is 530 kW.
- The power will be increased by carefully confirming the soundness of the neutron production target.
- The operation of the original beam power target of 1 MW was successfully demonstrated.

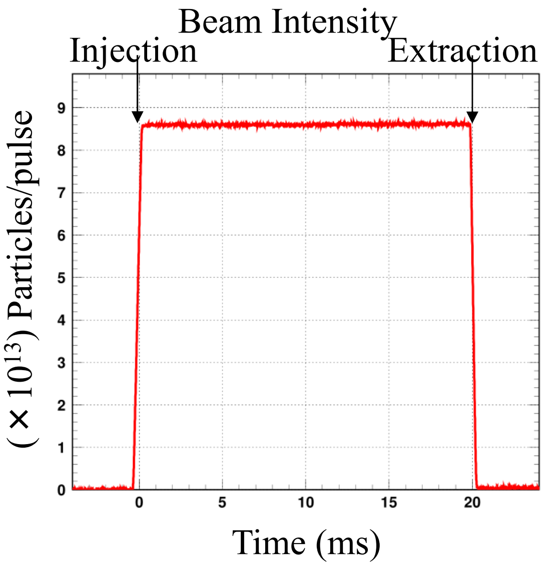


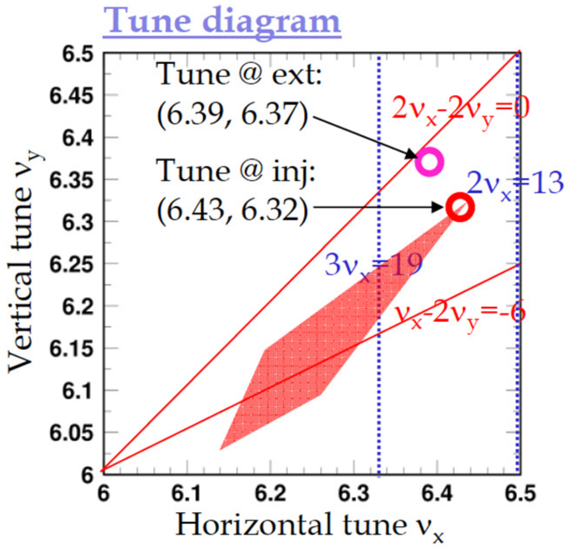




RCS: 1-MW Operation and the Beam Loss Reduction

- A stable 1-hour operation of the 1-MW beam was successfully achieved with 25 Hz and the following operational parameters.
  - Transverse painting area: 200π mmmrad.
  - Sextupole field patterns:
    - Correction of the resonance of $\nu x - 2\nu y = -6$ for beam loss reduction ($t < 5$ ms)
    - Chromaticity manipulation for instability suppression ($t > 9$ ms)
  - Momentum offset applied in longitudinal painting: −0.1 %
  - The 2nd harmonic RF is applied for the larger bunching factor.
- The beam loss of 10^{-3} level was achieved and the loss was localized at the collimators.

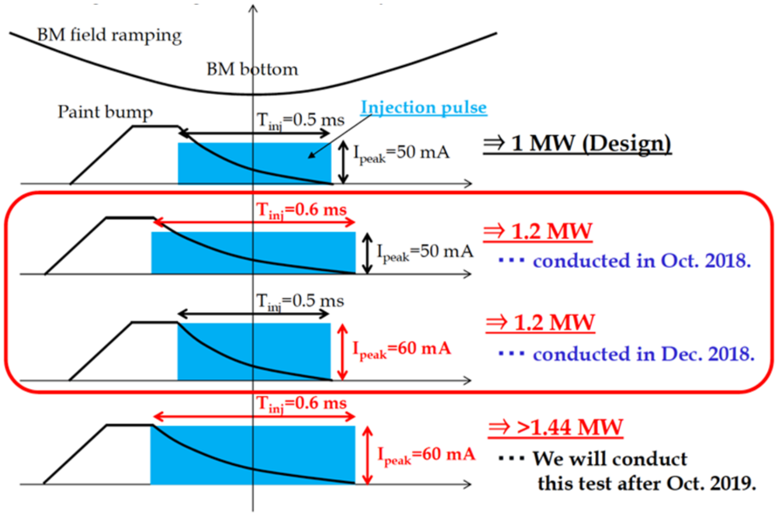


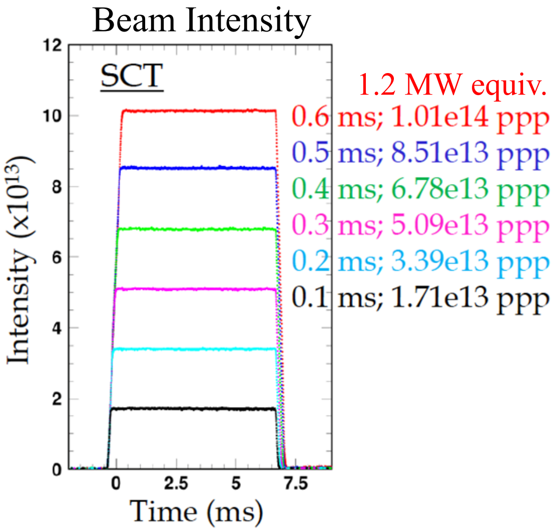


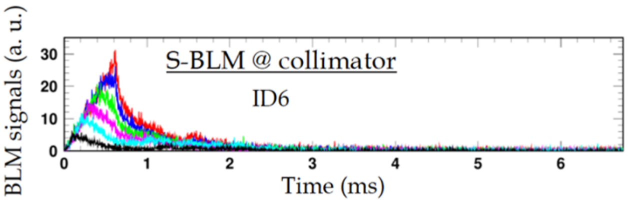
RCS: High Power Operation beyond 1 MW

H. Hotchi TUPTS033
M. Yamamoto TUPTS035
F. TamuraWEPRB026

- The upgrade is planned for 1.5 MW with the 2nd target station of MLF.
- The operation of 1.2 MW equiv. was demonstrated for the acceleration of up to 1 GeV.
- RF system will be upgraded this summer for the beam loading compensation for the beam power beyond 1 MW.







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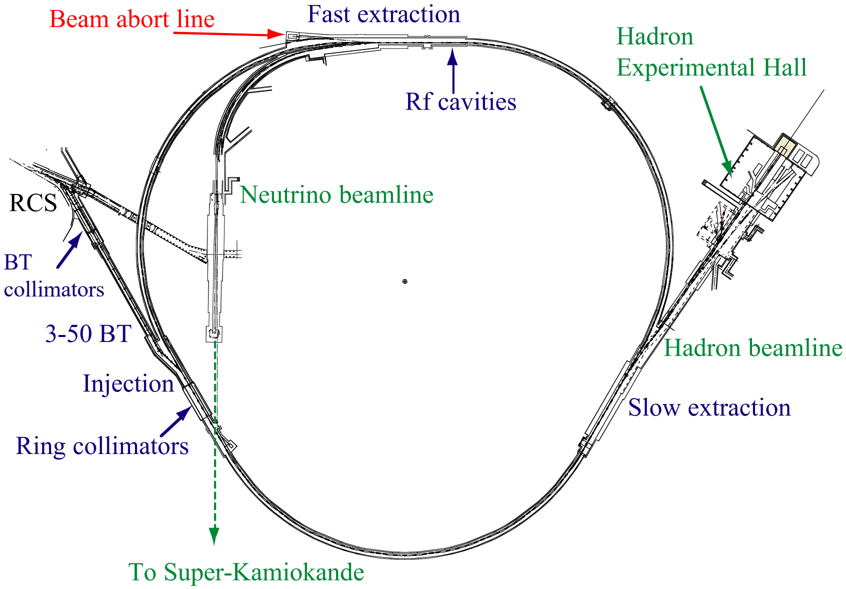
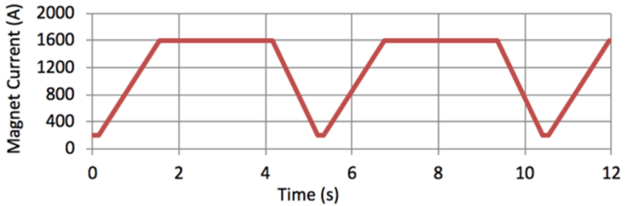
MR Design and Operation Modes

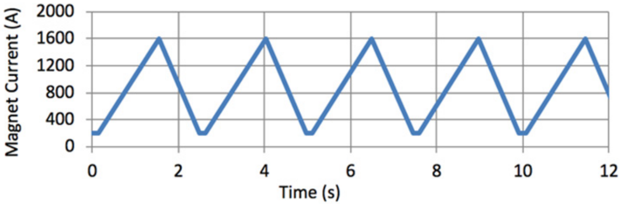
- Circumference: 1567.5 m
- Three-fold symmetry
- Harmonic number: 9
- Original Design Beam Power: 750 kW
  - Large Aperture
  - Beam Loss Localization
  - Imaginary Transition γ Lattice

- Slow extraction mode (SX) for the hadron hall: 2s-spill extraction.
- Fast extraction mode (FX) for the neutrino Facility: 1 turn extraction.





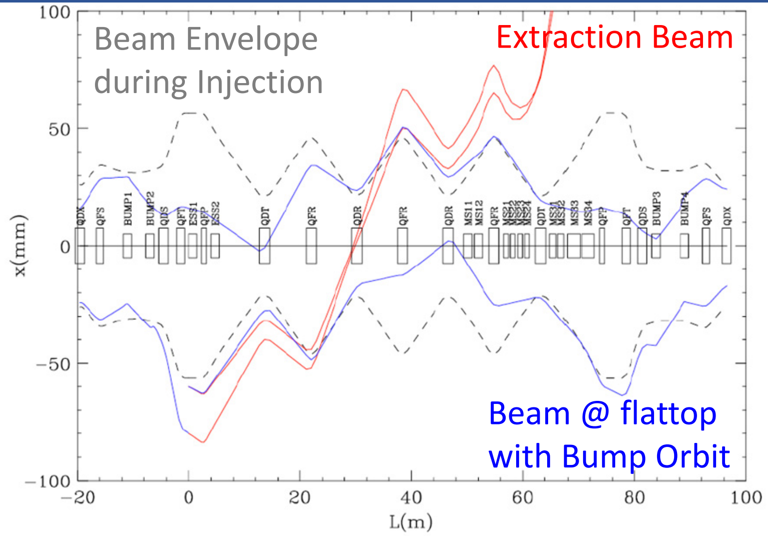
SX (5.2 s)



FX (2.48 s)

Slow Extraction Tunings and the Beam Loss Reduction

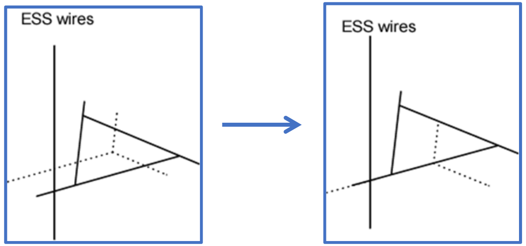
- Extraction scheme with a third order resonance of νx = 22.33
- The extraction efficiency of 99.5% was achieved with fine tunings of
  - Main Quadrupole Magnets
  - Resonant Sextupole Magnets
  - Bump Magnets
  - Electro-Static Septum (ESS) 30 μm W ribbons at high β=40 m
  - Septum Magnets (SMS)



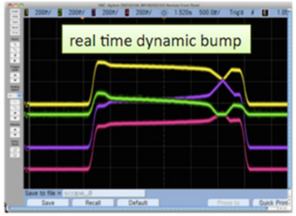
Fixed Bump

Dynamic Bump

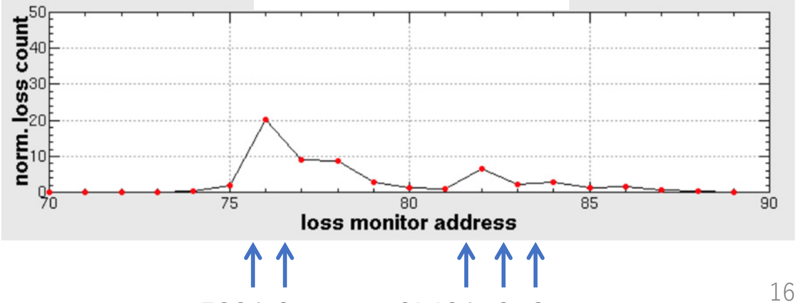
x – x’
phase space
Step size 20 mm



Bump 1 – 4
current
vs. time



Beam Loss Distribution

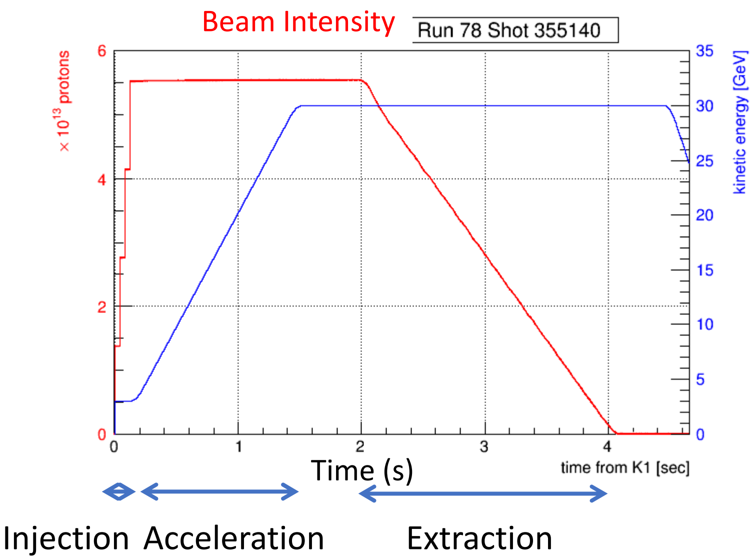


ESS1 2   SMS1 2 3

Slow Extraction Tunings for the Beam Spill

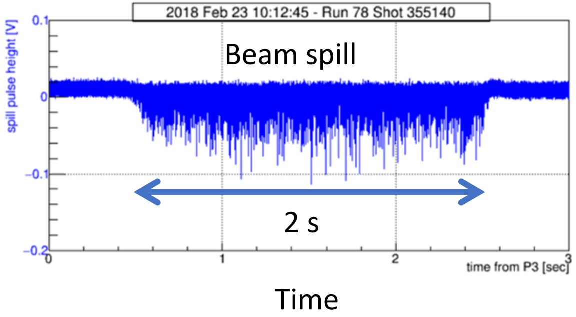
R. Muto WEPMP007
K. Okamura WEPMP008

- The SX beam power of 51 kW is achieved for user operation, which is limited by the target capacity.
- Users prefer uniform extraction of beam spill in 2 s.
- The spill duty is tuned with the following instruments.
  - Main quadrupole magnets are ramped to move the tune toward the resonance of 3νx = 67.
  - Correction Quadrupoles (EQ and RQ) are feedbacked by the signals of the spill monitor.
  - Transverse RF is adapted for further improvement of spill duty.
- The target will be upgraded this summer for the capacity of 57 kW → 95 kW.



Beam Power 51 kW
Ext. Efficiency 99.52%
Spill length 2 s
Spill Duty Factor 48%

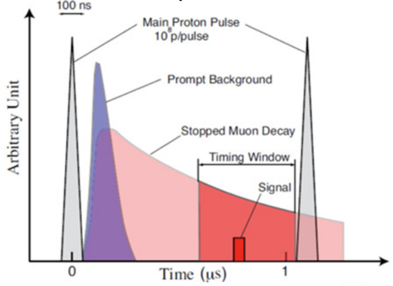
$$D = \left[\int_{T_1}^{T_2} I(t)dt\right]^2 \Big/ \left[\int_{T_1}^{T_2} dt \cdot \int_{T_1}^{T_2} I^2(t)dt\right]$$

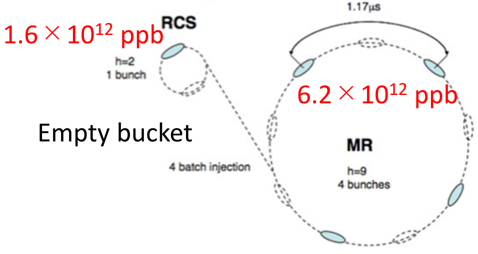


SX for the μ to e conversion search experiment

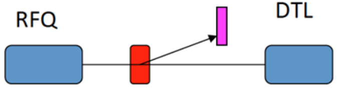
- The COherent Muon to Electron Transition (COMET) experiment to search for the process of lepton flavor violation requires
  - slow extraction of 8 GeV beam for suppression of the anti-proton production and
  - sparse bunched beam for the signal detection with the extinction ratio of 10^{-10} for the empty bucket.
    - Empty bucket production with RF chopper
    - 1 bunch acceleration in RCS
    - Injection kicker timing shift in MR
- The proton beam required for the phase 1 was delivered to Hadron hall to measure extinction factor of secondary beam.

8GeV 1MHz pulsed beam

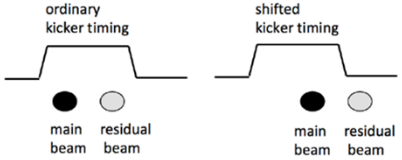


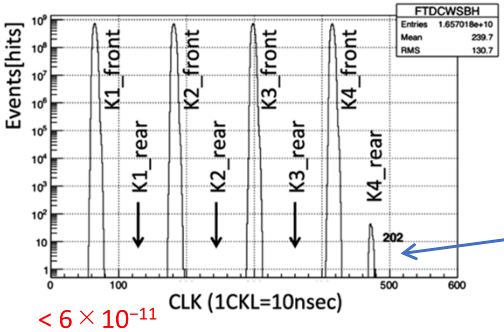


Empty bucket production by chopper
Leak rate is 10^-6



The beam in the empty bucket is killed by MR injection kicker timing shift





We found the solution for the extinction for K4_rear.

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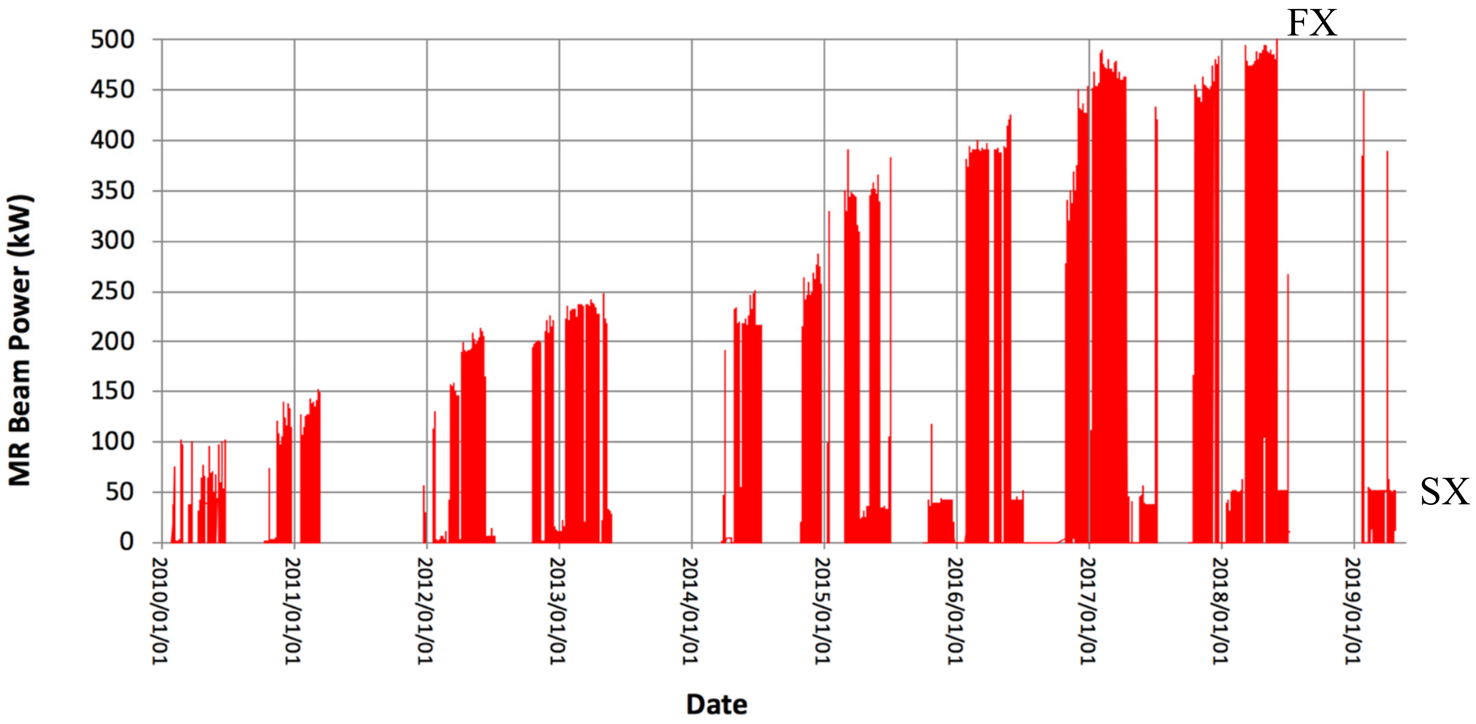
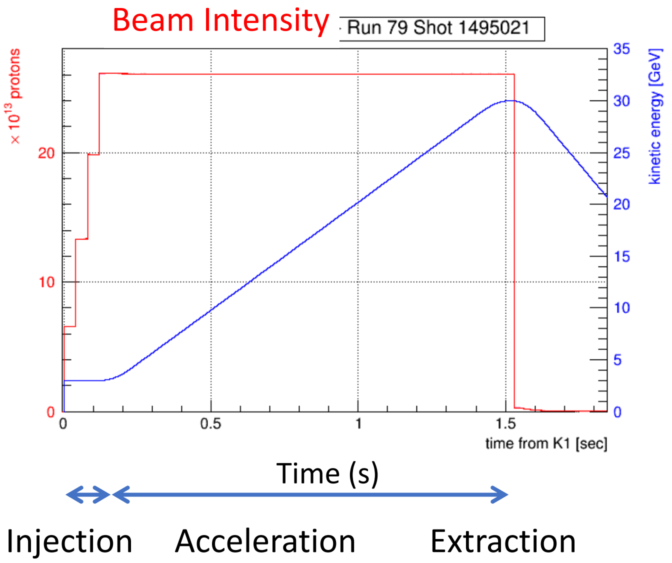
MR Beam Power History

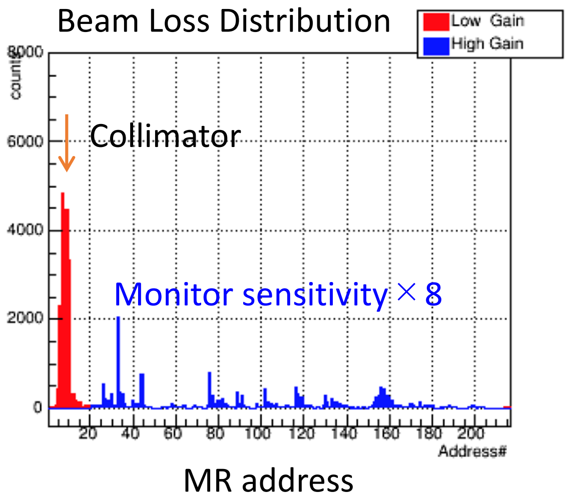
- The beam of 490 kW has been provided stably with the beam loss of 500 W in the recent FX operation.
- The user operation of 500 kW for 50 shots was achieved with the beam loss of 700 W.



Typical Operation Status for FX

- Beam Power : 504 kW
- Cycle Time : 2.48 sec
- Number of protons at injection : 3.3×10^{13} protons per bunch (ppb) $\times$ 8
- Number of protons at extraction : 2.61×10^{14} protons per pulse (ppp)
- Beam Loss : ~700 W < Collimator Capacity: 2 kW

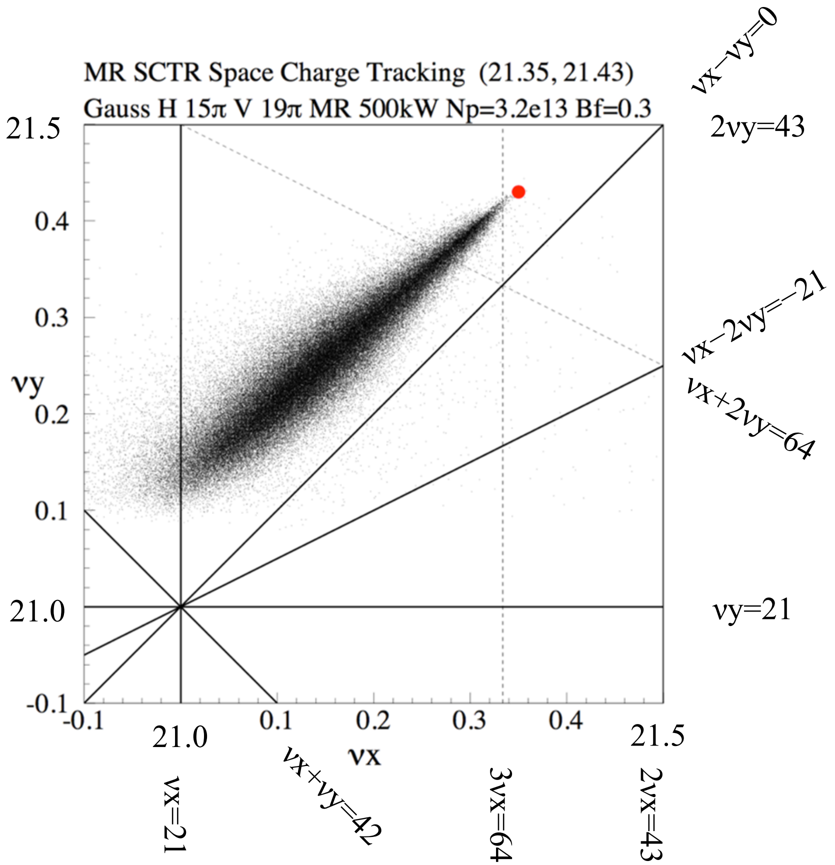




Tunings for the Beam Loss Reduction

- MR Power 500 kW
- Space Charge Tune Shift: 0.4
  - Simulation based on the measured transverse emittances and bunching factor

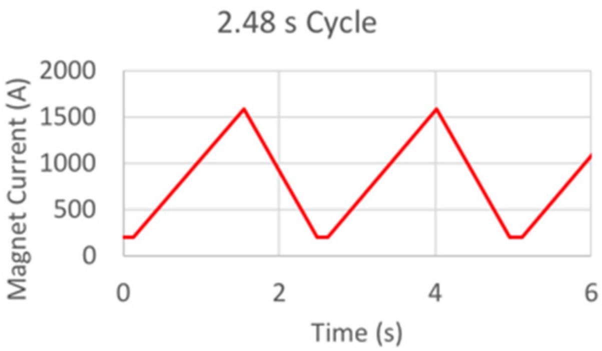
- RCS parameters optimization for the injection beam
- 2nd harmonic RF
- Optics measurements and corrections
  - with trim coils of main Q magnets for the leak fields of the FX septum magnets.
- Third order resonance corrections
  - with trim coils of four S magnets.
- Transverse instability suppression
  - with chromaticity parameters and
  - Intra-bunch feedback system.

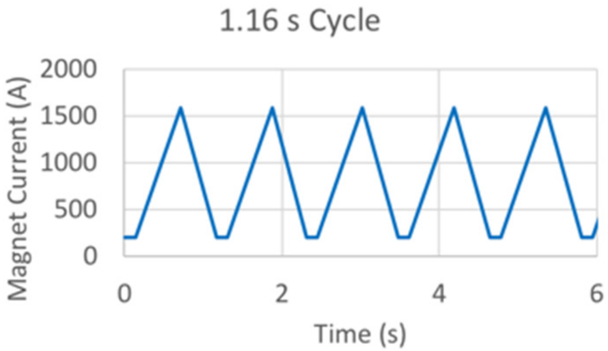


Beam Power Upgrade Concept

	Beam Power	Cycle Time	Number of accelerated protons	Equivalent beam power in RCS
Present	500 kW	2.48 s	2.6×10^{14} ppp	780 kW
Original Design	750 kW	1.32 s	2.1×10^{14} ppp	610 kW
New Plan	1.3 MW	1.16 s	3.3×10^{14} ppp	1 MW

- For the Beam power upgrade of 500 kW → 1.3 MW
  - Factor of 2 by faster cycling
  - ~30% gain by intensity increase





Mid-term Plan of MR

FX: Faster cycling: 2.48 s → 1.32 s for 750 kW → 1.16 s for 1.3 MW
SX: Mitigation of the residual radiation for 100 kW

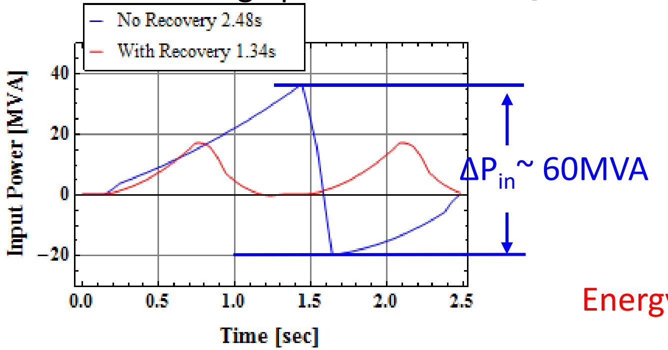
JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW]	475	500	500	500		>700	800	900
SX power [kW]	50	50	50	70		> 80	> 80	> 80
Cycle time of main magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32 s	<1.32s	<1.32s
New magnet PS		Mass production/installation/test						
High gradient rf system								
2^{nd} harmonic rf system		Manufacture, installation/test						
Ring collimators	Capacity 2 kW				Capacity 3.5kW			
Injection system	Kicker PS improvement, Septa manufacture /test							
FX system	Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields						Local shields		
Ti ducts and SX devices with Ti chamber	Ti-ESS-1							

New Magnet Power Supply for Faster Cycling

- A new power supply was designed with capacitor banks for the cycle of 1.3 s.
- The power supplies for the BM families are being constructed and tested.

Requirement : Higher Repetition Rate (2.48 s → 1.3 s)

Issue：Large power variation @ AC main grid $P = VI = \left(L\frac{dI}{dt} + RI\right)I$



1.3 sec cycle

$\cancel{\Delta P_{in} > 100\text{MVA}}$

Not allowed by Electric Power Supplier

Energy Recovery with Capacitor Banks

New PS for BM3

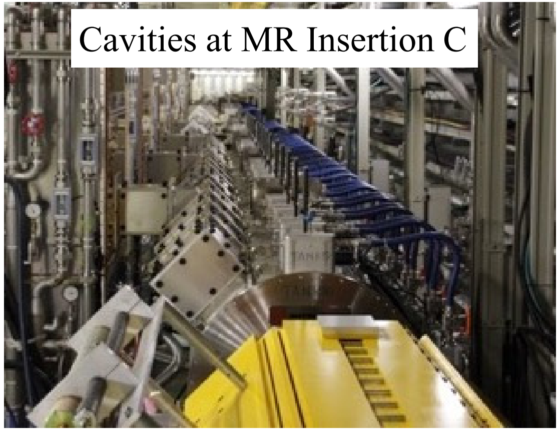
Capacitor Banks for BM3

Interior of Container

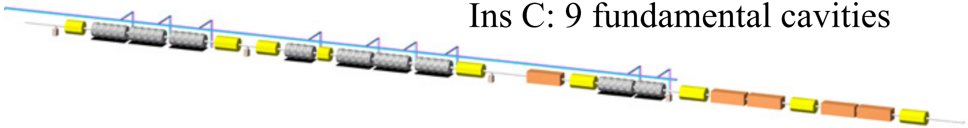
Installation Plan for RF Cavities

- Higher RF voltages are necessary for the faster cycling.
- The following numbers of RF cavities are necessary for the operation of 1.32 s and 1.16 s.
- For 1.16 s operation, 11 fundamental cavities and 2 second harmonic cavities.
- Upgrade of the anode power supplies are planned for the beam loading compensation.

	2016	2017	2018	2022	202X
Events				MR 1.32-sec operation	MR 1.16-sec operation
FT3L 4GAP Cavities	*7*	7	*7*	9	9
additional 4GAP Cavity	-	-	-	-	***2***
2nd harmonic cavity	2	2	***2***	***2***	***2***
Accelerating voltage	300-390 kV	300-390 kV	300-390 kV	510 kV	600 kV
(2nd Harmonic)	110 kV	110 kV	110 kV	120 kV	120 kV



Insertion C

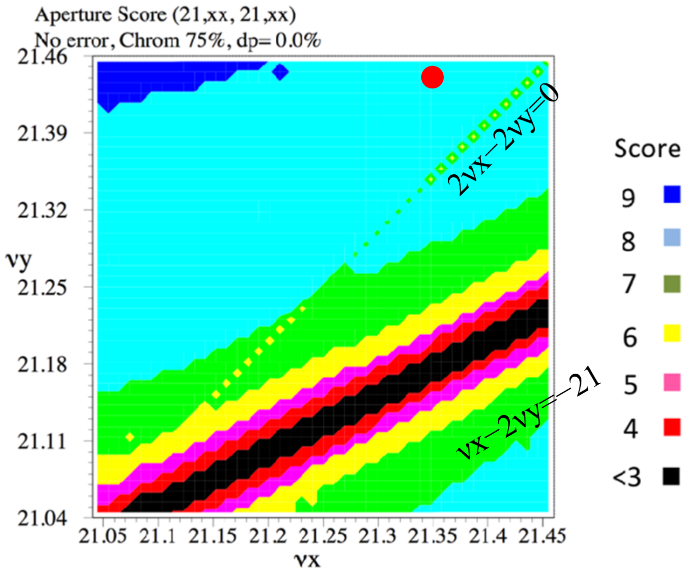


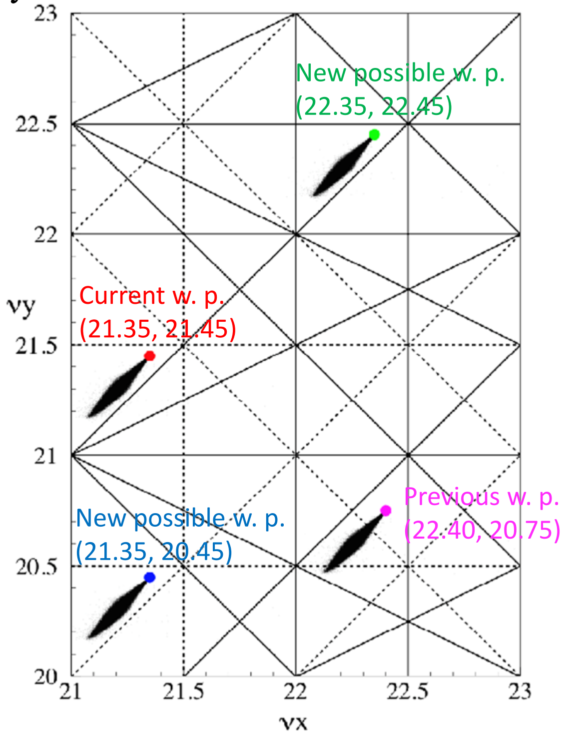
Ins A: 2 2nd harmonic cavities
Ins B: 2 fundamental cavities
Ins C: 9 fundamental cavities

Simulation Studies on Dynamic Aperture for the Beam Loss Reduction

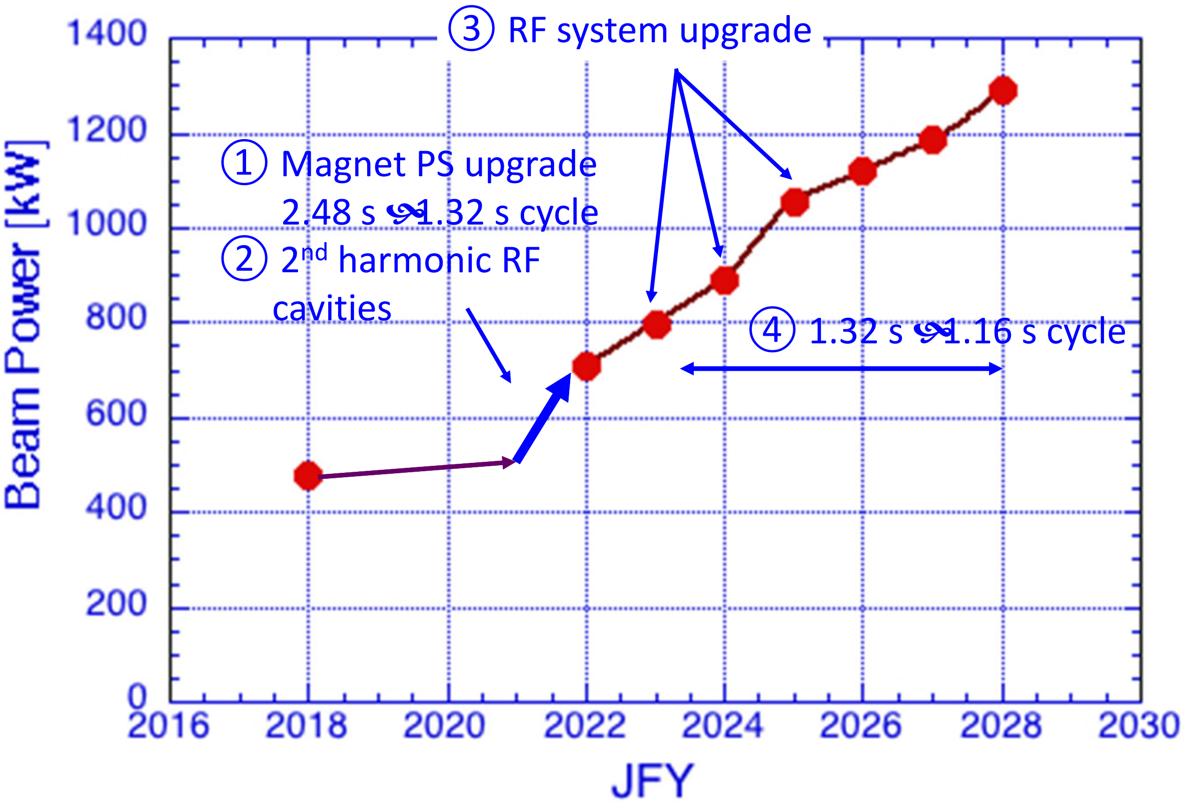
- Beam loss should be reduced for the beam intensity increase of ~30%.
- Dynamic aperture at the current operation tune of (21.35, 21.45) is affected by the structure resonance of $\nu x - 2\nu y = -21$.
- Working points of (22.35, 22.45) and (21.35, 20.45) may be free from the structure resonances.
- Beam study is necessary for the new working points.

Dynamic aperture survey
(No magnetic error/ no space charge)





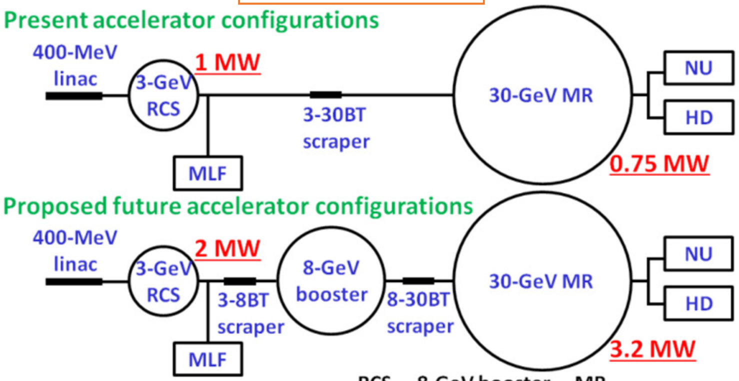
MR FX Beam Power Projection



Multi-MW Beams to the Neutrino Experiment

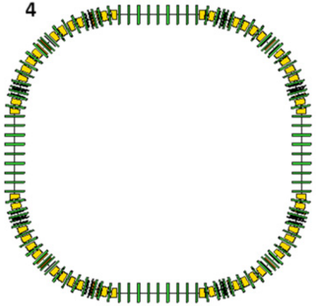
- 3.2 MW with a new 8-GeV Booster in J-PARC
- 9 MW with a 9-GeV proton driver in the KEKB Tunnel after the B-factory project.

J-PARC Tokai site

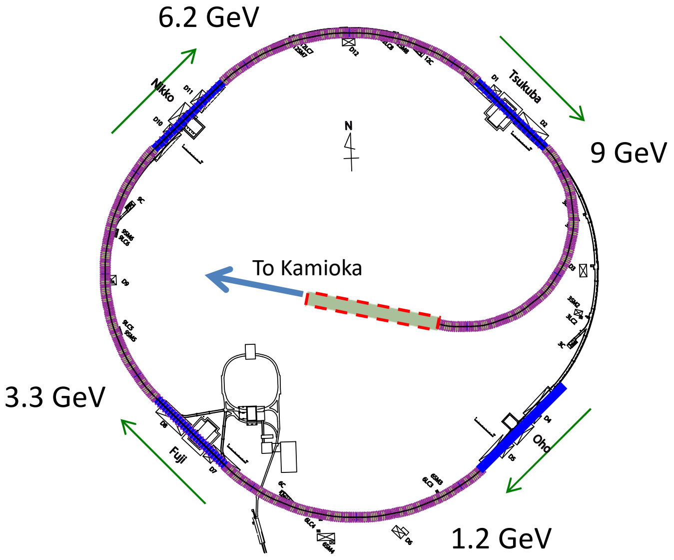


	RCS	8-GeV booster	MR
Physical aperture (mm mrad):	486π	189π	81π
Collimator aperture (mm mrad):	324π	126π	54-60π
Collimator capability (kW):	4	4	4
	3-8BT	8-30BT	
Scraper aperture (mm mrad):	126π	54-60π	
Scraper capability (kW):	2	2	

Conceptional Design of 8 GeV Ring
Circumference 696.666 m
Super-periodicity 4
Transition gamma ~15 GeV



KEK Tsukuba site



For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.
- Peak current : 100 mA (pulse)
- Beam duty : 1 %
- Beam power : 9 GeV x 0.1 A x 1 % = **9 MW**

R&Ds : High duty horn, higher gradient SC cavity, high power target...

Summary

- J-PARC accelerators have been providing high power beams for 10 or more years to users at
  - Materials and Life Science Experimental Facility
  - Hadron Experimental Hall
  - Neutrino Facility.
- The Linac original design current of 50 mA was achieved with efforts of beam loss reduction.
  - The operation of 60 mA was demonstrated in the beam study.
- With RCS, the one-hour stable operation of 1 MW was achieved with the loss of 10^{-3} level.
  - The beam power of 1.2 MW equivalent was demonstrated in the beam study.
  - The beam power of 1.44 MW will be tested for the upgrade plan.
- MR delivers the SX beam to the hadron hall with the beam power of 51 kW and the extraction efficiency of 99.5%.
  - Hadron target will be upgraded this summer for the capacity of 57 kW → 95 kW.
  - The proton beam of 8 GeV required for the phase 1 of the muon to electron conversion search experiment (COMET) was delivered to hadron hall to measure extinction factor of secondary beam.
- The beam power of 500 kW was achieved for the MR FX operation.
  - The beam power upgrade of 1.3 MW is planned with
    - faster cycling : 2.48 s → 1.16 s, and accelerated protons : 2.6×10^{14} ppp → 3.3×10^{14} ppp.
  - Possibilities are being explored for the beam power of multi-MW for the neutrino experiment.