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Study of the space charge effects for J-PARC Main Ring

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Outline of the talk:

- Main parameters of J-PARC Main Ring
- Tool-Box and Model for the space charge study for MR
- Resonance excitation and Emittance growth
- Lost beam power for MR

J-PARC Accelerator Complex

J-PARC Main Ring: Features

1. Imaginary Transition gamma: the missing bend structure
2. Slow extraction scheme based on the $3Q_x$ resonance ($3Q_x$=67)

Injection Energy	3 GeV
Extraction Energy	50 GeV (Maximum)
Circumference	1567.5 m
Maximum Beam Power	0.75 MW * for 50 GeV
Repetition Rate	0.285 Hz (T_{per}~ 3.5sec)
Harmonic Number	9 ⇨ 8 bunches
Nominal Tune (x/y)	22.4/20.8
Natural Chromaticity (x/y)	~ -30
Beam Emittance / Chamber Acceptance	54 / 81 π.mm.mrad

* … needs in 1MW beam power from RCS

J-PARC Main Ring: Beam Power

	"Day-1"	"Day-2"
LINAC Energy [MeV]	181	400
RCS Beam Power at 3 GeV [MW]	0.3 - 0.6	1.0
MR Beam Power at 3 GeV [kW] ~ 4.76% from RCS Beam Power	13.7 - 27.4	45.7
MR Beam Power at 50 GeV [kW]	228.5 - 457.1	760
MR Harmonic Number	9	9
Number of Bunches	8	8
Beam Intensity × 10^{14}	1.0 - 2.0	3.3
"Free-space" incoherent space charge tune shift (W_k=3GeV, Uniform:54π mm.mrad, B_f ~ 0.2*)	~(- 0.04) - (-0.08)	~ (-0.13)

* "Fundamental" harmonic RF-cavity

J-PARC Main Ring: Strict Limitation of Beam Losses

Technical Design Requirement:

MR Collimator should accept about 1% from the total beam power

Study of the Halo formation

Behavior of the 99% emittance …

Maximum particle losses at the MR collimator at the injection energy should be less than 450W.

Other areas around MR:: < 0.5W/m

Step 1: Single particle dynamics (COSY Infinity / M.Berz et al.)

- Combined effect of fringe field of the MR magnets and the 'chromatic' sextupole fields …

  - ✓ Main field nonlinearity for MR is the 'chromatic' sextupole fields.

- Optimization of the 'bare' working point for MR …

  - ✓ Recommended 'bare' working points are located in the region with the following betatron tunes to provide maximum beam survival at the MR scraper:

    $Q_x = 22.4$ / $Q_y = 20.8$ and $Q_x = 22.28$ / $Q_y = 20.9$

    (Requirements: the 'bare' working point should be located near the $3Q_x=67$ resonance line to use this resonance for the 'slow' extraction; the expecting space charge tune-shift is about $\Delta Q_{SpCh} = -0.2$).

Step 2: Multi particle tracking with ring dynamics and loss detection around the ring.

External E&M fields (LINEAR & NONLINEAR) :

→ Symplectic Tracking ("Teapot" type: Drift-Kick)

Space charge force:

→ self-consistent solution based on the PIC model with FFT (non-symplectic … convergence study)

TOOL-Box: ORBIT-MPI

Why the ORBIT Code

ORBIT: Developers and Collaborators

- **SNS at ORNL, FermiLab, SNS at Brookhaven, Indiana University, LANL, TRIUMF**

ORBIT is a particle tracking code in 6D phase space. Its purpose is the design and analysis of high intensity rings.

ORBIT is designed to simulate real machines: it has detailed models for

- **Injection foil and painting**
- **Single particle transport through various types of lattice elements**
- **Magnet Errors, Closed Orbit Calculation, Orbit Correction**
- **RF and acceleration**
- **Longitudinal impedance and 1D longitudinal space charge**
- **Transverse impedance**
- **2.5D space charge with or without conducting wall beam pipe**
- **3D space charge**
- **Apertures and collimation**
- **ORBIT has an excellent suite of routines for beam diagnostics**
- **. . . more**

ORBIT supports parallel processing based on MPI

ORBIT is open source code

- (contact person: Jeff Holmes, SNS project, ORNL)

Space charge model for Main Ring (ORBIT-MPI)

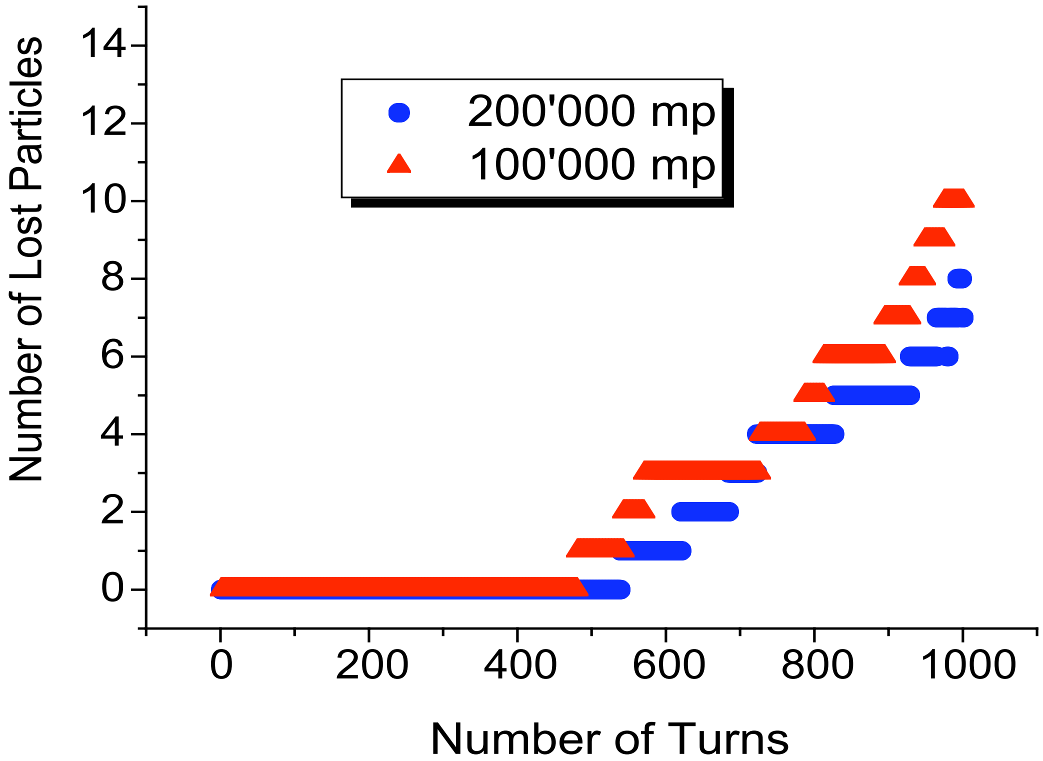
¬ At the injection energy the transverse beam size (< ± 6cm) is much smaller than the longitudinal one (~ 50m, for B_f = 0.3) and the synchrotron oscillation is slow (~ 500 turns) … then the (2&1/2)D FFT model for the space charge simulation can be used at least at the beginning.

¬ Poisson FFT solver with boundary conditions to involve the beam environment into calculation.

➢ Initial particle distribution for MR should be the 'realistic' one, obtained after the RCS tracking study… we used for this study the RCS particle distribution at 3GeV.

Convergence study for MR (c5)

Particle losses at the MR scraper position (60π mm.mrad)
for different number of the macro-particles:
200'000 mp & 100'000 mp



N_{FFT} = **100x100**

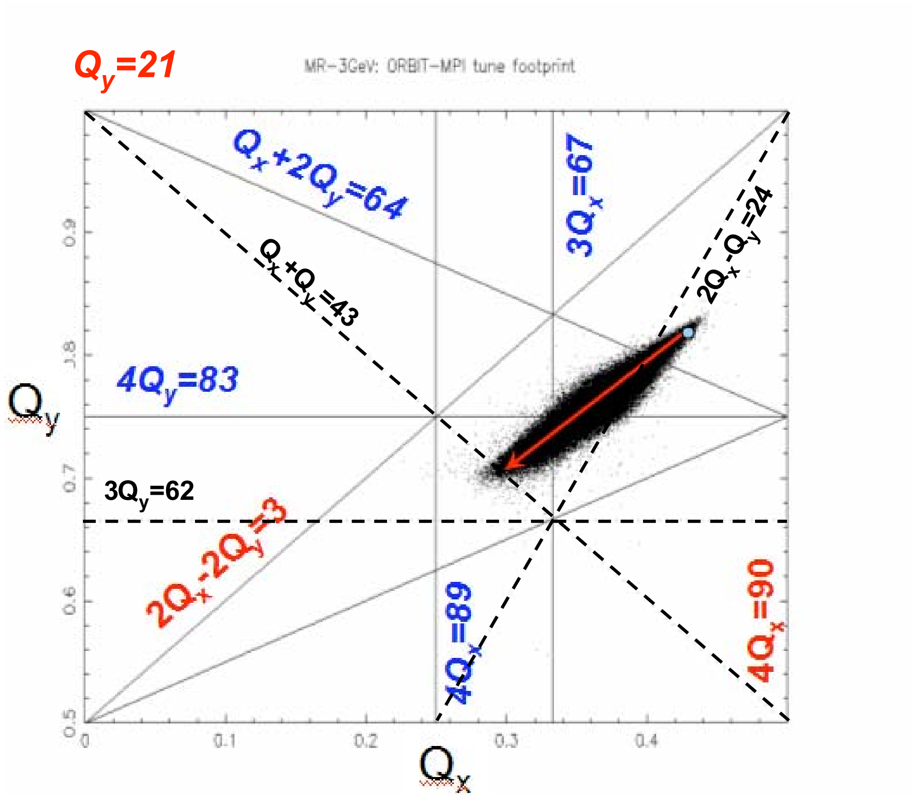
N_{az} = **1100**

N_{bin} = **512**

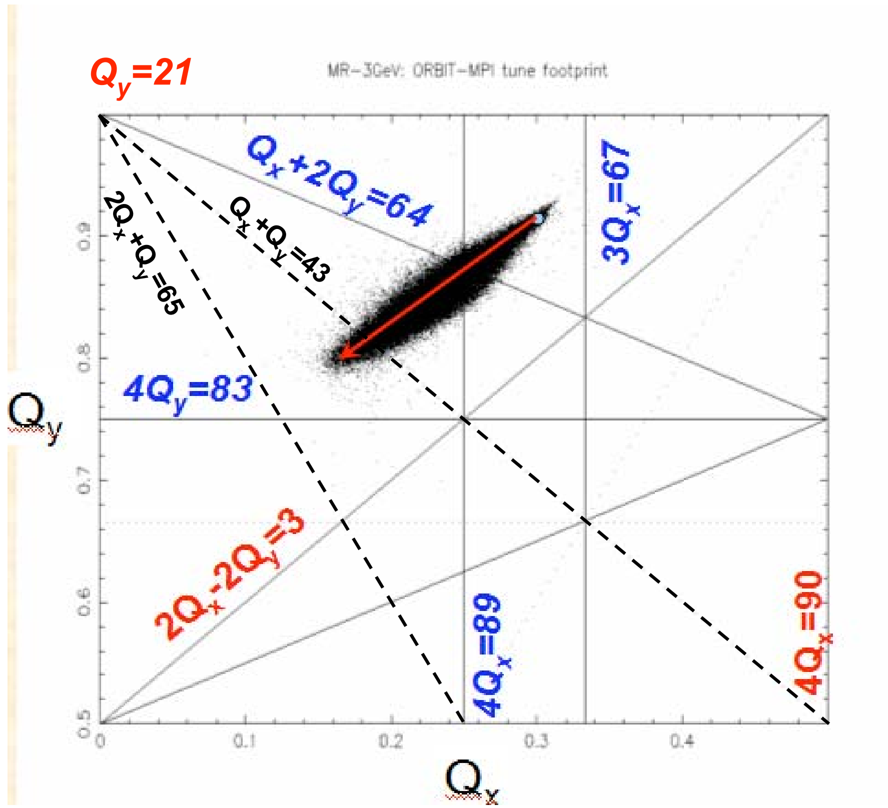
Bare working point:
Qx = 22.428 / Qy = 20.82

Footprint for 1.8 kW/bunch, B_f=0.2(LM)

WP#1: Qx=22.43, Qy=20.82



WP#2: Qx=22.30, Qy=20.92



Rectangular beam pipe :: ± 70 mm

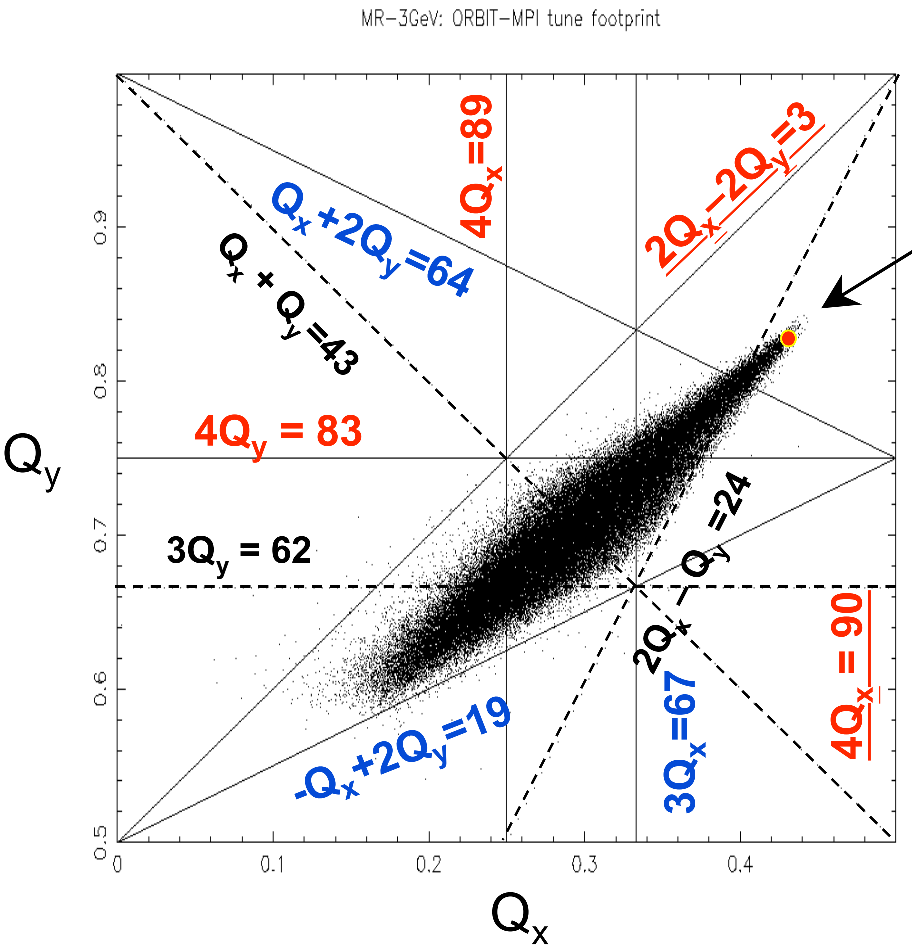
Footprint after 5000 turns

Laslett incoherent tune shift (estimation) :

$\varepsilon_{Parab.100\%}$ = 54 π mm.mrad:: $\Delta\nu_{incoh}$ ~ - 0.14 (for β~1)

Space charge tune shift
3.6kW/bunch, B_f =0.2LM

RCS Beam Power = 0.6 MW / 3NBT_CLM = 54 π



'Bare' working point:

Q_{x0} = 22.428

Q_{y0} = 20.824

Chromatic tune shift (after correction)

$\Delta\nu_{CH}$ ~ +0.01 for Δp/p = ± 1%

Amplitude dependent tune shift

$\Delta\nu_{AM}$ ~ + 0.02 for 54 π mm.mrad

Incoherent space charge tune shift
(including chamber boundary ± 70mm)
(0.6MW, RCS_Beam_050906, **B_f = 0.2**,
L-**matched** initial beam distribution)
$\Delta\nu_{SpCh}$ ~ - 0.30.

Resonance excitation for MR

Resonance	Harmonic number	Type of resonance	Source of resonance *	Status
[2,0]	**45**	Normal 'quadrupole'	Q-error & misalignment	√
[3,0] [1,2], [-1,2]	67 64 19	Normal 'sextupole'	Sextupole field comp. in BM + Sextupole errors + FF_BM	√ √
[4,0],[2,-2], [2,2], [0,4]	**90, 3** 86, 83	Normal 'octupole'	Space charge Sextupole Field	√ √
[1,-1]	*43*	*Skew 'quadrupole'*	*Magnet errors,* *Q magnet tilt*	---- √
[0,3], [2,1], *[2,-1]*	*62, 65,* *24*	*Skew 'sextupole'*	*Magnet error,* *SX magnet tilt*	---- √

* … at the leading order

Measured* field components, involved into consideration …

- Sextupole component of **MR Bending magnets** (96+1) at the injection energy…

  $<k2L>_{MAD}$ ~ **5.2×10^{-3}** $[m^{-2}]$ :: $1\sigma = 4.2\times10^{-3}$ $[m^{-2}]$, cut=3σ.

- Sextupole component of **MR Sextupole magnets** (72) at the injection energy …

  average relative deviation from the required values is

  $|\delta b_3| < 0.002$

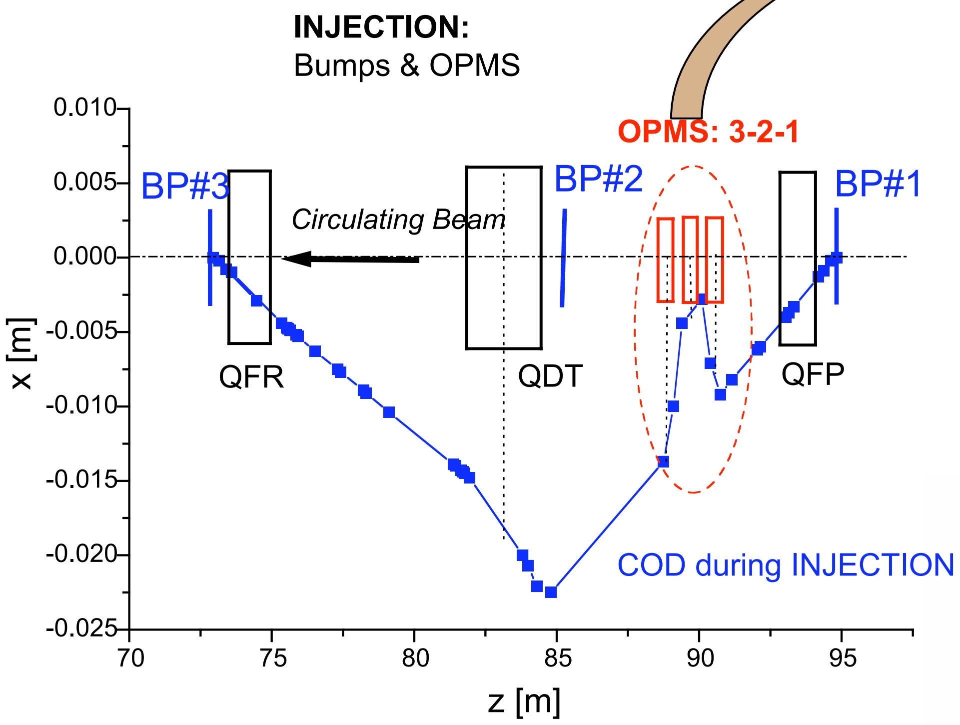
- Quadrupole strength of **MR Quadrupole magnets** (216) at the injection energy …

  $\{\Delta B'L / (B'L)\}_k$ :: 1σ = 3.26703_10^{-4}, cut = 4σ

Location of each magnet is fixed after the shuffling procedure.

* Measurement has been performed by using the rotating coil (March, 2006)

Injection study:

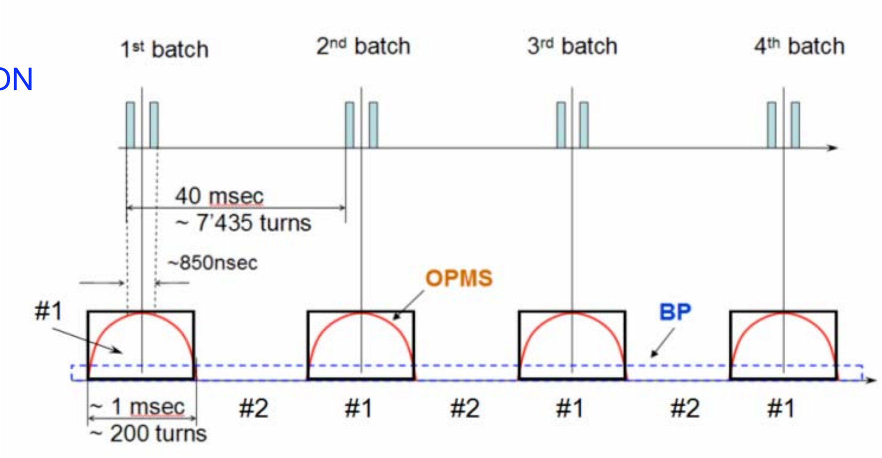


Timing of Opposite Field Magnet Septum

Edge focusing … Vertical β-beating effect::

$(\Delta\beta/\beta)_y$ ~ 2…3 % (without quadrupole components of OMS)

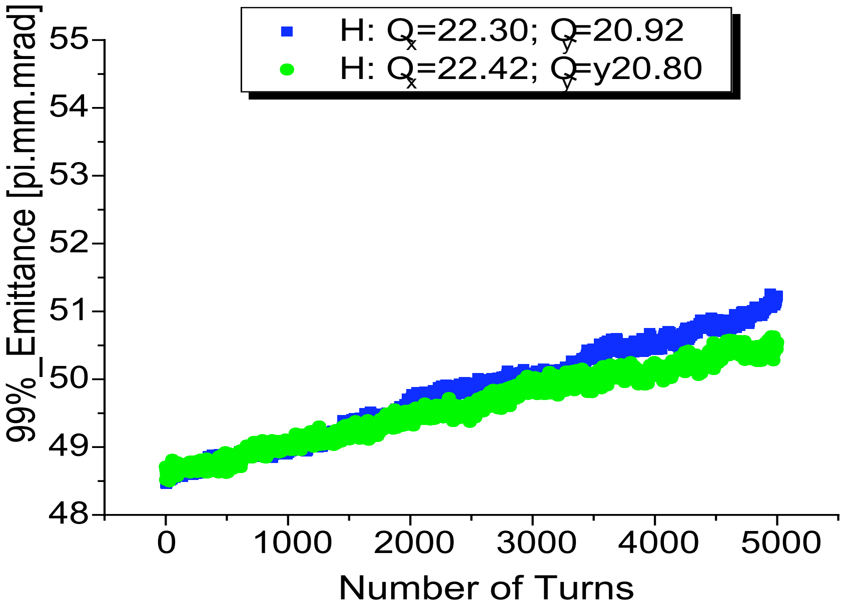
Simulation approach (timing) #1

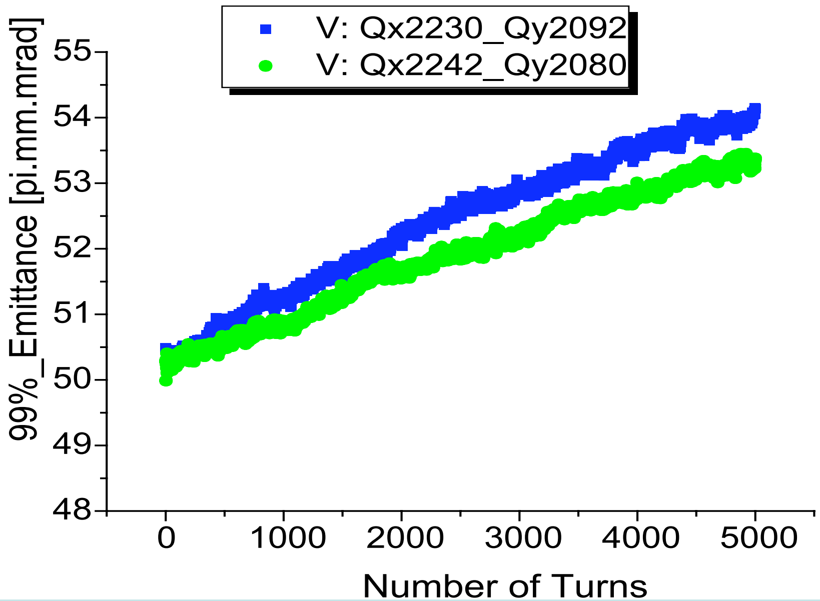


#1 … Lattice with BP & OMS (rectangular pulse) & CFQDT:: 200 turns
#2 … Lattice with BP & --- & CFQDT :: 7'235 turns

Space Charge effect & Nonlinearities: 'IDEAL' lattice

99% emittance (H/V) vz Turns_Number
for different 'bare' working points





Beam Power: 1.8kW/bunch

Emittance growth is caused by the 'structure' resonances: combined effect of the space charge and the sextupole field nonlinearity:

Space Charge effect & Nonlinearities: 'ideal' lattice

Effect of the emittance growth in both transverse phase planes has been observed for both 'bare' working points.

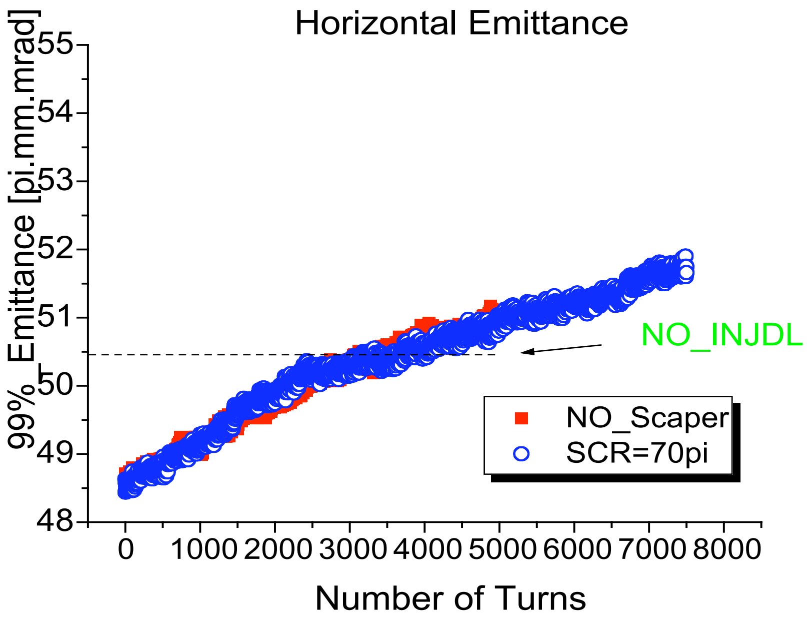
Explanation of the effect:

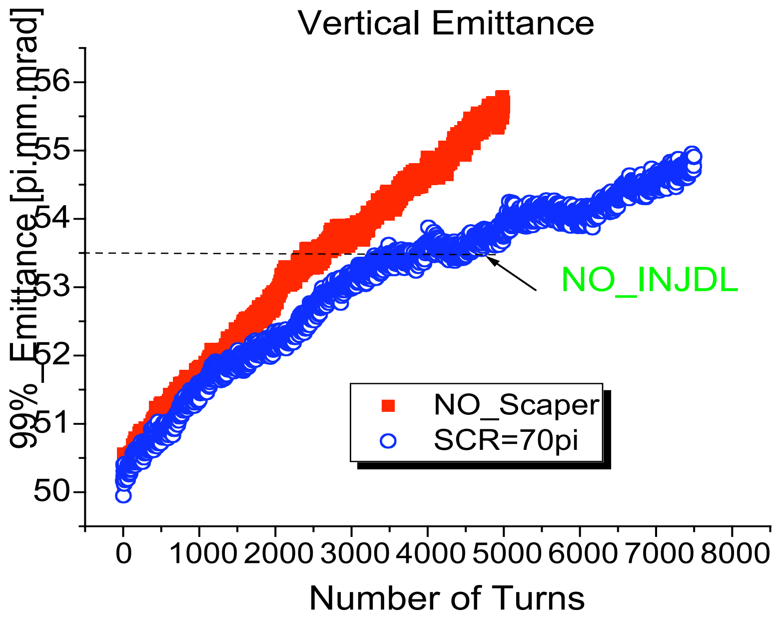
- for the working point with Q_x=20.42, the 'tail' particles can be trapped by the $4Q_x$=90 resonance, excited first of all by the sextupole field nonlinearities of the chromatic sextupole magnets (the second-order effect of the sextupole nonlinearity) … plus the coupling effect, caused by the $2Q_x$-$2Q_y$=3 resonance.

- for the working point with Q_x=20.42, the 'tail' particles have influence of the 'lattice' resonance Q_y=21 … … plus the coupling effect, caused by the $2Q_x$-$2Q_y$=3 resonance.

Effect of the Injection Dogleg

Wp1: $Q_x = 22.42$, $Q_y = 20.80$





<u>Injection 'dogleg':</u>

- break the MR super-periodicity
- Excitation of 'non-structure' resonances, in particular [1,2,64], [3,0,67] and [0,4,83]

Excitation non-structure resonances

- Normal quadrupole resonances in addition to normal sextupole&octupole resonances

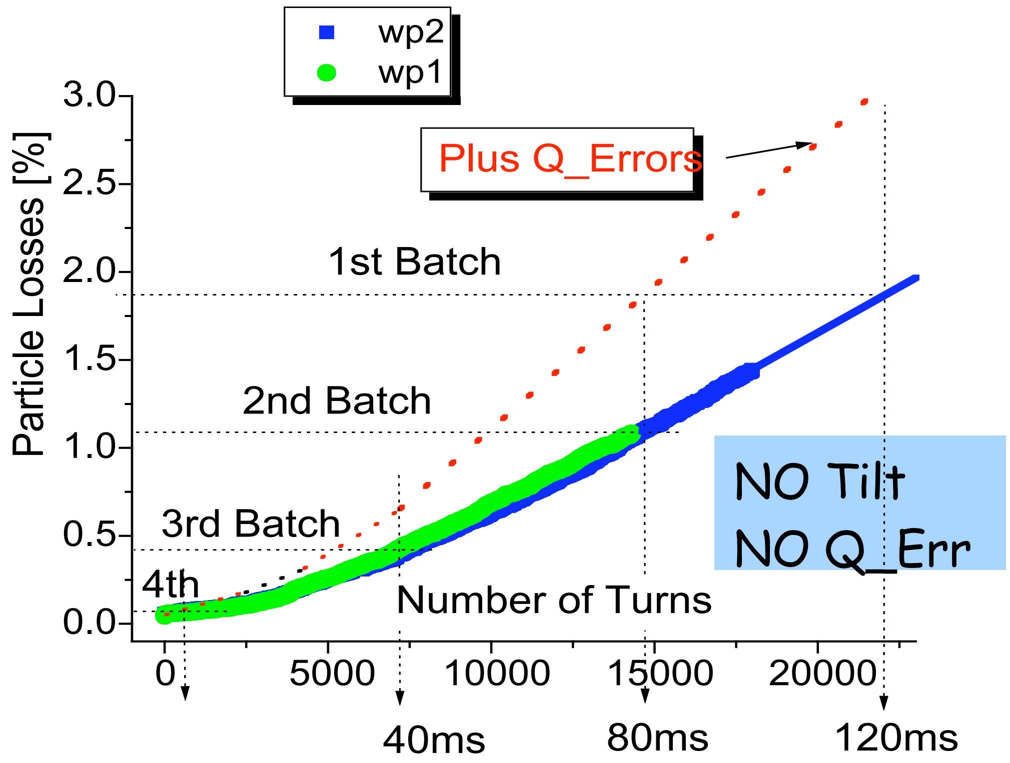
➢ Add to simulations … quadrupole strength errors (measured) in combination with the measured sextupole components of the dipole magnets and the measured sextupole strength errors. After the 'shuffling' procedure' the positions of BM/QM/SM have been fixed.

- Skew quadrupole and sextupole resonances

➢ Add to simulations … misalignment error (transverse tilt) of the quadrupole and sextupole magnets

Budget of the beam losses

MR Scraper Acceptance = 70 π mm.mrad



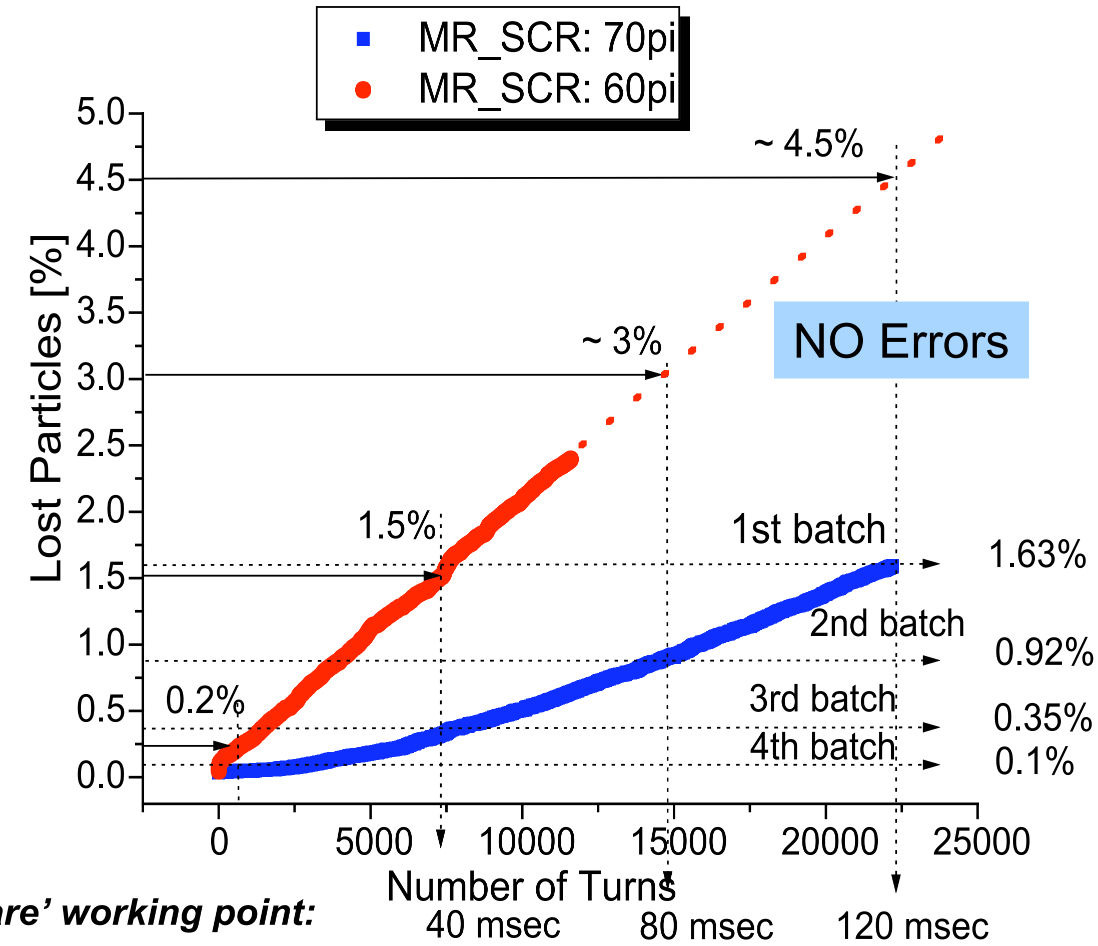
Batch number	Lost %	Lost Power
1st	1.85	66.6 W
2nd	1.1	39.6 W
3rd	0.4	14.4 W
4th	0.1	3.6 W
Total	3.45%	**124.2 W** **250 W**

MR Beam Power: 1.8kW/bunch … RCS Beam Power: 0.3MW

B_f = 0.2 (V_{RF}=210kV)

Estimation of Particle Losses (dual harmonic RF, B_f = **0.3**)

RCS Beam Power = 0.6 MW / 3NBT_CLM = 54 π



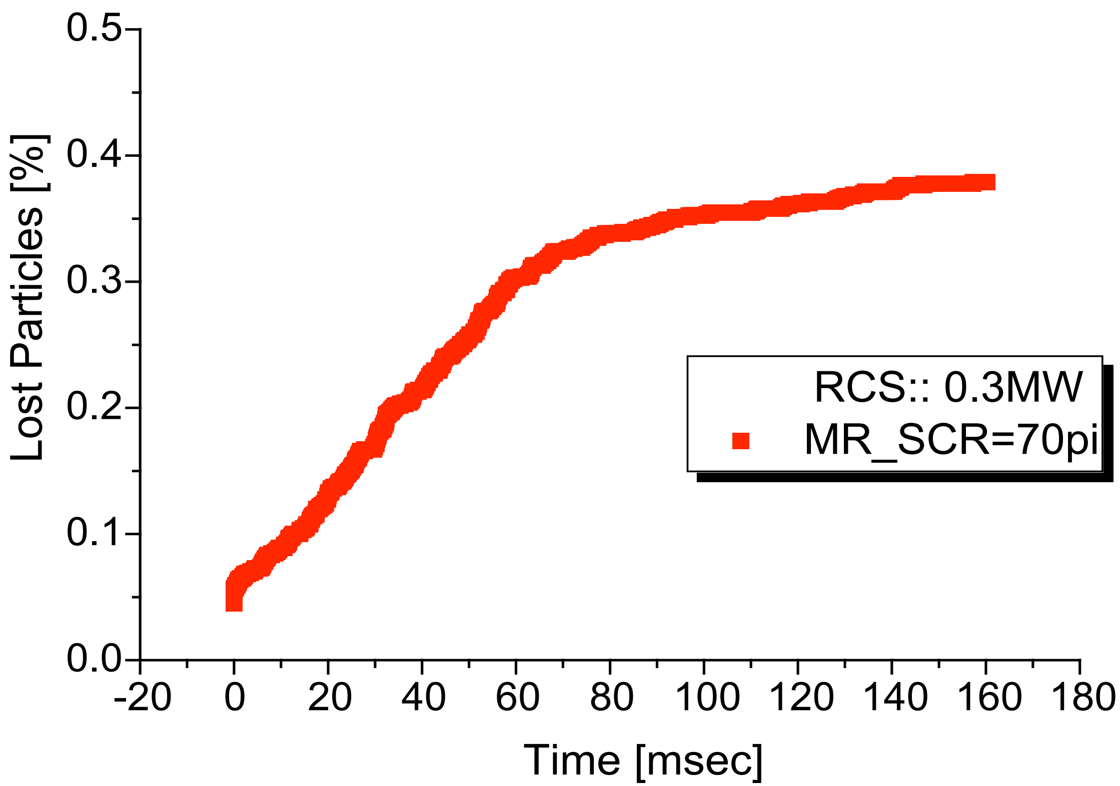
'Bare' working point:

Q_{x0} = 22.428
Q_{y0} = 20.824

Batch number	MR Scraper Acceptance	
	60π	**70π**
1st	0.2%	0.1%
2nd	1.5%	0.35%
3rd	3%	0.92%
4th	4.5%	1.63%
Lost Power	**~ 662** W	**~ 216** W

Mismatched initial longitudinal distribution

Acceleration:
Particle losses at MR Scraper



Wp#1
Realistic RF&BM-table

NO Errors !!!

Total losses for 8 bunches (h=9) ~ 50 W

ORBIT_MPI: Multi-Processor Machine operation

<u>Dell PowerEdge 6800:</u>
QUAD 64-bit Intel Xeon Processors:
… computational performance in a range of a few GFlops/CPU.

~ 100'000 mp (2&1/2 model) ... 1 day :: ~ 3500 turns

KEK SuperComputer (A):: <u>HITACHI SR11000 model K1</u> (April 2006)

… calculation server consisted of 16 nodes, each node has 16 CPUs (total 256CPUs).
The total peak performance is 2.15 TFlops (or 134.4 GFlops/node) and the maximum memory is 32GB/node.
Users have access at the same time to 4 nodes maximum (64 CPUs).
The CPU peak performance is about 8.4 GFlops/CPU.

Expected reduction of the simulation time is ~ **20 times.**

Conclusion:

- To provide reliable estimation of the emittance growth (in particular, the 99% emittance behavior) and the particle losses for the 'real' machine operation study, it is necessary to use the space charge tracking code, like ORBIT_MPI, designed for multi-CPU computers.
- For MR study we introduced different resonance excitation step-by-step by using measured field data.
- Estimated particle losses at the MR scraper is below the acceptable level.

Thanks for your attention.