Studies on collective phenomena related to J-PARC slow beam extraction

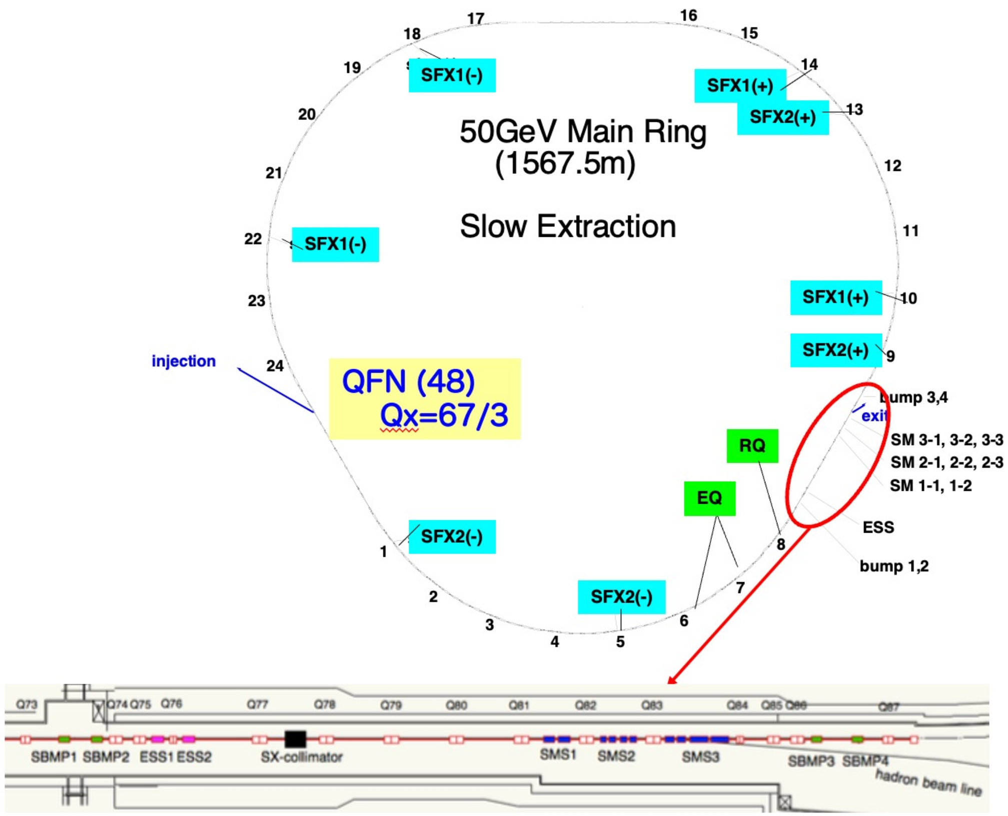
SX 2025, Stony Brook
Oct. 7, 2025

KEK/J-PARC M. Tomizawa

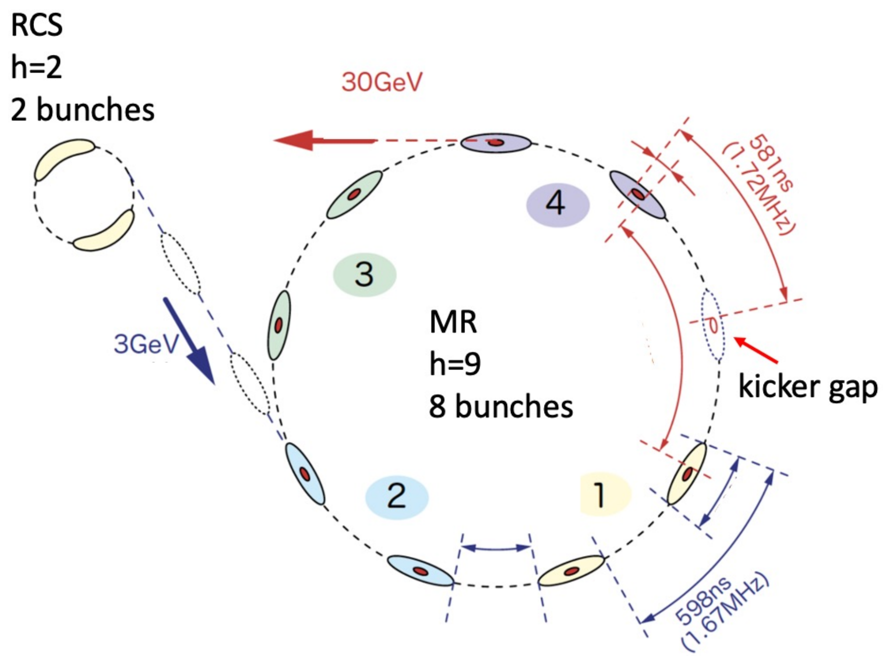
Acknowledgment:
SX-G: R. Muto, T. Asami, K. Itahashi (Soken-Univ.)
RF-G: Y. Sugiyama, K. Seiya, F. Tamura
Monitor-G: T. Toyama, A. Kobayashi, T. Nakamura
Vacuum-G: M. Uota

1. Beam instability during debunching
   mitigations for the beam instability
2. Observed “rebunching” at high beam intensity
3. Summary

J-PARC MR Slow Extraction Devices



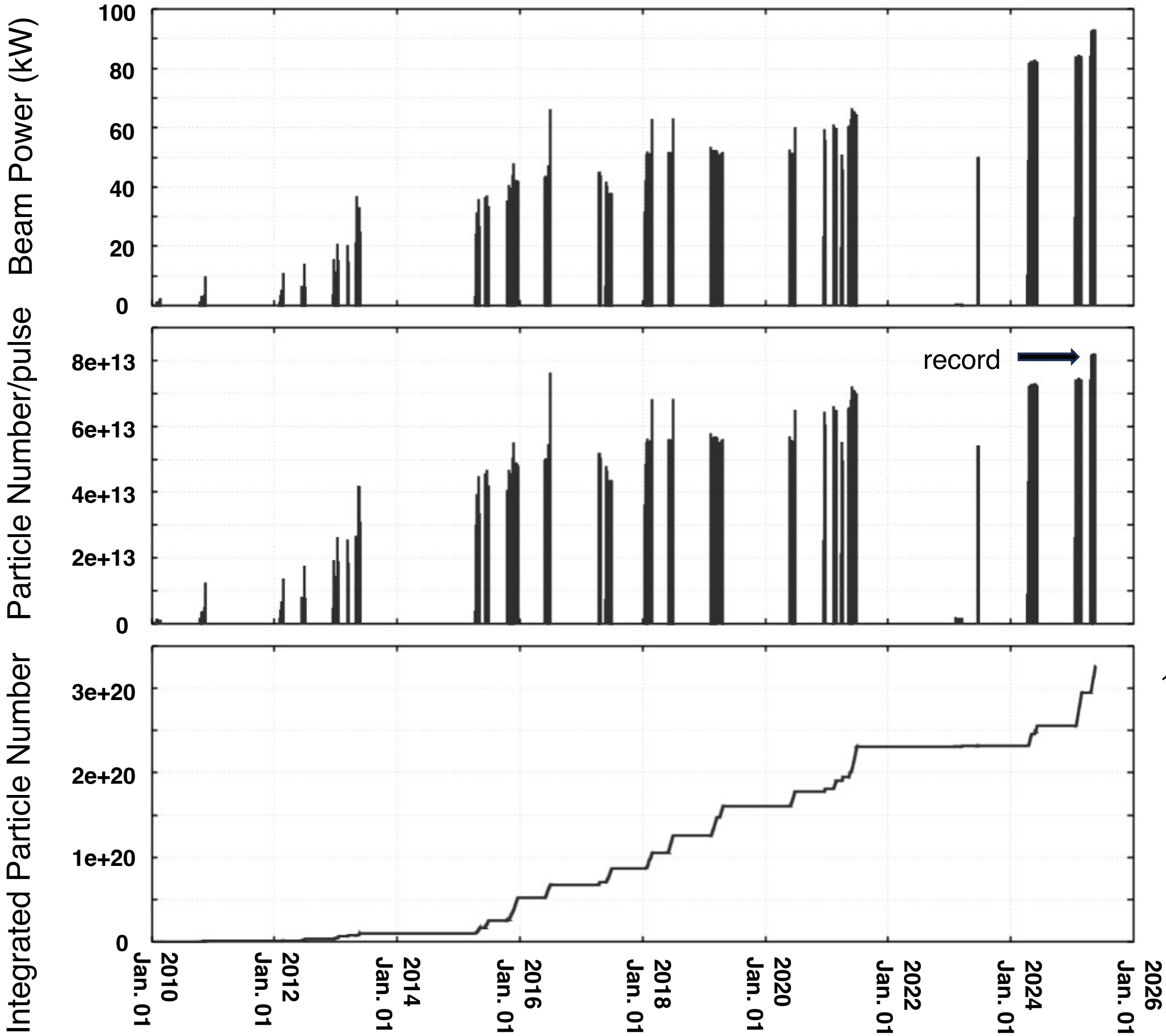
J-PARC MR Beam Bunches



A debunching manipulation before slow extraction at 30GeV

J-PARC SX operation history

Current 30GeV SX
4.24s cycle



92kW

8.1×10^{13} ppp

～3.3×10^{20} protons

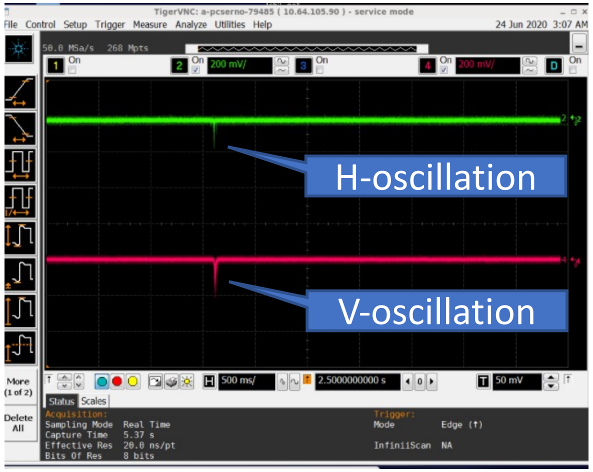
Beam Instability during debunching

Currently Limiting SX beam intensity (large beam loss for SX)

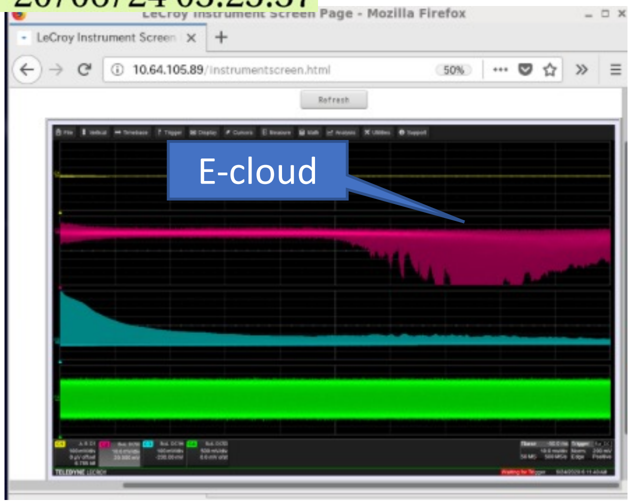
Abort destination, 60kW debunch , RF offset 65deg

BPM

Shot 311512 at 20/06/24 03:24:49
60.06 kW 20/06/24 03:25:37



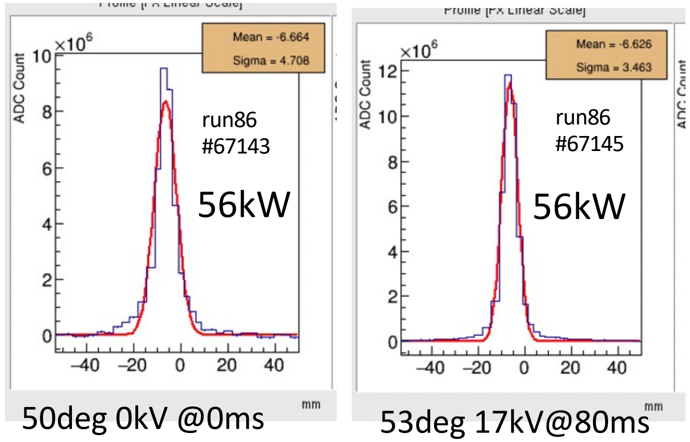
EC monitor



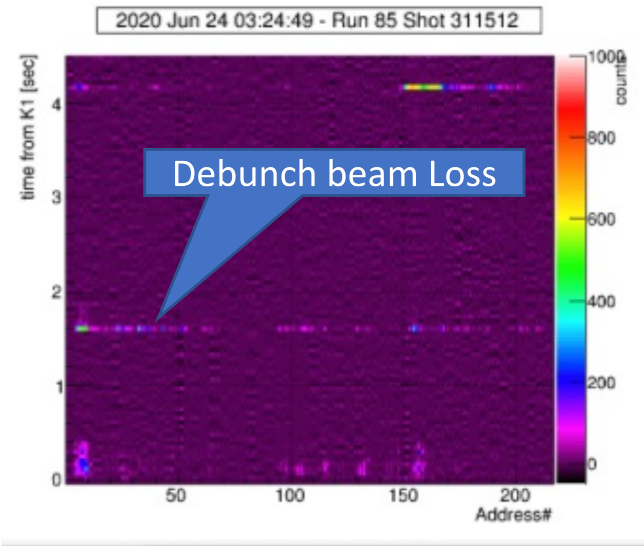
H, V beam size growth

56kW

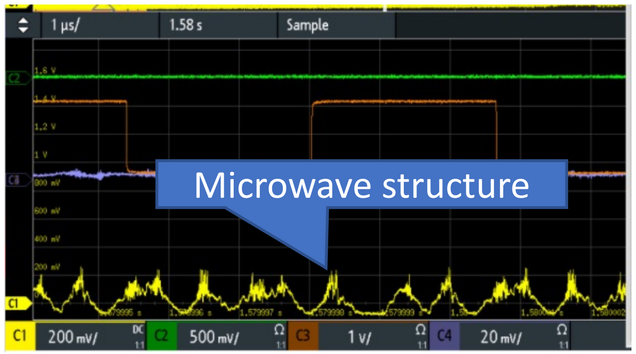
w/Insta. w/o Insta.



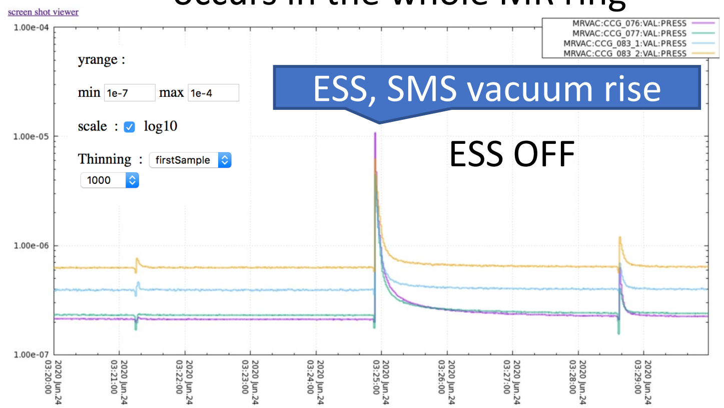
BLM



Wall Current Monitor



occurs in the whole MR ring



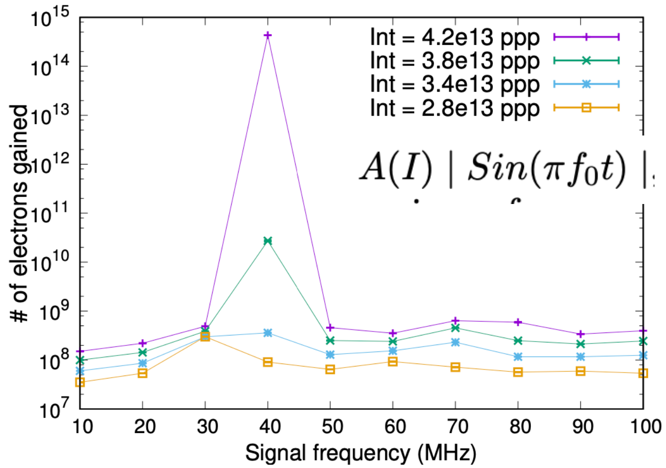
The Debunch Instability Mechanism Estimation

1. A longitudinal microwave structure during debunching is generated by longitudinal impedances Z_L

2. The microwave structure enhances the electron cloud generation (multipactor process)

3. Proton beam oscillates transversely by interaction with the electron cloud.
   -> results in the transverse instability and beam loss

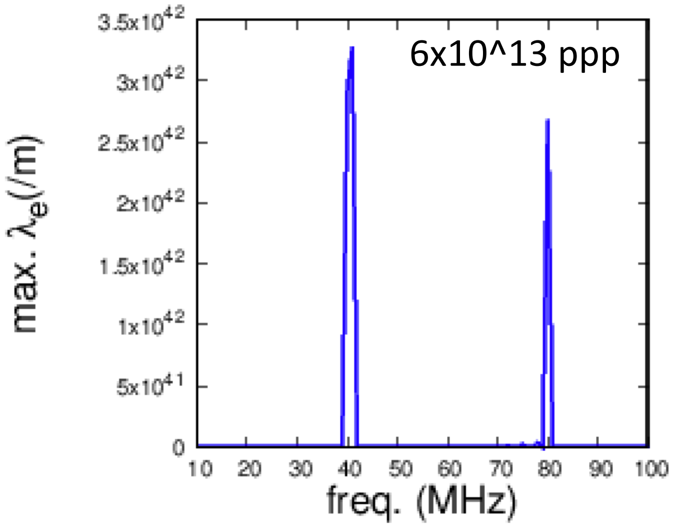
e-cloud simulation by B. Yee-Rendon



Bruce Yee-Rendon et. al, Journal of Physics: Conf. Series 874(2017)012

Multipactor condition around 40MHz

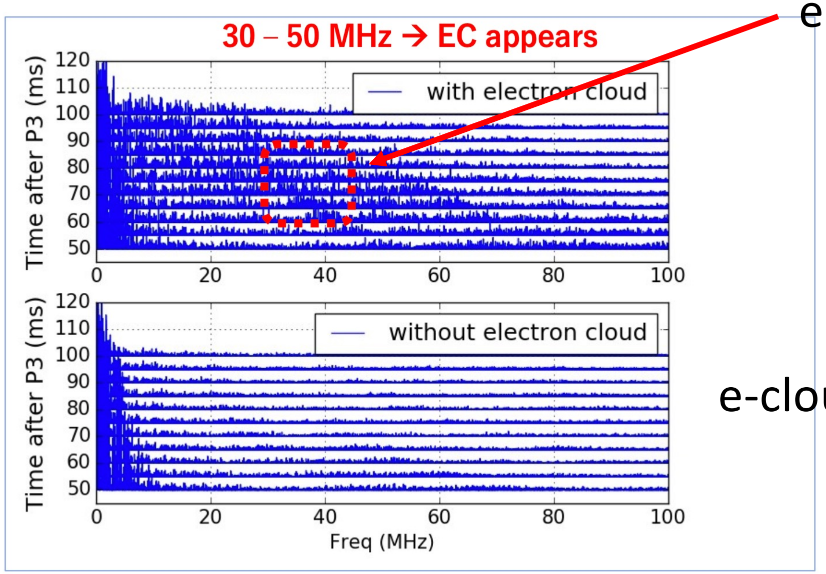
1-D e-cloud simulation



M. Tomizawa, Ecloud2022

Measured Beams Time Structure (FCT)

Frequency spectrum of the beam measured by the Fast CT



e-cloud seen

e-cloud not seen

ECLOUD'18, 3 - 7 June, 2018, La Biodola (Isola d'Elba) Italy

K. Ohmi

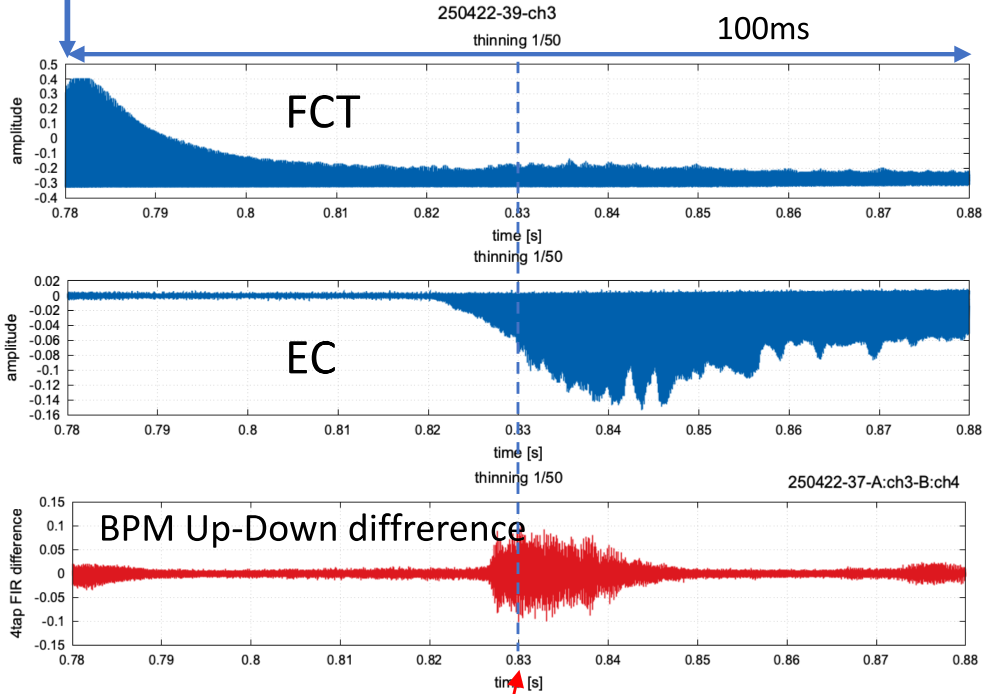
T. Toyama, B. Yee-Rendon, M. Tomizawa and R. Muto

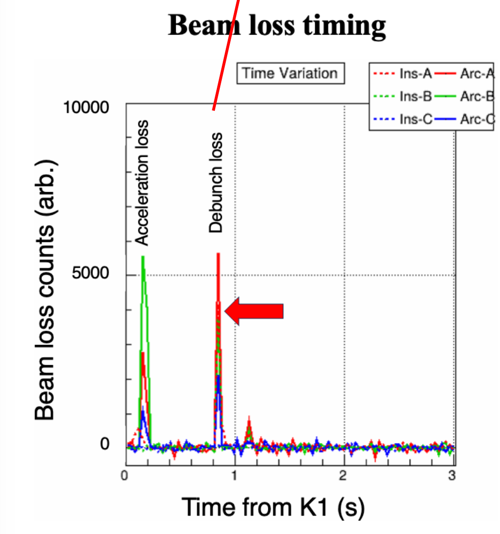
The e-cloud/FCT measurements and the simulations indicate that e-cloud is strongly built up by longitudinal 30-50MHz beam time structure.

Evidence to explain the assumed mechanism

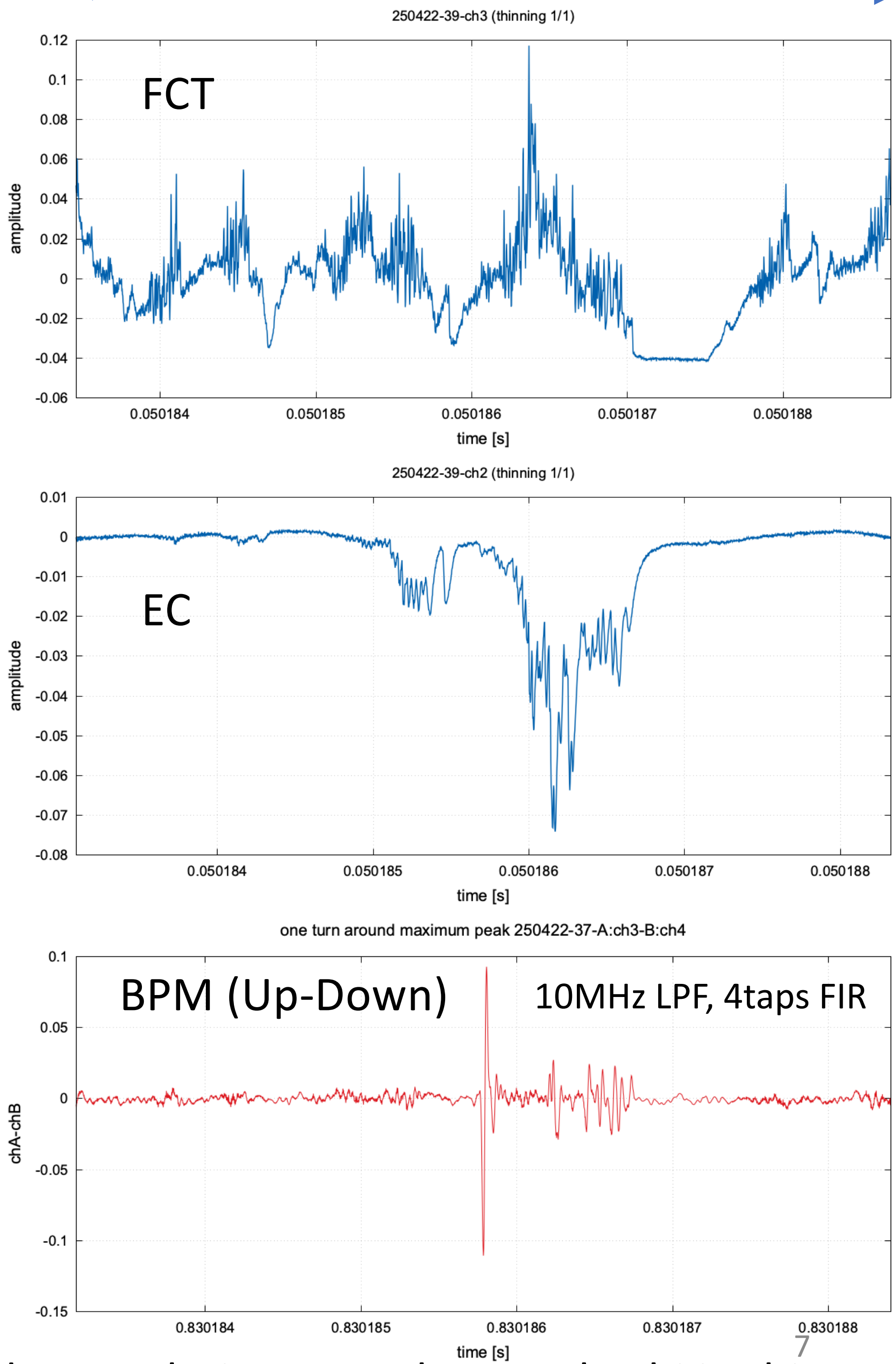
Fundamental and second RF+Phase offset one step debunch 94 kW Run92 #1885806

RF OFF (P3) Instability was intentionally induced





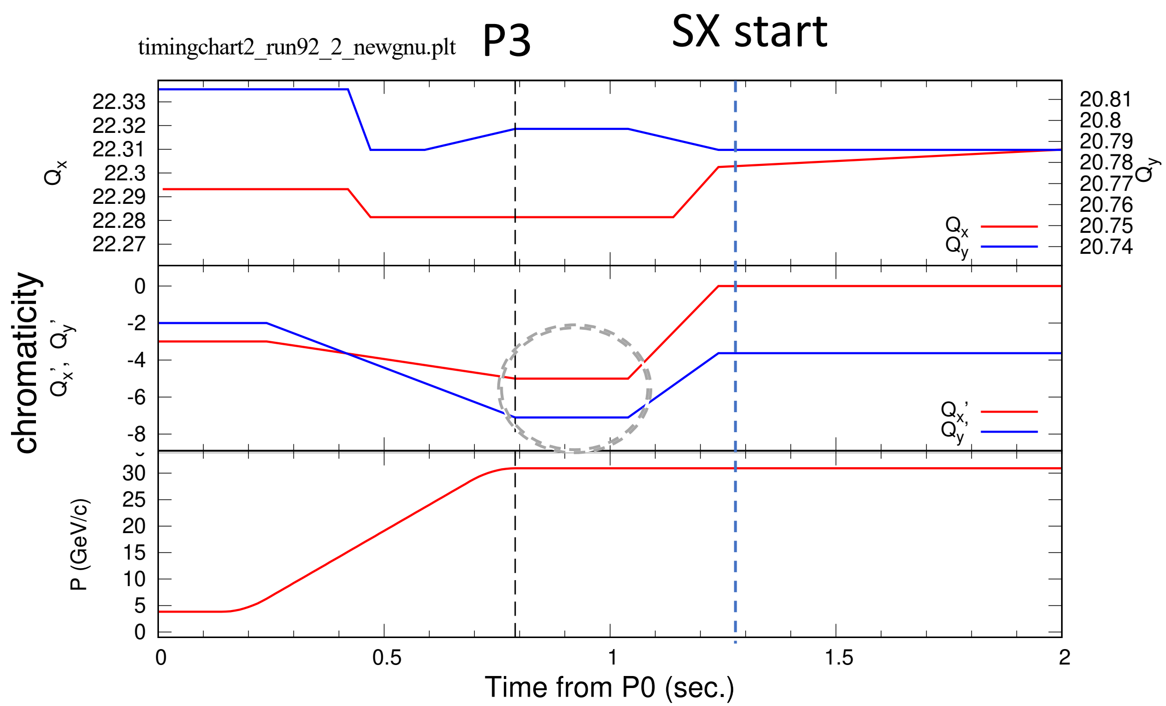
One turn (5.2μs)



Detailed data analysis: poster by K. Itahashi in this WS

Direct Transverse Instability Suppression

・H and V chromaticity corrections (negative value) are weakened during debunching.
J-PARC slow extraction needs a zero Qx' for high slow extraction efficiency.
This weakening is constrained by the power supply limitations.
-> partially works to suppress the instability, but not enough.



Our current main strategy to mitigate the instability with e-cloud is to suppress the longitudinal microwave time structure

Longitudinal microwave instability threshold (Keil-Schnell criterion)

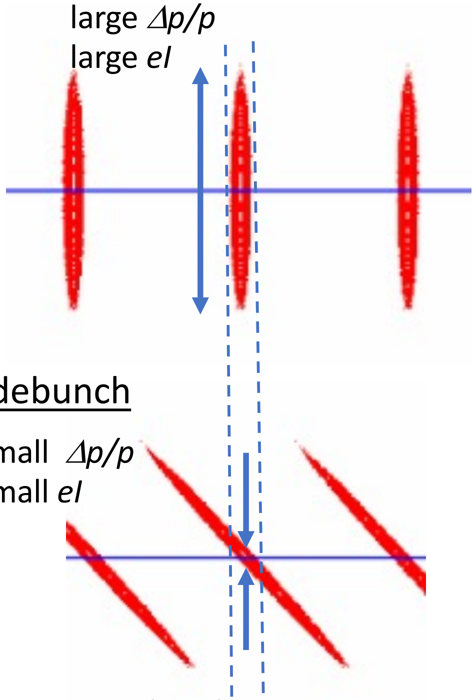
$$\left|\frac{Z_L}{n}\right| \leq \frac{2\pi\beta E\sigma_\delta^2|\eta|F}{eI},$$

σ_δ local rms-momentum spread

eI local beam current

Before debunch

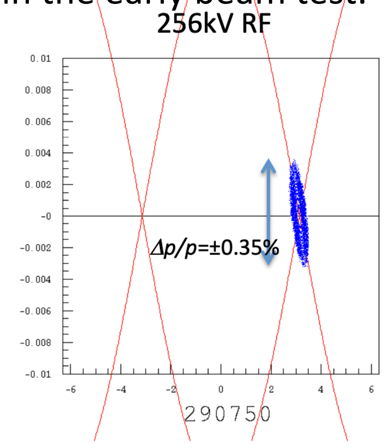
in debunch



$$\frac{\sigma_\delta^2}{eI} > \frac{\sigma_\delta^2}{eI}$$

Increase longitudinal emittance

Phase jump did not work well in the early beam test.



HB2018, M. Tomizawa

Reduce L-impedance

RF manipulations

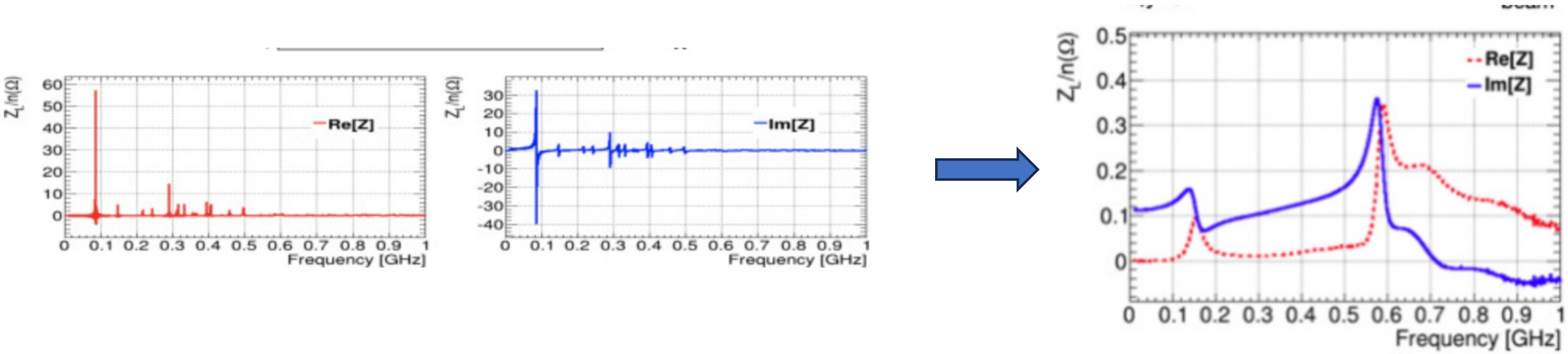
- Phase offset injection
- 2 step debunch

Enlarge $|\eta|$

MR L-Impedance Reduction

FX Eddy Current septa impedance reduction

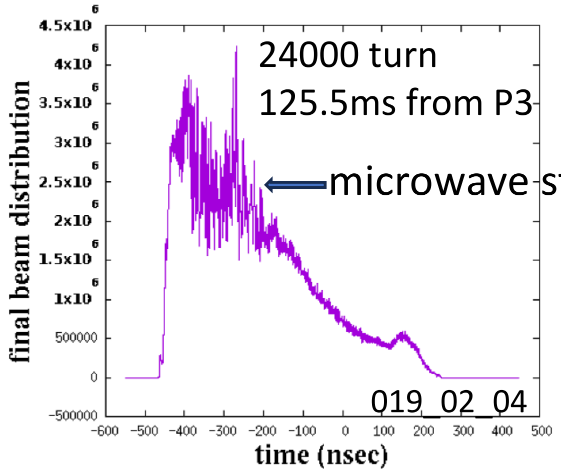
A. Kobayashi et al., NIM A 1031, 2022, 166515



Total MR L-impedances (RF, FX-MS, SX-MS, FX-KI, INJ-KI,COR-KI, Resistive Wall)

Two step debunching simulation
(60kW beam,6.5x10^13ppp)

2022 5.2s ZL, bunch2

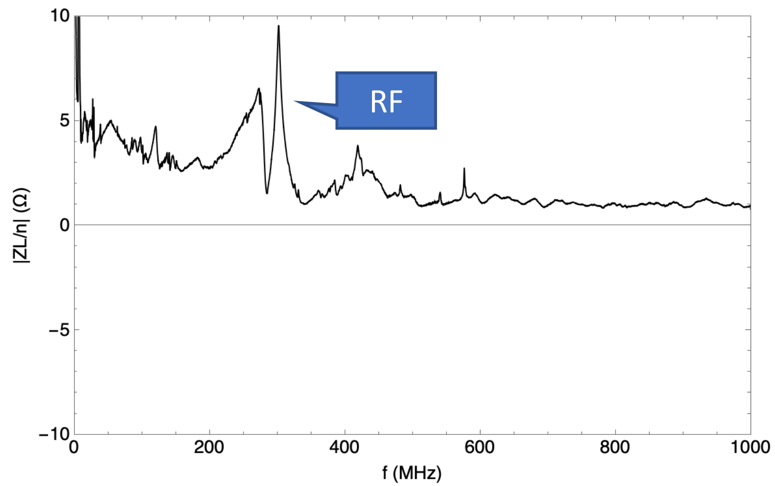


M. Tomizawa ecloud2022

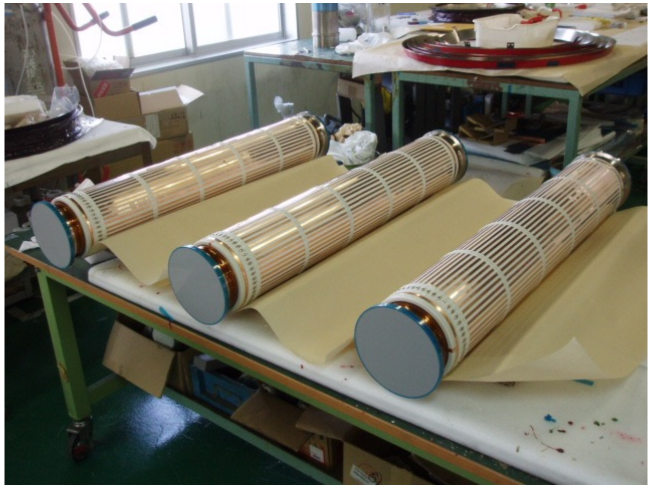
・4.2s cycle, JFY 2022 operation
8 RF cavities ON, 3 cavities shorted, New FXMS

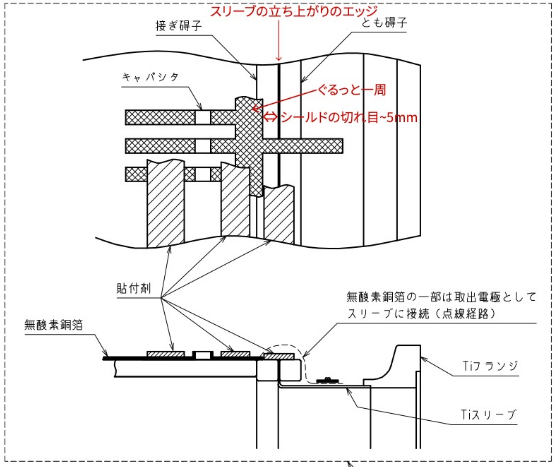
MR-LImpedance-RWRevised_20220202_003.nb

Total impedances from interpolated data and resistive wall

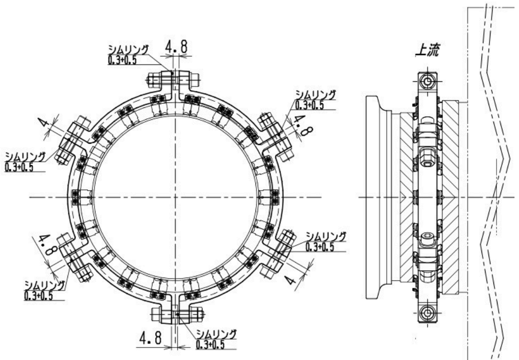


L-impedance reduction of spill feedback quadrupoles (EQ1-2,RQ) ceramic ducts

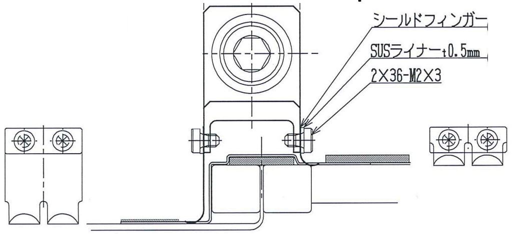


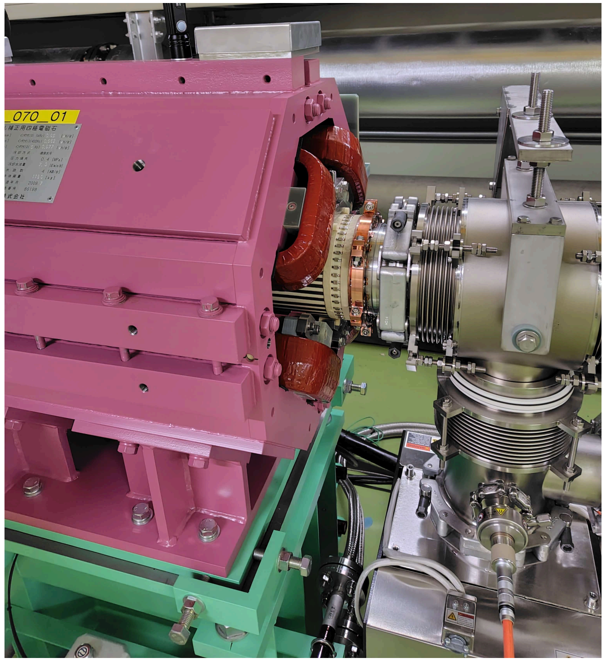


RF shield cramps



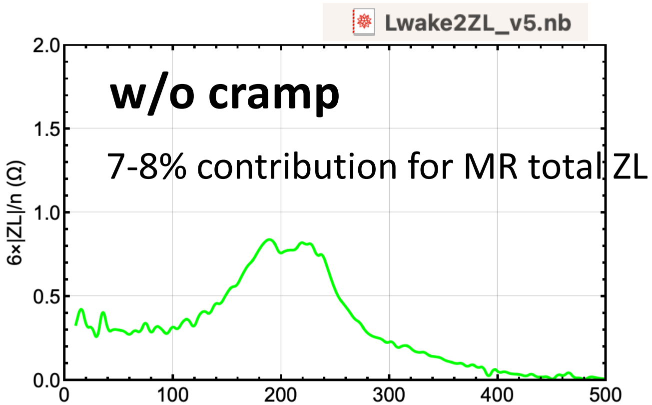
1 -> 16 wall current paths

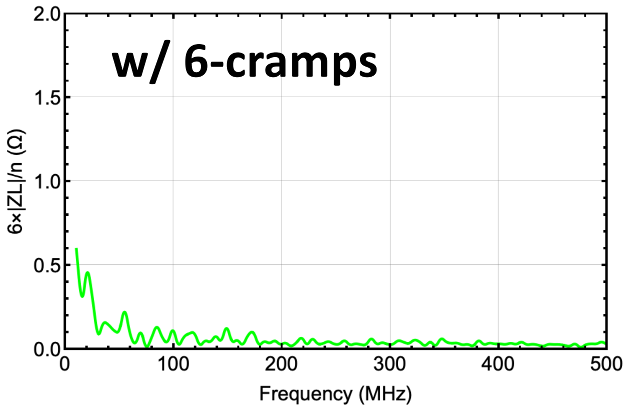




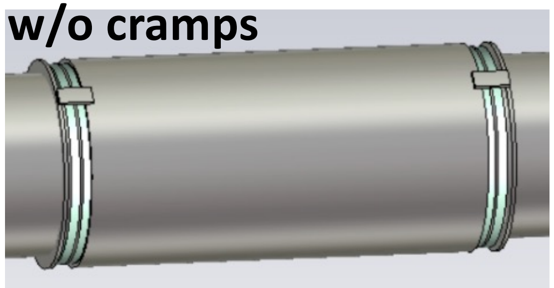
Installed
w/o air exposure
maintaining the existing strips

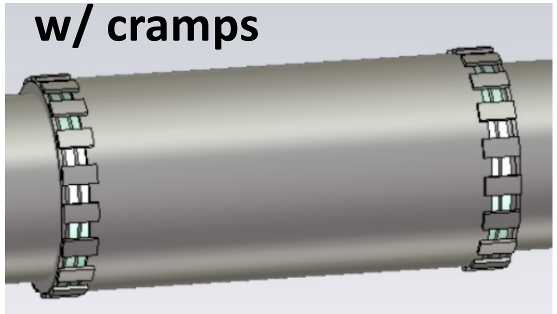
M. Tomizawa et al., Proc. of Annual Meeting of Particle Accelerator Society of Japan, 2025, WEP035, to be published

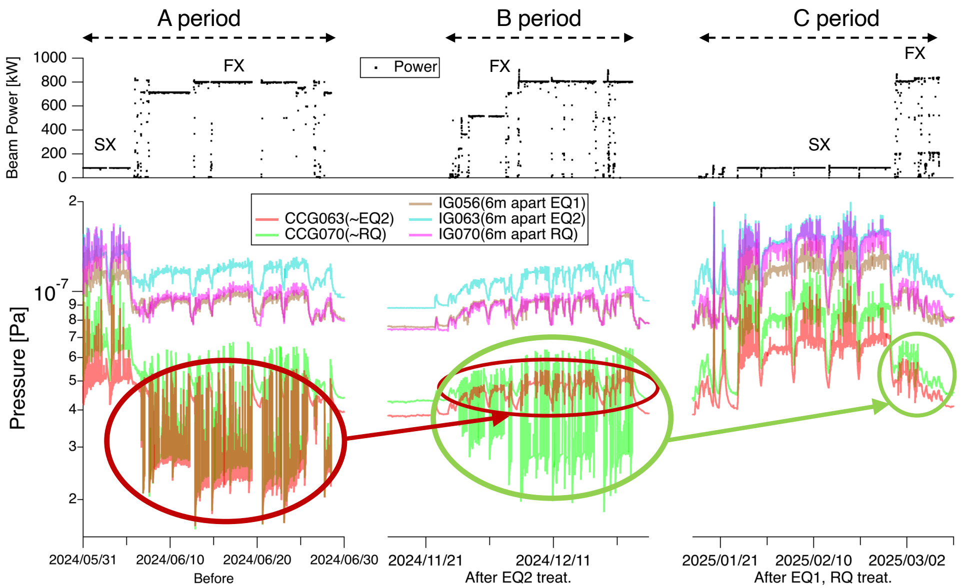




CST Studio model (by T. Nakamura)



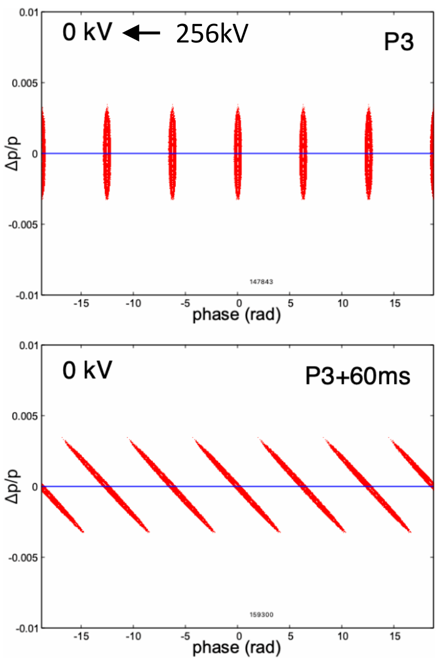




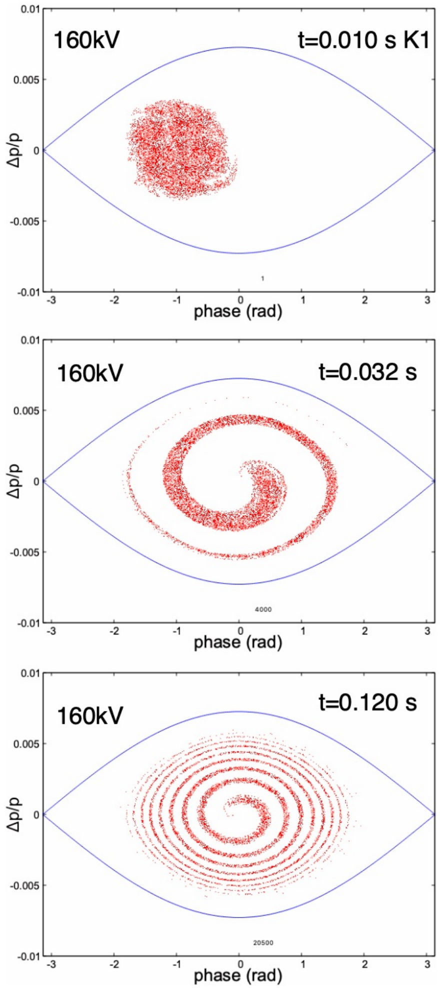
vacuum gauge noise
in very high-intensity FX runs
drastically improved

RF manipulations to suppress the instability

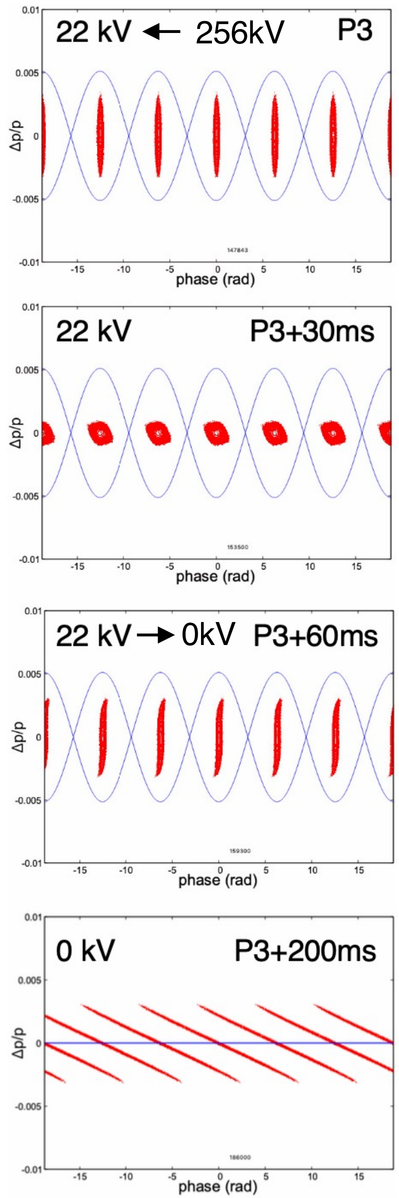
One step debunch



Phase offset injection



Two step debunch



also suppress T-instability at the FB

30 -> 45 kW (5.52s) since Oct.,2015

(30kW=3.5x10^13 ppp)

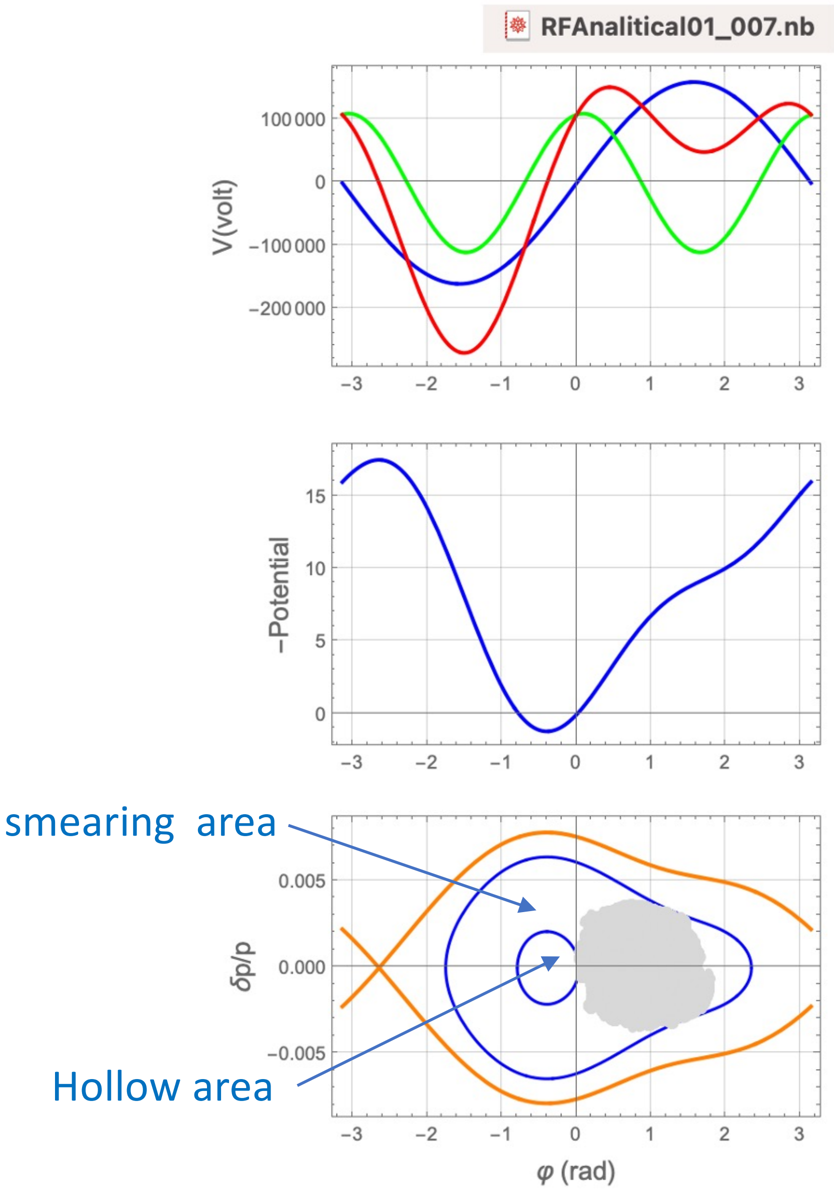
45 -> 50kW (5.20s) since Jan.,2018

50 -> 65kW (5.20s) since Dec., 2020

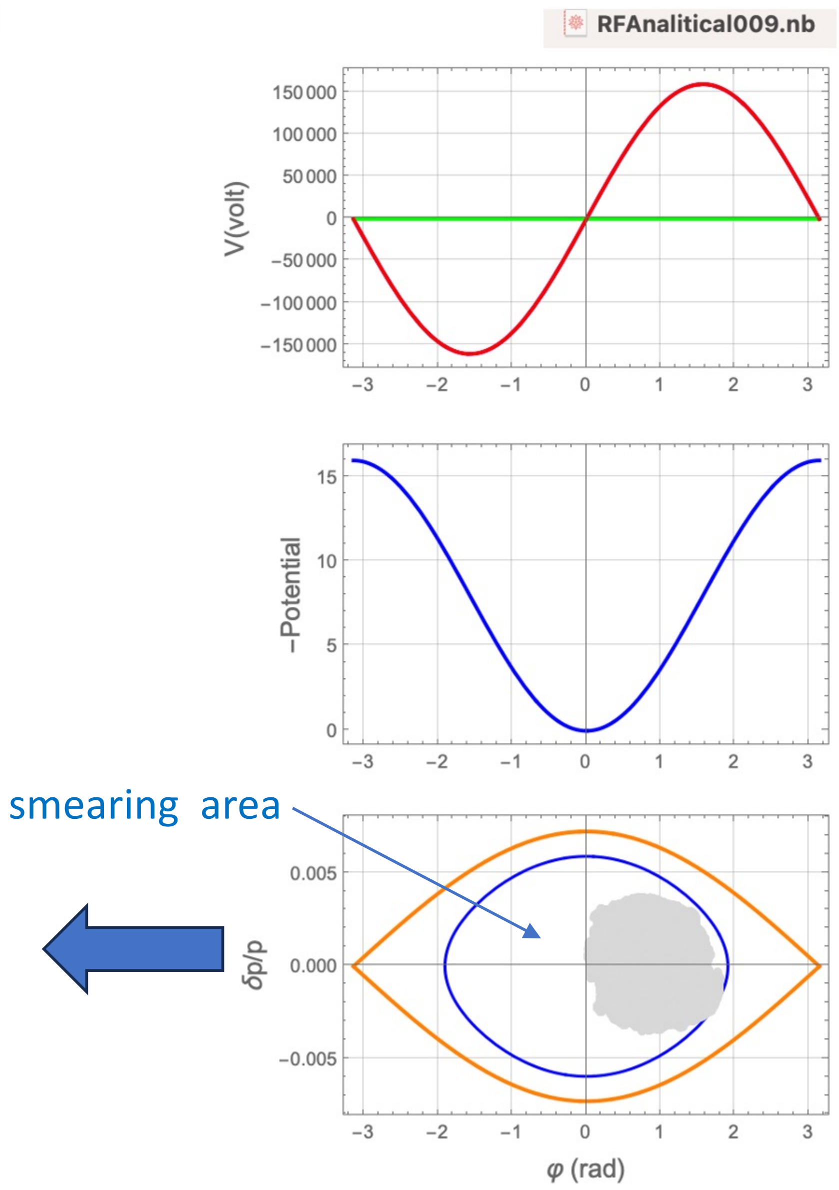
65 -> 80kW (4.24s) since Dec., 2022

Recent RF manipulation to suppress instability

Flat base V1=160kV, V2=110kV
Beam φshift = 50deg
V2 φshift= 50deg at V1 freq.



Flat base V1=160kV, V2=0kV
Beam φshift = 50deg

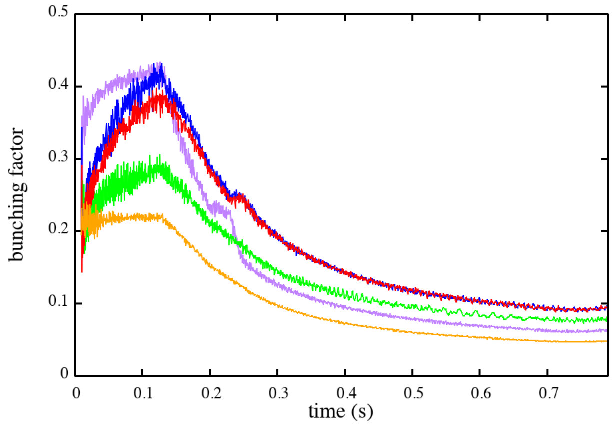


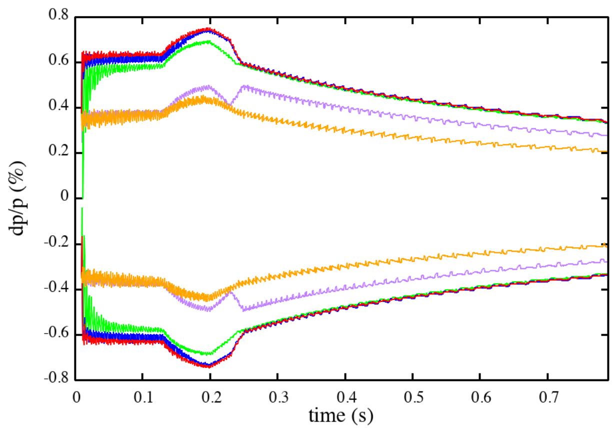
Longitudinal tracking simulations (w/o space charge, ZL)

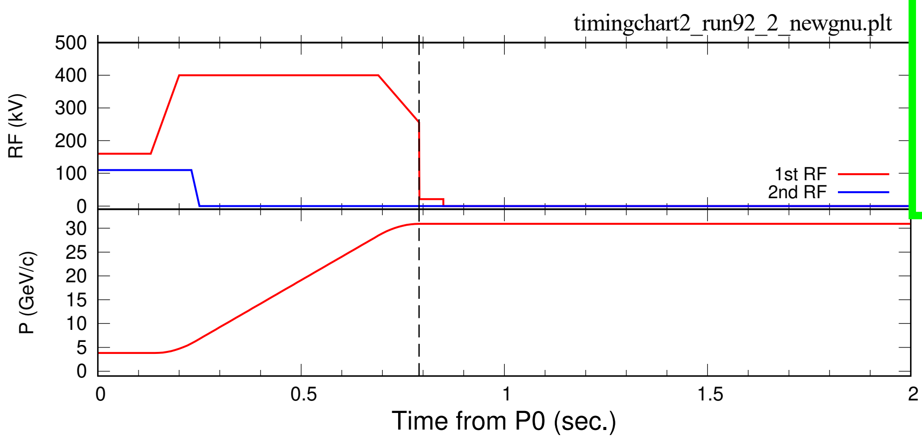
t=0.01s->0.79s plots. every 100 turn

V1 0.13-0.20s:160-400kV, 0.69-0.79s:400-256 kV

V2 0.23-0.25s:110-0 kV







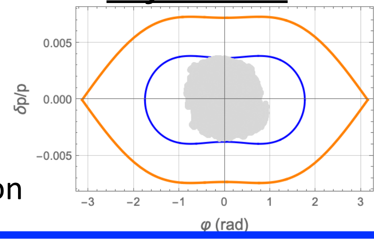
End of acceleration

Injection

w/ 2nd no offset

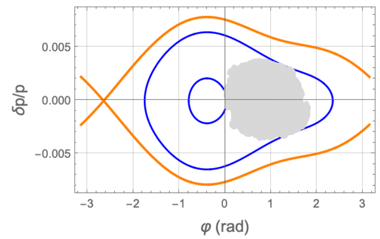
L-ε_{rms} = 0.41 eV L-ε_{full} = 7.8 eV

SX: (coupled bunch) T-instability after injection



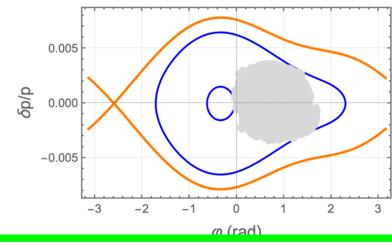
w/ 2nd beam 50deg. V2 50deg

L-ε_{rms} = 1.0 eV L-ε_{full} = 11.8 eV



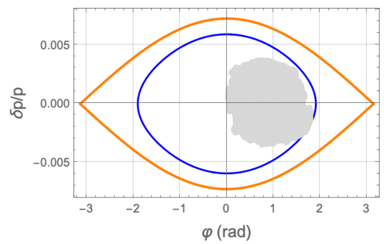
w/ 2nd beam 45deg. 2nd 55deg

L-ε_{rms} = 0.9 eV L-ε_{full} = 11.7 eV



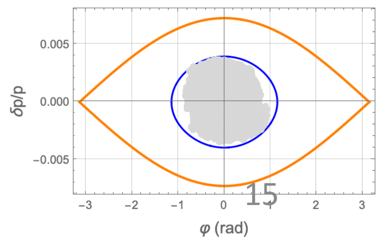
w/o 2nd offset +50deg

L-ε_{rms} = 0.67 eV L-ε_{full} = 11.4 eV



w/o 2nd offset 0deg

L-ε_{rms} = 0.23 eV L-ε_{full} = 4.5 eV

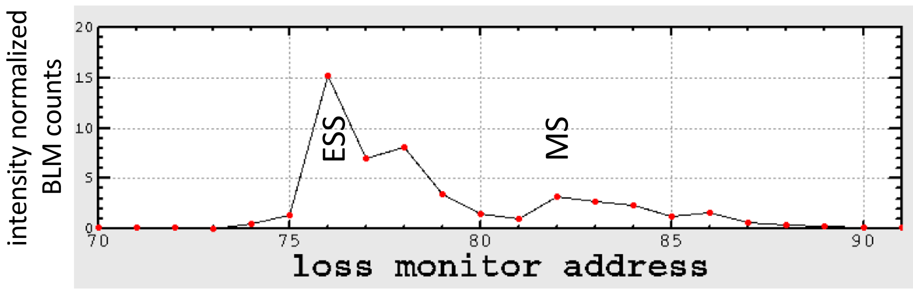


beam +50deg, 2ndRF +50deg for 1st RF center
2-step debunch
efficiency ～99.65% (tentative) w/ diffuser1

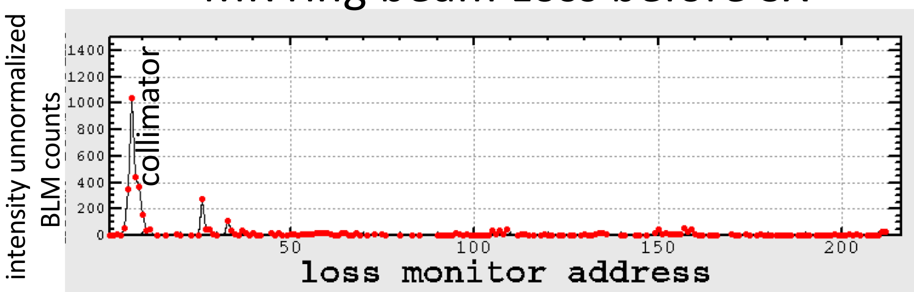
8.1e+13 ppb 91.8kW
physics run

Run92 #2262320

SX area beam Loss during SX



MR ring beam Loss before SX

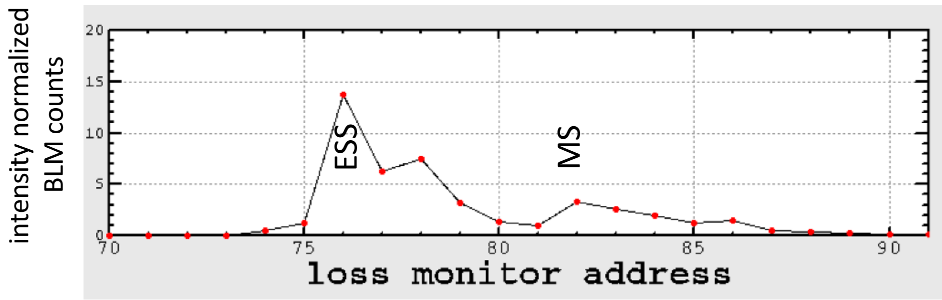


beam +45deg, 2ndRF +55deg for 1st RF center
2-step debunch
efficiency 99.68% (tentative) w/ diffuser1

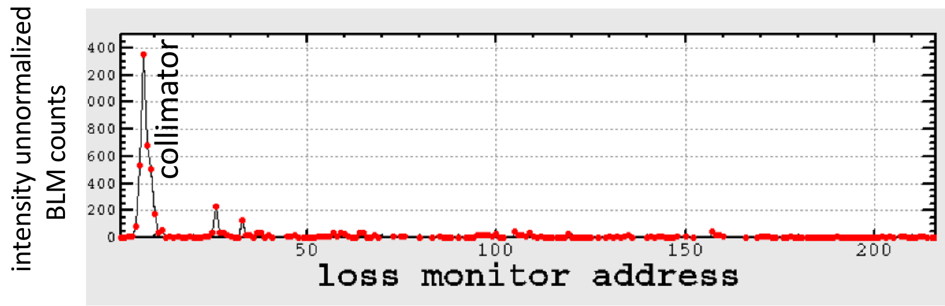
8.95e+13 ppb 101.5kW
One shot mode   (total 5 shots -> no instability)

Run92 #2265807

SX area beam Loss during SX



MR ring beam Loss before SX

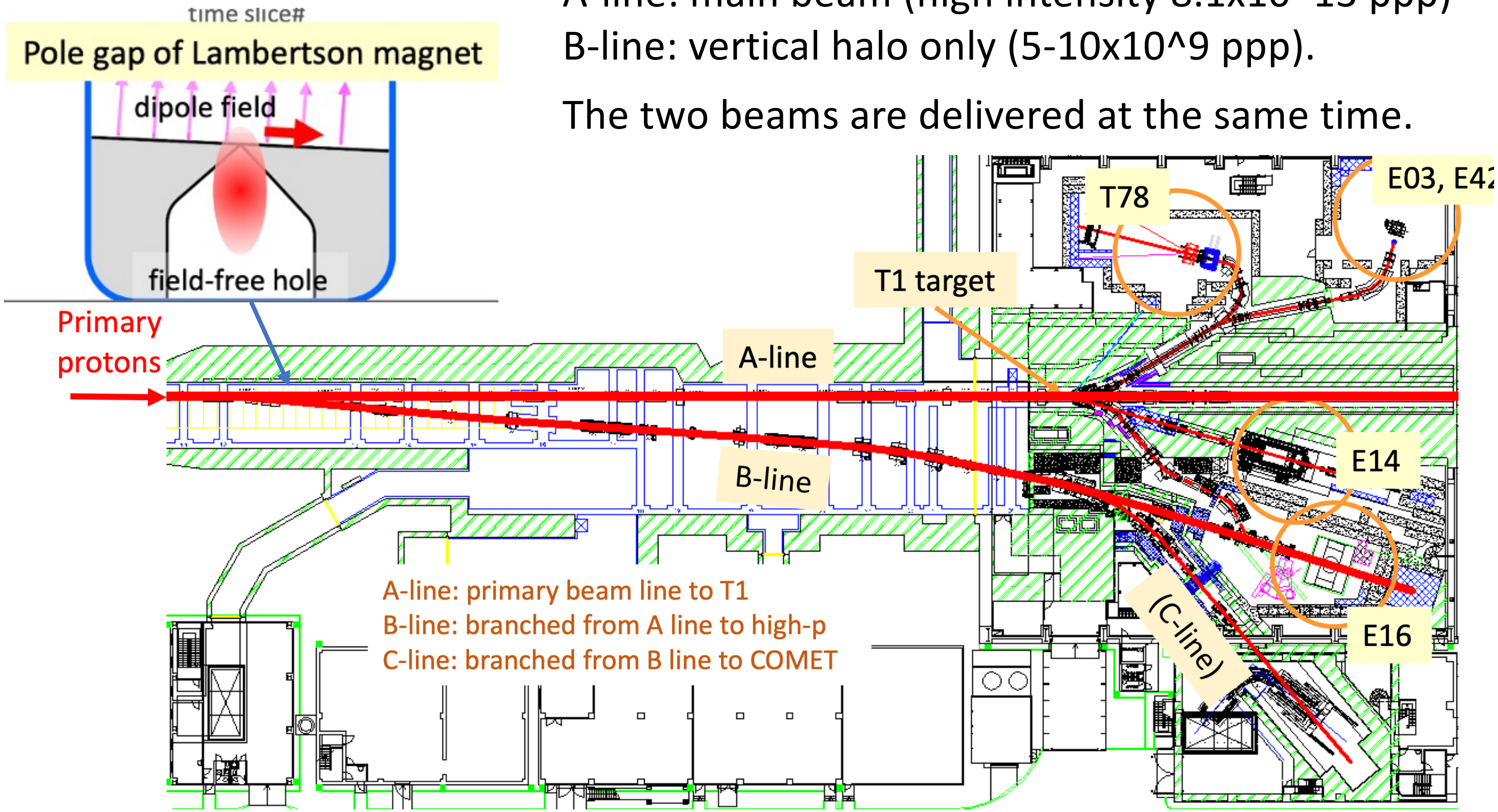


Beam loss at the FB has been reduced by the introduction of the 2nd RF

Beam splitting operation for slow-extracted beam

A-line: main beam (high intensity 8.1x10^13 ppp)
B-line: vertical halo only (5-10x10^9 ppp).

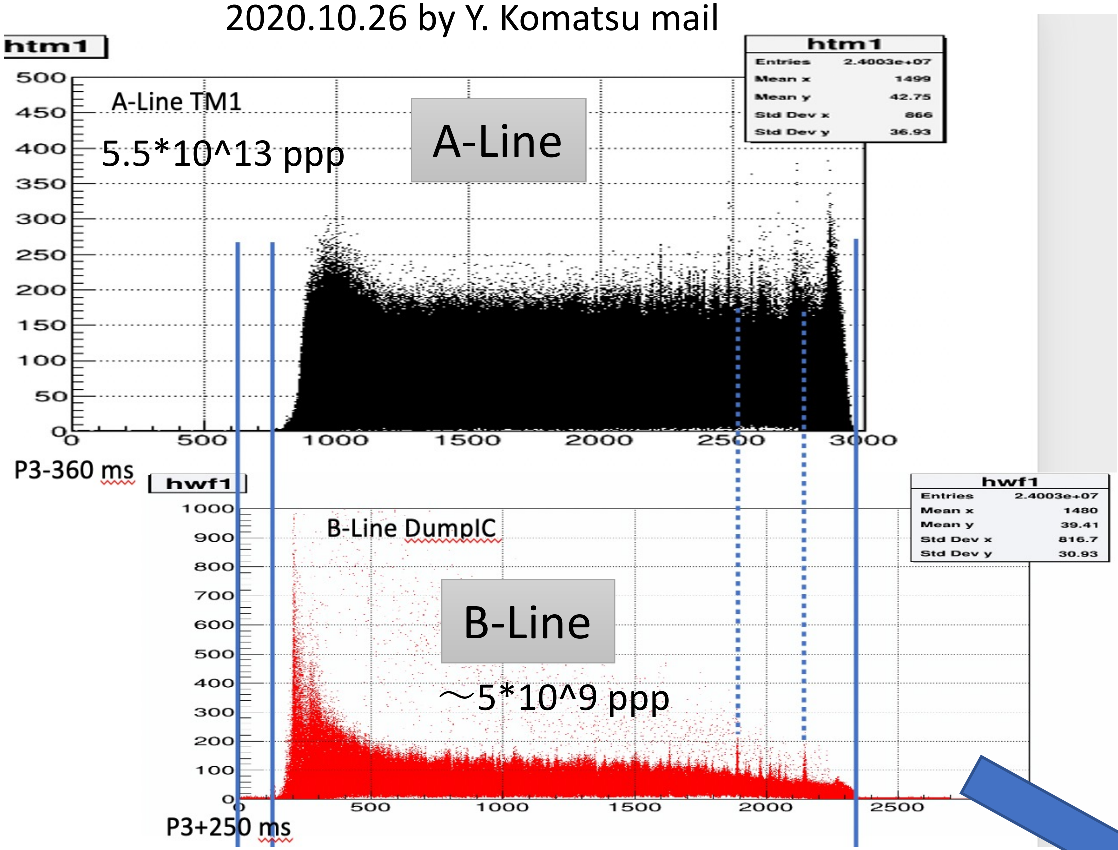
The two beams are delivered at the same time.



The beam splitter is located in the vertical slope.
The beam intensity of B-line is extremely sensitive to the vertical beam halo fluctuation.
Fine beam tunings for the SX and the HD transport line are required.

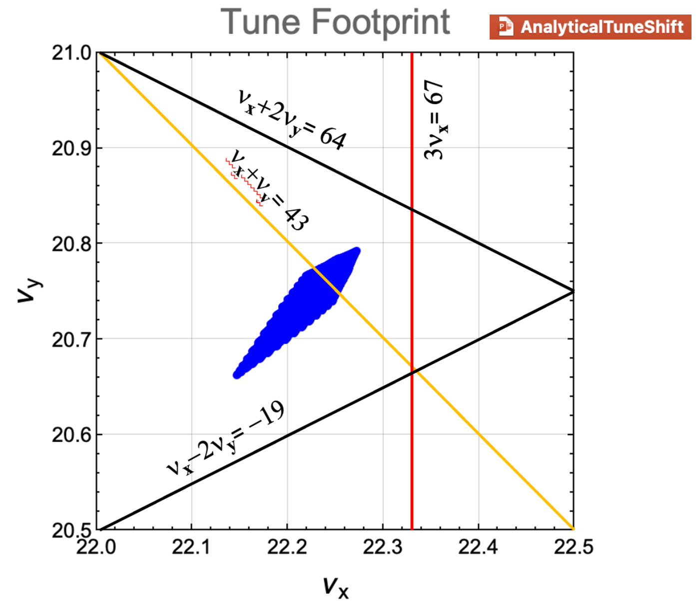
Effects of Linear coupling resonance on the B-line intensity

2020.10.26 by Y. Komatsu mail



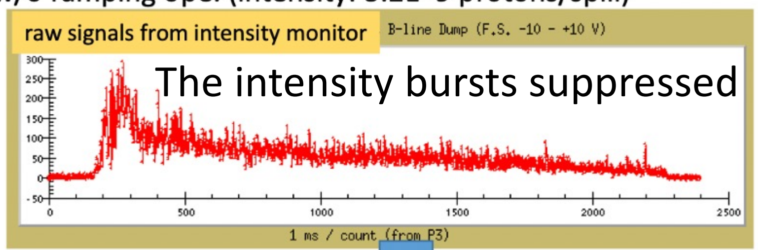
The intensity bursts frequently seen

3D Gauss distribution analytical
3GeV, 5.5/8*10^13 ppb
Space charge tune shift -0.15 @3 GeV

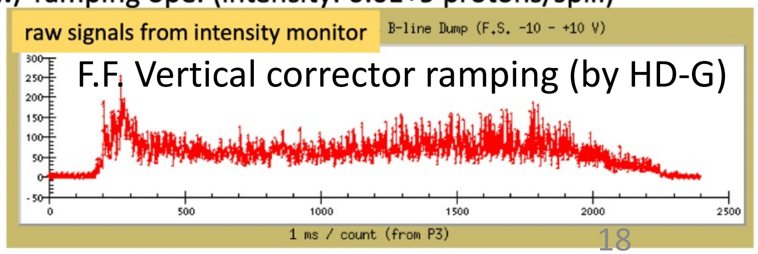


B-line beam intensity during a spill

w/o ramping ope. (intensity: 5.2E+9 protons/spill)



w/ ramping ope. (intensity: 6.0E+9 protons/spill)

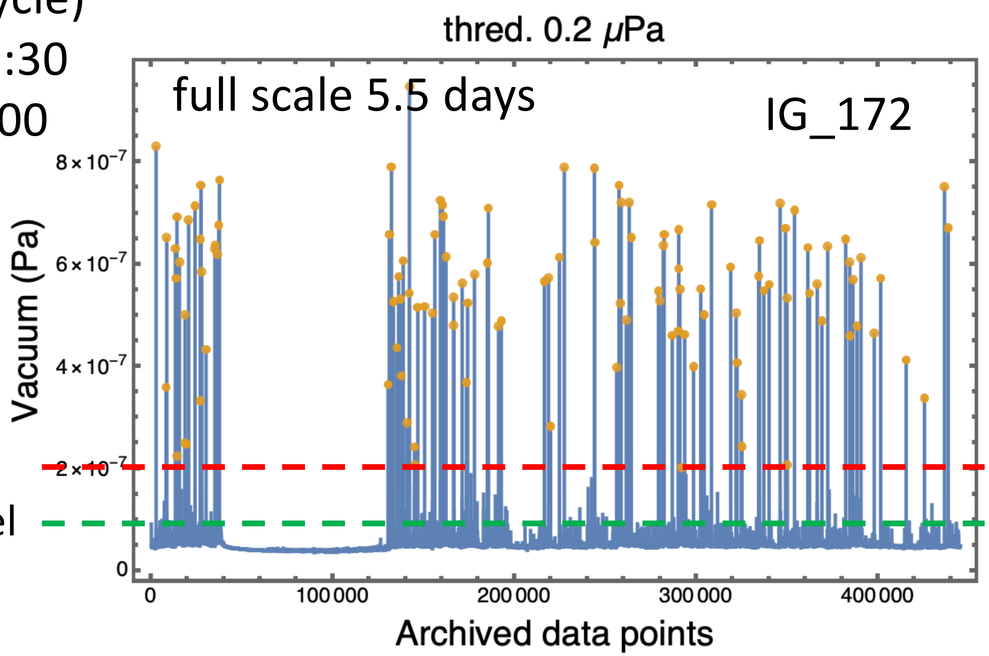


A linear coupling resonance correction by skew quads in the MR has drastically improved the strong burst spills.

Vacuum pressure rise induced by e-cloud

90kW (4.24s cycle)
2025.4.22 21:30
-> 2025.4.28 9:00

threshold level
normal vacuum level

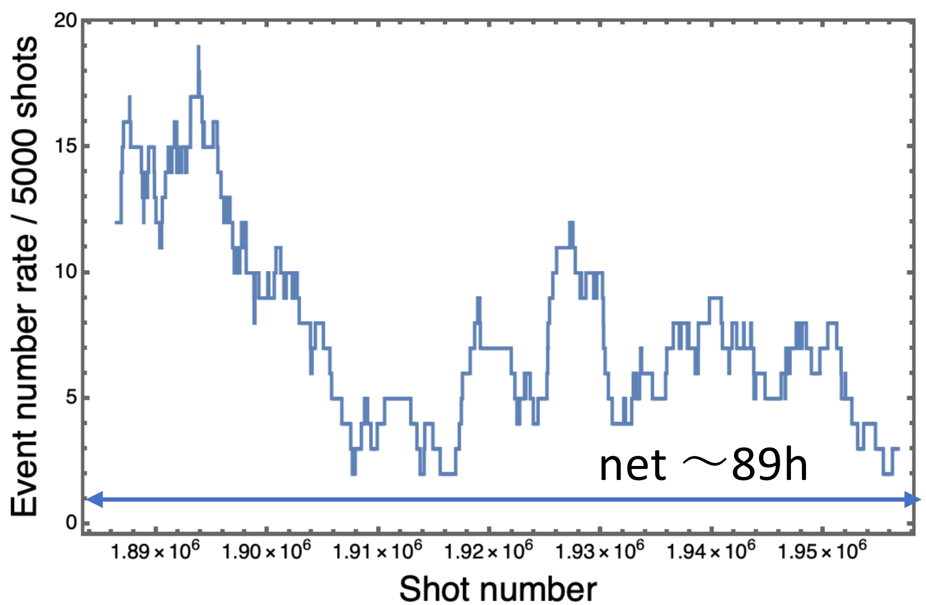


A-line only operation
not so serious instability
no BLM failure

V-halo might grow
for vacuum rise shots

For A+B operation,
vacuum rise shots
may induce
the B-line BLM failure

5000shots=5.9h
one shot 4.24s



Further instability
suppression effort might
be necessary
for the A+B operation

Good news:
"debunch beam scrubbing"
Improve the rise rate.

Slippage change during debunching for instability suppression

IPAC2025, WEPM028
M. Tomizawa et al.

$|\eta|$ enlarging during debunching
is expected to suppress the microwave structure.

J-PARC MR has an imaginary transition-γ lattice.
Momentum compaction factor
can be flexibly changed maintaining H and V tunes

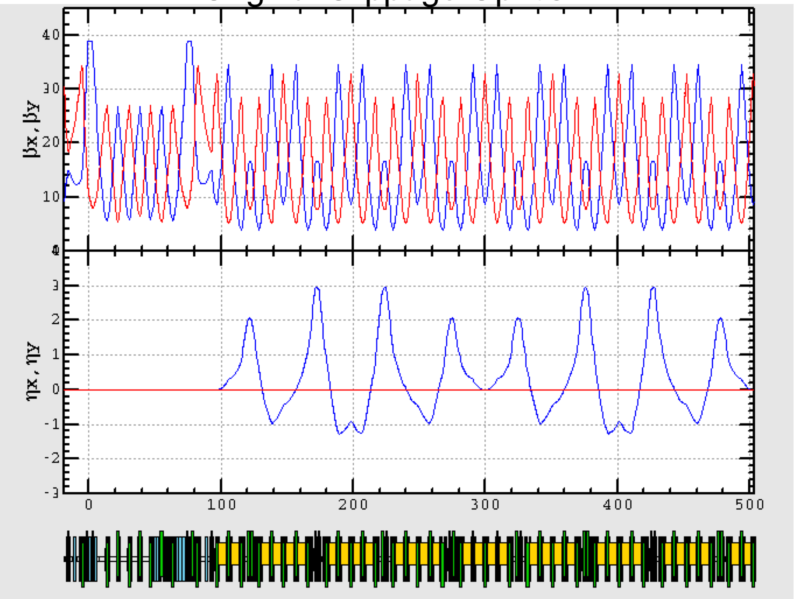
The longitudinal microwave instability threshold
(the Keil-Schnell criterion)

$$\left|\frac{Z_L}{n}\right| \leq \frac{2\pi\beta E\sigma_\delta^2 |\eta| F}{eI},$$

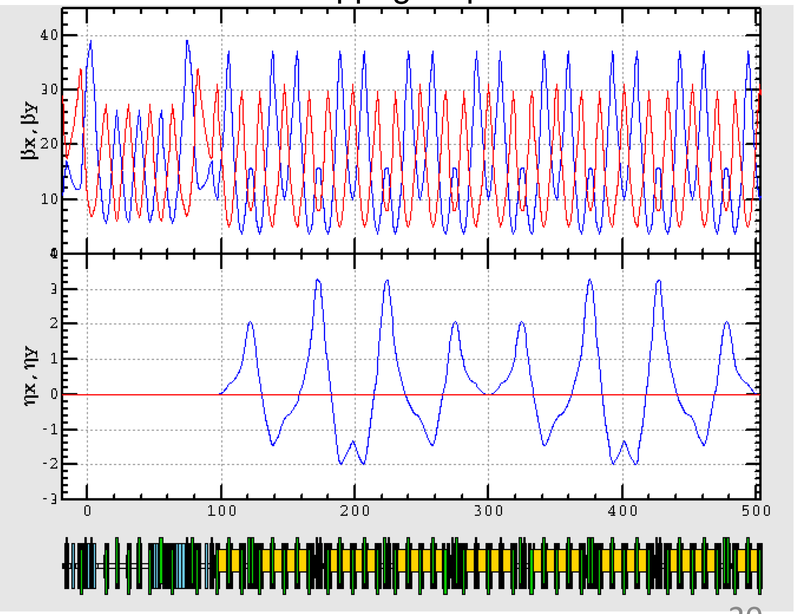
$$\eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2} = \alpha_c - \frac{1}{\gamma^2} < 0$$

A beam test is planned.

Original Slippage Optics



x1.5 Slippage Optics



VHF cavity for instability suppression

Longitudinal emittance growth by VHF cavity phase modulation

Y. Morita et al., JPS Conf. Proc. 33,011032(2021)

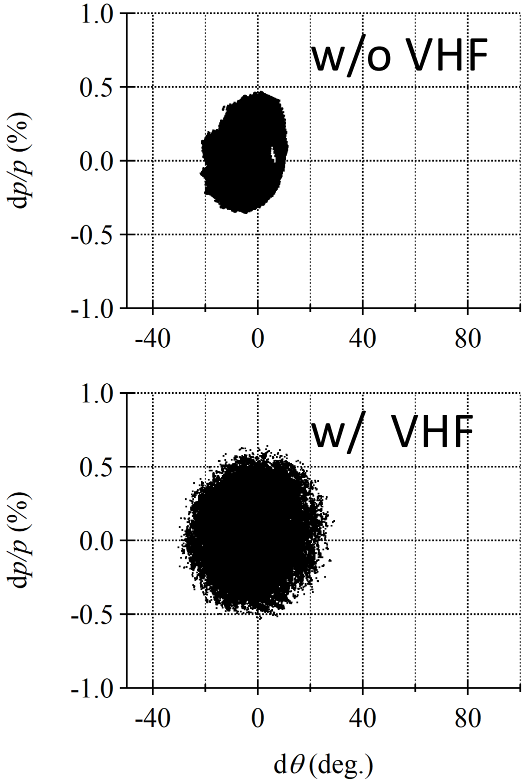
$$V_{total}(t) = V_0 \sin 2\pi f_0 t + V_b \sin(2\pi f_b t + \psi(t)).$$

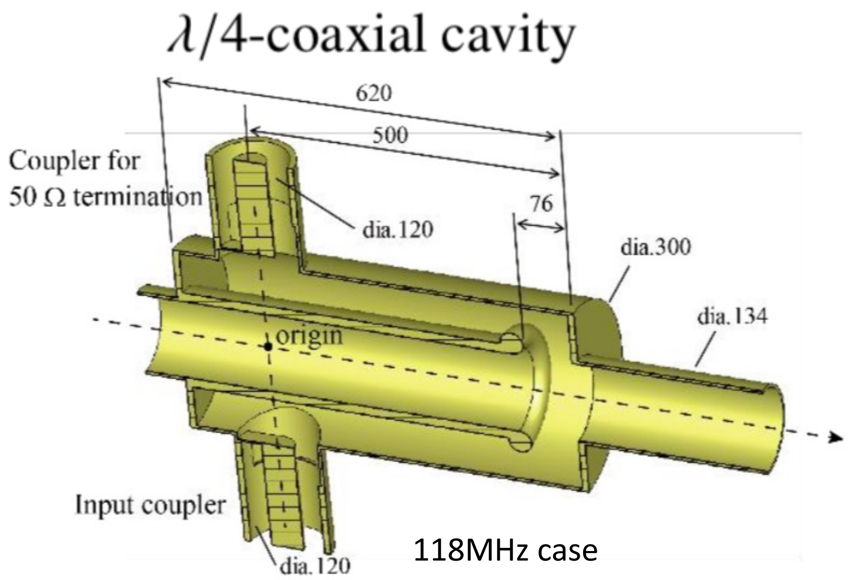
$$\psi(t) = \Delta\phi_m \sin 2\pi f_m t,$$

Controllable emittance growth with uniform distribution

Simulation example
～P3

by Y. Morita



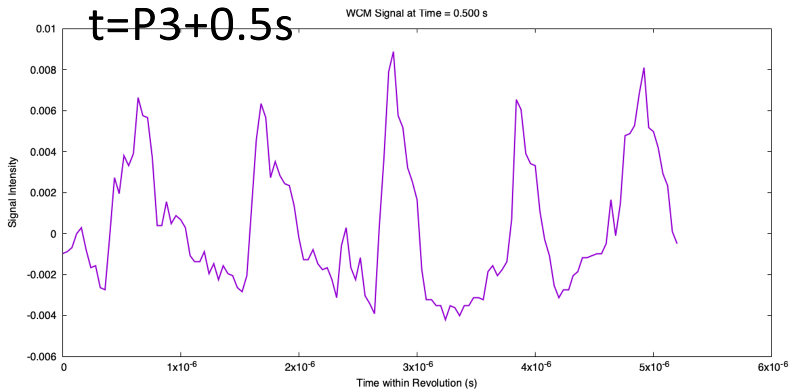


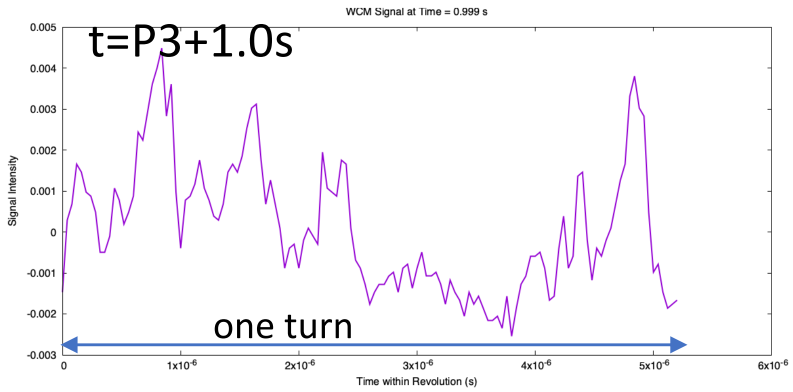
not yet funded

(large cost ～2M$)

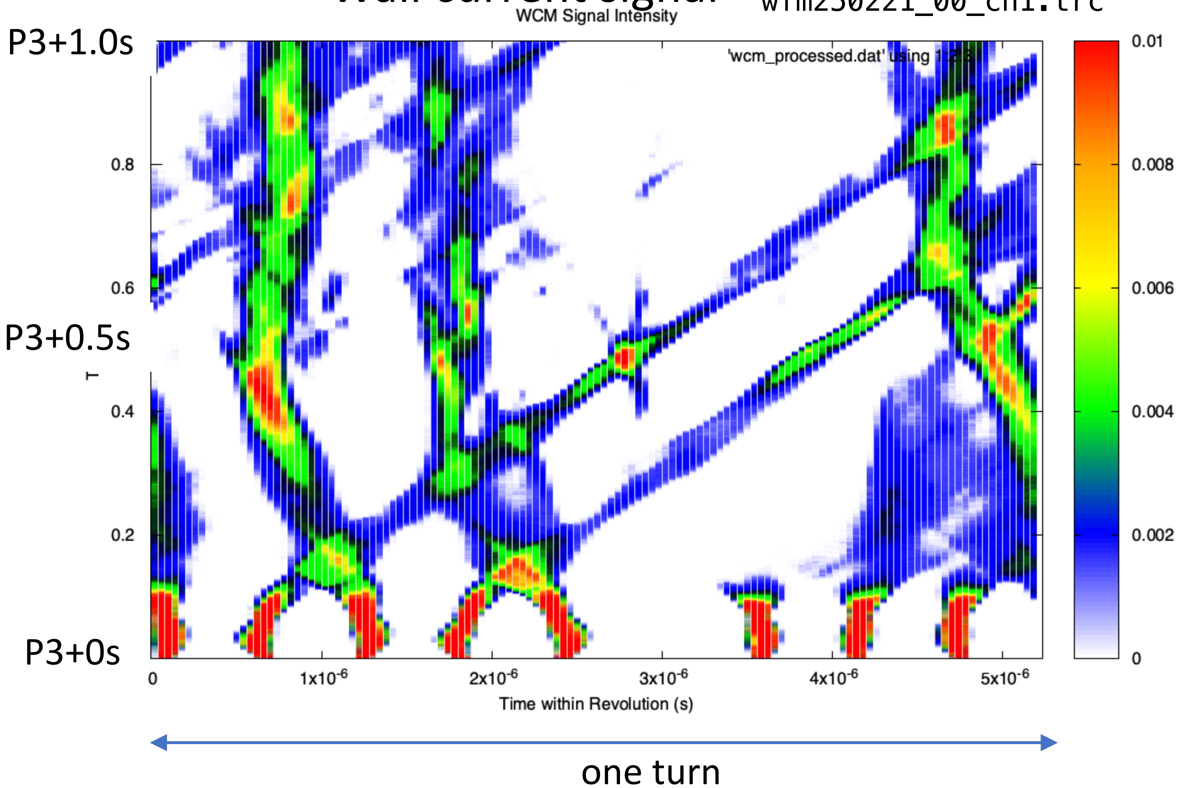
"rebunching" phenomenon

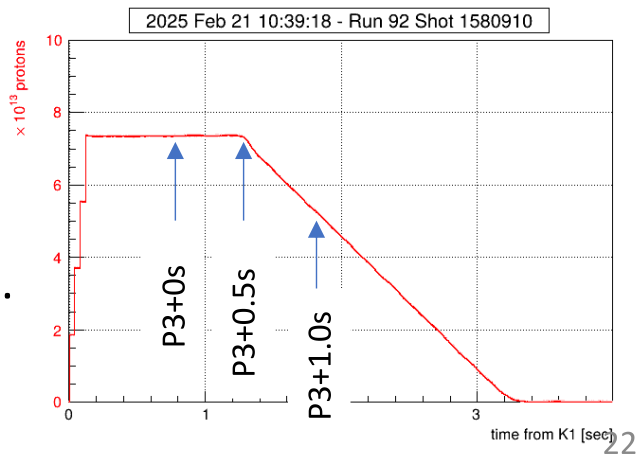
83kW 7.35x10^13ppp
Slow Extraction
(RF fundamental only, 2 step debunch)





Wall current signal





Our spill monitor is insensitive to such a MHz structure.
The impact of the experiments should be carefully investigated.

Summary

Beam instability during debunching is a major limiting factor in increasing the J-PARC SX beam intensity.

RF phase offset injection into the RF bucket and 2-step debunching effectively suppress the beam instability.

The recent implementation of a 2nd RF system increased the beam power from 82 kW to 92 kW (4.24 s cycle).

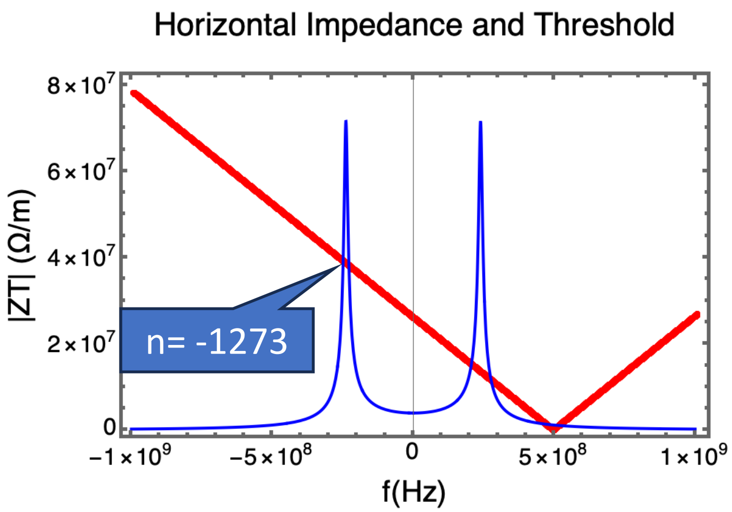
Further optimizations of the current RF manipulation scheme will be pursued.

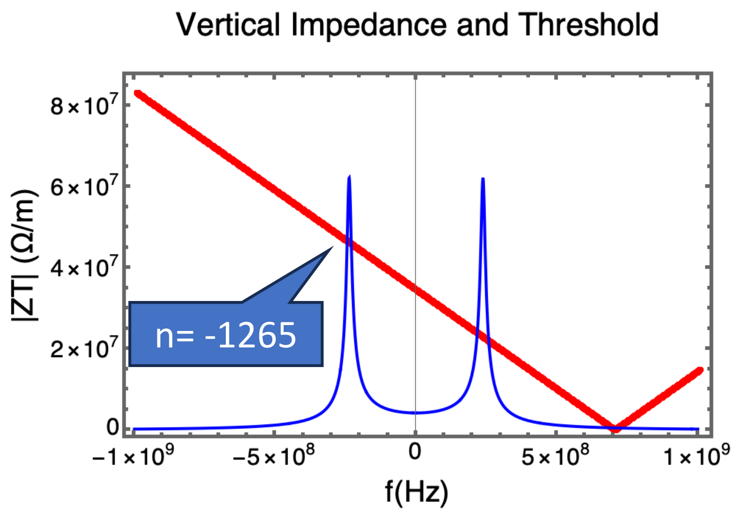
Slippage factor modification and VHF cavity installation have been proposed as future strategies to further suppress the instability.

The "rebunching" phenomenon and its impact on experiments should be carefully investigated, and mitigation measures will be implemented if necessary.

Dipole Impedance and coasting beam threshold

Transverse coasting instability threshold (K.Y.Ng text)
$|Z_1| \leq 4\pi\omega_\beta E_0/(3^{1/2}\ e\ I_0\ c)|S_\beta|\ (\delta p/p)_{FWHM}\ F$
$|S_\beta|=|Q'-(n+\nu_\beta)\eta|$
$F \sim 1$
ν_x=22.296, ν_y=20.808
Q'_x=-5, Q'_y=-7
η=-0.00192
I_0 =3.72A (see next page)
$(\delta p/p)_{FWHM}$ =0.0009697 (see next page)





The impedance is above threshold!

Note:

RF h=9 FF, h=8,10 FB <- 2021

RF h=8,9,10 FB 2022->