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Achievements and future upgrade of J-PARC accelerator

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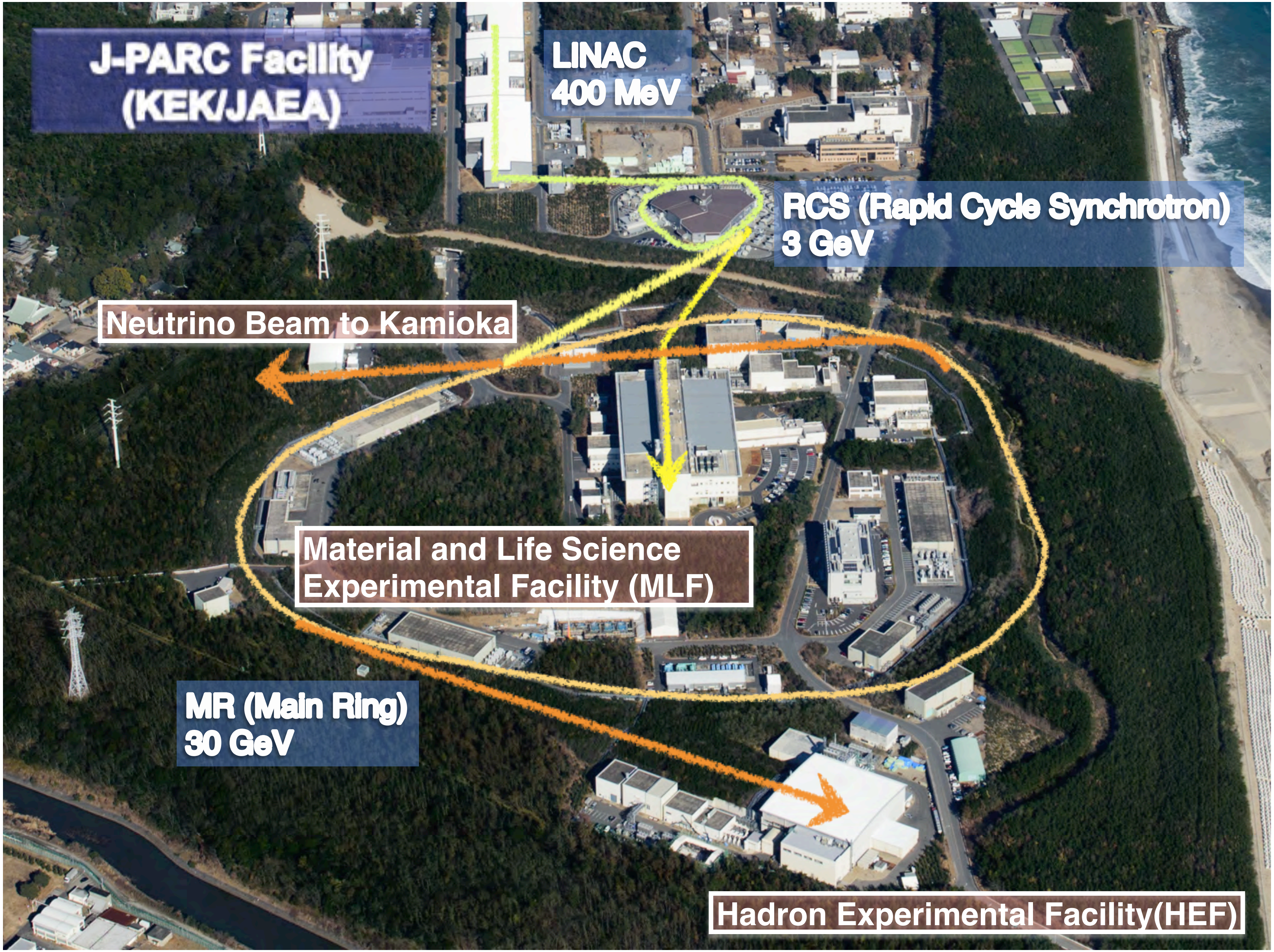
1. Status of accelerator operation and achievements
   - RCS
   - MR: Fast extraction for neutrino experiment
   - MR: Slow extraction for hadron experimental facility

2. Mid-term upgrade plans

3. Long-term plans

4. 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)

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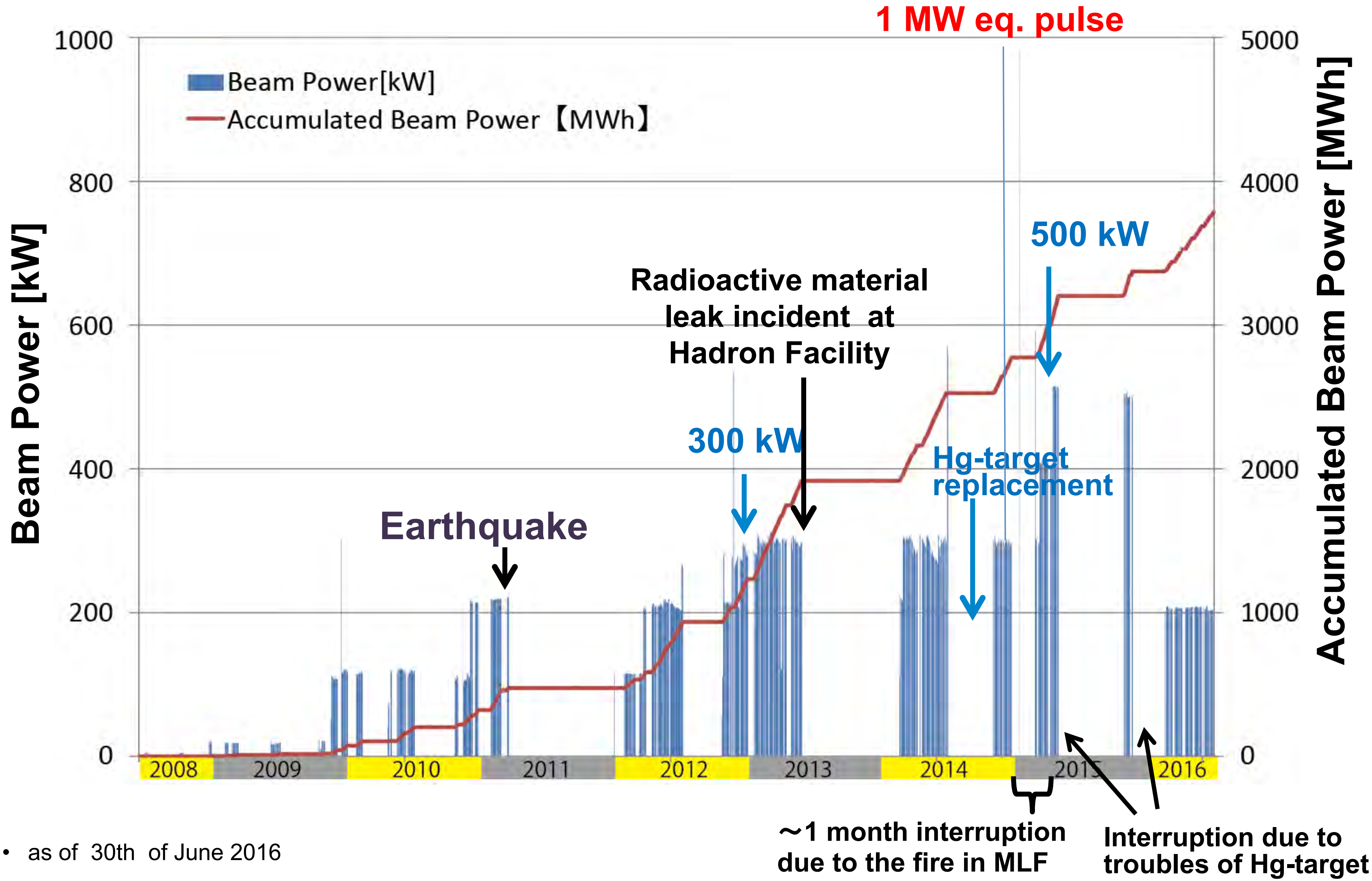
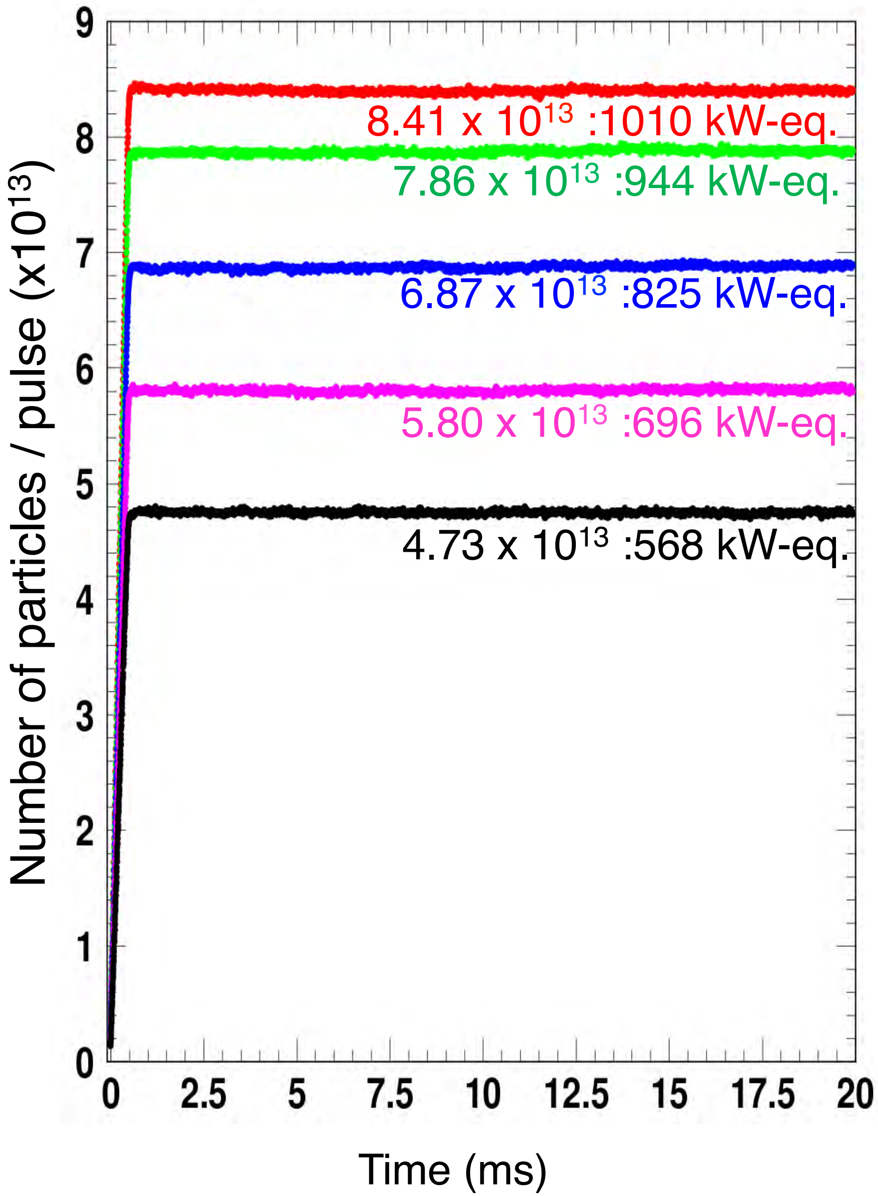
Beam Power History at MLF



- as of 30th of June 2016

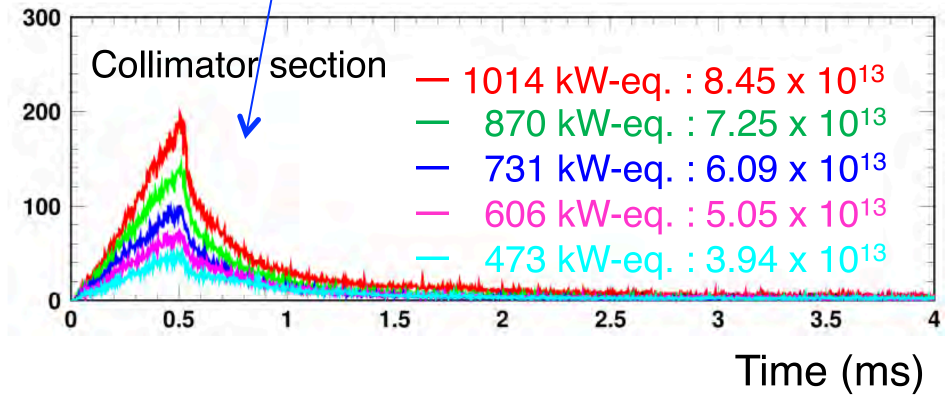
H. Hotchi

Demonstration of 1 MW-eq. beam in RCS

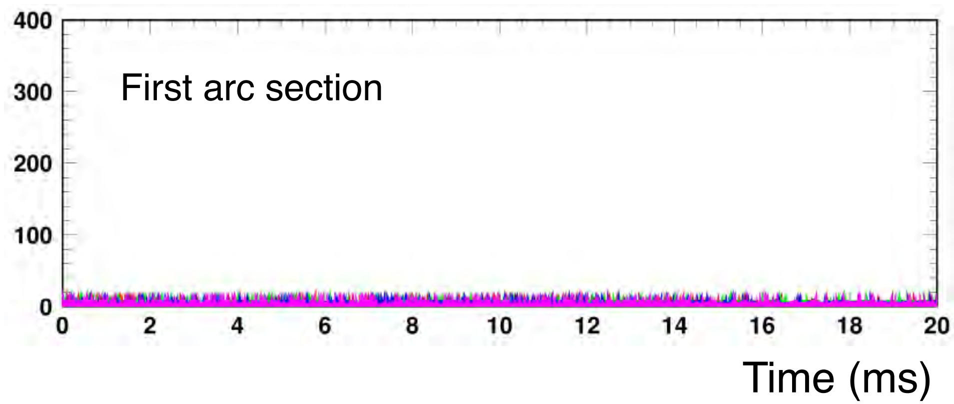


BLM signals @ collimator & arc sections

Mainly due foil scattering during injection

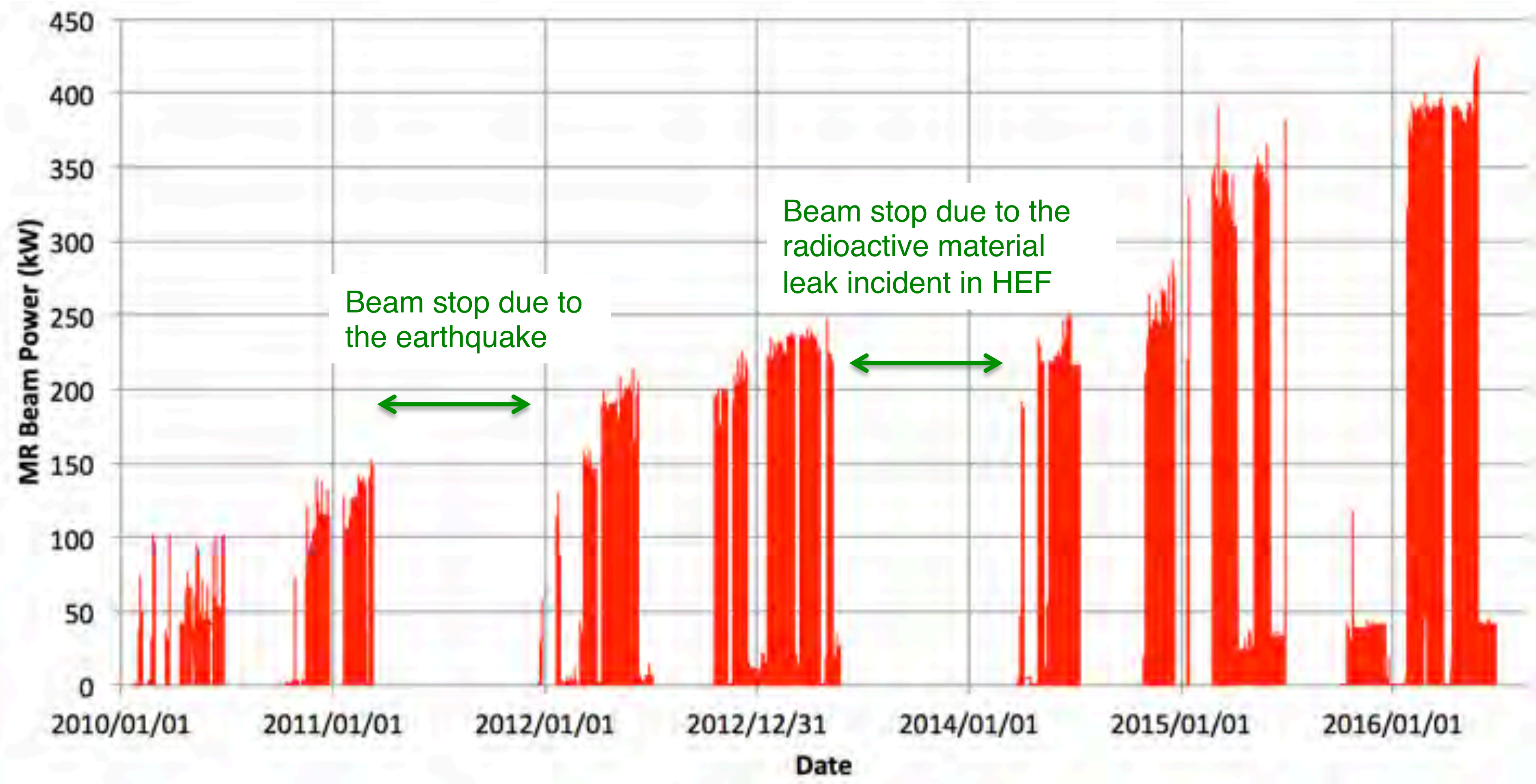


Beam loss < 0.1 % (< 133 W) << 4 kW collimator limit



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

Beam power history of MR

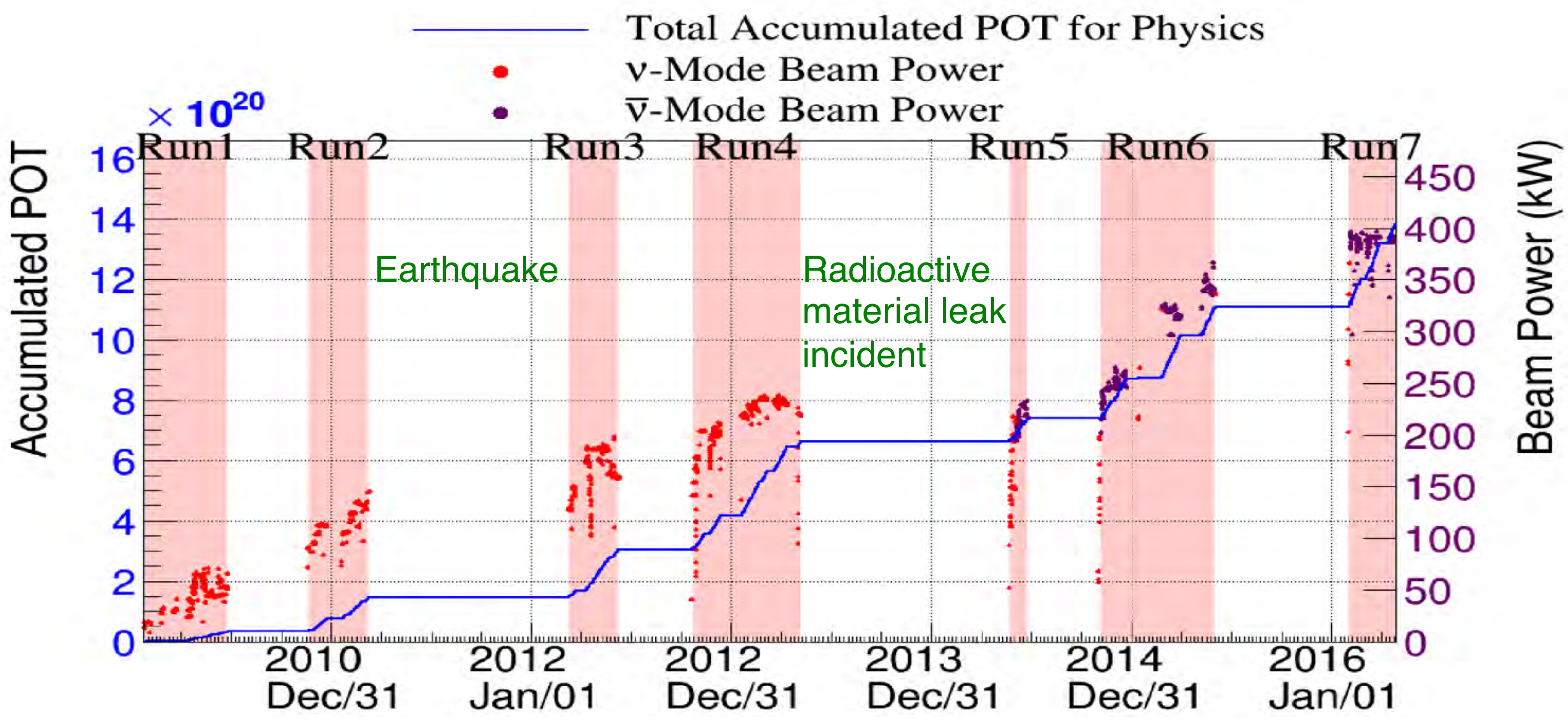


Max. delivered power:

Fast extraction ~ 425 kW (2.2×10^{14} ppp)

Slow extraction ~42 kW (4.9×10^{13} ppp)

POT neutrino



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

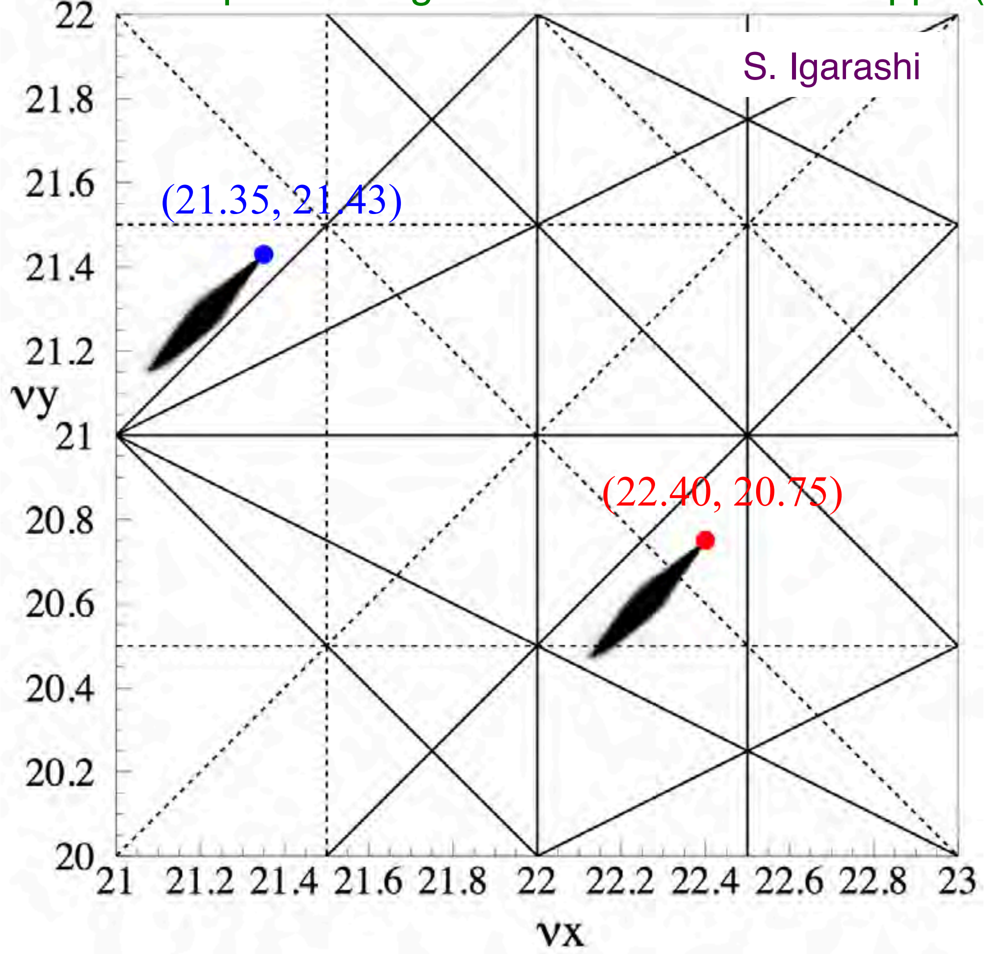
The latest results of T2K will be presented on Saturday in this conference.

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)

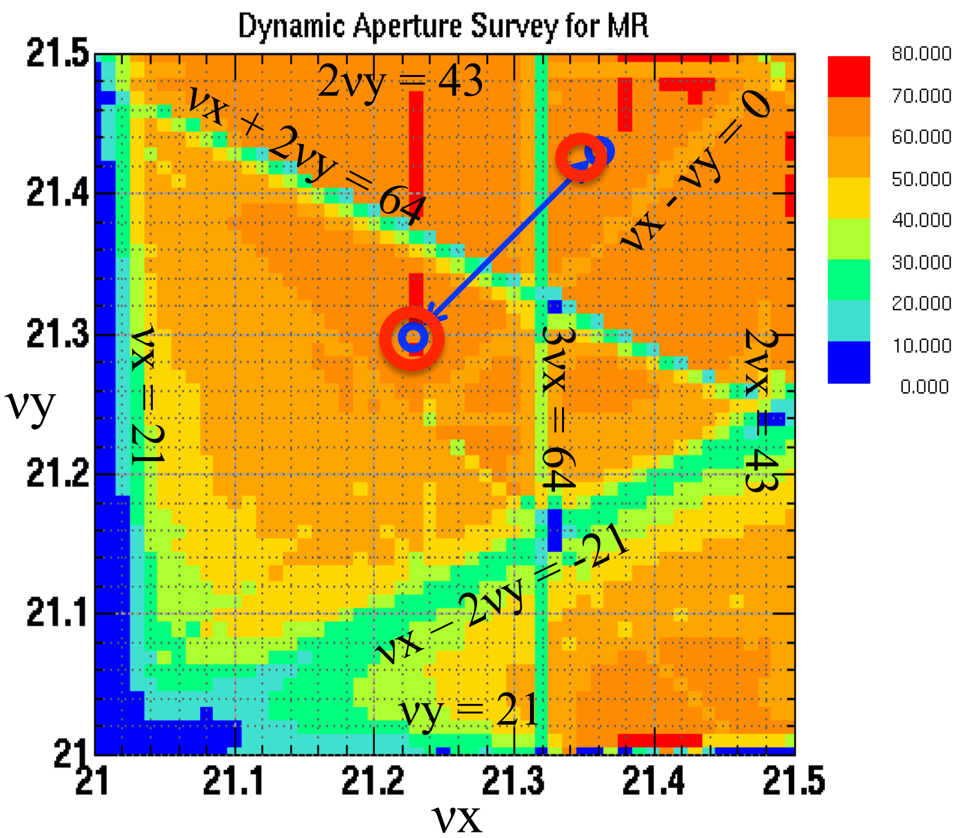
> 400 kW
New tune (21.35, 21.43) is adopted

Optimization for (21.x, 21.x)

S. Igarashi

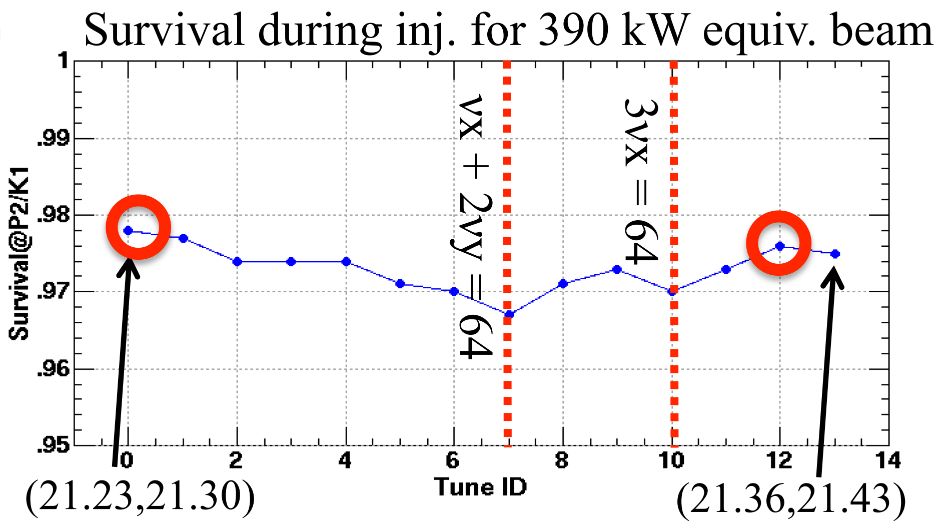
Dynamic aperture survey simulation

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



Measured beam survival at 3 GeV

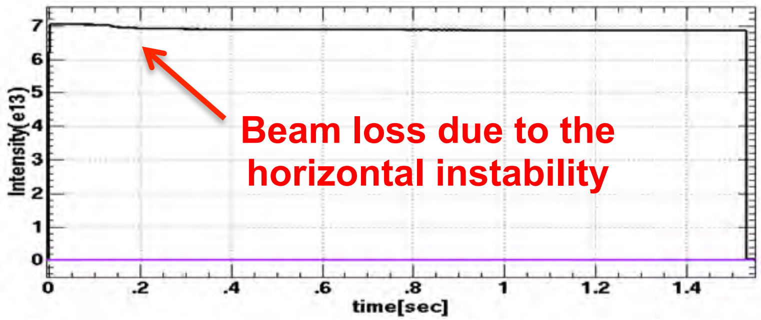
with beta and dispersion function corrections
- 2nd rf voltage
- 3rd order resonance correction
- skew Q correction for vx – vy = 0
- Instability suppression
  - Chromaticity: –7
  - Bunch by bunch and intra-bunch FB



High Intensity beam study

- at the new betatron tune (21.239, 21.310) -

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

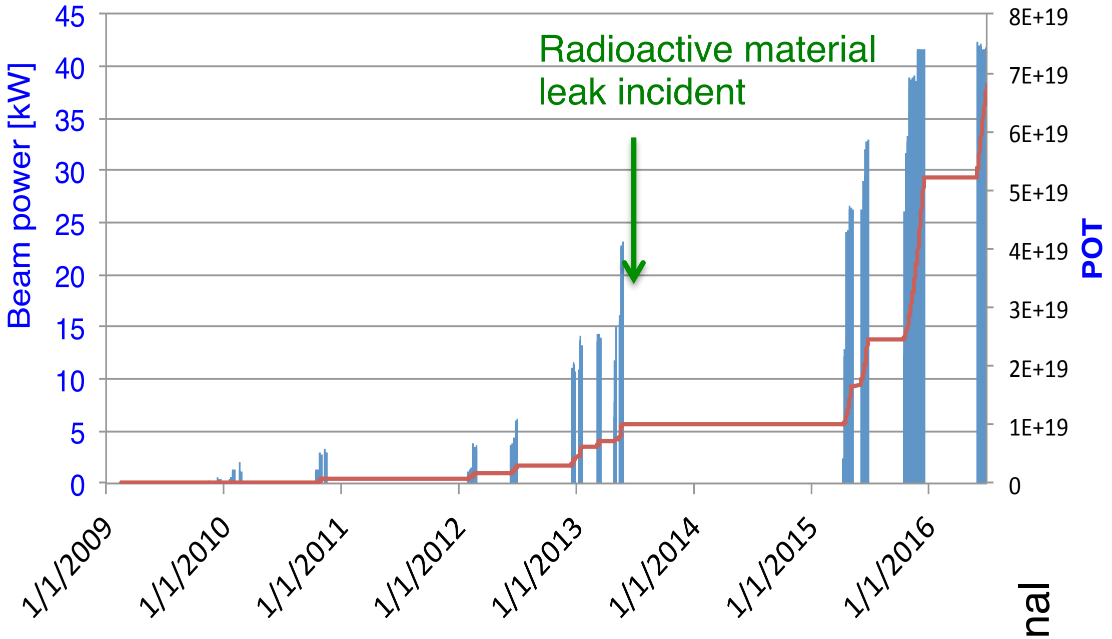
Near future tunable knobs to reduce the beam loss:
Injection kicker, BxB feed-back,
2nd harmonic cavity, VHF cavity, etc.

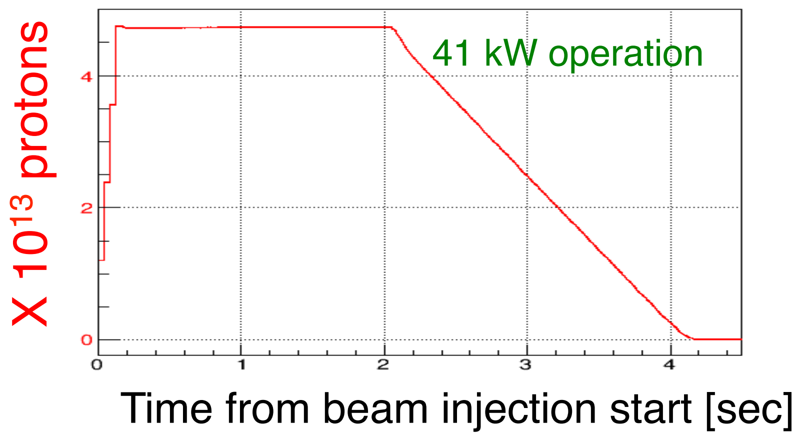
	Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2	2.48	132	0.42	measurement
2	8	2.48	529	1.7	estimation
3	8	1.3	1009	3.2	estimation

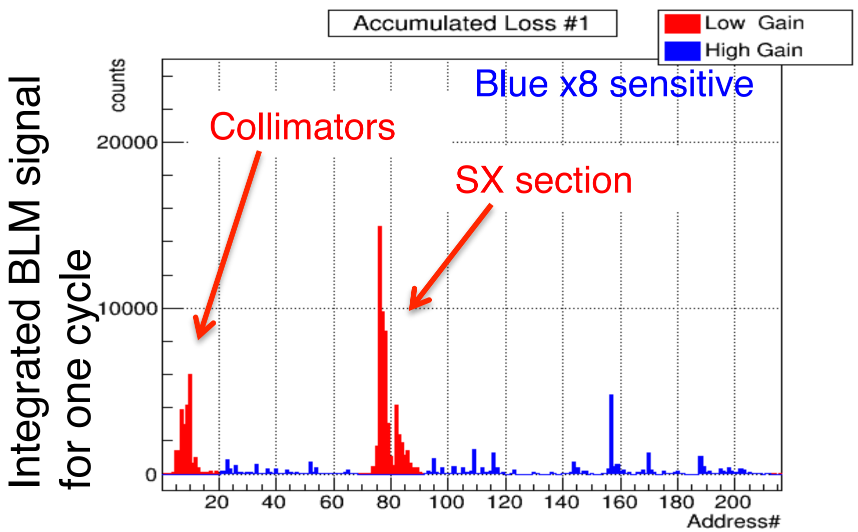
The MR has capability to reach 1MW with the high repetition rate operation.

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







Extraction efficiency ~99.5%

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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.

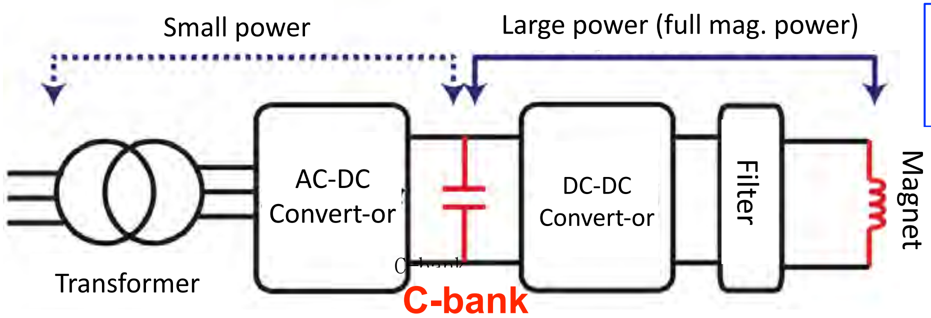
SX: The beam power of the MR will be gradually increased toward 100 kW watching the residual activity. In the HEF, the primary target will be replaced new ones which have more cooling capability in 2018 and 2021.

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 **2nd harmonic rf system**	Installation Manufacture, installation/test						
Ring collimators	Add.collimators (2 kW)		Add.colli. (3.5kW)				
Injection system **FX system**	Kicker PS improvement, Septa manufacture /test 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

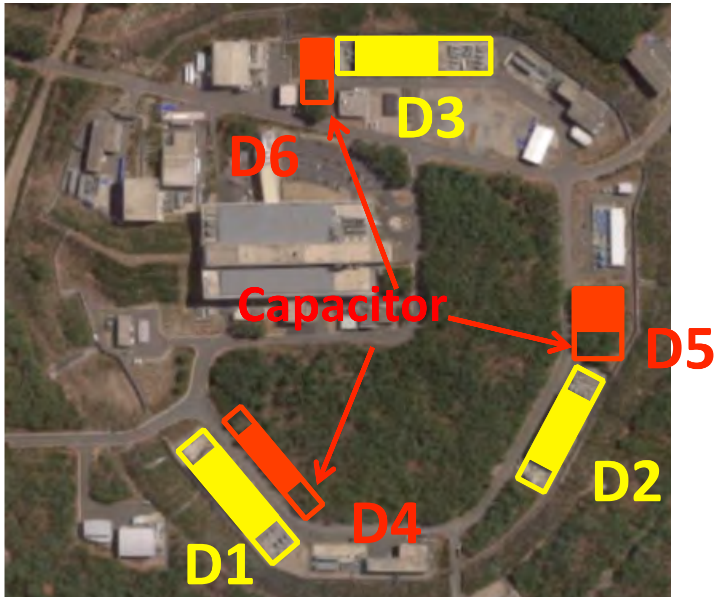
New power supply for high repetition rate operation

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

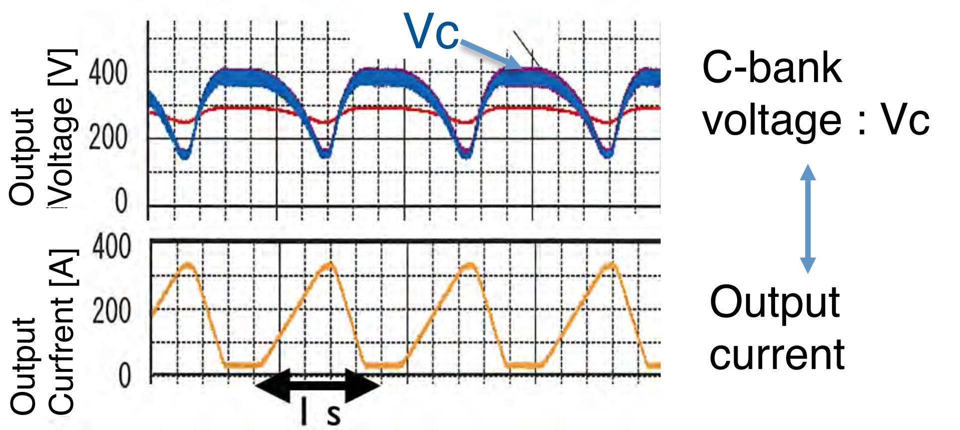


Two large converters and large capacitance for energy recovery, symmetric power module circuit

D1-3: existing buildings
D4-6: Newly constructed buildings



Results of prototype PS



Power recovery by C-bank

Y. Kurimoto

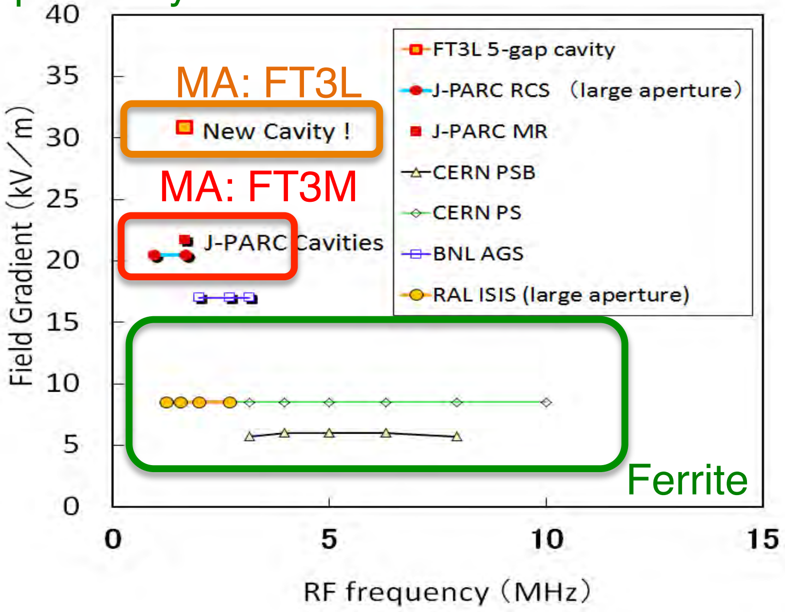
Budget for three buildings of the magnet PS's and for starting mass production of the PS's have been approved by the government in JFY2016.

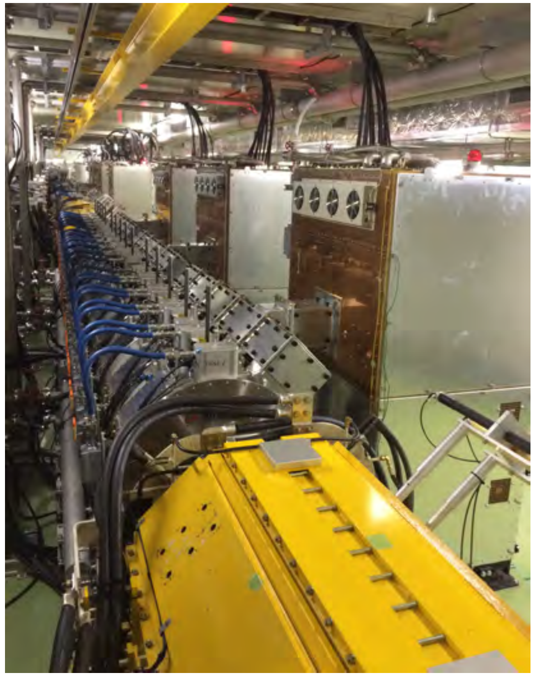
The 1st quadrupole PS will be transferred to J-PARC and tested in the 2016 summer shutdown period. Construction of the three buildings will be finished in August of 2017.

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.





	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*

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)

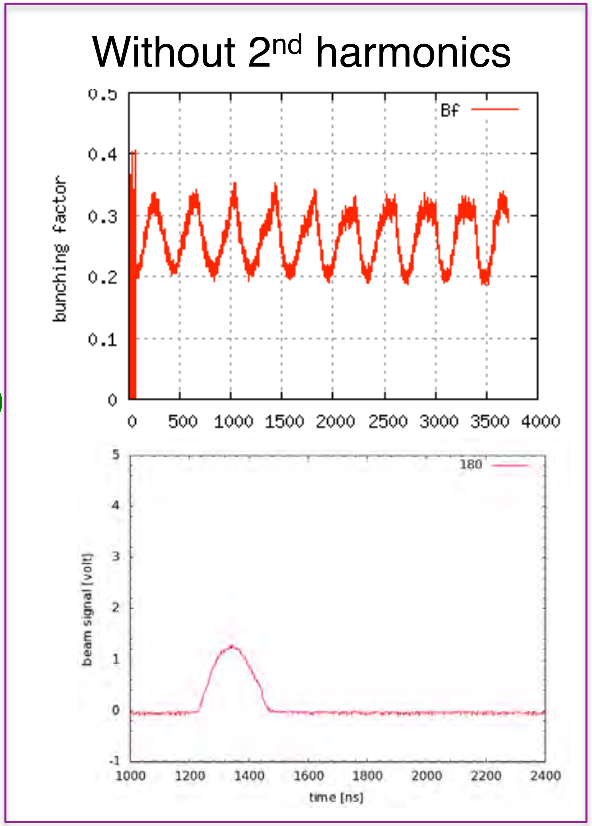
BPM upgrade

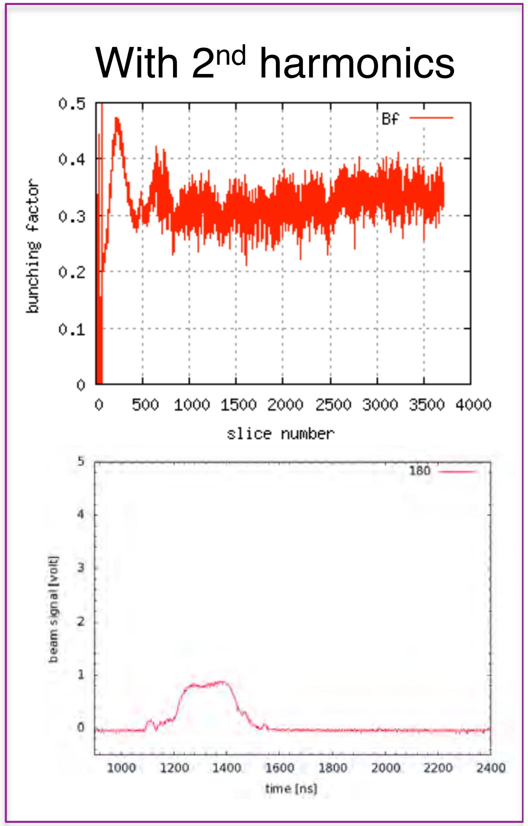
- more precise and faster measurement.

FX kicker upgrade

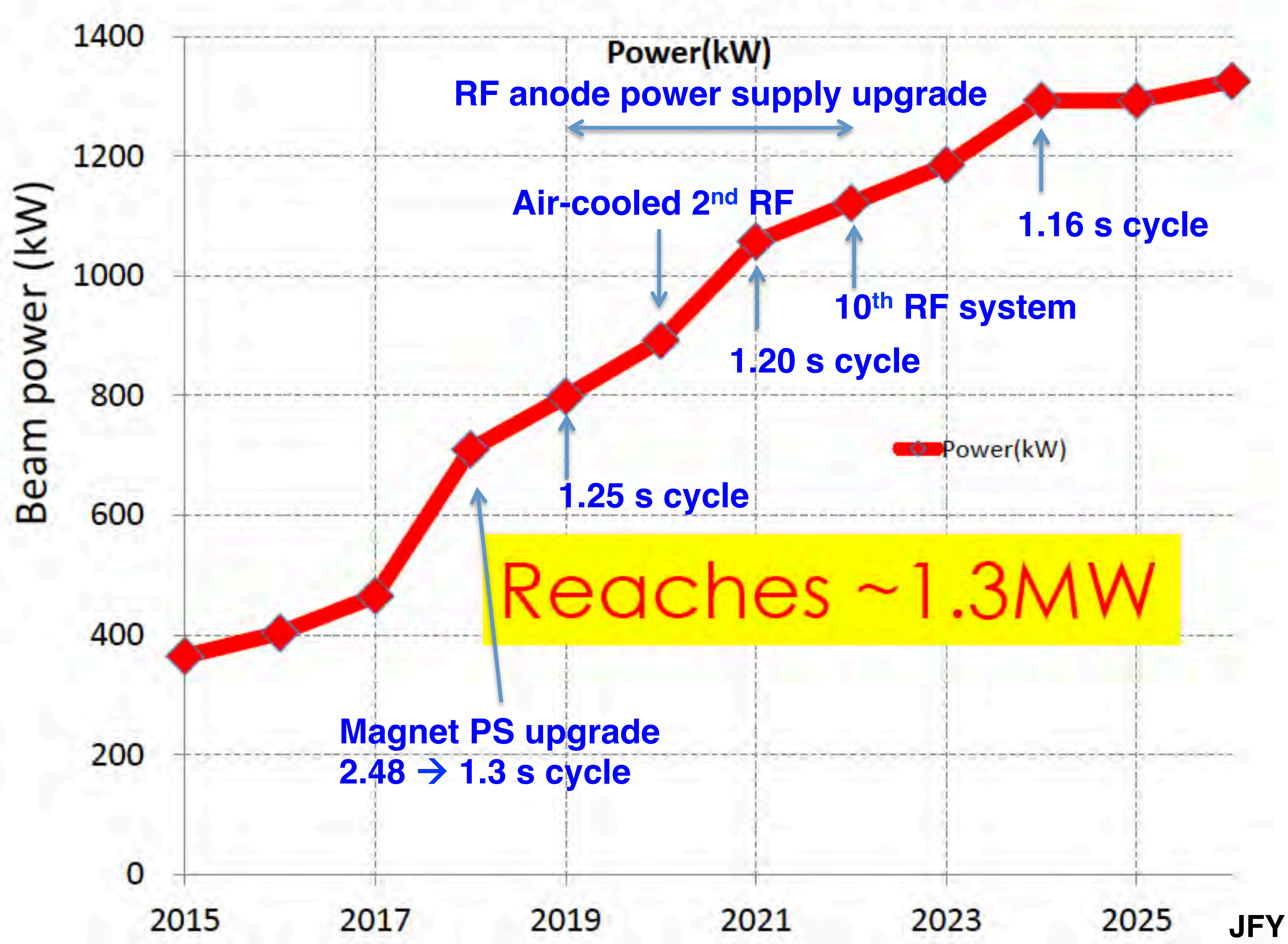
- Low beam coupling impedance

Measured bunching factor and longitudinal distribution of 3.2×10^{13} ppb (~1 MW for 1.3 s cycle)





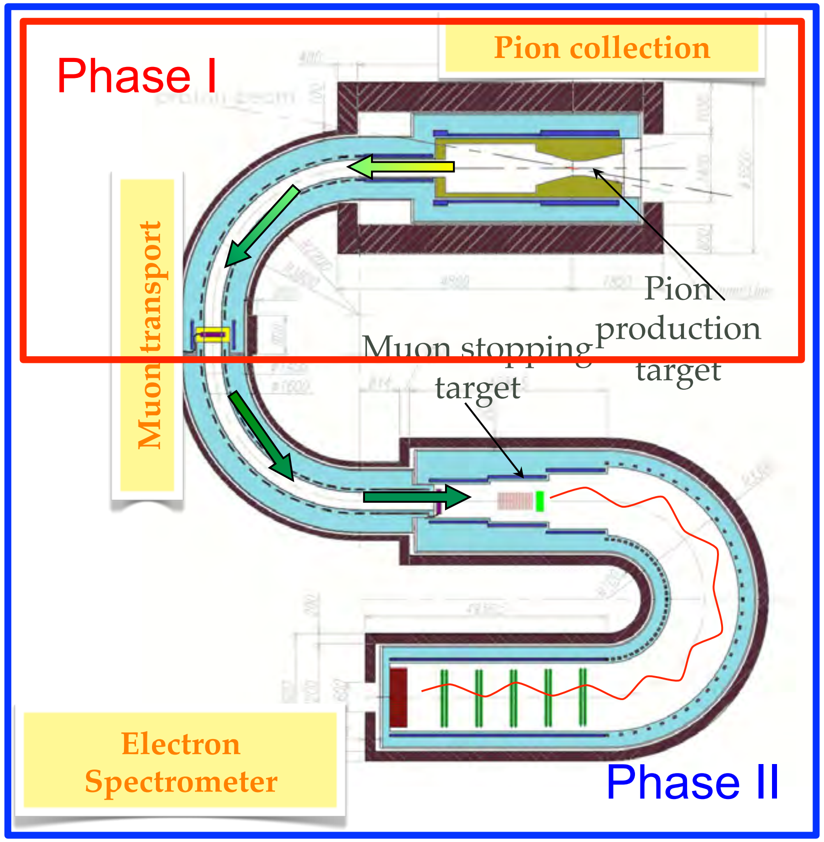
Beam power projection



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

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

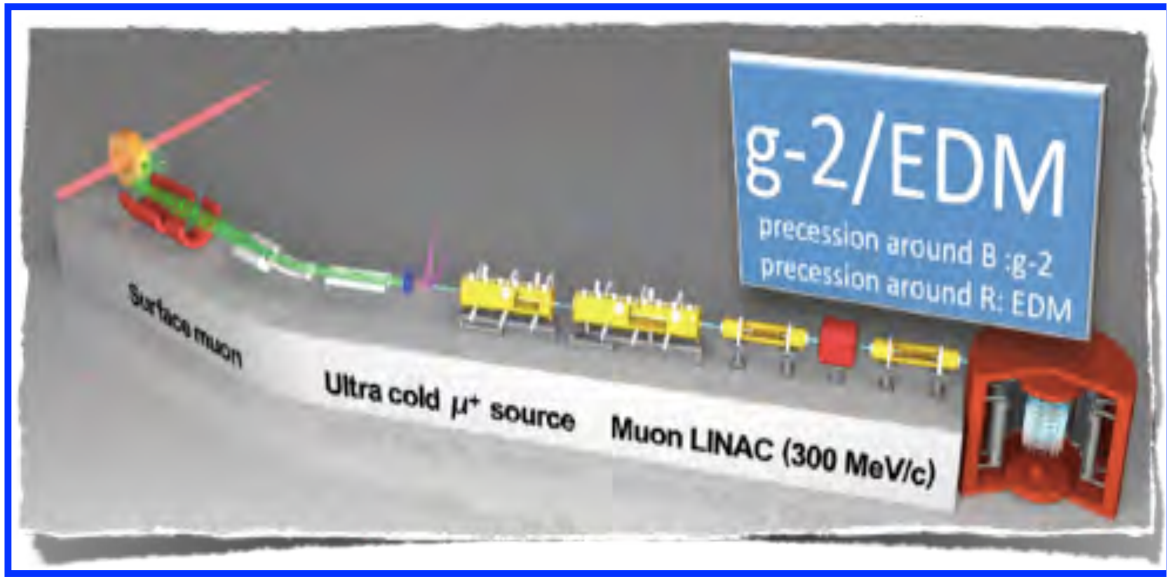
- 32 m SC solenoid magnet
- Beam extinction < 10^{-9}
- 8 GeV, 3.2 kW(Phase-I) and 56 kW(Phase-II)



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



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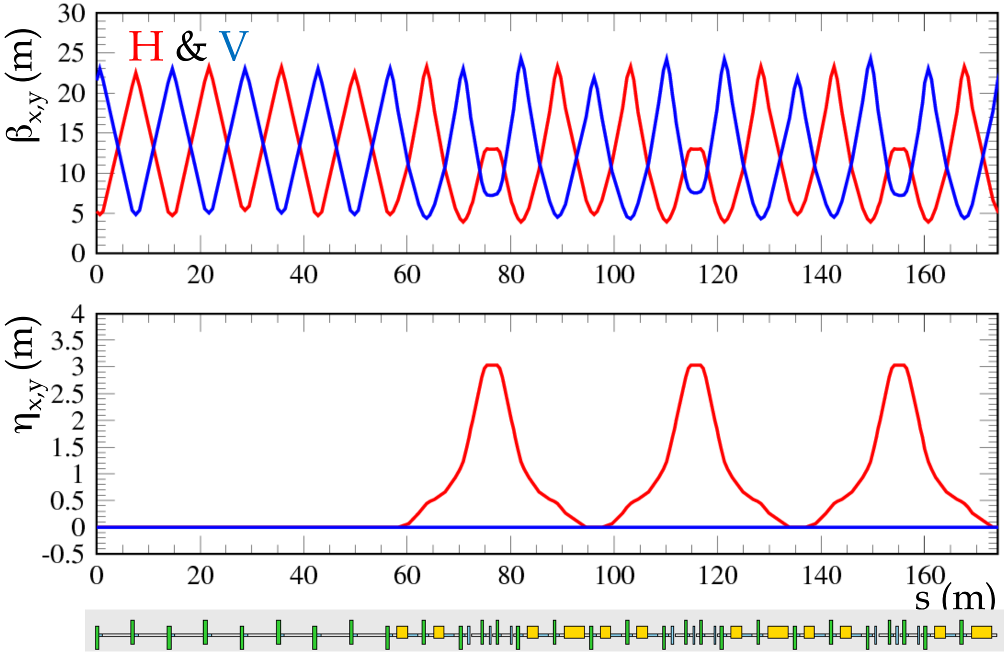
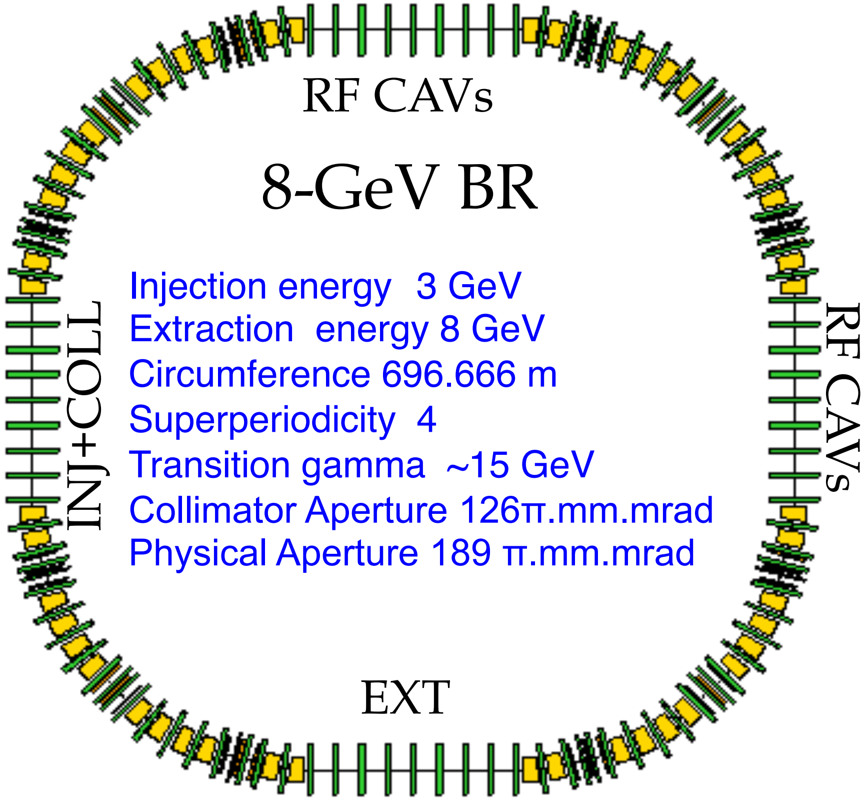
The 8-GeV booster ring

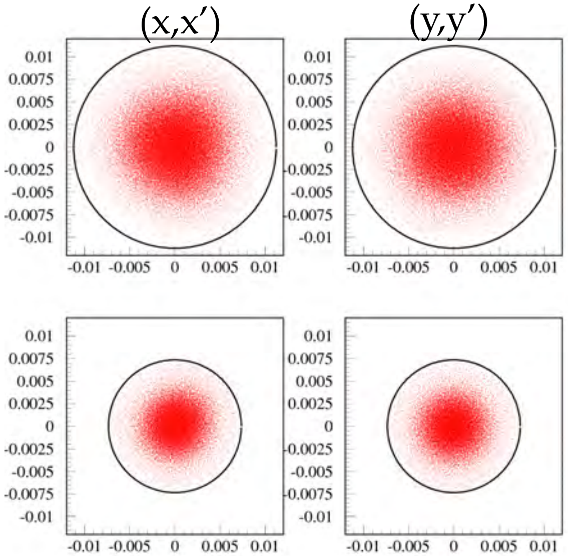
Beta & Dispersion for 1-superperiod





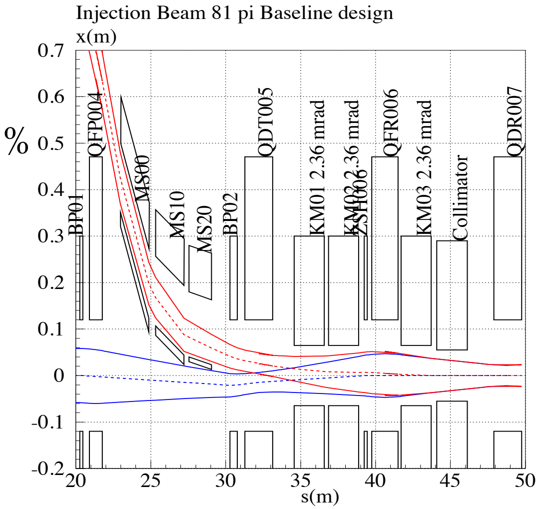
Injection energy 3 GeV
Extraction energy 8 GeV
Circumference 696.666 m
Superperiodicity 4
Transition gamma ~15 GeV
Collimator Aperture 126π.mm.mrad
Physical Aperture 189 π.mm.mrad

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

The proton driver in the KEKB Tunnel

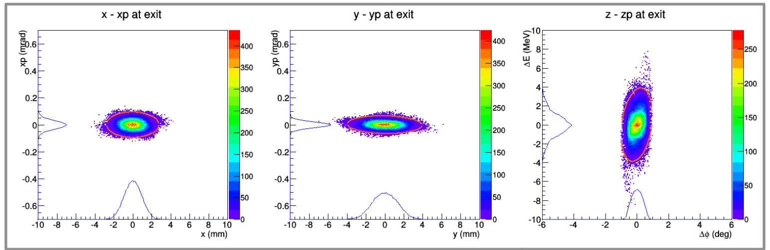
For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.

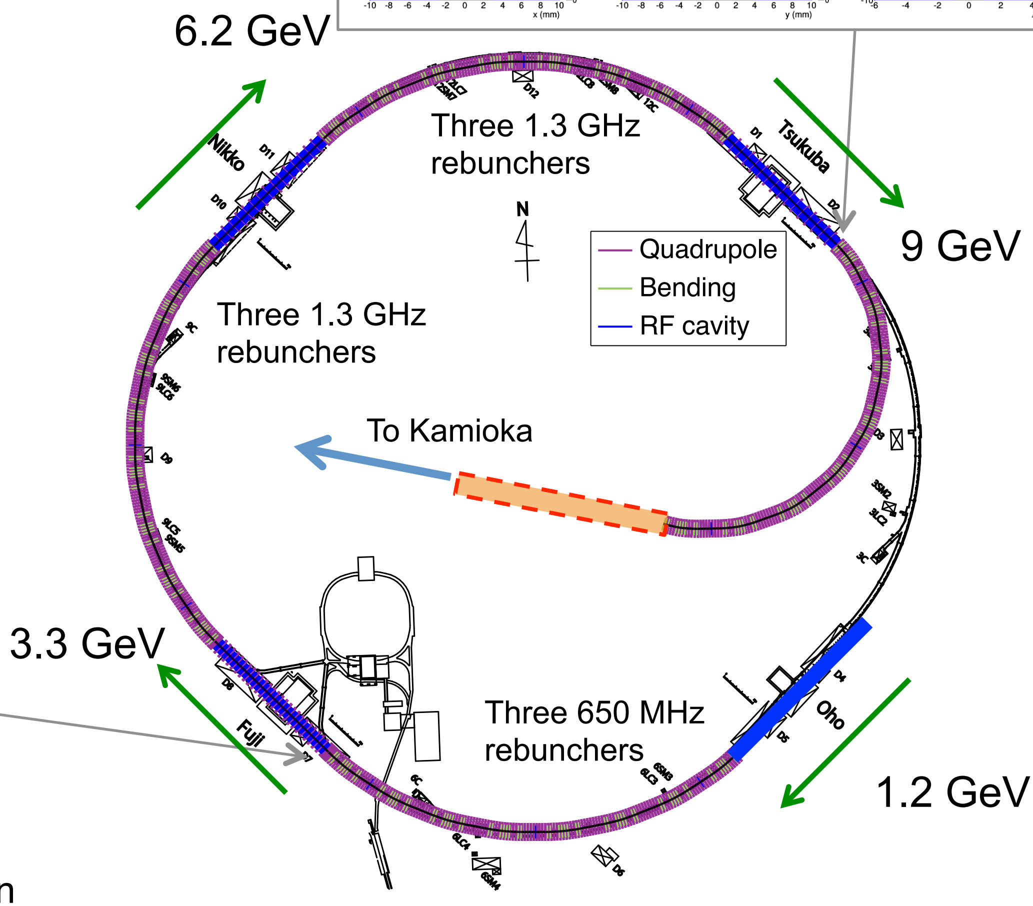
- Outline of acceleration :
    - 1.2 GeV in 1st straight.
    - 3.3 GeV in 2nd straight.
    - 2.9 GeV in 3rd and 4th straight.

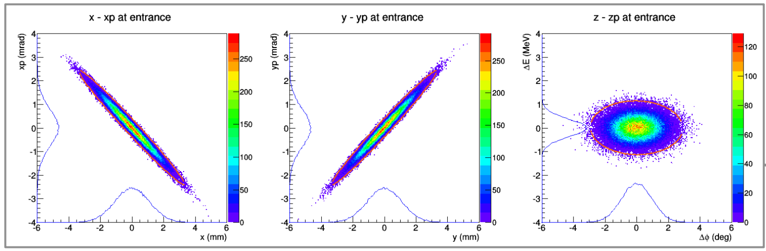
      3.3 + 2.9 x 2 = **9.0 GeV**

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

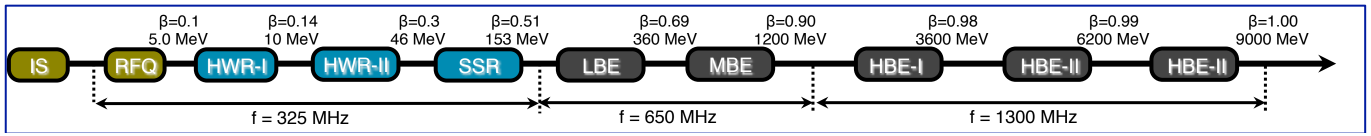
9 GeV x 0.1 A x 1 % = **9 MW**







Layout of front-end and the 1st straight section



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)

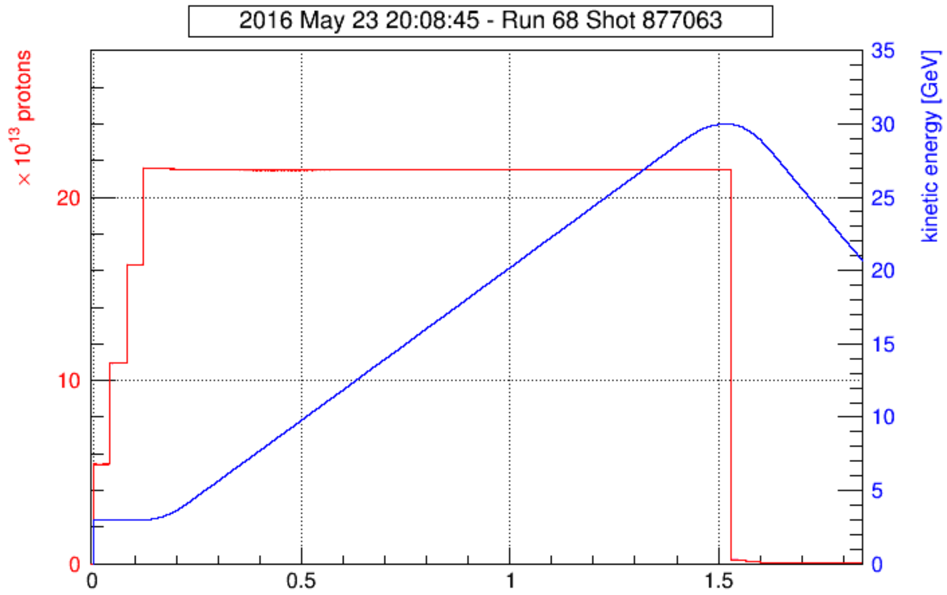
Long-term plan :

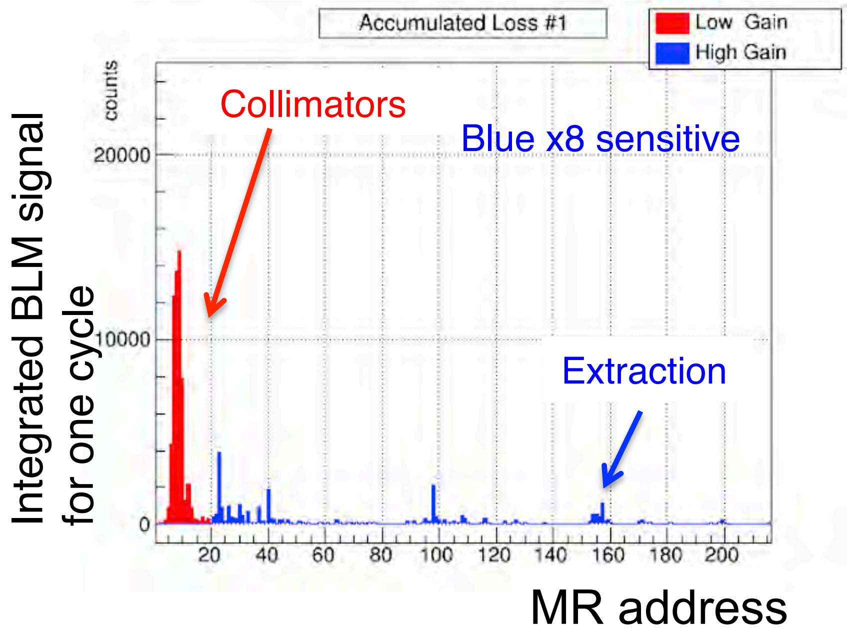
- Some scenarios to achieve beam power beyond current design for neutrino experiment are now under discussion; the 8 GeV booster, 9 GeV linac.

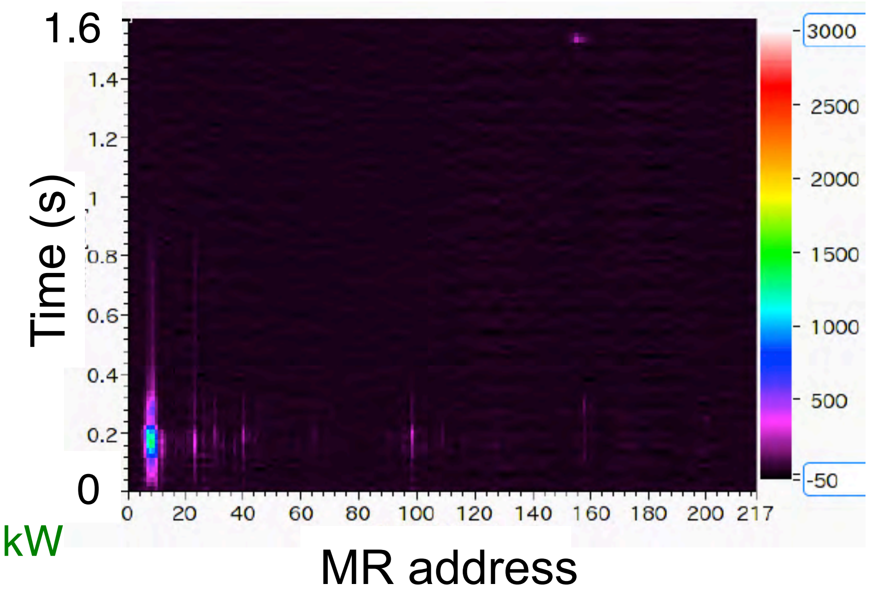
backup

Typical user operation of FX

- at (21.35,21.43) -





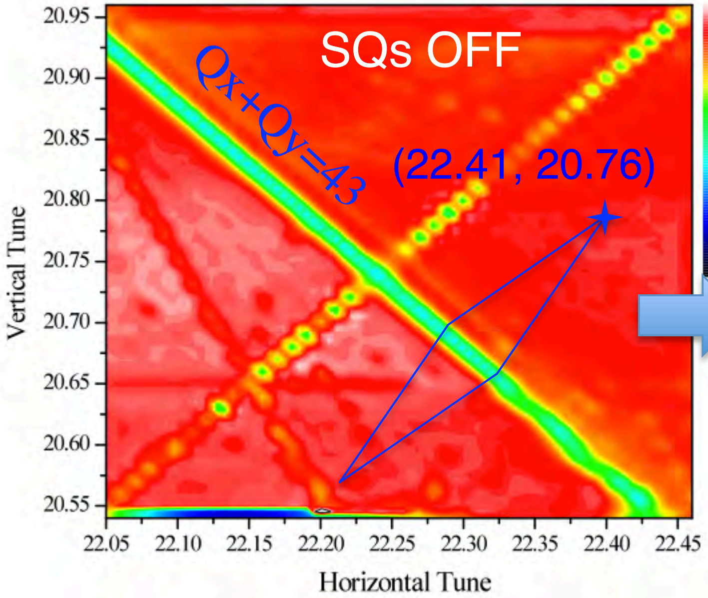


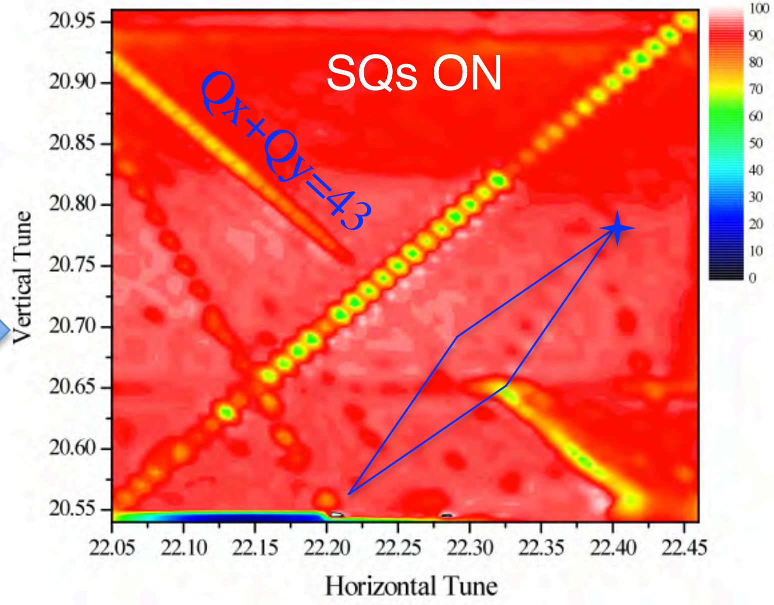
Power : 416 kW @ 2.48 sec
2.7e13 ppb × 8 @ Injection
2.15e14 ppp @ end of acceleration
Loss during the injection period : 170 W
Loss in the beginning of acceleration (0.12 s) : 417 W

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

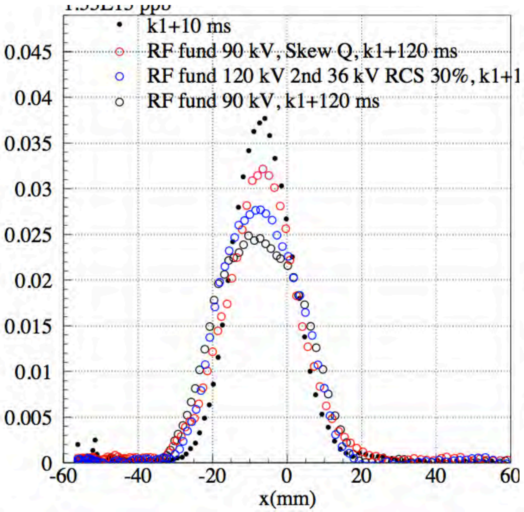
Resonance correction

Correction of linear coupling resonance with skew quadrupoles

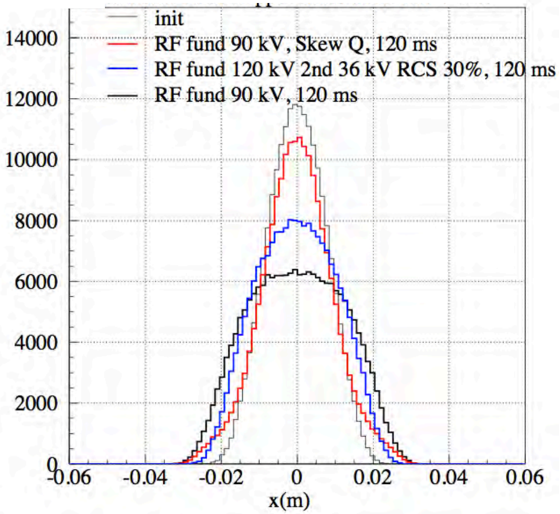




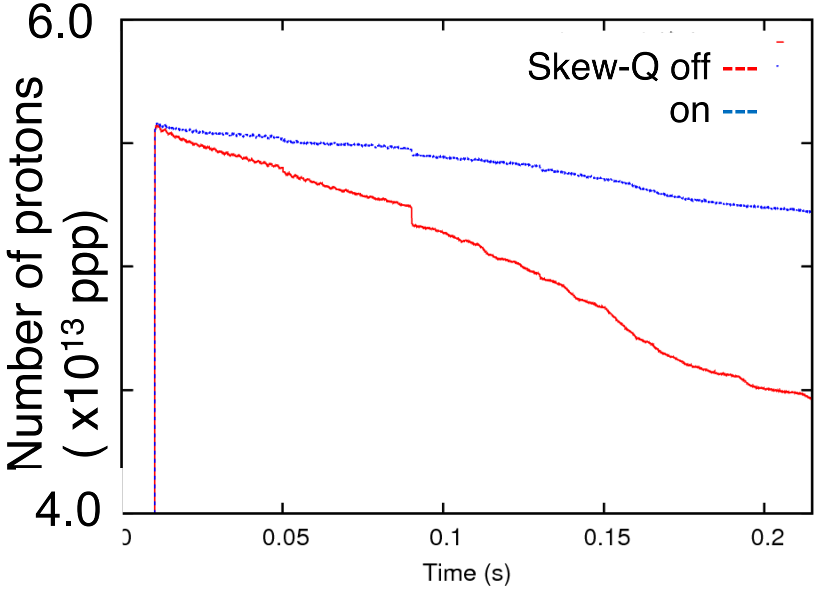
Hor. profile measured by FWPM



Simulation



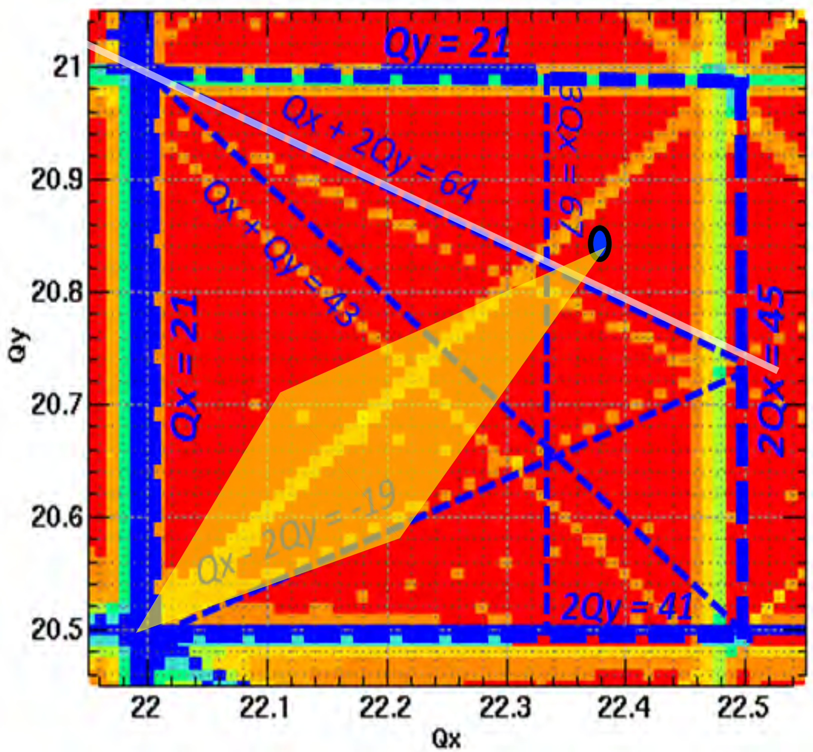
Beam survival for two bunches at 3 GeV

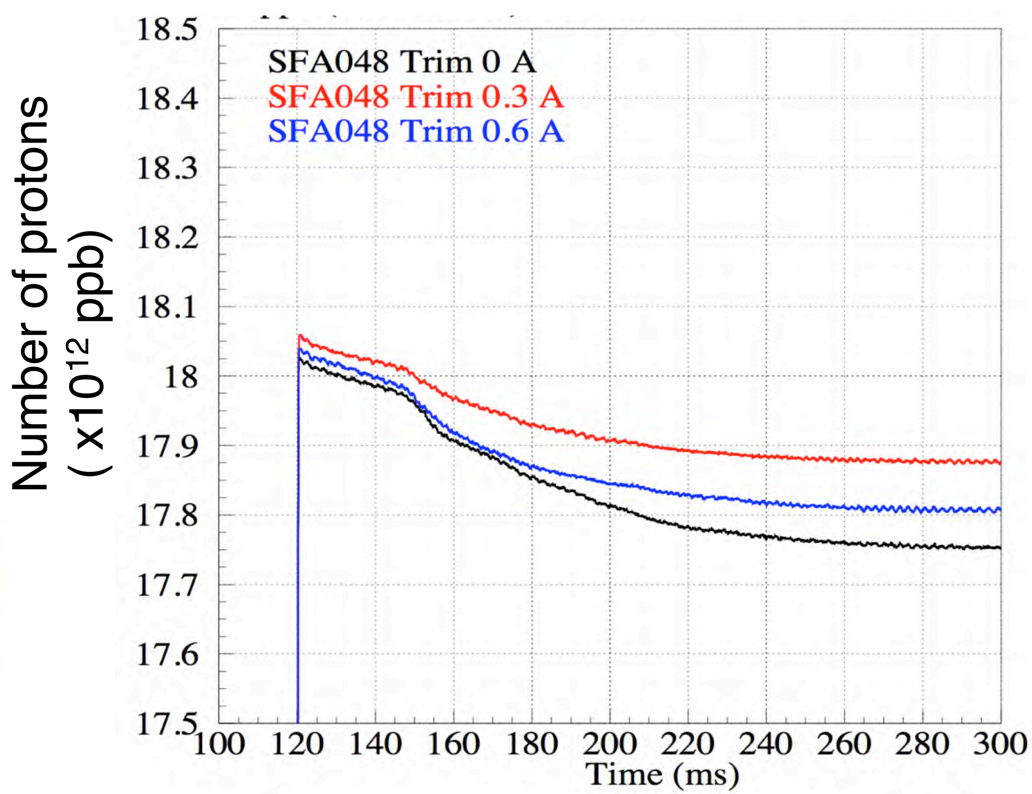


The simulation well reproduces the data.

Resonance correction (cont'd)

Correction of third-order resonances with trim sextupoles





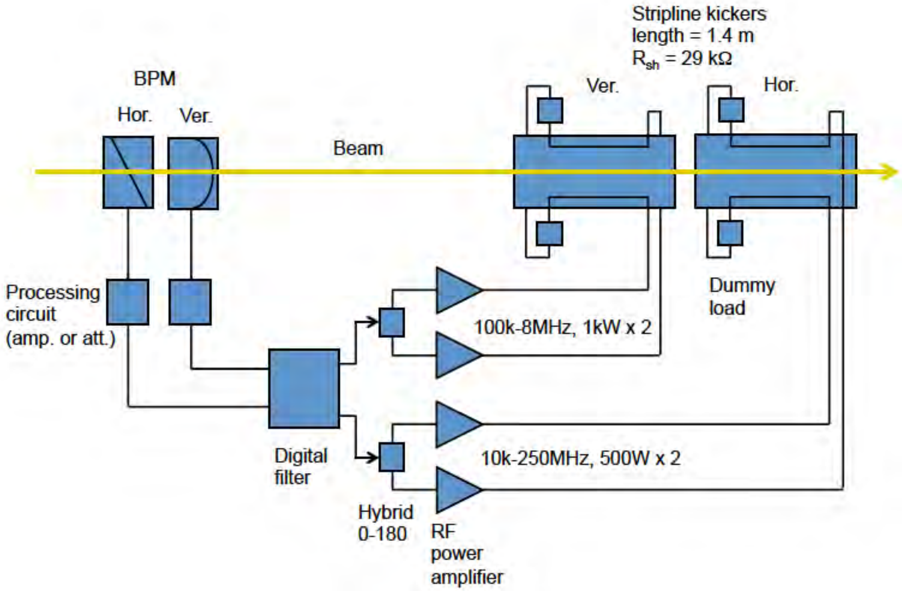
All sextupoles have auxiliary (trim) coils .
Trim-SFA048 set to be 0.3 A to correct Qx+2Qy=64

Suppression of beam instabilities

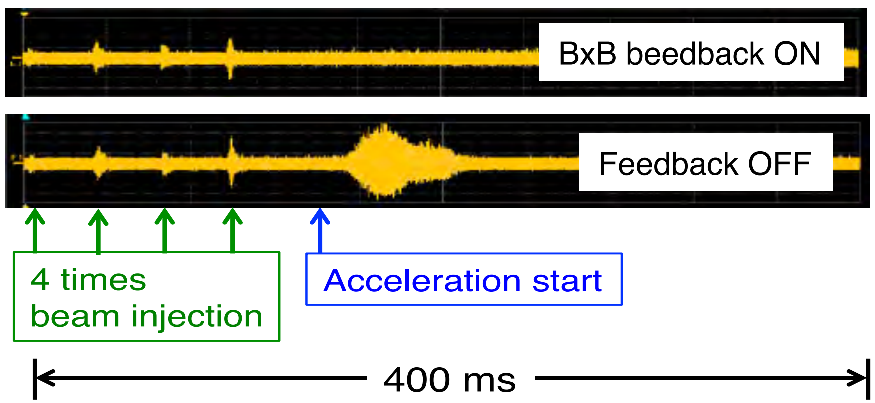
At high beam power operation, coupled-bunch instability and intra-bunch motion are observed .
To cure the instabilities, two approaches are adopted;

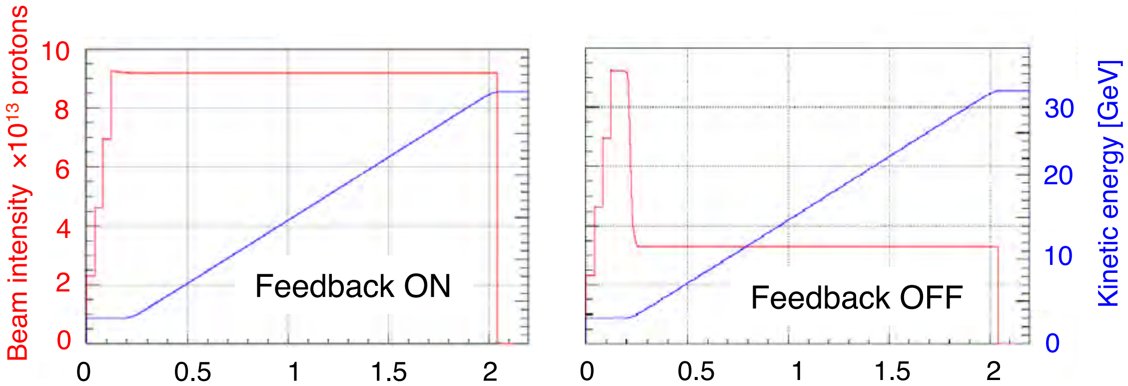
- optimization of chromaticity correction
- two bunch feedback systems, bunch−by−bunch (BXB) and intra-bunch feedback .

BXB feedback system



Delta signal of BPM (2.4e13 ppb)

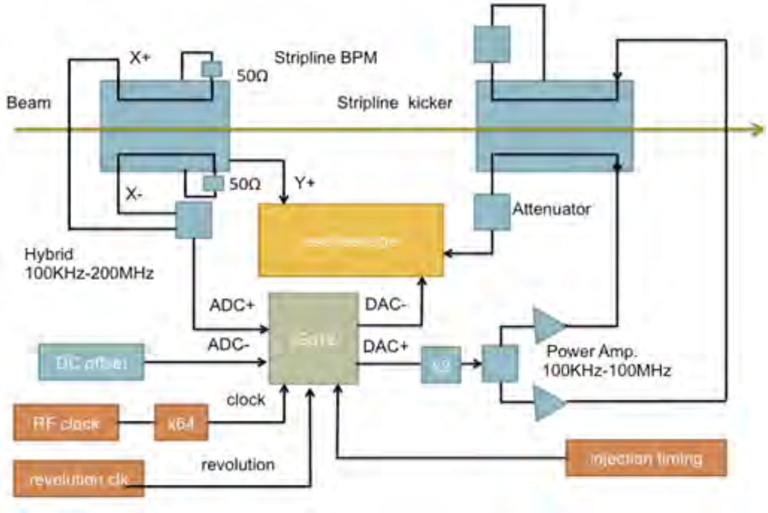




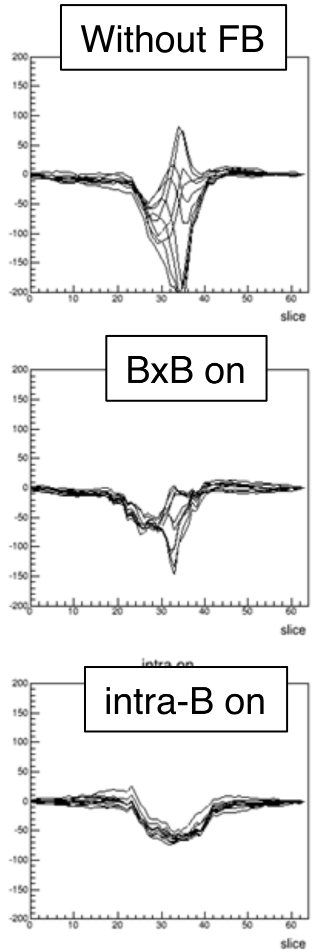
Intra-bunch feedback system (2014 ~)

At high power, intra-bunch motion was observed and it limits beam power around 300kW.

→ Intra-bunch FB system has been switched on since 2014.

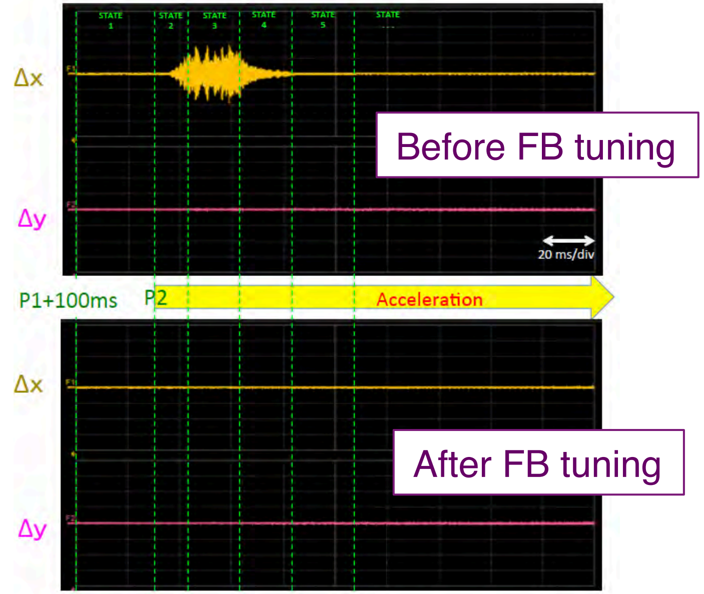


Bunch signal at 100 turns

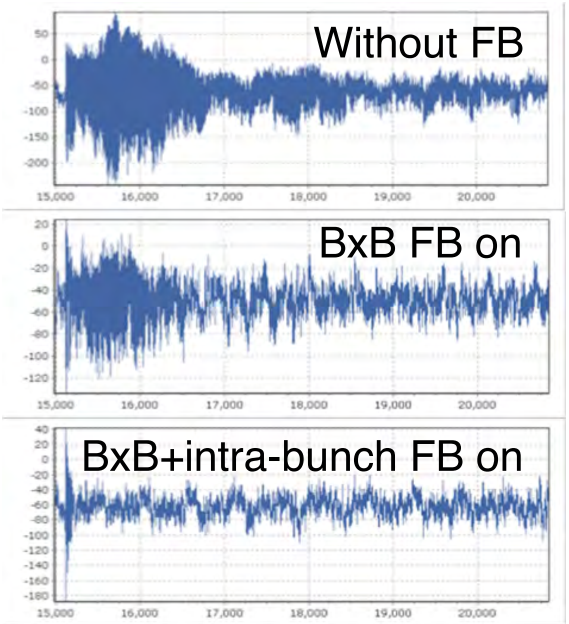


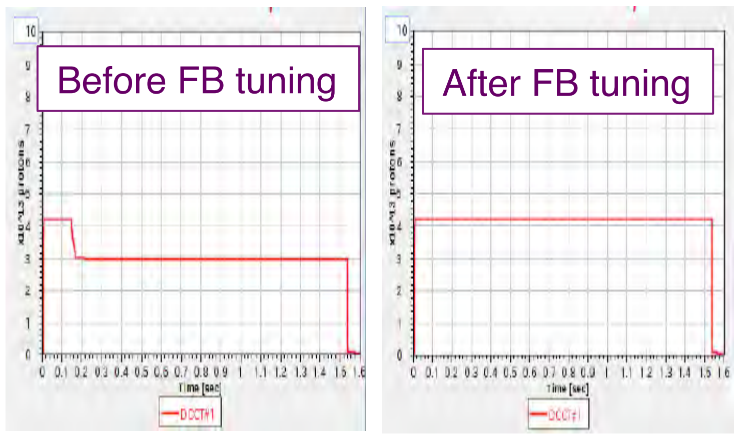
Delta signal of BPM (2.4e13 ppb)

ξ_x ~5.9, ξ_y ~5.2



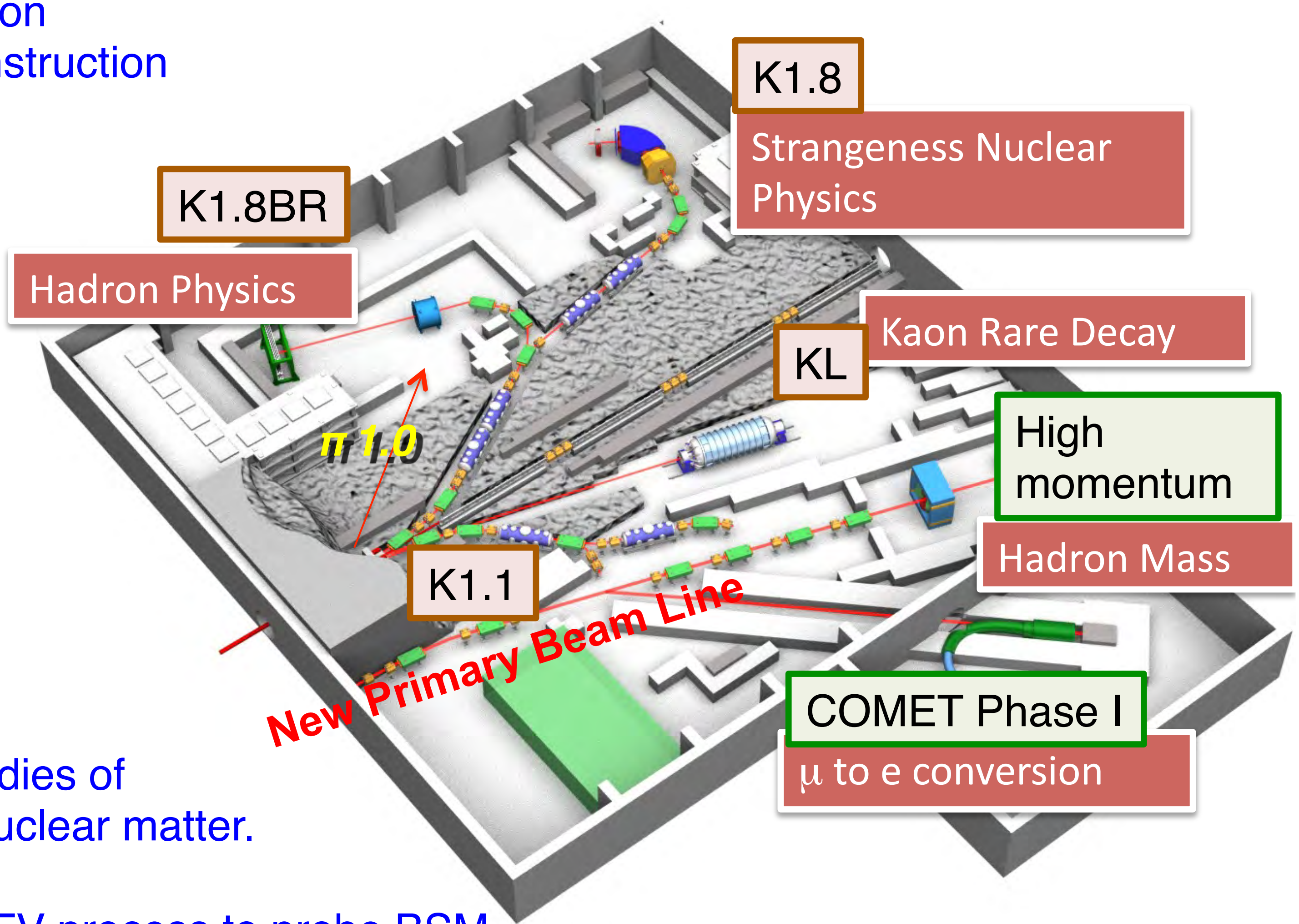
Oscillation of one bunch slice





Experiments at Hadron Experimental Facility

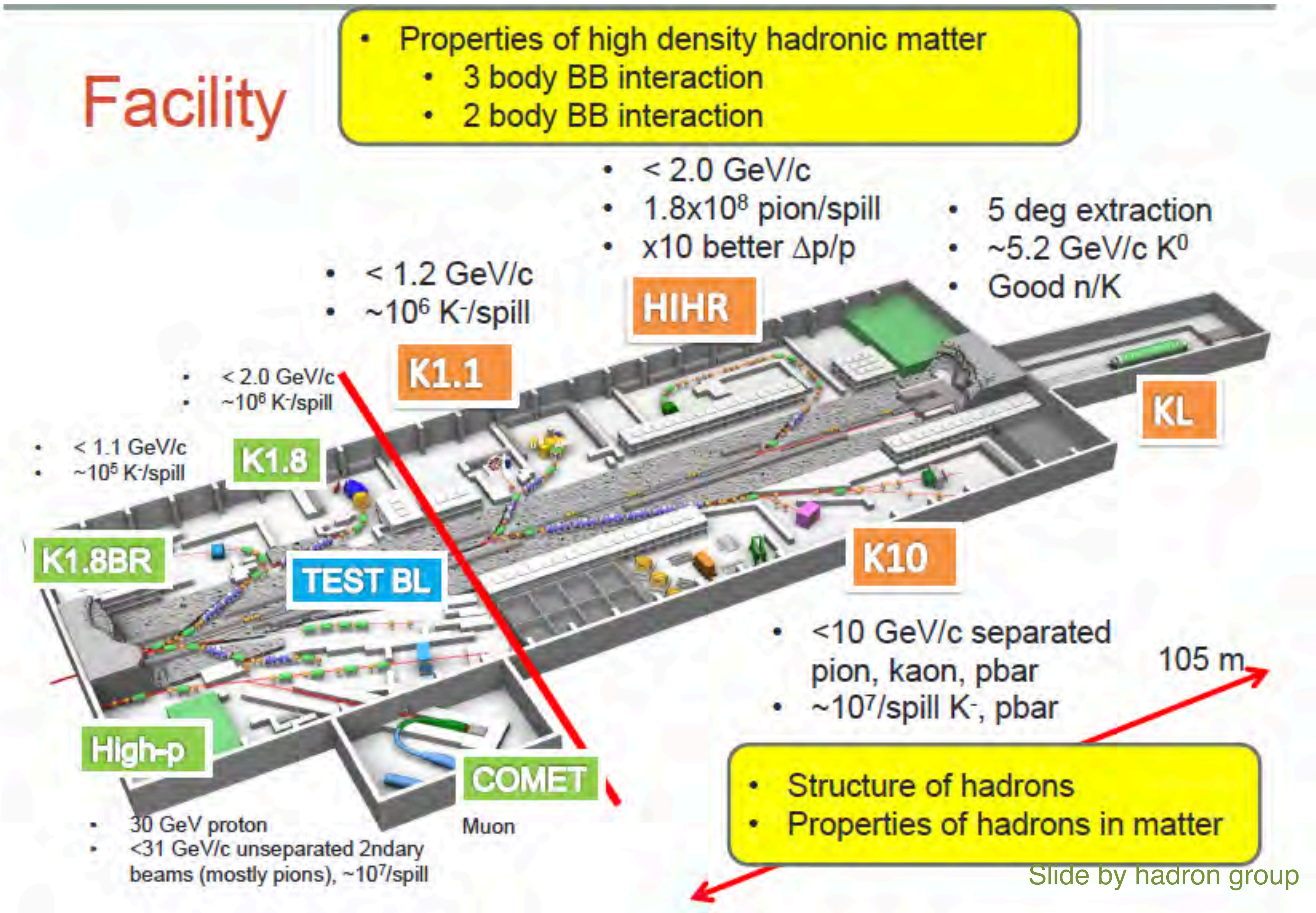
Four BLs : in operation
Two BLs : under construction



•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)
SX with 8-GeV beam will be studied in JFY2016.

Extension of Hadron Experimental Facility



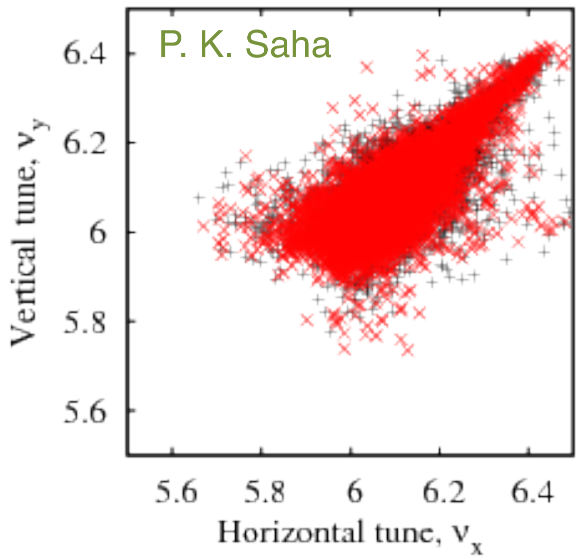
Slide by hadron group

Operation with beam intensity > 1MW in RCS

Beam power will be increased to 1 MW carefully watching beam loss and conditions of the MLF targets, and keeping high availability for users.

Laslett tune shift :
$$\Delta\nu_y = -\frac{N r_p F}{\pi\varepsilon_y\left(1+\sqrt{\frac{\varepsilon_x}{\varepsilon_y}}\right)\beta^2\gamma^3}\frac{1}{B_f}$$

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.

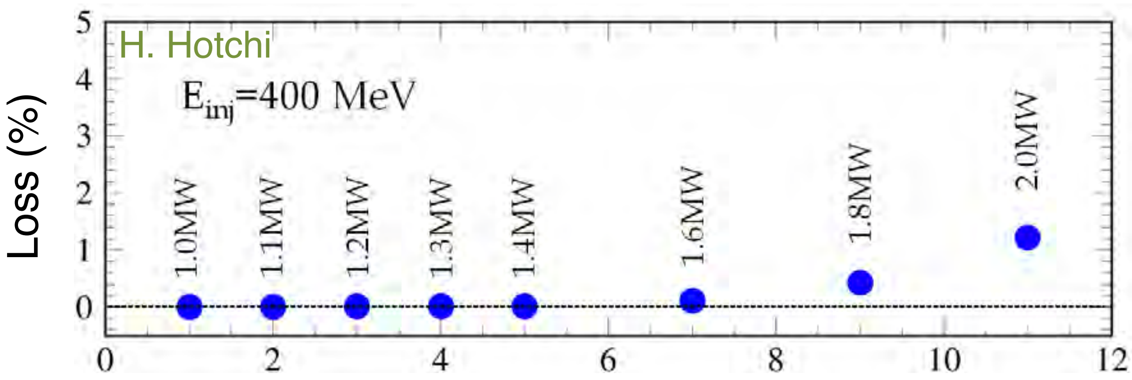
Beam intensity ~1.5 MW is a next goal in the mid-term.
- Second target station is also under discussion.

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.

Feasibility of the 2 MW operation in RCS



Collimator limit ~4 kW(1.5 % loss)

RCS has a feasibility to operate 2 MW.

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

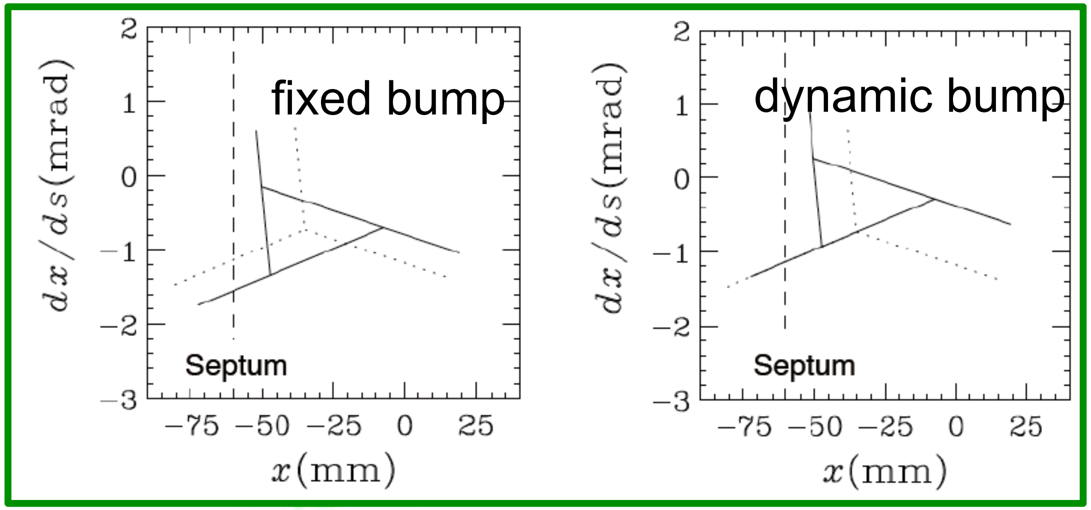
Issues to be solved for 2 MW beam power

- 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 ……

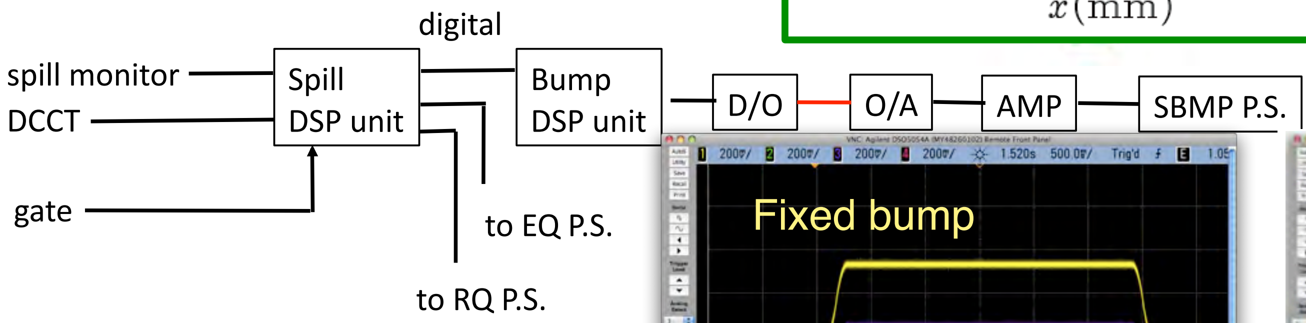
Slow extraction with dynamic bump system

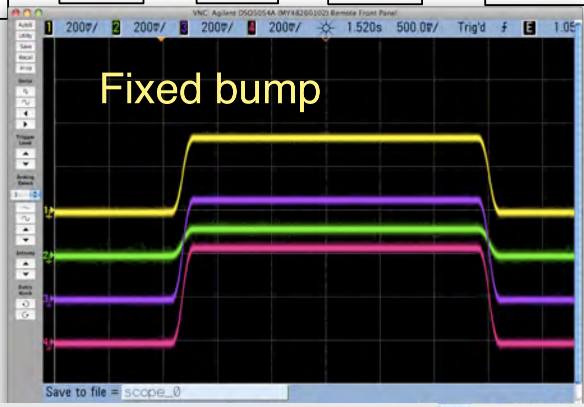
The center of the separatrix is adjusted to fix the beam angle at the ESS septum during the extraction
→ Reduce beam impact rate on septum.

Separatrices at the ESS



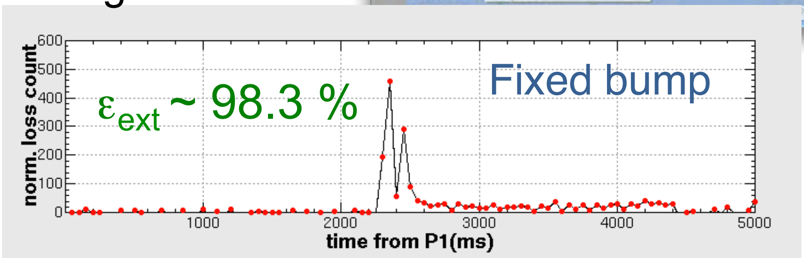
Dynamic bump system

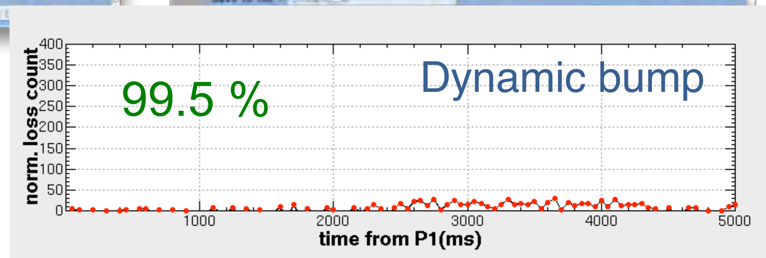




Beam loss at SX region

4e12ppp

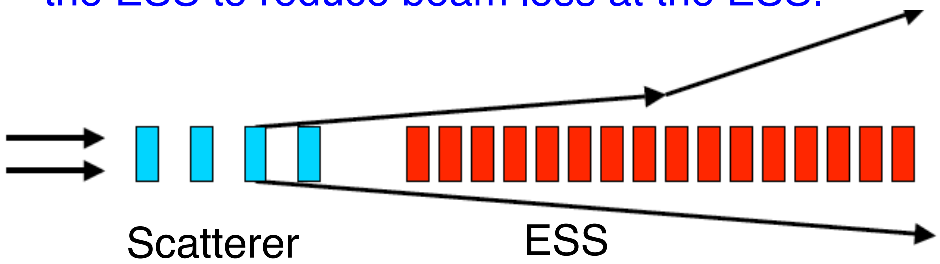


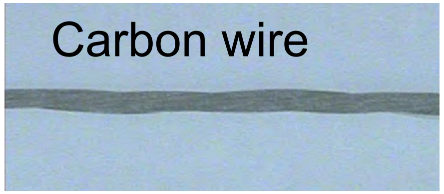


Slow extraction with beam power >> 100 kW

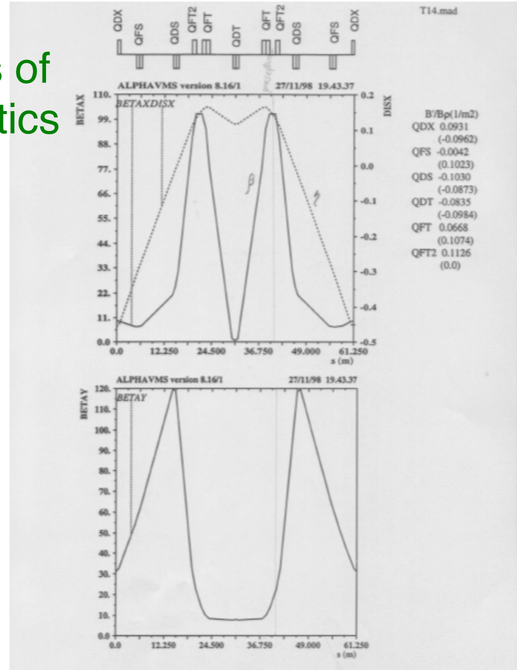
Feasibility for low-loss SX system
to reduce beam loss on the electrostatic septum (ESS) :

- 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.





Examples of high-β optics

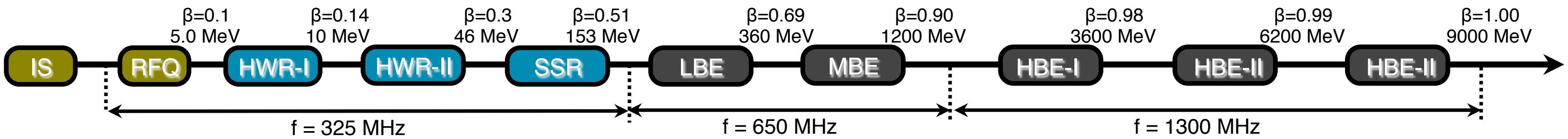


High voltage test of carbon wire ribbon

Present Design Parameters

T. Maruta and Gunn Tae Park

Baseline layout



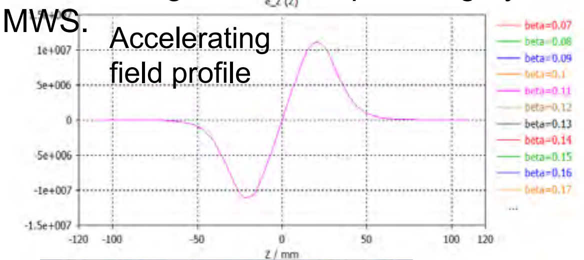
Accelerating cavity parameter

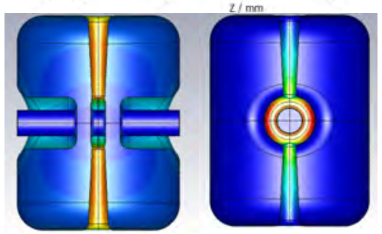
ILC cavities

	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.



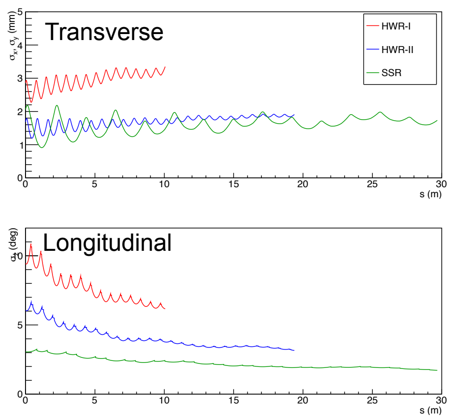


Electro-magnetic field strength

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