Operation of the J-PARC Main Ring with the Moderate Beam Power: predictions and observations

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on behalf of the J-PARC commissioning team

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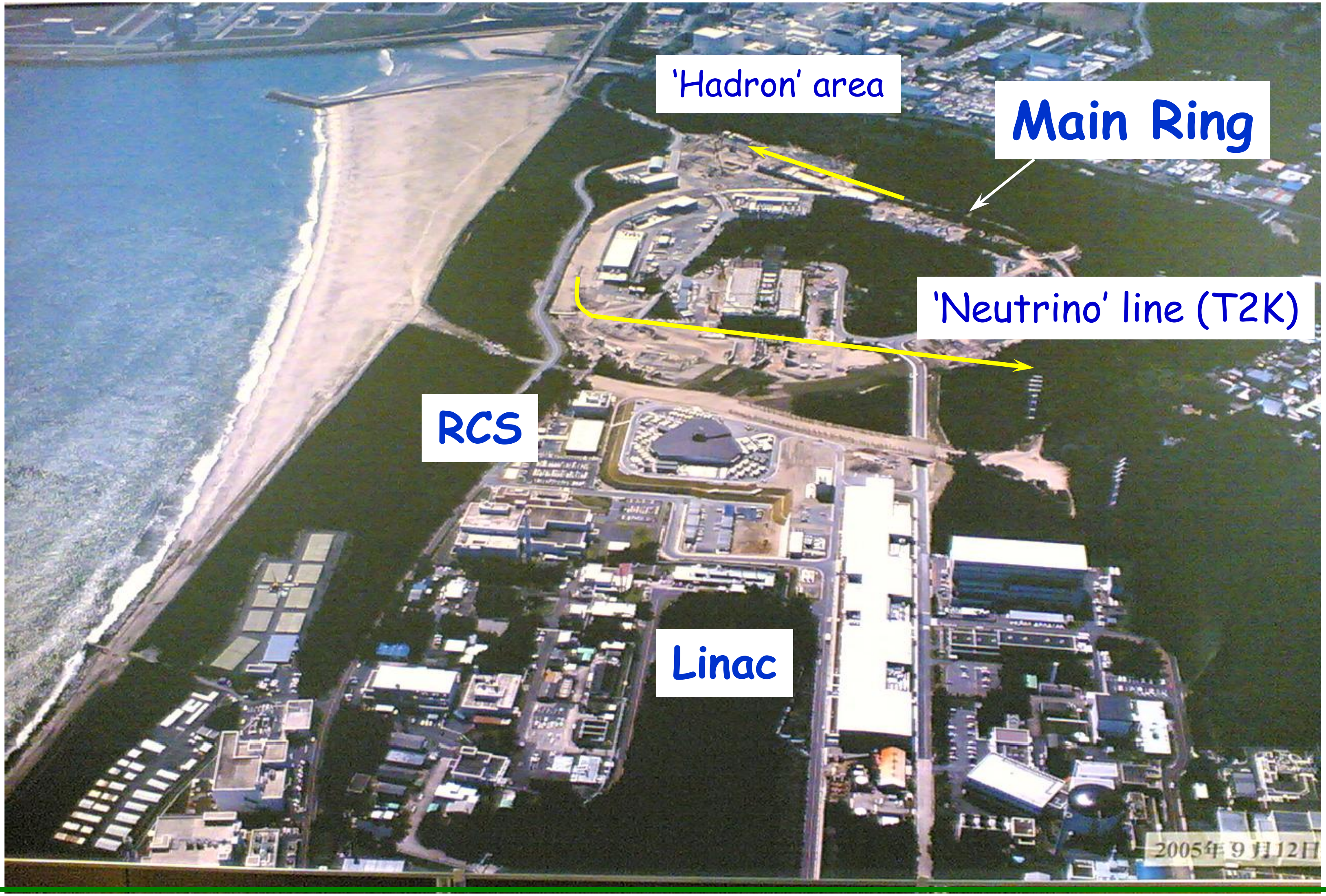
Morschach, Switzerland

OUTLINE:

- Overview of the J-PARC Main Ring
- Main Ring resonances and resonance correction for the 'zero' beam power: prediction and observation
- Main Ring predictions and observations for the moderate beam power … injection & acceleration

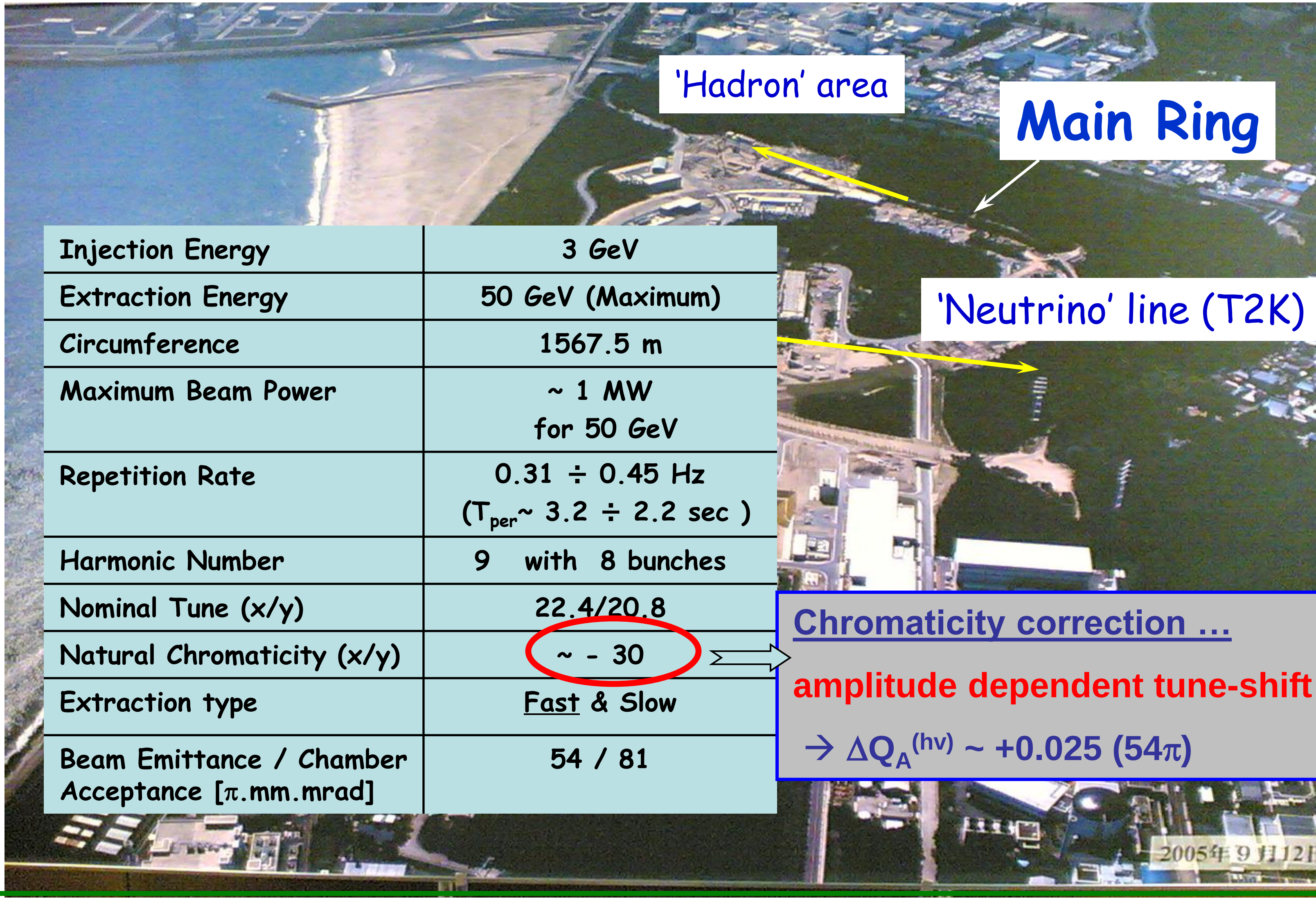
Design parameters of the JPARC Main Ring



Accelerator

J-PARC Japan Proton Accelerator Research Complex

Design parameters of the JPARC Main Ring



Injection Energy	3 GeV
Extraction Energy	50 GeV (Maximum)
Circumference	1567.5 m
Maximum Beam Power	~ 1 MW for 50 GeV
Repetition Rate	0.31 ÷ 0.45 Hz (T_{per}~ 3.2 ÷ 2.2 sec)
Harmonic Number	9 with 8 bunches
Nominal Tune (x/y)	22.4/20.8
Natural Chromaticity (x/y)	~ - 30
Extraction type	Fast & Slow
Beam Emittance / Chamber Acceptance [π.mm.mrad]	54 / 81

Chromaticity correction …

amplitude dependent tune-shift

→ $\Delta Q_A^{(hv)}$ ~ +0.025 (54π)

J-PARC Main Ring Performance

for the T2K experiment

	Linac [MeV]	RCS [kW]	$N_{bunches}$	T_{Rep} [sec]	RF system (45kV/cav)	Power/bunch @3GeV [kW/bunch]	Beam Power @30GeV [kW]
2010 *	**181**	**~ 300 (Dec'09)**	**6**	**3.2**	**4F**	**~ 1.8 (1.25 10^{13}ppb)**	**~ 112** ***Current status***
2010 2011							
2011 2012	181	600	8	2.47	6F+2H	~ 4.8	~ 388
2012 2014	400	600	8	2.23	6F+3H	~ 5.3	~ 430
		1000	8	2.23		**~ 8.9**	**~ 715** ***~1.1MW@50GeV***

MR Status (May 2010) :
*→ **70 kW** continuous operation;*
*→ demonstration of the '**100 kW equivalent**' beam operation of MR has been performed successfully by using the 'single shot' mode with the 6 bunches per shot.*

** Summer shutdown*

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Incoherent space-charge detuning:

ΔQ_{Inc} **~ -0.2** (B_f ~ 0.16)

** Summer shutdown*

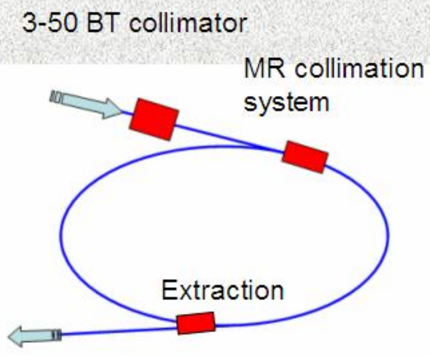
Motivation:

→ Combined effect of the machine resonances (realistic machine description) and the space charge at the injection energy by using the realistic 6D particle distribution …

→ Optimization the machine performance to minimize the particle losses …

Limitation of the LOST beam power for the J-PARC Main Ring (current status)

… to provide safe operation of the complex (< 0.03μSv/h on the ground)



Injection & Acceleration

	Acceptance [π mm.mrad]	Lost beam power capaticy [Watt]
3-50 BT	54 ÷ 81	450
MR collimator	54 ÷ 81	450
MR ring	81	~ 0.5 W/m

Other limitations for the lost beam power
'Fast' extraction → 1.12 kW
'Slow' extraction → 7.5 kW

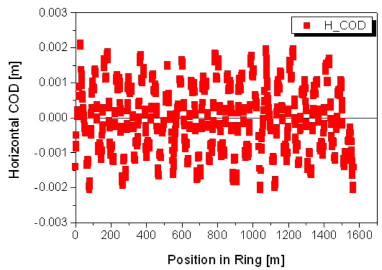
- MR operation with the 'zero' beam power: predictions & observation

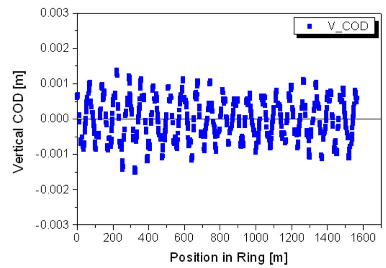
Main Ring computational model

- **The computational model of the MR** focusing structure has been developed by using all known data of the field measurements of each individual magnet of MR (MADX-PTC code) and the injection dog-leg, created by the bump-magnets (including edge-focusing).
- List **of measured field components** of different MR magnets, used for **the realistic MR lattice description:**
  - → *up to the sextupole components* $\{BM\}_{96}$
  - → *up to the* 5^{th} *order components* $\{QM\}_{216}$
  - → *up to the* 8^{th} *order* $\{SxM\}_{72.}$
  - → *field leakage of septum magnets …*
- **Measured alignment** and **strength errors** of each magnet .

COD and Beta function around MR: simulated and observed ('zero' beam power)

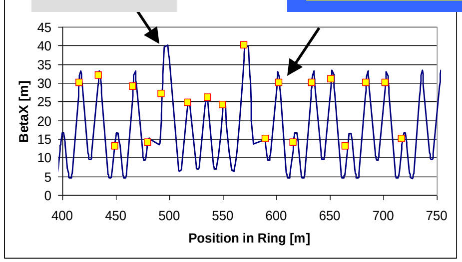
Model

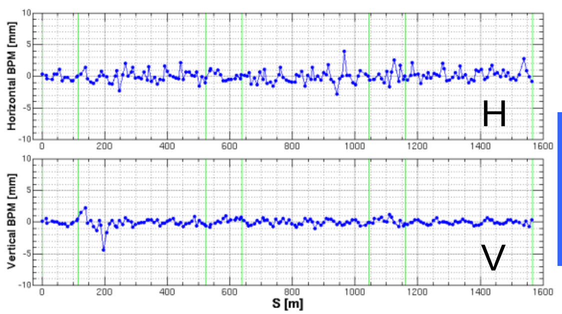




Model

Measured (2009)

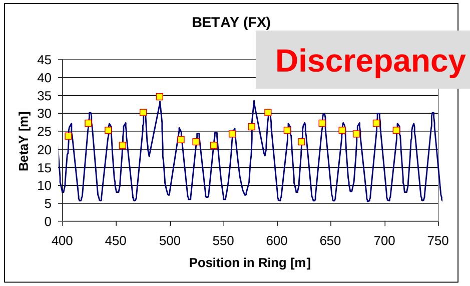




Observation (2010):

X_{COD} < (2 3) mm

Y_{COD} < 1 mm

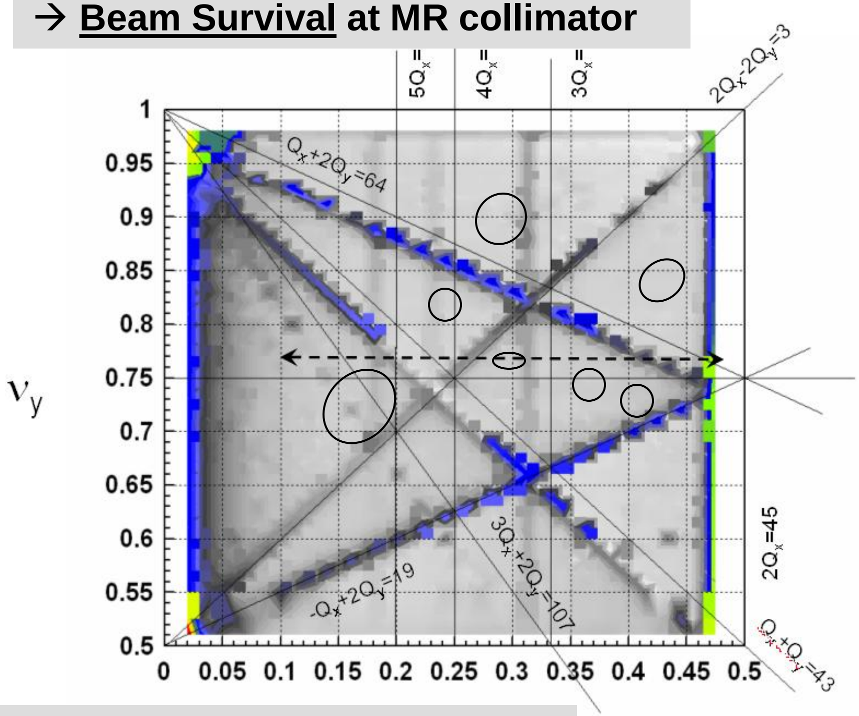


Discrepancy < 5%

Main Ring tune-scan study

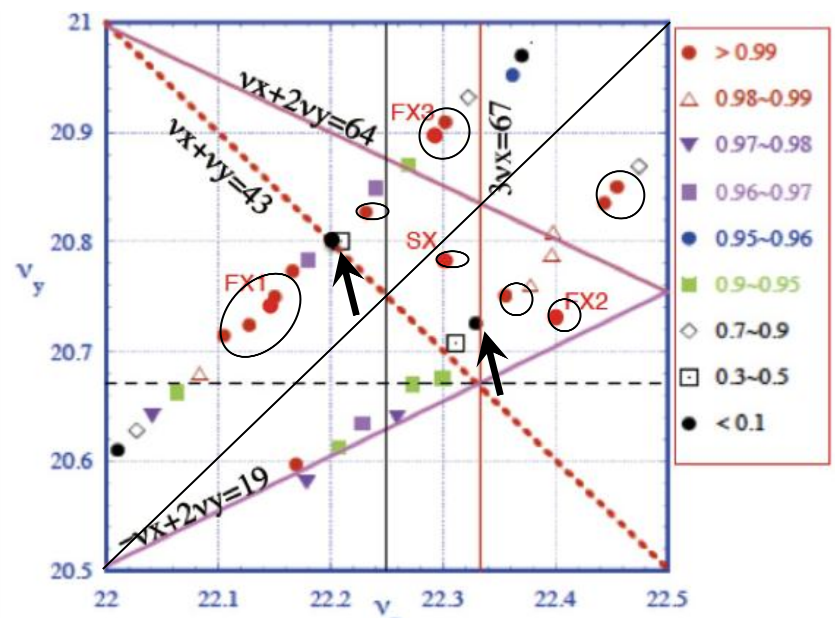
'zero' beam intensity (***4 10^{11} ppb***)

Single particle beam dynamics:
→ Dynamic aperture > 150π
→ <u>Beam Survival</u> at MR collimator



Tune-scan study (RUN #27- #28)

November 2009



Realistic MR imperfection
$HCOD_{max}$ < ± 2mm / $VCOD_{max}$ <   1mm
Chromaticity correction
ON&OFF momentum
Short-term tracking (4000 turns)
V_{RF} = 80kV (h=9)
MR Scraper = 60π
'PTC' code

◯ → Candidates of the 'bare' working points

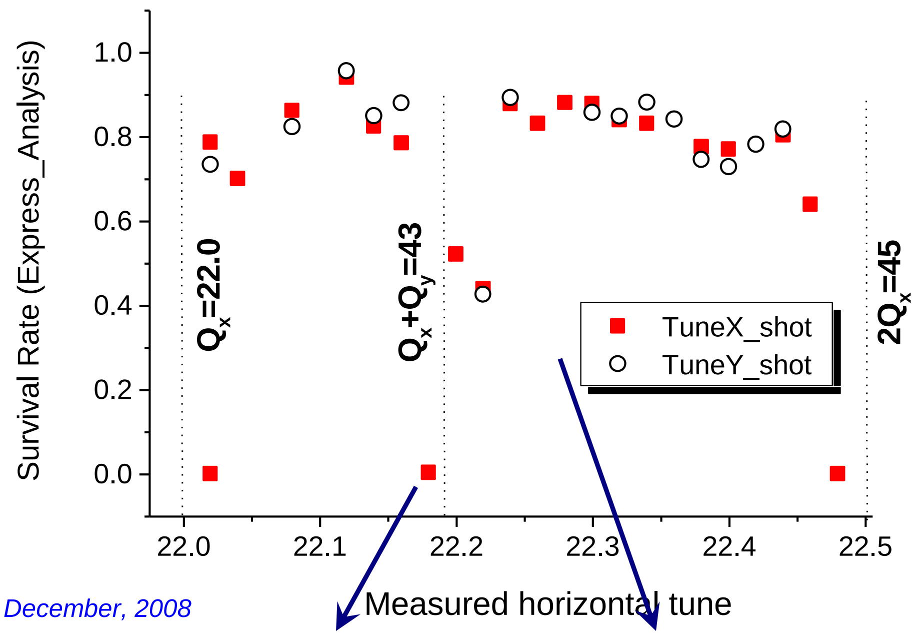
'DC' mode … $T_{capture}$ = 2sec
Beam transmission during 1.9 sec
Survival rate: p3/p2 → 40 msec
Corrected COD: HCOD < ± 2mm / VCOD < ± 1mm
Beam intensity <u>4 10^{11} pp bunch</u>
'Direct' injection with chromaticity correction
'Fast extraction' scenario

→ **significant particle losses: [1,1,43], [3,0,67]**

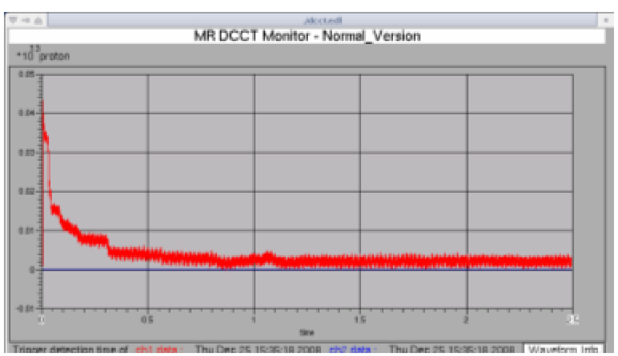
Main Ring tune-scan study

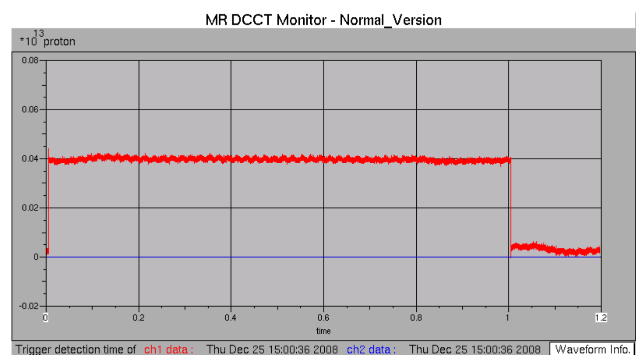
'zero' beam intensity (***4 10^{11} ppb***)

RUN#20: Tune scan / Q_y=20.79



December, 2008





Main Ring resonance observation and correction (model)

■ *<u>'Sum' linear coupling resonance [1,1,43]</u>*

Sources for MR:

{QM} measured alignment (XY-tilt) … Θ_{QM} : $1\sigma < 1\ \ 10^{-4}$ rad

VCOD at the MR chromatic sextupole magnets … < 1 mm

$Q_x + Q_y = 43$

Main Ring computational model (based on PTC)

→ <u>Local linear decoupling</u> by using 4 independent skew quads
→ <u>Global linear decoupling</u> by using 2 or 4 independent skew quads

<u>**Local linear decoupling** mechanism:</u>

- Based on the matrix decoupling at the point of observation …

<u>**Global linear decoupling** mechanism:</u>

- Based on minimization a 'Ripken' lattice function summed around the ring …

Main Ring resonance observation and correction (model)

$Q_x+Q_y=43$

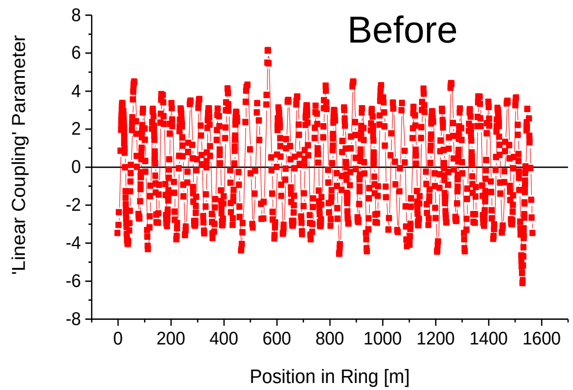
- 'Lattice' resonance correction (single particle dynamics / PTC)

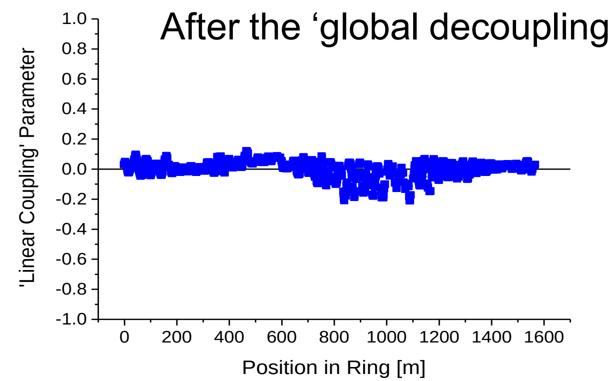
$\beta_{yx} \sim d\langle yx\rangle/dl$

$Q_x \sim 22.21$
$Q_y \sim 20.80$

[1,1,43] resonance

→ $(a_1L) < 5\% \, (k_1L)$
→ β-beat < 6%





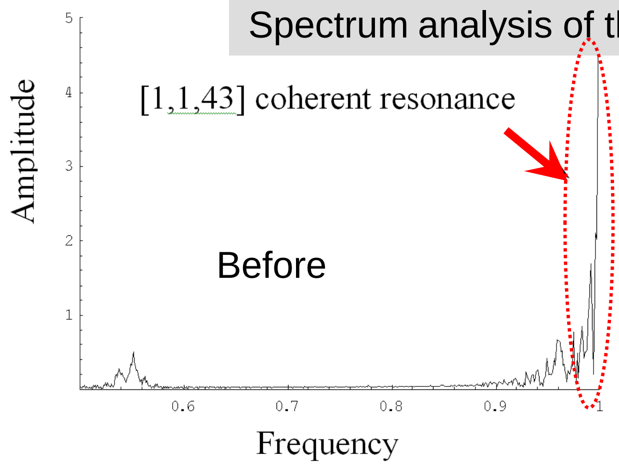
- Coherent response of the beam with the space charge effects (PTC-ORBIT)

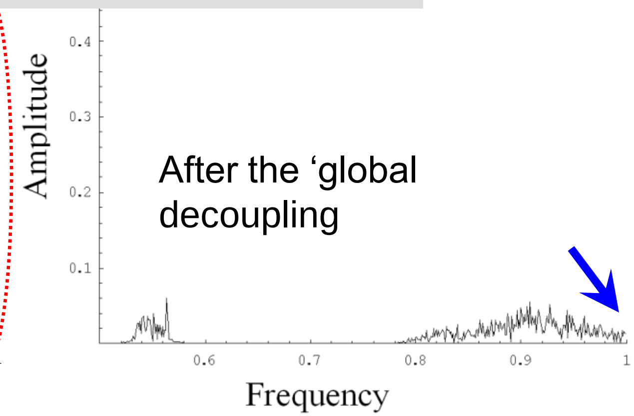
MR realistic model
$Q_x = 22.27$
$Q_y = 20.82$

RCS 6D beam
1.8kW/bunch

V_{RF} = 120kV
$B_f \sim 0.16$
$\Delta Q_{INC} \sim -0.15$

Spectrum analysis of the <xy> coherent mode





Main Ring resonance observation and correction

$Q_x+Q_y=43$

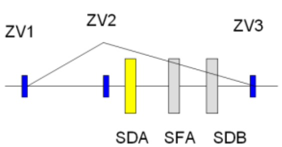
- … create the required skew quadrupole field component by using **the <u>local VERTICAL bump</u>** of the circulating orbit at the location of two sextupole magnets with the appropriate phase-advance to demonstrate ability to minimize the particle losses, caused by the [1,1,43] resonance.

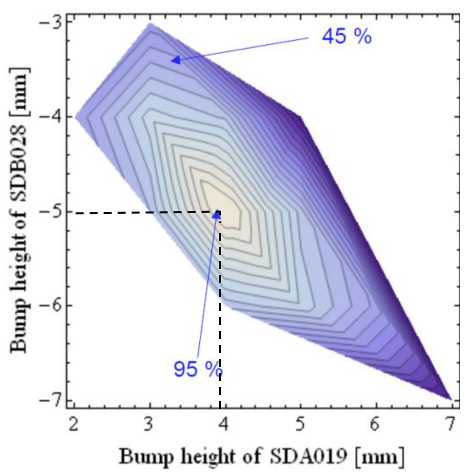
- … the global linear decoupling has been performed by using the MR computational model (PTC).

<u>PREDICTION:</u> the local vertical bump of the circulating orbit at the location of two appropriate sextupole magnets for the chromaticity correction should be about (2 3) mm.

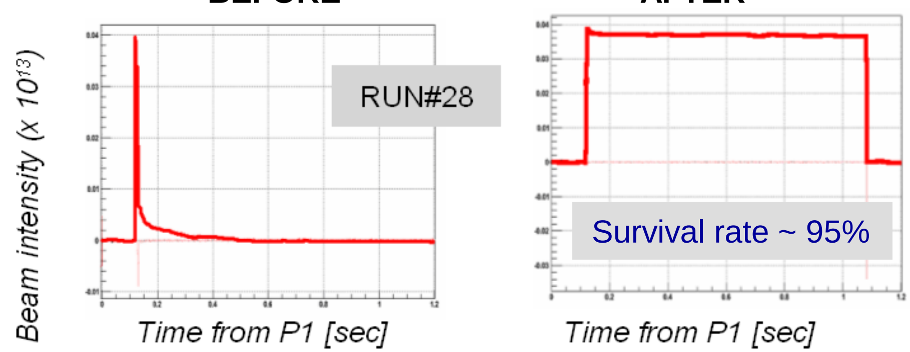
Observation ('zero' beam intensity)

'Lattice' tune:
$Q_x = 22.20$
$Q_y = 20.80$





BEFORE **AFTER**



*Measured beam intensity **BEFORE** and **AFTER** correction the [1,1,43] resonance by using the local V-bumps at the location of two sextupole magnets.*

* For real MR configuration it is not possible to make the local bump of the beam orbit without touching the nearest sextupole magnets …

A.Molodozhentsev (KEK)

MR operation with the moderate beam power:

predictions & observation

→ **Realistic 6D particle distribution from J-PARC RCS**, including effects of the 3-50BT collimation system.

→ **Realistic MR RF system** (4 cavities): fundamental harmonic (h=9) with V_{max}=45kV/cavity.

Purpose: predict the 'bare' working point to provide minimum particle losses for injection & acceleration for the case of 100kW@30GeV.

MR operation with the moderate beam power

REALISTIC 6D:

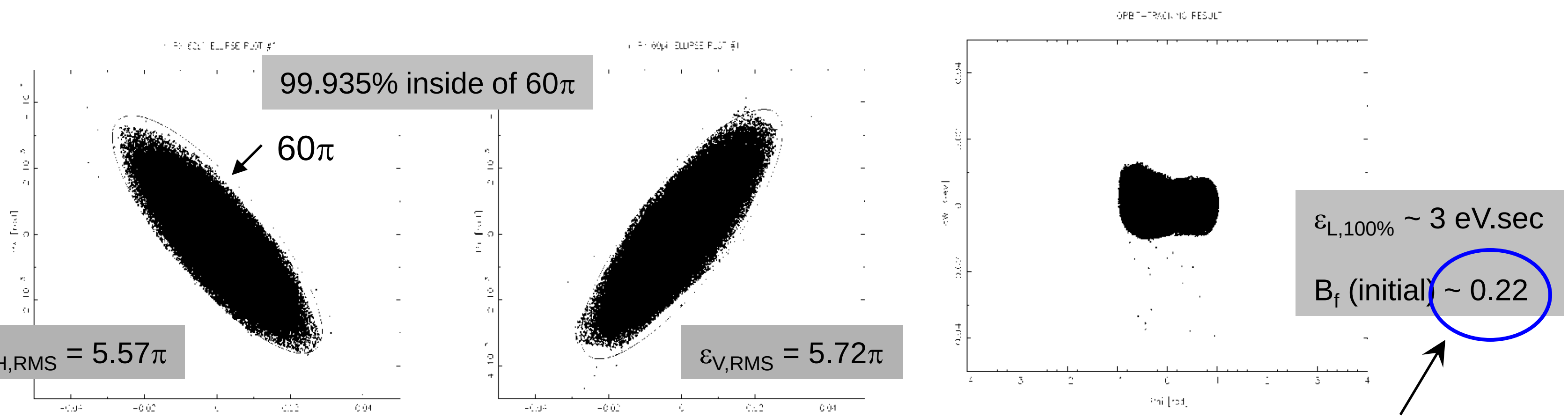
→ **6D@RCS@3GeV@322kW** (simulated/'T&L Paint' injection/'MR' extraction)

→ 3-50 Beam Transport (BT) line collimation system ('STRUCT' code)

*Estimated power of the lost beam **~ 100 W** (jaw@54/T_{REP}=3.2sec)*

→ 6D particle distribution at the primary MR collimator … as initial 6D for tracking …

N_{mp} = 197'844



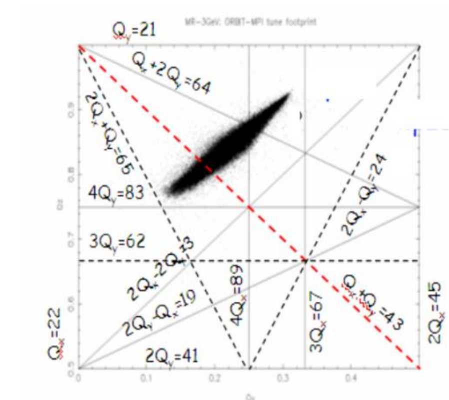
Transverse and COD matched injection

… by using the 2nd harmonic RF voltage just before the extraction from RCS

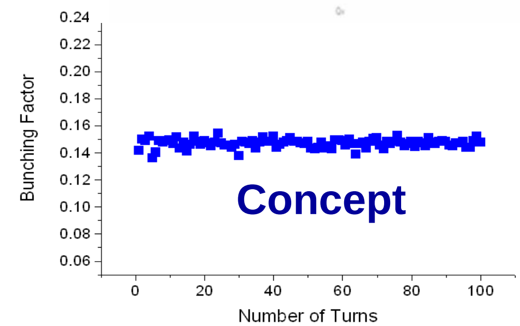
MR operation with the moderate beam power

→ ***J-PARC current status:***

*LINAC energy **181MeV***
RCS injection: Paint (Transverse & Longitudinal)
*RCS beam power for the MR operation **~ 300kW,** 2 bunches/pulse*
RCS RF manipulation to increase B_f for the MR injection
MR beam power ~ 10kW@3GeV (6bunches, T_{rep}= 3.6sec)



⌖ PREDICTIONS:
… to provide minimum particle losses during the MR operation, the bunching factor $B_f = <I>/I_{peak}$ **<u>should be more than 0.15</u>** for the moderate beam power from RCS. In this case the incoherent space charge detuning at the injection energy is about $\Delta Q_{INC} \leq 0.2$.

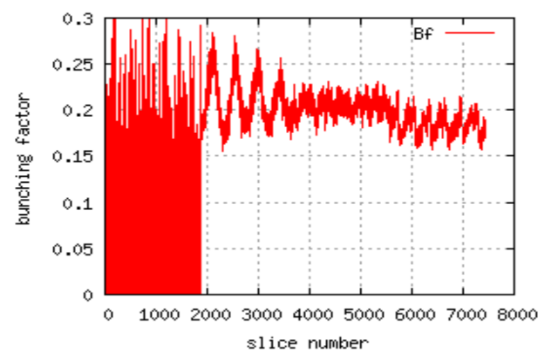


<u>Concept:</u> 'artificial' Longitudinal 2D with ε_L ~ 3eV.sec

■ Observation (**RUN#34** /July 2010)

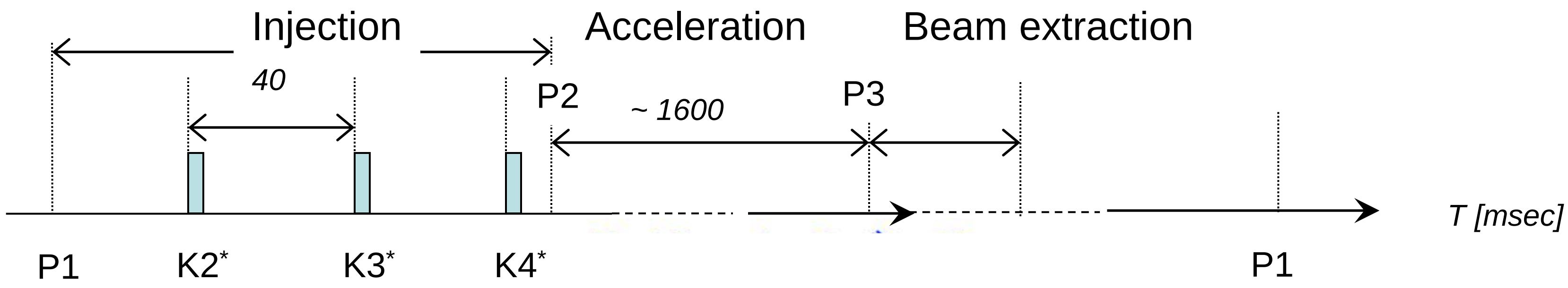
Measured B_f as a function of time at the beginning of the injection/capture process:

→ *Increase B_f up to 0.2*
→ *V_{RF} (h=9) ~ 65 70 kV* *

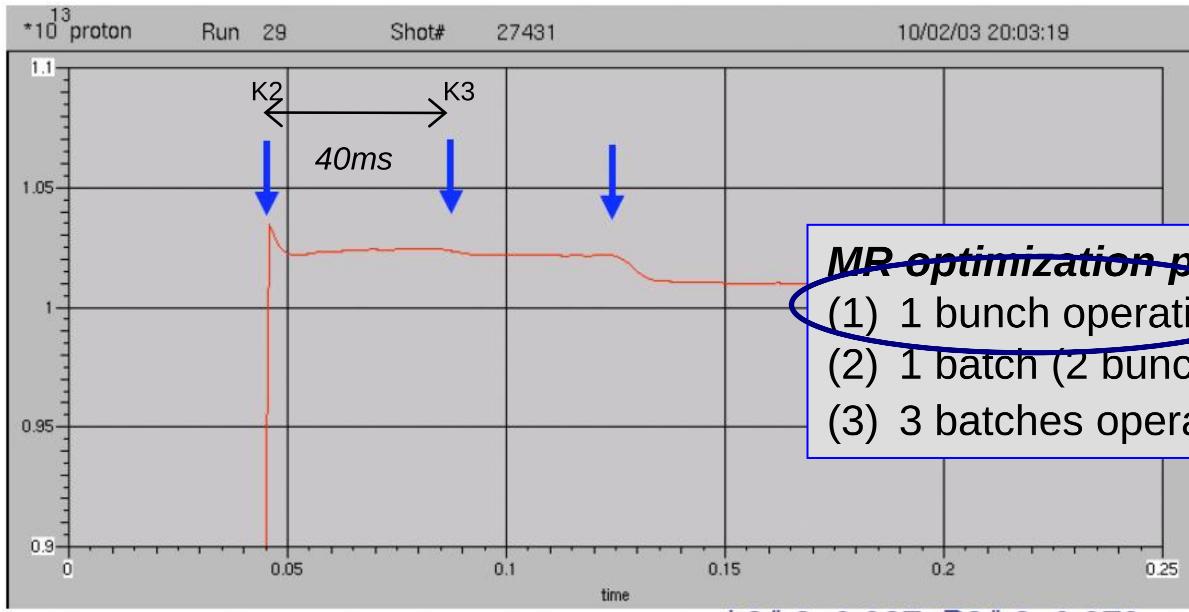


* *RF pattern during injection / acceleration to reduce beam losses*

Time structure of the MR operation



Injection septum2の漏れ磁場



MR optimization procedure:

(1) 1 bunch operation
(2) 1 batch (2 bunches) operation
(3) 3 batches operation

k3/k2=0.987, P3/k2=0.979

** One batch contains two bunches from RCS*

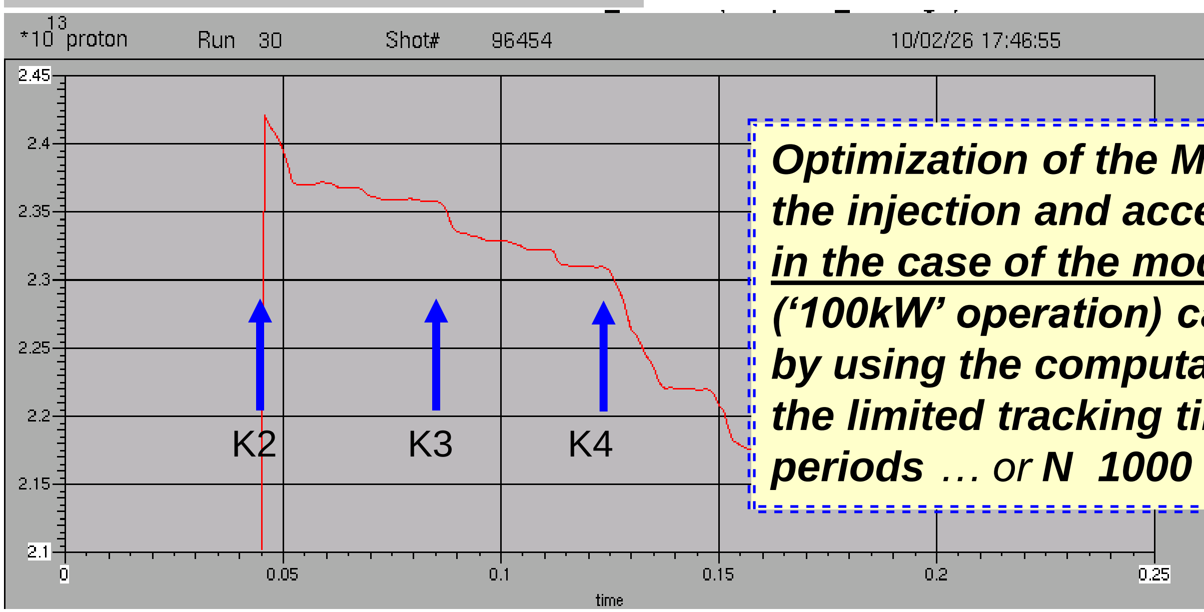
40ms (3GeV) → *~ 7200 turns*

1/24のロス(6バンチで1.2 % loss)を再現していない。

Time structure of the MR operation

- typical DCCT output for the **non-optimized** MR performance during the injection:
  → injection errors (‘fast’ losses … < 100 turns)
  → RF mismatching (‘fast’ losses … < 2 3 N_S … < 1000 turns)
  → Resonance effects (can be observed during (1 3) 1000 turns)

‘100kW@30GeV’ equivalent



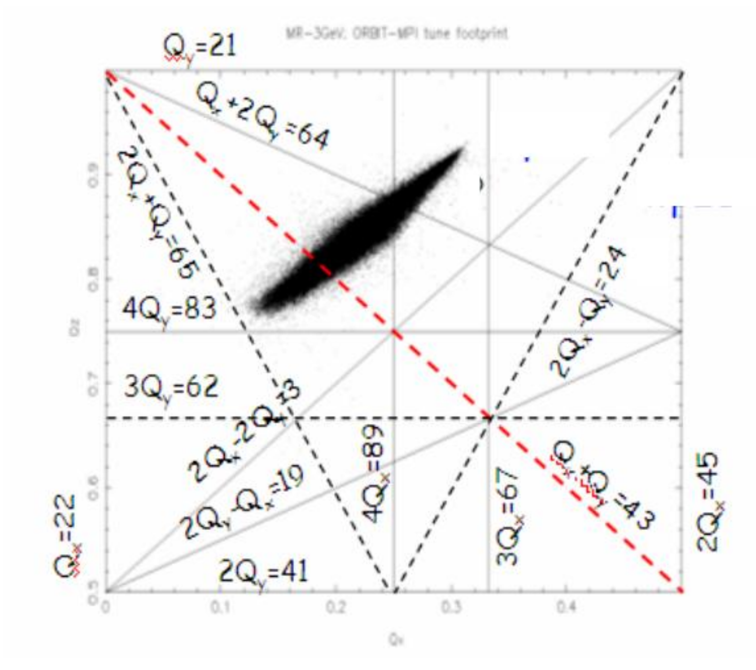
***Optimization of the MR performance during the injection and acceleration processes <u>in the case of the moderate beam power</u> (‘100kW’ operation) can be performed by using the computational MR model with the limited tracking time (a few synchrotron periods** … or **N 1000 turns**).*

** One batch contains two bunches from RCS*

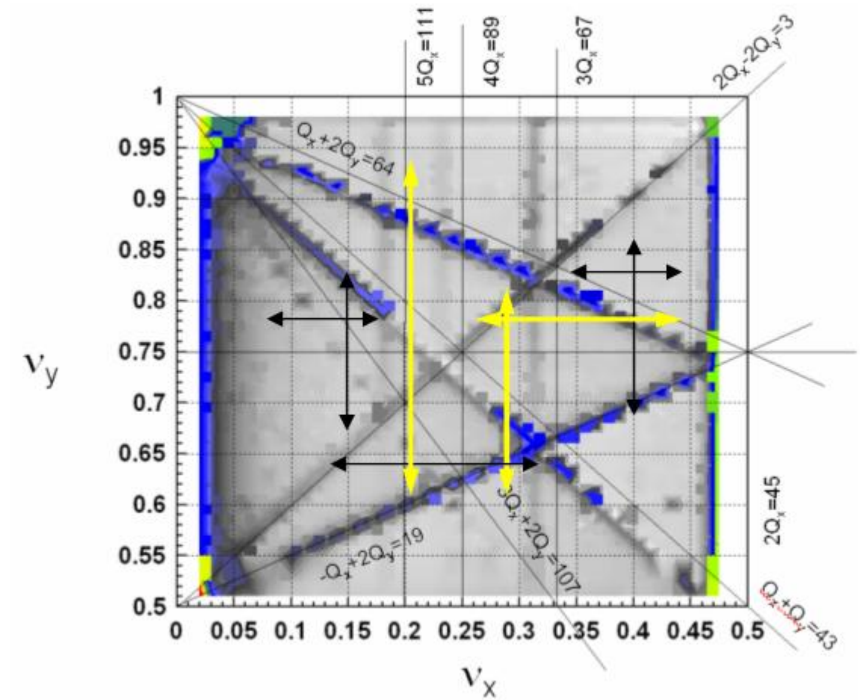
40ms (3GeV) → ~ 7200 turns

Main Ring tune-scan study:

moderate beam power (100kW@30GeV)



'Conceptual' space charge incoherent detuning (B_f ~ 0.15) for the case of the single harmonic RF system.



MR lattice resonances and performed tune-scanning (simulations) to minimize the beam loss.

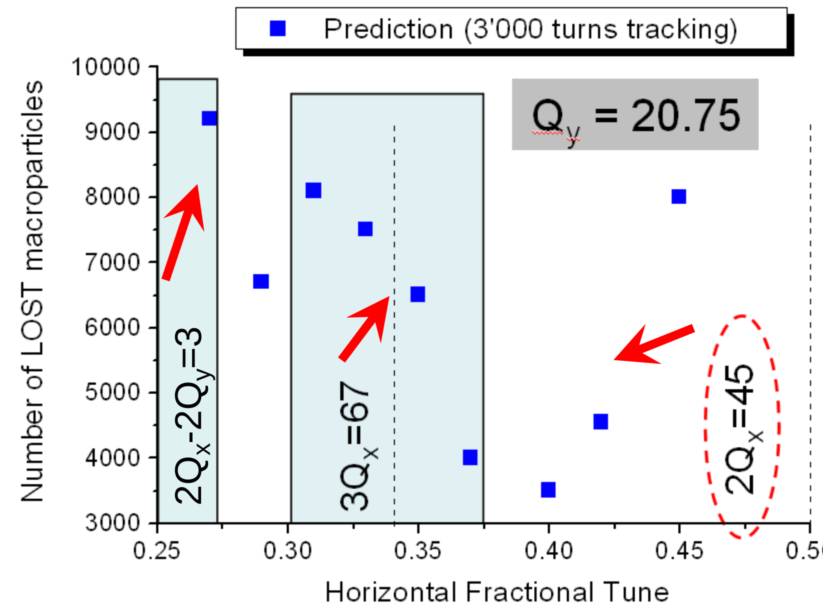
GOAL: minimization the particle losses during the injection process taken into consideration **the machine imperfection resonances and the low energy space charge effects** … to make predictions of the losses for different 'bare' tunes.

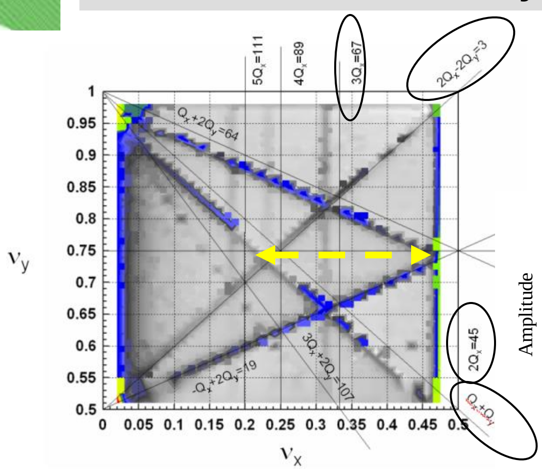
Main Ring tune-scan study:
moderate beam power (100kW@30GeV)

Prediction #1 (injection) / PTC_ORBIT

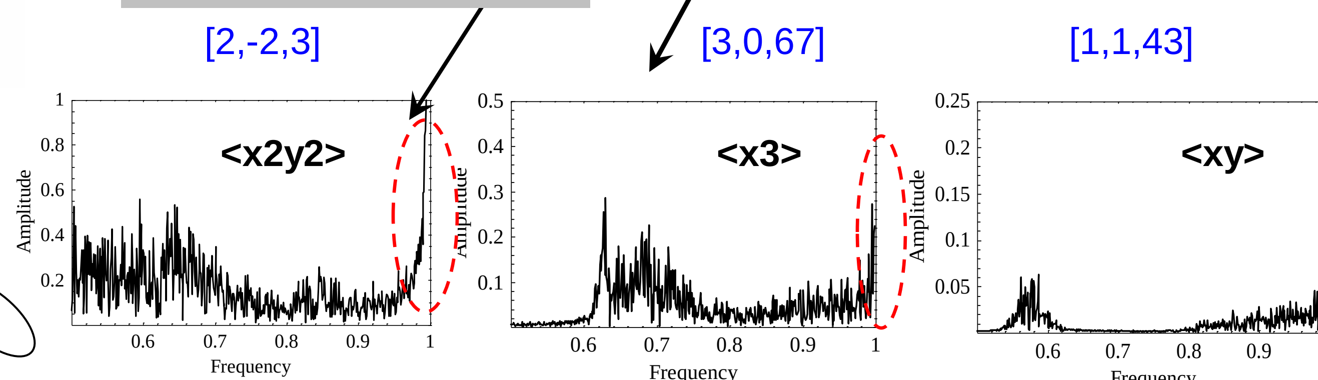
Simulation conditions (~ 200'000mp):

- → ***6D RCS beam***
- → ***3-50BT collimator @ 54π***
- → ***Beam intensity 1.2e13 ppbunch***
- → ***Global correction of [1,1,43] by using 2 skew quads***
- → ***V_{RF} = 80kV (h=9) … B_f ~ 0.18***
- → ***MR scraper acceptance = 60π***
- → ***Matched injection (Transverse & COD)***
- → ***H_COD_{max} ~ 3mm, V_COD_{max} ~ 1.5mm***
- → ***full linear chromaticity correction***





Coherent mode analysis



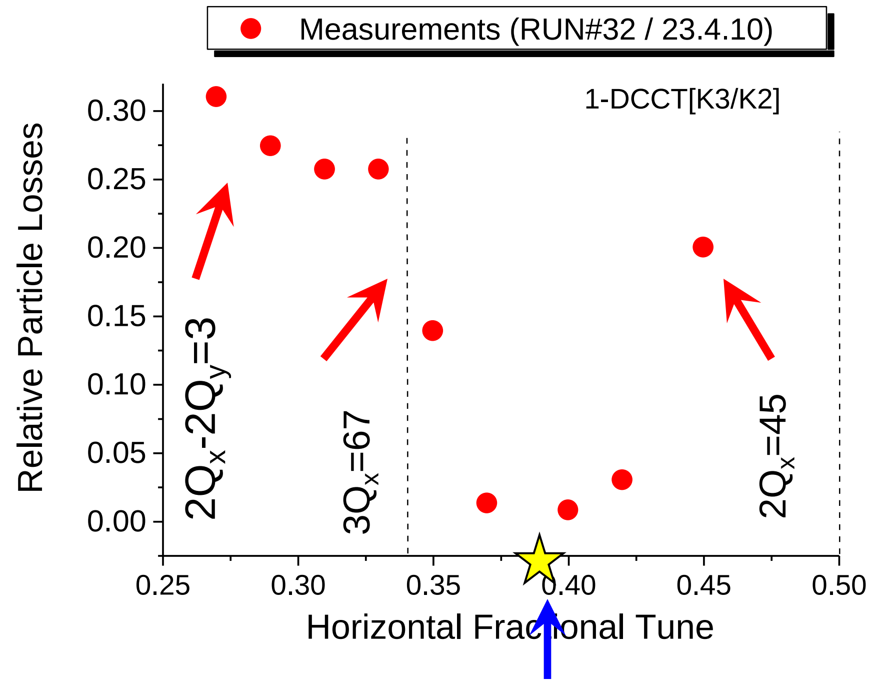
Main Ring tune-scan study:
moderate beam power (100kW@30GeV)

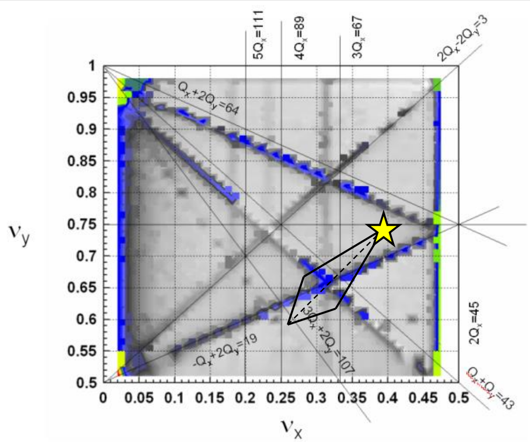
Observation: *RUN#31- #32*

Measurement conditions:

- → ***RCS beam power 300kW***
- → ***3-50BT collimator → OPEN***
- → ***Beam intensity 1.3e13 ppbunch***
- → ***[1,1,43] correction by local V_bump at 2SX***
- → ***V_{RF} = 80kV (h=9) … B_f ~ 0.18***
- → ***MR scraper acceptance = 60π***
- → ***Matched injection (Transverse & COD)***
- → ***H_COD_{max} ~ 3mm, V_COD_{max} ~ 1.5mm***
- → ***full linear chromaticity correction***
- → ***1 batch operation (K2)***

Q_y = 20.75





Minimum particle losses (3 batches):

DCCT: K3/K2 = 0.987 (injection)

P3/P2 = 0.983 (acceleration)

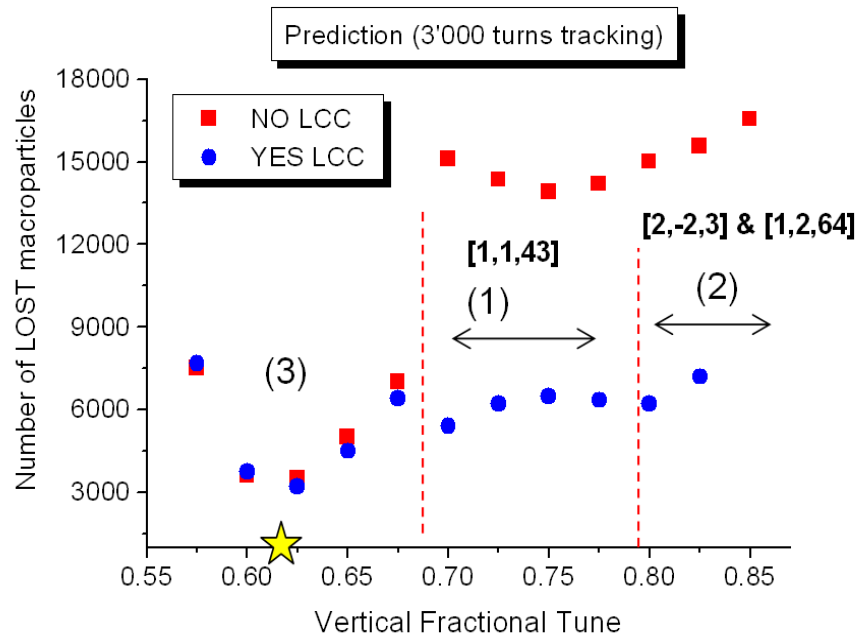
Main Ring tune-scan study:
<u>moderate beam power (100kW@30GeV)</u>

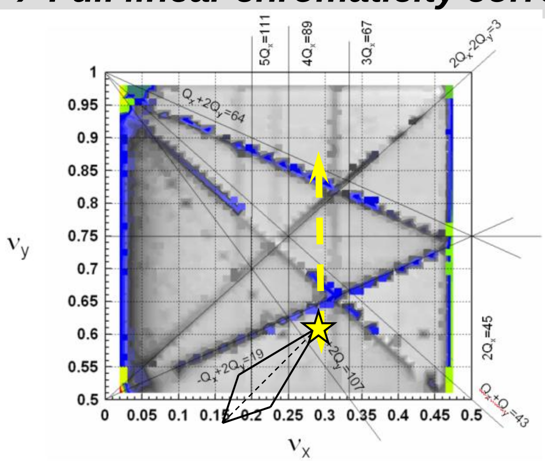
<u>Prediction #2</u> (injection) / PTC_ORBIT

Q_x=22.30

<u>Simulation conditions (~ 200'000mp):</u>

- ***→ 6D RCS beam***
- ***→ 3-50BT collimator @ 54π***
- ***→ Beam intensity 1.2e13 ppbunch (1.8kW/b)***
- ***→ Global correction of [1,1,43] by using 2 skew quads***
- ***→ V_{RF} = 80kV (h=9) … B_f ~ 0.18***
- ***→ MR scraper acceptance = 60π***
- ***→ Matched injection (Transverse & COD)***
- ***→ H_COD_{max} ~ 3mm, V_COD_{max} ~ 1.5mm***
- ***→ Full linear chromaticity correction***





<u>Predictions:</u>

(1) → correction of the [1,1,43] resonance should reduce the particle losses significantly for the corresponding tunes;

(2) → [2,-2,3] and [1,2,64] resonances lead to particle losses;

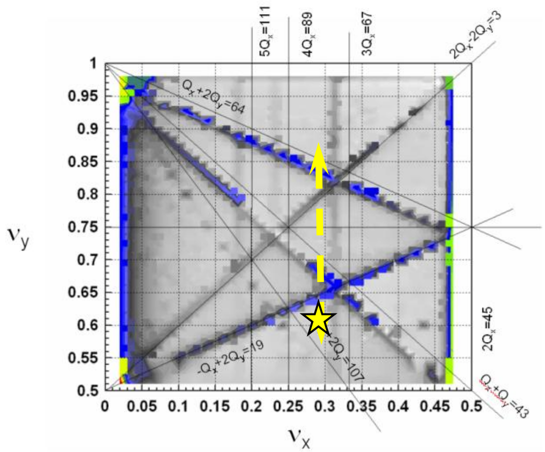
(3) → *<u>minimum particle losses</u>* should be observed below the [1,1,43] resonance line <u>even without correction of the linear coupling</u> → ☆

Main Ring tune-scan study: moderate beam power (100kW@30GeV)

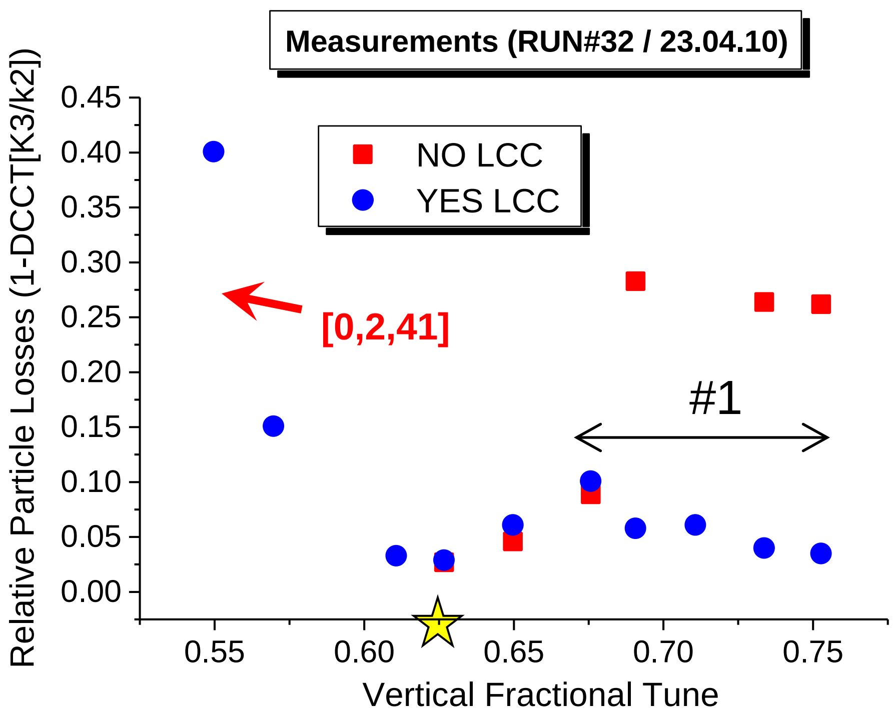
Observation: *RUN#32/#34*

Measurement conditions:

- → ***RCS beam power 300kW***
- → ***3-50BT collimator → OPEN***
- → ***Beam intensity 1.3e13 ppbunch***
- → ***[1,1,43] correction by local V_bump at 2SX***
- → ***V_{RF} = 80kV (h=9) … B_f ~ 0.18***
- → ***MR scraper acceptance = 60π***
- → ***Matched injection (Transverse & COD)***
- → ***H_COD$_{max}$ ~ 3mm, V_COD$_{max}$ ~ 1.5mm***
- → ***full linear chromaticity correction***
- → ***1 batch operation (K2)***



Q_y = 22.30



#1 → effect of the linear coupling correction

☆ → minimum particle losses have been observed below the [1,1,43] resonance without any resonance corrections (as predicted)

A.Molodozhentsev (KEK)

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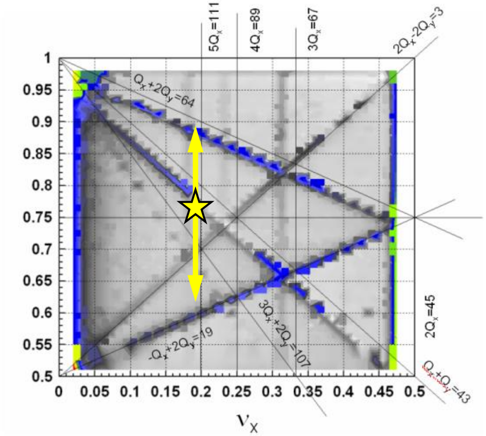
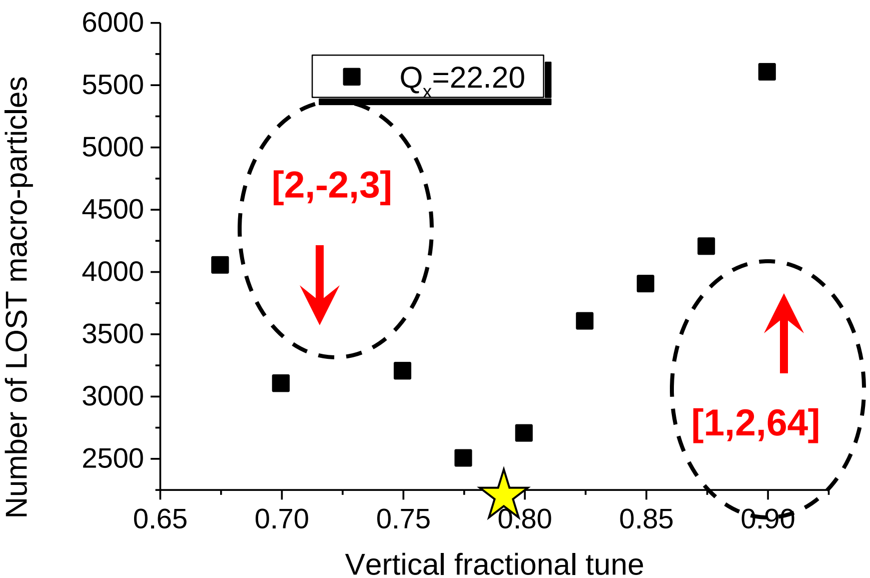


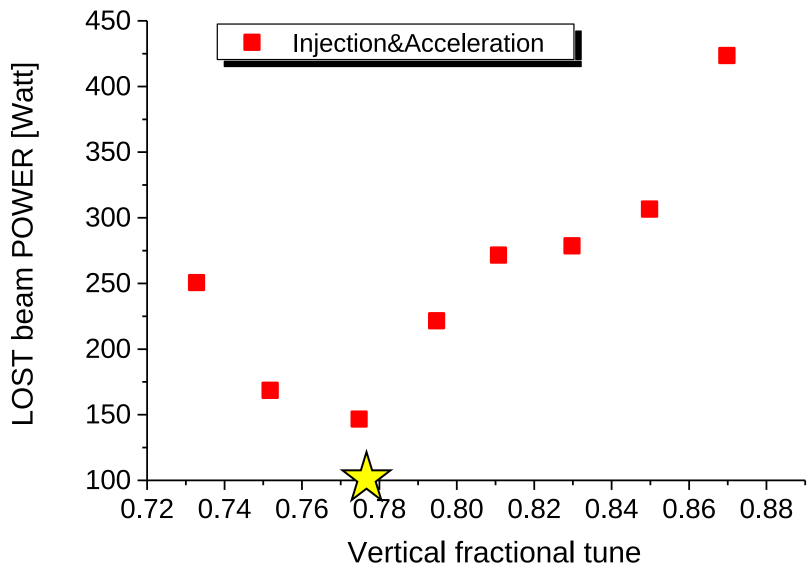
Predictions and observations:

- → With correction the [1,1,43] resonance
- → **Prediction** for the injection process only
- → **Observation:** injection and acceleration (~ 2sec)

Prediction (3'000 turns tracking)



Observation: RUN#33 (10/05/10)



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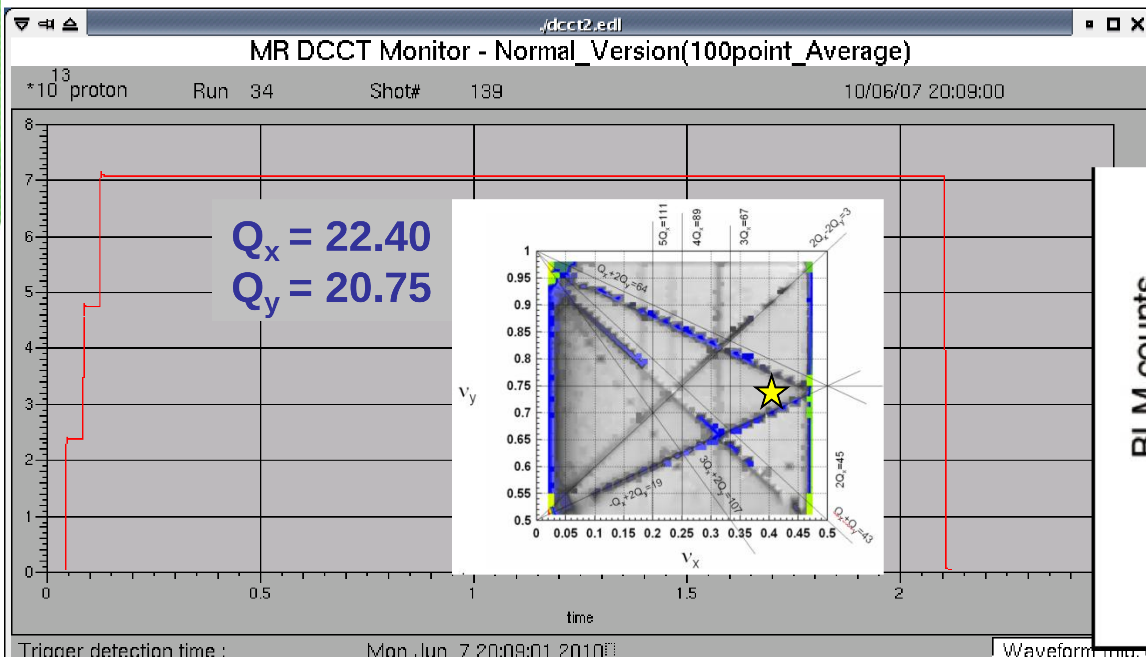
Demonstration of the **'100kW equivalent'** MR operation by using the **'single-shot' mode** (not continuous operation) **has been performed successfully** (June 7, 2010):

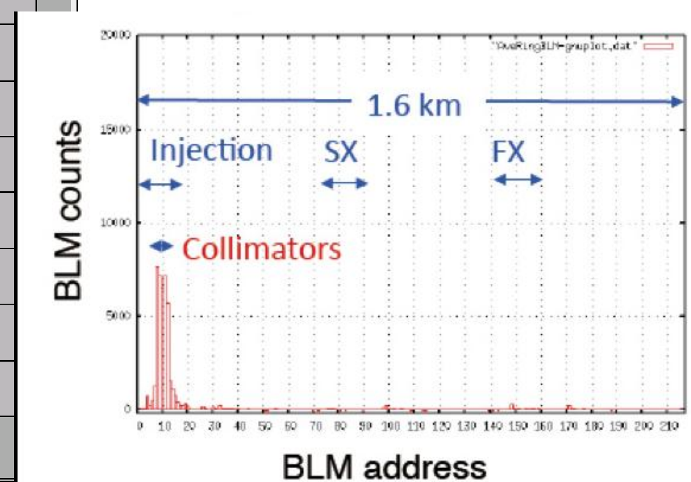
→ the extracted beam to the abort beam dump was 7.2 10^{13} proton per pulse with the six-bunch operation;

→ including the [1,1,43] resonance correction;

→ the particle losses are localized at the collimation section during the ***injection&acceleration processes*** … the total loss is about 7.7 10^{11}, which corresponds to **~ 120W** (as predicted).



MR collimator = 60π



J-PARC
Accelerator
Japan Proton Accelerator Research Complex

Conclusions:

- Predictions, made by using the computational model of J-PARC Main Ring, and experimental results for the moderate beam power are in the reasonable agreement.
- Performed optimization of the J-PARC Main Ring performance allows to provide the total particle losses ~ 120Watt during the injection and acceleration processes (~ 0.12% from the beam power at 30GeV).
- The developed computational model will be used to optimize the J-PARC MR performance for the high beam power operation.

Thank you for your attention !