"Beam Dynamics meets Diagnostics" Workshop
4 November 2015, Florence, Italy.

Experience of beam commissioning of J-PARC MR

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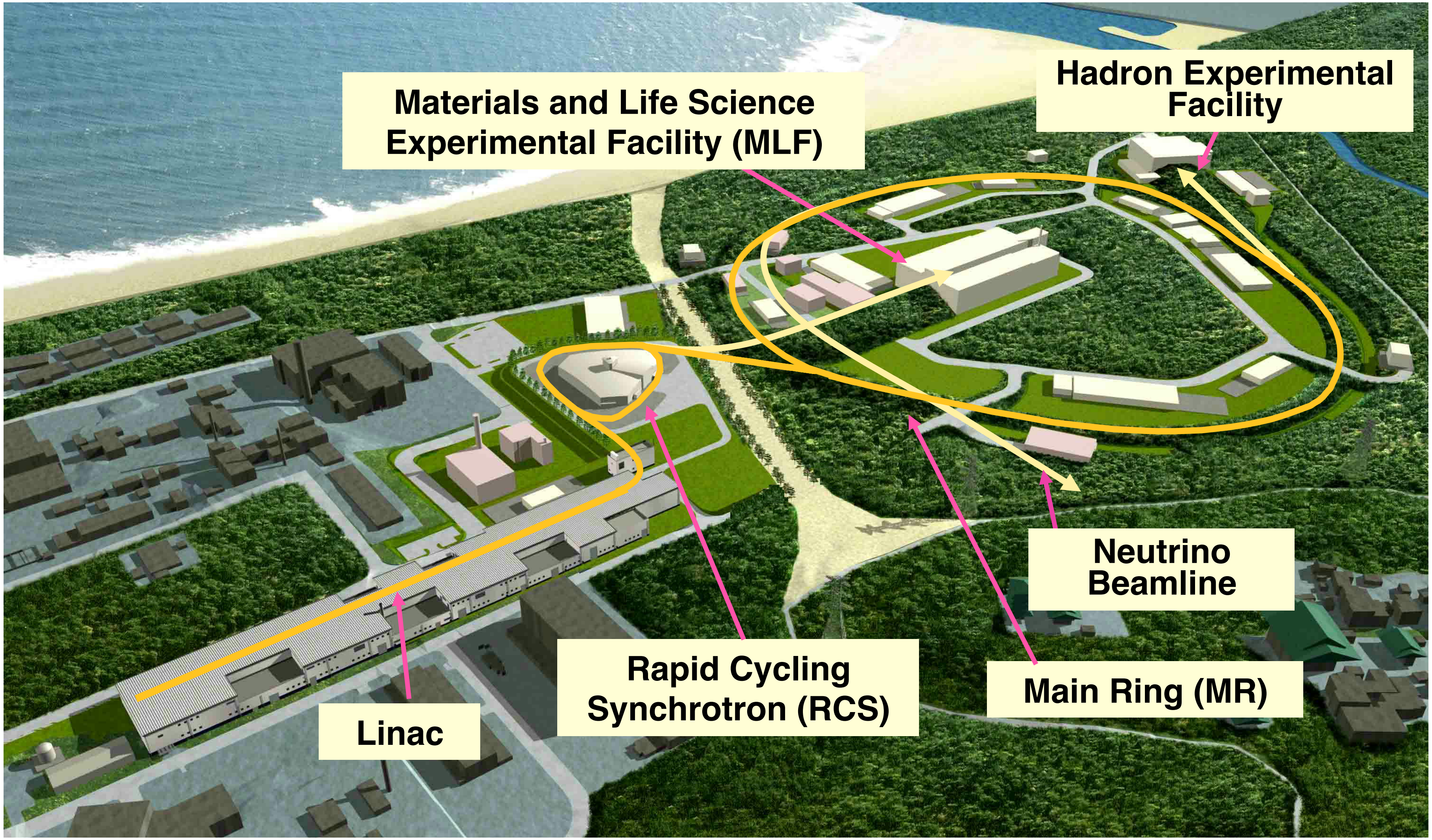
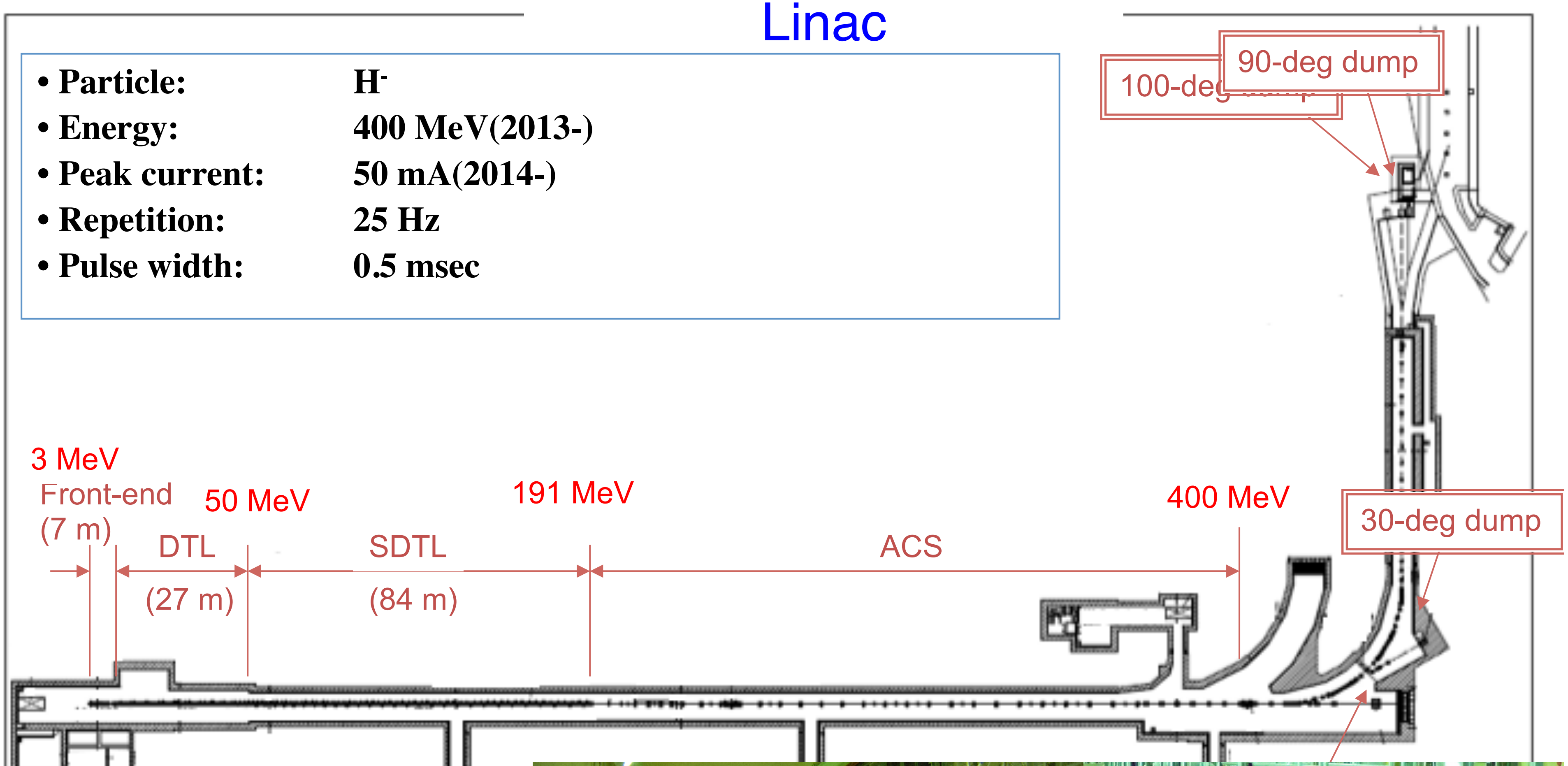
J-PARC Facility

Joint project between KEK and JAEA



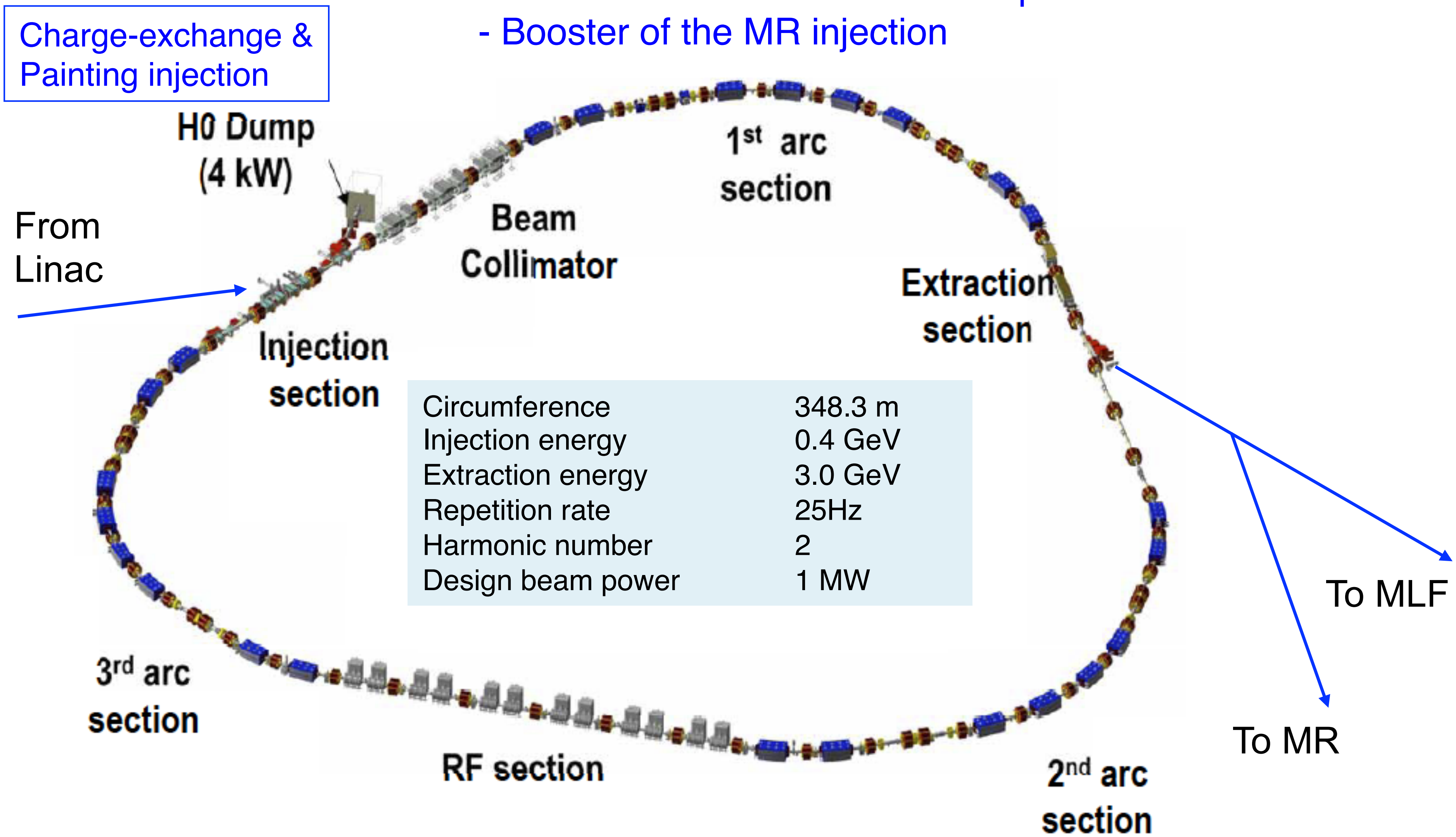
Linac

- **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

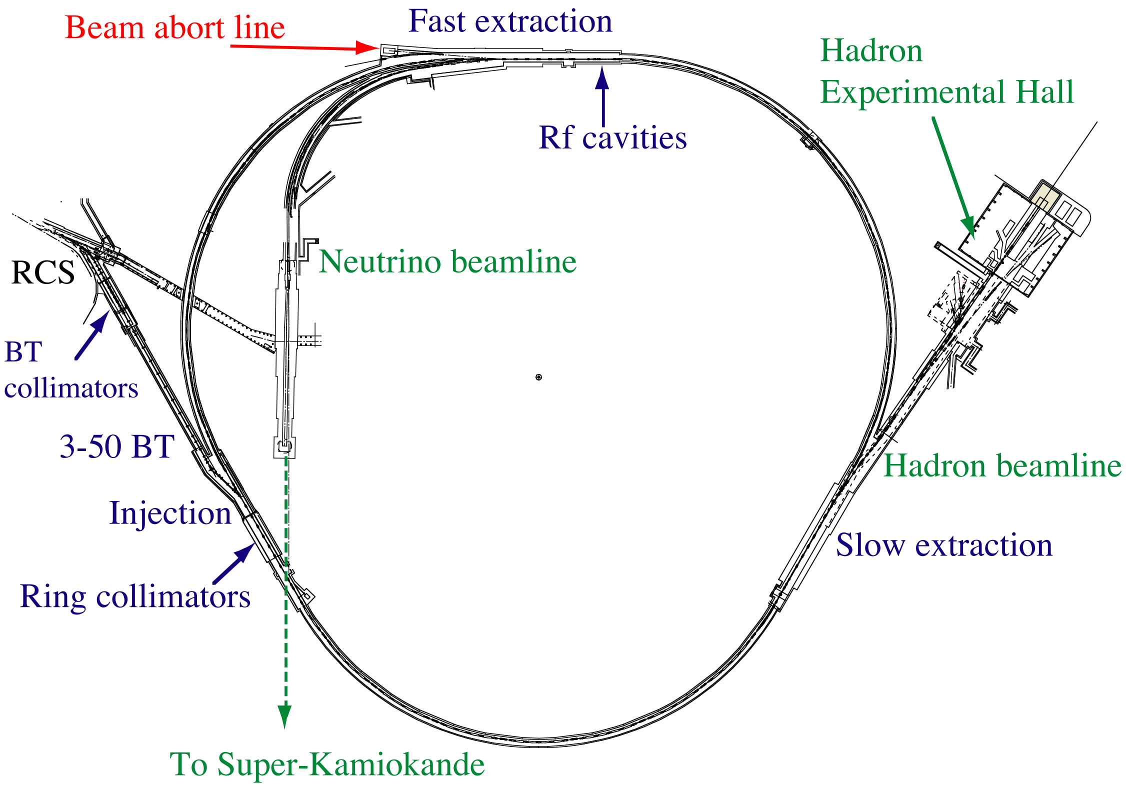


Circumference	348.3 m
Injection energy	0.4 GeV
Extraction energy	3.0 GeV
Repetition rate	25Hz
Harmonic number	2
Design beam power	1 MW

Main parameters of MR

Circumference	1567.5 m
Cycle time	5.52-6.0 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)

Physical Aperture	
3-50 BT Collimator	54-65 π.mm.mrad
3-50 BT physical ap.	> 120 π.mm.mrad
Ring Collimator	54-65 π.mm.mrad
Ring physical ap.	> 81 π.mm.mrad

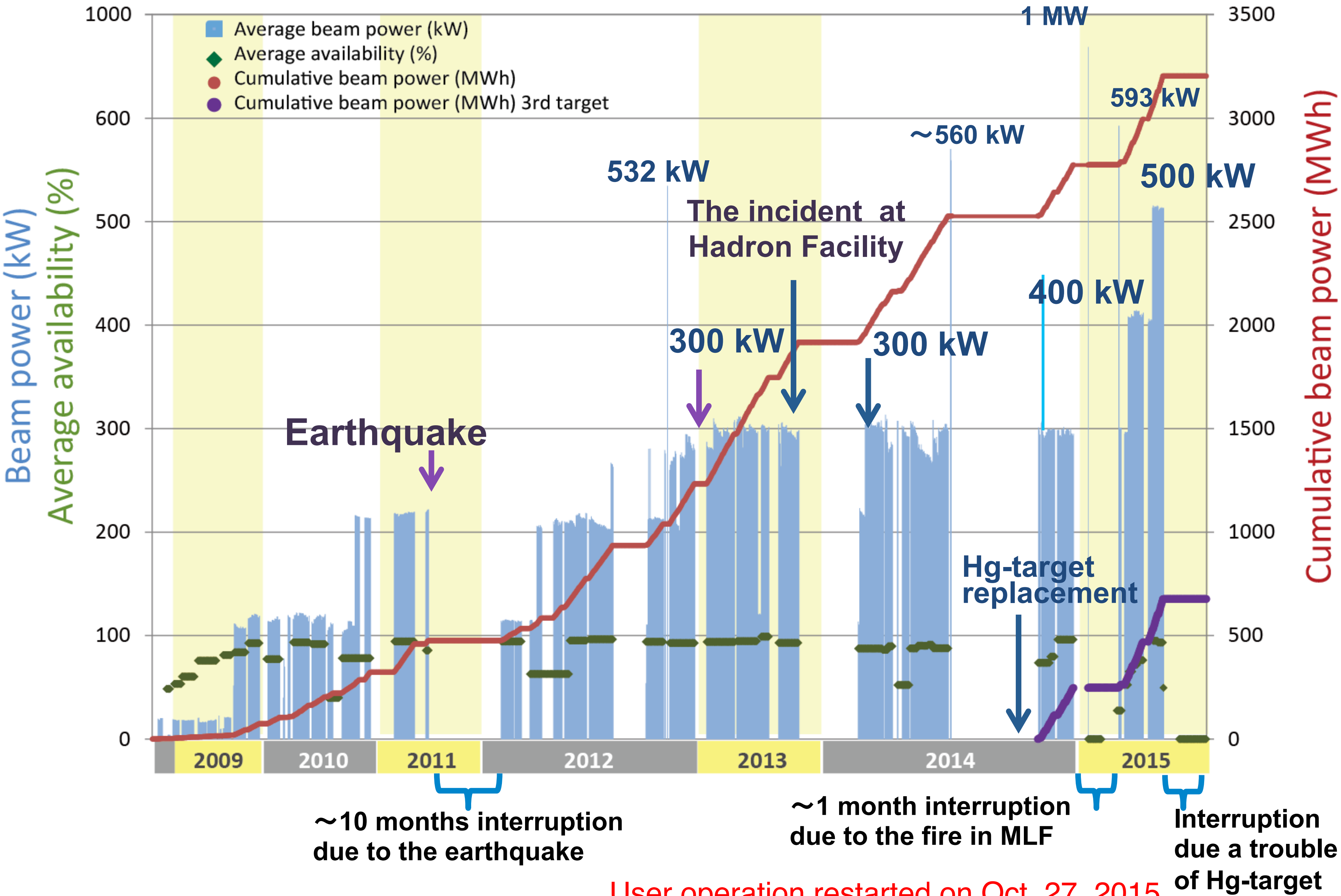


Three dispersion free straight sections of 116-m long:

- 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)

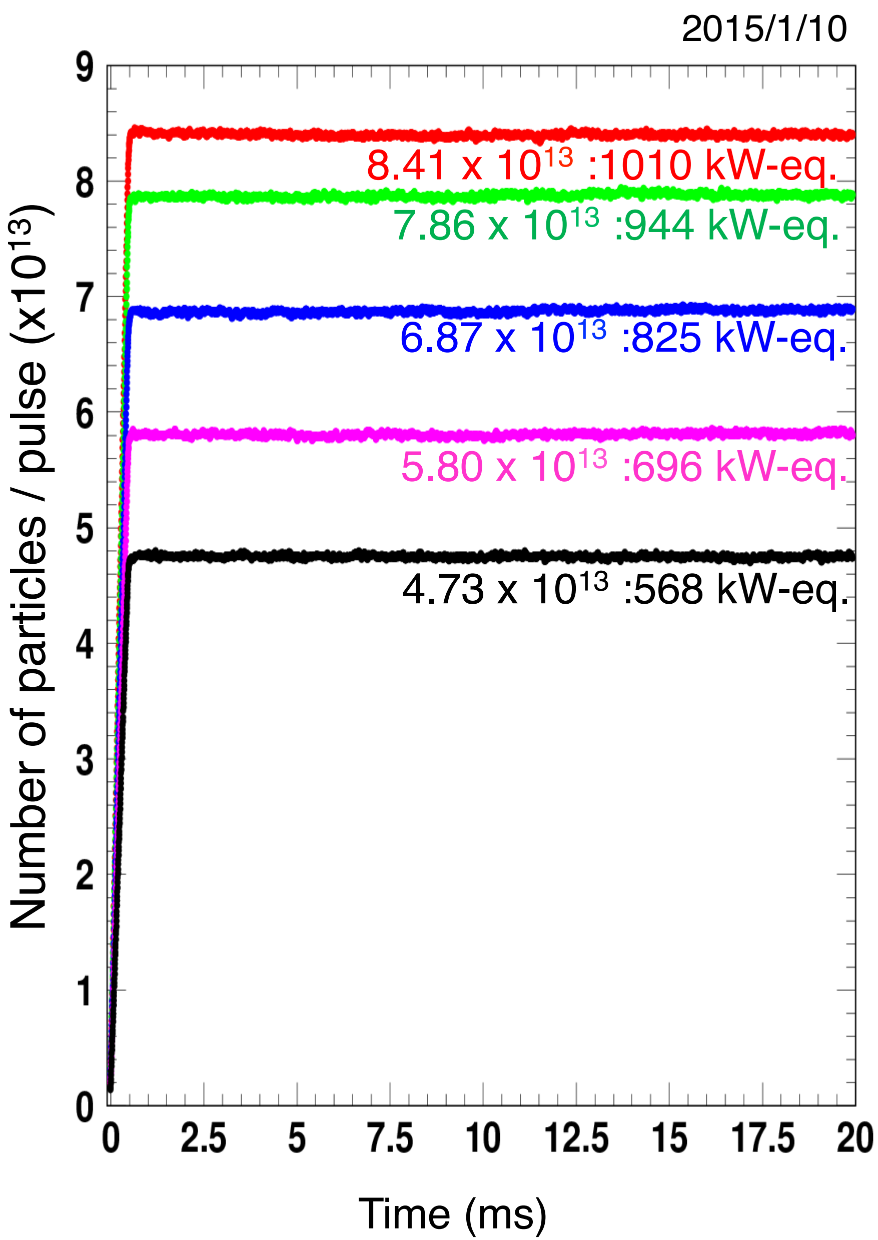
History of beam delivery to the MLF

• as of 3rd of June 2015

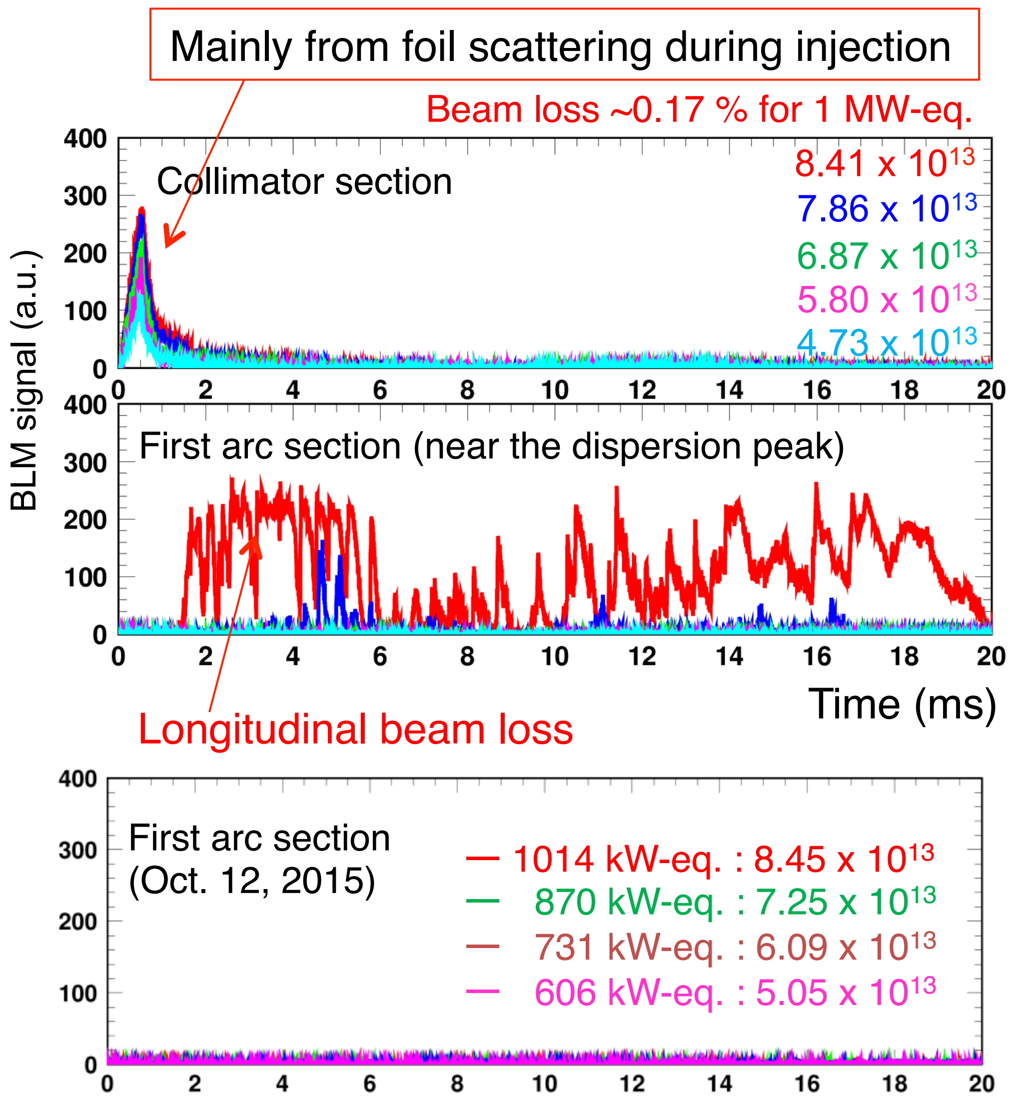


User operation restarted on Oct. 27, 2015.

Demonstration of 1 MW-eq. beam

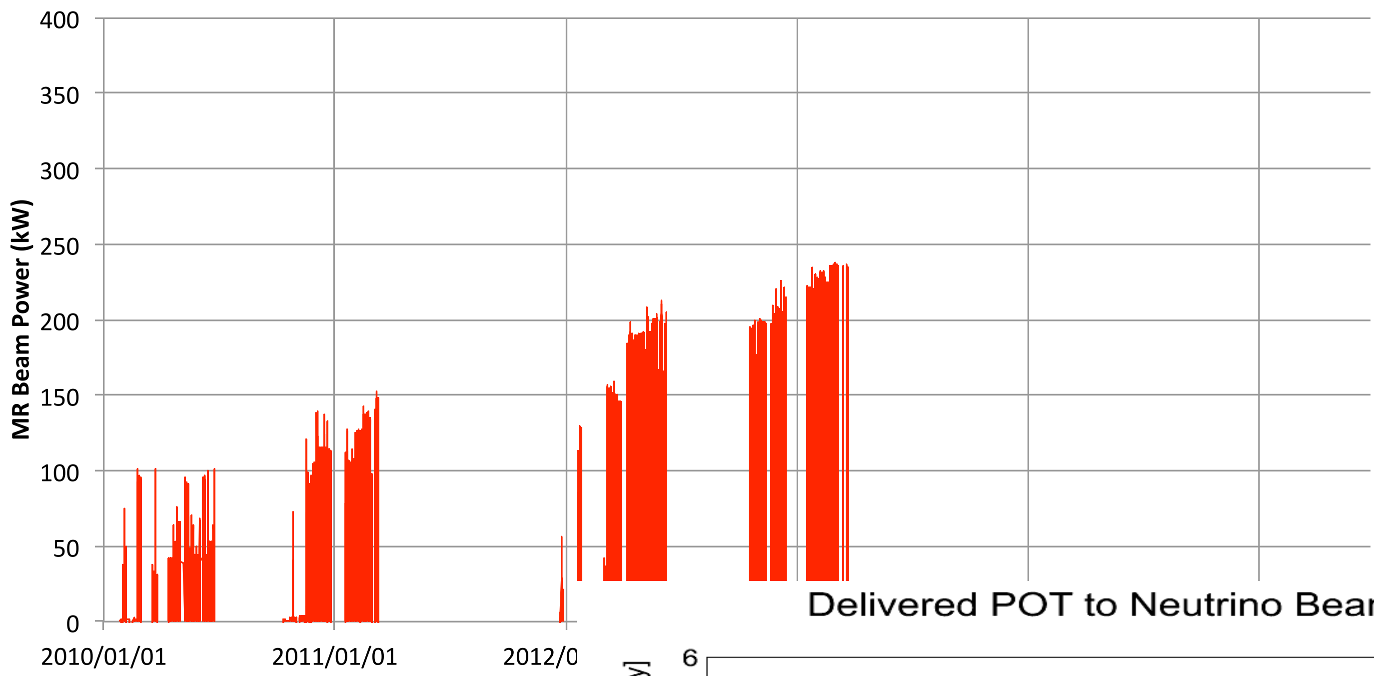


BLM signals @ collimator & arc sections

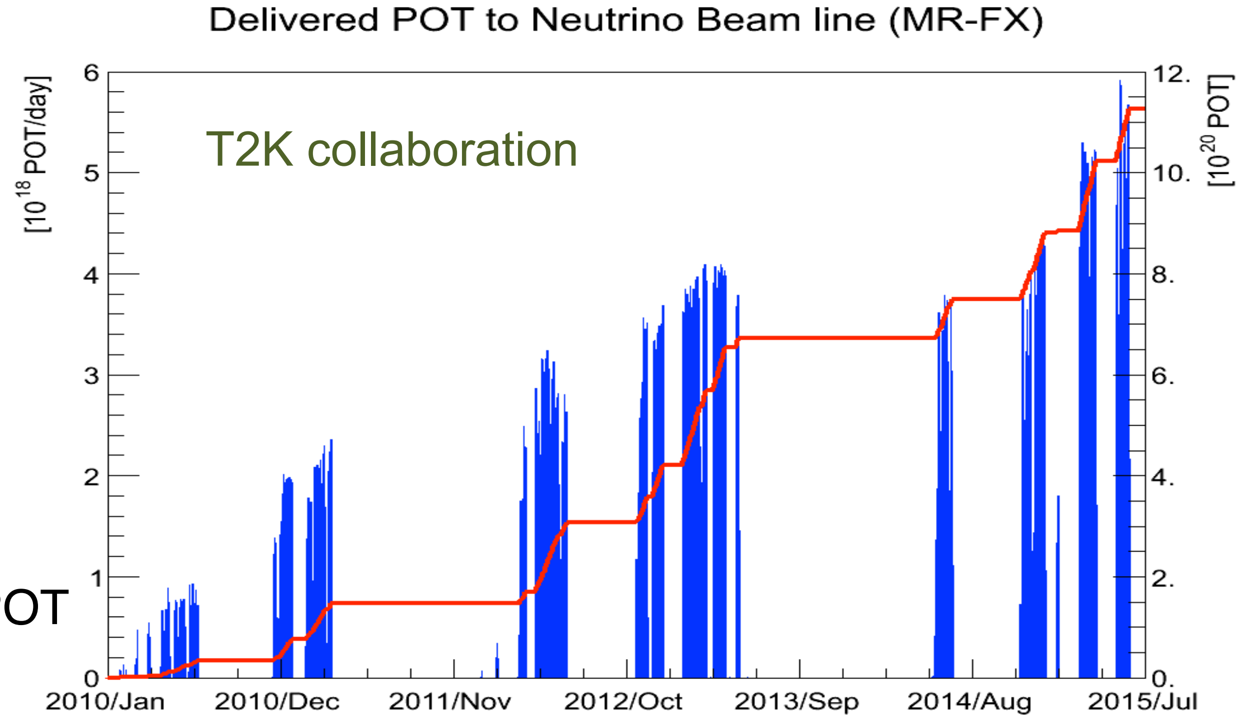


Details will be given by Hotchi.

History of MR beam power



Delivered maximum beam

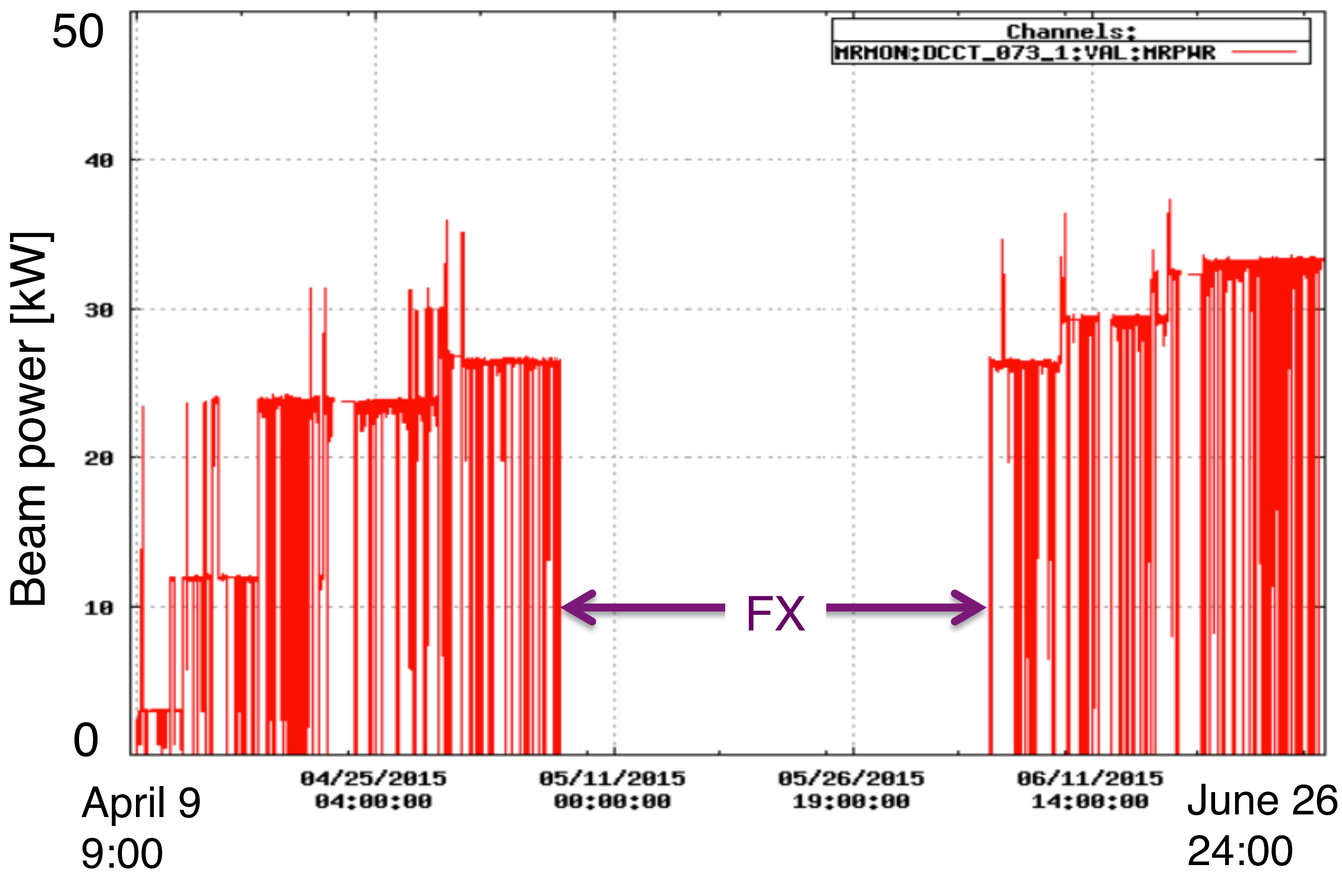


Total number is > 1.1×10^{21} POT as of June 3.

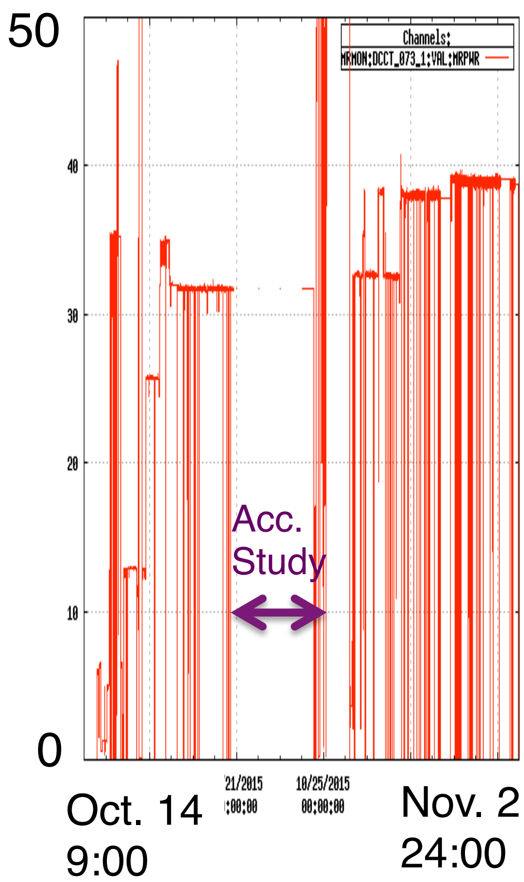
Slow extraction operation

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

April 9, 2015 - June 26, 2015



Oct. 14, 2015 -



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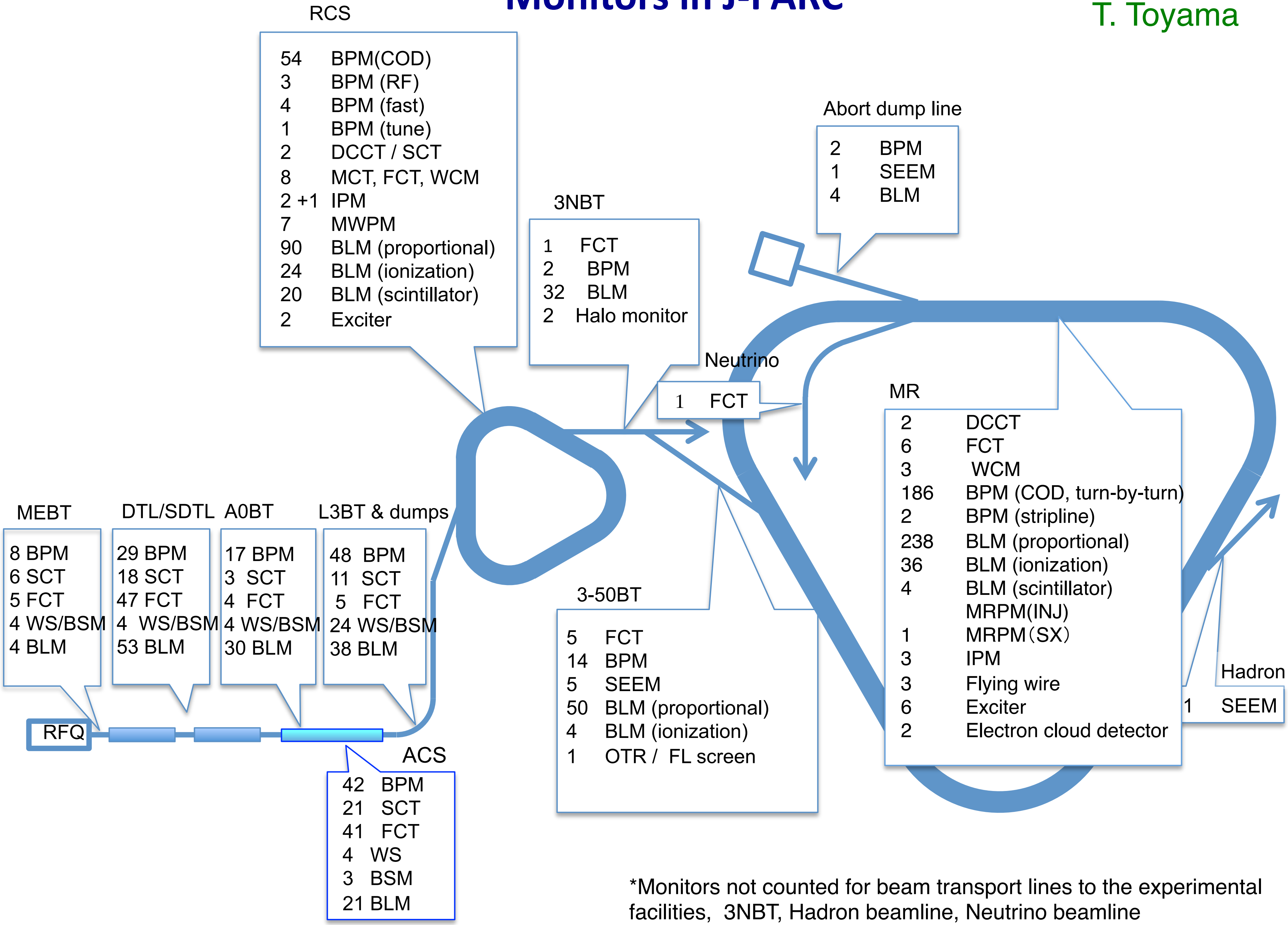
Monitors in J-PARC

T. Toyama



*Monitors not counted for beam transport lines to the experimental facilities, 3NBT, Hadron beamline, Neutrino beamline

BPMs and profiles monitors are important devices for modeling and beam control at high intensities.

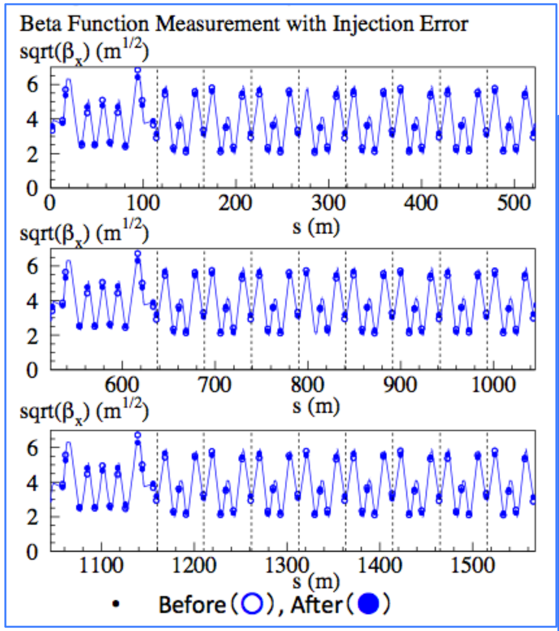
The BPM data provides a lot of information

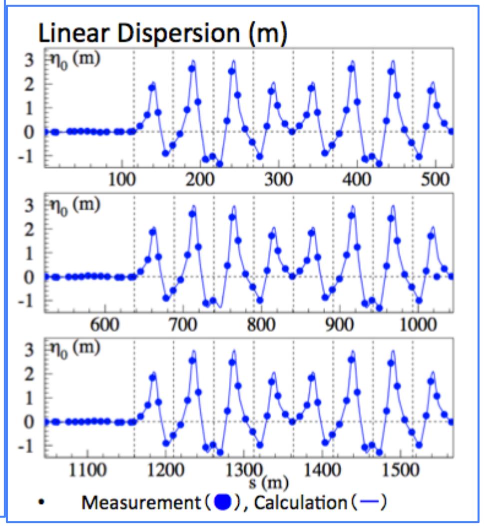
$$x,\ y = \sqrt{\varepsilon\beta}\cos\left[\left(\nu_0 + \xi\frac{\Delta p}{p}\right)\phi + \psi_0\right] + \eta\frac{\Delta p}{p}$$

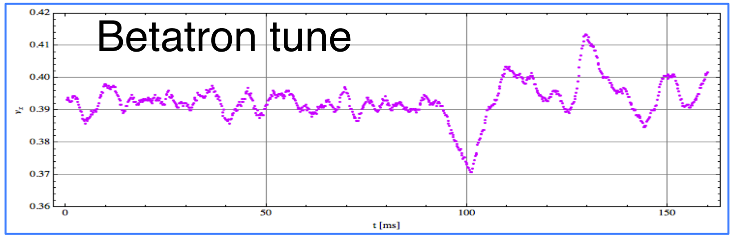
COD
bunch position
intra-bunch position

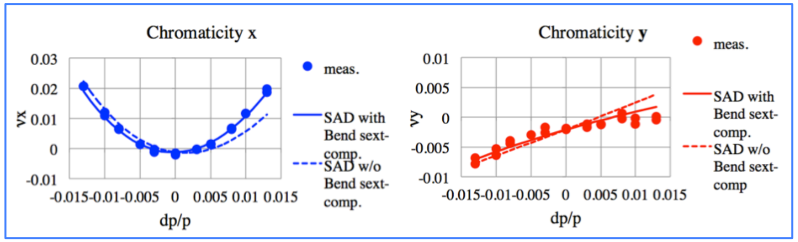
need high precision, high resolution

~ 20-40 μm resolution at the best,
~ 100 μm accuracy after BBA







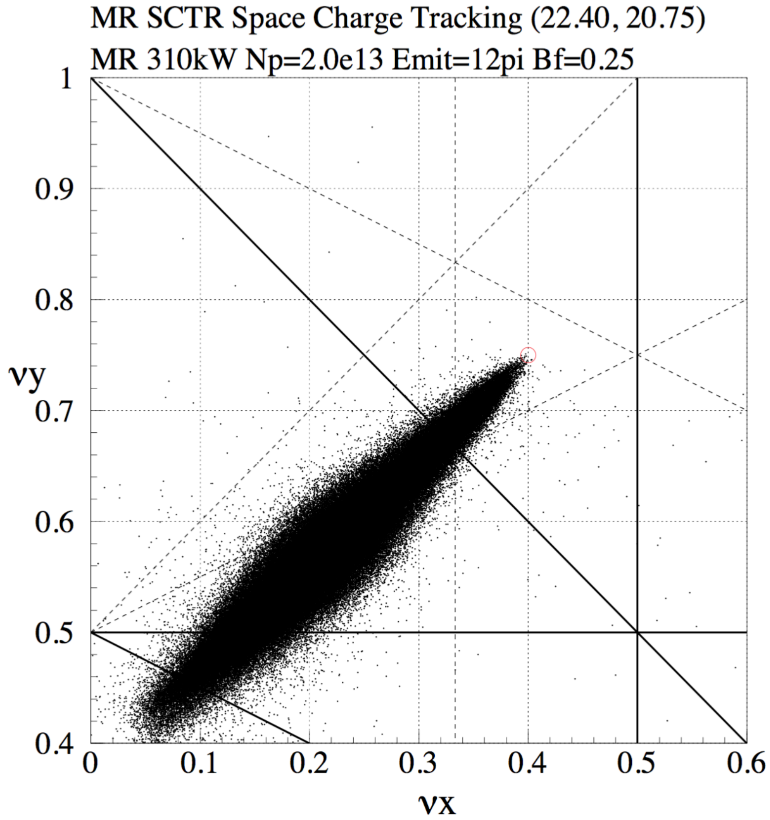


Space charge effect in J-PARC MR

J-PARC MR :

- Power 310 kW
- Number of protons: 2e13 ppb
- Transverse Emittance: 12π mm.mrad
- Bunching Factor: 0.25
- Space Charge Tune Shift: 0.4

$$\Delta\nu = \frac{2\pi R N r_0}{4\pi\sigma^2 / \beta(v/c)^2\gamma^3 B_f} = 0.4$$

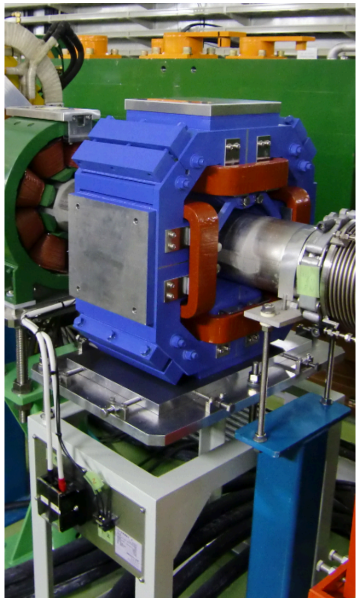


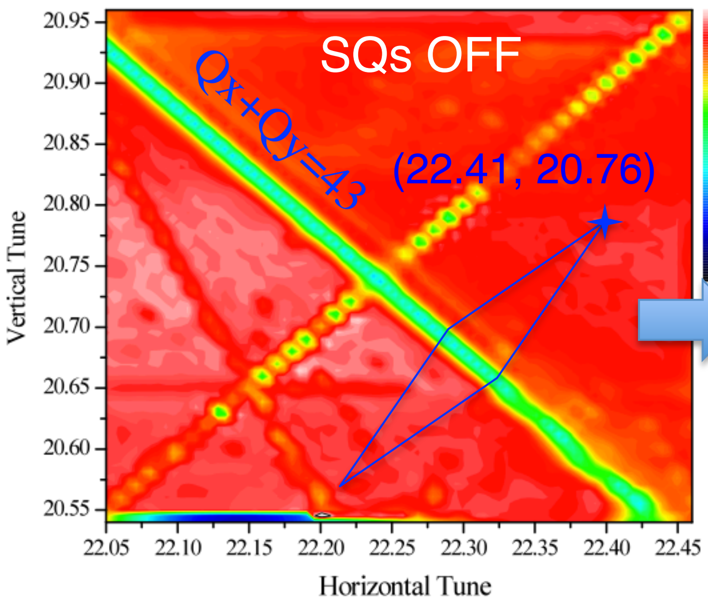
For high power beam operation, it is necessary to avoid betatron resonances in the presence of space charge tune shift by

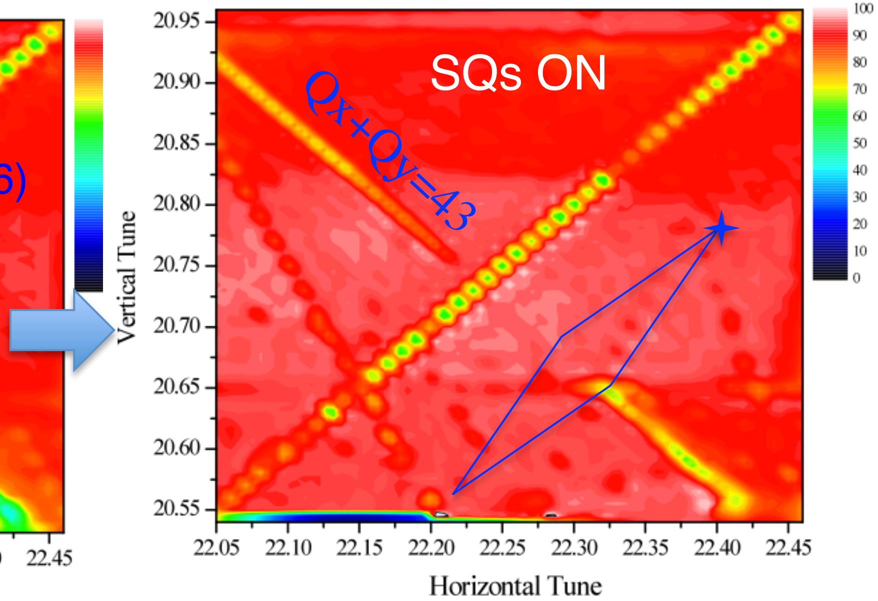
- resonance correction
- large bunching factor

Resonance correction

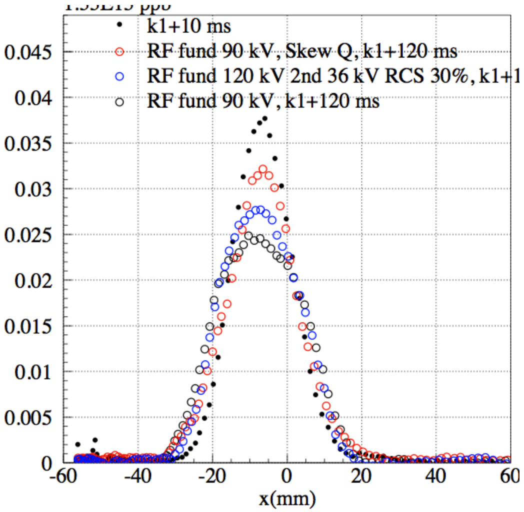
Correction of linear coupling resonance with skew quadrupoles



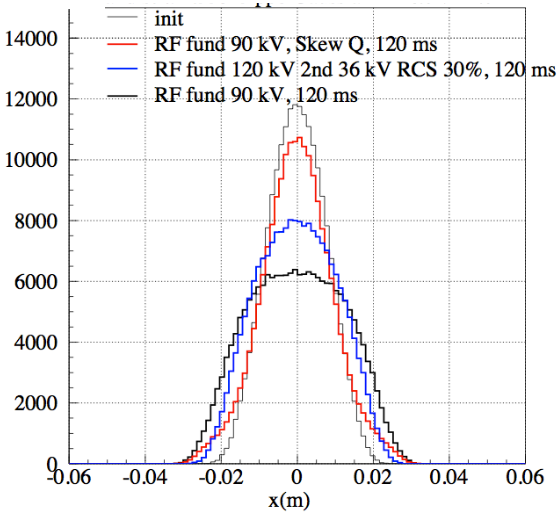




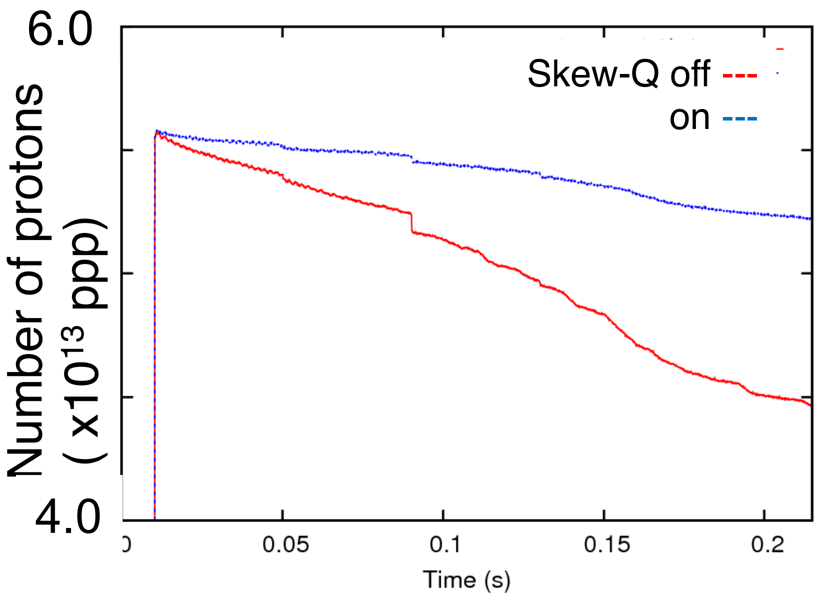
Hor. profile measured by FWPM



Simulation



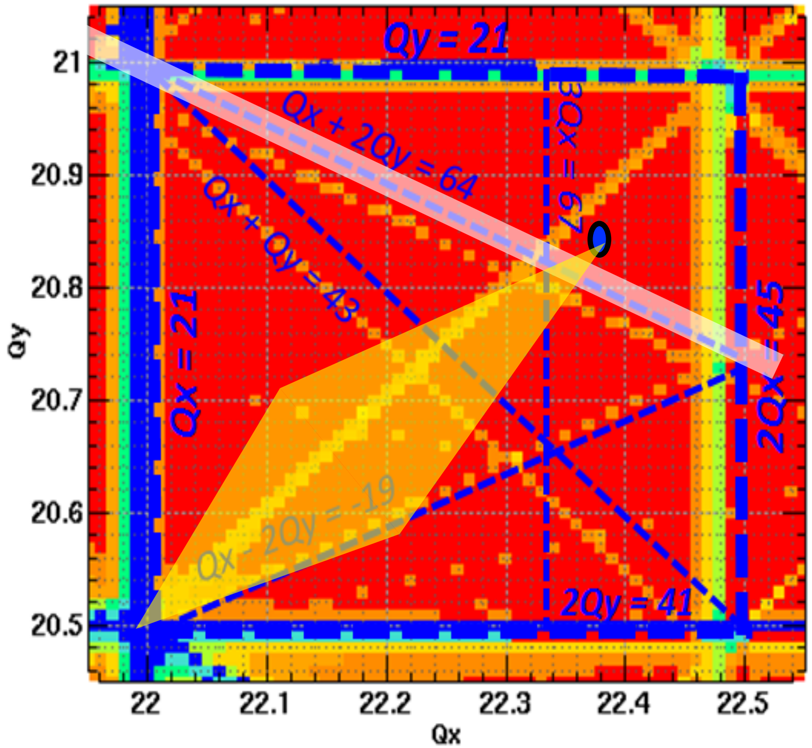
Beam survival for two bunches at 3 GeV

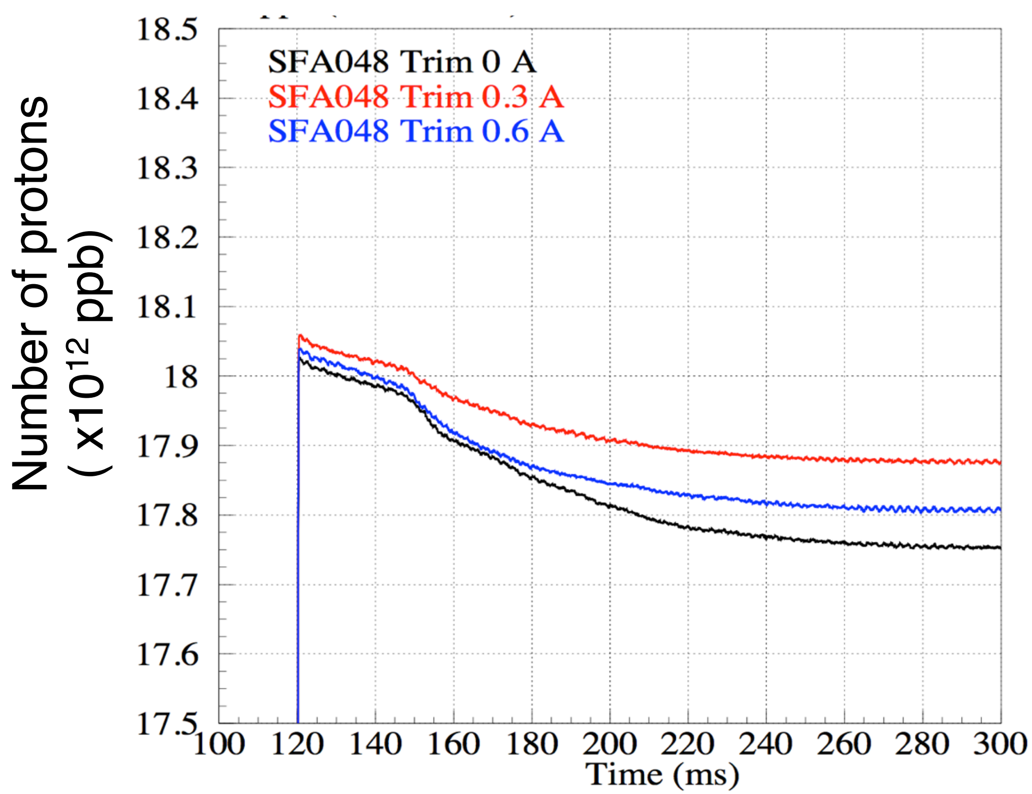


The simulation well reproduces the data.

Resonance correction (cont'd)

Correction of third-order resonances with trim sextupoles

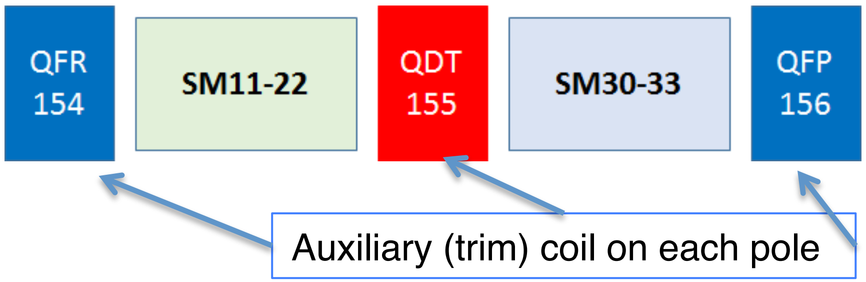


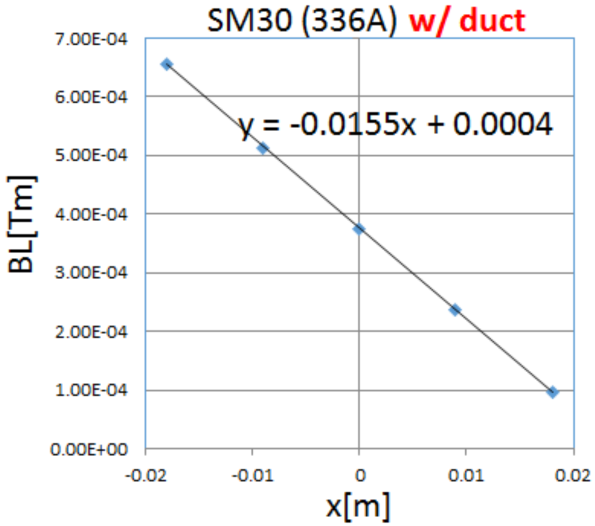


All sextupoles have auxiliary (trim) coils .
Trim-SFA048 set to be 0.3 A to correct Qx+2Qy=64

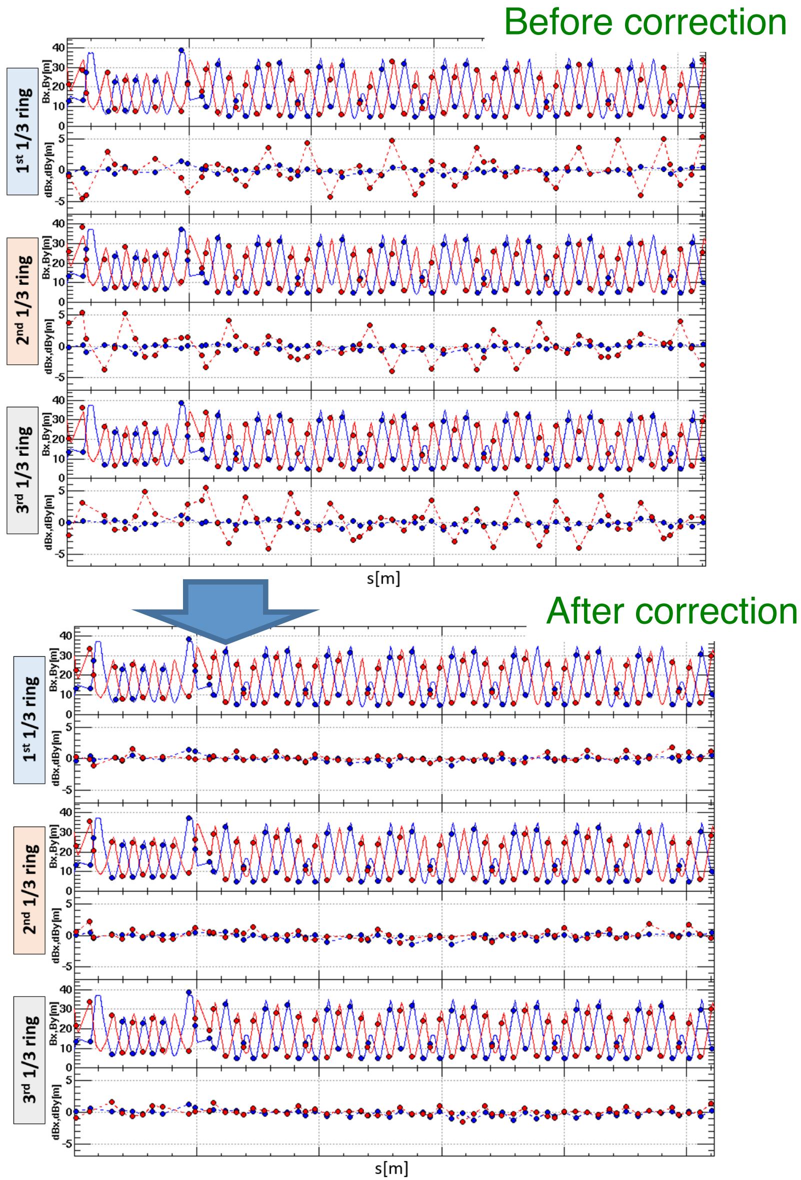
Correction of leakage fields of FX septa

Configuration of FX septa





Leakage field at the circulating beam position of FX septa is compensated by 3 trim coil systems at quads. #154,#155,#156.

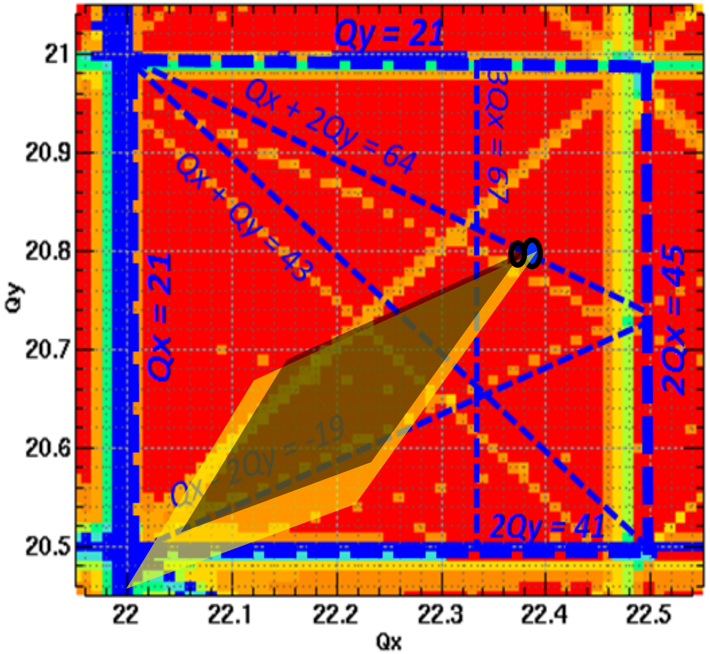


MR 350 kW operation (2015 May)

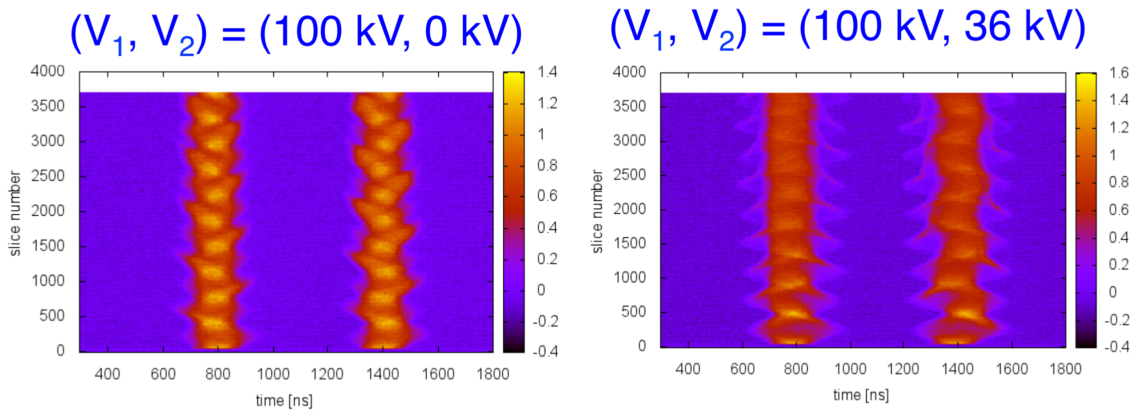
Without correction: Beam loss ~270 W

With correction: Beam loss ~200 W

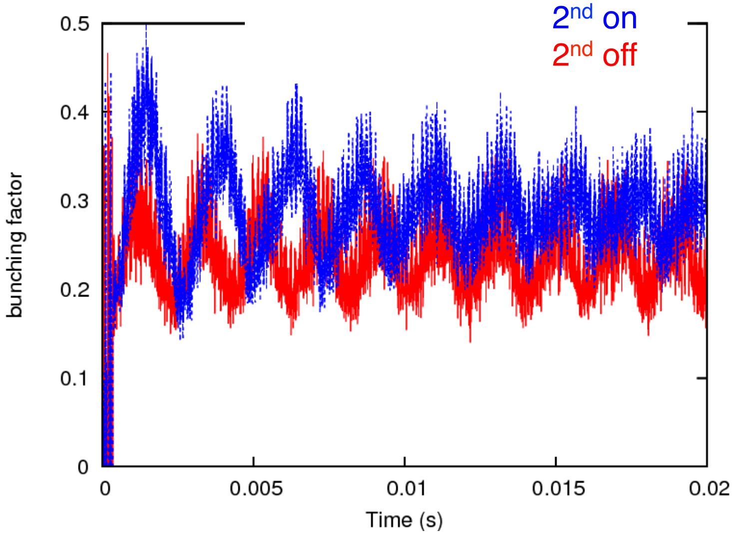
2^{nd} harmonic rf voltage



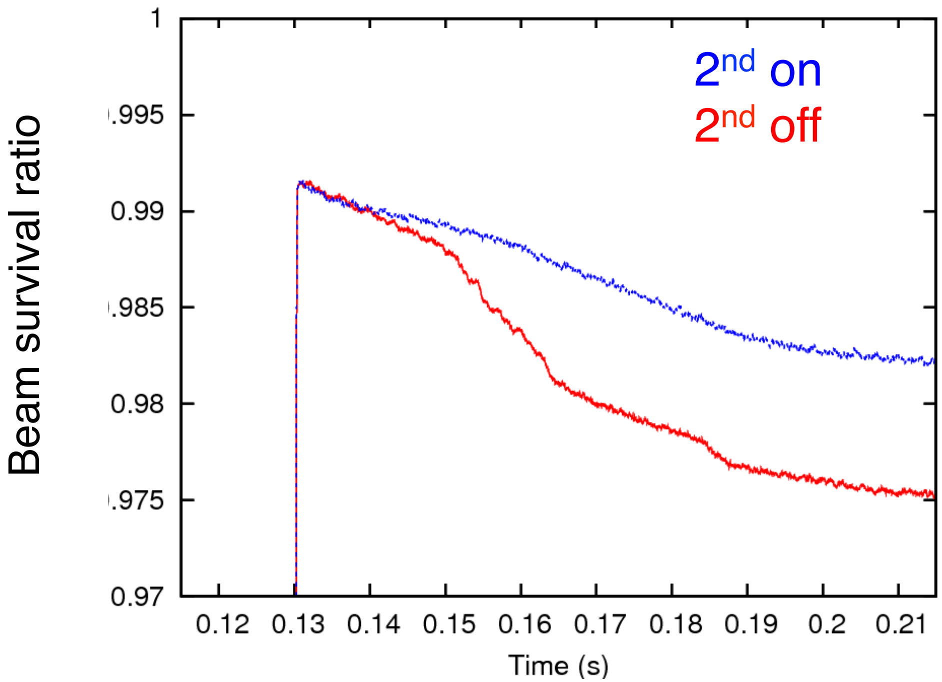
Mountain plot of WCM data at beam injection



Bunching factor measured by WCM



Beam survival measured by DCCT for 360 kW operation

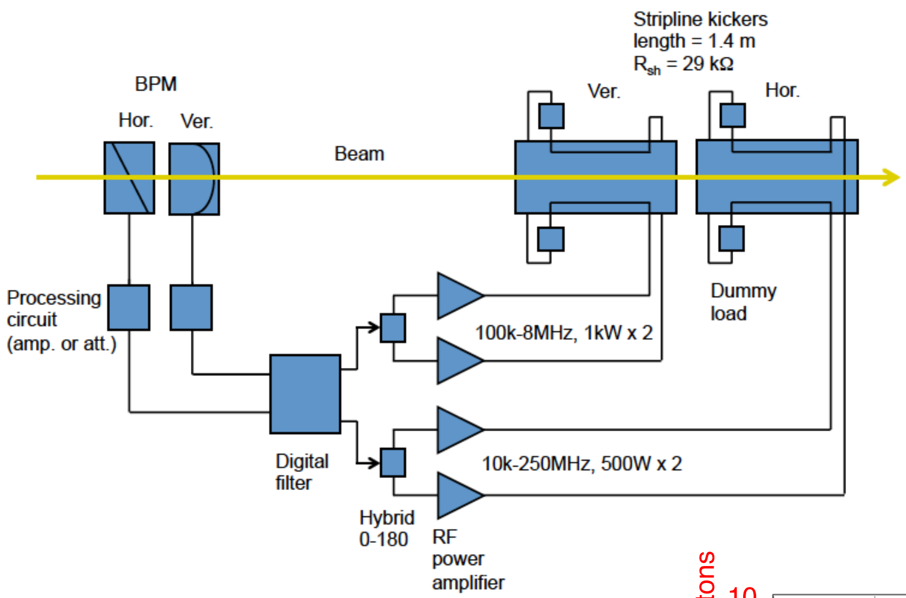


Suppression of beam instabilities

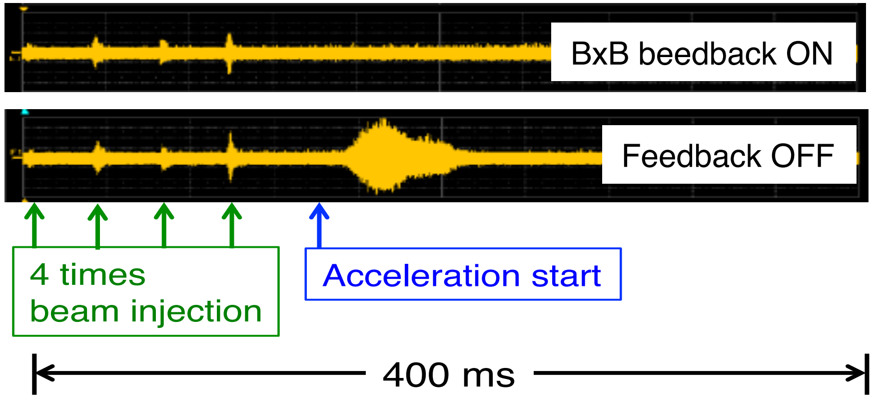
At high beam power operation, coupled-bunch instability and intra-bunch motion are observed .
To cure the instabilities, two approaches are adopted;

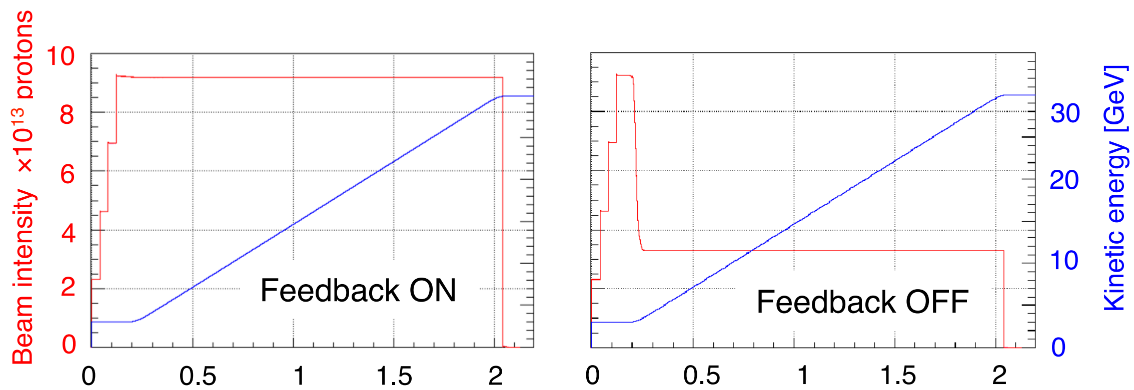
- optimization of chromaticity correction
- two bunch feedback systems, bunch−by−bunch (BXB) and intra-bunch feedback .

BXB feedback system



Delta signal of BPM (2.4e13 ppb)

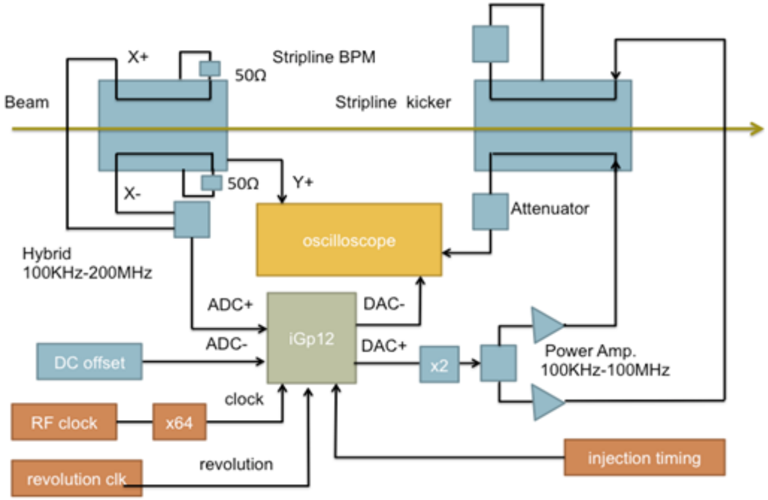




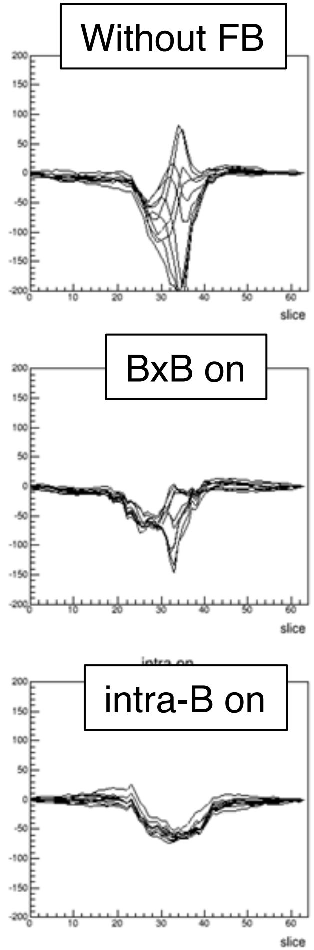
Intra-bunch feedback system (2014 ~)

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.

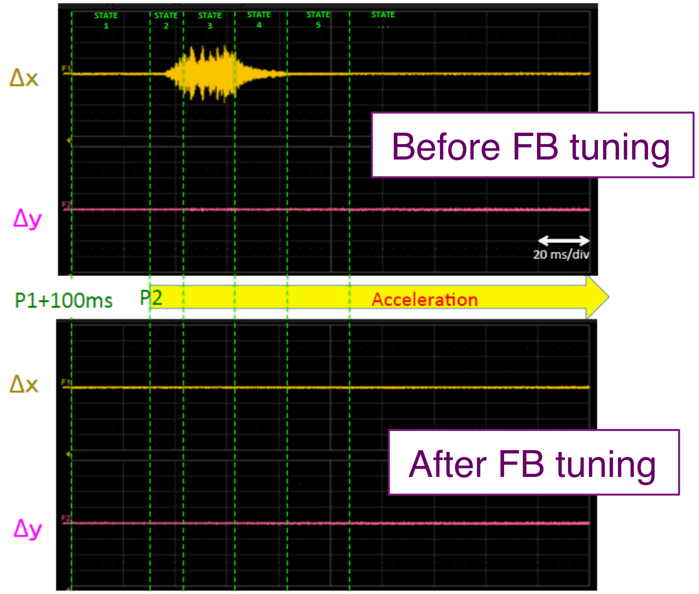


Bunch signal at 100 turns

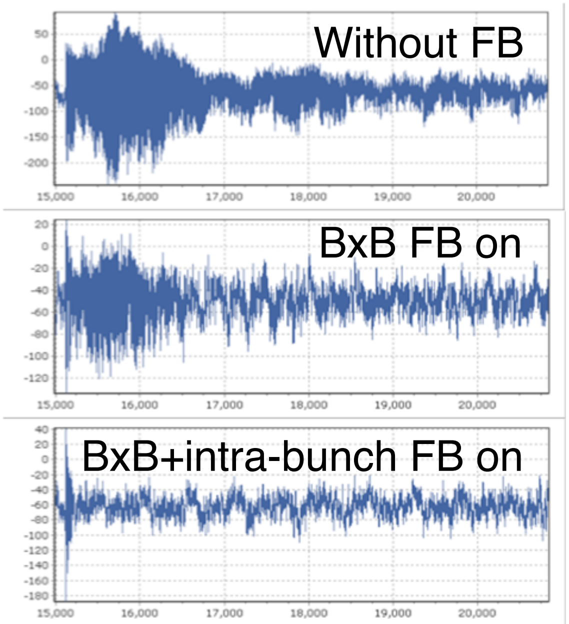


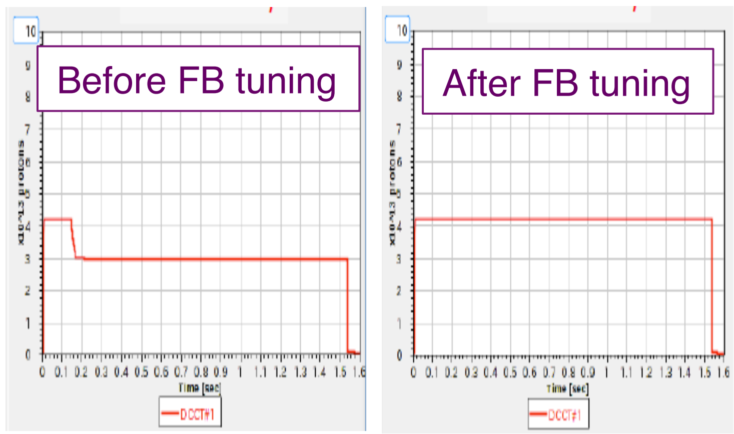
Delta signal of BPM (2.4e13 ppb)

ξ_x ~5.9, ξ_y ~5.2



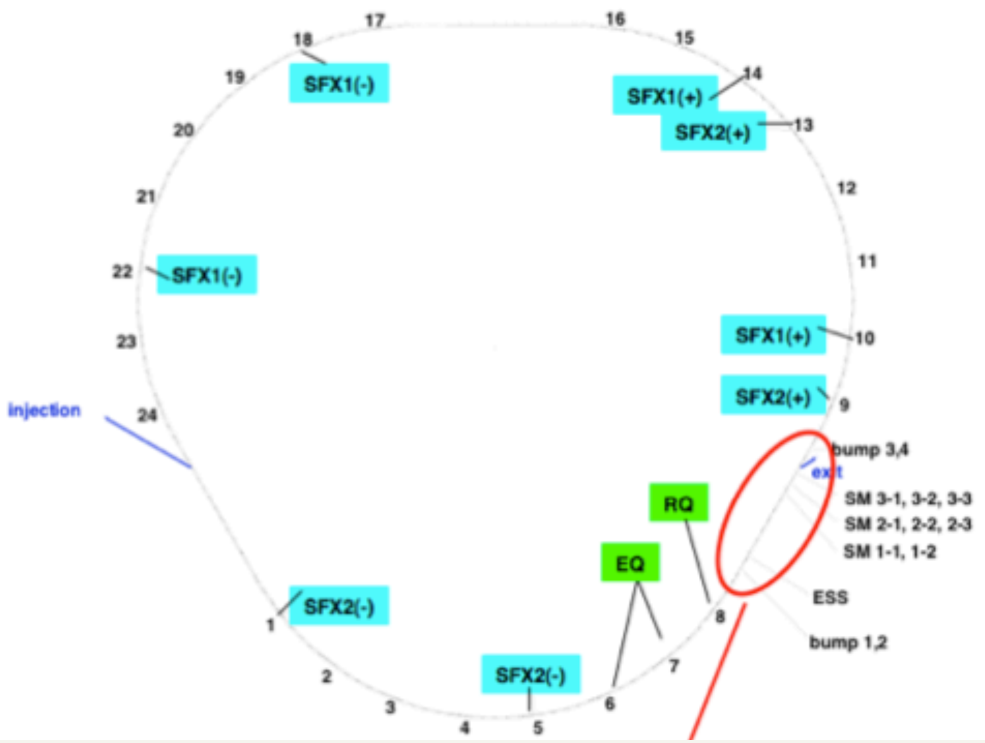
Oscillation of one bunch slice

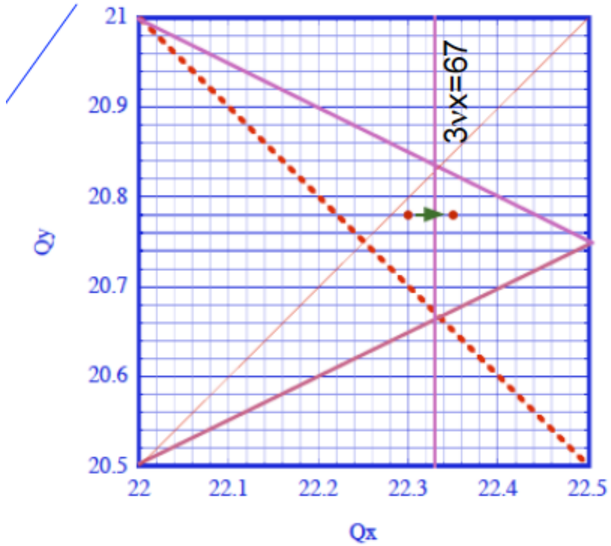




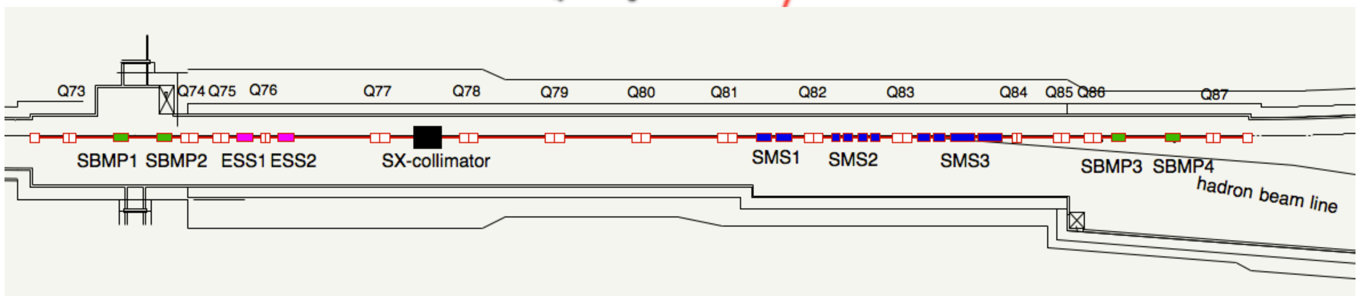
Slow extraction

- Third-integer resonance extraction(νx=67/3)
- High β of 40 m at electromagnetic septum (ESS) -> Large step size ~20 mm
- Dispersion free at ESS and low horizontal chromaticity
- Dynamic bump scheme





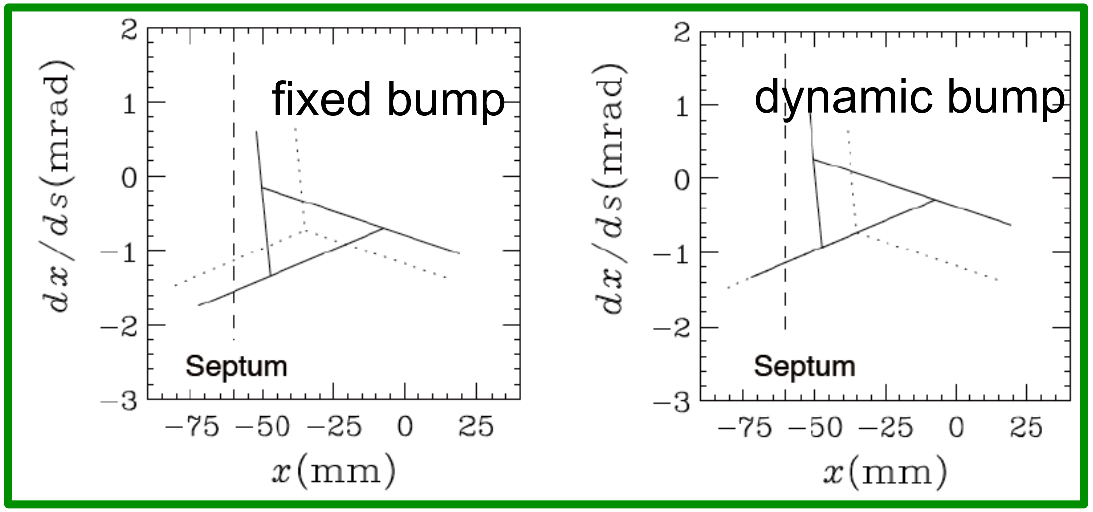
Horizontal tune is approached linealy to 22.333 resonance by one of the arc quadrupole families, QFN (48 magnets in total).



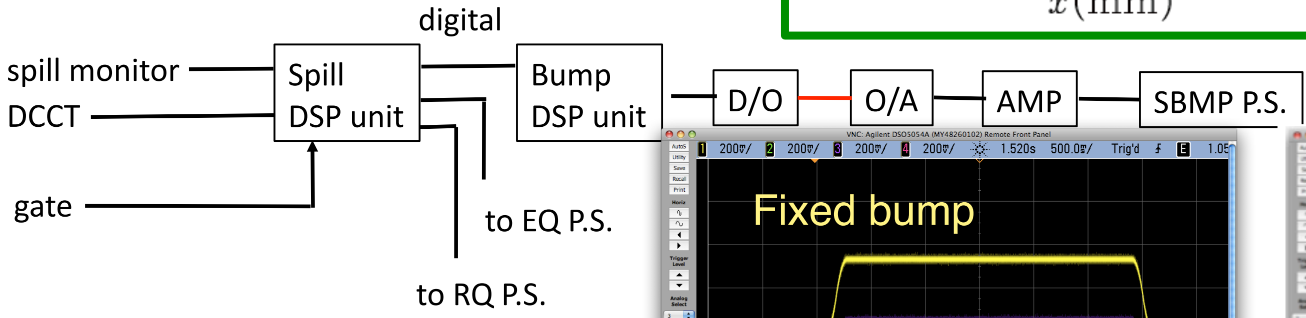
Slow extraction with dynamic bump system

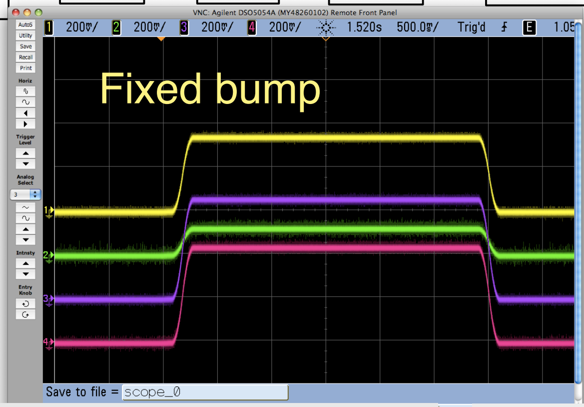
The center of the separatrix is adjusted to fix the beam angle at the ESS septum during the extraction
→ Reduce beam impact rate on septum.

Separatrices at the ESS



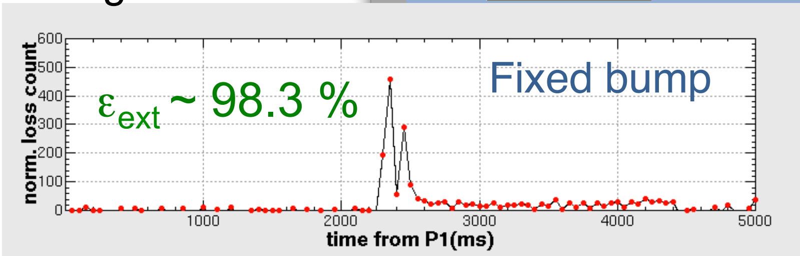
Dynamic bump system

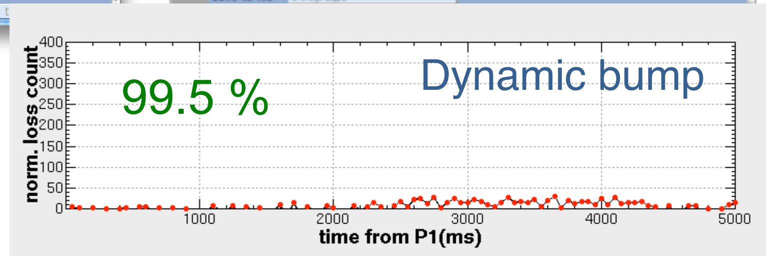




Beam loss at SX region

4e12ppp

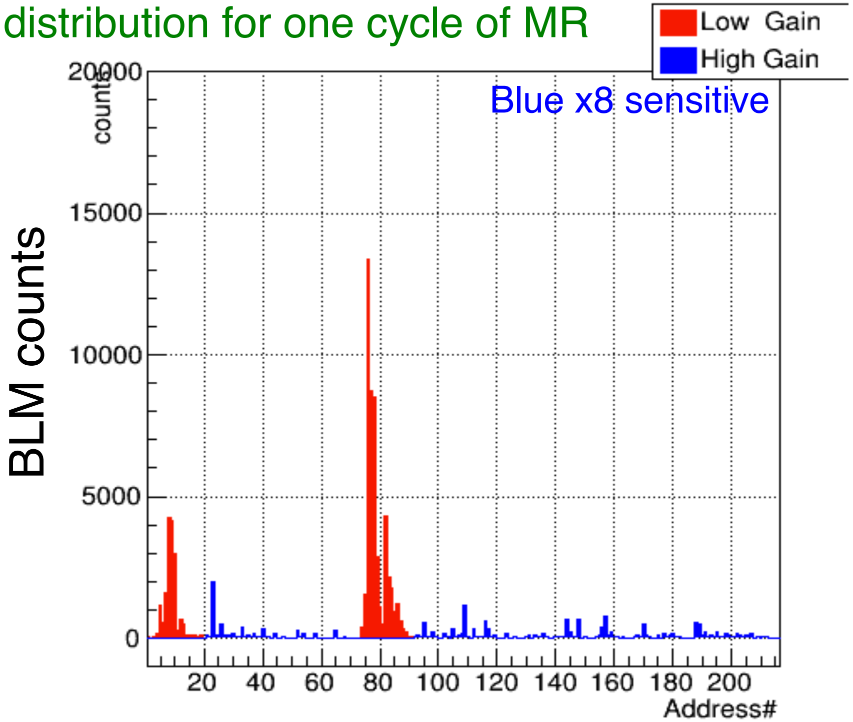


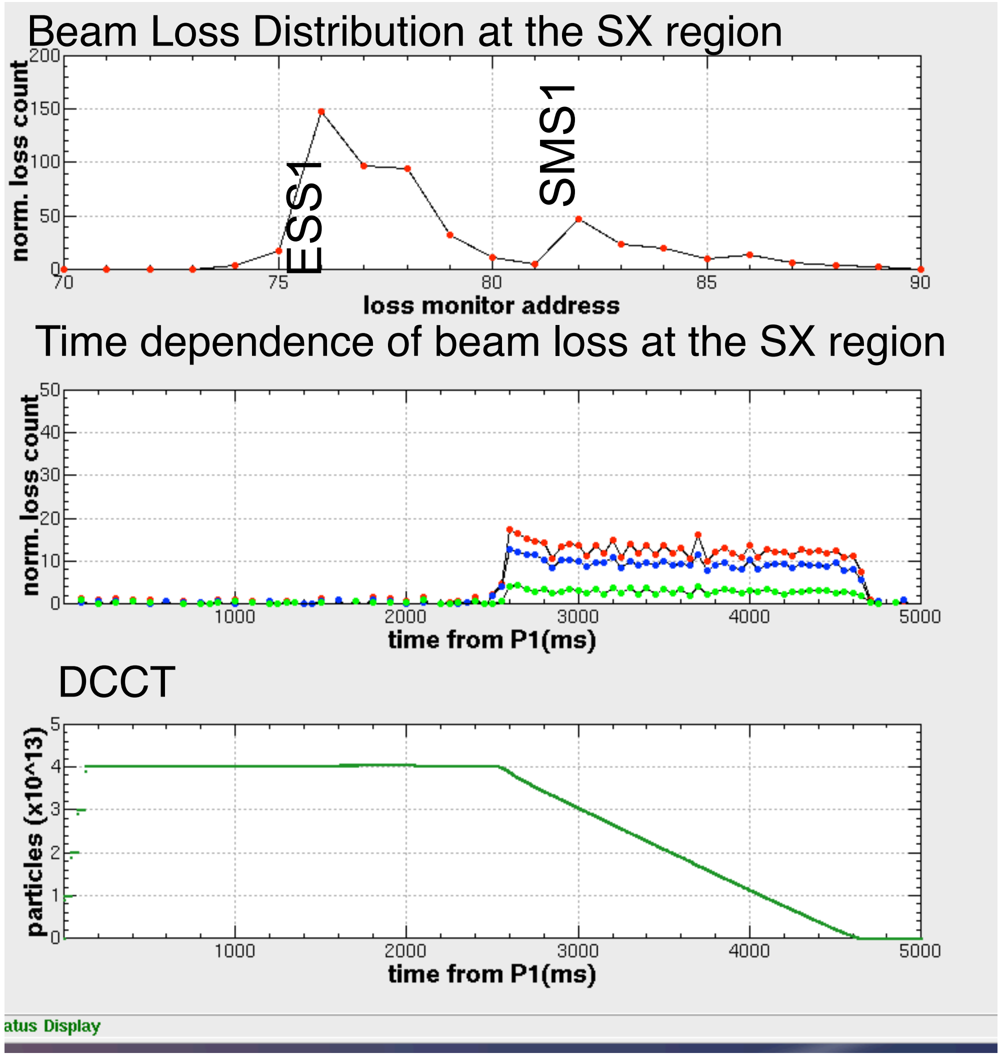


Beam loss of slow extraction

Beam intensity : 4.1 e13 ppp (32.4kW at 6 s cycle)
Extraction efficiency : 99.53%

Typical integrated beam loss distribution for one cycle of MR

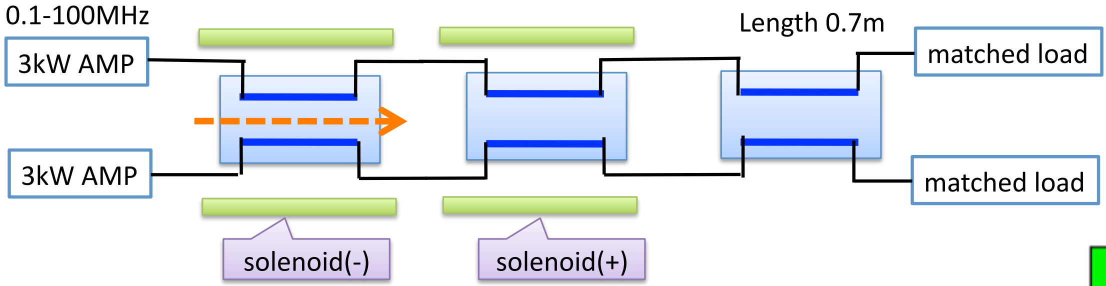


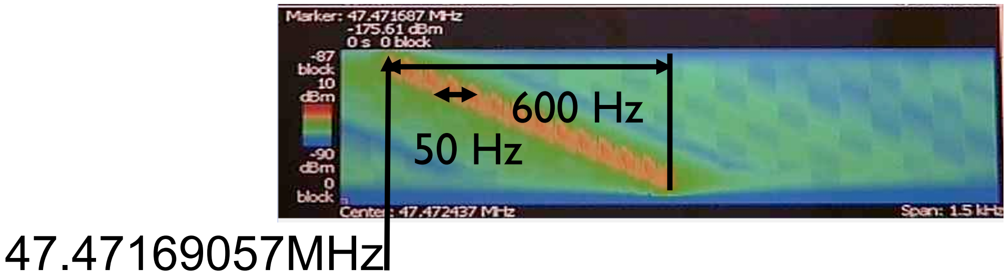


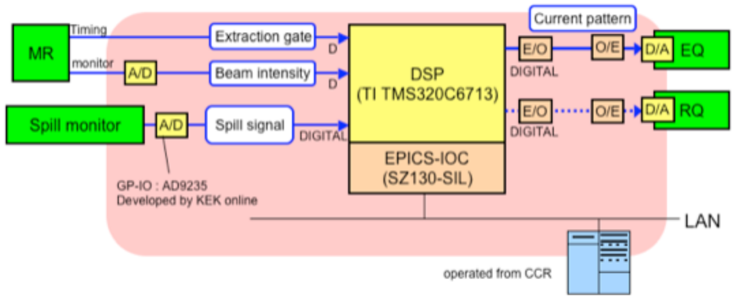
Spill time structure of SX beam

Beam spill is deteriorated by the dipole and quadupoles field ripple, due to current ripple of magnet power supplies.

- Transverse RF to grow the amplitude of beam.
- Feedback control using fast response quadrupoles

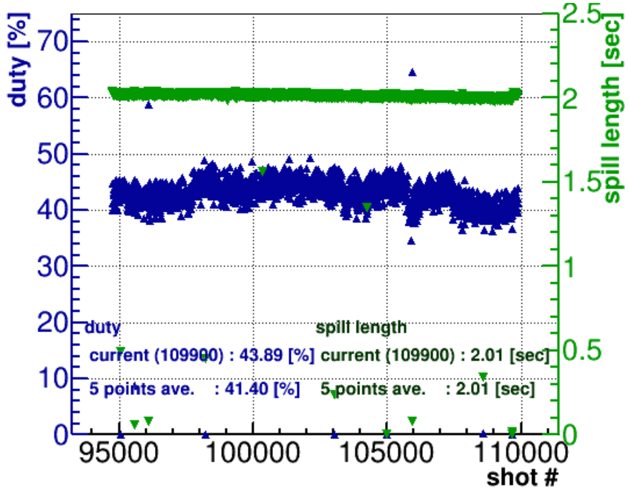


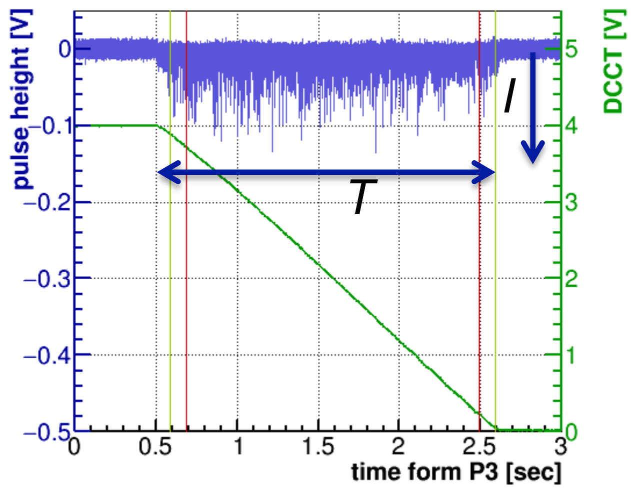




Spill duty factor

$$Duty = \frac{\left(\int_0^T I\,dt\right)^2}{\int_0^T dt \int_0^T I^2\,dt}$$



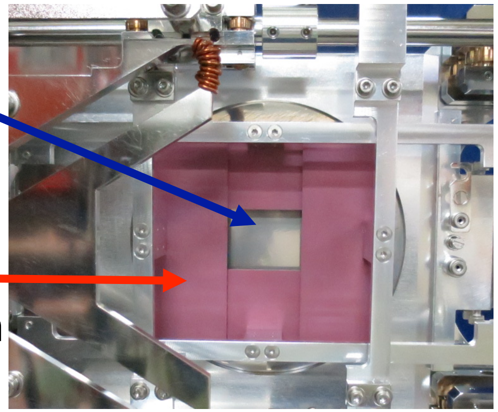


Profile/halo monitor for high-power beam in 3-50BT

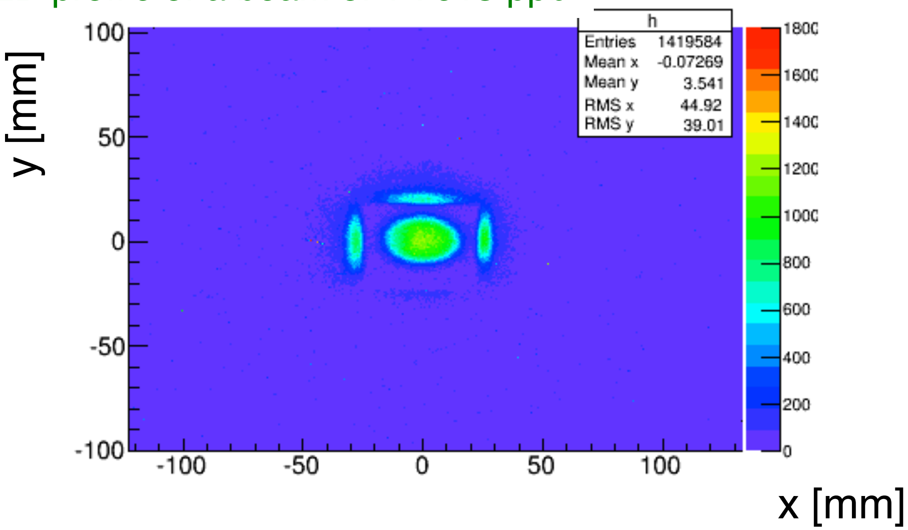
Newly developed OTR (Optical Transition Radiation) with FL (Fluorescence) system installed in 3-50 BT can measure beam profile with the dynamic range of $> 10^5$ in two dimension.

OTR
Solid Screen
for Beam Core

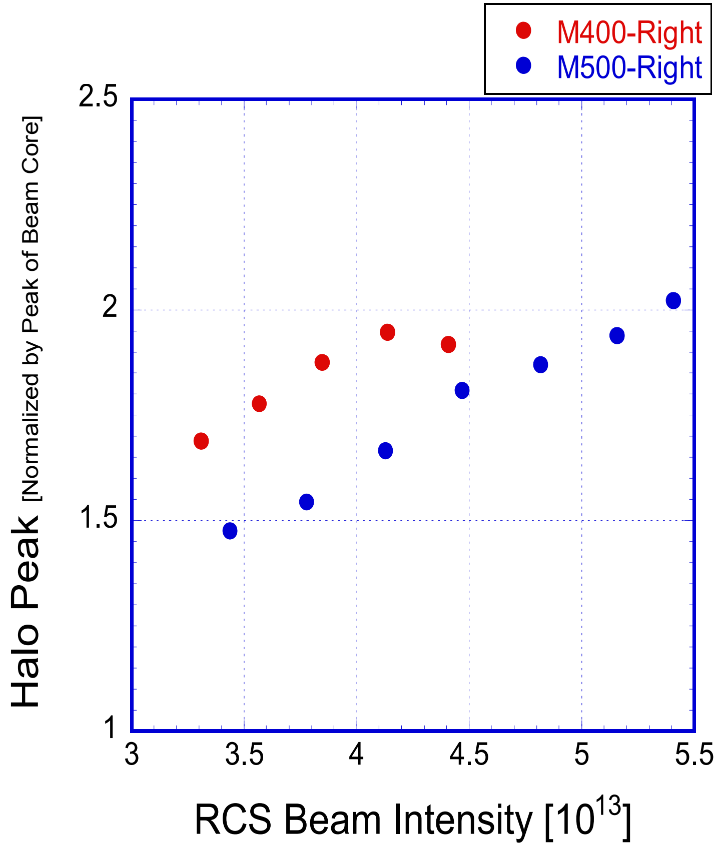
Fluorescence
Alumina Screen
for Beam Halo



2D profile of a beam of 1.7e13 ppb



Beam power dep. of halo intensity

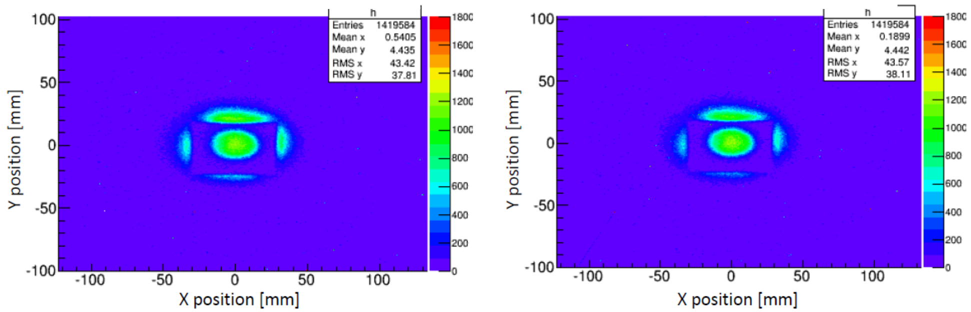


Study of upstream conditions with 3-50BT OTR

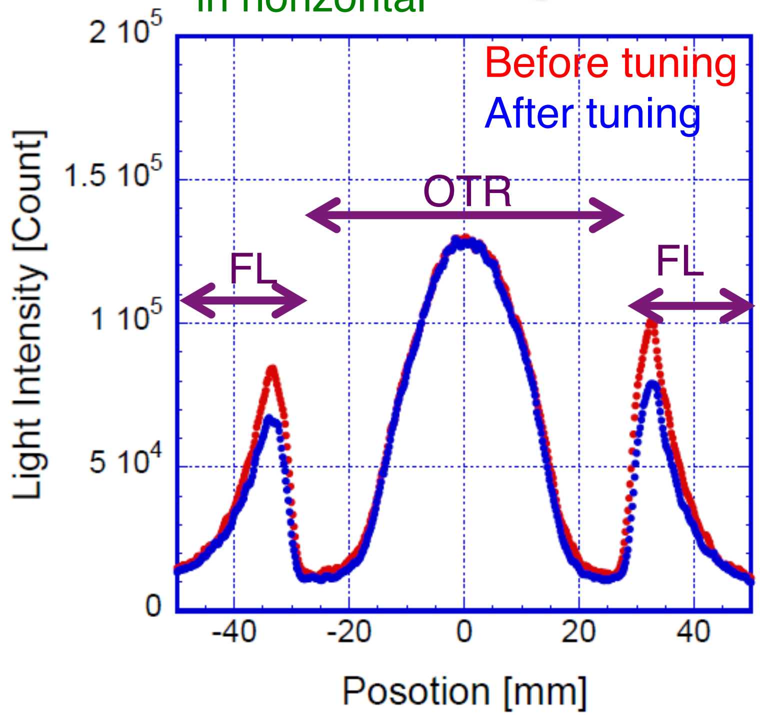
The OTR with FL monitor is a useful tool for tuning the upstream conditions/parameters to minimize beam halo in the MR injection.

A comparison of RCS injection conditions before / after Twiss parameter matching tuning in L3BT and RCS for 1.9e13 ppb.

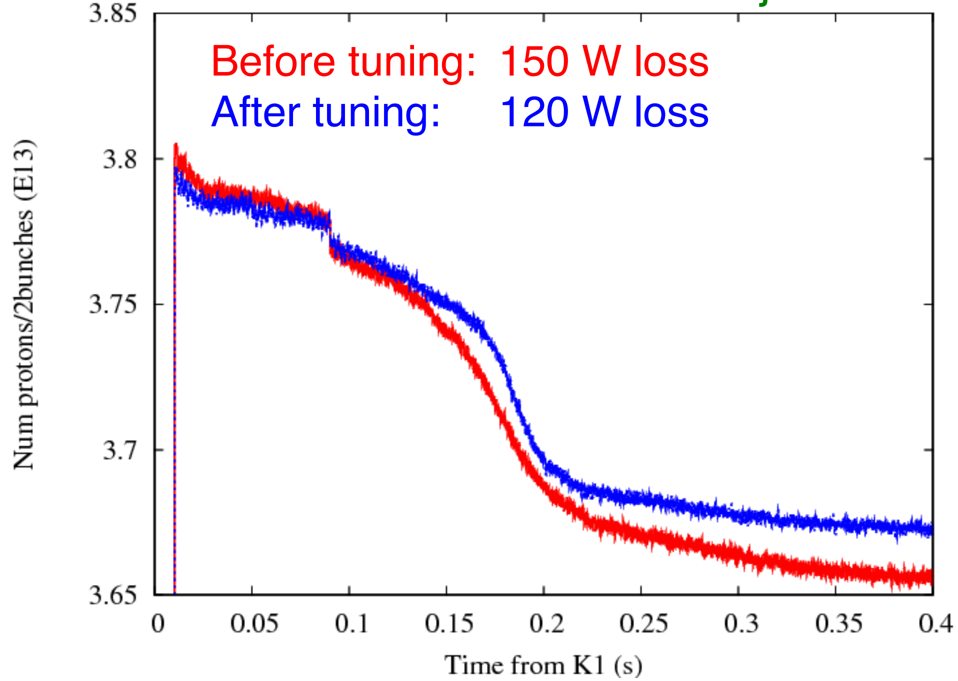
Before tuning After tuning



Projection in horizontal

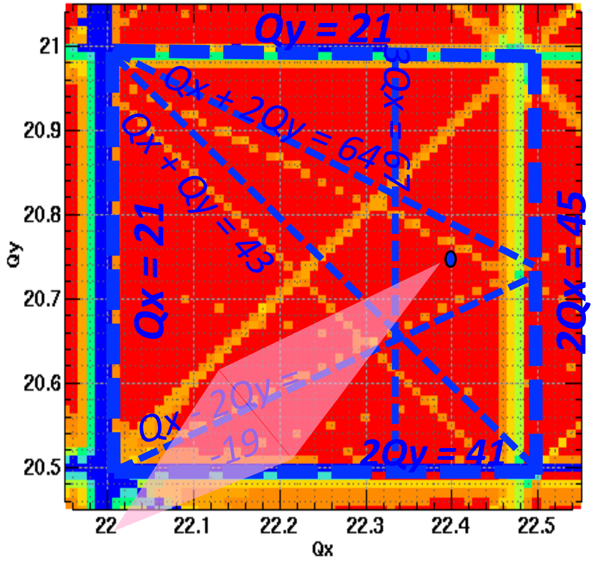


Beam survival in MR injection

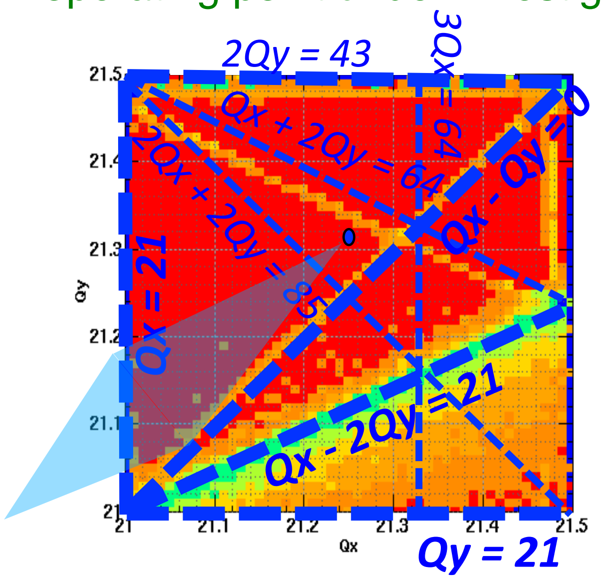


Operating point (21.23, 21.31)

Present operating point for FX users

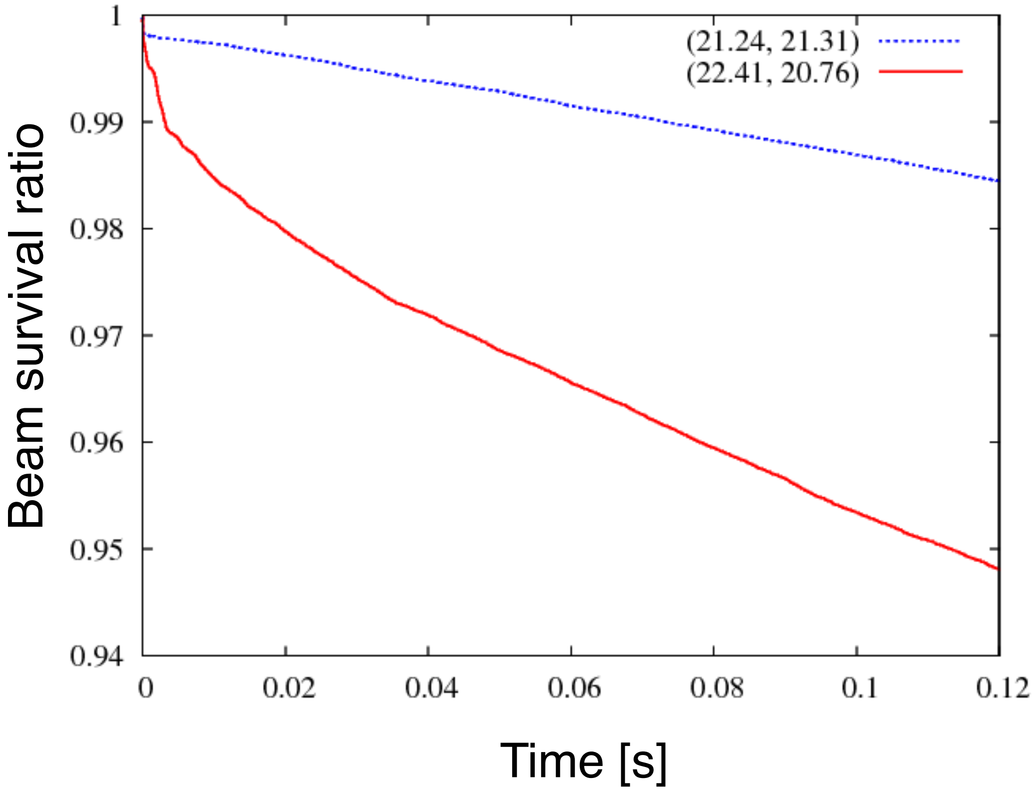


New operating point under investigation



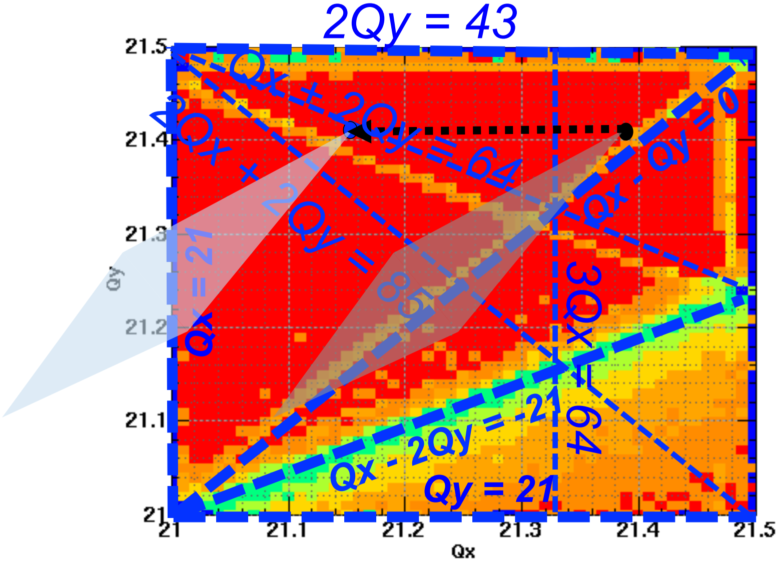
MR for 4.1e13 ppb

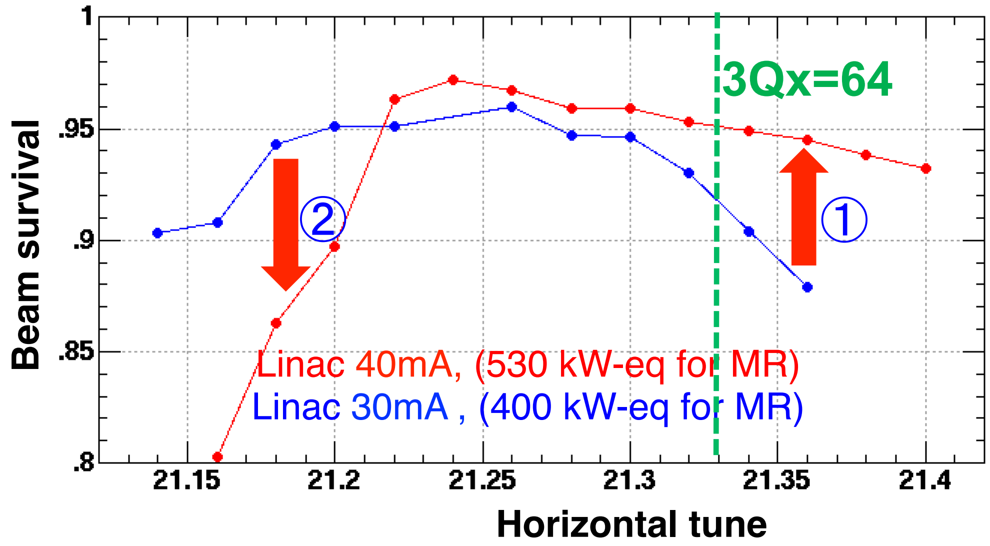
- Injection from RCS: 1MW
- Multipoles, Alignment errors
- BF 0.35 w (V1,V2)=(100,70) kV
- No instabilities
- No FX septum leakage field
- No residual mag. of RSXs



High Intensity beam study at (21.3, 21.3) area

Horizontal tune survey at 3 GeV

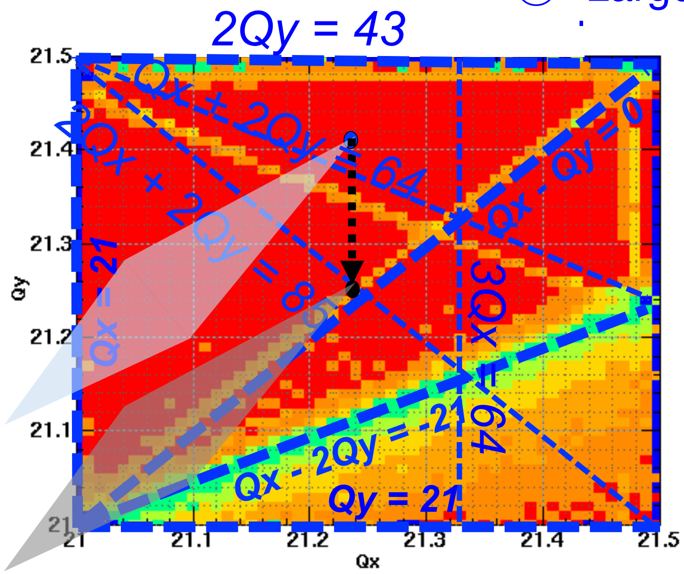


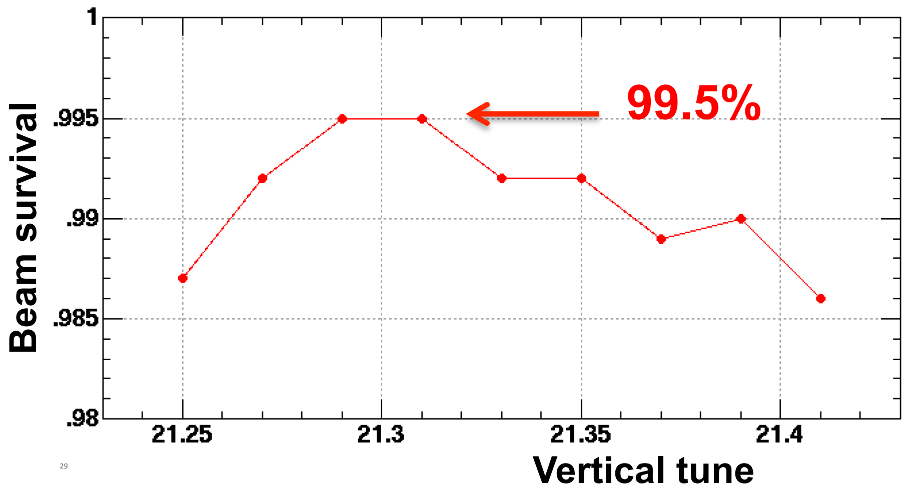


① 3^{rd} Integer resonance correction (3Qx=64) by Trim-Sext.

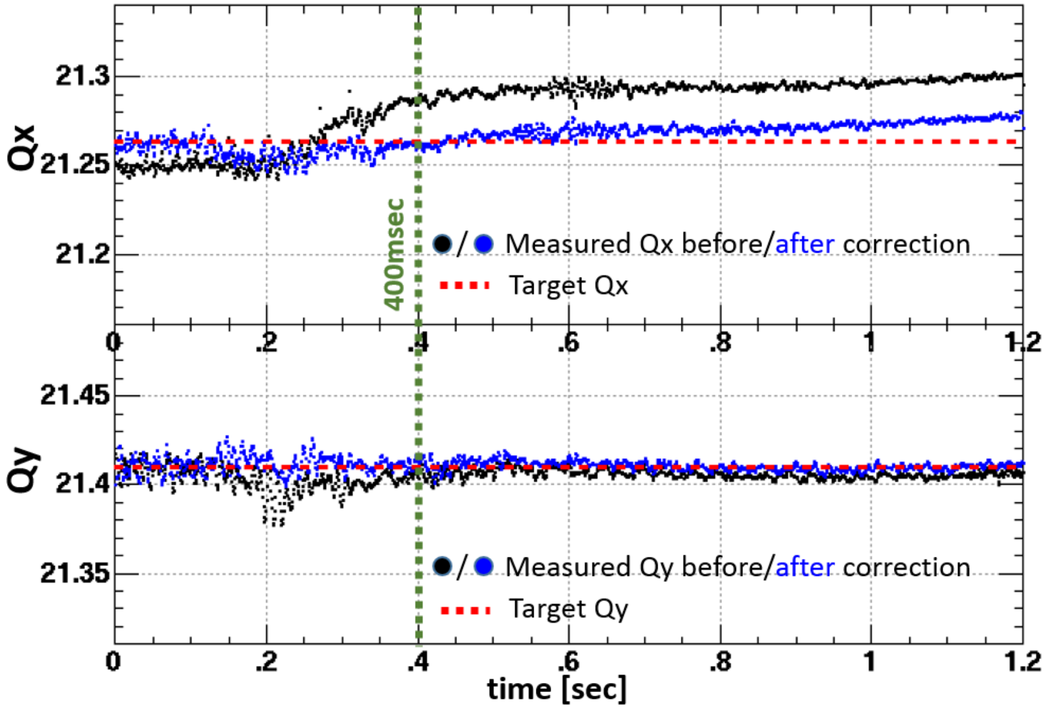
② Larger tune spread and crossing integer resonance (Qx=21)

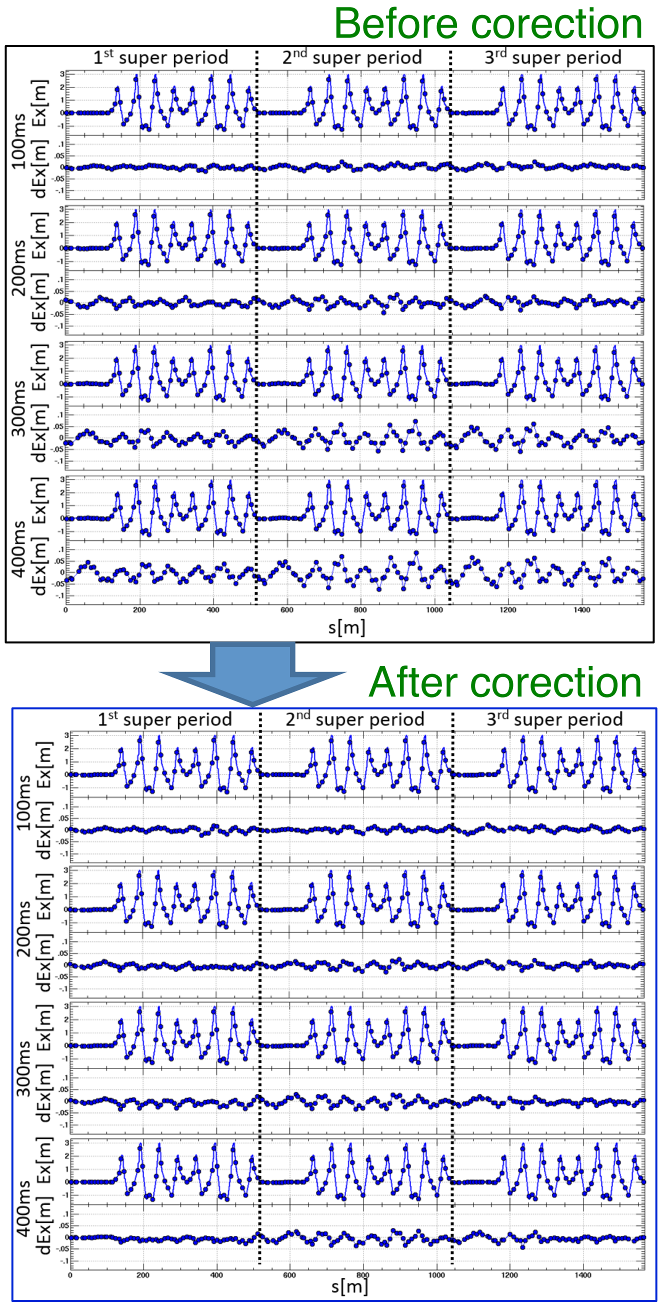
Vertical tune survey at 3 GeV





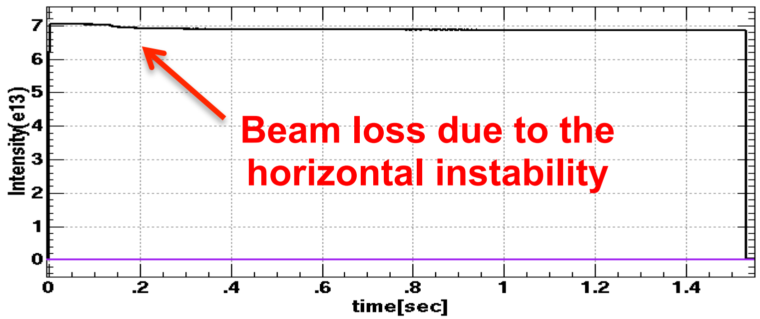
Optics correction during acceleration





High Intensity beam study at the betatron tune (22.239, 21.310)

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.

Contents

Mid-term plan of MR

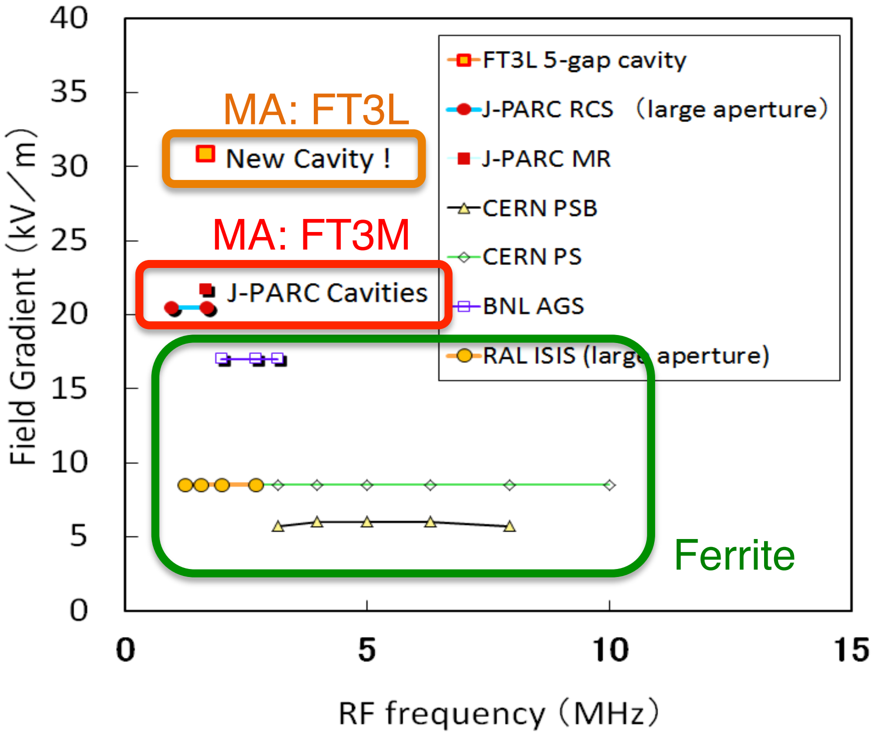
FX：The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, RF cavities and some injection and extraction devices.
SX： Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose. The beam power will be gradually increased toward 100 kW watching the residual activity.

JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	**320**	**> 360**	**400**	**450**	**700**	**800**	**900**
SX power [kW] (study/trial)	**-**	**> 38**	**50**	**50-70**	**50-70**	**~100**	**~100**
Cycle time of main magnet PS	**2.48 s**				**1.3 s**	**1.3 s**	**1.2 s**
New magnet PS	R&D	Large scale 1st PS		Mass production installation/test			
High gradient rf system	Manufacture, installation/test						
2nd harmonic rf system		R&D, manufacture, installation/test					
VHF cavity	R&D						
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system	Kicker PS improvement, Septa manufacture /test						
FX system	Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields			Local shields				
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

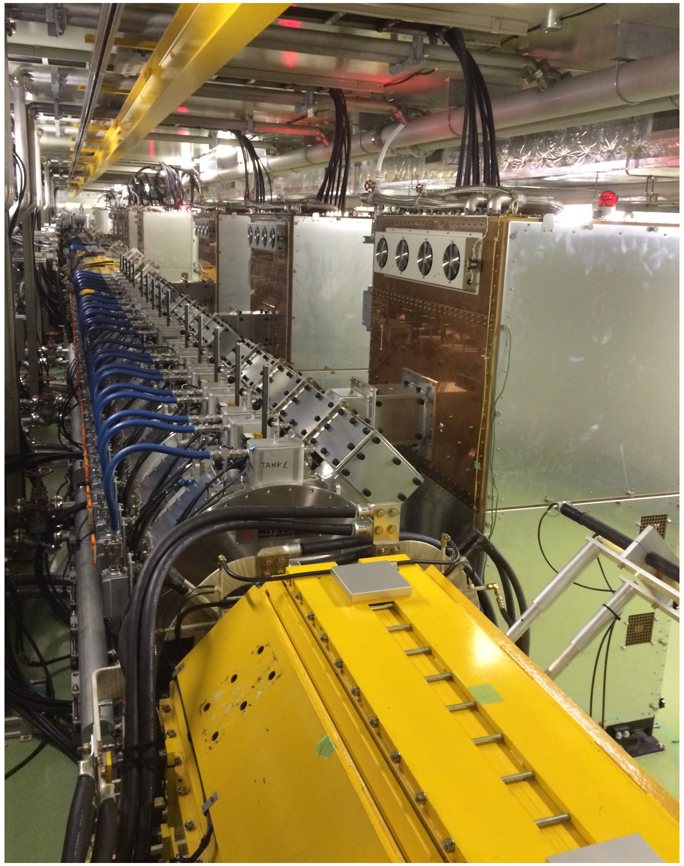
High impedance rf system

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 is operated stably for one year in the MR.
- Four new FT3L cavities was installed in the 2015 summer shutdown.

Summary

Achievements in MR user operation:

- Beam power in user operation :

  360 kW and 38 kW for the T2K experiment and HD users, respectively.

- High power demonstration :

  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 near future plan :

- The design power of 750 kW for the FX, and 100 kW for the SX will be achieved in 2018-2019 after the replacement of main magnet power supplies.

Thanks to the colleagues for the materials in this talk;

H. Harada, Y. Hashimoto, H. Hotchi, S. Igarashi, N. Kamikubota, Y. Kurimoto, F. Naito, K. Nakamura, C. Ohmori, Y. Sato, K. Satoh, M. Shirakata, J. Takano, F. Tamura, M. Tomizawa, T. Toyama and M. Yoshii.