J-PARC Slow Extraction Project

FNAL Acc. Seminar
2015.08.27

KEK/J-PARC

Masahito Tomizawa

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J-PARC Slow Extraction Brief History

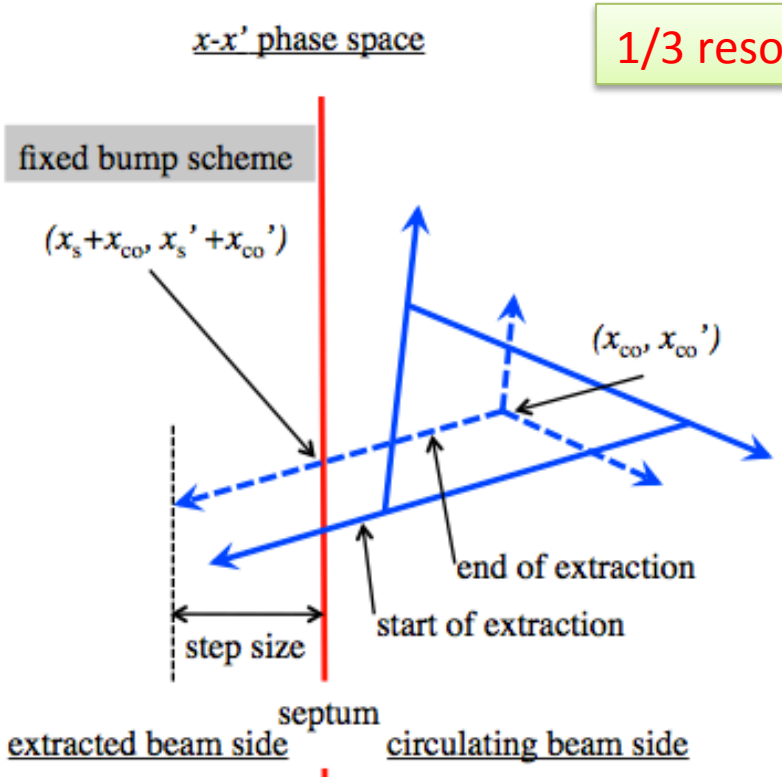
- First Slow Beam Jan., 2009
- East Japan Earth Quake March, 2011
- Slow Beam Operation recovered in Jan. 2012
- Radiation leakage incident at the experimental hall in May, 2013
- Slow Beam Operation recovered in April, 2015

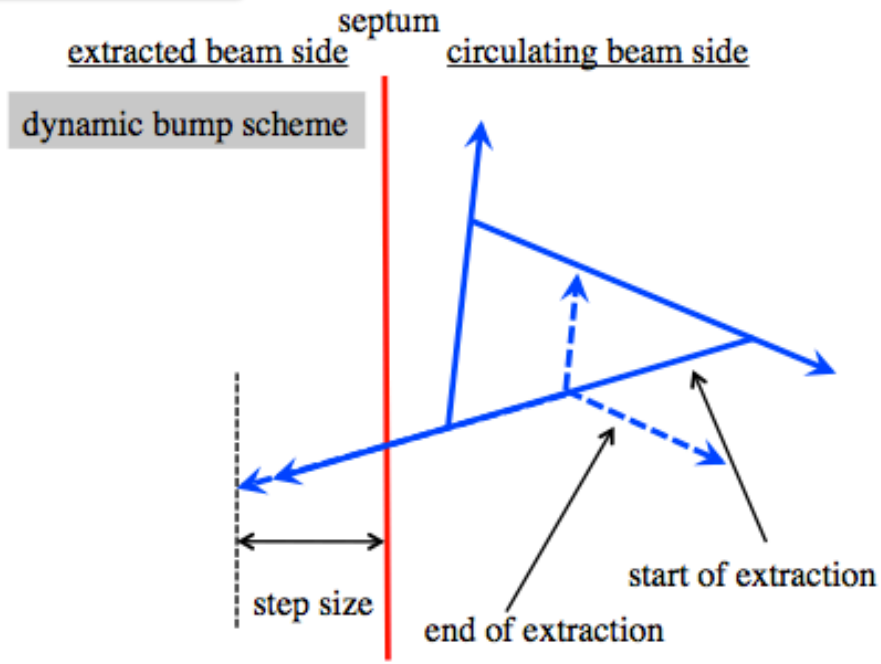
Schemes for Very High Extraction Efficiency (low beam loss)

◎Electrostatic Septum (ESS) QF-QF high β (small α) 40m
-> large step size (20mm)

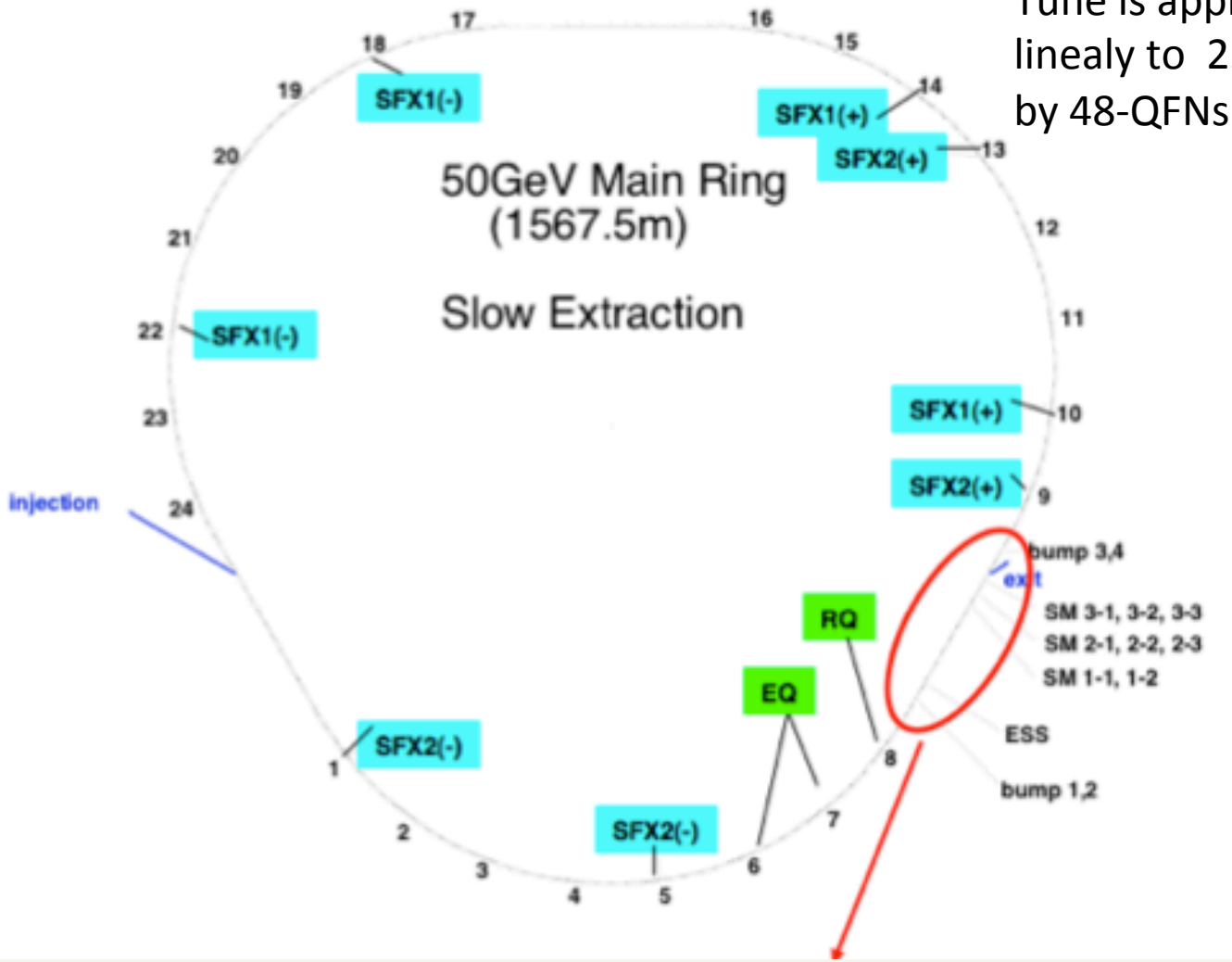
◎dispersion free at ESS + low horizontal chromaticity
-> Separatrix is independent of $\Delta p/p$
depends on tune (constant resonant sextupole)

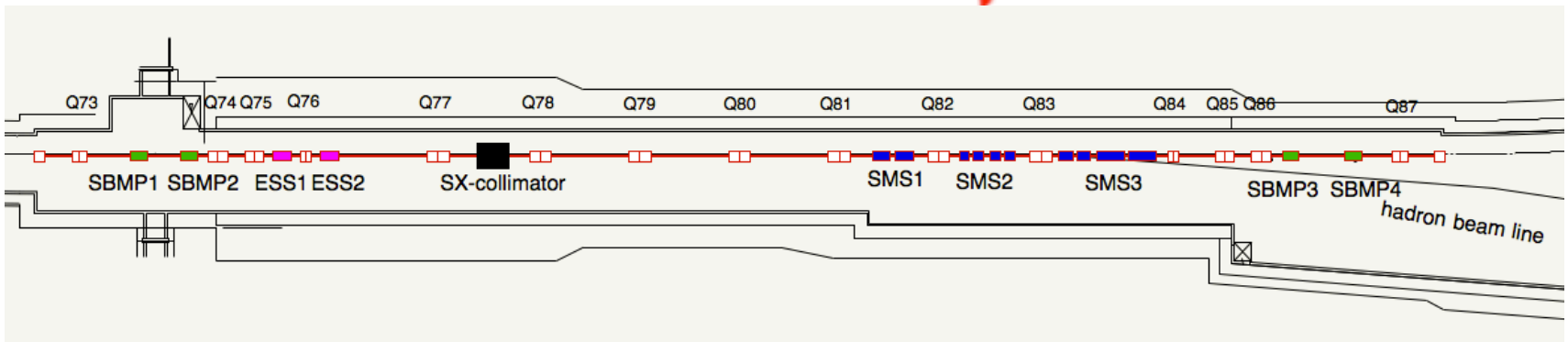
1/3 resonant extraction





Tune is approached linealy to 22.333 resonance by 48-QFNs in the arcs





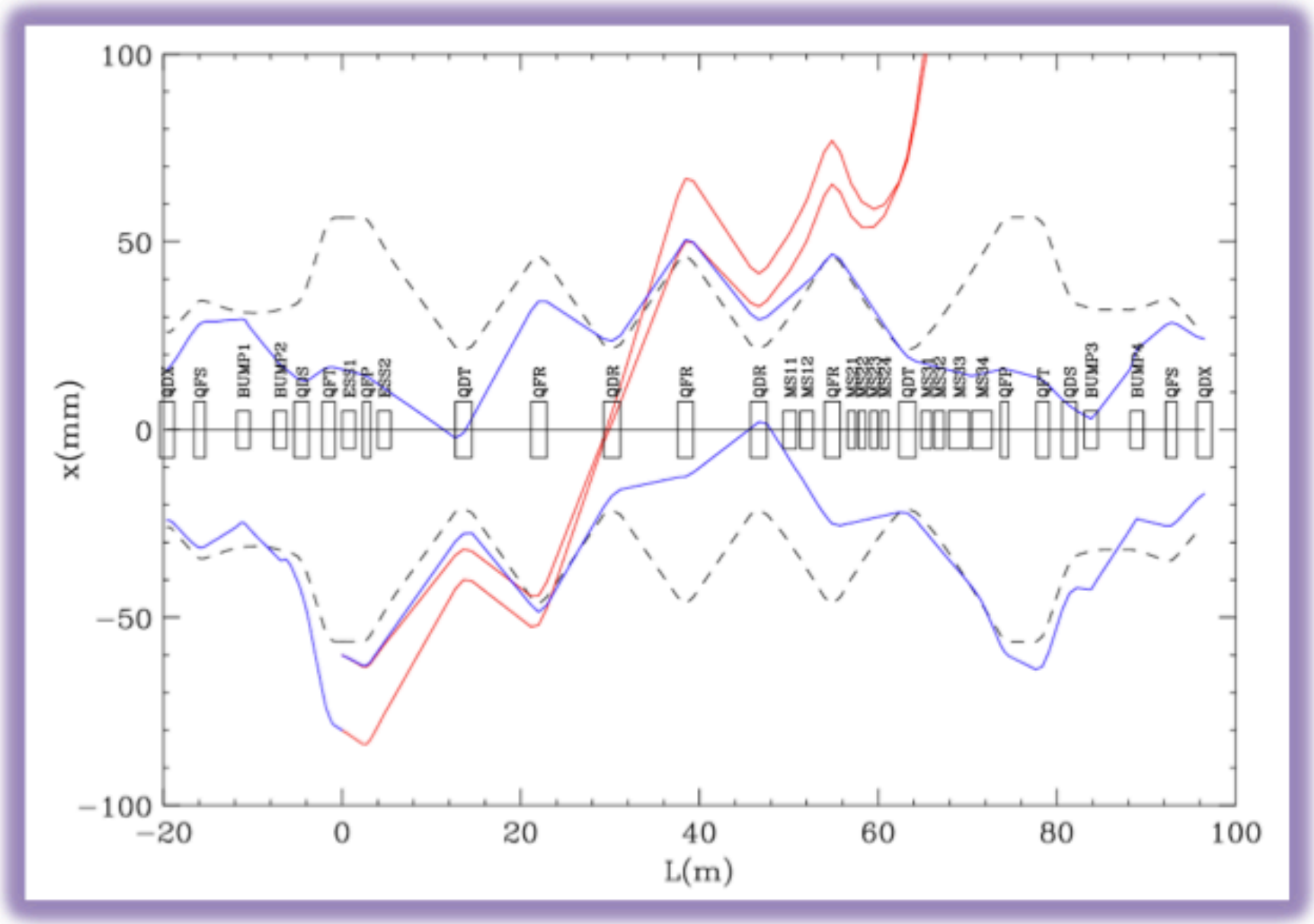
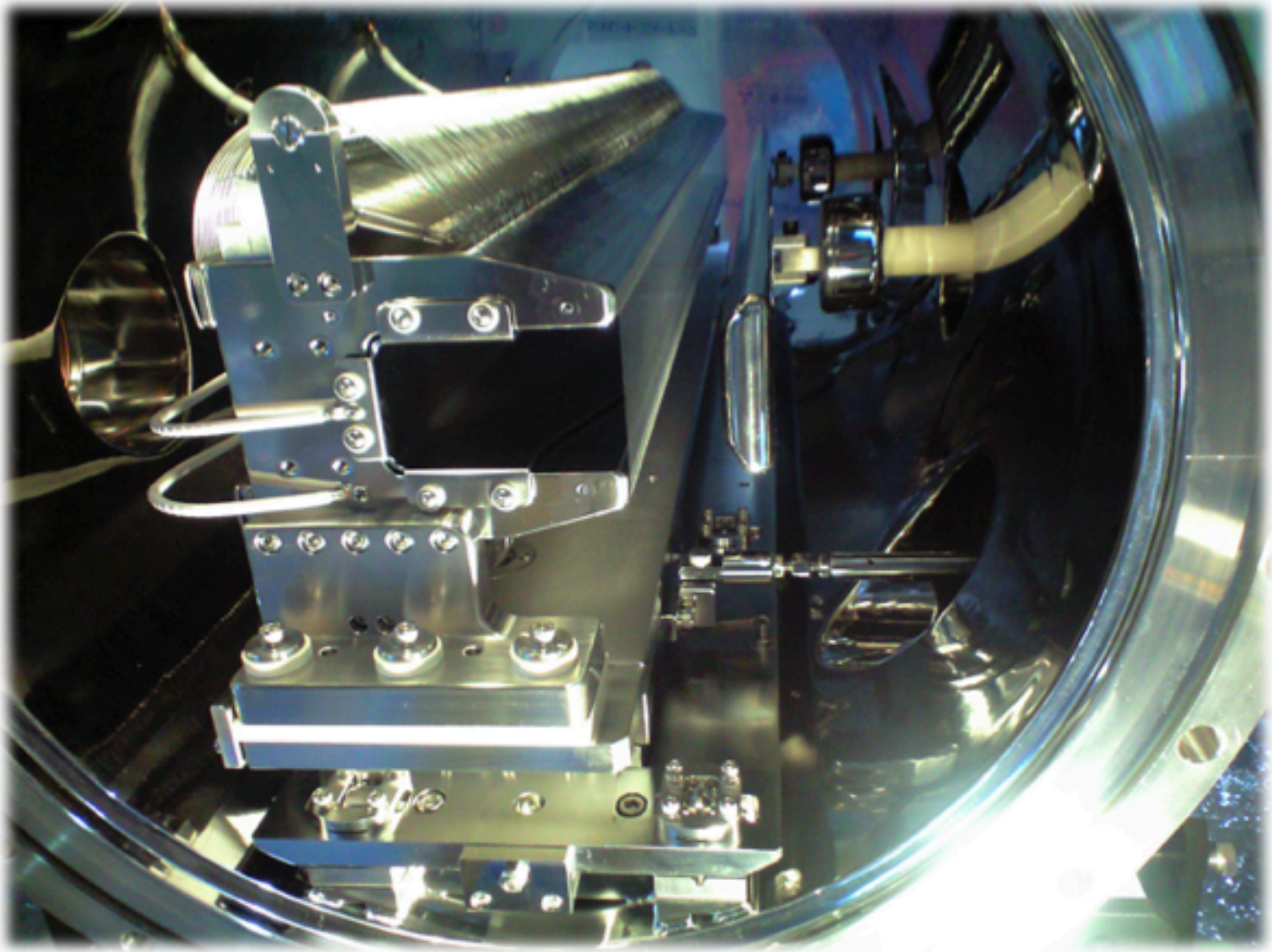

100
50
0
−50
−100
x(mm)
−20
0
20
40
60
80
100
L(m)
QDX
QFS
BUMP1
BUMP2
QDS
QFT
ESS1
QFP
ESS2
QDT
QFR
QDR
QFR
QDR
MS11
MS12
QFR
QDT
MS13
MS14
QFP
QFT
QDS
BUMP3
BUMP4
QFS
QDX

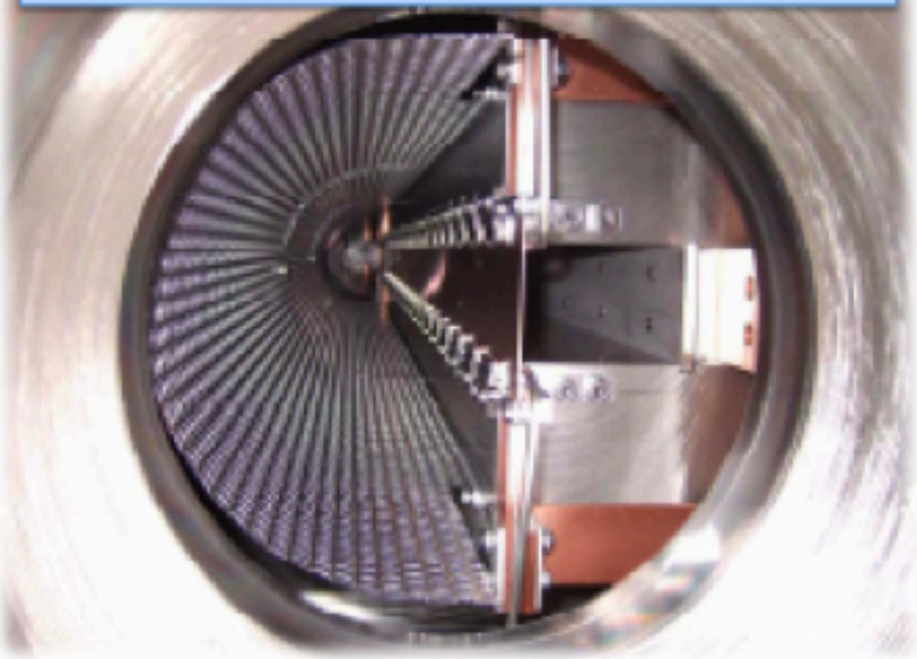
Table 1: Parameters of slow extraction devices (30 GeV)

device name	core length	septum thickness	field strength	p.s. output
ESS1∼2	1.48 m	∼0.08 mm	4.2 MV/m	104 kV
SMS11	1.5 m	1.5 mm	0.071 T	3000 A
SMS12	1.5 m	3.5 mm	0.142 T	2×3000 A
SMS21∼24	0.838 m	8.5 mm	0.33 T	4×3000 A
SMS31∼32	1.14 m	35 mm	0.91 T	16×3400 A
SMS33∼34	2.28 m	64 mm	1.00 T	18×2800 A
SBMP1∼4	1.4 m	–	0.375 T	360 A
RSX1∼8	0.7 m	–	130 T/m^2	340 A
EQ1∼2	0.62 m	–	3.2 T/m^2	340 A ±260 V
RQ	0.62 m	–	0.89 T/m^2	±340 A ±300 V

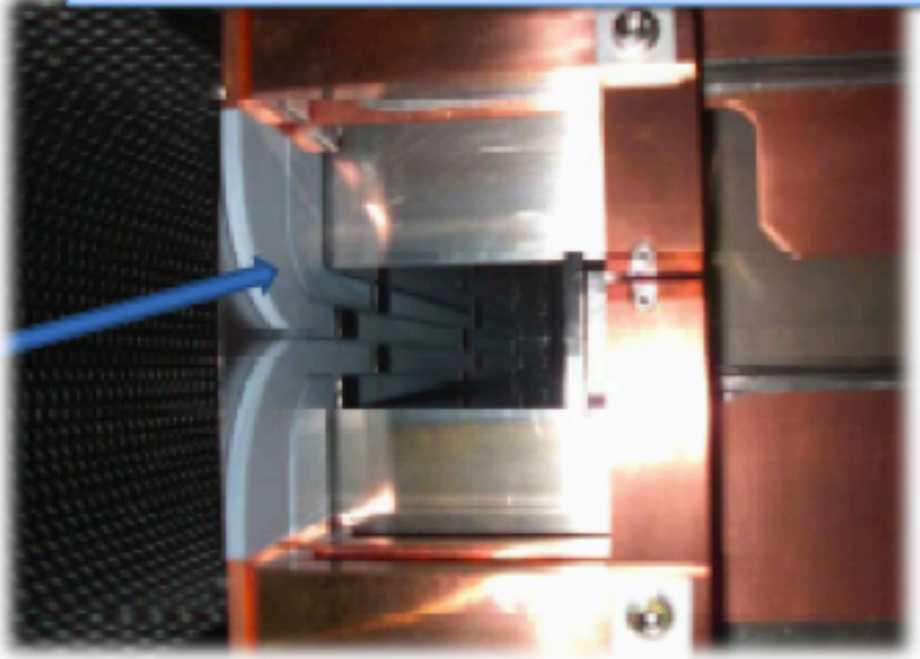
Electro Static Septa (ESS1,2)



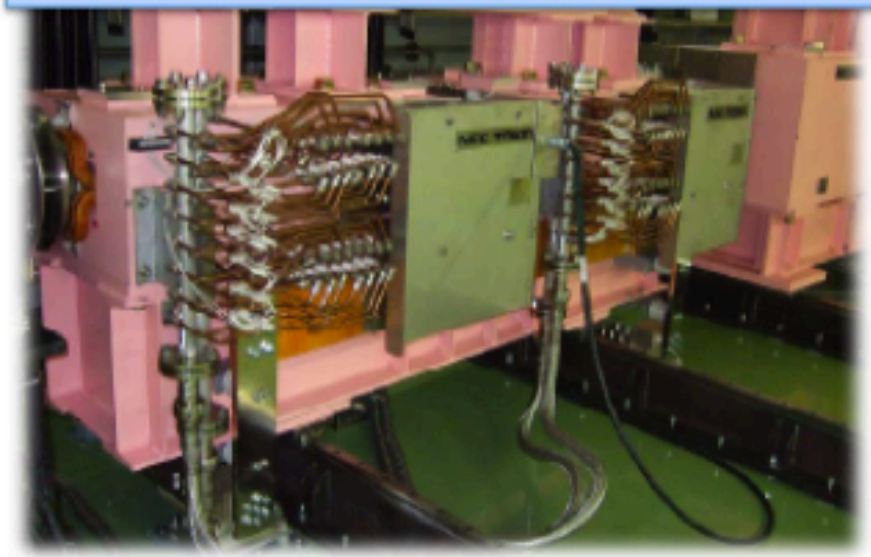
Low field magnetic septa (SMS11,12)



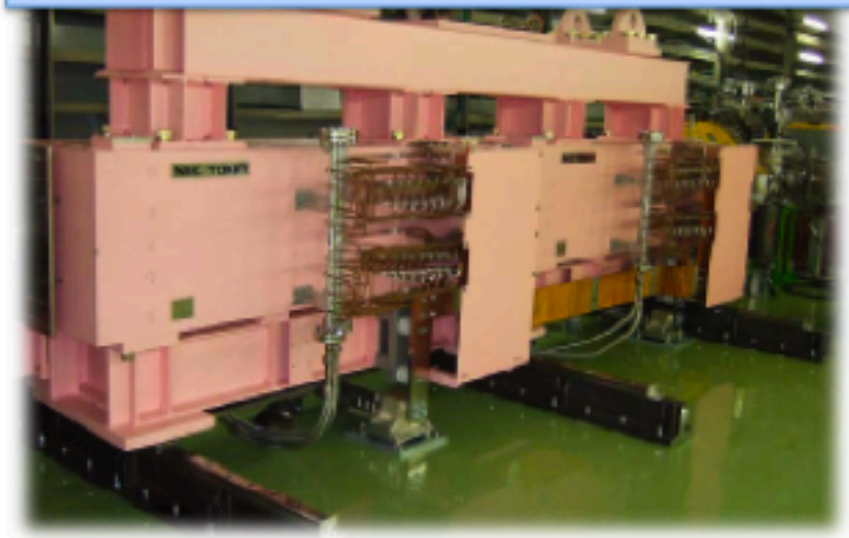
Mid field magnetic septa (SMS21-24)

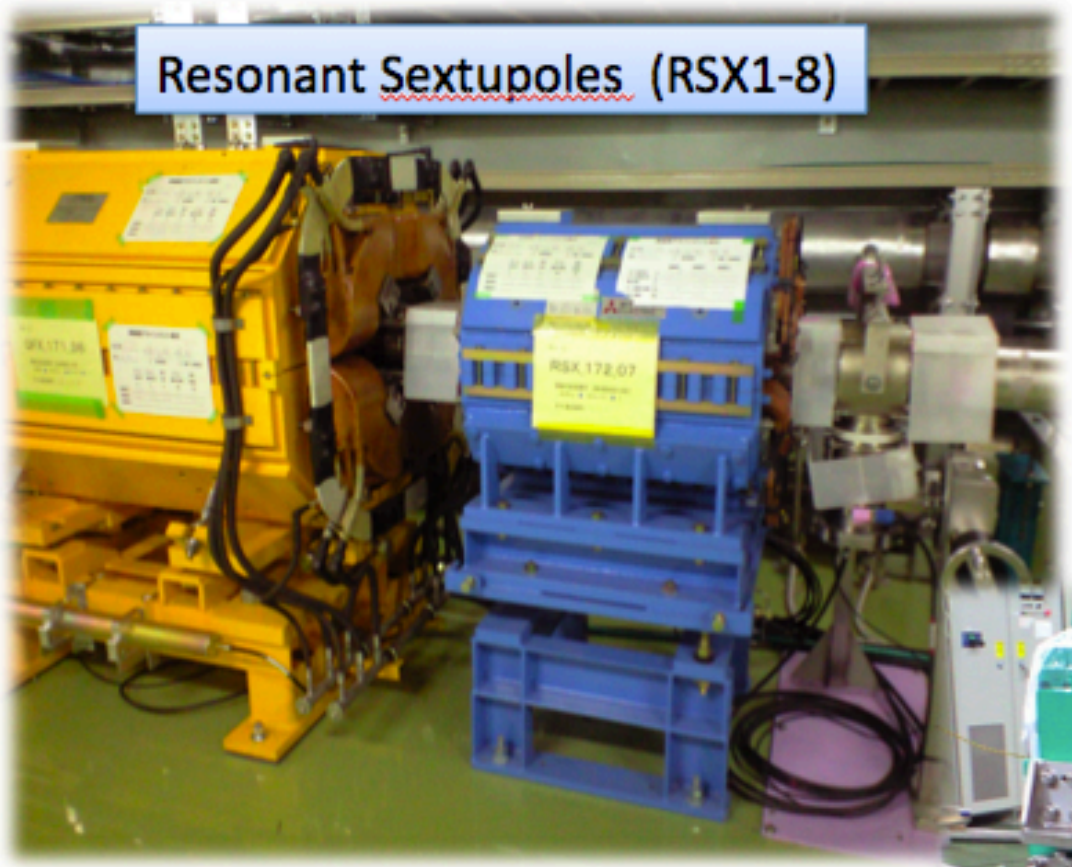


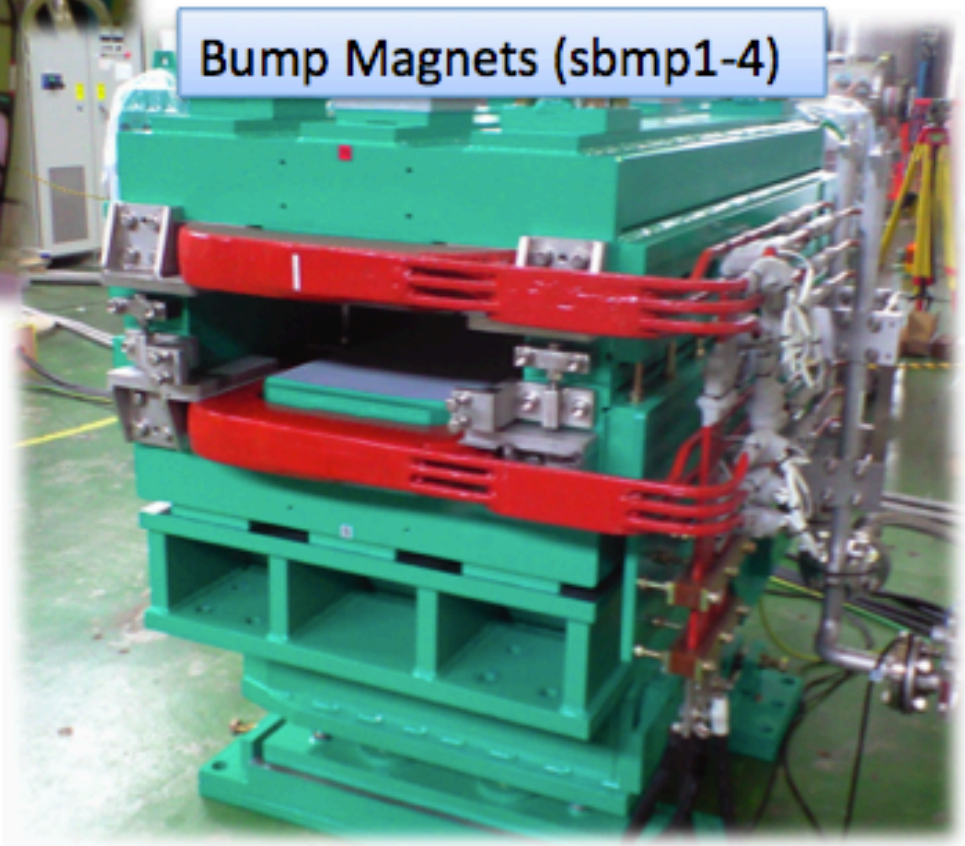
High field magnetic septa (SMS31,32)



High field magnetic septa (SMS33,34)

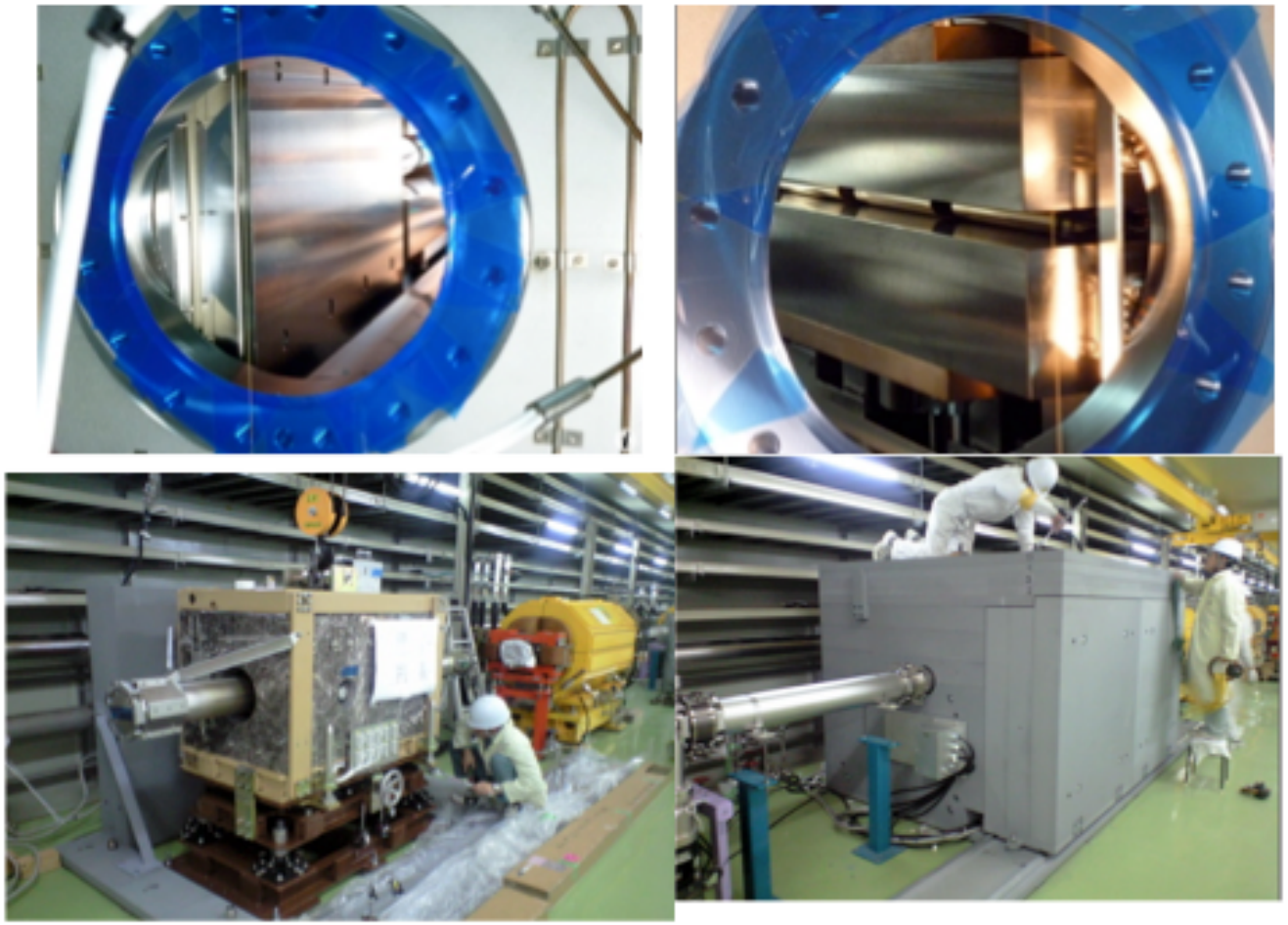



Resonant Sextupoles (RSX1-8)


Bump Magnets (sbmp1-4)

Slow Collimators

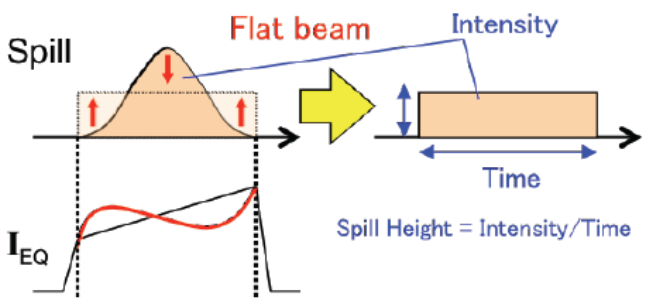
scrape beam hallo produced by hitting on the ESS ribbons

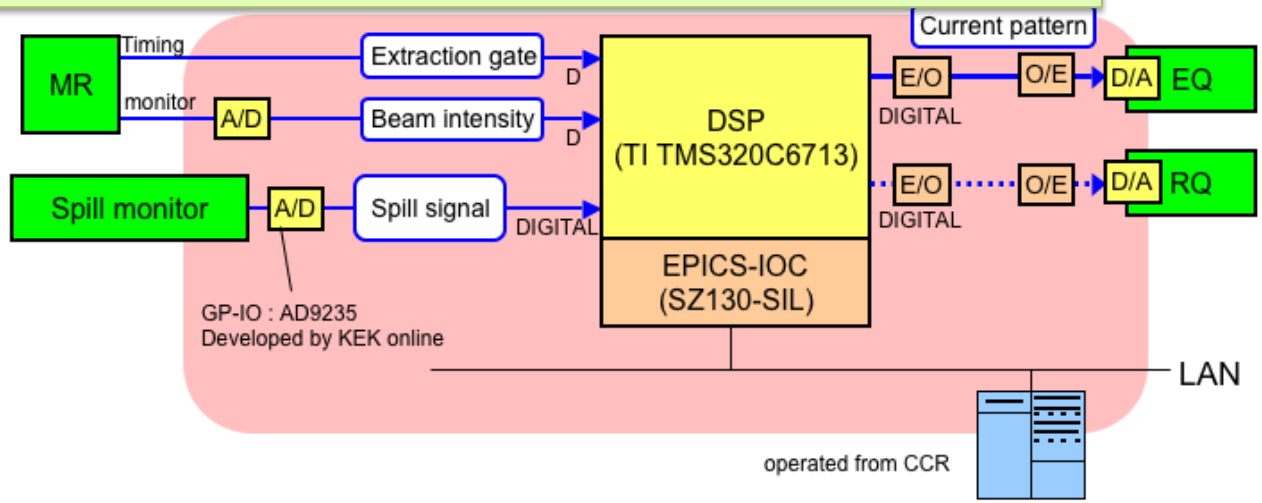


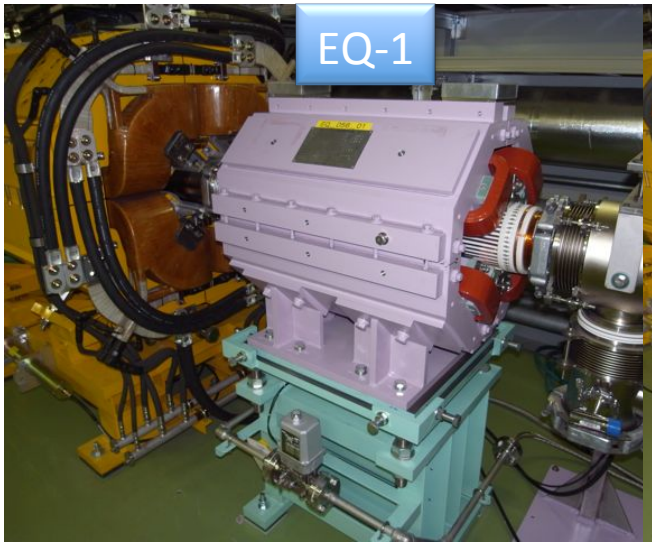
residual radioactivity improvement by SX collimator
900μSv/h -> 150μSv/h @downstream quadrupole duct (on contact, 4hr. cooling)

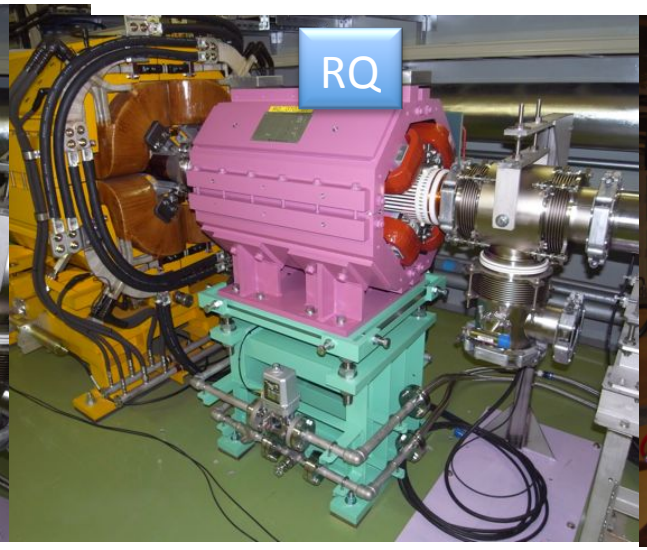
Beam Spill Feedback System

A beam intensity monitor is placed in external beam line.
Uniform beam spill shape is obtained from tune modulation by quadrupoles EQ
Tune ripples are compensated by quadrupole RQ (and EQ)
A DSP processes EQ and RQ current values from the monitor signal



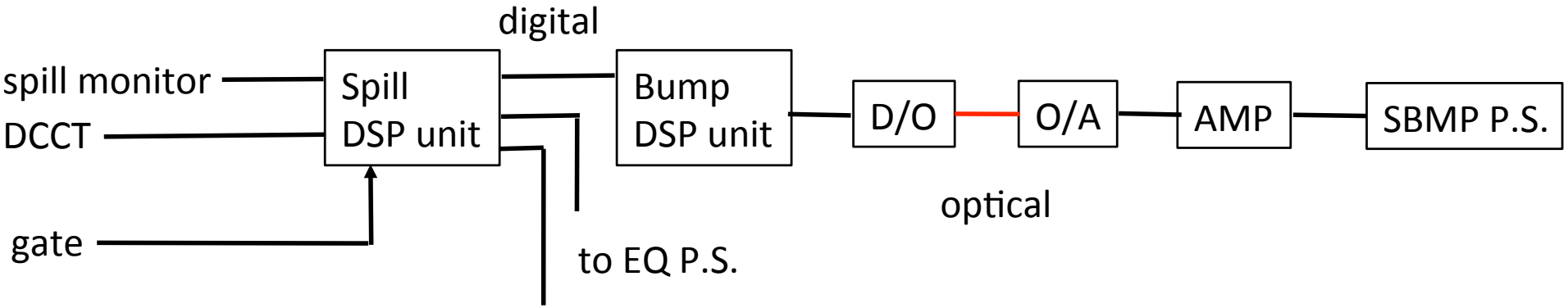




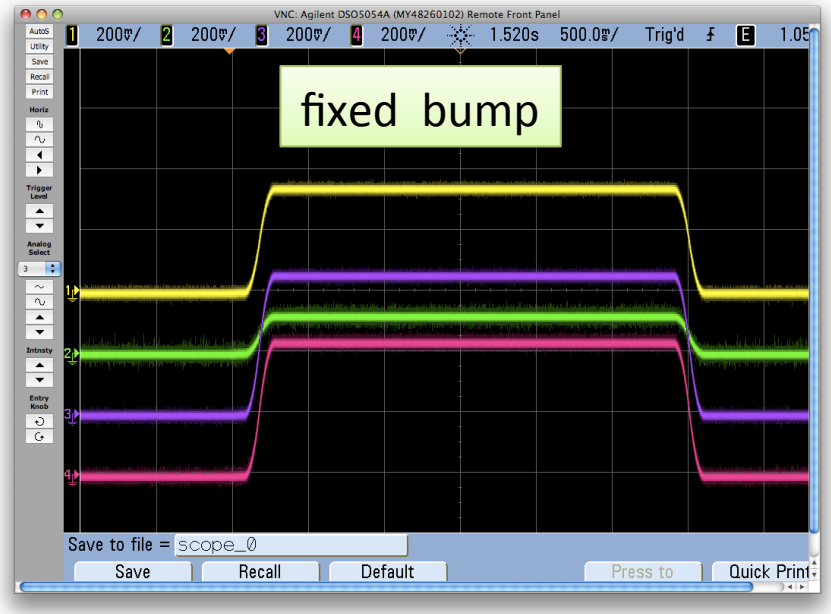


Dynamic Bump System

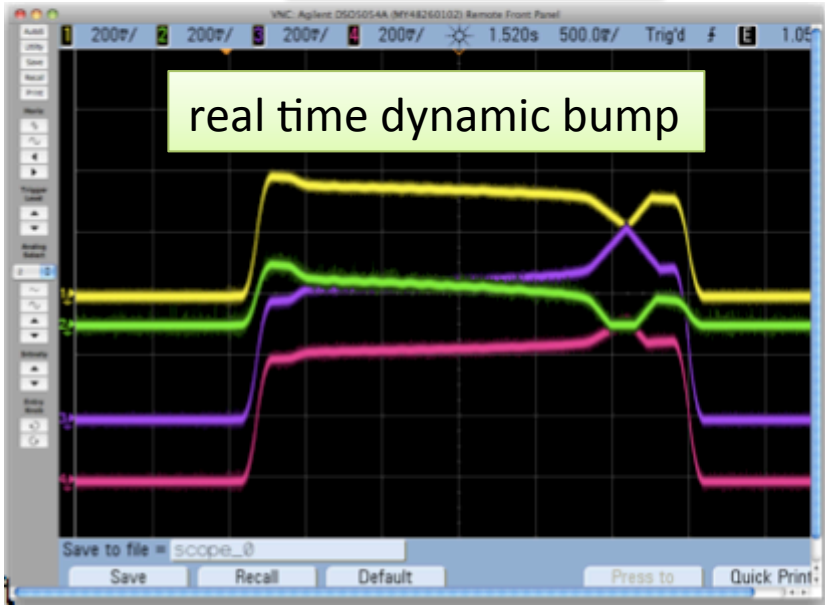
Dynamic bump parameters are processed by a DSP from QFN pattern and real time EQ currents



efficiency 98.3%



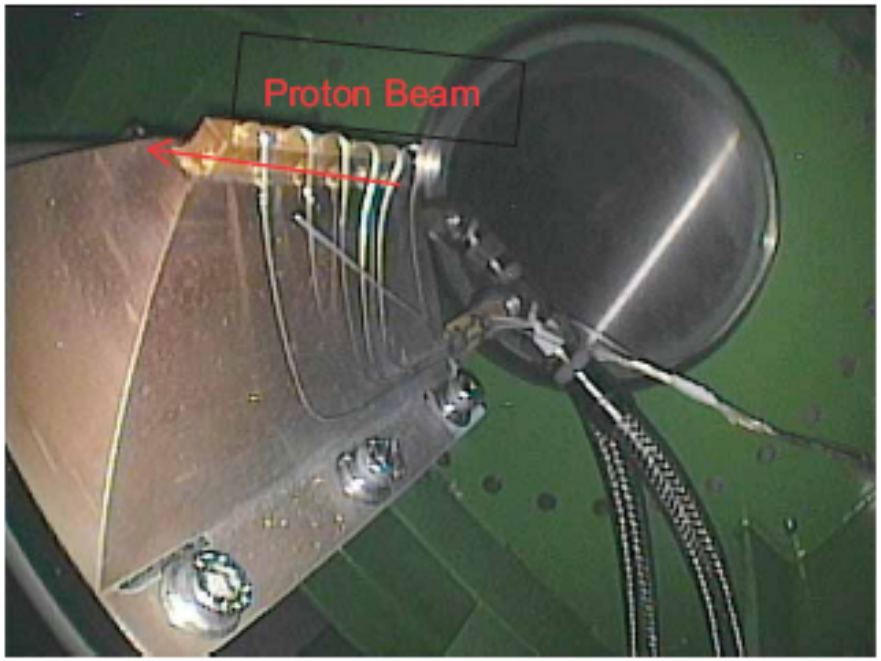
efficiency 99.5%



Radioactive Material Leak Incident at the Hadron Experimental Hall

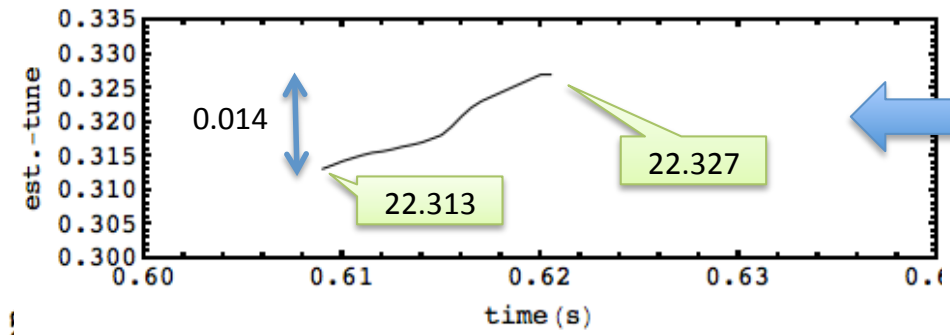
occurred 11:55 a.m. on May 23, 2013.

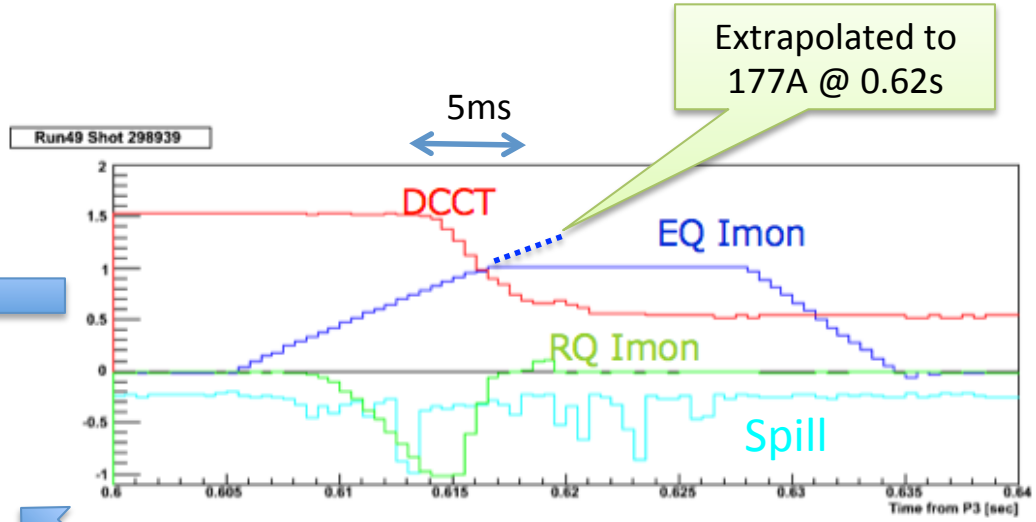
Beam spot of the gold target was melted, evaporated and radioactive materials were leaked outside.
This incident was triggered from a short-pulsed beam by the EQ power supply malfunction.

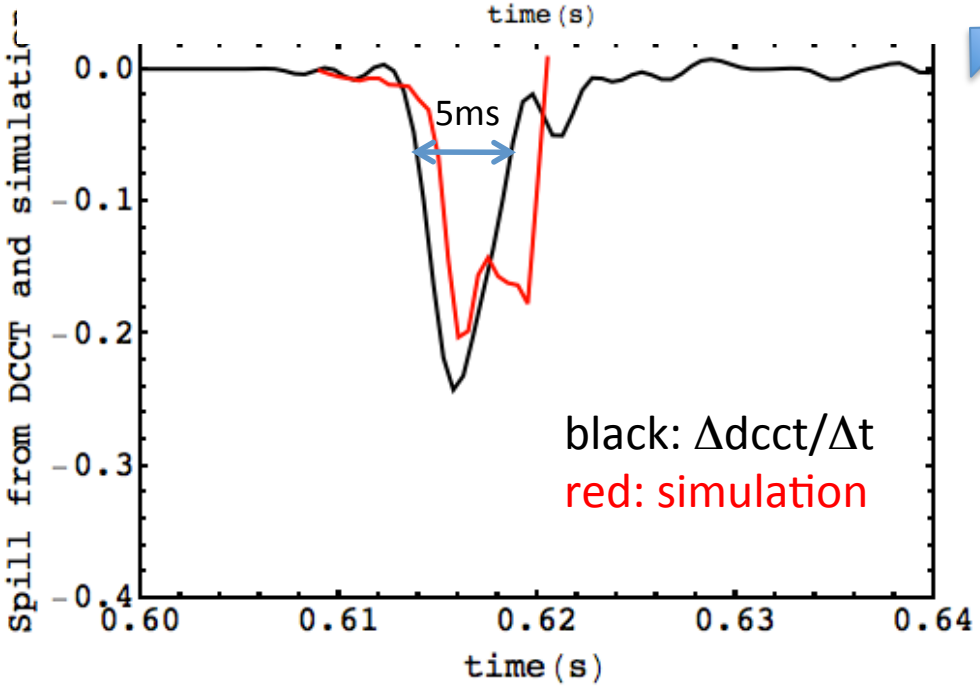


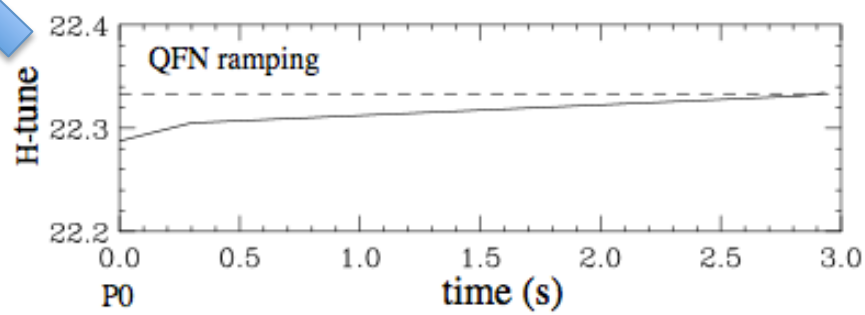
Mulfunction shot analysis

sampling 2KHz







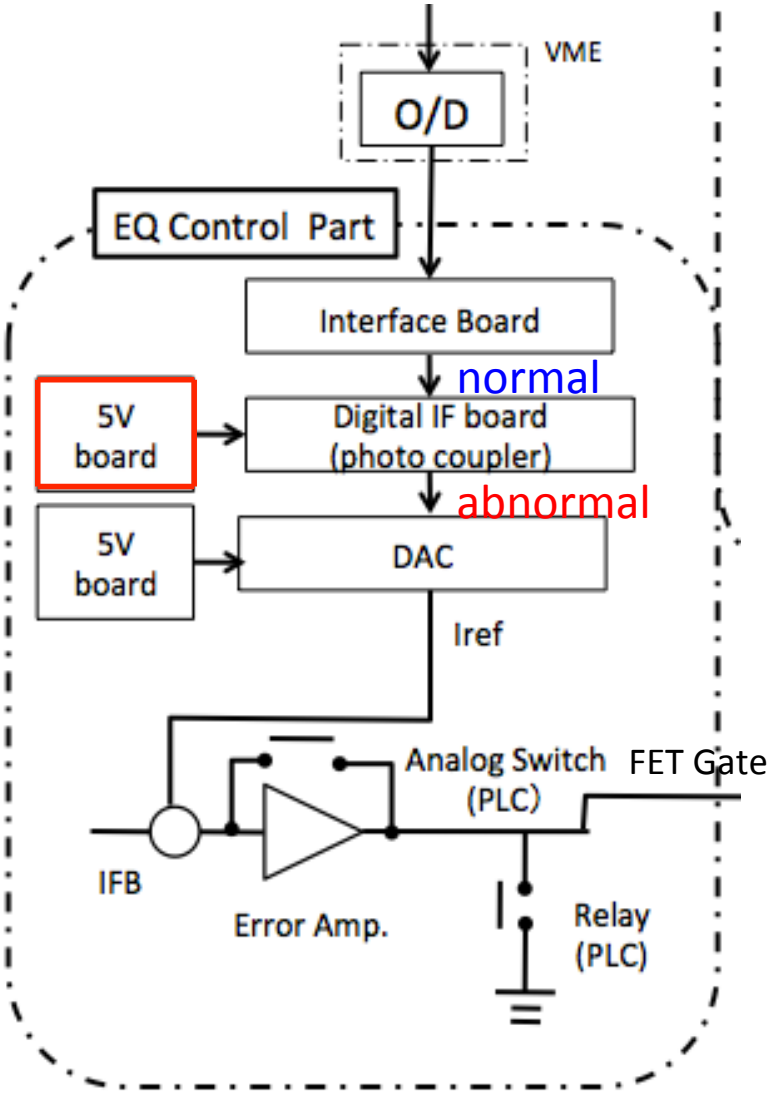


2x10^13 particles were extracted just in 5ms by a rapid tune change to the resonance due to the EQ malfunction
"Fast Slow Extraction "

Cause of Malfunction

To investigate the cause of the malfunction,
the EQ P.S. was continuously operated
at 6 s current pattern
after the accident (June 6 - Aug. 27)

Trips (malfunction) of the EQ P.S.
rarely happened also in the test.
Trips by overvoltage were just
4 of 774600 cycles.

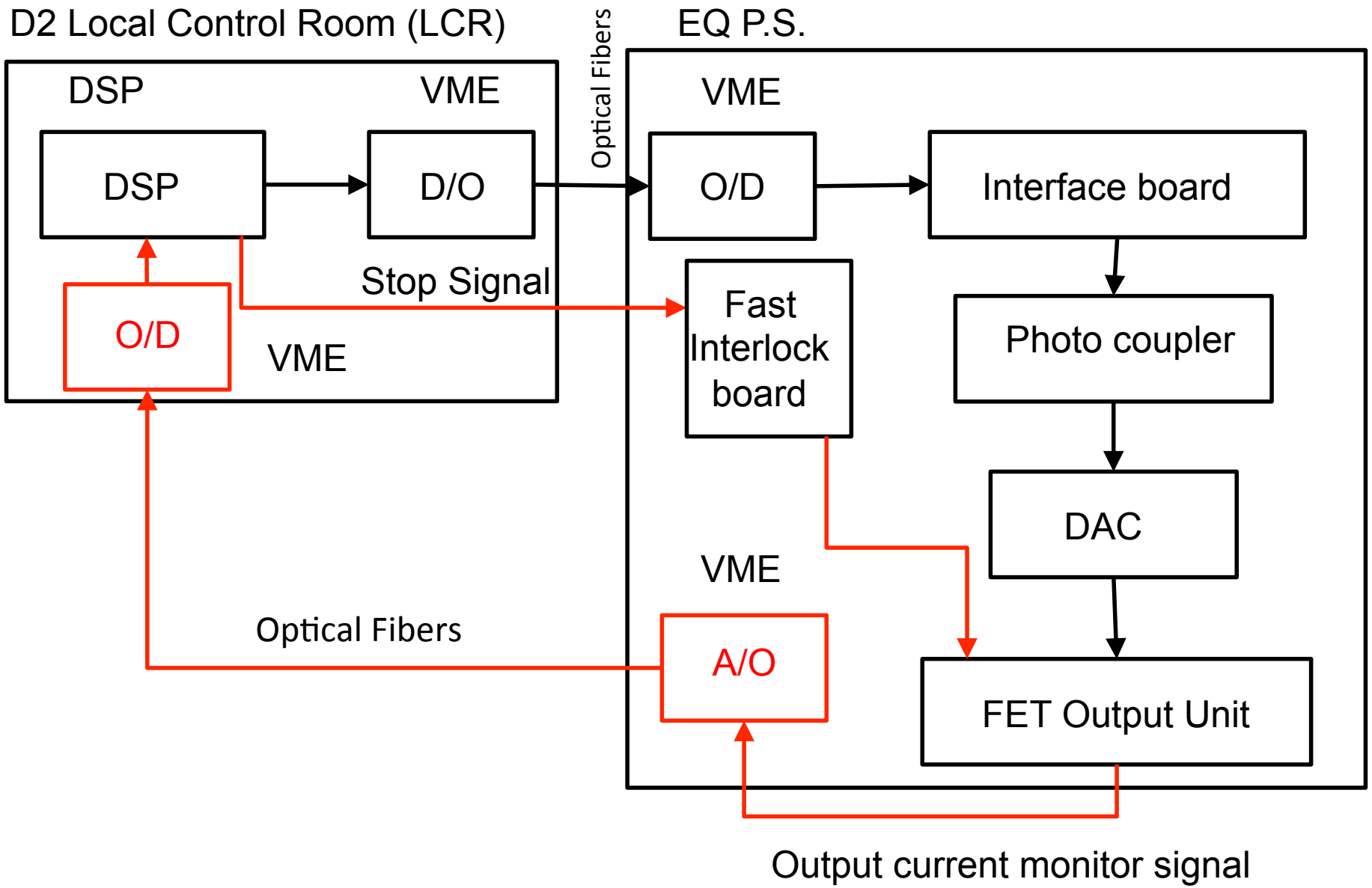


Digital signal transmission
for the EQ current set was unstable

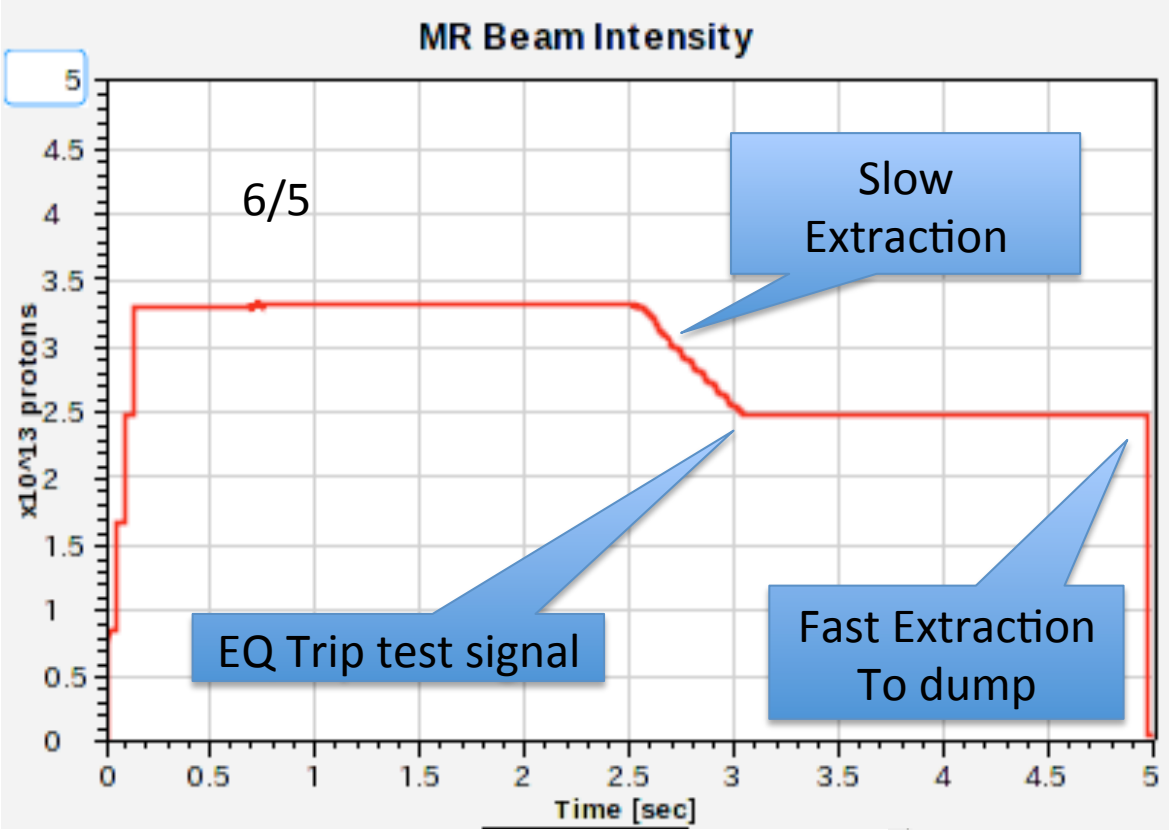
Overheat of the voltage regulator
in the 5V power supply board
-> replaced to a high power type board
with a cooling fin
and a power transistor supporting the electric current

Preventive Measures

- Fast interlock board (～100μs)
- New System to check tracking error between DSP command value and Output Current



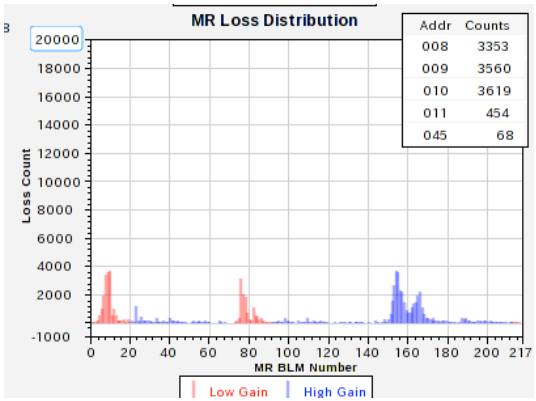
Beam test to stop the slow extraction by EQ trip



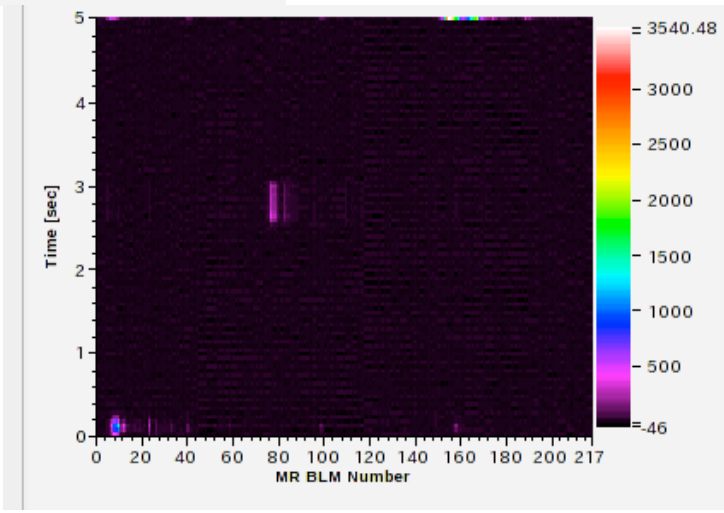
Present MR can not abort beam at any timing

RSX p.s. are turned off
Slow bump currents
are decreased to zero
to keep the closed orbit.

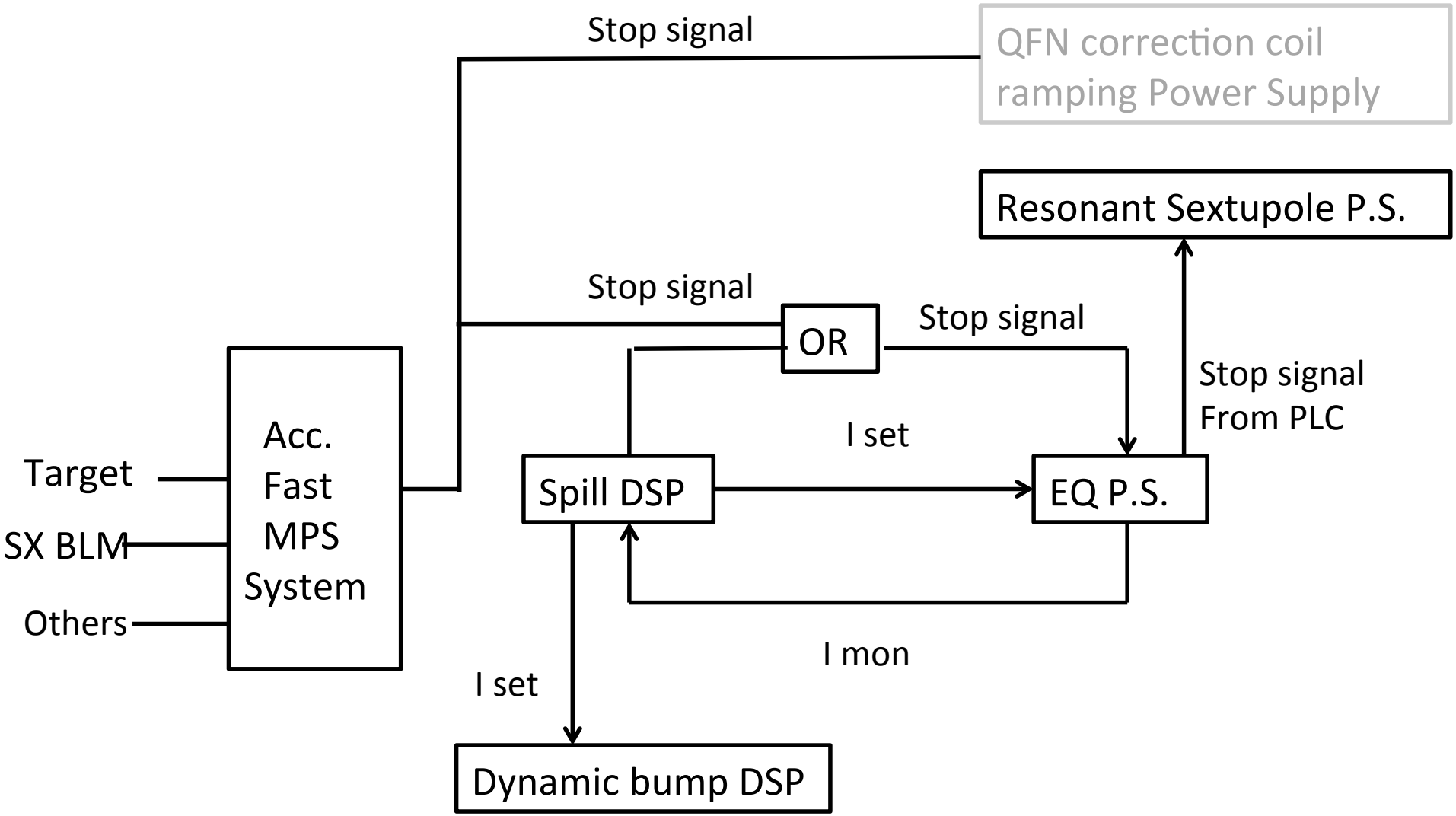
The tune ramping continues.
Beam is partially extracted.



Introduced from2015 6/9 for user operation



From next Fall

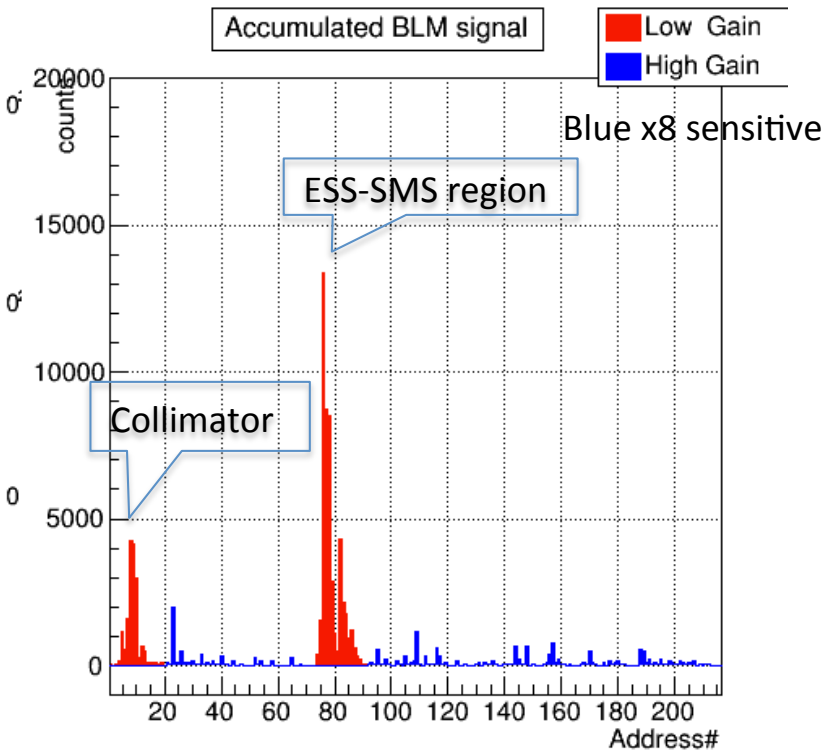


4 magnets currents are proportionally decreased to zero.

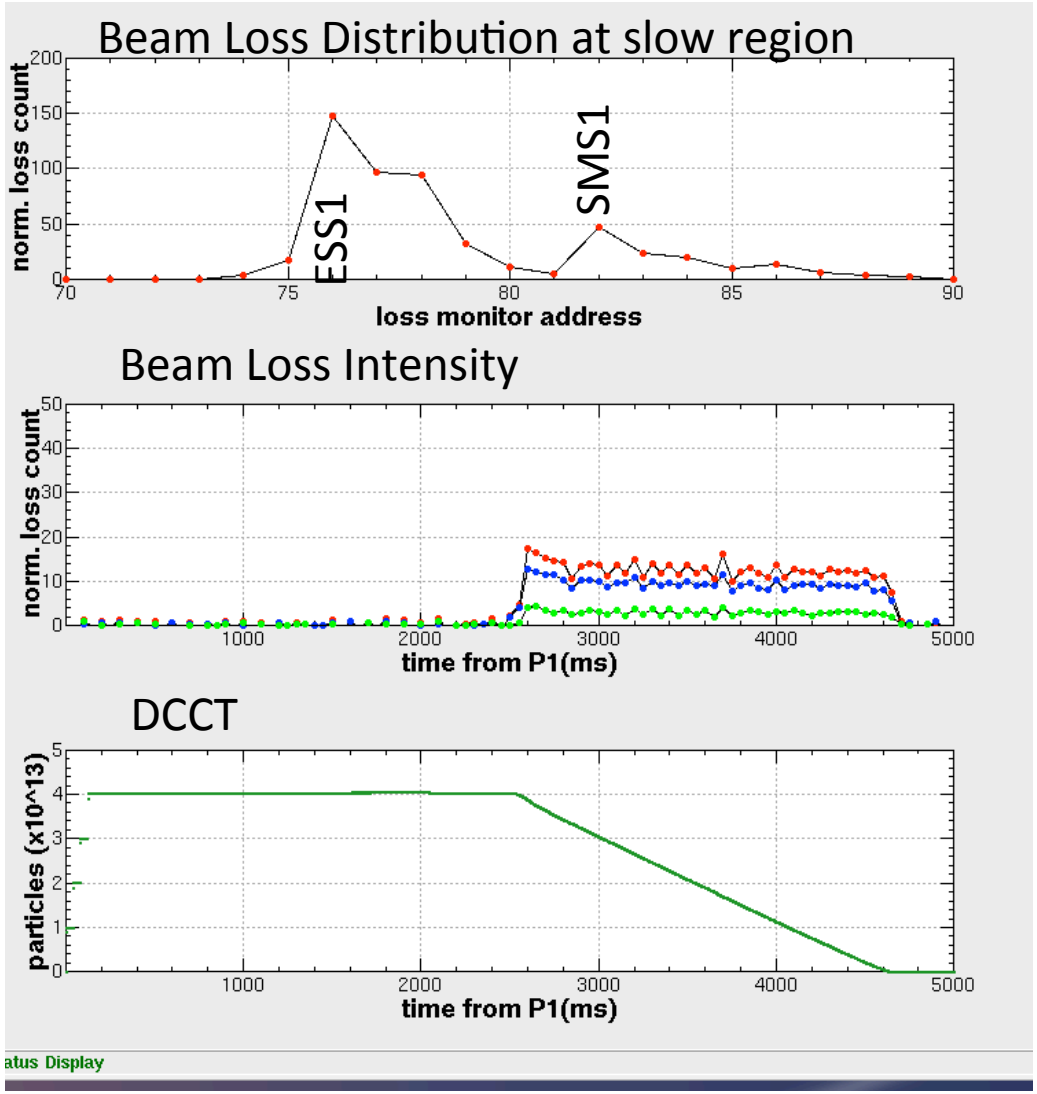
32.4kW 6s cycle (6/16)

Extraction efficiency 99.53% (after dynamic bump tuning)

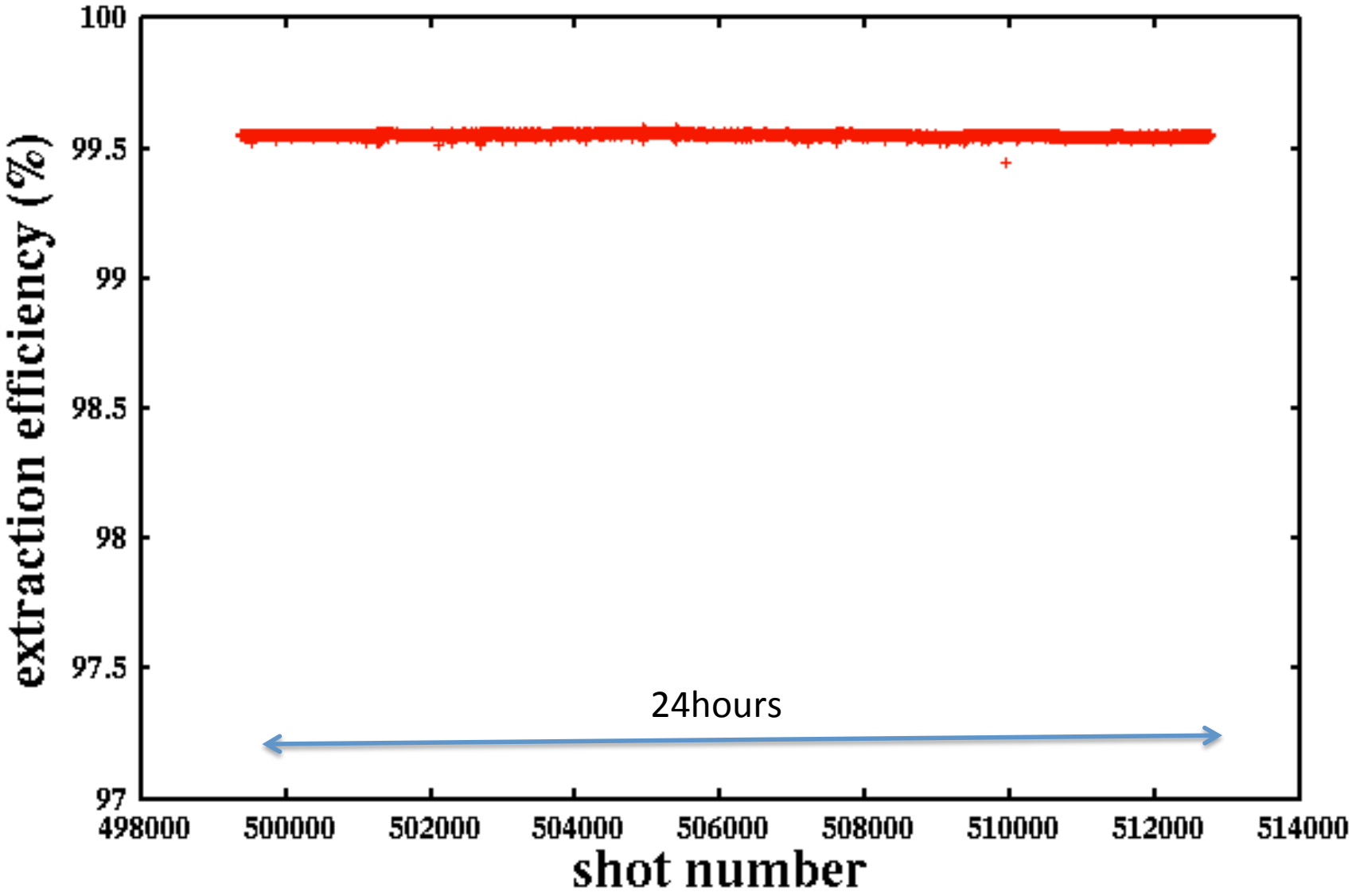
duty 37%



Beam loss distribution
(whole ring)

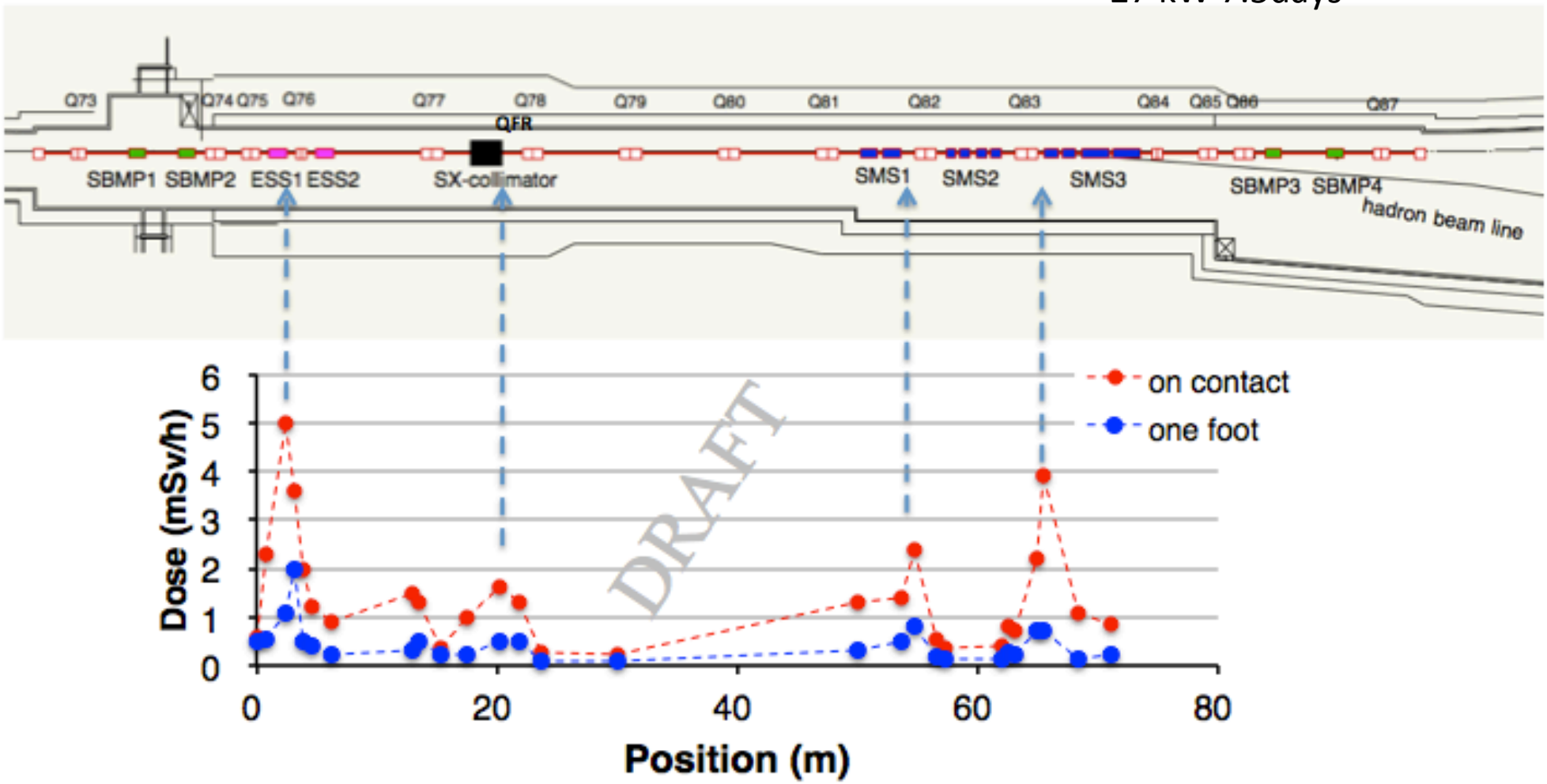


33.3kW (4.1×10^{13}ppp) Extraction Efficiency

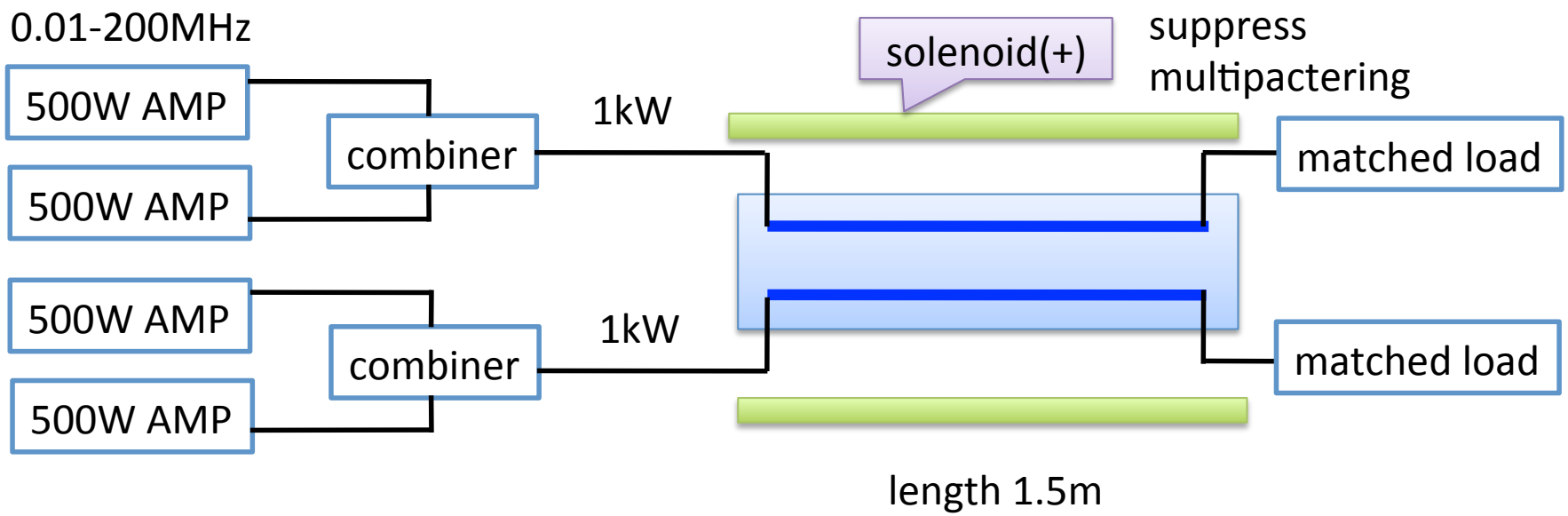


Residual radioactivity at 4 hours cooling after 27 kW beam operation

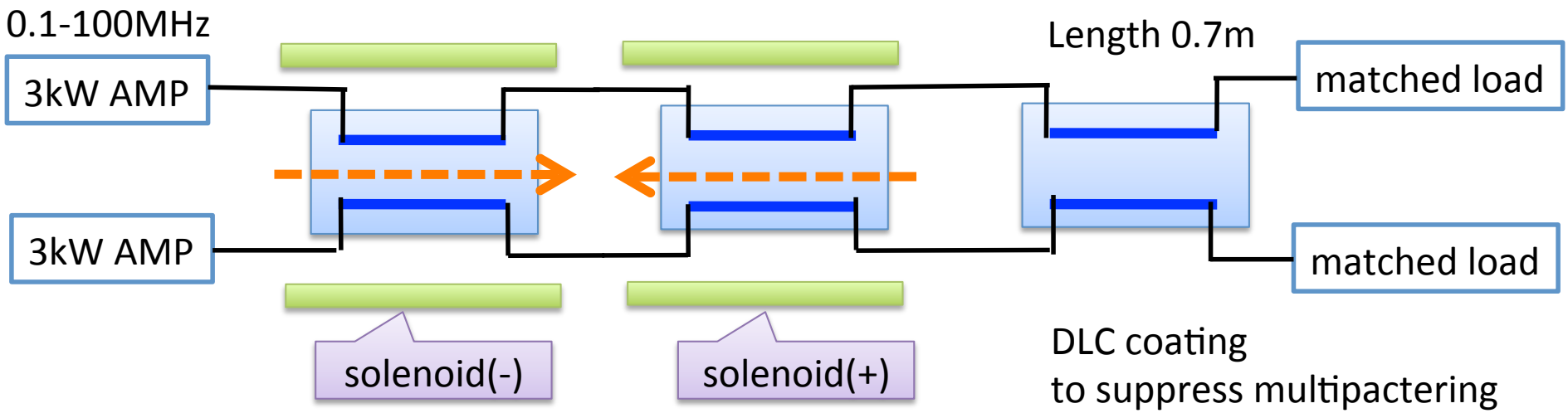
24kW 5.5days
27 kW 7.5days



Exciter System (strip line kicker)



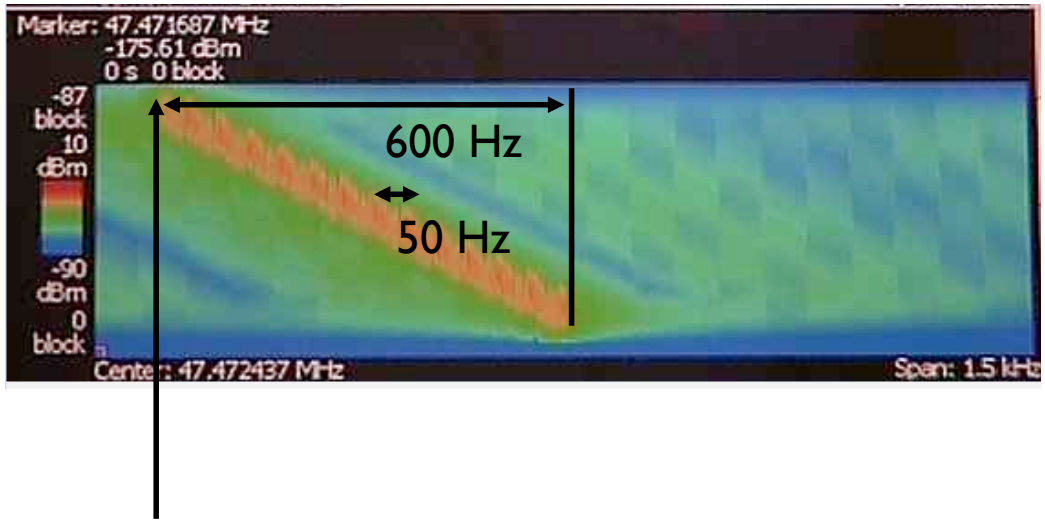
Transverse RF System (strip line kickers in series)



H-exciter

mixing

H-Transverse RF



47.47169057MHz

frev=0.191167307692307MHz

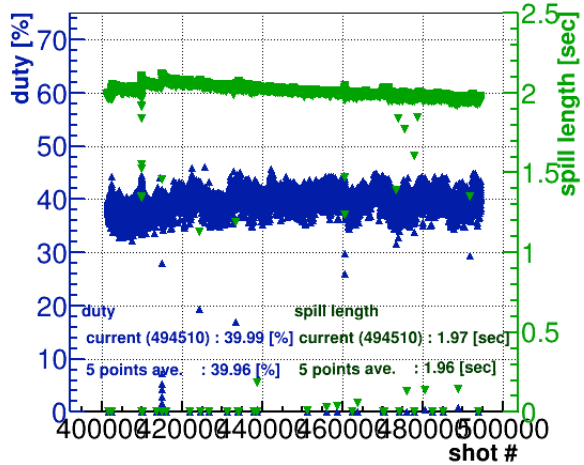
2015.6.8 tuning

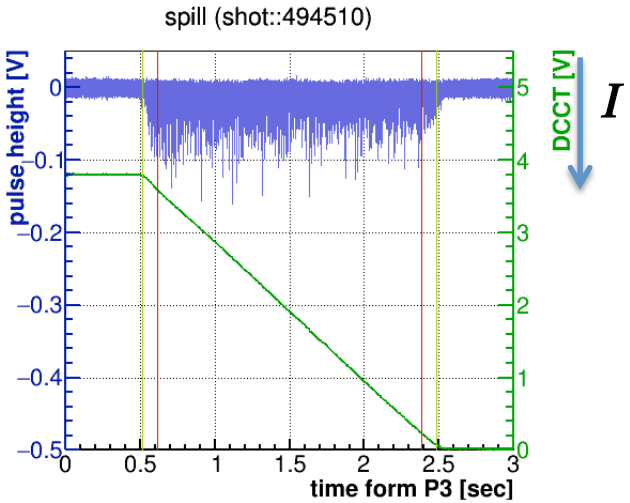
33kW Beam Spill (6/25)

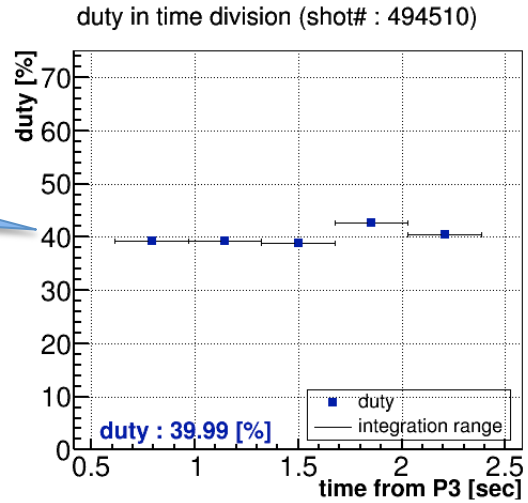
$$Spill\,Duty\,Factor = \left[\int_0^T I(t)dt\right]^2 \Big/ \left[\int_0^T dt \cdot \int_0^T I^2(t)dt\right]$$

ideal spill -> 100%

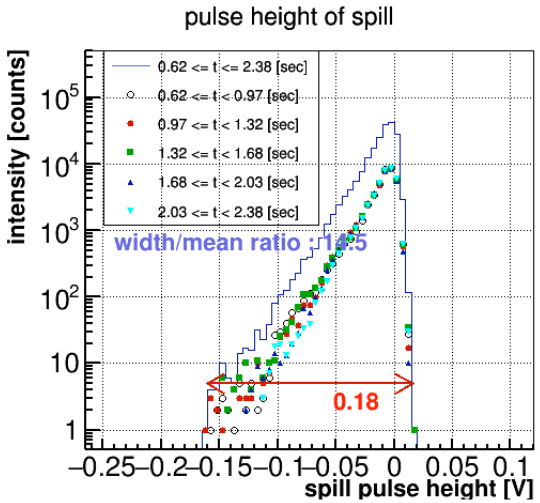
I(t): PM signal sampled at 100KHz through 10KHz LPF







Duty=40%



Beam Intensity dependent phenomena

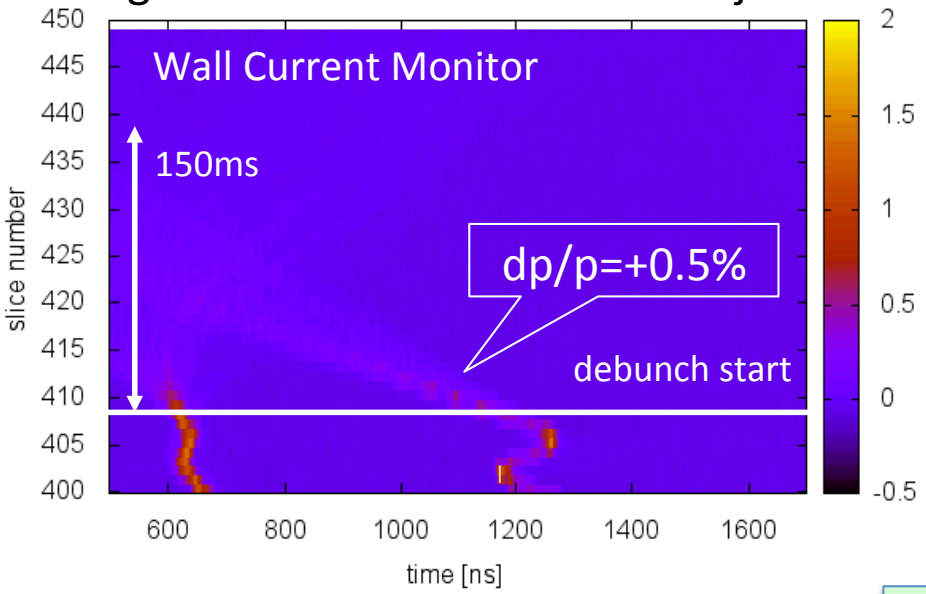
- Injection period and beginning of acceleration
  transverse instability
  present cures -> tune and chromaticity adjust and BxB F.B.

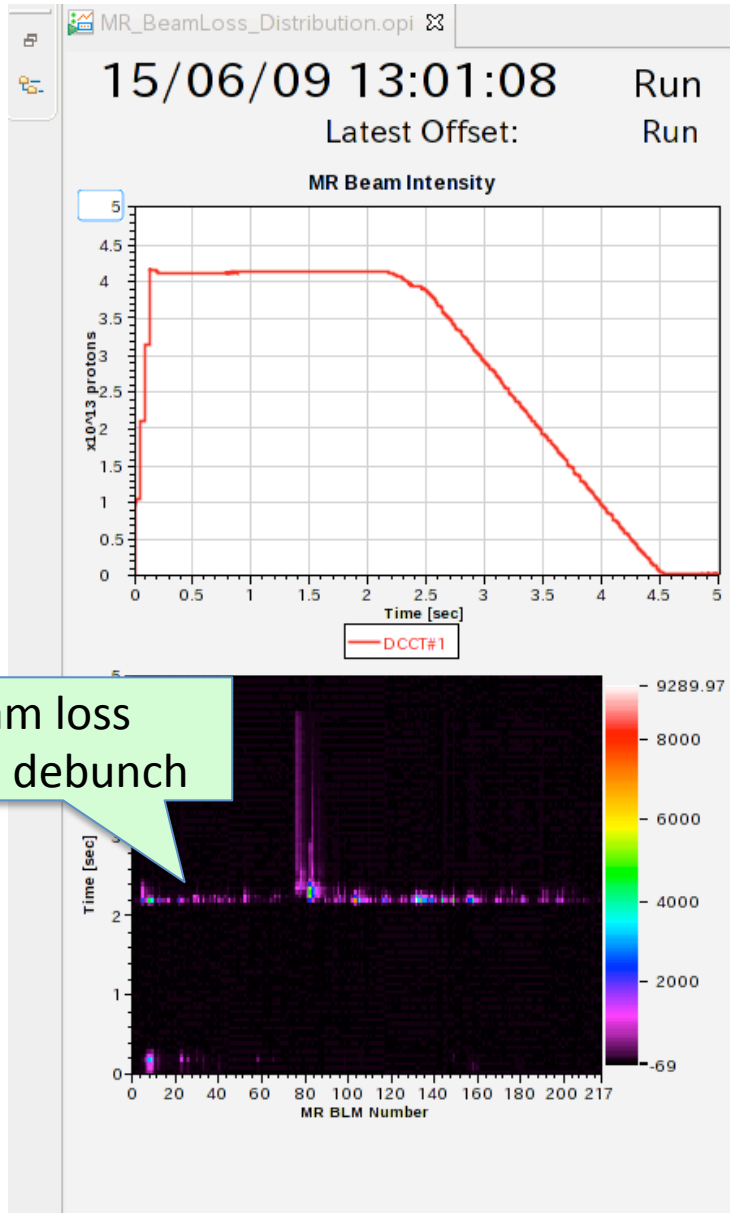
- different dipole oscillation of each bunch at before debunch
  present cure -> RF phase adjustment for the injected beam
  (dipole oscillation is effective?)

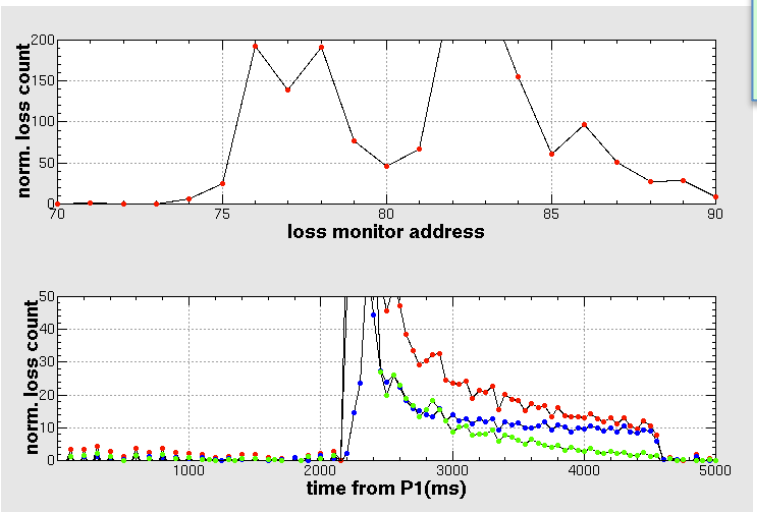
Debunch process
- vacuum pressure rise in the whole ring (any time)
- electron cloud (any time)
- beam loss in the whole ring occurred (commissioning)
  related with dipole oscillation?

Beam loss in the whole ring during debunch

6/9
33.1kW
Efficiency 97.14%
global offset -88° （before adjustment）







Beam loss during debunch

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

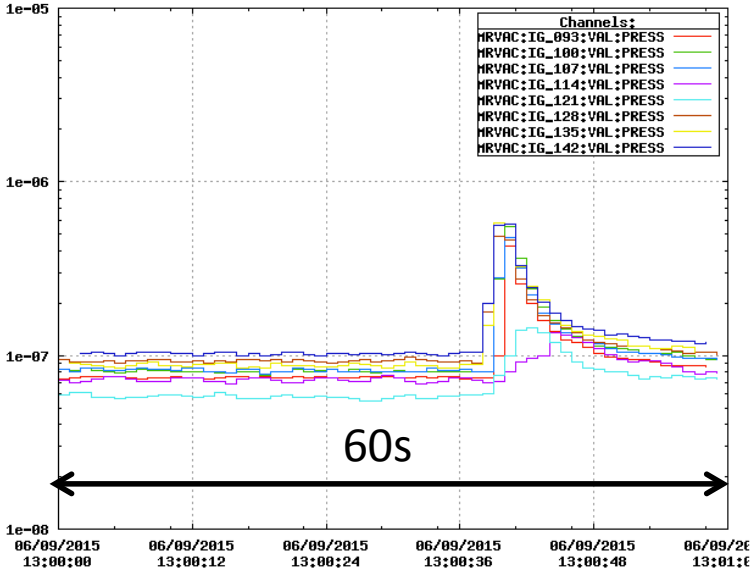
Electron cloud monitor

200ms

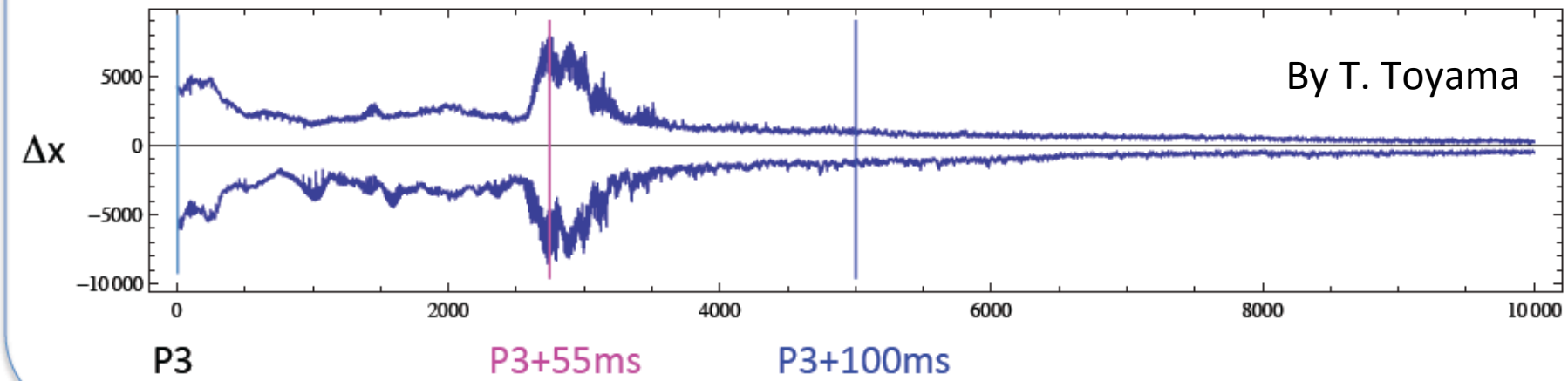
Flat top start(P3)

By T. Toyama

Vacuum (ARC-B)



Peak of the horizontal oscillation



By T. Toyama

Plans for higher beam power

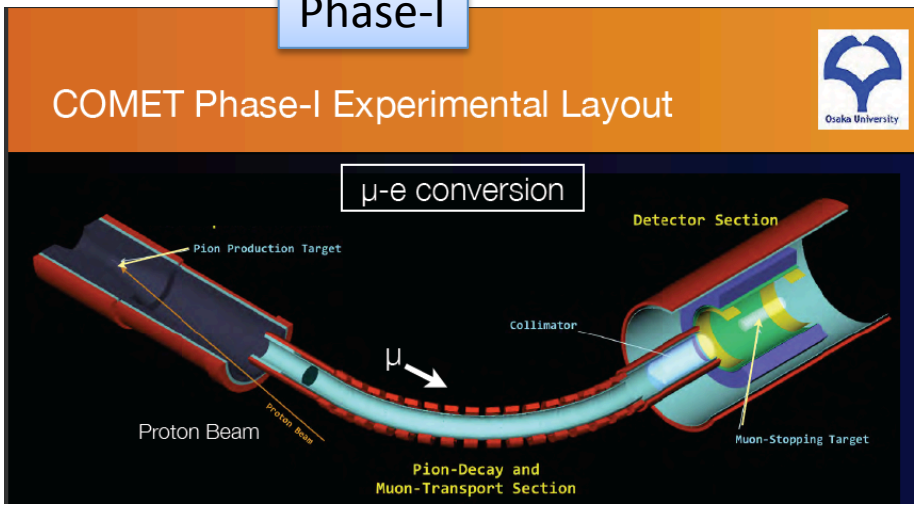
- intra-bunch F.B.
  --- the instability at the beginning of the acceleration
- Further beam loading compensation tuning of RF
  --- dipole oscillation different for the bunches
- 2nd harmonic cavities
- longitudinal VHF cavity (2 years later?)
  large dp/p (lower peak current)
  --- longitudinal instability
- lower chromaticity correction during debunch
  ---transverse instability during debunch

◎Repetition rate up for a higher beam power (～100kW)
6s -> 3.5s and 7×10^{13} ppp (under discussion)

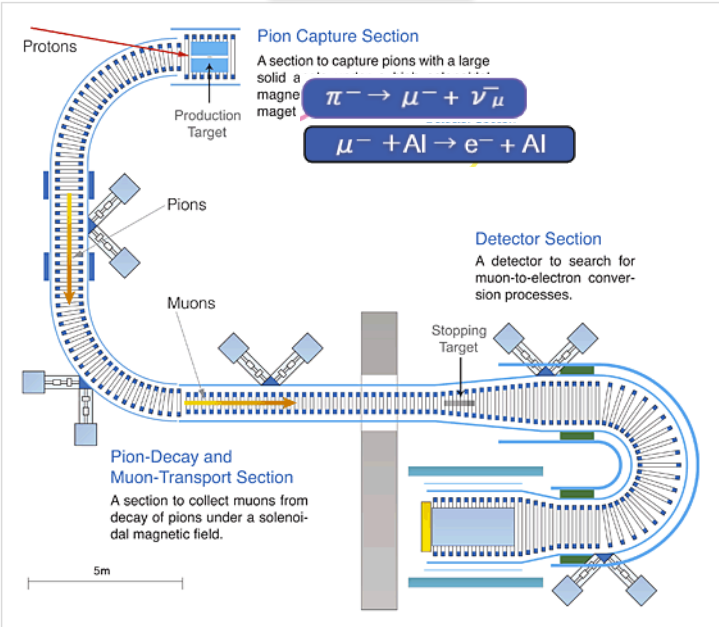
COMET

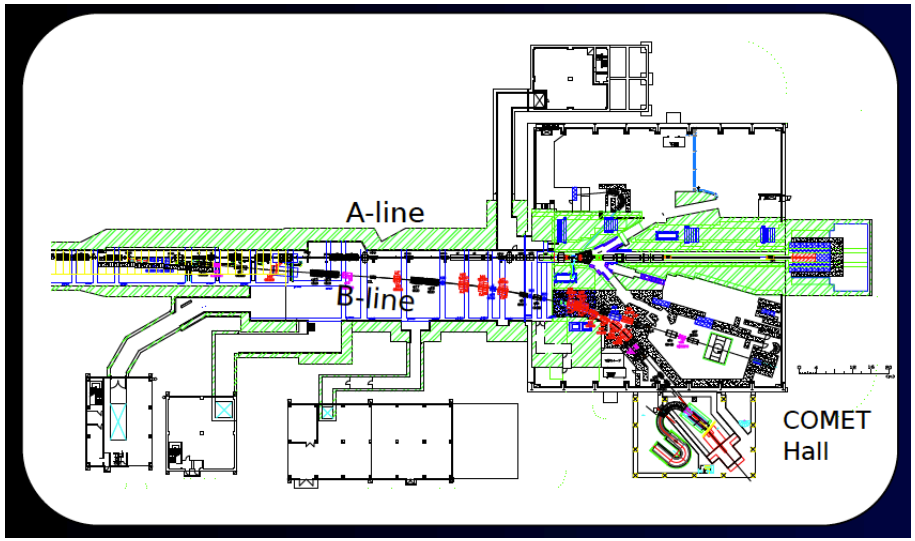
(COherent Muon to Electron Transition)

Phase-I



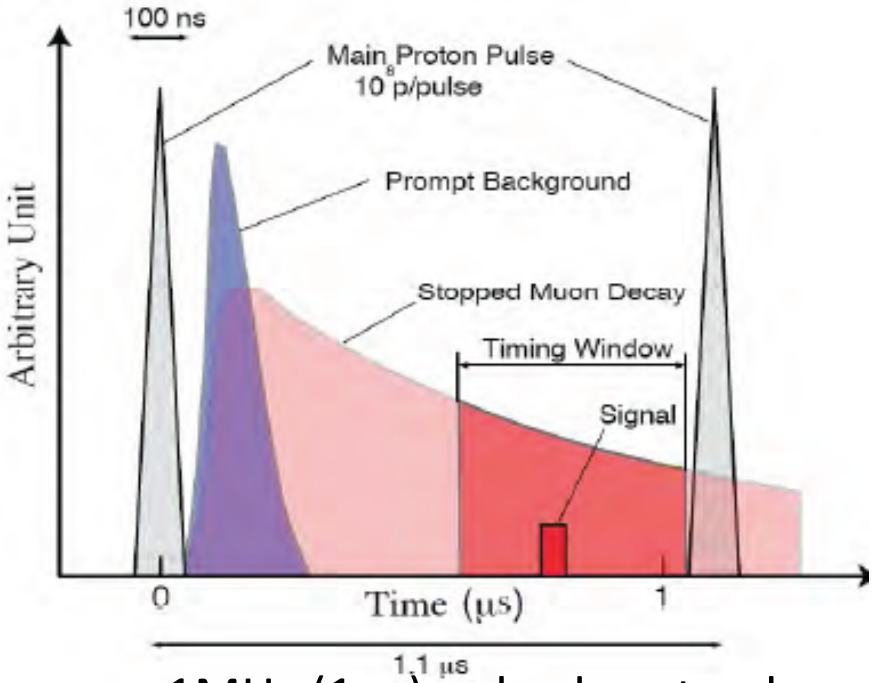
Phase-II





COMET beam line and building are under construction in the Hadron Facility

Pulsed Proton Beam



Prompt Background Example

Radiative pion capture

$\pi^- + (A,Z) \rightarrow (AZ\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1), \gamma \rightarrow e^+e^-$

Muon decay in flight

$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Pion decay in flight

$\pi^- \rightarrow e^- + \bar{\nu}_e$

1MHz (1μs) pulsed proton beam

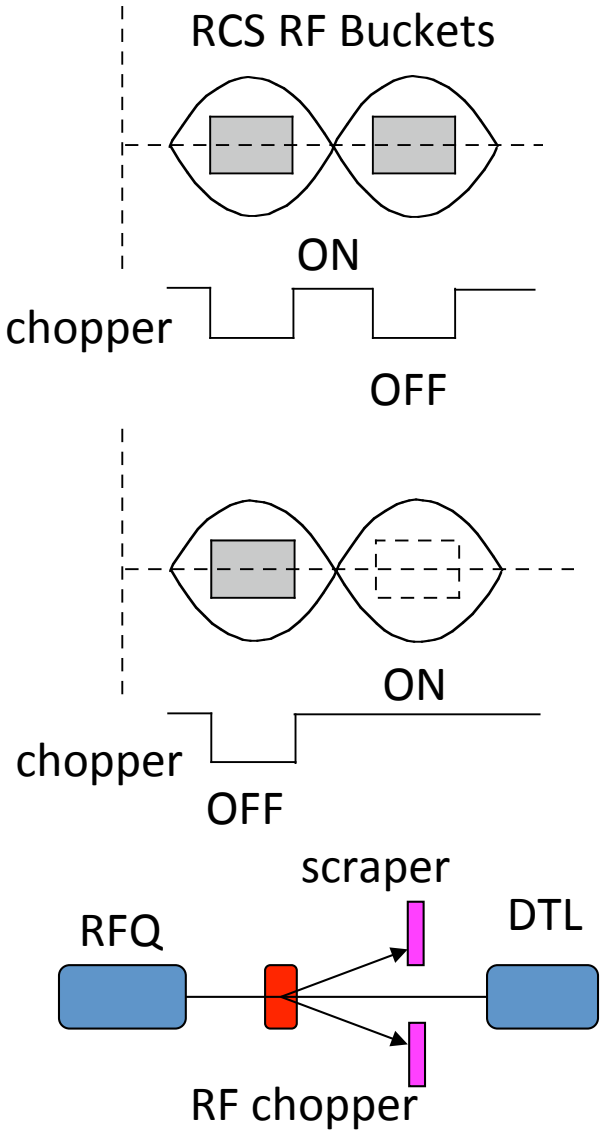
Very low background beam between two beam bunches

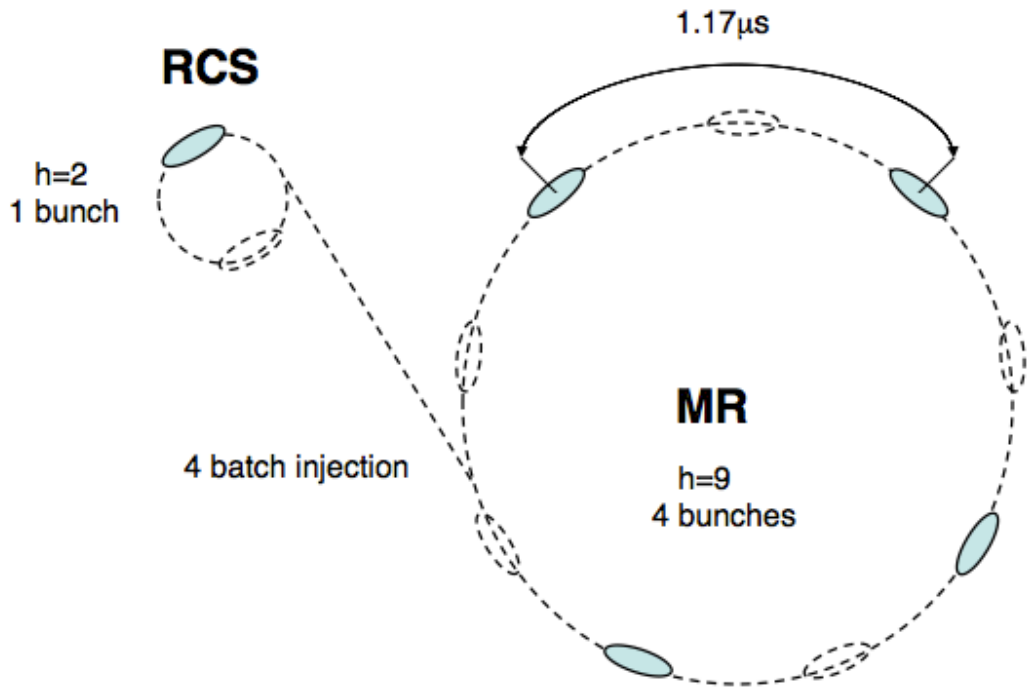
Extinction: Intensity ratio of background beam and bunched beam

$\sim 10^{-9}$

Proton beam energy is 8 GeV (untiproton background)

1MHz Pulsed Beam Scheme





Bunched Slow Extraction at 8 GeV

Requirements

Phase-I

- 3.2 kW at 8 GeV
- sensitivity (SES) 3×10^{-15}
- running time 110days
- will start from FY 2017

Phase-II

- 56 kW at 8 GeV
- sensitivity (SES) 2.6×10^{-17}
- running time 2×10^{7} s (232days)
- will start from 2019-2020

Solutions for beam size Issue

ε(30GeV) /ε(3GeV) = 0.124 ε(8GeV) /ε(3GeV) = 0.430

Strategy

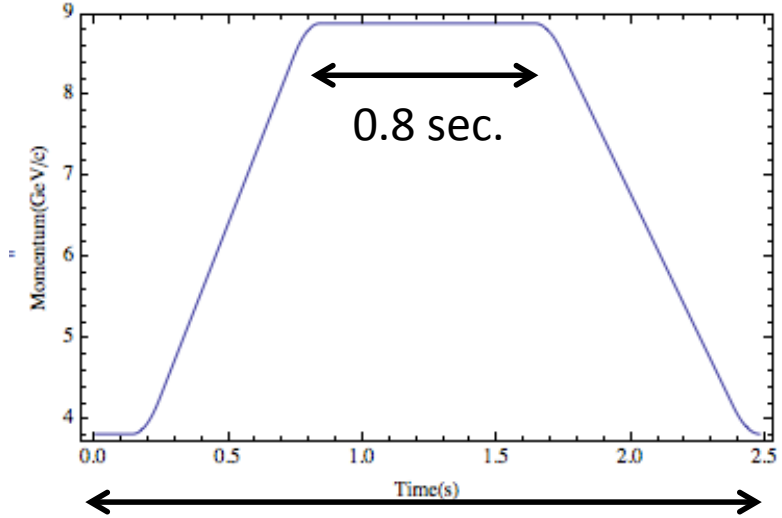
- reduce beam size (Phase-I)
- enlarge apertures of magnetic septa and QDT (Phase-II)

Particle number in phase-I is moderate
Space charge effect is not so serious for RCS and MR

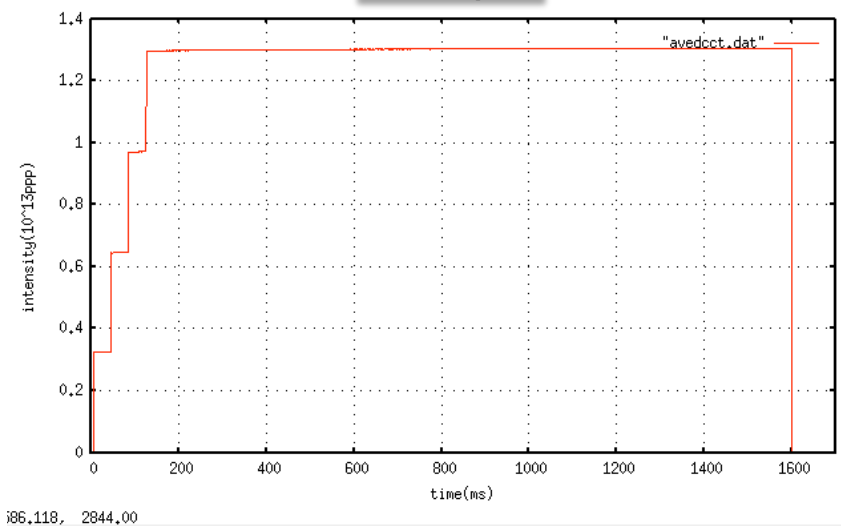
Transverse beam painting area in RCS injection
can be reduced than the ordinary high intensity one.

Emittance growth could be suppressed
for RCS and MR by careful tunings.

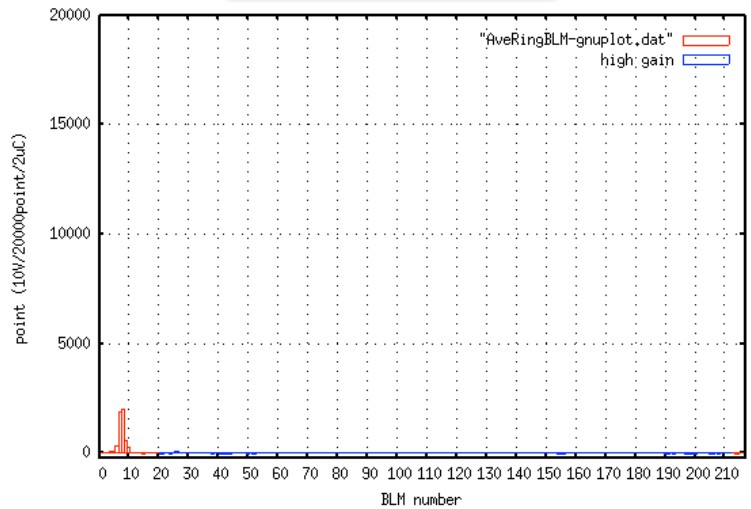
8 GeV Acceleration Test for Phase-I (Fast Extraction)



DCCT



Beam Loss

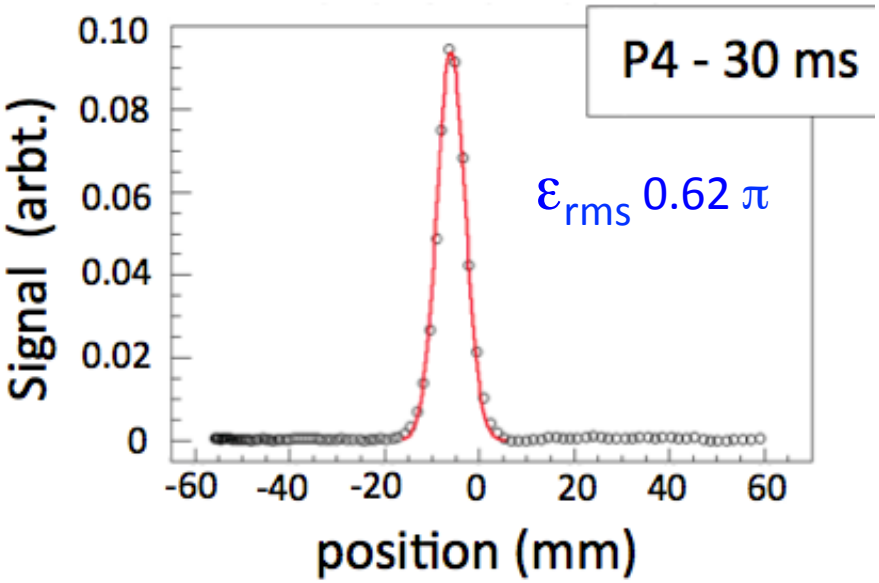


In an acceleration test (w/o slow extraction) beam was successfully accelerated to 8 GeV.

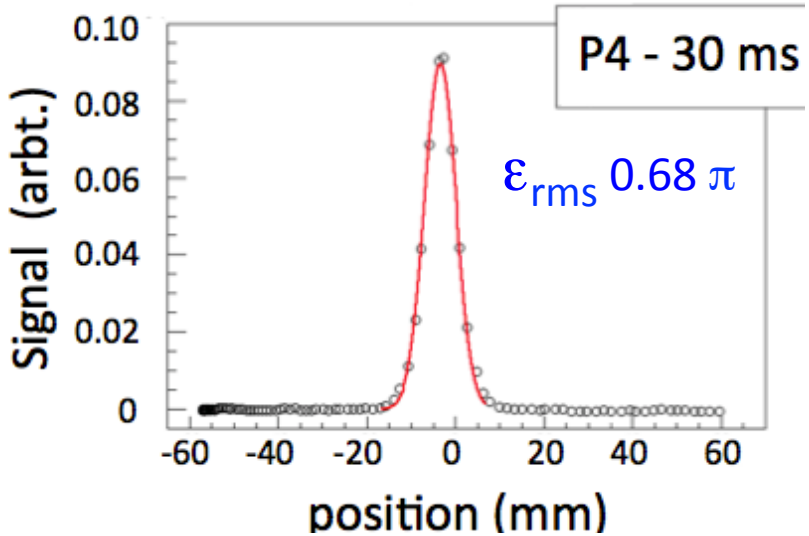
Measured Profile Summary

Emittances obtained from Ideal β functions at (22.29,20.78) by SAD

Horizontal



Vertical



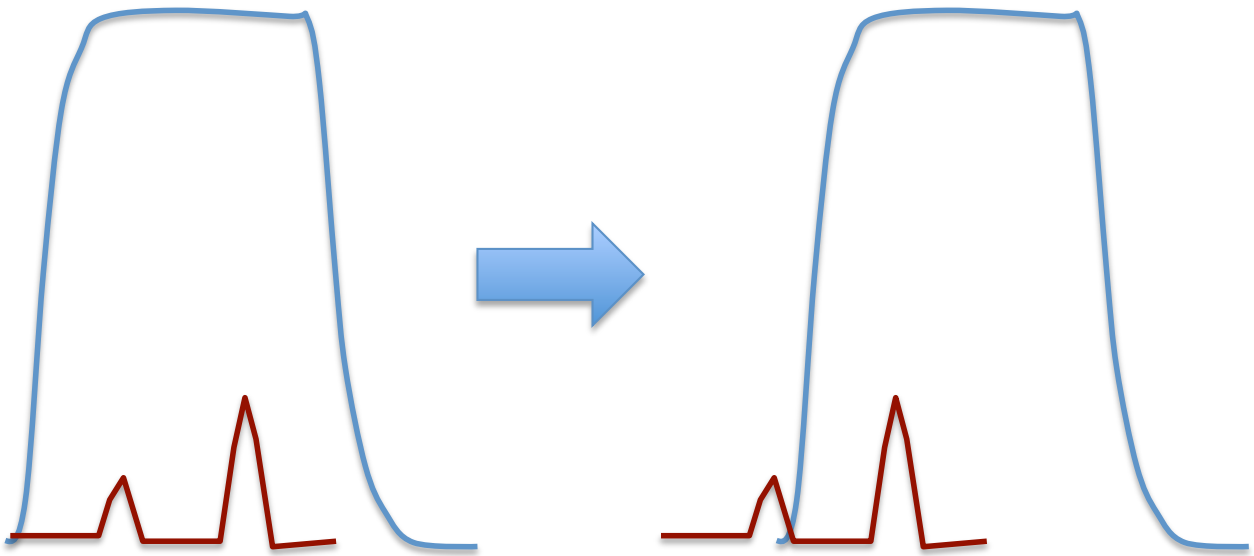
Measured rms-emittance at 8 GeV is small and near vertical one of 0.78 π measured in hadron beam line for 30 GeV slow extraction,

which suggests the present magnets can accept 8 GeV phase-I beam.

Extinction Improvement

ordinary kicker wave

delayed kicker wave



measured extinction O(10^{-7}) w/o slow

Improve extinction

MR Injection kicker delay Idea by **F. Tamura**

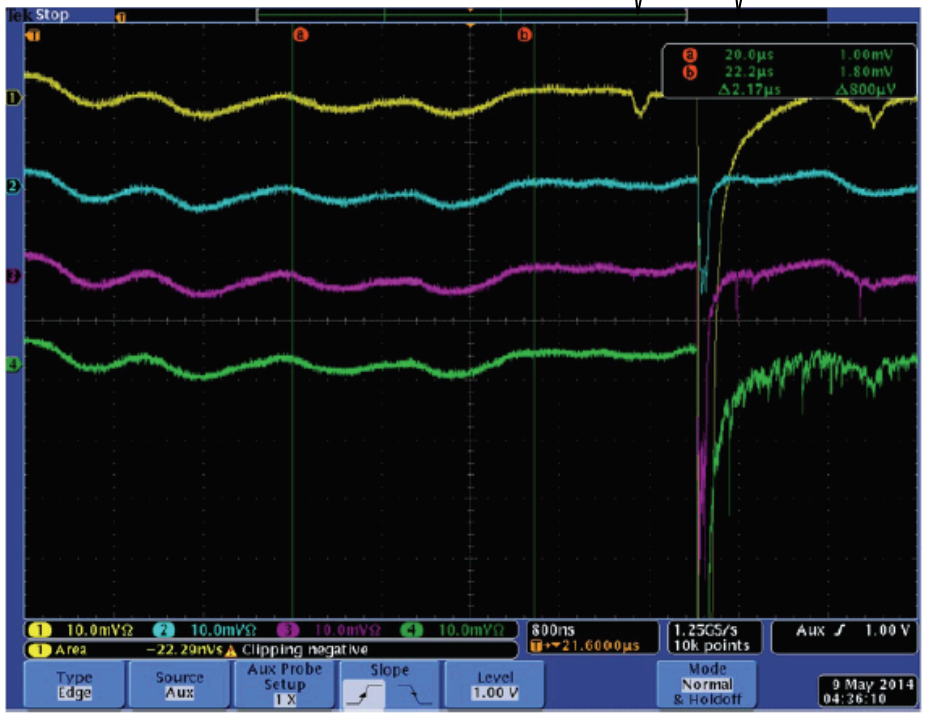
Extinction for fast-extracted beam at 8GeV

by a monitor in the abort beam line

Kicker no delay

7 th bunch

8 th bunch

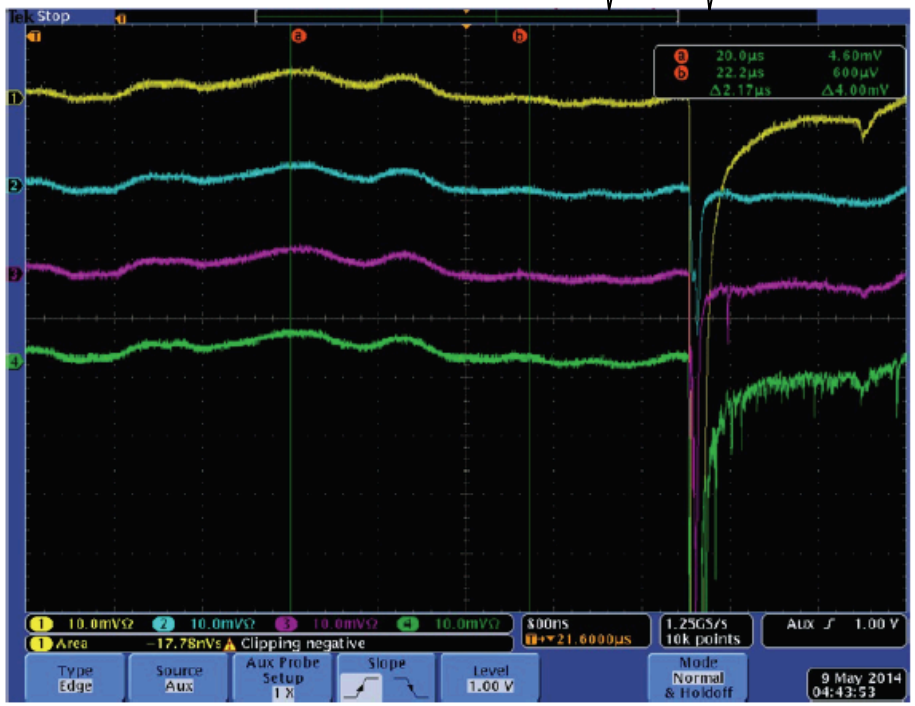


shot# 1354

Kicker 598ns delay

7 th bunch

8 th bunch

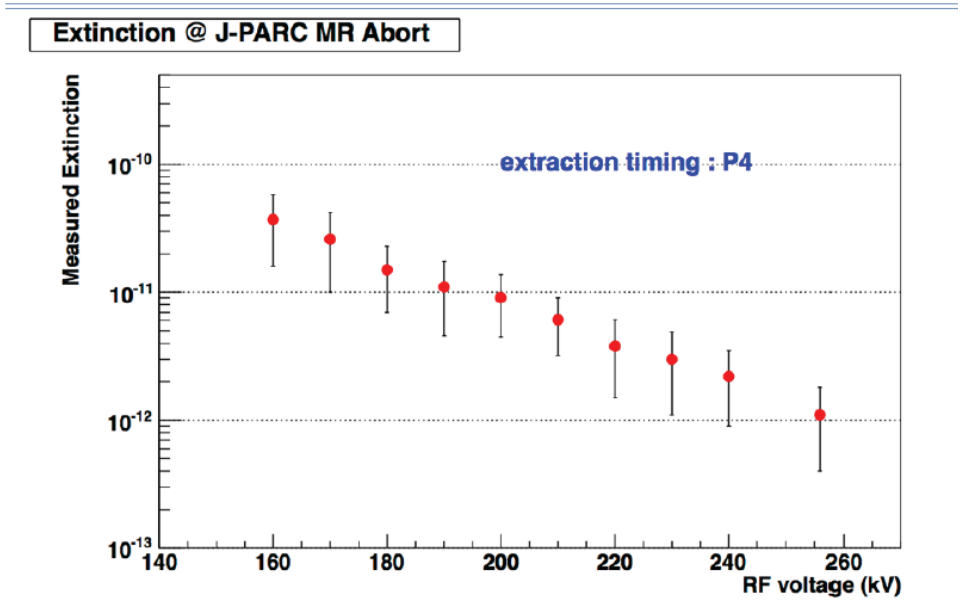


shot# 1355

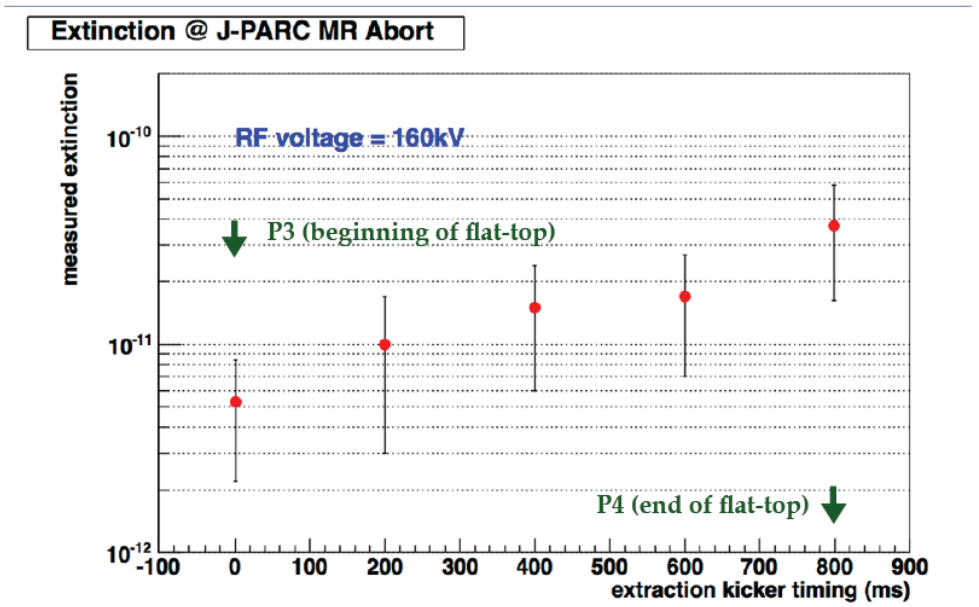
Measured by COMET-G
from Nishiguchi's slide

Extinction for fast-extracted beam at 8GeV

RF voltage dependence



Extraction timing dependence



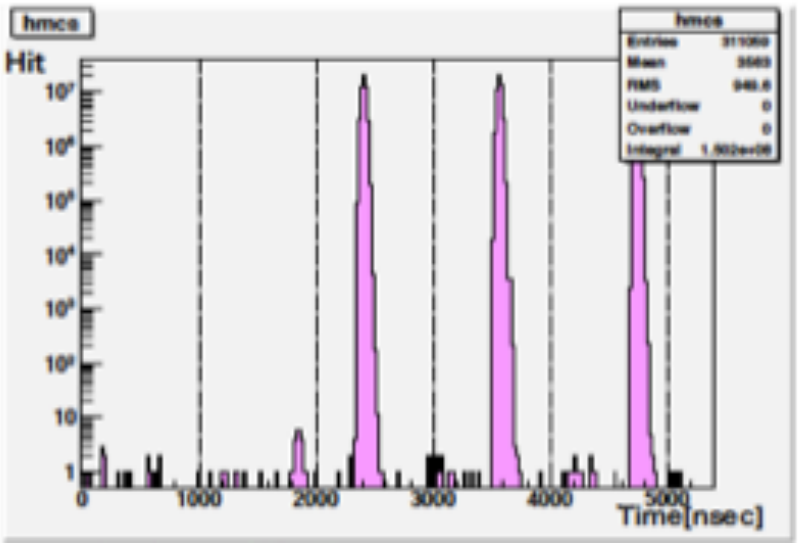
Measured by COMET-G
from Nishiguchi's slide

Extinction Measurement for 30GeV Slow Extraction

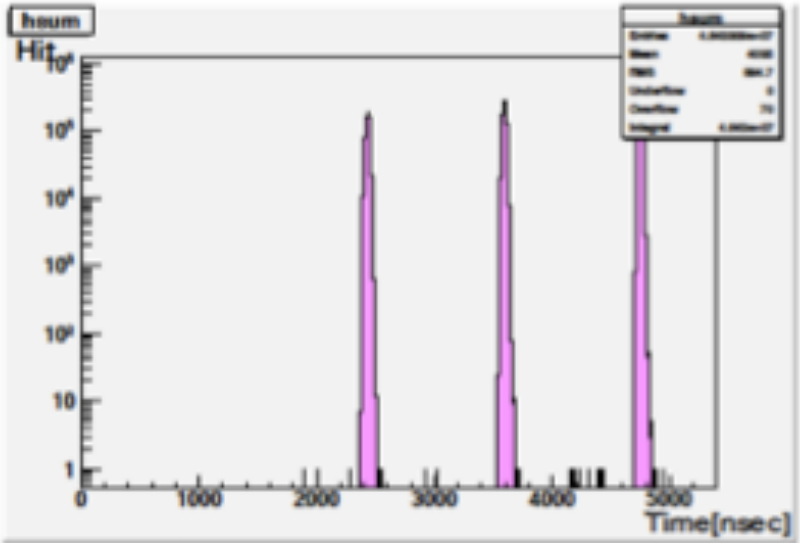
(w/o kicker delay)

Measured by COMET-G
from Nakai's slide

MCS data
Hodoscope & TOF1



Multi-stop TDC data
Hodoscope & TOF1&TOF2



Main protons 1.5×10^{8}
Leaked protons 81
Extinction $5.4 \pm 0.6 \times 10^{-7}$

Main protons 1.5×10^{7}
Leaked protons 15
Extinction $3.3 \pm 0.8 \times 10^{-7}$

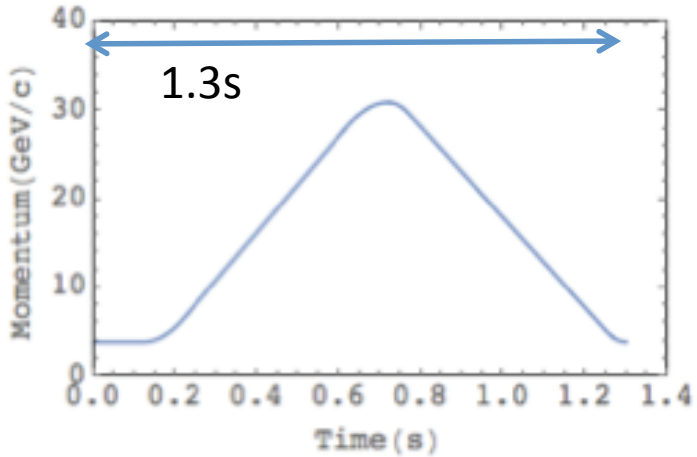
The data suggest the main source is residual beam from RCS by w/o kicker delay.

Phase II Parameters (Very Preliminary)

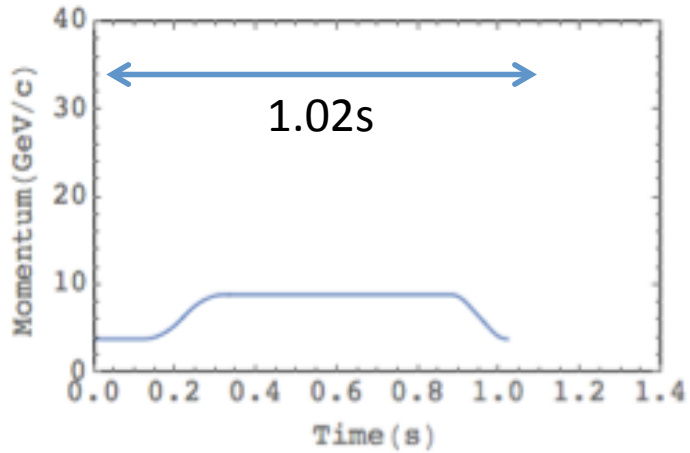
	Phase I		phase II	
Beam Power @8GeV	3.2kW	->	56kW	(x17.5)
MR rep. rate	2.48 s	->	1.0	High rep. power supply
particles number (TP)	1.6		11.3	
Long.-emittance(eVs)	6	->	12	VHF cavity
Bunching factor @ 8GeV	0.1	->	0.2	2nd harmonic RF and manipulation
8GeV-rms-Emittance	1	->	2.6	Large aperture septa and QDT quadrupole
tune shift @ 8GeV	~0.02	->	~0.027	

Dynamic Collimator to eliminate halo during MR acceleration

30 GeV high rep. pattern for neutrino



8 GeV high rep. pattern for COMET Phase II



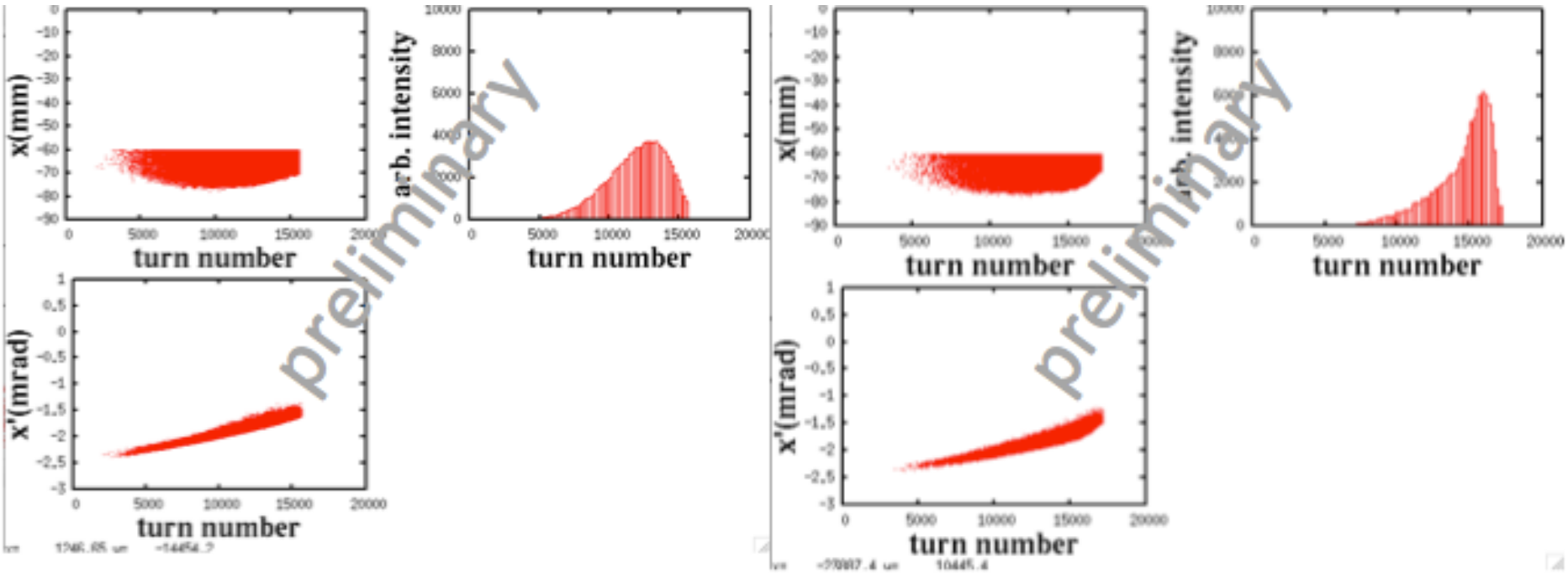
Space Charge Simulation for Phase II Slow Extraction

PTC-ORBIT on KEK super computer

Resonant sextupole and bump orbit are tuned for phase II large beam size
Extracted spill is not regulated to have a flat intensity
RF voltage is reduced to 100kV to get a high bunching factor (0.18)
instead of introducing 2nd harmonic

0.016TP /bunch
ESS1 entrance

11.3TP /bunch
ESS1 entrance



Serious problem on the slow extraction due to the space charge force is not seen.