US-Japan mini workshop at Fermilab
Nov. 9-10, 2016

J-PARC Introduction

- Status and future upgrade plans of J-PARC accelerator -

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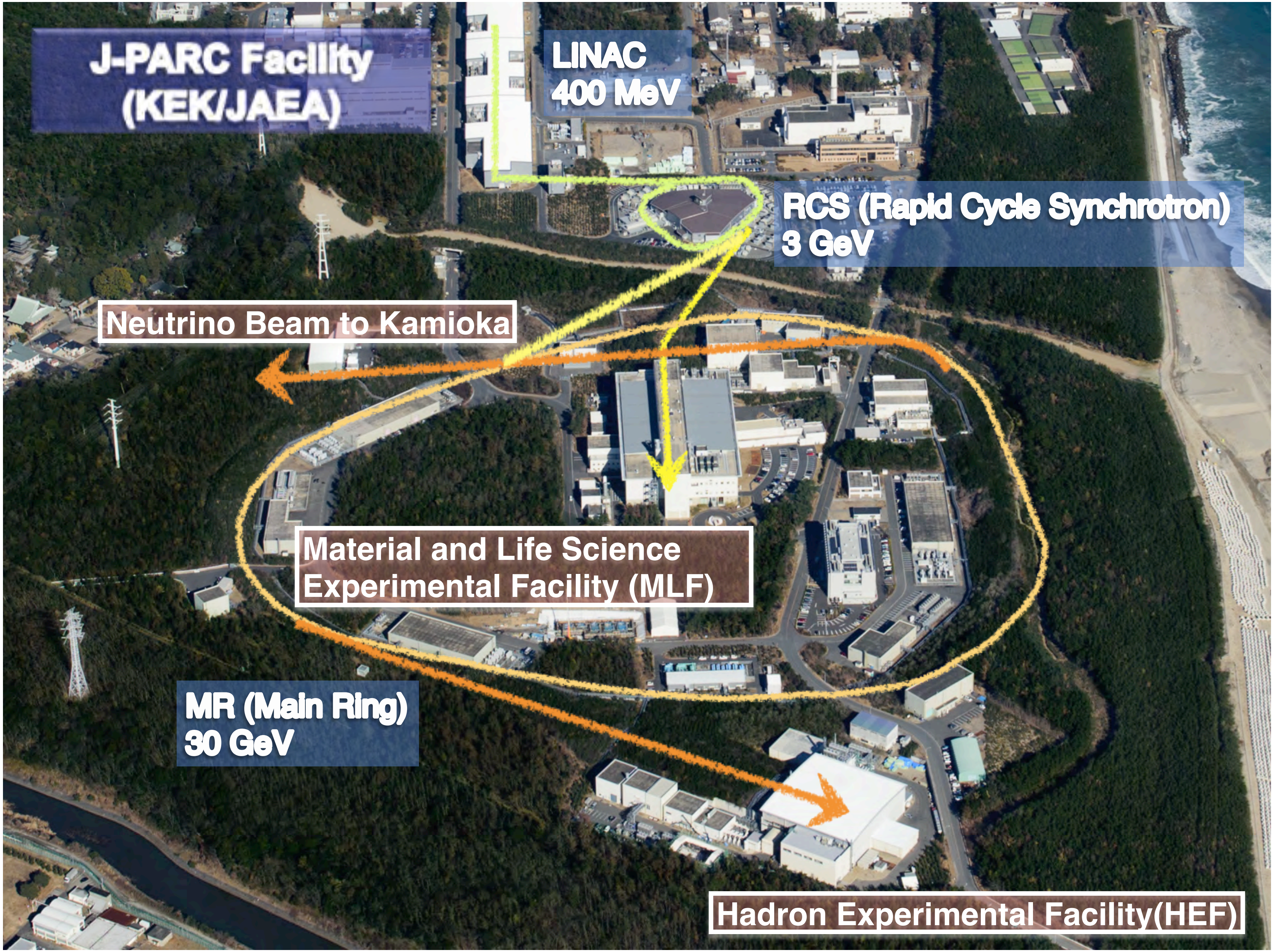
1. Facility overview

2. Status of accelerator operation and achievements
   - RCS
   - MR: Fast extraction for neutrino experiment
   - MR: Slow extraction for hadron experimental facility

3. Mid-term upgrade plans

4. Long-term plans

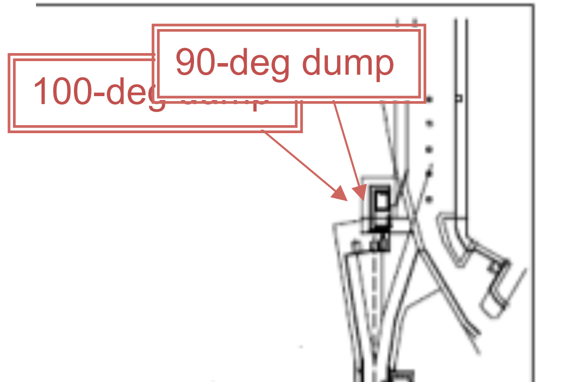
5. Summary

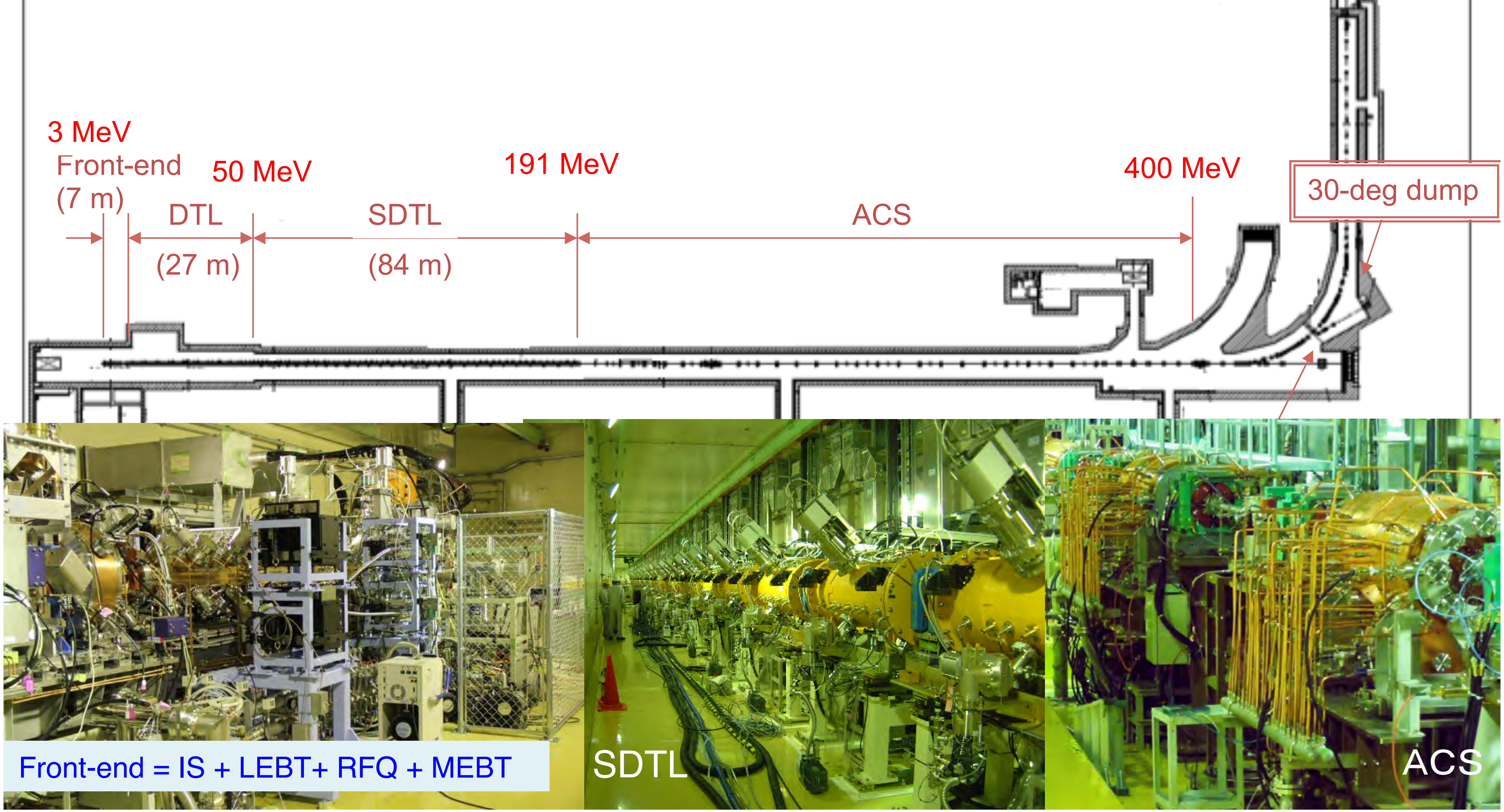


J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
RCS (Rapid Cycle Synchrotron)
3 GeV
Neutrino Beam to Kamioka
Material and Life Science
Experimental Facility (MLF)
MR (Main Ring)
30 GeV
Hadron Experimental Facility(HEF)

Linac

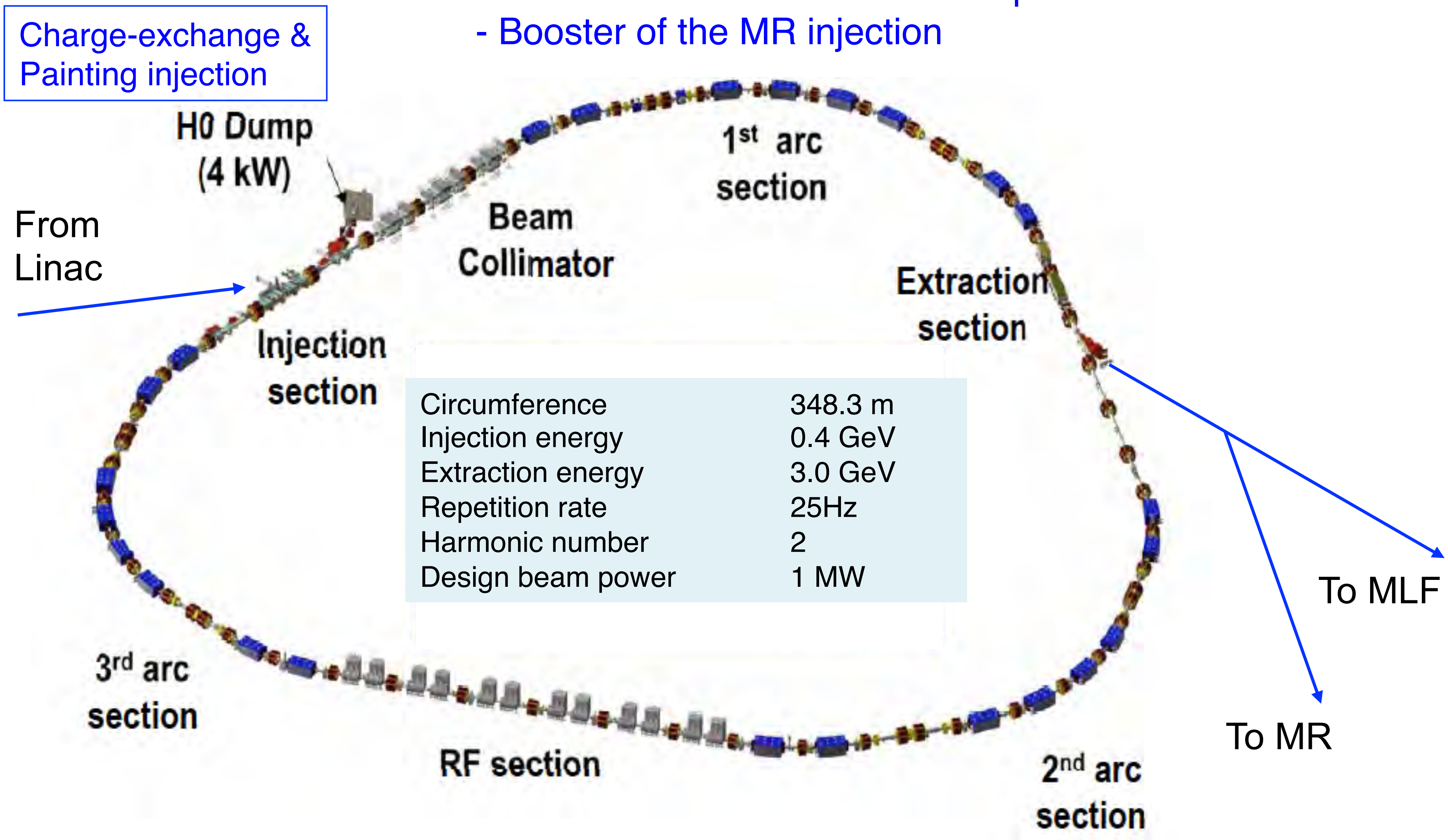
- **Particle:** **H^-**
- **Energy:** **400 MeV(2013-)**
- **Peak current:** **50 mA(2014-)**
- **Repetition:** **25 Hz**
- **Pulse width:** **0.5 msec**





RCS (Rapid Cycling Synchrotron)

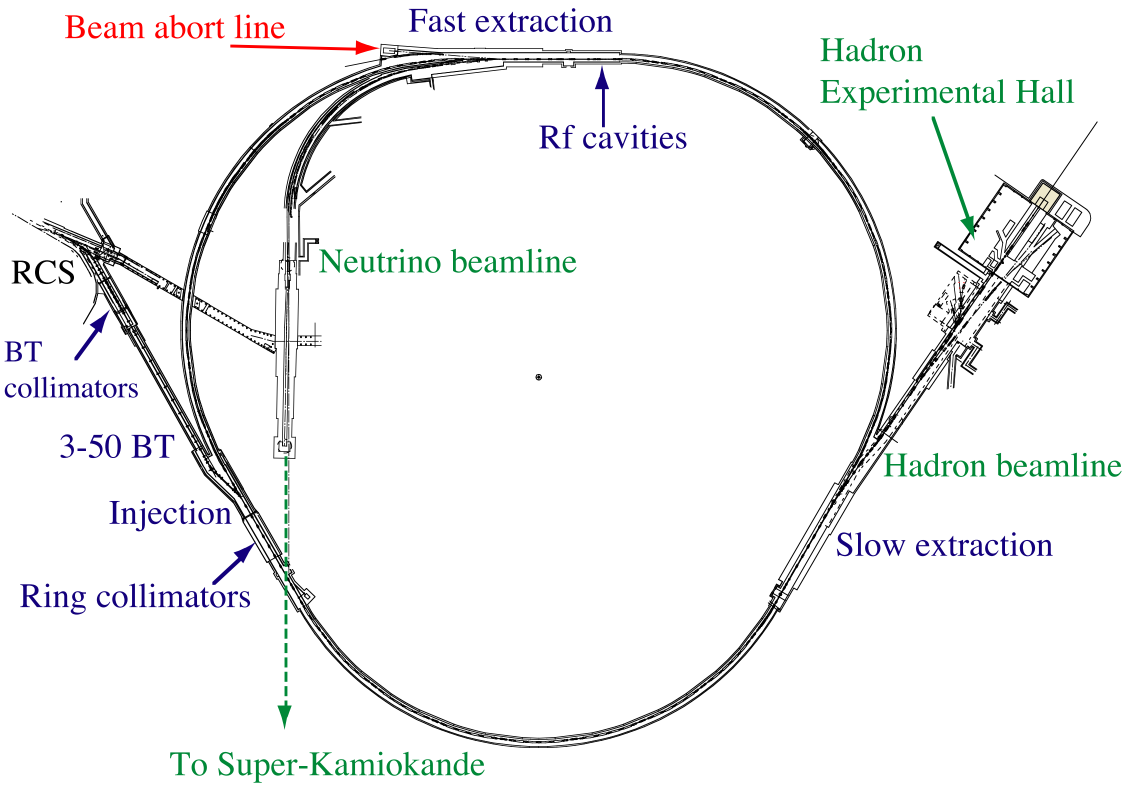
Two purposes of the RCS:
- Proton driver for neutron/muon production in MLF
- Booster of the MR injection



Circumference	348.3 m
Injection energy	0.4 GeV
Extraction energy	3.0 GeV
Repetition rate	25Hz
Harmonic number	2
Design beam power	1 MW

Main parameters of MR

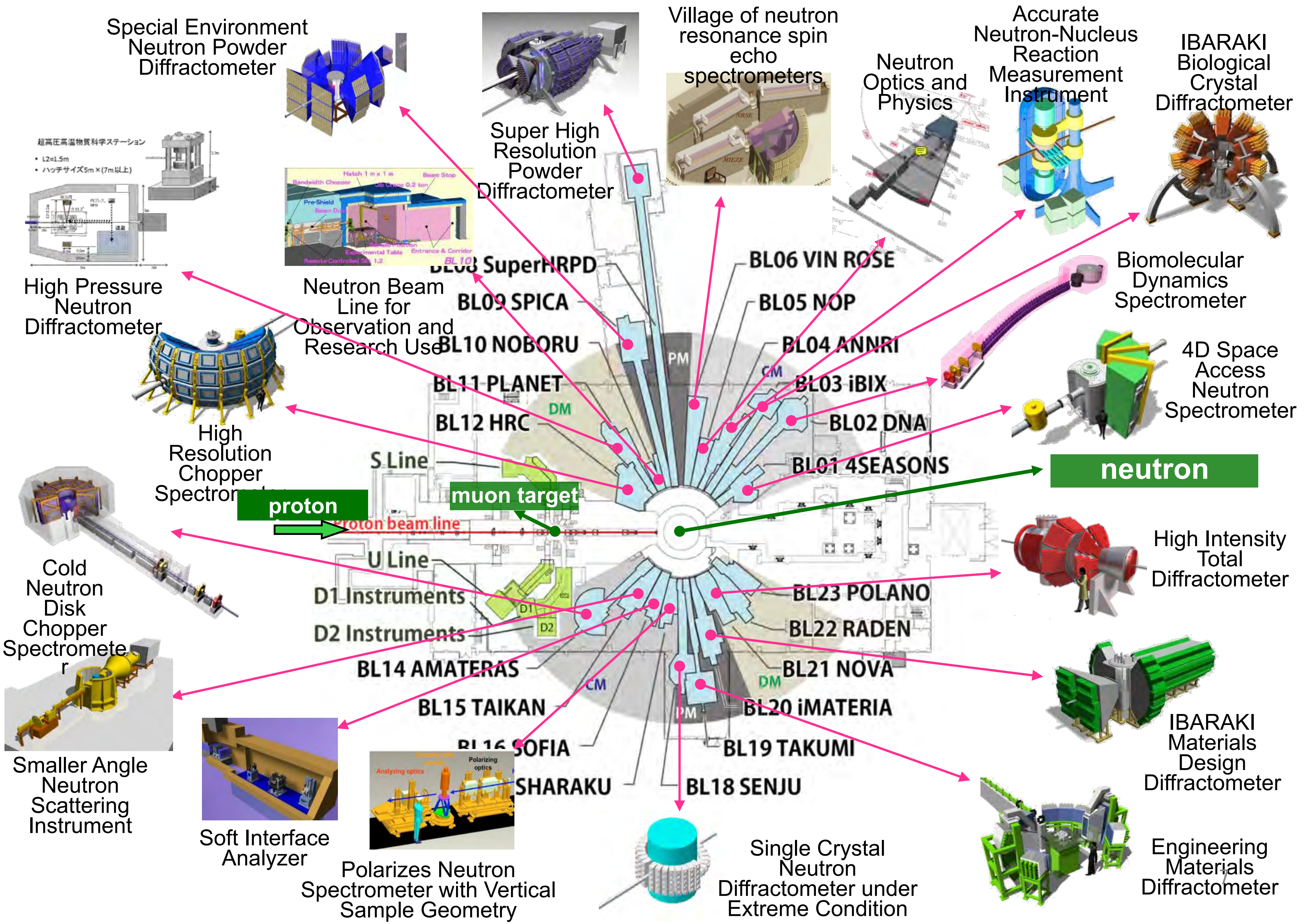
Circumference	**1567.5 m**
Cycle time	**5.52 s for SX**
	2.48 s for FX
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
Number of bunches	**8**
Rf frequency	**1.67 - 1.72 MHz**
Transition γ	**j 31.7 (typical)**
Design Beam Power	**750 kW**



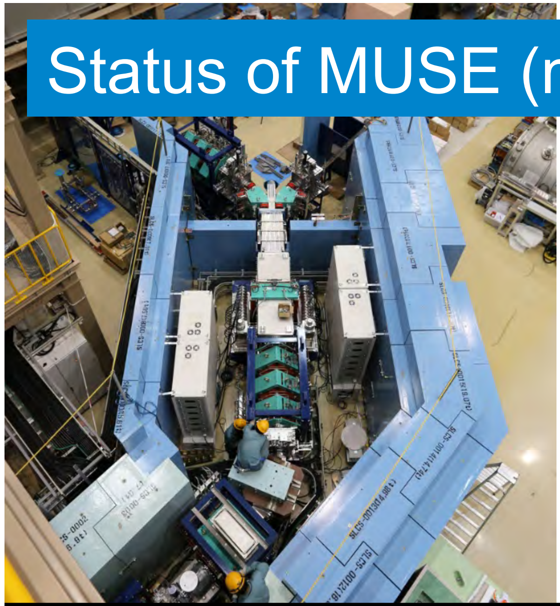
Three dispersion free straight sections of 116-m long:
- **Injection and collimator systems**
- **Slow extraction（SX)**
  to Hadron experimental Hall
- **MA loaded rf cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)**
  outside: Beam abort line
  inside: Neutrino beamline (intense ν beam is send to SK)

Neutron Instruments in MLF

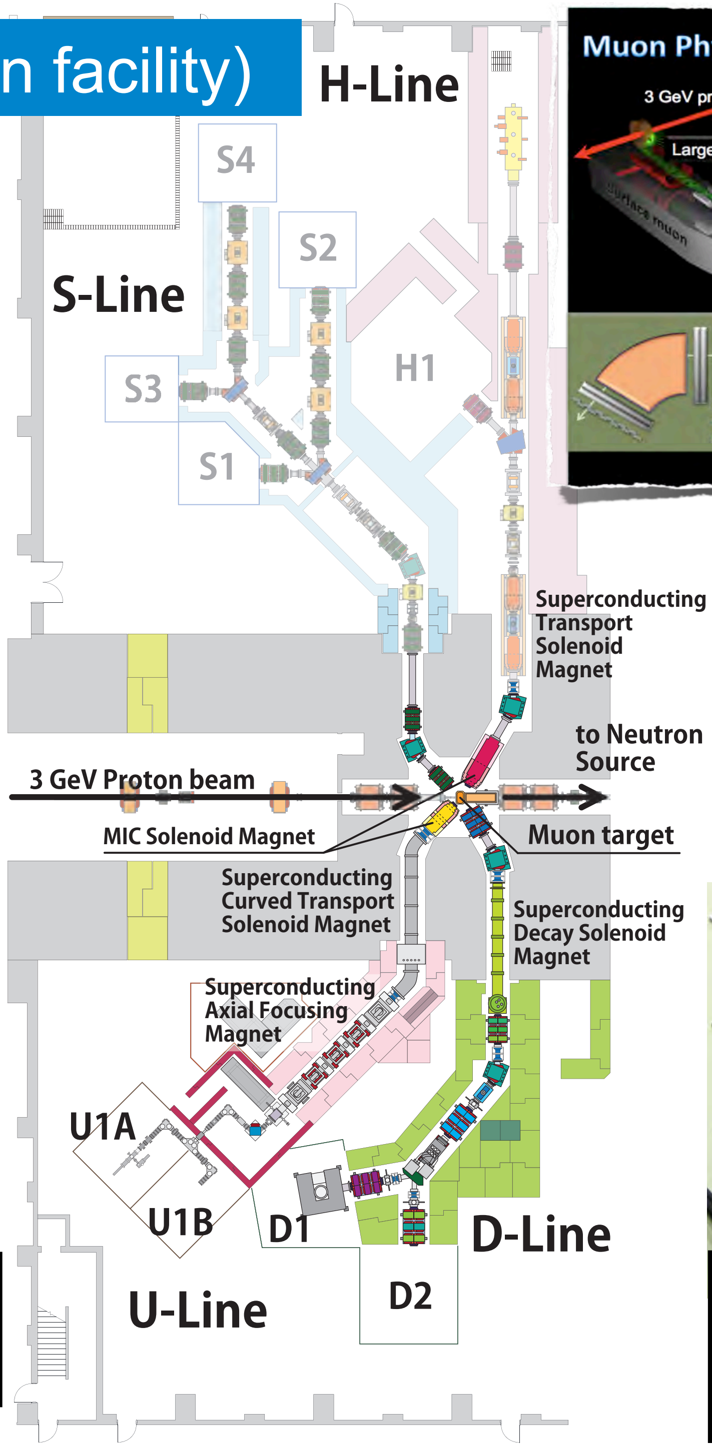
23 ports In operation : 19
Under construction : 2

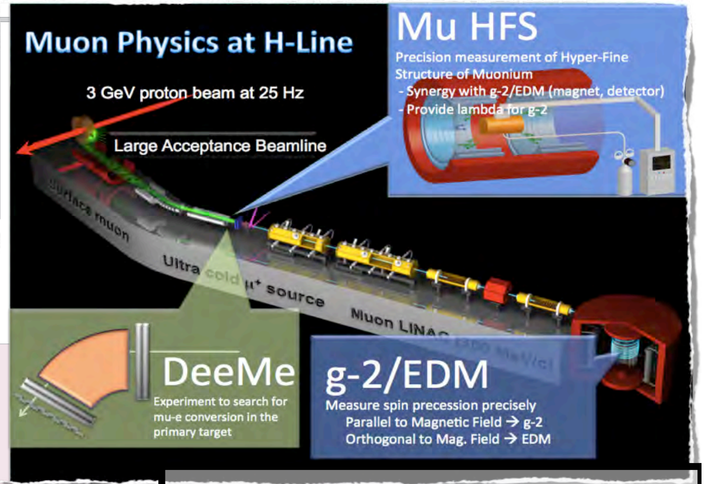


Status of MUSE (muon facility)

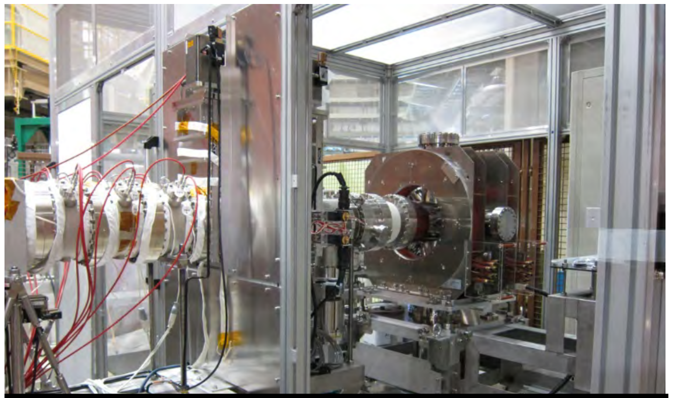


S-Line
Surface μ⁺(30 MeV/c) S1 area is ready to extract μ⁺ beam.
Open for users.

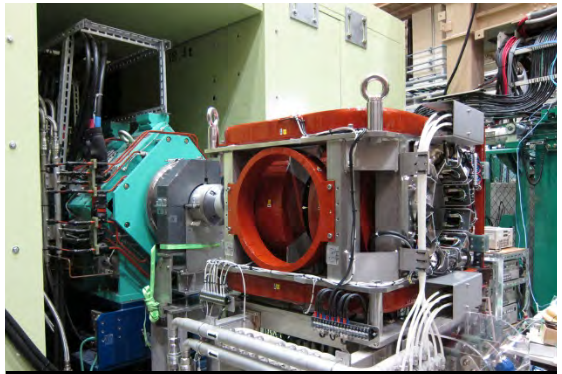




H-Line
Beamline for fundamental physics and muon microscopy
Surface μ⁺ For Mu-HF, g-2/EDM
Under construction.



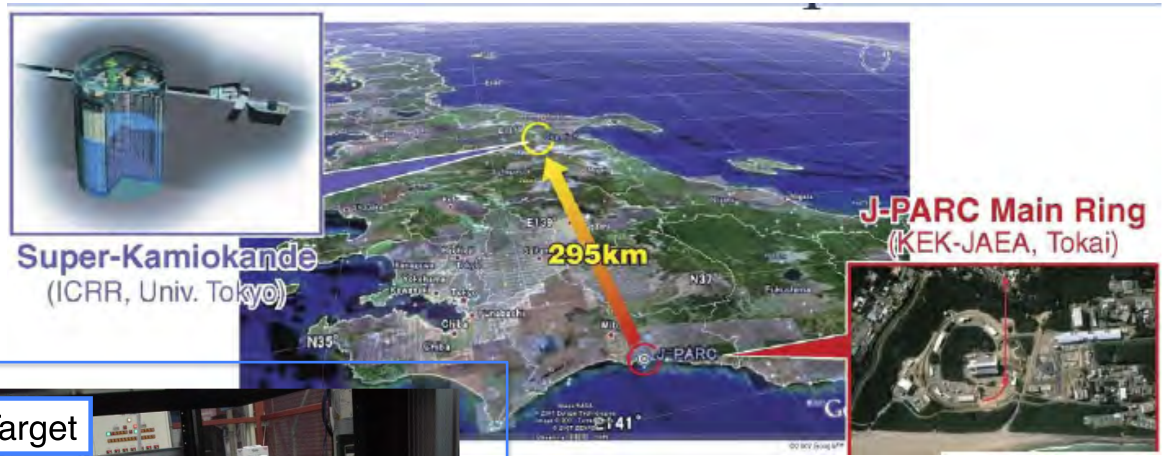
U-Line
Ultra Slow μ⁺ (0.05-60keV)
Under beam commissioning.

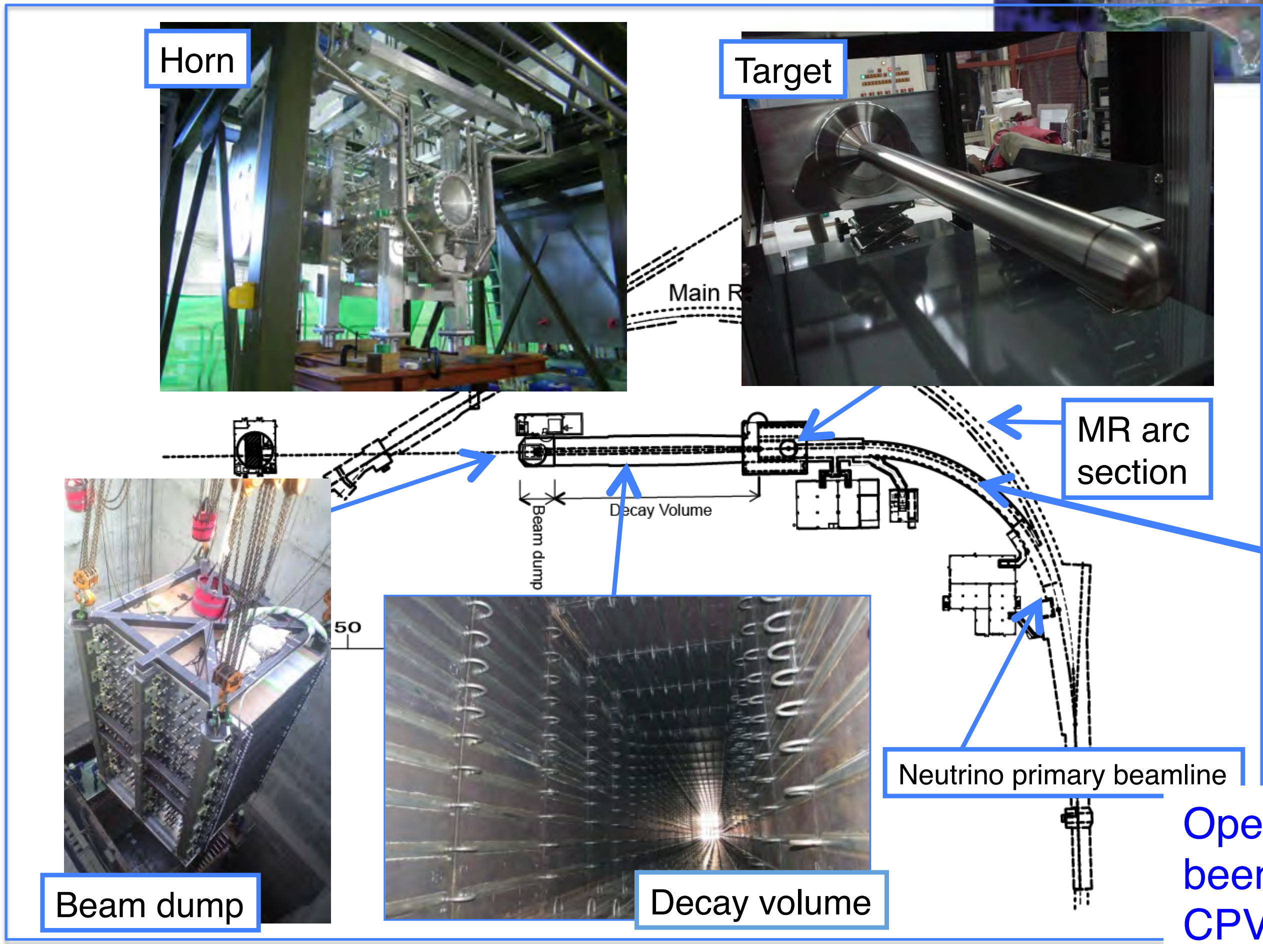


D-Line
Surface μ⁺(30 MeV/c)
Decay μ⁺/μ⁻(5-120 MeV/c)
Open for users.

Neutrino Experimental Facility

Long-baseline neutrino oscillation experiment: T2K (Tokai to Kamioka)

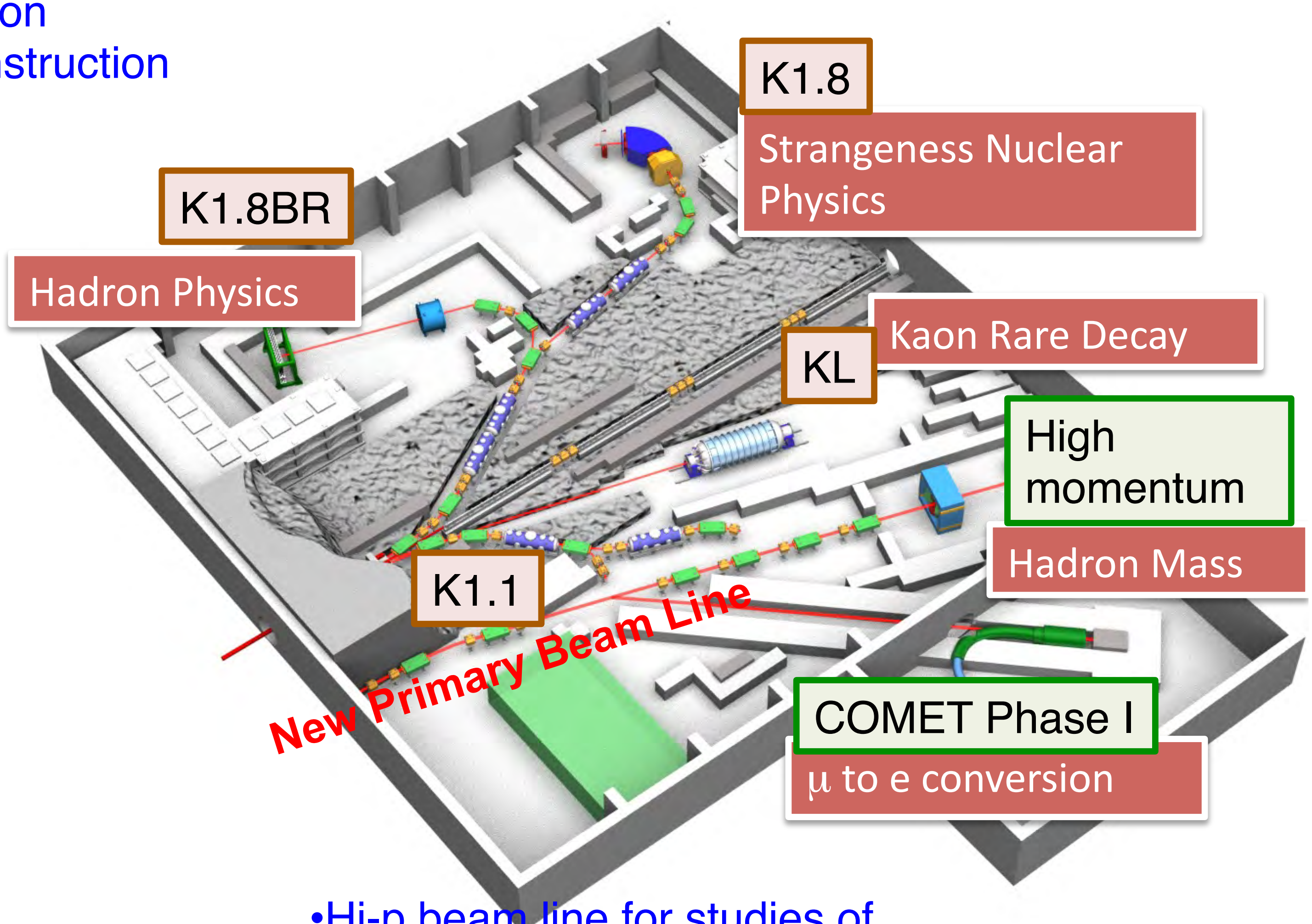




Operation of anti-neutrino mode has been started since 2015 to study CPV in the neutrino sector.

Experiments at Hadron Experimental Facility

Four BLs : in operation
Two BLs : under construction



•Hi-p beam line for studies of hadron properties in nuclear matter.

•Search for charged LFV process to probe BSM. (First phase of the COMET experiment)

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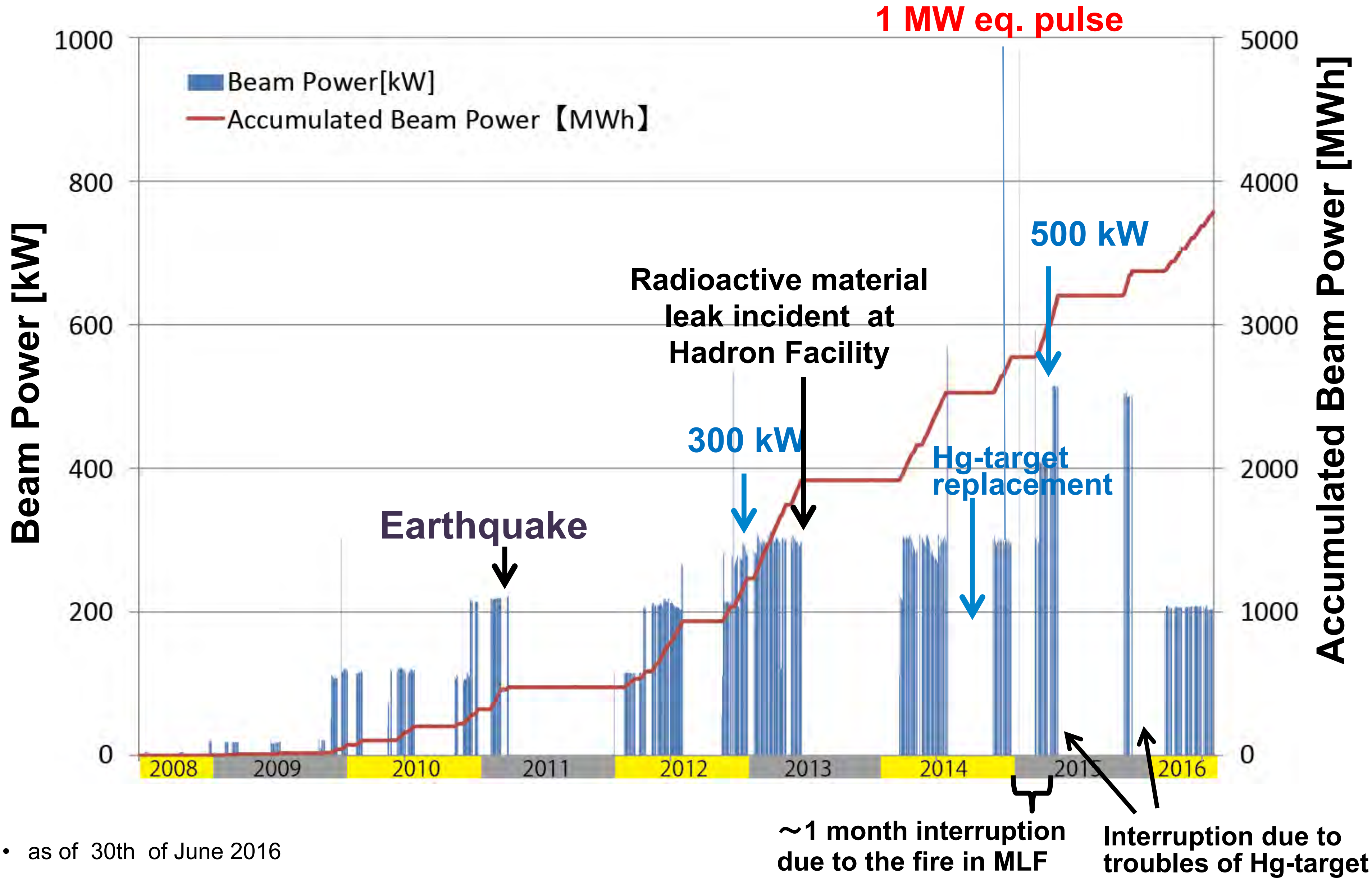
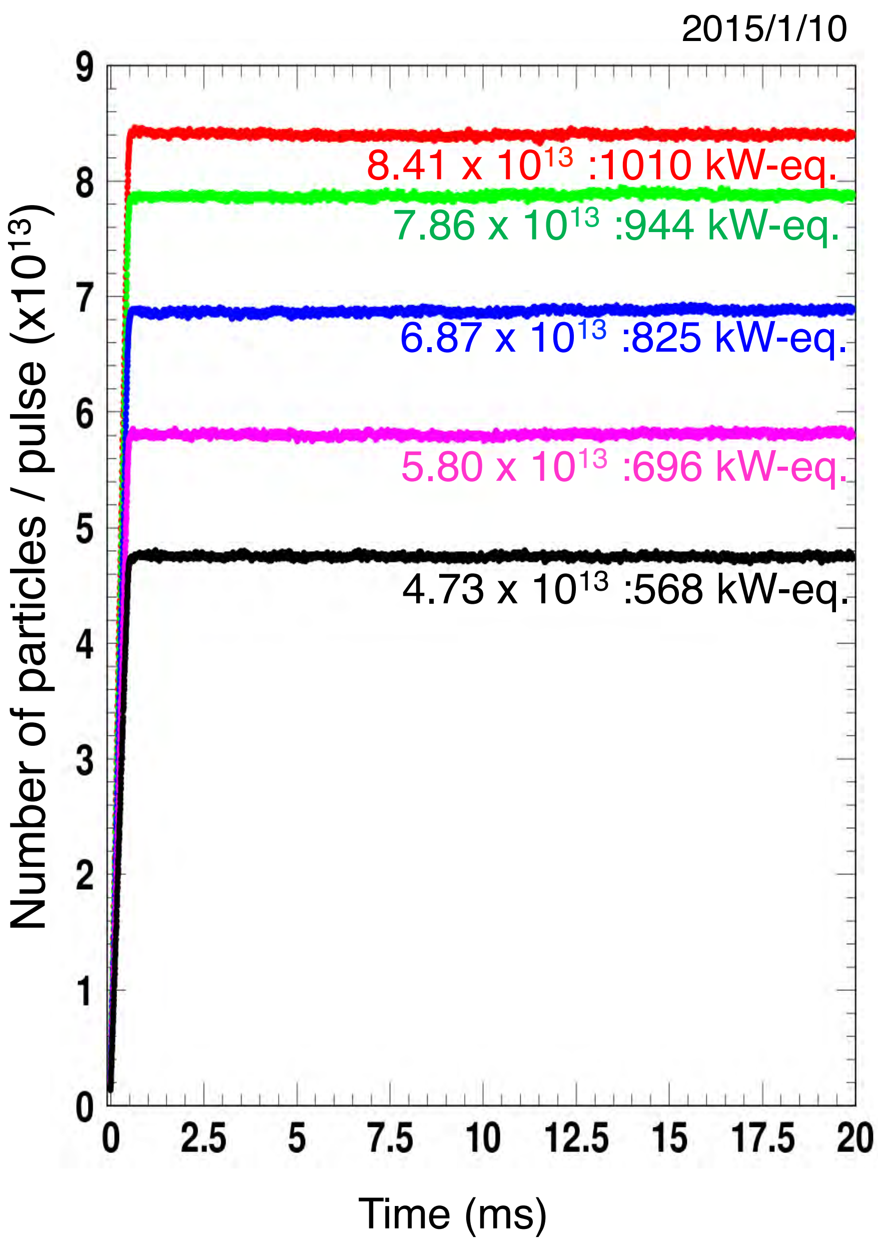
Beam Power History at MLF



- as of 30th of June 2016

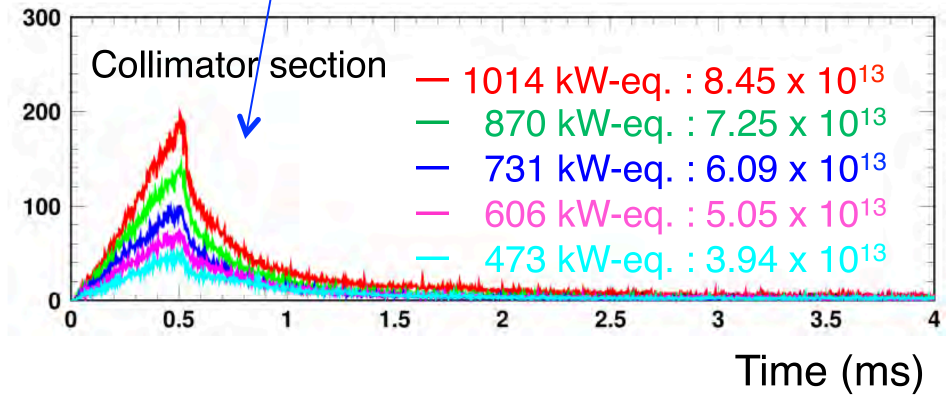
Demonstration of 1 MW-eq. beam in RCS



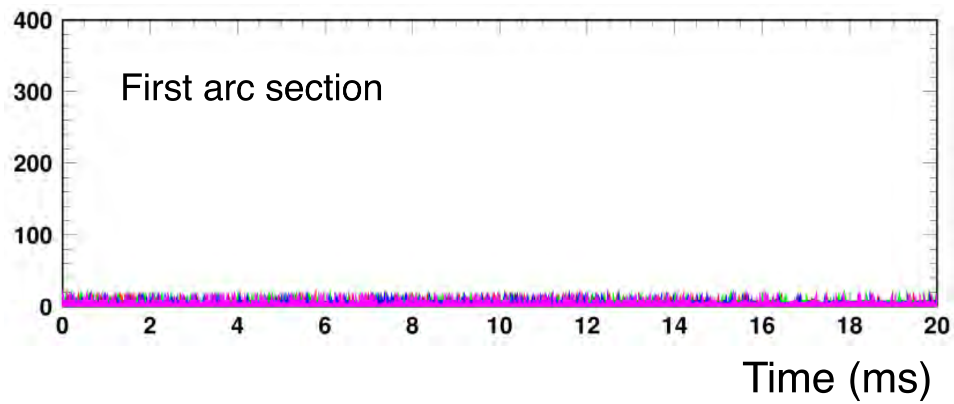
BLM signals @ collimator & arc sections

2015/10/12

Mainly due foil scattering during injection

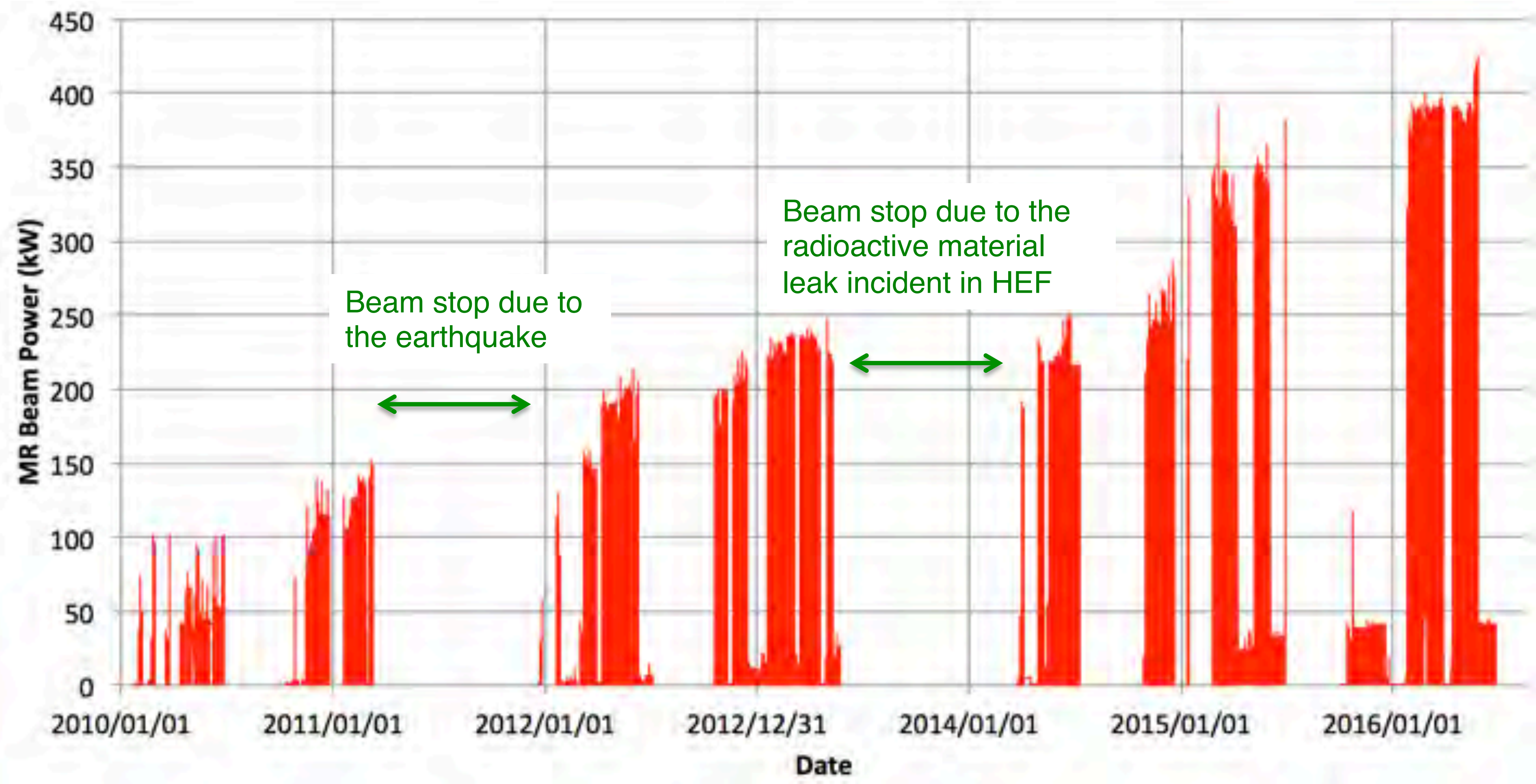


Beam loss < 0.1 % (< 133 W) << 4 kW collimator limit



We are ready to start 1 MW operation in the RCS.

Beam power history of MR

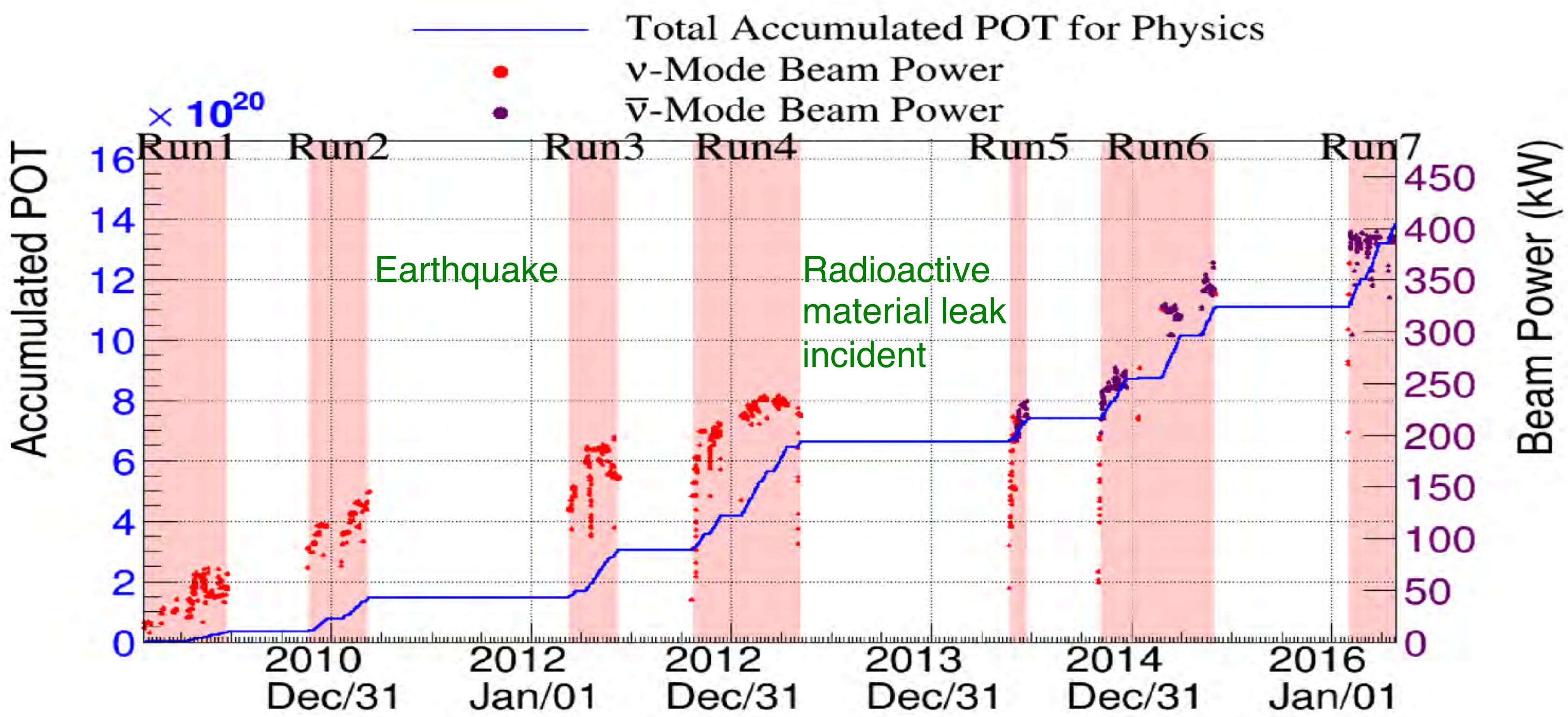


Max. delivered power:

Fast extraction ~ 425 kW ($2.2x10^{14}$ ppp)

Slow extraction ~42 kW ($4.9\ x10^{13}$ ppp)

POT neutrino



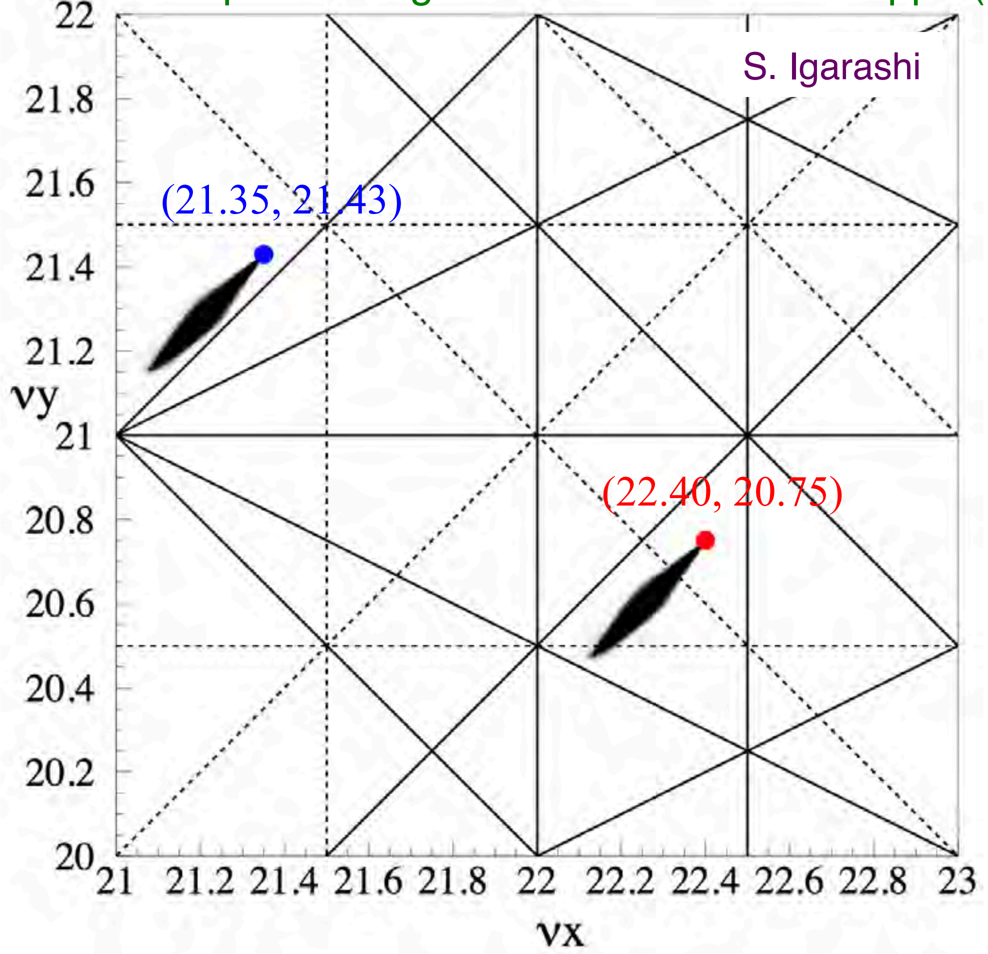
Neutrino POT: 6.91×10^{20} in ~3.5 years
Anti-Neutrino POT: 7.53×10^{20} in ~2 years.

High power operation of MR

For high power beam operation of the MR , key items on beam dynamics are

- Instability suppression by chromaticity optimization, BxB and intra-bunch feedback system
- Correction of betatron funchtion, dispersion function and betatron tune during acceleration
- Correction of linear coupling sum resonance, some third-order resonances
- Mitigation of space charge tune shift by 2nd harmonic rf system

Incoherent space charge tune shift for 2.5×10^{13} ppb (380 kW-eq)



Structure resonances of up to 3rd order (Solid lines)
Non-structure resonances of half integer and linear coupling resonances (Dashed lines)

< 400 kW
Nominal tune was (22.40, 20.75)

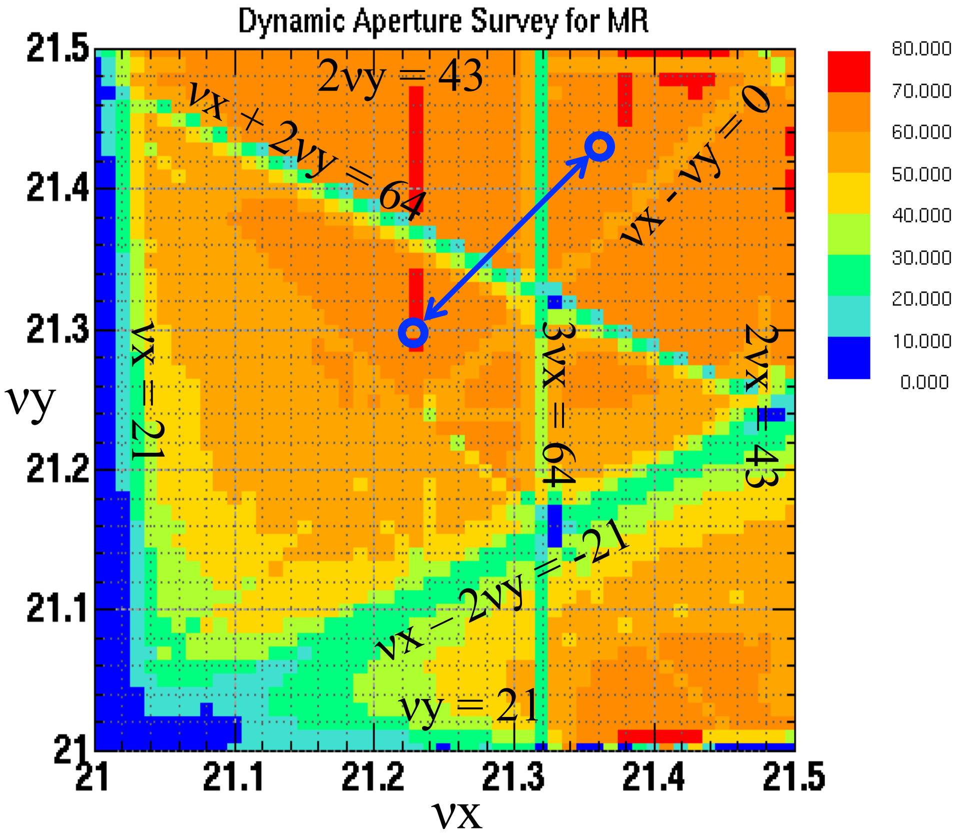
> 400 kW
New tune (21.35, 21.43) is adopted

Optimization for (21.x, 21.x)

S. Igarashi

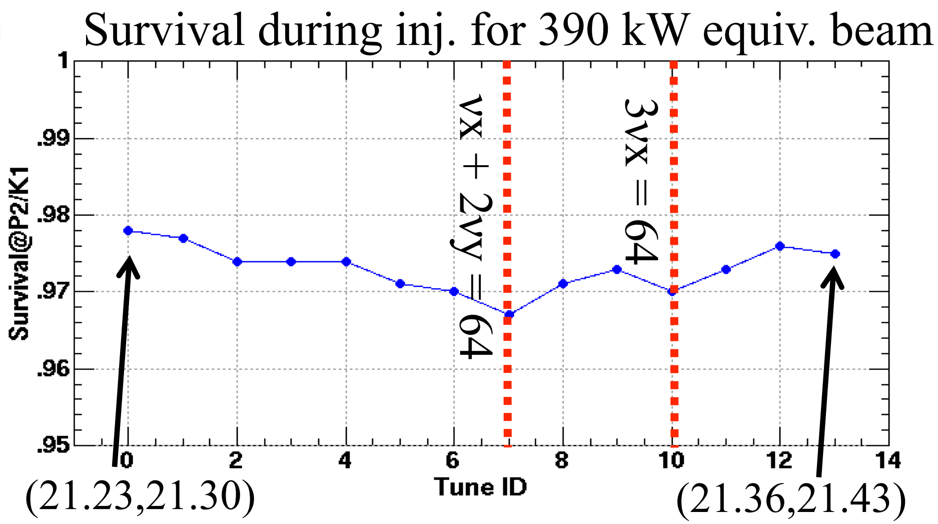
Dynamic aperture survey simulation

with B,Q,S field errors and alignment errors
$dp/p_0 = 0.0\%$



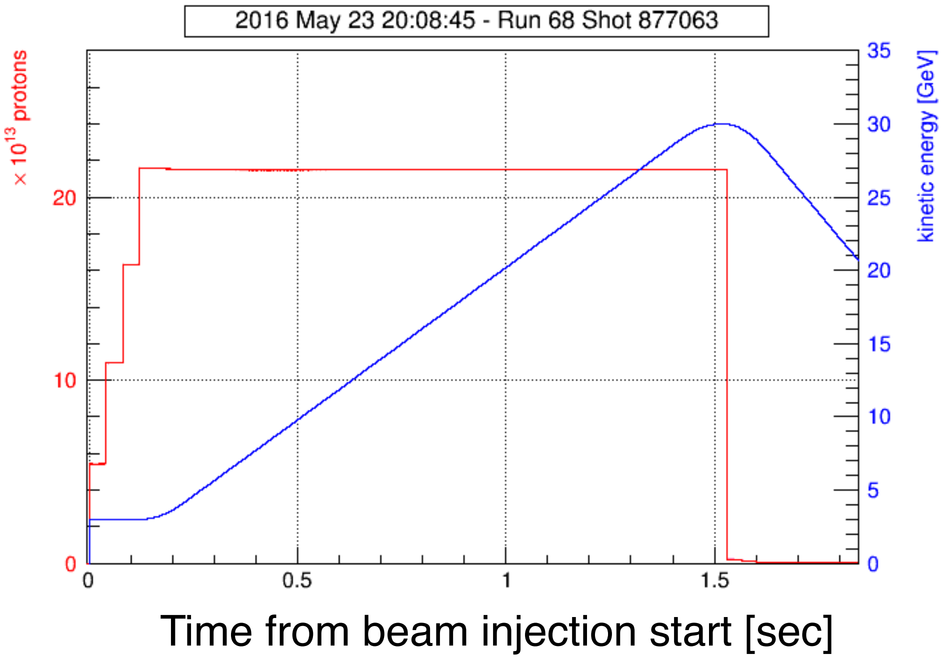
Measured beam survival at 3 GeV

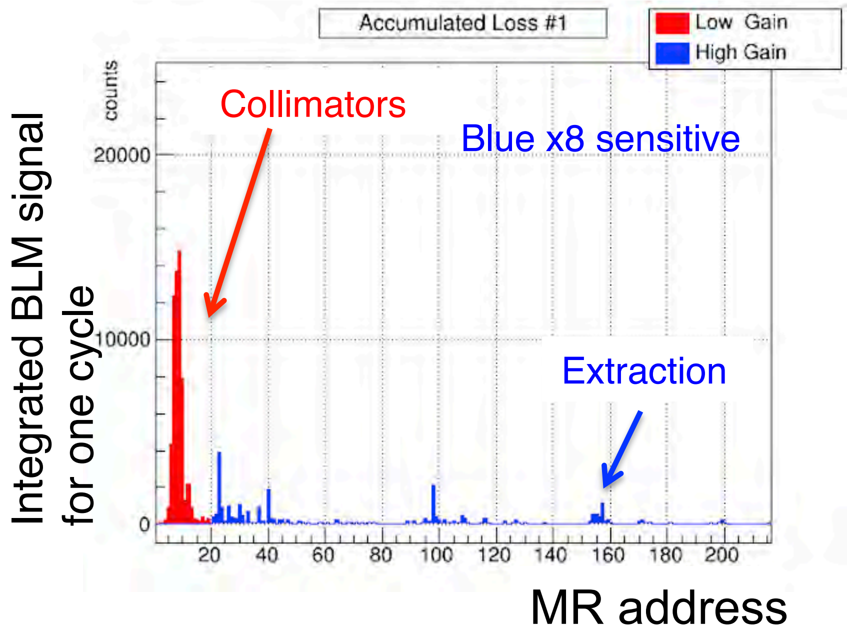
with beta and dispersion function corrections
2nd rf voltage
3rd order resonance correction
skew Q correction for vx – vy = 0
Instability suppression
- Chromaticity: –7
- Bunch by bunch and intra-bunch FB

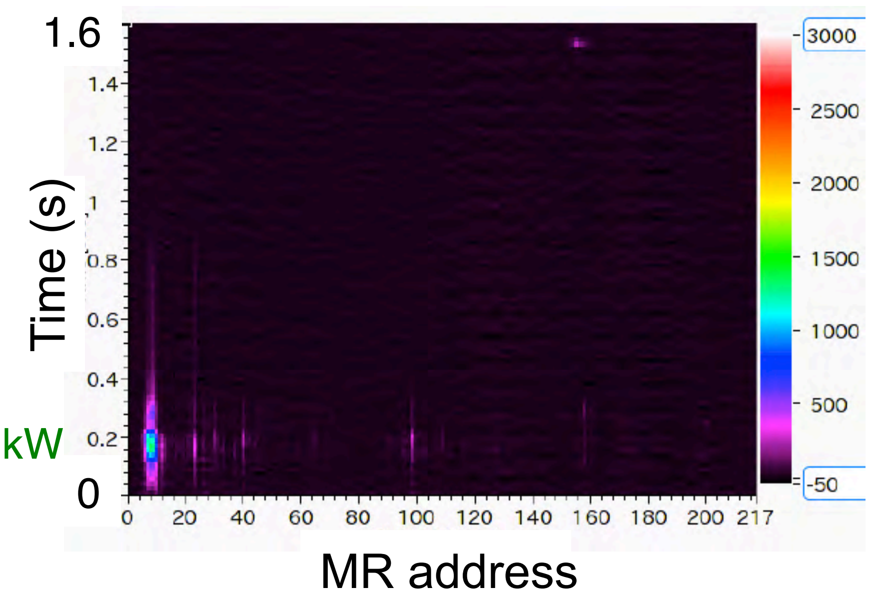


Typical user operation of FX

- at (21.35,21.43) -







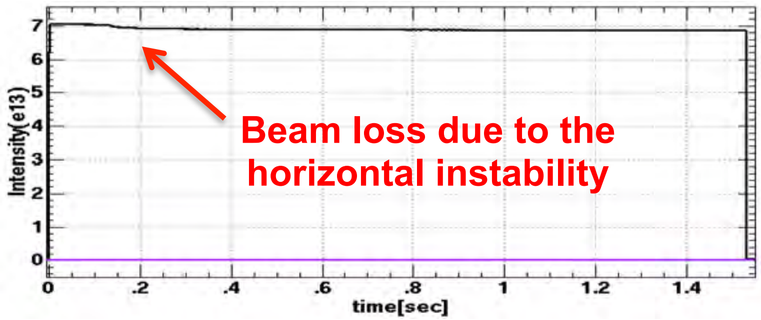
Power : 416 kW @ 2.48 sec
2.7e13 ppb × 8 @ Injection
2.15e14 ppp @ end of acceleration

Loss at MR ~ 600 W < MR collimator limit of 2 kW .
Loss at 3-50BT <100 W < 3-50BT collimator limit of 2 kW

High Intensity beam study

- at the new betatron tune (21.24, 21.31) -

High power trial with two bunches



Extracted beam : 3.41e13 ppb
6.82e13 ppp (132 kW eq. ,2 bunches)

	Beam loss[Watt]	
INJ(K1+K2+K3+K4)	144	7.43e+11
P2 --> +90ms	241	1.00e+12
P2+90ms --> +120ms	31	1.30e+11
P2+100ms ---> EXT		1.83e+11

Total beam loss ~ 420 W

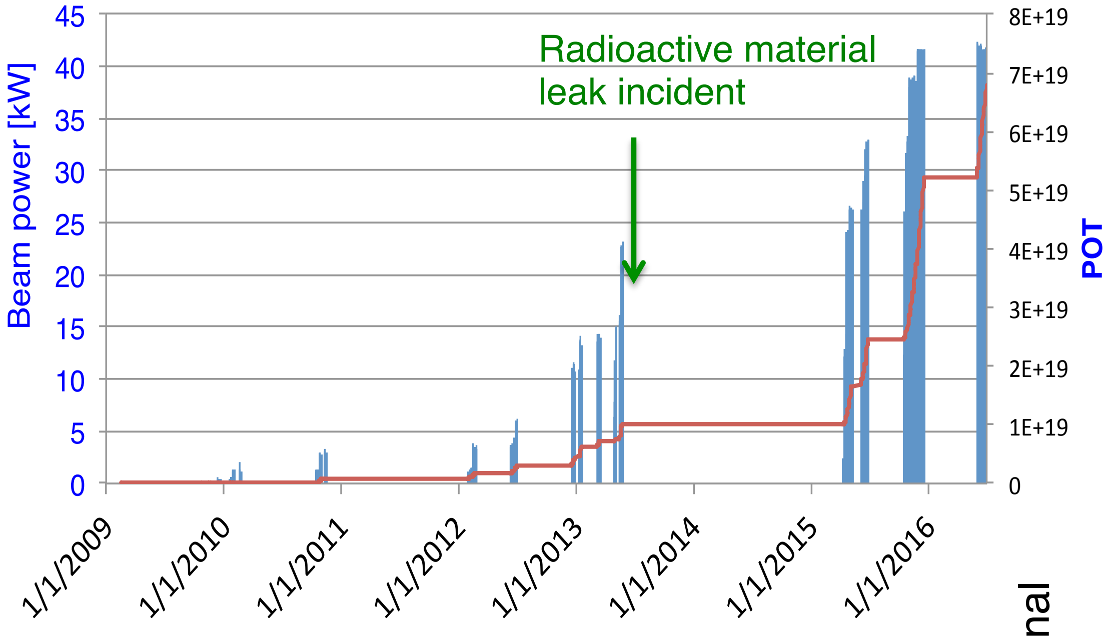
Near future tunable knobs to reduce the beam loss:
Injection kicker, BxB feed-back,
2nd harmonic cavity, VHF cavity, etc.

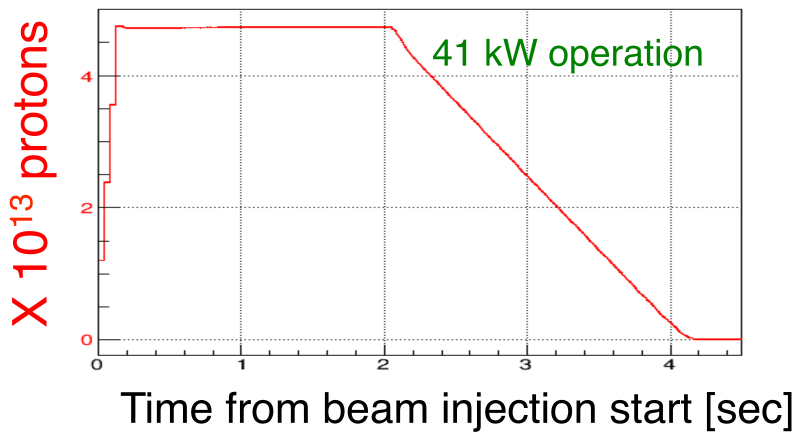
	Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2	2.48	132	0.42	measurement
2	8	2.48	529	1.7	estimation
3	8	1.3	1009	3.2	estimation

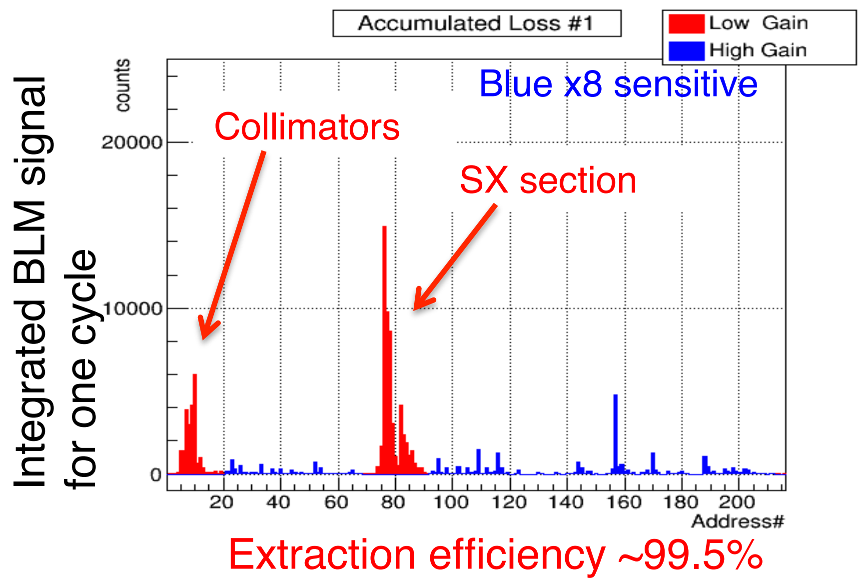
The MR has capability to reach 1MW with the high repetition rate operation.

Slow extraction

- Third-integer resonance extraction($\nu x=67/3$)
- High β of 40 m at electrostatic septum (ESS) -> Large step size ~20 mm
- Dispersion free at ESS and low horizontal chromaticity
- Dynamic bump scheme for high extraction efficiency







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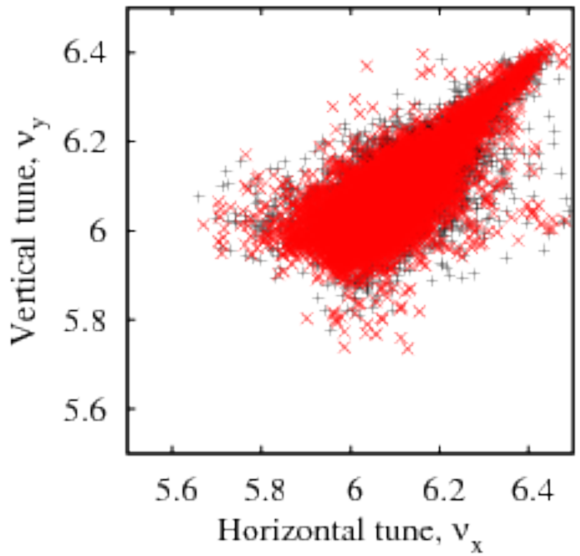
Operation with beam intensity > 1MW in RCS

Incoherent tune shift :

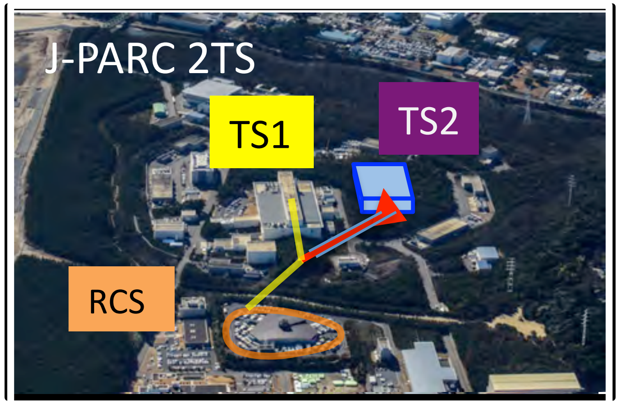
$$\Delta\nu = -\frac{n_t r_0}{2\pi\varepsilon\beta^2\gamma^3}\frac{1}{B_f}$$

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	-
400	13.3	1.6	-0.53	-



Black: 181 MeV inj., 540 kW-eq.
Red: 400 MeV inj., 1.5 MW-eq.

Beam intensity ~1.5 MW is a next goal in the mid-term.
The intensity is required the second target station project, which is under discussion.



Challenges:

Linac : Peak current 50mA →~60mA
Macropulse width 0.5ms →~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.

Mid-term plan of MR

FX: The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, RF cavities and some injection and extraction devices.
SX: The beam power of the MR will be gradually increased toward 100 kW watching the residual activity. In the HEF, the primary target will be replaced new ones which have more cooling capability in 2018 and 2021.

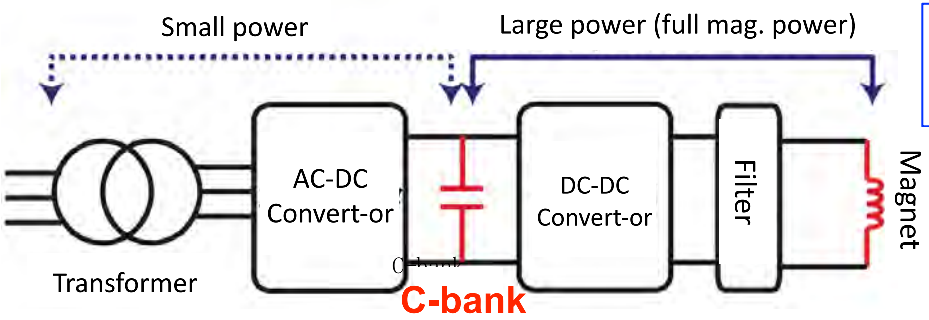
JFY	2015	2016	2017	2018	2019	2020	2021
		New PS buildings →		HD target (80kW)			HD target (>100 kW)
FX power [kW]	390	425-450	450-500	700	800	900	1060
SX power [kW]	42	42-50	50	50-70	80	80	~100
Cycle time of main magnet PS New magnet PS	2.48 s	Mass production installation/test →		1.3 s	1.3 s	1.25 s	
High gradient rf system	Installation →						
2nd harmonic rf system	Manufacture, installation/test →						
Ring collimators	Add.collimators (2 kW)		Add.colli. (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			ESS				

COMET / high-p physics run →

New power supply for high repetition rate operation

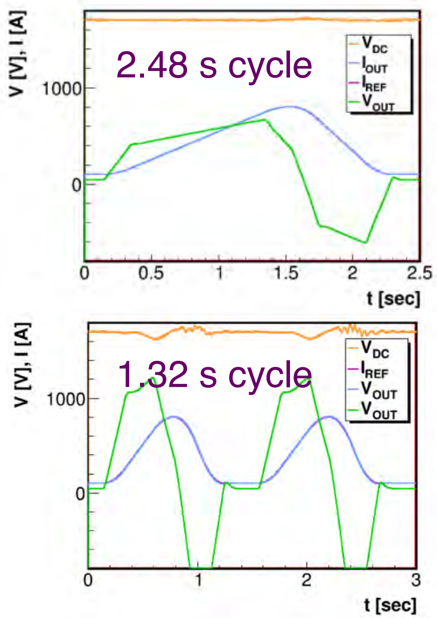
Budget for three buildings of the magnet PS's and for starting mass production of the PS's have been approved by the government in JFY2016.

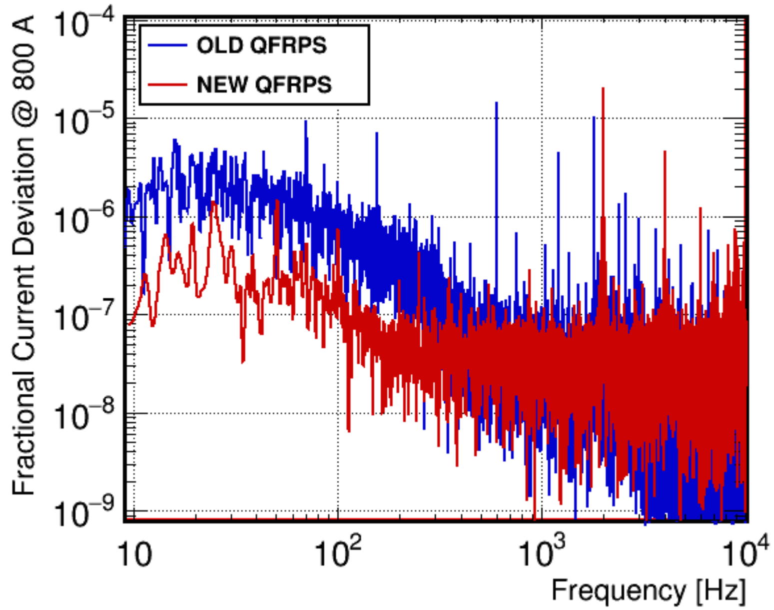
Large scale PS for bending magnets and quad. magnets in arc setions



Two large converters and large capacitance for energy recovery, symmetric power module circuit

The 1st power supply (for the middle class family "QFR") has been delivered to J-PARC in the end of September 2016. It has been started to use in user operation since October 2016.

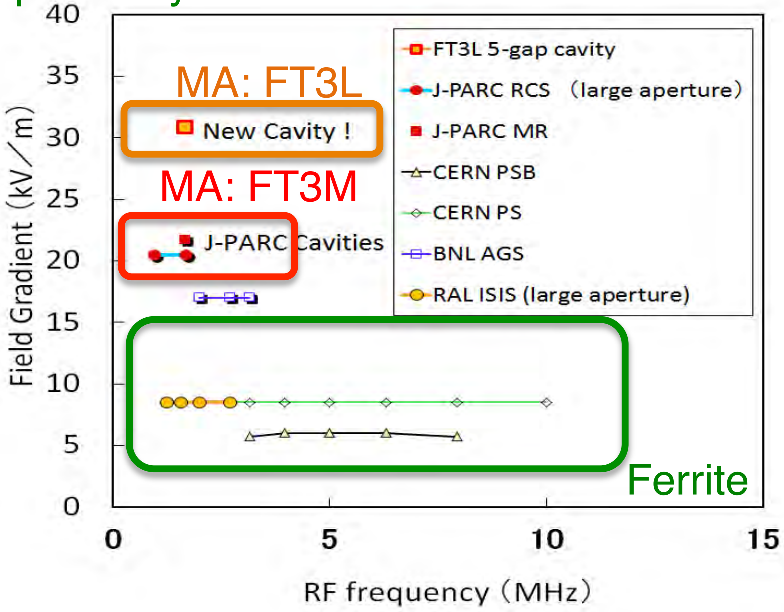




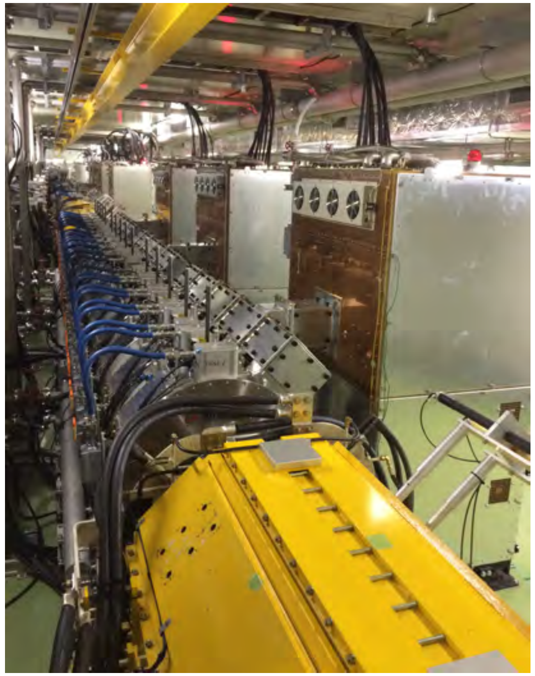
High impedance rf system

A magnetic alloy (MA) core, FT3L, is adopted to increase shunt impedance of the rf cavity. The core material was developed in a close collaboration between J-PARC and Hitachi Metal Co. Ltd. The core is processed by annealing with magnetic field.

Comparison of field gradient of rf cavities for proton synchrotron.

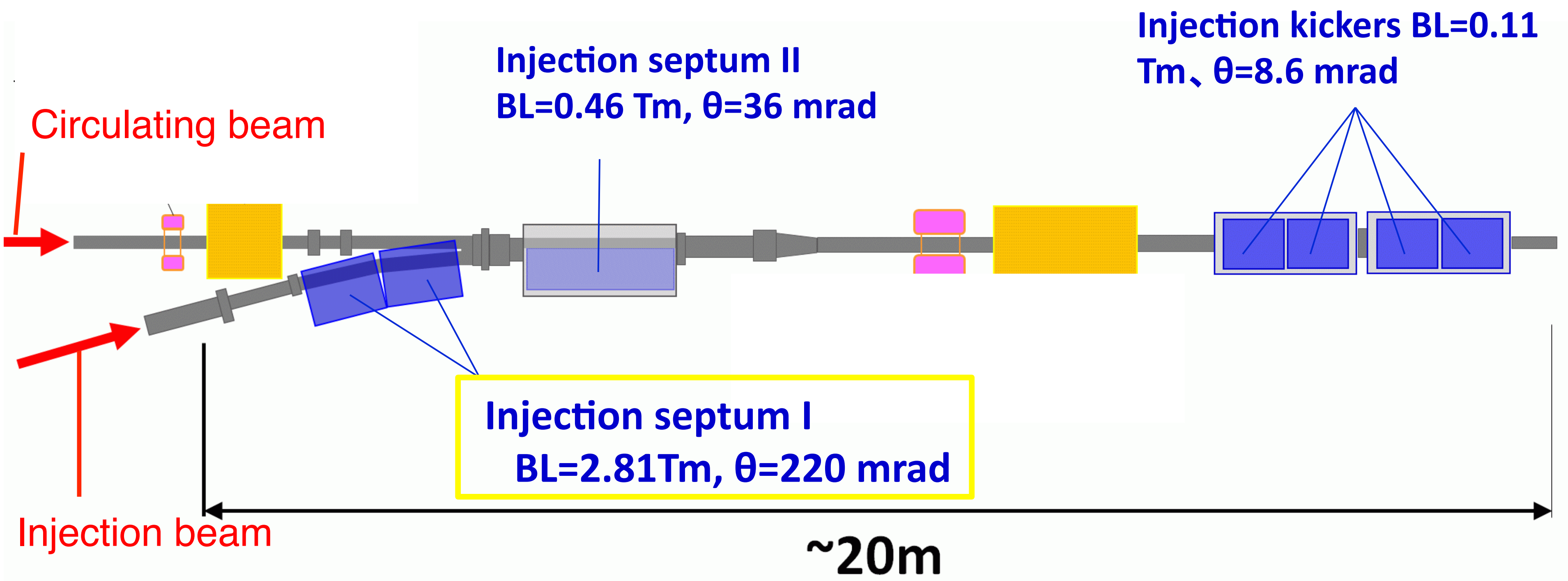


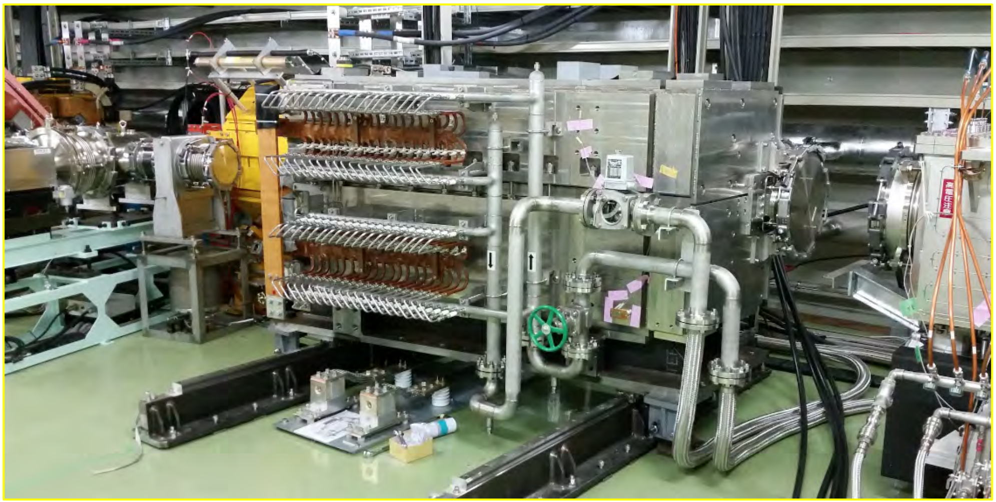
C. Ohmori



	2013	2014	2015	2016	2017	2018
Original FT3M cavities	9	8	4	0	0	0
New FT3L Cavities	0	1	5	9	9	9
New FT3L 2nd cavities	0	0	0	0	2	2
Available voltage	315 kV	355 kV	485 kV	602 kV	602 kV	602 kV
(2nd Harmonic)	(35 kV)	(70 kV)	(70 kV)	(70 kV)	(70 kV)	80 kV

New injection septum I for high repetition operation





T. Shibata

Toward the beam intensity > 1MW

Beam Power (kW)	425 (Achieved)	813	1000	1326
#ppp(10^{14})	2.2	2.2	2.6	3.2
Rep T (s)	2.48	1.3	1.3	1.16

Higher rf voltage and more operating margin

- Reinforcement of anode power supplies to increase anode current of power amplifier
- Additional rf system (# 10)

Air-cooled second harmonic rf system

- mitigating space charge effect.

VHF rf system

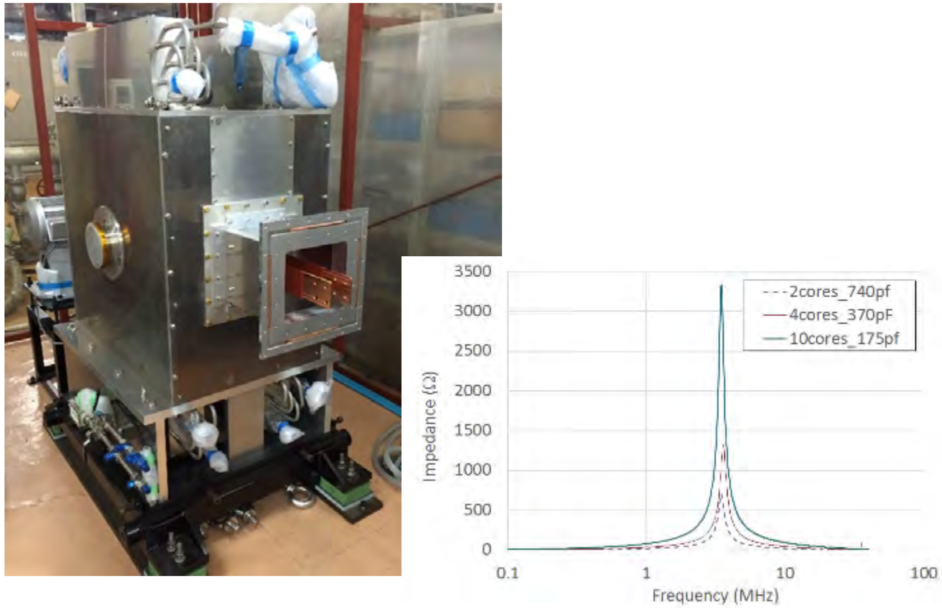
- mitigating space charge effect.
- (Suppression of the longitudinal instabilities)

BPM upgrade

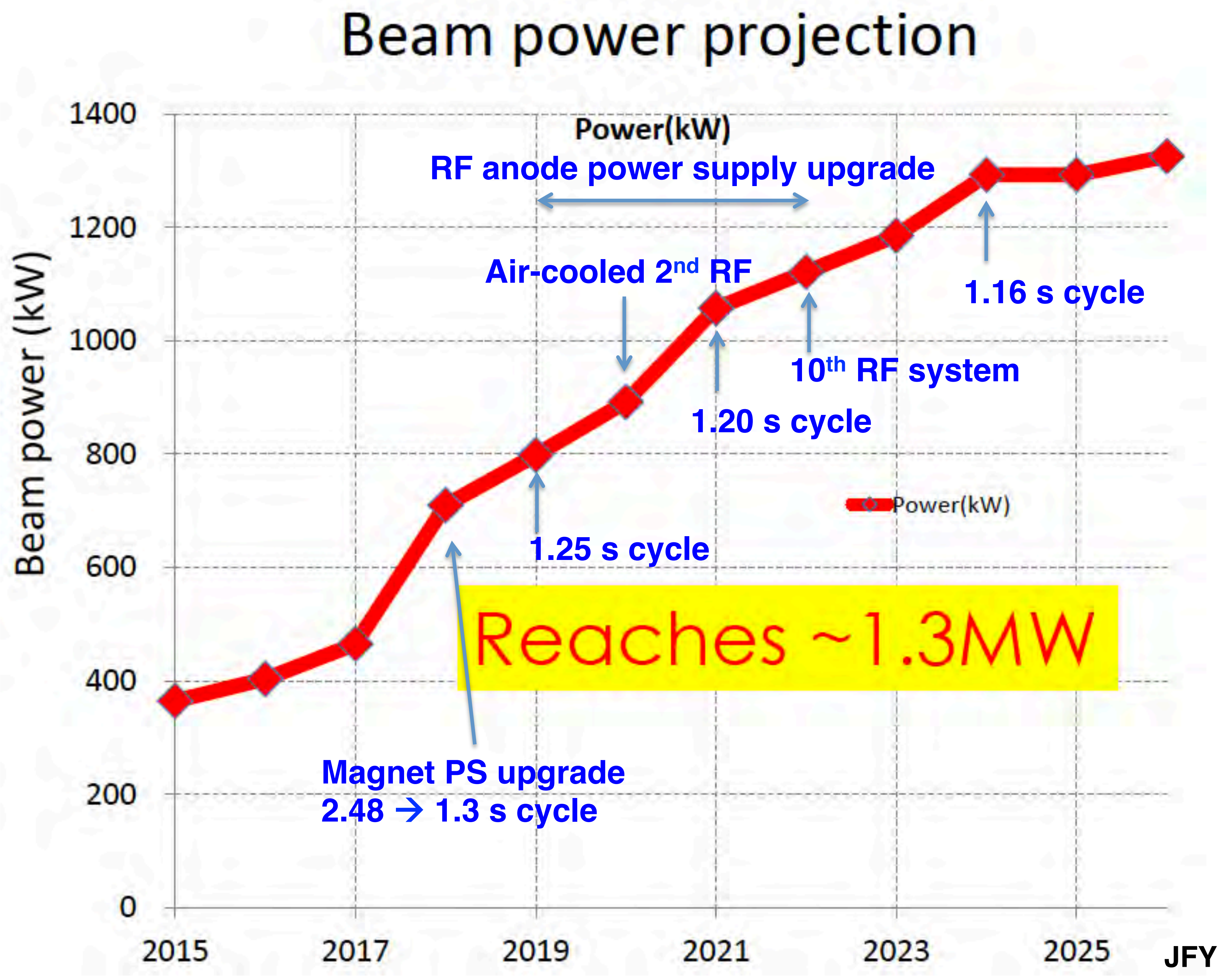
- more precise and faster measurement.

FX kicker upgrade

- Low beam coupling impedance



Prototype of air cooled 2nd harmonic rf cavity

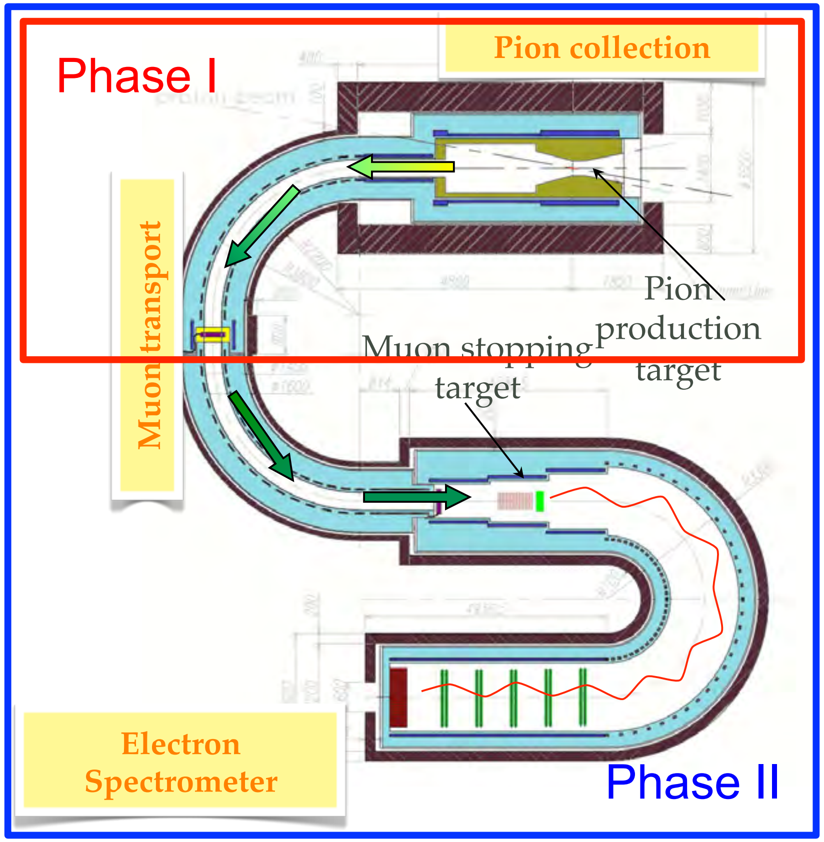


Beam power projection
Power(kW)
RF anode power supply upgrade
Air-cooled 2nd RF
1.16 s cycle
10th RF system
1.20 s cycle
1.25 s cycle
Power(kW)
Reaches ~1.3MW
Magnet PS upgrade
2.48 → 1.3 s cycle
Beam power (kW)
1400
1200
1000
800
600
400
200
0
2015
2017
2019
2021
2023
2025
JFY

COMET (I <10^{-14}; II < 10^{-16})

Search for muon to electron conversion
Adopted staging approach
Phase-I: 10^{-14} (funded)
Phase-II: 10^{-16}

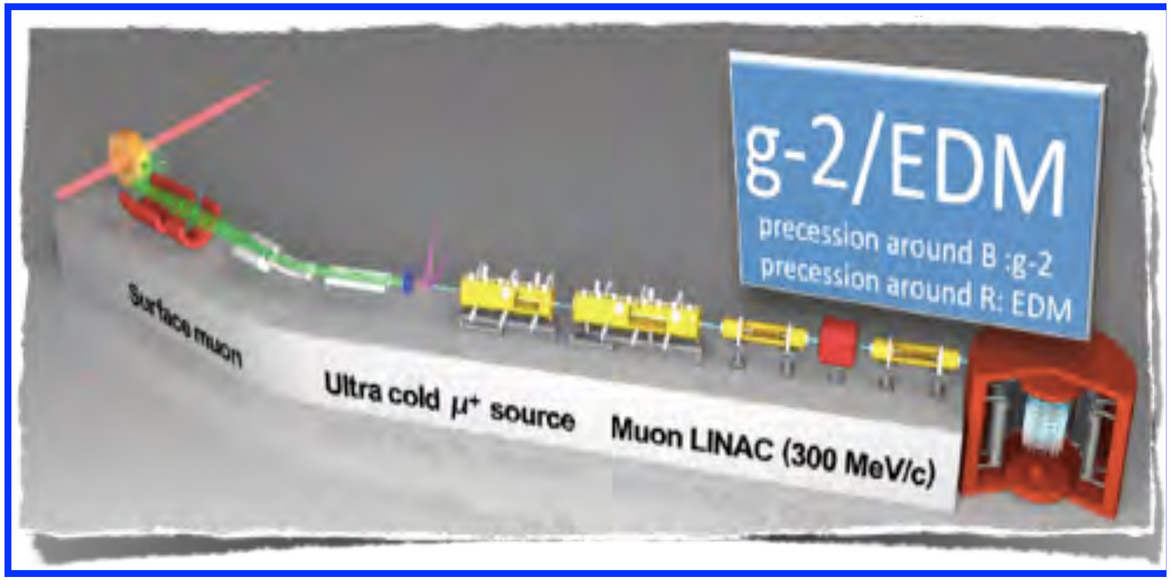
- 32 m SC solenoid magnet
- Beam extinction < 10^{-9}
- 8 GeV, 3.2 kW(Phase- I) and 56 kW(II)



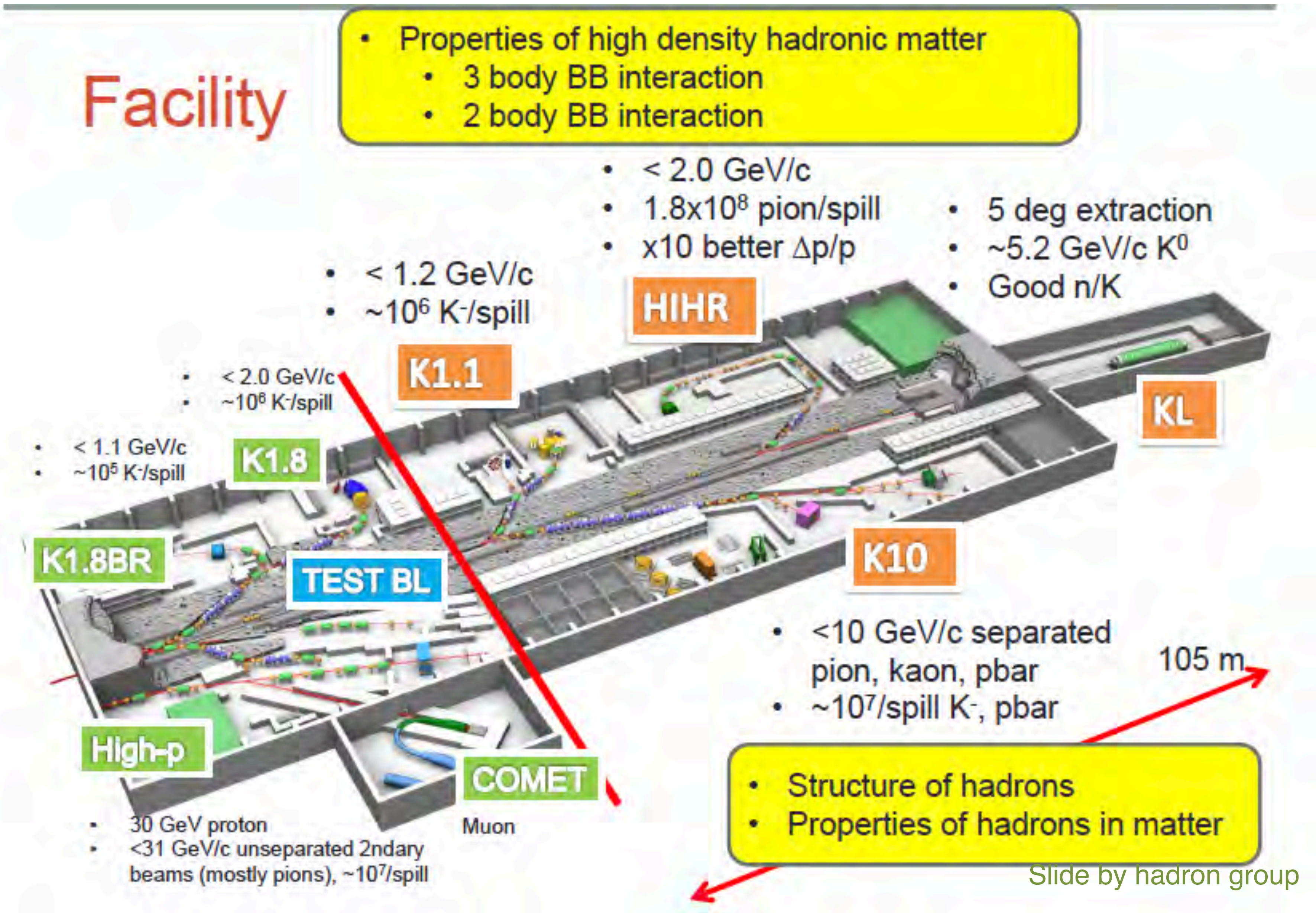
g-2/EDM (0.1ppm/10^{-21} e cm)

at MUSE in the MLF

- Ultra-Cold Muon Beam
  RFQ,IH,disk-loaded
- Ultra-Precision Magnetic Field
  3T, 1 ppm



Extension of Hadron Experimental Facility

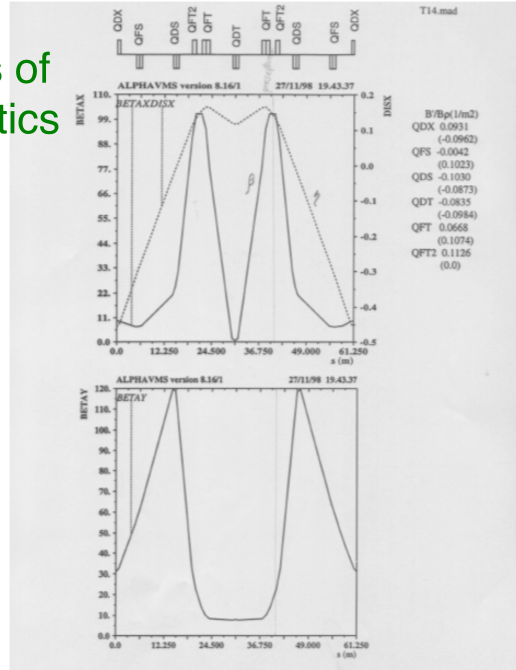


Slide by hadron group

Slow extraction with beam power >> 100 kW

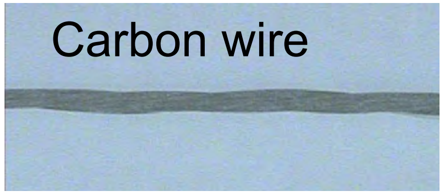
Feasibility for low-loss SX system
to reduce beam loss on the electrostatic septum (ESS) :

Examples of
high-β optics

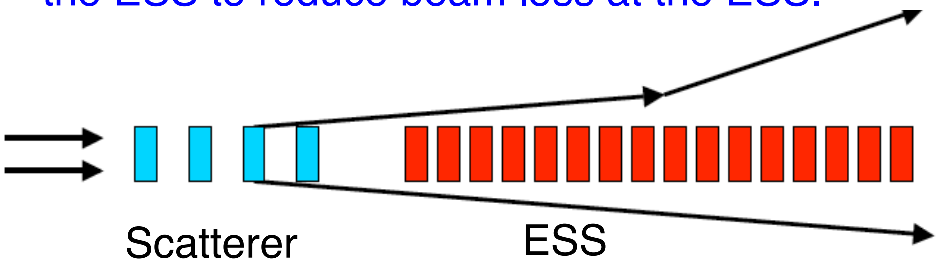


- High β insertion optics
  - β >> 100m @ESS
  - Q-PS separated in the SX straight section
  - Add extra Qs in the SX
  - Larger-bore Qs in SX

- Low-Z material for ESS ribbon
  - carbon-wire
  - carbon-nanotube



- Combination of low-z scatterer and ESS
  - Scatterer made of low-Z material is installed upstream of the ESS to reduce beam loss at the ESS.



High voltage test of
carbon wire ribbon

1. Facility overview

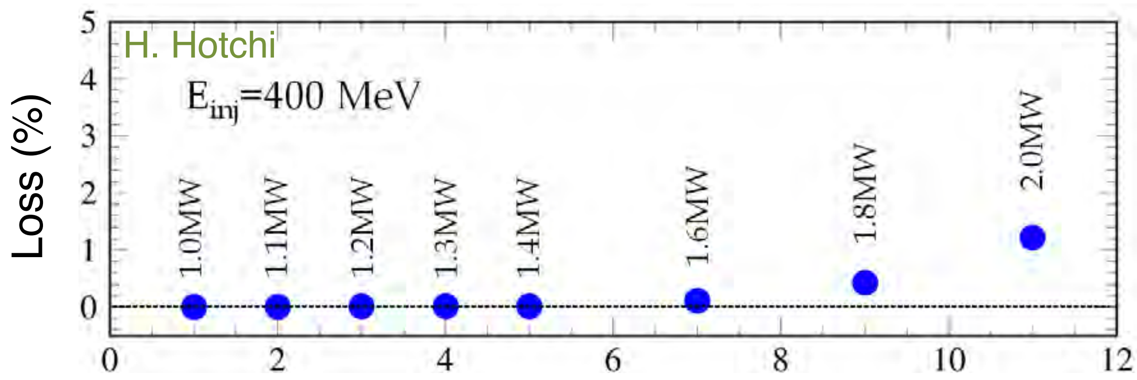
2. Status of accelerator operation and achievements
   - RCS
   - MR: Fast extraction for neutrino experiment
   - MR: Slow extraction for hadron experimental facility

3. Mid-term upgrade plans

4. Long-term plans

5. Summary

Feasibility of the 2 MW operation in RCS



RCS intensity	Loss	Loss power at 25 Hz
1.0 MW	~0.3%	400 W
1.1 MW	~0.3%	440W
1.2 MW	~0.3%	480 W
1.3 MW	~0.3%	520 W
1.4 MW	~0.3%	560 W
1.6 MW	~0.5%	1067 W
1.8 MW	~0.7%	1680 W
2.0 MW	~1.5%	4000 W

Collimator limit ~4 kW(1.5 % loss)

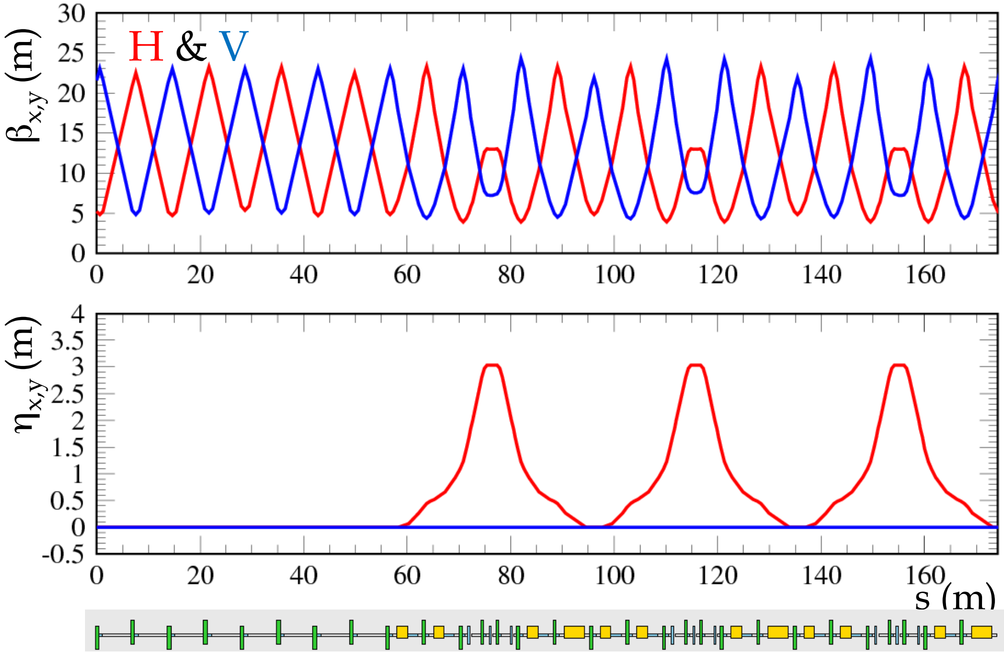
RCS has a feasibility to operate 2 MW.

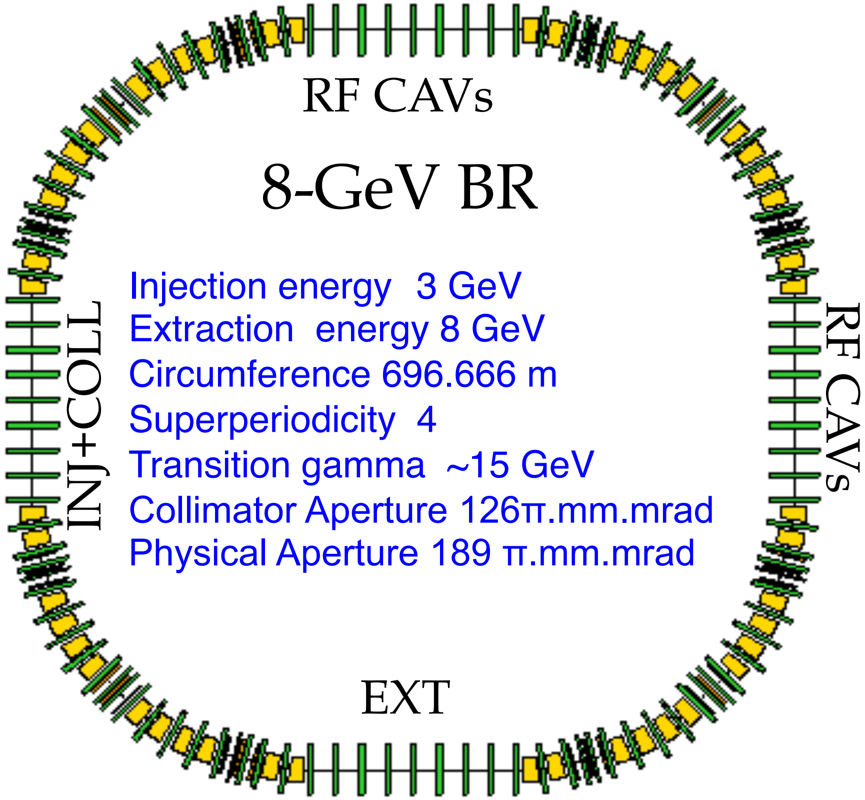
Issues to be solved for 2 MW beam power

- Reinforcement of the rf system to compensate a heavy beam loading
- R&D of ion source / long pulse operation of linac / RCS injection for beam > 1.5 MW-eq.
- R&D of the charge stripping for the high intensity beam
- Methods to cure the instability due to kicker impedance at the high intensity ……

The 8-GeV booster ring

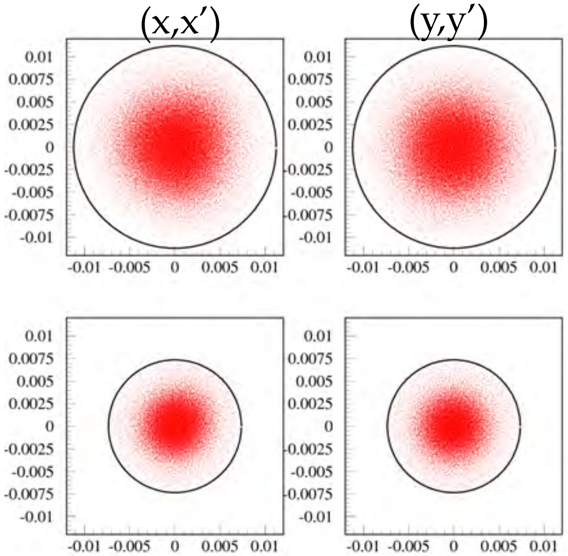
Beta & Dispersion for 1-superperiod





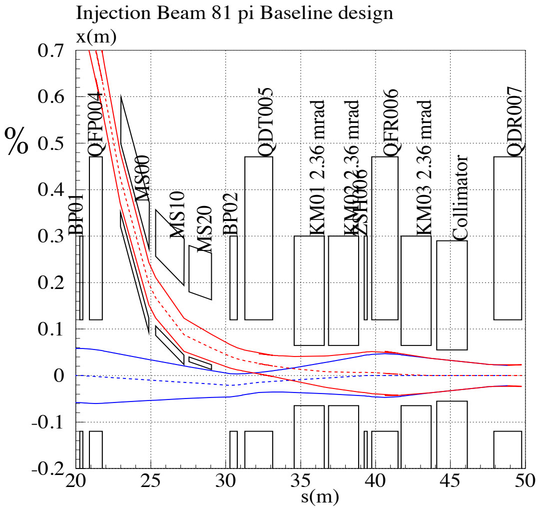
Injection energy 3 GeV
Extraction energy 8 GeV
Circumference 696.666 m
Superperiodicity 4
Transition gamma ~15 GeV
Collimator Aperture 126π.mm.mrad
Physical Aperture 189 π.mm.mrad

Phase plot @ inj.(3GeV) & extr.(8GeV)



@ 3GeV
ε>125.5π ~0.04%

@ 8GeV
ε>54π ~0.06%



8 GeV injection in the MR using new septa&kickers

RCS : 1.4 MW
MR > 2.2 MW

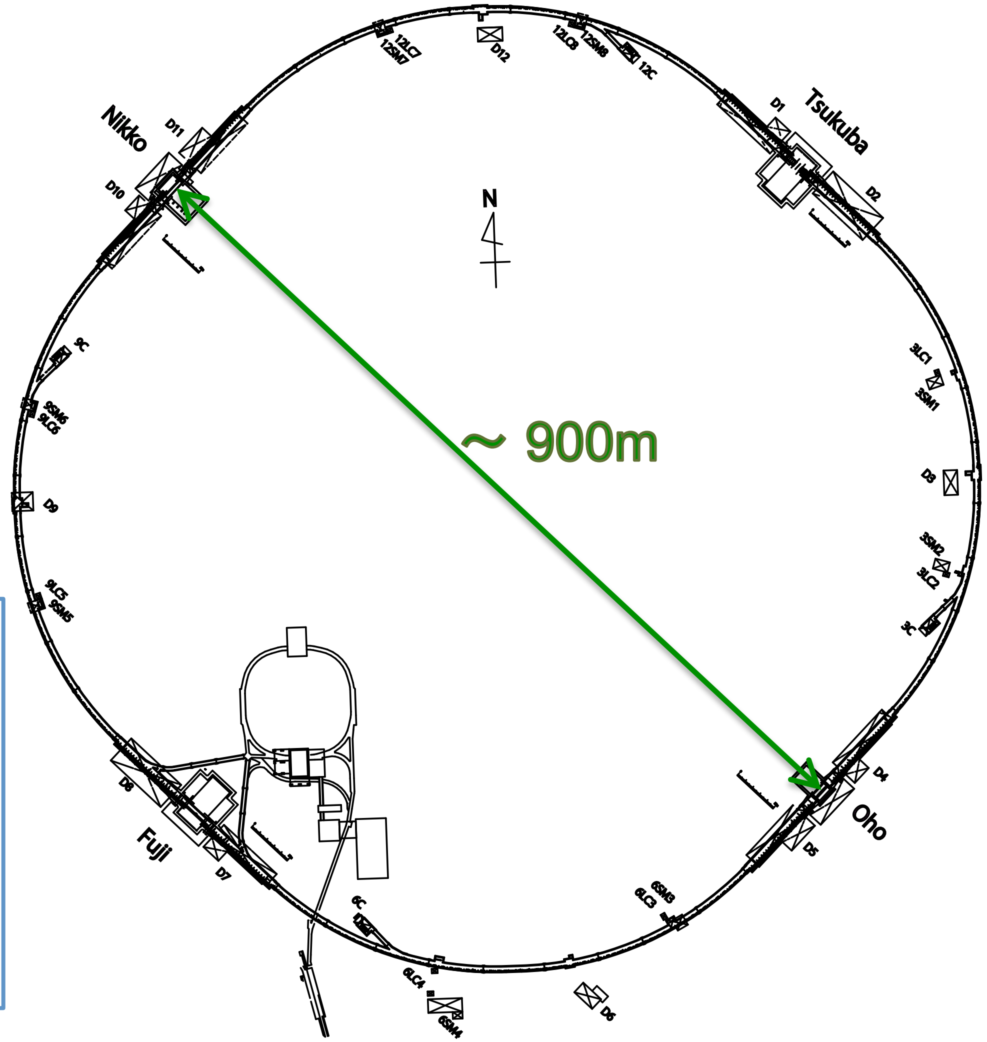
RCS : 2 MW
MR > 3.2 MW

Proton Driver in the KEKB Tunnel

- As the post-Super KEKB projects in KEK -

KEKB tunnel:

- fourfold symmetric configuration.
- Circumference: ~ 3 km
  - Straight section : beam acceleration
    200 m x 4 = 800 m
  - Arc section : beam transportation to
    the next straight section.
    550 m x 4 = 2200 m



Subjects :

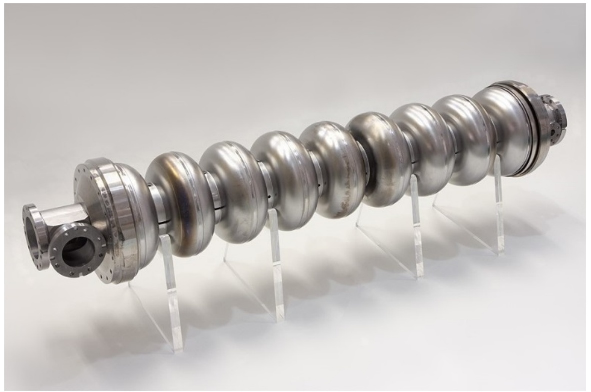
- Feasibility of 9 GeV proton linac in straight sections of 800 m.
  ⇒ High acceleration field is required.
  ⇒ SC accelerator is essential.
- Beam transport at Arc sections.

- In this scenario, the MR is operated only for the SX users

SC Cavity for 2nd to 4th Straight Sections

For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.

ILC cavity



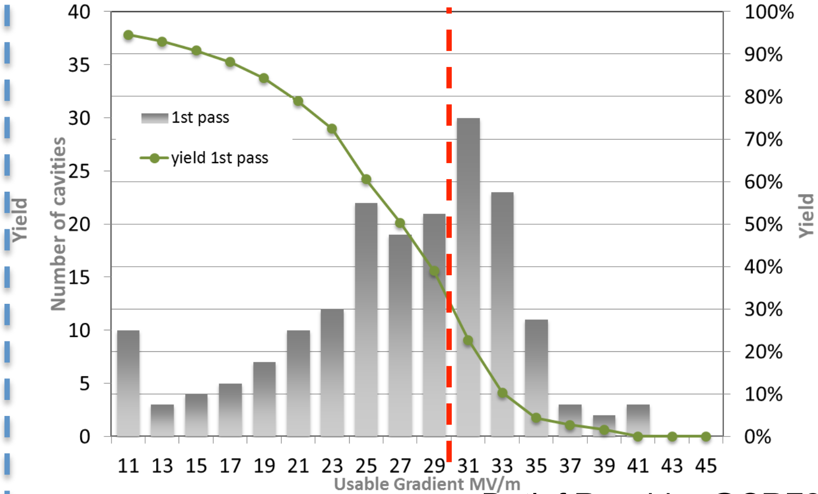
Shape	ellipse
RF frequency	1.3 GHz
# of cells per cavity	9
Quality factor	> 1 x 10^{10} @ 2K

ILC cryomodule

KEK has rich experience and know-how of ILC cavity and cryomodule fabrication.

Average gradient (E_0)

Yield of usable gradient of 185 ILC cavities as received (European XFEL)



Detlef Reschke @SRF2013

Average **usable** gradient:

(26.2 ± 7.5) MV/m

With the expectation of further R&D, we set the E_0 to **30 MV/m**.

The proton driver in the KEKB Tunnel

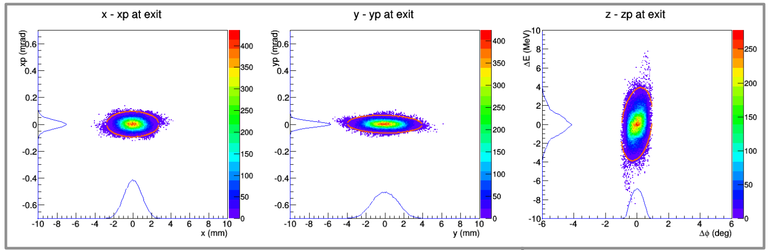
For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.

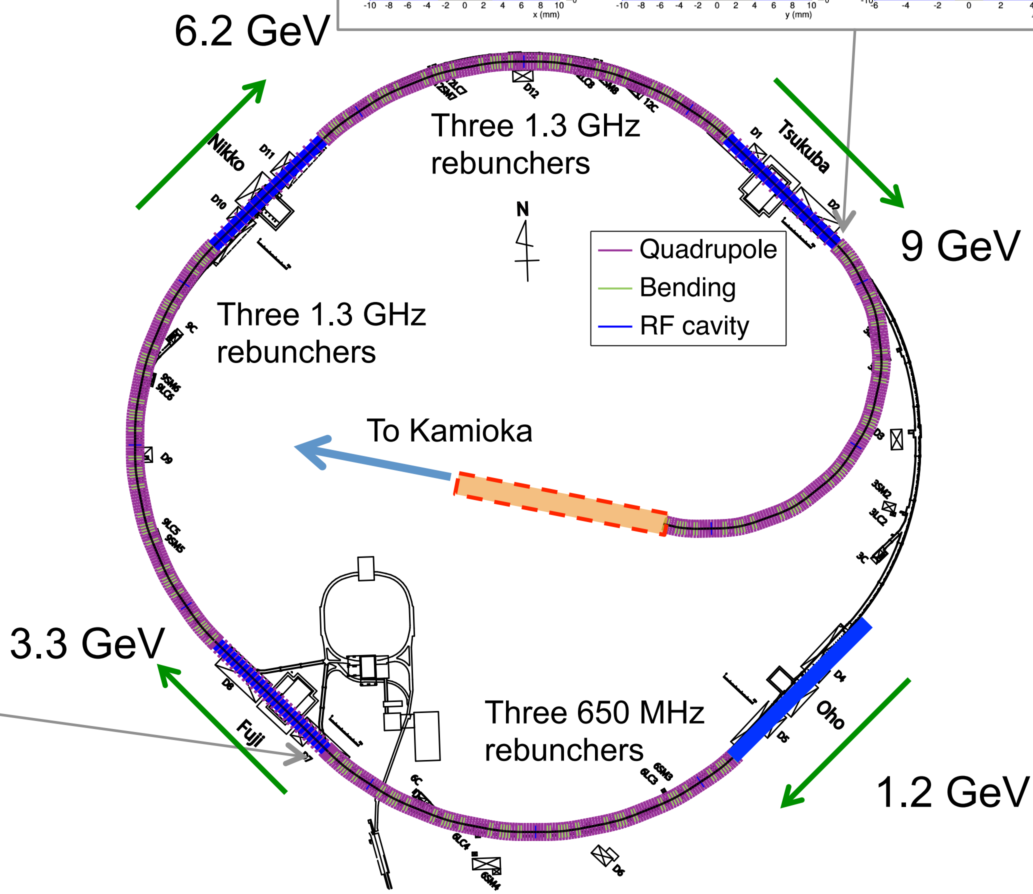
- Outline of acceleration :
  - 1.2 GeV in 1st straight.
  - 3.3 GeV in 2nd straight.
  - 2.9 GeV in 3rd and 4th straight.

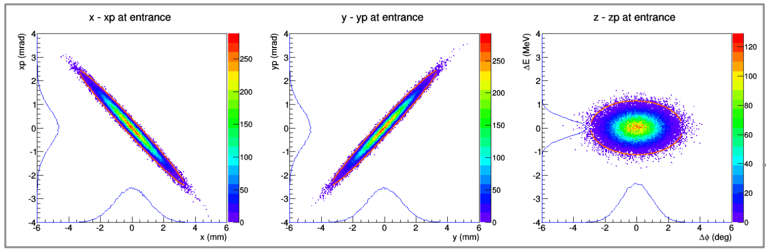
    3.3 + 2.9 x 2 = 9.0 GeV

- Peak current : 100 mA (pulse)
- Beam duty : 1 %
- Beam power :

9 GeV x 0.1 A x 1 % = **9 MW**





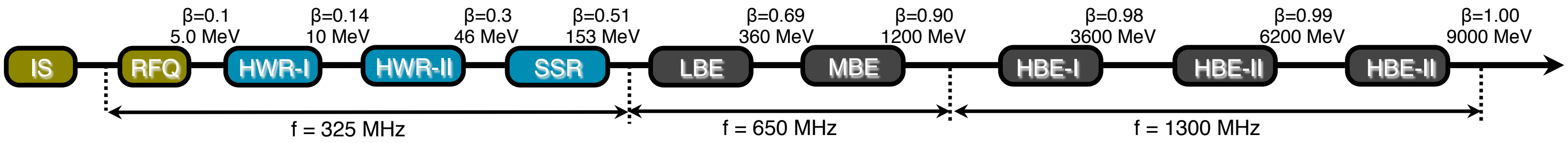


R&Ds are necessary : Higher gradient SC cavities, High power target, Horn…

Present design parameters

T. Maruta and Gunn Tae Park

◻ Baseline layout



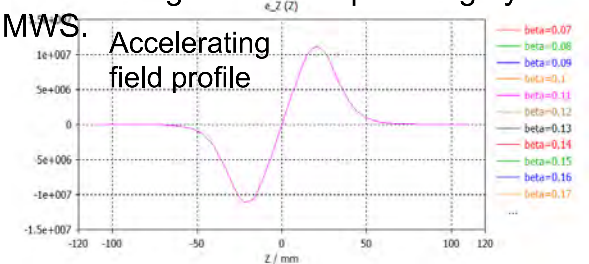
◻ Accelerating cavity parameter

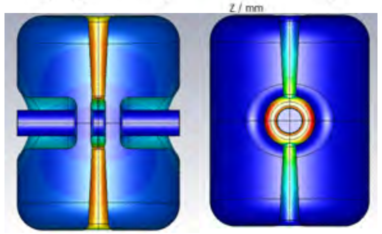
ILC cavities (HBE-I, HBE-II)

	RFQ	HWR-I	HWR-II	SSR	LBE	MBE	HBE-I	HBE-II
β_{opt}	0.01 – 0.10	0.13	0.21	0.38	0.62	0.73	0.93	1.0
V_{acc}	–	0.89 MV	3.7 MV	4.5 MV	11.9 MV	16.2 MV	30 MV	30 MV
E_{out}	–	10 MeV	46 MeV	153 MeV	360 MeV	1200 MeV	3600 MeV	9000 MeV
cavity no.	1	6	16	29	13	74	108	256
cm no.	–	1	2	6	5	25	27	32
cavity/cm	–	6	8	5	3	3	4	8

◻ Cavity R&D

HWR-I design is under optimizing by CST-MWS.



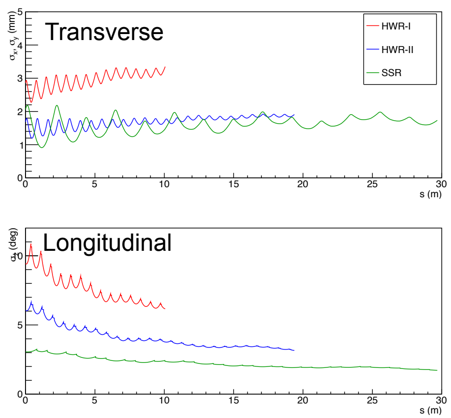


Electro-magnetic field strength

Figures of merit	Value
V_{acc}	0.89 MV
E_{acc}	7.42 MV/m
R/Q_0	395.3
G	40.2
Q_0	3.78E+09
P_{wall}	0.54W
E_p/E_{acc}	4.71
B_p/E_{acc}	9.57 mT/(MV/m)
P_g	89 kW

◻ Beam dynamics simulation

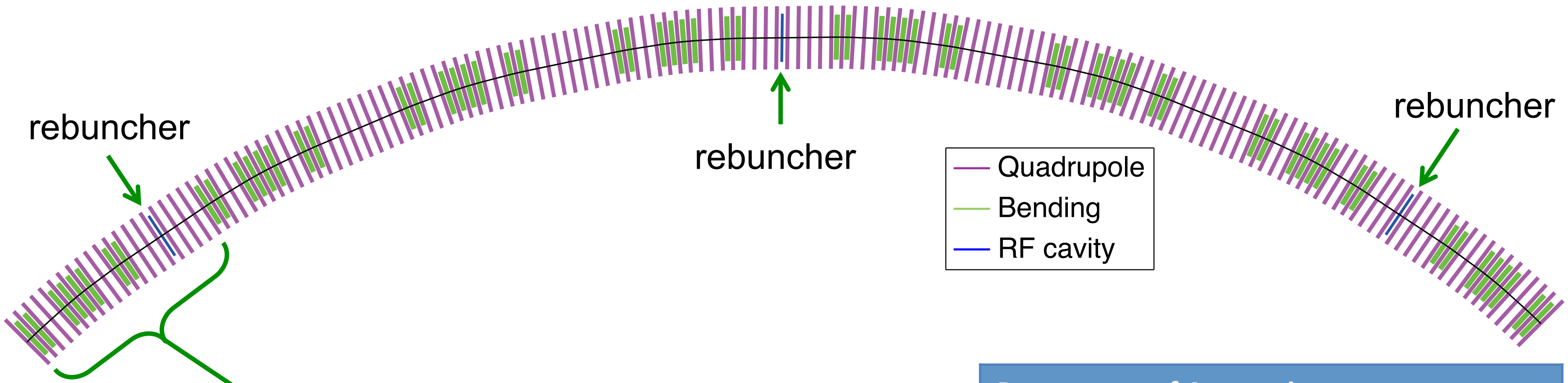
Beam envelope of HWR-I to SSR



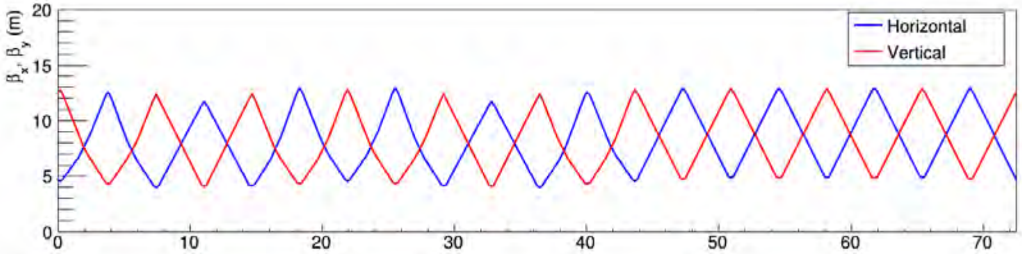
	ϕ_s (deg)	Acc. gradient (MV/m)
HWR-I	-30	0.61
HWR-II	-30	1.9
SSR	-27	3.7
HBE-I	-24	10.9
HBE-II	-20	14.9

Lattice of Arc section

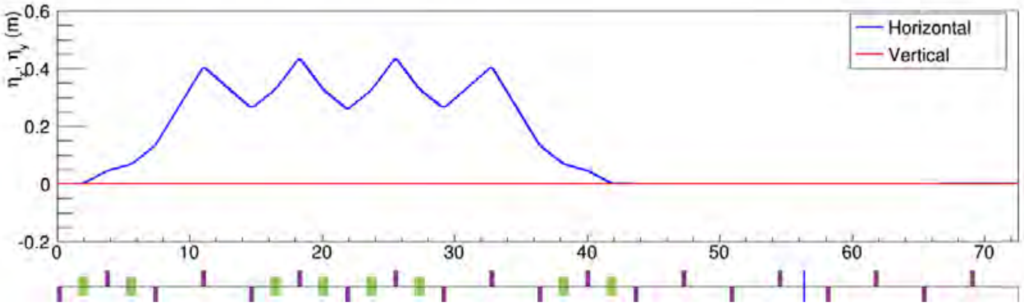
H. Hotchi



Beta function



Dispersion



Parameters of Arc section	
Length	550 m
Aperture	70 mm
Momentum acceptance	±0.8 %
Bending magnet	
# of magnets	64
core length	0.8 m
Quadrupole magnet	
# of magnets	152
core length	0.375 m
drift length between Qs	3.25 m
Rebuncher	
# of cavities	3
RF frequency	0.65 / 1.3 GHz

Summary of SC cavity and magnets

- 2nd – 4th straight section
  - Super conducting cavity : 364
    - βg = 0.93 : 108
    - βg = 1.0 : 256
  - SC quadrupole magnet : 164

- Arc section
  - Rebuncher cavity : 9
  - NC quadrupole magnet : 608
  - NC bending magnet : 256

} SuperKEKB magnets could reuse.

Summary

Status and operation summary of accelerators:

- Achieved beam power in user operation :
  - 500 kW for the MLF users
  - 425 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 (It corresponds 530 kW with 8 bunches)
  - The MR has a capability to reach beam power ~ 1 MW with the high rep rate operation.

The mid-term upgrade plan :

- Beam power of the RCS will be increased step by step carefully watching beam loss and conditions of the MLF targets, and keeping high availability for users. We will be able to reach 1MW and beyond in routine operation in near future.
- The design power of 750 kW for the FX, and 70 kW for the SX will be achieved in 2018-2019 after the replacement of main magnet power supplies and the primary target in the HEF.
- The MR-FX will reach > 1 MW in 2020 - 2025.
- Goal of the MR-FX is 1.3 MW (full beam of 1 MW-eq from the RCS, injected and extracted with 1.16 s cycle)

Long-term plan :

- Some scenarios to achieve beam power beyond current design for neutrino experiment are now under discussion; the 8 GeV booster, 9 GeV linac.