ORBIT simulation, measurement and mitigation of Transverse Beam Instability in the Presence of Strong Space Charge in the 3-GeV RCS of J-PARC

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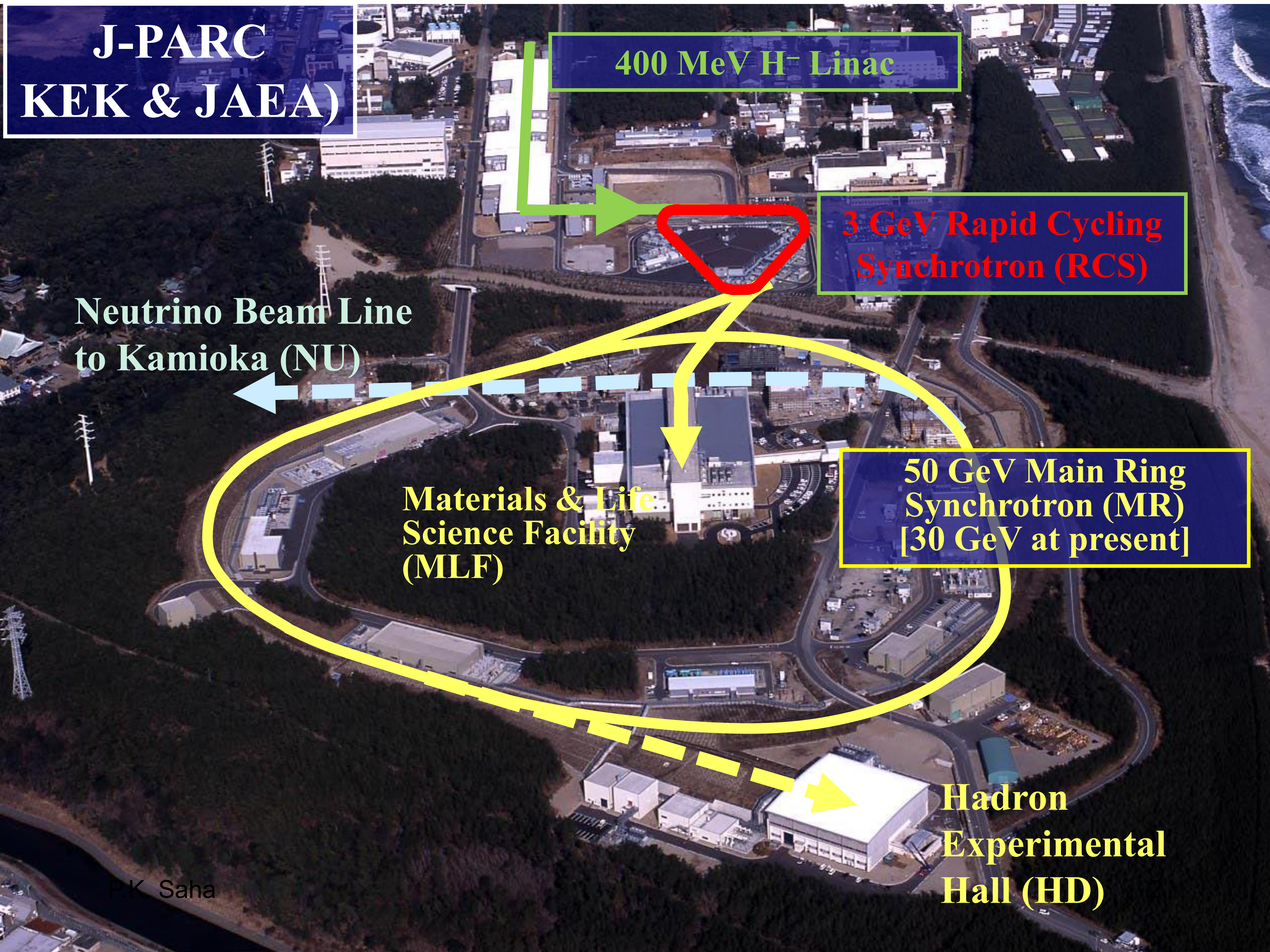
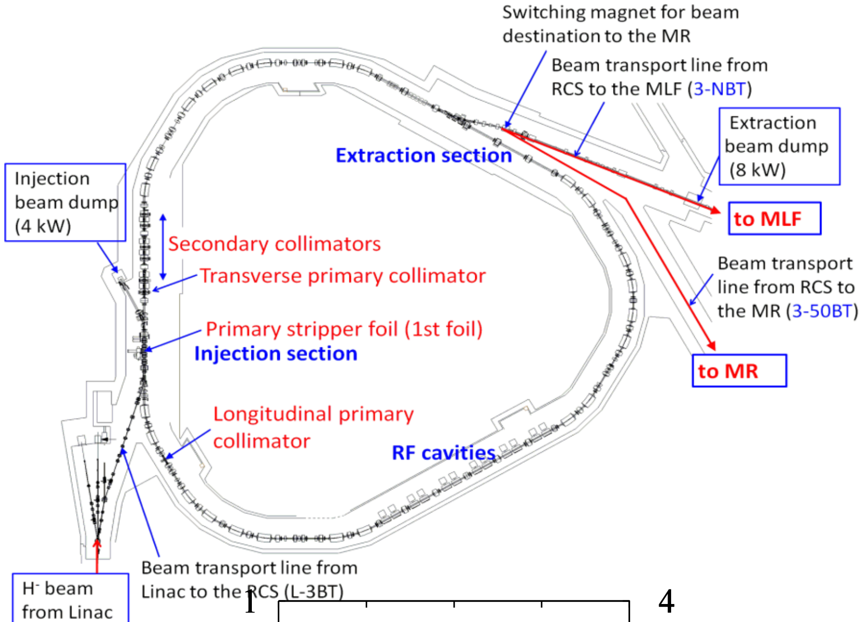
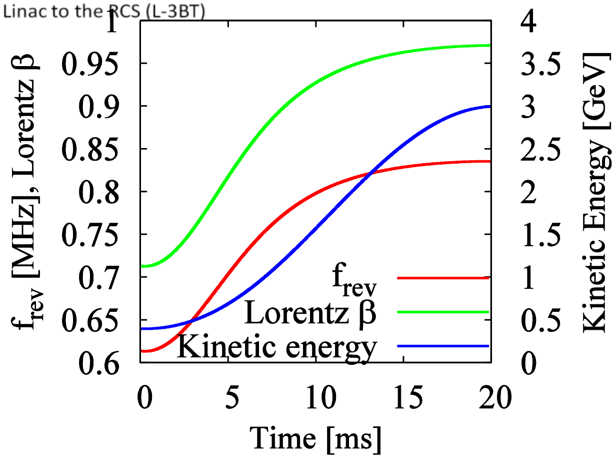

J-PARC
KEK & JAEA)
400 MeV H⁻ Linac
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino Beam Line
to Kamioka (NU)
Materials & Life
Science Facility
(MLF)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Hadron
Experimental
Hall (HD)
P.K. Saha

Outline:

1. Introduction of J-PARC RCS, Kicker Impedance and Motivation of the present study
2. Beam instability up to 0.5 MW beam power
3. Space Charge effect on the Beam Instability
4. Beam instability suppression strategy at 1 MW -- Simulation and measurement results
5. Summary and Outlook

1. Introduction of 3-GeV RCS



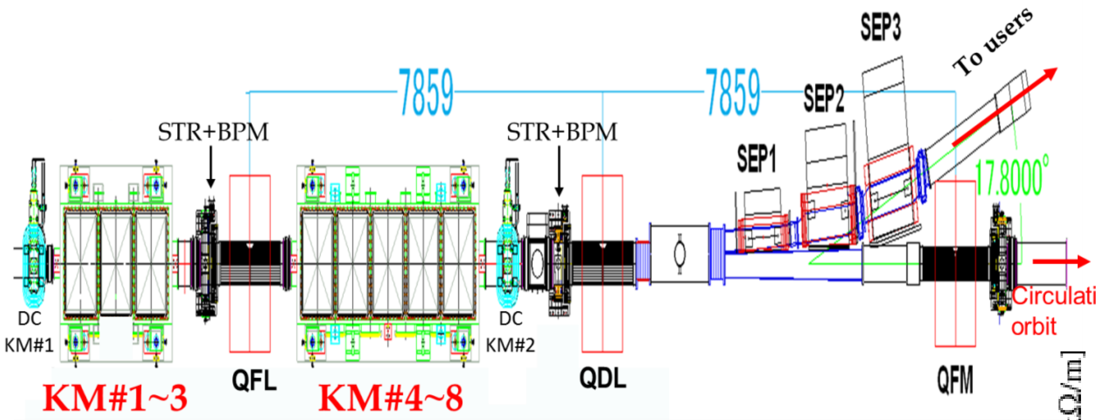


Parameter	Value	
Circumference [m]	348.333	
Repetition [Hz]	25	
Harmonic no, bunches	2, 2	
Protons/pulse (PPP)	8.33E13	
Beam power [MW]	**1**	
	Injection	**Extraction**
Energy [GeV]	0.4	3
f_0 [MHz]	0.614	0.84
$\Delta p/p$ [99%]	0.8	0.4
τ_z (bunch length) [m]	160	60
ν_s (synchrotron tune)	**0.006**	**0.0005**
ν_x, ν_y (betatron tune)	6.45, 6.42	Variable
ξ_x, ξ_y (Nat. chromaticity)	-10, -7	Variable
B_f (Bunching factor)	0.47	0.21
$\Delta\nu_{incoh}$, $\Delta\nu_{coh}$	**-0.3, -0.03**	**-0.05, -0.005**

To reduce the space charge effect longitudinal painting (LP) and transverse painting (TP) at injection are adopted.
ε_{tp} = 100π mm mrad in this study

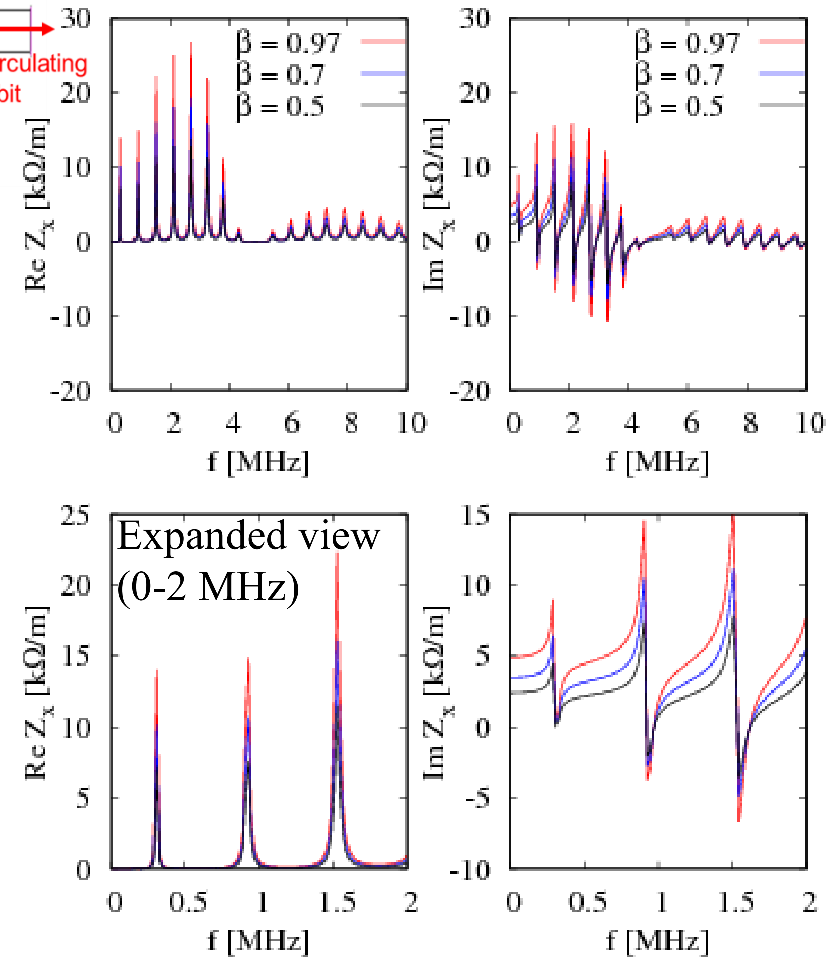
RCS Beam power at present:
To MLF: 0.5 MW; To MR: ~0.8 MW-eqv.

1. RCS Kicker Impedance



Horizontal impedance of one KM

Y. Shobuda et al., NIMA 713, 52 (2013)



×10 of SNS KM impedance!

The impedances are also time dependent, higher w.r.t. energy.

– Should be properly implementation in the simulation code

-- Done

Motivation

■ R&D studies to reduce the KM impedance are in progress, but long way to go for realistic implementation.

■ Theoretical works provide overview (threshold) of the beam instability, but realistic strategy for the beam instability suppression should be determined by detailed simulation studies.

■ The space charge effect (SC) on the beam instability should be considered seriously.

-- ORBIT 3D SC code is used. We should determine realistic parameters to accomplish 1 MW beam power.

◎ We enhanced ORBIT by implementing all realistic time dependent machine parameters:

Injection process, transverse & longitudinal injection paintings, error sources, PS ripples, ... and also the KM impedance.

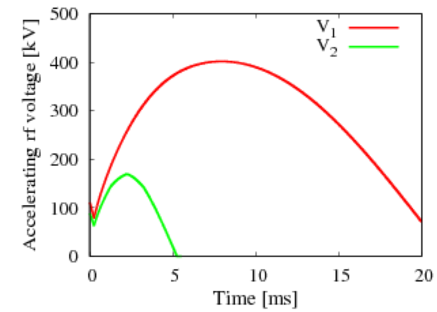
ORBIT takes indirect SC into account. The radius of the perfect conducting wall boundary for RCS, ρ = 0.145 m.

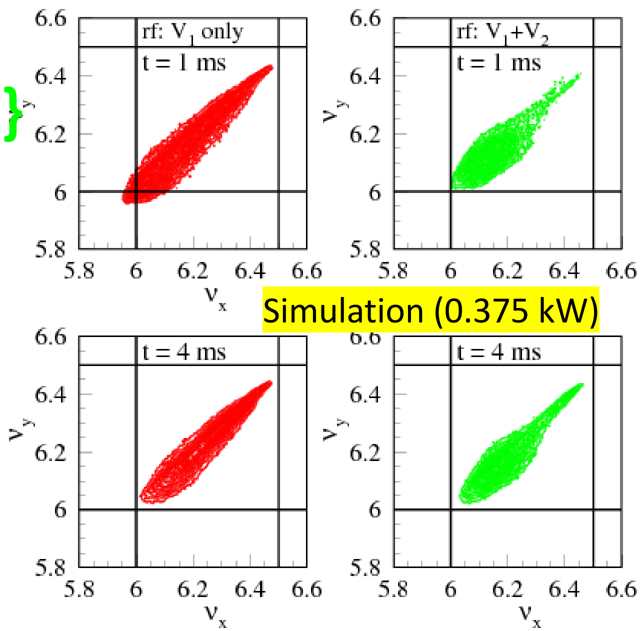
Space charge simulation results

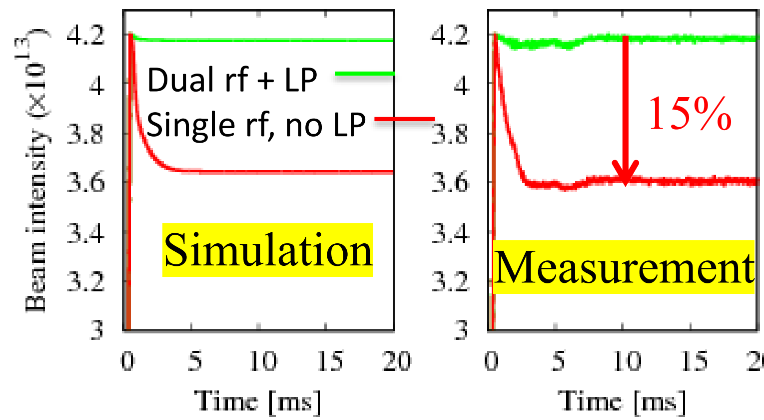
The space charge force is controlled by the choice of Einj., rf pattern and LP

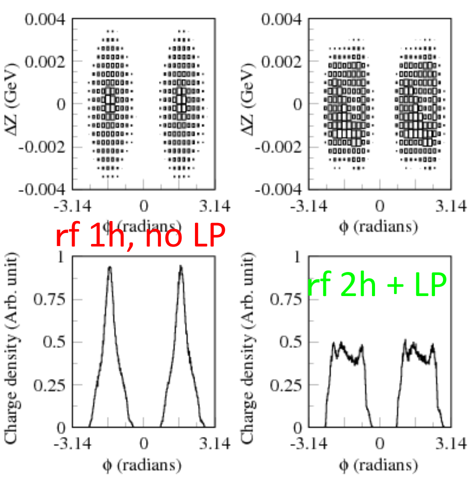
Einj: 0.181 GeV
TP= 100π mm mrad
PPP: 4.2E13 (0.5 MW)

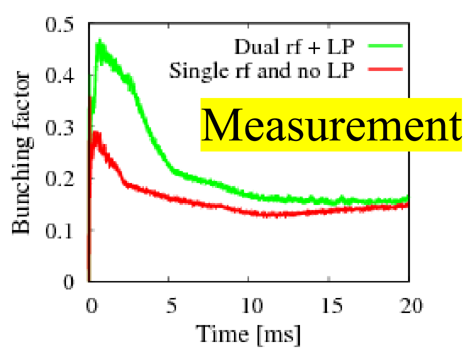
$V_{rf} = V_1 \sin\phi + V_2 \sin\{2(\phi-\phi_s) + \phi_2\}$







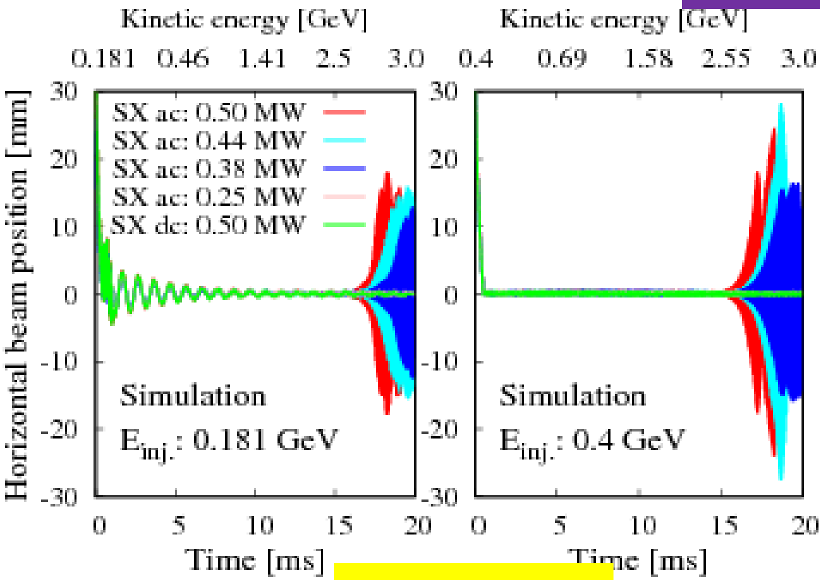




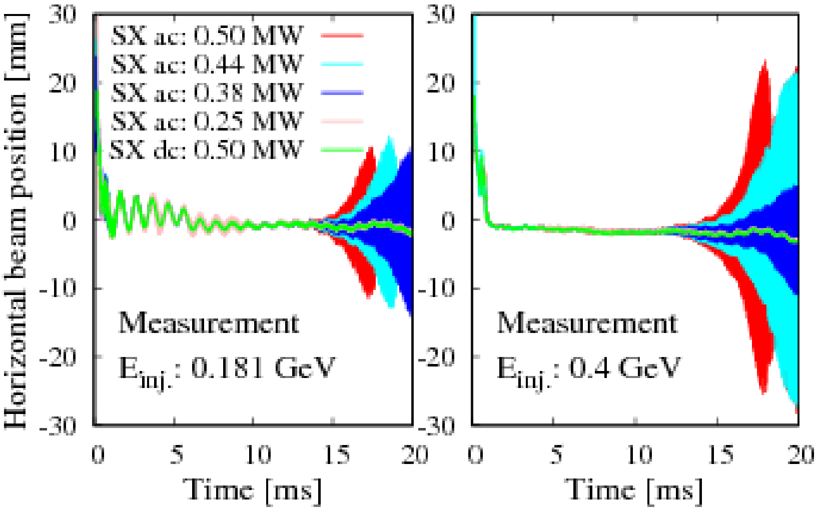
$\Delta\nu \sim -0.45$ at inj. even with rf 2h + LP.
Further increased by using rf 1h only.
Particles at $\nu_{xy}=6$ resonances increase.
Emittance blowup beyond aperture and huge particle losses with rf 1h.
Well mitigated by using rf 2h + LP.

$\Delta\nu = -0.45$ corresponds to1.25E14 ppp (1.5 MW beam power) as $\Delta\nu \propto 1/\beta^2\gamma^3$

Beam instability up to 0.5 MW



Simulation



Measurement

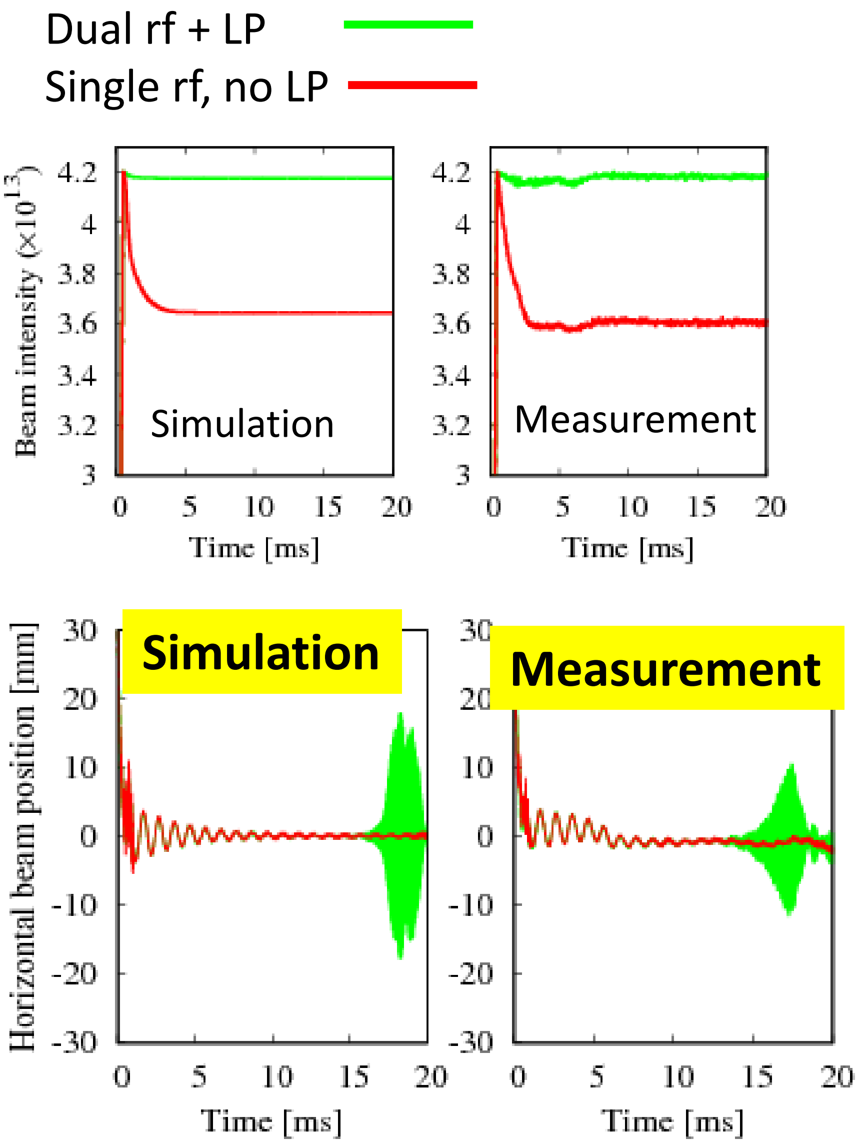
- Beam instability occurs even for a beam power exceeding 0.25 MW when the ξ is fully corrected for the entire acc. cycle by **SX ac fields.**
- **No instability occurs for ξ fully corrected only at inj. by SX dc fields**

Simulation results are well reproduced in the measurements.

Beam instability occurs at relativistic energy.
-- Beam is stabilized by the SC at lower energy.

The growth rate is higher for Einj. is higher.
--The Landau damping effect of the nonlinear SC force is smaller for higher injection energy.

Beam instability suppression by the SC



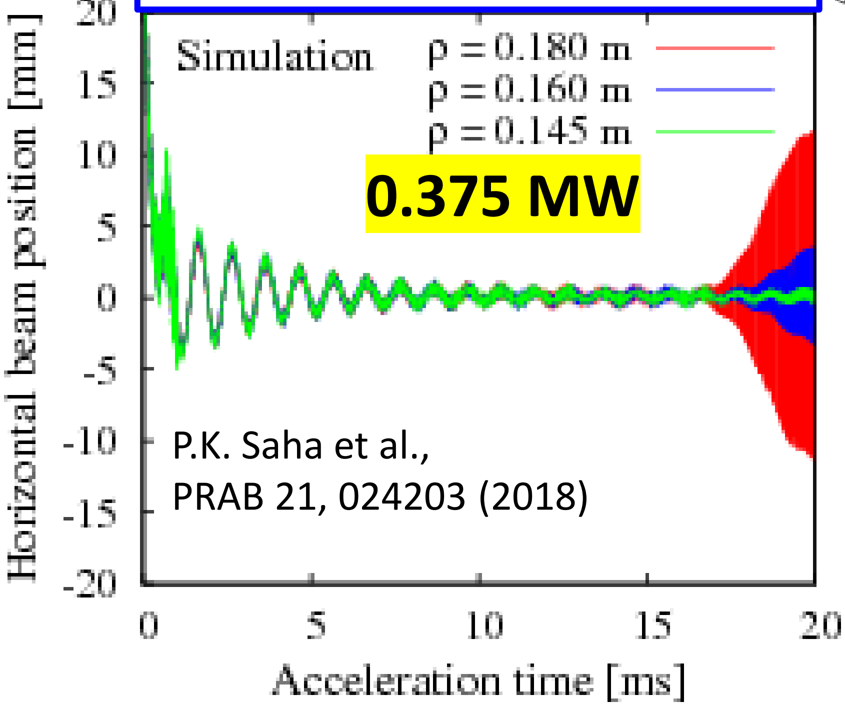
Einj. = 0.181 GeV, **SX ac** (ξ =0)
PPP: 4.2E13 (0.5 MW)
$\Delta\nu/\nu_s$ >> 1 (strong space charge)

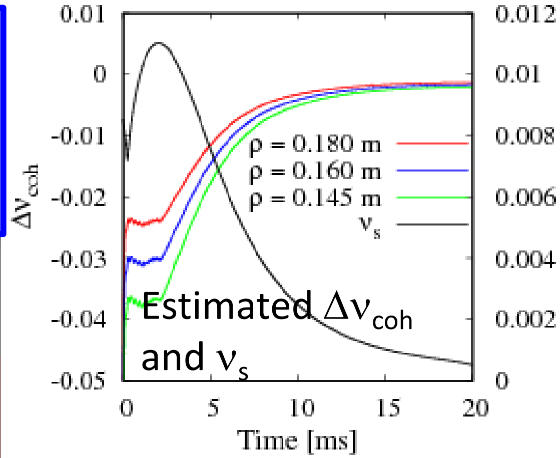
- Beam instability occurs when the SC effect is reduced by applying dual harmonic rf voltage and also the LP.
- However, beam is stable when SC is stronger by omitting 2nd harmonic rf voltage and also the LP.
- The Landau damping effect of non-linear SC force becomes more effective to stabilize the beam.

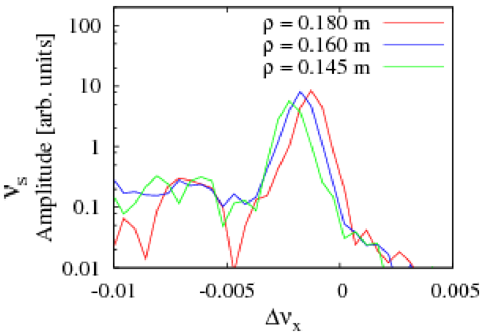
The ORBIT code takes **indirect SC** into account, which is important to study the beam instability with SC.

Circular shape perfect conducting wall boundary is defined with radius ρ = 0.145 m.

Einj. = 0.181 GeV, SX ac (ξ =0)
0.375 MW, single rf
$\Delta\nu/\nu_s >> 1$







Betatron frequency spectra at beam instability onset.

- The beam tends to unstable and more destabilized as ρ is increased.
- The Landau damping effect vanishes earlier by increasing ρ and the **growth rate increases**

Beam Instability suppression at 1MW beam power

At 1 MW beam power, the SC effect, especially at lower energy should be sufficiently reduced to mitigate the beam losses.

→ Wider $\Delta p/p$ of the injected beam, apply LP and TP (100π mm mrad)

→ Choice of the betatron tunes, ξ correction, ……

However, reduction of the SC enhance the beam instability at higher energy.

We consider following 3 measures:

(1) Manipulation of the betatron tune (ν_x) during acceleration.

(to avoid characteristics (resonances) of the KM impedance)

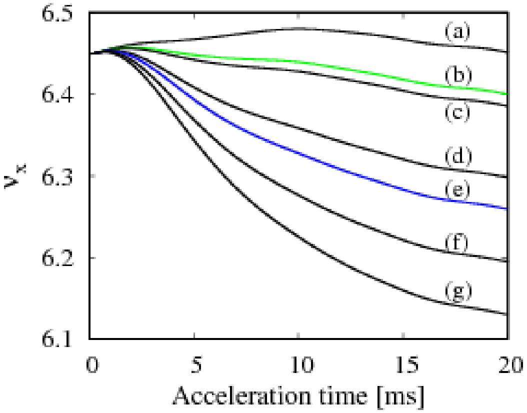
(2) Further reduction of the DC ξ correction.

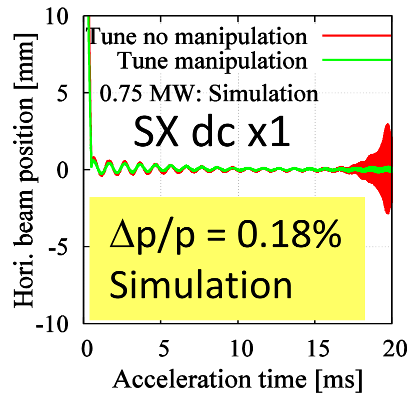
(to enhance the Landau damping)

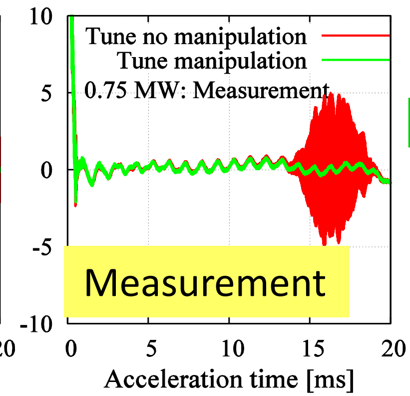
(3) Smaller $\Delta p/p$ of the injected beam (should be <0.1%)

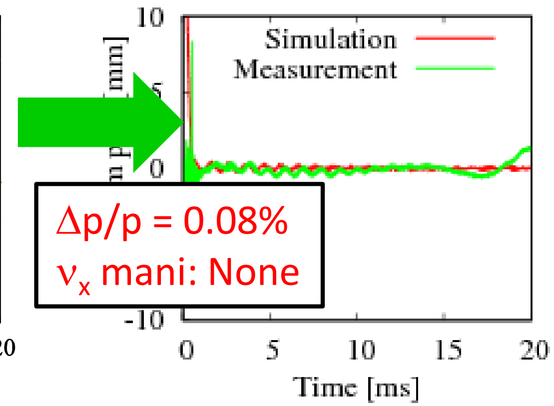
(same as (2))

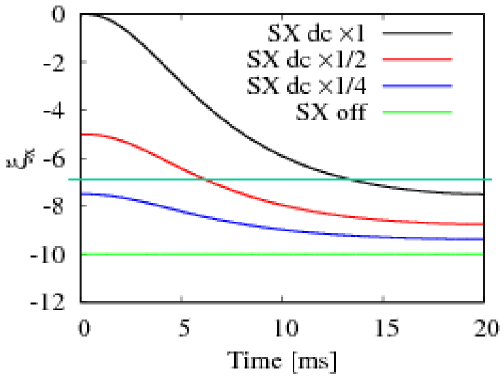
Suppression of Beam Instability at 1MW beam power











Even at 0.75 MW beam power:

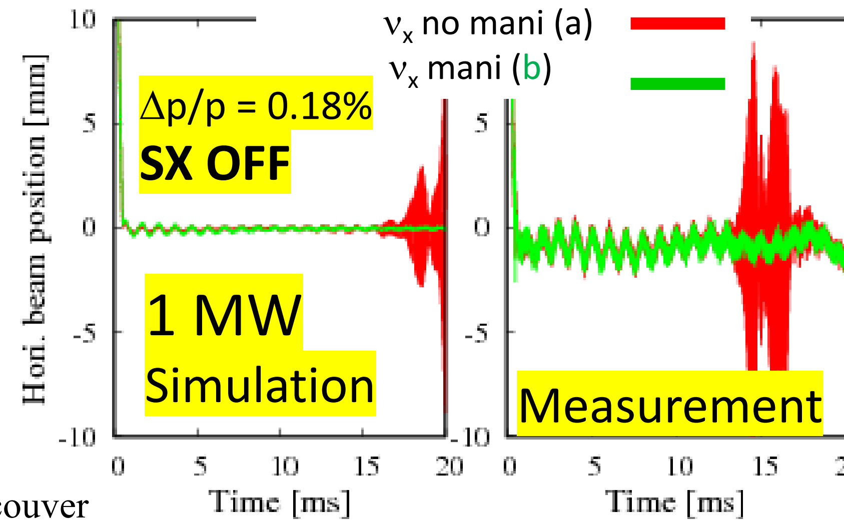
- Beam instability w/o ν_x manipulation, but
- ✓ **A proper ν_x manipulation stabilizes the beam.**
- ✓ **A narrower Δp/p (inj. beam) gives no instability.**

However, at 1 MW,

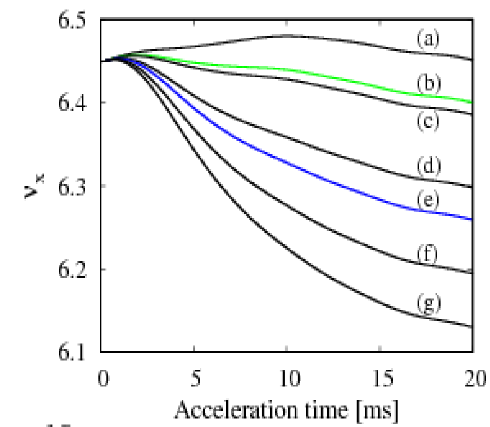
A partial ξ correction is desired.

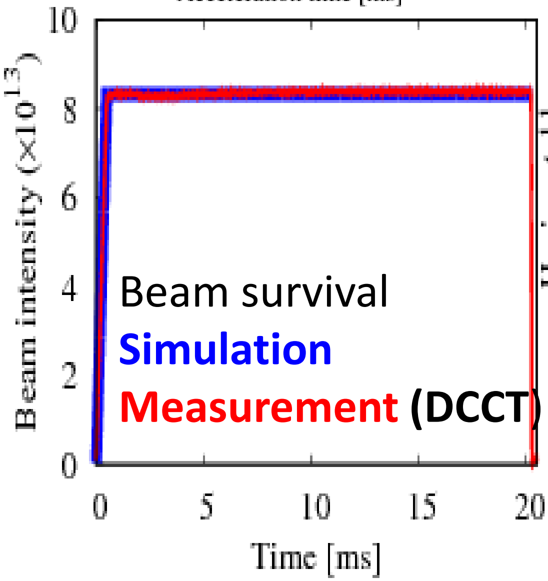
Growth rate further increases!

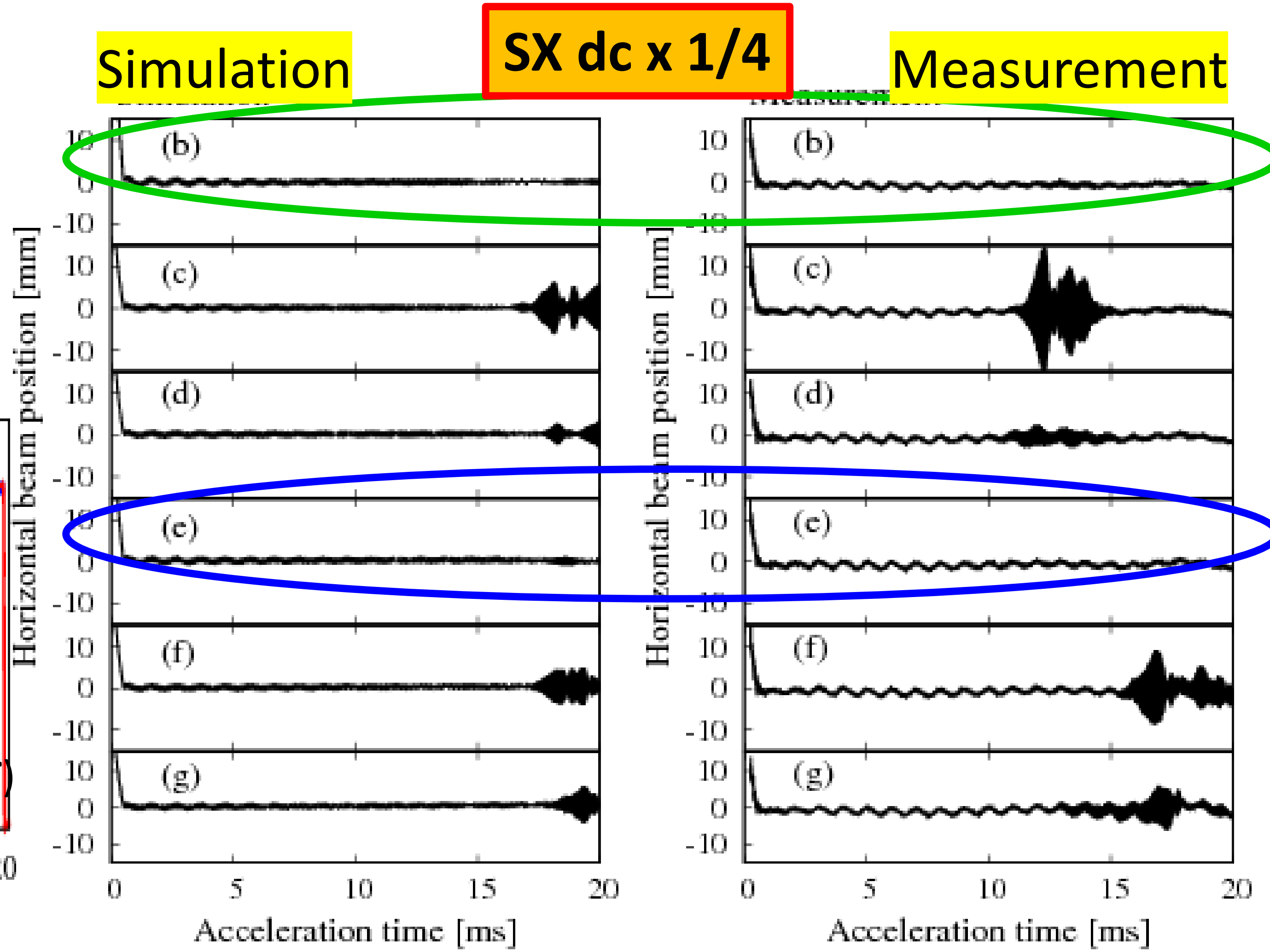
Detail tune survey done.



Accomplishment of 1 MW beam power



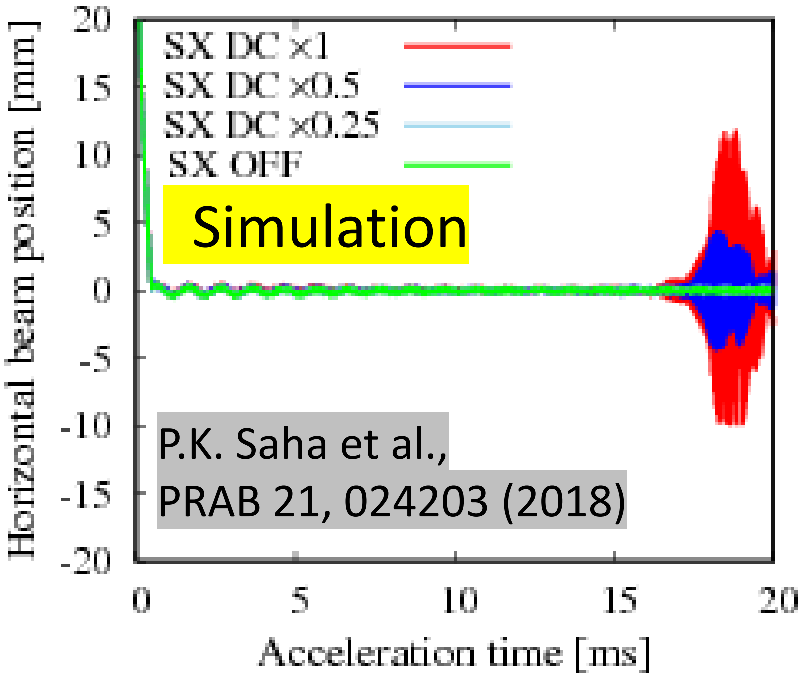


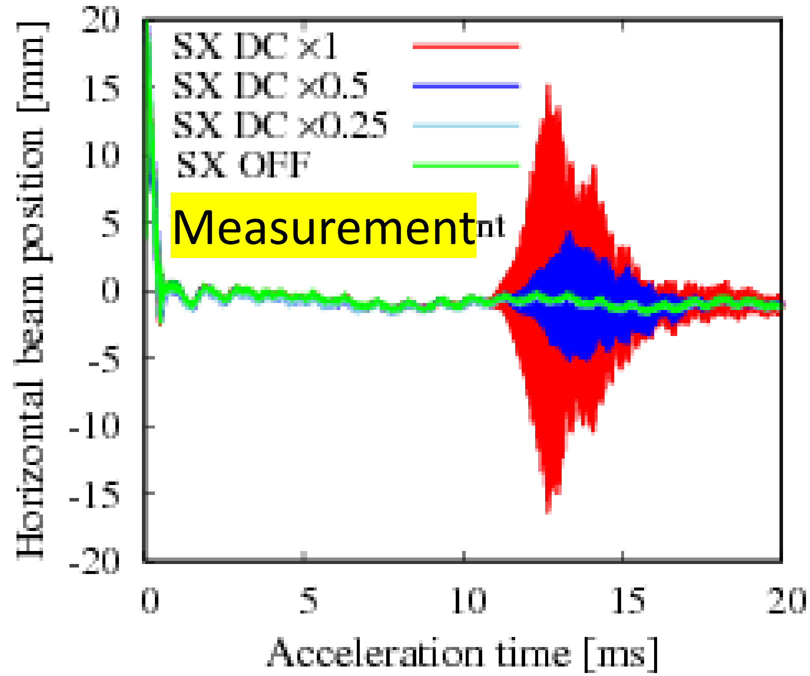


◎ Acceleration of 1 MW beam power was barely accomplished.

◎ Simulation results are well reproduced in the measurements.

SX (ξ) dependence at 1 MW





In addition to a proper betatron tune manipulation, the ξ 1/4 or loes correction at injection and **almost no correction at extraction** were utilized to accomplish 1 MW beam power.

Summary and outlook

■ Transverse Impedance of the KM is a significant beam instability source in J-PARC RCS.

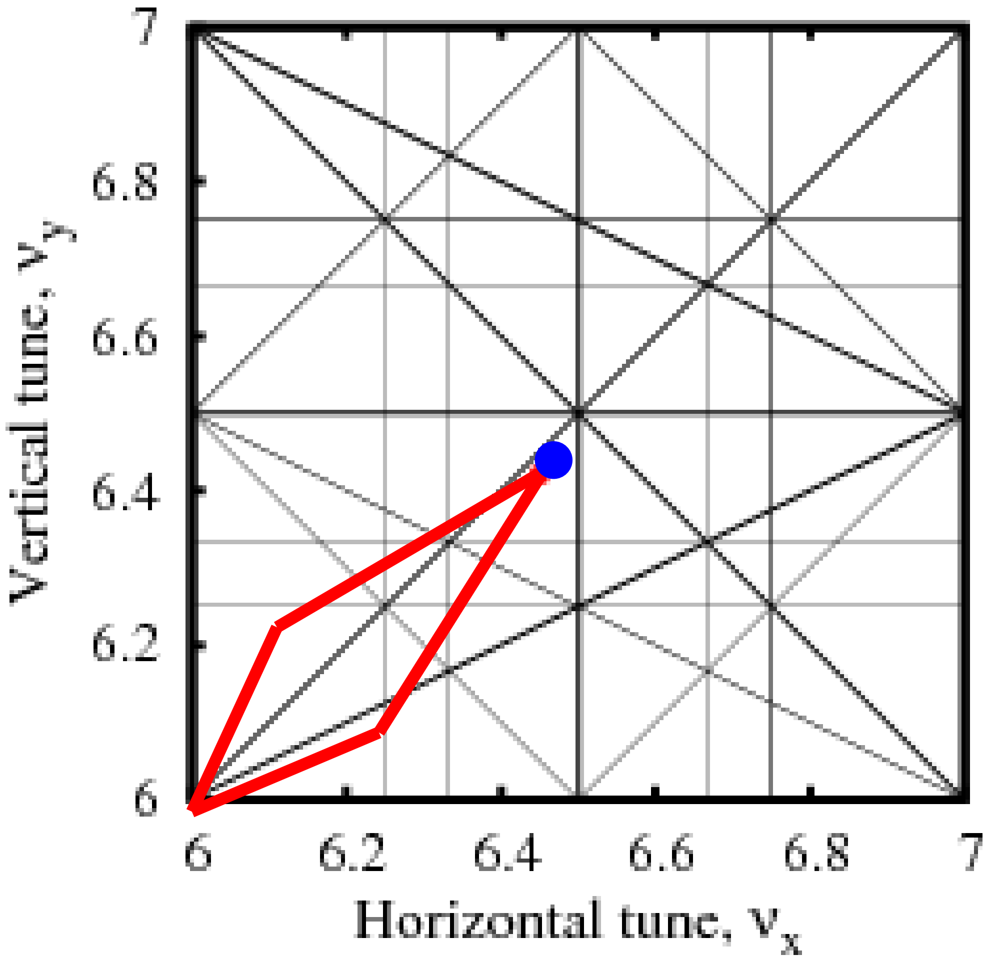
■ The ORBIT code was enhanced to cope with all time dependent Parameters for realistic beam instability studies with SC.
The beam instability suppression by the SC has been studied in detail.

■ A proper ν_x manipulation and minimal ξ corrections were applied to accomplish the designed 1 MW beam power successfully.
The simulation results are well reproduced in the measurements.

● KM impedance restricts RCS flexible parameter choice for multi-user operation. R&D studies to reduce the KM impedance are in progress.

● **We can achieve 1.5 MW beam power, if the KM impedance is reduced by even a half.**

Acknowledgement
We acknowledge many of our colleagues for continuous support and encouragement.
M. Kinsho, N. Tani, Y. Watanabe, M. Yamamoto, K. Yamamoto, Y. Irie..
We thank *Dr. J.A. Holmes of SNS for continuous support on the ORBIT code development.*



RCS tune diagram and the operating point at injection.