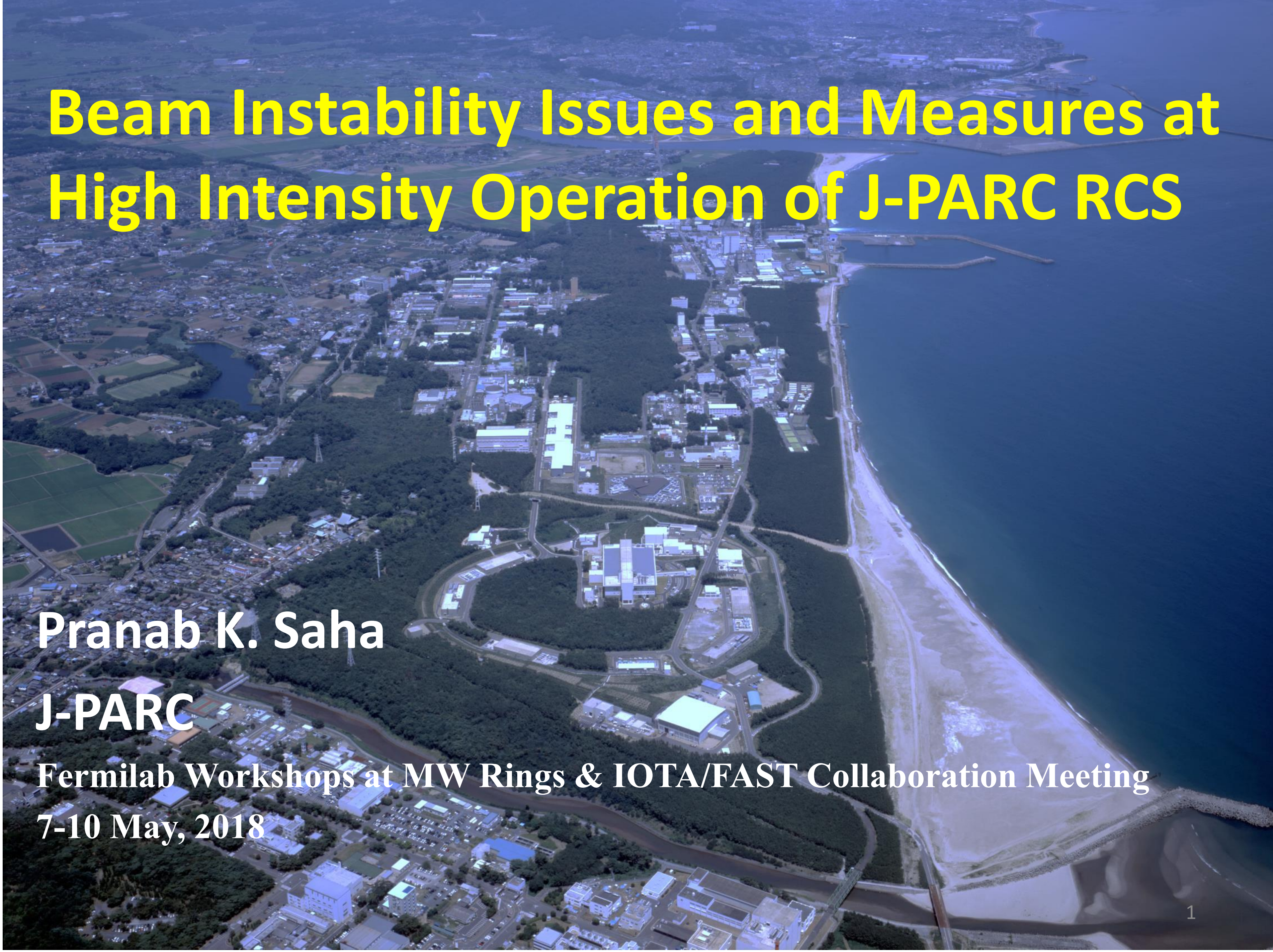
Beam Instability Issues and Measures at High Intensity Operation of J-PARC RCS



Pranab K. Saha

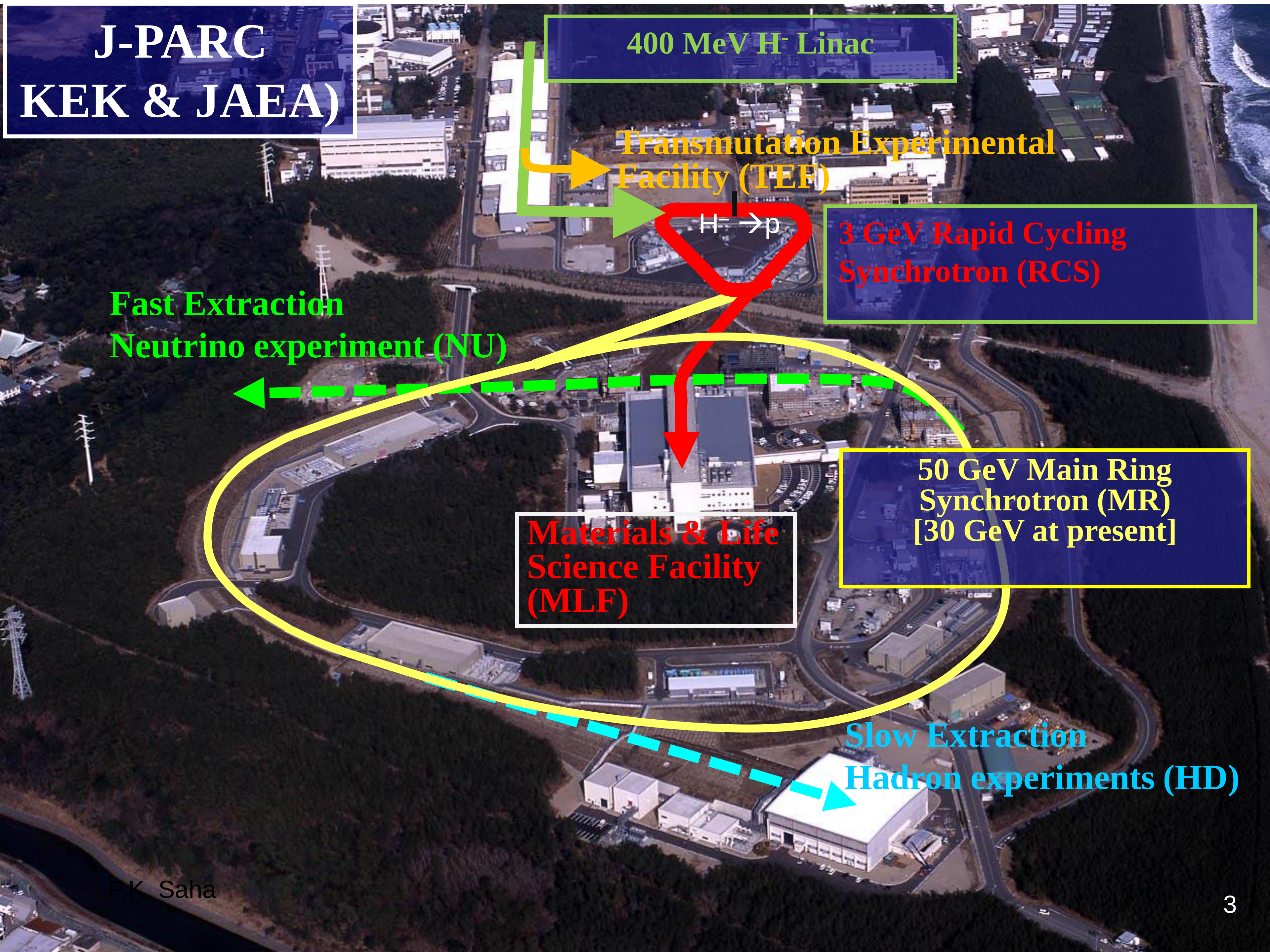
J-PARC

Fermilab Workshops at MW Rings & IOTA/FAST Collaboration Meeting

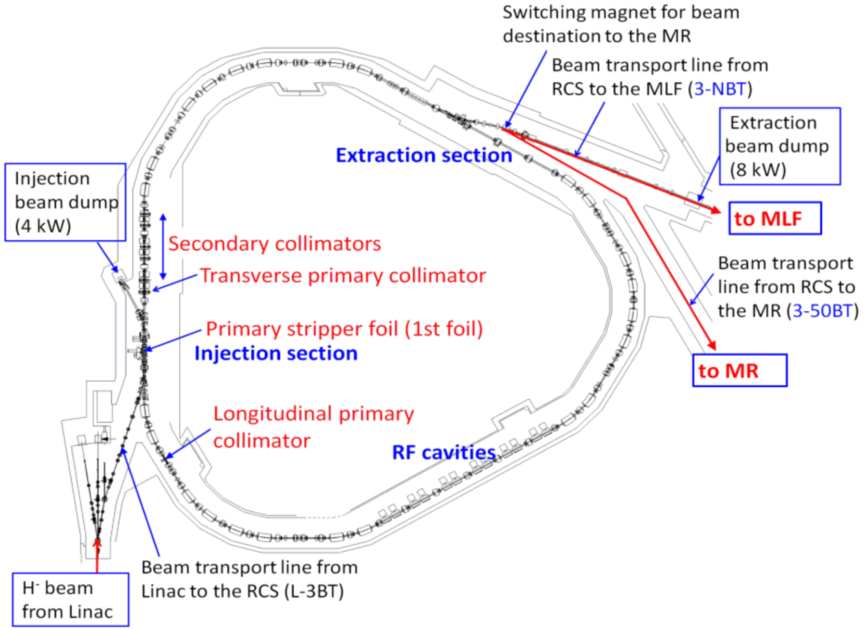
7-10 May, 2018

Outline:

1. Brief Introduction of J-PARC and the 3-GeV RCS
2. Impedance sources in the RCS
3. Beam instability due to the Kicker Impedance
4. Space Charge effect on the Beam Instability
5. Beam instability mitigation at 1 MW beam power and beyond
6. Summary and Outlook


J-PARC
KEK & JAEA)
400 MeV H- Linac
Transmutation Experimental
Facility (TEF)
H- →p
3 GeV Rapid Cycling
Synchrotron (RCS)
Fast Extraction
Neutrino experiment (NU)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Materials & Life
Science Facility
(MLF)
Slow Extraction
Hadron experiments (HD)
P.K. Saha

1. Introduction of 3-GeV RCS



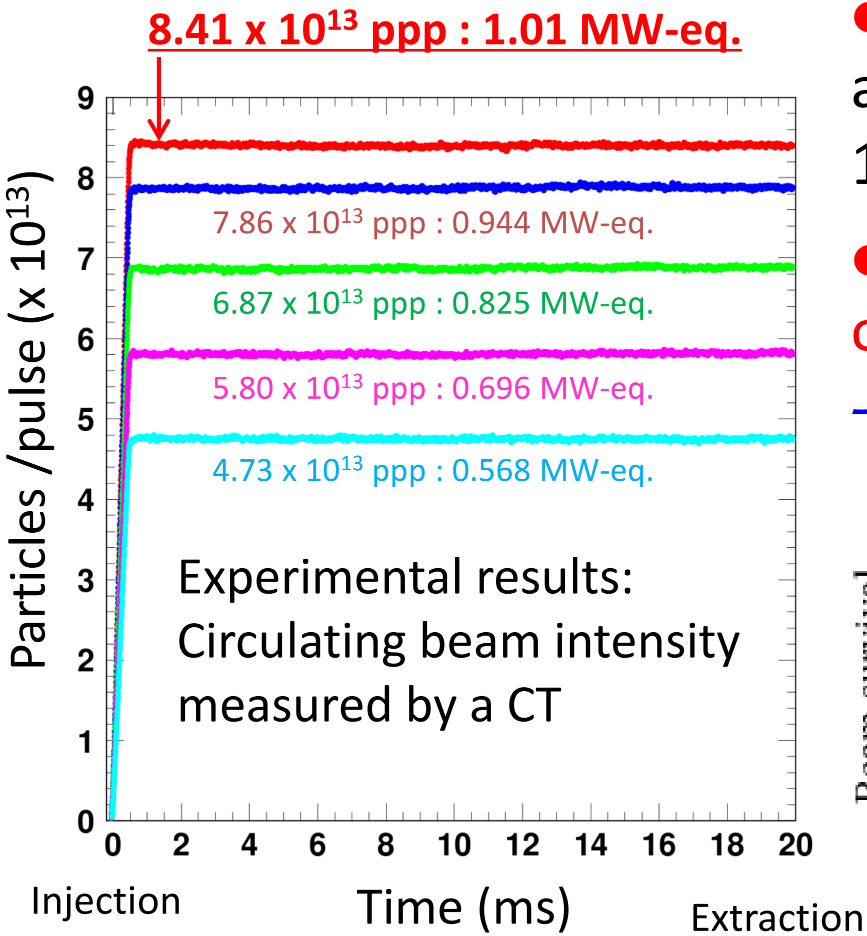
To reduce the SC effect longitudinal painting (LP) and transverse painting (TP) at injection are adopted.

ε_{tp} = 100π mm mrad in this work

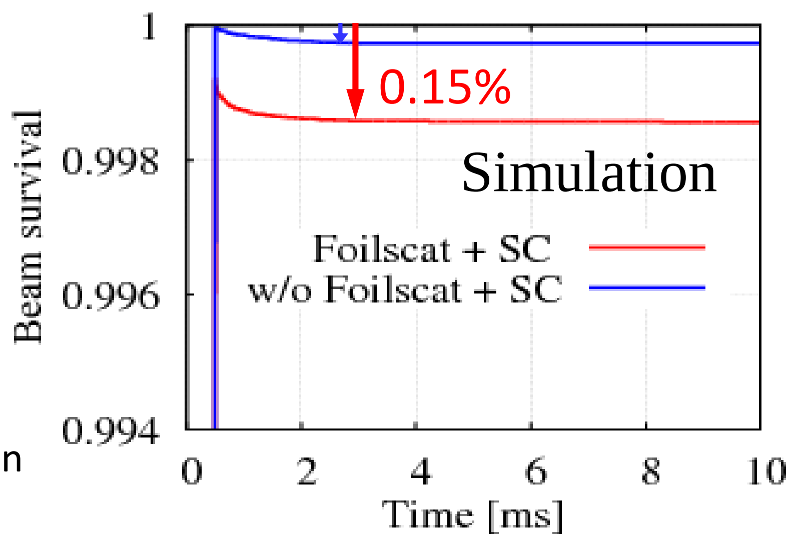
RCS Beam power at present:
To MLF: 0.5 MW
To MR: ~0.8 MW-eqv.

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**

Demonstration of 1 MW beam power



- Successfully demonstrated acceleration of the designed 1 MW beam power.
- Beam loss at 1 MW: <0.2% and only at injection energy
-- mostly due to the foil scattering.

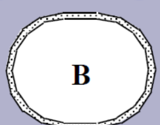


We have also established RCS parameters for operation at the 1 MW beam power.

Impedance sources in the RCS

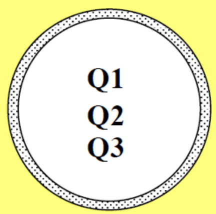
- Acceleration of 1 MW power beam was not that much simple.
- We had to do a lot of works to mitigate the beam instability caused by the transverse Impedance of the extraction kicker magnets.
- The Impedance sources in the machine were carefully addressed, but unfortunately the KM impedance remained untouched.

Dipole Magnets



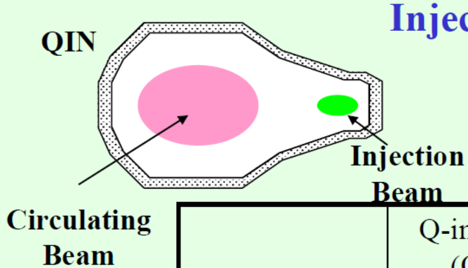
Inner size (mm)	187 x 245
Length (mm)	3500
Shape	15° bend

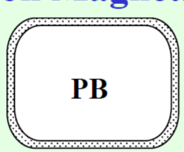
Quadrupole Magnets

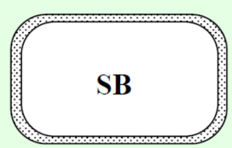


	Q1	Q2	Q3
Inner dia. (mm)	377	297	257
Length (mm)	1500	1600	1300

Injection Magnets







	Q-injection (QIN)	Painting Bump (PB)	Shift Bump (SB)
Inner size(mm)	Max. 500	350 x 250	460 x 270
Length(mm)	1500	770	1350

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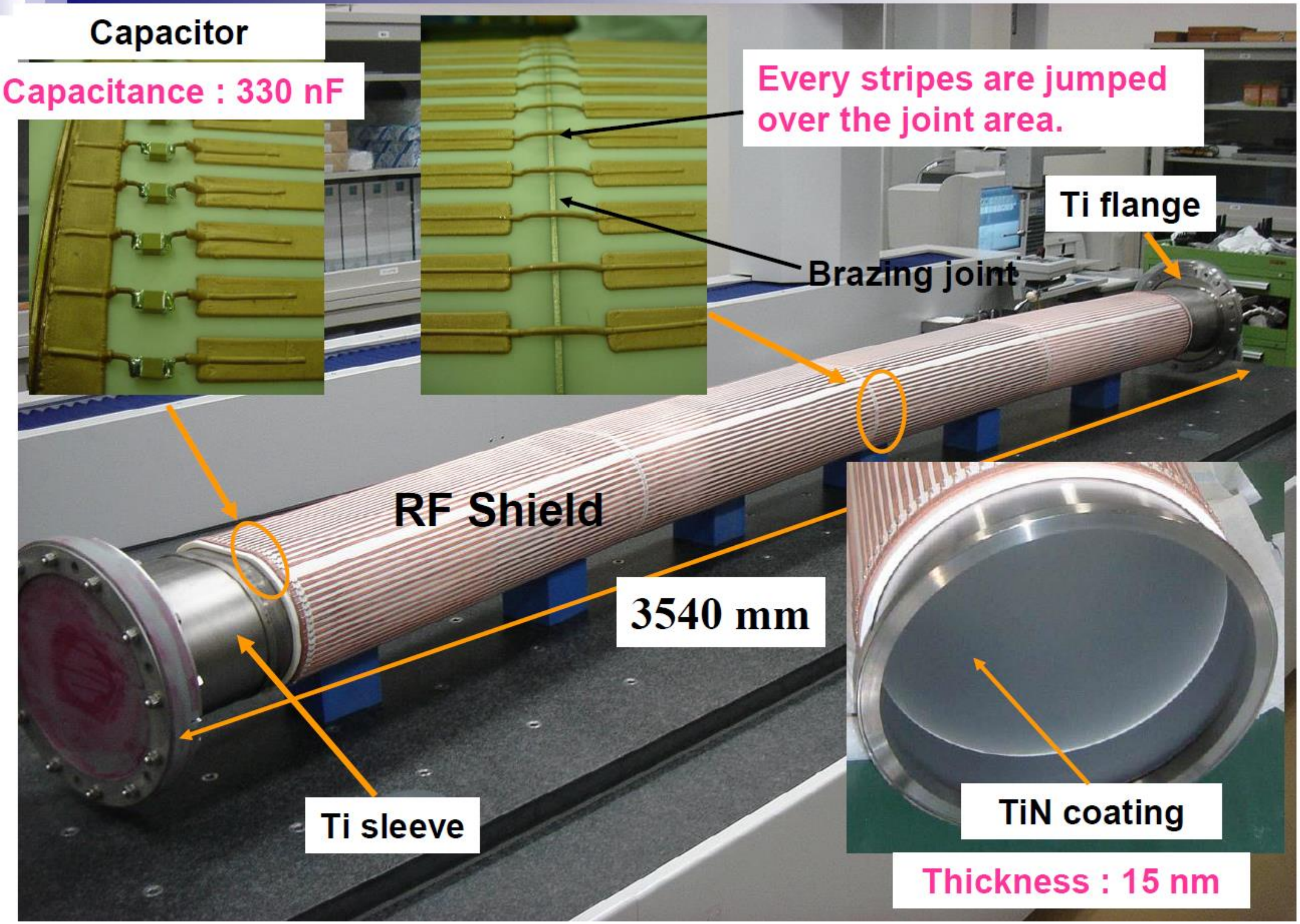
RCS Vacuum chambers types and their parameters.

Titanium flanged alumina ceramics vacuum chambers with RF shields were developed.

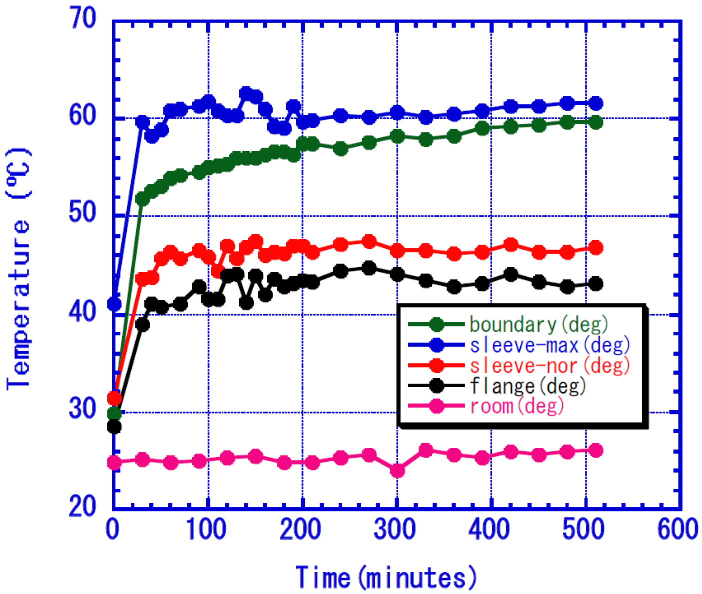
Courtesy: M. Kinsho

Ceramics chamber - picture -

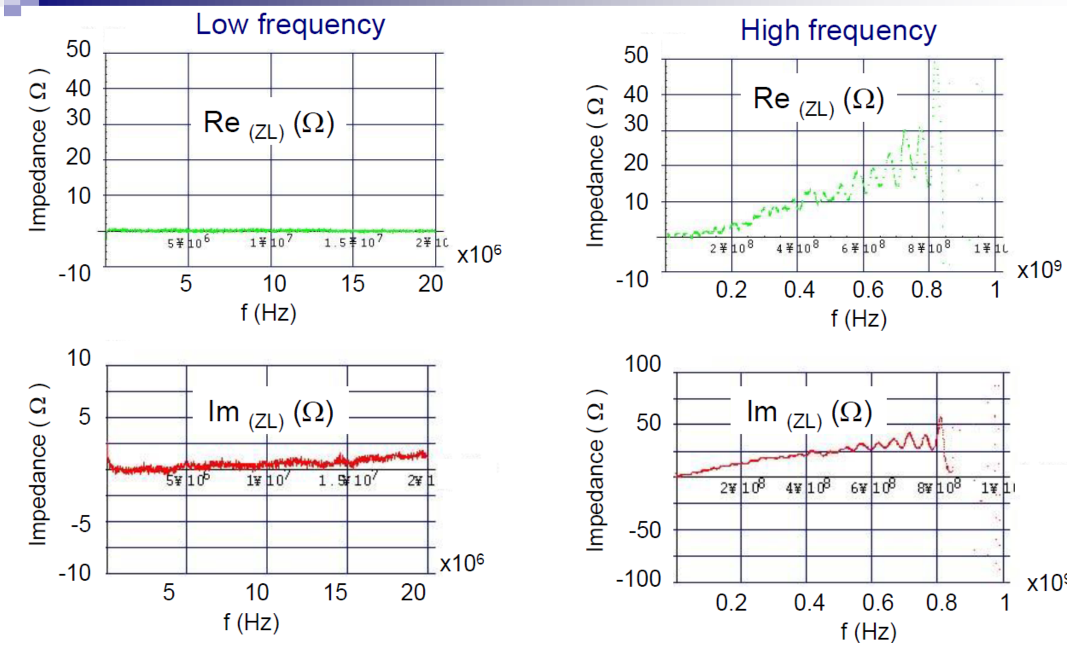


Ceramic duct properties

Temperature measurement - resul



Impedance measurements - results -



The temperature for dipole magnet was measured at various point with ramping and at 25 Hz.

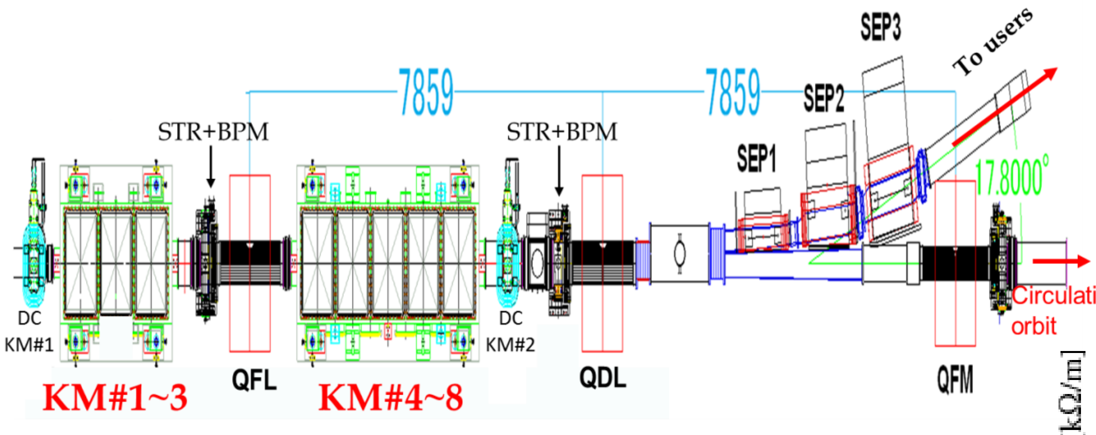
◎ The Eddy current heating of the Ti Sleeve and flange was not high.

The longitudinal impedance was measured by single wire method.

◎ The impedance at low frequency was very small.

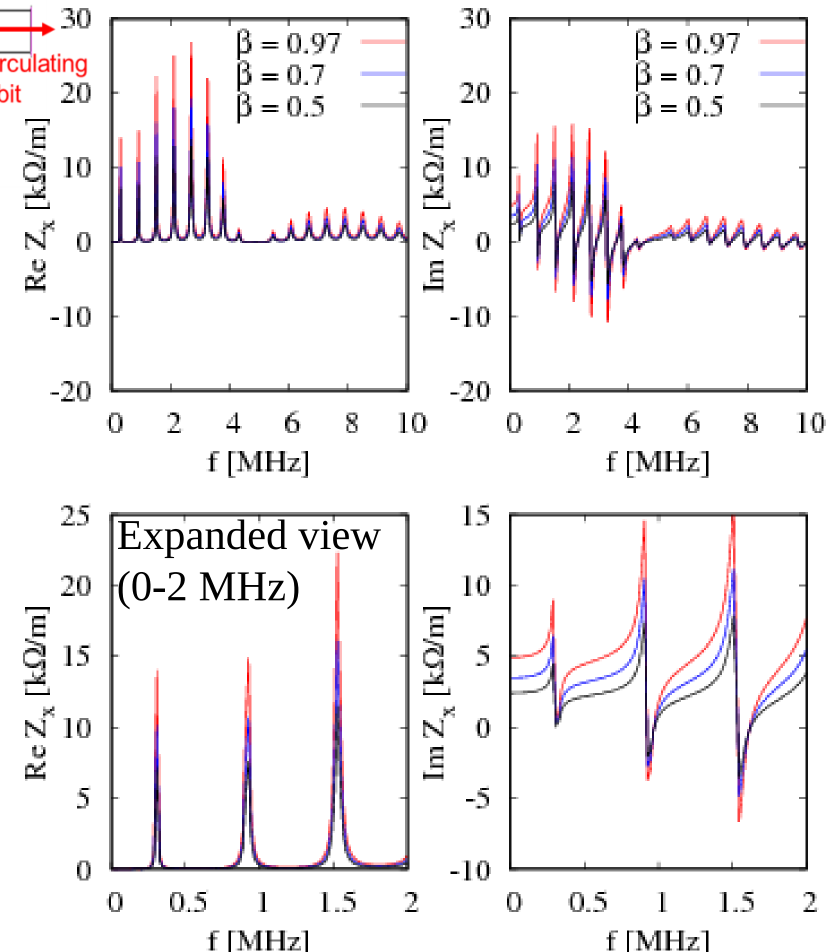
◎ The impedance at higher frequency was also not so big.

RCS Kicker Impedance



Horizontal impedance of one KM

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



×10 of SNS KM impedance!

The KM impedance is the most significant beam instability source in the RCS.

Beam instability occurs even at a beam power exceeding 0.25 MW!

Beam Instability simulations and mitigation methods

■ 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:

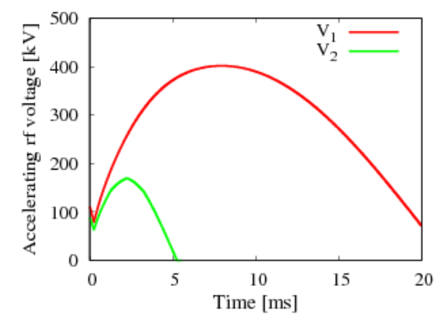
Injection process, transverse & longitudinal injection paintings, error sources, PS ripples, ... and also the KM impedance.

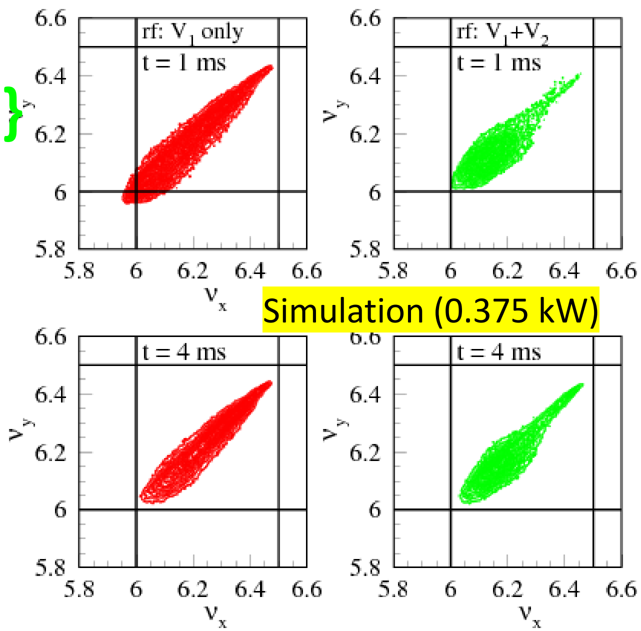
Space charge simulation results

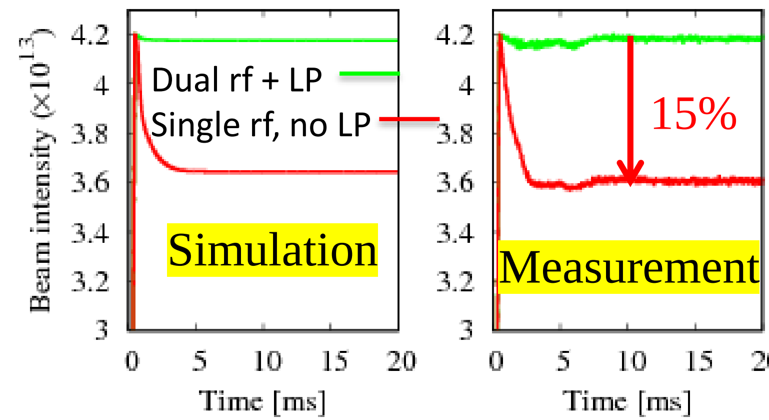
The space charge force is controlled by the choice of Einj., rf pattern and LP

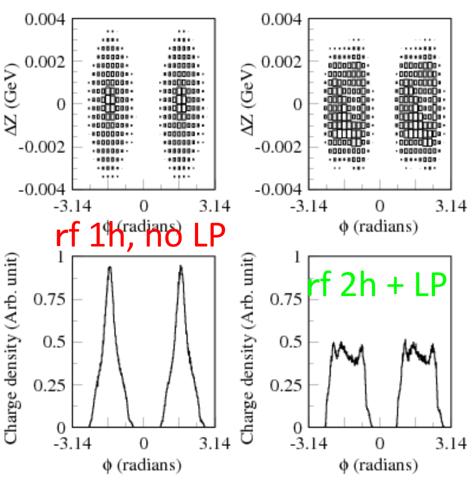
Einj: 0.181 GeV
TP= 100π mm mrad
PPP: 4.2E13 (0.5 MW)

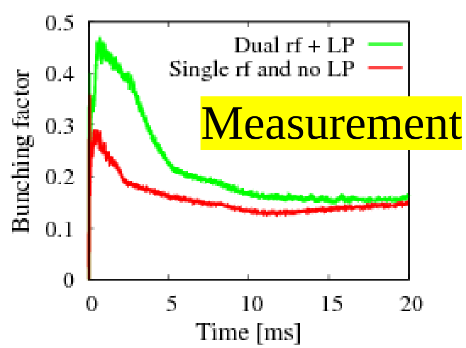
$V_{rf} = V_1 \sin\phi + V_2 \sin\{2(\phi-\phi_s) + \phi_2\}$







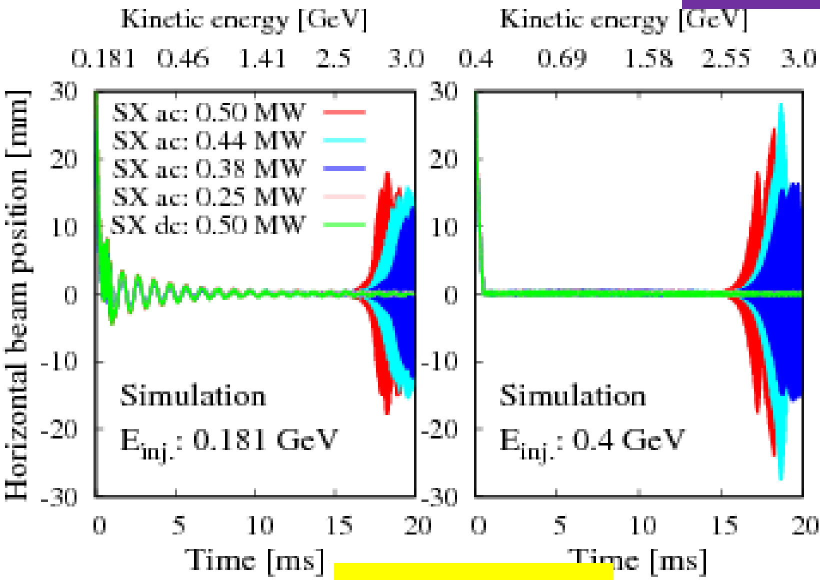




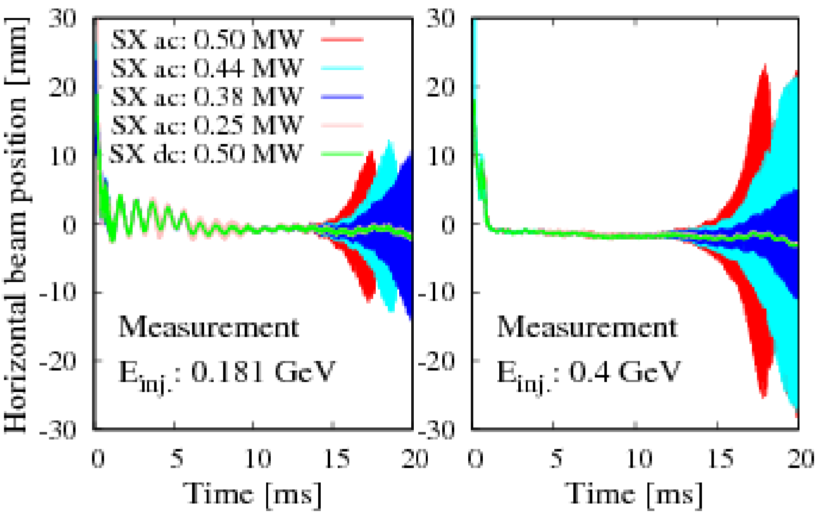
$\Delta\nu \sim -0.45$ at inj. even with rf 2h + LP.
Further increased by using rf 1h only.
Particles at ν_{xy}=6 resonances increase.
Emittance blowup beyond aperture and huge particle losses with rf 1h.
Well mitigated by using rf 2h + LP.

$\Delta\nu = -0.45$ 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**

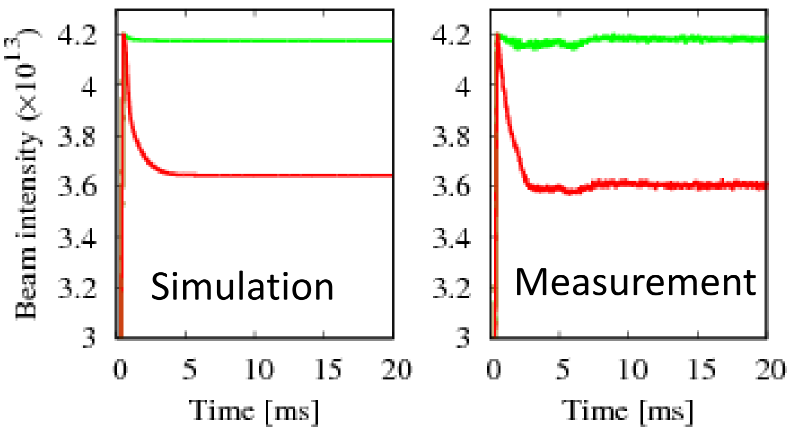
Simulation results are well reproduced in the measurements.

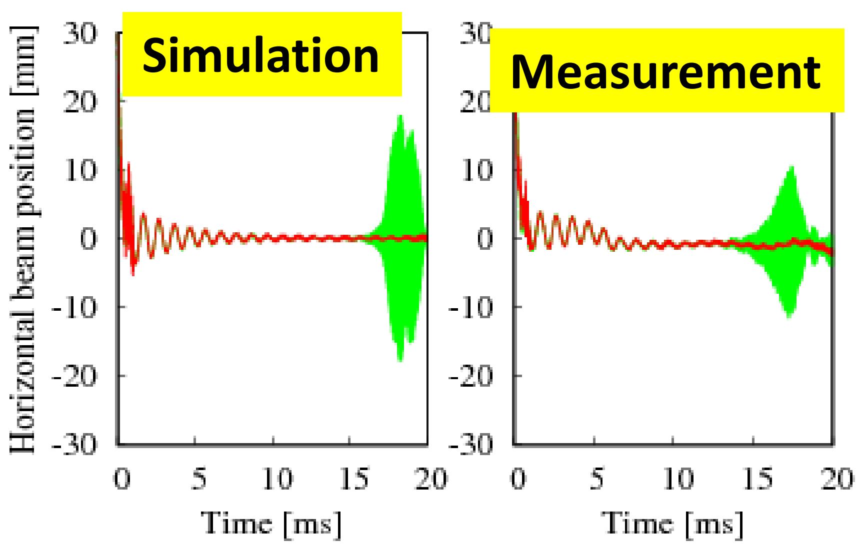
Beam instability occurs at relativistic energy.
-- Beam is stabilized by the SC at lower energy.

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

Dual rf + LP
Single rf, no LP





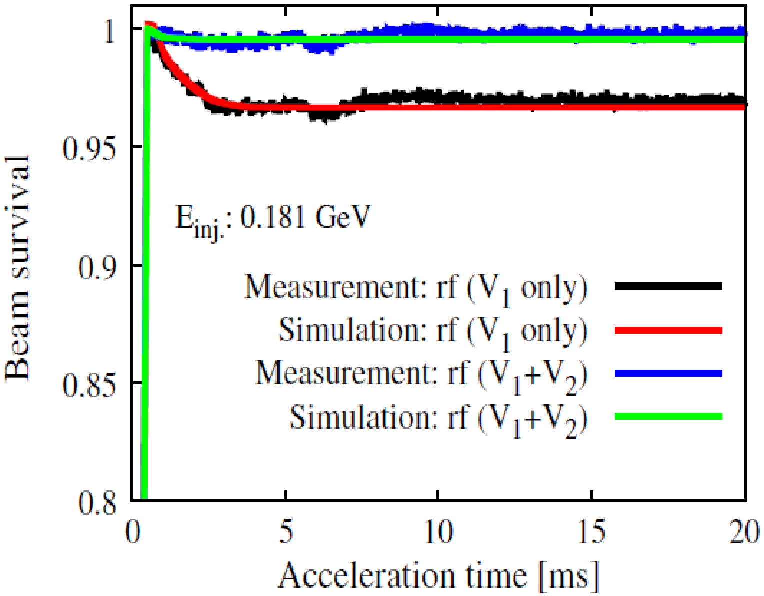
Einj. = 0.181 GeV, **SX ac** (ξ =0)
PPP: 4.2E13 (0.5 MW)
$\Delta\nu/\nu_s$ >> 1 (strong space charge)

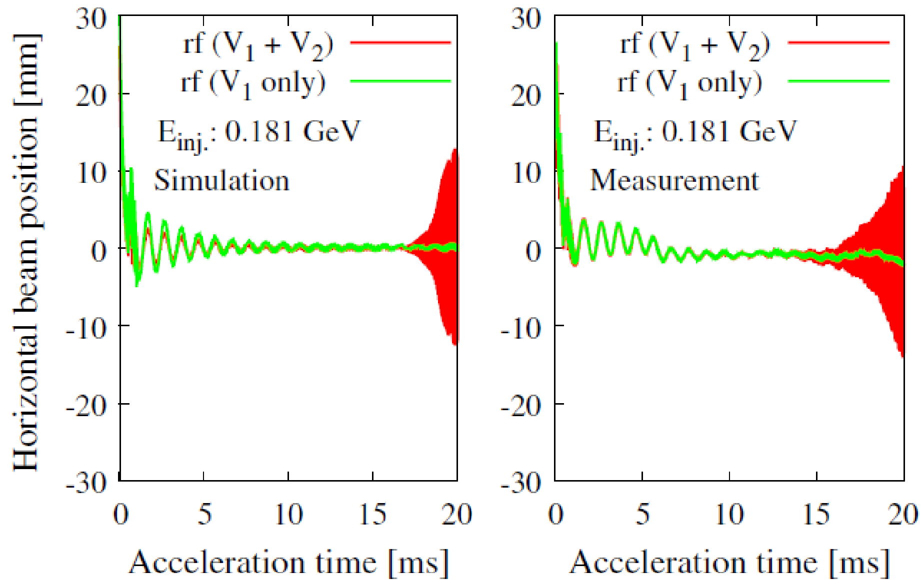
- Beam instability occurs when the SC effect is reduced by applying dual harmonic rf voltage and also the LP.
- However, beam is stable when SC is stronger by omitting 2nd harmonic rf voltage and also the LP.

Beam instability suppression by the SC

How about at lower beam intensity?

Beam power: 0.375 MW (3.1E13). **ξ = 0,** Beam loss with rf 1h: 3%





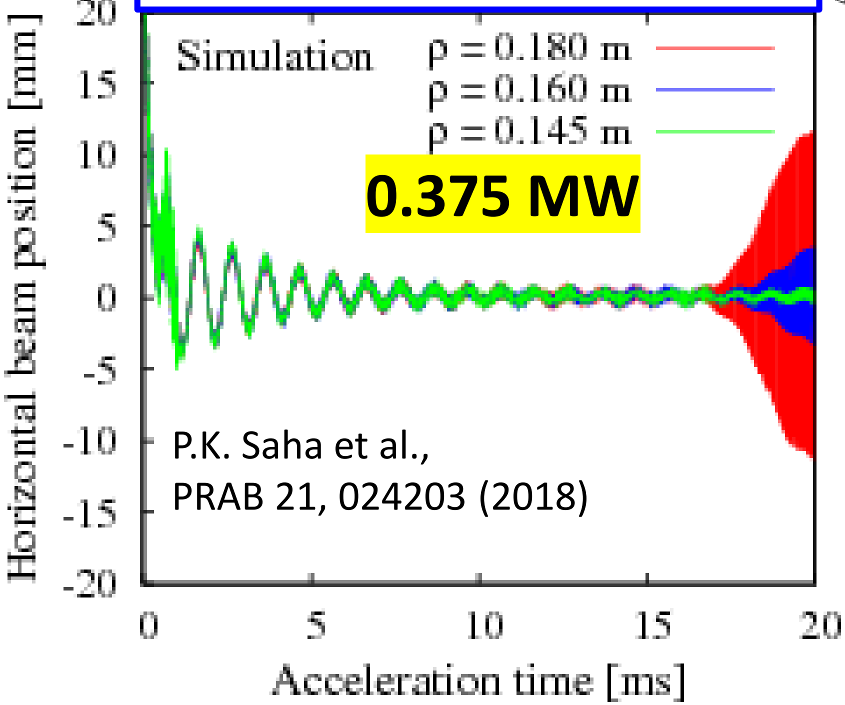
P.K. Saha et al., PRAB 21, 024203 (2018)

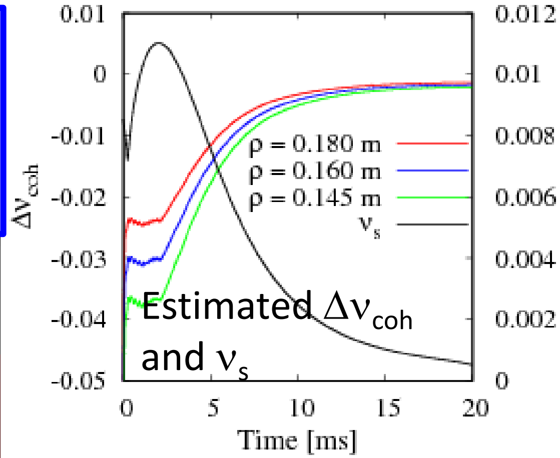
The Landau damping effect of the non-linear SC force becomes more effective to stabilize the beam.

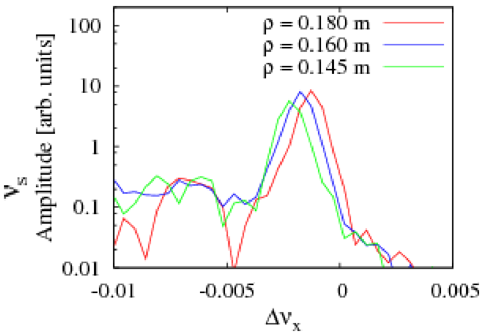
The ORBIT code takes **indirect SC** into account, which is important to study the beam instability with SC.

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 as ρ is increased so as the **growth rates.**

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)

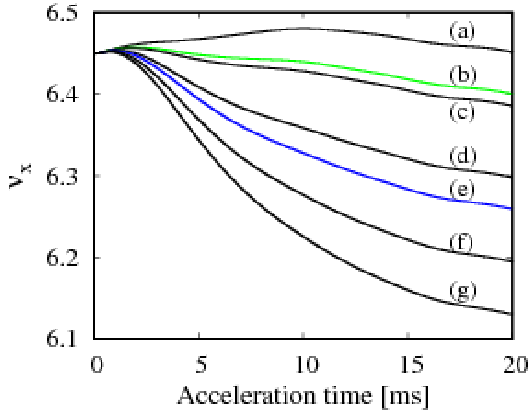
(2) Further reduction of the DC ξ correction.

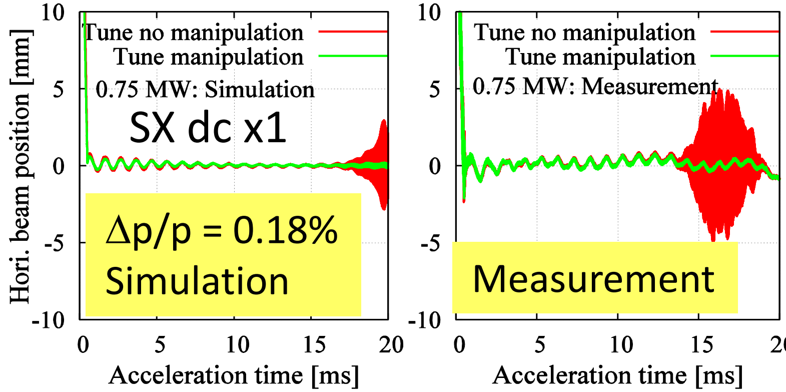
(to enhance the Landau damping)

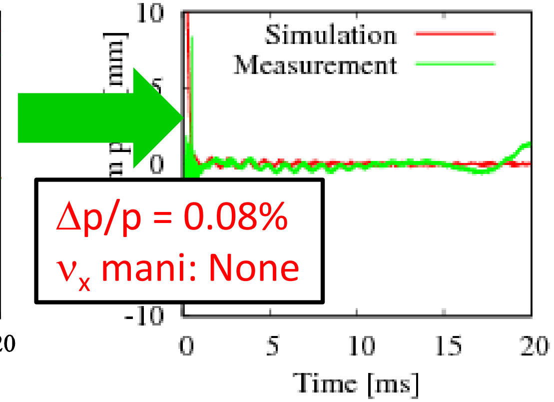
(3) Smaller $\Delta p/p$ of the injected beam (should be <0.1%)

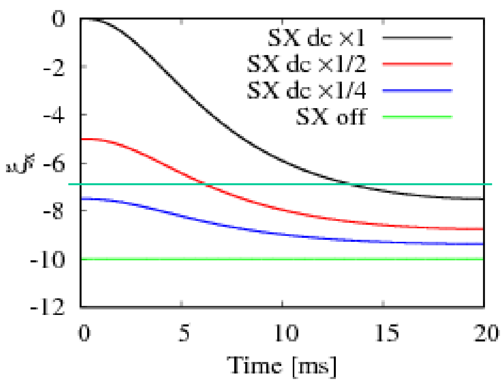
(same as (2))

Suppression of Beam Instability at 1MW beam power









Even at 0.75 MW beam power:

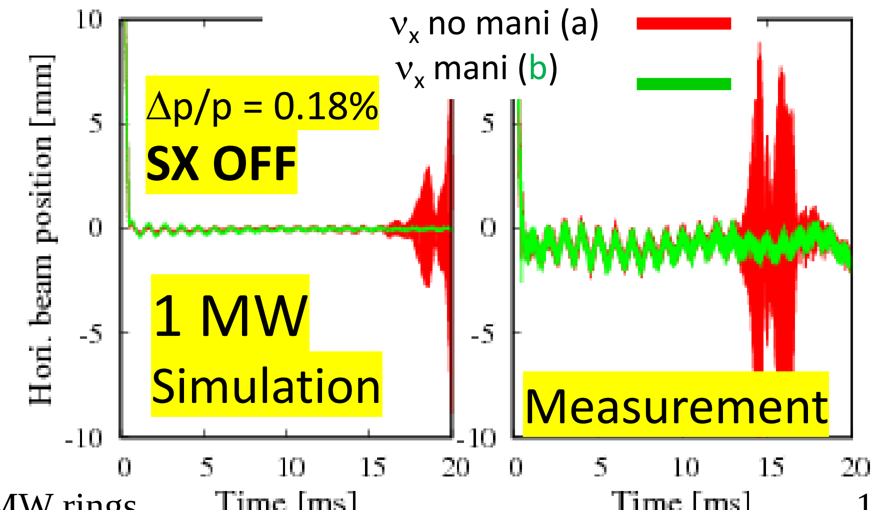
- Beam instability w/o ν_x manipulation, but
- ✓ **A proper ν_x manipulation stabilizes the beam.**
- ✓ **A narrower $\Delta p/p$ (inj. beam) gives no instability.**

However, at 1 MW,

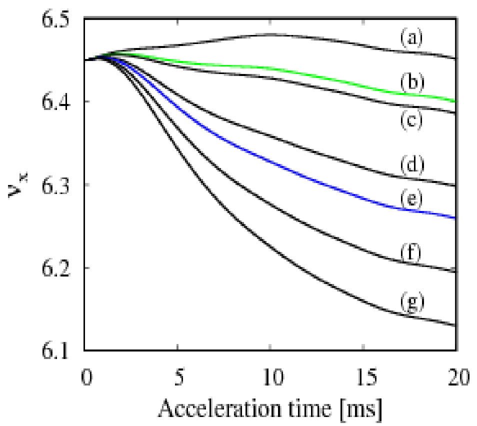
A partial ξ correction is desired.

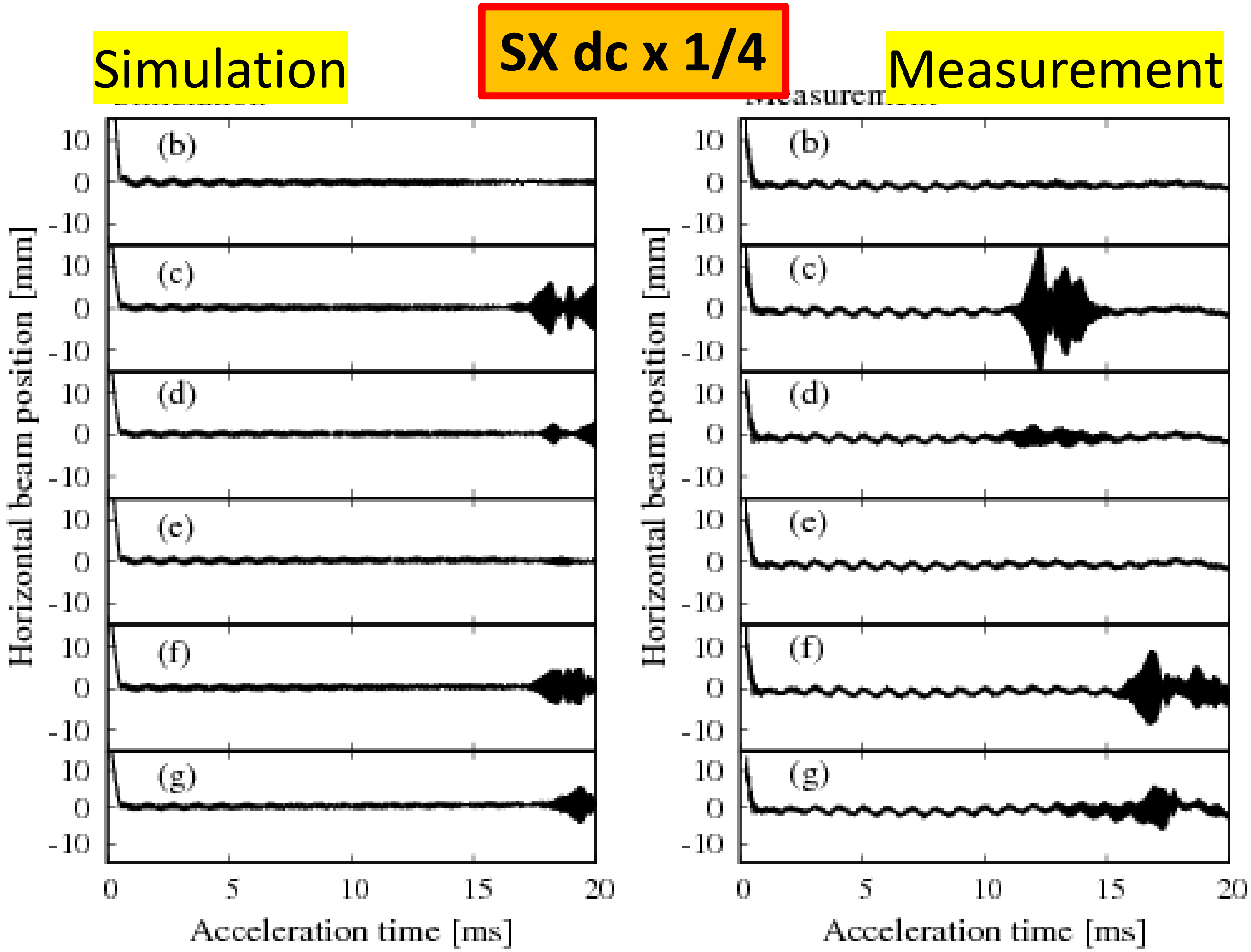
Growth rate further increases!

Detail tune survey done.



Betatron tune dependence 1 MW beam power

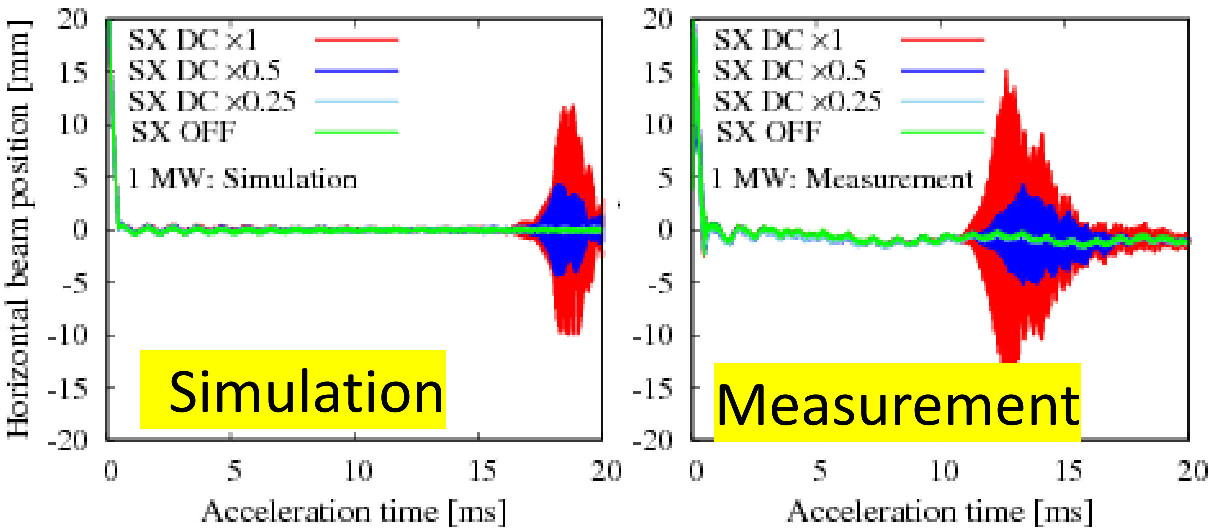


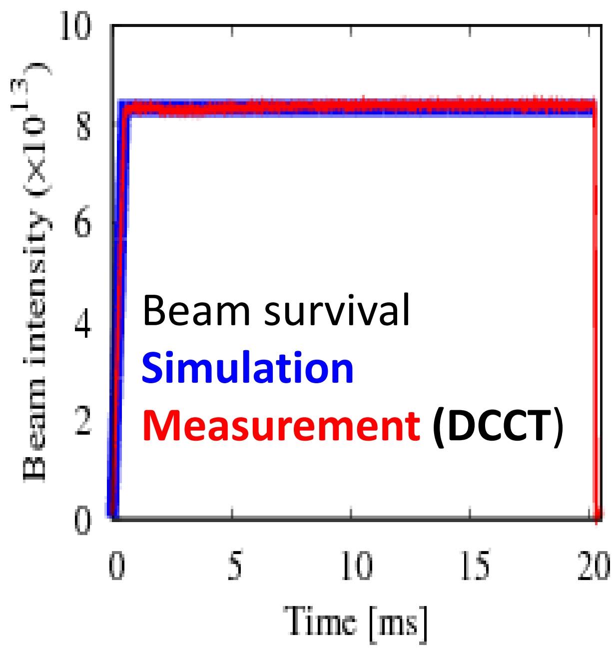


- ◎ Choice of betatron tunes are very limited.
- ◎ Simulation results are well reproduced in the measurements.

ξ dependence at 1 MW

P.K. Saha et al., PRAB 21, 024203 (2018)



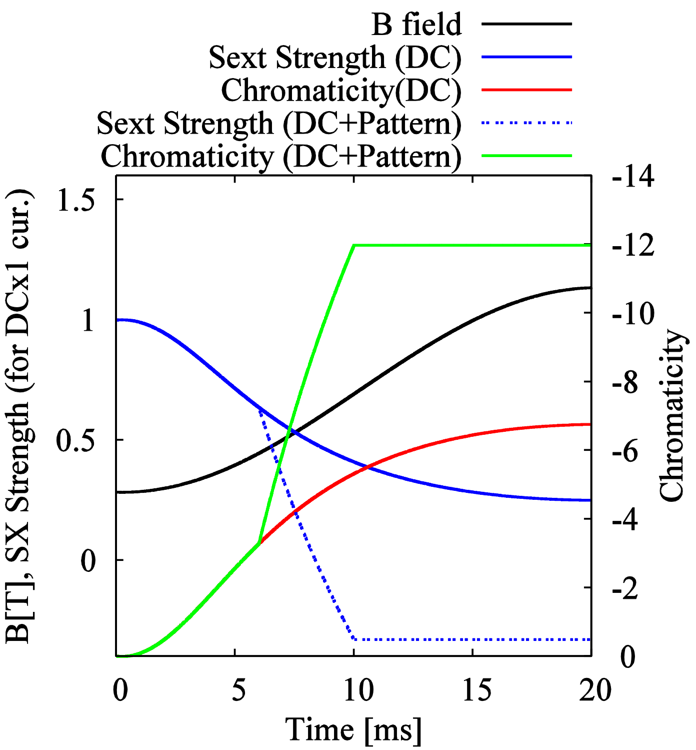


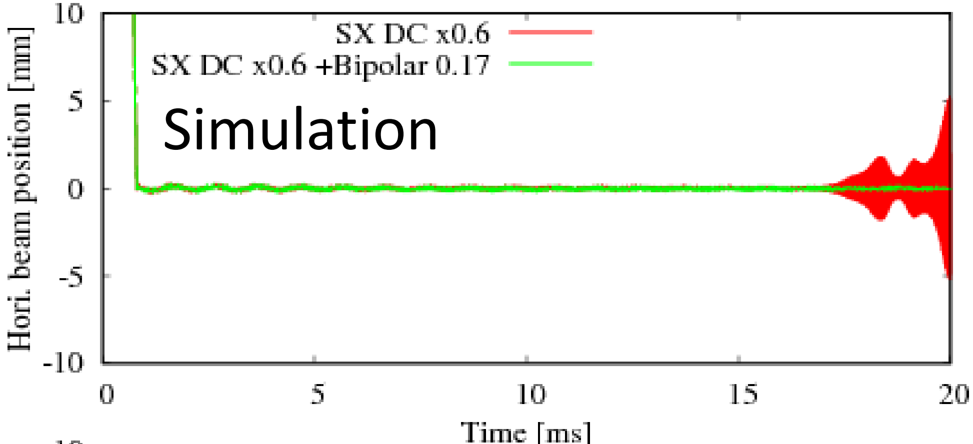
In addition to a proper betatron tune manipulation, the ξ correction of 1/4 or less at injection and **almost no ξ correction at extraction** were utilized to accomplish 1 MW beam power.

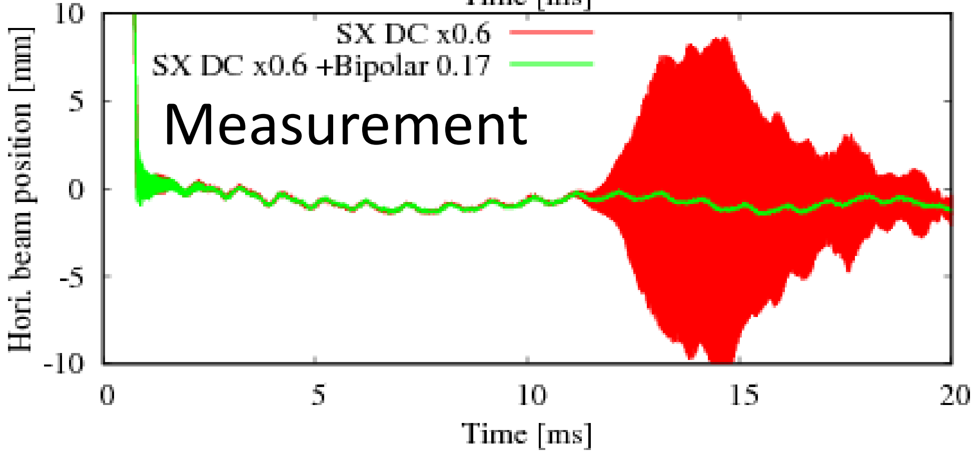
Recent results

In the RCS, particular tune choice, smaller transverse painting and SX dc ×** are required for smaller beam emittance **for the MR**. Beam instability occurs in this case.

Introduced extra ξ by SX bipolar field.





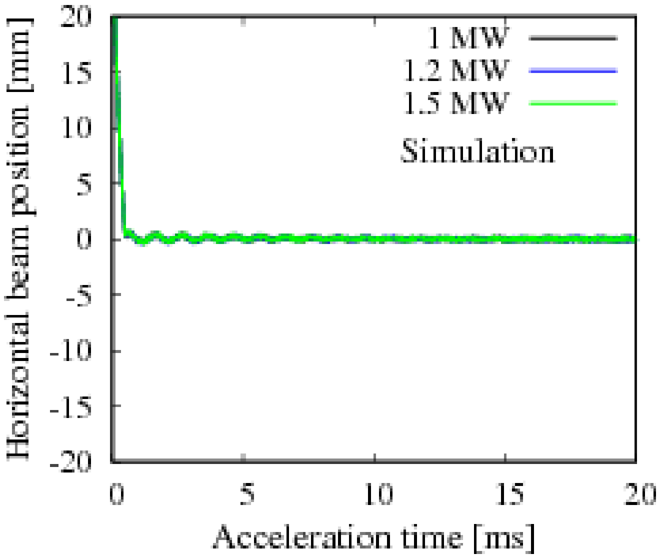


Beyond 1 MW beam power

In order to make sure 1 MW beam power to the MLF, even if MR cycle is upgraded from 2.48s to ~1s and also when a 2nd target station at the MLF is constructed, **RCS beam power upgrade is planned to be 1.5 MW.**

However, beam instability occurs even if ξ is not corrected at all.

R&D studies to reduce the KM is in progress. The impedance can be reduced by at least a half (Y. Shobuda, IPAC18).



The given reduced impedance is used in the simulation.

Beam is stable up to 1.5 MW even if ξ is fully corrected at injection by SX dc.

SX bipolar field for 20% extra ξ at the later half cycle also stabilizes the beam.

Summary and outlook

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

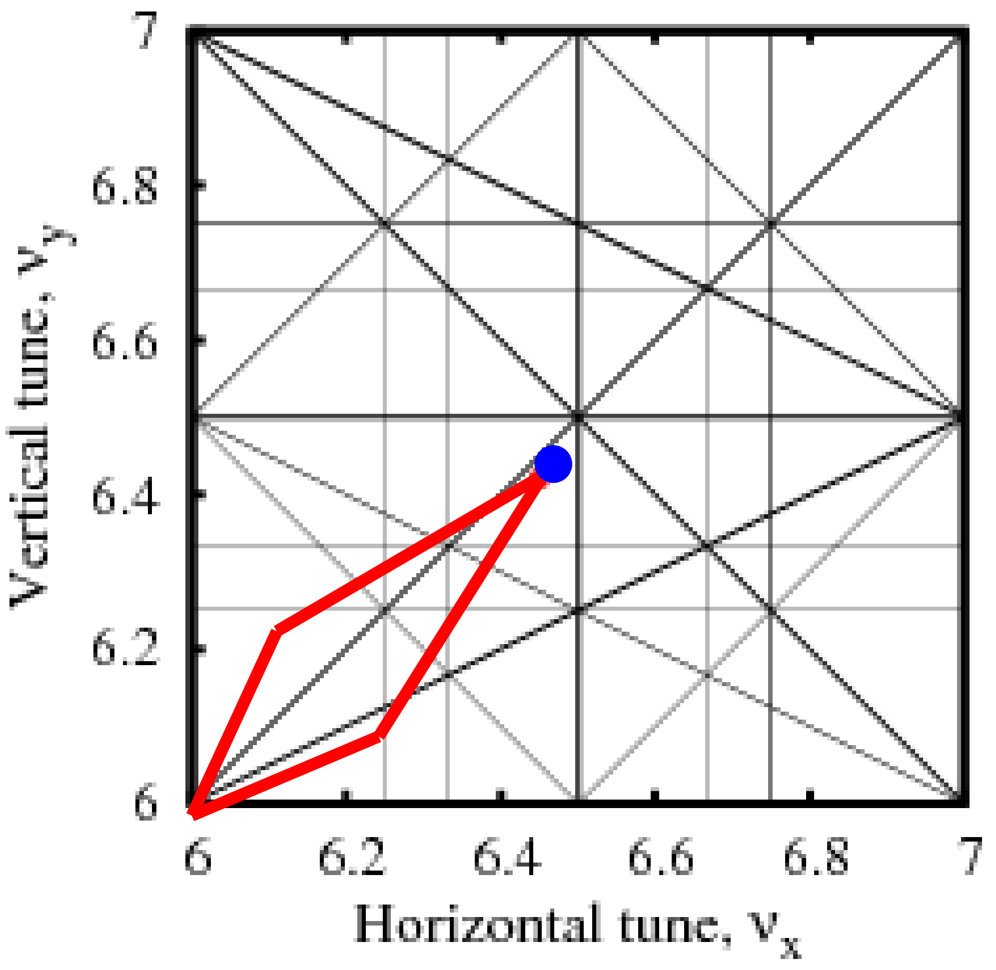
■ The ORBIT code was enhanced to cope with all time dependent Parameters for realistic beam instability studies with SC.
The beam instability suppression by the SC has been studied in detail.

■ 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.

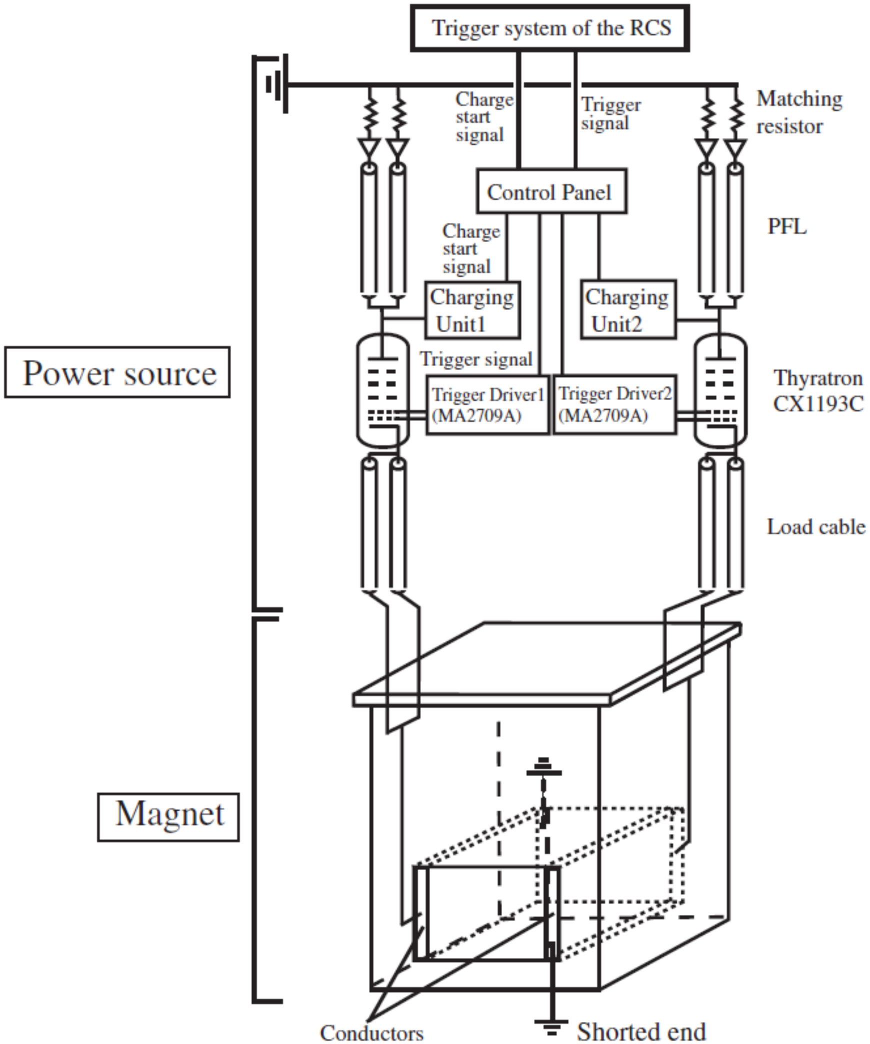


FIG. 1. Outline structure of the kicker system.

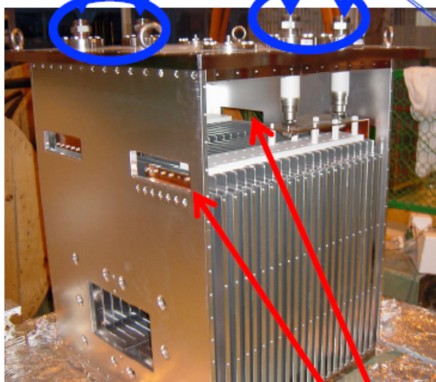
TABLE I. Specifications of the RCS kicker system.

Numbers	8 (Nos. 1–8)
Maximum repetition rate	25 Hz
Characteristic impedance	10 Ω
PFL	Coaxial cable, about 102 m
Load cable	Same as PFL, about 130 m
High power switch	Thyratron CX1193C, e2V Ltd.
Maximum output current	4 kA
Operation output current	3 kA
Flattop length	840 ns for two beam bunches
Rise time	25 ns (typical)
Jitter	Less than 10 ns
Flatness	6% without correction
	2% with correction
Maximum charging voltage	80 kV
Operation charging voltage	60 kV
Maximum exciting current	8 kA
Operation exciting current	6 kA
Magnet structure	Distributed parameter line
Magnet core	Ni-Zn ferrite PE14, TDK Ltd.
Magnet gap height	153 mm (S-type: No. 3, 4, 5)
	173 mm (M-type: No. 2, 6)
	199 mm (L-type: No. 1, 7, 8)
Magnet gap width	280 mm
Magnet longitudinal length	638 mm
Magnetic field	460 G (S-type)
	410 G (M-type)
	360 G (L-type)

Courtesy: Y. Shobuda (IPAC18, Vancouver)

➤ The characteristic of the present RCS kicker

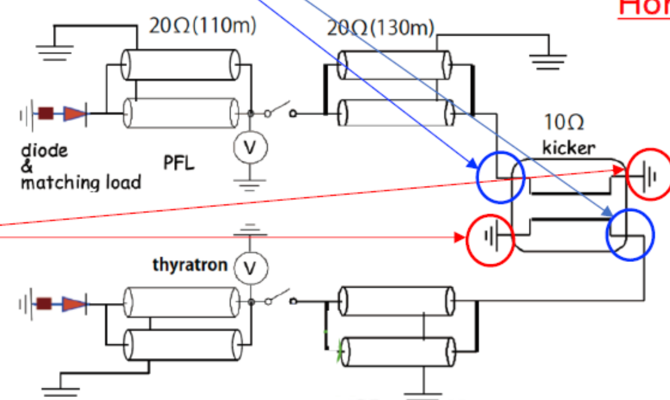
Inputs for 130m coaxial cables



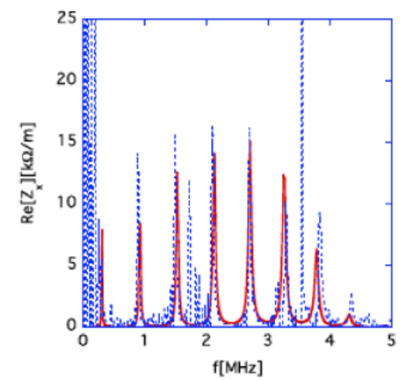
Kicker magnet

Short plates

- The kicker magnet at the RCS has four terminals.
- Two are connected to Pulse Forming Line (PFL), while the others are terminated by **the short plates**
- **The short plates generate a power saving benefit** by doubling the excitation current by superposing the forward and backward currents, when a beam is extracted from the RCS.



Horizontal impedance at β=0.55



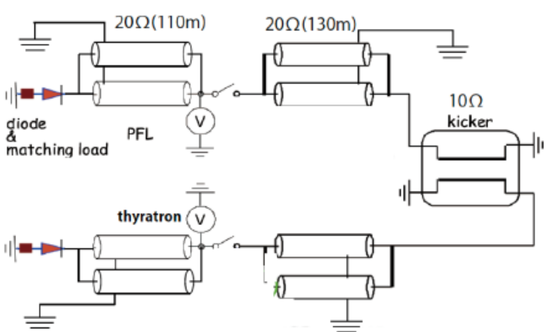
- On the other hand, **the short plates create the resonance structure** in the kicker impedance in combination with the coaxial cables.

Courtesy: Y. Shobuda (IPAC18, Vancouver)

➢ A new scheme to reduce the kicker impedance

- In order to reduce the impedance, one possible solution is inserting **a resistor** between the coaxial cable and PFN.
  - Notice that we must retain the benefit of short plates.
  - Thus, the resistor has to be isolated from the PFN, but needs to be seen by a beam.
  - We need a mechanism to isolate the damping resistor from the pulse current from the PFN.
  - From a mechanical point of view, the easiest way is to insert a **diode** in front of the resistor.

present



Modified