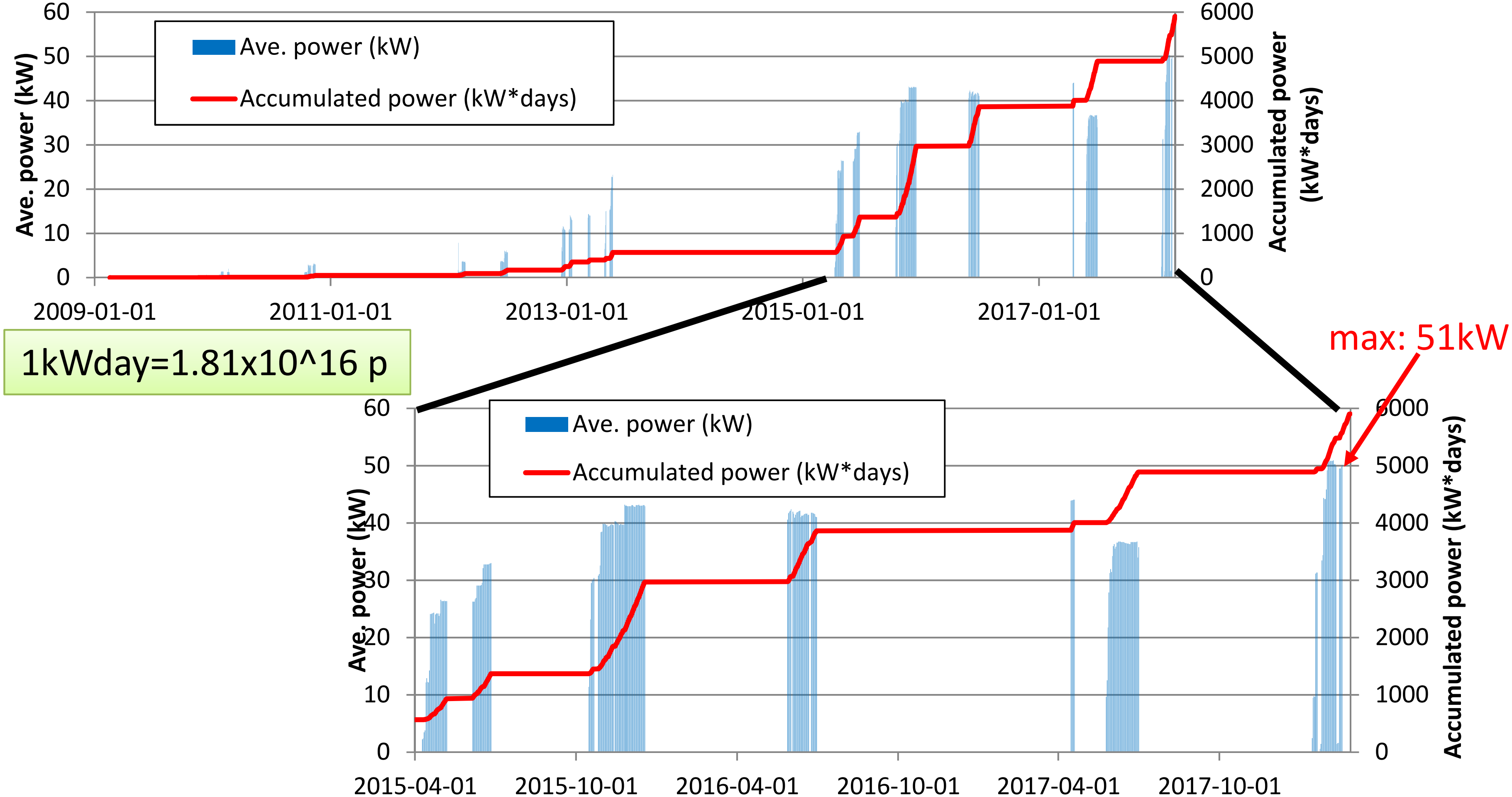
Status and Beam Power Ramp-Up Plans of the Slow Extraction Operation at J-PARC Main Ring

HB, June 21, 2018, Daejeon

KEK/J-PARC
M.Tomizawa,
Y. Arakaki, T. Kimura, R. Muto, S. Murasugi,
K. Okamura, Y. Shirakabe and E.Yanaoka

◎J-PARC slow extraction (SX) schemes
◎ 30 GeV SE status
  High efficient slow extraction
  Beam spill regulation
◎8 GeV SX test
◎SX Plans

Progress of 30 GeV SX Beam Intensity



1kWday=1.81x10^16 p

Accumulated beam time and intensity for HD

※spill: # of beam shots to HD

Before accident (Feb, 2009 – May, 2013): 1.26×10^{6} spills, 560 kW*days

JFY2015 run (Apr, 2015 – Dec, 2015): 1.05×10^{6} spills, 2338 kW*days

JFY2016 run (May, 2016 – Jun, 2016): 0.33×10^{6} spills, 875 kW*days

JFY2017 run (Apr, 2017 – Feb, 2018): 0.83×10^{6} spills, 2038 kW*days

Schemes for Very High Extraction Efficiency (low beam loss)

◎Electrostatic Septum (ESS) QF-QF high β (small α) 40m

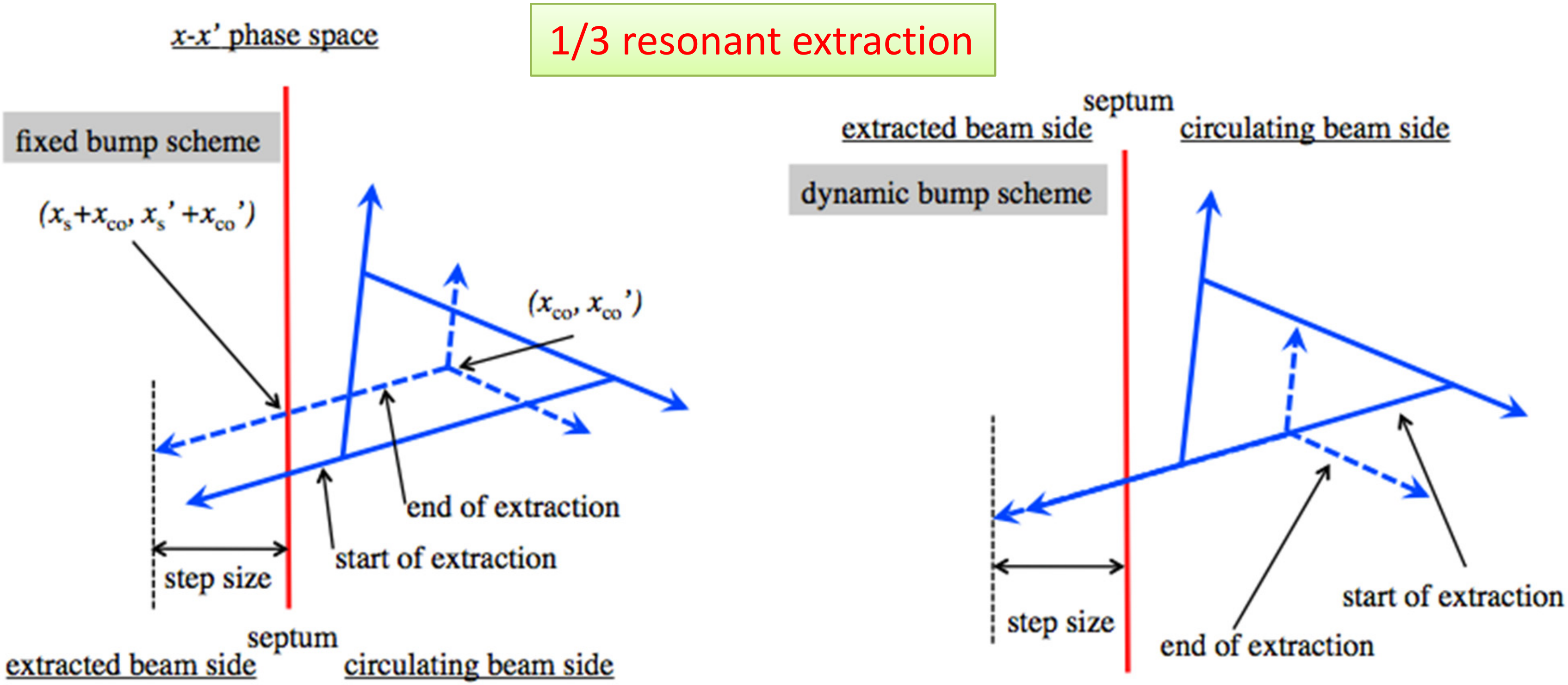
-> large step size (20mm)

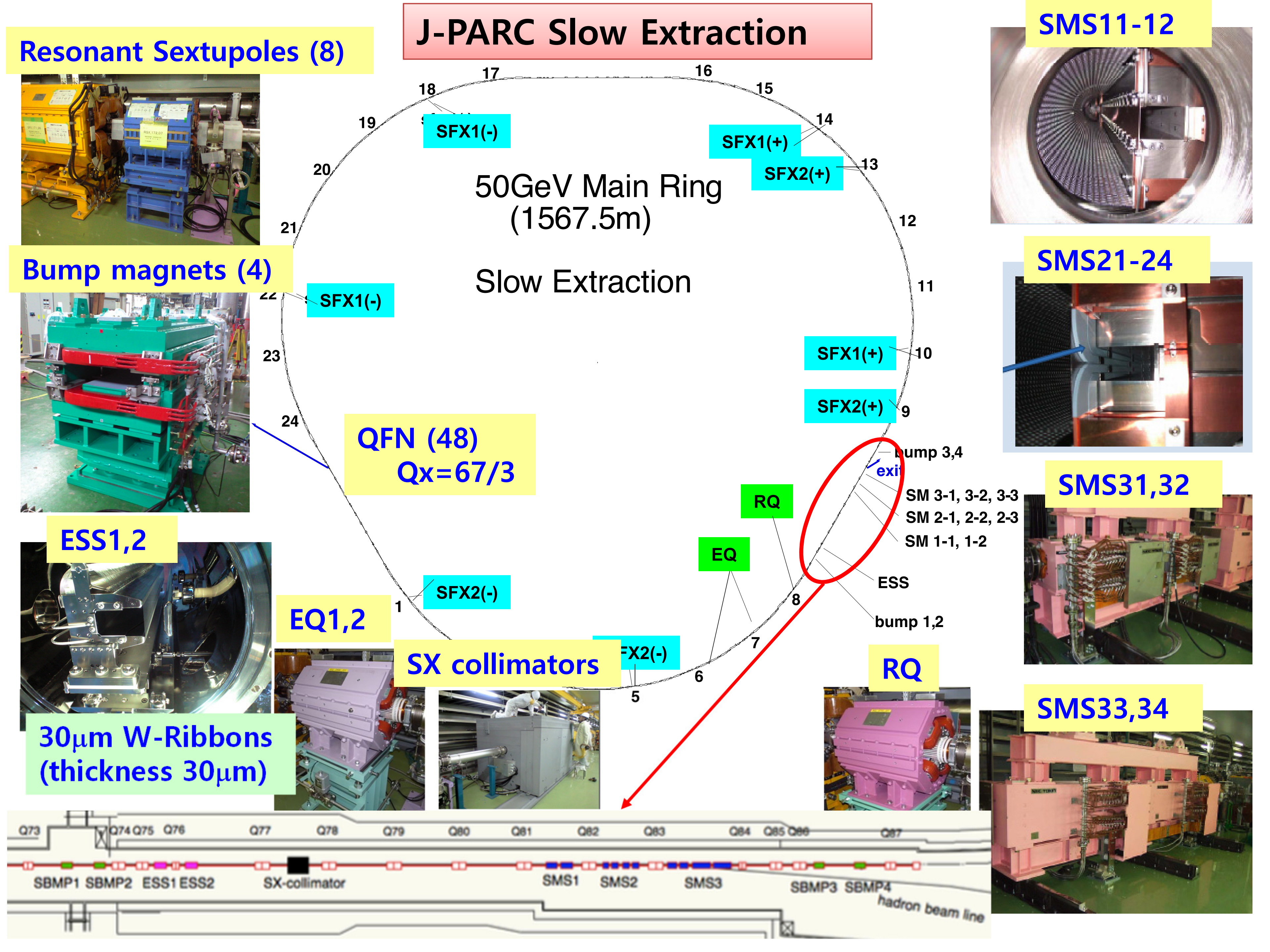
◎dispersion free at ESS + low horizontal chromaticity

-> Separatrix is independent of $\Delta p/p$

depends on tune (constant resonant sextupole)

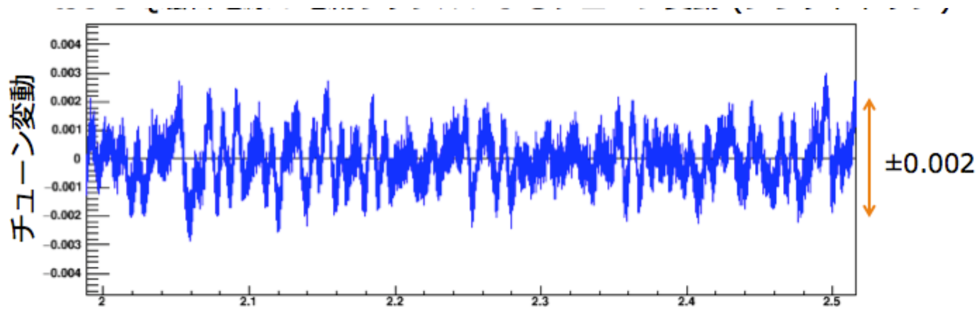
1/3 resonant extraction




J-PARC Slow Extraction
Resonant Sextupoles (8)
Bump magnets (4)
ESS1,2
30μm W-Ribbons
(thickness 30μm)
EQ1,2
SX collimators
QFN (48)
Qx=67/3
50GeV Main Ring
(1567.5m)
Slow Extraction
SFX1(-)
SFX1(-)
SFX1(+)
SFX2(+)
SFX1(+)
SFX2(+)
SFX2(-)
SFX2(-)
RQ
EQ
bump 3,4
exit
SM 3-1, 3-2, 3-3
SM 2-1, 2-2, 2-3
SM 1-1, 1-2
ESS
bump 1,2
1
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
SMS11-12
SMS21-24
SMS31,32
RQ
SMS33,34
Q73
Q74 Q75
Q76
Q77
Q78
Q79
Q80
Q81
Q82
Q83
Q84
Q85 Q86
Q87
SBMP1 SBMP2 ESS1 ESS2
SX-collimator
SMS1
SMS2
SMS3
SBMP3 SBMP4
hadron beam line

Beam Spill Regulations

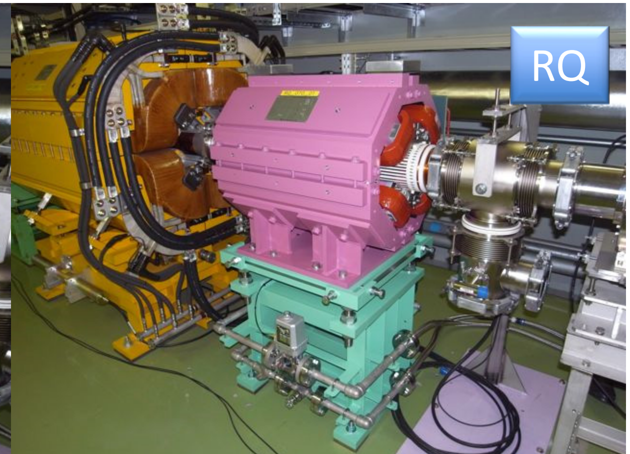
○ BMs and QMs P.S. current ripples $\Delta I/I$ 10^{-4} each

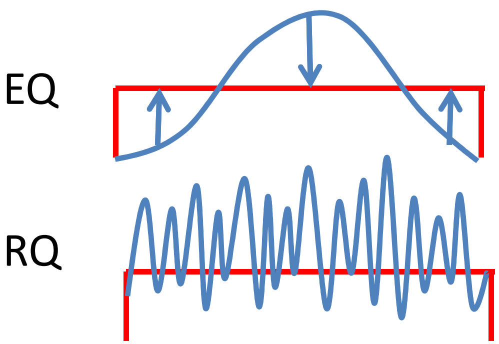


○48 QFNs in arcs are linearly ramped to the 67/3 resonance

○A feedback by EQ1 and EQ2 makes a rectangular spill shape

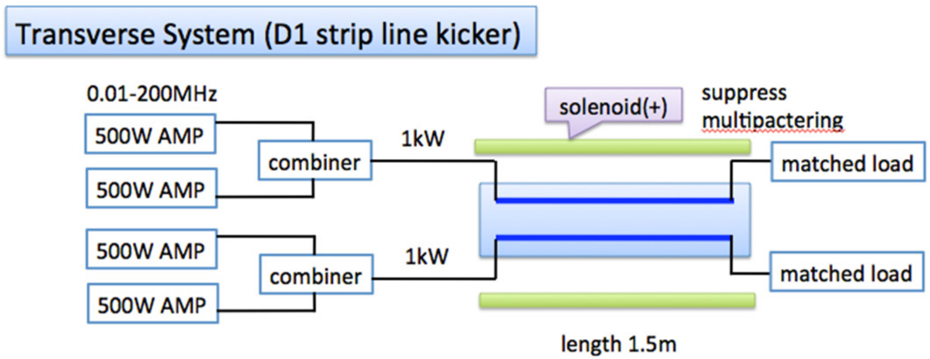
○A feedback by Fast response RQ improves a spill ripple.

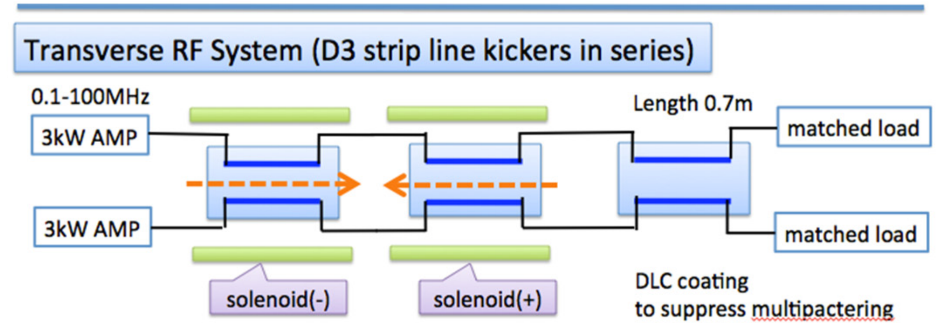




Transverse RF (RF knockout)

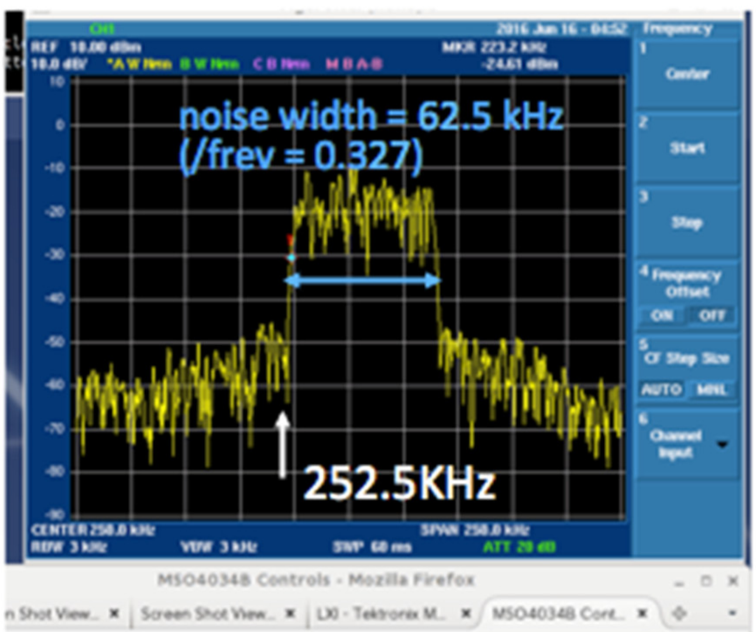
applied to the circulating beam (no Feedback)





Qx=22.3333

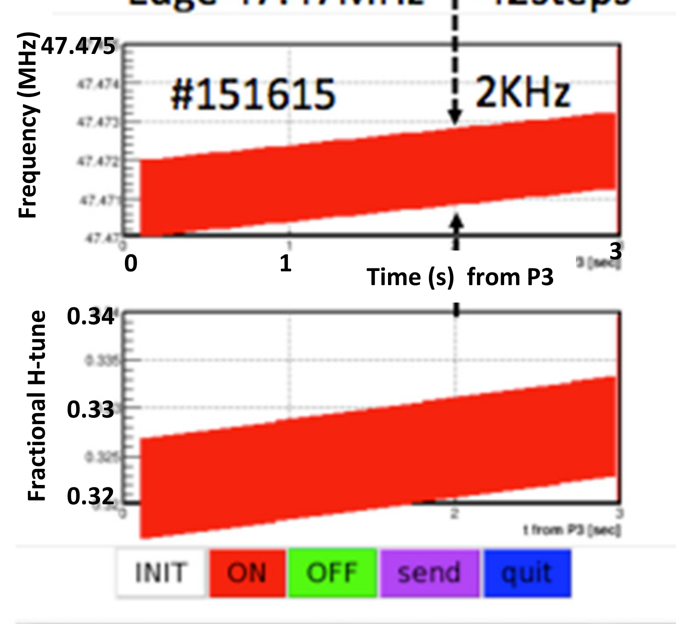
D1 strip line kicker



H-tune: 0.320-0.648

D3 strip line kicker

Edge 47.47MHz 42steps



frv=0.191167438MHz

TRF ON
EQ,RQ ON

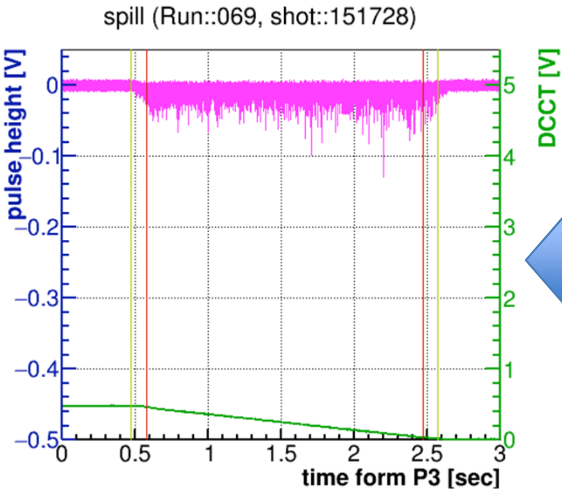
#151728

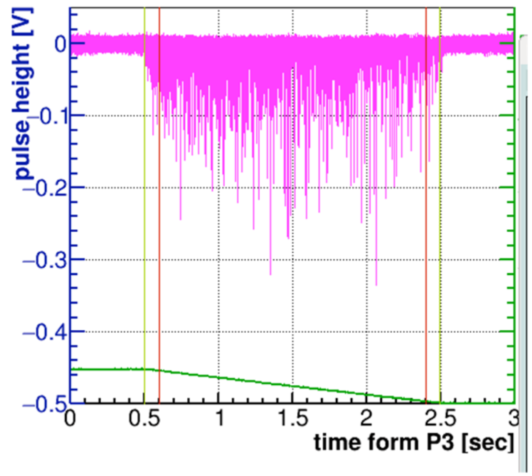
41kW

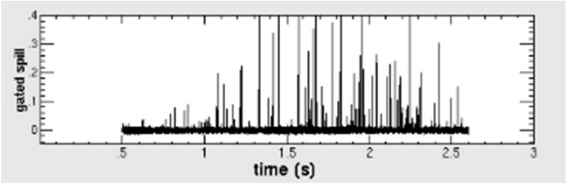
TRF OFF
EQ,RQ ON

6/15 #151515

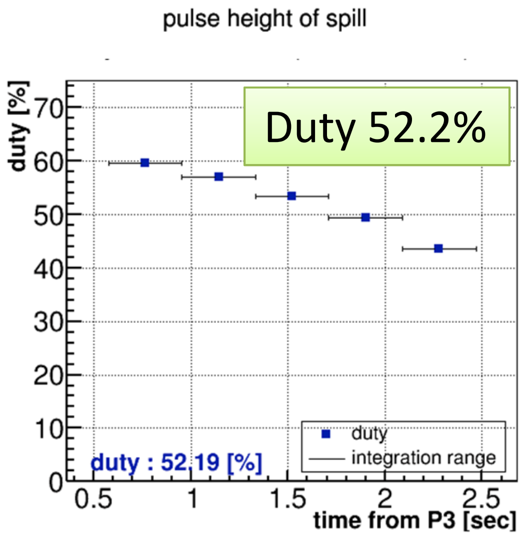
w/o EQ,RQ



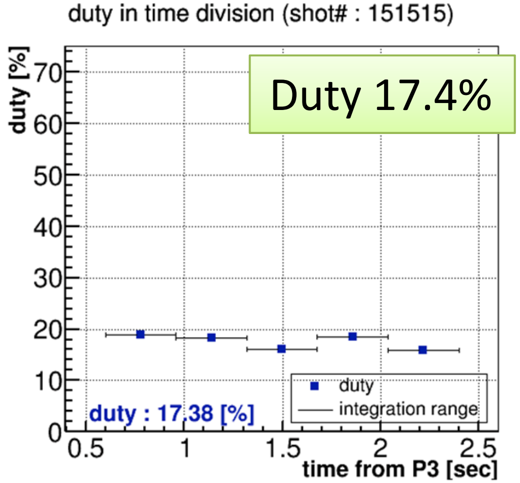




Duty 2-3%



Duty 52.2%



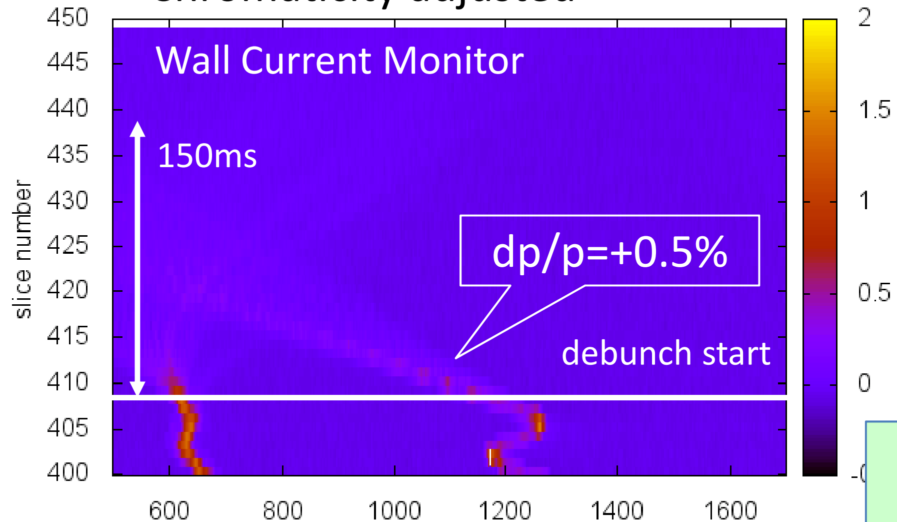
Duty 17.4%

$$Spill\,Duty\,Factor = \left[\int_0^T I(t)dt\right]^2 \Big/ \left[\int_0^T dt \cdot \int_0^T I^2(t)dt\right]$$

ideal spill -> 100%

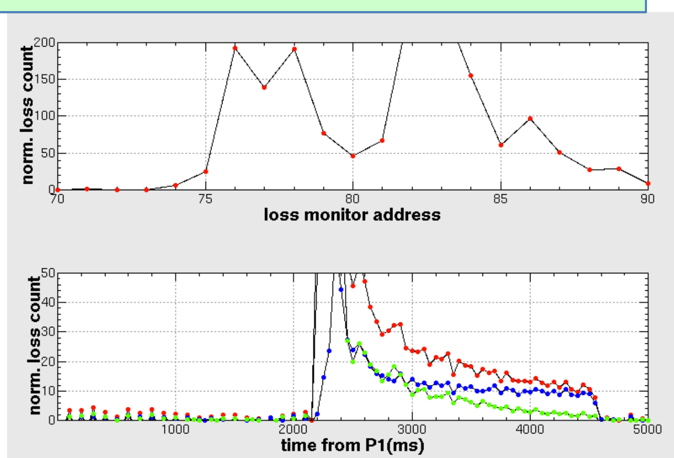
Beam Instability during debunching

6/9, 2015
33.1kW (4.1x10^13 ppp)
RF phase offset 0°
Chromaticity adjusted

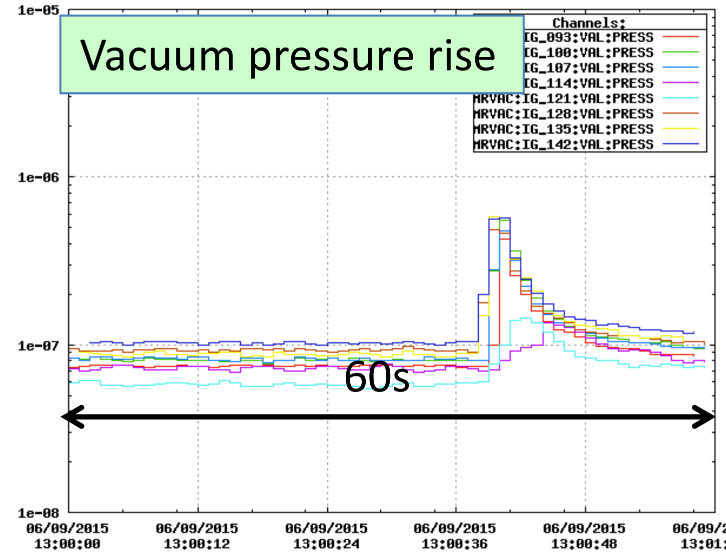


Large beam loss in slow extraction

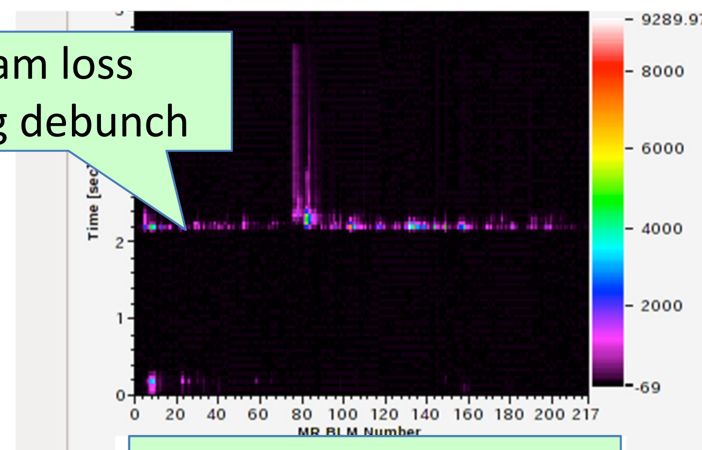
Efficiency
97.14%



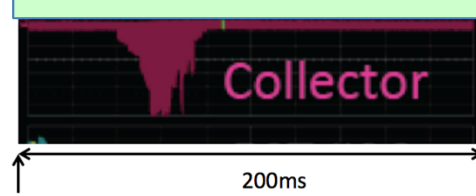
Vacuum (ARC-B)



Beam loss
during debunch



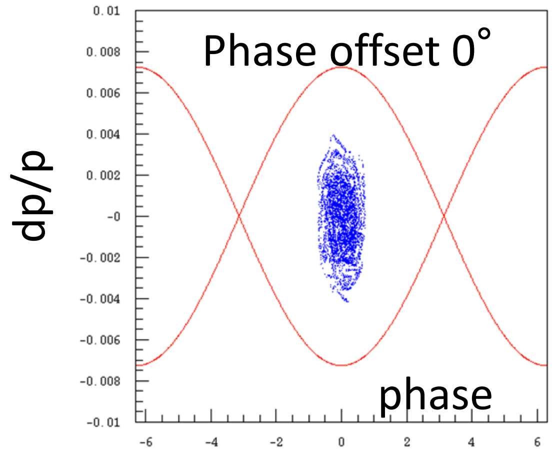
Electron cloud monitor

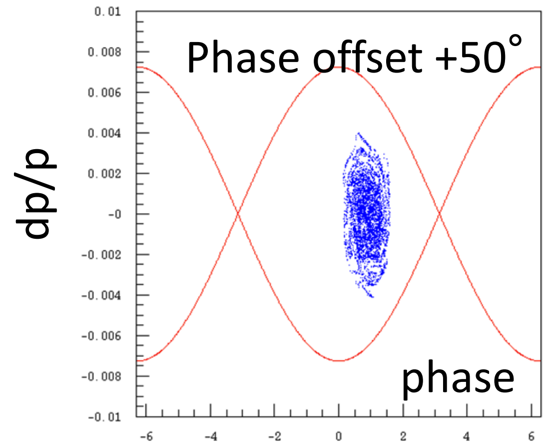


Beam Instability Mitigation

Phase offset injection into RF bucket

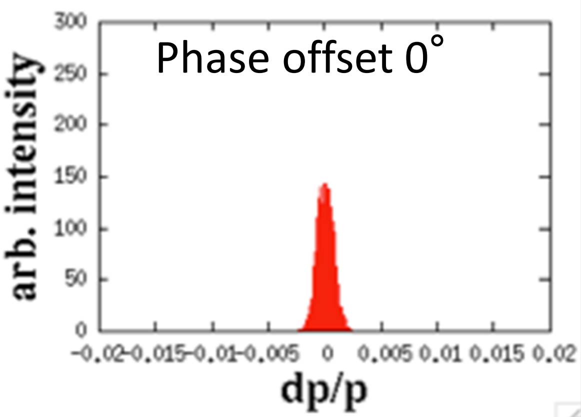
160kV
Injection

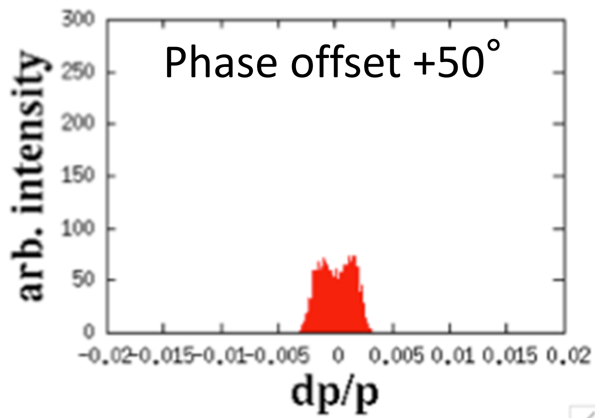




Dipole oscillation
Smear

256kV
Flat top
Before debunch





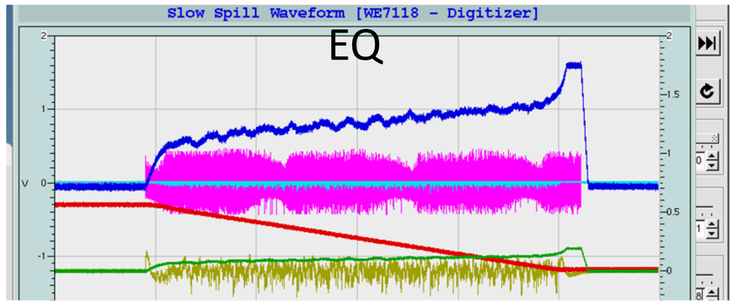
This mitigation is essential to achieve the present beam power and reduce at the beginning of the acceleration

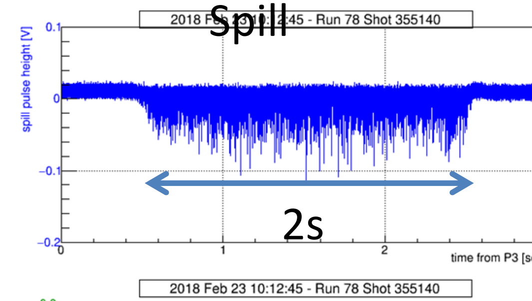
30 GeV Slow Extraction

Rep. rate 5.20 s (<- 5.52s)
flat top is 2.61 s (<- 2.93 s)

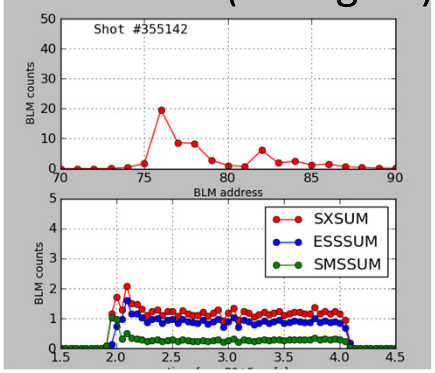
2/23 10:13

5.6x10^13 ppp
RF phase offset 50 deg
Efficiency 99.52%
Spill Duty 48%
Spill length 2.05s

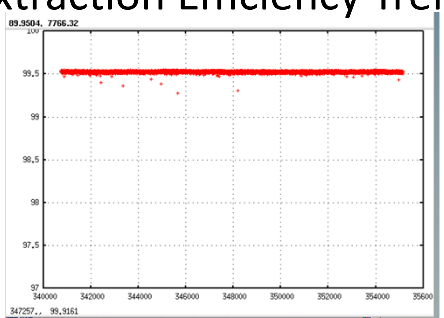




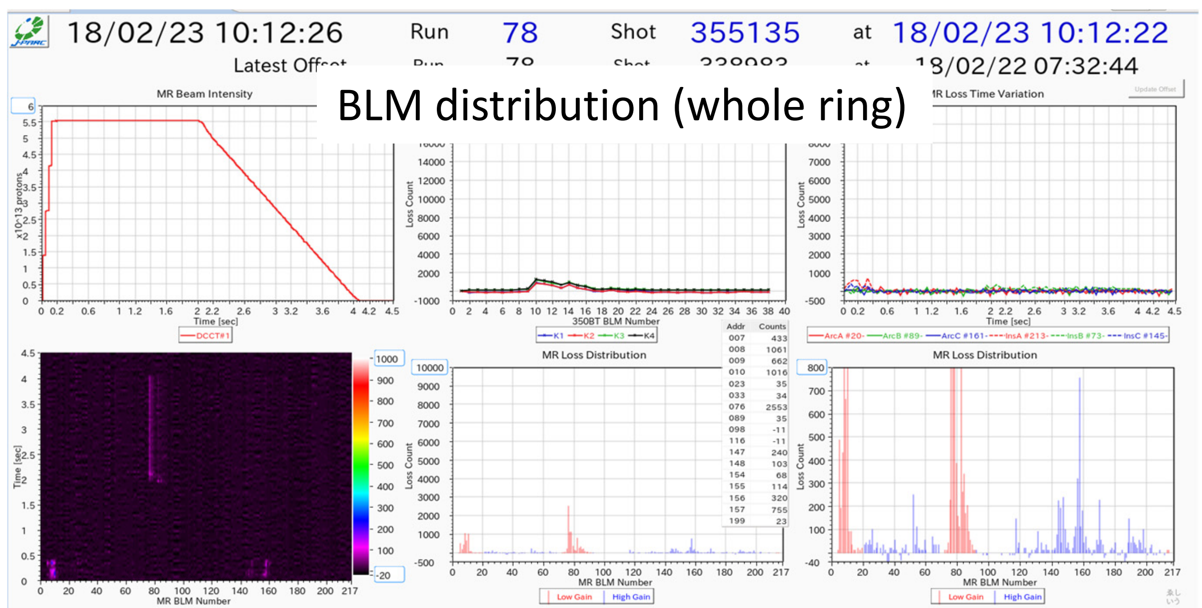
Beam Loss (SX region)



Extraction Efficiency Trend

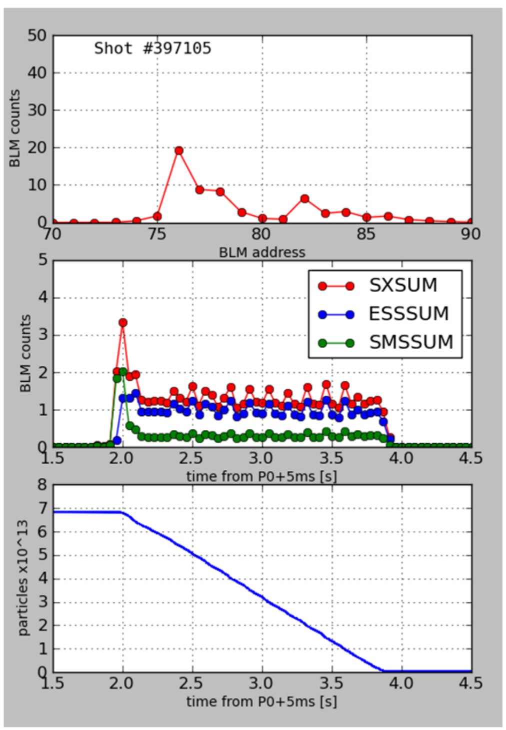


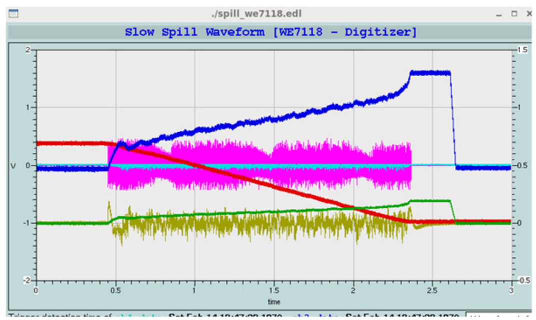
BLM distribution (whole ring)

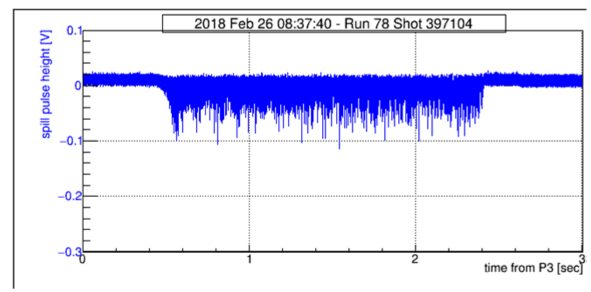


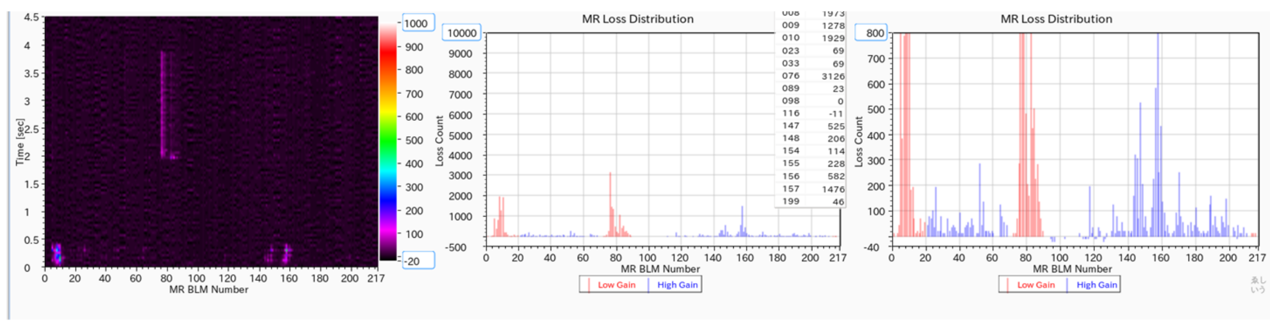
Higher Power SX Demonstration (2 shots)

Beam power 62.8kW (rep. 5.2s)
6.8x10^13 ppp
Efficiency 99.47%
Spill Duty 56%
Spill length 1.82s
RF phase offset 50deg

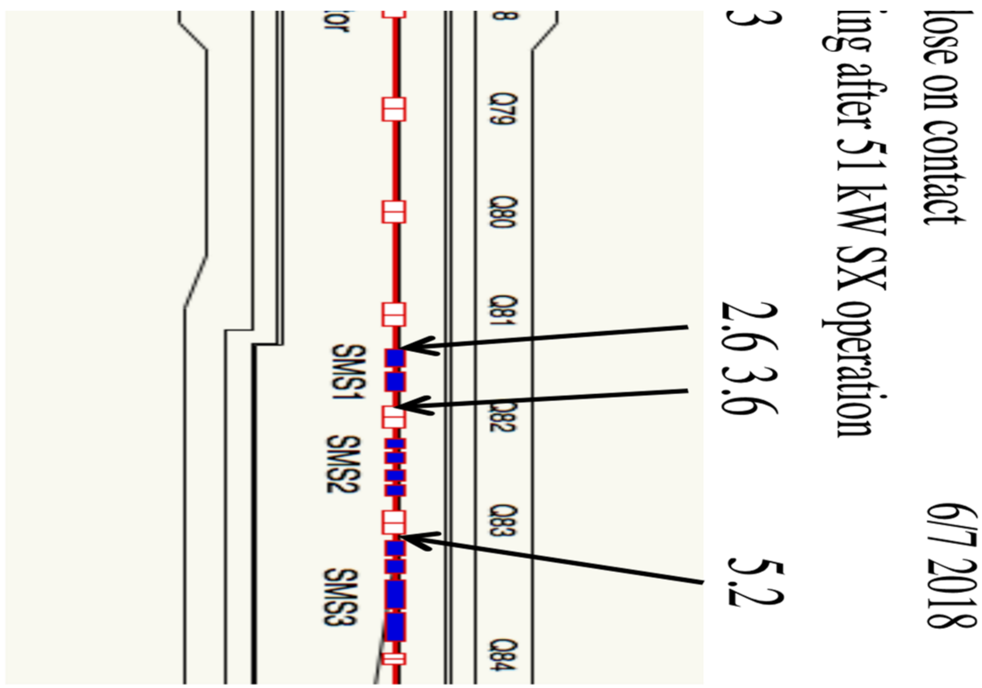








Residual Radiation



SE Beam Stop System

We can stop SE beam for the machine or beam loss trip to protect the devices (target,ESS,SMS,,,) within 1ms.

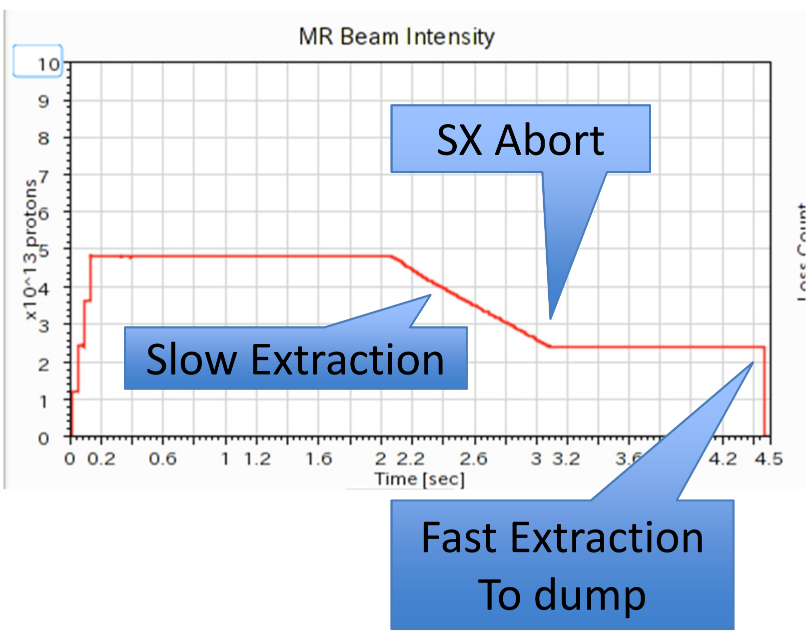
The beam is dumped at the end of flat top.

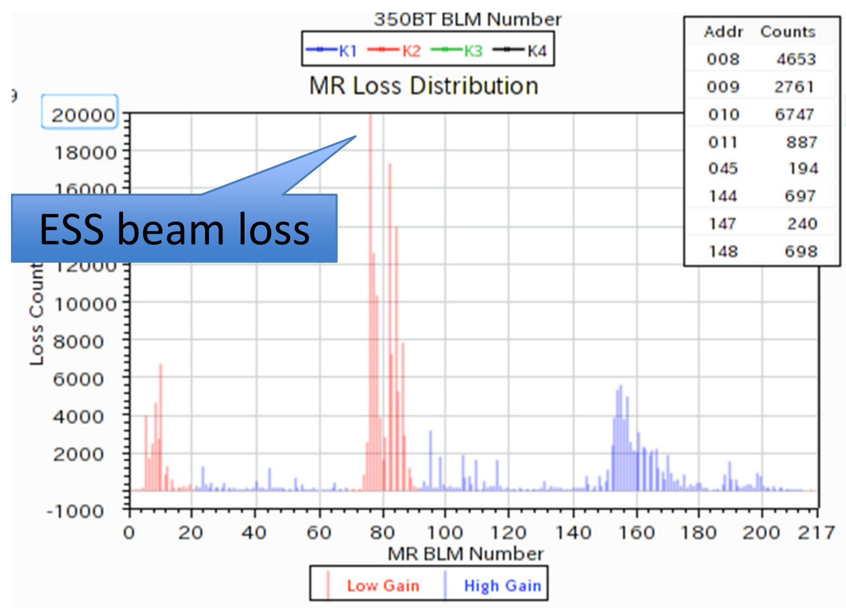
This system is indispensable for present high intensity runs

SX Beam Study BLM76 (ESS1) beam loss count increase

2015/11/25 12:07 run65 #109878

Present MR can not abort beam at any timing



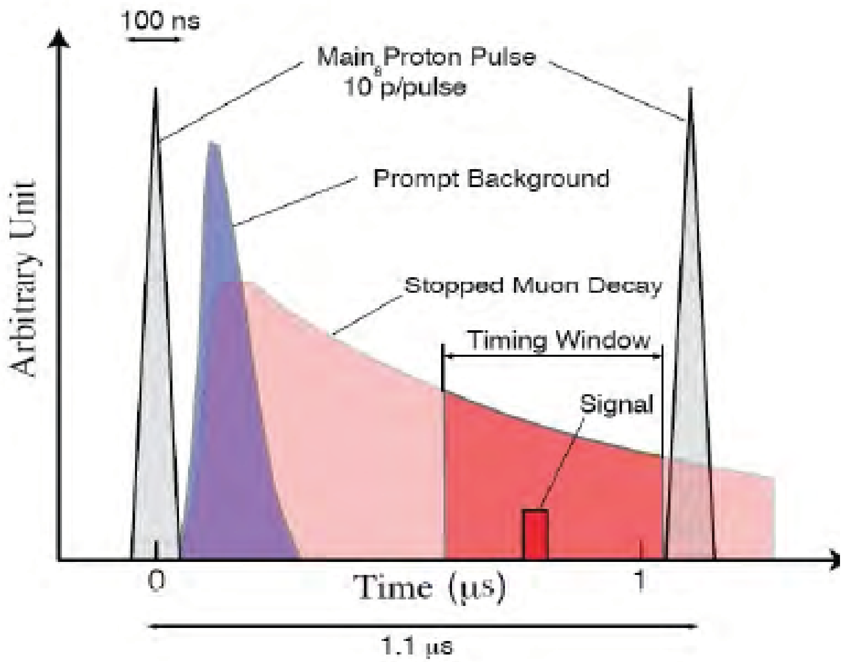


8 GeV SE for COMET

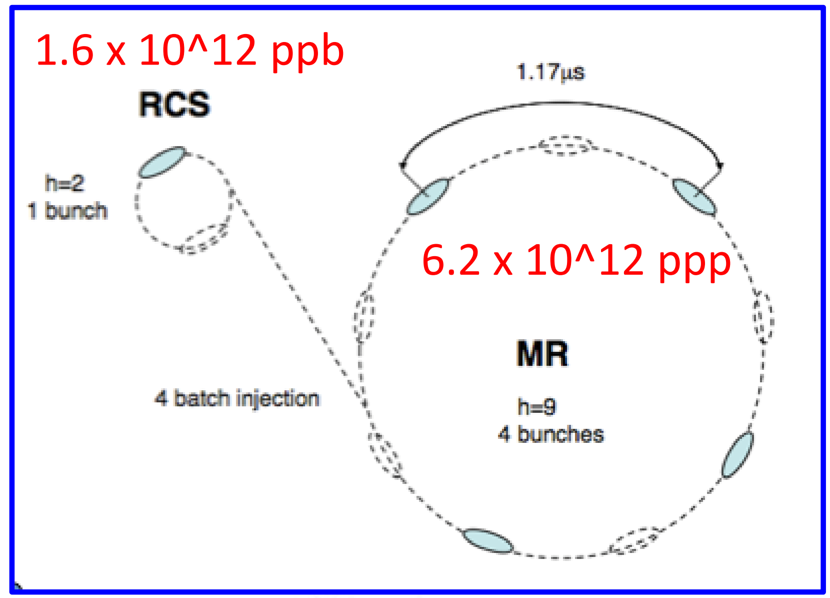
(COherent Muon to Electron Transition)

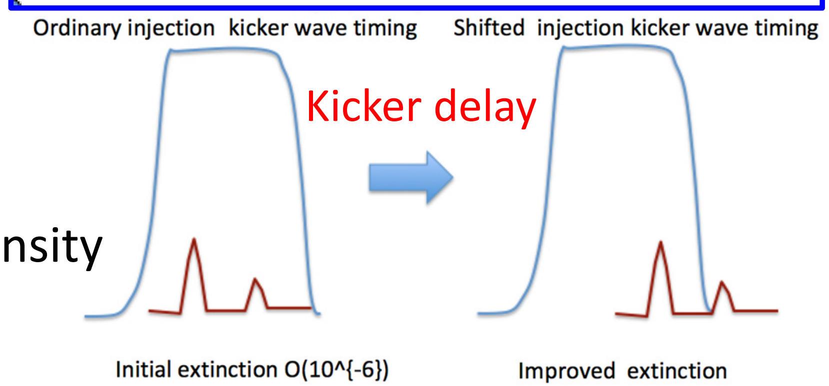
searches muon to an electron conversion event (LFV)

8GeV 1MHz pulsed beam



RCS 1 bunch acceleration
4 (or3) bunches are injected and SE in MR
COMET phase-I 3.2kW (2.48 s cycle)





◎8 GeV SE adiabatic dumping is small aperture of magnetic septa

◎Ratio of inter-bunchs and main bunch intensity Extinction < 10^{-9}

8 GeV Slow Extraction Test

(Feb, 2018)

◎ We have succeeded in 8 GeV slow extraction

7.3x10^12 ppp (4bunches) w kicker delay, 5.20s cycle

Average beam power 1.8kW (corresponding to 3.2 kW at 2.48s cycle)

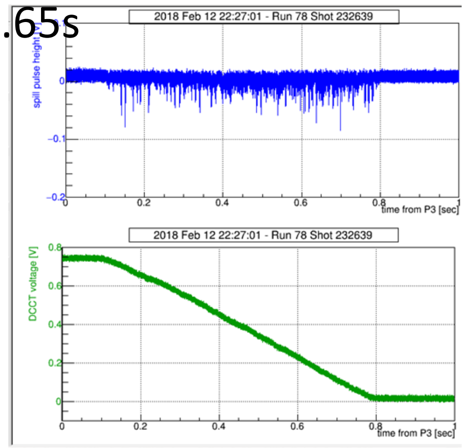
Efficiency 97.3% (could be improved by further beam-based alignment for the ESSs and SMSs)

Duty factor 16% (w/o Transverse RF)

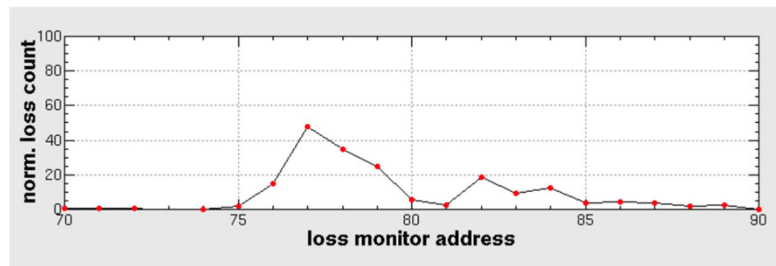
Spill length 0.65s

Spill

DCCT

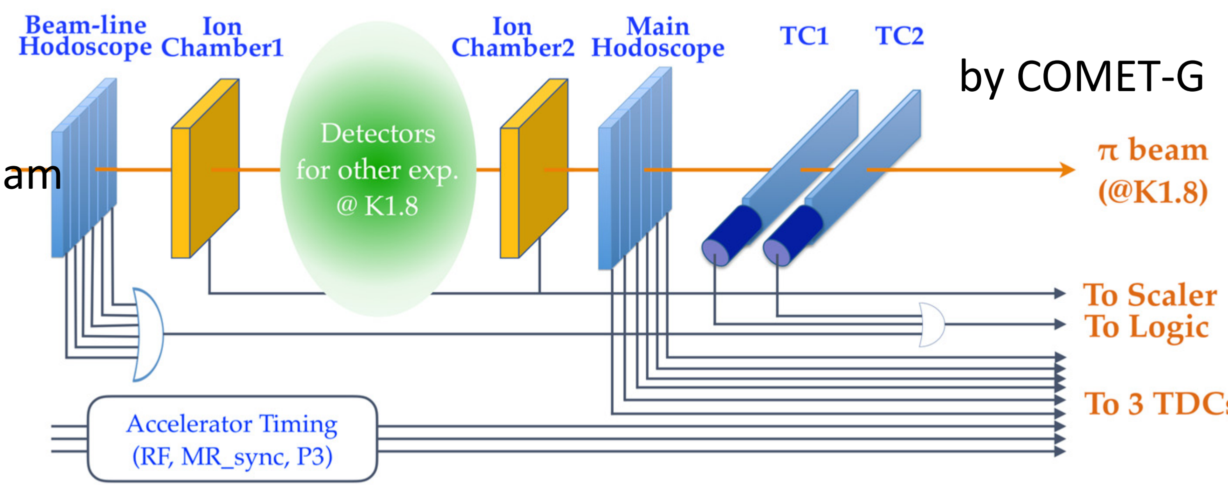


Beam loss distribution in SX area



Measure a time structure of secondary pions

by COMET-G



◎Extinction has been measured for slow extracted beam

Preliminary result

Kicker delay

w/o w/

8.0 E-6 -> **< 6.0E-11**

Beam power ramp-up plans for SX

◯ ▪51 kW is beam power limit due to present target capacity (administrative 53.3kW)
▪The target will be upgraded to 80-90 kW (administrative)

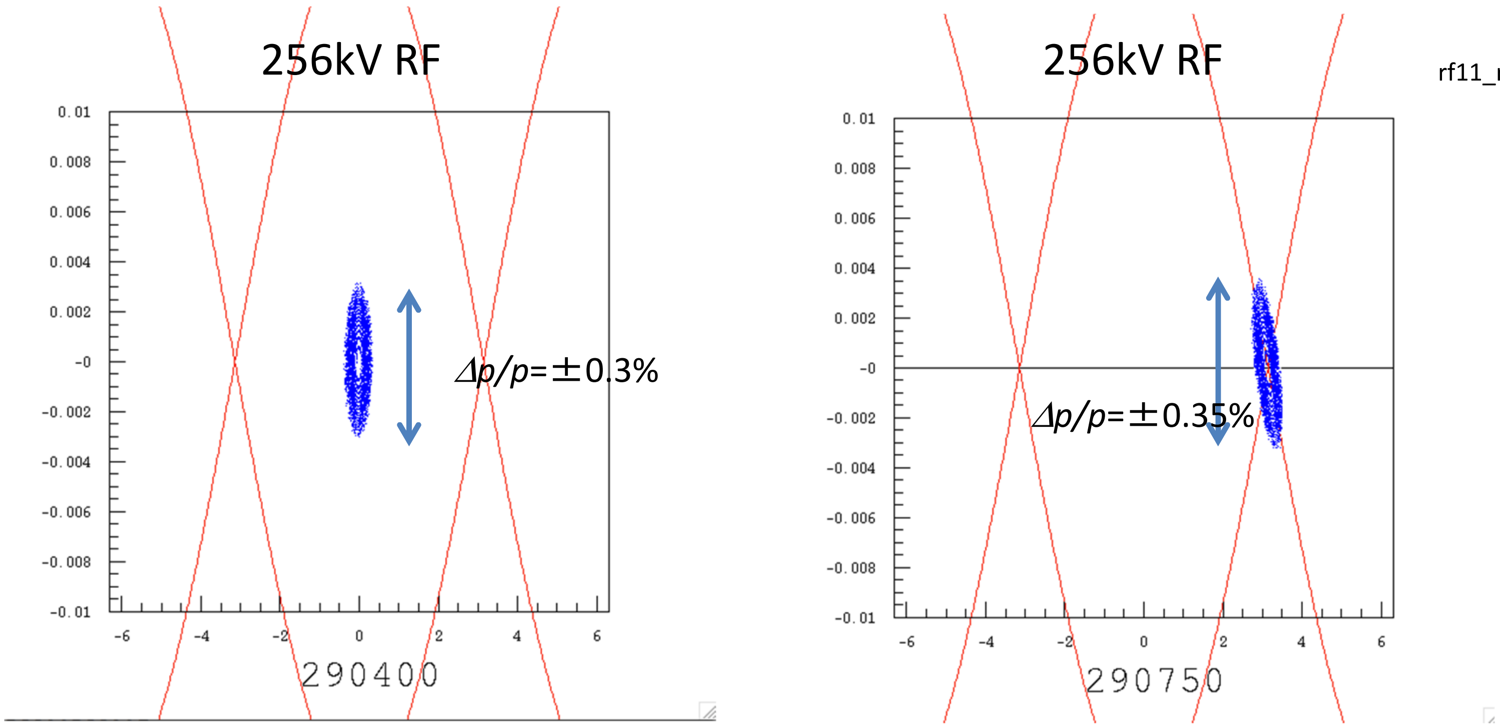
◯ We will Increase proton numbers stored in the ring
to 70 kW (7.6x10^13 ppp) at 5.2 s cycle (62.8 kW = 6.8x10^13 demonstrated)
We have already succeeded to suppress the instability at 7.6x10^13 (66.3kW at rep. 5.52s)
at phase offset of 60 deg. w/o SE

◯ BM and QM power supply upgrade (2021)
▪ Rep. 2.48s -> 1.3 s (FX, neutrino T2K)
▪ flat top 2.63s -> 2.43 s (not to shorten spill length)
Rep. 1.3 + 2.43 =3.73 s (SX)
5.2/3.73 *70 kW -> 98 kW ~100kW

◯ Ideas to reduce a beam loss and an exposure for maintenance workers
▪ESS with a titanium vessel decrease residual dose . First ESS done, Second is planned
▪Diffusers/scatterer upstream of the ESS
▪Carbon nanotube ESS R&D
▪Local shield for maintenance

Further Mitigation Plans of the instability during debunch

◎debunch after RF phase jump at flat top

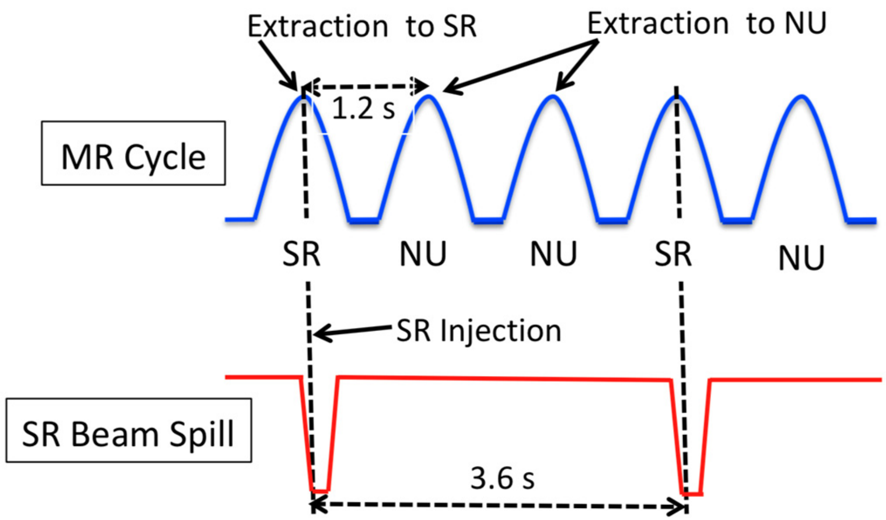


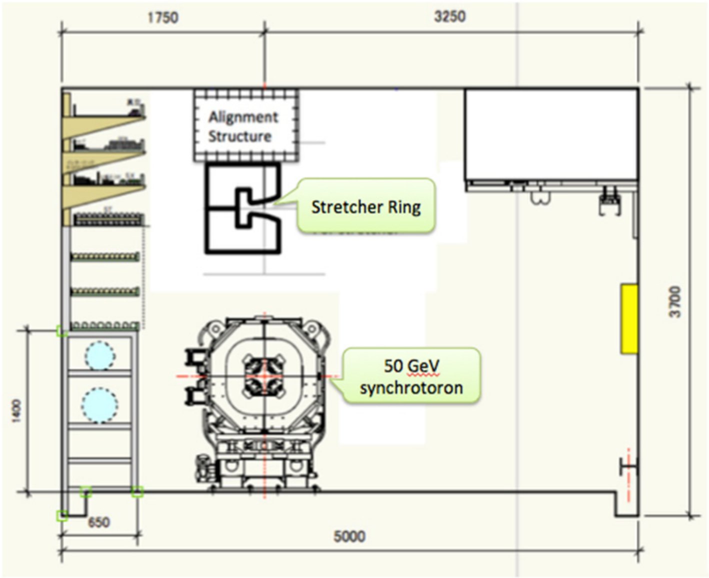
Combination with RF phase offset

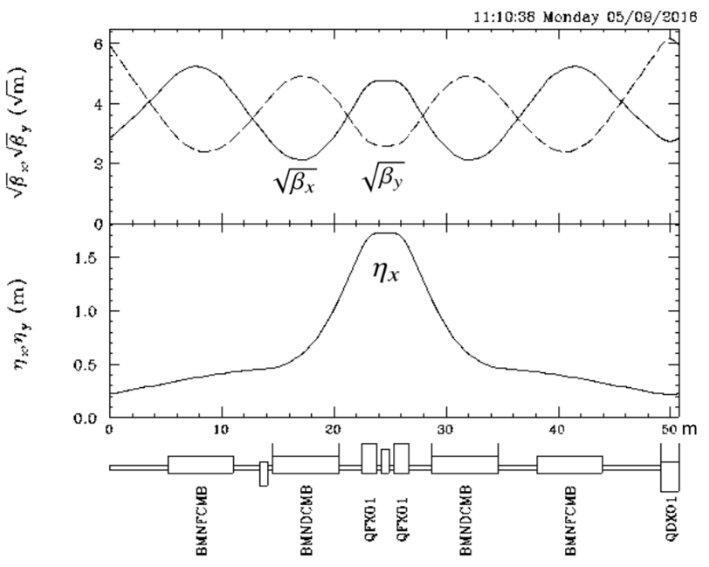
◎VHF cavities: uniform and enlarge longitudinal emittance

SX Stretcher Ring (proposal)

MR ARC tunnel







triples slow beam POT for same POT to Neutrino

Super conducting combined function magnets in the arc section

S.C. magnets design has started
by cryogenic group in KEK

Summary

- 51 kW (5.5x10^13 ppp) beam with 99.5% efficiency
  has been stably supplied for physics runs
  62.8kW (6.8x10^13 ppp) slow extraction has been successfully demonstrated.

- We observed transverse instability during debunch above 30kW.
  (estimated to be triggered by longitudinal instability)
  The beam instability during debunch has been well suppressed by
  an RF phase offset injection idea (and Qx' tuning),

- Spill feedbacks and transverse RFs have improved a duty factor to 50%.

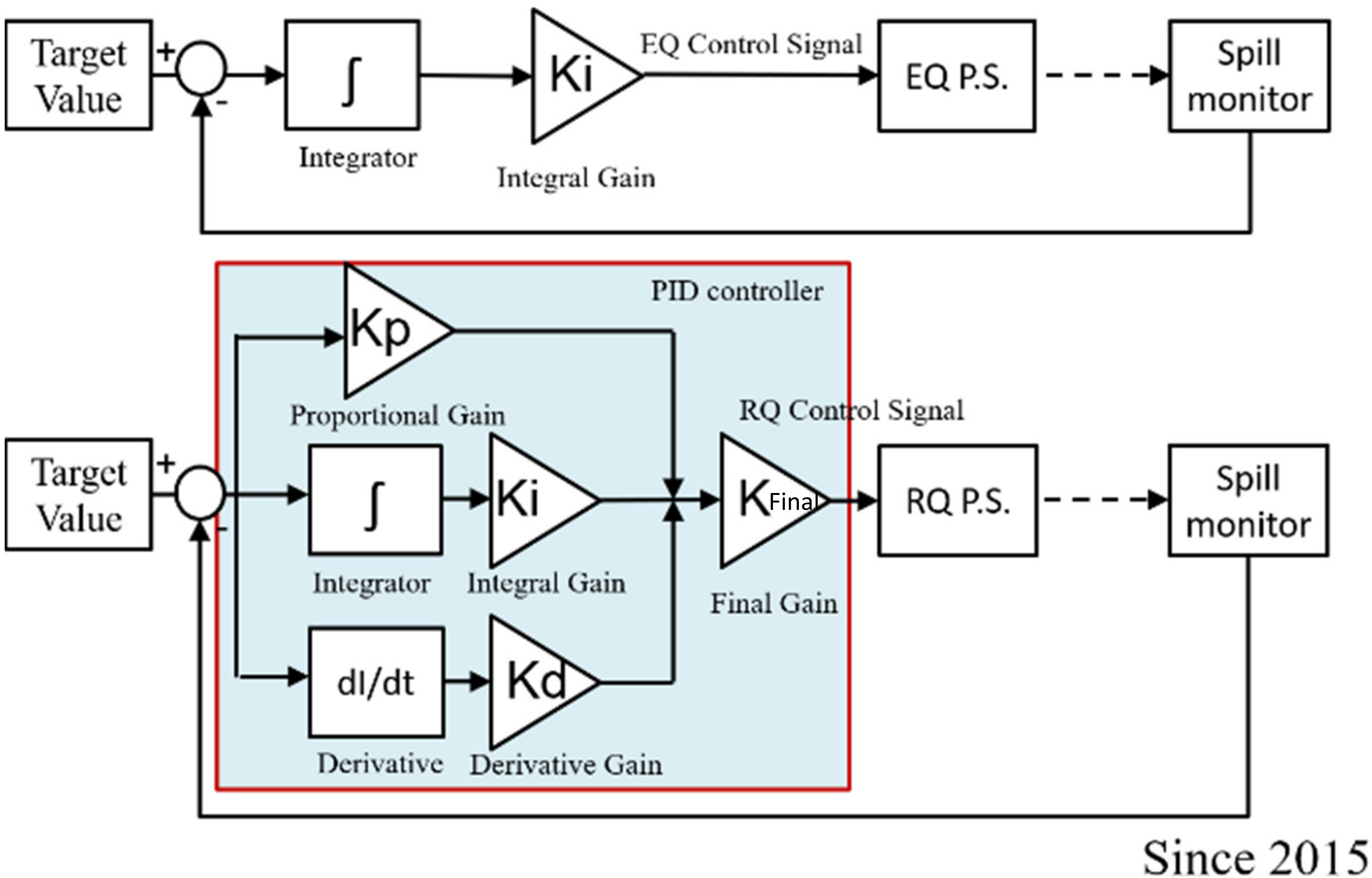
- 8 GeV slow extraction test shows a promising result for extinction.

- Beam power ramp-up scenario to ～100 kW
  Ideas to reduce a beam loss and an exposure for maintenance workers
  a stretcher proposal
  were shown

- Present residual radioactivity is still tolerable from the J-PARC dose limit.
  Exposure ～1mSv/y (limit 7mSv/y) (ALALA)

Backup slides

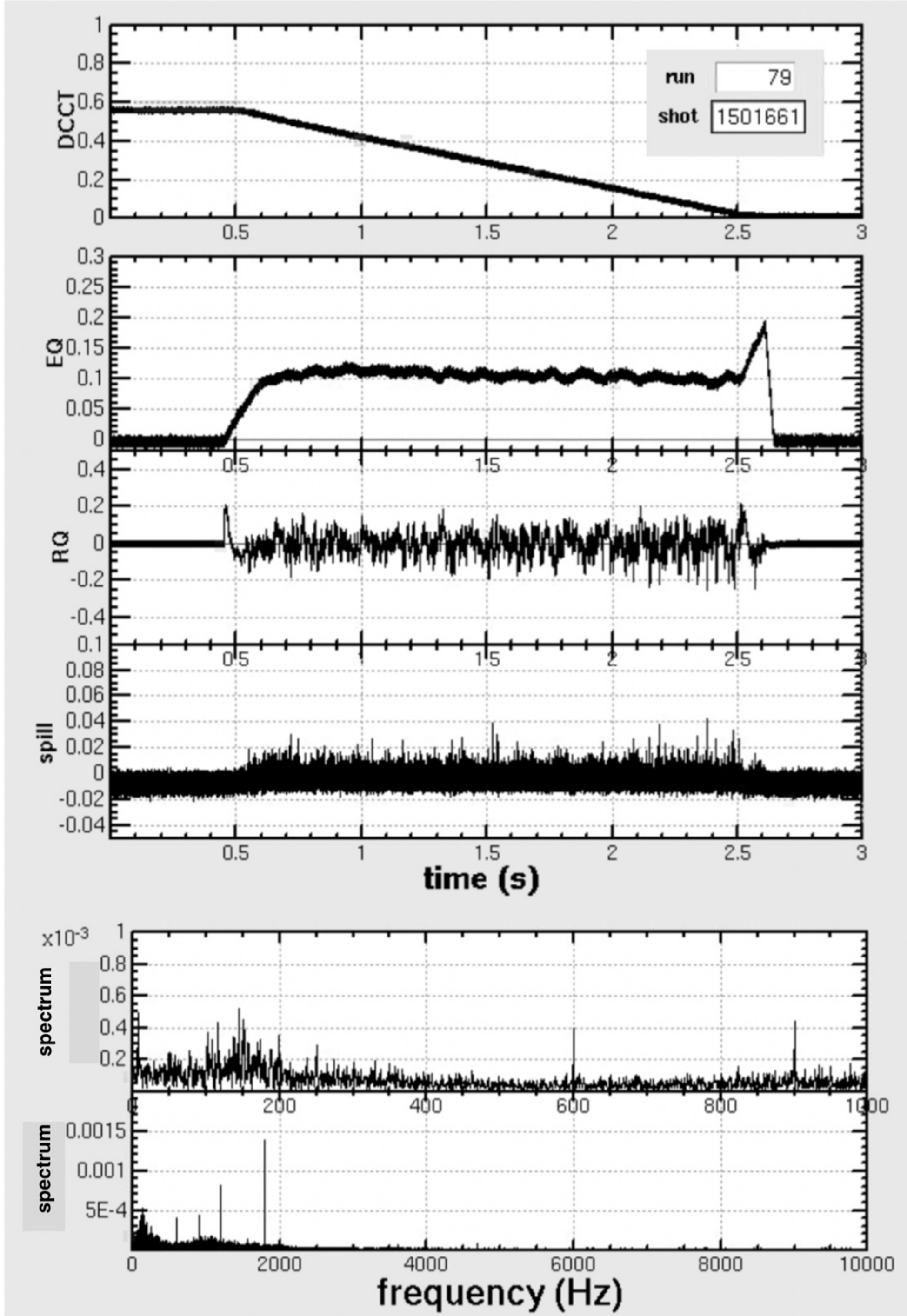
Feedback Algorithm



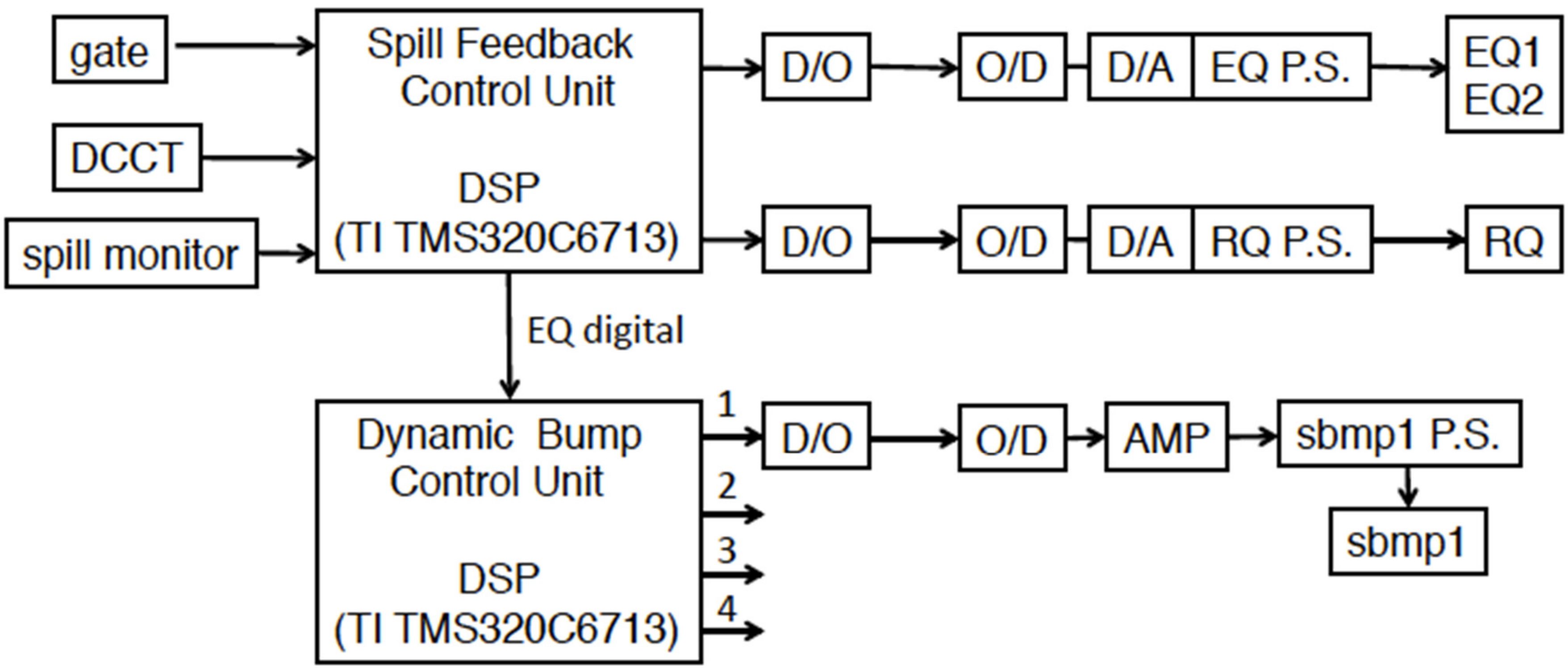
- Feedback Gain (June 2018)
  - EQ: Ki=50*0.006289
  - RQ: Kp=1.0, Ki=0.2, Kd=2.0, K_{Final}=0.75
    T=0.998

$$C_{EQ}(s) = K_i \, \frac{1}{s}$$

$$C_{RQ}(s) = K_{Final} \left(K_p + K_i \, \frac{1}{Ts+1} + K_d s\right)$$


run
79
shot
1501661
DCCT
EQ
RQ
spill
time (s)
x10-3
spectrum
spectrum
frequency (Hz)

Spill DSP and Dynamic Bump DSP



Dynamic bump parameters are determined by H-tune shift

- QFN linear ramping current: scheduled pattern
- EQ current: real-time processed by the dynamic bump DSP

Beam Intensity dependent phenomena

◎Beam Deceleration during debunch process
by RF cavity impedances
----cured by RF beam loading compensation of feed forward at flat top

◎beam loss at the beginning of acceleration
due to space charge tune shift or transverse instability
--- cured by tune, chromaticity adjust and BxB F.B.

◎Instability during debunch process
- vacuum pressure rise in the whole ring
- electron cloud
- beam loss in debunch and slow process

present cures -> chromaticity, longitudinal dipole oscillation

2015. 6. 9 13:00:34 shot 349376 P_{BEAM} = 33 kW

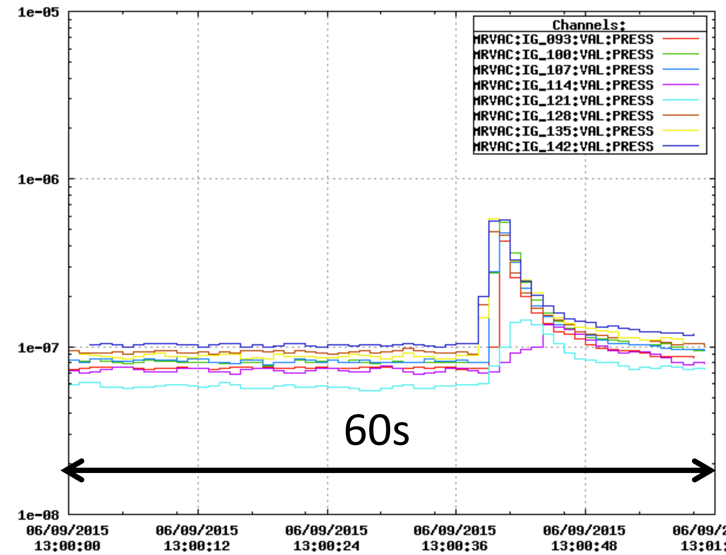
Electron cloud monitor

200ms

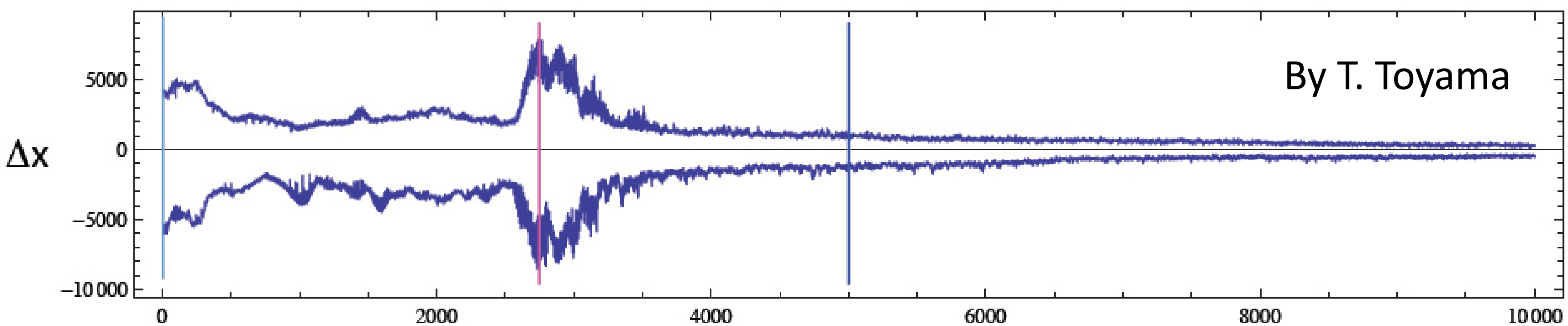
Flat top start(P3)

By T. Toyama

Vacuum (ARC-B)



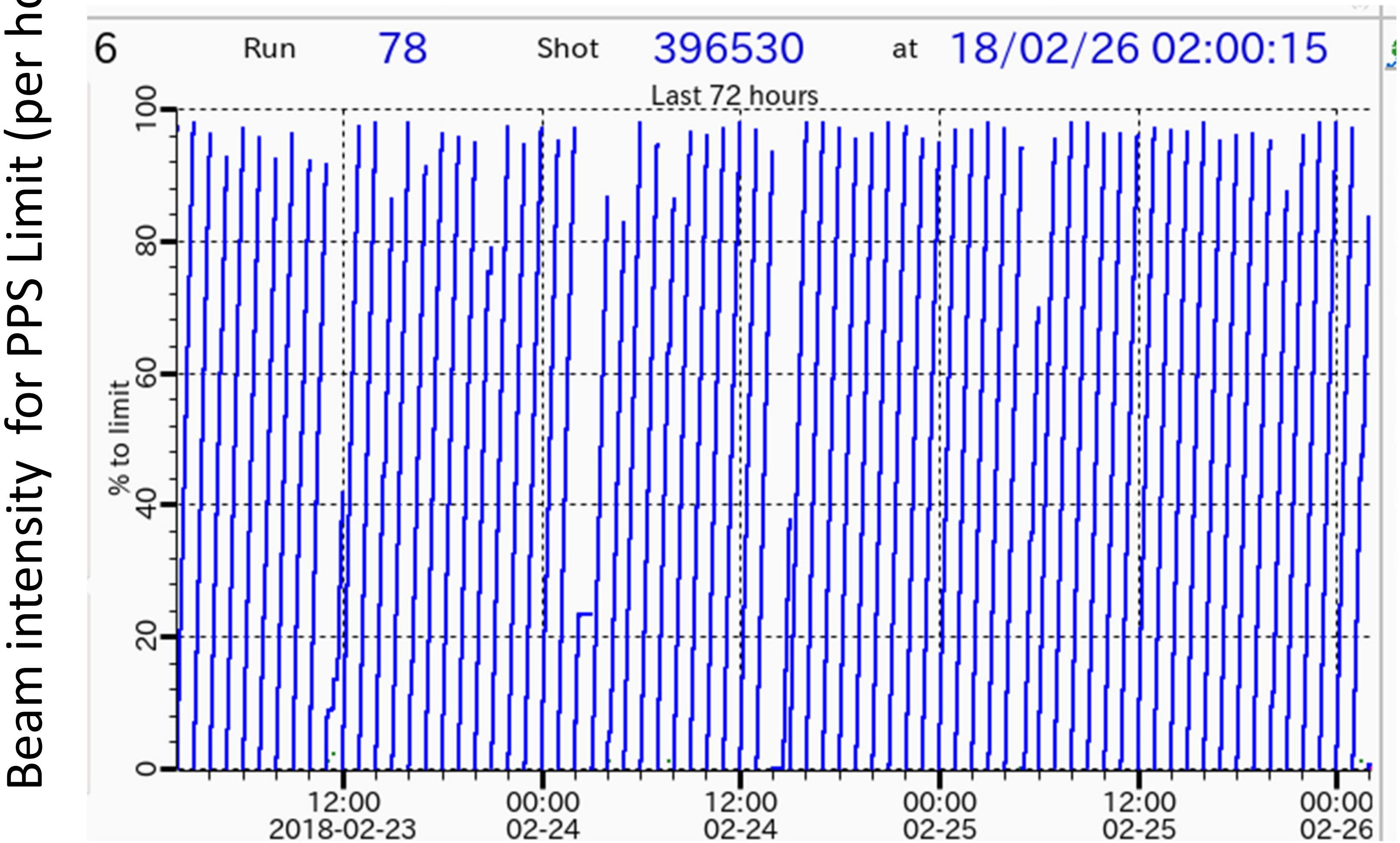
Peak of the horizontal oscillation



P3 P3+55ms P3+100ms

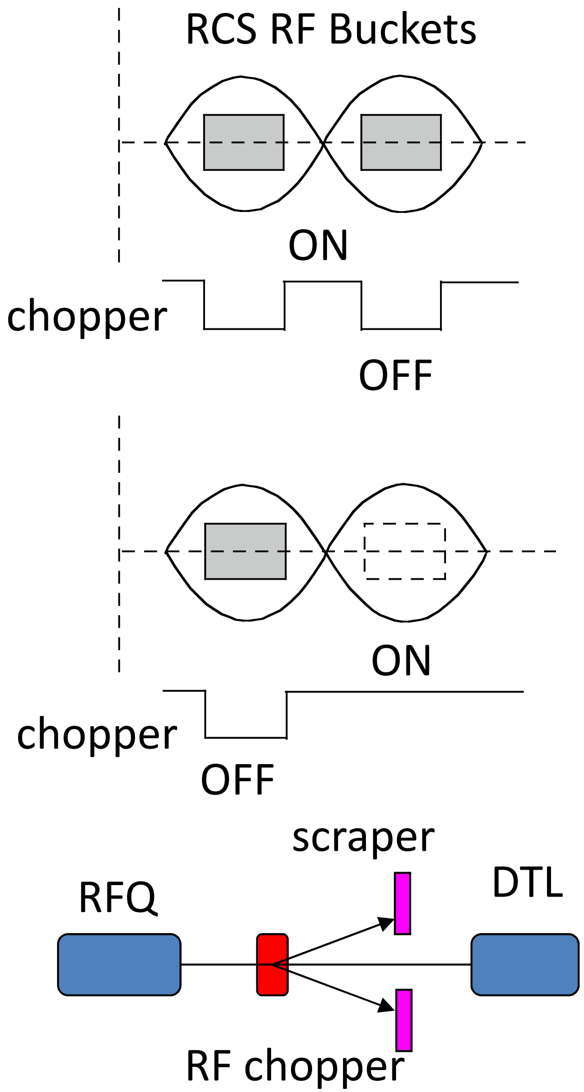
MR Beam intensity normalized at PPS limit for RUN78 SX operation

Lifted administrative beam power limit 53.4 kW x1h
PPS beam power limit 52.3kW x 1h (2% less)
MPS beam power limit 51.8kW x 1h (3% less)

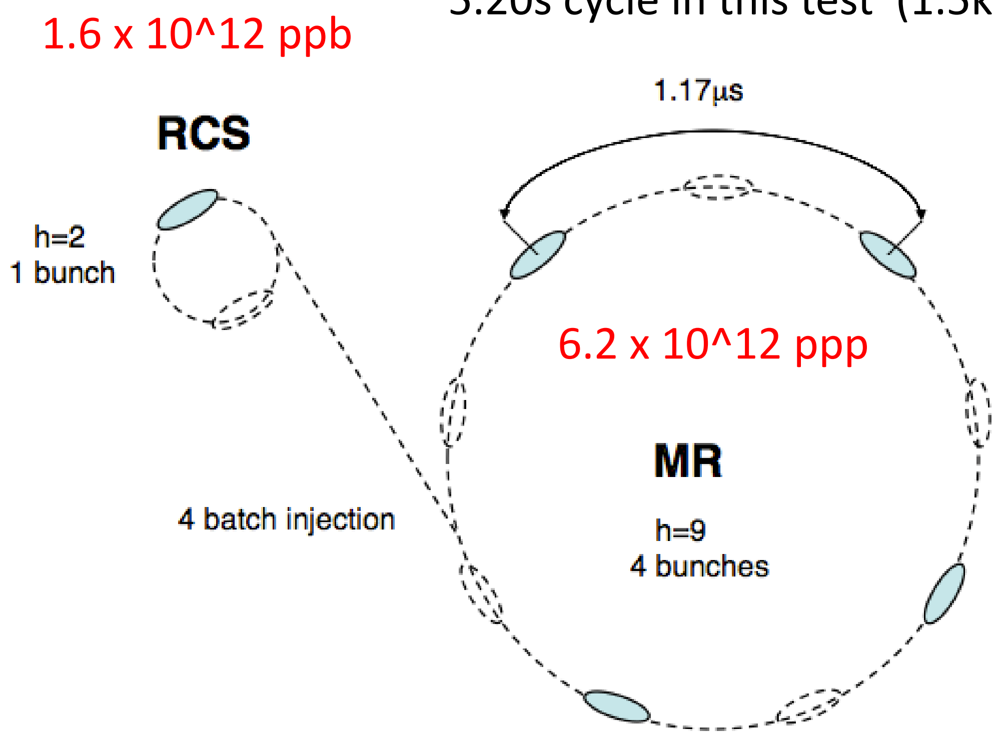


Last 3 days

8GeV 1MHz-Pulsed Beam Scheme for COMET



2.48s cycle for physics run (3.2kW)
5.20s cycle in this test (1.5kW)

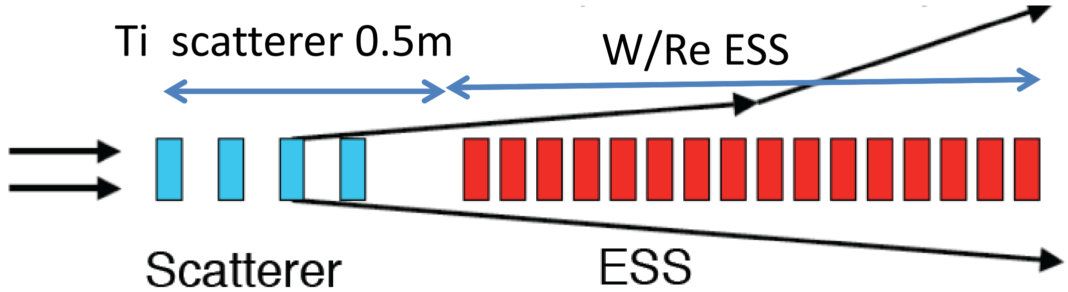


Bunched Slow Extraction at 8 GeV
(option: 3 bunches in h=9)

Scatterers/diffusers

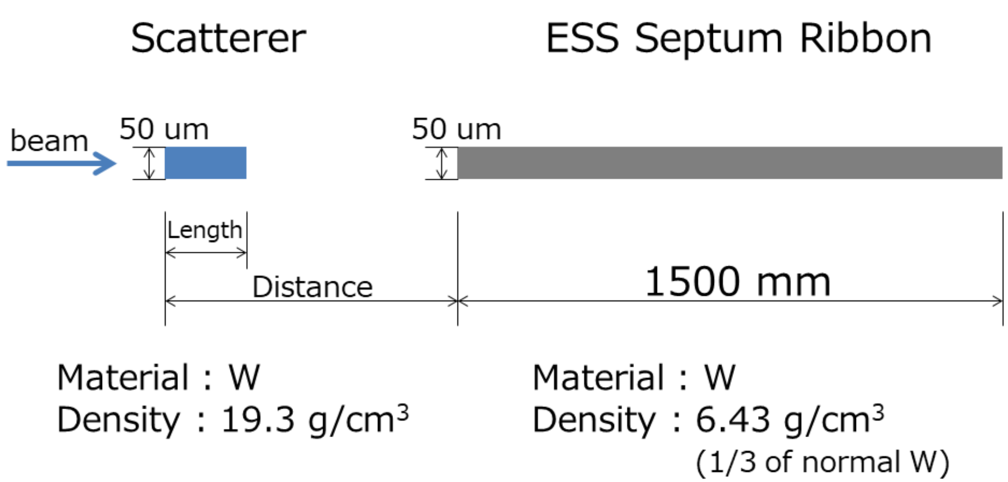
- multiple scattering（diffuse beam ）
- Reaction（beam loss）

(Some schemes are under study)



1.5m long, 3mm pitch W ->
0.5m long, 9mm pitch Ti + 1m long, 3mm pitch W
residual dose at ESS downstream duct is reduced by 50% (MARS simulation)

By M. Tomizawa



1mm ribbon width
Distance 350mm
Loss reduced by 36%
(MARS)

By R. Muto

Low-Z septum materials

CNT

・wires

ϕ30-90μm

90μm 2.3N (361MPa)

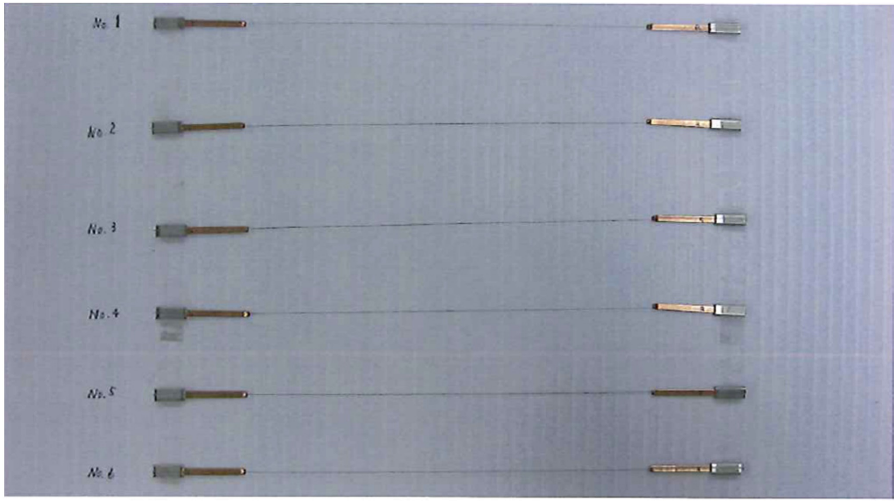
・Ribbons

1mm width 30μm thick 400mm long

6N (200MPa)

・A high voltage test by a short yoke model will be planned

Φ90μm CNT



Grants-in-Aid for Scientific Research 2017-2019